STUDY AND DESIGN OF ION BEAM PRODUCTION DEVICES FOR THE SPES PROJECT

Coordinator: Ch.mo Prof. Paolo Colombo
Supervisor: Ch.mo Prof. Giovanni Meneghetti
Co-Supervisor: Dr. Alberto Andrighetto

Ph.D. Student: Massimo Rossignoli
To my family
Contents

Introduction ......................................................................................................................... 1

Chapter 1 - SPES project: the Isotope Separation On-Line (ISOL) facility at LNL .... 3
1.1 Introduction .................................................................................................................. 3
1.2 Radioactive Ion Beams (RIBs) applications ............................................................... 5
   1.2.1 Physics of solid state .......................................................................................... 5
   1.2.2 Nuclear astrophysics ....................................................................................... 6
   1.2.3 Nuclear medicine ............................................................................................ 6
1.3 RIB production: ISOL and “in-flight” techniques ...................................................... 7
   1.3.1 Type of nuclear reactions ............................................................................... 7
   1.3.2 “In Flight” separation technique .................................................................... 8
   1.3.3 The Isotope Separation On-Line (ISOL) technique ....................................... 8
1.4 SPES Project: ISOL facility at LNL .......................................................................... 11
   1.4.1 Introduction ...................................................................................................... 11
   1.4.1 The primary driver: cyclotron ....................................................................... 12
   1.4.2 Target Ion Source Unit (TIS) .......................................................................... 13
       1.4.2.1 Surface Ion Source .................................................................................. 15
       1.4.2.2 Laser Ion Source .................................................................................... 16
       1.4.2.3 Plasma Ion Source ................................................................................. 16
   1.4.3 Front End and beam transport devices ......................................................... 17
   1.4.4 Post-acceleration ............................................................................................. 18
1.5 Conclusion ................................................................................................................... 19

Chapter 2 – Laser Front End design ............................................................................. 23
2.1 Introduction ................................................................................................................ 23
2.2 Resonant Laser Ionization technique (RILIS) .......................................................... 23
   2.2.1 Photoionization .............................................................................................. 23
   2.2.2 Contaminants in the RILIS technique ........................................................... 24
3.3.3.1 Emittance and Twiss parameters .......................................................... 97
3.3.3.2 Numerical-Experimental beam transport data comparison .................. 98
3.4 Preliminary optimization of the ratio R/a .................................................... 101
  3.4.1 Experimental test .................................................................................. 106
3.5 Conclusion .................................................................................................. 110

Chapter 4 – Preliminary design of vacuum and gas recovery systems ............ 113
4.1 Introduction .................................................................................................. 113
4.2 Vacuum technology .................................................................................... 114
  4.2.1 Laminar, Knudsen and Molecular flows ................................................ 115
  4.2.2 Gas Flow through pipes: conductance equations .................................... 116
    4.2.2.1 Continuous flow ............................................................................. 117
    4.2.2.2 Molecular flow ............................................................................. 118
    4.2.2.3 Knudsen flow .............................................................................. 119
4.3 Low-vacuum line design .......................................................................... 120
  4.3.1 Vacuum layout of the off-line Front End ................................................ 121
  4.3.2 Design and installation of the low-vacuum line ..................................... 123
  4.3.1 Experimental test of the low-pressure vacuum line ............................... 127
  4.3.2 Pumps failure testing ........................................................................... 130
4.4 Gas Recovery System design ..................................................................... 136
  4.4.1 Experimental test of the Gas Recovery System ..................................... 137
  4.4.2 Preliminary layout of the vacuum and gas recovery systems ............... 142
4.5 Conclusion .................................................................................................. 144

Chapter 5 – Flexible transmission joint re-design ............................................ 147
5.1 Introduction .................................................................................................. 147
5.2 Joint installation and fatigue failure description ....................................... 148
5.3 Analysis of the material ............................................................................ 153
5.4 Coil geometry analysis .............................................................................. 155
5.5 Experimental tests: torque and strain gauge measurements .................... 156
  5.5.1 Load cell design for torque measurements .......................................... 156
Contents

5.5.1.1 Finite Element Model of the load cell .................................................. 158
5.5.1.2 Load cell calibration ........................................................................... 161
5.5.2 Strain gauge acquisition ........................................................................ 164

5.6 Finite Element Model of the joint ............................................................... 171
5.7 Fatigue analysis and joint re-design ............................................................. 175
5.8 Conclusion ................................................................................................. 179

Chapter 6 - Conclusion ................................................................................... 183

APPENDIX A - APDL commands .................................................................. 185
APDL commands referred to the finite element model of §2.4.3 ..................... 185
APDL commands referred to the finite element model of §2.5.3 ..................... 191
APDL commands referred to the finite element model of §5.6 ......................... 203
Introduction

The structure of matter and the fundamental lows of nature have always marked the interest of the nuclear physics community, especially in the understanding of the atomic nucleus stability. The knowledge of how the fundamental particles behave is besides leading a strong development of applied science, with the consequent improvement or invention of useful technologies in industry, medicine and scientific research.

European Council for Nuclear Research, CERN (Geneva – Swiss) is the most important nuclear physic laboratory, which houses the world’s largest and most complex scientific instruments devoted to these purposes. In Italy, from the mid-twentieth century and especially in the recent decades, the National Institute of Nuclear Physics (INFN) became one of the main members, participating with shared activities and offering new projects of interest. At Legnaro National Laboratory (INFN-LNL, Padua, Italy), the SPES project, ie Selective Production of Exotic Species, is the flagship of INFN under development and construction, which has the goal to produce pure radioactive ion beams in the neutron rich side of the so-called “valley of stability”. The construction of the SPES facility involves multidisciplinary teams and worldwide collaborations as the University of Padua (Italy), Laboratory for Emerging Nanometrology (LENA, Germany), Isotope Separator On Line Device project (ISOLDE-CERN, Swiss), Oak Ridge National Laboratory (ORNL, USA) and iThemba LAB (South Africa).

The ion-sources dedicated to the production of Radioactive Ion Beams (RIB) have to be highly efficient, selective (to reduce the isobar contamination) and fast (to limit the decay losses of short-lived isotopes). For radioactive beam generation the source must operate steadily for extended periods of time at elevated temperatures (up to 2000°C). The selection of the most appropriate choice for the target/ion source is of paramount importance since its performance determines the intensity, the beam quality, and the number of radioactive beams that can be provided for experimental use. The world wide spread RIB facilities came up with a large variety of solutions to meet part or all of these requirements such as: surface, plasma, electron cyclotron resonance and laser ion-sources. The latter, which is based on the Resonant Laser Ionization (RLI) technique is fundamental in the ISOL facility due principally to the high ionization efficiency can be obtained and to the high mass-selectivity of the process. Nowadays, many letters of intent have allowed many agreements between
Introduction

LNL-INFN and other facilities or users, which increasingly require this kind of ion beams for newly application in many scientific fields. As provided by the pie chart below, the wide number of radioactive ion beams will be produced in the context of the SPES project by laser technique justifies the intense research effort aimed to improvements and optimization of the laser ion source.

![Pie chart showing RIBs vs Ion Source](image)

Number of SPES Radioactive Ion Beams produced by different ion sources.

Its selectivity, namely the low production rate of unwanted species, is strongly affected by the surface ionization mechanism, which occurs since both laser and surface ion sources share same components where the ionization process takes place. The production of pure beams and the knowledge of its efficiency in the context of ISOL facilities, is the most important aspect on which the research activities are actually focused. For these reasons, the main goal of the work here presented was the development of a test bench, called Laser Front End, which allows estimating the ionization efficiency of the laser in absence of contaminants and thus providing essential information for the future on-line tests. Beside the Laser Front End, ancillary devices for its construction have been designed, developed, constructed and finally tested.

Chapter 1 gives a general overview of the ISOL facilities, their applications and a general overview of the SPES project. Chapter 2 will present the design of the Laser Front End, with particular attention to the Knudsen cell design aimed to estimate the laser ionization efficiency. Then, in Chapter 3, the re-design of the quadrupole triplet for the ion beam transport will be provided, whereas in Chapter 4 the preliminary design of both vacuum and gas recovery systems are described. Finally, Chapter 5 provides the study, the test and the re-design of a commercial flexible transmission joint on which fatigue failure occurred despite compliance with installation recommendations had been assured.
Chapter 1

SPES project: the Isotope Separation On-Line (ISOL) facility at LNL

1.1 Introduction

The structure of matter is strictly connected to the atoms it is mainly made of, their interactions and arrangement in the space. In the nucleus of atoms, the nucleons, protons (positively charged) and neutrons (electrically neutral), compose the near-total mass of the atoms, while the electrons bound to the nucleus and with the same but negative charge of the protons led to a global electrical equilibrium. The Strong Interaction between nucleons guarantees the nucleus stability opposing to the Coulumbian repulsion of like charges protons. The strong nuclear force holds the matter together binding neutrons and protons. It follows a high energy is required to overcome this force and brake the nucleus of the atoms. The complex branch of physics involved in the study of these aspects is therefore the nuclear physic.

Stable atoms, which means they are not radioactive, have the same number of protons (Z) and neutrons (N), as shown in the chart of nuclides in Fig. 1.1 by means of the black squares (“valley of stability”). For atomic masses greater than 40, the nuclear interaction

![Fig. 1.1. Chart of the nuclides [1.1].](image)
become stronger with respect to the Coulumbian repulsion since the higher number of nucleons in the nucleus and the stable region in the chart moves to the neutron rich side. Contrary, with a further increasing of the atomic mass, the nucleus dimension rises, the nuclear interaction efficiency decreases and the stable region is shifted in the proton rich side.

In the nuclides chart, beside the “valley of stability”, there are two different areas where isotopes are protons and neutrons rich, respectively (Fig. 1.1). The latter are strongly unstable and the emissions of radioactive particles and electromagnetic radiations, as a consequence of the natural decay into different elements, make these nuclides of wide interest in the nuclear research.

The types of decays are fundamentally four [1.2]:

- Alpha decay: typically related to atoms with atomic mass $Z > 83$, it consist in the emission of an alpha particle identical to an helium nucleus (2 protons and 2 neutrons). Thus, the alpha decay process results in a reduction of both atomic mass ($A$) and proton number ($Z$) according to: $Z_D = Z - 2$; $A_D = A - 2$, where $Z_D$ and $A_D$ are referred to the atom after decay (see yellow area in Fig. 1.1).

- Beta decay: it corresponds to isotopes in the blue ($\beta^-$ decay) and red ($\beta^+$ decay) areas (Fig. 1.1). In the first case, neutron rich nuclides lose neutrons reaching the stable region. For each neutron, a proton is generated with the emission of one antineutrino and one electron ($\beta^-$), assuring therefore the equilibrium in terms of mass and charge. In the second case, instead, atoms with an excess of protons move towards the “valley of stability” converting a proton into a neutron with the relative emission of one neutrino and one positron ($\beta^+$).

- Spontaneous fission: the atoms of this category are represented by green squares in Fig. 1.1. Since their heavy mass, they naturally tend to brake the nucleus in two large mass fragments with a high energy emitted by the reactions. An example is the Californium $^{252}$Cf.

- Gamma ray emission: this phenomenon consists in the emission of high frequency electromagnetic radiation simultaneously or subsequently the decay processes described above and due to the exited status of the newly forming isotopes.

Even though many unstable isotopes have been studied and their nuclear properties have been characterized, in many facilities in the research institutes around the world it is
theoretically assessed the existence of more than 6000 “exotic nuclei” confined by the driplines in Fig. 1.1. There are then many unknown isotopes to be discovered and to be studied, especially in the neutron rich area. The nuclear research activities aim to produce Radioactive Ion Beams (RIBs) starting from the knowledge of the isotopes far from the “valley of stability”, leading thus to refine applications and technologies useful in many fields as the nuclear physics, physics of solid state, nuclear astrophysics and nuclear medicine.

### 1.2 Radioactive Ion Beams (RIBs) applications [1.3]

At present all over the world, facilities provide the production of radioactive ion beams with the purpose to study isotopes far from the stable conditions. Due to the ease with which they can be produced, up to now the most commons research activities are focused on unstable nuclei, which are close the “valley of stability”, or in other words, with a proton-to-neutron ratio not so different with the respect to the stable atoms. The models thus developed have been adapted to describe the atomic nucleus in the neutron-rich region (see nuclides chart in Fig. 1.1) but the unknown region exploration permitted by the recent experiments and studies confirms that some of the basis of the nuclear physics have to be redrafted. The “liquid drop model” developed by Niels Bohr and John Archibald Wheeler is one of the most clear example which shows the error committed in the evaluation of the atomic nucleus radius, described according to $R=R_0A^{1/3}$, where $R$ is a constant and $A$ the atomic mass. Some atoms, in fact, have nuclear radii larger than that predicted by the liquid drop model because of the presence of one or two nucleons that orbiting around the core: they are called Halo nuclei and they are discovered in the mid-1980s.

Radioactive Ion Beams (RIBs) are nowadays useful in nuclear spectroscopy, physics of super heavy elements and other topics. Moreover, the capability to produce pure ion beam lays the foundation for the introduction of new applications also in the nuclear astrophysics, solid-state physics and nuclear medicine.

#### 1.2.1 Physics of solid state

Radioactive ion beams are a powerful diagnostic tool to provide information about the environment in which they are implanted [1.4]. The Emission Channeling technique is one of the applications that uses this property to study the combination of impurities and defects in solid, especially in semiconductor where defect play an important role in their functioning.
Once the radioactive ions has be implanted in the crystal, the movements and the emission (α or β particles) of the charged particles can be monitored by means a 2-dimensional position sensitive detector. The distribution of the radiation intensity is in fact strongly influenced by the orientation of the host crystal and the position occupied by the radioactive ion can be thus determined. The technique described is useful in the study of the semiconductor doping.

### 1.2.2 Nuclear astrophysics

Nuclear astrophysics is a fundamental branch of science involved in the understanding of the dynamic evolution of the Universe. One of the main phenomena, which therefore describes the endless process of the cosmos, is the stars formation [1.5]. The latter is characterized by nuclear reactions between stable and unstable atoms with a high-energy release, as an example the so-called CNO cycle (CNO stands for Carbon-Nitrogen-Oxygen). Nucleosynthesis, namely the element formation processes in the stars life, is a combination of reactions arise close to the “valley of stability” and many others unidentified occur in an untapped region of the nuclides chart. It follows that radioactive ion beams can provide the information to describe these reactions and permit theoretical models development for the Universe comprehension. Moreover, the experimental test using RIBs are also useful to verify models already developed and nowadays accepted by the scientific community since they currently are the only way to measure the properties of unstable nuclei.

### 1.2.3 Nuclear medicine

In nuclear medicine, the use of radioactive isotopes can be applied for diagnosis and treatment of human disease. Positron Emission Tomography (PET) is a medicine imagine technique that reveals the functional processes in a three-dimensional image, useful mainly in clinical oncology, especially in the searching of tumours, metastases and brain diseases in neuroscience. Generally, short half-life isotopes such as $^{11}\text{C}$, $^{13}\text{N}$, $^{15}\text{O}$, $^{18}\text{F}$ are commonly used for this application. The radionuclides are introduced intravenously bounded to glucose, water, ammonia or to different molecules involved in the functional processes of interest. While the positron emitted during the β+ decay has the same mass of an electron, the electric charge is $+1\text{e}$ and when a collision with an electron takes place the result of the annihilation is the production of gamma rays travel in the opposite direction. Different scintillators combined in a diagnostic device detect and localize the photons, providing to describe the area of interest with a proper image.
1.3 RIB production: ISOL and “in-flight” techniques

1.3.1 Type of nuclear reactions

Before giving a description of the two main RIBs production techniques, the main types of the nuclear reactions are listed and briefly outlined as following:

- Fission: it consists in the nucleus fission of heavy atoms obtaining several, smaller and similar in mass fragment products, typically in the range of 80 and 150 amu. The sum of the fission products is less than the original mass since few neutrons are emitted and other mass converted in energy.

- Spallation: here, the nuclear reactions occurs when energetic particles as protons, neutrons interact with an atomic nucleus. In the first stage, the primary particle reacts with the nucleus and due to this interaction some of energetic particles are emitted; in the second step, low-energy particles (neutrons, protons and alpha particles) are emitted since the relaxation of the nucleus in the evaporation process. The results is the production of proton rich isotopes.

- Fragmentation: as the name refers, fragmentation is the production of several smaller nuclei (fragment) after the decay of a starting nucleus. This reaction can be obtained by bombarding a target with a primary beam of few GeV of energy composed by small particles with small nuclei, or through the collision of one particle that impinges two nuclei have nearly the same mass. The process allows the production of a wide range of isotopes.

- Fusion Evaporation reactions: it is a common method to produce highly exited nuclei starting from two stable atoms and a certain amount of energy sufficient to overtake the Coulomb repulsion. Proton rich species are then produced since the process evaporates nucleons with the consequent gamma ray emission due to the system decay.

The main aspects related to the production of radioactive isotopes far from the stability and useful to the applications mentioned in the previous paragraphs are:

- The cross section of the reaction, called yield, which have to be low in order to produce the requested nuclei.

- The presence of contamination that influences the purity of the beam with additional undesired isotopes.
• The half-live of the nuclei, which has to be short respect to all the process in the path from the release of the nuclei (production) to the experiment station (experiments).

The two techniques permit to obtain exotic beams of a good quality are the “In Flight” separation technique and the “Isotope Separation On-Line (ISOL)” technique. Since the nuclear reaction cannot provides isotopes of a single species, after the production phase a series of devices arranged along the beam line allow to purify, energize and “shape” the exotic ion beam until the experimental station, usually far from the production zone also for the intensity of the radiation that can influenced the measurements and the devices integrity.

1.3.2 “In Flight” separation technique [1.6]

In this technique, a primary beam made of heavy ions impinge on a light mass target generating desired radioactive nuclei, which will constitute the secondary beam. In other words the primary beam. The products of the primary beam fragmentation are first selected in mass by means an electro-magnetic separator and subsequently accelerated-transported for the experimental activities. The energy of the primary beam is in the order of tens of mega-electron-volts per nucleons; nevertheless, the nuclear reaction products and the impinging nuclei typically show the same energy. The optical elements have to provide a proper suppression of the primary beam that collides with the target and performs an adequate separation of the secondary beam, guaranteeing a good quality of the accelerated species.

The aforementioned technique is usually implemented in existing heavy-ion accelerators and allows obtaining isotopes close to the “valley of stability” without limitations due to lifetime or chemical properties. Despite these considerations, the weaknesses of the present technique are the difficulty in the high quality beam production along with the low number of ion species that can be obtained.

1.3.3 The Isotope Separation On-Line (ISOL) technique [1.7], [1.8]

In the Isotope Separation On-Line technique, the radioactive isotopes are produced in a solid, liquid or gaseous target on which the primary beam impinged. The nuclides are then transported to the ion source (usually close to the target), where they lose an electron becoming $+1e$ charged permitting thus to extract the ions by means an extraction system.
The different exotic species are selected by using a dipole magnet and then post-accelerated to reach the required energy (Fig. 1.1). The entire process, from the production to the acceleration stage, have to be:

- **Efficient**: efficiency can be defined as the capability of the entire system to limits the isotopes losses after the production stage until the acceleration phase and usually it is affected by both the thermal state of the main target components and the extraction-transportation steps.

- **Fast**: since the different species produced are exotic isotopes with a specific half-live, it is important to reduce the time the particles take to reach the experimental room along with losses due to the decay processes.

- **Selective**: in the production phase, radioactive isotopes are produced from the target material itself or from other components of the target unit. The result is a wide presence of contaminants, namely different unwanted isotopes have to be removed from the exotic ion beam to be used.

Moreover, the selection of the target material determines the highest energy of the primary beam allows increasing the production rate of the exotic species and at the same time preserving the integrity of the target and those ancillary components under the power of the primary beam.

The use of the ISOL technique required the construction of the so-called ISOL **facility** [1.9], in order to produce pure beam of high energy and intensity. Fig. 1.2 shows the arrangement of the main devices at the basis of typical facilities constructed in Europe and all over the word. As in the figure below, the layout of the devices of an ISOL facility are:

![ISOL Facility Scheme](image)

Fig. 1.2. ISOL facility scheme.
Chapter 1

- The primary driver.
- The Target Unit System (TIS).
- The Front End (Low Energy Beam Transport system).
- Mass separators as dipole magnets.
- Post accelerator.

Despite small changes can be performed in the arrangement of the devices, an important parameter regards the production rate that occurs in the target is the beam intensity, which can be estimated by the following equation:

\[ I_{\text{reaction-products}} = \sigma N_{\text{target}} \Phi \varepsilon_1 \varepsilon_2 \varepsilon_3 \]  \hspace{1cm} (1.1)

Where:

- \( \sigma \) is the cross section provides the probability that certain nuclear reaction occurs [cm\(^2\)].
- \( \Phi \) is the primary beam intensity.
- \( N_{\text{target}} \) is the number of atoms per surface area [cm\(^2\)].
- \( \varepsilon_1 \) is the target release efficiency.
- \( \varepsilon_2 \) is the ionization efficiency of the ion source.
- \( \varepsilon_3 \) is the extraction system and beam transport efficiency.

As the aforementioned equation suggests, the target system, along with the ion source and the extraction system have to be well coupled because it is the core of an ISOL facility that determines its performances. Moreover, both the exotic species releasing occurs in the target system and the following extraction are temperature dependent processes. In fact, as the overall thermal level rises, the particles diffusion increases and this affects principally the species with a short half-life. Reducing the release and extraction time, the probability to lose atoms due to the natural decay is minimized. Maintain the target unit components at the highest temperature is thus become a challenge that involves various disciplines. The technological limits together with the RIBs scientific interest were followed by the construction of many ISOL facilities in Europe with the goal to develop an European ISOL facility called EURISOL. In the Legnaro National Laboratory (LNL), one of the seven laboratories of the National Institute of Nuclear Physic (INFN – Italy) is ongoing the construction of an ISOL facility with the aim to produce radioactive ion beams with
consistently high quality than those nowadays available. In the next paragraph a description of the main ISOL facility devices above aforementioned will be described in reference to the SPES project (Selective Production of Exotic Species) at LNL-INFN.

1.4 SPES Project: ISOL facility at LNL

1.4.1 Introduction

The Selective Production of Exotic Species (SPES) is a multidisciplinary project actually in the construction phase at LNL-INF (Legnaro, Padua – Italy). The project is essentially divided in four phases, each one related to different applications:

- **SPES-α:** this phase, nowadays in the last stage, consists in the installation of a cyclotron with high energy and current intensity (~0.7 mA, 70 MeV). The cyclotron will provide the production of two different proton beams, one for the applied physics studies and the other for the production of neutron rich isotopes.

- **SPES-β:** here, neutron rich species will be focused on different targets and the nuclear reaction products, which have a short half-life, will be studied to extend the knowledge regards the star life cycle and the Universe formation.

- **SPES-γ:** the proposal of this phase is to produce exotic nuclei of medical interest that can be adopted in the radiopharmaceutical sector. Innovative radiopharmaceuticals will be produces using nuclear species as Sr-82/Rb-82 and Ga-68/Ge-68).

- **SPES-δ:** a neutrons source, coming from the cyclotron or from a linear accelerator based on the *radio-frequency quadrupole technology* (RFQ) will be used in the experimental treatment of tumours, nuclear waste characterization and more generally in the astrophysical studies.

The SPES facility is thus mainly devoted to the production of neutron-rich isotopes with masses in the range 80-160 amu by impinging the high-energy proton beam (40 MeV) on seven uranium carbide (UC₆) disks. Since the highly radioactive environment close to the production zone, an appropriate building has to ensure the health and safety compliance during the operations. In Fig. 1.3, the SPES beam facility along with the main apparatus will be installed are illustrated. On the right side of the 2D CAD drawing, the large thickness of the concrete walls for the radioprotection aspects can be appreciated.
1.4.1 The primary driver: cyclotron

The primary driver, already installed in the new SPES building (Fig. 1.4), allows the production of a high-energy proton beam (max 70 MeV – 49 kW) properly focused onto the uranium carbide disks, which are hosted in the target unit system. It is a 70p commercial cyclotron [1.10] of the BEST Cyclotron System Inc. (TeamBest™) and it accelerates, by means a radio frequency (RF) system, the negative hydrogen into a beam current of a maximum 15-20 mA, produced in a multi-cusp ion source. The magnet, which has a 200 tons mass, provides a magnetic field fixed to 1.6 T. The conditioning of the machine, namely the process to reach the nominally working condition, is highly dependent on the vacuum level inside the tank, which is in the order of $10^{-7}$ mbar because of the cryogenic pumps installed on the cyclotron.
1.4.2 Target Ion Source Unit (TIS)

The production target, as the ionization and extraction systems, are installed in a target chamber (Fig. 1.5a), properly water cooled due to the high power deposition. Moreover, to avoid the components oxidation since the high temperature reached, the pressure level inside the chamber has to be lower as possible (~10⁻⁶ mbar) and this condition is guaranteed by using vacuum pumps. As shown in Fig. 1.5b, the target is composed by seven uranium carbide disks, which have a diameter of 40 mm and approximately 1 mm thickness and they are not equally spaced in order to dissipate properly the primary beam power by thermal radiation. All the disks are houses in a graphite tube with an external diameter and a length of 40 mm and 200 mm, respectively.

The proton beam, before to collide with the uranium carbide, passes through two thin graphite windows that have both to shield the external UCₓ disk maintaining the proper temperature and to limit the contamination of the adjacent zones. Similarly, after the nuclear reaction, the proton beam stops against three graphite dumper s, which dissipate the last part of the primary beam power and avoid radioactive products leaks.

![Fig. 1.5. a) Target chamber and main components; b) illustration of the target system and the UCₓ disks.](image)

The target box is maintained at about 2200 °C to improve the diffusion process of the exotic nuclei. In order to reach the required temperature, beside the use of the primary beam, an additional heating system is integrated in the target unit complex. The heater (Fig. 1.5b) permits also to assure the uniformity of the temperature during unexpected cyclotron shut downs, preserving the disks integrity. It is made of a tantalum tube, at whose edges two tantalum wings are welded. Tantalum, in fact, is a corrosion-resistant material with good characteristics in terms of electrical conduction and thermal resistance. With two copper clamps, the electrical power can be supplied in the electrical circuit thus created and the thermal condition could be controlled by Joule effect.

After the nuclear fissions, the exotic nuclei diffuse in the transfer line reaching the ion
source, where they lose one electron. The transfer line is a tantalum tube welded to the tantalum box at one edge and mechanically fixed to the ion source on the opposite end. Both the transfer line and the ion source are parts of a second electrical circuit heated by Joule effect in order to promote the atoms diffusion and at the same time avoid particle sticking on the cold spot, which otherwise would exist.

The type of the ion source adopted is strongly influenced by the ionization potential of the species of interest as Fig. 1.6 shows. The ionization potential can be defined as the energy required to remove an electron from a neutral atom and if we are removing the first electron from the first shell it can be noted as first ionization potential. The three ion sources developed for the SPES project are the Surface Ion Source (SIS) [1.11], the Laser Ion Source (LIS) [1.12] and the Plasma Ion Source (PIS) [1.13]. In the next part of this chapter, a detailed description of the different ion sources will be presented.

Between the target chamber and the Front End, which is the whole machine for the low
energy beam transport, the potential difference of 40 kV extracts the ions from the small hole at the end of the ion source to the ground electrode made of Ti₆Al₄V alloy (Fig. 1.5a). In the Front End, the first species selection occurs and the main exotic isotopes will be produced in the context of the SPES project are represented in Fig. 1.7.

**1.4.2.1 Surface Ion Source**

In this type of ion source, the atoms ionization is promoted by the interaction between the particles and the inner surface of the hot cavity as shown in Fig. 1.8a and the efficiency of the process is a function of both the hot cavity material and the temperature. The work function of the material, \( W \), namely the minimum energy necessary to remove an electron from its surface, has to be higher than the ionization potential of the exotic species in the production on positive ions. The temperature of the ion source also affect the efficiency of the process and actually 2200 °C is the technological limit reached. These two aspects confine the material selection to few metals such as rhenium (\( W = 5 \) eV), tantalum and tungsten; the ionization process is efficiently performed but thus restricted to the periodic table group I and II elements.

The hot cavity is essentially a small tube of an internal and external diameter of 2.8 mm and 5.1 mm, respectively. On one side, the ion source is hold by the transfer line and in the other by a tantalum support, with a total length of 28 mm. Since the small dimension, adequate alignment between the ion source and the extraction system axes is required to
accelerate the particles in the straight-line direction, thereby facilitating the optical device setup.

### 1.4.2.2 Laser Ion Source

This method is one of the most used ionization technique leading an extremely pure ion beam. The atoms arrive in the ion cavity (the same of the surface ion source) where one up to four laser (photons), with a precise energy lever corresponding to the element of interest, are focused. The laser thus remove an electron only from the corresponding atoms and therefore is very selective. A schematic representation of both laser and surface ion sources are shown in Fig. 1.8. Since the hot cavity is at high temperature, the ions coming from the surface ionization process is the main contamination in the laser technique.

![Image of laser ion source](image)

**Fig. 1.8. a) Surface Ion Source (SIS); b) Laser Ion Source (RILIS)**

### 1.4.2.3 Plasma Ion Source

The plasma ion source in Fig. 1.9 is essentially based on the FEBIAD technique

![Image of plasma ion source](image)

**Fig. 1.9. Cross section of the Plasma Ion Source (PIS).**
SPES project: the Isotope Separation On-Line (ISOL) facility at LNL

(Forced Electron Beam Induced Discharge), where ions are produced in the collision between the atoms and electrons generated and accelerated by thermionic effect. A cathode is heated by Joule effect by a direct current of 330-340 A, reaching thus the required temperature inducing the electrons emission by the cathode. A potential different of 150 V then accelerates the electrons in the anode, where the ionization takes place. It is a very unselective method, often used to create multiply charged ions or to ionize the species which require high ionization energy (noble gases and halogens).

1.4.3 Front End and beam transport devices

The ion beam, once it has been extracted and accelerated, needs to be controlled, focused and preliminary purified in a complex machine called Front End, as shown in Fig. 1.10.

Fig. 1.10. a) Main devices of the SPES Front End; b) Front end installed in the off-line laboratory.
Since the possible misalignment between the ion source and the extractor, the ion beam could deflect respect to the theoretical path, which is coincident with the Front End axis. For this reason, in the first stage a set of four steerers are adopted. They consists in a pair of cylindrical plates at high voltage, usually one with a positive potential and the other with a negative potential. The electric field so generated surrounds the ions coming from the extractor, allowing the beam trajectory adjustment. Using four steerers it is possible to perform correction in the four Cartesian directions (left, right, up and down considering the direction of the ion beam). The other significant reason to reach the proper beam alignment is that the optical devices performances (electrostatic lenses and mass separator) are extremely influenced by this condition.

The electrostatic device that follows the steerers complex is usually a quadrupole triplet. A detailed description will be presented in Chapter 1 along with the re-design of this optical element. It is essentially a combination of three set of four cylindrical electrodes at high voltage, which create an electrical field able to control the beam size along the beam line.

The last stage in the Front End is the purification of the beam performed by means a Wien Filter. The resolution of the mass separator, $\Delta M/M$, where $M$ is the isotope mass, is $1/300$.

### 1.4.4 Post-acceleration

The beam leaves the Front End out of the bunker (Fig. 1.3) and it is injected into a Beam Cooler (BC) that reduces the beam emittance, a parameter describes the beam shape quality.

![Fig. 1.11. (Left) Portion of the ALPI linac at LNL; (Right) the interior of a cryostat, lodging 4 accelerating, high purity copper-based, cavities is shown (cavity inner surface is covered by a niobium layer).](#)
The following step is the purification of the beam from unwanted isobar masses by means the High Resolution Mass Spectrometer (HRMS). Now the ion beam could be delivered to the low energy experiments or it can be sent to the Charge Breeder, where its charge state is increased. After another mass separation that occurs in the Medium Resolution Mass Spectrometer (MRMS), the beam is injected into a Radio Frequency Quadrupole (RFQ) and finally accelerated in the ALPI Linac, which is represented in Fig. 1.11.

### 1.5 Conclusion

In this chapter the features of the SPES project and more generally of an ISOL facility were presented together with the main applications of a Radioactive Ion Beam in the nuclear medicine, solid state physics and astrophysics research. A detailed description of an ISOL facility was given and introduces the studies performed in the next chapters regarding the construction of a Laser Front End, in order to determine the efficiency of the laser ionization technique. Along with the latter, different devices and apparatus, as the vacuum system, the quadrupole triplet and a flexible transmission joint will be studied, re-designed and tested to answer to the radioactive environment requirements.
References

Chapter 2

Laser Front End design

2.1 Introduction

The Resonant Laser Ionization (RLI) technique is fundamental in the ISOL facility due principally to the high ionization efficiency can be obtained and to the high mass-selectivity of the process. As briefly explained in §1.4.2.2, the laser technique is performed with the using of the surface ion source hot cavity, which introduces contaminants of undesired species. In this respect, at LNL is ongoing the development of the Laser Front End, a system based on the Time of Flight (ToF) mass spectrometry, to understand how Resonant Ionization Ion Source (RILIS)[2.1] behaves by means an estimation of its efficiency. The latter will be useful when the first ion beam will be produced in the SPES facility. Therefore, a Knudsen cell system, which provides controlled atoms effusion of the species of interest, was designed and finally tested. Ancillary devices as the alignment-support and extraction systems completed the design of the Laser Front End chamber, permitting thus to conduct the first experimental test. This chapter comprises the description of all the study, design phases and tests that have brought the initial idea to the final construction of this apparatus.

2.2 Resonant Laser Ionization technique (RILIS)

2.2.1 Photoionization

The lasers used for the ionization and based on this technique are usually a combination of one up to four different photons lasers with a wavelengths corresponding to different energetic levels. The monochromatic energy photon, \( E \), follows the Planck’s law:

\[
E = h f
\]  
(2.1)

Where:

- \( h \) is the Planck’s constant.
- \( f \) is the wave frequency.
The photoionization pathway (Fig. 2.1) usually involves a photon absorption ladder within the electronic levels of the atom, each step being resonant with the optical transition of the desired atomic species. In this stepwise model, a valence electron is brought or directly to the continuum or to a highly excited Rydberg level in presence of an electric field or to an auto-ionizing state. These latter two techniques, when feasible, have better efficiency. Of course, each optical transition requires a dedicated laser wavelength, i.e. colour. Usually two or three different colours are required for a given chemical element. Using tuneable lasers (solid state or dye or a combination of the two) it is possible to match the photon energy of the laser lights to the electronic transitions of the desired atomic species.

RILIS technique shows particular advantages for the species with an intermediate ionization potential. In fact, low ionization potential elements such as alkali metals can be efficiently ionized by mean the surface ionization method, while halogens, for example, have a high ionization potential such a way making the laser ionization impossible. The latter is significant for the elements in the middle of the periodic table as reported in Fig. 1.6.

### 2.2.2 Contaminants in the RILIS technique

Despite the high selectivity of the laser technique, one of the main criticality concerning those components used to construct the whole apparatus, which are the same used for the surface ion source: in particular, the hot cavity. The latter, provides the surface ionization in the same extraction region where the laser is focused and it severely affects the strengths of
this technique. Nevertheless, different shrewdness can be adopted in order to minimize these contaminants coming from the surface ionization mechanism:

- **Ionization efficiency reduction [2.2].**
  
  The surface ionization process is extremely influence by two main factors: the temperature and the material work function. While a temperature reduction, especially concerning the hot cavity, means a decreasing of the surface ionization, at the same time it corresponds to a lower atoms diffusion. Furthermore, “cold surfaces” could be the cause of particles sticking with a consequent reduction of both surface and laser ionizations. The other preferable way is to study alternative materials for the hot cavity manufacturing. GdB₆ or tungsten with BaO+SrO coating are two solutions well tested at CERN to prove the possibility to change the hot cavity material [2.3]. Despite the excellent results during off-line tests, on-line experiments have been followed by the ions formation inside the target.

- **Spatial separation of the laser and surface ionization products.**

  If the laser ionization were carried out immediately outside the hot cavity, it would be possible to reduce contaminants by using an opportune electrode, positively charged. This solution requires specific electrode design since it could affect the laser ionization if the laser focus is too close to the extraction region.

- **Time separation of the laser and surface ionization products.**

  This method is based on the ToFLIS technique and consists in the use of a beam-gate, which is synchronized with the pulse laser.

- **Polarity inversion in the ion source electrical circuit [2.4][2.5].**

  The hot cavity, together with the transfer line, composes the electrical circuit, which permits to heat components by Joule effect. In agreement to the Ohm’s low, potential drop occurs when the electrical current passes through a resistance. If the electrical potential decreases moving towards the hot cavity hole, then both +1e ions and 1+e contaminants would be accelerated until the extraction system. Contrary, only ions close to the hot cavity exit hole should be accelerated by means the electrical field generated by the extractor. An intermediate configuration that mitigates the disadvantages of the last two solutions is presented in Fig. 2.2. The hot cavity is characterized by a reversed polarity with the respect to the transfer line. This permits to reduce the presence of ions produced in the transfer line accepting, nonetheless, all the species
ionized in the hot cavity. The disadvantage of this system is the introduction of two electrical circuits instead of one, condition often avoided since the not increasing of benefits compared to the complexity of the system.

Fig. 2.2. Hot cavity polarity inversion technique for contaminants reduction.

### 2.3 The Time of Flight chamber at LNL

The most important device of the Laser Front End is the so-called Time of Flight (ToF) chamber. In Fig. 2.3 are shown the main apparatus and its operating principles. The time of flight mass spectrometer technique is based on the measured time that ions take to cover the distance from the acceleration stage until the detector. The acceleration occurs at constant kinetic energy and ions velocity is inversely proportional to their mass; consequently the light mass will take less time to cover the same distance than the heavier masses.

Fig. 2.3. Scheme of the Laser Front End based on the Time of Flight (ToF) mass spectrometer technique.
With reference to Fig. 2.3, to simplify the following discussion, the functioning of the Laser Front End is described: the Knudsen cell, which contains the solid sample of the species to be analyzed, is heated by Joule effect and the sample starts evaporating at a proper temperature. The position of the cell respect to the laser beam is controlled by means an alignment system, which incorporates a special screen to reduce the effusion cone aperture. After the ionization, ions travel until the diagnostic box, where the time is measured. The main three areas characterize the Laser Front End are:

- The production zone: Knudsen cell, alignment system and screen.
- Extraction zone: different grids at high voltage provide to furnish the kinetic energy to the particles equal to the potential energy thus obtained.
- Flight zone: here, ions travel until the diagnostic with a constant velocity.

An example of the spectrum resulted from the analysis is illustrated in Fig. 2.4. The m/z ratio, where m is the mass of the element and z the electric charge, is plotted on the abscissa, while the ordinate represents the intensity of the current. The matter fragmentation processes are a function of the molecules structure and their chemical bonds and ionization energy. The spectrum clearly defines the analyzed species. Despite this fundamentals, the Miller

![Fig. 2.4. Spectrum example results from the time of flight mass spectrometer.](image)

Armatys’s low has to be considered:

- The current intensity of different molecules has almost the same variation along with the temperature.
- The potentials of ions formed by simple ionization are lower than the potentials of fragments obtained from the same neutral precursor.
 Fragmentation processes information can be extracted from the spectrum plot. 
The fragment ions have additional kinetic energy than the ions produced by simple ionization. 
Homologous chemical species show similar fragmentation process.

The vacuum level in this kind of apparatus determines the mean free path of the ions produced inside the chamber. It affects the interaction between the accelerated particles and the residual gas with a consistent effect in the goodness of the results. For this reason, turbomolecular pumps assure a pressure in the order of $10^{-6}$ mbar inside the chamber. All conditions above described were the input to develop a system, namely the Laser Front End, with the aim to estimate the laser ionization efficiency. This purpose required the design of a device where both evaporated atoms quantity and their spatial distribution had to be well known. In the next paragraphs, the design of each system showed in Fig. 2.3 will be deeply described following the sequence listed below:

- Knudsen cell.
- Alignment system and screen.
- Extraction system.
- Time of flight Chamber.
- Laser Front End.

### 2.4 Knudsen cell

The Knudsen cell was developed in the 900 century by Martin H. C. Knudsen in the context of the kinetic theory of gasses. Knudsen has demonstrated the free molecular flow starting from experimental tests which treated low-pressure gasses, thus laying the foundation for the vacuum technique. The extreme low pressure combined to the high temperature required the use of the kinetic theory of gasses, since collisions between particles are lower than those occurs between the atoms and the wall of the vacuum chamber. The mean free path of the molecules is than larger than the size of the chamber [2.6][2.7]. The results were obtained heating a small chamber with a small hole contains a liquid or a solid mass. After the thermodynamic equilibrium between the liquid and the vapour phases was reached, a fraction of the vapours leaked out of the bore. Due to the molecular flow, the probability that a particle directly effusing out of the hole was higher compared to the amount of atoms leaked after the collision with the chamber walls as shown in Fig. 2.5.
The flux through the bore depends on both the temperature and the pressure inside the cell, if the flux itself is smaller respect to the total mass, guaranteeing thus the thermodynamic equilibrium. The latter can be described with the Lambert’s cosine law, considering the direction perpendicular to the outlet surface [2.8]. The number of particles effuse in the time through the hole can be than estimated considering the Hertz – Knudsen equation:

\[
\frac{dn(i)}{dt} = \frac{p \cdot s}{\sqrt{2\pi \cdot PM(i) \cdot RT}}
\]

(2.2)

Where:

- \(dn(i)/dt\) is the total number of particles per unit time [mol/s].
- \(p\) is the pressure inside the Knudsen cell [Pa].
- \(s\) is the hole area [m²].
- \(PM(i)\) is the molecular weight of the evaporated species [g/mol].
- \(R\) is the ideal gas constant [J/mol K].
- \(T\) is the temperature of the Knudsen cell.

In the real condition, the Clausing coefficient, \(C\), has to be introduced in the eq. 2.2 to consider the shape of the Knudsen cell hole and it is calculated as the integral of the molecular flow relative to the solid angle in the real case. Usually, instead of the theoretical equation, deposition tests are performed using a target on which the evaporated species condense. By measuring the sample before and after the deposition, an estimation of the total atoms or molecules can be furnished. In the 1948 the Knudsen Effusion Mass Spectrometry (KEMS) was introduces to study the thermodynamic behaviour of many species coupling the Knudsen cell to a mass spectrometer. Nowadays, this is the most common method to conduct research activities permitting to study metals, alloys, oxides, carbides, fullerenes and homogeneous mixture reactions.
2.4.1 Knudsen Effusion Mass Spectrometry (KEMS)

KEMS technique is based on the coupling of the Knudsen cell to a mass spectrometer, in order to analyse the effusion gasses. The benefits in the using of this technique are principally related to the possibility of a continuous functioning, without interruptions for the target weighing or analysis. Moreover, the resulting spectrum contains other remarkable information such as the partial pressure of element vapour or enthalpy and entropy of the vaporization process [2.9]. The mass spectrometer is a flexible tool since it could work in a wide range of temperature and pressure. The temperature can reach 2000 °C, compatibly with the material resistance, while the upper limit of the pressure depends as aforementioned on both the shape and the dimension of the hole of the Knudsen cell. The pressure lower limit is typically about $10^{-11}$ mbar, namely the instrument sensitivity.

The device structure is essentially composed by the Knudesn cell properly connected to the ionization chamber. Between the cell and the ionization area is normally to interpose a shielding collimator provides to reduce the overheating of components close to the cell (Fig. 2.6b). Furthermore, the screen works as a trap for the parasitic flow that would inevitably be deposited on the chamber walls. Beside this aspects, additional screens properly holed can be installed to restrict the evaporation cone (restricted collimation). This is a common practice in the KEMS technique allowing to reduce the parasitic flow contamination (Fig. 2.6a). The latter are mainly composed by unwanted molecules mixed to the vapour and due to molecules condensation and re-vaporization processes on the external cell surfaces [2.10]. The solid angle of the “effusion cone” is exclusively determined by the bore diameter of the screen, if it is aligned with the aperture of the Knudsen cell (Fig. 2.6c). The whole system, designated to hold collimators and screen, thus requires an X-Y alignment device fully integrated in the vacuum chamber to maintain the proper axial concentricity.

Fig. 2.6. KEMS technique: a) without restrict collimator; b) with restrict collimation; c) with collimation and misalignment between the cell and the shields axes (Heyrman et al., 2004).
2.4.2 Knudsen cell design

The main features regards the design of the Knudsen cell are the material selection and its geometry, which determine the satisfaction of two predominant conditions: the temperature and pressure uniformity inside the Knudsen cell. Moreover, the chemical inertia of the material avoid unwanted chemical reactions during the evaporation stage. Since the Knudsen cell is usually heated by Joule effect, high mechanical strength is required, especially at high temperature. Ceramics as alumina, zirconia, boron nitride or higher-melting metals such as tungsten, tantalum and molybdenum are common choices in the material selection. For all these reasons, the Knudsen cell material designated for the Laser Front End construction is graphite, which couples its chemical inertia to the high strength at high temperature and to the excellent machinability. The latter aspect is very important in the cell construction because of the necessity to realize small and at the same time elaborate geometrical shapes. In particular, the EDM-3® (POCOGRAPHITE Inc.) [2.11][2.12], adopted for the cell construction, shows excellent electro-thermal and mechanical properties due to the small grains dimension (~4 μm) and to the low presence of impurities in the microstructure. Conventional graphite has a grains dimension of about 20-25 μm. Despite the material brittleness, the small dimension of the grains combined to the low presence of impurities give to this graphite a high tensile strength, as reported in Fig. 2.7 as a function of the temperature. Contrary to the traditional graphite, EDM-3® shows a lower coefficient of thermal expansion.

![Graph showing tensile strength-temperature plot for EDM-3 graphite.](image)

---

Fig. 2.7. Tensile strength- temperature plot referred to the EDM-3 graphite.

The material selection is followed by the CAD modelling, which plays a fundamental role since the main dimensions of the cell are here decided (Fig. 2.8). The shape of the cell will have a high impact on the uniformity of the temperature on its inner surfaces, on the evaporation process and on the ancillary devices design. In fact, the temperature is a
consequence of the electrical current (Joule effect) and the presence of cold spots, namely points on which the temperature is lower than the others, could be the cause of the evaporation rate reduction, due to the particles condensation phenomena. The dimension of the hole of the Knudsen cell also affects the evaporation and the particles effusion. Knudsen found the relation between the diameter of the exit hole and the volume of the heating chamber (Fig. 2.8). The bore diameter should be in the range of 1-2 mm when the heating chamber is equal to 1 cm³. More generally, the surface of the sample to be vaporized has to be at least hundred times the bore area. This permits guaranteeing high vacuum inside the cell, condition determines the molecular flow and so the mean free path of the particles higher than the orifice diameter of an order of magnitude. The geometry, considering the electrical properties of the selected material, determines the potential drop \((V_0 - V_1)\) in the electrical circuit in agreement to the Ohm’s law and it has to be lower than the maximum voltage provided by the power supply.

![Fig. 2.8. Main design features of the Knudsen cell prototype.](image)

The parameters and the main geometrical dimensions of the Knudsen cell developed are summarized as following:

- Material: EDM-3® graphite.
- Heating chamber volume = 2500 mm³ (inner diameter equal to 20 mm).
- Exit hole diameter = 2 mm.
- Heating chamber wall thickness = 2 mm.

Two symmetrical halves, despite the small edge provides to seal the heating chamber and the four alignment holes, compose the Knudsen cell as shown if Fig. 2.8. This configuration allows to a uniform current density in the cell and therefore a uniform temperature on both the upper and lower halves. The technical drawings of the Knudsen cell are showed in Fig. 2.9 and Fig. 2.10. The construction of a single element, in fact, and the presence of a cap to close the cell, would introduce a localized thermal contact resistance and the
Fig. 2.9. Technical drawing of the lower part of the Knudsen cell prototype.
Fig. 2.10. Technical drawing of the upper part of the Knudsen cell prototype.
consequent thermal gradients formation. Moreover, the two symmetric halves configuration allows to an easy introduction of the sample in the cell if the placement of the species through the exit hole should become difficult.

The next step was the development of components which connect the Knudsen cell to the power supply feedthroughs, completing thus the electrical circuit provides the current to the system. In Fig. 2.11, the CAD model of the Knudsen cell system and the ancillary components are represented. Four sets of fifteen tantalum foils of 0.1 mm of thickness are properly shaped and bent in order to reduce the compression stresses induced by the thermal expansion at high temperature. On one side, tantalum foils are connected to the copper clump by means M6 bolts. In the other side, they are compressed between two tantalum spacer plates. To avoid any gaps between the foils, a set of tantalum studs are fixed in the lower spacer plate, which has two threaded holes. The upper spacer plate, conversely, is fixed by means four square nuts that are screwed on the tantalum studs. Coupling different material is an important aspect of mechanical connections because of the lower chemical affinity, which avoids or reduces welding between components at high temperature. It should be noted that the sample of material to be studied and subsequently evaporated, is introduced from the exit hole of the Knudsen cell or by opening the cell removing the upper half.

Fig. 2.11. Components and materials used for the Knudsen cell thermal characterization.

The copper clamps, instead, were developed considering the power supply feedthroughs available at the Legnaro’s Laboratory. The first set of clamps were designed to match the feedthroughs of the test bench chamber used to validate the Finite Element Model (FEM) of the Knudsen cell (Fig. 2.12a). The second set of clamps were developed to fit the power supply feedthroughs installed on the final configuration of the Time of Flight (ToF) chamber,
as represented in Fig. 2.12b. The design of the Knudsen cell was followed by the study of its thermal behaviour by using the finite element method approach. This is an important step since by using the numerical model it will be possible to investigate the temperature on the inner surface of the cell, which have to be uniform as possible in order to control the evaporation process. The geometry of the cell prevents the possibility to carry out temperature measurements inside the cell since the presence of a small exit hole. The strategy was to conduct both numerical simulation and experimental tests to validate the model by the comparison between the temperatures on the outer surfaces. Once the model was validated, the latter permit to analyse the thermal field inside the Knudsen cell. The finite element model permits also to verify the working conditions of the ancillary components used to hold the cell.

### 2.4.3 Electro-thermal Finite Element Model (FEM)

The main purpose of the following paragraphs is to describe the thermal behaviour of the Knudsen cell with the aim to guarantee the temperature uniformity on its inner surfaces. The finite element model is a useful method to evaluate different parameters of devices during their functioning after the numerical model validation, which is the first step in the finite element analysis.

The Knudsen designed is heated by means Joule effect thus electro-thermal analyses have been performed.

The heat transfer occurs at low pressure (10⁻⁶ mbar) and therefore the convection can be neglected due to the lack of a fluid and consequently the bulk current flows is irrelevant. Contrary, radiation and conduction heat transfer play a fundamental role in the finite element analysis, especially in the solving processes. Both radiation and conduction problems are solved by iterative methods; the conduction heat transfer solution is thus used as boundary conditions for the radiation problem and the latter, once it is solved, furnishes the inputs for the thermal conduction problem in the next integration. Fig. 2.13 illustrates a scheme of the
heat transfer phenomena due to thermal radiation and conduction. The thermal conduction is described by the eq. 2.3 as following:

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + h = \delta c \frac{\partial T}{\partial t}
\]  

(2.3)

Where \(T(x,y,z,t)\) is the temperature, \(k\) is the thermal conductivity, \(\delta\) is the material density, \(c\) is the heat capacity and \(h\) is the volumetric heat source. The solution of this equation required both the initial and boundary condition assignment; the first one, coincides with the temperature values in some reference domain in time designated as the initial time \((t = t_i = 0)\), while the second specifies the value that solution has to assume along the boundary of the domain. The initial condition is expressed by:

\[
T(x,y,z,0) = T_i(x,y,z) \quad \forall (x,y,z) \in \Omega
\]  

(2.4)

The boundary conditions are assigned to the surfaces contain the domain or volume \(\Omega\) and they are generally expressed by the equations (2.5), (2.6), and (2.7):

\[
T(x,y,z,t) = T_{assign}(x,y,z,t) \quad \forall (x,y,z) \in S_{assign}
\]  

(2.5)

\[
-k \frac{\partial T}{\partial n}(x,y,z,t) = q_{assign} + q_{conv} + q_{rad} \quad \forall (x,y,z) \in (S_{assign} \cup S_{conv} \cup S_{rad})
\]  

(2.6)

\[
-k \frac{\partial T}{\partial n}(x,y,z,t) = q_{enc} \quad \forall (x,y,z) \in S_{enc}
\]  

(2.7)

Fig. 2.13. Scheme of the coupled thermal radiation and conduction problem.
The terms in the equations, \( q_{\text{assign}} \), \( q_{\text{conv}} \), \( q_{\text{rad}} \) and \( q_{\text{enc}} \) are positive when the heat flux has the same direction of the surface normal, \( n \). In particular, \( q_{\text{conv}}, q_{\text{rad}}, \) indicate the heat exchange due to the thermal convection and radiation through the surfaces \( S_{\text{conv}} \) and \( S_{\text{rad}} \) and can be calculated by:

\[
q_{\text{conv}} = h(T - T_C)
\]

\[
q_{\text{rad}} = \varepsilon \sigma (T^4 - T_r^4)
\]

Where \( h \) is the heat transfer coefficient, \( T_C \) is the fluid temperature surrounds the surface where convection occurs, \( \varepsilon \) is the hemispherical emissivity of a grey body surface, \( \sigma \) is the Stefan-Boltzman constant and \( T_r \) is the temperature of an isothermal surface, which completely encloses the surface \( S \). The boundary conditions related to the enclosure \( S_{\text{enc}} \) are defined by the eq. 2.7, in which \( q_{\text{enc}} \) is the thermal energy radiated through the area \( A_i \). Since the convection can be neglected, when the stationary condition is reached, the thermal energy exchanged by thermal radiation is equal to the heat transferred by convection through the surface \( S_{\text{enc}} \), which contains the domain \( D \).

The solution of the radiation problem can be solved by means the eq. 2.10 considering all the radiating areas, \( N \), belong to a grey body and a uniform thermal field.

\[
q_{\text{enc}, i} = \sum_{j=1}^{N} \left( \frac{\delta_{ij}}{\varepsilon_i} - F_{j,i} \left( \frac{1}{\varepsilon_i} \right) \right) \sigma T_i^4
\]

Where \( \delta_{ij} \) is Kronecker delta (1 if \( i=j \) and 0 if \( i \neq j \)), \( \varepsilon_i \) is hemispherical emissivity of the surface \( i \), \( F_{i,j} \) is the view factor between the surfaces \( i \) and \( j \), \( q_{\text{enc}} \) is the thermal energy radiated by the area \( A_i \), \( \sigma \) is the Stefan-Boltzman constant and \( T_i \) [K] is the surface thermodynamic temperature. The view factor, \( F_{i,j} \), is defined as:

\[
F_{j,i} = \frac{1}{A_j} \int_{A_i} \int_{A_j} \frac{\cos \theta_j \cos \theta_i}{\pi r^2} dA_i dA_j
\]

From the other side the electrical problem is completely associated to the thermal problem due to the close relationship between the nodal temperature and the Joule effect. The Ohm’s law combines the current density vector \( j(x,y,z) \) and the potential gradient \( \nabla V \):

\[
j = -\frac{1}{\rho(T)} \nabla V
\]
Where \( \rho \) is the electrical resistivity, which is a temperature dependent parameter. At stationary condition, the following equation is satisfied:

\[
\nabla \cdot \mathbf{j} = 0
\]

(2.13)

In agreement with the Joule effect definition, the equation describes the relation between the current density vector and the volumetric heat source, \( h \), is defined as:

\[
h = -\nabla V \cdot \mathbf{j}
\]

(2.14)

This short treatment essentially describe the main equations of both electrical and thermal problems will be coupled in the solve processing of the finite element analysis.

### 2.4.3.1 Knudsen cell: electro-thermal Finite Element Analysis (FEA)

The finite element model used to describe the electro-thermal behaviour of the Knudsen cell, with the aim to guarantee a temperature uniformity on its inner surfaces, is based on the geometry of a test-bench already available in the laboratory. The cell was installed in a vacuum chamber by means two electrical feedthrough allowing to supply the current in the electrical circuit thus realized (see Fig. 2.14 a-b). The functioning of the entire system will be described in the next paragraph where experimental tests are discussed. An aluminium transition, on which a Kodial viewport was installed, was positioned between the vacuum chamber and the water cooled end plate (Fig. 2.14a).

The finite element model was performed considering the assembly reported in Fig. 2.14b, neglecting the vacuum chamber, the transition and the end plate. The latter, in fact, are water cooled in order to control the temperature increasing and 25-30 °C are always reached on these components. The heat transfer due to the thermal radiation is thus affected by the high temperature of the Knudsen cell and a simplified model can be considered as few components at high temperature radiate to the environment. In fact, the total radiant energy emitted is proportional to the fourth power of the temperature.
difference between the Knudsen cell and the cooled components. This means the term related to the water cooled component became smaller than the others (see eq. 2.9). The model was simplified also reducing the complexity of each component allowing to a smooth mesh of the entire model.

Finite Element Model (FEM) is the easier method to study complex system, especially when the analytic solution would require strong simplification and hypothesis diverting the treatment from the real case. The numerical method, implemented by the use of Ansys\textsuperscript{TM} code, consists in the solution of boundary value problems for partial differential equations. The domain are discretized by finite elements on which nodes the solution is approximated and by using variational methods from the calculus of variations, the associated error function can be minimized assembling the simple equations of each elements in a large system contains the equations of all nodes. The thermal radiation solution, which is solved by the use of Ansys\textsuperscript{TM} Radiosity Solver, determines the temperature of each node belong to the surfaces of each component and therefore the radiation thermal energy. The latter is then used as boundary condition for the thermal conduction problem, which provides the temperature reached in the whole domain, D. Since the two problems depend on each other, iterative method provides the convergence of the final solution. The electrical problem, on the other hand, furnish the power heating generated. The boundary condition of this problem is associated to the definition of both the electric potential and current flow values on at list one surface. This considerations force the use of the SOLID226 element, which couples both the thermal and the electrical problems. In the numerical model, ten nodes element with tetrahedral configuration was used as shown in Fig. 2.15.

![Fig. 2.15. SOLID226 element used for the electro-thermal finite element analysis.](image-url)
The main parameters and hypothesis adopted in the non-linear transient Finite Element Analysis (FEA) are listed below with reference to Fig. 2.16:

- Material properties, such as electrical resistivity, emissivity and thermal capacity are temperature dependent parameters and their variation within the temperature was assigned by different APDL macros → non-linear problem

- Ideal contact region → shared areas are represented as a continuous boundary of different components → no thermal contact resistance affects the thermal field.

- The thermal energy exchanged by thermal radiation is defined by the construction of a single enclosure, where the Knudsen cell radiates to an infinite environment set at 25°C (space temperature) → non-linear problem.

- A temperature of 25°C was set on the inner areas of the water-cooled feedthrough (temperature constrain).

- A potential of 0V was imposed on the edge of one of the two electrical feedthroughs (voltage constrain).

- An electrical current defines the input of the electrical problem (electrical current load). It was applied at the free edge of the electrical feedthrough as a function of the time. This introduced another non-linearity expressed by the time. The temperature was evaluated in corresponding to different electrical currents (100-800 A) allowing to characterize the Knudsen cell in a wide range of working conditions. The electrical load was implemented defining a vector by...
the *DIM,I_LINE(TABLE,19,1,1,TIME APDL command as represented in Fig. 2.17. Each load step corresponds to an increment of 100 A in 1000 s, except for the first load step (t=2000 s) and both the second and last one load steps (t=1500 s). This condition has been applied to reach stationary conditions thus permitting the electro-thermal problem convergence.

![Current-time load vector assigned to the Knudsen cell transient FEA.](image)

Despite the transient analysis is affected by the duration of each load step, the numerical convergence of the solution depends principally on the elements size of each components along with the respect of the boundary condition formulation. The components element sizes obtained after the convergence analysis are reported in the Table 2.1 as following (see also Fig. 2.11 and Fig. 2.16):

<table>
<thead>
<tr>
<th>Knudsen cell</th>
<th>Feedthrough</th>
<th>Clump</th>
<th>Flexible connector</th>
<th>Square nut</th>
<th>Spacer plate</th>
<th>Threaded rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element size [mm]</td>
<td>1.15</td>
<td>6.9</td>
<td>6.9</td>
<td>3.45</td>
<td>3.45</td>
<td>3.45</td>
</tr>
</tbody>
</table>

Table 2.1. Element size of the Knudsen cell components adopted in the Finite Element Model (FEM).

The thermal field of the Knudsen cell heated by means a current of 800 A is showed in Fig. 2.18a. The maximum temperature reached is approximately equal to 1920 °C and the potential drop between the two electrical feedthroughs is 4.75 V (Fig. 2.19). The maximum temperature provides indirect information of the temperature on the inner surfaces of the cell, which should be higher than the external surface since the presence of thermal radiation in a small enclosure. A temperature of 2000°C, in fact, would guarantee the possibility to evaporate a wide range of species. In the other hand, the maximum potential difference and the current supplied are in agreement with the maximum power provided by the power supply actually available, as described in the paragraph 2.4.4.
The numerical simulations thus allowed determining different reference paths on which the temperature was evaluated in accordance with the possibility to measure the temperature on the same points by mean optical instruments. Four path are hence defined as Fig. 2.18 shown.

The numerical results, related to the mentioned paths, are represented in Fig. 2.20, Fig. 2.21, Fig. 2.22 and Fig. 2.23. It should be observed the temperature uniformity on the Knudsen cell, especially for applied current in the range of 100-600 A. The goodness of the design can also be noted by the temperature field registered in the nearby components as the tantalum flexible connectors, the tantalum spacer plate and the molybdenum nuts. While the Knudsen cell reaches the maximum temperature ($I_{\text{max}}=800$ A, $T_{\text{max}}=1920^\circ$C) the other components never exceeds 1150 $^\circ$C, which is acceptable for materials as tantalum and molybdenum.

**Fig. 2.18.** a) Temperature contour plot [$^\circ$C] of the Knudsen cell for a current, $I=800$A; b) reference paths used for the experimental-numerical data comparison.

**Fig. 2.19.** Numerical potential drop-current plot referred to the Knudsen cell circuit.
Fig. 2.20. Temperature distribution along the Path 1 for a current range of 100-800A.

Fig. 2.21. Temperature distribution along the Path 2 for a current range of 100-800A.
Fig. 2.22. Temperature distribution along the Path 3 for a current range of 100-800A.

Fig. 2.23. Temperature distribution along the Path 4 for a current range of 100-800A.
2.4.4 Experimental test and data comparison

In this paragraph a series of experimental tests, mainly focused to the validation of the previous finite element model, are presented and discussed. It is necessary to underline the goal of the whole treatment, namely to obtain a numerical model able to furnish the temperature distribution on the inner surfaces of the Knudsen cell. If the temperature is nearly constant inside the cell, more efficient will be the evaporation process and thus the accuracy in the estimation of the effused atoms. The experimental test were performed by using a test bench already installed at the laboratory and it is illustrated in Fig. 2.24.

![Fig. 2.24. Main devices of the test bench used for the experimental test on the Knudsen cell.](image)

The test bench is essentially composed by:

- The vacuum chamber (1) which host the Knudsen cell system. It is made of aluminium and a water cooling circuit is obtained by a series of flow channel on the outer surface of the chamber itself.
- The transition (2). This component is used as a spacer between the vacuum chamber and the base plate. On the transition, a Kodial view port allows visibility inside the chamber and therefore the measurements of the Knudsen cell temperature.
- The gate valve (3), which is important to connect the vacuum chamber and the vacuum system.
- The barometer (4) gives information about the pressure in the vacuum chamber, as a redundant device together with the vacuum gauges.
- The Kodial viewports (5). In the presented test bench, two observation windows are installed to measure the temperature of the cell by means different measuring instruments. One of them, was positioned on the transition along the vertical direction allowing the measuring of the temperature with reference to the paths 1-2-3 (Fig. 2.18). The second viewport, instead, was installed on the back of the test bench and the corresponding measurements referred to path 4 (Fig. 2.18) has been performed. The second viewport can be of two different materials, Kodial or zinc selenide, as depending of the measuring instruments adopted.

- Turbomolecular pump. It is a type of vacuum pump used to obtain and maintain high vacuum ($10^{-6}$ mbar). These pumps work on the principle that gas molecules can be given momentum in a desired direction by repeated collision with a moving solid surface. In a turbomolecular pump, a rapidly spinning fan rotor hits gas molecules from the inlet of the pump towards the exhaust in order to create or maintain the vacuum.

- Primary pump. This pump has the purpose to create a good level of vacuum at the turbomolecular pump outlet (usually $10^{-2}$ mbar), allowing to the latter to explain the best performance, namely a lowest pressure in the vacuum chamber.

- Pyrometers (IRCON Modline® 5), which measures the temperature evaluating the radiation ratio of the thermal energy emitted for two spectral wavelengths [2.13]. This technique do not require the knowledge of the emissivity of the target but it needs the hemispherical emissivity ratio of the components referred to two measuring wavelengths. In the tests, two different pyrometers were used, one for temperature in the range of 600-1000°C and the second for temperatures varying from 1000 up to 2000°C. For temperature lower than 600 °C, namely out from the pyrometer measuring range, an infrared camera (IRIS 4030) has been used [2.14].

- The water cooling system, which is adopted to guarantee a temperature of 25-30 °C on both the vacuum chamber and the base plate of the test bench.

Before starting the measurements, the Knudsen cell and the ancillary components have been constructed in the laboratory’s workshop as Fig. 2.25a shown. Then the removing of oxides, dust and the residual machining oil by mean an ultrasonic washing machine has been performed. The following assembly phase (Fig. 2.25b) has required high sensibility in the screws tighten, especially for those that guarantee the absence of gaps in the flexible connector, made of tantalum foils. In the same picture is possible to observe the electrical
current flow, which has been supplied by the water cooled electrical feedthrough.

The electrical current was varied from 0 to 800 A with increments of 20 A/min, while measurements, contrary, were performed in a current range of 100-800 A with steps of 100 A. The power supply has the following characteristics: \( P_{\text{max}} = 10 \text{ kV}, \ I_{\text{max}} = 1000 \text{ A} \) (direct current) and \( V_{\text{max}} = 10 \text{ V} \). For each point, the temperature has been evaluated three times during two current rumps-up and one current rump down, alternately. Before temperature readings, 10 min has been waited to reach stationary conditions. The mean value of the three measurement has been used to compare experimental and numerical results. Since the maximum temperature variation for each set of measurement never exceed 4 °C, the error bands are unnoticeable in the following graphs. The reference points, on which the temperature has been evaluated are represented in Fig. 2.26. It should be noted points from 1 to 6 are referred to the path 1, point from 7 to 12 are referred to the path 2.
2.26a) and points from 13 to 15 are referred to the path 4 (Fig. 2.26b). For the points related to paths 1 and 2, the temperature has been measured by using the pyrometer and the Kodial viewport, while for points 13, 14 and 15 both pyrometer and infrared camera have been used since the wide accessibility permitted by the viewport. The infrared camera was adopted for temperature readings in corresponding of a current equal to 100 and 200 A by the use of optical filters extend the measurement range of the infrared camera to 200-900 °C. At this current, in fact, the temperature was too low for the pyrometer employment. The camera could be used after the installation of a 5 mm thickness zince selenide (ZnSe) view port, a necessary condition to increase the total transmission up to 73% in the wavelength range of 0.6-20 μm (see Fig. 2.27). The graphite emissivity (0.8) multiply by the transmissivity (0.73) was set in the infrared camera as well as the space temperature equal to 25°C.

![Fig. 2.26. a) Reference points for the temperature measurements on the Knudsen cell lateral side; b) reference points for the temperature measurements on the Knudsen cell top surface.](image)

![Fig. 2.27. Installation of the zinc selenide viewport window adopted for the measurement performed by means the thermographic camera; b) total transmission of a 5 mm thick uncoated ZnSe window.](image)
The results of these kind of measurements are a set of pictures can be managed with a dedicated software, from which the temperatures could be extracted from the colour map. Fig. 2.28, Fig. 2.29 and Fig. 2.30 show the comparison between the numerical and the experimental temperature referred to the path 1, path 2 and path 4, respectively (see Fig. 2.18b). The maximum error in the first graph is registered in the measurement point 1 (Fig. 2.26b) for a current of 300 A and it is equal to 5.8 % (Fig. 2.31). The error decreases within the supplied current and becomes lower than 2 % from 400 A to 800 A. In the same manner, as shown in Fig. 2.31, along the path 2 the maximum error is evaluated equal to 6.4% at 300 A, in corresponding of the measurement point 7. Also here, a reduction of the error between the numerical and the experimental data, is registered along with the current increasing. In the last graph (Fig. 2.30), namely corresponding to the path 4 and experimental points 13, 14 and 15, the experimental and numerical comparison should be discussed separately in the range of 100-200 A (infrared camera) and in the range of 300-800 A (pyrometer). In fact, the maximum error using the infrared camera is close to 12.5% at 100 A, while by using the pyrometer a maximum error of 4.9 % is observed for a current of 300 A. The reason of the decreasing of the error between the numerical and experimental data could be explained considering two different aspects: the measuring instrument and the simplification. The numerical-experimental temperature comparison referred to the Path 1 for a current range of 100 - 800 A.
Fig. 2.29. Numerical-experimental temperature comparison referred to the Path 2 for a current range of 100 - 800 A.

Fig. 2.30. Numerical-experimental temperature comparison referred to the Path 1 for a current range of 100 - 800 A.
introduced in the fine element model. The infrared camera, in fact, is affected by the space temperature, which is not constant and some variations could be present. Moreover the zinc selenide transmissivity is considerably reduced by the thin-film deposition occurred at high temperature and due both to the outgassing and the partial evaporation of the hot components. It should be pointed out that the maximum error is showed always in corresponding to measuring points nearby the Knudsen cell edge. In respect of such, the pyrometer reading spot has a diameter of 3 mm and thus thermal radiations coming from the coldest background could determine a reduction in the temperature estimation.

In the other hand, the numerical model simplification influence can be explained by using the numerical and experimental comparison of the potential drop measured by mean a digital multimeter on the feedthroughs, as reported in Fig. 2.34. The numerical potential difference is lower than the experimental one. The reason should be fund in the FEM hypothesis of perfect contact between elements of different components that share the same area. The real situation, contrary, is governed by the thermal contact resistance existing between adjacent components, which can be traduced in a local increasing of the electrical resistance and thus a higher potential difference. As the picture illustrates, the numerical-experimental difference decreases within the electrical current. The components
temperature increases within the current and the contacts become closer to the ideal condition since initial welding processes occur. Part of the numerical-experimental voltage difference also depends on the point on which the voltage was measured. In fact, the digital multimeter was used out of the vacuum chamber but at the same time close to the feedthrough connection, while the numerical model do not consider the presence of the chamber itself.

As a conclusion of this paragraph, the finite element model could be considered in agreement with the experimental data, especially in a range of current of 400-800 A, which means a temperature range on the cell outer surface of about 1150-1750°C. The finite element model thus validated was used to design the ancillary devices which compose the Time of Flight (ToF) chamber as the support, the screen and the extraction systems. All of these components were then assembled in the Laser Front End and the first evaporation and ionization test were successfully performed.

### 2.5 The Time of Flight Chamber (ToF) design

The KEMS (Knudsen Cell Mass Spectrometry), whose conceptual design is illustrated in Fig. 2.3, was developed in order to complete the last part of the Laser Front End. The treatments was simplified showing in Fig. 2.35 the final CAD layout of the Laser Front End. The main devices of the Laser Front End are:

- The Time of Flight chamber (ToF), which contains the Knudsen cell (paragraph 2.4.2), the alignment and support system, the shielding apparatus and the extraction system.
- The beam pipe, namely a stainless steel tube wit diameter of 100 mm, which
connects the vacuum chamber to the diagnostic box.

- The diagnostic box, which is mainly composed by a detector able to measure the ion beam current and thus the number of particles collected.
- The frame, basically made of standard aluminium profile.
- The vacuum pumps, which allow reaching a pressure in the system of about $10^{-6}$ mbar.

In this paragraph, the design phases of each device contained in the TOF chamber are described. The comprehension could be facilitate by showing the operating principle of each device, as shown in Fig. 2.36. The vacuum chamber (AISI 304L) has an inner diameter of 245 mm, while the wall thickness is equal to 3 mm. On its lateral surface, three DN 100 mm and one DN 130 mm pipes are welded. On each DN 100 pipe end, a Kodial viewport are
installed, allowing the laser passage in the ionization area (Fig. 2.35 and Fig. 2.36). Usually, only one of these viewports is used. Contrary, the DN 130 pipe are connected to the Laser Front End by means an edge welded bellow and finally to the beam pipe. The top of the vacuum chamber is equipped with a stainless steel flange, useful in the installation phase since it leaves the free space for maintenance and services. In the lower part, a bore of 100 mm of diameter allows the lowest impedance in the vacuum operation, with a consequent shorter time to reach the required pressure. The electrical current that “heats” the Knudsen cell is supplied by two electrical feedthrough (MDC vacuum LLC; type VHC1000-C40; UHV series), which furnish a maximum current of 1000A and allow a maximum potential difference of 3 kV (direct current). The electrical feedthroughs are water-cooled and can operate in a range of temperature of 100-450°C.

2.5.1 Support-alignment system design

The Knudsen cell position, during its functioning, has to be controlled by means a system which guarantees the proper alignment with respect to the laser beam. In fact, the evaporation plume which comes directly from the cell should be intercepted by the laser, which ionizes the atoms by electrons removing (Fig. 2.36). The support system also provides to fix the cell position preventing the bending of the flexible connector. Since the Knudsen cell is one of the main components in the electrical circuit, insulators have to be used to not affect the current flow. The main constrain in the design of this system was the limited available

![Fig. 2.37. CAD model of the support-alignment system design coupled to the Knudsen cell.](image-url)
space. The whole supporting device is composed by four modules (Fig. 2.38) evenly spaced and fixed on the base plate of the vacuum chamber. Each module is principally composed by the stainless steel horizontal part, which is fixed to the chamber base plate by means a set of M3 screws. The latter do not touch directly the horizontal part due to the presence of the Macor® ring insulators, preserving the current flow in the Knudsen cell and at the same time controlling the module rotational position. The vertical part, also made of AISI 304 L, is coupled with the horizontal part that works as a crosshead guides and a threaded stud adjusts the relative movement. The stud is fixed on one side by mean a clamping ring, while in the other side it is screwed on a threaded plate rigidly connected to the vertical part. This permits to control the vertical adjustment (Fig. 2.38). A tungsten pin, whose edge can reach the alignment hole of the cell (see Fig. 2.39a), permits the horizontal regulation. It is adjusted by the use of a graphite screw, which also avoid any unwanted pin movements. Macor is a trademark glass ceramic, which combines good machinability,
insulation and high working temperature ($T_{\text{max}} \sim 800^\circ\text{C}$). The pin is made of thoriated tungsten, since the high temperature reached on the smallest edge. On its lateral surface, a small groove reduces the virtual leak due to the presence of a gap between the graphite pin and the vertical part (Fig. 2.39). A virtual leak is a trapped volume of gas connected to the vacuum side of a chamber that cannot be pumped out easily due to the restriction in the path connecting the trapped gas volume to the chamber volume.

### 2.5.2 Shielding system design

The main function of the shielding system is to provide the collimation of the evaporation plume and the reduction of the parasitic flows (see § 2.4). Moreover, the screen closer to the Knudsen cell allows reflecting part of the thermal radiation with an increasing of the temperature uniformity on the cell. The design of the shielding system is presented in Fig. 2.40 and the technical drawings of the EDM-3 graphite screen is shown in Fig. 2.41.

The main dimensions of the shielding device are:

- The hole diameter of the graphite screen, $d_{\text{GS}} = 2$ mm.
- The thickness of the main screen, $t_{\text{GS}} = 2$ mm.
- The hole diameter of the tantalum screen, $d_{\text{TS}} = 2$ mm.
- The distance between the two screens, $h_{\text{GS-TS}} = 1.5$ mm.
- The distance between the main screen and the Knudsen cell, $h_{\text{KS-GS}} = \text{variable}$.

---

**Fig. 2.40.** Exploded view of the main components, material employed and adjustment regulation of the shielding system.
Fig. 2.41. Technical drawing of the EDM-3 screen installed on the shielding system.
It should be observed the insulation between the two screens obtained by means Macor insulators. Moreover, an insulation is also present between the shielding system base and the vacuum chamber. This configuration, in fact, permits to feed the screens at high voltage thus preventing the contamination of the evaporation plume by ions eventually formed in the cell or in the path between the cell and the screens themselves. The main screen is made of graphite since the high temperature of the Knudsen cell. The second screen, contrary, is made of a tantalum sheet, since the manufacturing simplicity and the small thickness required to reduce its influence on the evaporated atoms. As for the support system, the screen holes need to be aligned to the Knudsen cell bore and thus four regulation adjustments are require. As Fig. 2.40 shows, screens and the regulation plates are provided by slots to control the position in the horizontal plane. The height of the entire system and additional rotational movement are the result of the well coupling between the vertical pin and the regulation plates.

The limited space available around the Knudsen cell has obliged to design each component considering the possible interferences could be exist in different adjusting configurations, as shown in Fig. 2.42 (the tantalum screen is currently hidden). The component which was more affected by this condition is the graphite screen. The shielding around the cell was obtained with a double rounded cut edge on the lateral surface of the screen. Furthermore, this permits to leave the space for the coupling between the tungsten pin (support system) and the Knudsen cell. All tests performed and actually ongoing in the laboratory are presented in the paragraph 2.6.

Fig. 2.42. Knudsen cell-support system-alignment system assembly details. Note the graphite edge shape allows the tungsten pin placing.
2.5.3 Extraction system design

The extraction system provides the atoms acceleration after the laser ionization, which generates 1+ ions. A combination of plates and grids allowing electrostatic fields inside the extraction system and thus the ions potential energy then converted in kinetic energy. Fig. 2.43 shows the CAD model of the extraction system designed for the Laser Front End.

![CAD model of the extraction system](image)

**Fig. 2.43.** Detail of the material and components used in the extraction system design.

The first acceleration stage occurs in the region between the stainless steel plate (+V electrode) and the first grid (-V electrode). The latter is mainly composed by a stainless steel ring (D = 65 mm; d= 55 mm), on the inner diameter of which a stainless steel grid has been welded. The grid is a set of wires (0.5 mm of diameter) equally spaced of 3.5 mm, thus allowing the ions passage during their acceleration. The distance between the plate and the first grid is equal to 50 mm and it is guaranteed by means Macor bars, which also provide the proper electrical insulation. The grid and the main plate are supported by the use of stainless steel clamps with a bill shape (Fig. 2.44b) fixed by a screw and permitting the electrode adjustment. In this phase only longitudinal components of the electrostatic field has to be guaranteed.

The second acceleration stage takes place between the aforementioned grid and the einzel lens, which are spaced of 50 mm by means the Macor bars. In this case, the einzel lens or unipotential lens is a positive charged ring made of stainless steel (D=85mm; d=68 mm) that focuses without changing the energy of the beam. It is used in ion optics to
focus ions in flight, which is accomplished through manipulation of the electric field in the path of the ions. Since the presence of the bore, despite the longitudinal electrostatic field decelerates the ions but with a lower intensity than in the previous stage, transverse components of the electrostatic field are present. These components permits the ion beam focusing along the beam pipe, thus controlling the point on which the ion beam reaches the minimum size, usually at the diagnostic device. It is fixed and adjusted by a set of clumps as illustrated in Fig. 2.44a. These clamps allow the diameter reduction between the second and third acceleration stages. On one end, it should be observed the presence of a slot to support the einzel lens.

The third acceleration phase is obtained in the region between the einzel lens and the ground electrode. The final electrode has the same characteristics of the +V electrode already described. It differs by the diameter of the ring (D=120 mm; d=100 mm) and by the electrical potential set equal to zero. Contrary to the previous case, the longitudinal component of the electrostatic field accelerates the ions thus mitigating the deceleration of previous stage, but at the same time transversal components continue focusing the ion beam. Four stainless steel bars of 10 mm of diameter connect the extraction system to the external flange by the clamps showed in Fig. 2.44c.

![Different stainless steel clamps](image.png)

Fig. 2.44. Different stainless steel clamps used in the extraction system assembly: a) einzel lens clamp; b) +V/-V electrode clamp; c) ground electrode clamp.

The different lens are fed at high voltage by means the use of a stainless steel wire (0.15 mm) properly connected to SHV connectors. These feedthroughs are welded on the top of the vacuum chamber and each one allows 5 kV. The electrical potential set on each lens depends on the type of the species considered in the test and adjustments are usually required to find the best setting which maximizes the beam current. However, in the design phase, an electrostatic simulation was performed to prove the supports (Fig. 2.44) do not affect the electrical field thus generated. The solution was compared to the numerical result of the same model without the presence of the connectors.
2.5.3.1 Electrical Finite Element Model

The electrical numerical simulation was performed by using Ansys™. The finite element model consists in a one eighth of the entire system, exploiting the cylindrical symmetry condition. This permitted to study conveniently the potential distribution regarding two main cases: the first, with the presence of the clamps, which fix the electrodes to the Macor bars and the second, where only electrodes were present. The CAD model was obtained by using the negative part of the volume occupied by the extraction system and a mesh was then performed using SOLID232 finite elements. Boundary conditions, considering the maximum electrical potential on the electrodes, are represented in Fig. 2.45 along with the results of both cases. From the comparison, it could be noted the equipotential lines of the electrical potential are likewise arranged in a volume described by a cylinder of a diameter equal to 40 mm and its axis coincident to the ion beam direction. Nevertheless, out of this virtual cylinder, equipotential lines are similarly arranged in both case despite in this region no beam could be present.

![Fig. 2.45. Electric finite element analysis of the extraction system: a) electric potential contour lines of extraction system electrodes without the use of supports; b) electric potential contour lines of extraction system electrodes with the use of supports.](image-url)
The equipotential lines and thus the equipotential surfaces are normal to the beam direction along the extraction system axis. This is valid in the acceleration stage I and partially true in the stage II and III, where the effect of the einzel lens introduces transversal component of the electrical field for the beam focusing.

### 2.5.4 Electro-thermal Finite Element Model of the ToF

The main purposes of the Finite Element Analysis of the whole Time of Flight (ToF) chamber are essentially two:

- Analysis of the temperature inside the Knudsen cell.
- Thermal behaviour analysis of the ancillary devices as the alignment and shielding devices.

The first item is the most important aspect of the FE analysis since it gives information on the temperature uniformity inside the cell. Moreover, because of the numerical simulations, the mean temperature, $T$, of the inner surfaces of the cell could be plotted as a function of current, $I$, supplied in the electrical circuit. In fact, once the ancillary devices are installed, it is completely impossible to measure directly the temperature due to the presence of the shield (Fig. 2.40). The function $T=f(I)$ allows to reconstruct the thermal field in the Knudsen cell during the experimental test by setting the current required to reach the desired temperature. The indirect method above described is based on the validation of the Knudsen cell finite element model presented in the paragraph 2.4.3.

Additional information obtained by the ToF finite element model is the possibility to estimate the temperature reached by components close to the cell and therefore the comparison between the maximum temperature for a given current and the material specifications could be performed.

The numerical simulations were performed by using Ansys™ and APDL commands has been written. The main conditions, on which the finite element model is based, are equivalent to those described in the paragraph 2.4.3. The components and the devices considered in the following simulation are the Knudsen cell, the alignment-support system, the shielding device and the vacuum chamber (see Fig. 2.36, Fig. 2.37, Fig. 2.38, Fig. 2.40, Fig. 2.42 and Fig. 2.46). The extraction system was not considered since it does not affect the thermal behaviour of the cell. Two different type of elements were used as following:

- **SOLID87**: this 3-D 10 node tetrahedral thermal solid element has one degree of freedom, temperature, at each node. It was used to perform the mesh of those
components not part of the electrical circuit. This family of components regard the vacuum chamber, the shielding system and the support-alignment device. The latter, in fact, is connected to the cell by means the tungsten pin, but is properly insulated by the Macor components.

- SOLID226: the 3-D 20 nodes coupled field solid element has been used to study the thermal behaviour of the Knudsen cell heated by Joule effect, since it provides the electrical and thermal fields coupling. It was used to discretize the volumes, which belong to the electrical circuit.

The boundary conditions were assigned considering two enclosures: one containing all the components inside the vacuum chamber, where thermal radiation and conduction are predominant; the other, contrary, takes into account the natural convection between the external surfaces of the chamber and the external space, which had a temperature fixed equal to 25°C. The thermal load regards the assignment of a constant temperature on those components provided by a water cooling circuit as the electrical feedthrough and the base plate of the vacuum chamber. The electrical current was varied from 150 A to 750 A by steps of 150 A and it was assigned to the electrical feedthrough end. The other feedthrough extremity has the condition of zero volt. Sine STATIC analyses were performed, the transient thermal variations were not considered and a step of 150 A permits to well describe the ToF behaviour. Despite the Knudsen cell analysis performed in the previous paragraph, a maximum of 700 A has been fixed due to the maximum working temperature reached by the ancillary devices.

![Fig. 2.46.CAD model (a) and finite element model (b) of the Time of Flight (ToF) chamber.](image-url)
Before to introduce the results, the convergence was studied reducing the element size of each component of 15% assuring a temperature difference between two consecutive iterations lower than 1%. In the Table 2.2 the element size adopted for the mesh of the ToF chamber along with the element type used for each components are listed. The temperature contour plot as result of a general analysis of the time of flight chamber for a current, $I = 800 \, \text{A}$, is illustrated in Fig. 2.47.

<table>
<thead>
<tr>
<th>Component</th>
<th>Element Type</th>
<th>E size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knudsen cell</td>
<td>SOLID 226</td>
<td>1.15</td>
</tr>
<tr>
<td>Knudsen cell (upper part)</td>
<td>SOLID 226</td>
<td>1.15</td>
</tr>
<tr>
<td>Knudsen cell (lower part)</td>
<td>SOLID 226</td>
<td>6.9</td>
</tr>
<tr>
<td>Cupper feedthrough and clumps</td>
<td>SOLID 226</td>
<td>3.45</td>
</tr>
<tr>
<td>Tantalum spacer plate</td>
<td>SOLID 226</td>
<td>3.45</td>
</tr>
<tr>
<td>Tantalum stud</td>
<td>SOLID 226</td>
<td>3.45</td>
</tr>
<tr>
<td>Molibdenum nut</td>
<td>SOLID 226</td>
<td>3.45</td>
</tr>
<tr>
<td>Tantalum foil connector</td>
<td>SOLID 226</td>
<td>3.45</td>
</tr>
<tr>
<td>Support-alignment system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical part</td>
<td>SOLID 87</td>
<td>3.45</td>
</tr>
<tr>
<td>Horizontal part</td>
<td>SOLID 87</td>
<td>2.875</td>
</tr>
<tr>
<td>Stud and threaded plate</td>
<td>SOLID 87</td>
<td>4.6</td>
</tr>
<tr>
<td>Macor insulators</td>
<td>SOLID 87</td>
<td>4.6</td>
</tr>
<tr>
<td>Tungsten pin</td>
<td>SOLID 87</td>
<td>1.15</td>
</tr>
<tr>
<td>Vacuum chamber</td>
<td>SOLID 87</td>
<td>11.5</td>
</tr>
<tr>
<td>Base plate</td>
<td>SOLID 87</td>
<td>11.5</td>
</tr>
<tr>
<td>Shielding system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite and tantalum screens</td>
<td>SOLID 87</td>
<td>1.3</td>
</tr>
<tr>
<td>Macor insulators</td>
<td>SOLID 87</td>
<td>3.1</td>
</tr>
<tr>
<td>Regulation plate and vertical pin</td>
<td>SOLID 87</td>
<td>3.45</td>
</tr>
<tr>
<td>Base</td>
<td>SOLID 87</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 2.2. Element type and elements size of the ToF finite element model.

Fig. 2.47. Temperature contour plot of the Time of Flight chamber simulation for a current, $I = 800 \, \text{A}$.
The isosurfaces plot in Fig. 2.48b, which is related to the aforementioned FE analysis, shows the presence of two extreme thermal gradients in the cell. This suggested to identify two reference paths on which the temperature was evaluated, allowing to completely describe the best and worst conditions in the thermal field distribution inside the cell. As Fig. 2.48a shows, paths S1 and S2 start in the center of the lower surface and continue along the inner surface up to the exit hole of the Knudsen cell.

![Fig. 2.48. a) Reference paths allows monitoring the cell inner surfaces temperature; b) isosurfaces of the cell temperature for a current I=800A. The temperature shows two thermal gradients on two main directions.](image)

The temperature registered on the two-reference paths are plotted in Fig. 2.49 as parametric curves for different currents. The temperature difference ($T_{\text{max}} - T_{\text{min}}$) related to each curve rises with the increasing of the supplied current. The temperature uniformity inside the cell

![Fig. 2.49. Temperature distribution inside the cell referred to the S1 and S2 paths for a current, I=150-750 A.](image)
is thus affected by the amount of current furnished to the system. Nevertheless, the most interesting region for the ongoing effusion experiments is included in a range of temperature of 400-1500 °C. It also should be noted the temperature for a given current is always higher in the upper surface of the cell. This means during the evaporation process the sample is positioned in the lower surface of the cell and the particles leaving the surface can directly escape from the exit hole or, more probably, collide on the upper surface until they reach the exit bore. In this situation, since the higher temperature on the upper surface, a low probability of sticking phenomena are expected. In Fig. 2.50 the maximum, minimum and mean temperatures for each current level are plotted with reference to the paths 1 and 2 (extreme cases). The graph is useful in the experimental test during the current setting. In fact, in relation to the required temperature, the corresponding current could be furnished by means the power supply. For all the reason aforementioned, the minimum temperature plot was used for this purpose. The numerical simulations were used to construct the plots referred to a region that cannot be observed. The model validation (§ 2.4.3.1) allows the thermal analysis here presented with a margin of error of 3%. The calibration curves obtained are an important instrument, which was employed in the experimental test for the deposition of aluminium and lead sample on a target, allowing to check the proper functioning of the entire apparatus.

---

![Graph](image_url)

**Fig. 2.50.** Plots of the minimum, maximum and mean temperatures on the inner cell surfaces for a current, I=150-750 A
Despite additional simulation were performed up to 800 A, the upper working condition was fixed equal to 700 A. This because for the given current the maximum acceptable temperature of the ancillary components material were reached. Fig. 2.51 shows the temperature contour plots of both support and shielding systems. It should be noted the temperature of the Macor insulator of the shielding system is approximately equal to 650 °C, while for the stainless steel components the maximum temperature registered is of about 600 °C. In this condition, both Macor and stainless steel (AISI 304 L) work close to the maximum temperature permitted, which is of about 700 °C and 800 °C, respectively (Fig. 2.51a). In the other hand, the support system module showed the worst condition. In fact, while the maximum temperature of the tungsten pin is equal to 830 °C and the tungsten temperature limit is approximately of 2000 °C, the vertical support made of stainless steel shows a temperature of 710 °C. The latter is observed in a single point close to the coupling zone with the tungsten pin. Therefore, a current of 700 A should be considered the maximum working current. Nevertheless, in the first test a current of 450 A was supplied to the Knudsen cell and future development and research activity will be conducted to extend the electrical current range achievable.

Fig. 2.51. Temperature contour plots for a current, I=700 A referred to: a) the shielding system; b) the support system module.

2.6 Experimental test: depositions and ionization

2.6.1 Introduction

The goal of the Laser Front End design is to test and thus estimate the laser ionization efficiency. With the using of the Knudsen cell, the shape of the evaporation plume could be well described and by knowing the laser property and its focus position the particle
theoretically ionisable can be evaluated. This study required several calibration tests, which permit to manage properly all the parameters or conditions involved in the process as:

- The current supplied to the Knudsen cell.
- The position of the laser respect the cell.
- The laser source stability.
- The shields behaviour and their axes orientation.
- The shape of the evaporation plume.
- The extraction potential applied to the electrodes and the ions trajectory.
- The pressure inside the cell during the sample evaporation.
- The evaporation rate of the sample.
- The vacuum distribution during both the evaporation and ionization processes.
- The parameter changing during the cell heating and their variation along the time.

In this condition, the efficiency could be estimated as the ratio between the atoms furnished to the ionization process and the ions collected in the diagnostic box at the end of the Laser Front End. In this paragraph, a preliminary description of the ongoing tests will be presented as well as the installation of the designed devices presented in the previous chapter. It should be underlined that all components, except the laser source, were constructed in the LNL workshop, which permits to check all components requirements during the construction. The tests focused on the evaporation and deposition of aluminium and lead samples, in order to describe the dimension of evaporation plume as a function of the target distance respect to the cell exit hole. The results were than compared to the numerical data of MolFlow simulations with the aim to estimate the number of the particles evaporated. Subsequently, the first ionization test was performed using aluminium in order to check the extraction system performance or, more generally, the functioning of the Laser Front End device.

2.6.2 Laser Front End construction and installation

The construction of the Laser Front End was performed in the laser laboratory at LNL (Lengaro’s National Laboratory – INFN), where the laser source is already installed. The nearness between the laser source and the Time of Flight (ToF) chamber is fundamental since the reduction of the path length and thus safety observances has been achieved.
Chapter 2

The first step was the construction of all components of the time of flight chamber as represented in Fig. 2.52. After the components machining, dust, residual oils and lubricant were present. Therefore, ultrasonic cleaner was adopted according to the high vacuum specifications. Before to assembly the Knudsen cell and the ancillary devices, the vacuum chamber has been installed (see Fig. 2.53a). A frame made of aluminium standard profiles was assembly parallel to the optical table, on which the laser source was placed. The vacuum chamber base plate was installed on the frame by means a sliding support, which permitted the vacuum chamber adjustment. Moreover the base plate, a stainless steel sheet of 15 mm of thickness, was provided by a water cooling circuit obtained by milling a circular groove on which a thin plate with the same shape has been welded. This system permits to reduce the maximum temperature of both the base plate and the vacuum chamber, since the large contact surface between the two components. Additional cooling fans were installed on the vacuum chamber to reduce the maximum temperature also on the top of the chamber itself. Additional cooling system have been adopted since between the base plate and the vacuum chamber and between the latter and the upper flange viton o-ring sealing were used. Two
pumping stations, which are installed close to the time of flight chamber and to the diagnostic box, respectively, allow the proper pressure inside the Laser Front End.

Two power cables were connected to each electrical feedthrough, which furnish the electrical current to the cell. On the other side, the cables were connected to two power supplies, which provides 300 A for a maximum of 3 kV, each one. For this reason, the power supplies were connected in parallel to increase the maximum current available. The pipe connects the TOF with the diagnostic was provided by a thermal belt allowing to clean the inner surface of the system during the vacuum operation (bake-out).

Fig. 2.53a shows the laser laboratory as result of the Laser Front End installation. The following experimental tests were performed with reference of two main configuration of the time of flight system: the first include the Knudsen cell and the support and alignment systems (Fig. 2.53b), while the second configuration was also provided by the shielding system, as shown in Fig. 2.53c. The graphite shield was positioned 10 mm above the Knudsen cell, with reference to the upper and lower surfaces of the Knudsen cell and shield, respectively. Note the space optimisation in the second and more complex configuration.
2.6.3 Aluminium and lead depositions using the ToF chamber

The experimental tests here presented allowed verifying the capability of the Knudsen cell to evaporate properly different sample, in this case aluminium and lead depositions were considered since the low temperature needed to reach the vapour pressure equilibrium. The pressure inside the cell was the unknown variable, therefore the current, namely the temperature, was increased until the deposition spot on the target was observed. Tests were performed considering two different configuration for lead and aluminium deposition, respectively:

CASE 1: inside the vacuum chamber the Knudsen cell was heated without the shielding system up to 250 A, increasing the current with a step of 20 A/min. The sample, a lead wire of 1 mm diameter and 5 mm of length, was introduced from the exit hole of the cell before to perform the vacuum in the chamber. The maximum temperature reached at 250 A was approximately equal to 550 °C. Once the stationary condition was achieved, the Knudsen cell remained at the maximum temperature for two hours, in order to consider the lead evaporation process completed. The particles evaporated were deposited on a molybdenum target, which has been fixed on a stainless steel rod. The position of the target plate was adjusted to ensure a distance between the exit hole of the cell and the target itself of 5 mm, 10 mm and 15 mm. For each case the heating, the evaporation and sample insertion steps were repeated following the same procedure. A picture of the cell during the heating phase is shown in Fig. 2.54.

![Fig. 2.54. Conditioning test: Knudsen cell heated by Joule effect (I=450A; T_{max}=1250°C)](image)

The purpose of this test was to evaluate the shape of the effusion plume at different distances from the Knudsen cell, assuring lead deposition on the molybdenum target. The results of the deposition tests are well visible in Fig. 2.55. It should be noted the increasing of the deposition spots as a function of the distance of the target. Each deposition spot was
analyzed by mean both Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy technique (EDS). The first one, produces images of a sample by scanning the surface with a focused beam of electrons, while, the second, is an analytical method used for the element analysis or chemical characterization of a sample. Fig. 2.56 shows the EDS spectrum of the sample of Fig. 2.55b, in the measuring point located in the center of the spot. The spectrum shows two significant peaks. Since the overlapping X-ray emission peaks of molybdenum and lead (K-electron shell), the increasing of the electron energy was needed. In this condition, 25 kV electron beam allows to determine the second peak from L shell of lead. SEM and EDS analysis were performed in other reference points, which confirmed the presence of lead in all the visible spot areas of each sample.

Together with the preliminary deposition test, a set of numerical simulations were performed by using MolFlow. The software, which is based on the Monte Carlo method, is usually adopted for vacuum analyses, where molecular flow occurs. The simulations consist in the discretization of the empty volume surrounds the Knudsen cell. On each surface, once Lambert’s emission law was chosen to describe the angular distribution of the desorbed particles, the temperature furnished by the finite element analysis (see § 2.5.4) was applied.
From the vapor pressure chart of different metal, the pressure of the equilibrium point referred to lead at 550 °C was found equal to $1.5 \times 10^{-4}$ mbar. In fact, at this equilibrium condition the experimental tests have assured the lead evaporation, as presented above. Different reference surfaces were implemented in order to evaluate the particles distribution (particle/mm$^2$ s) at 5 mm, 10 mm ad 15 mm, which corresponded to the distance of the target in the experimental tests. The outgassing rate, namely the number of lead particles evaporated per unit time from the inner surface of the cell (the lower one) were gradually increased to reach the aforementioned temperature-pressure condition at equilibrium. For each outgassing rate corresponded one simulation, in which 12 Ghits was registers (Ghits is the total number of collision inside the reference volume). The first result is shown in Fig. 2.57 and represents a qualitative assessment of the effusion cone divergence: for experimental tests (Fig. 2.57a), a CAD model shows the dimension of the lead spots obtained by measuring the diameter of the deposition circles as shown in Fig. 2.55; for the numerical simulation the same procedure was adopted in the measurement of the spot diameter at each height (Fig. 2.57b). In this case, contrary, a mean value corresponds to the background was subtract from the deposition rate registered in each cell of the reference surface. Therefore, the qualitative comparison between the numerical and experimental measurements were performed. For target distance of 5 mm, the experimental spot diameter is equal to 19 mm, while the numerical diameter is equal to 13 mm. For a target distance of 10 mm, the experimental spot diameter of 21 mm is resulted lower than the numerical one, which is equal to 5 mm. The last case, i.e. 15 mm distance between the target and the cell, the experimental spot diameter is equal to 35 mm and the corresponding numerical diameter equal to 33 mm.

The first deposition test confirmed a good agreement between the dimension of the effusion plume and the one obtained by the numerical simulation. Despite the numerical and
experimental comparison is a qualitative and preliminary assessment of the evaporation process, ongoing tests could permit a more detailed and deep analyses, which will allow the estimation of the particle deposition rate in each point of the effusion cone. This will require a lot of effort, both in term of number of deposition test and numerical simulations. Additional tests will be provided by a water-cooled microbalance close to the Knudsen cell.

**CASE 2**: the configuration of the following test provided the use of the graphite shield, which was positioned 5 mm from the exit hole of the cell (distance between the lower surface of the screen and the upper surface of the cell), thus allowing the restrict collimation. 10 mg of aluminium was inserted inside the cell and the complete evaporation of the sample was obtained. The deposition target, contrary to the previous case, was a combination of two molybdenum sheets (0.25 mm of thickness) assembled on a rotatable rod. The regulation system allowed controlling the distance of the target from the graphite shield and also the possibility to switch the target by a rotation of 180° of the rod (Fig. 2.58a & Fig. 2.58b). For the preliminary deposition test using the restrict collimation, the screen was positioned at 10 mm from the graphite screen. Before the deposition, different tests were performed allowing to verify the thermal behaviour of whole time of flight system in the final configuration (Fig. 2.58c).

![Fig. 2.58. a) Aluminium deposition by using the Knudsen cell coupled to the graphite shield; b) double molybdenum target adjustments; c) heating cycle of the Knudsen cell and the shielding system at high .](image)

The current was set equal to 330 A, gradually supplied with a rate of 5 A/min. During the rump-up stage, parameter as the electric potential of the power supply (TDK-Lambda), the potential measured on the feedthrough (TeK volts), the total power supplied and the pressure inside the chamber were monitored. In fact, at stationary condition (I=330A) their variation was fundamental in the understanding of failures of malfunctions that could occur to the system.

The total power fluctuation or variation, for example, would probably means the changing of the electrical resistance of the Knudsen cell. If the cell failure occurs, the electrical resistance increases and for the same current higher total power would be observed. The plots in Fig. 2.59 shows the parameters monitoring during the deposition test.
Fig. 2.59. Monitoring chart of the Time of Flight parameters during the aluminium deposition test.
It should be noted the uniformity of the electrical power in the time (more than 7 h), a clear demonstration of the electro-thermal stability of the system. After 4 h, since the maximum current has been reached, the stainless steel rod has been rotated and consequently the second molybdenum target was used. The targets handling was permitted by a tight coupling between the rotatable rod and the upper flange of the vacuum chamber, which is provided by a set of Viton O-rings.

The results of the most significant deposition tests are presented in Fig. 2.60a & Fig. 2.60b. The first picture is referred to the molybdenum target positioned above the shield and therefore the cell after four hours from the test stating. The second one, instead, shows the aluminium spot obtained in the first part of the deposition test. The first remark concerns the clear difference in terms of colours. In fact, the first spot, is the result of the thermal radiation which through the shield hole reaches the target surface. In the second target, contrary, the “white” spot is the consequence of the presence of aluminium oxide. SEM and EDS scanning have been then performed along different path to understand the nature of the deposition spot (Fig. 2.60c).

Here is presented the result of the EDS analysis referred to path 13, as shown in Fig. 2.60c and Fig. 2.61. From the plot and more generally from the test, with reference to the previous deposition test, the main comments are:

- the EDS analysis allowed determining the radius of the aluminium spot, which is for this test equal to 3 mm. In the center of the spot the number of counts (aluminium X-ray read from the EDS sensor), which are a qualitative indication of the amount of aluminium deposited, assumes the maximum value and at the same time a wide data dispersion is observed. This occur because the long-time heating and the wetting surface properties. Therefore, along the path, region where low presence of aluminium is observed mean a low number of counts.
- The dimension of the spot is smaller than the previous case since the restrict collimation has been adopted. This also allows to reduce sample deposition on the components present in the vacuum chamber.
- This configuration could be studied by using MolFlow as a benchmark to estimate the number of atoms in a specific position of the vacuum chamber.

![Graph showing EDS results](image)

Fig. 2.61. EDS results obtained along the reference path 13. Counts are referred to aluminium.

The tests presented are the first step for a study of a method which permits to characterize the laser ionization efficiency. As aforementioned, many parameters affect the entire process and ongoing experiments are aimed to discover the influence of each parameter on the other. Despite the preliminary deposition test, the first ionization test using aluminium will be presented and the extraction system will be tested.

### 2.6.4 First ionization test using the Laser Front End

In this paragraph, the laser ionization test will be presented, which consist in the use of all the devices designed and individually tested in the previous sections. The purpose of this test is to ionize and to accelerate aluminium sample by means the Knudsen cell coupled to the shielding system (restrict collimation). Moreover, the extraction system has been installed in the time of flight chamber to accelerate the ions until the diagnostic box. Fig. 2.62 shows different phases of the installation of the extraction system (§2.5.3). The first step was the preliminary assembly, verifying the electrodes alignment with the respect to the longitudinal axis. In particular the stainless steel clamp have to be connected to the Macor®
insulators by means M3 and M2 screws. The clamps of Fig. 2.62c and Fig. 2.62d could be adjusted until the electrodes coupling are obtained because of the thin slots of which they are provided. Contrary, clamps of Fig. 2.62b were fixed to the support bars, they hold the ground electrode and they were the reference for the others electrodes assembling. Screws provided to fix stainless steel wires, which feed the electrodes at high voltage. Once the preliminary off-line assembly has been completed, the extraction system has been installed in the vacuum chamber as shown in Fig. 2.62e.

Fig. 2.62. a) Extraction system assembly; b) ground electrode clamp; c) einzel lens clamp; d) electrodes clamp; e) Extraction installation inside the time of flight chamber.

The time of flight chamber, in its final configuration was then coupled to the laser source as shown in Fig. 2.63. It should be noted the initial conceptual design (Fig. 2.3, Fig. 2.35 and Fig. 2.36) and the final assembly which permits the ionization tests.

The main parameters related to the experimental ionization test are:

- The aluminium sample weight of 40 mg, a quantity which allow 10 hours of evaporation, thus guaranteeing the time necessary for both parameters setting and data acquisition
- The Knudsen cell current, I = 420 A. This condition allows to a maximum temperature in the cell of 1200°C, which is clearly higher than the temperature of the deposition test described in the previous paragraph, in order to ensure the evaporation process.
• The voltage on the extraction system electrodes (Fig. 2.43):
  +V electrode = 4312 V; -V electrode = -1808 V; einzel lens = 4036 V. These values referred to the electric potential assigned to each electrode to maximize the ion beam current read in the diagnostic device.

• The vacuum level, which have to correspond to a final pressure lower than $10^{-5}$ mbar, in order to avoid both electrical discharge in the chamber and ions interaction with residual gasses.

During aluminium evaporation, a pulse laser with 10 Hz of frequency was 90 ° steered over the Knudsen cell between the +V and –V electrodes of the extraction system by means an optical mirror. Passing through the kodial viewport, it interacted with the aluminium atoms effused from the Knudsen cell and the electrostatic fields, provided by the extraction system, accelerated the ions until the diagnostic device. The diagnostic was synchronized with the laser source, therefore the time between each laser pulse and the diagnostic measurements was monitored. Since the acceleration stage (red line) is a function of the mass over ions-charge ratio (in this case the charge is always q=+1e) the time could be associated to the mass of the ionized particles. In particular, with reference to the parameters above listed, the time that aluminium ions take from the ionization to reach the diagnostic was equal to 12.5 µs.

![Image](fig263.png)

Fig. 2.63. Laser Front End during laser ionization tests.

The laser source wavelength can be tuned in a range of frequencies, allowing to detect the maximum signal read by the diagnostic. The concept is similar to the resonant in mechanical system. For a generic atoms, there is a particular frequency causes resonant and thus the ionization because the removing of one electron. Fig. 2.64 shows the signal peak
varying with the laser frequency. The maximum is registered for a wavelength of 308.226 nm, as expected.

![Graph](image.png)

Fig. 2.64. Diagnostic signal registered varying the laser frequency during Al ionization tests.

### 2.7 Conclusion

In this chapter the design of the Laser Front End has been performed in order to develop a complex device which permits to estimate the efficiency of the laser ionization mechanism. The laser ionization is one of the most selective method to produce radioactive ion beams (RIBs) and the contamination due to the surface ionization affects this process since the use of a tungsten hot cavity. The main device of the Laser Front End is the Knudsen cell, a crucible composed by two graphite halves heated by Joule effect, which permits the evaporation of a solid sample inside the vacuum chamber. The atoms thus produces are ionized by means a pulse laser and then accelerated until the diagnostic device, where the ion beam is analysed. The entire process is governed by the knowledge of both the temperature and the pressure inside the Knudsen cell. This was obtained by electro-thermal studies based on the comparison of experimental and numerical data, allowing to validate a finite element model (FEM) which furnish the temperature distribution inside the Knudsen cell. Along with the Knudsen cell, ancillary devices as the support system and the shielding system have been designed to fix the cell in the vacuum chamber and to ensure the restrict collimation of the evaporation plume, respectively. The time of flight thus designed and constructed was used to perform preliminary deposition and ionization tests of aluminium and lead sample. The deposition spots analyses allow to lay the basis for the development of a numerical model (MolFlow) through which the number of particles effused in the
ionization area could be estimated. The latter has been presented as a preliminary study, which requires a test campaign to control all the parameters involved in the process. The chapter culminates with the first ionization test performed by coupling the Time of Flight (ToF) to the pulse laser, allowing to extract and analyse aluminium ion beam. The tests, which are ongoing in the Legnaro’s National Laboratory (LNL-INFN), will aim to understand the variation of many parameters often affect each other. The Laser Front End could then permit to estimate the efficiency of the laser source, since the Knudsen cell furnish atoms without interfering with the ionization process.
References


Chapter 3

SPES quadrupole triplet re-design

3.1 Introduction

The ions production and the following acceleration phase are the first and typical steps in the ion beam generation. The ion beam thus produced has to be transported through the beam pipe, which consists in a series of stainless steel pipes, until the experimental hall, where ions are collected and analyzed. Ion beams of +1 or +n charge state particles are usually transported by mean electrostatic or magnetic devices, which focus and deflect the ions in order to follow a specific trajectory. Despite the importance function of each device in the facility, one of the most important parameter governs the beam transport performances is the vacuum distribution inside both pipes and optical devices themselves. In fact, as shown in Fig. 3.1 [3.1], particles losses per meter are proportional to the vacuum level, in a double logarithmic scale. Moreover, the losses function could be describes as parametric curves, where the independent variable is the charge state, q, of the ions. It therefore follows that a pressure as lower as possible shall be provided, allowing the increasing of the beam transport efficiency, namely a reduction of the particles loss along the beam pipe due the interaction with the residual gas.

Fig. 3.1. Particles loss per meter – pressure plot for different ions charge states.
The aforementioned discussion is the general introduction of the re-design of one of the beam transport device will be used in the Laser Front End for beam focusing: the quadrupole triplet lens (See Fig. 2.3). In fact, due to the low extraction potential, which never exceed 45 keV, the electrostatic lenses are the common device used for this purpose since the electrostatic field uniformity can be well controlled by the shape of the electrodes. Moreover, the easy construction, assembly and the low-cost power supply (instead of high current power supply) are the main features characterize the use of electrostatic lenses instead of magnetic devices.

Nowadays, a special quadrupole triplet is used in the radioactive Front End [3.2] in the context of the SPES project. This device, along with other apparatus, was developed with the aim to reduce the overall dimension of the whole machine, which will be used in a strongly radioactive environment. The construction of a spare Front End (Off-line FE) has permitted the quadrupole triplet disassembly, allows studying its weakness without the influence of the other devices. This laid the basis for the re-design of a new quadrupole triplet, which combines vacuum improvement, easy of assembly and beam transport performance. Furthermore, the new device is a completely stand-alone apparatus, thus permitting its use in different situation where focusing is required.

Results of early prototype testing are presented here, as well as complementary simulations of vacuum performance and beam transport.
3.2 Off-line Front End quadrupole triplet study

3.2.1 Quadrupole triplet description

The original Front-End electrostatic lens, as designed for the ISOLDE [3.3] facility at CERN, is a combination of an einzel lens with a quadrupole triplet, as shown in Fig. 3.3. The optical design of the device followed the usual conventions for constructing quadrupole elements using cylindrically shaped electrodes. It is well-known (Banford [3.4], e.g.) that, for a quadrupole whose axis lies along $z$, the equipotentials are hyperbolic in $x$ and $y$, and this shape can be approximated optimally using sections of cylinders whose radius of curvature is $1.145a$, where $a$ is the quadrupole aperture radius, i.e. half the distance between opposing electrodes. The hyperbolic shape of the pure quadrupole will be distorted by the presence of higher-order multipoles that arise principally from the planar truncation of the electrodes perpendicular to the quadrupole axis. Because of the symmetry, the next possible multipole, i.e. the strongest field error, is the 12-pole. The choice of $r = 1.145a$ has the effect of cancelling the 12-pole component to a reasonable degree within an aperture of $\sim 0.9a$ if the electrode width is at least $1.6a$. For the Front End quadrupole triplet, these lead to specific values of $r = 68.56 \text{ mm}$, $a = 60 \text{ mm}$, and the electrode width is $116 \text{ mm}$. Because quadrupoles focus in one plane and defocus in the other, they are usually employed in pairs, i.e. in a doublet configuration.

Fig. 3.3. Quadrupole triplet CAD model of the off-line Front End based on the ISOLDE design.

A triplet is formed essentially by splitting one quadrupole of the doublet in half, placing one half before and one half after the other quadrupole. This triplet configuration yields the additional benefit of permitting symmetric focusing in $x$ and $y$. The lengths of the first and
the third (outer) sets of electrodes are $L_1 = L_3 = 170$ mm, while the center quadrupole has electrodes of length, $L_2 = 480$ mm. The maximum potential applied to the electrodes is 5 kV.

In the off-line Front End mechanical design, the vacuum chamber is not a single tube but it is split into three cylindrical sections connected by o-ring sealed stainless steel mating flanges. The center section is a cross, with the two transverse ports, a DN 150 and a DN 200, intended for vacuum pump mounting. The electrodes are mounted from the flanges using insulating standoffs machined from PEEK, a strong UHV compatible plastic. The electrically grounded flanges incorporate specially shaped apertures, centered in the 40-mm gap between quadrupole sections, intended to isolate the three sections of the triplet from each other and to terminate the electrostatic field of each section. The inner aperture of each intermediate flange has a radius, $r_2 = 50$ mm and an axial length of 51 mm such that the aperture is reentrant into the quadrupole sections by 5.5 mm in each direction as seen in Fig. 3.3 and Fig. 3.4. At each end there is an einzel lens electrode with the same geometry as the intermediate flange apertures to provide additional focusing if required. The einzel lenses were grounded for all of the tests in the present work. Details of the mechanical design are shown in Fig. 3.4.

**Electrodes radius, $r_1 = 68.56$ mm**

![Diagram of the quadrupole triplet](image)

Fig. 3.4. Technical details of the quadrupole triplet used for the vacuum study.

### 3.2.2 Vacuum test

As illustrated in Fig. 3.3, the pump intakes are partially occluded by the nearby electrodes, causing significant reduction in the conductance to the pumps. A re-evaluation of the pumping scheme was thus deemed necessary. Both simulations and actual pump-down measurements using the off-line Front-End triplet were performed as described below.
For this series of vacuum tests, the quadrupole triplet was removed from the Front End and installed on a test bench, as shown in Fig. 3.5. The pumping system consisted of a 550 l/s turbomolecular pump backed by one dry pump (multi-roots type) of 28 l/s pumping speed. Two vacuum heads, Pirani and cold cathode Penning gauges, measure the low and the high vacuum level respectively in the triplet chamber during pump down to steady-state vacuum level. The first runs were performed on the triplet by itself with the ends blanked off (Fig. 3.5a). Then tubes of 2.5 m length (Fig. 3.5b) were added to each end of the triplet in order to simulate the triplet as installed on the beam line. Because of their locations on the quadrupole triplet chamber, the gauges measured the pressure close to the inlet of the pumps and not along the beam axis.

To gain a better understanding of the pressure profile along the beam axis, several numerical simulations were performed as described in the next section, with the actual measurements serving to calibrate the simulations. Results of the stand-alone pump-down measurements are shown in Fig. 3.6 and Fig. 3.7. For these tests, the system was pumped down from atmosphere to an ultimate pressure, $p_{1t} = 1.7 \times 10^{-7}$ mbar after 300 h pumping, with a variation of less than 2% in the pump-down time over several runs.

The pump-down tests were then repeated (Fig. 3.7) after attaching a 2.5-m length of pipe to each end of the triplet. While the time evolution of the pressure, $p_{1t}$, was recorded as before, only the final, steady-state pressure, $p_{2t}$ at the end of the 2.5-m pipe was recorded. Typical values were $p_{1t} = 1.8 \times 10^{-7}$ mbar, and $p_{2t} = 1.10 \times 10^{-6}$ mbar.
Fig. 3.6. Pump-down time results for the stand-alone triplet.

Fig. 3.7. Pump-down time results for the triplet with two additional pipes attached.
3.2.3 MolFlow: numerical-experimental data comparison

To gain a better understanding of the axial pressure profile along the beam line and in the quadrupole triplet under the molecular flow conditions present during normal operation, Monte Carlo simulations were performed using the commercial code MolFlow+[3.5] as follows. Lambert’s emission law [3.6] was chosen to describe the angular distribution of the desorbed particles leaving the surfaces. To each surface we applied standard corresponding material outgassing values [3.7]. In particular, for the aluminum components, as the electrodes and the field restrictors, the desorption rate was $F_{Al} = 7E^{-9}$ mbar·l·s$^{-1}$·cm$^{-2}$, which corresponds to the outgassing rate for a generic aluminum after 24 h of pumping. Conversely, the stainless steel parts, namely the triplet chamber and pipes, were assigned a desorption rate of $F_{ss} = 3E^{-8}$ mbar·l·s$^{-1}$·cm$^{-2}$, corresponding to 316L stainless steel pumped for at least 75 h without heat treatment. Under these conditions, and without cleaning with organic solvents such as trichloroethylene, the outgassing is composed principally of H$_2$O, H$_2$, CO and CO$_2$. Thus, we set the molecular mass of the desorbed particles to an average value of 20. To complete the setup of the analysis, we had to account for the 550 l/s pumping speed. This was done by applying the appropriate “sticking factor,” which gives the probability that a particle hitting the surface will be adsorbed, to the surface corresponding to the inlet of the pump.

To extract the pressures along the beam axis in both cases, a dummy surface was created in the midplane of the triplet (Fig. 3.8). In conjunction with this, surfaces corresponding to the vacuum gauge heads have been meshed to compare the numerical and the experimental data and thus validate the numerical model.

![Fig. 3.8. MolFlow analysis and pressure maps field distribution. Are shown the numerical measurement points corresponding to the position of vacuum gauges (experimental tests).](image)
Fig. 3.9 and Fig. 3.10 show the pressure in the triplet upon reaching equilibrium, i.e. the stationary condition, for the two cases.

Fig. 3.9. Experimental and numerical comparison of the pressure distribution in the triplet, first configuration (stand-alone ETQ with blanked-off end flanges).

Fig. 3.10. Experimental and numerical comparison of the pressure distribution in the triplet, second configuration (ETQ with additional pipes).
The numerical and the experimental gauge pressures are in good agreement: in the first case, \( p_{1,MolFlow} = 2.24 \times 10^{-7} \text{ mbar} \) and \( p_1 = 1.70 \times 10^{-7} \text{ mbar} \), while in the second case (triplet with additional tubes) \( p_{1t,MolFlow} = 3.20 \times 10^{-7} \text{ mbar} \) and \( p_{1t} = 1.80 \times 10^{-7} \text{ mbar} \).

The comparison of numerical and experimental results for the pressure at the end of the additional tube provides further confirmation of the quality of the agreement. In this case, \( p_{2t} = 1.10 \times 10^{-6} \text{ mbar} \) and \( p_{2t,MolFlow} = 1.20 \times 10^{-6} \text{ mbar} \).

These analyses of the pressure data along the triplet axis led us to two important conclusions:

1. There is a large gradient in the pressure between the inlet of the pump and the center of the triplet, as indicated by \( \Delta p_n \) in indicates a large reduction in the pumping speed of the turbopump resulting from the impedance presented by the triplet electrode in front of the pump inlet.

2. There are two large pressure gradients on axis corresponding to the locations of the inter-electrode apertures (as indicated in Fig. 3.10). Since these aperture flanges also support the quadrupole electrodes, they occlude most of the flow cross section, resulting in a low probability for a residual gas molecule at the inlet of the triplet to be transported to the pump without sticking to a surface on the way. This causes an overall increase in the pressure.

These conclusions provide sufficient justification for a re-design of the triplet to improve the vacuum. The numerical model appears to reproduce the pressure field of the triplet reasonably well, with the numerical-experimental differences easily explained by the variation in outgassing rate during the test that occurs as the surfaces progressively clean themselves. We are thus confident that the model will accurately predict the improvements in vacuum performance resulting from the modifications to the mechanical design of the triplet described in the next paragraph.

### 3.3 Quadrupole triplet re-design

#### 3.3.1 CAD model of the modular quadrupole triplet

Based on the results of the previous section, several changes to the mechanical design of the off-line front end quadrupole triplet have been performed to improve the vacuum performance. First, we concluded that it was not practical to pump the triplet chamber through transverse ports because of the impedance provided by the electrodes. The axial
conductance through the ends of the chamber is always much greater than that of these ports. Therefore, pumps were located out of the quadrupole triplet using standard crosses that provide no conductance limit to the pumping speed, such that the full speed rating of the turbopumps can be achieved.

Having moved the pumps to beamline locations external to the triplets, we were able to improve significantly on their chamber design, making it all one tubular piece of aluminum, rather than having three sections, and eliminating several vacuum sealing surfaces (primarily the two turbopump flanges). Fig. 3.11 shows the CAD model of the new triplet.

In addition to vacuum-related improvements, a number of changes have been made to simplify the assembly and improve the mechanical integrity. Most of these were related to the mounting of the quadrupole electrodes, which now comprise a stand-alone assembly, independent from the rest of the triplet and connected directly to the vacuum chamber by a double-flange system, as shown in Fig. 3.12.

The new electrode assembly consists of six components: 1) the electrode, 2) three high-voltage-insulating supports made of PEEK, 3) a lower stainless steel flange that supports the PEEK insulators, and 5) an upper stainless steel flange that is mounted to the lower flange.
by means a series of screws, and finally, 6) a standard DN 16 CF, 5kV SHV feedthrough to supply the proper high voltage to the electrode. Correct alignment of the electrodes relative to the chamber and to each other is achieved by appropriate, high-precision tolerancing of the machined mating surfaces. A series of reference surfaces were created on the outside of the chamber for the mounting of a laser-tracker alignment system that controls the position of the quadrupole triplet along the beam line.

### 3.3.2 MolFlow and experimental data comparison of the new triplet

The redesign of the electrode mounting system made it possible to simplify the intermediate ground electrode geometry and increase the axial vacuum conductance significantly. These changes could also be applied to the einzel electrodes. In total, from the mechanical point of view, the changes in the triplet design resulted in easier construction, assembly and maintenance. In particular, the redesign makes it significantly easier both to align the triplets upon installation and to maintain the alignment during subsequent operation.

The effect of these changes on the vacuum performance was evaluated by repeating the MolFlow+ simulation of the previous section. With the exception of the change in material for the electrode supports, now PEEK with an outgassing rate of about $3 \times 10^{-7}$ mbar∙l∙s$^{-1}$∙cm$^{-2}$ [3.8], the input parameters, e.g. the pumping speed, the outgassing rate of the aluminum and stainless steel components, the molecular mass of the desorbed particles, and the time of the analysis (total particles generated), remained unchanged. Fig. 3.13 shows the calculated pressure field on the reference surfaces and the locations of the pressure gauges in the new configuration.

![Fig. 3.13. Layout of the experimental tests and numerical analysis (MolFlow) on the new quadrupole triplet. $p_{1t,new}$ and $p_{2t,new}$ are the pressures measured experimentally on the cross and at the end of the pipes, respectively.](image)
The numerical pressure data obtained from the MolFlow simulations were compared to the experimental pressure values related to the experimental test on the re-designed quadrupole triplet. In Fig. 3.14 is shown the typical layout of a vacuum test. The new triplet was connected to the 6-way cross, on which the vacuum station was installed. It is mainly composed by two lines: the first is used as a bypass to make the rough vacuum moving from the atmospheric pressure to a $10^{-2}$ mbar by means a multi-roots primary pump, $P_p$. The electro pneumatic and manual valves, $V_{s2}$ and $V_{b2}$, allow to manage properly the operations avoiding overpressure in the backing section. In fact, after the rough vacuum is performed, the low pressure line was closed and the turbomolecular pump, $P_t$, provided the high vacuum in the chamber. The gate valve, $V_a$, separates the vacuum chamber from the pumping station allowing to verify the tightness of the system. Additional electro pneumatic and manual valves, $V_{b1}$ and $V_{s1}$, controlled the rough and high vacuum sequences during the operations. A vacuum gauge, $G_{b0}$, monitored the pressure at the turbopump outlet, which could be lower of $10^{-2}$ mbar and provided by the primary pump. By means the gauge pressure, $p_{1,\text{new}}$, the pressure inside the triplet was monitored along the time. With reference to the vacuum test with the new triplet and additional pipes, the pressure variables was renamed $p_{1,\text{new}}$ and the pressure registered at the pipe end was $p_{2,\text{new}}$.

![Fig. 3.14. Vacuum test set-up of the re-designed quadrupole triplet.](image)

The plot in Fig. 3.15 shows the comparison between the simulations of the old and new triplet configurations, along with actual test-stand pressure measurements on the new triplet at the positions indicated in Fig. 3.13.

The simulations show that the pressure in the new quadrupole triplet will be an order of magnitude lower than in the old triplet (Fig. 3.15 dotted line). This is confirmed by the experimental measurements, which showed excellent agreement with the numerical data.
Additionally, there should be a marked improvement in the uniformity of the pressure along the beam axis.

3.3.3 Beam transport tests using the new quadrupole triplet

3.3.3.1 Emittance and Twiss parameters

The beam transport of a generic ion beam is characterize by the understanding of the variation of different optical parameters here presented. The first parameter is the emittance, which corresponds to the beam size in the phase space [3.9]. Due to the Liouville’s theorem [3.10], the emittance is constant in the absence of non-linear effect. The transversal emittance can be considered as the product between the beam size and its divergence. The latter is the calculated as the angle due to the beam diameter increasing for a unit length. Different emittance definitions are accepted and differently used depending of the context:

- Geometrical RMS emittance: it is the product of the semi-axes of the ellipse in the phase space \((x-x', y-y')\) calculated assuming a Gaussian beam particle distribution both for the position and the particle angle.
- Geometrical N% emittance: it is the product of the ellipse semi-axes in the phase space \((x-x', y-y')\) which contains the N% of the beam particle.
- Normalized emittance: it is the geometrical emittance multiplied by the relativistic function \(\beta\) and \(\gamma\). Essentially, the emittance is normalized on the beam
momentum and, in absence of beam interactions and non-linear effects, it remains constant during an eventual acceleration.

Together with the emittance, Twiss parameters [3.11] allow to describe and define the ellipse in the phase space and therefore to characterize the beam properties:

- The β Twiss parameter defines the maximum size of the beam.
- The β Twiss parameter defines the maximum beam divergence.
- The β Twiss parameter defines the position according to the focus.

3.3.3.2 Numerical-Experimental beam transport data comparison

A series of emittance measurements with the quadrupole triplet prototype were undertaken at the SPES radioactive Front-End (FE) Test Facility in order to ensure that the necessary mechanical changes to the triplet did not impact its optical performance. Additionally, the Front End beamline was modelled with TraceWin [3.12] to facilitate beam setup and also to begin work on the downstream beamline optical design.

Fig. 3.16 shows the new quadrupole installation and the distances from the plasma ion source (PIS) [3.13] aperture to the center of each of the optical devices on the beamline.

A series of emittance measurements have been performed with an approximately steady current of 200 nA of N⁺ at 25 keV. Two of those measurements are here reported, called Test 1 and Test 2. In the Table 3.1 are presented the main parameters values used on each device, namely the electrode voltage of the steerers (ST), the Front End quadrupole triplet (ETQ1), the Wien filter current and thus the magnetic field and the electrode voltage of the new quadrupole triplet (ETQ2). Table 3.2, contrary, shows the Twiss parameters and
emittances obtained from the TraceWin simulations and the experimental tests. In the first graphs of Fig. 3.17, the beam envelopes as calculate with TraceWin for the EQT settings are shown, along with a phase space plot comparing the emittance meter measurements with the TraceWin calculation (Fig. 3.18). In this case, EQT1 has been adjusted to produce a focus in both x and y at the first beam profile monitor (DB1) and with EQT2 adjusted to focus the beam at the EM.

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>WF</th>
<th>Hall Probe</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[A]</td>
<td>[T]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
</tr>
<tr>
<td>58/-82</td>
<td>75/-72</td>
<td>1/-1</td>
<td>34/-32</td>
<td>1300</td>
<td>699</td>
<td>1300</td>
<td>0.75</td>
<td>0.0028</td>
<td>1519.37</td>
<td>722.88</td>
<td>1519.37</td>
</tr>
</tbody>
</table>

Table 3.1: Configuration of the set-up parameters related to Test 1.

<table>
<thead>
<tr>
<th>X axis</th>
<th>Y axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_x )</td>
<td>( \beta_x )</td>
</tr>
<tr>
<td>[mrad]</td>
<td>[mm]</td>
</tr>
<tr>
<td>EXP:</td>
<td>-0.1568</td>
</tr>
<tr>
<td>Trace Win</td>
<td>-0.0092</td>
</tr>
</tbody>
</table>

Table 3.2: Emittance and Twiss parameters along X and Y axes measured in the Test 1.

Fig. 3.17. Beam envelopes referred to the Test 1.

With the gentle focusing of this test, a good agreement between the calculation and the measurement has been observed, and the measured emittance, \( \varepsilon_{\text{rms},y} = 5.58 \pi \text{ mm mrad} \), is in agreement with other measurements reported for this ion source [3.14][3.15]. This gives us confidence that the modifications to the EQT did not have deleterious effect on the optical performance under normal beam tuning conditions.
However, in the second measurement, the y focusing of EQT1 has been increased in order to increase the vertical size of the beam in EQT2, and then increased that effect further by adjusting EQT2 to produce a focus at DB2 rather than at the EM (see Table 3.3), as can be seen in the 2nd beam envelope plot of Fig. 3.19.

In Table 3.4, the comparison between the experimental and numerical Twiss parameters and emittance are presented.

<table>
<thead>
<tr>
<th></th>
<th>ST</th>
<th>ETQ1</th>
<th>WF</th>
<th>ETQ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
</tr>
<tr>
<td>D2</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
</tr>
<tr>
<td>D3</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
</tr>
<tr>
<td>D4</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
</tr>
<tr>
<td>Q1</td>
<td></td>
<td></td>
<td></td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td></td>
<td></td>
<td></td>
<td>Q2</td>
</tr>
<tr>
<td>Q3</td>
<td></td>
<td></td>
<td></td>
<td>Q3</td>
</tr>
<tr>
<td>1 WF</td>
<td></td>
<td></td>
<td></td>
<td>[A]</td>
</tr>
<tr>
<td>Hall</td>
<td></td>
<td></td>
<td></td>
<td>[T]</td>
</tr>
<tr>
<td>Probe</td>
<td></td>
<td></td>
<td></td>
<td>[V]</td>
</tr>
<tr>
<td>Q1</td>
<td></td>
<td></td>
<td></td>
<td>[V]</td>
</tr>
<tr>
<td>Q2</td>
<td></td>
<td></td>
<td></td>
<td>[V]</td>
</tr>
<tr>
<td>Q3</td>
<td></td>
<td></td>
<td></td>
<td>[V]</td>
</tr>
</tbody>
</table>

Table 3.3. Configuration of the set-up parameters related to Test 2.

<table>
<thead>
<tr>
<th></th>
<th>X axis</th>
<th></th>
<th>Y axis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>αx</td>
<td>βx</td>
<td>γx</td>
<td>Emit. rms x</td>
</tr>
<tr>
<td></td>
<td>[mrad]</td>
<td>[mm]</td>
<td>[mm⁻¹]</td>
<td>[π mm mrad]</td>
</tr>
<tr>
<td>EXP:</td>
<td>-0.8609</td>
<td>0.6492</td>
<td>2.682</td>
<td>5.135</td>
</tr>
<tr>
<td>Trace Win</td>
<td>-0.6946</td>
<td>0.8064</td>
<td></td>
<td>0.0064</td>
</tr>
</tbody>
</table>

Table 3.4. Emittance and Twiss parameters along X and Y axes measured in the Test 2.

In the phase space plot of Fig. 3.20, less agreement between the TraceWin calculation has been observed and the emittance measurement, \( \varepsilon_{\text{rms,y}} = 6.28 \, \pi \cdot \text{mm-mrad} \), a 12.5% increase. We attribute this to the influence of the spherical aberration, which is greater when the quadrupole is overfilled as provided in this test. This effect will be discussed further in the next section.
The quadrupole triplet re-designed well behaves in the ion beam transport and no influences of the mechanical changes affect the optical performances. Despite this consideration, the new quadrupole triplet prototype shows an overall length of about 1.3 m (the same of the triplet installed on the off-line FE) and even though it will be used in the Laser Front End, a deep study of a possible optical changes could allow further improvements, especially in the reduction of the overall dimensions.

### 3.4 Preliminary optimization of the ratio $R/a$

Looking at the CAD model of Fig. 3.11, a number of changes in the mechanical design could reduce the overall length removing the einzel lenses at the ends and replacing the reducing flange section with a zero-length adapter were the obvious first changes. Unfortunately, greater reduction was needed, the removal of the inter-electrode aperture elements was investigated, reducing the inter-electrode gaps, and finally significantly reducing the length of the center electrodes, which were much longer than typical (more than 2.8 times the length of the outer elements), resulting in much higher voltages for the outer electrodes relative to the center elements. In order to shorten significantly the lengths of the quadrupole electrodes themselves, a reduction in the bore radius seemed prudent.
To evaluate the impact of the changes to the geometry, multiparticle simulations of ion trajectories have been run through several SIMION [3.16] models, investigating separately the effects of varying the center electrode lengths, of removing the inter-electrode grounded apertures, and of varying the bore, 2a, and electrode radii, R, of the triplets, namely the ratio R/a. The salient features of the configurations tested are listed in Table 3.5.

<table>
<thead>
<tr>
<th>Case</th>
<th>V_{Out}</th>
<th>V_{Ctr}</th>
<th>L_{Out}</th>
<th>L_{Ctr}</th>
<th>Gaps</th>
<th>R/a</th>
<th>Bore Dia.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3531</td>
<td>1587</td>
<td>170</td>
<td>480</td>
<td>40</td>
<td>1.15</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>3242</td>
<td>1615</td>
<td>170</td>
<td>480</td>
<td>40</td>
<td>1.15</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>3463</td>
<td>1744</td>
<td>170</td>
<td>480</td>
<td>14</td>
<td>1.15</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>3080</td>
<td>3020</td>
<td>170</td>
<td>280</td>
<td>28</td>
<td>1.15</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>1663</td>
<td>1643</td>
<td>170</td>
<td>280</td>
<td>28</td>
<td>1.73</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>1686</td>
<td>1667</td>
<td>170</td>
<td>280</td>
<td>28</td>
<td>1.15</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 3.5. Geometries tested in SIMION. The dimensions are in millimeters for the lengths and volts for the potentials. The subscripts “Out” and “Ctr” refer to the outer and center quadrupole elements, respectively. The inter-electrode apertures are only present in the Case 1 model, which corresponds to the origin CERN-ISOLDE EQT geometry.

The results of the first triplet simulation (Case 1) were also checked using the finite-element code COMSOL [3.17] to calculate the quadrupole fields, and then, using the resulting field-map data as input to the ion optics code TraceWin, a multiparticle tracking simulation was performed, with results agreeing quite well with SIMION.

To perform the SIMION particle tracking simulations a “standard 40 keV beam” has been generated, comprising a single 10,001-particle bunch of mass-132 ions having a 3D Gaussian distribution in position and with Gaussian distributions in the azimuthal and elevation angles as well. The same set of ions was run through each of the model cases listed in Table 3.5. The Twiss parameters for this set of ions are listed in the first row of Table 3.6 (Case 0). The beam was generated with identical initial conditions (an rms beam radius of 0.50 mm and rms beam divergence of 8.35 mrad) in the horizontal (x) and vertical (y) planes, and the differences between the corresponding x and y parameters of the initial beam are indicative of the statistics of the 10k-particle distribution. Two versions of the standard beam were run, one with and one without a Gaussian energy spread of 19 eV FWHM, but for clarity in the graphical results, the zero-energy-spread cases are what is report here. The simulations with the energy spread were negligibly different in the effective emittance growth. The emittance of this “standard beam” is typical of the plasma ion source that will be implemented at SPES. The standard beam was launched 1.0 m upstream from the center of each triplet, with initial centroid at \((x, y, z) = (0, 0, 0)\), and brought to a waist 1.0 m
downstream \((z = 2 \text{ m})\) from the center of the triplets by appropriate adjustment of the triplet voltages. The resulting Twiss parameters for the beam bunch at the waist in each case are listed in Table 3.6. The parameters are given in mm and mrad, with the areas of the emittance ellipses being \(\pi\) times the \(\varepsilon\)-values listed.

Looking at the results in detail, it becomes apparent that the inter-electrode apertures have very little impact on the effective emittance growth; the growth in Case 2 is only slightly larger than that of Case 1. Reducing the inter-electrode gaps also has a small effect; compare Cases 2 and 3. It is well known that the principal source of aberrations is the departure from the pure quadrupole field that results from the finite length of the physical quadrupoles. Even when the electrodes are shaped to form hyperbolic equipotential surfaces, a simple termination of the electrodes via cutting planes perpendicular to the optical axis introduces other (higher-order) multipole components to the electric fields. No shaping of the fringe fields can ameliorate this effect. It is quite common, therefore, for quadrupole lenses to be built with electrode lengths that are long relative to the bore of the lens. Comparing Cases 3 & 4 (and also Case 6), one can see the large increase in effective emittance that apparently results from violating this rule.

However, by relaxing the constraint that the equipotentials in the transverse directions (parallel to the x-y plane) be approximately hyperbolic, it seems that the effects of the undesirable multipoles, integrated over the length of the quadrupole, can be minimized. The geometries of Cases 5 and 6 are identical (the same length, bore and inter-electrode gaps), except for the bore-to-electrode radius ratio, \(R/a\). If it is primarily the length-to-bore ratio, \(L/2a\), that is driving the aberrations that result in the large effective emittance increases, then

<table>
<thead>
<tr>
<th>Case</th>
<th>(\alpha_x)</th>
<th>(\alpha_y)</th>
<th>(\beta_x)</th>
<th>(\beta_y)</th>
<th>(\varepsilon_x)</th>
<th>(\varepsilon_y)</th>
<th>(\sqrt{\varepsilon_x\varepsilon_y})</th>
<th>(\Delta\varepsilon/\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.002</td>
<td>-0.001</td>
<td>0.060</td>
<td>0.060</td>
<td>4.179</td>
<td>4.151</td>
<td>4.165</td>
<td>0.0%</td>
</tr>
<tr>
<td>1</td>
<td>0.002</td>
<td>-0.002</td>
<td>0.060</td>
<td>0.076</td>
<td>4.191</td>
<td>5.257</td>
<td>4.694</td>
<td>12.7%</td>
</tr>
<tr>
<td>2</td>
<td>0.000</td>
<td>0.000</td>
<td>0.060</td>
<td>0.081</td>
<td>4.191</td>
<td>5.631</td>
<td>4.759</td>
<td>14.3%</td>
</tr>
<tr>
<td>3</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.060</td>
<td>0.126</td>
<td>4.227</td>
<td>8.620</td>
<td>6.036</td>
<td>44.9%</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
<td>0.001</td>
<td>0.061</td>
<td>0.111</td>
<td>4.289</td>
<td>5.454</td>
<td>4.837</td>
<td>16.1%</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
<td>0.000</td>
<td>0.061</td>
<td>0.079</td>
<td>4.248</td>
<td>7.591</td>
<td>5.679</td>
<td>36.3%</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>0.000</td>
<td>0.061</td>
<td>0.111</td>
<td>4.248</td>
<td>7.591</td>
<td>5.679</td>
<td>36.3%</td>
</tr>
</tbody>
</table>

Table 3.6. Twiss parameters from the SIMION runs. Case 0 is the input beam. The last column shows the increase in the effective emittances, \(\sqrt{\varepsilon_x\varepsilon_y}\), of Cases 1 – 6 relative to the input beam, as measured at the downstream waists.
those two cases should have similar emittance results. However, Case 5, with \( R/a = 1.73 \), exhibited only a 16% increase, as compared with the 45% increase of Case 6. In fact, Case 5 is slightly better than the long, small-gap triplet of Case 3, and almost as good as the original EQT. Transverse phase-space plots of cases 1, 4, 5, and 6 are shown in Fig. 3.21. Only the \( y-y' \) phase planes are shown because the effects are greatest in these planes, given that the center EQT element is focusing in the \( y \) direction, and it is the center electrodes whose lengths are being shortened. To better visualize and compare the effects of the various geometries, an initial beam divergence that nearly filled the EQT in the \( y \) direction at the center of the triplet has been chosen. The phase-space plots show the classic, S-shaped distortion that results from the quadrupoles being over filled. The effect is most dramatic in the short triplets of Cases 4 & 6, which are the same length, but the bore of Case 6 is only 75% of the Case 4 bore. In other words, a 25% reduction in bore size and \( L_{Ctri}/2a \) ratio (with all other dimensions being identical), resulted in a 19% decrease in effective emittance growth.

Interestingly, when comparing Cases 5 and 6, for which the only difference in geometry is the \( R/a \) ratio (specifically, the two cases have the same \( L_{Ctri}/2a \) ratio), a 56% reduction in the emittance growth has been seen with the increasing of the \( R/a \) ratio by 50%. Looking at the Case 5 phase space plot, we see that the tails of the particle distribution are being compressed back toward the centroid of the phase-space area, a kind of “aberration correction” that presumably comes from increasing \( R/a \).

According to Banford, the choice of \( R/a = 1.145 \) will minimize the spherical aberration caused by the higher-order multipole field components. The result of this aberration is to decrease the focal length as the radius of the incoming particle beam increases. To illustrate this effect, a set of five ions was passed through each of the SIMION models in the cases described above, with their voltages set as before to produce a waist at \( z = 2 \) m. The ions all originated at \((0, 0, 0)\) but had elevation angles (in the \( y-z \) plane) stepping uniformly from \(-1.5^\circ\) to \(+1.5^\circ\). Plots of these trajectories overlayed on the EQT geometries of Cases 1, 5, and 6 are shown in Fig. 3.22, with a zoomed-in view of the focal points for Case 5 and 6 shown in Fig. 3.23. All of them, except for Case 5, clearly show the spherical-aberration effect, with the ions having greater divergence (and thus larger radii) coming to a focus earlier. In Case 5, all of the ions cross the beam axis at nearly the same \( z \), which is suggestive of a cancellation effect between the aberrations produced by the axially truncated electrodes and those due to the “non-optimal” transverse profile of the electrodes.

The uncompensated effect in these studies is that of the variation in ion energy along the
non-ideal trajectory that arises as the potential seen by the off-axis ions varies.

![Phase space plots](image)

**Fig. 3.21.** Phase space plots of the SIMION results for Cases 1, 4, 5, & 6. The smaller ellipses (in red online) are the rms and the larger (in green online) are the 95% ellipses. For clarity, only slightly less than half of the particles are plotted in each case.

![Ion trajectories](image)

**Fig. 3.22.** Representative ion trajectories through the SIMION models of Cases 1, 5, & 6. Ions all originated at (0, 0, 0) on the left in each figure, and the voltages were tuned in each case to produce a waist at the vertical mark on the right in each Case at \( z = 2 \) m.

No attempt was made to quantify and/or correct for this effect, which is a feature of all electrostatic beam transport elements.

A last item to point out is the comparison between the SIMION calculations and the measurements. In the two reported measurements, a 12.5% increase in the emittance has been noted when EQT2 has been overfilled. In the SIMION calculations, our input beam
was generated such that it similarly overfilled the EQT in the model. The model in Case 1 (see Table 3.5 and Table 3.6) corresponds to the EQT configuration used in the emittance measurements, and the value of the emittance increase for that simulation was 12.7%, a remarkable agreement between simulation and measurement. This gives us confidence, not only in our interpretation of the source of the effective emittance growth, but also ultimately in our conclusion that the design of the new, compact EQT will suffer no significant optical defects as compared with the original, proven EQT design.

### 3.4.1 Experimental test

In this section will be presented experimental tests based on the main results obtained in the numerical analyses above described. Since each case required the construction of different set of twelve electrodes, two main cases have been considered. In fact, the results of the previous analyses could be summarized in the plots of Fig. 3.24. The focal error and the emittance growth in the y direction show a maximum and minimum values for $R/a = 1.15$ and $R/a = 1.73$, respectively. These correspond to the Case 6 and Case 5 of Table 3.5.
Fig. 3.24. Numerical focal error and rms emittance for different electrode R/a ratio.

Despite the different electrodes geometry respect to the new triplet prototype (§ 3.3), the two aforementioned cases have been studied by the construction of 24 new electrodes, namely 12 electrodes for each case (Fig. 3.25a). In both cases, the length of the outer electrodes is equal to 170 mm and the center quadrupole elements have a length of 240 mm. The gap between adjacent quadrupole elements is 28 mm and the inner bore of the triplet is equal to 90 mm.

Fig. 3.25. Construction phase (a), cables insulation checking (b), assembly (c-d) and installation (e) of the modified electrodes with R/a = 1.15 and R/a=1.73 with bore aperture equal to 90 mm.

With the respect to the prototype main dimensions (Table 3.5 Case 1), a reduction of the overall dimension was obtained. Moreover, the prototype electrode assemblies were fixed to the triplet tank by means a not-adjustable system (§ 3.3.1). For these reasons, PVC adapters
have been constructed and connected to the electrode supports allowing to hold the new electrodes in the exact position of Case 5 and 6 (Fig. 3.25b-c-d). This solution allowed testing different triplet configurations by using the tank of the triplet prototype (Fig. 3.25e), saving time, preserving the triplet alignment respect to the beam line and allowed considering the same layout of Fig. 3.16.

Both Case 5 and Case 6 configurations have been studied by performing seven tests, each of which allowed focusing the ion beam in different points along the beam line. Moreover, each test provided the parameter setting which guarantees the same focusing for both Case 5 and Case 6. For example, test 1 of Case 5 shows the same focusing of test 1 of Case 6. Table 3.7 and Table 3.8 show the parameters set on the ETQ1 (electric potential on the quadrupole electrodes, Q1, Q2 and Q3), on the Wien filter (electric current and thus the magnetic field), on the ETQ2 (electric potential on the quadrupole electrodes, Q1, Q2 and Q3) and the emittance rms monitored by the emittance meter along both x and y directions.

<table>
<thead>
<tr>
<th>ETQ1</th>
<th>Wien Filter (inverted)</th>
<th>ETQ2 (R/a=1,15)</th>
<th>Emittance meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1, Q2, Q3, I WF, Hall Probe</td>
<td>Q1, Q2, Q3</td>
<td>εRMS,X, εRMS,Y</td>
</tr>
<tr>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[A]</td>
</tr>
<tr>
<td>Test 1</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 2</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 3</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 4</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 5</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 6</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 7</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
</tbody>
</table>

Table 3.7. Parameters set on the triplets and the Wien filter in the Case 6 configuration. Experimental emittance results of x and y direction are presented.

<table>
<thead>
<tr>
<th>ETQ1</th>
<th>Wien Filter (inverted)</th>
<th>ETQ2 (R/a=1,73)</th>
<th>Emittance meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1, Q2, Q3, I WF, Hall Probe</td>
<td>Q1, Q2, Q3</td>
<td>εRMS,X, εRMS,Y</td>
</tr>
<tr>
<td>[V]</td>
<td>[V]</td>
<td>[V]</td>
<td>[A]</td>
</tr>
<tr>
<td>Test 1</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 2</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 3</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 4</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 5</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 6</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
<tr>
<td>Test 7</td>
<td>1330</td>
<td>717</td>
<td>1330</td>
</tr>
</tbody>
</table>

Table 3.8. Parameters set on the triplets and the Wien filter in the Case 5 configuration. Experimental emittance results of x and y direction are presented.
The experimental emittance results reported in the table are the mean values obtained from the statistical analysis of thirty measurements. Fig. 3.26 and Fig. 3.27 show the results and the error bars of the emittances on the x and y directions for Case 5 and the Case 6. In both plots, data comparison allows showing the emittance growth reduction in the Case 5, namely where the quadrupole triplet electrodes have a ratio, $R/a = 1.73$. Furthermore, in both cases, moving from test 1 to test 7, the emittance rms decreases since the relaxation of the focal strength, i.e., the potential voltage applied to the electrodes. The plots show the capability of the triplet to transport and focus ion beams reducing the non-linear phenomena introduced by the truncation of the theoretical infinite length electrode. The results could be used to refine the quadrupole design allowing a reduction of the triplet overall length of about 30%. Due to the smaller bore aperture, the external diameter of the tank can also be
reduced of 10 %. From the mechanical point of view, it means lower manufacturing costs and a reduction in size, which become essential as Fig. 2.3 Fig. 2.35 and Fig. 2.63 shown.

### 3.5 Conclusion

The SPES Laser Front End is being built at LNL for the Knudsen cell mass spectroscopy. These ion beams will be transported to the diagnostic device via beamlines employing electrostatic quadrupole triplet for focusing of the singly charged, positive ions. A simplified, robust version of the CERN-ISOLDE electrostatic quadrupole triplet (ETQ) has been developed, resulting in significant improvements in the vacuum performance, as well the ease of assembly. The key point of the new design consist in a special double-flange systems which hold the electrodes, now directly assembled on the triplet tank. Additionally, a compact EQT based on this design has been developed by reducing the length and bore of the triplet, and by eliminating the internal, grounded electrodes and reducing the inter-electrode axial gaps as well. The measurements of the emittance of the Front-End EQT in our off-line test facility agree with the SIMION results, both validating the mechanical changes from the ISOLDE triplet and giving confidence in the simulations of the compact triplet. In the process of evaluating the various dimensional changes in the EQT, it was found that we could reduce phase space distortions and their associated effective emittance growths by increasing the electrode-radius-to-bore-radius ratio relative to the “standard” ratio of 1.145. This surprising effect warrants further study, and measurements of beam profiles and emittances are planned at LNL for the near future, along with a systematic simulation study, to confirm these results.
References


Chapter 4

Preliminary design of vacuum and gas recovery systems

4.1 Introduction

The Laser Front End has been designed accordingly to the mechanical and physical requirements which allow off-line tests using stable atoms. The high temperature reached by the Knudsen cell during operations, which is made of graphite, makes the pressure inside the vacuum chamber one of the most important aspects in the system functioning. Moreover, the particle loss, due to the interaction between the ion beam and the residual gasses, is strongly affected by the vacuum level achieved in the beam pipes. Furthermore, future upgrades will provide the use of radioactive ions as well, therefore increasing the complexity of the system since additional radioprotection shrewdness have to be considered. The Laser Front End, as it has been designed, requires the design and the installation of both the vacuum system and the gas recovery system, where gasses pumped out should be stored. Both vacuum lines and gas storage tanks have been designed to work in a range of pressure lower than the atmospheric ones. Here below, the CAD model of the Laser Front End preliminarily used for the deposition and ionization tests shows the presence of two turbomolecular pumps (Fig. 4.1). Since most of the devices developed and here described have been designed simultaneously, the vacuum and gas recovery system have been studied by considering an

Fig. 4.1. CAD model of the Laser Front End system.
equivalent system, namely the off-line SPES Front End, which is already installed in the LNL laboratory and for many aspects similar to the Laser Front End configuration. This condition allows testing different solutions according to the requirements of safety, performances and devices reliability. In the next paragraphs a brief introduction of the vacuum technology will be followed by the description of the test bench used for the vacuum tests. The results will be used to design the fore vacuum line accordingly both to the pumps performances and to the available space in the laboratory. The fore vacuum line implementation will be presented as well as the preliminary design and tests of the gas recovery system. Finally, failure test will be presented, showing the impact of the pumps failure on the vacuum level during operations.

### 4.2 Vacuum technology [4.1][4.2]

A vacuum is defined as a diluted gas, or the corresponding state at which its pressure or density is lower than of the ambient surrounding atmosphere. The gasses behave inside a vacuum chamber or pipe characterize the vacuum system design, the final pressure achievable and the time needed to reach the stable conditions. The fundamental lows govern the gas distribution inside a vessel are strongly affected by the vessel dimensions, the type of flow and by the gas state.

Gas flow is generally intended as the quantity of gas flows through an isothermal plane per time unit. Usually volumetric flow, $F$, is defined as:

$$F = p \frac{dV}{dt} \ [\text{mbar m}^3/\text{s}] \quad (4.1)$$

Where $p$ is the pressure measured on the reference plane and $dV/dt$ is the volume variation per time unit. It is thus clear the gas flow is proportional to the number of particles move through the isothermal plane. In fact, the general gas equation, which describes the state of a gas as a function of the pressure and the volume, is provided by the following equation:

$$p \cdot V = \frac{m}{M} \cdot R \cdot T = n \cdot V \cdot k \cdot T \quad (4.2)$$

Thus:

$$p = n \cdot k \cdot T \quad (4.3)$$
Where:

- \( p \) = pressure [Pa].
- \( V \) = volume \([m^3]\).
- \( m \) = mass [kg].
- \( M \) = molar mass [kg/kmol].
- \( R \) = general gas constant \( R=8.314510 \) kJ/(kmol K).
- \( T \) = thermodynamic temperature [K].
- \( n \) = molecular number density \([1/m^3]\).
- \( k \) = Boltzmann’s constant \( k = 1.380 \times 10^{-23} \) J/K.

The gas flow, \( F \), or the gas mass flow, \( F_m \), of equation (4.1) become:

\[
F = \frac{dN}{dt} k T \quad \text{or} \quad F_m = \frac{dN k TM}{dt RT} \tag{4.4}
\]

It should be noted that the pressure is proportional to the molecular number density and due to the high number of molecules per unit of volume at standard condition, under vacuum conditions molecules are still present. For this reason, the types of gas flow in vacuum is determined by the mean free path length, \( \bar{T} \), that a molecule traverses between two successive impacts with other molecules. It depends upon molecular diameter, \( d_m \), and temperature, \( T \), in accordance to the following equation:

\[
\bar{T} p = \frac{k T}{\pi \sqrt{2} d_m^2} \tag{4.5}
\]

### 4.2.1 Laminar, Knudsen and Molecular flows

The three types of gas flow occur in vacuum are a function of the pressure, the mean free path and the component dimension, \( d \) (see Fig. 4.2). The latter is intended as the diameter of a theoretical aperture in which the gas flow takes place.

**Continuous flow in low vacuum** corresponds to a pressure in the range of \( 10^3 - 10^6 \) mbar, where \( \bar{T}<<d \). What characterize continuous flow, as well as viscous flow, is frequent contact between gas molecules and less frequent contact with the walls of the vessel. In this case, the mean free path of the gas molecules is significantly shorter than the dimension, \( d \), of the vacuum chamber. For this reason, the Knudsen number, \( Kn \), is defined as the ratio between the mean free path and the component diameter:
In the continuous flow, the Knudsen number \( \text{Kn} < 0.01 \). If the product between the pressure and the diameter of the components \((p \cdot d) \geq 6 \times 10^{-1} \text{ mbar} \cdot \text{cm}\), then the flow could be considered viscous. The viscous flow is also defined laminar or turbulent depending on whether the value assumed by the Raynolds number. Turbulent flow usually occurs in vacuum system during the starting operation at high pressure and this process necessitates of pumps which produce higher volume flow rates.

**Knudsen flow in medium vacuum** corresponds to a pressure in the range of \(10^0\) - \(10^{-3}\) mbar, where \( \bar{T} \leq d \). This type of flow is related to a Knudsen number which varies between 0.01 and 0.5. It frequency occurs since many process pressures are in the medium vacuum range. Typically, the Knudsen flow is a transient stage coming up during pumping down of vacuum chambers. This means that the influence of the conductivity on pump-down times is correspondingly low. The calculation of pipes conductivity when both laminar and molecular flows coexist is affected by other parameters, whose knowledge not always gives precision information on the pressure distribution. Usually, it is common practice approximating the conductance as the mean value of the conductance referred to the laminar and molecular flows.

**Molecular flow in high vacuum** \((p = 10^{-3} - 10^{-7} \text{ mbar}; \bar{T} > d)\) and in **ultra-high vacuum** \((p < 10^{-7} \text{ mbar}; \bar{T} > > d)\). Here no longer molecular interactions occur and simultaneously molecular flow prevails. The product between the pressure and the component diameter, \(p \cdot d \leq 1.3 \times 10^{-2} \text{ mbar} \cdot \text{cm}\).

### 4.2.2 Gas Flow through pipes: conductance equations

Generally, vacuum chamber are connected to a vacuum pump via piping. Flow resistance occurs as a result of external friction (gas molecules-wall surface) and internal
friction (molecules-molecules). It emerged that the flow rate through a tube depends on the pressure difference at the ends of the piping, as well as the diameter of the tube and the gas state. To describe the conductivity of pipes it is necessary to introduce the conductance, C, expressed as the ratio between the flow rate, F, and the pressure difference between the piping ends:

\[ C = \frac{F}{(p_1 - p_2)} \] (4.7)

Usually, conductance C is expressed in litre per second or, less frequently it is expressed in m³/s in accordance to the International System (SI). Since the conductance could be easily calculated, the gas flow is thereby obtained by the product between the conductance and the pressure difference. Eq. 4.7 becomes thus extremely important in the molecular flow calculations since the conductance is independent from the pressure.

**4.2.2.1 Continuous flow**

The gas flow equation related to the continuous laminar flow through a straight-lined pipe of diameter d, is provided by the Poiseuille’s equation as follows:

\[ F = \frac{\pi d^4 \bar{p} (p_1 - p_2)}{(128 l \eta)} \text{ [SI: Pa m}^3\text{/s}] \] (4.8)

Where:

\( \bar{p} = (p_1 + p_2)/2 \) is the mean value of the pressure registered on the pipe ends (\( p_1 \) and \( p_2 \)).

\( d \) = inner diameter of the pipe.

\( l \) = piping length.

\( \eta \) = gas viscosity.

From eq. 4.7 and eq. 4.8, the conductance is thus calculates as:

\[ C = \frac{\pi d^4 \bar{p}}{(128 l \eta)} \text{ [SI: m}^3\text{/s}] \] (4.9)

For dry air at 273 K the equation become:

\[ C = 1357.8 \frac{\pi d^4 \bar{p}}{l} \text{ [SI: m}^3\text{/s}] \] (4.10)
The equation could be used if the length of the tube is much greater than the pipe diameter ($l >> d$) and the maximum error in the conductance calculation is less than 10% if $d \cdot \bar{p} > 0.66 \text{ Pa m}$. It should be noted that in this flow condition the conductance is a function of the piping dimensions, the gas viscosity and the mean pressure. Moreover, the Poiseuille’s equation is based on the hypotheses of constant gas density, constant gas flow rate and laminar flow.

The gas flow in turbulent condition, follows the Fanning’s equation, which is defined as:

$$F = \frac{\pi}{4} \sqrt{\frac{(p_1^2 - p_2^2)}{f \cdot p \cdot l}} \text{ [SI: Pa m}^3 \text{/s]} \quad (4.11)$$

The conductance, keeping in mind eq. 4.7, is then defined as:

$$C = \frac{\pi}{4} \sqrt{\frac{2 \bar{p}}{(p_1 - p_2)} \cdot \frac{d^5}{f \cdot p \cdot l}} \text{ [SI: m}^3 \text{/s]} \quad (4.12)$$

Where:

- $\rho'$ = is the gas density for unit of pressure $[\text{kg m}^{-3} \text{ Pa}^{-1}]$.
- $f$ = is the Fanning friction factor.
- $\bar{p} = (p_1 + p_2)/2$ is the mean value of the pressure registered on the pipe ends ($p_1$ and $p_2$).
- $d$ = inner diameter of the pipe.
- $l$ = piping length.

### 4.2.2.2 Molecular flow

The molecular flow is characterized by the molecules-walls interactions, which are predominant in reference to the molecules-molecules collisions. Conductance no longer depends on the pressure, while piping dimensions and molecules velocity are the two main parameters in this flow condition. Conductance is therefore an intrinsic property of both piping and gas. It follows that the gas flow is merely proportional to the pressure difference between the piping ends (eq. 4.7).

For a long pipe, where its length, $l$, is much greater than the dimensions characterize its transversal section (area $A$ and perimeter $H$), the general equation describes the gas flow has been formulated by Knudsen:
Preliminary design of vacuum and gas recovery systems

\[ F = \frac{4}{3} \frac{v_m (p_1 - p_2)}{\int_0^l (H A) \, dl} \]  

(4.13)

The conductance is thus:

\[ C = \frac{4}{3} \frac{v_m}{\int_0^l (H A) \, dl} \]  

(4.14)

Equations (4.13) and (4.14) have to be modified by introducing the term \( K_f \), which considers the shape of the piping cross section. This factor is equal to 1 for circular pipe, while it becomes greater than 1 for other geometries. The most common vacuum applications are referred to circular long tubes and solving the eq. 4.14, the corresponding conductance is:

\[ C = \frac{1}{121} \frac{\pi d^3 v_m}{l} \]  

(4.15)

For dry air at 273 K a simplified formulae could be calculated as:

\[ C = 11.62 \frac{d^3}{l} \text{ [l/s]} \]  

(4.16)

If the pipe length is not much greater than its diameter (short tube), then the conductance equation has to be correct since the inlet and outlet impedances reach a not negligible value. Moreover, in presence of pipe elbow, the conductance increases since some particles travel in the opposite direction of the flow. In the first case, an equivalent pipe length of \( l + \frac{4}{3}d \) has to be used for the calculations, while in the second case the equivalent length of the pipe should be equal to \( l + 1.33d \). In the last case, if the length is much greater than the pipe diameter, the correction is basically irrelevant.

**4.2.2.3 Knudsen flow**

Since the complexity of the analytic treatment, which gives the equation of the conductance for the Knudsen flow, it is common practice to estimate the conductance as the sum of the conductance would have been calculated for both the continuous and molecular flows.

The equations above described will be used for the fore vacuum line design according to the pumping speed of the pumps.
4.3 Low-vacuum line design

The Laser Front End provides the ionization of atoms which are obtained by the evaporation of solid sample. This process is provided by controlling the temperature of the Knudsen cell. The latter, which is mainly composed by two graphite halves, is heated up to 2000 °C by mean Joule effect. The high temperature reached requires the absence of residual gasses in the vacuum chamber, especially oxygen, to avoid the cell igniting. Moreover, the vacuum level affects the particle loss in the ion beam transport. This conditions fix the ultimate pressure value achievable, which has to be lower than $10^{-6}$ mbar. The pressure level is guaranteed by the using of turbomolecular pumps. In fact, turbomolecular pumps work on the principle that gas molecules can be given momentum in a desired direction by repeated collision with a moving solid surface. The rapidly spinning fan rotor hits gas molecules from the inlet of the pump towards the exhaust in order to create high-vacuum in the chamber. The turbomolecular pump performances are influenced by the total gasses to be pumped out and by the pressure guaranteed in proximity of the pumps outlet. For these reason, in vacuum technology turbomolecular pumps are commonly coupled to a primary pump, allowing a low pressure, usually in the order of $10^{-2}$ mbar, on the turbopump outlet. The primary pumps also play a fundamental role in the rough-vacuum or fore-vacuum generation. In fact, turbopumps are connected to the vacuum chamber by means a gate valves, once the pressure in the chamber is lower than $10^{-3}$ mbar. From the turbopumps datasheet, higher inlet pressure is allowed if water cooling systems are provided to the turbopumps.

The Laser Front End is equipped with two turbomolecular pumps, which are installed on the Time of Flight chamber and on the diagnostic box, respectively. Since the large inner volume of the system, the rough vacuum (from 1000 to $10^{-2}$ mbar) means a huge quantity of gas. Moreover the rough vacuum operations are performed before the Knudsen cell heating and the laser ionization. Therefore, also by using radioactive species, the rough vacuum gasses could be expelled directly to the environment after radioprotection checks. Contrary, once the Laser Front End operates, a direct discharge of the radioactive gas mixture pumped out by the turbopumps and by their backing primary pumps into the atmosphere is not allowed. This requires the design of a storage system, the Gas Recovery System (GRS), in order to reduce the gas radioactivity before to expel the gasses in the atmosphere. Moreover, for safety requisites, in both vacuum and gas recovery systems the pressure are always maintained under the atmospheric ones, avoiding leak which could be contaminate the surrounding environment. In addition, the primary pumps have to be installed far from the
Laser Front End room, allowing maintenance operations and reducing the activation of the pumps due to the high level of radiation.

The vacuum system design have been performed by using the off-line SPES Front End as a test bench useful to design all the single apparatus.

### 4.3.1 Vacuum layout of the off-line Front End

The off-line SPES Front End is shown in Fig. 4.3. Four turbomolecular pumps are installed on it allowing a pressure of $10^{-7}$ mbar during operations. The turbopump TP0 (Adixen ATH 300 with a pumping speed $S_{TP0}=250$ l/s referred to $N_2$ [4.3]) is installed on the protractive channel, while the pump TP1 (Adixen ATH 400 with a pumping speed $S_{TP1}=400$ l/s referred to $N_2$) is fixed to the steerers box nearby the target ion source system. Under the quadrupole triplet we find the pump TP2 (Edwards STP-A803/A 1303 series with a pumping speed $S_{TP2}=1300$ l/s referred to $N_2$ [4.4]), while after the Wien filter the turbopump TP3 (Oerlikon TURBOVAC MAG W 600 with a pumping speed $S_{TP3}=550$ l/s referred to $N_2$ [4.5]) is installed on the diagnostic 6-way standard cross.

![Fig. 4.3. Layout of the off-line SPES Front End and pumps location.](image)

The total pumping speed, $S_t$, is obtained as the sum of the single pumps speed and it is equal to 2500 l/s ($N_2$). Each turbopumps is served by a multi-stage roots primary pump, PP2, (Adixen ACP 28). The configuration of each pumping station is presented in Fig. 4.4. The vacuum chamber is connected to the pumping station by means a gate valve equipped with a by-pass inlet system. The by-pass system allows performing both the fore-vacuum and the
high vacuum by means the use of a single primary pump. In fact, starting from the atmospheric pressure in the chamber, the pneumatic valves are switched in order to connect the primary pump to the vacuum chamber (blue dotted line Fig. 4.4). Once the pressure reaches $10^{-2}$ mbar, the pneumatic valve VF2 will be closed and the primary pump connected to the turbopump outlet (VB2 open). In the starting phase, the turbopump reaches the maximum rotation speed and the following valve V2 opening brings the pressure to $10^{-7}$ mbar (red dotted line Fig. 4.4). Two different types of vacuum head, Pirani and cold cathode Penning gauges, are used to monitor the pressure in the vacuum chamber and at the turbopump outlet. Additional barometer allows a fast pressure checking, useful for the operator inspections during the experiments. The pressure switch, contrary, gives information to the PLC allowing to execute the command to perform different operations (fore-vacuum, high-vacuum or operations stopping). The venting operation, namely the process which supplies dry air in the chamber until the atmospheric pressure, is obtained by the opening of the electro pneumatic valve VR2. The gasses flow is controlled by the use of a variable leak valve coupled to a gas filter, avoiding shock waves and dust in the vacuum chamber, respectively.

**Symbols**

- **HV.2.B1**: high vacuum gauge
- **FV.2.B2**: low vacuum gauge
- **FV.2.B3**: low vacuum gauge
- **PS.2**: pressure switch
- **BR.2**: barometer
- **VR2**: electro pneumatic valve
- **V2**: electro pneumatic gate valve
- **VF2**: electro pneumatic valve
- **VM2**: valve, manually actuated
- **VB2**: electro pneumatic valve
- **TP2**: turbomolecular pump
- **PP2**: primary pump

Fig. 4.4. Illustration of a section of the off-line Front End vacuum system.

In this configuration the primary pumps are installed close to the turbopumps under the Front End frame. In the next section the fore-vacuum line design will be presents, as well as the vacuum layout and its installation.
4.3.2 Design and installation of the low-vacuum line

The main purpose of the fore-vacuum line design is to split the backing and rough vacuum lines in two stand-alone vacuum lines provided by two different primary pumps, allowing to store only the gasses pumped out by the turbopumps, with a reduction of the storage tanks volume. Moreover, both backing and fore vacuum primary pumps have to be installed in a dedicated room, where maintenance operations could be safely performed since the low level of radiation. In the other hand, the pumping speed of the primary pumps is strongly affected by the piping diameter and length, namely the piping conductance. Fig. 4.5 shows the vacuum system layout modified for these purposes. It should be noted the difference between the modified layout and the corresponding old solution (Fig. 4.4). The piping length, L, is approximately equal to 20 m, which is the distance from the Front End to the primary pumps.

The functioning of all the devices involved in the vacuum system depends on the level of pressure guaranteed by the primary pumps at the turbopumps outlet. Since the length of the pipe has been fixed, the other parameter affects the piping conductance is the inner diameter of the tube. Here below are presented the calculations on the basis of which the main dimension of the piping have been fixed.

Input data and hypotheses.
- \( p_{FE} = 10^{-6} \text{ mbar} \) → Ultimate pressure achievable in the vacuum chamber;
- \( St = 2500 \text{ l/s} \) → Total pumping speed of the turbopumps. It is the sum of each turbopump speed in accordance to the operating pressure (\( 10^{-6} \text{ mbar} \)) and referred to \( N_2 \);
- \( L = 20 \text{ m} \) → Pipe length from the turbopump outlet to the primary pump inlet;
- Piping diameter = 25 mm or 40 mm.

Calculation procedure
- \( F = (p_{FE} \cdot St) = 2.5 \times 10^{-3} \text{ mbar l/s} \) → Gas flow pumped out by the turbopumps.
- From the datasheet of Fig. 4.6, this flow rate is guaranteed by the primary pump at \( 2.2 \times 10^{-2} \text{ mbar} \) (pressure \( p_2 \) which correspond to the pressure monitored by the vacuum gauge FV.B.F2 of Fig. 4.5 at the primary pump inlet).
- For a piping diameter, \( d \), equal to 25 mm and in the hypothesis of a mean pressure, \( \bar{p} \), between the primary pump inlet and the turbopump outlet equal to \( 3 \times 10^{-2} \text{ mbar} \), the product \( \bar{p} \cdot d = 0.075 \text{ mbar} \cdot \text{cm} \), which correspond to the Knudsen flow condition (§ 4.2.1).
Fig. 4.5. Layout of the re-designed vacuum system, where the fore-vacuum and backing line are now separated. The primary and turbopumps distance is represented by the length L.
The conductance of the pipe should be calculated as the mean value of the conductance would have been calculated for the molecular and laminar flows by using eq. 4.10 and eq. 4.16, respectively. The conductance, C, thus results equal to 0.087 l/s.

From eq. 4.7, the pressure at the turbopump outlet can be calculate as:

\[ p_1 = \frac{F}{C} + p_2 = 5.9 \times 10^{-2} \text{ mbar} \]

Pressure \( p_2 \) corresponds to the pressure measured by the vacuum gauge FV.B.F2 of Fig. 4.5 at the turbopump outlet. This result allows the functioning of the turbopumps without additional water cooling system. The mean pressure \( \bar{p} = \frac{p_1 - p_2}{2} = 3.1 \times 10^{-2} \text{ mbar} \), which is in agreement with the initial mean pressure assumption.

If the pressure \( p_{1,\text{max}} = 1 \text{ mbar} \), namely the maximum pressure allowable at the turbopump outlet, the maximum gas flow \( F_{\text{max}} = (p_{1,\text{max}} - p_2) \frac{F}{C} = 11.13 \text{ mbar l/s} \). The pressure at the turbopump inlet become \( p_{\text{TP,IN}} = F_{\text{max}} / S_i = 4.3 \times 10^{-3} \text{ mbar} \) and it is lower than the pressure at which the gate valve is usually opened. Therefore, the piping allows the good functioning of the turbopumps even in extremely outgassing condition.

Despite the results aforementioned, DN 40 standard tubes have been used for the piping installation in order to increase the conductance of the overall system and allowing better condition during vacuum operations.

Vacuum components, as electro pneumatic valves, vacuum gauges, nipples, corrugate hose, etc. have been installed following the layout of Fig. 4.5 by using ISO-KF, ISO-CF and ISO-F flanges coupled to metal or Viton® gaskets.

Fig. 4.7a shows a section of the vacuum system. It should be noted the paths of the fore-vacuum and backing lines, namely the blue and red dotted lines, respectively. A series
of corrugate hoses connect the vacuum lines to rigid DN 40 standard pipes, which follow the room walls until the primary pumps. Here, others corrugates hoses allow the connection of the multi-roots pumps, where the vacuum gauge FV.B.F2 (see Fig. 4.7c and Fig. 4.5) could measures the low pressure on the primary pump inlet (backing line). Contrary, the low pressure vacuum gauge FV.B.F1 (see Fig. 4.7 and Fig. 4.5) allows monitoring the pressure at the turbopumps outlet. As it could be seen from Fig. 4.7b, the rigid pipes bending means an increasing of the piping impedance, which is however negligible since the considerable length of the tubes (~20 m) as described in §4.2.2.2. Is important to underline the turbopump TP1 outlet is the point where the others turbopumps outlets converge. This means the pressure measured by the vacuum head FV.B.F1 could not register the pressure drop along the hoses which connect the fore-vacuum line to the outlet of turbopumps (TP0-TP1-TP3).

In the other hand, the hoses adopted for this purpose have a length in a range of 1-1.5 m and the vacuum impedance do not affect significantly the pressure drop.

![Diagram of vacuum system installation](image)

Fig. 4.7. a) re-designed vacuum system installation; b) fore-vacuum and backing lines paths; c) primary pumps installed 20 m far from the turbopumps.

The rigid pipes have been welded during the installation and an acid solution have been used for the piping cleaning. In fact, since they are made of stainless steel AISI304L, the benefits of this material for its low outgassing rate could be affected by the impurities due to the welding process. Moreover, dust and process residues are extremely dangerous for the primary pumps even though special filters and valves are installed on each pump inlet.
4.3.1 Experimental test of the low-pressure vacuum line

The vacuum system, which was obtained after the modifications and based on the theoretical calculations, have been tested by monitoring the pressure at the turbopumps outlet (vacuum head FV.B.F1) and at the primary pump inlet (FV.B.F2), respectively. This condition allowed verifying the low-pressure backing-line behaviour since the opening of the gate valves, complying with the vacuum requisites described in §4.3.2. The tests have been be performed following these steps (see Fig. 4.5).

1. Fore-vacuum: the pressure in the vacuum chamber rapidly decrease to $10^{-2}$ mbar by means the primary pump PP2. The pressure is monitored by Pirani vacuum heads (FV.0.D2, FV.1.A2, FV.2.B2 and FV.3.C2) nearby the by-pass of the gate valve (V0-V1-V2 and V3).
2. Turbopumps starting phase: simultaneously, the primary pump PP1 perform the vacuum in the turbopumps making the vacuum on themselves (gate valves are actually closed).
3. Fore-vacuum line shutdown: once the pressure in the vacuum chamber reaches $10^{-2}$ mbar, the by-pass is closed by means the electro pneumatic valves VF0, VF1, VF2 and VF3. The pressure in the chamber is guaranteed by the seals tightness. A tiny pressure raise could be registered in this phase because of the surfaces outgassing. The primary pump PP2 is turned off.
4. High-vacuum: the gate valves are opened and a very fast pressure drop is measured in the vacuum chamber by means penning vacuum head (HV.0.D1, HV.1.A1, HV.2.B1 and HV.3.C1).
5. Once gates valves are opened, the pressure on the backing line (between the turbopumps outlet and the primary pump inlet) is monitored until the stationary condition is reached.

The results of the two significant pump down tests are reported in Fig. 4.8. The plot shows the pressures measured since the opening of the gate valves. It should be observed the initial pressure values is about $10^{-3}$ mbar. This is a misleading information due to the high gas flow rate occurred once the gate valves are opened. In fact, the turbopump inlet in a high vacuum condition immediately find a large volume whose pressure is in the order of $10^{-2}$ mbar. Therefore, a wrong measurements of the pressure obtained by means the vacuum gauges occurs and after few second trustworthy measurements become available.
Fig. 4.8. Pump down curves referred to the pressures monitored on the low-vacuum line ends.

The black and green lines in the graph represent the pressure profile in the time at the turbopumps outlets (FV.B.F1 head). In the second run the pressure was always lower than the pressure monitored in the first run. This is mainly due both to the gradual cleaning of the piping and the reducing of the humidity inside the vacuum chamber. Notwithstanding this observation, no longer decreasing of the pressure in the time has been observed in the following tests. In the other hand, the pressure measured by the head FV.B.F2, namely close to the primary pump inlet (red line), remained clearly unchanged during different tests, the reason because only one curve is represented in the plot.

The pressure condition in the vacuum chamber at stationary condition, i.e. after 12 h from the beginning of the tests, were as following:

- \( p_{HV.0.D1} = 6.3 \times 10^{-7} \) mbar
- \( p_{HV.1.A1} = 6.4 \times 10^{-7} \) mbar
- \( p_{HV.2.B1} = 8.5 \times 10^{-7} \) mbar
- \( p_{HV.3.C1} = 6.5 \times 10^{-7} \) mbar

For simplicity, the curves are plotted in a range of time from 0 to 58 min which allow appreciating the “plateau” confirms the stationary condition achievement.
In both cases, namely the 1° and 2° runs, stationary conditions were reached after 25 min since the measurements starting. The comparison between the pressure estimated by the calculation and the pressure measured are listed in Table 4.1. The good accordance between the results confirms that the design of the low-pressure line allows the pumps functioning at standard rating condition. Furthermore, the pressure drop along the pipe is lower than that predicted by the calculations, which means a lower conductance of the piping. The reason could be explained in the use of DN 40 standard tubes instead of the DN 25, in accordance to the conductance equation where the numerator contains the diameter of the tube.

<table>
<thead>
<tr>
<th>Position</th>
<th>Theoretical pressure [mbar]</th>
<th>Experimental pressure 1° run [mbar]</th>
<th>Experimental pressure 2° run [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbopump Outlet</td>
<td>$p_2 = 5.9 \times 10^{-2}$ mbar</td>
<td>$p_{FV.B.F1} = 5.2 \times 10^{-2}$ mbar</td>
<td>$p_{FV.B.F1} = 4.8 \times 10^{-2}$ mbar</td>
</tr>
<tr>
<td>Primary pump inlet</td>
<td>$p_1 = 2.2 \times 10^{-2}$ mbar</td>
<td>$p_{FV.B.F2} = 4.0 \times 10^{-2}$ mbar</td>
<td>$p_{FV.B.F2} = 4.0 \times 10^{-2}$ mbar</td>
</tr>
</tbody>
</table>

Table 4.1. Comparison between the theoretical and experimental pressures evaluated on the low-vacuum line ends.

In Fig. 4.9, a close view of the pump down monitoring is shown. The pressure at the primary pump inlet reached quite fast the stationary condition, while the pressure at the turbopump outlet decreased in the time until a pressure of $4.0 \times 10^{-2}$ mbar was achieved. At a
glance, it could be in conflict with the equation describe the gas flow through piping. The gas flow, F, could be calculated indeed as the product between the primary pump pumping speed and the pressure monitored at its inlet. This pressure is constant as the plot shows and the pumping speed, which is a function of the pressure, is constant as well. For all these reasons, the gas flow assumes a specific value in the range of 7 – 28 min. Contrary, the pressure at the turbopump outlet decreases gradually in this range of time. From eq. 4.5, if the pressure drop decreases, then even the ratio F/C decrease (C is the piping conductance) and since the gas flow is constant, the increasing of the conductance is the only way to satisfy the equation. An explanation of the conductance variation in the pump down phase could be found in the Knudsen flow nature. In fact, at this level of vacuum the gas flow is typically between the continuous and molecular flows, which means the conductance is partially affected by the pressure drop at the piping ends. From the experimental data, the gas flow is equal to the product between the mean pressure in the chamber (7×10^{-7} mbar) and the total turbopumps pumping speed (2500 l/s), which is equal to F = 1.75 10^{-3} mbar l/s. Since the pressure drop is \( \Delta p = p_{FV,B,F1} - p_{FV,B,F2} = 5.2\times10^{-2} - 4.0\times10^{-2} = 1.2\times10^{-2} \) mbar, then the conductance of the piping results equal to C = F/\( \Delta p \) = 0.145 l/s.

**4.3.2 Pumps failure testing**

Generally, failure testing is a scheduled sequence of operations allows to study and verify the reliable of the system, where one or more devices, for example, fails. In the context of vacuum, the application of the failure testing is demanded since the turbopump failure could affect the pressure in the vacuum chamber. In the previous paragraphs the necessity to achieve and to maintain a pressure in the order of 10^{-6} mbar was widely stressed. In the Front End, as well as in the Laser Front End, this level of pressure preserves the integrity of devices at high temperature and it simultaneously reduces the particle loss in the ion beam transport. The instantaneous pressure increasing should not be considered a serious problem if the pressure do not exceed a certain level. In fact, for example, if the pressure rise up to 10^{-5} mbar, there are no reasons which would justify the system shutdown. Two different pressure limits have been fixed for this purpose. The first limit is referred to the pressure at the turbopumps inlet, namely the maximum pressure at which the turbopumps could work even assuming additional water cooling system. The maximum pressure have been fixed equal to 10^{-2} mbar. Obviously, operators have to manage properly this emergency situation and precautionary pumps showdown could be admitted even though the pressure do not exceed the limit and no PLC outputs are expected.
The other pressure limit, contrary, has been fixed equal to $10^{-3}$ mbar with regards to the maximum pressure allowable in the vacuum chamber during the target (off-line Front End) or the Knudsen cell (Laser Front End) heating. Therefore, the aforementioned limitation should be seen as the input signal for the power supply start/stop interlock function, which not affects the vacuum system.

The failure tests have been performed by using the off-line Front End, where only turbopumps TP1, TP2 and TP3 were running. The failures have been simulated by excluding the pumps from the vacuum chamber by manually closing the gate valves V1, V2 and V3. Different combination in the time have been tested following the scheme presented in the table of Fig. 4.10. It should be reminded the pumping speed of the pumps referred to N$_2$, which are: STP1 = 400 l/s; STP2 = 1300 l/s; STP3 = 550 l/s.

<table>
<thead>
<tr>
<th>Initial condition</th>
<th>opened</th>
<th>opened</th>
<th>opened</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td>closed</td>
<td>opened</td>
<td>00:04:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>00:19:00</td>
</tr>
<tr>
<td>Test 2</td>
<td>closed</td>
<td></td>
<td>opened</td>
<td>00:34:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>00:49:00</td>
</tr>
<tr>
<td>Test 3</td>
<td>closed</td>
<td>opened</td>
<td></td>
<td>01:04:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>01:19:00</td>
</tr>
<tr>
<td>Test 4</td>
<td>closed</td>
<td>opened</td>
<td>closed</td>
<td>01:34:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>01:49:00</td>
</tr>
<tr>
<td>Test 5</td>
<td>closed</td>
<td>opened</td>
<td>closed</td>
<td>02:02:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>02:03:00</td>
</tr>
<tr>
<td>Test 6</td>
<td>closed</td>
<td>opened</td>
<td>closed</td>
<td>02:38:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>02:57:00</td>
</tr>
</tbody>
</table>

Fig. 4.10. Illustration of the test bench coupled to the table which describes the tests carried out.

Besides, inside the target unit system both the tantalum box and the surface ion source were heated in order to reproduce the operating conditions. A target temperature of 2150 °C was reached by supplying a current of 1300 A (10.8 kW), while a current of 350 A (2 kW) in the second circuit allowed reaching a temperature of about 1580 °C on the ion source. The
purpose of the tests was not focused on the PLC slew rate assessment, but the heating of the system have been performed since it strongly increases the outgassing rate of the components nearby the turbopumps TP1. The pressure has been monitored in three different points by means the vacuum heads HV.1.A1, HV.2.B1, HV.3.C1 (see Fig. 4.5). The results of the pressures monitoring are illustrated in Fig. 4.11, Fig. 4.12, Fig. 4.13, Fig. 4.14, Fig. 4.15 and Fig. 4.16. From the plots of the different failure simulations, the stability of the system could be appreciated. In fact, the pressures never exceeds both the limits mentioned above. The worst case has been observed for the failure simulation of the turbopumps TP2 and TP3, whose pumping speeds are higher than the turbopump TP1 (Fig. 4.16). Despite this pumping deficiency, a pressure of $5 \times 10^{-5}$ mbar was the maximum registered by the vacuum heads. Furthermore, the vacuum gauges are installed on a DN 25 pipe, which branches off from the gate valves by-pass and this means a significant overestimation of the pressure inside the vacuum chamber.

It should also be outlined the unexpected behaviour of the pressure trend once the gate valve V1 has been closed (TP1 failure case of Fig. 4.13). The pressure read by the HV.1.A1 gauge raised, while the pressures measured by means the HV.2.B1 and HV.3.C1 heads slightly and unusually decreased. This behaviour occurs since the large difference in terms of pumping speed between the three turbopumps and because of the presence of a single backing primary pump. In fact, once the pump TP1 is “excluded”, at the turbopumps outlet the pressure decrease (the primary pump now backs only TP2 and TP3) and thus pumping performance improvements were achieved. Locally, these improvements have significant effects on the vacuum level compared with the lower contribution in pumping speed due to the TP1 absence. The low impact of TP1 on the pressure in the vacuum chamber is well appreciable looking at the curves of Fig. 4.13, where negligible pressure fluctuations were observed during the test.

As a conclusion of the backing-line design, the vacuum system layout of the off-line Front End (Fig. 4.5) will be a helpful and fundamental tool for the implementation of the Laser Front End vacuum system, despite the different number of turbopumps adopted. Moreover from the failure tests results, information of the pumping speed required for the Laser Front End could be deducted in relation to the lower volume to be pumped. Firstly, two turbomolecular pumps with a pumping speed of 550 l/s have been installed and they have been connected to an ACP28 primary pump, which is located 20 m far from the Laser Front End according to the layout scheme above illustrated. It is now ongoing the completion of the whole plant in order to test the system during the Knudsen cell functioning.
Fig. 4.11. Pressure monitoring during the simulation of the turbopump TP3 failure.

Fig. 4.12. Pressure monitoring during the simulation of the turbopump TP2 failure.
Fig. 4.13. Pressure monitoring during the simulation of the turbopump TP1 failure.

Fig. 4.14. Pressure monitoring during the simulation of the turbopumps TP1 and TP2 failure.
Fig. 4.15. Pressure monitoring during the simulation of the turbopumps TP1 and TP3 failure.

Fig. 4.16. Pressure monitoring during the simulation of the turbopumps TP2 and TP3 failure.
4.4 Gas Recovery System design

Vacuum is one of the most critical systems of a facility for radioactive ion beams production. The pumps have to produce and to maintain high vacuum condition in spaces where radioactive volatiles and their progenies are present. Moreover, some devices must operate in areas subject to extremely high radiation levels. Both these conditions pose stringent constraints on the characteristics of usable equipment. Accelerated radioactive beams and their contaminants carry radioactivity along all the beam pipes [4.6] [4.7]. However, in general, the level of contamination attenuates gradually moving away from the source. Gases emitted from the radioactive target may migrate along beam lines thus contaminating pipes, vacuum chambers and beam intercepting devices [4.8] [4.9] [4.10]. Vacuum pumps act as a filter for the radioisotopes; consequently, they could concentrate significant amounts of radioactivity, becoming themselves sources of external exposures and also of contamination risks not only during the operations, but also after the system shut-down [4.11]. The output of backing pumps can contain radioactive isotopes. Therefore, the delivered gasses must be checked and eventually stored up until their radioactivity has dropped to acceptable levels [4.12] [4.13] [4.14]. The same vacuum pumps maintenance could be critical, both when pumps are located in sites where high radiation doses are present and also when the radioactivity accumulated inside the pumps themselves become significant. Therefore a complete clothing and breathing protections during maintenance operations are required [4.15]. Contamination, even at lower level, may also be present in the whole beam line. This possibility makes it necessary a qualified preliminary contamination check before pumps or beam line venting [4.16]. It is thus clear that radioactivity is one of the most important issues in the study and design of a vacuum recovery system, especially in the time estimation which stored gas takes before a safety tank emptying is allowed. Moreover the level of radioactivity affects the reliability of all the components as pumps, electro pneumatic valves and elastomeric gaskets.

Despite the importance of the aforementioned item, here below the technical installation of a preliminary gas recovery system will be presented. The aims of the activities are to perform a preliminary feasibility study and to conduct experimental tests, thus verifying the possibility to store gasses with the respect of the pressure limitation in the whole vacuum system. In fact, possible leaks from the vacuum line to the environment should be avoided (the lines have to be sealed, but failures in components are always possible). For this reason the main boundary condition for the vacuum system design is that the pressure in the vacuum
lines have to be kept lower than the atmospheric pressure both during the operations and also after them. Similarly, as it is foreseen in other facilities as TRIUMF [4.17] and EXCIT [4.18], the pressure in the vacuum lines downstream the primary pumps as well as the pressure in the storage tanks will be kept lower than the atmospheric pressure.

### 4.4.1 Experimental test of the Gas Recovery System

In the following paragraph, experimental test data about the gas delivered by the backing pumps of the off-line Front End are reported. The knowledge of the gas build up is necessary both to design the Gas Recovery System (GRS) for the Laser Front End and to get familiar with different parameters on which the final design will be based. It should be underlined again that the Laser Front End differs from the off-line Front End both for the inner volume and for the number of turbopumps adopted. The Laser Front End is a smaller machine (§2.6.2) provided by two turbopumps which allow reaching the high-vacuum in the chamber. The results of the tests, therefore, should not be considered as the same would be obtained by using the Laser Front End, but they could give precious information of how the GRS should be designed. For this purpose, a modification of the test bench layout presented in Fig. 4.5 and Fig. 4.7 is below illustrated (Fig. 4.17).

![Test bench layout of the gas recovery system for preliminary gas loading estimation.](image)

The fore-vacuum line (black line) has been connected to the primary pump, whose function is to discharge the gas of the rough-vacuum directly into the environment. Contrary, the turbopumps backing-line (red-line) has been linked to the Gas Recovery System line
downstream the primary pump PP1. Only gasses coming from the turbopumps outlet have been collected and stored in 40 l volume tank. The description of the system and the preliminary leak test of the gas recovery system have been performed as following:

- The GRS, downstream the manual valve VM6, has been pumped down by means the primary pump PP3 up to reach of about $10^{-2}$ mbar as measured by pirani/capacitive pressure gauges G1 and G2. Here both manual valves VM7 and VM8 were opened and manual valve VM6 was closed. The turbopumps exhausting gasses were meantime discharged by the valve VM5.

- Subsequently, the GRS has been isolated after the valve VM8 closure. Fig. 4.18 shows the pressure rising in five hours and measured by the gauge G1. The initial sharp pressure increasing is due to the valve closing operation. Later on, the linear pressure build-up shows a growth of $8.83 \times 10^{-7}$ mbar/s, which gives an upper limit to the outgassing/leak rate of the isolate storage circuit of 0.076 mbar/day.

- The following step was the closing of the valve VM5 and the simultaneous opening of valves VM6, VM7 and VM8, in order to pump down the circuit downstream the primary pump PP1 by means PP3.

- The valve VM8 was closed and by means the gas dosing valve GDV1 air was blown into the system up reaching a pressure of few millibar, in order to start gas collection in a pressure range where outgassing and leaks in the stored circuit do not affect the gas throughput in an appreciable way. Once the desired pressure was reached, then valve GDV1 was closed in order to start measuring the pressure rise in the storage bottle.

![Fig. 4.18. Leak test of the tank used for the gas storage.](image)
The gas production measurements have been carried out simultaneously to other stress tests on the target ion source unit, which has been heated until its working temperature has been reached. The pressure monitoring on both backing-line and tank was started once steady-state condition was obtained in the vacuum chamber, namely a pressure of \( \sim 3 \times 10^{-6} \) mbar. A constant pressure of about \( 3 \times 10^{-2} \) mbar was registered upstream the primary pump PP1. Since the long-time taken by the tests and in compliance with the safety procedures, the target unit have been heated at 2000°C only during the day, while a temperature of 1600°C have been set at night.

The test has lasted 10 days and data acquisitions have been performed in the first 4 days and in the last 3 days while the system was working. The plots of the pressure measured each day by means the gauges G1 and G2 in the time are presented in the following figures. To the right of each plot, the pressure monitoring obtained by means the vacuum head FV.B.F2 in the same range of time is illustrated.

The first observation regards the pressure difference between the values registered by the gauges G1 and G2. In fact, since the empty tank works sucking the gasses coming from the pump PP1 outlet, the pressure drop is the results of frictional forces, caused by the resistance to flow, act on the fluid as it flows through the tube. It should be underlined that the pressure in the gas recovery system at the beginning of the test was 4 mbar, clearly referred to a continuous flow. This difference was approximately constant during all the test.

The second remark, instead, is referred to the gradually increasing of the pressure registered by the gauge FV.B.F2. While in the first day the pressure was equal to \( 7.5 \times 10^{-3} \) mbar, in the following days the pressure was raised up to a pressure of about \( 9.5 \times 10^{-3} \) mbar. This effect could be explained by the gradually tank filling. In fact, the greater the pressure at the primary pump outlet is, the greater will be the pressure at the primary pump inlet.
Fig. 4.21. Pressure trend inside the tank measured by the vacuum gauge G1 and G2 from 23 and 33 hours since the starting of the test.

Fig. 4.22. Pressure measured by the head FV.B.F2 at the primary pump inlet from 23 and 33 hours since the starting of the test.

Fig. 4.23. Pressure trend inside the tank measured by the vacuum gauge G1 and G2 from 48 and 57 hours since the starting of the test.

Fig. 4.24. Pressure measured by the head FV.B.F2 at the primary pump inlet from 48 and 57 hours since the starting of the test.

Fig. 4.25. Pressure trend inside the tank measured by the vacuum gauge G1 and G2 from 70 and 79 hours since the starting of the test.

Fig. 4.26. Pressure measured by the head FV.B.F2 at the primary pump inlet from 70 and 79 hours since the starting of the test.

Fig. 4.27. Pressure trend inside the tank measured by the vacuum gauge G1 and G2 from 194 and 199 hours since the starting of the test.

Fig. 4.28. Pressure measured by the head FV.B.F2 at the primary pump inlet from 194 and 199 hours since the starting of the test.
A further evidence is obtained comparing the present data to the pressure measured in the previous test (Table 4.1), where the primary pump PP1 discharged the gas directly to the environment at atmospheric pressure. Here, the pressure at the primary pump inlet was higher than in this case of one order of magnitude.

Fig. 4.33 summarizes the pressure growth in the tank monitored by the vacuum head G1 in all the 10 days of measurements. During the first two days a faster pressure rising has
been registered, before decreasing in the following days until a uniform linear growth have been reached. Despite the reasons of this initial deviation from the linearity are not clear, it is probably the results of the long time needed to reach stationarity conditions in the tank after its emptying, since the small diameter of the connection nozzle which is equal to 1.5 mm. From the line of best fit showed in Fig. 4.33, the pressure rising speed is thus estimated equal to 5.85 mbar/day, namely 6.77×10⁻⁵ mbar/s, which is much greater than the pressure growth rate obtained by the leak test of the tank (8.83×10⁻⁷ mbar/s - Fig. 4.18). Since the lower volume of the connecting pipes (green line - Fig. 4.17) compared to the tank volume (40 l), the amount of gas stored per unit of time is equal to 240 SCCM/day.

The absence of pressure growth during the night clearly evidences the irrelevance of both target and ion source temperature in the gas production (the Knudsen cell shows similar thermal fields). Therefore, the gas production could be mainly referred to the outgassing of the off-line Front End surfaces, since to the low leak rate in the gas recovery system (less than 10⁻⁹ mbar l/s/junction). As a matter of fact, the ACP28 leakage (data sheet value is 5×10⁻⁷ mbar l/s) should be at least an order of magnitude lower than the gas rate stored in the tank.

As a conclusion of this paragraph, the tests performed on the test bench of the gas recovery system have given information on the amount of gas which has to be stored considering the off-line Front End. Moreover, they have given the possibility to define and to refine the GRS test bench layout which will be used to design vacuum system of the Laser Front End, once it will be completed.

### 4.4.2 Preliminary layout of the Vacuum and Gas Recovery systems

In this paragraph, the main features of the Gas Recovery System for the Laser Front End will be presented. Fig. 4.34 shows the preliminary layout of the storage system which will be finalized once complementary study based on the radioprotection aspects will be performed. The layout is based on the EXCYT/INFN-LNS storage system. The double-walled tanks allow pressure measurement in the gap, thus permitting to detect possible leaks of the inner shell. Since the pressure in the vacuum line downstream the primary pumps varies in a range of 0.1 - 980 mbar, an expansion vessel is provided in order to avoid overpressures in case of sudden accidental air vent in the vacuum chamber. Furthermore, it could control possible pressure waves generated by the commutation between backing and fore-vacuum lines during the operation. The vessel will be designed
considering the total turbopumps pumping speed, the maximum pressure in the vacuum chamber (§ 4.3.2) before the interlock switch activation and the time that the gate valves take to completely isolate the Laser Front End (approximately 2 s). Additional conductance control valve is provided downstream the vessel and it is retroactively actuated by means a control unit in order to assure a pressure in the vacuum line below the fixed limit. In the layout, double valves and double pumps installation allow increasing redundancy and thus the system safety. Filters have also to be introduced before the storage tank, allowing to reduce the radioactivity level before gasses storing. This will reduce the tank contamination with a consequent ease of regular maintenance. Three tanks are connected by means pipes and a piston vacuum pump affords both the gas transfer from a tank to another after isotopes decay and the gas discharging to the chimney.

![Diagram](image)

**Fig. 4.34. Preliminary layout of the Gas Recovery System.**

The rough vacuum could be stored as well if the radioactivity during the initial operations will not be compatible with the limitation imposed by the law. For this purpose, one of the three tank will be characterize by a larger volume compared to the other two, since
the higher pressure in the vacuum chamber for a given pumping speed. The plant shows many vacuum gauges along the vacuum pipes for a continuous pressure monitoring.

The present layout should be the starting point of a more detailed design which necessitates a strong collaboration between different working groups in order to integrate different mechanical, electronical and nuclear aspects. Ongoing activities are aimed to this purposes with reference to the preliminary study above described.

4.5 Conclusion

In this chapter the preliminary Laser Front End vacuum system design have been developed by means calculations provided the impedance of all the main parts in reference with vacuum pipe constrains and types of pumps adopted. The plant layout has been carried out considering the available space and the performances of the pumps, which limit the length of the pipes between primary and turbomolecular pumps. The vacuum system has been constructed and then tested using the off-line SPES Front End as a test bench, since it represents the worst conditions in terms of outgassing rate. In the off-line Front End, since the high temperature on several components, high level of vacuum is required inside the beam line (about $10^{-6}$ mbar). Moreover, the lower is the pressure in the beam pipe and lower will be the particle losses due to the interaction between the ions and the residual gasses. The gasses have been stored in a Gas Recovery System, which has been designed and installed on the vacuum system to estimate the gasses production rate. This has required the installation of vacuum gauges along the vacuum pipes to monitor the pressure in the time. In fact, downstream the pumps the pressure is maintained lower than the atmospheric pressure, in order to reduce the possibility to have leaks towards the external environment. Expansion vessel coupled to a conductance control valve has been designed to avoid overpressure inside the pipes during the system functioning and to control the maximum pressure reached in the tubes. Three 40 l tanks have been installed downstream the primary pump in order to perform experimental tests whose results gave indications of the amount of gasses pumped in the time. The main result of the vacuum system design is the final layout of the vacuum plant. Furthermore, several tests have been performed excluding pumping stations by means the use of gate valves, monitoring the pressure drop and the corresponding status of the gas recovery system.
References


Chapter 5

Flexible transmission joint re-design

5.1 Introduction

In the context of RIB facility, the use of radiation-hard devices or components are often required since the high level of radiation during operations. Alongside the components reliability, the development of systems which allow the absence of oils, lubricant or greases goes hand in hand with these purposes. Furthermore, the reduction of both number of connections and components, especially on those systems which are employed for handling operations, is one of the goal in the RIB facility design.

A flexible joint made of high strength 455 HT stainless steel (UNS S45500) adopted for handling some devices in radioactive environment has been re-designed in the context of the SPES project (Selective Production of Exotic Species) at the Istituto Nazionale di Fisica Nucleare (INFN, Legnaro (Padova, Italy)). The application is demanding since a 90° angle must be guaranteed in absence of lubricants and plastics components. Fatigue failures have occurred on the original component despite compliance with installation recommendations had been assured.

Initially, material and geometry investigations have been performed in order to determine the unknown characteristics of the joint. Then, strain gauge acquisitions were performed to measure the torque and the local stresses on the joint undergoes in-service. After that, a large-displacement, non-linear finite element (FE) analysis was performed and numerical and experimental stresses acting on the joint were successfully compared. After validation, the FE model was used to re-design the joint in order to comply with the in-service fatigue life requirements and, at the same time, to avoid increasing of the overall joint dimensions. The latter was based on the Wöhler obtained from the material static strength properties, since the lack of fatigue data.

The re-designed joint will be used for all handling devices with the respects to the maximum torque allowed and installation recommendations. In the next paragraphs, the steps of the re-designed joint will be presented, with particular attention to the experimental tests, which allow interesting results related to the stress field on the joint.
5.2 Joint installation and fatigue failure description

The component under study is a commercial U-joint used in a variety of applications, wherever handling significant misalignments is the main focus. A universal joint is a mechanical connection between rotating shaft which are generally not parallel, but intersecting. In particular, this kind of joint could compensate irregularities such as angular and skewed misalignments, parallel offset and axial motion. All of this can be accomplished while maintaining constant rotational velocity and smooth bearing loads. Fig. 5.1 shows the U-joint which has been installed and used for handling operations. As it could be seen, it is a flexible helix (curved beam) machined from one piece of material into a specific configuration which has at the edges two massive heads. Each head is properly drilled, allowing coupling the joint to rotary shafts for the power transmission. Radially, M4 screws avoid relative motion between the shafts respect to the joint body. In the central part, coils have both constant pitch and coil thickness. Since the spring shape is obtained by the machining of a single metal piece, both inner and external diameter of the joint determine the height of each coil. Despite these considerations, the cross section of the coil will not result rectangular as expected.

![Fig. 5.1. Picture of the flexible transmission joint.](image)

The joint has been installed on the coupling table of the off-line Front End (SPES project) in order to couple and uncouple the target chamber for an automatic handling sequence operation, due to the high level of radiation. For the sake of completeness, it should be stated that the target chamber, once it is uncoupled, has to be removed and replaced with a new one every 15 days. Fig. 5.2 shows the joint installation and the components involved in the handling operations. The joint is connected on one side to the transmission shaft, which is rigidly connected to a radiation-hard pneumatic motor. On the other side, the joint edge, which is 90° bent respect to the transmission shaft axis, is fixed to an endless screw with a pitch equal to 4 mm. The coupling and uncoupling operations are performed by means a threaded plate which moves the target chamber by means the endless screw rotation. The chamber slides 200 mm forward and backward onto a metal guides in order to reach the position where a robot could perform the replacement. According to the endless screw pitch,
the coupling and uncoupling of the target chamber (red arrow and blue arrow, respectively) means 50+50 joint rotations. The most part of the chamber movements occurs with a low counter-torque acts on the joint, since only friction between the chamber and sliding guides is present. The highest torque, contrary, has to be applied by the motor in the last few millimeter of the target chamber coupling. Here, in fact, electrical, water and sensor connection fastenings produce high resistance.

![CAD drawing of the off-line SPES Front End and their handling apparatus.](image)

The chamber replacement (coupling and uncoupling) is performed 12 times per year and the system are completely dismissed after 10 years, after which a completely new Front End will be installed. This means that the minimum number of cycle $N_{\text{min}}$ the joint shell ensure are (cycle is defined as equal to one joint rotation):

$$N_{\text{min}} = 100 \frac{\text{Cycles}}{\text{Chamber handling}} \times 12 \frac{\text{Cycles}}{\text{Chamber handling}} \times 10 \text{ year} = 12000 \text{ cycles} \quad (5.1)$$

The joint prototype has been provided by the company with the aim to preserve the available space in the region where the joint would have been installed and neglecting the load condition, which was not investigated at the beginning. In the respect of this considerations, the prototype properties and characteristics are presented in Fig. 5.3. The torque acts on the joint gets different values depending on the rotation direction. In fact, the torque which “un-rolls” the coils is half than that “rolls up” the spring. During handling
operation starting, a maximum torque of 15 Nm is allowed, as provided by the table in Fig. 5.3.

![Technical drawing and main features of the joint prototype.](image)

<table>
<thead>
<tr>
<th>Tolerance block</th>
<th>Torque (Nm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.05 mm/-0.00 mm</td>
<td>Non-Rev</td>
<td>Rev</td>
</tr>
<tr>
<td>Ø A1 Ø A2</td>
<td>12.00 mm</td>
<td>12.00 mm</td>
</tr>
<tr>
<td></td>
<td>12 mm</td>
<td>Angular: 90°</td>
</tr>
</tbody>
</table>

Fig. 5.3. Technical drawing and main features of the joint prototype.

In this application, reversible pneumatic motors have been used, in particular type 20M58R-D10 Fiam (Fiamgroup Company) is a custom motor specifically developed for LNL-INFN. Performances of an air motor depends on the dynamic air inlet pressure measured at the intake of the motor; therefore by simply adjusting the air supplied, using pressure regulation valve, characteristic of linear output torque or speed can be obtained. The power and torque lines of a general pneumatic motor are shown in Fig. 5.4. The

![Torque-speed chart of the pneumatic motor used for the power transmission.](image)

Fig. 5.4. Torque-speed chart of the pneumatic motor used for the power transmission [5.1].
maximum power occurs at about 50% of the idle speed. At the maximum speed (idle speed) the torque (turning movement) as taken at the output shaft, is nil, while, as load is applied, the speed will decrease inversely proportional to the torque. The datasheet furnishes the main parameters of the present motor referred to an inlet pressure of 6.3 bar (ISO 2787), while the static pressure in the compressed air circuit in the laboratory is equal to 6 bar and become equal to 4 bar during the motor functioning. This allows the motor parameters correction by coefficients provided by the company, which are 0.55 for power, 0.67 for torque, 0.87 for speed and 0.65 for the air consumption. Updated parameters referred to a pressure of 4 bar are reported below in Table 5.1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20M58R-D10</td>
<td>88</td>
<td>261</td>
<td>3.81</td>
<td>5.03</td>
<td>504.6</td>
<td>2.25</td>
<td>7.64</td>
</tr>
</tbody>
</table>

Table 5.1. Main parameter of the Fiam 20M58R-D10 pneumatic motor.

Fatigue failure has occurred on two joints after 15000 and 15400 cycles, namely 150 and 154 handling operations respectively, as shown in Fig. 5.5 (1 operations =1 coupling + 1 uncoupling). In particular, the failures have occurred in corresponding to the coil

Fig. 5.5. a) Joint installation; b) picture of the joint failure; c) details of the broken joint; d) close-up view of the fatigue fracture.
attachment to the joint massive head, which has been connected to the motor shaft (Fig. 5.5b-c). The fatigue failure initiation was located on the inner surface of the coil, where the cutter tool leave the components to complete the milling operations. As a result of this type of milling, the sharp angle edge thus obtained means a high stress concentration in proximity to the coil edge. Further evidence is furnished by the fracture shown in Fig. 5.5d, in which the initiation, fatigue crack propagation and final failure are visible. Despite both torque at maximum power and stall torque provided by the motor at 4 bar are lower or at least equal than the torque admitted by the joint (Fig. 5.3 and Table 5.1), fatigue failure has been observed. The unusual and evident coils-to-joint head connection has been modified by the company, which introduced a different shape of the coil-joint head attachment, as shown in Fig. 5.6. The 4 mm diameter of the new edge suppressed the stress concentration problem. Despite this improvement, the modified joint has failed after 16900 cycles. The fatigue failure has occurred between the first and second coils as reported in Fig. 5.7. The analysis of the fracture surface of the joint allows different considerations on which the following studies, tests and developments are based:

- The material properties were not well-known since the general information CC 455 HT is referred to a Carpenter Technology Corporation® stainless steel [5.2].
Despite datasheets of these steels are easily provided by the company, the abbreviation HT is referred to an age hardened heat treatment which could be performed at 482 °C, 510 °C or 538 °C depending on the complete designation of the material (CC455 condition H900, CC455 condition H950 or CC455 condition H1000, respectively). This has forced to a deep investigation of the joint material in order to obtain the tensile strength and the elastic modulus necessary for the following numerical analyses and fatigue studies.

- The geometry of the cross section of the coils could not be approximated by a rectangle. The thickness of the coil on the inner surface are clearly higher than the external one and this extremely affect the stress field on the joint. Coordinate measuring machine and scanning electron microscope have been adopted to describe the geometry of the joint, then useful for the CAD model drawing.

- The torque applied to the joint by means the pneumatic motor was an unknown parameter, since it varied during the chamber coupling and uncoupling operations. The construction and the following installation of a load cell have allowed to monitor the loads in the time measuring the torque supplied by the pneumatic motor.

The study of the three main parameters aforementioned has laid the basis for the re-designing of a new joint with the respect of the available space and keeping the same boundary condition of the original joint.

### 5.3 Analysis of the material

The purpose of the material analysis was to identify the type of CC 455 HT steel in order to obtain the material properties useful for the following research activities. Several tests on a broken joint (the one modified by the company) have been carried out at the Material Laboratory (University of Padua).

The chemical composition of the stainless steel adopted for the joint manufacturing is reported in Table 5.2.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.04</td>
<td>0.44</td>
<td>0.32</td>
<td>0.02</td>
<td>0.02</td>
<td>12.23</td>
<td>8.22</td>
<td>1.87</td>
<td>0.26</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 5.2. Chemical composition of the joint material (CC 455 HT)

Thereafter, 10 Micro-Vickers hardness tests have been performed by using a load of 500 g. The hardness has result equal to 533 HV ± 1. The equivalent Brinell and Rockwell hardness are approximately 500 HB and 50 HRC, respectively.
The steel microstructure, instead, has been analysed attacking the material surface by chemical processes with the use of hydrochloric acid, glacial acetic acid, trinitrophenol and ethyl alcohol. Results of the microstructure analysis are presented in Fig. 5.8.

![Microstructure analyses of the CC 455 HT stainless steel.](image)

The fracture surface of the material has been observed and analyzed by means both stereoscopic and electron scanning microscopes. Here below different images which show the crack growth and the corresponding progression marks. The crack initiation was located on the inner surface of the joint, as expected. Moreover, the absence of relevant inclusions or porosities, which might have determined the crack initiation, has been observed on the surface sample. Fig. 5.9d shows the large presence of titanium carbide precipitates, whose dimensions are smaller than the mean length of the clamshell marking lines. This allows excluding their possible contribution in the crack initiation or propagation related to the fatigue failure.

![Scanning electron microscope topography of the fracture.](image)
In conclusion, therefore, the material of which the joint is made is a high quality stainless steel according to its microstructure and chemical composition. The martensitic structure, the absence of residual austenite, the uniform distribution of precipitates and the hardness measured on the sample are in accordance with the properties of the stainless steel CC 455 Condition H950, age hardened at 510 °C (S45500).

The mechanical properties of the stainless steel thus identified are the following:

- Rupture strength, $\sigma_r = 1665$ MPa
- Elastic modulus, $E = 206$ Gpa
- Poisson ratio, $\nu = 0.3$

5.4 **Coil geometry analysis**

The cross section of the coil is one of the most critical aspects in the joint study. In particular, the assumption of a rectangular cross section could severely affect the finite element analyses results. For this reason, scanning electron microscope technique has been adopted to investigate the coil cross section and meantime to determine the main dimensions on which the CAD model has been bases. Moreover, acquisitions allow constructing different grid and reference system (see blue lines in Fig. 5.10a) on the images obtained, useful to reconstruct the 2 dimensional geometry of the coil. Here below the main parameters of the cross section are presented. In particular, the coil thickness on both inner and outer

![Fig. 5.10. Parameters adopted to describe the coil cross section geometry. A coordinate system has been fixed to monitor the coil profile.](image-url)
surfaces, T and t, the height of the coils, L (Fig. 5.10a), and the radii of the four corner R1, R2 (Fig. 5.10b), R3, R4 (Fig. 5.10c), have been measured. Table 5.3 summarizes the mean values of 10 measurements:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.033</td>
<td>2.835</td>
<td>9.3</td>
<td>39.6</td>
<td>67.7</td>
<td>84.2</td>
<td>41.3</td>
</tr>
</tbody>
</table>

Table 5.3. Mean value of the coil parameters measured by means the SEM analyses.

The spring pitch has been obtained by mean the use of a coordinate-measuring machine. The measuring of the space between each coil, h, allows indirect estimation of the pitch, p, since it can be determined as the sum of the mean coil thickness and the distance h.

\[ P = t + h = 2.033 + 2.851 = 4.884 \text{ mm} \quad (5.2) \]

As a conclusion of this paragraph, it should be underlined the irregular geometry of the coils, probably due the manufacturing process which not ensure a perfect rectangular shape of the coil cross section. Moreover, there are not symmetries in the cross section of the coils, which results in a different joint behaviour in relation to the direction of the joint rotation under service. The analysis allows to a significant improvement in the CAD modelling, reducing the possible discordance between the numerical and experimental results due to the not reasonable geometry representation.

**5.5 Experimental tests: torque and strain gauge measurements**

**5.5.1 Load cell design for torque measurements**

The torque applied to the joint has been measured by means a load cell, properly designed according to the available space nearby the pneumatic motor. With reference to Fig. 5.2 and Fig. 5.11a, it should be observed that the motor transmits the power to the driven shaft by means an elastic joint. The motor has fixed to the frame by an aluminium support, properly connected to the coupling table. The load cell has been considered as composed by four sensitive elements, parts of an aluminium component which replace the support allowing measuring the reaction torque (Fig. 5.11b). Each sensitive element is subjects to a bending load and its deformation has monitored by strain gauges, properly placed in order to guarantee the required accuracy.
Since the elastic joint has a diameter of 29 mm and it allows a distance between the frame and the motor of 65 mm, the overall dimension of the load cell has been obtained from a 50 x 50 x 65 [mm x mm x mm] bulk piece. The end faces of the cell have a thickness of 7.50 mm, on one side fixed by means four screws to the frame and in the other side to the motor support. Two different diameters of the holes permit the installation of the driven shaft and the motor, respectively. Since the radius between the sensitive elements and the cell bases has been fixed equal to 3 mm, their height is automatically equal to 9 mm. Fig. 5.12 shows the load cell design and the main dimensions.

The thickness of sensitive elements, \( a \), has been preliminarily calculated in order to assure a large deformation of the cell never exceeding the maximum tensile stress limit. In the hypothesis of a torque \( \text{Mt} = 12 \text{ Nm} \), namely the maximum torque provided by the motor at 6 bar, and supposing the torque obtained by 4 forces equally distributed on the 4 elements at a distance \( r = (50/2) - (b/2) = 20.5 \text{ mm} \), then each force, \( F \), can be calculated as following:

\[
F = \frac{\text{Mt}}{4 \cdot r} = \frac{12000}{4 \cdot 20.5} = 146.34 \text{ N}
\]
The structural scheme and the cross section of each element is presented in Fig. 5.13 [5.3]. At points A and B, the bending moment, $M_{fa}$ and $M_{fb}$ can be easily calculated as:

$$M_{fa} = \frac{F \cdot 1}{2} = \frac{146.34 \cdot 50}{4 \cdot 20.5} = -3658.5 \text{ Nm}$$

$$M_{fb} = \frac{F \cdot 1}{2} = \frac{146.34 \cdot 50}{4 \cdot 20.5} = 3658.5 \text{ Nm}$$

(5.4)

![Fig. 5.13. Structural scheme of one of the four sensitive elements of the cell.](image)

In the cross section referred to the point A, where the bending moment is maximum (in the point B same conditions are reached) the tensile stress, $\sigma_{zz}$, for $x = b/2$ can be calculated as:

$$\sigma_{zz} \left( x = \frac{b}{2} \right) = \frac{M_{fa} b}{I_{yy}} \frac{1}{2} = \frac{M_{fa}}{12 \ a \ b^2} \frac{b}{2}$$

(5.5)

The material of the cell was aluminium Al 7075 T6 (E=72 GPa; $\nu=0.33$), whose tensile stress at yield $\sigma_{p,0.2} = 510$ MPa; considering a safety factor of 2.5 and substituting into the eq. 5.5, the thickness of the sensitive element, $b$, has been determined as:

$$b = \sqrt{\frac{M_{fa}}{2 a \ \frac{1}{12} \ \sigma_{p,0.2}}} = \sqrt{\frac{368.5}{2 \ 9 \ \frac{1}{12} \ 204}} = 3.45 \text{mm} = 3.5 \text{ mm}$$

(5.6)

It should be noted that the shear stress has been neglected in the calculation since it was extremely lower compared to the tensile stress.

### 5.5.1.1 Finite Element Model of the load cell

Several linear elastic finite element analyses have been performed by using Ansys™, in order to verify the stress distribution on the load cell and at the same time to determine the position of the strain gauge according to the deformation required for a suitable voltage output. The element type adopted for discretization of the domain is the SOLID 186 (tetrahedral option - 20 nodes)[5.4]. The element size has been fixed equal to 1 mm, refining then the mesh on the areas which belong to the four sensitive elements (Fig. 5.14a). On the external area, all degrees of freedom have been restrained (Ux=Uy=Uz=0), while in the
opposite side, a combination of forces have been applied in order to obtain a torque up to 14 Nm (extreme case). Three reference paths, S, M, D have been considered on both sides, L1, L2, of one of the four cell arms. On those paths, the strain $\varepsilon_{zz}$ along the z axis has been evaluated since it is the deformation component measured by the strain gauge.

Fig. 5.14. Mesh and reference paths of the load cell Finite Element Model (FEM).

Load has been applied to the cell by increasing the torque from 0 to 14 Nm by step increment of 2 Nm. Here below, the results of the numerical analyses are presented. The plots are referred to the strain and the tensile stress measured on both side L1 and L2 of the cell arm in corresponding to the path M. This because no significant changes (lower than 2%) have been registered comparing the results obtained along paths S and D.

Fig. 5.15. Strain $\varepsilon_{zz}$ measured along the path M on the side L1.
Fig. 5.16. Stress $\sigma_{zz}$ measured along the path M on the side L1.

Fig. 5.17. Strain $\varepsilon_{zz}$ measured along the path M on the side L2.
Both $\sigma_{zz}$ and $\varepsilon_{zz}$ are linear along the z coordinate except in the region where the cell arms match the cell base plate by a fillet radius of 3 mm. For this reason the strain gauges position has been fixed considering a distance of 5 mm from the tip radius, as shown in Fig. 5.19.

5.5.1.2 Load cell calibration

The numerical results have been adopted to define the numerical calibration curve, then verified by the construction of a test bench allowed applying the corresponding torque on the lead cell. The latter has been constructed by machining a bulk piece of AL 7075 T6, whose specifications have been provided by the material datasheet. Subsequently, four strain
gauges have been applied on two opposite cell arms, in accordance to the position defined by the numerical simulation. Full-bridge strain gauge configuration has been adopted to measure the pure torque associated to the cell arms bending, as represented in Fig. 5.20.

Since the weight of the motor, the configuration adopted allows suppressing the contribution of other load sources. KYOWA KFG-03-120-C1-23 strain gauge has been adopted since the small dimension of the grid [5.5]. The latter, made of aluminium, is characterised by width and length of 1.3 mm and 3 mm, respectively. After the strain gauges bonding, electrical cables have been fixed and connected to the IMC-CRONOS PL2 control unit [5.6]. The gauge factor was 2.24, while the voltage on the full-bridge circuit was fixed to 5 V; the gauge resistance was equal to 120 Ω. Sampling rate of 50 Hz has been used for the calibration of the cell.

The test bench adopted for the calibration was essentially composed by a base plate on which the cell has been installed by means four screws. On the top of the cell, a thin aluminium sheet, with a length of 300 mm, has been centered and fixed, allowing to obtain two arms of 150 mm of length. On those levers, two opposite wires transmitted the forces of different weights by means two plastic pulleys. In this way, pure torque was applied to the cell, as shown in Fig. 5.21.

The calibration test has been carried out by using different masses or a combination of them in order to reproduce the same torque considered in the finite element model. The available masses were 50 g, 200 g, 500 g 1000 g and 2000 g. Two different supports were used depending on the dimension of the masses adopted and their weights were equal to 1.78 N and 1.68 N, respectively.
For each torque value, the load has been applied for 90 s. In order to verify the presence of hysteresis phenomena in the material behaviour, between each load step the masses were completely removed. The results of the three calibration tests and the mean value registered for each load case are presented in Table 5.4. It should be noted the torque did not match the corresponding numerical values since the slight masses deterioration.

<table>
<thead>
<tr>
<th>Mt [Nm]</th>
<th>Test 1 $\varepsilon_{zz} [\mu m/m]$</th>
<th>Test 2 $\varepsilon_{zz} [\mu m/m]$</th>
<th>Test 3 $\varepsilon_{zz} [\mu m/m]$</th>
<th>Mean value $\varepsilon_{zz} [\mu m/m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2.19</td>
<td>216.50</td>
<td>215.30</td>
<td>214.92</td>
<td>215.57</td>
</tr>
<tr>
<td>4.25</td>
<td>422.06</td>
<td>418.72</td>
<td>418.97</td>
<td>419.92</td>
</tr>
<tr>
<td>6.90</td>
<td>682.00</td>
<td>677.72</td>
<td>680.88</td>
<td>680.20</td>
</tr>
<tr>
<td>8.07</td>
<td>798.40</td>
<td>797.34</td>
<td>798.06</td>
<td></td>
</tr>
<tr>
<td>10.13</td>
<td>1003.08</td>
<td>1002.56</td>
<td>1000.54</td>
<td>1002.06</td>
</tr>
<tr>
<td>12.78</td>
<td>1262.65</td>
<td>1262.65</td>
<td>1259.84</td>
<td>1261.71</td>
</tr>
<tr>
<td>14.25</td>
<td>1412.59</td>
<td>1410.88</td>
<td>1410.17</td>
<td>1411.21</td>
</tr>
</tbody>
</table>

Table 5.4. Results of the calibration tests for different torques applied to the cell.

The results thus obtained have been used to plot the calibration curve, which returns the torque applied to the cell for a given strain. Fig. 5.22 shows the numerical-experimental data comparison. The equation of the straight line is essentially the main result of this study, since the slope of the curve allowed determining the coefficient which has to be multiplied to the strain to obtain the torque value, as provided by the calculations below:

$$\varepsilon_{zz}(Mt) = A \cdot Mt = 98.86 \: Mt$$

$$Mt (\varepsilon_{zz}) = Y \: \varepsilon_{zz} = 1.012 \times 10^{-2} \: \frac{Nm}{\mu m/m}$$  \hspace{1cm} (5.7)
The coefficient $Y$ of eq. 5.7 has been introduced in the software of the control unit, allowing to measure the torque supplied by the pneumatic motor in real time. In the next paragraph, experimental tests based on the measurement of both the strain of the coils and the torque applied to the joint will be presented. The result allowed fundamental data for the finite element model validation and the consequent fatigue failure analysis.

5.5.2 Strain gauge acquisition

The chamber handling operations, which have determined the fatigue failure of the joint, has been shortly described in §5.2. Similarly, a test bench has been installed in order to study the joint behaviour as shown in Fig. 5.23. The chamber coupling and uncoupling are respectively indicated by the red and blue arrows. Laterally, the pressure reducing valve assured a static pressure of 6 bar in the circuit and electro pneumatic valves supplied the compressed air to the pneumatic motor. The latter has been actuated by means two limit switches, which detected the chamber position once the handling operation was completed. This means that the position of the limit switches affect the torque applied to the joint. The longer is the time between the limit switch activation and the pneumatic motor deactivation, higher will be the torque since the reaching of the stall condition. For this reason, all the handling sequence parameters have been implemented in the PLC as equal to the original system, where joint failure occurred.

The purposes of the tests were monitoring the torque applied to the joint and simultaneously determine the strain along reference coils. Therefore, the knowledge of both
load and strain allowed to perform a finite element model of the joint and thus numerical-experimental data comparison. The validation of the model then permitted the stress field analysis in the region of the joint where failure has been observed.

![Test bench adopted for the strain gauge acquisition. Chamber handling operations are illustrated by the blue and red arrows.](image)

The first step regarded the installation of the load cell, which replaced the support of the pneumatic motor as shown in Fig. 5.24. It should be observed the limited space between the load cell and the test bench frame. The control unit registered the output voltage of the strain gauges (full bridge configuration) and by means the calibration factor the torque have been monitored.

![Support replacement and load cell installation.](image)

From the other side, the joint has been provided by three strain gauges, properly positioned on the external surface of the second, eighth and fifteenth of the 16 coils starting from the pneumatic motor side, along a line intersecting the coil attachment to the joint massive head. Each stain gauge was glued in the middle of the coil thickness and a quarter-bridge configuration has been used. Fig. 5.25 shows the strain gauges position. The
Figure also provides the illustration of the coordinate system (XYZ) which allowed the alignment of the strain gauges at 0° before the operation starting. This was fundamental since the rotation of the joint. In fact, the knowledge of the joint position in the time permitted to find out the corresponding torque which acted on the joint and monitored by the load cell. For this purpose, video recording has been performed to synchronize the data acquisition with the joint position. The strain measured on the coils have been then plotted as a function of the joint rotation, from 0° to 360° with reference to the coordinate system XYZ.

The handling operation sequence used for the tests consisted in 4 chamber uncoupling and 3 chamber coupling, alternately. For an easy comprehension of the results, the following table provides the information about the coupling operations and the related torque sign, the coils behaviour and the stress state on the external surface of the coils.

<table>
<thead>
<tr>
<th>Handling operation</th>
<th>Torque sign</th>
<th>Coils behaviour</th>
<th>Stress state on the external surface of the coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling</td>
<td>-</td>
<td>Rolled</td>
<td>Compression</td>
</tr>
<tr>
<td>Uncoupling</td>
<td>+</td>
<td>Un-rolled</td>
<td>Tension</td>
</tr>
</tbody>
</table>

Table 5.5. Torque sign convention and joint behaviour related to the handling operations

The results of the data acquisition are reported in Fig. 5.26, Fig. 5.27, Fig. 5.28 and Fig. 5.29. The sampling rate of 100 Hz allowed measuring the peaks of each parameter with particular accuracy without missing relevant data. Despite the first chamber uncoupling, high repeatability and reproducibility should be observed. Torque and strain peaks were observed during the starting of each handling sequence. While in the chamber uncoupling this is due
Flexible transmission joint re-design

to the mechanical resistance of water, signals and electrical cables connections, in the coupling operation this effect is a consequence of mass inertia forces of the chamber.

Fig. 5.26. Torque monitored in the time by the load cell during 4 chamber uncoupling and 3 chamber coupling operations.

Fig. 5.27. Strain measured along the coil in the A position during 4 chamber uncoupling and 3 chamber coupling operations.
Similarly, peaks have been monitored at the end of the handling operations. A close view of torque supplied during a single coupling-uncoupling operations is presented in Fig. 5.30 along with the plots of strains measured by the strain gauges in positions A and C, as shown.
in Fig. 5.30 and Fig. 5.31. The initial torque of -0.56 Nm (due to the chamber inertia forces) is followed by a nearly constant torque of -0.26 Nm in the free chamber path. Finally, -3.88 Nm are supplied to overcome the resistance offered by the service connectors. Here, the limit switch interrupted the air flux to the pneumatic motor and 0.89 Nm is observed; the elastic energy of the joint determines a slight counter rotation until the stable condition was reached. Contrary, in the uncoupling operation, a starting torque of 2.80 Nm was necessary to unplug the chamber connectors, while the reverse chamber free path was characterized by a constant torque of 0.34 Nm. In the final stage, where the chamber is completely disconnected, a torque of 2.80 Nm is the result of the force which the chamber has exerted on a mechanical end stop. This was due because of the delay-time set on the control unit after the limit switch activation. Similarly of the coupling operation, elastic energy released by the joint determine a negative torque of -0.56 Nm, after the uncoupling sequence completion. It should be observed that the torque necessary to couple the chamber after the free path (absolute value equal to 3.88 Nm) is considerably greater than the torque applied to the joint to disengage the connection during the reverse motion. Contrary, the absolute value of the torque along the chamber free path during the coupling is slightly lower than that observed during the uncoupling phase. The strains measured on the coils of the joint in the same range of time are presented in Fig. 5.31 and Fig. 5.32. The strain gauge measurements, referred to positions A and C, have been used to validate the numerical model. For this purpose, a torque of 0.26 Nm has been considered since it was constant
Fig. 5.31. Strain measured along the coil in the A position during 1 chamber coupling and 1 chamber uncoupling operations (range of time = 50-70 s).

Fig. 5.32. Strain measured along the coil in the C position during 1 chamber coupling and 1 chamber uncoupling operations (range of time = 50-70 s).

for a considerable period of time. Furthermore, in the same range of time the strain monitored by the strain gauges in positions A and C have been easily determined (Fig. 5.31 and Fig. 5.32). The strains in the time have been then plotted as a function of the joint position thanks to the video clip synchronization, as shown in Fig. 5.33. This result was extremely important in this phase. In fact, from these plots, reference orientations of the joint to be used in the
Flexible transmission joint re-design

finite element model have been decided in relation to the torque applied. In this way, the following numerical-experimental strain comparison could be performed along one joint rotation. After, the other torque peaks determined in Fig. 5.30 have been used during the fatigue analysis by running several finite element simulations in order to reconstruct the histogram loading cycle based on the rainflow counting method.

![Numerical strain referred to position A (left) and B (right) during one joint rotation — Torque, Mt = -0.26 Nm.](image)

Before moving to the next paragraph, considerations about the previous results have to be provided. The strain amplitude measured during one joint rotation in the position A (motor side) is greater than the strain monitored in the position C (shaft side), as shown in Fig. 5.33 and this has been observed for all the load cases (different torques). Moreover, the failure occurred between the first and second coils of the joint nearby the position A, indeed. The reason could be explained with reference to Fig. 5.5a, which provides that the distances between the joint massive heads are not equivalent. As a result of the assembly configuration, the coils at motor side were largely stressed then the other and this result has then confirmed by the finite element model results.

### 5.6 Finite Element Model of the joint

Several non-linear, large-displacement numeric analysis were performed using Ansys™ software. Referring to Fig. 5.34, 0°-90°-180°-270° joint configurations were analysed, where the angle indicates the location of the strain gauges in the XYZ coordinate system.

Bending was applied to the joint with respect to four orientations around the Z axis as shown in the sketch reported in Fig. 5.34 (0°, 90°, 180°, 270°).

The model was meshed using SOLID 186, 3D, 20 node structural tetrahedral elements, with an element size of 0.75 mm for the sweep meshed coils, and 1.5 mm for the massive cylinder free meshed heads. Young modulus was set 206000 MPa, while Poisson coefficient was 0.3. To bend the joint at a 90° angle according to the installation configuration and to
twist the joint, BEAM 188 elements [5.7] were adopted to connect the nodes of the extreme area to a reference node, on which displacements were applied: more precisely, a displacement was applied to reproduce first the 90° bending (ROT X), and then a Y-axis rotation (ROT Y) was applied to reproduce the in-service torque. Y-axis rotation, as a function of the torque, Mt, has been obtained running a set of numerical simulations allowing to obtain the function ROTY=f(Mt) as following:

\[
\text{ROTY }[^\circ] = 2.681 \cdot M_t \text{ [Nm]} + 1,271 \quad (5.8)
\]

Since \( M_t = -0.26 \text{ Nm} \) has been adopted for the model validation, the corresponding rotation \( \text{ROTY} = 0.574^\circ \) has been applied to the joint. Such boundary conditions were applied to the model according to Fig. 5.34 in order to simulate the in-service conditions. The joint was restrained at the other side (\( U_x=U_y=U_z=0 \)), where it was fixed to the driving shaft.

![Finite Element Model (FEM) of the joint. Boundary conditions and loads (displacements) reproduce the in-service conditions.](image)

Experimental and numerical data were compared in order to validate the finite element model. Considering the uncertainty in strain gauge position, here assumed \( \pm 0.1 \text{ mm} \) with respect to the mid-thickness of the coil, the uncertainty band was evaluated numerically, as shown in Fig. 5.35. The latter also provides the number of nodes on which the strain has been evaluated to extrapolate the values on the desired position. It should be observed that a proper oriented working plane has been adopted to consider the strain along the coil direction.
In the $0^\circ(360^\circ)$ - $180^\circ$ configuration, high strain gradient is present along the thickness. Conversely, in the $90^\circ$ and $270^\circ$ configurations strains are nearly constant through the thickness, and the absolute value of the strain in the mid-thickness is higher as compared to the other configurations.

Fig. 5.35. Representation of the uncertainty in strain gauge position and the relative FEM nodes.

Fig. 5.36. Numerical strain in position A along the coil thickness for $M_t=-0.26$ Nm and $0^\circ$ joint orientation.

Fig. 5.37. Numerical strain in position C along the coil thickness for $M_t=-0.26$ Nm and $0^\circ$ joint orientation.

Fig. 5.38. Numerical strain in position A along the coil thickness for $M_t=-0.26$ Nm and $90^\circ$ joint orientation.

Fig. 5.39. Numerical strain in position C along the coil thickness for $M_t=-0.26$ Nm and $90^\circ$ joint orientation.
Fig. 5.40. Numerical strain in position A along the coil thickness for $M_t=-0.26$ Nm and 180° joint orientation.

Fig. 5.41. Numerical strain in position C along the coil thickness for $M_t=-0.26$ Nm and 180° joint orientation.

Fig. 5.42. Numerical strain in position A along the coil thickness for $M_t=-0.26$ Nm and 270° joint orientation.

Fig. 5.43. Numerical strain in position C along the coil thickness for $M_t=-0.26$ Nm and 270° joint orientation.

Fig. 5.44 and Fig. 5.45 show the comparison between the experimental and numerical strains in both positions A and C, during one joint rotation with -0.26 Nm torque applied.

It should be observed that the experimental results well matched the numerical data. Moreover, the higher strain amplitude registered on the position A during one joint rotation, compared to the strain referred to the position B, has been attempt by the strain gauge measurements. This leads to prove the strong influence of the joint installation on the stress field of the joint. In fact, with reference to Fig. 5.5a, where the non-symmetrical joint positioning can be appreciated, the higher bending of the coils nearby the motor side is clearly obtained despite 90° between the massive heads axes has been assured. This aspect will be deeply discussed in the next section and fatigue failure occurred close to position A will be justified by the fatigue analysis.

The finite element model validation has allowed analyzing the stress field of the joint as a function of both position and applied torque.
5.7 Fatigue analysis and joint re-design

A set of simulations were run using the experimental peak torques of Fig. 5.30 (-3.88 Nm, 2.80 Nm, 0.34 Nm, -0.56 Nm, 0.89 Nm and -0.26 Nm, respectively) applied to each joint orientation, namely Z orientation equal to 0°, 90°, 180° and 270°. In all simulations performed, the maximum stress condition occurs in the same node (node 383723) located in the inner diameter on the second coil (see Fig. 5.46), indeed where fatigue crack initiation took place. The total stress is due to two different contributions, the first one depending on the 90° bent configuration determined by the installation of the joint
between the two orthogonal shafts, and the second one caused by the applied torque. The prevailing effect is due to the 90° bending, which produces a symmetric stress cycle over one complete rotation. Conversely, the torque produces a nonzero but negligible mean stress.

Table 5.6 shows the principal stresses evaluated on node 383723 for different load and joint orientation cases. For each load case, the maximum (first) principal stress ($\sigma_1$) and the minimum (third) principal stress ($\sigma_3$) are always observed in corresponding to the joint orientation equal to 0° and 180°, respectively (yellow rows).

<table>
<thead>
<tr>
<th>Angle</th>
<th>Principal Stresses</th>
<th>Load case – Torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_1$ [MPa]</td>
<td>-0.56  -0.26  0.89  -3.88  -2.80  -0.34</td>
</tr>
<tr>
<td>0°</td>
<td>1217.7</td>
<td>1195.6  1145.0  1357.1  1050.2  1171.2</td>
</tr>
<tr>
<td></td>
<td>$\sigma_2$ [MPa]</td>
<td>31.1    31.1    31.2    30.9     31.1     31.1</td>
</tr>
<tr>
<td>90°</td>
<td>318.7</td>
<td>317.3    313.2    331.2    305.2    383.7</td>
</tr>
<tr>
<td></td>
<td>$\sigma_2$ [MPa]</td>
<td>-4.5    -4.5    -4.5    -4.5     -4.5     -4.5</td>
</tr>
<tr>
<td></td>
<td>$\sigma_3$ [MPa]</td>
<td>-131.1  -130.9  -130.1  -132.2   -128.6   -130.5</td>
</tr>
<tr>
<td>180°</td>
<td>6.2</td>
<td>6.3     6.5     5.5      6.9      6.4</td>
</tr>
<tr>
<td></td>
<td>$\sigma_2$ [MPa]</td>
<td>-30.4   -30.2   -29.4   -32.3    -28.1    -29.8</td>
</tr>
<tr>
<td></td>
<td>$\sigma_3$ [MPa]</td>
<td>-1110.3 -1119.2 -1142.9 -1022.5  -1180.1  -1131.0</td>
</tr>
<tr>
<td>270°</td>
<td>124.1</td>
<td>114.5    91.8    245.1    64.1     102.7</td>
</tr>
<tr>
<td></td>
<td>$\sigma_2$ [MPa]</td>
<td>3.8     3.9     3.8      3.5      3.6      3.9</td>
</tr>
<tr>
<td></td>
<td>$\sigma_3$ [MPa]</td>
<td>-218.6  -233.9  -281.1  -122.4   -376.7   -256.1</td>
</tr>
</tbody>
</table>

Table 5.6. Results of the numerical simulation on the node 383723: principal stresses are obtained as a function of the torque applied and the joint orientation.

Furthermore, the latter are defined by vectors, whose directions are coincident to the straight line which is tangents to the coil in the node 383723. This is the most important result in the fatigue analysis performed, since it allowed to calculate the stress range at the most stressed FE node as the difference between the maximum (first) principal stress
Flexible transmission joint re-design

(σ₁ – 0° position) and the minimum (third) principal stress (σ₃ – 180° position). On the other side by comparing the stresses in both orientations, for each load case a fully reversed stress condition (stress ratio R=−1) has been evaluated, as shown in Table 5.7.

<table>
<thead>
<tr>
<th>Torque [Nm]</th>
<th>σ₁ (0°) [MPa]</th>
<th>σ₃ (180°) [MPa]</th>
<th>R</th>
<th>Δσ [MPa]</th>
<th>σ_{ai} [MPa]</th>
<th>nᵢ [cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.56</td>
<td>1217.7</td>
<td>-1110.3</td>
<td>-1.1</td>
<td>2328.0</td>
<td>1164.0</td>
<td>1</td>
</tr>
<tr>
<td>-0.26</td>
<td>1195.6</td>
<td>-1119.2</td>
<td>-1.1</td>
<td>2314.8</td>
<td>1157.4</td>
<td>48</td>
</tr>
<tr>
<td>0.89</td>
<td>1145.0</td>
<td>-1142.9</td>
<td>-1.0</td>
<td>2287.9</td>
<td>1143.95</td>
<td>1</td>
</tr>
<tr>
<td>-3.88</td>
<td>1357.1</td>
<td>-1022.5</td>
<td>-1.3</td>
<td>2379.6</td>
<td>1189.7</td>
<td>1</td>
</tr>
<tr>
<td>-2.80</td>
<td>1050.2</td>
<td>1180.1</td>
<td>-0.9</td>
<td>2230.3</td>
<td>1130.2</td>
<td>1</td>
</tr>
<tr>
<td>-0.34</td>
<td>1171.2</td>
<td>-1131.0</td>
<td>-1.0</td>
<td>2248.2</td>
<td>1124.1</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 5.7. Fatigue parameters for each load condition: σ₁ is the maximum (first) principal stress, σ₃ is the minimum (third) principal stress, R is the stress ratio, Δσ is the range of stress, σ_{ai} is the stress amplitude, nᵢ is the number of joint rotation in one complete handling sequence.

Histogram loading cycles has been thus obtained for one handling sequence (one chamber coupling and uncoupling), which corresponds to 100 joint rotations (see § 5.2). With reference to Fig. 5.30, 1 joint rotation has been considered for applied torques equal to -0.56 Nm, -3.88 Nm, 0.89 Nm, 2.8 Nm and -0.56 Nm (local peaks), while 48 rotation has been counted for applied torque equal to -0.26 Nm and 0.34 Nm (free chamber paths).

Due to the lack of fatigue data relevant to the material, the Wöhler curve for zero mean stress was obtained from the static strength properties (Fig. 5.47); being the tensile strength, σ₉ = 1665 MPa, two points of the fatigue curve were estimated (N=1x10³ cycles, σ_{a,σ}= 1665 MPa and N= 2x10⁶ cycles, σ_{a,R=−1} = 0.35 x σ₉ = 583 MPa; inverse slope of the curve, k=7.24). Since the type of load, the coil dimensions and the surface roughness (0.5 µm<Ra<1.2 µm), no correction factors have been adopted to reduce the endurance limit.

According to the stress range data of Table 5.7, an equivalent cyclic stress amplitude could be calculated as:

\[ \sigma_{a,eq} = \sqrt{\frac{\sum n_i \cdot \sigma_{ai}^k}{\sum n_i}} = 1155 \text{ MPa} \]  \hspace{1cm} (5.9)

Where k is the inverse slope of the Wöhler curve, while σᵢ and nᵢ are the stress amplitude and the number of cycles for each load condition (Σnᵢ = 100 cycles). By using the Wöhler curve, the corresponding estimated life to failure is N_{f,est} = 14100 cycles, which is in optimum
agreement with the experimental number of cycles to failure $N_{f, \text{exp}} = 16900$ cycles (see § 5.2, p. 152) as shown in Fig. 5.47.

![Wöhler curve obtained from the material properties.](image)

The knowledge of the joint behaviour and the results obtained from the failure analysis allowed re-designing a new joint by maintaining the overall external dimension of the original joint. The parameters on which the re-design was focused are the pitch and the coil thickness, now equal to 3.5 mm and 1.75 mm, respectively (see Table 5.3 for the dimension of the original joint). Fig. 5.48 shows the technical drawing of the new joint.

According to eq. 5.1, the new joint was re-designed having a target fatigue life $N_{\text{tar}}$ equal to:

$$N_{\text{tar}} = 100 \frac{\text{Cycles}}{\text{Chamber handling}} \cdot 12 \frac{\text{Cycles}}{\text{Chamber handling}} \cdot 10 \text{ year} \cdot 30 (\nu) = 360000 \text{ cycles} \quad (5.10)$$

The safety factor, $\nu = 30$, is related to the statistic scatter in fatigue and is relevant to a design life evaluated with 97.7% survival probability. It was obtained by considering a stress reducing factor equal to $4/3\sqrt{1.5}$, which become equal to $\nu = \left(\frac{4}{3}\sqrt{1.5}\right)^k = \left(\frac{4}{3}\sqrt{1.5}\right)^{7.24} \approx 30$, referred to the number of cycles [5.8].

New finite element analyses were performed by keeping the same boundary condition adopted for the original joint. Here, the worst condition, which is referred to a torque of -3.88 Nm, has been adopted to run the first set of simulations; as provided by the plot of Fig. 5.48, the maximum (first) principal stress $\sigma_1 = 583.2$ MPa, while the minimum (third)
principal stress $\sigma_3 = -580.4$ MPa, after half rotation of the joint. Contrary to the fatigue analysis, the hypothesis that the full handling sequence occurs under this load condition allows on one side to overestimate the stresses act on the joint. On the other side, the $90^\circ$ bent configuration still provides most of the total stress. For these reason, the stress amplitude to evaluate the fatigue life of the re-designed joint has been fixed equal to $\sigma_{a,\text{new}} = 583$ MPa, since the stress ratio remains $R = \sigma_1/\sigma_3 = 583.2/-580.4 \sim -1$. The corresponding estimated life to failure of the new joint obtained by using the Wöhler curve is $N_{f,\text{est,new}} = 2\times10^6$ cycles, which is the number of cycles at the endurance limit. Therefore, the life-based safety factor is equal to $v_N = N_{f,\text{est,new}}/N_{\text{tar}} = 5.5$.

The joint thus designed has been contracted by the company and nowadays no longer fatigue failures have been observed in the joints installed on the off-line Front End.

### 5.8 Conclusion

A finite element model calibrated on experimental strain gauge results was used to estimate the large displacement structural behaviour of a flexible joint, on which fatigue failure occurred despite compliance with the installation recommendations. Thanks to the non-linear finite element analyses, a new prototype of the flexible joint was designed in order to satisfy the required fatigue life. The overall dimensions of the joint were preserved, while both thickness and pitch of the coils have been changed. The Wöhler curve of the material was estimated from the static strength properties. Non-linear, large-displacement finite element simulations proved to be useful in fatigue design of the new joint. The knowledge of stress field during the in-service conditions allows the use of the joint in many applications, especially where handling operations with absence of oils, lubricant or greases are required along with the reliability of the devices installed. The re-designed joint will be used in the context of the Laser Front End development, since both vacuum chamber and
extraction system are actually fixed to the frame. The latter will be handled by the use of adjusting systems on which the joint could be transmit torques lower than 4 Nm. For those applications where higher torque will be required, new joint dimensions will be defined starting from results of numerical simulations based on the validated finite element model.
References

Chapter 6

Conclusion

In the framework of the research and development activities of the SPES project, regarding the optimization of the radioactive ion beams production, a new home made Time of Flight Mass Spectrometer (ToF-MS) has built in the off-line laser laboratory. Thanks to this instrument it is possible to test resonant laser ionization processes of stable species in order to evaluate their ionization and even isotope separation capability. Nowadays, a Nd:YAG laser is used to evaporate atoms by laser ablation, making these atoms available for the laser resonant ionization. The new evaporation oven (the Knudsen cell), which replaces the ablation system, is designed to guarantee a more stable and calibrated atoms flux, making possible laser ionization efficiency measurements. The research activities carried out were mainly focused on the so called Laser Front End design. Since the aim of the study was find out an innovative method to estimate the laser ionization efficiency, the main result was surely the layout and the conceptual design of the Laser Front End. The Knudsen cell is the first and most important device has been designed, since from its performances depends the good functioning of the whole apparatus. Both temperature distribution and temperature uniformity inside the cell guarantee the proper evaporation of generic material sample. Moreover, the support system allows the alignment of the cell with the respect to the laser source, while the shielding system provides the restrict collimation of the evaporation “plume”. The extraction system has been designed and thus preliminary deposition tests along with the ionization tests were successfully performed.

In the second part of the thesis, we described the re-designing of the SPES quadrupole triplet, which is an optical device allows focusing the ion beam until the diagnostic device. The development of a simplified, robust version of the CERN-ISOLDE triplet resulting in a significant improvements in the vacuum performances along with the ease of assembly. Additionally, a compact triplet have been designed reducing the length and the bore of the electrode, which also provided an interesting result in the ion beam transport, namely a reduction in the phase space distortions and their associated effective emittance growth.

Nearby the previous two items, a deep study of the vacuum and the gas recovery systems have been finalized with the preliminary design of a vacuum plant, which guarantees to store
gasses of a generic system in vacuum. Moreover the gas production rate has been monitored by means several experimental tests. The results obtained will be useful to upgrade the actual Laser Front End vacuum system, especially once exotic species will be ionized by means laser technique.

The last topic regarded the re-design of a flexible transmission joint. A finite element model calibrated on experimental strain gauge results was used to estimate the large displacement structural behaviour of a flexible joint. Thanks to non-linear finite element analyses, a new prototype was designed in order to satisfy the required fatigue life. The Wöhler curve of the material was estimated from the static strength properties. Non-linear, large-displacement finite element simulations proved to be useful in fatigue design of the new joint.

Future works will be aimed to the development and the completion of the Laser Front End and several tests will be indispensable to collect data, which will permit to estimate the laser source efficiency.
APPENDIX A – APDL commands

APDL commands referred to the Finite Element Model of §2.4.3

!---------------------------------------initializing----------------------------------------
FINISH
/CLEAR, START
/TITLE, Knudsen cell - Thermal characterization test - Current=100->800A
/CONFIG,NRES,100000 !maximum number of substeps allowed on the result file

!----------------------------parameters----------------------------
T0=25 !temperature constraint [°C]

!----------------------------geometry import----------------------------
/AUX15 !enters the IGES file transfer processor
IOPTN,IGES,NODEFEAT !no defeaturing
IOPTN,MERG,YES !automatic merging of entities
IOPTN,SOLID,YES !solid is created automatically
IOPTN,SMALL,YES !small areas are deleted
IOPTN,GTOLER,0.00001 !merging tolerance
IGESIN,'kc_main_clamp_1','igs' !copper main clamp import
IGESIN,'kc_main_clamp_2','igs'
IGESIN,'kc_tct_aux_conn_1','igs'
IGESIN,'kc_tct_aux_conn_2','igs'
IGESIN,'kc_tct_aux_conn_3','igs'
IGESIN,'kc_tct_aux_conn_4','igs'
IGESIN,'kc_top','igs' !cell top import
IGESIN,'kc_bottom','igs' !cell bottom import
IGESIN,'kc_ta_plate_1','igs' !tantalum spacer plate import
IGESIN,'kc_ta_plate_2','igs'
IGESIN,'kc_ta_threaded_plate_1','igs'
IGESIN,'kc_ta_threaded_plate_2','igs'
IGESIN,'kc_ta_threaded_plate_3','igs'
IGESIN,'kc_ta_threaded_plate_4','igs'
IGESIN,'kc_ta_screw_1','igs'
IGESIN,'kc_ta_screw_2','igs'
IGESIN,'kc_ta_screw_3','igs'
IGESIN,'kc_ta_screw_4','igs'
IGESIN,'kc_ta_foil_conn_1','igs' !tantalum foil connector import
IGESIN,'kc_ta_foil_conn_2','igs'
IGESIN,'kc_ta_foil_conn_3','igs'
IGESIN,'kc_ta_foil_conn_4','igs'
IGESIN,'kc_mo_nut_1','igs' !molybdenum nut import
IGESIN,'kc_mo_nut_2','igs'
IGESIN,'kc_mo_nut_3','igs'
IGESIN,'kc_mo_nut_4','igs'

FINISH !

!----------------------------model definition----------------------------
/PREP7 !enters the model creation preprocessor
*USE,M26Ta.mac !tantalum macro
*USE,M10C_EDM3.mac !graphite edm-3 macro
APPENDIX A – APDL Commands

*USE,M28Cu.mac  !copper macro
*USE,M30Mo.mac  !molybdenum macro

ET,1,SOLID226  !3D element with element with multi-field formulation
KEYOPT,1,1,110  !specification of thermal-electric capability for ET 1

VGLUE,all  !generates new volumes by gluing volumes

NUMCMP,VOLU  !compresses volume numbers
NUMCMP,AREA  !compresses area numbers
NUMCMP,LINE  !compresses line numbers
NUMCMP,KP  !compresses keypoint numbers

ALLSEL, ALL  !selects all entities
VSCALE,ALL,,0.001,0.001,0.001,,0,1  !scaling from "mm" to "m"

!Meshing

!cell top&bottom meshing
VSEL,S,,,23,24,1
ALLSEL,BELOW,VOLU
MAT,C_EDM3
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00115
VMESH,ALL
ALLSEL

!Tantalum connectors meshing
VSEL,S,,,19,22,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!copper clamps meshing
VSEL,S,,,3,4,1
VSEL,A,,,9,10,1
VSEL,A,,,1,2,1
ALLSEL,BELOW,VOLU
MAT,Cu
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0069
VMESH,ALL
ALLSEL

!Tantalum plates meshing
VSEL,S,,,11,14,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Tantalum screws meshing
VSEL,S,,15,18,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Molibdenum nuts meshing
VSEL,S,,5,8,1
ALLSEL,BELOW,VOLU
MAT,Mo
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

/REPLAY
/replot

!Loads & Boundary conditions

!Ta components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Ta
!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,RDSF,-Ta,1
!specifies surface radiation as surface loads

!EDM-3 components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,C_EDM3
!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,RDSF,-C_EDM3,1
!specifies surface radiation as surface loads

!Cu components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Cu
!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,RDSF,-Cu,1
!specifies surface radiation as surface loads

!Mo components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Mo
!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,RDSF,-Mo,1
!specifies surface radiation as surface loads

!removal of the contact surfaces from the radiation problem
ALLSEL, ALL
*GET,nvolu,VOLU,0,COUNT
nn=0
*DO,i,1,nvolu
nn=vlnext(nn)
VSEL,ALL
VSEL,U,VOLU,,nn
ALLSEL,BELOW,VOLU
VSEL,S,VOLU,,nn
ASLV,R
SFADELE,ALL,,RDSF
ALLSEL,ALL
*ENDDO

!thermal initial conditions
TUNIF,T0 !assigns a uniform temperature to all nodes [°C]

!temperature DOF constraint
ASEL,S,,,16,17,1
ASEL,A,,,10,11,1
DA,ALL,TEMP,T0 !defines DOF constraints on areas [°C]
ALLSEL,ALL

electrical connector voltage DOF constraint
DA,9,VOLT,0 !defines DOF constraints on areas [V]

*DIM,I_LINE,TABLE,19,1,1,TIME

*SET,I_LINE(1,0),0 ! TIME [s]
*SET,I_LINE(1,1),0 ! I_LINE [A]

*SET,I_LINE(2,0),1
*SET,I_LINE(2,1),100

*SET,I_LINE(3,0),2000
*SET,I_LINE(3,1),100

*SET,I_LINE(4,0),2001
*SET,I_LINE(4,1),200

*SET,I_LINE(5,0),3500
*SET,I_LINE(5,1),200

*SET,I_LINE(6,0),3501
*SET,I_LINE(6,1),300

*SET,I_LINE(7,0),4500
*SET,I_LINE(7,1),300

*SET,I_LINE(8,0),4501
*SET,I_LINE(8,1),400

*SET,I_LINE(9,0),5500
*SET,I_LINE(9,1),400

*SET,I_LINE(10,0),5501
*SET,I_LINE(10,1),500

*SET,I_LINE(11,0),6500
*SET,I_LINE(11,1),500

*SET,I_LINE(12,0),6501
*SET,I_LINE(12,1),600

*SET,I_LINE(13,0),7500
*SET,I_LINE(13,1),600
APPENDIX A – APDL Commands

*SET,I_LINE(14,0),7501
*SET,I_LINE(14,1),700

*SET,I_LINE(15,0),8500
*SET,I_LINE(15,1),700

*SET,I_LINE(16,0),8501
*SET,I_LINE(16,1),800

*SET,I_LINE(17,0),9500
*SET,I_LINE(17,1),800

!power generation - Joule effect
ASEL,S,AREA,,15
ALLSEL,BELOW,AREA
ASEL,S,AREA,,15
NSLA,S,1
CP,3,VOLT,ALL
ni=kpnext(0)
FK,nix,AMPS,%I_LINE%
ALLSEL

ALLSEL

!power generation - Joule effect
ASEL,S,AREA,,15
ALLSEL,BELOW,AREA
ASEL,S,AREA,,15
NSLA,S,1
CP,3,VOLT,ALL
ni=kpnext(0)
FK,nix,AMPS,%I_LINE%
ALLSEL

!space temperature definition (open enclosure)
SPCTEMP,1,T0

!defining Solution Options
STEF,5.67e-8
RADOPT,0.5,0.006,,5000
TOFFST,273.15

!defining View Factor Options
HEMIOPT,100
VFOPT,OFF

FINISH
/REPLAY

!---------------------------------------solver---------------------------------------
/SOLU

SOLCONTROL,ON
ANTYPE,TRANS
AUTOTS,ON
KBC,1
DELTIM,0.0001,0.00005,100
OUTRES,NSOL,ALL
TIME,9500
SAVE,,,ALL
SOLVE
SAVE,,,ALL

FINISH
APPENDIX A – APDL Commands

APDL commands referred to the Finite Element Model of §2.5.4

!--------------------------------------------initializing--------------------------------------------!
FINISH
/CLEAR,START
/TITLE,TOF Chamber - Thermal/electrical analysis - Current=330A without screen
/CONFIG,NRES,100000 !maximum number of substeps allowed on the result file

!-------------------------------------------parameters-------------------------------------------!
T0=21 !temperature constraint [°C]
I_LINE=470 !line electric current [A]

!--------------------------------------------geometry import----------------------------------------!
/AUX15 !enters the IGES file transfer processor
IOPTN,IGES,NODEFEAT !no defeating
IOPTN,MERG,YES !automatic merging of entities
IOPTN,SOLID,YES !solid is created automatically
IOPTN,SMALL,YES !small areas are deleted
IOPTN,GTOLER,0.000001 !merging tolerance

!shielding system import
IGESIN,'graphite_screen','igs' !graphite screen import
IGESIN,'macor_upper_screen_support','igs' !Macor insulator import
IGESIN,'macor_upper_screen_support_cpy_1','igs' !Macor insulator import
IGESIN,'graphite_screen_support_4','igs' !regulation plate import
IGESIN,'graphite_screen_support_4_cpy_1','igs' !regulation plate import
IGESIN,'graphite_screen_support_3','igs' !regulation plate import
IGESIN,'graphite_screen_support_3_cpy_1','igs' !regulation plate import
IGESIN,'graphite_screen_support_2','igs' !vertical pin import
IGESIN,'graphite_screen_support_2_cpy_1','igs' !vertical pin import
IGESIN,'graphite_screen_support_1','igs' !base import
IGESIN,'graphite_screen_support_1_cpy_1','igs' !base import
IGESIN,'prt0067_cpy_16','igs' !Macor insulator import
IGESIN,'prt0067_cpy_17','igs' !Macor insulator import
IGESIN,'prt0067_cpy_18','igs' !Macor insulator import
IGESIN,'prt0067_cpy_19','igs' !Macor insulator import
IGESIN,'prt0067_cpy_20','igs' !Macor insulator import
IGESIN,'prt0067_cpy_21','igs' !Macor insulator import
IGESIN,'prt0067_cpy_22','igs' !Macor insulator import
IGESIN,'prt0067_cpy_23','igs' !Macor insulator import

!Knudsen cell import
IGESIN,'kc_top','igs' !Knudsen cell top part import
IGESIN,'kc_bottom','igs' !Knudsen cell bottom part import

IGESIN,'kc_ta_foil_conn','igs' !tantalum foil connector import
IGESIN,'kc_ta_foil_conn_cpy_1','igs' !tantalum foil connector import
IGESIN,'kc_ta_foil_conn_cpy_2','igs' !tantalum foil connector import
IGESIN,'kc_ta_foil_conn_cpy_3','igs' !tantalum foil connector import

IGESIN,'kc_ta_plate','igs' !tantalum plate import
IGESIN,'kc_ta_plate_cpy_1','igs' !tantalum plate import
IGESIN,'kc_ta_screwed_plate','igs' !tantalum threaded plate import
IGESIN,'kc_ta_screwed_plate_cpy_1','igs' !tantalum threaded plate import
IGESIN,'ta_screw','igs' !tantalum screw import
IGESIN,'ta_screw_cpy_1','igs' !tantalum screw import
IGESIN,'ta_screw_cpy_2','igs' !tantalum screw import
IGESIN,'ta_screw_cpy_3','igs' !tantalum screw import
IGESIN,'mo_nut','igs'!molybdenum nut import
IGESIN,'mo_nut_cpy_1','igs'!molybdenum nut import
IGESIN,'mo_nut_cpy_2','igs'!molybdenum nut import
IGESIN,'mo_nut_cpy_3','igs'!molybdenum nut import

IGESIN,'kc_tof_clamp_1a','igs'!copper clump import
IGESIN,'kc_tof_clamp_1b','igs'!copper clump import
IGESIN,'PRT0069','igs'!electrical feedthrough import
IGESIN,'PRT0069_cpy_1','igs'!electrical feedthrough import
IGESIN,'kc_tof_clamp_2','igs'!copper clump import
IGESIN,'kc_tof_clamp_2_cpy_1','igs'!copper clamp import

!Alignment system import
IGESIN,'centering_support','igs'!tungsten pin import
IGESIN,'centering_support_cpy_1','igs'!tungsten pin import
IGESIN,'centering_support_cpy_2','igs'!tungsten pin import
IGESIN,'centering_support_cpy_3','igs'!tungsten pin import

IGESIN,'comp_vert_reg_lato','igs'!vertical part import
IGESIN,'comp_vert_reg_lato_1','igs'!vertical part import
IGESIN,'comp_vert_reg_lato_cpy_1','igs'!vertical part import
IGESIN,'comp_vert_reg_lato_1_cpy_1','igs'!vertical part import

IGESIN,'PRT0068','igs'!graphite limit pin import
IGESIN,'PRT0068_cpy_1','igs'!graphite limit pin import
IGESIN,'PRT0068_cpy_2','igs'!graphite limit pin import
IGESIN,'PRT0068_cpy_3','igs'!graphite limit pin import

IGESIN,'COMP_ORIZZ','igs'!horizontal part import
IGESIN,'COMP_ORIZZ_cpy_1','igs'!horizontal part import
IGESIN,'prt0068_mir','igs'!horizontal part import
IGESIN,'prt0068_mir_cpy_1','igs'!horizontal part import

IGESIN,'placca_laterale_filettata','igs'!threaded plate import
IGESIN,'placca_laterale_filettata_cpy_1','igs'!threaded plate import
IGESIN,'placca_laterale_filettata_cpy_2','igs'!threaded plate import
IGESIN,'placca_laterale_filettata_cpy_3','igs'!threaded plate import

IGESIN,'vite_regolazione_verticale','igs'!stud import
IGESIN,'vite_regolazione_verticale_cpy_1','igs'!stud import
IGESIN,'vite_regolazione_verticale_cpy_2','igs'!stud import
IGESIN,'vite_regolazione_verticale_cpy_3','igs'!stud import

IGESIN,'prt0067','igs'!Macor insulator import
IGESIN,'prt0067_cpy_1','igs'!Macor insulator import
IGESIN,'prt0067_cpy_2','igs'!Macor insulator import
IGESIN,'prt0067_cpy_3','igs'!Macor insulator import
IGESIN,'prt0067_cpy_4','igs'!Macor insulator import
IGESIN,'prt0067_cpy_5','igs'!Macor insulator import
IGESIN,'prt0067_cpy_6','igs'!Macor insulator import
IGESIN,'prt0067_cpy_7','igs'!Macor insulator import
IGESIN,'prt0067_cpy_8','igs'!Macor insulator import
IGESIN,'prt0067_cpy_9','igs'!Macor insulator import
IGESIN,'prt0067_cpy_10','igs'!Macor insulator import
IGESIN,'prt0067_cpy_11','igs'!Macor insulator import
IGESIN,'prt0067_cpy_12','igs'!Macor insulator import
IGESIN,'prt0067_cpy_13','igs'!Macor insulator import
IGESIN,'prt0067_cpy_14','igs'!Macor insulator import
IGESIN,'prt0067_cpy_15','igs'!Macor insulator import
!Vacuum chamber import
IGESIN,'PRT0063','igs'
!chamber part import
IGESIN,'CAMERA_CROCE_001','igs'
!chamber part import
IGESIN,'prt0005_af0','igs'
!chamber part import
IGESIN,'prt0005_af0_cpy_1','igs'
!chamber part import
IGESIN,'TOPVETRO','igs'
!chamber part import
FINISH!

!-----------------------------------model definition-----------------------------------

/PREP7 !enters the model creation preprocessor

vsel,s,,,20,43,1
VGLUE,all
allsel,all

vsel,s,,,1,19,1
VGLUE,all
allsel,all

vsel,s,,,44
VGLUE,all
allsel,all

vsel,a,,,48
vsel,a,,,52
vsel,a,,,56
vsel,a,,,60
vsel,a,,,64
vsel,a,,,68,71,1
VGLUE,all
allsel,all

vsel,s,,,46
VGLUE,all
allsel,all

vsel,a,,,49
vsel,a,,,54
vsel,a,,,58
vsel,a,,,62
vsel,a,,,66
vsel,a,,,76,79,1
VGLUE,all
allsel,all

vsel,s,,,45
VGLUE,all
allsel,all

vsel,a,,,50
vsel,a,,,53
vsel,a,,,57
vsel,a,,,61
vsel,a,,,65
vsel,a,,,72,75,1
VGLUE,all
allsel,all

vsel,s,,,47
VGLUE,all
allsel,all

vsel,a,,,51
vsel,a,,,55
vsel,a,,,59
vsel,a,,,63
vsel,a,,,67
vsel,a,,,80,83,1
VGLUE,all
allsel,all

vsel,s,,,3
VGLUE,all
allsel,all
APPENDIX A – APDL Commands

vsel,a,,,4
vsel,a,,,12,13,1
vsel,a,,,40,41,1
vsel,a,,,52
vsel,a,,,50
vsel,a,,,84
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

NUMCMP,VOLU
!compresses volume numbers
NUMCMP,AREA
!compresses area numbers
NUMCMP,LINe
!compresses line numbers
NUMCMP,KP
!compresses keypoint numbers

!/PREP7
!enters the model creation preprocessor

ALLSEL, ALL
!selects all entities
VLSCALE,ALL,,,0.001,0.001,0.001,0,1
!scaling from "mm" to "m"
vsel,s,,,61
vsel,a,,,64
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

vsel,s,,,61,63,1
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

vsel,s,,,47
vsel,a,,,91
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

vsel,s,,,24,25,1
vsel,a,,,36
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

vsel,s,,,26,27,1
vsel,a,,,37
VGLUE,all
!generates new volumes by gluing volumes
allsel,all

!---------------------------------Macro and element--------------------------------

*USE,M26Ta.mac
!tantalum macro
*USE,M10C_EDM3.mac
!graphite edm-3 macro
*USE,M28Cu.mac
!copper macro
*USE,M30Mo.mac
!molybdenum macro
*USE,M50SS316.mac
!steel macro
*USE,M31Al2O3_XX.mac
!alumina macro
*USE,M25W.mac

ET,1,SOLID226
!3D element with element with multi-field formulation
KEYOPT,1,1,110
!specification of thermal-electric capability for ET 1
ET,2,SOLID87

!---------------------------------Meshing----------------------------------------

!----Knudsen Cell meshing
!cell top&bottom meshing
VSEL,S,,,87
VSEL,a,,,88
ALLSEL,BELOW,VOLU
MAT,C_EDM3
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00115
VMESH,ALL
ALLSEL

!Tantalum foil connectors meshing
VSEL,S,,,83,86,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Copper clamps meshing
VSEL,S,,,65
VSEL,A,,,68
VSEL,A,,,71,72,1
VSEL,A,,,75,76,1
ALLSEL,BELOW,VOLU
MAT,Cu
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0069
VMESH,ALL
ALLSEL

!Tantalum plates meshing
VSEL,S,,,81,82,1
VSEL,a,,,73,74,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Tantalum screws meshing
VSEL,S,,,77,80,1
ALLSEL,BELOW,VOLU
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Molibdenum nuts meshing
VSEL,S,,,69,70,1
APPENDIX A – APDL Commands

VSEL,A,,,66,67,1
ALLSEL,BELOW,VOLU
MAT,Mo
TYPE,1
MSHAPE,1,3D!mshape
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!-----------------------------------Support system meshing-----------------------------------!

!Tungsten pins meshing
VSEL,S,,,54
VSEL,a,,,7
VSEL,a,,,16
VSEL,a,,,44
ALLSEL,BELOW,VOLU
MAT,W
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00115
VMESH,ALL
ALLSEL

!graphite pin meshing
VSEL,S,,,52
VSEL,a,,,5
VSEL,a,,,42
VSEL,a,,,14
ALLSEL,BELOW,VOLU
MAT,C_EDM3
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.002
VMESH,ALL
ALLSEL

!horizontal parts meshing
VSEL,S,,,9
VSEL,a,,,18
VSEL,a,,,48
VSEL,a,,,56
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.002875
VMESH,ALL
ALLSEL

!vertical components meshing
VSEL,S,,,8
VSEL,a,,,17
VSEL,a,,,46
VSEL,a,,,55
ALLSEL,BELOW,VOLU
MAT,SS316
APPENDIX A – APDL Commands

TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!threaded plate meshing
VSEL,S,,,57,60,1
VSEL,a,,,15
VSEL,a,,,6
VSEL,a,,,53
VSEL,a,,,43
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0046
VMESH,ALL
ALLSEL

!Macor parts meshing
VSEL,S,,,1,4,1
VSEL,a,,,10,13,1
VSEL,a,,,45
VSEL,a,,,49,51,1
VSEL,a,,,19
VSEL,a,,,39,41,1
ALLSEL,BELOW,VOLU
MAT,Al2O3_XX
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0046
VMESH,ALL
ALLSEL

!---------------------------------------------------Shielding system mesh---------------------------------------------------

!Graphite screen meshing
VSEL,S,,,38
ALLSEL,BELOW,VOLU
MAT,C_EDM3
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0013
VMESH,ALL
ALLSEL

!Regulation plate support
VSEL,S,,,28,29,1
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL
!Regulation plate support
VSEL,S,,,32,33,1
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Regulation plate support
VSEL,S,,,34,35,1
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Regulation plate support
VSEL,S,,,36,37,1
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.00345
VMESH,ALL
ALLSEL

!Macor insulator
VSEL,S,,,30,31,1
ALLSEL,BELOW,VOLU
MAT,Al2O3_XX
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0025
VMESH,ALL
ALLSEL

!Macor isolator
VSEL,S,,,20,27,1
ALLSEL,BELOW,VOLU
MAT,Al2O3_XX
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0031
VMESH,ALL
ALLSEL

!----------------------------------vacuum chamber meshing----------------------------------

!chamber meshing
VSEL,S,,,64
VSEL,a,,,90
VSEL,a,,,91
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0115
VMESH,ALL
ALLSEL

!cover meshing
VSEL,S,,89
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0115
VMESH,ALL
ALLSEL

!plate meshing
VSEL,S,,61
ALLSEL,BELOW,VOLU
MAT,SS316
TYPE,2
MSHAPE,1,3D
MSHKEY,0
AESIZE,ALL,0.0115
VMESH,ALL
ALLSEL
/REPLOT

!------------------------------------------------------------------- Loads & Boundary conditions -----------------------------------!

!Ta components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Ta !reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-Ta,1 !specifies surface radiation as surface loads

!EDM-3 components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,C_EDM3 !reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-C_EDM3,1 !specifies surface radiation as surface loads

!Cu components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Cu !reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-Cu,1 !specifies surface radiation as surface loads

!Mo components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Mo !reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-Mo,1 !specifies surface radiation as surface loads

!Al2O3_XX components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,Al2O3_XX !reselects the volumes of a specific material
APPENDIX A – APDL Commands

ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-AI2O3_XX,1  \!specifies surface radiation as surface loads

!A316L_X components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,SS316  \!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-SS316,1  \!specifies surface radiation as surface loads

!W components radiating surfaces
ALLSEL, ALL
VSEL,R,MAT,,W  \!reselects the volumes of a specific material
ALLSEL,BELOW,VOLU
SFA,ALL,,RDSF,-W,1  \!specifies surface radiation as surface loads

!removal of the contact surfaces from the radiation problem
ALLSEL, ALL
*GET,nvolu,VOLU,0,COUNT
nn=0
*DO,i,1,nvolu
nn=vnexx(nn)
VSEL,ALL
VSEL,U,VOLU,,nn
ALLSEL,BELOW,VOLU
VSEL,S,VOLU,,nn
ASLV,R
SFADELE,ALL,,RDSF
ALLSEL,ALL
*ENDDO

!removal of the surfaces that exchange by convection
ASEL,S,,993,994,1  \!natural convection
ASEL,A,,996
ASEL,A,,1001
ASEL,A,,1008,1009,1
ASEL,A,,1016,1021,1
ASEL,A,,1025,1027,1
ASEL,A,,1040,1042,1
ASEL,A,,1064,1066,1
ASEL,A,,1094,1105,1
ASEL,A,,1106,1111,1
ASEL,A,,1314,1315,1
ASEL,A,,1321,1322,1
SFADELE,ALL,,RDSF
ALLSEL

!removal of the surfaces that exchange by convection
ASEL,S,,1324,1325,1  \!forced heat convection
SFADELE,ALL,,RDSF
ALLSEL

!removal of the surfaces water cooled plate
ASEL,S,,1028,1039,1
SFADELE,ALL,,RDSF
ALLSEL

!removal of the surfaces water cooled pin
ASEL,S,,553,556,1
ASEL,A,,546,549,1
SFADELE,ALL,,RDSF
ALLSEL
!Definition of convective heat transfer surfaces
ASEL,S,,,993,994,1
ASEL,A,,,996
ASEL,A,,,1001
ASEL,A,,,1008,1009,1
ASEL,A,,,1016,1021,1
ASEL,A,,,1025,1027,1
ASEL,A,,,1040,1042,1
ASEL,A,,,1064,1066,1
ASEL,A,,,1094,1105,1
ASEL,A,,,1106,1111,1
ASEL,A,,,1314,1315,1
ASEL,A,,,1321,1322,1
SFA,ALL,,CONV,28,25
!Tf=25°C ; alfa=10 W/m²°C
ALLSEL

!Definition of convective heat transfer surfaces
ASEL,S,,,1324,1325,1
SFA,ALL,,CONV,28,25
!Tf=25°C ; alfa=10 W/m²°C
ALLSEL

!thermal initial conditions
TUNIF,25
!assigns a uniform temperature to all nodes [°C]
TREF,25

!temperature DOF constraint on the cooled surfaces of the chamber
ASEL,S,,,1028,1039,1
DA,ALL,TEMP,T0
!defines DOF constraints on areas [°C]
ALLSEL

!temperature DOF constraint on the cooled surfaces of the electrical feedthrough
ASEL,S,,,553,556,1
ASEL,A,,,546,549,1
DA,ALL,TEMP,T0
!defines DOF constraints on areas [°C]
ALLSEL

!electrical feedthrough voltage DOF constraint
DA,553,VOLT,0
!defines DOF constraints on areas [V]

!power generation - Joule effect
ASEL,S,AREA,,546
ASEL,BELOW,AREA
NSLA,S,1
CP,3,VOLT,ALL
ni=knpext(0)
FK,ni,AMPS,I_LINE
ALLSEL

!defining Solution Options
STEF,5.67e-8
RADOPT,0.5,0.006,.,5000
TOFFST,273.15
SPCTEMP,1,25

!defining View Factor Options
HEMIOPT,100
VFOPT,OFF

/REPLOT
/INPUT,IC_simulation_11,'dat',,0,1
FINISH
APPENDIX A – APDL Commands

!--------------------------------------- solver ---------------------------------------!
/SOLU !enters the solution processor

SOLCONTROL,ON
ANTYPE,STATIC
AUTOTS,ON
KBC,1
NSUBST,1000,10000,20
!NSUBST,1,1,1
OUTRES,NSOL,ALL
TIME,1
SAVE,,,,ALL
SOLVE
SAVE,,,,ALL
FINISH

!specifies to use optimized nonlinear solution defaults
!specifies to perform a transient analysis, valid for all DOF
!specifies to use automatic time stepping
!specifies stepped loading within a load step
!specifies the time step sizes to be used for this load step
!specifies the time step sizes to be used for this load step
!specifies to save the nodal DOF solution for every substep
!sets the time for a load step
!saves all current database information
!starts a solution
APDL commands referred to the Finite Element Model of §5.6

!---------------------------------initializing----------------------------------
FINISH
/CLEAR, START
/TITLE, Flexible transmission joint
/CONFIG,NRES,100000 !maximum number of substeps allowed on the result file

!---------------------------------geometry import----------------------------------
/AUX15 !enters the IGES file transfer processor
IOPTN,IGES,NODEFEAT !no defeating
IOPTN,MERG,YES !automatic merging of entities
IOPTN,SOLID,YES !solid is created automatically
IOPTN,SMALL,YES !small areas are deleted
IOPTN,GTOLER,0.000001 !merging tolerance
BTOL,DEFA
IGESIN,ASSIEME_RUOTATO,igs !joint import

!Material properties (CC455HT)
/PREP7
MP,EX,1,206000
MP,PRXY,1,0.3

!Element type
ET,1,SOLID186

!Joint mesh
/PROEP7
ALLSEL, ALL !selects all entities
VLScale,ALL,,0.001,0.001,0.001,,0.1 !scaling from "mm" to "m"
VGLUE,all
ALSELL
NUMMRG,All,0.01,0.01
TYPE,1
MAT,1

!coils selection
VSEL,S,VOLU,,21
VSEL,A,VOLU,,7
VSEL,A,VOLU,,22
VSEL,A,VOLU,,8
VSEL,A,VOLU,,27
VSEL,A,VOLU,,13
VSEL,A,VOLU,,28
VSEL,A,VOLU,,14
VSEL,A,VOLU,,33
VSEL,A,VOLU,,19
VSEL,A,VOLU,,34
VSEL,A,VOLU,,20

!coils mesh
ESIZE,0.00075
VSweep,ALL

!massive heads selection and meshing
VSEL,INVE
APPENDIX A – APDL Commands

ESIZE,0.0012
MSHKEY,0
MSHAPE,1
VMESH,All

!BEAM188 key options setting
/PREP7
ET,2,BEAM188
KEYOPT,2,1,0
KEYOPT,2,2,1
KEYOPT,2,3,3
SECTYPE,1,BEAM,ASEC,PROF_INF_RIG
SECDATA,10000,10000,10000,100000000,10000,10000,10000,10000,10000,10000,10000,10000

!generation of the node on which displacements are applied to obtain different torques.
N,11111111,0,0,128.938,,,,

! Constraints of one massive head area.
ASEL,S,AREA,,18
ASEL,A,AREA,,23
NSLA,S,1
D,ALL,UX,0
D,ALL,UY,0
D,ALL,UZ,0
ALLSEL,ALL

! Beam188 elements generation
ASEL,S,AREA,,47
ASEL,A,AREA,,66
NSLA,S,1
TYPE,2
SECNUM,1
*GET,ND_NBR,NODE,0,COUNT
nn=0
*DO,i,1,ND_NBR
nn=NDNEXT(nn)
E,11111111,nn
*ENDDO
ALLSEL,ALL

! Node 11111111 constraints
D,11111111,UX,0
D,11111111,ROTZ,0
ALLSEL,ALL

!-------------------------------------------------solver-------------------------------------------------
/SOL
!-------------------------------------------------load cases-------------------------------------------------
D,11111111,ROTX,0.087266
LSWRITE,1
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*2
LSWRITE,2
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*3
LSWRITE,3
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*4
LSWRITE,4
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*5
LSWRITE,5
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*6
LSWRITE,6
/SOL
DSUM,ADD
D,11111111,ROTX,0.087266*7
LSWRITE,7
LSWRITE, 4
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*5
LSWRITE, 5
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*6
LSWRITE, 6
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*7
LSWRITE, 7
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*8
LSWRITE, 8
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*9
LSWRITE, 9
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*10
LSWRITE, 10
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*11
LSWRITE, 11
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*12
LSWRITE, 12
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*13
LSWRITE, 13
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*14
LSWRITE, 14
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*15
LSWRITE, 15
/SOL
DSUM, ADD
D, 11111111, ROTX, 0.087266*16
LSWRITE, 16
/SOL
DSUM, ADD
D, 11111111, ROTX, 1.5708
LSWRITE, 17
/SOL
DSUM, ADD
D, 11111111, UY, -73.5
LSWRITE, 18
/SOL
DSUM, ADD
D, 11111111, UY, -73.5
LSWRITE, 19
/SOL
DSUM,ADD
D,11111111,UY,-74.5
LSWRITE,20
/SOL
DSUM,ADD
D,11111111,UZ,-53.94
LSWRITE,21
/SOL
DSUM,ADD
D,11111111,UZ,-52.94
LSWRITE,22
/SOL
DSUM,ADD
D,11111111,UZ,-51.94
LSWRITE,23
/SOL
DSUM,ADD
D,11111111,UZ,-50.94
LSWRITE,24
/SOL
DSUM,ADD
D,11111111,UZ,-49.94
LSWRITE,25
/SOL
DSUM,ADD
D,11111111,UZ,-48.94
LSWRITE,26

ANTYPE,0
NLGEOM,ON                     !large-deflection effects activation
AUTOTS,1
LSSOLVE,1,26,1
SAVE,Flexible_transmission_Join,db,,SOLU