Design of 50 W Helicon Plasma Thruster

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Abstract: This paper is focused on the description of simulation codes developed to design a helicon plasma thruster for a small satellite under development in the research project Helicon plasma hydrazine combined micro (HPH.com) conducted within the 7th Framework Program of the EU by a European consortium.

I. Introduction

THE objective of the HPH.com research program (Helicon Plasma hydrazine combined micro) 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 control (Figure 1). 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,

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in order to develop a two mode thruster, high-efficiency low-thrust plasma-thruster mode and a low-efficiency high-trust secondary-propellant-plasma–enhanced mode.

Target of this research program are applications in the range of 50 W power. Expected thruster performance are: 1.5 mN of thrust and $I_{sp} > 1200$ s. HPH.com will develop through the following steps:

a) Deep numerical-theoretical investigation through dedicated plasma-simulation tools;

b) Extensive experimental campaign to validate codes, to investigate the physics phenomena involved and to prove thruster performance;

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 a mini-satellite;

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 results of the project, a detailed analysis will be conducted in order to evaluate the possible application of the thruster in space missions requiring low-thrust accurate-attitude and position control. In this paper it will be presented the set of code used for thruster design.

II. Codes Description

Several codes will be developed in the frame of HPH.com in order to design the thruster and to optimize it. Codes for thruster design allow extensive analysis of the apparatus in a reasonable computational time. More detailed optimization codes will allow for detailed thruster design once a preliminary configuration has been selected. A set of software tools for designing the plasma of the helicon plasma thruster has been developed, each code accomplishing a dedicated subtask. The main software requirements of these codes are to:

• Simulate the propagation, absorption and mode conversion of all relevant waves in the plasma;

• Compute how much plasma is produced, and at what plasma temperature, for a given amount of power absorption;

• Compute the thruster specific impulse and thrust with a given plasma source;

• Be computationally efficient to allow a large parameter scan in reasonable time and with reasonable computational resources.

The software tools will be used to systematically compare helicon waves launched with different axial and azimuthal mode numbers to find the one that gives optimal power absorption, and which input power to the antenna is needed to achieve a specified specific impulse and thrust. With the optimal mode numbers identified, the antenna that excites the desired mode is designed. Specifically, we used the XOOPIC[2] code to compute the specific impulse and thrust and an existing zero-dimensional model to calculate the plasma production.

New codes has been developed to achieve the first requirement above: to simulate wave propagation, absorption and mode conversion. The codes are:

(1) a global source code: it is a zero dimensional time dependent radiative model of the plasma source expressly

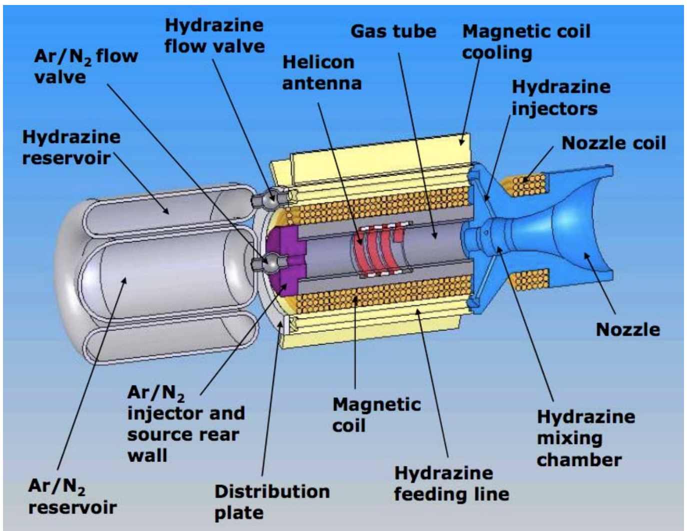


Figure 1. Schematics of the HPH.com helicon thruster.

developed to analyze globally the source behavior;

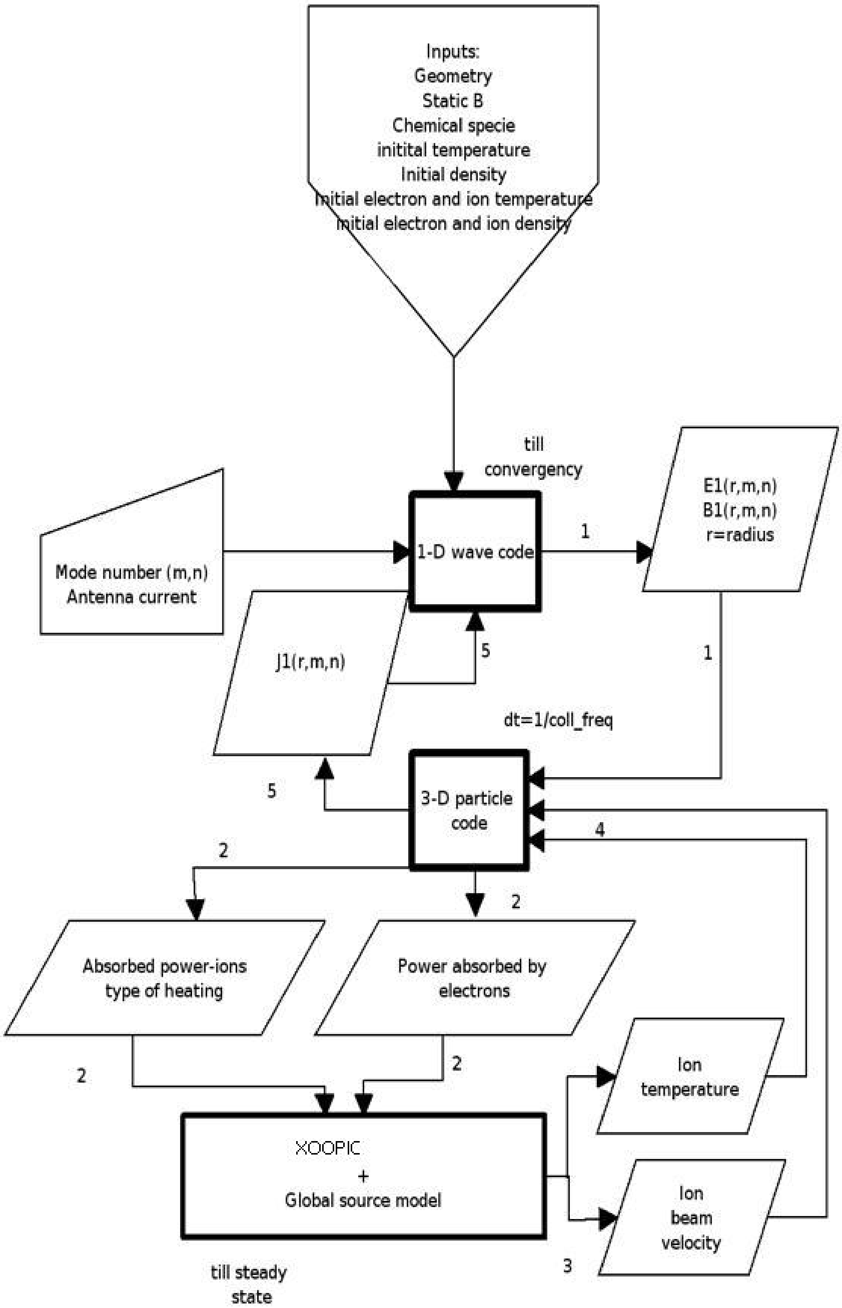


Figure 2. Flow chart of the flux of information between the codes.

(2) 1-D wave code combined with a 3-D particle code expressly developed to analyze the power coupling within the source.

III. Quick-Source

A zero-dimensional global model (volume-averaged) of the helicon plasma source has been developed. Such global model (named "QuickSource") implements a simplified collisional-radiative model of Argon and accounts for mass and energy balances in the control volume. Isentropic flow and sheath losses are also simulated.

A highly simplified Argon atomic model has been developed by averaging those energy levels that appear close to each other. Such minimal model includes the Ground Levels of Ar I, Ar II and Ar III plus a few excited levels for Ar I and Ar II, summoning to 12 different energy levels.

The important processes that are taken into account are the following:

a) excitation and de-excitation induced by electronic impact
b) electron-induced impact ionization
c) radiative de-excitation
d) radiative recombination

Minor processes are disregarded for the sake of simplicity:

e) three-body recombination
f) radiative excitation (hypothesis of optically thin plasma)
g) excitation and ionization induced by heavy particles impact

QuickSource allows for a generic non-Maxwellian distribution function for electrons, assuming isotropy in velocity space. Hence, it works with the Electron Energy Distribution Function (EEDF), the shape of which can be defined a priori, or calculated self-consistently using a simplified Boltzmann's equation.

In helicon plasma sources the EEDF is often far from Maxwellian, and there is currently much interest in understanding whether this condition may affect the propulsive performances of a Helicon Thruster [1]: if so, this fact should be exploited in the optimization phase. Hence, the peculiar capacity to provide for a fully-generic non-maxwellian EEDF is the big advantage of QuickSource over the common global models applied to plasma sources and thrusters [7,8]. In order to account for sheath losses in a non-Maxwellian plasma, the generalized sheath model of Amemiya has been implemented [9].

From the EEDF the mean kinetic electron energy $\langle\varepsilon\rangle$ may be obtained by integration:

$$\langle\varepsilon\rangle = \int_0^\infty \varepsilon\ F(\varepsilon)\ d\varepsilon$$

Now, the "energy parameter" α is introduced as the ratio between the actual electron kinetic energy and the mean value just defined:

and this new quantity can be regarded as an independent variable for the "Energy-Parameter Function" (EPF):

$$\alpha = \frac{\varepsilon}{\langle\varepsilon\rangle}$$

which has two interesting properties:

1. from the EEDF it inherits the common normalization to unity

$$f(\alpha)d\alpha = F(\varepsilon)d\varepsilon$$

2. moreover, the mean value of the energy parameter is unity, too:

$$\int_0^\infty \alpha f(\alpha)d\alpha = 1$$

This way, the EPF is a "pure shape function" that can parametrized as Maxwellian, bi-Maxwellian, Druyvestein-like, or whatever, or it can come directly from experimental measurements. An explicit formula to obtain the EPF from the more common EEDF is the following, once the mean kinetic energy has been computed:

$$f(\alpha) = F\left(\langle\varepsilon\rangle\alpha\right)\langle\varepsilon\rangle$$

The mean kinetic energy is now an independent variable, and the EPF completes the normalizing process that started when deriving the EEDF from the isotropic velocity distribution function:

$$f(v) \Rightarrow \begin{bmatrix} F(\varepsilon) \\ n_e \end{bmatrix} \Rightarrow \begin{bmatrix} f(\alpha) \\ n_e \\ \langle\varepsilon\rangle \end{bmatrix}$$

This allows for both the density and the mean kinetic energy of electrons to be computed using standard global balances over the spatial domain, i.e. the continuity and energy equations, without restricting the EPF to any particular shape. Hereafter are given some analytical expressions for the more typical Energy Parameter Functions:

- Maxwellian:

$$f(\alpha) = 3\sqrt{\frac{3\alpha}{2\pi}}\exp\left(-\frac{3}{2}\alpha\right)$$

- Druyvestein:

$$f(\alpha) = x\frac{\left[\Gamma\left(\frac{5}{2x}\right)\right]^{\frac{3}{2}}}{\left[\Gamma\left(\frac{3}{2x}\right)\right]^{\frac{5}{2}}}\exp\left[-\left(\frac{\Gamma\left(\frac{5}{2x}\right)}{\Gamma\left(\frac{3}{2x}\right)}\alpha\right)^{x}\right]$$

where x is a free parameter and Γ is the gamma function. For x=1 the maxwellian distribution is obtained

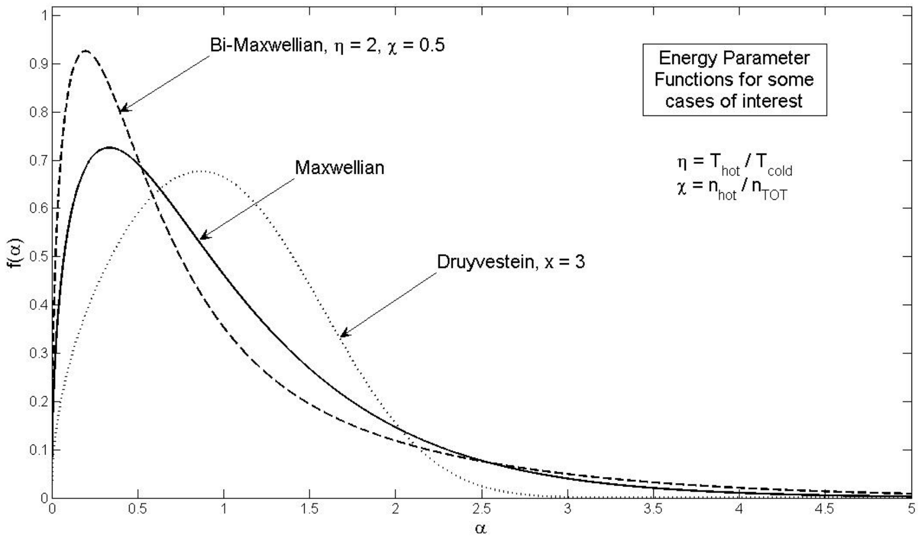
- bi-Maxwellian:

$$f(\alpha) = 3\sqrt{\frac{3}{2\pi}}\left[\frac{\chi_1}{\beta_1}\sqrt{\frac{\alpha}{\beta_1}}\exp\left(-\frac{3}{2}\frac{\alpha}{\beta_1}\right) + \frac{\chi_2}{\beta_2}\sqrt{\frac{\alpha}{\beta_2}}\exp\left(-\frac{3}{2}\frac{\alpha}{\beta_2}\right)\right]$$

where the free parameters are defined as follows:

$$\chi_1 = \frac{n_1}{n} \qquad \beta_1 = \frac{\langle\varepsilon\rangle_1}{\langle\varepsilon\rangle} = \frac{\eta}{\eta\chi_1 + \chi_2} \qquad \eta = \frac{T_1}{T_2}$$
$$\chi_2 = \frac{n_2}{n} \qquad \beta_2 = \frac{\langle\varepsilon\rangle_2}{\langle\varepsilon\rangle} = \frac{1}{\eta\chi_1 + \chi_2}$$

The aforementioned EPFs are shown in the next figure.



If one wants to evaluate the EPF self-consistently rather than imposing it a-priori, this may be accomplished by coupling the Collisional-Radiative model to a modified Boltzmann's equation. Since these two models act on very different time scales, they are allowed to evolve independently according to the example of Rockwood [6]:

1. the Collisional-Radiative model converges to steady-state using a fixed EPF;
2. the densities of all species populations plus the density and mean energy of electrons are passed to the modified Boltzmann's equation, which is time-integrated to steady-state maintaining constant densities and temperature;
3. the new EPF is passed back to the CR-model, and the process is iterated until convergence (see next figure).

QuickSource accepts as input the geometry of the source, the intensity of the axial magnetic field and the neutral inflow. In the fixed-EPF mode, the input RF power is calculated by the Wave+Particles codes, whereas in the Boltzmann mode the same codes provide also a power distribution function for electron heating.

Basically, QuickSource outputs are the densities of Argon population at each energy level, the mean electron energy and the EPF shape (in Boltzmann mode). Since QuickSource also provides line intensities of a simplified Argon spectrum, preliminary results are used to define the experimental diagnostics at Cisas Helicon Source

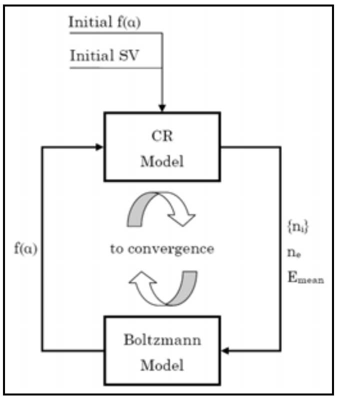


Figure 1. Schematics of the Quick Source cycle.

experiment, and to interpret the spectroscopy results.

QuickSource is undergoing validation against more sophisticated numerical tools by LPGP-Paris and it will be used as a fast optimization tool for the preliminary design of the Helicon Double Layer Thruster.

IV. Wavecode 1D

Wavecode, which is specifically designed for the treatment of radiofrequency wave excitation and propagation in cylindrical plasma source, solves Ampere's circuital Law and Faraday's Law of induction in 1-D (radial only) and in the frequency domain, in order to obtain the values of the Electric field and Magnetic field acting on plasma particles. In the governing equations, which follow:

$$\nabla \times \mathbf{E} = i\omega\mathbf{B} \tag{1}$$

$$\nabla \times \mathbf{H} = i\omega\mathbf{D} + \mathbf{J} \tag{2}$$

each quantity is assumed to vary as $e^{i(m\theta + kz - \omega t)}$ and the $\hat{\mathbf{z}}$ axis is aligned with the DC equilibrium magnetic field: $\mathbf{B}_0 = B_0\,\hat{\mathbf{z}}$.

This set-up allows for very low computational time without loosing significative information along the azimutal θ and axial z coordinate since each frequency is related to a specific wave mode which is periodical along θ and z.

Moreover, for the geometry and the input RF power levels considered, relatively weak fields are expected so that: the antenna spectrum can be described as a linear superimposition of individual modes, all waves of interest have the same frequency as the driving antenna current and, finally, simplified constitutive relations can be used to close the electromagnetic problem, which means that $\mathbf{D} = \varepsilon\mathbf{E}$ and $\mathbf{B} = \mu\mathbf{H}$.

Last but not least, it is worth noticing that in the RHS of Eq (2) (Ampere's law) the current density $\mathbf{J}$ should take into account both the antenna current density and the plasma current density. One can split $\mathbf{J}$ into $\mathbf{J}_a$ (antenna current) and $\mathbf{J}_p$ (plasma current). Then one could model $\mathbf{J}_p$ by extending the dielectric tensor ε in this way:

$$\varepsilon = \varepsilon_0 \begin{bmatrix} K_1 & K_3 & 0 \\ -K_3 & K_1 & 0 \\ 0 & 0 & K_2 \end{bmatrix} \tag{3}$$

This is the canonical way of doing it in plasma-wave codes, but there are many disadvantages, and it's only convenient for cold plasmas.

We want our code setup to directly calculate $\mathbf{J}_p$ with a 3D Particle Code that uses the fields from the Wavecode to move charged particles in the plasma, instead of trying to make the dielectric tensor model it. This will make it much easier to fully take into account all kinetic effects (finite gyro radius, non-Maxwellian particle distributions, etc...). In Wavecode the radial derivatives is approximated by second-order finite differences scheme in a staggered mesh of Yee type, while the azimuthal and axial derivatives is modeled by wave numbers. The discretized differential equations become a linear system with complex data type and a square, sparse matrix. This kind of problem will be solved by the implementation into the code of the MUltifrontal Massively Parallel Solver (MUMPS), which solves linear systems with a direct method in a computationally efficient and numerically accurate way.

The output provides time-harmonic electromagnetic fields generated by the antenna, both in vacuum and plasma conditions; vacuum solutions are calculated imposing PML boundary conditions, while plasma ones are obtained calculating self-consistently the plasma current driven by the waves with 3D Particle Code.

Wavecode simulations are currently running both in the standalone configuration (plasma current modelled by dieletric tensor) and in the coupled one (plasma current evaluated by 3D Particle Code). As a matter of fact, a detailed quantitative comparison has been done to make an independent benchmarking of the Wavecode. Analytical validations have been completed so far and other validation test are running.

V. Particle Code

The Particle Code computes the driven current of the species in the helicon source (ions and electrons) in response to the wave field produced by the Wavecode. Full 3D geometry and time domain are used for the orbit integration and current density calculation.

The Particle Code implements a Scrambled Halton Sequence quasi-random numbers generator and a Gaussian number generator to load particles with a specified initial density distribution and Maxwell-Boltzmann speed distribution.

Particles subjected to Lorentz force are pushed in time and space using different integrators. The code currently implements a custom 4th order explicit Runge-Kutta, in both Cylindrical and Cartesian coordinates with rotations, and a variation of the Buneman-Boris Leapfrog integrator which use rotation matrices to couple a Cartesian integrator with Cylindrical fields and state vectors. The equation of motion for charged particles are:

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}\left(\mathbf{E} + v \times \mathbf{B}\right)$$

Where $\mathbf{E}$ and $\mathbf{B}$ are respectively the Electric and Magnetic field acting on the charged particles. The radiofrequency part of the fields is given by the Wavecode after interpolation to particle positions and simulation time. The DC equilibrium magnetic field is considered as an addictive term for the radiofrequency $\mathbf{B}$ field. In addition, the Particle Code implements a fast radial finite volumes solver for Gauss' Law:

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\varepsilon_0}$$

This allows to account for self-consistent electrostatic field effects arising from non uniform radial density profiles. The electric field computed from Gauss' Law solution is added to the radiofrequency $\mathbf{E}$ field.

Collisions with neutrals appear as a decorrelation time that truncates the equations of motion integration backward in time when the driven current is calculated.

To be able to use the driven current in the Wavecode, it must be partially Fourier transformed. The Particle Code uses the Fast Fourier Transform in the West (FFTW) to transform the current density in the space and time domain to the current density in frequency domain, obtaining a quantity function of radius, antenna angular frequency, azimuthal and axial wave numbers.

The power absorbed by the plasma for the frequency and wave numbers analyzed is computed as a function of radius, using the complex vectors $\mathbf{E}$ and $\mathbf{J}_p$ at the current codes iteration, using:

$$P_{abs}(r) = \mathbf{E}(r) \cdot \mathbf{J}(r) dV$$

The inputs are the last iteration wave field from the Wavecode, the static magnetic field provided by the DC equilibrium magnetic field generated by confinement coils or permanent magnets, the radius of the plasma source and collision frequency against neutrals. Each species is characterized by density, temperature and drift velocity.

The outputs are the driven current for the Wavecode, and the power coupled to the plasma plus Electron Energy Distribution Function for the Quicksource.

VI. System simulation

The wave code and the particle code are linked together in a computational loop, exchanging each other the quantities described above, until the convergence of the value of power deposition and of the wave field. The coupling between the electromagnetic wave coming from the antenna and the plasma particles leads to a non-Maxwellian plasma. The output of the Wavecode+Particle Code is able to predict this, leading a non-Maxwellian distribution function. All the codes are driven by a single code which is able to run fully automated test matrices, and to scan different parameters performance. Validations are ongoing for the coupled codes setup.

The merge, interaction between codes and the simulation of entire system is performed using a modified version of XOOPIC: the modification of the source class allows the implementation of a non-maxwellian distribution. The simulation of the system is driven by a simplified model of a three-species plasma expansion[1]. XOOPIC has been used to simulate a three-species plasma, composed of one or two electron species (hot and cold electrons) plus the ion species. Codes results will be experimentally validated through an extensive experimental campaign at CISAS and Onera.

VII. Conclusion

In this paper the simulation codes used in the framework of the HPH.com research program have been presented. The physics of the helicon is simulated by means of several codes, each one accomplishing a particular task.

At first, the power deposition of the helicon antenna inside the plasma is taken into account using QuickSource, a 0-dimensional collisional-radiative code which is capable to evaluate how the power deposition affects the plasma distribution function. The Wavecode-1D numerically integrates the two Maxwell wave equations along the radius of the cylindrical source, to evaluate the E,B vectors along this coordinate. The Wavecode is coupled with the Particle Code, a 3D code which integrates the particles trajectories using a Boris-Buneman leapfrog integrator. The two codes are coupled together in a computational loop that allows evaluating the power deposition of the antenna inside the plasma. The outputs of this computational loop are the inputs for a modified version of XOOPIC capable to simulate a plasma with arbitrary distribution function. From the simulation with XOOPIC the ion beam temperature, velocity and mass flow are obtained, and used to evaluate the propulsive performance of the thruster.

Acknowledgments

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