To Jessica,

Michele and my parents
Development and Manufacturing of the IFMIF/EVEDA RFQ Modules

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FOREWORD

The fulfilment of the research project presented in this Thesis has involved the financial and intellectual support of many people, to whom the author is most grateful. Most of the research activity that led to the results and achievements summarised in the Thesis has been developed at the Department of Physics and Astronomy at the University of Padova (DFA), under the supervision of Prof. Giovanni Meneghetti. The work has been carried out at the I.N.F.N.-Padova Unit under the supervision of Ing. Adriano Pepato a rare person, not only for humanity but for his great engineering knowledge. The realisation of this study has been made possible thanks to the financial support of I.N.F.N.-L.N.L. All the material presented in this thesis is original, unless explicit references provided by the author.
ABSTRACT

The IFMIF (International Fusion Material Irradiation Facility) project aim is to build a facility for the mechanical characterization of material that will constitute the wall of the nuclear reactor for DEMO (DEMONstration power plant). The complexity of this facility, containing numerous components with peculiar specifications, requires the development of a preliminary stage for the engineeristic evaluation that will led to outline the framework of the activities, the so called EVEDA (Engineering Validation Engineering Design Activities) phase, including the LIPAc prototype construction that involve many research institutes around the world each one has in charge the realization of a line components. The description of the IFMIF project and also each contribution of the participating research institutes are briefly reported on chapter 1. Such facility require the realization of a RFQ four-vane particle accelerator, composed of 18 modules, whose part of mechanical design and construction has been entrusted respectively to mechanical design office and workshop of the I.N.F.N. Padova Unit (Istituto Nazionale di Fisica Nucleare). Since the mechanical design of the accelerator ha almost completed, we faced on the production covering over all metrological quality control phases. Metrologic control and qualification stages are strictly related to the cavity behaviour therefore we focus our attention to its working principle. Thus, in the second chapter it has been summarised the basics to understand the basic working principles of such machines, the main parameter affecting their performances and finally the main geometrical parameter of the accelerator concerned. The most critical issues arise from the production concerning the brazing process which does not permit adjustment except with re-brazing causing a strong deterioration of the mechanical properties of the copper components. It should be mentioned that brazing turned out to be an uncertainty source for the quality of the pieces, therefore, part of the activities have been carried out on the resolution of such problems. The possible causes of defect on brazed geometries have been found and one-dimensional considerations about thermal expansion as well as 3d thermo-structural simulation confirm all the statements. Such problematics has been reported on third chapter which, moreover, consists on their resolutions: the design of a new brazing cycle with an intermediate plateau. All the remaining modules are then brazed with this new cycle that permitted the disappearance of the brazing distortion. This confirms the reliability of the production phases and methods for the obtainments of modules respecting the project specifications. The quality control of the modules include: vacuum tightening test of the cavity, the coolant circuits seal test, Ultrasonic Test (UT) of the brazed joints, dimensional inspection using a CMM (Coordinate Measuring Machine) and Radio-Frequency (RF) test that identifies the electromagnetic behaviour of the single modules. These two last quality controls are strictly correlated each other in such a way that the deviations from the nominal dimensions could be used to predict the electromagnetic ones. Therefore in the last chapter, along with descriptions of the production phases and their metrological controls, it exposes a method for predicting the frequency deviation based on the
deviations of measurements. The method validation is done thank to the comparison between metrological control results and those of the RF test.

To sum up, the first chapter talks about the IFMIF project, its purpose and its main components; the second summarizes the principle of operation of the four-vane RFQ and describes the main parameters of the one used for the project IFMIF / EVEDA; the third introduces the basic concepts of the brazing process, the identification of defects and determining causes by means of a thermal-structural simulation and finally outlines a new brazing cycle; the last chapter describes the main stages of production, the metrological control between them, culminating in an metrological characterization method to predict the electromagnetic behaviour of the cavity.
Riassunto

Il progetto IFMIF (International Fusion Material Irradiation Facility) prevede la costruzione di un impianto per la caratterizzazione meccanica dei materiali candidati a costituire la parete del reattore a fusione nucleare per il progetto DEMO. La complessità di questo impianto, con numerosi con peculiari specifiche, richiede lo sviluppo di una fase preliminare di validazione ingegneristica e che porterà a delineare il quadro delle attività, la cosiddetta fase EVEDA (Engineering Validation Engineering Design Activities), che include la costruzione di un prototipo di linea acceleratrice LIPAc che coinvolge più enti di ricerca sparsi nel mondo e ad ognuno è affidato il compito della realizzazione di un componente della linea. La descrizione del progetto IFMIF nonché ciascun contributo degli istituti di ricerca partecipanti vengono riportati brevemente nel capitolo 1. Tale impianto richiede la realizzazione di un acceleratore di tipo RFQ four-vane, composto da 18 moduli, la cui progettazione meccanica e parte della produzione è affidata rispettivamente all’ufficio tecnico di progettazione e all’officina meccanica presso la Sezione di Padova dell’I.N.F.N.. Siccome la progettazione meccanica dell’acceleratore era quasi finita, ci si è affacciati alla produzione e le relative fasi di controllo e qualifica metrologica dei componenti. I controlli e le qualifiche di tipo metrologico sono strettamente correlati al comportamento della cavità pertanto si è data particolare attenzione ai principi di funzionamento della stessa. Nel secondo capitolo quindi si riassumono le nozioni necessarie per comprendere il principio di funzionamento di tali macchine, i parametri che più influiscono sulle prestazioni ed infine le fondamentali caratteristiche geometriche della cavità. La criticità maggiore nella produzione si ha col processo di brasatura che non permette correzioni se non con ri-brasatura e forte deterioramento delle caratteristiche meccaniche dei componenti in rame. Va detto che tale processo si è rilevato fonte di incertezza per la qualità di manufatti per cui parte delle attività sono state spese nella risoluzioni di tali problematiche. Osservando i difetti dei componenti brasati se ne sono individuate le cause, la cui conferma vien data da considerazioni basate sui coefficienti di espansione termica ed infine da una simulazione termo-strutturale. Tali problematiche si sono riportate nel capitolo 3 che peraltro contiene la loro risoluzione: la progettazione di un nuovo ciclo di brasatura con plateau intermedio. Tutti i moduli restanti quindi si sono brasati con tale ciclo permettendo la scomparsa dei difetti. Questo conferma l’affidabilità delle fasi di produzione e dei metodi per l’ottenimento di manufatti che rispettano le specifiche di progetto. I controlli di qualità dei moduli comprendono: tenuta a vuoto della cavità, tenuta in pressione dei canali di raffreddamento, controlli ultrasuoni (UT) dei giunti brasati, misure metrologiche con l’uso di una CMM (Coordinate Measuring Machine) e test di Radio-Frequenza (RF) che identifica il comportamento elettromagnetico del singoli moduli. Questi ultimi due controlli sono strettamente legati tra loro a tal punto che le deviazioni della geometria nominale possono predirne con il comportamento elettromagnetico. Per tanto nell’ultimo capitolo, insieme alla descrizione delle fasi di produzione e ai relativi controlli metrologici, espone un metodo per la predizione della deviazione in frequenza.
basato sulle deviazione delle misure. La conferma del metodo viene dal confronto dei risultati metrologici e quelli ottenuti mediante test in Radio Frequenza.

Ricapitolando, il primo capitolo parla del progetto IFMIF, del suo scopo è dei suoi componenti; il secondo riassume il principio di funzionamento degli RFQ four-vane e descrive le principali parametri di quello usato per il progetto IFMIF/EVEDA; il terzo introduce i concetti fondamentali del processo di brasatura, l'identificazione dei difetti e delle loro cause mediante una simulazione termo-strutturale e infine delinea un nuovo ciclo di brasatura; l'ultimo capitolo descrive le principali fasi della produzione, il controllo metrologico tra di esse e si conclude con un metodo di caratterizzazione metrologica per prevedere il comportamento elettromagnetico della cavità.
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CHAPTER 1

IFMIF (INTERNATIONAL FUSION MATERIAL IRRADIATION FACILITY) PROJECT

1.1 INTRODUCTION

The energy consumption in the world is increasing and the increasing in CO2 emission would resultanty lead to global warming. Notwithstanding every possible measure incorporated into the energy supply system, such as CO2 sequestrated fossil fuel, nuclear fission, and renewable energy such as wind power, photo-voltaic power, bio-mass power, etc., there is still a shortage of energy supply. A significant amount of energy should be supplied by some innovative energy systems not presently developed. Among possible energy resources, nuclear fusion is notable for its substantial advantages over other forms of energy generation in terms of safety, fuel availability and environmental protection. The earth has an abundant supply of the fuel and raw material required for nuclear fusion. Magnetic fusion reactor is inherently safe and does not create high-level radioactive waste, nor are global warming emissions a concern associated with the generation of fusion energy. For these reasons, worldwide effort in research and development has been continuing towards the practical utilization of fusion energy as a long-term ultimate energy source [1]. The IFMIF/EVEDA and IFERC projects will be implemented in Japan at Rokkasho while the Satellite Tokamak Programme will be implemented at JT-60 Naka in Japan. (Figure 1). At the time of ITER site decision in Moscow on 28 June 2005, representatives of EURATOM (EU) and the Government of Japan (JA) set out the main principles for the implementation of the broader approach activities by the “Joint Paper” and jointly declared their intention to implement broader approach activities in support of ITER on a time frame compatible with its construction phase.

The broader approach activities comprise the following three projects:

- Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA).
- International Fusion Energy Research Center (IFERC), comprising:
  - A DEMO Design and, R&D Coordination Center aiming at establishing a common basis for a DEMO design.
- A Computational Simulation Center composed of super-computer facilities for large-scale simulation activities.
- An ITER Remote Experimentation Center to facilitate broad participation of scientists into ITER experiments.

- Satellite Tokamak Programme including participation in the upgrade of JT-60 Tokamak to an advanced superconducting tokamak and participation in its exploitation, to support ITER experimentation and research towards DEMO reactor.

Thus, the objective of the BA activities is to prepare the scientific and technological basis complementary to ITER for DEMO reactor realization [2].

Figure 1: Road map toward fusion DEMO reactor from the Japanese Fusion Programme. In parallel to ITER, Blanket Materials Development and Satellite Tokamak Research will be needed. [2]
1.2 **INTRODUCTION TO IFMIF**

While for ITER or first generation fission reactor designs the maximum damage level achieved by core structural materials is of the order of a few displacements per atom (dpa), the structural materials of DEMO reactors will operate up to damage levels approaching 150–200 dpa. Such damage levels are achievable in some material test reactors available today. However, as fusion neutrons will generate, besides dpa damage, also high production rates of He and hydrogen isotopes, enhancing sensitively irradiation embrittlement, an intense neutron source with a fusion specific spectrum is needed to generate a reliable materials database. For this purpose, the International Fusion Material Irradiation Facility, IFMIF, has been tailor-designed. IFMIF is the world’s most powerful accelerator-based neutron source project. IFMIF is also a major element of the ‘Broader Approach’ that has been signed by the European and Japanese governments. Within this Broader Approach, IFMIF entered in 2007 a 6 years ‘Engineering Validation Engineering Design Activity’ phase to allow a subsequent start of construction at the end of 2012 [3].

The International Fusion Materials Irradiation Facility, also known as IFMIF, is a projected materials test facility in which candidate materials can be fully qualified for the use in an energy producing fusion reactor. The IFMIF project was started in 1994 as an international scientific research program, carried out by Japan, the European Union, the United States, and Russia, and managed by the International Energy Agency.
IFMIF is an accelerator-based neutron source that produces, using deuterium-lithium nuclear reactions, a large neutron flux with a spectrum similar to that expected at the first wall of a fusion reactor. Safe design, construction and licensing of a fusion power facility by the corresponding Nuclear Regulatory agency Commission will require data on the materials degradation under neutron irradiation during the life-time of a fusion reactor. Whereas in the currently under construction large fusion experiment, ITER, structural damage in the reactor steels will not exceed 2 dpa at the end of its operational life, damage creation in a fusion power plant is expected to amount to 15 dpa per year of operation.
In DEMO, like in future fusion power plants, the deuterium-tritium nuclear fusion reactions will generate neutron fluxes in the order of $10^{18}$ m$^{-2}$s$^{-1}$ with an energy of 14.1 MeV that will collide with the first wall of the reactor vessel, which provides the physical boundary for the plasma and contributes to the thermal and nuclear shielding of the external machine components such as the superconducting magnets. Neutrons will interact with the material structures of the reactor by which their spectrum will be broadened and softened. The main source of materials degradation is structural damage which is typically quantified in terms of “displacements per atom” (dpa). None of the most commonly available neutron sources are adequate for fusion materials testing, for various reasons. The accumulation of gas in the material microstructure is intimately related to the energy of the colliding neutrons. Conventional fission reactors, which produce neutrons with an average energy around 1-2 MeV, cannot adequately match the testing requirements for fusion materials.

IFMIF, the International Fusion Materials Irradiation Facility, will generate, thanks to two parallel deuteron accelerators, a neutron flux with a broad peak at 14 MeV by Li (d,xn) nuclear reactions that will collide in a liquid Li screen with a footprint of 20 cm x 5 cm. The energy of the beam (40 MeV) and the current of the parallel accelerators (2 x 125 mA) have been tuned to maximize the neutrons flux to get irradiation conditions comparable to those of a fusion reactor in a volume of 0.5l that will house around 1000 small specimens. The successful validation of the small specimens test technique under the Broader Approach Agreement between Japan and
EURATOM will allow the full mechanical characterization of suitable materials, and allow the understanding of the degradation that will lead to the design of constituents better tolerant to radiations.

Figure 6: Schematic of the IFMIF Facilities [7].

The IFMIF main expected contributions can be summarized in the following:

- provide data for the engineering design for DEMO
- provide information to define performance limits of materials and materials systems for DEMO and beyond
- contribute to the completion and validation of (existing) databases to gather and confirm data required for licensing and safety assessment
- contribute to the selection or optimization of different alternative fusion materials
- validate the fundamental understanding of radiation response of materials including benchmarking of irradiation effects modelling at length-scale and time-scale relevant for engineering application
- tests blankets and functional materials prior to or complementary to ITER test blanket modules
Since 2007, it has been pursued by the Japanese Government and EURATOM under the Broader Approach Agreement in the field of fusion energy research which conducts engineering validation and engineering design activities for IFMIF, through the IFMIF/EVEDA project. The primary objective of the IFMIF Engineering Design Activities, as a sub-project of the IFMIF/EVEDA Project, is to produce a complete and fully integrated engineering design of the IFMIF plant by incorporating the technical feedback from the accompanying validation activities of key technological elements.

### 1.3 The IFMIF/EVEDA (Engineering Validation and Engineering Design of Activities) Project

The IFMIF Engineering Validation and Engineering Design Activities (EVEDA) aim at producing a detailed, complete and fully integrated engineering design of IFMIF and at validating continuous and stable operation of prototypes of each IFMIF subsystem. The validation activities have been the subject of a successful Japan-Europe scientific collaboration. In order to produce the experimental backing of the IFMIF Design during the EVEDA phase, 3 major prototypes have been designed and manufactured:

- an Accelerator Prototype (LIPAc) at Rokkasho, fully representative of the IFMIF low energy (9 MeV) accelerator (125 mA of D\(^+\) beam in continuous wave) to be completed in June 2017;
• a Lithium Test Loop (ELTL) at Oarai, integrating all elements of the IFMIF lithium target facility, already commissioned in February 2011, complemented by corrosion experiments performed at the LIFUS6 lithium loop at Brasimone; with the development of needed diagnostics and purification systems, will demonstrate that IFMIF’s liquid lithium loop is achievable.
• the High Flux Test Module and its internals to be irradiated in a fission reactor and tested in the helium loop HELOKA, complemented the Creep Fatigue Test Module manufactured and tested in full scale at Villigen.

1.4 THE LIPAc (LINEAR IFMIF PROTOTYPE ACCELERATOR) COMPONENTS

The linear IFMIF prototype accelerator (LIPAc) has been launched within the framework of the Broader Approach Agreement with the objective to validate the low energy part (9 MeV) for the IFMIF LINAC (40 MeV, 125 mA of D+ beam in continuous wave). Starting in mid-2007, the project is managed by the two Home Teams (JA-HT and EU-HT) and headed by the Project Team at the Broader Approach site in Rokkasho with the aim to complete the validation activity with the installation and commissioning of the whole LIPAc by June 2017[8].

1.4.1 INJECTOR + LEBT

The Injector is designed to deliver a deuteron beam of 140 mA at energy of 100 keV. The beam extracted from an ECR (Electron Cyclotron Resonance) source is driven and focused along the LEBT (Low Energy Beam Transport line) before its injection in the RFQ. The total length of the beam line, from the plasma electrode to the internal face of the RFQ entrance flange is 2.05
The LIPAC ECR source, based on the SILHI design, is operating at 2.45 GHz that has been optimized to extract, at 100 keV, total beam intensity from 150 mA to 175 mA in order to meet the required 140 mA of D+, as D+2 and D+3 are also produced in the ECR plasma. Diagnostics are located between the two solenoids SOL of the LEBT to characterize the beam.

A beam chopper produces short pulses with sharp rise/fall times. The LEBT is based on a dual solenoid focusing system to transport the beam and to match it into the RFQ. At the end of the LEBT, a cone with an half-angle of 8° is located just before the RFQ injection to allow the injection of the beam of interest (D+) while stopping the other beam species (i.e. D+2 and D+3 ). Beam intensity can be measured at three locations: between the two solenoids with a beam stopper (BS1), at the end of the injection cone with an ACCT and after the cone with a second beam stopper (BS2) which is auto-polarized. Emittance measurement Unit (EMU) that is used for the LIPAC injector is an Allison scanner. The beam species fraction (D+,D+2 and D+3) is measured by Doppler shift analysis [9,10].
1.4.2 Radio-Frequency Quadrupole

The RFQ is 9.8 m long 175 MHz cavity divided into 18 modules. Its function is to bunch the beam and to accelerate it up to 5 MeV. The RF tuning of the RFQ is ensured by 22 slug tuners per quadrant. The RF power (about 1300 kW) is injected by 8 loop couplers, using 6 1/8” RF windows. The resonance field is tuned by varying the temperatures of vane and walls thanks to a sensitive cooling system. This machine will be exhaustively described on the following chapter.

![Conceptual assembly of the RFQ](image)

Figure 8: Conceptual assembly of the RFQ [100th National congress, Italian Phisics Society, Invted Talks, Fagotti]

1.4.3 MEBT

![Section of the assembly of the Medium Energy Beam Transport line](image)

Figure 9 Section of the assembly of the Medium Energy Beam Transport line [http://www.ifmif.org/].
The objective of the MEBT (Medium Energy Beam Transport line) is to transport and to match the beam to the SRF (Superconducting Radio Frequency) linac input by a transversal and a longitudinal action. The longitudinal action makes use of two RF resonant cavities (Bunchers). A 5-gap interdigital H-mode configuration has been selected as a buncher cavity as the best compromise in terms of total power dissipation, power density, and space occupied. Regarding the transversal action, the radial dimensions of the beam are controlled for injection into the SRF Linac by one Quadrupole triplet and one Quadrupole doublet.

![Figure 9 Assembly of the Medium Energy Beam Transport line with its main dimension](image)

The transverse position of the beam is corrected by the magnetic steerers integrated into the quadrupoles. In order to cut the beam edges and to determine beam losses, the unmatched particles coming from the RFQ are collected by two 4-axis water cooled and movable metallic plates, called scrapers, inserted between the magnets of the triplet. To achieve the vacuum conditions required by the proximity of the RFQ and Superconducting Radiofrequency Linac, a pumping system in the range of $10^{3}$ l/s for H$_2$ will be installed at the vacuum ports of the bunchers.

### 1.4.4 SRF Superconductive Radio Frequency LINAC

The SRF Linac accelerates and focusses the deuteron beam from 5 MeV up to 9 MeV. It contains 8 superconducting cavities coupled with solenoid packages, both operating at 4.4 K, and RF power couplers for the power transmission to the cavities capable of transmitting up to 200 kW in CW. (Power Couplers provide RF power to the cavities up to 70 kW CW in the LIPAc case and 200 kW CW in the IFMIF case). The RF coupler is composed of a water-cooled Cu antenna, a disk ceramic window, an external conductor made of helium cooled double wall tube and a tee transition between the input coaxial line and the coupler. The beam focusing and orbit corrections are performed by 8 sets of superconducting solenoids/steerers and beam position...
monitors, located before each HWR. The cryomodules includes the magnetic shielding to protect the HWR from the earth magnetic field, two independent 4.4 K helium circuits to cool down the cavities and the magnets, a helium phase separator and a thermal shield cooled at 60 K by gaseous He [11,12]

Figure 10: A module of the Superconductive Radio-Frequency accelerator for IFMIF [8]

1.4.5 HEBT AND BEAM DUMP

Figure 11 High Energy Beam Transport [http://www.ifmif.org/].
The HEBT (High Energy Beam Transport line) contains a first set of quadrupoles to tune the beam before its arrival at a D-plate (diagnostics plate) where it will be characterized. A second set of quadrupoles expands the beam before its entry into the BD (Beam Dump). During EVEDA, a special diagnostic plate will be inserted in the HEBT to perform a thorough characterisation of the beam, before its collection in the beam dump. High energy beam transport (HEBT) which includes a series of non-linear optics elements, required to tailor the beam as a flat rectangular beam profile on the flowing lithium target. The High Energy Beam Transport line: this line propagates the beam to the liquid lithium target and transforms the initial cylindrical beam cross section into a rectangular one of 200mm x 50mm. The conceptual design for the IFMIF-EVEDA accelerator beam dump is based on a conical beam stop made of OFE copper. The cooling system uses an axial high velocity flow of water pressurized up to $3.4 \times 10^5$ Pa, to avoid boiling, able to dissipate the beam power up to 1.12 MW.

The conceptual design is based on the LEDA beam dump concept. The reduction of this power density is achieved by defocusing the beam to increase its size and by using a very low incidence angle in the beam stop thus maximizing the material surface area hit by the beam. A dipole placed before the last triplet bends the beam to limit activation along the accelerator due to neutron back streaming from the Beam Dump [13].

Figure 12: Section-view of the beam dump for LIPAc [8].
1.5 **TARGET AND TEST FACILITY**

The engineering design of the IFMIF plant is intimately linked with the validation activities, and was conducted during the first phase of the IFMIF/EVEDA project. The IFMIF Intermediate Engineering Design Report was established in June 2013 and adopted by the stakeholders in December 2013. The IFMIF Intermediate Engineering Design defines the major systems in outline. Accelerator Facility: The two accelerator CW deuteron beams of 5 MW each impinge in an overlapping manner at an angle of ±9° with a footprint of 200 mm x 50 mm and a steady time profile on the liquid Li jet, with the Bragg’s peak absorption region at about 20 mm depth [14].

1.5.1 **THE TARGET FACILITY**

The Target Facility which holds the inventory of about 10 m³ of Li, forms and conditions the beam target. The Li screen fulfils two main functions: 1) to react with the deuterons to generate a stable neutron flux in the forward direction and 2) to dissipate the beam power in a continuous manner. The flowing Li (15 m/s; 250 °C) is shaped and accelerated in the proximity of the beam interaction region by a two-stage reducer nozzle forming a concave jet of 25 mm thickness with a minimum radius of curvature of 250 mm in the beam footprint area. The resulting centrifugal pressure raises the boiling point of the flowing Li and thus ensures a stable liquid phase. The beam power absorbed by the Li is evacuated by the heat removal system and the lithium is cooled to 250 °C by a serial of heat exchangers.

![Diagram of the Target Facility](image)

Figure 13: The Experimental Lithium Test Loop (ELTL) at Oarai (Japan), integrating all elements essential to the IFMIF lithium target facility [7].
The control of impurities, essential for the quality of the liquid screen, will be done through a tailored design of cold and hot trap systems, and purities of Li during operation better than 99.9% are expected. On-line monitoring of impurities will detect impurity levels over 50 ppm. Based on numerical analyses carried out in the last three decades, the beam-target interaction is not expected to have a critical impact on jet stability.

1.5.2 **THE TEST FACILITY**

The Test Facility will provide high, medium and low flux regions ranging from >20 dpa/full power year (fpy) to <1 dpa/fpy with increasingly available irradiation volumes of 0.5 l, 6 l and 8 l that will house different metallic and non-metallic materials potentially subjected to the different irradiation levels in a power plant. More specifically, in the high flux region, fluences of 50 dpa in <3.5 years in a region of 0.5 l, together with power plant relevant fluences of >120 dpa in <5 years in a region of 0.2 l, are planned. According to these needs, the test volume downstream the neutron-producing Li-target has been partitioned into (i) a high flux region with an available volume of 0.5 l and a damage rate of 20–55 dpa/fpy (full power year); (ii) a medium flux region of 6 l with a damage rate of 1–20 dpa/fpy; and (iii) a low flux region of more than 1m3 with a damage rate of less than 1 dpa/fpy.

![Critical components of the High Flux Test Modules tested in the helium cooling loop (HELOKA-LP), at Karlsruhe (Germany)](image)

Figure 14: Critical components of the High Flux Test Modules tested in the helium cooling loop (HELOKA-LP), at Karlsruhe (Germany) [14].

The high flux region will accommodate about 1000 small specimens assembled in 12 individual capsules independently temperature controlled that will allow not only mechanical characterization of the candidate structural materials tested, but also an understanding of the influence in their degradation with material temperature during irradiation. All test modules...
used for the different flux zones have to be instrumented and able to control the irradiation temperature that might vary from 250 to 1000 °C in the high-flux and medium flux regions down to cryogenic temperatures in the low-flux zones. They are installed at the bottom of the vertical test assemblies (VTA) through which heating power, coolant and signal transmissions are provided. Substantial progress is made in the international materials community in developing a complete set of miniaturized samples providing material intrinsic properties and proven scaling laws. Significant volume reductions of 20–125 times have been achieved, and in case of the tensile, fatigue, creep tube and bench/charpy fracture toughness specimens, a quasi-standardization has become accepted worldwide. However, concerning the miniaturization of fracture toughness and fatigue crack growth specimens, the results depends on specimen size and shape with the consequence that still a lot more R&D of the international materials community is needed. The Post-Irradiation Examination Facility, an essential part of IFMIF, is hosted in a wing of the main building in order to minimize the handling operations of irradiated specimens. It will not only allow testing irradiated specimens out of the different testing modules, but also characterizing metallographically the specimens after destructive testing [15]
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CHAPTER 2

THE IFMIF/EVEDA RADIO-FREQUENCY QUADRUPOLE

2.1 INTRODUCTION

Before the description of the accelerating particle machine, it can be useful make some simple considerations that allows justifying the use of this kind of machine. The mass or the rest energy unit of a particle is $E_0 (MeV/c^2)$ with $c$ is the speed of light. The unit $eV$ are the corresponding energy gained, in term of kinetic energy, by an electron $1.602176565 \times 10^{-19} C$ that pass through two equipotential zones which have $1 V$ of voltage drop. One $eV$ corresponds to $1.602176565 \times 10^{-19} J$. Then, the rest mass (Newtonian mass) of an electron is $0.511 MeV/c^2$ $9.109 \cdot 10^{-31} kg$ while that of the protons is $938.27 MeV/c^2 (1.67 \cdot 10^{-27} kg)$. By introducing $\beta$ as the ratio between the particle velocity $v$ and the speed of light $c$, $\beta = v/c$, the dimensionless number $\gamma$ deriving from Lorentz transformation $\gamma = (1 - \beta^2)^{-1/2}$, the total energy $E$ of one moving particles could be expressed the product $E = E_0 \gamma$.

For example if a proton has a relative velocity $\beta = 0.99$ this implies that $\gamma = 7.088$ and its energy is $E = 6651 MeV$. For $\gamma \approx 1$ ones can consider acceptable the classic mechanic laws and the energy of a particle can be expressed by its kinetic contribution $E = mv^2/2$ (Figure 1).

In our case, particles have to be accelerated well below the speed of light where classic mechanic law are acceptable. If the particle velocity is not high, magnetic field interaction is negligible respect to the electric field as we can see from the well note Lorentz formula $F = q(E + v \times B)$. For that reason, particle accelerators that work at low energy level, make use of electric field interacting with ions. The older accelerating particle and those on the first stage of acceleration use that working principle. This is the case of generators similar to the Cockcroft-Walton type, Van de Graaf type or Tandem. The latter type are also installed in the LNL such as CN (7mV) and AN2000 (2MV) and are used on lines for studying in the fundamental and applied physics, materials science, radiobiology, radiation iterating matter, damage from radiation, dosimetry for dating but still finds the cross sections and/or the excitation functions for nuclear reaction channels still poorly investigated, as well as the neutron spectrometry / range [1]. Cockcroft-Walton accelerators have strong beam current with mA level, but its accelerating energy usually is below $1 MeV$. Electrostatic accelerators, the Van de Graaff kind or similar, can reach energy of $MeV$ level, but their beams current are usually below $10 \mu A$. However, this situation has been
changed since the Radio-Frequency Quadrupole (RFQ) accelerator appeared in 80’s thanks to Kapchinsky and Tepliakov [2].

![Graph showing particle velocity normalized to the speed of light as a function of kinetic energy.](image)

Figure 1: Particle velocity normalized to the speed of light as a function of kinetic energy.

(a) Protons: solid line, relativistic predicted, dashed line, Newtonian prediction.

(b) Relativistic predictions for various particles. [3]

Here follows a list of the quality of this kind of particle accelerator:

- Strong beam current as high as $10^1 - 2 \times 10^2$ mA
- Accelerating energy possibly reaching MeV per nucleon
- Small size respect to the electrostatic accelerator
- High transmission efficiency over 80% or 90%
- Low injector energy directly from ion source at ground potential
- Integrating more functions in a RF cavity without external elements: not only effective accelerating and strong focusing, but also beam bunching and transverse matching
- Operating and controlling simply and conveniently
Due to RFQ's favourable performances and its combining accelerating energy of MeV with beam current of mA, which cannot be both possessed for the accelerators of Cockcroft – Walton, Van de Graaff and tandem, now RFQs replace them widely in the low energy region not only used as the powerful injectors of ion LINACs and cyclic accelerators for high energy physics, spallation neutron source, accelerator-driven-system and medical therapy, etc., but also directly to be used.

2.2 WORKING PRINCIPLE OF AN RFQ

The aim of this paragraph is to introduce some used terms from expert in the field who treat particle accelerators as well as electronic engineers and physicist, just to remind some terms that usually are not considered every day from a mechanical engineer. The RFQ is a machine made by 4 electrodes placed in a high vacuum volume, for that usually it could be named cavity. Those electrodes could be joined with an external part, the vessel, forming the so called 4-vane geometry or supported and similar to slight beams forming the 4-rods geometry. For this text the 4 vane is considered (figure 2). As before mentioned the accelerator focus particle on transversal plane, gently bunch and make a longitudinal subdivision of the beam and then accelerate group of particles. All this actions are made possible by a resonant magnetic field, at a frequency specific of each cavity, that induce a transversal alternating electric field on the electrode tips.

The RFQ conception can be easily understood from the static electric quadrupole lenses, which are popularly used as focusing elements in the beam transport of accelerators, and have only transverse electric field for focusing as shown in figure 3. Consider 4 electrodes symmetrically placed around the z axis as in the figure 2 having an alternating potential, in the way that opposite electrodes have the same potential, and adjacent electrodes an opposite potential. This
is a so common electric quadrupole. A charged particle moving at an off-axis \( z \) position, interact with the alternating electric field with a quadrupolar symmetry, that made an alternating focusing in the 2 transversal direction \( x \) and \( y \). This is an analogue of the quadrupole magnetic lenses but in our case the electric component of the Lorentz force act in the charged particle instead of the magnetic one because of the low particles speed.

Figure 3: Electrostatic quadrupole field. (a) Equipotential lines, (b) field lines[3]

To make the electric quadrupole lenses having longitudinal electric field component for accelerating ions, the surfaces of the lenses can be made with periodic modulation along beam axis (figure 4).

Figure 4: Freeze-frame of a particle that moves thanks to a modulated electrode (continuous line). Note how the electric field describes the areas (dashed line) of synchronized motion of the particle.[3]
Then there are periodic accelerating and decelerating electric fields around the beam axis. To realize the continuous accelerating, the RF voltage can be used to the electrodes instead of DC voltage and the modulation period can be made to equal to $\beta \lambda$ as in linear ion accelerators with drift tubes, where $\beta$ and $\gamma$ are respectively relative velocity and RF wave length in free space (figure 5).

Then the ions can be accelerated synchronously and focused transversely as in the conventional linear ion accelerators. To completely explain the working principle of this kind machines, which require deeper studies of the complex beam dynamic theory, it could be useful a book that include the physic of the charged particle and the transmission of the magnetic wave [3]. Similarly to a complex mechanical system, cavities have infinity of resonant modes for electric and magnetic field each one with a correspondent resonant frequency.

![Figure 5: Box section showing the modulations of two adjacent electrodes, periods and voltage function.](image)

Each mode is characterized by the acronym TE(TM) stands for Transversal Electric (Magnetic) and means that the electric field could vary only in the transversal direction to the wave propagation. The lowest resonant frequency is called cut-off frequency. Usually, resonant modes are described by the terms TE, TM, TEM and three numbers that indicate the zero field along the considered coordinates. An example could give from the study of the wave guide in which the cylindrical PILLBOX cavity is used, so cylindrical coordinate system is considered. In this case TM010 modes imply that magnetic fields vary in the transversal direction and goes to zero only one time in the radial direction. For what concern the longitudinal and azimuthal coordinate, its value is different from zero.
When a RFQ cavity is considered, resonant modes of the electric field are the TE210 and TE110 that correspond to the quadrupole mode and the dipole mode (figure 6). The quadrupolar mode affects the focusing of the beam while dipole modes could introduce a steering effect of the particles.

This topic concerns a field of study whose concepts are difficult to summarize in a paragraph. Nevertheless, for some of the cases handled, the understanding of their simplified formulas is essential to who fabricate RFQ accelerator. Simple resonant cavities, e.g. wave guide, could be represented by simplified electric circuit as well as RLC. Considering a cross section of the cavity at a coordinate z of its length, one could associate an equivalent electric simplified circuit as in the figure 7.
The capacity per unit length depends on the tip radius $\rho$ and from the equivalent distance $R_0$ between electrodes and beam axis. While the inductance per unit length depends on the peripheral geometry of the cavity and is affected by the vane-base width $W_B$ and the vessel height $H$ dimensions. Variations of these parameters cause a variation in the cut-off and on the dipole frequency as well as the trend of the $V(z)$ along the cavity (figure 9).

The evaluation of such parameters can be done by using numerical codes two or three dimensional (SUPERFISH, COMSOL Multiphysics®, ANSYS®-HFSS, CST-MS®). This circuit (figure 9) can be simplified if $C_i=C$, $C_a=C_b$, $L_i=L$ e $L_{si}=L_s$ ($i=1,2,3,4$), which is equivalent to the fact that all the electrodes geometry are equal to each other. Using the before mentioned assumption, the equivalent circuit becomes as the one in the figure 10.
It should be noted that the multi-conductor transmission line will splits into two different types of transmission lines, a dipole and a quadrupole. Using the wiring diagram and phasor expression we can write the following equations:

\[ \frac{dV(z)}{dz} = -j\omega L_s I(z) \]
\[ \frac{dI(z)}{dz} = -\left( j\omega C + \frac{1}{j\omega L_s} \right) V(z) \]

By combining the two equations one could obtain:

\[ \rightarrow \frac{d^2V(z)}{dz^2} + k^2V(z) = 0 \]

And obtaining k we get the scriptures for the quadrupole and dipole frequency considering a symmetrical cavity:

\[ k = \sqrt{L_s C} \sqrt{\omega^2 - \frac{1}{L_s C}} \rightarrow \begin{cases} L_s C = \frac{1}{c^2} & (a) \\ \frac{1}{L_s C} = \omega_c = \omega_{g0} & (b) \end{cases} \]
\[ \omega_c = \frac{1}{\sqrt{L(C + C_a)}} = \omega_{d0} & (c) \]

(a) Uniform Waveguide representation;
(b) Cut-off frequency or quadrupole frequency
(c) Dipole frequency
The circuit diagram can be adopted for all the $z$ longitudinal coordinates except for the extremity ($z = 0$ and $z = L$) where $H$ has to be orthogonal to the initial and final wall of the RFQ where there are the closing caps. Here the conditions to be respected are $I(0) = I(L) = 0$ or $V'(0) = V'(L) = 0$. To satisfy these conditions an ideal magnetic conductor can be created in an artificial way, by using an undercut at the electrode extremity, permitting the magnetic field passing from a cavity quarter to the other adjacent. These cuts must have geometry such as to make the resonant frequency and voltage profile, equal to those of the cavity specification. Talking in terms of circuit, the undercut can be draw with a $LC$ closed circuit where its total equivalent admittance $Y_{EC}$ equals zero at the cut-off frequency. For this, it must to be $1/L_eC_e = \omega_0^2$ with $L_e$ depending on the undercut dimension and $C_e$ from the distance between the end-plate and the electrodes.

From what has written before, the voltage and the resonance frequency depend on the geometry of the electrodes. Consequently, geometric errors lead to fluctuations in $f_0$ and $V(z)$ with respect to the nominal values.

### 2.3 Geometrical Parameter Sensitivities

Taking in consideration a cross section of the cavity, for example in the high energy zone of the IFMIF RFQ as in the figure 8, small variation of the dimension can result in a deviation of cut off frequency. Using software code described before, one can obtain the sensitivity of the frequency based on the geometric deviation. Considering the geometry defined by $R_0 = 7.102mm, \rho = 0.75 * R_0, W_b = 16.9mm, H = 170mm$ the sensitivity study at the capacitance zone will give:
\[ \frac{\Delta f}{\Delta R_0} = 7.5 \text{ MHz/mm} \]
\[ \frac{\Delta f}{\Delta \rho} = -4.1 \text{ MHz/mm} \]

The approaching of the electrodes leads to an increase of the capacity and thus a reduction of the cut-off frequency. Whereas for the inductance zone:

\[ \frac{\Delta f}{\Delta H} = -0.9 \text{ MHz/mm} \]
\[ \frac{\Delta f}{\Delta W_b} = 0.5 \text{ MHz/mm} \]

An increase of the peripheral area of the cavity will lead to a negative variation of the frequency because of the increase of the inductance. Considering the possibility of an error construction of an RFQ, it is important to mention that is accepted a margin of error in terms of \( V(z) \) and frequency. Both, in fact, can affect the amount and the quality of the beam which is transmitted and the synchronism with the accelerating structures located downstream of the RFQ. These effects are particularly serious such as high-current machines, because if the beam is lost, and crashes into the electrodes, problems with activation of the structure may occur, because of nuclear reactions induced by this phenomenon. For this reason, the beam dynamics specifies the range of variation maximum allowable voltage \( V \) (typical values \( \pm 2\% \) or \( \pm 3\% \)). As regards the frequency, its maximum excursion is related to the frequency (typical values from \( \pm 100 kHz \) down) which can be corrected by the control systems of the cavity, holding the structure hooked to a master clock of fixed frequency. For example, in an RFQ as that of IFMIF, the control is affected by varying the temperature of the cooling water of the vessel RFQ walls compared to that of the vane electrodes.

### 2.4 Tuners

Nowadays RFQ is usually fabricated using CNC milling machine respecting demanding tolerances, ranging about \( 10 \div 50 \mu m \) of form profile. A deviation from the nominal profiles cause a deviation in terms of voltage profile and in quadrupole working frequency but these can be corrected by varying the inductive region at certain positions respect to the RFQ length. Such operation is named tuning and the devices that do these corrections are known as tuners. Tuners are metal cylinders that penetrate into the volume of the cavity and change the local frequency,
in order to compensate local frequency variation and the voltage distributions induced by geometrical imperfections of the single modules. However, they make a global impact on the voltage distribution, so the single amount of penetrations are obtained using a tuning algorithm.

Tuners vary the local inductance $L$ and so the frequency, depending on the penetration $H$ in the cavity volume. The frequency range $\Delta f_{\text{tuners}}$ managed by tuners is approximately proportional to the available range of penetrations $(0, H_{\text{max}})$. Both these intervals are called tuning range (TR).

2.5 COUPLERS

We have so far briefly observed the behaviour of a resonant cavity and the main effects which may disrupt the proper functioning. The elements that provide electromagnetic power to the cavity are wave guides and the couplers (figure 13). In order for such providing to be efficient, it is necessary that the termination of the waveguide has a component of the electric or magnetic field in common with the cavity, and then that all the RF power supplied by the generator goes into cavities without reflections along the guide. There are basically two ways to couple the cavity to the generator. The first uses a loop and performs a magnetic coupling while the second uses a linear antenna to perform an electrical coupling.
2.6 MAIN PHYSICAL PARAMETERS AND MERIT FIGURES OF A PARTICLE ACCELERATOR

Write all the information necessary to understand the basics of operation for this type of machine would be misleading with respect to the topic of the thesis. So for brevity we have chosen to exhibit only a list of the factors often used by industry experts (physicists and electronic engineers) to identify and qualify these types of accelerator. First we recall some basics of electromagnetism. The electric energy density in vacuum for a unit volume is:

\[ u_e = \frac{1}{2} \varepsilon_0 E_0^2 \]

Where \( \varepsilon_0 \) is the vacuum permittivity and \( E_0 \) is the magnitude of the phasor associated to the electric field \( E \). The magnetic energy density in vacuum, using the magnetic permeability in vacuum \( \mu = \mu_0 \mu_r = \mu_0 \), can be expressed by the relation:

\[ u_m = \frac{1}{2} \mu_0 H_0^2 \]

So, one can define the average electromagnetical energy stored by a cavity by the relation:

\[ U = \frac{1}{4} \int_V (\varepsilon_0 |E|^2 + \mu_0 |H|^2) dV \]
Consider a variable magnetic field $\mathbf{H}$ at a frequency $f$ facing a good conductor surface where it dissipates power. A good conductor is such if it is true expression $\sigma \gg \omega \varepsilon_0 \varepsilon_r$ where $\sigma$ is the electric conductivity and $\omega$ the angular frequency $\omega = 2\pi f$. One can calculate the amount of dissipated power by using the surface resistance $R_S$ where occur a skin effect $\delta$.

\[
R_S = \frac{1}{\sigma \delta} \\
\delta = \frac{2}{\sqrt{\omega \mu_0 \sigma}}
\]

In a perfect vacuum and conductor conditions, the discontinuity of the tangential component of $\mathbf{H}$ is supported by a current density $\mathbf{J}_S = \mathbf{n} \times \mathbf{H}$.

Figure 14: Skin effect and surface current $\mathbf{J}_S$ created by a magnetic field $\mathbf{H}$.

So the dissipated power on the surface $\mathbf{S}$ can be written as:

\[
P_d = \frac{R_S}{2} \int_S |\mathbf{n} \times \mathbf{H}|^2 \, dS
\]

This thermal power must to be removed by the cooling system to avoid any thermal expansion that change the cavity geometry and so the electromagnetic behavior of the cavity. A parameter often used in the language of the experts is $Q$, quality factor, the ratio between the electromagnetic energy stored in the cavity that operates at a certain frequency $f_0$ and the energy dissipated during one oscillation.

\[
Q_0 = \frac{2\pi f_0 U}{P_d}
\]
It is also called merit factor that for copper cavity usually has typical values for a RFQ are between 8000 and 15000. It is essential to stress that the energy stored in the cavity is part of the total supplied by the generator and the remaining is associated to the waveguide. So the merit factor of the cavity, previously defined, is part of the \( Q_L \) loaded by the generator containing also the amount \( Q_{ext} \) related to the waveguide for the signal transmission.

\[
\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}
\]

Therefore \( Q_L \) is lower than \( Q_0 \). Knowing that the particle acceleration is given by the effect of the accelerating longitudinal electric field accelerating \( E_{acc} \):

\[
E_{acc} = \frac{\int_{-L/2}^{L/2} |E_z(z)| dz}{L} = \frac{V}{L}
\]

One can define another merit index, the shunt impedance \( R_{sh} \), indicating how a cavity can accelerate a particle at the expense of its dissipated power:

\[
R_{sh} = \frac{|V|^2}{P_d}
\]

This parameter is often multiplied by the length of the cavity and is of the order of some hundreds of \( k\Omega \times m \) while \( V \) is usually between 50 and 150kV.

Examples:

- **IFMIF-RFQ**: \( V \approx 78 \div 132 \, kV \), \( f_0 = 175 \, MHz \), \( L = 9.9 \, m \), Current Beam \( I_{Beam} \approx 140 \, mA \), Gain of Particle Energy \( \Delta W \approx 4.9 \, MeV \), Dissipated Power \( P_d \approx 1200 \, kW \), \( Q \approx 15000 \div 17000 \);

- **TRASCO-RFQ**: \( V = 68 \, kV, f_0 = 350 \, MHz, L = 7 \, m \), Current Beam \( I_{beam} \approx 40 \, mA \), Gain of Particle Energy \( \Delta W = 4.9 \, MeV \), Dissipated Power \( P_d \approx 850 \, kW \), \( Q = 8000 \).
2.7 **Main geometric parameters and characteristics of the IFMIF/EVEDA RFQ**

The IFMIF RFQ has to accelerate 125mA of charged Deuterons beam from 0.1 to 5 MeV with a frequency of 175MHz. These RFQ will be composed of 3 Super-Module of each 6 modules of about 550mm each long.

<table>
<thead>
<tr>
<th>Particles</th>
<th>D+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>175 MHz</td>
</tr>
<tr>
<td>Input Current</td>
<td>130 mA</td>
</tr>
<tr>
<td>RMS Input emittance</td>
<td>0.25 Norm. mm mrad</td>
</tr>
<tr>
<td>Input Energy</td>
<td>0.1 MeV</td>
</tr>
<tr>
<td>Output Energy</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Max Surface Field</td>
<td>25.2 MV/m (1.8 Kp)</td>
</tr>
<tr>
<td>Length L</td>
<td>9.78 m</td>
</tr>
<tr>
<td>Voltage Min/Max</td>
<td>79.29/132 kV</td>
</tr>
<tr>
<td>R₀ min/Max</td>
<td>4.1 / 7.1 Mm</td>
</tr>
<tr>
<td>Transmission (Water Bag distr.)</td>
<td>98.9 %</td>
</tr>
<tr>
<td>Beam Power Loss</td>
<td>522 Watts</td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>206-270 kΩm</td>
</tr>
<tr>
<td>Q₀ (SF)</td>
<td>15100-16700</td>
</tr>
<tr>
<td>Copper Power (SF)</td>
<td>450 kW</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>6.6 J</td>
</tr>
<tr>
<td>Max H field</td>
<td>3000-4500 A/m</td>
</tr>
<tr>
<td>Max. Power Density</td>
<td>1.6-4.1 W/cm²</td>
</tr>
<tr>
<td>Total power</td>
<td>1.345 MW</td>
</tr>
</tbody>
</table>

Table 1: Main properties of the RFQ [5]

Each module can be furnished with two type of aperture: the greater ones are for the connections of the vacuum lines, the smaller ones are necessary for the insertion of the tuners or the input of the RF Power. The water cooled tuner, schematized as cylinder with 90mm diameter, main effect is to change the inductive region and so the frequency and voltage distribution along the cavity [4]. Since the variation from the nominal geometry of the cavity varies the operating frequency, tuners can be used to compensate the machining, assembly procedure errors and deformations due to the brazing process. There are 88 tuners with a tuning range of about ±15mm in order to compensate global variation of ±1MHz frequency. The sensitivity with respect to geometrical errors was addressed both numerically and analytically, and it was found that the maximum (minimum) sensitivity $\chi$ is located in the initial (final) section of the RFQ, where $\Delta f/\Delta R₀ = 11.8 MHz/mm (7.5 MHz/mm)$ [5]. Tuners can be used to compensate the machining, assembly procedure errors and deformations due to the brazing process. Power is injected by magnetic coupling field with 8 loop and their respective RF windows, alumina with 1.5 ÷ 3 nm TiN coating. Each single loop is water cooled. The choice of a
four-vane structure with variable R0 and voltage profile required an accurate tuning of the 2D section of the RFQ in order to compensate for local TE21 cut-off frequency $f(z)$ variation due both to voltage variation and aperture. Taking into consideration the nomenclature already exposed concerning the sensitivity, the following graphs shows the main dimensions variation of the capacitive region, the vane tips, and of the inductive region, the vane base.

Figure 15: Tip geometric parameter: Y1 modulation curve, tip radius Rho, average nominal distance from the centre axis respect to the position

$Y1$ is the spline that constitutes the modulation of tip electrode while Rho is the tip radius and also the tip thickness. $R_0$ is related to $\rho$ by the law $\rho = 0.75 \times R0$. 

Figure 16: Half the vane base thickness $W_b$ respect to the $z$ position.
From the graph of vane-base width, there are discontinuities between the modules. This curve takes into account the vacuum apertures. The curve of the thickness is non-linear considering the entire length of the cavity but on each module, the surfaces related to the base-vane have been changed, making them linear along z, in order to simplify the processing. Construction tolerances of the cavity are such as to ensure non-saturation of the tuning range. The main mechanical parameters in terms of admissible tolerances on the single elements of the module and on the entire module are reported on the following table.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target value</th>
<th>Acceptance Criteria</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation accuracy (pole tip form and position)</td>
<td>±10 μm</td>
<td>±30 μm</td>
<td>Each module before brazing</td>
</tr>
<tr>
<td>Roughness</td>
<td>0.7 μm</td>
<td>1 μm</td>
<td></td>
</tr>
<tr>
<td>Vane tips relative position respect to beam axis</td>
<td>±50 μm</td>
<td>±100 μm</td>
<td>Each module after brazing</td>
</tr>
<tr>
<td>Beam axis position</td>
<td>±50 μm</td>
<td>±100 μm</td>
<td>Correlation to external references and alignment of the entire assembled structure</td>
</tr>
<tr>
<td>Frequency Tuning Range with water temperature</td>
<td>+100 kHz</td>
<td>+50 kHz</td>
<td>Measured in High power test on modules</td>
</tr>
</tbody>
</table>

Table 2: Target and accepted geometric deviation from the nominal
BIBLIOGRAPHY


CHAPTER 3

VACUUM BRAZING OF THE IFMIF RFQ MODULES AT LNL

3.1 INTRODUCTION

The large number of connections to be done with high reproducibility, the capability for precision production tolerances, the ability to join dissimilar metal, are some of the reasons for choosing the brazing technique. A brazed joint generally produces less thermally induced distortion, because the entire part is brought up to the same brazing temperature. The brazed joints are not only expected to preserve electrical conduction between the pieces on the internal part of the cavity surface, but also to guarantee thermal flow on the whole section. All mechanical parts require strong, uniform, leak-proof joints (vacuum tightness of $10^{-9}$ mbar l/s, and water circuits able to work up to 3 bar) to produce structurally sound assemblies. With this chapter the author want to first present some concepts covering different aspects of the brazing, as wettability, deoxidation of surfaces and thermal expansion. Moreover, the curves of thermal expansion are used to develop a parametric graph useful in predicting the presence of distortions only through knowledge of the measured temperatures and the geometry of objects involved. Some basics on the transport of heat and irradiation are exposed, setting the basis to face the main vacuum brazing issues. Then will follow paragraphs showing the prototypes of brazing of the modules that have influenced the final design of the solder joints. An example of thermal FE model used is exposed, with the description of an algorithm used to obtain the parameters that permit matching between simulated and measured temperature during the brazing cycle. After that, temperature distribution is used, together with thermal expansion curve, in a structural simulation to explain defect encountered on the brazed object. Finally a new brazing cycle is proposed and, after a comparison between predicted and measured temperature, qualitative assessment of the brazing joint are reported.
3.2 Basics in Vacuum Brazing: Wettability and Oxides Reduction

Brazing is a commonly used joining method in which the melting temperatures of brazing alloy exceed 450 °C. When the brazing alloy melts, wets the base material and due to the capillary goes to cover the surfaces of the joint. This phenomenon is even more pronounced as the melted braze alloy wet the base material. The sessile drop test determines the wettability of the materials used and it is correlated at the angle extended between liquid-vapour interface of the drop and that of the liquid-solid material.

![Figure 1: Definition of a contact angle \( \theta \) in a solid/Liquid Vapour system.][3]

\[
\cos \theta = \frac{\sigma_{SV} - \sigma_{SL}}{\sigma_{LV}}
\]

Where \( \sigma_{SV}, \sigma_{SL}, \sigma_{LV} \) are respectively the surface energy of the solid-vapour, solid-liquid, liquid-vapour interfaces. Now take in consideration figure 2.

![Figure 2: Capillary infiltration. The filling is done from the bottom to the top of the joint. The arrow indicates the direction in which the capillary pressure is exerted. Letters S, L and V indicate solid, liquid and vapor phases respectively; e is the thickness of the gap.][3]

Consider the formation of a joint by non-reactive brazing of two flat parallel plates of unit width made of the same material, in a vertical position. The thickness of the gap is \( e \) and the infiltration
takes place from the bottom to the top of the gap (upward infiltration). An evaluation of the increase in free energy obtained by the system with the liquid front rise can be written as:

$$\Delta F = 2z(\sigma_{SL} - \sigma_{SV}) + ze\rho g \frac{z}{2} = -2z\sigma_{LV} \cos \theta + ze\rho g \frac{z}{2}$$

When system reach its equilibrium and there is no more rising of the liquid alloy, free energy stop to increase and

$$\frac{d(\Delta F)}{dz} = -2\sigma_{LV} \cos \theta + z_{eq} e \rho g = 0$$

By taking typical values for a metallic braze, \(\sigma_{LV} = 1 \text{ J/m}^2\) and \(\rho = 5000 \text{ kg/m}^3\) we find, for \(e = 20 \mu m\) and \(\theta = 45^\circ\) \(z_{eq} = 2m\). The values of \(z\) involved in brazing are usually much lower than \(z_{eq}\) meaning that the gravity forces are negligible compared with the capillary forces. Brazing can involve many type of material, metallic or not. Type of the joint material could be subdivided in non-reactive and reactive material. A joint is considered non-reactive if the brazing alloy, before to wet the base metal reacts with the protective layer surface of the base material. For example stainless steel is covered by tenacious oxide layers, making them resistant to oxidation. These passive films are also a barrier to wetting and brazing by liquid metal alloy. Temperature and permanence time of the melt alloy on the surface can affect the wettability of the base material, and then the liquid solid angle \(\theta\). [1]. A principal process requirement for successful brazing is to ensure that the joint surfaces are free from oxides and other films that can inhibit wetting by the molten braze and the formation of strong metallic bonds. A measure of the strength of a metal-to-oxygen chemical bond is given by the change in the Gibbs free energy that occurs when that metal reacts to form the oxide. In particular, many metals form different oxides of varying stability for example, copper oxidizes to form cuprous oxide (Cu\(_2\)O) and cupric oxide (CuO). All chemical reactions are reversible, including oxidation reactions. In general, the oxidation of any metal can be described by an equation of the form:

$$nM - \left[\frac{m}{2}\right]O_2 \rightarrow M_nO_m$$

The reaction will proceed spontaneously in either direction namely, oxidation of the metal, or, conversely, reduction of the oxide, if it is energetically favourable to do so. The free energy change \((\Delta G)\) for oxidation reactions involving a series of metals can be charted on a diagram as a function of temperature. This representation is known as an Ellingham diagram reported on the figure 3. The conditions of temperature and oxygen partial pressure required to spontaneously reduce a metal oxide can be deduced from the Ellingham diagram. Reduction will occur when the
free energy curve for metal-oxide formation lies above the oxygen partial pressure curve at the temperature of interest, that is, when the oxygen pressure in the atmosphere is less than that which will cause the metal under consideration to oxidize. These curves are marked on as dashed lines originating from point $O$ and intersecting the oxygen partial pressure side scale. The oxygen partial pressure in a vacuum furnace can be reduced substantially below the gas pressure of the vacuum by repeatedly pumping out and backfilling the chamber with a dry, oxygen-free gas.

If the partial oxygen pressure surrounding the workpiece cannot be sufficiently lowered by creating a vacuum or introducing an inert gas so as to effect oxide removal, then a reducing atmosphere might be able to remove the oxide. The three most widely used reducing gases are hydrogen, carbon monoxide, and "cracked" ammonia (that is, ammonia dissociated into nitrogen and hydrogen). Stainless steels are covered by tenacious oxide layers, making them highly resistant to oxidation. These passive films are also a barrier for wetting and brazing by liquid.
metals and alloys. However, above a certain temperature, heating in high vacuum leads to good wetting (contact angle $\theta \ll 90^\circ$) thus enabling these materials to be joined by brazing. In this type of vacuum system the partial pressure of oxygen may be several orders of magnitude lower than the total pressure. Wetting of stainless steels by Cu–Ag eutectic in high vacuum at temperatures of 800–900°C occurs by two reactive spreading stages. In the first stage, spreading is controlled by steel deoxidation and leads to a reduction in the contact angle from about 130° to 30–60° depending on the steel. The second stage is dissolutive wetting and leads to a further reduction in $\theta$ by 10–30° [2]. Occasionally, the desired joining alloy (chosen on the basis of melting temperature and physical properties) is metallurgically incompatible with the substrate in the sense that the filler does not wet the substrate, will wet nonuniformly, or forms embrittling phases by reaction. A solution is to apply a surface coating that will promote wetting by the brazed and reacts with it in a benign manner. For example, the native oxide on stainless steel prevents this metal's being wet by low-melting-point silver-base brazes in an inert atmosphere. However, a nickel coating, applied by electroplating and diffused in by heat treatment, akin to that used in sherardizing, substitutes for the oxide and renders the stainless steel wettable. As a general guide, plating of stainless steels and other heat-resistant alloys to facilitate brazing is generally recommended when the titanium content of the components exceeds 0.7%, the aluminum content exceeds 0.4%, or the combined aluminum and titanium contents exceed 0.7%. The nickel plating will need to be at least 10 $\mu$m thick to prevent these species’ diffusing through to the surface during the heating stage of a typical brazing cycle and also to accommodate the depth of alloying that usually takes place between a braze and a substrate. [3]. In our case all the 80 stainless steel part (AISI 316LN and 304L) as end flanges, cooling channels connections, and side ports for tuners and vacuum pumping are nickel plated. It’s clear that oil, dirt, and oxides must be fully removed from the base and filler metals before brazing, because only then can uniform capillary attraction be obtained, so for example chemical bath with phosphoric acid at 75°C initially with pH10 and then pH1 can be used to clean oily surface, residues from the WEDM and then to passivate the components [4].

3.3 THE THERMAL EXPANSION

A common error, which is implicit in the preceding discussion, is that materials expand and contract in a regular manner in response to thermal excursions. This is true only for simple single-phase materials. Many engineering materials have nonlinear thermal expansion characteristics. A further complication arises when two joined materials possess different thermal emissivities, specific heat capacities, and thermal conductivities. The combination of these factors means that in a thermal-dynamic environment, such as exists on cooling from the
peak temperature of a brazing process, transient differences in thermal expansion mismatch and accompanying stresses will be manifested. Different coefficient of thermal expansion data from literature for the same materials results in uncertainties for the expert who designs pieces with different brazing joint geometry. This is the case of the AISI316 or AISI304 stainless steel. These materials are mostly used in the vacuum technology for its good outgassing behaviour and mechanical properties especially for the nuclear experiment equipment. A useful example of comparison can be made by observing the value, or the graphs, reported in [5]. In particular for the most used in the vacuum technology, AISI 316, the differences of values are well below 0.1% at 800K as we can see form the figure 4.

![Figure 4: Thermal Strain curves of AISI316 and AISI304 from different literature: * (CINDAS, Thermal linear expansion of nine selected AISI stainless steel, P.D.Desai & C.Y.Ho, April 1978), **(Thermophysical Properties of Matter, v12, Y.S. Touloukian, R.K. Kirby, R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY and below 20K NIST, Physical and Chemical Properties Division, Cryogenics Technologies Group at http://cryogenics.nist.gov/), *** (The thermal expansion of some LINAC materials, R. Valdiviez et al., Los Alamos National Laboratory, Los Alamos, NM)](image)

Another important graph useful for the brazing expert [6], beside information regarding the welding of material subjected at high vacuum conditions are reported in [7].
The correctness of the linear thermal expansion curves are very important for the designer expert of the brazing joints because it can affect the design of thermal brazing cycle as well as the joint dimensioning especially in case of embedded expansion and the materials used. The coefficient of thermal expansion $\alpha$ can be defined as the fractional increase in length $l$ per unit increase in temperature $T$:

$$\alpha = \frac{dl}{l \, dT}$$

Since the differential of the logarithmic, or true, strain $\varepsilon^l$ is defined as:

$$d\varepsilon^l = d\left(\ln \frac{l}{l_0}\right) = \frac{dl}{l}$$

Where $l$ and $l_0$ are respectively the final and the initial length. Rearranging the above equations we get:

$$d\varepsilon^l = \alpha dT$$

That integrated becomes:

$$\varepsilon^l - \varepsilon^{l_0} = \alpha(T - T_0)$$
The strain \( \varepsilon^l \) at the reference temperature \( T_0 \) (usually 20°C) is supposed equal to zero (\( \varepsilon^{l_0} = 0 \)). In this condition the thermal strain correspond to the logarithmic strain. The final length \( l \), considering the thermal expansion of an object of initial length \( l_0 \) due to a variation in temperature respect to \( T_0 \), is:

\[
l = l_0 \exp(\varepsilon^l) = l_0 \exp[(\alpha(T - T_0))]
\]

If one, rather than the use of true strain to obtain wrote formulations, uses the engineering strain, will obtain a different formula for the final length:

\[
l' = l_0 (1 + \varepsilon^e) = l_0 [1 + \alpha(T - T_0)]
\]

And, as reported in [8], the difference \( (l - l') \) should be very small for:

\[
\alpha|T - T_0| \ll 1
\]

There are three types of data from literature you can use in finite element software: secant coefficient of thermal expansion, instantaneous coefficient of thermal expansion and thermal strain. These three properties are correlated as graphically explained in the figure 6.

![Figure 6: Thermal expansion curves and correlations with secant and instantaneous coefficient of thermal expansion.](image)

And in a mathematical form we have:

\[
\alpha^{se}(T_n) = \frac{\varepsilon^{th}(T_n)}{T_n - T_0} = \frac{\int_{T_0}^{T_n} \alpha^{in}(T) dT}{T_n - T_0}
\]

If one uses the ANSYS Mechanical APDL code for the thermal expansion, one could input directly the coefficient of thermal expansion (by the ALPX command) or calculate it by inputting the thermal strain curve (by the THSX command) or the instantaneous coefficient of thermal expansion (by the CTEX command) and the reference temperature (TREF) at which the thermal strain is zero. Taken the last two types of data from the same literature [9] for copper C10200 one could obtain different curves as showed in the figure 7:

3-44
Figure 7: a) mean Coefficient of Thermal Expansion for C10200 (mCTE from MPDB) input by the ALPX command; b) Coefficient of thermal expansion curve for C10200 obtained by the Thermal Strain (dL/L from MPDB) using the THSX command. The reference temperature is 19°C; c) Coefficient of thermal
expansion curve for C10200 obtained by the instantaneous coefficient of thermal expansion (CTE from MPDB) using the CTEX command. The reference temperature is 19°C.

As we can see from the figure 7, the first and the second thermal expansion coefficients calculated are almost equal for the first two except near the reference temperature because $T - T_0$ have a small value, then the third is always slightly below the other. Many other data, from different literature, accord with the first curve obtained. For what concern the stainless steel, we take into account the average curve of those exposed in the figure 4. The proximity of these curves suggests the reliability of the values used. Now consider two ideal linear bodies, one made by pure copper and the other made of AISI304 each one with the same temperature. The copper body, of length $L_{Cu}$, is contained by that made of stainless steel of length $L_{SS}$, so $L_{Cu} < L_{SS}$. There will be a temperature at which both bodies have the same final length:

$$L_{Cu} = L_{SS}$$

Using the above mathematical formulation one can write

$$[1 + \varepsilon^{th}_{Cu}(T)]L_{0\ Cu} = [1 + \varepsilon^{th}_{SS}(T)]L_{0\ SS}$$

Knowing the thermal expansion curves, ones can adjust $L_{0\ Cu}$ and $L_{0\ SS}$ to obtain the desired temperature $T$ at which bodies come in contact. If the two bodies present, aside from different initial length, also different temperatures, could be useful to find the increase in temperature $\Delta T$ of the stainless steel respect to copper, to obtain at the same final length.

$$[1 + \varepsilon^{th}_{Cu}(T)]L_{0\ Cu} = [1 + \varepsilon^{th}_{SS}(T + \Delta T)]L_{0\ SS}$$

An iterative scheme has been used to solve this equation. Take for example the initial lengths $L_{0\ Cu} = 177\ mm$ and $L_{0\ SS} = 177 + X\ mm$, where $X$ is the clearance at room temperature. At a fixed temperature $T$ we can adjust the $\Delta T$ by increasing iteratively its value of a sufficient small step with an IF...THEN...ELSE cycle to obtain the above equation. The smaller the step, the smaller the error, the higher the time calculation.
Figure 8: The curves represent the increase in temperature, respect to the copper ones, necessary for the stainless steel to obtain the same final length. Each curve considers an initial copper length of $L_{0,\text{Cu}} = 177\, \text{mm}$ while the initial stainless steel length is reported in mm on the legend.

The points of a curve represent the temperature at which the two bodies get in contact. The measured temperature individuates a point. Points above the selected curve means that there is no contact otherwise body are in contact and through a thermal contact conductance transmit a heat flux to uniform their temperatures. To notice that for pieces with same temperature, so $\Delta T = 0$, changes in clearance of few cents from 177.03mm means a high range of temperatures of the coming in contact. The curves could be very useful if we consider a uniform temperature in each single bodies of the brazing assembly. Once is known the temperatures of bodies, that could present embedded expansion and note their clearance at room temperature, with this kind of graph is possible to detect if interference occur or not in real time, during the brazing.
3.4 Introduction to Theory Fundamentals for the Radiative-Conductive-Contact Heat Transfer Problem

Consider a homogeneous medium within which there is no bulk motion (advection) and the temperature distribution \( T(x, y, z) \) is expressed in Cartesian coordinates. Following the methodology of applying conservation of energy, we first define an infinitesimally small (differential) control volume, \( dx \, dy \, dz \). In absence of motion (or without uniform motion) there is no change in mechanical energy and no work is done on the system. [10].

So the balance between the variation of thermal energy flow and that stored by the matter of an infinitesimal volume has to be guaranteed, and it is described by the general form of the heat diffusion equation:

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + q = \rho c_p \frac{\partial T}{\partial t}
\]

where \( q \) is the heat flow impinging into the volume control. Our case treats bodies heated in a high vacuum furnace during the brazing cycle so the system could be described by a body, of a certain mass and surface subjected to an irradiation heat flow coming from the reflecting screen of the vacuum furnace. Considering a surface of a certain material, the radiative fluxes at which this surface is subjected are then described. The emissive power \( E \) (emission) is the rate at which radiation is emitted from a surface per unit area

\[
E_i = \varepsilon_i(\lambda, \theta, T) \sigma T_i^4
\]

where \( \varepsilon \) is the emissivity depends on wavelength and directional distribution and also temperature of the body surfaces and \( \sigma \) the Stephan-Boltzmann constant. If we have a gray-diffuse surface \( i \) only temperature is considered and total hemispherical emissivity \( \varepsilon_i(T) \) has been used. The irradiation is the rate at which radiation is incident upon a surface per unit area. Irradiation can be reflected, absorbed or transmitted. Since we are using opaque bodies, transmission is not taking into account so the sum of absorbed with the reflected energy equal the incident irradiated energy of that grey-diffuse surface \( i.e.: \varepsilon + \rho = 1 \). Radiosity \( J_i \) is the rate at which radiation leaves a surface \( i \) per unit area.
Taking as reference the figure 9, the total heat flow that enters on surface $i$ is:

$$q_i = A_i (I_i - \varepsilon_i \sum J_i F_{ij})$$

If we have two or more surface, the exchange of heat between them, are strongly dependent on the view-factor, defined as the fraction of the energy leaving a surface $j$ intercepted by the surface $i$. Since our case considers a high vacuum pressure inside furnace, there is no medium between the two surfaces and with the indication of the figure 10 one can write the expression for the form-factor (or view-factor) for a finite area (or patch):

$$F_{ij} = \frac{1}{A_i A_j} \iint \frac{\cos \phi_i \cos \phi_j}{\pi r^2} \, dA_i dA_j$$

This expression for the form-factor does not account for the possibility of occluding objects hiding all or part of one patch from another. There is, therefore, a missing term within the integrand if hidden surfaces are to be accounted for. The form-factor is subjected to the reciprocity relation:

$$A_i F_{ij} = A_j F_{ji}$$
Given an enclosure with N surface, one could write the following matrix of i rows and j columns

\[
\begin{bmatrix}
F_{11} & \ldots & F_{iN} \\
\vdots & \ddots & \vdots \\
F_{N1} & \ldots & F_{NN}
\end{bmatrix}
\]

Figure 11: Radiation exchange in an enclosure. [10]

An important view factor rule pertains to the surfaces of an enclosure (figure 11) and, from the definition of the view factor, it possible to obtain the summation rule:

\[\sum_{j=1}^{N} F_{ij} = 1\]

If we have a leaky enclosure, the summation is equal or less than 1. Using the reciprocity relation and the summation rule one could obtain the number of the view factor to calculate to describe the entire enclosure

\[N(N - 1)/2\]

Using directly analytical formulations, to obtain form-factor, can be advantageous for simple geometries but for the complex ones another algorithm may be more efficient since the actual
availability of high computing powers. A geometric analogy for the form-factor integral was developed by Nusselt and has been used to obtain form-factors by both photography and planimetry. For a finite area, the form-factor is equivalent to the fraction of the circle (which is the base of the hemisphere) covered by projecting the area onto the hemisphere and then orthographically down onto the circle [11]. From the definition of the form-factor it can be seen that any two patches in the environment, when projected onto the hemisphere occupy the same area and location, will have the same form-factor value. This is also true for projections onto any other surrounding surface (Figure 12).

Instead of projecting onto a sphere, an imaginary cube is constructed around the center of the receiving patch (Figure 13). The environment is transformed to set the patches center at the origin with the patch’s normal. In this orientation the hemisphere described above is replaced by the upper half of the surface of the cube, the lower half being below the "horizon" of the patch. One full parallel face, and four half-faces facing in a orthogonal directions, replace the hemisphere. These faces are divided into square "pixels" at a given resolution, and the environment is then projected onto the five planar surfaces. Each pixel defines a particular direction and angle from the receiving patch’s centroid. Thus, each pixel contributes a specific delta-view factor value to the overall view factor between two surfaces if the pixel is covered by the projection of the transmitting surface onto the discretized hemi-cube. Since the accuracy/fineness of the numerical integration of the form-factor depends partially upon the area projected onto the hemi-cube, problems can occur due to aliasing for small projections. In general, objects whose projection onto the hemi-cube is small have little effect.

Figure 12: Area with the same form-factor,[11]
However, for very bright patches such as "light" sources, the effect of the inaccuracy can have a substantial deleterious effect. Moreover, to reduce the hidden surface, and respect the visibility assumption, as in the figure 14, surface 1 could be subdivided into smaller sub-elements with the hemi-cube method applied to each sub-element and the results combined to produce a more accurate value for the view factor. Another problem can occur whenever surfaces are close compared to their effective dimension or are adjacent to one another because the distance between the centroid of one surface to all points of the other surface can vary greatly. Because the view factor dependence on distance is nonlinear, the result is a poor estimate of the view factor [12].
Radiant energy exchange between neighbouring surfaces of a region or between a region and its surroundings can produce large effects in the overall heat transfer problem. It is demonstrated that the loss of heat flow $q_i$ from the surface $i$ is inhibited by the radiosity resistance (on bracket) going to other surface $j$

$$\frac{E_{bi} - J_i}{\left(1 - \varepsilon_i\right) / (\varepsilon_i A_i)} = \frac{\sigma T_i^4 - J_i}{\left(1 - \varepsilon_i\right) / (\varepsilon_i A_i)} = q_i$$

because a grey body is considered instead of a black one. One can tough $q_i$ as the sum of components $q_{ij}$ related to radiative exchange with the other surfaces $j$ by means of a space resistance $(A_i F_{ij})^{-1}$. By using the analogy with the electric resistance, a radiation network is constructed by first identifying nodes associated with the radiosity of each surface, and then each radiosity node is connected to each of the other radiosity nodes through the appropriate space resistance.

![Diagram of a radiation network](image)

**Figure 15:** Network representation of radiative exchange between surface $i$ and the remaining surfaces of an enclosure [10]

The radiation effects generally enter the heat transfer problem only through the boundary conditions and the coupling is especially strong due to nonlinear dependence of radiation on surface temperature. Extending the Stefan-Boltzmann Law for a system of $N$ enclosures, the energy balance for each surface in the enclosure for a grey diffuse body is given by Siegal and Howell, which relates the energy losses to the surface temperatures.
\[
\sum_{i=1}^{N} \left( \frac{\delta_{ji}}{\varepsilon_i} - F_{ji} \frac{1 - \varepsilon_i}{\varepsilon_i} \right) \frac{1}{A_i} q_i = \sum_{i=1}^{N} (\delta_{ji} - F_{ji}) T_i^4
\]

By knowing \(T_i\), the average temperature at surface \(i\), and \(F_{ij}\) the \(N\) equations could be resolved iteratively, in a rearranged form, by using the Gauss-Seidel iterative solver, Direct solver or Jacobi solver. In contrast to the greater efficiency that shows the first solver more efficient than the other, the last allows lower computation times because the parallelization of calculations is permitted by recent computers. As stated previously, we are considering a system in a transient state. The heated mass is constituted by a set of objects, adjacent to each other, but not always congruent, subject to radiation coming from the reflective screens of the oven. Bodies of different temperatures getting in contact may be subjected to heat flux on the contact surface and so a heat flows between them (e.g. reported in the figure 16: \(q''_{x'}\)). The thermal contact conductance \((1/R_{i,c}'')\) adjusts this flow, proportionally to the temperature difference on the contact surfaces. It increases if the areas are surrounded by a conductive medium, such as air or hydrogen. Also in the case where the temperature difference between the bodies is high, irradiation may increase its effect.

![Figure 16: Temperature drop in the contact surfaces due to the thermal contact resistance. [10]](image)

\[
R_{i,c}'' = \frac{T_A - T_B}{q''_{x'}}
\]

The net contact area is typically small, and, especially for rough surfaces, the major contribution to the resistance is made by the gaps. For solids whose thermal conductivities exceed that of the interfacial fluid, the contact resistance may be reduced by increasing the area of the contact spots. Such an increase may be affected by increasing the joint pressure and/or by
reducing the roughness of the mating surfaces. The number of variables that affect thermal contact resistance, as well as contact pressure, roughness, gas on gap, hardness of materials can cause in uncertainties of data literature. Taking as reference the data for pure copper under vacuum condition from [13], by using the similarities of electrical circuits and Ohm’s law, it can estimate the equivalent length that must have a continuous body, of a unit cross section area, to have the same temperature jump $\Delta T$, and heat flux $q''$, of that caused by contact resistance of the same material.

$$R''_{t,c} = R_{t,cond} = L/k$$

Assuming that for copper $k = 400 \left[ \frac{W}{m \cdot K} \right]$}

<table>
<thead>
<tr>
<th>$P$ [MPa]</th>
<th>$R''_{t,c}$ [m$^2$K/W]</th>
<th>$L$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>$10^{-3}$</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$</td>
<td>0.04</td>
</tr>
<tr>
<td>10</td>
<td>$5 \times 10^{-5}$</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$10^{-5}$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 1: Equivalent conductive length for the contact resistance at various contact pressure for copper in vacuum are reported.

Considering the variety of type contact between body surfaces, and in particular for our case, the control of that phenomenon is not guaranteed. But since contact pressures created by the tools are very small, as they provide a soft constraint, one can assume as first approximation that there are no contacts but only radiative heat transfers.

### 3.5 VACUUM BRAZING AT LNL: THE VACUUM FURNACE

The oven is a vertical charging type. The principal nominal characteristics of the oven are reported in [14]. The maximum allowable charge load is 1000 kg and is able to reach a vacuum of the order of $1e^{-7}$ mbar (high vacuum) total pressure. The oven uses thermal resistors, placed on the internal cylinder and at the bottom plate, heating the walls of the furnace that represent the radiating surfaces. A control system manages the current given to the resistor in order to maintain the correct set point temperature on the radiating surfaces. The managing of the thermal cycle can be done by means of the PLC or a computer with a software linked to the control system of the oven. The software installed on the PC permit also to monitor the principal parameters of the oven, such as vacuum level, the residual gases presents on the cavity and more important the set point temperatures of the oven and the temperatures measured on the components by means of the eleven thermocouples inside. The set point temperature of the oven
can be managed also manually. In this case it is impossible to control the duration of the heating ramp, but the oven will reach the set point temperature as fast as possible with a certain overshoot also, resulting on possible inhomogeneity of temperature on the component that can cause deformations of the geometry.

Figure 17: External view of the vacuum furnace at LNL[14].

Figure 18: Internal view of the oven with the resistors and the Molybdenum reflectors [14].
The unique possibility to furnish heat to a piece under vacuum condition, like into the oven, is by radiation, because convection and conduction are prevented by the lack of a means of transport of heat, respectively a moving gas or a good conductor in contact with the charge. The heat transfer energy increase with the fourth power of the temperature, so it becomes very intense at high temperatures. The temperatures of the radiating walls (hot zone) and on the components of the load are monitored with a set of respectively four and a maximum of twelve type K thermocouples. The accuracy on the measure of the thermocouples is on the order of ±2 °C. The walls are made with four layers of molybdenum in order to resist up to 1300 °C and the temperature is keep controlled and uniform by a cooling system. The maximum work dimension: 1300 mm of diameter, 1600 mm of height, for a total volume of 2 m³. This volume is considering a certain distance from the heating resistors in order to guarantee the uniformity of the heat flow on the components during the thermal cycle.
3.6 **Brazing Alloy Grooves and Small Prototype Test**

Campaigns of tests (block-test) were done to understand the effect of the gravity on the wetting of the brazing filler metal by changing the groove dispositions. The copper blocks with interrupted straight grooves were mounted in two different positions, horizontal and vertical to test the different wetting. The components were supported on a 400x400x40 mm stable AISI 316 LN base supported by some layers of alumina, in order to guarantee thermal insulation from the base.

![Figure 21: Block-tests with perpendicular and parallel groove disposition respect to the brazing planes.][15]

A cross section of the used groove for the brazing alloy wire, 1mm diameter, is reported in figure 22.

![Figure 22: cross section of groove for the brazing alloy wire.][15]

This test with parallel grooves was also mounted in vertical position. The slots of the brazing alloy have been designed to ensure the filling of the area of the joint considering a thickness of 0.04 mm. To avoid any wrong disposition of the wire during the assembly procedure, that often cause an incorrect assembly of the joint, operators may find help making use of a burin to deform plastically the wire or in some cases some small portion of the base material, in order to lock the wire into its seat. Considering the real case, a more complex joint geometry was taken into
account by a new test (C shaped samples) with the aim of studying the effect of the pieces and grooves orientations.

Figure 23: Disposition of the wire on the brazing area extremity.[15]

Figure 24: C-Test with two type of groove dispositions, longitudinal and tilted. Copper pieces were placed on alumina blocks in a vertical position.[15]

We tested also the brazing between materials with different thermal expansion (CuC2-AISI316LN) to understand if brazing alloy binds to the base material properly. A tooling of stainless steel bars in contact with copper by means of some alumina plates, molybdenum rods and Nimonic90 springs with a pre-load of 150-200 N, was mounted. The scope of the tooling was to keep a certain contact pressure on the brazing surfaces and to keep in position the two copper components avoiding sliding on the brazing plane [15].
Thermal cycle has been designed considering Palcusil10® as brazing alloy that have the liquidus at 852 °C and the solidus at 824 °C. A heating ramp of 150°C/h brings the components at about 10°C below the solidus temperature. Then temperature is set constant, waiting for the highest thermal inertia pieces thermalization. Then another heating ramp for the brazing is done, using a thermalization temperature higher than liquidus. This phase has to be quicker than the first to prevent any liquation of the brazing wire that affect the uniform filling of the brazing joint.

Unfortunally some problem occur on the control system and the measured temperature were non reliable. Although only optical inspections and vacuum testing evaluated the functionality of the brazing joint, the ultrasonic inspection gave much more detailed information on the quality of the mechanical coupling and the distribution of the brazing alloy at the brazing interface. Complete inspections by UT scan on all the pieces were done and the grooves result always completely empty and no significant voids
were detected on the brazing planes. In particular the measurement on slices of the brazed C shaped pieces reveals a fine mechanical joint both in the middle of the assembly and at the extremity, where the geometry is more complex due to the slot for the end flanges, despite the meniscus does not appear everywhere with the naked eye.

Both the vertical and the inclined grooves demonstrated a good mechanical coupling. The inclined grooves seem to demonstrate a much more uniform distribution of the brazing alloy, while the straight grooves seem to be more sensitive to gravitational effects. As a result, the chose was to adopt inclined grooves for the modules of the final production [15].
Afterwards as final test, a small prototype of a RFQ module was assembled and brazed vertically. The lateral dimensions of the vanes are half of those of the final RFQ module, whereas the height is around 400 mm. The brazing joints of the side flanges differ slightly from those adopted in final modules. The brazing cycle was designed with the help of experts from LNL with aids of 1-D thermal simulations. In spite of a mismatch between the measured temperatures and those predicted by the simulation, brazing joints seem, to the naked eye, present everywhere. A deeper observation comes from UT Test. Although the scans are difficult to perceive due to the complexity of the geometry, they show that the slots are empty and brazing exists uniformly on all joints. After this campaign of tests the vertical brazing seems feasible and the design of the grooves turned out to be correct.

3.7 **DOUBLE BRAZING STEP**

The first two Modules (M_16 and M_17) have been brazed by an external company adopting a two-step process. All the copper components are aligned to the nominal position and double checked, geometrically and RF. The assembly is then machined to refine the common planes for the placement of the brazing tooling. The components are then dismantled, chemically cleaned, and assembled in a clean environment by means of the tooling. In this step the 2 sealing stainless steel front rings have been mounted in order to provide a relevant constraint, embedding a smooth relative movement of components during the thermal cycle that could cause an excessive flow down of the brazing material. The alloy Palcusil 10 (59%Ag, 31%Cu, 10%Pd - liquidus: 852°C, solidus: 824°C) has been used as brazing material (optimal wetting of the surfaces while allowing for more brazing cycles repairs). The optical inspection of the brazing joints showed a uniform distribution of the brazing material both on copper-copper and copper-stainless steel joint. The vacuum tightness of the cavity and of the cooling ducts was well below the specifications (1x10⁻⁹ mbar/sec*l). Nonetheless a relative displacement between the "Ts" and the "Es" profiles was found. In the 2nd brazing step all the remaining stainless steel components are brazed with CuSil (eutectic composition: 72%Ag, 28%Cu - liquidus: 780°C, solidus: 780°C).

We encountered 2 problems. The junctions between the end side flanges and the copper were just partially brazed (as verified by UT inspection). The dimensional check of the cavity showed unexpected deformations. It was discovered that the heat treatment of the end side flanges was not done following our specifications (the cooling step was too fast thus resulting on an ineffective annealing process). Since the brazed connection was too poor, a 3rd brazing step
using Incusil® 10( 63%Ag, 27%Cu, 10%In - liquidus: 730°C, solidus: 685°C) was performed to join the copper and the stainless steel end side flanges by means of a series of pins.

Figure 29: Assembly of the M16 before 1st brazing phase[15].

Figure 30: Assembly of the M16 before 2nd brazing phase[15].
Beside all these problems the module 16 fulfils the specifications in terms of geometrical tolerances and vacuum tightness. Taking into account the experience on module 16, and the differential thermal expansion between copper and stainless steel AISI316, it has been decided to modify the design of the front and the side flanges. The sealing stainless steel ring clearance with the copper on the "T-s" sides (gap about 0.3 - 0.5 mm) was embedded, while the nominal coupling brazing tolerance on the "E-s" sides was maintained to ensure a relevant coupling pressure all along the thermal cycle (accepting the residual local deformation at the joint level).

![Figure 31: Allowance of the front flange respect to the seat on copper electrodes. [15].](image)

Furthermore cuts were introduced on the outer side of the side flanges to reduce the stiffness, allow a more correct brazing the assembly and limiting the distortions.

![Figure 32: Side flange with new cuts between the bolt holes.](image)

All these modifications were introduced and verified on the 1st brazing step of module 17.
3.8 Single Brazing Step

Rather than double stage brazing on all remaining modules, except for the module 2, a single stage brazing was adopted in order to prevent the loss of mechanical properties of the copper, improve precision of assembly and reduce brazing cost.

By the figure 33 one can understand the large number of parts that are involved in the single brazing step. Components are not only made of different material as well as stainless steel (AISI 316LN for the grey object except for the cooling tubes made of AISI304) and pure copper Cu-OFHC CuC2 but also they have different mass and exposed surfaces that can result in an independent thermal behaviour between them. As one can see, the FF gives a kinematical constraint to the copper components opening but for the other components some tools are needed to put in their seats the SF and the other stainless steel component. In the next picture, front flange tool (1-2) as well as common plane tool (3) and Molybdenum TZM® flat spring are
shown. Front flange tools permits to prevent eventual distortion of the FF due to the residual stress in order to adapt its brazing surface to the respective copper joint area. Besides preloading provided by Nimonic®90 springs, sustain the FF on the underside, by a molybdenum rod, which otherwise would fall by gravity. The same purpose is referred to the tool (5) respect to the side flanges. The flat springs (4) allow a weak attachment of components to high temperatures. The side plates (3) on the outer sides of the electrodes T, thanks to the common machined planes, maintain the relative positioning between copper component (<± 0.01 mm) in those planes.

Figure 34: Tools used during single step brazing. 1: Nimonic®90 Springs, 2: FF Containment Plates; 3 Common plane tool; 4 TZM® molybdenum springs, 5: SF support tool.
Figure 35: Exploded view to show tools for the sustainment of the side flanges during the brazing. Graphite foils are interposed between the bigger Alumina plates and between alumina and SF.

Figure 36: Module on the oven grid after the single brazing cycle. Twelve k type thermocouples are positioned in their seat holes on the external surface of copper (E and T) and near the brazing planes, on a central position of the SF and on the top FF.
3.8.1 **Issues from Single Brazing Step**

Through the small prototyping tests the optimum positions of the slots of the brazing wire were determined. Moreover have led to define the brazing cycle with rising ramp 90 ° C / h up to just below the solidus, stabilization for thermalization and final ramp up to put the components above the liquidus to melt the brazing alloy. The high energy modules that have been brazed with a single cycle of brazing did not show significant defects than those dealt with in the figures 37.

![Image](image1.jpg)

**Figure 37:** Step on the front face of a module between E and T (E at the bottom and T at the top) of module 15

![Image](image2.jpg)

**Figure 38:** Gap on the brazing area of the SF, T side (Top and Lateral views) on M13
For those of low energy, and therefore with greater mass and thermal capacitance compared to the irradiated surface, the trends of the temperatures are not justifiable for each of the components. Right from the beginning it was thought to an anomaly in the control system since even in the past similar problems occurred [15].

In fact the measures of some thermocouples is misleading because it have come out from its seat and has touched a hot object, such as a tool low thermal capacitance and high exposure. Another case was noted in the module 8, the first brazed to the laboratories LNL with a higher mass. This has been put in the oven with some thermocouples placed to measure the temperatures of T in its through holes. Actually the contact of the thermocouple was not insured and the copper surfaces surrounding have done a shield effect (thermocouple receives heat only by the irradiation coming from the surrounding copper).

Figure 39: Measured temperature during brazing cycle of M8.

Figure 40: E9 side of the M12.
Figure 41: End flange on a T side M12.

Figure 42: M8 T Side upper(a) and lower(b) zone M8, misalignment on the side flanges shoulder.
The repairmen of all this defect has been carried out by an additional brazing cycle in which cooling tubes was substituted and a reinforcement plate for the side flanges was added to sustain the structural shear load for the vacuum gasket squeezing and the gravity effect. Thermal cycle increases the average grain size of copper, causing further degradation of its mechanical properties from that of the annealed and brazed object. So we have absolutely to prevent this issue.

3.9 COUPLED THERMO-STRUCTURAL SIMULATION OF THE BRAZING PROCESS

Real body, during their warming or cooling could present lack of uniformity on the temperature field, due to the way we furnish heat in their volume or surfaces and also the mass distribution on its volume. Nowadays much software (ABAQUS, ANSYS, COMSOL...) can solve with good approximation, by the technique of finite elements, Partial Differential Equations PDE by determining for example the fields of temperatures, and displacements, of complex geometries subject to various types of boundary conditions. In our cases uncertainties on degree of freedom fields, displacement and/or temperature, are mostly affected by uncertainties on physical properties of the material. Considering a coupled thermo-structural simulation, at first temperature field has to be obtained then displacement field is evaluated by using the thermal expansion curves. To avoid any numerical problem with the use of software (ANSYS APDL) a 0.1mm separation gaps between faces of all adjacent bodies are modelled so adjacent surface
exchange heat flux only by radiation. Due to the complex geometries, analytical one-dimensional studies do not permit to describe temperature field of component as well as thermal differential expansion. Conversely, numerical model provided with all details of the real geometries, can be more time consuming for calculation. Thus, it was chosen to simplify geometry (by deleting holes and cut surfaces), and to maintain, in addition to the component to be welded except for the cooling tubes, the object with the highest shielding behaviour. Due to uncertainties in data literature but knowing that there are soft fixations of pieces, as stated before, we assume that heat fluxes via thermal contact are neglected. For transient radiative conductive problem involving a body of a certain volume and surface, the instantaneous temperature field depends not only from its thermal conductivity \( k(T) \), from density \( \rho(T) \) and specific heat \( c_p(T) \), but also from the heat sources coming on its surface by the total hemispherical emissivities \( \varepsilon(T) \). Some common values from literature and material suppliers are reported in table 2. Given that the characteristics which refer to the volume are easily found in the literature, attention should be paid for emissivities because the geometry simplification adopted as well as uncertainties on the surface condition (e.g. oxidation state) could result in a misleading temperature field. In fact from what we have seen from a preliminary simulation is that predicted temperatures are very underestimated if one uses the polished value. Instead of this value one could adopt the oxidized values but it results that simulated temperature almost overlap with those of the screen of the oven.

<table>
<thead>
<tr>
<th>Properties \ Material</th>
<th>Cu-OFHC</th>
<th>AISI 316L</th>
<th>Molybdenum</th>
<th>Alumina</th>
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<tr>
<td>Density [kg / m^3]</td>
<td>8960(20°C)..</td>
<td>7979(20°C)..</td>
<td>10200(20°C)..</td>
<td>3990(20°C)..</td>
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<td></td>
<td>8530(850°C)</td>
<td>7600(850°C)</td>
<td>10060(850°C)</td>
<td>3910(850°C)</td>
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<tr>
<td>Specific Heat [J / kg K]</td>
<td>383(20°C)..</td>
<td>485 (20°C)..</td>
<td>247(20°C)..</td>
<td>760(°C)..</td>
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<td></td>
<td>465(850°C)</td>
<td>676(850°C)</td>
<td>300(850°C)</td>
<td>1240(850°C)</td>
</tr>
<tr>
<td>Thermal Conductivity [W / m K]</td>
<td>398 (20°C)..</td>
<td>13 (20°C)..</td>
<td>138(20°C)..</td>
<td>0.06(20°C)..</td>
</tr>
<tr>
<td></td>
<td>344(850°C)</td>
<td>24(850°C)</td>
<td>108(850°C)</td>
<td>0.14(850°C)</td>
</tr>
<tr>
<td>Total hemispherical emissivity (polished)</td>
<td>0.03(20°C)..&lt;</td>
<td>0.1(20°C)..&lt;</td>
<td>0.06(195°C)..&lt;</td>
<td>0.7(20°C)..&lt;</td>
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<tr>
<td></td>
<td>0.05(850°C)</td>
<td>0.2(850°C)</td>
<td>0.13(850°C)</td>
<td>0.4(850°C)</td>
</tr>
</tbody>
</table>

Table 2: Example of thermal properties for the materials involved.
The right values for the emissivity to match simulated and measured temperature could be found using an algorithm based on the heat transfer equation with a radiative heat flow source. Consider a body with $\varepsilon_2(T)$ completely surrounded by a radiating surface at imposed temperature $T_{oven}$ with constant emissivities $\varepsilon_{oven} = \text{const}$. If the enclosed body has a high diffusivity $\alpha(T) = k(T)/(\rho(T)c_p(T))$ we expect that its temperature field is almost constant (there are no conductive heat flows inside it) and its external surface is almost at the same temperature. The net rate of radiation transfer from surface “oven”, must equal the net rate of radiation transfer to surface 2, $q_2$, and both quantities must equal the net rate at which radiation is exchanged between “oven” and 2. At this condition one can write the heat transfer equation at certain instant $t^*$:

$$mc_p \frac{dT_2}{dt} \bigg|_{t^*} = \frac{\sigma(T_{oven}^4 - T_2^4)}{\varepsilon_{oven}A_{oven} + \frac{1}{A_{oven}F_{oven-2}} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}} = q_2$$

Where $\sigma$ is the Stephan’s constant $\sigma = 5.67 \times 10^{-8} \text{ [W m}^{-2} \text{ K}^{-4}]$. Considering $A_{oven} \gg A_2$ and $\varepsilon_2 \ll 1$, the relation between the net rate of radiation $q_2$ and $\varepsilon_2$ can be approximated as linear. This suggests that an estimation of total hemispherical emissivity of the contained body could be found by changing its value in order to match the slope of the curve “measured T vs time” instead to match its single points.

Figure 45: Graphical explanation of the temperature slope comparison.
By using the curves, simulated and measured, but considering the same temperature \( T_2 \) one can use an algorithm to obtain the optimal estimated value for the total hemispherical emissivity. Imposing the estimated emissivity at iteration \( i, \varepsilon_{est,i} \), we obtain for a chosen \( T_2 \) the slope of the estimated temperature curve is \( \Delta T_{est,i}/\Delta t \) and that of measured curve is \( \Delta T_{meas}/\Delta t \). The ratio between the two slopes gives the coefficient \( x_i \) and the estimated emissivity are recalculated for the next iteration, as explained in the figure 46.

![Algorithm used for the estimation of the total hemispherical emissivity](image)

**Figure 46: Algorithm used for the estimation of the total hemispherical emissivity**

A quarter of the entire geometry considered of that correspondent used in the 3-d simulation is reported on figure 47. The conductive elements, about 70000, use a linear form function (SOLID 70). Also the radiative element (SURF252), about 25000, uses a linear form function and each element cover the external surfaces of the solid element. The boundary condition imposes temperature cycle of the oven in the molybdenum reflecting screen. This simulation are carried out with workstation with 2GHz 12-core processor, 32GB RAM (EEC). If we setup the simulation using the well note Gauss Seidel algorithm to solve the radiosity method, it takes about 16 Hours. It is to note that only one core seems to work at full speed. Otherwise, using the Jacoby method, we see 4-core working at full speed and the simulation takes about 5 hours, because of the improved calculation parallelization.
Figure 47: Quarter of the simulated geometry. In orange the molybdenum screen, light blue the AISI316LN stainless steel, in strong tan the copper OFHC electrode in yellow the alumina.

Figure 48: Estimated emissivity found with the algorithm, oxidized and polished correspondent values are reported in dashed lines. Colors are referred to the quarter geometry figure 47.

Using the emissivity estimation algorithm we found that, for an imposed value of emissivity for the molybdenum screen of 0.5, the emissivity of the copper stay between the polished and the
oxidized curves. At lower temperature it accommodates at the oxidized value than at the higher it decreases its value to get close the polished ones. This change in value was primarily due to the oxides desorption from the copper surface that start, in accordance with the Ellingham diagram, with the lowering in oxygen partial pressure and the increasing in temperature. A linear interpolation is used to connect the lower and the higher emissivity values from 200°C to 400°C. The emissivity values and the simulation are validated for module M12 and M08 respectively with lower and higher mass and then it has been used for other modules. Figure 49 reports the comparison between some measured and simulated temperature for M08.

![Figure 49: Graph of the simulated (dashed) and measured (continuous) temperature for the M8 brazing cycle](image)

One can see that simulated results fit those measured especially between 20÷400°C and at the brazing temperatures while for the range between 400÷800°C a discontinuity occur. This phenomenon could be explained by observing the temperature field on the electrodes. The high thermal conductivity of copper, also on high temperature, led to uniform the temperature field on each component, but due to the different exposed surfaces and mass, temperature on the T’s electrodes is lower than that of the E’s (figure 50 a and b).
Figure 50: a) Simulated temperature field for two electrodes of M8 during the ramp-up.
b) Simulated temperature field for some components of M12, two copper electrode upper and lower front flanges and Side flanges.
This phenomenon occurs also for module M12 with lower thermal capacitance where temperature is higher for E’s. Moreover in all simulated model front flanges temperature field is affected by the shielding effect coming from the tools. In fact triangular plates decrease temperature on the front flanges corner while temperature on its area directly exposed at the radiation from the mirror molybdenum screen is slightly higher. Also the bottom plate, that sustain the copper, decrease the radiative heat flow impinging on the bottom front flange and this results on mean temperature lower than the upper one (figure 50b). Side flanges instead have average temperature higher than the copper and front flanges because of their exposition. Now, using the results obtained, tough about the fact that in the real case side flanges on the E-side touch, with a certain pressure during all the brazing cycle, the adjacent area of the E. Depending on the pressure, a certain amount of heat flow passing through the thermal contact resistance, go from side flanges to E increasing the electrode temperature. As the E’s have a higher temperature than the T’s, and so are their expansion, side flanges afferent at the T-side is shifted from the adjacent area of the T by the E’, and detaching of the T from the adjacent T-side flange occur. Molybdenum flat spring, mounted on the side flanges, with their very low capacitance, assume temperature close to that of the furnace screen.

Figure 51: Simulated temperature field for all volumes at the brazing ramp-up stage.
The lower temperature expansion of molybdenum respect to that of copper could permit to obtain a certain constant contact pressure but gap between the molybdenum and Stainless steel + copper part at room temperature, necessary to mount this tool, could get in discontinuous contact behaviour during ramp-up. Apart from this, predicted temperature of side flanges show temperature just below the oven temperature cycle (figure 51).

Due to the different value in thermal expansion coefficient of copper and stainless steel and the difference in temperature, one can tough that discontinuity could occur when the closing action of the front flanges to the electrodes begin to act (GAP Front Flanges become zero). If at this instant E temperature differ from T temperature, distortion may occur and brazing fixes pieces at a wrong positions. As we can understand from the exploded view of modules (figure 33), cooling tubes pass through holes of side flanges. If T’s has lower temperature than E’s, shear forces could damage the three central tubes on the T side, put in traction also the T and damage the tube seats (Gap Side Flange). The optical inspection, as before reported, agree whit these statements. To upgrade the thermal model and improve its reliability, it was added a structural model simply by changing the finite element type. Its scope is to find if any possible distortions due to the losing action of the front flanges happen. Furthermore, the non-uniformity of the temperature, caused by the different emissivity and the different exposure of the surfaces of the body, cause of the misalignment between the tubes and the side flanges that can damage them and affect the seal. Coefficient of thermal expansion reported in the firsts paragraph of this chapter, is then used to evaluate the displacement on the FF seat and in the SF shoulder to confirm the assumptions.

Figure 52: GAP side flange (left) and GAP front flanges (right)

Linear mechanical properties from literature (Young modulus and Poisson coefficient) were taken into account reducing time calculation. A large use of the coupling degree of freedom is
done in order to compensate the absence of the spring compacting effect and to guarantee the common plane alignment but avoiding the coupling between nodes that, during the cycle, can cause stress-induced expansions. At last all the bodies are cinematically constrained and structural simulation is carried out. The displacements of the relevant nodes are then used to construct the graph of the GAPS.

It can be seen that at 9 hour, and when copper is at about 650°C, GAP front flanges become zero even if the GAP side flanges are in the order of 0.1mm. Real pieces are affected by these kinds of distortions so, although the model does not take into account all the thermal and structural interactions between the various components, it can be considered acceptable. Knowing that at room temperature, the front flanges gap is about 0.03mm, considering the thermal expansion curves one could introduce an intermediate plateau at 650°C to assure that front flange act when all bodies have the same temperature and no differential expansion appear on electrodes. For what concern temperature on pieces, this intermediate plateau, reduce the difference in temperature and so the differential expansion when the closing action of the upper front flanges occur. Figure 54 report the difference in temperature $\Delta T$ of E’s from T’s for the old (dashed lines) and the new (continuous line) cycle. The old cycle $\Delta T$ curve of the high energy modules (e.g. M12) is lower than that of the low energy modules (e.g. M8), because of the lower thermal inertia. The new cycle with the intermediate plateau permit to reduces $\Delta T$ in the first ramp up but it will generate a newer discontinuities on the second ramp-up (between 10 to 15 hours. If pieces are in contact, because of the front flanges closing effect, temperature between pieces will become uniform and such difference will not occur.

Figure 53: graph of the GAP side flange (green) and GAP front flanges (red) for M8
Figure 54: The graph report results form the thermal simulation. On the primary vertical axis (left) the difference in average temperature between E’s and T’s electrodes (i.e. $\Delta T = T_E - T_T$). The secondary instead report the temperature of the reflecting screen. Dahed lines indicates data correlated to the old brazing cycle.

Figure 55: The graph report results form the simulated temperature. Graph of the GAP side flange (green) and GAP front flanges (red); old (continuous) and new (dashed) cycle for M9

As we can appreciate from the figure 55, in the new cycle, when the closing action of the FF start to act, the misalignment on the SF shoulder has been reduced from 0.1 to 0.05mm with a few spent in terms of brazing cycle duration and so mechanical strength of copper. If the closing
action occurs, thermal contact conductance between bodies could uniform temperature for the successive ramp-up. This is confirmed by the results of a new simulation where temperature on nodes of adjacent areas for copper are coupled together, avoiding the existence of a thermal contact resistance. The comparisons between new simulated and measured temperatures for M9, brazed with the new cycle, are reported on figure 56.

The result of the new simulation with the “coupled temperature” on copper, cope the measure one on the second ramp-up and so confirm the assumption before mentioned. In order to prevent any possible damage of the central cooling tubes (Ø18, Ø22, Ø18) on the T-side, enlargements of few mm along the vertical direction (XC on figure 57) of central side flange holes have been done to permit the free motion between objects.

Figure 56: Simulated (continuous) and measured (dashed) temp. for the new brazing cycle of M9.

Figure 57: Modified central holes for the side flanges
3.10 **OPTICAL RESULTS OF THE BRAZING JOINTS WITH THE NEW CYCLE**

As we can see from the figures 58, 59 and 60 the optical inspections of the brazed joints show the presence of meniscus at all the joint contour. Ultrasound test on the side flanges confirm that all areas are well brazed and brazing alloy fill completely all the gap.

![Figure 58: brazing joint between E and T of M9. No shift are detected](image)

![Figure 59: brazing joint between side flanges and E+T common plane M9. Meniscus is on the entire brazing joint contour.](image)
Figure 60: Brazing joint on the upper external side of Module 9 E-electrode. Brazing meniscus compares on all the brazing joint contour and no shift are detected between E and T joint area.

Figure 61: Central cooling tubes brazed. It is possible to notice that brazing alloy wet the nickel plated stainless steel components and due to the capillarity phenomenon it cover the thinner gap zone between tubes and side flanges.
3.11 CONCLUSIONS

The intention of this chapter is to cover the problematics encountered in the brazing processes of the IFMIF RFQ modules by using a vacuum furnace. At first an introduction of notions concerning the affinity of the brazed materials, as wettability and thermal expansion, are reported. Data of thermal expansion for stainless steel can vary in literature so comparison has been carried for AISI 316LN and AISI 304L. The knowing of the oxidation state of the materials is
fundamental both for ensuring the good junction within a brazed joint, by reducing oxygen content, and to obtain a correct characterization of the material in use in terms of total hemispherical emissivities. Some 1-dimensional considerations have been reported, using the curves of thermal expansion, which can be helpful in preliminary definition of the brazing cycle. A couple of paragraphs deal with the most relevant aspects of the works previously done that has led to the definition of a joint geometry, i.e. grooves dispositions, and to the single cycle of brazing. Then it has given attention to the identification of defects, coming from the single brazing step, to indicate possible causes. The introductions of some basic analytical formulas were necessary to master the numerical thermal modelling, and in particular the radiative heat transfer. The goal in this case was to understand what issues major affect the reliability of the results obtained using a reasonable computation time. Consideration of shielding bodies, the geometry simplification and the customization of total hemispherical thermal emissivities permitted to obtain results, from thermal numeric model, that cope the measured temperature.

After that it was upgraded the thermal model with a coupled structural one to identify, at first, the type of the interactions between the components. These foundlings were in line with what it has been observed in the optical inspections. So it has been identified the instants in which embedded thermal expansions occur and distortions appear. In order to obtain reliable model, the characterization of thermal properties is essential and, in our case, the total hemispherical emissivity is the parameter that most influences the temperature field of the objects in the oven. Therefore an algorithm was used, by the matching between predicted and measured temperatures, to characterize the surface of the pieces with highest thermal inertia. All these issues suggest the definition of the new brazing cycle, with an intermediate plateau, that reduces distortions, but at the same time reduces the stationing of the components to high temperatures and prevents the decay of the mechanical properties. The validation of thermo-structural model for the new cycle has been done for M9 using coupling of temperature for nodes on adjacent area. Finally this model was used to predict temperature during the brazing cycle of the next modules. Given the many benefits of the designed new brazing cycle, it was used on the rest of both high and low energy modules to be produced. The optimal results obtained confirm that, for these kind of objects, single brazing cycle with intermediate plateau is fully validated.
**BIBLIOGRAPHY**


CAPITOLO 4

PRODUCTION QUALITY CONTROLS AND GEOMETRIC CHARACTERIZATION OF THE IFMIF RFQ MODULES VIA THE USAGE OF A CMM

4.1 INTRODUCTION

The mechanical specifications of the RFQ of IFMIF/EVEDA are very challenging and tight tolerances are required for the machining. The aim of the EVEDA phase being to qualify industries to the ‘turn to key supply of the RFQ line’, we assumed to centralise the procurement and qualification for all materials and to provide semi-finished raw blanks to the qualifying firms. A detailed documentation of the production drawings as well of the quality agreement protocols and of the brazing step and tooling, were reported on a web page: [http://ifmif.pd.infn.it:5210/](http://ifmif.pd.infn.it:5210/) that has been used as reference for collaborating Institutes and outsourcing firms. The mechanical design of the RFQ, as well as the realization of the modules 7 to 12 (2nd Supermodule) and the overall production control is in charge at INFN Padua through its Mechanical Design and Mechanical Workshop services. Moreover, INFN Turin is in charge of alignment and installation at Rokkasho site, and INFN-LNL is in charge of physics design. Finally, INFN-Bologna contributed to the Stainless Steel component production.

In this chapter an introduction to the production phases of the modules as well as the metrology quality control between them will be described. The material acceptance and qualification are described and the mechanical properties, for forged and annealed copper CuC2, are then reported. A detailed description of the metrological procedures and tests of the RFQ along its production and assembly phases will be given and it will be shown that the adopted procedure allowed the attainment of the tuning range specifications for each RFQ module.

The metrological measurements via CMM (Coordinate Measuring Machine) provided to be a very effective tool both for quality controls along the RFQ production phases and in the reconstruction of the cavity geometric profile for each module. The scans in the most sensitive regions with respect to RF frequency, such as modulation, tips, base-vane width and vessel height provided the values of the cavity deviations from nominal geometry to be compared with design physic-driven tolerances and with RF measurements. Moreover, the comparison between
mechanical and RF measurements suggests a methodology for the geometric reconstruction of the cavity axis and determines the final machining of the end surfaces of each module in view of the coupling with the adjacent ones. The main RFQ parameters are listed in Table 1.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>RF power [kW]</td>
<td>1250 (25% margin)</td>
</tr>
</tbody>
</table>

Table 1: IFMIF RFQ main parameters [1],[2].

In the following Figure 2, a picture of a transverse section of the RFQ is shown, aimed at indicating the main geometric parameters, that will be mentioned in the following.

Figure 1: transverse section of an RFQ quadrant, with the main geometric parameters: in particular ρ is the pole tip radius and R0 is the average aperture.

In this RFQ the voltage varies along z, as well as R0. This implies that, in order to get the nominal voltage profile, the vane base width Wb is varied accordingly [3] and therefore all the modules are different from one another both in mechanical (weight, dimensions etc.) and RF characteristics. It should be emphasized that the geometries related to the second supermodule assume in the most sensitive area, the pole-tip, a three-dimensional surface that for whose manufacture it was dedicated an accurate setup of the machining parameters that permitted to outline a standard quality control procedure followed by the charged firms.
4.2 MECHANICAL REQUIREMENTS INTRODUCTION

The RFQ of IFMIF performances are extremely challenging. Power deuteron beam (650 kW) will be accelerated in the narrow clearance between electrodes, with low beam losses to avoid the activation of the structure and to allow hands-on maintenance of the structure itself. The beam losses requirements translate into mechanical tolerances in three main ways:

- The vane modulation machined on each electrode must be accurate for electric field components, and with low roughness to sustain a high surface field.
- Beam axis accuracy along the accelerator, requires modules alignment and end faces parallelism.
- Field homogeneity along the structure requires very accurate pole tip positioning (capacitance between electrodes).

The first requirement is absolute on the machining, and is determined before brazing. For the positioning of the beam axis, we require a maximum of 0.1 mm uncertainties respect to external references. The most important thing is to avoid stepwise variation between one module and the following one, and for this reason at the end of the production module the best beam center of each module extremity is found and the modules are aligned respect to this center. Concerning the parallelism, reference faces are machined at the end of construction to obtain a uniform gap of 0.1 mm between copper face of adjacent modules, and calibrated spacers are introduced. Two slots are machined on side flanges in order to prevent rotation and stepwise position of beam axis.

Figure 2: Side flange slot and side flange face machined to accommodate calibrated shims.
The other requirements, concerning the field homogeneity, are determined by the local cross section shape and local cut off frequency. As the entire module components are well machined accordingly to the demanding drawing specifications, brazing is the last process that can permanently affect the cross section. Brazing distortion adjustment will be made by changing the magnetic field stored energy by tuning that uses cylinders introduced in the inductive region of the cavity. This adjustment, and the tolerances on the module geometry, corresponds to the freedom left by the tuning range of ±1MHz [1]. All these requirements are very severe, and determine the very stringent tolerances for module construction. The attainment of these tolerances required the usage of a CMM machine as a tool to verify the tool compensations in the production phases and in the determination of external references for module alignment.

4.3 Production Phases and Quality Controls

CMM-assisted measurements were necessary since the very beginning of production, in order to rapidly collect a sufficient number of points able to describe the complex 3D component geometries. Figure 3 shows synthetically the Copper component geometries through the various production phases of the cavity modules.

Phase 1: Deep drilling
Phase 2: Electro Discharge Cutting
Phase 3: Rough Milling
Phase 4: Finish Milling
Phase 5: Brazing of the four electrodes
Phase 6: Welding of the corners sheets connecting external side flanges
Phase 7: Front face and external references final milling for module alignment

Module construction starts from material procurement: CuC2 (Copper) for the electrodes, AISI 304 and AISI 316LN (Stainless Steel) for cooling tubes and front and side flange respectively. Grain dimension, isotopy and homogeneity of the copper blocks are checked via UT scan (squared 3d array on all blocks and a full C-scan on a prototype block), tensile strength on
specimens recovered from the block along three orthogonal directions, SEM analysis (on specimens recovered and for the tensile strength test). After the block forging, these tests have verified that the grain size was less than 90 μm and the deep drilling was done to create the cooling channel (fig 2.a). Then an EDM (Electric Discharge Machining) machine performs the block cuts, thus creating the electrodes: each module is composed of four electrodes, one couple is T-shaped (T electrodes) and another couple is E-shaped (E electrodes). In this phase the electrodes are machined with about 1 mm metal allowance (fig. 2.b). Then final machining of the components is performed on a CNC (Computer Numerical Control) 5-axes milling machine. At the same time, the AISI316LN and AISI304 Stainless steels, after proper thermal treatments, underwent a nickel electroplating procedure, in order to prevent spontaneous passivation of the base material, which would result dangerous for brazing. Finally, a deep chemical cleaning eliminated the presence of oils and oxides from all the components. At this point, after final assembly, the vacuum brazing took place with the usage of a PalCuSil® 10 alloy at the temperature of 850°C. The coupling geometries of the components called for a very careful design of the brazing cycle in order to avoid distortions especially for the heaviest modules located in the low energy sections of the RFQ, since there are materials with different thermal expansions. Finally, the end surfaces of the brazed modules are machined, as well as their external reference surfaces. This is necessary in order to ensure geometric coherence with the most sensitive geometries of the cavity (such as pole tips and modulation), in view of the attainment of a correct alignment.

4.3.1 Material Procurement

The material choice for the RFQ modules production was essentially driven by the large mass and extreme high purity of the CuC2 (ultra-pure copper: hot and cold forging on OFE blanks); the AISI 316LN components procurements being less critical. The CuC2 requested mass was 5 times larger than the raw blanks used at the time, with the need of exchanging the production technology (large press instead of the forging pillars). The material specifications and quality controls were borrowed by the CERN metallurgy group (EN-MME-MM). The acceptance tests were also performed by the CERN staff. The acceptance test specifications on the CuC2 (ultra-pure copper) are checked in terms of:

- UT scan (squared 3D array on all blocks and a full C-scan on a prototype block);
- tensile strength on specimens recovered from the block along three orthogonal directions;
- SEM analysis (on specimens recovered as for the tensile strength test).

The CuC2 blocks production was commissioned to Auber & Duval on two sets of dimension for the T and E profiles. After the block forging, the above described tests have verified the blocks
homogeneity, material isotropy and that grains size, declared as an internal specification referred to [4], was less than 90μm. After the squaring, the deep hole drillings have been done to house the cooling channels.

![Figure 4: Raw blocks for the E (left) and T (right) shaped profile.](image)

![Figure 5: Microscopy showing the etched surface or the forged material (100x).](image)

### 4.3.2 Electro-discharge cutting

Due to the extremely large dimensions to be milled from the blocks, we used the EDM approach, limiting the induced stress and minimising the annealing process on the CuC2 raw blanks obtained (mandatory for a stable geometry during the brazing process at high temperature). The waste of material was also minimised, having conversely the opportunity of producing spare parts as tuners body and copper plugs for free (maintaining the same mechanical properties). The raw E & T elements were produced in parallel at INFN Padova and INFN Torino units with the largest EDM distributed in Europe. In this phase the electrodes are machined with about 1 mm metal allowance (figure 6 and 7). Right after a rough machining is performed, i.e. tuner and vacuum port holes, as well as external back face. Then pickling and oven annealing for 6 hours at 850°C is performed in order to release residual tensions and to
keep geometry in view of the next final machining steps and brazing cycle. At this point a metrological control is accomplished, with the aim of revealing possible distortions and the correct distribution of metal thickness allowance with respect to the cooling channels.

Figure 6: Raw blocks and the raw electrode to obtain with WEDM machining.

Figure 7: WEDM (SODICK AQ750LH) at INFN-PD for the raw cutting of the blocks.
4.3.3 **Tensile Test for Forged and Annealed CUC2**

The tensile tests were carried out at the Mechanical department at the University of Padova in order to obtain the main mechanical properties of the used copper. Since thermo-structural analysis validations require huge time, not compatible with the production schedule and with the issues here addressed, it has been reported only the results obtained from tensile tests, referring to existing literature the appropriate considerations. With the waste material of the block preventing from the WEDM, it was possible to obtain a raw bar from which get 3 samples for the tensile test. These three specimens are machined respecting the drawing showed on the figure 8. Axial extensometers MTS 634.12 has been positioned in the middle of the sample for measuring engineeristic strain. It has a gage length of 25 mm and a travel of −2.5 to +12.5 mm. The strain range is −10% to +50%. The test has been carried out following the [5] using a speed test of about 0.017mm/s which correspond to the strain rate $\dot{\varepsilon}_e \cong 1.65E − 4 \ [1/s]$. The cell load, connected in series, measure the load directly applied to the specimen and the total force applied is always below the 23kN. The engineeristic stress-strain curve are reported together with the parallel line for the obtainment of the 0.2%, 0.02% proof stress. The curve reported is the lower of the three obtained.

![Figure 8: dimension of the tensile test sample in accord with the UNI EN-ISO 22768-mH.](image_url)
Main mechanical properties obtained for forged material are: $E=117\text{GPa}$, $R_{p0.02}=218\text{MPa}$, $R_{p0.2}=280\text{MPa}$ and $R_m=285\text{MPa}$; the material can be approximated with an elastic-perfect plastic behaviour. Knowing that thermal heat treatment, as well as brazing, affect the mechanical properties and there is an increase in grain size, a tensile test was also carried out considering the annealed material. A raw bar as the previous explained for forged samples, is heated in the vacuum furnace using a ramp-up at $150^\circ\text{C}/\text{h}$ up to $850^\circ\text{C}$ and then after 6h is cooled with $180^\circ\text{C}/\text{h}$ to reach $300^\circ\text{C}$ and then cold argon has been inflated to the vacuum furnace to reach room temperature. Then specimens are machined according to the figure above. The speed test was about $0.03\text{mm/s}$ which correspond to the strain rate $\dot{\varepsilon}_e \approx 5E - 4 [1/\text{s}]$. Again the lower curve of the three, as well as the forged one, is shown. Due to the earlier plastic behaviour of the annealed copper, the engineeristic stress strain curve could not be appropriate so a logarithmic (true) stress-strain curve has to be considered instead of the engineeristic one. As we can see from the graph, if we use the notation $\sigma_t = K \varepsilon_t^n$ we can obtain $K$ and $n$ by the following equation:

$$\log(\sigma_t) = \log(K) + n \log(\varepsilon_t)$$
While in the forged tensile tests the elongation was acceptable for the extensometer, in the annealed tests it reach value greater than 25mm (50% of initial length light blue curve on figure 10) so it has been decided to remove it to prevent its damage.
In our case using the graph we obtain: \( \log(K) \cong 2.0454 \rightarrow K \cong 111 \text{ MPa} \) and \( n \cong 1.045 \). The error of the curve is less than 5\% for \( \varepsilon_t > 0.55 \). The graphs below instead, could be used with a proper value of yield stress \( Y \) ranging from \( 6 \div 14 \text{ MPa} \), for large displacement on a structural non-linear simulation.

![Graph](image)

Figure 12: True stress-strain CuC2 curve for strain < 0.55. Blue for measured, and red for the evaluated by the K and n coefficients.

### 4.4 ELECTRODES MILLING

Final machining of the components are performed on a CNC (Computer Numerical Control) 5-axes milling machine.

![OKUMA MILLAC800VH 5-axis milling machine](image)

Figure 13: OKUMA MILLAC800VH 5-axis milling machine
Of these axes, 3 are used to form the electrode modulation. It has to be noticed that the attainment of the nominal electrode geometry took place with a light metal allowance, which, by means of CMM usage, permitted to determine the tools compensations necessary for the finishing phase of each surface.

Figure 14. E-shaped electrode placed in the Zeiss Accura CMM.

Figure 15: Set of stylus systems used.
Measurements, and quality control, are performed with Zeiss Accura CMM equipped with VAST XT active scanning head (MPEe=2.2+L/300[μm], ISO 10360-2), placed in a temperature-controlled environment at 20°C, with controlled humidity and without any direct exposition external heat sources. As an example, an E-shaped electrode is considered, and the same procedure holds for T-shaped electrodes too. After semifinishing, the electrode is isostatically placed on the plane of the measuring machine and up to its thermalization at the room temperature of 20°C. The CAD model of the piece is pre-loaded on the measuring machine, in order to have all references necessary for comparison. At this point, an initial reference system (Base Alignment) is associated to the piece in the following way: first, a base plane is created by using the milling-machined surfaces A1 to A4 (Figure 16). Therefore, rotations about x and z axes are constrained. Then, by joining the symmetry points B1 and B2, rotations about y axis are constrained as well. Finally, translations about y and x axis are constrained by the previously introduced base plane and by the line joining B1 and B2 points respectively, and translations about z axis by the groove C1.

The right choice of reference elements to adjust the coordinate system affects not only the measurement in term of position but also in curve profiles form. The use of four elements, instead of three, to define the base plane will increase the robustness of the measure and its repeatability. However the “A” surfaces are also used to seat the electrodes on the machine.
milling tool making use of four M10 screws. Plastic deformation of these support area could arise because of the very low yield stress of copper.

Figure 17: Milling tool for the electrode cavity surfaces machining

Figure 18: Some of the external features to control respect the base alignment
Mounting and dismounting operations, necessary to obtain the right tool compensations and to machine brazing surfaces, could result in loss of flatness of the base planes and of the measure accuracy (figure 19).

![Figure 19: Report showing the deviation of flatness on the base plane.](image)

So for further quality control, plane on internal cavity surface will used instead of the A planes. With reference to this coordinate system, dimensions of all external features (holes, planes, grooves etc. on figure 18) are checked via a Stylus System composed of five Synthetic Ruby Probes with 5 mm diameter (figure 15). Last, vacuum-exposed surfaces (vessels, vanes, modulation) are checked with a Zircon Probes with 15 mm diameter. The continuous active scanning survey of the tip geometry is mandatory to check the real geometry with adequate accuracy. The measurements for each component were:

- Modulation longitudinal profile;
- Modulation transversal profile;
- Full profile

Such check was performed along planes parallel to the xy one, thus creating section profiles (shown in red and orange in Figure 20). Moreover, modulation profile was checked as well (yellow curve in Figure 20). In order both to reduce inertial and vibrational effects of the Stylus System and to have acceptable measuring times, the probe velocity was chosen to be equal to 3mm/s and the probing force to 100mN.
An important aspect to be considered is the tool compensation: during the working phases, the tool geometries have to be verified and well-known, in order to ensure a correct machining execution. The tool compensation is an operation in which the main tool parameters (diameter and height), which are subject to wear, thermal dilatation etc., are modified in the CAM (Computer Aided Machine) and/or on milling machine board in order match the nominal and the machined geometry. In this machining procedure, the presence of parallel and perpendicular planes in the nominal geometry as well as the metal allowance permitted the tool compensation prior to final machining. In figure 21 the scanning of the full profile electrode is shown. For the moment modulation is not taken into account. From the figure 21 it is possible to notice that a translation effect of about 0.05 mm along y axis occurs, while translations along x axes are within the tolerances. This fact can be explained by a reference system translation along y, due to a machining error on the A1 to A4 surfaces. Once this offset is taken into account, the tool compensation for both x and y planes can be determined. As for electrode modulation is concerned, it has to be taken into account that the reference for modulation profile is the C1 groove and the A1 to A4 surfaces. Then the modulated machined profile and the nominal one are compared via best fit, which accommodate the nominal and the real profiles. The machining errors revealed by this comparison do not exceed 0.01 mm (Figure 22). Nevertheless, this operation can result in a translation of the modulation along z axis and translation/rotation along the yz plane.
This can give rise to the appearance of electrode form errors when the profiles are measured again along the cut-planes of Figure 20, since, in this case, the best fit-induced offsets are not taken into account (Figures 21 and 22). Such translations-rotations, however, are not due to modulation positioning or machining errors, but rather to machining errors of the reference elements, which can be corrected by introducing the above-mentioned errors as offsets in the CAD module. As for the details of the pole tip geometry is concerned, it is possible to notice from Figure 22 that the pole tip radius exhibits an error of less than 0.01 mm due to the fact that its working phases are performed with different cutters of the same tools, the side for the vane planes and the spherical tip for the modulation.
4.5 DRY ASSEMBLY, PRE AND POST-BRAZE RF MEASUREMENTS

After the machining of brazing surfaces, the four electrodes are assembled and aligned by using as a reference the lower electrode. In particular, the four lines A1 to A4 are used for determining the base plane, whilst for the other reference elements the consideration of the previous paragraph holds. It has to be taken into account that, in this phase, the compensation of the grooves is taken into account. On this basis, it is possible to determine the amount of
displacement of the other three electrodes in order to get the nominal electrode positioning. Such displacement is accomplished by using calibrated spacers placed on the external surfaces of the T elements (Figure 23). In order to check the alignment the scanning of the electrode tips is performed (Figure 24). The longitudinal positioning of the four elements is made by measuring the positions of the grooves (light blue, blue, yellow and violet) and manually displacing the electrodes up to the attainment of the alignment within 0.01 mm by using a rubber mallet.

Figure 23: the four electrode assembly: it is possible to notice the reference elements and the position of the calibrated spacers.

The alignment of the electrode is checked by RF test too. In order to perform these tests, at both ends of each module, two straight sections of WaveGuide, 300 mm long and short-circuited at their ends are connected, figure 25. If \( f_0 \) is the “natural” resonant frequency of each module, and \( f_{WG} \) is the resonant frequency of the same module connected with the waveguides, a linear relationship (characteristic for each module) holds between the two above-mentioned quantities.
In particular $f_0$ is the resonant frequency of each module when closed with perfect H boundaries at both ends for modules 2 to 17, and when closed with E boundary at the initial (final) section for module 1 (18) and with perfect H boundary at the initial (final) section of module 1 (18). These RF tests are performed before and after each brazing step (Figure 24).

After the achievements of the nominal frequency in air, the assembly is machined to refine the common planes (green on figure 23) for the placement of the stainless steel parts and brazing tools. The components are then dismantled, chemically cleaned, and reassembled in a clean environment by means of the tooling. In this step the 2 sealing stainless steel front rings were
mounted in order to provide a relevant constraint, embedding a smooth relative movement of components during the thermal cycle that could cause an excessive flow down of the brazing material. Brazing involves not only brazing components (CUC2 e AISI 316LN e AISI 304) but also tooling components (molybdenum bars, Nimonic ® 90 and molybdenum springs and Alumina plates. These objects provide a weak fixation that avoids accidental displacements of the components during the thermal cycling, as deep explained on previous chapter. Vacuum brazing cycle is studied in order to keep component temperatures as much homogeneous as possible and avoid residual deformations. During the cycle temperatures have to reach a value above 850°C so as to allow the fusion of the brazing alloy (PalCuSil 10 ®). Numerical thermo-structural models of the brazing process inside furnace were carried out with ANSYS APDL simulations to clarify some non-realistic measured temperature encountered during the cycles. It was found that, considering the total hemispherical emissivity, data literature for polished material [6] did not provide a good trend of simulated temperature because the outgassing of the oxides starts at about 200°C, changing surface condition and so its emissivity value. Thanks to an accurate observation of the structural model results, in order to prevent any possible distortion of the brazed pieces, an intermediate plateau was introduced at 650°C waiting for the piece thermalization at this temperature. As expected by structural model, the copper bodies came in contact and tightened by the stainless steel ring flanges, so after that homogenous temperature is obtained over the electrodes. About the dimensional quality control of the modules, they are checked by UT (Ultrasonic Tests) and vacuum tests. The brazing of front flanges and side flanges with the copper is verified with ultrasonic testing as well.

4.6 GEOMETRIC CONSIDERATIONS UPON RF MEASUREMENTS

For the sake of using RF measurements to determine RFQ geometric parameter deviation, it is necessary to determine frequency sensitivities of these parameters. It is evident that a key parameter is the dependence of frequency deviation \( \Delta f_0 \) (and consequently \( \Delta f_{WG} \)) on the geometric errors in the RFQ. Since these quantities depend via the Slater Theorem [7] on the unbalance between electric and magnetic energies, the effect of geometric errors on frequency is dominated by the geometric errors related to \( \rho \) and \( R_0 \), the pole tip region being characterized of a concentration [8] of electric energy. Therefore it is possible to write \( \Delta f_{WG} \approx \chi_{R_0} \Delta R_0 + \chi_\rho \Delta \rho \). Simulations performed in both 2D (SUPERFISH) and 3D environments (HFSS v.15) showed that \( \chi_{R_0} \) ranges from 11 MHz/mm for the first modules up to 7 MHz/mm for the last ones and that \( \chi_\rho \) is approximately equal to \( \chi_{R_0} R_0 / \rho = 1.3 \chi_{R_0} \) in our case. The same sensitivities are found for the \( \Delta f_0 \) vs \( \Delta R_0 \) and \( \Delta \rho \) relationships. On the other hand, it should be observed that, while \( \Delta \rho \) depends only on construction accuracy (±10 \( \mu \)m in our case), \( \Delta R_0 \) depends on electrode positioning due to
alignment and/or brazing, that are significantly higher. Therefore, above expression was furtherly simplified to $\Delta f_{WG} \approx \chi R_0 \Delta R_0$. As for $\Delta f_{WG}$ is concerned, such value is determined by difference of the $f_{WG}$ obtained with RF measurement on each module with the $f_{WG0}$ nominal frequency obtained with HFSS simulations. It has to be pointed out that the $\Delta R_0$ determined in this way takes into account the average displacement on the four electrodes of the average aperture $R_0$ of each module.

4.7 BEAM AXIS INDIVIDUATION AND FINAL MACHINING

As for longitudinal electrode positioning (that can cause a de-phasing of the modulation between electrodes), measurements show that such errors do not exceed 0.05 mm. This value can be considered safe, as it is much less than the minimum length of a cell ($\beta_{\min}/\lambda/2=8.76$ mm). Measuring methodology after brazing is the same as described earlier in the assembly phase, in which the CAD model has the Low Energy groove coherently compensated with the modulation. For sake of simplicity, such groove is used as a reference for the longitudinal absolute position, with respect to the initial cavity section.

Figure 26: full profiles (blue) of the cavity surface
Figure 27: Measured points for a RFQ module section: the vertices A, B, C and D determine a quadrilateral, whose center determine the section center point G. The measured R0’s are the distances between each of the points A, B, C and D from G.

Figure 28: Average $\Delta R_0$ estimation for each RFQ module. The red curve represent the outcome of mechanical measurements, while the blue curve represents the outcome of RF measurements.
In this way, for each module, it is possible not only to scan almost all internal surfaces (figure 26), but also to measure both $\rho$ and $R_0$ for each electrode, with the translation of measured best fit data. The tip measurements are performed at the beginning and at the end of each module, since it is not possible with this setup to reach inner longitudinal positions. Once these values are known, it is possible both to determine the actual axis position and the average $R_0$ value to be compared with RF measurement results. With reference to Figure 27, it is possible to determine the position of the beam axis G by connecting the centers of the two quadrilaterals for both the two measured module sections. In the figure 28, the comparison between the average $\Delta R_0$ values as measured with RF and mechanical measurements.

From the graph it is possible to notice the following:

1) Almost all $\Delta R_0$ values are positive: this circumstance can be explained with the production methodology. In fact, during brazing, when temperatures approach 850°C, thermal deformations of stainless steel are slightly less than the corresponding one of copper [9]. In particular, the brazing alloy tends to consolidate the components making copper and stainless steel to become congruent at the solidus temperature (820°C). After brazing, mechanical measurements show a stretching of the E-shaped electrodes on the surface where vacuum, tuner and coupler flanges are placed, with little effects on the pole tip displacements. Conversely, the T-shaped modules turn out to undergo a displacement of pole tips to the outside from beam axis (Figure 29). The overall effect is a decrease of inter-electrode capacitance and an increase of frequency.

2) All the measured values are such that $|\Delta R_0| < 100 \mu m$, with an average value on all the modules of 46 $\mu m$ for the RF measured data and of 50 $\mu m$ for the mechanical measurement data. For the given frequency sensitivities $\chi_{R_0}$ they correspond to a 0.5 MHz overall frequency shift and are all within the ±1 MHz tuning range established for the IFMIF RFQ.

3) The two curves show for almost all samples a good correspondence between RF and mechanical data, both as trends and numerical values is concerned. In particular, an offset of about 25 $\mu m$ can be observed in the central modules of the RFQ.
Figure 29: Full profile measurements of the module 3 of the RFQ: comparison between nominal (black) and measured (blue) electrode profiles. The red and green areas represent the differences between the two profiles. The T-shaped (E-shaped) electrodes are the horizontal (vertical) ones.

Figure 30: The final machining on the RFQ module: the front faces are in green, as well as the sets for Laser Trackers.
Difference between $\Delta R_0^{\text{RF}}$ and $\Delta R_0^{\text{Measured}}$ on graph could be explained by a possible bending of the electrode that cause a variation of tip position on the longitudinal profile of the module but this can't be evaluated because it is impossible to reach inner longitudinal positions with the stylus system possessed.

Each module, once the acceptance tests are passed, is machined on the front faces and on the seats for Laser Tracker inserts, in order to be ready for alignment and assembly. Such machining is made coherently with the measured beam axis (Figure 30).

Then, the modules have been certified with the following measurements:

- Full profile scan to qualify the cavity profile;
- Dimensional and geometric checks for the tolerances compliance of the mating surfaces;
- The determination of the laser tracker inserts coordinates along the system reference based on beam axis.

Furthermore, the thickness to insert between the modules for their placement in the supporting structure was calculated. Over the dimensional qualify of the modules, they are checked by UT Test and vacuum test. The brazing of front flanges and side flanges with the copper is verified with ultrasonic testing. The cooling channels are tested with dry inert gas to the pressure of 5 bars for verify the plugs brazing. The cavity is tested to vacuum tight.

The vacuum tightness test is performed with a leak-detector calibrated on a standard leak. The admitted loss rate is less than $10^{-9}$ mbar lt/sec.

### 4.8 Conclusions

Quality controls for the IFMIF-EVEDA RFQ were performed since the earliest production phases. In particular, dimensional controls were performed along the various production phases with a CMM machine equipped with an active scanning head. This kind of instrument (along with 5-axes CNC machines) were used by all the laboratories and industries involved in the RFQ construction, allowing sharing of information and R&D time reduction. In particular, continuous scanning of the RFQ profiles proved essential in order to determine proper compensations both related to tool usage and thermal effects. The usage of a CMM machine allowed the characterization of the modulation surface and its proper positioning in the space through simple reference surfaces, furtherly used for the pre-braze alignment. Moreover, it allowed the beam axis measurement and of the corresponding $\Delta R_0$'s. Measured data, confirmed by RF tests as well, show that electrodes move apart from beam axis. This fact is due to the peculiar construction methodology, involving materials with different thermal behavior at high
temperatures. The good correspondence between RF and mechanical measurements suggests that both the analyses are a primary element of the module quality control. Such quality control proved to be successful in the case of this RFQ in the sense that all modules resulted within tuning range specifications. Finally, the obtained results suggest that, from cavity scanning it is possible to reconstruct the geometric model in any part and then to perform a sort of reverse engineering, by forecasting its Electromagnetic Properties.
BIBLIOGRAPHY


