

Development of Plasma Codes for the Design of Mini-Helicon Thrusters

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A compact low-power plasma thruster using high-efficiency radiofrequency sources is currently under development by the European consortium HPH.com “Helicon plasma hydrazine combined micro” (7th Framework Programme of European Union). The main objective of the HPH.com research is to design, optimize and develop a spacecraft thruster based on radiofrequency plasma source working in the helicon range, and investigate on applications to mini-satellites for attitude and position control. The design of the thruster is pursued with a synergic theoretical and experimental approach, also thanks to the development of highly innovative plasma codes. These codes are allowing for the first time a detailed and quantitative characterization of the helicon physics involved in the RF coupling, and also on the physical mechanisms involved in the the plasma acceleration.

In the present work we will give a brief overview of the four main codes developed during HPH.com. The two codes “Wavecode” and “EQM” allows to solve the RF electromagnetic fields occurring within the source and the macroscopic transport of plasma within the discharge at equilibrium. When coupled together, they allow a consistent evaluation of the discharge balances. The electromagnetic Particel-in-Cell “PartyWave” in cylindrical coordinates allows the evaluation of non-linear effects on the RF coupling. Finally, the 3D Particle-in-Cell F3MPIC will be briefly presented. It’s a generic and versatile three-dimensional Particle-in-Cell working with a 3D mesh of tetrahedra moving particles in time domain, used for the thruster optimization, and working both in electrostatic and electromagnetic conditions, in kinetic-kinetic or hybrid kinetic-Boltzmann conditions. Finally few results obtained from the codes concerning the design of a low-power mini helicon thruster will be shown.

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Nomenclature

c	= speed of light 29979458 [m/s]
$\Lambda_{1,2}$	= wavelength of the full perpendicular mode, 1: Helicon, 2: TG [rad/m]
$n_{\parallel}$	= parallel wave number, $n_{\parallel} = k/k_0$
k	= parallel wave number [rad/m]
k_0	= vacuum wave number [rad/m]
ω	= antenna working frequency [rad/s]
ω_{ce}	= electron cyclotron frequency [rad/s]
ω_p	= plasma frequency [rad/s]

I. Introduction

The project HPH.com Helicon plasma hydrazine combined micro of the 7th Framework Programme EU (European Union)(grant n. 218862), operated by an European consortium, aims to develop a compact low-power plasma thruster using an high-efficiency plasma source. The main objective of the HPH.com research is to design, optimize and develop a space plasma thruster based on helicon radio-frequency technology, and its application to a mini-satellite for attitude and position control¹⁻⁵. Moreover a detailed feasibility study will be also conducted to evaluate the possibility of using the plasma thruster to heat and/or decompose a secondary propellant, in order to develop a two-mode thruster, operating at high-efficiency-low-thrust in the plasma mode, and at low-efficiency-high-thrust in the secondary-propellant plasma-enhanced mode. The target applications are small satellites operating with an available propulsion power in the range of 50 W.

The main steps of HPH.com can be resumed as following: (a) deep numerical-theoretical investigation through dedicated plasma-simulation tools; (b) extensive experimental campaign to validate the codes, to investigate the physical phenomena involved and to proof thruster performances; (c) the development of a full-scale thruster-prototype to be mounted on board of a mini-satellite to demonstrate technology feasibility; (d) the study of all the critical issues related to the application to mini-satellites; (e) the design and manufacturing of the mini-satellite mock up including all critical components; (f) analysis of scaling law to lower and higher power. As a final step of the project, a detailed analysis will be conducted, in order to evaluate the possible applications of the thruster in space missions requiring low-thrust and accurate attitude and position control.

Four main codes have been developed and are under optimization within HPH.com, used for the helicon thruster design and its optimization. Within an helicon source, the plasma is magnetized in order to enhance the lateral confinement and to permit the propagation of plasma waves (helicon and cyclotron waves) excited by the RF antenna. Differently than industrial helicon sources, an high kinetic energy must be delivered to ions. Furthermore, the plasma-wave coupling has to be optimized in order to maximize the ionization fraction. This makes necessary a deep understanding of the physical mechanisms involved, of both the electromagnetic coupling and the transport processes. The innovative set of codes developed during HPH.com are allowing the detailed analysis of the thruster behavior.

Usual plasma codes⁹⁻¹⁰ are not completely suitable for HPH.com project constraints. The codes developed into HPH.com frame required a complex non-convex geometries that are not easy to be treated in a structured mesh. In particular the antenna geometry is important because is necessary to impose the current distribution on it to calculate the exact wave propagation in near field so a flexible unstructured mesh becomes mandatory for helicon antennas.

Section II will describe shortly the codes Wavecode, EQM and PartyWave, used for rapid design with short computational times. Section III will give an overview of F3MPIC, the 3D Particle-in-Cell used for the detailed design and optimization of the system. Finally in Sec. IV a brief discussion on the design of a low-power helicon thruster will be given.

II. Design codes

In practical applications, plasma discharges have often a cylindrical shape. Since the same axis-symmetry configuration is used in the thruster two simplified design tools have been developed, useful for a rapid evaluation of the discharge properties. The two tools, called Wavecode and EQM, solve two connected problems related to the equilibrium conditions of the plasma discharge. From the iteration of the two codes

together, the absolute values of the discharge are calculated. The presence of non-linear effects involved during the RF coupling is investigated using PartyWave, an innovative three-dimensional electromagnetic Particle-in-Cell combining a time-domain 3D particle mover with a 1D frequency-domain electromagnetic solver.

A. Wavecode

Wavecode calculates the electromagnetic fields propagating inside the plasma column, by solving the two Maxwell wave equations (the Faraday-Lorentz and Ampere-Maxwell equations) in cylindrical coordinates plus a generalized Ohms law. The plasma is represented by the classical Stix cold plasma tensor. The radial profiles of plasma density, neutral pressure and electron temperature are given as inputs. The fields are solved along the radius of the plasma cylinder, and Fourier transformed along the other spatial directions and in time. WaveCode allows the calculation of the electric and magnetic field along the radial coordinate, plus important derived quantities like plasma currents and deposited power. As far as Wavecode is conceived as a standalone tool, it has been validated against different analytical test cases so far; recently, the benchmark has been extended with a numerical cross-check between Wavecode and DISEMAG. DISEMAG⁶ solves the electromagnetic dispersion relation in the complex domain of the wavenumber and includes a simple model for keeping into account the collisional damping. Its primary objective is to study the propagation of electromagnetic waves in plasmas for fusion applications. Wavecode has been compared successfully to DISEMAG in uniform, non-uniform and collisional plasma models.

B. EQM

EQM solves the macroscopic transport of plasma and neutral species and the equilibrium of the discharge for a given deposited power. As in Wavecode, it uses a one-dimensional radial coordinate. EQM⁷⁻⁸ allows the evaluation of the radial configuration of the plasma column as forced by the electromagnetic waves. More specifically, it calculates the profiles of plasma drift velocity, plasma potential, plasma density, neutral pressure and electron temperature. The code has been used to study the effect of radio-frequency power deposition inside the plasma column of the thruster. The analysis revealed the great complexity and interconnection of the phenomena involved within the discharge, and particularly that wave propagation phenomena and transport phenomena of all species (neutral and charged) are tightly linked together, and they concur to the global equilibrium conditions of the discharge.

C. PartyWave

PartyWave is a particle-based tool for the analysis of distribution functions of plasma species, especially for the study of electron distribution functions and the possible appearance of hot tails at low pressures. This code allows the evaluation of finite-temperature and wave-particle non-linear effects. The code is an electromagnetic Particle-in-Cell, with a 1D radial solver of Maxwell equations in frequency domain, and a 3D particle mover in cylindrical coordinates and time domain. This coupled code can evaluate the plasma currents in two different ways: by modeling the plasma as a tensor, or by modeling the plasma using particle discretization. As a matter of fact, this double configuration got the chance to do the benchmark of PartyWave code. At first, the coupled code run evaluating the plasma currents by means of a cold plasma Stix tensor and then it run simulating plasma as charged particles moving in an electromagnetic field; finally, the converged results, in terms of plasma current density, have been compared showing a good agreement. The advantage of this code is to provide a fast 1D EM solver for preliminary design to identify configurations that could analyzed in details by means of F3MPIC.

III. Optimization code: F3MPIC

F3MPIC is a three-dimensional plasma Particle-in-Cell code with an unstructured mesh of tetrahedra coupled with a 3D FEM electrostatic and electromagnetic solver in time domain. It can manage geometries of arbitrary complexity thanks to the mesh of tetrahedra, with an arbitrary number of plasma species, both charged and neutral. The geometry of the simulated device can be easily imported from a generic 3D CAD tool. F3MPIC was developed for the optimization and detailed design of helicon and general-purpose

spacecraft thrusters. The code is structured with several parts and features, summarized in the next following subsections.

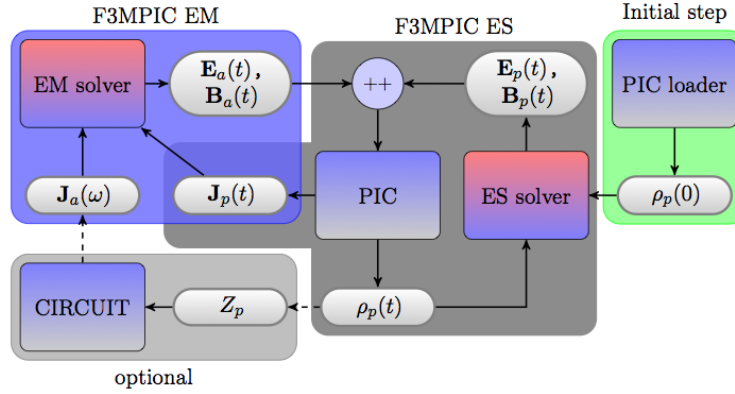


Figure 1. F3MPIC structure

A. Particle-in-Cell

The code evaluates the particles trajectories of an n-species plasmas with a Boris-Leapfrog scheme under the action of electromagnetic fields generated by the plasma itself and by other external sources. An arbitrary number of charged species can be treated. Both plasma and non-plasma regions can be managed. At each time step, charge and current densities on nodes of the unstructured mesh are obtained by means of appropriate weighting schemes.

B. Unstructured Mesh

An unstructured mesh composed of tetrahedra has been chosen for its larger flexibility to treat with arbitrary-complexity geometries in three dimensions with respect to regular Cartesian cells. Particle tracking locates particles in the mesh, using a fast and simple priority-sorting algorithm. The main effort of the development of F3MPIC was devoted to realize a robust and fast algorithm for tracking each particle inside the unstructured mesh. Several different algorithms for the management of exception case have been implemented to avoid long searching loop. The topology of the mesh graph is obtained by means of an efficient front advancing scheme to allow a low computational cost. As a result, devices with shapes of arbitrary complexity can be easily treated, as for example imported from a 3D CAD model.

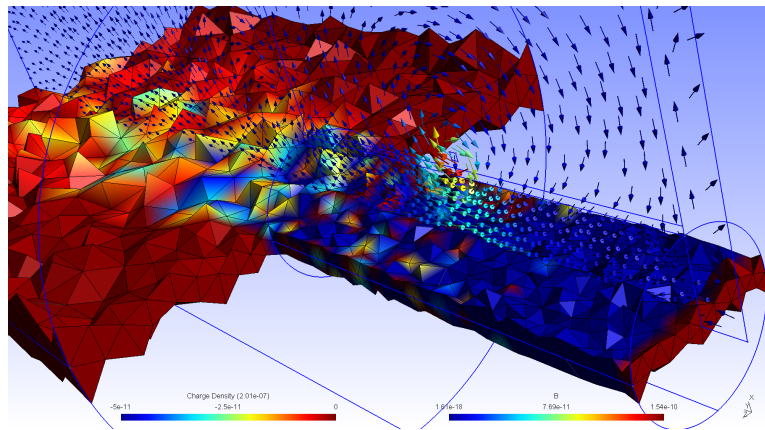


Figure 2. F3MPIC tetrahedral mesh with superimposed fields

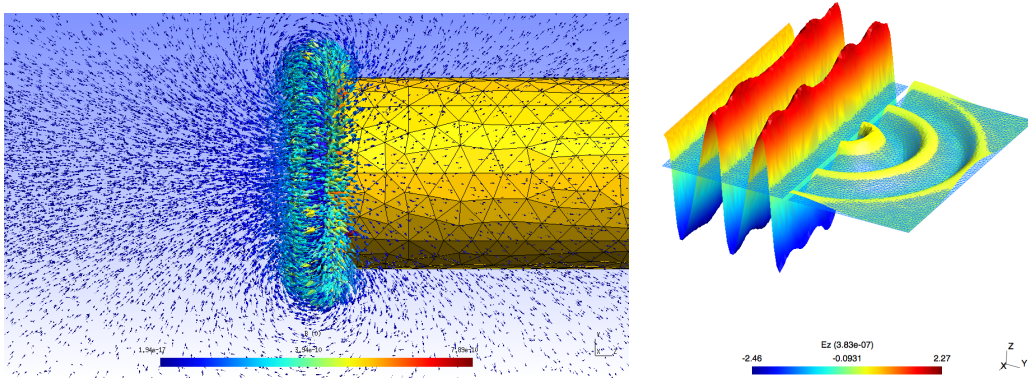


Figure 3. Electrostatic and electromagnetic solution of fields

C. Consistent solutions of electrostatic and electromagnetic fields

Static and dynamic electromagnetic interactions among charged particles are treated consistently. Their electrodynamics is solved at each time step together with the solutions of their fields plus the fields generated by any assumed external source. The electromagnetic problem can be electrostatic, magnetostatic or electromagnetic in nature. For example, a static magnetic field of arbitrary shape can be over-imposed on the simulated volume, in order to study the plasma dynamics inside fields of arbitrary topology. Furthermore, the presence of oscillating current sources, like antenna or electromagnetic emitters, can be accounted for, consistently with the full set of Maxwell equations. The solution of the electromagnetic fields produced by the antenna current and by particle motion is implemented through linking of the particle solver to an electromagnetic finite-element solver.

D. Boltzmann electrons

In some cases, the full-kinetic treatment of all the plasma species is unneeded, especially in all cases when the ion dynamics is more relevant than electron dynamics. In these cases a Maxwell-Boltzmann treatment of electrons is appropriate. The Boltzmann-electrons formulation has been included in the Poisson electrostatic solver of F3MPIC as an optional tool that can be activated on demand.

E. Interaction of charged particles with neutrals and collisions

F3MPIC can manage also not-charged particles. The collision between charge particles and neutrals involves a MonteCarlo Collision (MCC) tool¹¹. The cross-sections of the involved species need to be provided from literature, depending on the chemical components to be simulated. To properly simulate the correct interaction between species with different macroparticle weight (e.g. due to computational convenience of using different weights if their densities are appreciably different) the concept of time-varying-weight particle is implemented.

F. Computational efficiency

A big effort in the development of the code has been put on optimization of linking efficiency, in order to minimize computational time. In particular, the parallelization of the electromagnetic solver and the building of the solver as a unique program revealed to be key issues during the code development. F3MPIC uses and/or integrates several open source codes for management of subtasks. A big effort was spent in the parallelization of the code. F3MPIC is multiplatform (Linux, AIX, Mac OS X) and was tested on High Performance Computing (HPC) facilities (CINECA, ENEA-Grid).

G. Boundary management

Different types of boundary conditions are implemented, both for particles and for the field solver: particle emitter, neutral injectors, particle exit port, floating and biased conductor and simple dielectric.

High-density plasmas are known for their stiff requirements from the computational point of view. In fact, high-density plasmas have a small Debye length that in turn means small sizes of the spatial grid and thus huge meshes. In order to avoid these problems, a logical sheath boundary condition has been implemented.

H. Diagnostic

A large amount of different diagnostics has been implemented to validate the code and to provide optimization tools to identify the better thrust configuration for HPHcom requirements. Electric and magnetic fields can be recorded at each time step and it is also possible to have a wide diagnostic tools for particles. Numerical probes can be used in code (also with arbitrary internal control surfaces) to calculate the velocity distribution function of each species and the required data as temperature, density, flux through the surface, current, emittance, beam divergence, kinetic energy, potential, phase space, etc.

I. F3MPIC validation

F3MPIC has been validated on all the single parts of the code involving its fundamental physics. Validations on more general cases are now undergoing, and they refers to cases of practical interest. The electrostatic solver has been widely tested, both as a standalone Poisson solver, and coupled with the particle section of the code. Some validation tests include: plasma sheath formation, diffusion time of charged species, the plasma drift subject to a constant electric field, etc. The electromagnetic solver has been tested with a set of standard literature tests, like EM wave diffraction, reflection, and interference. Also the particle mover has been widely tested, in order to estimate the errors on particle orbits, the stability of the calculated particle trajectories subject to simple and known forcing fields, the initial distribution of particle positions and velocities, and the reliability of the particle tracker during the transit between tetrahedra.

IV. Low-power helicon thruster

The design of a mini-helicon thruster working at low-power presents most of the problems involved in the design of helicon sources used for industrial applications, except that the ionization efficiency and the electron temperature have to be maximized despite the low electric power, in order to reach high specific impulses. As a propulsion system, an helicon thruster can be simply thought as composed by two stages, the plasma source and the acceleration stage.

Small source volumes in the range of 1.0-20 cm³ are required in order to operate with high-specific-powers of the order of 1-10 MW/m³ typical of the helicon regime. A cylindrical source of 2 cm diameter has been selected for the numerical and experimental investigations. The power coupling physics of the thruster has been studied thanks to the two codes Wavecode and EQM. The power deposition from the RF antenna to the plasma column is mediated by the excitation of two coupled plasma waves, namely the Helicon wave (fast wave) and the Trivelpiece-Gould wave (slow wave). The two plasma waves are coupled together, and in general conditions they occurs simultaneously inside the plasma volume. Most of the power is transferred from the RF field into the plasma by the rapid absorption of the slow TG wave, which is rapidly dumped in a small region near the boundary of the plasma cylinder. Furthermore, the plasma-wave coupling in cylinders of small volume has to account for finite-boundary effects of the two coupled plasma waves propagating inside the plasma column. In helicon conditions the local relation among the perpendicular and the parallel wavenumber of the two coupled plasma waves is expressed by the following relation:

$$\Lambda_{1,2}(n_{\parallel}) = 2\pi \left[n_{\parallel}^2 \frac{\omega_{ce}^2}{4c^2} \left(1 \mp \sqrt{1 - 4 \frac{\omega_p^2}{\omega_{ce}^2} \frac{1}{n_{\parallel}^2}} \right)^2 - n_{\parallel}^2 \frac{\omega^2}{c^2} \right]^{-1/2} \quad (1)$$

where $\Lambda_{1,2}$ is the wavelength of the full perpendicular mode (plasma and vacuum), the subscript “1” stays for Helicon and “2” for Trivelpiece-Gould mode respectively, and $n_{\parallel}$ is the parallel wave number, the other symbols having the usual meaning. The dispersive properties of the plasma waves have been investigated thanks to the code Wavecode, which allows the evaluation of the stationary electromagnetic fields excited

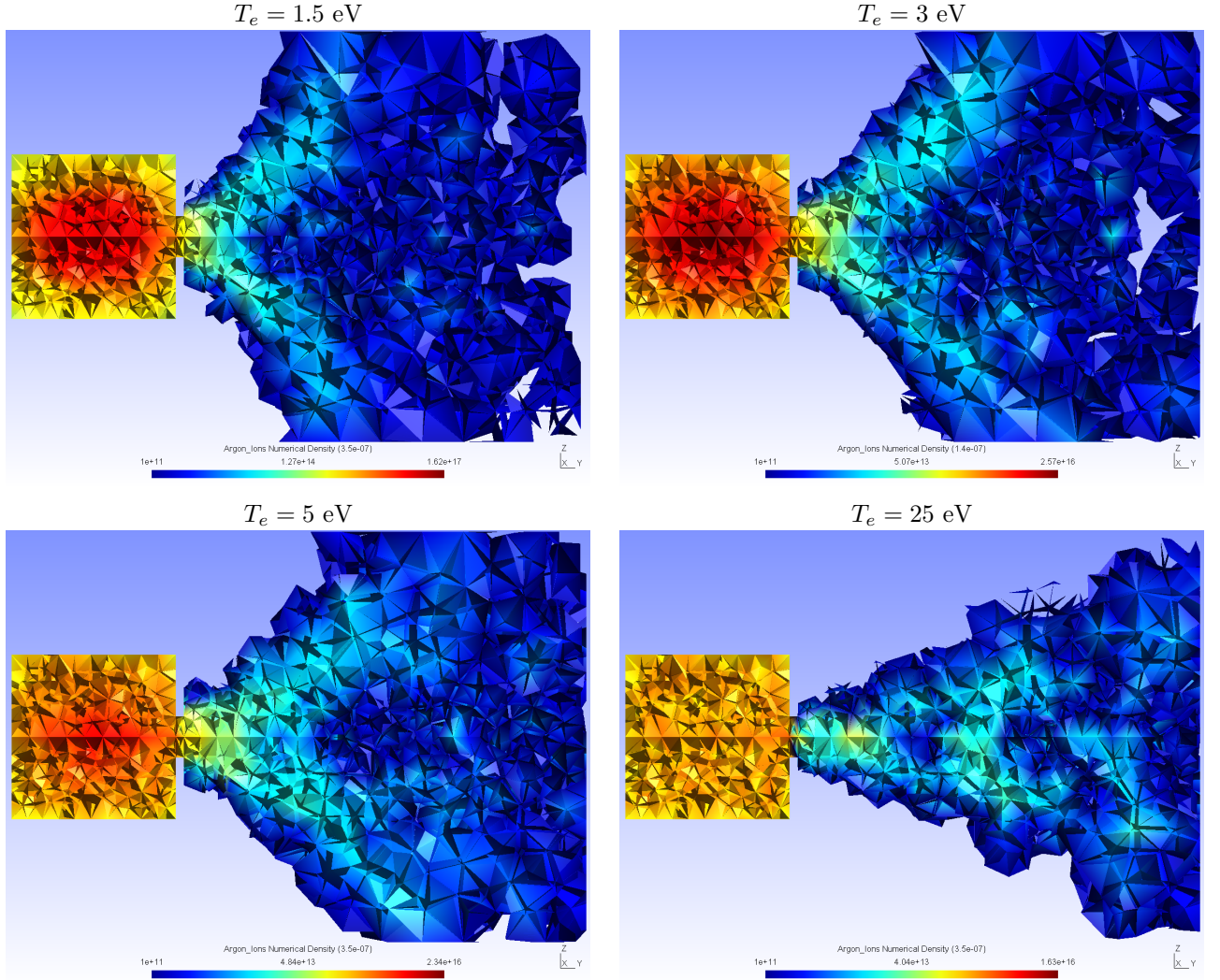


Figure 4. Plume expansion at four different electron temperatures, in a simulation with light ions $M_i = 10m_e$

by the RF antenna and the evaluation of the deposited RF power. In highly-magnetized conditions, the helicon wave propagates at low perpendicular modes. The associated radial wavelength is not compatible with sources of small radii of the order of centimeters. As a consequence, the helicon mode is not an efficient way for power deposition in small cylinders. Most of the power is deposited by the Trivelpiece-Gould mode, which is rapidly dumped at the external boundary of the plasma column. The picture changes when the magnetostatic field is reduced down to values where the perpendicular modes are compatible with the radial extension of the discharge. Peaked power coupling have been found within the range of 40-80 Gauss.

The plasma produced in the source cylinder is then ejected outside thanks to a small circular aperture (diaphragm) placed on one basis of the source cylinder. Ions are produced at rest inside the source, and then they drift outward gaining kinetic energy from the local ambipolar potential which is scaled on the electron temperature. Ions are accelerated outside at velocities of the order of the ions acoustic velocity, plus the kinetic energy gained on the sheath potential drop. The detailed dynamics of plasma acceleration at the exit section of a helicon thruster is nowadays an open and strongly debated question. Several experimental observations, and different theories of explanation have been proposed. In some cases a current-free double layer has been observed and several explanations on its formation have been proposed.

We have studied the dynamics of ion acceleration outside the thruster thanks to the 3D Particle-in-Cell F3MPIC, here we show the preliminary results obtained. Electrons are treated as Boltzmann, ions as kinetic particles. Fields are purely electrostatics. An homogeneous Maxwellian plasma is produced inside

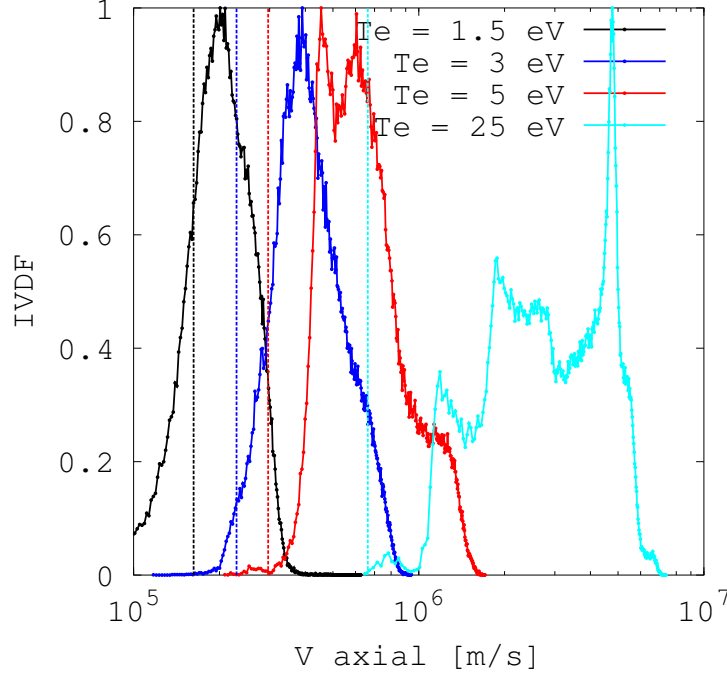


Figure 5. Ion velocity distribution function at the exit section of the thruster, at four different values of electron temperatures, in a simulation with light ions $M_i = 10m_e$. For each curve the ion acoustic velocity is marked with a vertical line of the same color.

the cylindrical volume of 2 cm diameter and 2 cm length. The plasma is free to expand in a vacuum chamber through a 5 mm diaphragm. Figure 4 shows the ion particle density (logarithmic scale) for four different electron temperatures inside the source of $T_e = 1.5, 3.0, 5.0, 25.0$ eV. The associated increase of plasma potential rises the potential drop at the exit section, imparting more energy to the ions. The divergence of the ejected plasma beam decreases at higher electron temperatures. In Fig. 5 the stationary ion distribution functions of ions crossing the exit diaphragm, corresponding to the four cases of Fig. 4 have been reported. Ion acoustic velocity is marked with a vertical line of the same color of the corresponding IVDF. At low electron temperatures (cases at 1.5 eV and 3.0 eV) the IVDF of outgoing ions is a drifted Maxwellian, with the velocity peak at 1.2 and 1.7 times higher than the ion Bohm velocity. Non-linear effects appear when the electron temperature is increased. The IVDF becomes multi-peaked and spread in the velocity space. Electron temperatures as high as 25 eV have never been observed in real experiments. Common helicon experiments are done using Argon gas, with maximum electron electron temperatures of 5-10 eV at low pressure. Double-peaked ion distributions have been observed by several groups^{12,13}. The same double-peaked IVDF has been observed by our group at electron temperatures in that range. Further quantitative investigations and sensitivity analysis will confirm this result.

V. Conclusion

In this paper the four codes developed in the framework of the HPH.com project have been presented. The codes, differently from what has been done in the past, are allowing for the first time the investigation of low pressure radiofrequency plasma sources considering both the electromagnetic wave propagation and the macroscopic transport of plasma species within the volume. Two family of codes have been designed, the simplified codes for plasma-source design at low computational time, and the three dimensional Particle-in-Cell for the detailed optimization of the thruster. Finally, examples of physical investigations made possible by the new codes have been presented. Their applications to design and optimization of mini-helicon plasma thruster have been highlighted.

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