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ACRONYMS AND SYMBOLS

ANU: Australian National University
ARIADNA: ESA Interaction with Academia on Advanced Research Topics
DL: Double Layer
ESA: European Space Agency
ICRH: Ion Cyclotron Resonance Heating
IEDF: Ion Energy Distribution Function
LPTP: Laboratoire de Physique et Technologie des Plasmas, Ecole Polytechnique Paris
MG: MultiGrid differential equations solve
DADI: Dynamic Alternating Direction Implicit differential equations solve
OOPIC: Object-Oriented Particle In Cell by Berkeley University
PIC: Particle In Cell
VASIMR: Variable Specific Impulse Magnetoplasma Rocket

λ_d: Debye length = \sqrt(\frac{\varepsilon_0 K T_e}{(n q_e)})
K: Boltzmann constant = 1.38065 \times 10^{-23} \text{ Joule/kelvin}
B_0: external magnetic field
ABSTRACT

The future of space explorations will not register a big evolution until new families of engines will be qualified. High specific impulse has been achieved with ion thrusters but significant improvements are still waited such as high thrust, variable impulse and long lifetime. Starting with the analysis of a new phenomenon, the helicon double layer, the thesis investigates new space propulsion techniques, principally testing and developing computer simulations for the analysis of thrusters performances and diagnostic devices for their laboratory tests.

The helicon Double Layer (DL) is a narrow potential jump, recently measured at the open end of a helicon source, able to produce a supersonic ion beam. From an extent bibliographic review the main characteristics of the phenomenon are: constant axial magnetic field into the source tube (>4.5 \(10^{-3}\) T) which diverges in the external chamber, low neutral pressure (<0.4Pa), ion beam velocity which is two times the ions sound speed, potential jump lower then 20V and source walls somehow able to charge with respect the plasma potential. Utilizing the Object Oriented Particle In-cell (OOPIC) software the experimental behaviour is reproduced in cylindrical geometry and with electrostatic approximation. Suggestions to apply the fluid Boltzmann electrons (hybrid PIC) are found in bibliography, this could simplify and make the simulations faster, but tests of the OOPIC nonlinear Poisson solve have revealed critical problems. It appears that the floating source wall is a key point which permits to increase the plasma potential inside the helicon tube. The potential jump is confirmed around 10-20V. The ion beam is measured with velocities around two times the sound speed, as expected, however the ions trajectories seem to have a higher divergence to respect the experimental data. Utilizing a left source wall with constant biased potential it is possible to increase the plasma potential and, consequently, the DL jump. The exhaust flux performances have then been analyzed.

Another very promising engine concept is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) which uses a Ion Cyclotron Resonance Heating (ICRH) section to increase the exhaust velocity and thrust. Again OOPIC could be utilized to reproduce some aspects of this new device. Here we have to deal with the full electromagnetic solve and a complex geometry that make the simulations more difficult. The software parallelization has been tested obtaining a gain in the performances but the calculations remain prohibitive in terms of time and memory. Consequently a new method has to be applied and the most interesting and useful is a wave equation solve integrated with a Monte-Carlo particles’ trajectories calculator, to have a full self-consistent model. The model is constructed starting from fundamental simplified hypothesis: cold plasma theory, negligible electric field along the magnetic field lines, time and poloidal Fourier expansions. The particle model is not a PIC but a trajectory predictor which propagates the particles from a given starting position and distribution considering the external and antenna fields under steady state hypothesis. From the trajectories the plasma density distribution can be constructed, which is the main input of the partial differences wave solve. The first version of the software has been written and its test and utilization is started.

Following the interesting experiments done by Charles our CISAS Space Propulsion Team is developing a new device to test a micro engine for satellite applying the Double Layer phenomenon. This new experiment utilizes a reduced scale helicon source. The contribution of the thesis is the design and characterization of probes for the plasma discharge diagnostic. After have analyzed the basic physics of Langmuir probes and retarding field energy analyzers, PIC simulations have been performed to verify the particles behaviour for our helicon source geometry. An innovative RFEA model is here proposed. It is composed of successive layers of conducting and dielectric rings inserted in a grounded stainless steel tube. The main parameter of a RFEA is the grid to grid distance which must be of the order of the Debye length and as little as possible and it has been dimensioned here around 0.5 mm.
RIASSUNTO

Ideati per rispondere alle esigenze delle future missioni spaziali, i propulsori al plasma svilupperanno spinte rilevanti unite a bassi consumi di carburante ed elevata versatilità. I gas verranno prima ionizzati per poi essere accelerati ed espulsi ad alta velocità mediante l’uso di campi elettromagneticì, sfruttando le elevate potenze elettriche fornite da un generatore atomico. Alcune delle più promettenti tecnologie attualmente in fase di studio fanno uso di campi in radiofrequenza per la generazione e/o il riscaldamento del plasma. Scopo della tesi è lo studio di alcune di queste tecnologie ricorrendo a una nuova famiglia di algoritmi di calcolo detti particellari perché discretizzano il plasma in un certo numero di macroparticelle campione sottoposte alle forze elettromagnetiche generate esternamente o dovute ai loro stessi moti e posizioni reciproche. Tali software saranno applicati allo studio di un nuovo fenomeno recentemente rilevato in laboratorio detto Helicon Double Layer (HDL), alla modellizzazione di due dispositivi (sorgente elicoidale e sistema di riscaldamento per risonanza ionica ICRH) e alla caratterizzazione e progettazione di diagnostiche per misure di plasmi.

L’HDL è un nuovo fenomeno recentemente misurato in laboratorio dall’ANU e l’LPTP. Si tratta di un improvviso e repentino salto di potenziale che si registra a valle di una sorgente elicoidale in presenza di un campo magnetico esterno divergente e una bassa pressione dei gas neutri. Il salto di potenziale è di 5-10 V ed è accompagnato da un flusso di ioni a bassa divergenza e con velocità assiale di due volte la velocità sonica ionica. In presenza di ioni elettronegativi inoltre il salto di potenziale si potrebbe presentare anche in assenza del campo magnetico. Questo fenomeno, se correttamente interpretato e riprodotto, potrebbe essere applicato per la realizzazione di propulsori spaziali.

Analizzando le pubblicazioni degli ultimi venti anni è possibile ritrovare esperimenti e studi teorici in cui simili fenomeni sono stati analizzati o proposti, spesso riconducibili alla propagazione e amplificazione di instabilità o onde generate dal plasma da particolari condizioni al contorno.

Lo studio eseguito fa uso dell’ Object Oriented Particle in Cell Code (OOPIC) un algoritmo particellare open-source prodotto dalla Berkeley University. Il software permette di definire diversi tipi di condizioni al contorno e dispone di risolutori elettromagneticì e elettrostatici. Ha una versatile interfaccia grafica e l’utente è in grado di introdurre svariate diagnostiche. Una indagine approfondita ha però mostrato l’inadeguatezza del modello ibrido, in cui gli elettroni sono considerati in continuo equilibrio termico, che avrebbe permesso di semplificare il modello.

Si sono realizzate quattro campagne di simulazioni: tre a densità via via crescente in modo da avvicinarsi ai valori sperimentali (non è stato possibile raggiungere la densità di plasma sperimentale perché avrebbe richiesto una potenza e di calcolo eccessivi) e un’ultima riproducendo l’ambiente spaziale esterno per poter valutare spinta e impulso specifico generati dal dispositivo. Le caratteristiche del plasma sono state definite il più possibile vicine a quelle sperimentali: temperature degli elettroni tra 4 e 9 eV, campo magnetico di 1.25 10^{-2} T nella sorgente e pressione dei neutrì inferiori a 0.26 Pa.

Durante la prima campagna di simulazioni si sono variate le principali condizioni al contorno: caratteristiche elettriche delle pareti e pressione dei neutrì. Utilizzando delle superfici dielettriche per riprodurre le pareti della sorgente elicoidale il potenziale elettrico del plasma crolla drasticamente. Pareti conduttrici posizionate a potenziali sufficientemente elevati permettono invece di ottenere dei salti di potenziale simili a quelli misurati in laboratorio; ciò accredita la interpretazione di Boswell secondo cui le pareti dielettriche della sorgente in determinate condizioni sarebbero in grado di caricarsi ad un potenziale fluttuante permettendo al salto di potenziale di instaurarsi. La densità dei neutrì si dimostra essere inversamente proporzionale all’ampiezza del salto di potenziale anche se non in modo così evidente come risulta dai dati sperimentali.

Durante la seconda campagna di simulazioni si sono variate le principali condizioni al contorno: caratteristiche elettriche delle pareti e pressione dei neutrì. Utilizzando delle superfici dielettriche per riprodurre le pareti della sorgente elicoidale il potenziale elettrico del plasma crolla drasticamente. Pareti conduttrici posizionate a potenziali sufficientemente elevati permettono invece di ottenere dei salti di potenziale simili a quelli misurati in laboratorio; ciò accredita la interpretazione di Boswell secondo cui le pareti dielettriche della sorgente in determinate condizioni sarebbero in grado di caricarsi ad un potenziale fluttuante permettendo al salto di potenziale di instaurarsi. La densità dei neutrì si dimostra essere inversamente proporzionale all’ampiezza del salto di potenziale anche se non in modo così evidente come risulta dai dati sperimentali.

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Fig R.2: Funzione di distribuzione degli ioni in funzione della loro velocità assiale all’uscita della sorgente elicoidale. Si evidenzia un picco per velocità circa 1.8 volte la velocità ionica sonica.

Fig R.3: Confronto di potenziali assiali di plasma per Te=9 e Te=5 eV (tratto).
La terza campagna di simulazioni ha avuto come scopo la riproduzione di scariche di plasma a maggiore densità (circa 10 volte inferiori a quelle sperimentali) in presenza di un elevato potenziale di plasma nella sorgente, imposto inserendo pareti conduttrici ad elevato potenziale. In queste condizioni la larghezza del salto di potenziale aumenta drasticamente differendo dai risultati sperimentali.

Simulando una camera di espansione di lunghezza doppia si è poi indagato il distacco del flusso di plasma dal propulsore e la spinta da esso generato, riproducendo ciò che dovrebbe accadere nello spazio aperto. La spinta valutata facendo uso di un metodo parametrico è compresa tra $10^{-9}$ e $10^{-8}$ N e l’impulso specifico intorno a 3000 s.

La sorgente elicoidale è un dispositivo di produzione di plasma che sfrutta la propagazione di onde elettromagnetiche in radiofrequenza. Un’antenna, posta attorno al tubo di materiale dielettrico che costituisce la sorgente, produce un segnale in grado di eccitare gli elettroni liberi contenuti nel gas e innescare un processo di ionizzazione ad elevata efficienza e del quale non sono ancora note tutte le cause. Esistono diverse tipologie di antenne tra le quali quella proposta da Boswell è una delle più efficienti. Un altro dispositivo simile che fa uso dell’interazione di onde elettromagnetiche questa volta per riscaldare e accelerare il plasma è l’ICRH. Intensamente utilizzato per esperimenti di fusione è attualmente in fase di studio come componente del VASIMR.

Per simulare un dispositivo di questo genere è necessario utilizzare modelli particellari elettromagnetici in grado, cioè, di calcolare l’effetto della propagazione di onde EM all’interno del plasma. Questi modelli sono molto più complessi di quelli elettrostatici utilizzati, ad esempio, per lo studio dell’HDL, principalmente perché necessitano di passi temporali e spaziali notevolmente inferiori per la loro convergenza. Infatti in tal caso è necessario soddisfare il criterio di Courant.

OOPIC, essendo un modello bidimensionale, può essere utilizzato nel caso di antenne a simmetria cilindrica, progettate cioè per eccitare il modo $m=0$ di oscillazione del plasma. I tempi di risoluzione sono però proibitivi. È’ possibile ricorrere alla versione del software da calcolo parallelo aumentando così la velocità di calcolo, ma i tempi necessari per realizzare simulazioni in grado di apprezzare l’intero fenomeno su scale di centinaia di µs rimangono elevati.

Per lo studio dell’ICRH si propone dunque un nuovo tipo di algoritmo che ricorre a semplificazioni sostanziali per la soluzione del problema in tempi ragionevoli. Un risolutore delle equazioni di Maxwell modella il plasma secondo la teoria di plasma freddo nota in letteratura. Si definisce un tensore dielettrico del plasma dal quale si ricava l’effetto di assorbimento e propagazione delle onde elettromagnetiche al suo
interno. Un algoritmo particellare verifica poi le traiettorie di alcune particelle campione sottoposte ai campi calcolati dal modello precedente e ricava la densità del plasma in ogni punto dell’area di simulazione, che costituisce l’input principale del risolutore di Maxwell. Gli algoritmi vengono utilizzati in sequenza fino a convergenza della soluzione.

Le simulazioni appena descritte possono essere di particolare utilità anche per la progettazione e la caratterizzazione di diagnostiche per plasmi. L’esperimento a cui fare riferimento è ora il test di un micro propulsore per applicazioni spaziali composto da una sorgente elicoidale che sfrutta il fenomeno del Double Layer, così come proposto da Charles. L’esperimento è in fase di sviluppo presso i laboratori del CISAS. I dispositivi più utilizzati per lo studio di plasmi per sistemi propulsivi sono le sonde di Langmuir e i Retarding field Energy Analyzer (RFEA). Entrambe sonde invasive, sono utilizzate per ricavare densità dei plasmi, temperature elettroniche e le funzioni di distribuzione degli ioni al loro interno.

Una sonda di Langmuir può essere simulata inserendo nel plasma una parete conduttrice a potenziale noto o variabile.

Il RFEA dispone di quattro griglie successive e di un collettore che registra una corrente dovuta al moto degli ioni nelle sue immediate vicinanze e che è funzione del potenziale della griglia discriminatrice, che ha cioè il compito di selezionare l’energia degli ioni in grado di attraversarla. Modificando posizione e forma del dispositivo è possibile, sotto approssimazione elettrostatica, verificare la corrente misurata dal collettore e ricavare l’output che il RFEA fornisce e dal quale calcolare le proprietà del plasma in ingresso allo strumento.
Per rispondere alle esigenze di ridotto ingombro del nuovo esperimento è necessario ricorrere ad un disegno compatto e il più possibile semplice e versatile. Lo strumento in corso di realizzazione è composto da strati successivi di materiali isolanti e conduttori, allumina e rame o acciaio. Le rondelle dielettriche sono dotate di apposite scanalature per permettere il passaggio dei contatti elettrici. Al centro di ogni rondella conduttrice è poi saldata una griglia di nickel composta da fili di 20-30 µm di diametro (tipicamente utilizzate per microscopia elettronica). La distanza tra le griglie deve essere dell’ordine della lunghezza di Debye del plasma che per scariche di densità dell’ordine di Ni~10^{15} m^{-3} è inferiore a 1 mm. L’involucro esterno è composto da un tubo di acciaio del diametro di circa 18 mm al quale è avvitato un tappo dello stesso materiale che in questo modo provvede all’assemblaggio delle rondelle per compressione.

Con riferimento alla figura R.8, la prima rondella che compone lo strumento è in acciaio (A) e al suo centro è praticato il foro di ingresso del plasma di 1-2 mm di diametro provvisto di una prima griglia di nickel. Rondelle indicate con la lettera B sono composte di allumina mentre le rondelle C sono in rame. Le rondelle conduttrici sono dotate anch’esse di griglie per il passaggio del plasma all’interno del loro foro centrale e ciascuna di esse è contenuta all’interno di un anello di allumina così da provvedere al loro isolamento elettrico. Il collettore è realizzato in rame e non presenta il foro centrale per il passaggio del plasma. L’ultima rondella (D) è nuovamente in acciaio e realizza l’assemblaggio dello strumento per compressione, premendo sull’involucro esterno di acciaio.

Fig R.7: Posizione degli ioni dopo 0.5 µs per un RFEA a 3 diverse distanze di griglia: 0.37mm (a), 0.625 mm (b) and 0.83 mm (c)
Fig R.8: Disegno del RFEA proposto per l’esperimento del Micro Helicon Thruster al CISAS. Lo strumento è composto da rondelle alternate di acciaio (A e D), allumina (B) e rame (C).

Fig R.9: Modello complessivo del RFEA per l’esperimento del Micro Helicon Thruster. Le connessioni elettriche sono ricavate saldando dei fili di rame schermati ai contatti a “L” delle rondelle conduttrici, che si richiudono verso il centro dello strumento subito dopo il collettore.
INTRODUCTION

New frontiers of space exploration impose high performance thrusters. Next generation missions have as targets the exploration of external Solar System and human flights to Mars, these goals could not be totally achieved by actual technologies. An interplanetary spaceship has to be fast and it should have several abort options for crew safety. The travel duration must be minimized in order to reduce risks like the crew's exposure to radiation and weightlessness. Short transfer trajectories can be obtained only with high thrust and high power and fast exhaust fluxes reduces the fuel consumption and therefore the total thruster’s weight. Future engines will accelerate the plasma propellants by using electric or electromagnetic fields, reaching high exhaust velocities and thrust. Their high efficiency and versatility will be beyond the possibilities of the present chemical rockets and electric propulsors. Two key technologies have to be developed to obtain such results: nuclear electric generators designed and qualified for space and versatile high power plasma accelerators with a long life-time.

Some of the most promising thrusters presently under evaluation use electromagnetic waves to ionize and accelerate plasmas. The VASIMR (Variable Specific Impulse Magneto-plasma Rocket) thruster follows this way. Several are the advantages: high ionization rate, absence of electrodes corrosion, possibility of high power scaling. The VASIMR thruster is developed and studied by NASA at the Johnson Space Flight Centre (JSC).

Another class of systems came from recent experiments that have shown a phenomenon which could be used as a new thruster technology: the Helicon Double Layer (HDL). The main team involved in the HDL studies are the Australian National University (ANU) and the Laboratoire de Physique et Technologie des Plasmas of the Ecole Polytechnique Paris (LPTP). Further studies have been sponsored by the European Space Agency (ESA) of which this thesis is part.

The present work has been motivated by the intention to gain experiences on the simulations of such innovative plasma devices for space propulsion and the characterization of probes for their laboratory analysis. In particular a mathematical model has been utilized which has gained importance during the last decade due to the increase of the computers’ power: the particles method. The thesis has been divided in three chapters.

The first and main part of the activity concerns the HDL. Helicon is a very efficient plasma source. It is composed of a dielectric tube, surrounded by a helical antennae which ionizes the gas with its radiofrequency waves. In particular conditions a dip potential step forms just downstream the helicon tube and there a energetic ion beam has been measured. The HDL has been measured only for particular geometry, density and external magnetic field configurations.

At this stage the research goes following two main directions: laboratory experiments and computer simulations. The space environment is reproduced inside vacuum and thermal controlled chambers. The measurements are analyzed and reproduced with numerical simulations in order to test end evaluate the experimental data. The plasma parameters obtained with experiments need then to be interpreted, when the physics of the phenomenon is under discussion.

The first chapter investigates the HDL phenomenon and its applicability as space thruster. Here the first paragraphs are a brief review of the theoretical and experimental understanding of the phenomenon, made to introduce the problem. The successive section describes OOPIC (Object Oriented Particle In-Cell), a software for plasma simulations developed by Berkeley University and maintained by Tech-X Corporation, and its application to the HDL analysis. OOPIC is a innovative open-source system for two-dimensional particles simulations which has been carefully analyzed and tested verifying its performances and features like the hybrid electrons code and the software parallelization on clusters.

The simulations of the HDL investigate the plasma behaviour for different boundary conditions to analyze when the potential jump forms and which are its characteristics. Finally the device has to be simulated in space conditions evaluating the thrust and specific impulse obtained. This is one of the main output of the work, because from that one can argue the performances of this class of thrusters.
While electrostatic phenomenon, like HDL, allow a relevant simplification of the models, full electromagnetic phenomenon require more complicated algorithms because more physics has to be attained. The second chapter describes studies of electromagnetic plasma devices where plasma production, heating and acceleration happen by electromagnetic waves absorption. The PIC paradigm is here applied to the reproduction of a helicon source. Successively a new technique is proposed for the second section of the VASIMR system, devoted to the plasma heating and acceleration.

The third and last chapter describes the design and characterization of a plasma diagnostic for the Helicon Micro Thruster experiment under construction at the CISAS laboratory. The intention is study and reproduce the physics that are behind invasive systems like Langmuir probe and Retarding field Energy Analyzers under the geometry and boundary conditions of our device. The invasive probes are the most versatile and utilized systems to detect the particles temperature and distribution functions. Simulations are here essential to interpret the probes output and characterize the plasma. The probe interference on the plasma which affects the measurements must also be analyzed and subtract to their results. The most used probe to analyze the plasma discharge and detect particles fluxes like during the Helicon Double Layer experiments is the Retarded Energy Analyzer. It consists of successive grids biased at constant electric potentials that select the ions flux and its current. The best probe minimize its dimensions, therefore its interference on the plasma, and maximize the resolution.
Chapter 1

ELECTROSTATIC SIMULATIONS OF THE HELICON DOUBLE LAYER

1.1 HELICON DOUBLE LAYER CURRENT UNDERSTANDING

1.1.1 INTRODUCTION

The helicon double layer has been first reported by Charles and Boswell [6-9,31]. Successively some research groups have reproduced their results [22,23,24] while, analyzing older plasma experiments, one finds that similar conditions were met by other authors [5,19], under different conditions and with partial or original interpretations of the phenomenon.

This section exposes the actual theoretical understanding of the Helicon Double Layer formation processes and the experimental results.

1.1.2 DOUBLE LAYER

Double-layers (DLs) are electrostatic structures able to support a potential jump in a narrow spatial region of plasmas. DLs have been studied intensively interpreting and reproducing magnetospheric, solar and extragalactic plasma phenomena [1,2]. The motions of charged particles determine the internal structure of a DL and, by the net charge distribution, its electric field. In the most general DL structure both free and reflected electrons and ions are required (Figure 1.1).

FIG 1.1: Double layer structure. Left: charge density distribution gives the electric field; incoming particles are reflected or accelerated depending on their charge, velocity and side of entry. Right: areas of phase space occupied by populations of ions.
The electric field acts as a barrier for the reflected particles while the accelerated ones emerge downstream as energetic beams. The current is carried by the free particles. Usually DLs studied by laboratory tests and theoretical models require an electron current or an external imposed electric field. Sometimes their formation is ascribed to evolution of plasma instabilities.

The most used way to determine the structure of a DL is the Sagdeev or Classical Potential method. Solution of the Vlasov equations

\[
\frac{Df_{i,e}}{Dt} = \frac{\partial f_{i,e}}{\partial t} + v \frac{\partial f_{i,e}}{\partial x} + \frac{q_{i,e} \cdot E}{m_{i,e}} = 0 \tag{1.1}
\]

are determined by defining the ions and electrons distribution functions to be functions of the energies \(w_{i,e} = \frac{1}{2}m_{i,e}v^2 + q_{i,e}\phi\), which are integrals of the motion. The particles densities are obtained by integrating the distribution functions over velocity, so they depend only on the electric potential. Poisson’s equation

\[
\varepsilon_0 \frac{d^2 \phi}{dx^2} = -\left[q_i n_i(\phi) + q_e n_e(\phi)\right] \tag{1.2}
\]

can be integrated once assuming \(V(\phi) = \int V(\psi) \cdot d\psi\) (the Sagdeev potential) and giving

\[
\frac{1}{2} \varepsilon_0 \left(\frac{d\phi}{dx}\right)^2 + V(\phi) = \Pi = \cos t \tag{1.3}
\]

Formally the integral may be regarded as the energy of a fictitious particle located at position \(\phi\) where the time is given by \(x\).

The matching conditions between DL and the ambient plasma require that the net charges and the electric field at the edge of the DL tend to zero. These conditions ensure that the plasma in contact with the DL is shielded from the internal structure of the DL and hence undisturbed. In terms of the Sagdeev potential this means:

\[
V'(0) = V'(\phi_{DL}) = 0 \quad V(0) = V(\phi_{DL}) = \Pi \tag{1.4}
\]

Then from (1.2) \(V(\phi) < \pi\) everywhere inside the DL. These existence criteria require that the Sagdeev potential has two equal maximum at \(\phi = 0\) and \(\phi = \phi_{DL}\) and, in terms of the fictitious particle interpretation, the solution may be regarded to a particle starting at rest at one of the maxima, rolling down the potential \(V(\phi)\) and then upward coming to rest at the other maxima.

### 1.1.3 CURRENT FREE DOUBLE LAYER

Double Layers have generally appeared to require a relative electron-ion drift but some experiments, computer simulations and theoretical studies have shown the possibility of low amplitude potential drops with little or no plasma currents. Since they may be related to electrostatic plasma modes they are termed ion-acoustic double layers and slow ion-acoustic double layers by Raadu in his monumental work [2].

One of the first study of this sort was reported by Sato [13] more than twenty years ago, simulating double layers along the auroral field lines, where the electron drift velocity was supposed much lower then the thermal one. He studied ion-acoustic instabilities by performing one-dimensional particle simulations and
considering a long system with Maxwellian electrons with low drift velocity. Then he found that, no matter how small, the starting dc potential associated with the instability, became high enough to accelerate electrons and be enhanced by a sort of bootstrap processes. Double layers were generated when the system was long enough and they became stronger as the system length became longer. This process required that the anomalous resistivity, associated with the ion-acoustic instability, persisted by the time the double layer was formed. The final current was only a tiny fraction of its original value and the resistivity was negligible. The DL potential jump was comparable to the electron thermal potential and it required a system with a fundamental length of about $10^3$ times the $\lambda_d$ (Debye Length) to form. A negative potential dip at the low potential side was seen to be associated to this type of DL which, for that, does not have a monotonic shape.

Successively Perkins [3] demonstrated the possibility for current-free DL, solving the Vlasov-Poisson equations. The key to obtaining these solutions was to recognize that electrostatically trapped ions can exist on the double layer’s low-density, low-potential side. The density of these trapped ions, together with the magnitude of the potential drop, provided the two parameters that were sufficient to satisfy the criteria for double layer formation: quasi neutrality of the low potential side and zero total charge in the double layer (zero electric filed at the borders). The electron distribution function was Maxwellian everywhere and it was shown that without trapped ions it would be impossible to satisfy the double layer conditions. These type of DLs have a monotonic potential function, without the negative potential dip reported by Sato, and they have been defined elsewhere as slow ion-acoustic or currentless.

A similar analytic evidence of small amplitude monotonic double layers was then expressed by Kim [14]. A two temperature Maxwell-Boltzmann electron distribution function was assumed, while the ions function was drawn with trapped particles distribution shaped as a hole: have a minimum for zero velocity. Then, again imposing charge neutrality and zero electric field at the borders (equations 1.3), the author obtained the electric potential. The solution did not require a discontinue trapped-particle distribution and could exist with an ion drift velocity lower than the electron thermal velocity, so compatible with the simulations of Sato.

Chan, few years later, made experiments in his triple-plasma device were ion-acoustic [5] and slow ion-acoustic [4] DLs, similar to the Perkins solutions, were found. If we exclude some controversial observations in the auroral plasma [10] this is probably the first time that such DLs were measured. The device consisted of two source plasmas bounding a target plasma, where potential and density could be varied separately. Five grids were used to separate the target plasma from the sources and pulsing one of them an electron drift was produced, exciting an ion-acoustic wave. The double layer was found to evolve from a virtual cathode potential well at the electron injection boundary, born to limit the injection of unneutralized electrons into a collisionless plasma. The potential well evolved in a stable DL of length $50/60\lambda_d$ after about 500\,$\mu$s. The current-limiting nature of these double layer, the measured properties of $\phi/T_e \sim 1$, the propagating velocity near the ion thermal velocity and the small drift velocity associated them with the currentfree, currentless or slow ion-acoustic DL type previously reported.
More recently a current-free DL was found by Hairapetian [19]. The plasma, made by a filamentary cathode, expanded under a weak axial magnetic field producing a current-free DL. In this case after its production the DL propagated along the magnetic field, it slowed down in 1-2 hundreds μs and then it evolved in a steady-state current-free DL.

The physical interpretation was that few energetic electrons, directly produced by the plasma source (Figure 1.4), realized a space charge potential that trapped the colder ones. In fact the source produced a non-Maxwellian electron distribution, composed of a Maxwellian plus an energetic tail. The expansion front propagated along the vacuum chamber at a velocity near the ion sound speed, until it reached the stable configuration. The importance of the high-speed electrons on the DL formation was proved deflecting their trajectories with a permanent magnet and changing the end-plate potential allowing the collection of more electron current: the DL became weak or didn’t form. The steady-state DL position and amplitude changed with the ratio of the two electrons families’ densities: highest tail density increased the potential jump and moved it upstream.

Two distinct electron temperature were measured upstream and downstream the double layer and a supersonic ion beam was measured on the low-potential side, which disappeared increasing the chamber pressure.
1.1.4 HELICON DOUBLE LAYER

As partially anticipated by Hairapetian, the plasma expansion in a weak magnetic field can form a stable current-free DL. Charles and Boswell have first shown the existence of a similar phenomenon for helicon discharges along a diverging magnetic field [6-9]. Their experiment then has been reproduced by Sun [21,22] and Cohen [20] with some differences. Successively the helicon double layer has been reported by Plihon [28] in a similar reactor but using an electronegative mixture and without magnetic field.

In a recent paper Fruchtman [25] has analyzed the “double layer” electric and magnetic fields configuration. It is shown that the net momentum delivered by the large electric field inside a one-dimensional double layer is zero. Considering a double layer in a current-free plasma expanding along a divergent magnetic field, an
analysis of the evolution of the radially averaged variables shown that the increase of plasma thrust results from the magnetic-field pressure balancing the plasma pressure in the direction of acceleration, rather than from electrostatic pressure.

The Charles-Boswell experiment consisted of a horizontal helicon system composed of a 15 cm diameter helicon source (31 cm long cylindrical glass tube terminated with a 0.5 cm thick glass plate and surrounded by an 18 cm long double-saddle antenna) is attached contiguously to a 30 cm long 16 cm radius earthed aluminum diffusion chamber. The antenna operated at 13.56MHz providing a plasma column, which expands in the vacuum diffusion chamber along an axial diverging magnetic field (Figure 1.7 and 1.8). The gas could be introduced on the side of the chamber or at the closed end of the source. Deeply changes in the plasma potential have been reported just inside the source, accompanied by a dip in its density (Figure 1.9). The potential drop is around 25V. The typical experiment conditions were: chamber pressure 0.04Pa (0.3mTorr), axial magnetic field in the source center 0.015 T, radio-Frequency power between 250 and 800W, gas Argon or Hydrogen.
In some ways the plasma expansion, associated with an axial diverging magnetic field and low chamber pressures, evolved to a stable current-free DL. Comparing the floating plasma potential of two pulsed discharges, with and without DL, its formation was found during plasma break-down, during the first 100μs (when high energy electrons are present). For a stable DL pressure had to be below 0.13Pa (1mTorr), while the magnetic field along the source had to be higher than 0.0125 T.

Axial ion energy distribution function (IEDF) measurements have been done just downstream the source-chamber connection (z=37cm); they showed a function with two peaks (29 and 47V, Figure 1.10), the second representing a supersonic ion beam at

$$v_{beam} = \sqrt{\frac{2e(V_{beam} - V_p)}{m_i}} \approx \sqrt{\frac{2e \cdot (47 - 29)}{m_i}} \approx \sqrt{\frac{4.5 \cdot kT_e}{m_i}} \approx 2.1 \cdot c_s$$

where $c_s=\sqrt{\left(\frac{kT_e}{m_i}\right)}$ is the ion-sound speed and considering $T_e$, downstream the double layer, around 8eV (9eV for hydrogen discharge).

The second peak cannot be seen during the “non DL” experiment: higher chamber pressure 0.17 Pa, lower magnetic field 0.01T (Figure 1.10). The axial ion energy distribution function measurements (IEDF) were interpreted as the collection of two families of ions: one with density $n_s$ and velocity $c_s$, the second, $n_{beam}$ and $v_{beam}$, was accelerated by the DL. Comparing the two data the beam density has been evaluated as: $n_{beam}/n_s=0.15$ for Ar and 0.17 for H, but higher beam densities were successively reported reducing the source length. In that case a movable glass plate was inserted in the source at $z=2$cm so at the maximum of the magnetic field at the source’s closed end (Figure 1.11) [31]. The potential drop remained approximately constant while the ratio between the beam density and the downstream density was increased from 0.15 to 0.5.

For pressures below 0.25 Pa high potentials have been measured in the middle of the helicon source (Figure 1.11), while an energetic ion beam is detected in the diffusion chamber, an indirect evidence of the double layer.

The experiment has been reproduced reducing the magnetic field near the closed end of the source [31]. As can be seen in Figure 1.12 low values of the first solenoid currents, corresponding to lowest magnetic fields, did not show the double peak distributions typical of the double layer.
The ion beam was detected near the source radius ($r<6.8\text{cm}$) and its divergence very low. In other words, no ion acceleration was seen near the chamber wall. The ion beam appears as a plasma column. It also means that the diverging magnet field does not have big effects on the ion beam and DL acceleration process. Figure 1.13 shows the ions’ energy functions and density ratio calculated across the chamber radius at $z=37\text{cm}$, far downstream the double layer. Similar results were described by Sun: ion flow velocity did not change varying the chamber magnetic field strength and source frequency.
Fig 1.11: Left: plasma potential in the source, ion beam energy, chamber and double-layer potential drop as function of gas pressure. Right: ion energy distribution functions with (dotted) and without (solid) the addition of a second glass plate at z=2cm

Fig 1.12: Left: axial components of the static magnetic field measured along axis for different solenoid currents near the closed end of the source. Right: ion energy distribution functions for those magnetic field configurations.

It is important to stress that Langmuir probe data near the closed end of the source (z=3cm) were compatible with the presence of an electrons beam. The data have also been considered consistent with some charging of the source walls.
It has to be noted also that the DL was located close to the source-chamber diameter change, so near the highest value of the magnetic field, and its thickness was less than 1 cm (about 50 $\lambda_d$).
Boswell, at the end of his papers, suggested some important hypotheses:

1. The condition for DL existence came from the electrons dynamic
2. The DL formation should happen during the first 100μs of the discharge, when high-energy electrons are important
3. The source walls should be allowed to charge.

Results similar to the Boswell experiments have been obtained by the Ecole Polytechnique de Paris and reported by Plhon [23,24] (Figure 1.14 and Figure 1.15). Early work by this group has shown that DLs can form without a magnetic field when traces of electronegative plasmas (SF₆) are mixed in with electropositive ones (Ar). As previously reported [30] for radio-frequency sources, helicon electronegative discharges are subject to transport instability, occurring downstream when a sufficiently long expanding chamber is present. The instability has been interpreted as a DL formation and propagation at a velocity around 150 m/s (near ion thermal velocity). The double-layer formation frequency and the propagation speed are such that the first double layer had not reached the bottom of the diffusion chamber when a new double layer formed upstream (Figure 1.15).

The DL formation requires a certain fraction of negative ions. For negative ions concentrations between 8 and 13% the DL was stationary, at the source-chamber interface. The stable DL separated high-density low-electronegative plasma upstream from a low-density high-electronegative downstream and the minimum required power increased increasing neutral pressure. Electrons were near the Boltzmann equilibrium both upstream and downstream.

It is important to remember that the DL formed also when no chamber-source diameter discontinuities were present.

Figure 1.13 shows some experimental results. The electronegative mixture produces a strong reduction of electron density that, in some way, could reproduce the diverging magnetic field plasma conditions of the Charles experiment.
The same authors have also reproduced the Charles approach [28] reporting some important considerations (see figure 1.18):

- minimum magnetic field required for the DL formation is around 45G
- DL amplitude is independent of the magnetic field, as plasma and beam potentials, but may vary with the field gradient
- pressure has to be below 0.4 and above 0.01 Pa (below 3 and above 0.1mTorr)
- DL amplitude and beam flux increase decreasing pressure
- DL amplitude remains almost constant increasing antenna power while plasma and beam potential decrease
- beam density slightly increases with power, but not at the same rate of plasma density

Fig 1.14: Plihon experiment: electronegativity and potential; electron temperatures

Fig 1.15: Plihon experiment: particles densities and mapping of the plasma potential, showing the propagation of the unstable double layer
It appeared that the position of the glass tube in the Charles’ experiment plays an important role in the beam amplitude [31]. To evidence the effects of the source wall geometry, three configurations have been tested, showing some differences on the beam potential (Figure 1.17). The peaks amplitudes decreased by a few percent from geometry (a) to geometry (c), the local plasma potential decreased (26.5, 25.5 and 24.5 V), while the beam potential increased (42.5, 44.2, 46.5 V) for geometry (a), (b) and (c) respectively. However
the broadening of the peaks slightly grew when scanning from geometry (a) to geometry (c), with significantly differences from those published in [31].

The double layer was found for all boundary conditions, including the dc connected (condition a) case, but its amplitude changed noticeably with the boundary conditions: the higher DL amplitude was obtained for the floating conducting grid (16 V case a, against 22 V for condition c). It has to be noted that the system was operating with the pump at the closed end of the source tube, so with a different geometry respect the Charles’ experiments.

Fig 1.18: Main results of the Plihon [28] reproduction of the Charles’ experiment.
1.1.5 CHEN STUDIES

A different theoretical explanation of the phenomenon first reported by Charles has been proposed by Chen [18]. He wrote that the so-called double layers are in fact the result of a sheath instability connected with the Bohm criterion. Diverging magnetic field lines cause presheath acceleration of ions, causing a potential jump resembling that of a double layer. To demonstrate his hypothesis he has considered the classical sheath theory, normally applied to boundaries, with only one assumption, that of Maxwellian electrons:

\[ n_e = n_0 \cdot e^{-\eta} \quad \eta = -\frac{eV}{kT_e} \]  

(1.6)

When \( \eta = 1/2 \) the Bohm criterion is satisfied: the ions, assumed cold, will have fallen through a potential of \( \frac{1}{2} kT_e/e \) and thus achieved a speed of \( (kT_e/M)^{1/2} = c_s \). The ions cannot be accelerated much further since, in the absence of a biased electrode, there is no energy source to drive them. The ions will have a density that falls more slowly than that of the electrons as \( \eta \) increases further, and the quasi-neutral solution becomes unstable. A further increase in \( z \) causes \( n \) to drop and \( \eta \) to increase. With \( n_i > n_e \), \( V''(z) \) drops rapidly, and an ion sheath must form, even in “mid-air”. This occurs at a position where \( n/n_0 = e^{-1/2} \). Thus, considering a plasma frozen to the field lines, where the field \( B(z) \) and the density \( n(z) \) in the expansion region are related to the plasma radius \( r \) by \( B/B_0 = n/n_0 = (r_0/r)^2 \), it happens when the plasma radius has expanded by 28%.

Normally in sheath theory, the ion energy of \( \frac{1}{2} kT_e \) is gained in a presheath field, whose extent is governed by collisions and ionization and is therefore specific to each plasma discharge. The author supposed that in the Charles experiments the plasma expansion has taken the place of the presheath in accelerating ions to the Bohm velocity, even in collisionless plasma conditions. As \( n_i \) and \( n_e \) separate, quasi-neutrality is broken, the sheath builds up until it reaches the floating potential which imposes the forward fluxes of ions and electrons to be equal; at this point a current-free single layer is formed.

1.1.6 MEIGE SIMULATIONS

1D-PIC simulations have been made by Meige and Boswell [16] as shown in Figure 1.19. Two separated parts took care of plasma heating and expansion. The left wall is allowed to charge while the right one is grounded, in order to reproduce the experimental setup and impose the current absence. The heating process, in the first half of the model, did not solve the field equations: an oscillating electric field of 10MHz was applied, orthogonal to the PIC axis and evaluated by finite difference method. This simplified approach reduced the computational time. If \( J_0 \) is the current density amplitude (around 100A/m²), \( v_{e,y,i} \) the orthogonal velocity of the \( i \)-th electron inside the source, \( L \) the source length and \( N_e \) the weight of a macroparticle per square meter:

\[
J_{\text{tot}} = J_0 \cdot \sin(\omega_0 \cdot t) = e_0 \frac{\partial E_y}{\partial t} + e \Gamma_{e,y} \quad \Gamma_{e,y} = n_e v_{e,y} = \frac{N_e}{L} \sum_{i,source} v_{e,y,i} 
\]  

(1.7)

\[
\frac{\partial E_y}{\partial t} = \frac{1}{e_0} \left[ J_0 \sin(\omega_0 t) - \frac{eN_e}{L} \sum_{i,source} v_{e,y,i} \right] 
\]  

(1.8)

After demonstrating that this heating process did not produce any particular effect on the plasma potential at low pressure (even if different source positions and dimensions were considered) they started to study the plasma expansion. This was modeled with a routine that removed particles with a given loss frequency function. Different loss frequency functions have been used, those are null in the source and have a maximum at the beginning of the expansion or few centimeters after it. The DL formation has been reported
Most of the electrons were Maxwellian (both upstream and downstream) and in Boltzmann equilibrium \( n = n_0 \exp[-e\phi/kT_e] \) also within the DL. Two population coexisted: colder downstream (3.9eV) and warmer upstream (5.2eV) (for the Tab1 case). No electron beams were reported upstream the DL. The ion beam is accelerated downstream to twice the sound speed.

The study of the DL formation has shown that:

- The simplified heating model does not affect the potential jumps for low pressures
- Both the profile and amplitude of the loss function are critical for the DL formation
- The DL is current-free if the source wall is floating in potential
- DL position and potential jump are not affected by the right grounded wall position
- The potential drop reduces increasing the gas pressure

A paper describing a two dimensional simulations of electronegative plasmas has been recently presented by the same authors [17]. The computer code assumed Boltzmann electrons while both, positive and negative ions were treated as particles. The simulated space has been divided into two regions, the source and the diffusion chamber. The effects of the ionization, attachment and recombination profiles are studied with respect to the formation of the double-layer. Electric double-layers (DLs) are formed in the expanding region of the electronegative plasma. Different regimes have been found: from a non double-layer state to a stable double-layer state, via an unstable double-layer state depending on the different coefficients that have been used to reproduce ionization, attachment and recombination in the source and expansion regions. The results agree with the Plihon measurements.
1.1.7 IONS DETACHMENT

The expanding magnetic field, produced by the solenoids, creates a “magnetic nozzle” which influences the shape of the ion beam as it expands into space, giving the beam divergence and thereby affecting the net thrust. In the extreme case no thrust will be provided, where the magnetic-field intensity is high enough and the charged particles exiting the nozzle will be attached to the closed magnetic-field lines returning to the flight vehicle. A charged particle is unmagnetized if its trajectory has zero curvature. At that point the ion is totally detached and it provides thrust pushing not only against the vacuum magnetic field but also against the double-layer electric field, as it flows out of the nozzle volume. The net thrust generated over time depends upon these reaction forces.

Simulations of the ions detachment from the helicon double layer has been made by Gesto and Blackwell [15]. The authors reproduced ions trajectories imposing an analytic diverging magnetic field and a stable orthogonal potential difference near the magnetic field maximum. The simulations have been guided by the experiments, where the low divergence of the ion beam downstream of the electric double layer suggests that the ion beam is well neutralized and that a transport mechanism exists that allows the electrons to follow the ions. It was not believed that the electron motion can change the trajectories of the ions substantially so the authors have investigated only them, remembering also that the momentum carried by the ion beam provides the main source of thrust and is directly measurable in the laboratory experiment. In reality, the faster transport of electrons along the magnetic field lines, because of their smaller mass, will set up an ambipolar electric field that will allow the high-energy tail of the electron distribution to drift toward the ions. In fact the neutralization of the ion beams by electrons cannot be simply explained by linear fluid or particle dynamics and it is still an active area of research.

For the purpose of the study the arbitrary detachment point for an orbit on the beam cross section has been defined as the point on the orbit of maximum curvature. Past this point, the centrifugal force provided by the magnetic field begins its asymptotic approach to zero. The results shown that the ion beam detaches from the magnetic field and that the simulated flow has a small angle of divergence, which increases radially in the direction of magnetic-field curvature. The geometry of the simulated beam in the detachment region was in substantial agreement with laboratory measurements.

1.2 DEFINITION OF THE MODEL

1.2.1 INTRODUCTION

The Particle-In-Cell algorithm (PIC) [10] is a popular way to solve the coupled Maxwell-Vlasov equations. The Maxwell equations are solved on a discrete grid and at discrete times. The Vlasov equation for each charged particle species is solved by aggregating a large number of physical particles into numerical macroparticles, which are advanced by solving their time-discretized equation of motion. The particles acceleration follow the Lorentz force \( F = q(E + v \times B) \). The macroparticles move in contiguous space and the Lorentz force is found by interpolating the fields between discrete gridpoints. The velocity moment of the solution to the Vlasov equation provides the current closure to the Maxwell equations. Practically this is done by current weighting, basically an inverse interpolation where the current at the particle location is distributed between surrounding gridpoints of the discretized fields. The PIC algorithm structure is illustrated in Figure 1.20.
The great advantage of PIC is that it provides a first-principles, detailed model of low-collisional plasmas, including nonlinear effects. The disadvantage of PIC is that it is computationally demanding due to strict limitations on cell size (spacing between gridpoints) and timestep. If the Debye sphere is not resolved, spurious, numerical grid heating will increase the particle temperature until the Debye sphere fills the cell. The timescale of this process is a few dozen plasma periods. Several limits are imposed on the timestep. If the standard PIC field solver, the explicit Yee solver, is used a Courant condition is imposed on the timestep. The Courant condition demands that the fastest mode that satisfies the Maxwell equations (light waves) does not cross a cell in a single timestep. As will be discussed below, the Courant condition can impose a severe limitation on the timestep. The Courant condition can be avoided by using an implicit field solver or if the electrostatic approximation is valid.

Implicit field solvers are considerably harder to implement than the explicit Yee solver. Also, to our knowledge no implicit field solver exists that can handle as general boundary conditions (time-dependent Dirichlet, etc.) as Yee and still have the same good convergence properties (second-order accurate in both space and time).

If the electrostatic approximation is valid, Maxwell’s equations can be replaced by the Poisson equation, which is independent of time and therefore is not subject to a Courant condition. Even without a Courant limit, the particle advance has its own timestep limitations. If the standard leapfrog or Boris particle advances are used, both the gyromotion and the plasma oscillation (Langmuir wave) must be temporally resolved. If the gyration is not relevant for the physics under study, it can be removed by using drift kinetic particles. Similarly, if the plasma oscillation is irrelevant, it can be suppressed by an implicit particle advance.

In some cases more drastic simplifications can be made. E.g., on electron timescales, the ions can sometimes be treated as immobile (and ambipolar effects neglected). For slow phenomena it is sometimes sufficient to use fluid electrons. However, one should be careful not to exclude relevant physics by using too simplistic approximations. For example, some physical processes such as air breakdown phenomena involve energy distributions that are partially Maxwellian but include a long, high energy tail. The particles in the high-energy tail are those responsible for the majority of interactions that lead to a qualitative change in physical behavior. Thus, a fluid description that neglects the high-energy tail fails to capture the physics of interest. A hybrid plasma description simultaneously employs the fluid and PIC treatments, which has the potential to capture the relevant physics in a tractable computational time.

Developing a consistent way to divide the simulated plasma into fluid and particle portions is one of the most complicated aspects of this approach. Several details need to be considered. Most importantly, the distinction between the fluid and particle descriptions is not a physical one, but rather a computational necessity. As such, it is crucial that dividing the plasma into two separate populations does not introduce any spurious observable behaviors in the physics. The mechanism for exchanging particles into fluid (and vice versa) must be seamless enough that it does not affect the global properties of the plasma. Besides, the fluctuations in density, pressure, and temperature in the fluid must affect the dynamics of the PIC particles in exactly the same way as if those fluctuations had occurred in a purely PIC model. In the special case where the density contained in the fluid is significantly greater than the density in the particles, it may be a good approximation to neglect these fluctuations in the PIC particles.
Another important priority in the development of a useful hybrid model is to determine the optimal way to divide the plasma. An appropriate criterion must be found for the exchange of PIC particles with fluid density. It is important to treat as much of the plasma as possible with the fluid model, since this minimizes computation time. On the other hand, if the decision criterion is computationally expensive, it would not be sensible to perform the particle-fluid exchange in every time step. A balance must be found between the time saved by moving particles into the fluid and the time spent deciding whether the particles can be moved without sabotaging the accuracy of the simulation. The standard PIC algorithm neglects collisions. To allow simulations of low-temperature plasmas, where collisions with neutrals play an important role, PIC has been extended with Monte-Carlo collisions. The direct simulation Monte Carlo (DSMC) method models the collisions of the heavy particles (ions and atoms) while the Particle In Cell (PIC) method models the transport of the ions in electric fields.

1.2.2 OOPIC MAIN FEATURES

The adopted code is OOPIC (or XOOPIC, which has a GUI), both of them are opensource from Berkeley (University of California). OOPIC (Object-Oriented Particle-In-Cell) is a 2D-3V relativistic electromagnetic PIC code. The object-oriented paradigm provides an opportunity for advanced PIC modelling, increased flexibility, extensibility and efficiency [1]. One of the principal advantages of the object-oriented method is the potential for rapid extension and enhancement of the code, adding algorithms to extend it to model a new phenomenon or adjusting an existing model. The X11 version, XOOPIC, uses the XGrafix package and some additional diagnostics can be added without recompiling the code. The applicability of this code ranges from plasma discharges, such as glow and RF discharges, to microwave-beam devices.

Researchers around the world have used the OOPIC physics kernel since 1995 to simulate a wide range of challenging problems. These include plasma display panels, ion implantation, high-power microwave devices, advanced particle acceleration concepts, and many other systems. OOPIC includes 2-dimensional orthogonal grid: cartesian (x,y) or cylindrically symmetric (r,z) and moving window, 2D x-y (slab) and r-z (cylindrical) models, electrostatic and electromagnetic fields, and relativistic particles. The boundaries can be determined at runtime and include many models of emitters, collectors, wave boundary conditions and equipotentials. Because the dependence on the azimuthal angle is not expected to be relevant for DL experiments, we can use a 2D r-z cylindrical PIC simulation. The OOPIC code [1] fits this and most other of our requirements. The code can handle an arbitrary number of species, particles, and boundaries. It also includes Monte Carlo collision (MCC) algorithms for modelling collisions of charged particles with a variety of neutral background gasses, including such effects as ion/neutral charge exchange, elastic electron scattering, inelastic scattering due to electron impact excitation, and electron impact ionization. OOPIC can also simulate field-induced tunneling ionization of selected neutral gasses and charged macro-particles. The particles follow the relativistic equations of motion in electric and magnetic fields, generating a source current for the field equations. OOPIC employs the relativistic time-centered Boris advance. The object-oriented methodology is employed ranging from the physical device to the mathematical model, and finally to the discrete model for simulation. The mathematical model may divide the device into various regimes with different physical properties, which are best described with heterogeneous sets of equations. XOOPIC permits to use parallel and distributed processing to optimize the simulation of large problem. It may use parallel libraries such MPI (Message Passing Interface).

1.2.3 OOPIC DIAGNOSTIC TOOLS AND OUTPUT

OOPIC can work with its Graphical User Interface (GUI) which permits to display some default diagnostics while the user can define new output of his specific interest. OOPIC presents several types of diagnostics:
2D particle plots
2D vector plot
3D surface plot of scalar field component
Time history of scalar diagnostic

Usually, to reduce the memory requested by the software, the simulation is launched without the GUI in batch mode. In this way it is also possible to write sequential output files that contain the particles and some field data of the simulation’s time step when they have been created. Another important feature is the possibility to start a simulation from one of those: the calculation begins from time and particles’ configuration saved on the specified file. When the user defines new diagnostics he can decide whether they have to be saved in the output files or not. Consequently the post-processing methods can be the following:

- Display pictures by using the OOPIC GUI and save them in graphical or text modes
- Read directly the output files of OOPIC with external Matlab or IDL routines
- Define new diagnostics and display them with the GUI or store and read from the output files

We have preferred the first two methods: from the GUI we have obtained the field data like the plasma potential and particle densities that are part of the default diagnostics, from the output files we have read the particles’ positions and velocities that there are stored. We have used some user defined diagnostics but only occasionally also because their storage inside the output files can make the necessary disk and memory space big and therefore difficult to manage.

1.2.4 GEOMETRY

A detailed model of the helicon source is not our intention. It should require a radiofrequency electromagnetic solver working in parallel with the PIC model and the electromagnetic fields generated by the antenna should be defined and considered during the calculation of particle trajectories. This approach needs high computational power and specific physical assumptions.

The heating process can be avoided by imposing ad hoc electron and ions families, emerging from the helicon. This is a versatile approach because we could change the parameters, simulating plasma expansion in different conditions. The resolution of the particles motion can be done under electrostatic assumption. Modeling the Charles-Boswell experiment we must draw a first dielectric open-ended cylinder connected to a conducting one, representing the source and diffusion chamber walls. The source and chamber radiuses are 6 and 16 cm while the length is 30 cm for both. We could implement a half thruster stressing its cylindrical symmetry (Figure 1.21). The source walls can be defined using the Dielectric and DielectricRegion objects of OOPIC. They permit to define a wall and a rectangle with particular permittivity and reflection properties. The region object is used for the upper source wall. The variable Quseflag can switch off the dielectric charge accumulation, neglecting the wall/plasma potential difference like the charged particles drain off through the wall. This allows a sort of wall floating which is like the case of an ExitPort, so the plasma is not confined. The chamber walls could be realized by using the Equipotential or Conductor objects. The first realizes a wall maintaining it at a potential, which can be defined by the user (put to zero but also time-dependent functions could be used). A multiple Segments line reproduces the experimental configuration. To set the cylindrical geometry we must define the Geometry flag equal to zero inside the Grid block of the input file. Then we have to give the axis position by writing its coordinates in the CylindricalAxis block at the end of the input file. The ExitPort object should be used to model the pump absorption at the chamber walls.
The particles passing along this segment will be treated as if they were escaping the boundaries of the simulation. Only one segment can be defined, so it should be carefully positioned. Particular attention must be paid to set the port resistance and impedance because sometimes it can produce reflections and absorptions of particles and/or electromagnetic waves. Few particles are immediately loaded into the source region, to represent the high energy electrons produced during the breakdown and to start without a empty region, while the most are created during the simulation. The plasma production is represented by the OOPIC PlasmaSource object. The particles are created at a given rate in a rectangular area and with Maxwellian velocity distribution and a changeable density distribution. The plasma production density is defined in order to model the typical helicon source behaviour: maximum density near $r=0$ and after the tube half (see Figure 1.22).

1.2.5 STATIC MAGNETIC FIELD

The static magnetic field has been calculated by solving the equations for circular filamentary coils. The two solenoids of the Charles-Boswell and Plihon experiments are located around the source tube. Their dimensions have been extrapolated from the figures of the ANU and LPTP publications, from there we can also figure out that the current is below 12A and the magnetic field has two maximums along the axis inside the helicon. Each solenoid is schematized as a series of filamentary coils along $r$ and $z$, at constant current and inside the areas defined from the published pictures: radius between 10 and 13cm, axial
positions of 1 and 20 cm (from the left source wall) and 8 cm long. The total magnetic field is obtained as sum of the fields generated by each coil, calculated for the greed points and stored in a text file which can be imported by OOPIC at the initialization of the simulation.

![Graph](image)

Fig 1.23: Axial static magnetic field for the simulations of the Charles experiments

### 1.2.6 TEST OF THE OOPIC HYBRID CONFIGURATION

While ions are always computed as real particles, the electrons can be considered like a fluid at isothermal equilibrium. This assumption is usually reported as “Hybrid” PIC paradigm and allows a space and time scales enhancing because electrons, that move faster then ions due to their lower inertia, can be treated as a uniform background.

The measurements and simulations reported by Charles and Meige suggest the utilization of a hybrid configuration. In this case the electrons can be assumed to be in Boltzmann equilibrium:

$$n_e(r,t) = n_o(r,t) \cdot \exp \left[ \frac{e \cdot \phi(r,t)}{k_B \cdot T_e(r,t)} \right]$$

(1.9)

Where $e$ is the elementary charge and $\phi$ is the electrostatic potential. The total charge density becomes:

$$\rho(r,t) = e \sum_i Z_i \cdot n_i(r,t) - n_o(r,t) \cdot \exp \left[ \frac{e \cdot \phi(r,t)}{k_B \cdot T_e(r,t)} \right]$$
If the plasma is quasi neutral we must then have:

\[ n_0(r,t) = \sum_i Z_i \cdot n_i(r,t) \]  

(1.11)

In electrostatic approximation the Poisson’s equation determines the field in the plasma, but with (2) and (3) it becomes nonlinear:

\[ \nabla^2 \phi + \frac{e \cdot n_e}{\varepsilon_0} \left( 1 - \exp \left( \frac{e \cdot \phi(r,t)}{k_B \cdot T_e(r,t)} \right) \right) = 0 \]  

(1.12)

The above relation can be linearized but only in absence of sheaths or DLs.

OOPIC admits Boltzmann electrons and it has both linear and nonlinear Poisson solves but it had to be modified in order to use always the nonlinear solve, except the initialization of the simulation. In the original source codes OOPIC decided to use the linear or nonlinear solve from the total charge of the system. Our modifications have just changed the subroutines call sequence, eliminating the linear solve utilizations.

Two equation solves can be used: Dynamic Alternating Direction Implicit (DADI) and, with a better performance, MultiGrid. Unfortunately, during our tests, the Poisson solve does not converge properly: the system-equations residue remains too high also after several iterations and these errors remain also with the original OOPIC code. Figure 1.24 shows the plasma potential differences between full and hybrid-PIC inside the source tube (to solve the simulation with the hybrid method we had to allow a residue of the Poisson solve five times bigger then the default value). Using the fluid electrons the plasma potential is 20-25% higher then the case with particle electrons and remains almost constant after the first 5-6 \( \mu \text{s} \) when the full PIC simulation still change.

These results suggested to change the paradigm of the simulations and adopt a new method which does not involve the Boltzmann electrons. Both ions and electrons will be computed as real particles.

Fig 1.24: Example of plasma potential difference for hybrid and full (dashed) DL OOPIC simulations
1.3 SPARSE GRID SIMULATIONS

1.3.1 INTRODUCTION

As we pointed out before, due to the low Hybrid-OOPIC performances the simulations had to be made using a full electrostatic configuration. The analysis have been done by considering high time steps and low plasma densities: this permits to reduce the particles’ number and the spatial grid, which is scaled with \( \lambda_d \), and the dimension of the fields’ matrixes that consequently OOPIC can manipulate without the need of a supercomputer in a reasonable time. The time step has been set at \( 10^{-9} \)s in accordance with the electron cyclotron and plasma frequencies and a comparison test between the case with \( dt=10^{-11} \)s showed a low discrepancies, of the order of 1%, on the plasma potential after 5 \( \mu \)s.

1.3.2 COMPARISION WITH NOT CONFINED PLASMA EXPANSION

The source walls’ characteristics can be chosen by adopting three OOPIC objects: conducting surface with constant potential, dielectric and dielectric without the accumulated surface charge property. This last configuration has been chosen as reference case because it represents a non confining wall. The dielectric in the reference simulation has a relative permittivity of 1, so as the free space.
Fig 1.25: Plasma r-z phase space, ions axial velocity, potential and ions number density for the reference case at t=11µs. The source walls are not confining and the parameters of Tab 6.1 applies.

In our dual-core computers the simulations took 20-30 hours each to reach 15-20 µs, their results are shown below and the reference parameters follow:
From Figure 1.26 one can suggest that, for the reference case, the plasma potential and its jump are well defined after 10μs, therefore our simulations, that last 15-20μs, should be indicative of the phenomenon. The plasma potential at z>30cm increases between 5 and 10μs but it remains almost unchanged during the successive 5μs, showing that also the ions flux inside the chamber should be stable after 10μs. In fact the ions travel around the ion sound speed which is now $\sqrt{\frac{k}{m}}\approx 2.5 \times 10^4$ m/s, so they should pass the 30cm diffusion chamber and reach its right wall after 10-11μs. With the adopted source rate the densities inside the source after 10μs are few times $10^{12}$ m$^{-3}$ so more than two orders of magnitude lower than the experimental values.

Switching off the magnetic field, particles are not confined and electrons are uniformly spread inside the helicon tube. Also the ions’ trajectories change and their divergence increases. See Figure 1.27 for more details.
Fig 1.27: Ions (left) and electrons positions after 11µs for the non confining source walls with (a) and without magnetic field (b).
Using “real” dielectric as source walls the confining effect of the magnetic field seems to be enhanced and it grows using high permittivity. In particular electrons are much more confined at lower radius inside the helicon and the ions density at $r<R_{\text{source}}$ grows inside the diffusion chamber. See Figure 1.28.

Figure 1.29 confirms the Boswell suggestion: the potential of the left source wall is a critical point for the formation of the potential jump. If the left wall is made of conductors set to a low fixed potential or dielectric (so if it is able to produce a sheath mainly lowering its potential to negative values by accumulating the faster electrons in order to attract ions and neglect the total current) the source plasma potential is sensibly reduced. Another information coming from the picture is that increasing the left wall potential above the value obtained in the not biased case, the potential jump varies, but only of few Volts. Finally allowing the accumulation charge (true dielectric surface) both at the left and up source walls, the potential jump is drastically reduced, showing that the ion flux is sensibly changed.
Fig 1.29: Plasma potential at $r=0$ and $t=11\mu s$ for different dc biased source left walls. $T_e=7\text{eV}$ final $N_{\text{ions}} \sim 10^{12}\text{m}^{-3}$.

Figures 1.30 and 1.31 represent the time evolutions of axial plasma potential and density for three left source walls, they show that the stabilization of the flux is not an easy attempt. The up source wall is there a non confining dielectric wall ($Q_{\text{useFlag}}$ is 1). For all the three cases the plasma potential change very rapidly during the first 5-6 $\mu$s, when the ions flux starts to penetrate the expanding chamber, and almost it does not change after 9-10 $\mu$s. Not the same happens for the plasma density: if the left wall potential remains far below the plasma’s one, the ions’ density does not stop to grow, reaching values three times greater and the potential jump decreases of about 25%.

Fig 1.30: Axial plasma potentials for conducting 20V dc biased source left wall. The up wall is a non confining dielectric. The red arrow represents the width of the potential jump measured by Charles. $T_e=7\text{eV}$ final $N_{\text{ions}} \sim 10^{12}\text{m}^{-3}$.
Fig 1.31: Axial plasma potentials for reference case (non confining left wall) and conducting 10V dc biased source left wall (down). The up wall is a non confining dielectric. The red arrow represents the width of the potential jump measured by Charles. $T_e=7eV$ final $N_{ion}\sim10^{12} m^{-3}$.
Fig 1.32: Axial plasma density for conducting 10 and 20V dc biased source left walls. The up wall is a non confining dielectric.
Fig 1.33: Axial plasma density for reference case (non confining source left wall). The up wall is a non confining dielectric.

Fig 1.34: Ions relative density as function of the axial velocity and radius, for z=40-45cm (10cm outside the helicon tube).
Fig 1.35: Ions relative density as function of the axial velocity and radius and for z=40-45cm (10cm outside the helicon tube). The height of each bar represents the relative density of ions having that velocity; e.g. for the reference case 4.5% of the ions at r=12-14cm have axial velocity of $3 \times 10^4$ m/s while less then 1% of the ions at r=0-2cm have that value.

Fig 1.34 and 1.35 represent the Ion Energy Distribution Function (IEDF) measurements made by Charles and Plihon. It is shown that the greater percentage of the ions inside the expansion chamber and at the source axis has velocities between 4 and $5 \times 10^4$ m/s (yellow bars), while for higher radius the peak velocity decreases to $3-3.5 \times 10^4$ m/s. The ion sound speed for hydrogenous and $T_e=7$ eV is $\sqrt{(k T_e/m_i)} \approx 2.5 \times 10^4$ m/s, so the peak velocity for r~0 is around two times $C_s$ as reported by Charles and Plihon. The two peaks shape of the measurements, typical of the DL case, is better reproduced adopting a cold ions family at the source ($T_i=0.01$ eV). The density of the ion beam is increased with the 20V dc biased left wall, while the ions velocity remains almost unchanged, comparing it with the present reference case (non-confining source wall). It has to be noted that several ions at two times the sound speed are registered also with a low or zero magnetic field.

Increasing the neutral pressure of a factor 10 the potential jump remains almost unchanged. To obtain significant differences the pressure has to grow of two order of magnitudes. Fig 1.36 shows how the ions’ axial velocity distribution inside the diffusion chamber can be modified by the same factor: high pressures allow the gas ionization by the electrons that escape from the source. For pressures above 13 Pa
(100 mTorr) the number of low velocity ions reaches the high energy ions, that forms the second peak of the distribution function.

During the experiments the potential jump disappeared for pressures above 0.6 Pa. Our simulations show a similar effect but for pressure greater than 13 Pa, so almost two orders of magnitude higher. The discrepancy can be explained considering that the real ions’ density inside the helicon source was between $10^{15}$ and $10^{16}$ m$^{-3}$ while for our studies we obtained values significantly lower: around $5 \times 10^{12}$ m$^{-3}$. The computed ionization process is therefore underestimated: the ions density is more than two orders of magnitude lower and the neutral pressure which shows a reduction of the potential jump is overestimated of almost the same factor. In fact the potential jump reduction happens for similar values of the $N_{i}/N_{n}$ factor.

![Fig 1.36: Up: Ions relative density as function of the axial velocity and radius, for z=40-45cm (10cm outside the helicon tube). Neutral pressures of 13 Pa (left) and 0.01 Pa (right). Yellow bars represent the velocities for r=0-2cm, red r=5-8cm and blue r=12-14cm. Down: Plasma potential after 11µs for three different neutral pressures: 0.13 (black), 1.3 (red) and 13 Pa (blue)](image-url)
Fig 1.37: Potential jump amplitude as function of the ions times neutral density ratios. The results of the simulations (triangles) are shown together with the Plihon (squares) and Charles (stars) measurements.

Fig 1.38: Velocity components of the ions along z and for r=0.02 m
Fig 1.39: Ions magnetic, electric, kinetic and total energies of the ions along z and for r=0.02 m. Ions are axially accelerated through the potential jump, mainly converting their electric energy into kinetic energy and converting the velocity around the magnetic field lines (Vort) into their axial velocity.

Figure 1.38 shows how the axial velocity increases through the potential jump which is positioned between \( z = 0.2 \) and \( z = 0.4 \) m. The variation of the axial velocity is joined to the reduction of the electric energy (\( N_i e \phi \), see Figure 1.39) and the conservation of the magnetic momentum. This affects the evolution of the ions gyro-motion around the magnetic field lines which is the main effect of the magnetic field on the particles motion. The diverging magnetic field converts the circular motion of the ions around its lines into rectilinear motion along the z axis.
1.3.3 HIGHER SOURCE RATE

Considering a spatial step of 1.2mm the maximum plasma density we can simulate is around $10^{14}$ m$^{-3}$ in order to remain below $\lambda_d$ with our grid dimension. Therefore into the simulations reported above we could increase the plasma production rate and analyze higher densities without changing the simulation scheme. Moreover OOPIC admits to restart a new simulation from the output file of another one that has to have the same dimensions and main border conditions. Inside the file are recorded the particles configuration (positions and velocities) of the old case, which the software will use as starting point for the new calculation. In this way, instead of begin new simulations, we propagated a starting condition increasing the source rate and changing some border conditions or plasma properties. This method saved some hours of computational time.

The diffusion chamber is now made only of grounded conducting walls (the ExitPort has been removed) while the dielectrics have $\varepsilon_r=4$. The propagations lasted for 6 $\mu$s and they started all from the same simulation at $t=11\mu$s. The starting condition, which was also propagated for the same 6 $\mu$s and then reported as reference case, was the one of the last paragraph except for the dielectric walls that had the accumulation charge property switched on. The propagations have a new source rate which has been set ten times bigger then the one of the last paragraph: $5 \times 10^{18}$ m$^{-3}$/s$^{-1}$.

We have analyzed separately the main plasma parameters and their effects on the potential and ions density. The parameters we have varied are: electrons and ions temperatures, source walls characteristics and plasma production properties.

![Graph](image)

Fig 1.38: Comparison of axial plasma potential for $T_i=0.01$ and $T_i=1$ eV (dash). The red arrow represents the width of the potential jump measured by Charles. $T_e=6$ eV final $N_{\text{ion}} \sim 10^{13}$ m$^{-3}$.

Increasing the ions’ temperature and remaining below 1 eV, the plasma potential remains almost unchanged, see Figure 1.38. The main effect of this ions temperature enhancing is measured on the particles’ axial velocity. Higher temperatures make the ions faster also at radii greater than the source tube. See Figure 1.39.
As anticipated by Boswell the electrons temperature is responsible of the potential jump amplitude. Increasing the temperature from 5eV to 9eV the plasma potential inside the helicon tube increases of 5-6 V and the maximum ions axial velocity just downstream the source is enhanced from 5 to 6 $10^4$ m/s.

Fig 1.40: Comparison of axial plasma potentials for $T_e=9$ and $T_e=5$ eV (dash). The red arrow represents the width of the potential jump measured by Charles. Final $N_{ions}=10^{13}$ m$^{-3}$.
During the simulation, plasma is produced inside an area which is schematized in Figure 1.21 and 1.22. Here we have increased and reduced the area length of 6 cm. It has to be remembered that, as reported by bibliography, varying the magnetic field strength the position where most of the electromagnetic energy is absorbed, so where ionization happens, changes. Therefore this case should be one of the effects of the external magnetic field variation.

The results are shown in Figure 1.42 and 1.43. Enlarging the plasma’s source area the potential becomes a little bit deeper, but the main differences concern the axial velocity. With a larger area the ions, just outside the helicon tube, are slower; this because a lot of particles are created downstream the potential jump and they can not be accelerated.
As anticipated by the low density simulations the dc biased left wall can increase the plasma potential if its potential is fixed to a sufficiently high value. From Figure 1.43 we see that also the ions velocity is increased.
Fig 1.43: Ions relative density as function of the axial velocity, for \( z=40\text{-}45\text{cm} \) (10\text{cm} outside the helicon tube) and for large (right) and thin (left) plasma source areas. Yellow bars represent the velocities for \( r=0\text{-}2\text{cm} \), red \( r=5\text{-}8\text{cm} \) and blue \( r=12\text{-}14\text{cm} \).

Fig 1.44: Axial plasma potential for 20\text{V} dc biased left wall (dash) and dielectric source wall. The red arrow represents the width of the potential jump measured by Charles. \( T_e=6\text{eV} \) final \( N_{\text{ions}}\sim 10^{13} \text{ m}^{-3} \).
For the same case we have then increased the length of the dielectric tube (the dielectric up source wall) and the ions trajectories appear less divergent (Figure 1.46).
1.4 DENSER GRID SIMULATIONS

1.4.1 HIGH DENSITY

Trying to increase the plasma production rate we have halved the spatial step in order to allow a plasma density higher than $10^{14} \text{m}^{-3}$, which was the limit we had. In this way our grid dimension remains again below $\lambda_d$ for higher densities. The nodes number goes from 128x512 to 256x1024 because using the MultiGrid solve they have to be $2^N \times 2^M$.

As first step we have reproduced the reference simulation of Paragraph 6.1 in order to check the computational speed and compare the results with the case of sparser grid; as shown in Figure 1.47 non significant discrepancies have been met. The computation time grows with a factor around 4, it takes almost 3 days to have a simulation of 20 µs.

![Fig 1.47: Reproduction of the low density simulation of the unconfined plasma with halved cells’ length.](image)

The electrons temperature has been set at 6eV while ions at 0.01eV. We have simulated the most interesting cases: source tube completely made of dielectric and conducting DC biased left walls.

Using a dielectric source tube and source rate of $10^{20} \text{m}^{-1} \text{s}^{-1}$ the density does not reach a constant value. The potential becomes instable and almost disappears after 10µs, but this should be due to the plasma density which grows above the limit imposed by our grid dimension. In fact for densities around $8 \times 10^{14} \text{ m}^{-3}$ $\lambda_d$ is higher than our cell length, so the simulation can not work properly.
Fig 1.48: Ions plasma axial density and potential for source walls made of dielectrics with $\varepsilon_r=1$, halved cell dimension and increased source rate at $10^{20}\text{m}^3\text{s}^{-1}$. The potential becomes unstable due to the high plasma density which grows above the limit imposed by $\lambda_d$ and our cell dimension.
Fig 1.49: Axial plasma ions density and potential for the 20V dc biased left wall and true dielectric as up source wall with $\varepsilon_r=4$. Halved cell dimension. Source rate is $8 \times 10^{19} \text{ m}^{-3}\text{s}^{-1}$. Below a zoom for $t=12\mu\text{s}$. The red arrow represents the width of the potential jump measured by Charles.

Fig 1.50: Axial plasma potential, zoom for $t=12\mu\text{s}$ of the picture above. 20V dc biased left wall and true dielectric as up source wall with $\varepsilon_r=4$. Source rate is $8 \times 10^{19} \text{ m}^{-3}\text{s}^{-1}$.
The simulations have been repeated changing the plasma generation rate and the source wall properties. In particular we gradually reduced the particles creation rate to find a stable configuration. The results are reported in Figure 1.49 – 1.54 and in Figure 1.55 the potential is compared with the experimental data. With a source rate of $8 \times 10^{19}$ m$^{-3}$ s$^{-1}$ the density does not stop to grow for a conducting left wall biased of 20V and the same happens for the 30V case. Reducing the source rate from $8 \times 10^{19}$ to $10^{19}$ m$^{-3}$ s$^{-1}$ the density starts to decrease showing that the rate which comports a stable density has to be between these two values. Finally the simulation have been repeated with a source rate of $2 \times 10^{19}$ m$^{-3}$s$^{-1}$, this value gives a plasma density almost stable and around $5 \times 10^{14}$ m$^{-3}$. In general it appears that the potential jump is smooth and not as deep as during the experiments.

Fig 1.51: Axial plasma ions density and potential for the 30V dc biased left wall and true dielectric as up source wall with $\varepsilon_r=4$. Halved cell dimension and source rate of $8 \times 10^{19}$ m$^{-3}$s$^{-1}$. The red arrow represents the width of the potential jump measured by Charles.
Fig 1.52: Axial plasma ions density and potential for the 40V dc biased left wall and true dielectric as up source wall with $\varepsilon_r=4$. Halved cell dimension and source rate of $8 \times 10^{19} \text{m}^{-3}\text{s}^{-1}$ for the first 10µs and 10^19 after.

The red arrow represents the width of the potential jump measured by Charles.
Fig 1.53: Plasma potential for 40 (up) and 70 V DC biased conducting left walls and halved cell dimension. The simulations are made with a plasma production rate of $2 \times 10^{19}$ m$^{-3}$s$^{-1}$ which gives a constant plasma density inside the source tube around $5 \times 10^{14}$ m$^{-3}$. The red arrow represents the width of the potential jump measured by Charles.
Fig 1.54: Axial plasma density for the case with source rate of $2 \times 10^{19} \text{ m}^{-3}\text{s}^{-1}$ and 70V conducting dc biased left wall. After 15µs the density remains almost constant.

Fig 1.55: Potential of the 40 and 70 DC biased left wall simulations after 22µs compared with the measurements made by Charles (squares).

1.4.2 LONGER DIFFUSION CHAMBER

To evaluate the performances in space and the ions detachment we have increased the chamber dimension by maintaining the node numbers of Paragraph 1.6.1 (the denser grid of 256x1024) and increasing the spatial step (returning to the value of 1.2mm of Section 1.5). In this way we obtained a expanding chamber 1.2 m long. The best OOPIC configuration to simulate out space can be obtained by substituting the grounded walls with ExitPorts. The simulations started to diverge after 15-20 µs, therefore we repeated the calculations with a diffusion chamber having grounded conducting walls. It is also necessary to neglect the neutral pressure inside the expanding chamber. The plasma ions are again H because with Ar the sound speed decreases too much and the time necessary to fill the diffusion chamber is prohibitively high.
To evaluate the detachment from the magnetic field lines we have analyzed the ions’ trajectories inside the diffusion chamber. The particle velocity is curvilinear until the magnetic field acts on it, after a certain distance from the source the trajectory starts to be almost rectilinear, there we can suppose the detachment takes place. From the next picture we can argue that the detachment is function of the radius and it happens not before \( z \) of 0.7 and 1.2 m respectively for \( r=0 \) and 15 cm, so at a distance between 0.4 and 0.8 m from the source tube.

![Ions speed direction inside the diffusion chamber for \( r \) between 1 and 10 cm. The trajectories are almost rectilinear after 0.7, 1 and 1.2 meters respectively for \( r=1 \), 3 and 10cm. The detachment should happen there.](image)

**Fig 1.56:** Ions speed direction inside the diffusion chamber for \( r \) between 1 and 10 cm. The trajectories are almost rectilinear after 0.7, 1 and 1.2 meters respectively for \( r=1 \), 3 and 10cm. The detachment should happen there.

### 1.4.3 THRUST AND SPECIFIC IMPULSE EVALUATION

The thrust is evaluated by means of the formula \( T = m \cdot N \cdot V_a^2 \cdot A \) iterated for every \( r_i \) along the supposed detachment line:

\[
T = \sum_{i=1}^{N_m} m \cdot N_i^{det} \cdot (V_{a_i}^{det})^2 \cdot A_i
\]

and where:

- \( m \) is the ion mass
- \( N \) is the density of ions inside the detachment cell at radius \( r_i \)
- \( V_a \) is the average axial velocity inside the detachment cell
- \( A \) is the cross surface of the cell revolution along \( \varphi = \pi \cdot [(r_i+dr)^2-r_i^2] \)
- \( N_m \) is the number of cells along the radius

Thrust and specific impulse have been calculated for 4 detachment lines, that are represented in Figure 1.57, defined as the positions where, at a particular \( r \), the ions’ speed direction changes of 2° (lines 1 and 2), 6° (line 3), and 8° (line 4) for higher \( z \).

For all the cells that follow the selected line, we have evaluated the ions’ density, which is a default output of OOPIC, and the average ions’ axial velocity. The results are reported in Table 1.2, that is an average of three simulations made with \( T_e=8eV, 70V \) dc bised left wall and diffusion chambers represented by *ExitPorts* or *ExitPorts*. 
The simulations we made reached a density, inside the source tube, around $5 \times 10^{13}$ m$^{-3}$, the source rate has been set between $10^{18}$ and $3 \times 10^{18}$ m$^{-3}$ s$^{-1}$.

The specific impulse ($I_s$) can be calculated by means of the following formula, where $g$ is gravitational acceleration:

$$I_s = \frac{\sum_{i=1}^{N_n} N_i^{\text{det}} \cdot V a_i^{\text{det}}}{\sum_{i=1}^{N_n} N_i^{\text{det}}} \cdot \frac{1}{g}$$

(1.14)

<table>
<thead>
<tr>
<th>Detachment line</th>
<th>Ions</th>
<th>Specific Impulse (s)</th>
<th>Thrust (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H</td>
<td>~2800</td>
<td>~2E-9</td>
</tr>
<tr>
<td>2</td>
<td>H</td>
<td>~2900</td>
<td>~3E-9</td>
</tr>
<tr>
<td>3</td>
<td>H</td>
<td>~3600</td>
<td>~7E-9</td>
</tr>
<tr>
<td>4</td>
<td>H</td>
<td>~4000</td>
<td>2E-8</td>
</tr>
</tbody>
</table>

Table 1.2: Thrust performance as function of the detachment line, computed as average of three simulations with same geometry and $T_e=8$eV but different electrical properties of the diffusion chamber and dc biased of 70V. Final $N_{\text{ions}}=5 \times 10^{13}$ m$^{-3}$. 

Fig 1.57: Detachment lines adopted for the thrust evaluation
Chapter 2

ELECTROMAGNETIC SIMULATIONS

2.1 INTRODUCTION

When the internal magnetic field of the particles can not be neglected the calculations becomes computationally harder to perform. OOPIC admits electromagnetic simulations and allows a MPI parallelization which is not possible during the electrostatic calculations. Another important application of the electromagnetic particle simulations is the VASIMR thruster. It is composed of two subsequent sections that both use radiofrequency fields: plasma production and heating. The charged particles, produced by the helicon source, flow through a larger tube surrounded by an antennae which launches a circularly polarized wave, matched with the plasma ion cyclotron resonance frequency.

The Ion Cyclotron Resonance Heating (ICRH) simulations can be made in several ways [33]. From the wave’s viewpoint plasma heating is a loss process and solving the wave equation, reveals where the wave energy is lost. From the particle’s point of view, plasma heating is the process of being accelerated or decelerated by electric and magnetic fields and the net diffusion of particles resulting from this is described by the Fokker-Planck equation. Another method, which is gaining in importance from the growing power of computers, is again the PIC approach.

The next two paragraphs describe the OOPIC applicability at the electromagnetic simulations of a helicon source and a innovative solution which integrates the waves and particle methods in a self-consistent model of the ICRH. This model has been evaluated following the idea reported by Ilin et al [34-39] for the VASIMR simulations.

2.2 PIC SOLUTIONS

The PIC algorithms directly solve the coupled set of Maxwell’s equations and the equations of motion for a distribution of macro-particles, representing the real particles. The directness of the PIC approach does however make it computationally demanding; small time steps and many macro-particles are necessary for converging the solution. In fact utilizing OOPIC with its electromagnetic solve the user has to observe the Courant limit which states that during a time step the electromagnetic waves (the couriers of the information) can not travel from one cell side to the other. Usually the limit is respected by applying the following relation:

\[
\Delta t < 0.5 \frac{\Delta x}{c} \approx \frac{\Delta x}{6 \times 10^8 \text{m/s}}
\]  

where \( \Delta \) represents the spatial and temporal steps.

Adopting the electromagnetic solve and reducing the time step in order to satisfy the Courant limit we can compare the new solutions with the electrostatic simulations of Chapter 1. The particles motion is now affected by the electromagnetic field self generated by their motion and position. Figure 2.2 and 2.5 show the differences in velocity of electrons for simulations of 4 and \( 5 \times 10^{10} \) s and without static magnetic field.
To compute the electromagnetic simulations not only the time step has been reduced to respect the Courant limit but also the spatial step. It goes from 1.2mm for the electrostatic cases to below 0.6mm. The time step from 1e-9 s to 5e-13 s.

During the first 4e-10 s of simulations no significant discrepancies have been seen between the electrostatic and electromagnetic cases. After that time step the axial and radial velocities, computed by the electromagnetic solve, start to diverge. These effects show the more difficulties of the electromagnetic solve to converge properly and the necessity to use lower spatial steps that make the simulations long and expensive.

Helicon reactors, based on the propagation of helicon waves to produce high density plasmas, are used in various applications including plasma processing. The source tube is usually made of quartz or pyrex and is therefore a dielectric, i.e. the plasma boundaries are dielectric. Helicon processing reactors may use two different antenna types: either antenna that excites the m = 0 or the m = 1 azimuthal modes. The Boswell type, exciting the m = 1 azimuthal mode, has been found to be one of the most efficient antenna in term of ionization.

The helicon discharge is supported by circularly polarized waves (whistlers) excited using an external antenna that, propagating into the plasma, produces bulk ionization, in contrast with usual inductive discharges where ionization occurs in a skin layer. Various antennas were proposed and tested (Figure 2.1): azimuthally symmetric or asymmetric, axial straight or helical [42]. The Boswell antenna, adopted by Charles and Plihon for the Double Layer experiments, is designed to excite the m=1 mode (right-hand rotation with respect to the static magnetic field B0) and it is of the azimuthally asymmetric type. It was drawn to reproduce the wave radial magnetic field and its length, as well as its position, was found to be a critical parameter for the helicon discharge resonance [43].

The hypothesis of Landau damping was proposed by Chen and supported by the evidence of fast electrons traveling at the phase velocity of the wave. But it was then reported that there may be too few electrons to account for a major portion of the ionization to occur by Landau damping [44]. Helicon and Trivelpiece-Gould waves are found to be coupled strongly in plasma with non-conducting walls. Being nearly electrostatic, these waves are strongly absorbed as they propagate perpendicular to the external magnetic field [44]. This “surface channel” of power flow at the boundary, should account for the high efficiency of helicons. Theory predicts that TG modes propagation is enhanced by increasing the magnetic field [45].

Bose [46,47] and Kinder [48,49] have done numerical simulations of an azimuthally symmetric helicon source (m=0, which can be reproduced by using OOPIC), with geometry very similar to the apparatus utilized by Charles for the helicon double layer but with a different antenna. From there we could get
important information about the electric fields, the electron temperature and power deposition for different applied magnetic fields. In particular the peak of power absorption moves downstream as the static magnetic field is increased.

![Energy deposition for growing magnetic fields](image)

Fig 2.2: Geometry, magnetic and electric fields of the helicon source studied by Bose and Kinder and example of their reports: power deposition for different magnetic fields

In a cylindrical bidimensional geometry it is possible to simulate a double loop antenna, as shown in Figure 2.3, utilizing OOPIC. The antenna sections can be modelled as incoming regions of orthogonal currents. In this way the electromagnetic fields generated by the antenna are added to the self generated fields of the particles.

The PIC paradigm is very demanding in terms of computational power and duration of the simulations. It is a direct method and therefore able to reproduce the processes involved in a helicon discharge, but its applicability to this studies is limited. The electromagnetic solve requires very low time step and little grid dimensions, therefore dramatically increase the necessary memory and time. The Particle in- Cell (PIC) algorithm directly solves the coupled set of Maxwell’s equations and the equations of motion for a distribution of macro particles (representing the real particles). Because few approximations are made the relevant nonlinear physics is retained and reproduced by PIC simulations. The directness of the PIC approach does however make it computationally demanding; small timesteps and many macroparticles are necessary for converging the solution. To make such simulations feasible the standard PIC approach will need to be modified to remove fast timescales or applied to computers more powerful than the present state of the art.
The OOPIC software can be parallelized when the electromagnetic solve is applied. It has been installed in an IBM Linux Cluster 1350, made of 512 2way IBM X335 nodes. Each computing node contains 2 Xeon Pentium IV processors with 2GB of memory (1GB per processor). Figure 2.5 shows the number of time steps computed during simulations of 30 minutes utilizing the MPI parallelization and as function of the processors (CPUs) applied in parallel. Increasing the number of processors utilized during the calculation, the velocity increases of the 21% going from 2 to 4 processors and of the 46% going from 2 to 6. It has to be considered that the simulation time depends on the nodes number, the particles number and the write sequence of the output files which the user requires.

The simulation area is divided in rectangular sections one for each processor. Therefore the simulation speed depends also on the position of the particles: processors applied to regions where particles are not present will be used only for the definition of the electromagnetic fields there and the propagation of the macro-particles will be made by the other CPUs. The best condition would be the case of uniform plasma distribution on the entire simulation area.
From Figure 2.4 we argue that the simulation velocity grows with the number of processors involved, but not as expected. The duration of a full electromagnetic simulation of a helicon source discharge still remains very high.

2.3 ICRH HYBRID SELF-CONSISTENT MODEL

Radio frequency (RF) power has been successfully used to heat ions in experimental fusion plasmas. The Variable Specific Magnetoplasma Rocket (VASIMR) is a RF driven device where the ionization of the propellant is done by a helicon type discharge. The plasma ions are further accelerated in the second stage by Ion Cyclotron Resonance Heating (ICRH), a technique extensively used in fusion research. The energy is there stored in the ion velocity components perpendicular to the static magnetic field and then converted into axial energy by the expansion of the static magnetic field.

The schematic layout of VASIMR is shown in Figure 2.5. The device consists of three main components: the low energy plasma source, ion cyclotron-resonance heating (ICRH) section, and magnetic nozzle. The helicon source creates a cold plasma ionizing the injected gas via rf-discharge. The VASIMR concept employs ICRH as the mechanism for rf-power deposition in the plasma. In the ICRH section, the ion gyro-frequency \( \omega_{ci} \) matches the ICRH antenna frequency \( \omega \) to ensure wave energy conversion into the ion gyro-motion. Following the magnetic field lines, the ions leave the ICRH section and enter the magnetic nozzle. At the nozzle entrance, the energy stored in the ion gyro-motion significantly exceeds the energy of the ion motion along the field lines. The magnetic field lines in the nozzle gradually diverge, so that the magnetic field \( B \) decreases along the field lines. Since the ion magnetic moment and total ion kinetic energy are conserved, the nozzle transforms the ion rotational motion into the longitudinal motion.

Interesting features make the VASIMR a member of the next generation thrusters for interplanetary space missions:

- Variable Specific Impulse provides high operational flexibility
- Electrodeless design with magnetic insulation contribute to the increase of the engine’s life time
- High power density
- High efficiency

VASIMR could be an interesting candidate for future manned space missions because:

- Rapid interplanetary transfers reduce radiation dosage and physiological problems due to weightless on astronauts
- Magnetic shielding provides additional protection against solar radiation
- Low atomic number for propellant (hydrogen or helium) provides high shielding against high energy protons
- Thrust versus Specific Impulse variation enables wide range of abort capabilities
An innovative self-consistent model of the ICRH has been evaluated, following the idea described by Ilin [34-39] and applied to the VASIMR thruster.

The software consists of three main parts: external static magnetic field builder, wave equations solve and Monte-Carlo particles’ trajectories evaluator. The wave equations are solved in cold plasma hypothesis which requires, as input, the plasma density; this is obtained from the Monte-Carlo routine applied to the external and the just calculated radiofrequency fields. The global block diagram of the model is reported in Figure 2.6: a iterative scheme which proceeds until the power absorptions, calculated by wave and particles methods, converge.
The external field is reconstructed using the same methods of the helicon DL investigation. The other parts of the software are constructed in Matlab where matrix and graphic tools are easy to implement.

### 2.3.1 ELECTROMAGNETIC SOLVE

Combining Maxwell’s and Lorentz force equations gives the cold plasma theory [40],

\[
\begin{align*}
\nabla \times \mathbf{E} &= i \omega \mathbf{B} \\
\nabla \times \mathbf{H} &= \mathbf{J}_{\text{ext}} - i \omega (\varepsilon_0 \mathbf{K} \cdot \mathbf{E}) \\
\n\nabla \cdot (\varepsilon_0 \mathbf{K} \cdot \mathbf{E}) &= \rho_{\text{ext}} \\
\n\nabla \cdot \mathbf{B} &= 0
\end{align*}
\]

(2.2)

Where time-harmonic dependence of the fields has been assumed with the form $e^{i\omega t}$. In (2.2) $\mathbf{K}$ is the cold plasma dielectric tensor; in the coordinate system with the external applied magnetic field along $z$ it can be written as:

\[
\mathbf{K} = \mathbf{I} + \frac{i}{\omega \varepsilon_0} \sigma = \begin{bmatrix}
K_\perp & -iK_x & 0 \\
iK_x & K_\perp & 0 \\
0 & 0 & K_\parallel
\end{bmatrix}
\]

(2.3)

Where $\mathbf{I}$ is the unity tensor, $\sigma$ is the cold plasma conductivity tensor and

\[
\begin{align*}
K_\perp &= 1 - \frac{\omega_p^2}{\omega^2 - \Omega^2} \quad \text{(2.4a)} \\
K_\parallel &= 1 - \frac{\omega_p^2}{\omega^2} \quad \text{(2.4b)} \\
K_x &= \frac{\Omega}{\omega} - \frac{\omega_p^2}{\omega^2 - \Omega^2} \quad \text{(2.4c)}
\end{align*}
\]
In the above relations $\omega_p^2 = nq^2/(me_0)$, $\Omega = qB_0/m$, $q$ and $m$ are mass and charge of the ions, $B_0$ is the external magnetic field and $\rho_{\text{ext}}$ and $J_{\text{ext}}$ are the external charge and current densities.

The approximate effect of collisions can be included by adding a collisional damping term to the Lorentz force equation [41]:

\( m \frac{\partial \mathbf{v}}{\partial t} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \eta m \mathbf{v} \) \hspace{1cm} (2.5a)

\( -m \left(1 + i \frac{\eta}{\omega}\right) i\omega \mathbf{v} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \) \hspace{1cm} (2.5b)

where the ion speed $\mathbf{v}$ has been assumed proportional to $\exp(-i\omega t)$ and $\eta$ represents the collision frequency.

Thus the effect of collisions can be included in the cold plasma theory by replacing the mass $m$ with $m^* = m(1 + i\frac{\eta}{\omega})$.

Taking the curl of the first two equations in (2.2) gives the wave equation:

\[-\nabla \times \nabla \times \mathbf{E} + \frac{\omega^2}{c^2} \mathbf{K} \cdot \mathbf{E} = -i \omega \mu_0 J_{\text{ext}} \] \hspace{1cm} (2.6)

To simplify this problem it is possible to assume that the high mobility of electrons along the external magnetic field lines shorts out the component of the wave electric field parallel to $\mathbf{B}_0$. Under this hypothesis the $K\cdot E$ factor is substantially simplified [41]. Now considering a cylindrical symmetric $\mathbf{B}_0$ and Fourier expanding $\mathbf{J}$ and $\mathbf{E}$ along $\theta$

\[ \mathbf{E}(r, \theta, z) = \sum_m E_m(r, z)e^{im\theta} \] \hspace{1cm} (2.7)

\[ \mathbf{J}(r, \theta, z) = \sum_m J_m(r, z)e^{im\theta} \]

the tridimensional problem (2.6) reduces to a system of two differential equations to be resolved with respect to $v = r E_m^r$ and $u = r E_m^\theta$:

\[
\begin{align*}
\frac{\partial^2 u}{\partial z^2} + \frac{r}{R} \frac{\partial^2 u}{\partial r \partial z} + \left(\frac{\omega^2}{c^2} K_\perp - \frac{m^2}{r^2}\right) \frac{1}{b_2} \frac{r}{R} u - i \frac{\omega^2}{c^2} K_\perp \frac{b_2}{r^2} u = & - \frac{i \omega \mu_0}{R} \left( J_m^r - \frac{ar}{R} J_m^z \right) \\
\frac{r}{R} \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial v}{\partial r} \right) + \frac{\partial^2 v}{\partial z^2} + \left(\frac{\omega^2}{c^2} K_\perp \right) v + i \frac{\omega^2}{c^2} K_\perp u = & -im \left[ \frac{r}{R} \frac{\partial u}{\partial r} \left( \frac{1}{r^2} - \frac{1}{\partial z} \right) \right] = \frac{\omega \mu_0}{R} J_m^\theta
\end{align*}
\] \hspace{1cm} (2.8)
Where $\alpha = \bar{b}_r R / \bar{b}_z r$, $\bar{b}_r$ and $\bar{b}_z$ represent the $\bar{B}_0$’s versor components along $r$ and $z$ and $R$ is the radius of the metal wall considered as boundary and where the tangential components of $E$ vanish with the normal component of $B$. $E_z$ is then obtained from the $E_z = 0$ assumption as $E_z = -E_r \bar{b}_r / \bar{b}_z$.

Fig 2.7: Electric field contour for the $m=-1$ poloidal mode in a mirror machine as in ref [41]. $E^+$ penetrates the plasma more easily than does $E^-$. 

The system (2.8) can be solved with a finite difference scheme of the second order by using Matlab. The routine has been realized and tested for the case analyzed by Jaeger [41] which considered a magnetic mirror device of 1.2 m length for the $m=-1$ mode. The solution is reported in Figure 2.7 which shows the different penetration inside a H plasma for the right and left hand polarized waves.

$$E_+ = E_\varphi + i E_\theta \quad (LHP)$$
$$E_- = E_\varphi - i E_\theta \quad (RHP)$$
2.3.2 MONTECARLO PARTICLES METHOD

With a given distribution for the initial position and velocity vectors at a axial position left the ICRH antenna and near the helicon source exit, thousands ion trajectories are calculated. The ions are aggregated in macroparticles as done by the PIC codes, but the plasma fluid characteristics (density, velocity, temperature) are assumed time-independent and collisions are neglected. Each single trajectory is used to generate many particles distributed along it. The ion motion satisfies the following equation, with respect to ion position and velocity vectors $\mathbf{x}_i = (x_r, x_\theta, x_z)$ and $\mathbf{v}_i = (v_r, v_\theta, v_z)$, as functions of time $t$:

$$ m \frac{d\mathbf{v}_i}{dt} = q \left( \mathbf{v}_i \times \mathbf{B}(\mathbf{x}_i, t) + \mathbf{E}(\mathbf{x}_i, t) \right) \quad \frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i \quad (2.9) $$

Implementation of the above formula requires interpolation of the pre-calculated fields $\mathbf{B}$ and $\mathbf{E}$ from their grids to the arbitrary position.

The propagation is computed adopting the Boris method (leap frog scheme). There the electric and magnetic forces are completely separated defining the $\mathbf{v}^-$ and $\mathbf{v}^+$ vectors:

$$ \frac{v_{r+\Delta/2} - v_{r-\Delta/2}}{\Delta t} = \frac{q}{m} \left[ E + \frac{v_{r+\Delta/2} + v_{r-\Delta/2}}{2} \times B \right] $$

$$ v^- = v_{r-\Delta/2} + \frac{qE}{m} \frac{\Delta t}{2} $$

$$ v^+ = v_{r+\Delta/2} - \frac{qE}{m} \frac{\Delta t}{2} $$

Once defined the $v^-$ vector, the magnetic field effect, which is a rotation along $\mathbf{v} \times \mathbf{B}$, is calculated defining two new vectors $\mathbf{v}'$ and $\mathbf{t}$:

$$ \mathbf{v}' = v^- + v^- \times t $$

$$ t = \frac{qB}{m} \frac{\Delta t}{2} $$

The vector $\mathbf{v}'$ is perpendicular to $(\mathbf{v}^- \cdot \mathbf{v}^-)$ and $\mathbf{B}$, so

$$ v^+ = v^- + v' \times s $$

$$ s = \frac{2t}{1 + t^2} $$

Finally, defined $\mathbf{v}'$ the routine calculates $v_i$ as average between $v_{r+\Delta/2}$ and $v_{r-\Delta/2}$.

At every time step of the ion propagation, the density of the cell where the ion is located has to be increased of an amount proportional to $w \ dt \ Sr$ where $w$ is the macroparticle weigth, $Sr$ is the helicon plasma production rate and $dt$ the propagation time step. The macroparticle weight $w$ is considered function of the starting ion radius and velocity, in order to reproduce the VASIMR helicon experimental data and a given
starting velocity distribution (usually Maxwellian). The ion trajectory is propagated until the right border of
the simulation area. At the end the plasma density is interpolated at the grid locations used to solve equations
(2.7) and, if necessary, smoothed to reduce noise level coming from the computation.
Particular attention must be paid calculating the radiofrequency magnetic field, which has to be reconstructed
from the electric field solving the Maxwell curl equation at the particle position in order to reduce the
necessary memory.

Fig 2.8: Particles trajectories. Test particles trajectories for a diverging magnetic field configuration.
Chapter 3

SIMULATIONS AND DESIGN OF PLASMA DIAGNOSTICS

3.1 INTRODUCTION

Plasma is a quasineutral gas of charged and neutral particles which exhibits collective behaviour. The objective of plasma diagnostics is to deduce information about the state of the plasma from practical observations of physical processes and their effects. This usually requires an elaborate sequence of deductions based on an understanding of the physical processes involved. Plasma diagnostics are based on a multitude of different physical processes. Many different techniques are being employed for measuring the spatial profile and evolution of various plasma parameters. Although most of them are already well established, plasma diagnostics is still a very challenging discipline. On the one hand this is caused by the always-continuing effort to attain a better spatial and temporal resolution, to reach higher accuracies and to measure with more spatial channels. On the other hand diagnostic techniques based on more subtle physical processes are continuously developed. The main plasma probes utilized are: Langmuir probe, retarding potential analyzer, bolometer and interferometers. Langmuir (electric) probe is one of the earliest and most used diagnostic first proposed by Langmuir in 1920s. The retarding potential analyzer is a more sophisticated probe where a system of grids at different potential are used to evaluate the ions distribution function. Bolometer is a device which detects incoming radiation by producing a change in its electric resistance. Interferometers evaluate the modulation or fluorescence effects which a plasma produces on an incoming laser or microwave signal to understand its properties. This chapter gives a brief description of plasma diagnostic techniques followed by the analysis of simulations for the design and utilization of a energy analyzer. The goal is the realization a RFEA for the space plasma thruster experiments of the CISAS laboratory. We are developing a new design of the helicon discharge which should be used as micro thruster for satellite maneuvers.

3.2 SHEATH THEORY

The effects of a perturbing charge in a plasma are shorter-range than in vacuum. The effect can be deduced by Poisson’s equation by assuming that electrons adopt a thermal equilibrium distribution in which the electron density is determined by the Bolzmann factor

\[ n_e = n_e^\infty \exp(eV/T_e) \]  \hspace{1cm} (3.1)

\( T_e \) is the electron temperature and \( n_e^\infty \) is the electron density far from the perturbing charge, where the potential \( V \) is considered zero. Poisson’s equation is then:

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\[ \nabla^2 V = \frac{-\rho}{\varepsilon_0} = \frac{-e}{\varepsilon_0} (n_i - n_e) = \frac{-e}{\varepsilon_0} n_e \left[ 1 - \exp \left( \frac{eV}{T_e} \right) \right] \]  

(3.2)

If we suppose that \( eV \ll T_e \) we can approximate \( \exp(eV/T_e) \) by \( 1 + eV/T_e \) and obtain the equation:

\[ \nabla^2 V - \frac{1}{\lambda_D^2} V = 0 \]  

(3.3)

where

\[ \lambda_D = \left( \frac{\varepsilon_0 T_e}{e^2 n_e} \right)^{1/2} \]  

(3.4)

is called the Debye length. The solutions of this equation show exponential dependence upon distance, with \( \lambda_D \) the characteristic length. The perturbing effect of a charge will tend to penetrate into the plasma a distance only of the order of the Debye length.

In a simplest form the interaction of a plasma with a absorbing wall can be characterized as follow: because of the different mobility of electrons and ions the wall has a negative potential with respect to the plasma. Therefore the neutral plasma is shielded by a positive space charge region called sheath, extended over several Debye lengths. Because of distortions of ion distribution by wall losses the formation of a stationary sheath is possible only if the “Bohm criterion” is fulfilled. In its simplest form it requires that the ions enter the sheath region with a high velocity:

\[ v_0 > \frac{kT_e}{M} \]  

(3.5)

Consequently the ions must be accelerated by an electric field penetrating a “pre-sheath” region.

### 3.3 Langmuir Probe

A Langmuir probe system consists of a small measuring electrode and an external control unit. It works by inserting one or more electrodes into a plasma, with a constant or time-varying electric potential. The wall of a plasma chamber often represents the reference electrode, while the probe itself is made of a small piece of metal wire, a sphere or a plate. The external electrical circuit allows the variation of the probe voltage to obtain the ion and electron currents. A computer with digital-analog converter generates a voltage sequence, that is sampled and fed to the probe. The probe potential dependent current is then digitized and sampled with the computer.

The relation between the probe current and the applied probe voltage \( I = f(V) \) is called the "probe characteristic". The resulting current is dependent on the geometry of the probe and the plasma density, potential and temperatures; so once one has a theory of the I-V characteristic of an electrode, he can fit the data with the theoretical curve to extract the plasma parameters. Starting in 1924, Langmuir has developed the method of electrostatic probes for measuring the properties of plasmas.

A variable voltage \( V_p \) is applied to the probe-tip and the corresponding current \( I_p \) from the plasma is measured to obtain a characteristic as shown in Figure 3.1. The ion saturation region is located to the left and shows when a continuously decreasing negative bias produces a relatively steady probe current. There a strong negatively biased probe attracts only the positive ions and the ion current in this regime is only
slightly dependent on the probe voltage. The current collected by the probe is then due entirely to positive ions which encounter an attractive electric field thus it is termed the ion saturation current (Isi).

On account of their high thermal energy compared to the ions, the electrons can reach the probe even at a moderate negative bias with respect the plasma potential \( \phi_p \). Increasing the probe potential the number of electrons which are able to overcome the repelling electric field increases reducing the current from the value Isi.

At the floating potential \( \phi_f \) the absolute values of electron and ion current are equal. An isolated body in a plasma will charge up to \( \phi_f \) and it will become surrounded by a symmetrical cloud of oppositely charged particles. The floating potential is lower then the plasma potential because the electron thermal velocity is \((m_i/m_e)^{1/2}\) times greater then that of the ions.

The electron retardation current part of the characteristic ends in an injection point called “knee” which is located at the plasma potential. The electron saturation current is the regime of the probe I(V) characteristic with \( V > \phi_p \), it is the region on the opposite side showing the same ions phenomenon except with electron collection. There the electrons dominate and any further increase on the potential will only add energy to the electrons, not increasing the current. That limit is termed the electrons saturation current (Ise).

In RF plasmas, the potential is fluctuating, with respect to ground and the dc probe bias. The voltage fluctuations across the probe-plasma sheath lead to an additional unknown voltage between probe and plasma, distorting the sampling of the probe characteristic. It has been demonstrated, that these interferences result in a shifting of the floating potential (probe potential, at which the collected ion and electron currents are equal) towards more negative values and an attending of the probe characteristic.

To overcome these problems, two approaches can be distinguished: the active and the passive RF compensation. Both have in common that they try to superpose the bias at the probe-tip with an RF signal mostly identical to the space potential fluctuations.

In the active RF compensation method, the signal to overlay on the probe-tip is generated externally and matched in amplitude and phase to the local plasma potential. This technique implies the knowledge of the potential fluctuations at the probe positions or amplifier and phase shifter must be empirically tuned until the most positive floating potential is reached.

The passive RF compensation needs no extend signal conditioning. The idea is that the probe-tip “floats” with the plasma potential fluctuations when the RF voltage drops mainly across an additional impedance in
the measurement circuit and not across the probe-plasma sheath. Therefore, a series of inductors blocks the probe from the external measurement circuit for RF signals, while letting the dc and slowly varying signals pass. Since the capacity of the probe-plasma sheath is limited by the small area of the probe-tip, the coupling of the RF signal onto the probe has to be enhanced by an additional large area reference electrode close to the measuring probe-tip to pick up the local space potential fluctuations. The electrically floating reference electrode then feeds the signal over a capacitor to the probe-tip.

3.4 RETARDING FIELD ENERGY ANALYZER

Spatial ion energy distribution function (IEDF) measurements have been made by Charles and Plihon for the helicon double layer experiment, with four-grid energy analyzers (RFEA) [27,28,29]. It consists of four grids (a grounded grid, a repeller, a discriminator, and a secondary) and a collector separated by insulators and encased in a metal casing attached to a supporting tube and inserted through a port on the diffusion chamber, moveable along the main axis of a helicon reactor. When assembled the analyser used by Charles was 26 mm long by 18 mm wide and 13.5 mm deep (35 mm long by 50 mm in diameter was the instrument of Plihon). The housing has been mounted on a 9.5 mm diameter stainless steel tube which carries the 3 mm diameter copper water cooling pipe, the k-type thermocouple wires and the electrical connections for the grids. The three grids, repellor, discriminator and secondary suppressor, each consisted of a repeated single layer of mesh, copper grid support and mica sheet. The entrance grid was grounded, a second grid was negatively biased to repel the electrons of the incoming plasma, the third grid was used to select the ion energy by scanning positive voltages and a fourth grid was inserted after the discriminator in order to minimize the effect of secondary electrons produced by the collector plate.

Figure 3.3 shows a typical analyser bias circuit and Figure 3.2 the potential distribution along the axis of the instrument. The collector current is measured as a voltage across a resistor $R_m\sim10-100\,\Omega$ using a buffer amplifier.

The current collected for a single species and for a plate collector of area $A$ is:

$$I(V_0) = eA \int_{u_0}^{\infty} v \cdot f(v) \, dv$$  \hspace{1cm} (3.6)

where

$$u_0 = \sqrt{\frac{2eV_d}{M}}$$  \hspace{1cm} (3.7)

and $V_d$ is the discriminator voltage. Differentiating this we get:

$$f(v) = -\frac{M}{eA} \frac{dI}{dV_d}$$  \hspace{1cm} (3.8)

The ion energy distribution function (IEDF) is therefore computed as $-dI/dV_d$. Figure 3.4 shows the collector current versus the discriminator voltage characteristics measured by Charles for the HDL experiment, the corresponding derivative (IEDF) has been reproduced on the right of the picture.
An example of detection of an ions beam is given in Figure 3.5 in which the I-V characteristics and the corresponding ion distributions are depicted. When a beam is directed into the analyzer, all the beam ions are collected whenever the discriminator potential $V_d$ is such that $eV_d < E_b$, where $E_b$ is the beam energy. For $eV_d > E_b$, the beam ions are repelled so the I-V characteristic has the step function shape as in Figure 3.5 b. When the I-V characteristic is differentiated to obtain the ion velocity distribution function, $f(v)$ versus $E$, the ion beam appears as a bump on the tail centred around the beam's energy.

Typically each ion I-V curve is a single sweep from 0 to the maximum value of the discriminator voltage, in few tens of mV steps with 200-600 current measurements averaged per voltage step. A full sweep usually lasts less the 10 seconds. For the helicon reactor conditions of Chapter 1 a repellor voltage between $-60$ V and $-100$ V is sufficient to repel all plasma electrons during IED measurements. The ion current to the collector was recorded as a function of the dc voltage applied to the discriminator. The collector current and discriminator voltage are digitized and recorded by a computer, then differentiated numerically to give the energy distribution functions.

![Fig 3.2: Typical grid potentials of a RFEA](image-url)
Fig 3.3: Electronic scheme of a RFEA

Fig 3.4: Collector current (right) measured by Charles for the Fig 1.12 IEDF (left) of the helicon double layer experiment.
The analyzer is mounted in a grounded case usually made of stainless steel. It consists of four-plane square – mesh grids, parallel to each other and stacked on top of a plane collector. The proposed design provides electrical insulation between grids and analyzer components adopting mica or alumina sheets.

Ions enter the analyzer through the entrance grid and are decelerated and filtered depending on their kinetic energy in the z direction. Ions with energy high enough to overcome the potential barrier will reach the collector where they can release secondary electrons.

Inside the analyzer electrostatic lens effects occur due to different field strength on either side of each grid, as indicated qualitatively in Figure 3.6. The stronger field always penetrates in the region of the weaker field, forming convex surface towards the weaker field. Ions are submitted to these deviating effects when traveling through the analyzer. The charged particle losses in the direction perpendicular to the analyzer axis can be reduced by decreasing the grid to grid distance which has to be few times the mesh size (usually around 1.5-3).
Analyzer resolution depends on the deviation of incoming ions from their original trajectories parallel to the analyzer $z$ axis before being filtered by the discriminator grid. Any deviation from this direction results in a decrease $\Delta E$ of the component of the ion kinetic energy oriented parallel to the analyzer $z$ axis. The ratio $\Delta E/E$ is defined the analyzer resolution. It is a function of the initial ion kinetic energy, of the potential distribution between grids and of many other factors such as the grid distance, the design of the sampling orifice and the mesh size.

Many studies have been done [50, 51] to study the influence of geometrical factors on the energy resolution of an electrostatic analyzer. Although the proposed theory applies to specific conditions and hypothesis one can retain the fact that $\Delta E/E$ is proportional to $l^{-1}$ where $l$ is the grid to grid distance. Therefore greater distances provide better resolutions. However the grid to grid distance must be lower the ions mean free path in order to minimize the effect of ions and electrons collisions inside the instrument. This provides an upper limit on the definition of $l$. The same studies considered above [50,51] an others [27] suggest a maximum grid to grid distance around 0.6mm.

One of the most important parameters is the design of the sampling orifice. It must be the smallest aperture in the system, and second the sampling orifice must be as thin as tolerable in order to prevent ions losses to its inner surface and subsequent secondary electrons emission. See Figure 3.9.

![Figure 3.7: Qualitatively effects of the width of the plasma entrance hole.](image)

If the mesh size is not small enough electrostatic lens effects may deteriorate $\Delta E/E$: with respect to the discharge facing the analyzer the mesh size should be of the order of the Debye length. All the analyzer’s grids have to be fixed in planes parallel to each other. Grids that are not parallel to each other or are even allowed to curve will further reduce the analyzer resolution. To ensure their position, all grids are spot welded on adequate supports.
3.5 PIC SIMULATION OF A LANGMUIR PROBE

A Langmuir probe can be reproduced and studied as reported in Figure 3.8. The sensor is simulated by a conductor segment in (r,θ) or (x,y) geometry and with a constant or time dependent potential. Grounded conducting segments represent the external case of the probe. The probe’s position and orientation can be changed in order to evaluate the variation on the collected currents. The particles are produced inside the dielectric tube which represents the helicon source. Simulations with different probe shape and positions can characterize the instrument. The simulations are performed with electrostatic approximation to reduce the simulation time. The static magnetic field, usually applied inside the helicon sources by external coils, can be considered as well.

Fig 3.8: Examples of models adopted for the simulations of a Langmuir probe positioned just outside the helicon source. The plate sensor is surrounded by a grounded conducting case.

3.6 PIC SIMULATION OF A RETARDING FIELD ENERGY ANALYZER

Measuring the energy distribution of charged particles is a constantly recurring problem in plasma physics and retardig electrostatic field is a quite frequently solution for this task. The measurement of in velocity distributions consists of recording the ion current to the collector as function the discriminator potential. The ions plasma frequency is usually smaller then the rf cycle so the ion current is almost time independent. A retarding field energy analyzer can be simulated under electrostatic conditions drawing four rectangular grids in a (r,θ) or (x,y) geometry. The grids can be surrounded by conducting segments that represent the external case of the probe. After the fourth grid a conducting plate simulates the collector.
The discriminator voltage can be defined with a time dependent function in order to have a rising potential from zero to the maximum desired value. The plasma is produced inside the tube which forms the helicon source and starts to expand entering the diffusion chamber, both electrons and ions are loaded with Maxwellian distributions.

The first type of simulations that can reproduce the experimental approach maintain the potential of the discriminator at zero Volts for few µs in order to give time to ions to enter inside the probe. After that time the potential starts to grow with a linear function up to 80-100 V. The swap is made in 6-10 µs instead of the few seconds usually utilized as rising time during the experiments, this to reduce the simulation time to one or two days depending on the number of macro-particles. Saving successive output files the software can archive the macro-particles’ position and velocity. From them one can calculate the average velocity of the ions that are between the fourth grid and the collector at a particular instant of time and therefore the current-voltage characteristic.

Another method consists on repeating some simulations made with constant discriminator voltages. From each simulation the user can define the collector current measured by the instrument for that particular potential of the discriminator.

Consequently the ions axial velocity reduces and the total ions current can be calculated by detecting the average velocity of the ions that are between the last grid and the collector at a particular time step.

Figure 3.10 and 3.11 show the ions positions and velocities for successive time steps when a swap of 100V and 2µs of duration is applied to a preliminary scheme of figure 3.9 where the grid are drawn greater than the correct dimensions to have an acceptable computational time.
Fig 3.10: Ions positions (left) and velocities (right) for a retarding field energy analyzer with constant discriminator voltage after 4µs. Grids positions: z = 0.2, 0.205, 0.21, 0.215 and collector at z = 0.22 m. Grids potentials: 0, -50, -100, -20, -10 V.

Fig 3.11: Example of time sequence of the ions velocities for the retarding field energy analyzer of Figure 3.12, when the discriminator potential remains constant at -100V for 2µs and then it grows linearly from -100 to 0V in 2µs. The discriminator is positioned at z=0.21 m.
Reducing the spatial step and dimensions it is possible to simulate the internal behavior of ions and electrons inside the instrument. The grids now can be modeled little as necessary: wires with diameters and distances few tens of µm. The particles trajectories are computed and compared for grids of different dimensions, distances and shapes. Also the width of the first grounded wall, where the plasma entrance aperture is realized, can be evaluated. Figure 3.12 shows the ions positions after 0.5 µs: electrons are shielded out of the instruments but ions can reach the collector where they provide a current to be measured.

Fig 3.12: Ions positions after 0.5 µs for a RFEA of three types of grids’ distances: 0.37mm (a), 0.625 mm (b) and 0.83 mm (c)
Fig 3.13: Ions densities inside the RFEA for two types of grids’ distances. The density near the collector goes from $10^{14}$ when the grids distance is 0.37 mm (left) to 0.5 $10^{14}$ when it is 0.625 mm (right). The ions source rate is constant and equal to $10^{23}$ m$^{-3}$ s$^{-1}$ and it provides a density at the instrument entrance hole around $1.5 \times 10^{16}$ m$^{-3}$.

Fig 3.14: Ions densities inside the RFEA near the collector for two types of grids: wires of 25µm diameters and 25µm distance (black) or 50µm distance (red). Grids distances of 0.625 mm.

Fig 3.15: Plasma potential inside the RFEA for two types of grids: wires of 25µm diameters and 25µm distance (black) or 50µm distance (red). Grids distances of 0.625 mm.
Fig 3.16: Ions positions inside the RFEA for two types of grids: wires of 25µm diameters and 25µm distance (right) or 50µm distance (left). Grids distances of 0.625 mm.

Fig 3.17: Ions positions near the entrance hole for conducting grounded walls of 0.1 and 0.2 mm. Larger entrance rings provide higher divergence of the ions trajectories.
Fig 3.18: Ratio of the Ions densities at the RFEA entrance and at the collector for three simulations and their cubic interpolation as function of the grids distance for the case with \( N_i = 3 \times 10^{15} \text{ m}^{-3} \) at the instrument entrance (\( \lambda_d \approx 0.2 \text{mm} \)). Higher distances increase the flux dispersion along \( r \), reducing the plasma density near the collector and so the ions current.

Fig 3.19: Ratio of the average axial ions velocity at the collector versus RFEA entrance as function of the grid to grid distance for three simulations. The line represents the cubic interpolation of the function. The cases are the same of Figure 3.21.
The main effect of the grid to grid distance is the reduction of the ions density near the collector (Figures 3.13 and 3.14). The ions trajectories are deviating due to the lens effect of the grids (Figure 3.16 and 3.18). Lower is the grid to grid distance lower is the ions dispersion and therefore higher is the ions density near the collector. As reported above according to some studies [50, 51], the RFEA resolution $\Delta E/E$ is inversely proportional to the grid to grid distance. It means that approximately at 1mm the resolution is a half of the value at 0.5 mm for the grid to grid distance. So the grid distance has to be carefully dimensioned considering the two effects together.

An important factor concerning a RFEA design is its position inside the plasma reactor. The analyzer must be positioned near the plasma to be measured but reducing the effects on the plasma discharge. The measurements must be as similar as possible to the condition of instrument’s absence. Again PIC simulations can be used to understand when the plasma starts to be modified by the analyzer. Now the instrument can be schematized by its grounded case because its internal particles behavior is not here important. The simulations have been done considering the geometry and magnetic configuration of the Helicon reactor under construction at the CISAS’ laboratory. Figure 3.20 shows the reactor and Figure 3.21 represents its numerical model. It is composed of four successive tubes of 0.01, 0.012, 0.032 and 0.06 m radius and long 0.06, 0.05, 0.05 and 0.1 m. The first tube is made of dielectric material and it is surrounded by the magnetic coils that provide the static magnetic field. The effects of the instrument position has been evaluated by comparing the plasma potentials of different simulations but with the same duration and starting properties and border conditions.

Fig 3.20: Picture of the helicon reactor under construction at CISAS. The glass tube is surrounded by the magnetic coils. Three tubes of stainless steel then connect the source to the diffusion chamber.
The helicon reactor is composed of three tubes of growing diameters. The ions axial velocity increases due to the potential jump which appears inside the second tube (the first grounded tube after the dielectric one). The instrument will be positioned inside the third tube, because it is larger than the second, therefore downstream the potential jump. PIC simulations show that for low density plasmas the ions behavior does not change. The potential jump occurs at $z<0.1$ m, the instrument does not affect its shape if positioned downstream.

Fig 3.21: Model of the Helicon reactor under construction at CISAS and RFEA position.

Fig 3.22: Ions (squares) and electrons (dots) axial velocities as function of $z$. The result does not change for $X_s>0.12$ m, so when the instrument is positioned after the first grounded tube. The ions expansion happens immediately after the dielectric tube, where the magnetic field lines start to diverge.
The collector current can be calculated by the formula

\[ I_c = N_i^C \cdot V_z^C \cdot q = \frac{A}{m^2} \]

Where \( N_i^C \) and \( V_z^C \) are the average ions density and velocity at the collector and \( q \) is the ions charge (for hydrogen it is the electron charge). Density and axial velocity of ions at the collector are functions of the values at the instrument entrance and of the grid performances. Considering a not perfect planarity of the grids and of the dielectric rings that provide electric insulation between them we can evaluate the RFEA uncertainty when applied to measure the ions density. Consider a theoretical grid to grid distance of 0.5 mm and a tolerance on the instrument realization which could be comparable to a variation on this distance of +/- 0.05 mm. From Figure 3.18 and 3.19 we can argue that the ratio between ions density and axial average velocity at the RFEA entrance and collector are between 5.86-6.15 and 1.30-1.35. These factors allow the definition of a maximum and minimum instrument characteristic function which provides the instrument uncertainty under the above hypothesis:

\[ 4.50 \cdot \frac{I_c}{V_z \cdot e} < N_i < 4.55 \cdot \frac{I_c}{V_z \cdot e} \]

The micro thruster experiment which is starting at CISAS should provide a plasma density inside the helicon source comparable with the values of the Charles and Boswell experiments \( N_i \approx 10^{16} \text{ m}^{-3} \). After 0.1 m, near the position where the RFEA will be positioned (\( z > 0.12 \text{ m} \)), the ions density will be \( 10^{14}-10^{15} \text{ m}^{-3} \). The average axial velocity at the same \( z \) position will be \( 4-7 \times 10^4 \text{ m/s} \). These are the expected values at the instrument entrance. Therefore the collector current density is expected to be \( 0.14-0.25 \text{ A/m}^2 \).

Other sources of uncertainties which affect the ions velocity and density at the instrument entrance are the electron temperature and the magnetic field configuration. The electronic temperature is planned to be
measured by using a Langmuir probe meanwhile the magnetic field uncertainty, depending on the coils geometry and on the RFEA position, is considered negligible because the instrument will be positioned downstream the helicon source in a region where the magnetic field has lower intensities.

3.7 DESIGN OF A RFEA

The proposed instrument will be composed of successive layers of conducting and dielectric materials. Each layer will be made of a ring of copper or stainless steel and mica or alumina. The dielectric rings provide the electric insulation between the grids that are welded on the conducting rings. Externally the instrument will be a stainless steel tube of 18mm diameter. The sandwich, which will be composed of successive conducting and dielectric rings, is inserted inside the tube. The tube is composed of two parts that compress the rings when joined. The plasma entrance hole is performed inside the first stainless steel wall which is grounded. Its diameter is between 1 and 2 mm. The conducting rings have a 3 mm hole where the grid are inserted and welded, meanwhile the dielectric rings have a greater hole of 4 mm which does not interfere with the plasma discharge. The grids are made of nickel and they are circle of 3 mm of diameter usually utilized for electronic microscopy. They are of 400 lines/inch with layer of 30 µm and distant 35 µm. According with the PIC simulations and the considerations of the previous section, the grid distance must be of the order of 0.5 mm and its dimension near the Debye Length. Therefore the rings’ width must be lower then 0.3 mm both for conducting and dielectric. To reduce the diameter of the instrument the electronic connection are obtained on the sides of the conducting rings by a sort of wings that proceed along the stainless steel tube without touch it, therefore maintaining the electric insulation. In this way the instrument must not be larger then the rings reducing its maximum dimension and the influence on the plasma discharge.

Fig 3.24: Design of the proposed RFEA for the CISAS laboratory. The first rings is made of stainless steel (A) and it contains the first grid at zero Volts. Rings B are made of alumina and they provide the electric insulation, C are the copper L shaped rings and D is the stainless steel lid which compress the sandwich. The grids are welded inside the central holes of the copper rings. Each copper ring is inserted inside a larger alumina ring.
Fig 3.25: Global model of the proposed RFEA for the CISAS laboratory. The electric connections of the grids are provided by the L wings of the copper rings. They go along the lateral apertures of the alumina rings. Behind the collector (C) and before the stainless steel lid (D) they are welded to electric wires that enter inside the instrument through the second tube.
CONCLUSIONS

The Helicon Double Layer has been first analyzed by a bibliographic review of the theoretical and experimental data currently known and reported. The plasma computer simulations done to interpret the physics have been studied as well. A similar phenomenon has been reported by other authors since 1980, the experiments require a plasma expansion into vacuum or a second plasma chamber.

The phenomenon should be ascribed to the electrons dynamic during the first period of the plasma discharge. In some way the high kinetic energy imparted to the electrons at the ignition and the expanding trajectories done by the diverging magnetic field, produce a particle trapping and a stable potential jump near the opened end of the source tube. The ions are then accelerated, forming a cylindrical and stable jet at a velocity around two times the sound speed (~5 \times 10^4 \text{m/s} for H ions). A key point for the DL formation is the source walls’ potential that, due to the dielectric material utilized, is allowed to charge during the plasma discharge.

The simulations reported here show a potential jump, larger than the reported one, which is enhanced when the source walls are able to charge at the plasma potential. The faster ions are accelerated downstream the source at velocities near the expected values. When the dielectric left source wall is replaced by a dc biased conducting wall at a potential higher than the plasma potential, the DL is marginally increased while the ions beam density becomes larger. Reducing the magnetic field the potential jump is reduced as well but the fast ions are still present when it should disappear. The neutral density affects the potential jump amplitude, but its reduction with the increasing density is not fast than expected.

In conclusion the simulations report a behavior similar to the experiments but it is still open the question if the potential jump is a full double layer or a less exotic phenomenon related to the particles expansion into vacuum and explained by the sheath theory. The thrust performances show the possibility to utilize the phenomenon for low and medium power thrust applications, but the high power scaling is doubtful due to the limited potential jump.

Simulating a helicon source or the Ion Cyclotron Resonance Heating section of the VASIMR engine one has to deal with a full electromagnetic problem. OOPIC can again be utilized but the geometry and the border conditions now make the simulations very demanding. Therefore next step has been the configuration of a cluster computer in order to perform full electromagnetic simulations in a reasonable time by stressing the OOPIC MPI parallelization, but the necessary for a full simulation still remains high.

An innovative self-consistent model of the ICRH has been proposed which combines a wave field solve with a particles trajectories calculator. The two main routines of the software have been written in MatLab and tests have started considering these two parts isolated before make the integration between them. The model should reproduce true ICRH antennas and permit the calculation of the exhaust plasma behavior of the VASIMR system.

Finally PIC simulations are useful for the characterization and design of plasma diagnostics. Langmuir probes and retarding field energy analyzers can be simulated under electrostatic hypothesis in a reasonable time. The currents near the collectors can be evaluated by computing the average velocities of ions after the last grid. The positions, shape and electrical properties of the probes can be evaluated helping on their design. In particular the grid to grid distance plays an important role on the definition of the instrument’s resolution and the maximum collector current. Distances of the order of 0.5mm have been tested.
Appendix A

Software Review

Plasma is made of charged particles which feel forces due to magnetic and electric fields. Plasmas are difficult to control and understand because of the feedback between the electromagnetic field and the motions of the particles. Numerical simulations are very useful verifying, reproducing and extending laboratory tests and measurements.

Plasma space thrusters use ionized gas accelerated and expelled at very high velocity by electric and magnetic fields to generate a propulsive force. Numerical simulations are here used also to analyze the thrusters performance and help during the project.

The PhD study proceeds the activity on space plasma thrusters started at CISAS years ago. The main intention is collect experiences on plasma simulations utilizing and, when possible, realizing appropriate models. As result the candidate should define a library of tools for plasma simulation, collect experiences on their utilization, characteristics and limits, affine its plasma physics knowledge and apply this experience to the study of particular devices such as plasma thrusters and laboratory plasma probes.

1 SCOPE OF THE SOFTWARE

The study concerns plasma simulations for two types of space thrusters: the Helicon Double Layer (HDL) and the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and, in particular, its Ion Cyclotron Resonance Heating (ICRH) section.

Mainly the software has to realize plasma particle simulations (PIC) to study the HDL concept. The second application is devoted to the simulation of the VASIMR, following the method utilized by Ilin at NASA JSC.

2 USER REQUIREMENTS

This section gives the description of the user requirements. The software must calculate the plasma characteristics following a precise physical approach and under specified border conditions and geometries. Finally the operators and facilities where the software will be applied are defined.

2.1 Software perspectives

The software must give to the user the opportunity to simulate specific systems but under different starting conditions, border conditions and scales. Therefore the model has to be shaped following a precise approach in order to define and solve a particular physical problem, meanwhile some parameters, that affect the results but not the starting physical hypothesis, must be easily changeable.
The devices and experiments to be simulated and studied are the HDL phenomenon and the ICRH section of the VASIMR engine.

2.2 Plasma model

The plasma model must utilize the PIC paradigm. The software must follow the time evolution of test particles (macro-particles) under the supposed electric and magnetic fields. From their trajectories the model have to evaluate the main plasma parameters. Since the definition of such models can be very difficult, when possible the software must utilize existing tools.

2.3 Specific requirements

The study is devoted to the analysis and reproduction of plasmas under specific physical hypothesis, border conditions and geometries, in order to verify their effects on the thrusters’ performances. In particular the software have to represent walls with different dimensions and electric properties. An external magnetic field is usually generated inside the thrusters, its shape and value has to be defined by the user.

The thrusters’ geometries are cylindrical \((r, \theta, z)\). For the HDL study and under specific conditions the axial symmetry can be supposed, this reduces the three dimensional problem in a two dimensions \((r, z)\) geometry.

For the HDL simulations an electrostatic simplified model has to be applied where the internal plasma magnetic field is neglected and only the electric field is calculated. Under the assumption of electrostatic condition the software must investigate the opportunity to apply the so called Hybrid approach, where the electrons’ time evolution is calculated with fluid approximation.

A second option is requested by the ICRH simulations: the plasma electromagnetic field has to be self-consistently calculated from the internal motion of the charged particles. To reduce the model complexity the calculation of the internal magnetic field has to be made under particular physical hypothesis that can simplify the equations to be solved. The software must follow the approach defined by Ilin for the study managed by NASA/JSC.

An axial static magnetic field is generated inside the thrusters by external coils. The software has to calculate the field before the simulation under the hypothesis of axial symmetry. The field has to be inserted on the calculation of the plasma particles evolution also under electrostatic approximation.

The systems to be simulated confine plasma into walls with dielectric or conducting electrical properties. The conducting walls must be considered at constant electric potential (dc biased or grounded). The user should be able to define different walls’ geometry and characteristics.

The user must be free to define a wide range of graphs and pictures to analyze, verify and compare the output of the simulations. Therefore the output data must be collected in binary and/or ASCII files and imported, when not calculated, in a environment especially devoted for the post-processing like Matlab and/or IDL.

The main output to be analyze are: plasma densities, electric potential, electric and magnetic fields and the macro-particles velocities and positions. The software must evaluate trust and specific impulse.

2.4 User characteristics

The users of the software will be engineers with a basic knowledge of plasma physics, working on the design and analysis of specific space plasma devices.
2.5 Operational environment

The software must work on Linux and/or Windows PCs. The simulations’ maximum duration can be defined of the order of seven days to simulate a process of ten µs. The possibility to utilize the software on a Linux cluster must be investigated.

3 ARCHITECTURAL DESIGN

The software is composed of four tools:

- Object Oriented Particle In-cell Code (OOPIC)
- External Tools for the OOPIC Output Management (ETOOM)
- Icrh Model Prototype (IMP)
- External Magnetostatic Builder (EMB)

OOPIC is a free code from Berkeley University, it has been chosen for its versatility and compliance with the HDL study requirements. ETOOM is composed of two routines written for Matlab and IDL to read the output files of OOPIC and allow a post-processing of the simulations. IMP is a software written in Matlab to reproduce the NASA model constructed by Ilin at JSC. EMB is a C routine originally written by Manente and Carlsson and modified in order to define the static magnetic field to be applied during the OOPIC and IMP simulations.

3.1 Model description

OOPIC and IMP implement two different physical models both following the PIC paradigm.

OOPIC follows the PIC method described in Figure 3.1. The macro-particles are advanced step by step calculating their velocities under the effect of the electric and magnetic fields. During a OOPIC simulation particles advance following the equations of motion that are integrated by interpolating the fields from the mesh’s nodes to the particles’ positions. The fields are then recalculated on the basis of the particles positions and velocities, from which the model evaluate the plasma currents. The process is self-consistent and it is reiterated since the final simulation time.

To have an accurate description of OOPIC please consult the user manual and the reference papers.

The ICRH analysis involve a more complicate approach because the device does not have a azimuthal symmetry and second because the plasma magnetic field can not be neglected. For these reasons OOPIC can not be applied and a specific tool has to be realized. The model has been realized in Matlab due to its high versatility and the wide mathematical library which is there present.

The model (IMP) follows a simplified approach described by Ilin for the NASA/JSC activities: the ions are treated as real particles like the PIC paradigm, meanwhile both electric and magnetic fields are calculated on the basis of a fluid model. The software resolves a system of equations which has the plasma density as main input, that it is calculated by the particles trajectories.

IMP consists on a Electromagnetic plasma field solve based on the Cold Plasma Theory, iterating with a Monte-Carlo particles trajectories evaluator to calculate the plasma density from the particles’ motion and which is the main input of the field solve.

A starting family of macro-particles (following the PIC paradigm) is created on the left side of the simulation area. Their weight and velocity distributions are imposed trying to reproduce the measurements made downstream the helicon source of VASIMR and reported by Ilin et al. The test particles are then propagated.
from left to right applying them the electromagnetic field just calculated by the solve. In this way the routine can evaluate the plasma density along the ICRH tube.

3.2 OOPIC data flow

A full OOPIC simulation involves two distinct systems: a Linux powerful workstation where OOPIC is executed and a Windows or Linux platform equipped with Matlab and IDL where the OOPIC post-processing takes place utilizing the appropriate tools (ETOOM).

![Data flow of a OOPIC's simulation and post-processing](image)

4 SOFTWARE REQUIREMENTS

The tools that composed the software run under different systems: Linux/g++, Matlab and IDL. The user must provide the licenses, compilers and libraries for these languages. Concerning OOPIC simulations the workstation where the calculation is performed must be as powerful as possible. The possibility to use a cluster has been investigated with the hybrid PIC method (fluid electrons) which reduces the memory requested, but both solutions does not work under the specific requirements of the HDL simulations. Finally the software must respect stringent interface requirements between OOPIC and the post-processing tools and also with respect the magnetostatic builder.

4.1 Resource requirements

The software utilizes two systems: a powerful Linux workstation, where OOPIC is installed, and a Windows or Linux Workstation equipped with Matlab and IDL licenses where operate the OOPIC post-processing and execute the ICRH model prototype. The Linux version applied have been the FedoraCore4 and Mandriva2006.
To compile and install XOOPIC, we need the following public domain software packages:

- g++
- libg++

and the following libraries:

- libtc17.4.a (or later)
- libtk4.0.a (or later)
- libXpm.a
- libXGrafix2.50 (or later)

OOPIC does not require licenses because it is a free software from Berkeley University and there can be discharged (http://ptsg.eecs.berkeley.edu/). The OOPIC post-processing tools (ETOOM) work inside IDL and Matlab environment, so they require the appropriate licenses to run. During our study we have utilized the Matlab 6.1 and IDL 6.2 versions.

For the HDL simulations with OOPIC approximately $2 \times 10^6$ cells are needed to fill the domain and with almost 10 macro-particles per cell more than 1GB of memory will be used.

The simulations have been made utilizing workstations equipped with at least 2 GBytes of RAM memory and a minimum CPU clock of 2 GHz.

The required disk space must take care that the output files of OOPIC can be of 100 MBytes, so to collect the sequence of output files generated during a simulation the free space must be of the order of 20 GBytes.

4.2 Interface requirements

The main interface requirement is between OOPIC and the post-processing IDL and Matlab tools. The tools must read the output files of OOPIC that are in ASCII or binary format.

The ASCII files have a 1 line header where it is reported the time instant of the simulation with the format: 

```
##### time = 1.99999e-06
```

The following lines contain three columns: z and r positions and the field value.

The OOPIC binary (.dmp) files, that are read by the Matlab routine, has a data sequence which has been deduced by its manual and mainly analysing the source code, as follows:

**Initialization:**

4 char Version code

4 char Version code

1 int random number seed

1 int length of name

n+1 char the chars of the name

1 float simulation time

4 float Physical region covered

1 int Number of boundaries

//This next is a repeating block, repeating as many times as there are boundaries:

```
{ 

```
// This is the format for a Dielectric and DielectricRegion
{
1 int       number of datapoints
    physics/dielectr.cpp
1 int       (unused)
1 int       (unused)
4n float      x,y,Q(x,y),unused
    physics/dielectr.cpp
}

1 int       number of diagnostics
    physics/sptlrgn.cpp
// This next is a repeating block, repeating as many times as there are diagnostics: they must ALL follow this format:

// This is the format for a generic Diagnostic
{
4 float      dimension descriptor
    xg/newdiag.cpp (xs,ys,xf,yf)
l int       xlength
l int       ylength
l int       title length
    xg/newdiag.cpp
n+1 char      the title
    xg/newdiag.cpp
l int       history flag
    xg/newdiag.cpp

// additional stuff for a generic History, which all follow this format:
//  3 int as shown below, hist_num floats, 1 int n, 11 more ints, n floats.
l int       hist_num
    otools/history.cpp
l int       hist_hi
    otools/history.cpp
l int       alloc_size
    otools/history.cpp
hist_num   floats (the time array)
    otools/history.cpp

// All derived histories need to be in the following data format: 1 int n, 11 user-defined ints, n floats.

// additional stuff forming a Scalar_History
l int       hist_num
l int       comb
    xg/history.cpp
l int       n_comb
    xg/history.cpp
l int       take_state
    xg/history.cpp
hist_num   floats (the data array)
    xg/history.cpp

// additional stuff forming a Scalar_Ave_Local_History
l int         hist_num
l int         left_shift
    xg/history.cpp
l int         ave
    xg/history.cpp
l int         step
    xg/history.cpp
l int         take_state
    xg/history.cpp
7 ints       unused
hist_num   floats (the data array)
    xg/history.cpp

// additional stuff forming a Scalar_Ave_History
l int        hist_num
l int        left_shift
l int        ave
l int        step_ave
l int        take_state_ave
l int        comb
l int        n_comb
l int        take_state_comb
2 int        unused
hist_num floats (the data array)
    xg/history.cpp

// additional stuff for Vec_Pointers_History
l int        datasize = hist_num * vector_size
int        comb
int        n_comb
int        take_state
int        step
int        vector_size
(int unused)
hist_num  * vector_size floats (the data)

// additional stuff for Vec_Pointers_History_Ave
int        datasize = hist_num * vector_size
int        comb
int        ave
int        n_comb
int        take_state
int        step
int        vector_size
(int unused)
hist_num  * vector_size floats (the data)

// additional stuff for Vec_Pointers_History_Local_Ave
int        datasize = hist_num * vector_size
int        comb
int        ave
int        n_comb
int        take_state
int        step
int        vector_size
(int unused)
hist_num  * vector_size floats (the data)

// additional stuff for Vector_History
int        datasize = hist_num * vector_size
int        comb
int        n_comb
int        take_state
int        step
int        vector_size
(int unused)
hist_num  * vector_size floats (the data)

// additional stuff for Vec_Pointers_Local_History
int        datasize = hist_num * vector_size
int        comb
int        step
int        vector_size
(int unused)
hist_num  * vector_size floats (the data)

// additional stuff for JE_Region_History
int        datasize = x*y
int        Ave
int        x_array_size
int        y_array_size
(int unused)
x*y floats data

// additional stuff for Region_History
int        datasize = x*y
int        hist_hi
int        Ave
int        x_array_size
int        y_array_size
(int unused)
x*y floats data

Fields format:
"Fields.cpp"

1 int        J
1 int        K

if NOT ElectrostaticFlag:
{
    Repeating block J*K :
    {
    1 float     x location of these fields
    1 float     y location of these fields
    1 Vector3   intEdl(x,y)
    1 Vector3   intBdS(x,y)
    1 Vector3   l(x,y)
    }
    if EMDAMING > 0
        repeating block J*K {
        1 float     xloc
        1 float     yloc
        1 Vector3   intEdlBar(x,y)
        }
}

if BoltzmannFlag:
    J*K     Floats   Phi(j,k)

Neutral Gas Density
"NGD.cpp":
If MCCactivated:
    {
    1 int         J
    1 int         K
    1 int           isTIOn
    Repeating block J*K :
    {
    1 float     x location
    1 float     y location
    }
The third interface requirement concerns the magnetostatic builder (EMB). Its output file must be compatible with OOPIC and it must be composed of lines in the format x1 x2 B1 B2 B3, where x1 and x2 are ignored but must be present, B1 B2 and B3 are magnetic field components in Gauss. B1 B2 and B3 actually exist on the mesh points, and are read in the X2 direction most rapidly. (i.e., j=0, read k=0,k=1,k=2,...,k=K, j=1, read k=0,...k=K)
Appendix B

Temperature

The International System of Units considers as standard unit for the temperature the Kelvin (K). During plasma discharges the temperature is not so easy to be detected and defined due to the high energy of the particles and their electromagnetic behavior. Usually plasma physicists adopt the eV unit for the temperature, showing the direct dependence of this quantity on the kinetic energy of the charged particles.

The thesis follows this definition which is standard on plasma bibliography. The conversion between units is reported below:

\[
1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}
\]

\[
1 \text{ eV} / k_B = 11604.505 \text{ K}
\]

where \( k_B \) is the Boltzman constant.
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BIBLIOGRAPHY

18. Francis F. Chen, “Physical mechanism of current-free double layers”, report University of California, Los Angeles, California 90095-1594
35. A. V. Ilin1, F. R. Chang Diaz, “Modeling of ion cyclotron waves in VASIMR”,