Particle-in-Cell modeling of SPIDER negative ion source

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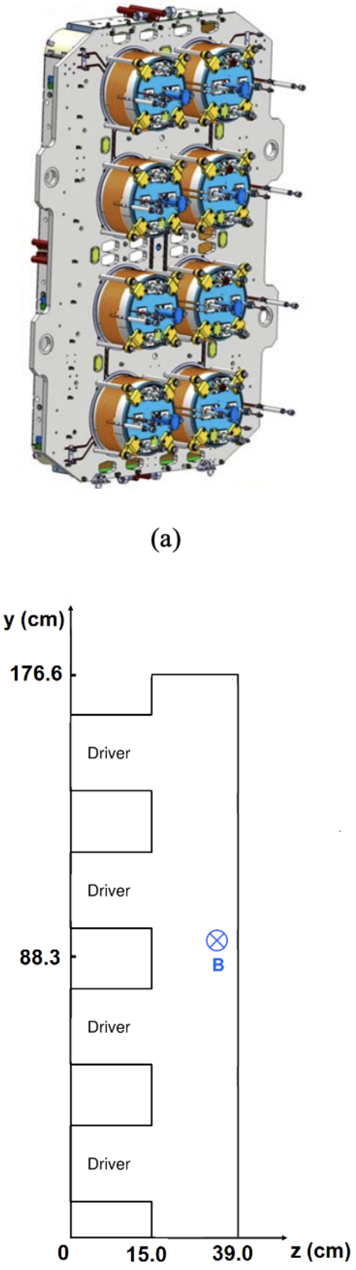
SPIDER (Source for the Production of Ions of Deuterium Extracted from a Radio frequency plasma) is the ITER prototype negative ion source used for neutral beam injection (NBI). It is composed of 8 drivers, which are inductively coupled plasma discharges, where the plasma is produced [1]. Each driver is connected to a common expansion chamber and is coupled to an antenna connected to 1MHz RF generators (Fig.1) with the aim of maximizing the power transmitted to the ionized gas in order to generate and sustain the plasma.

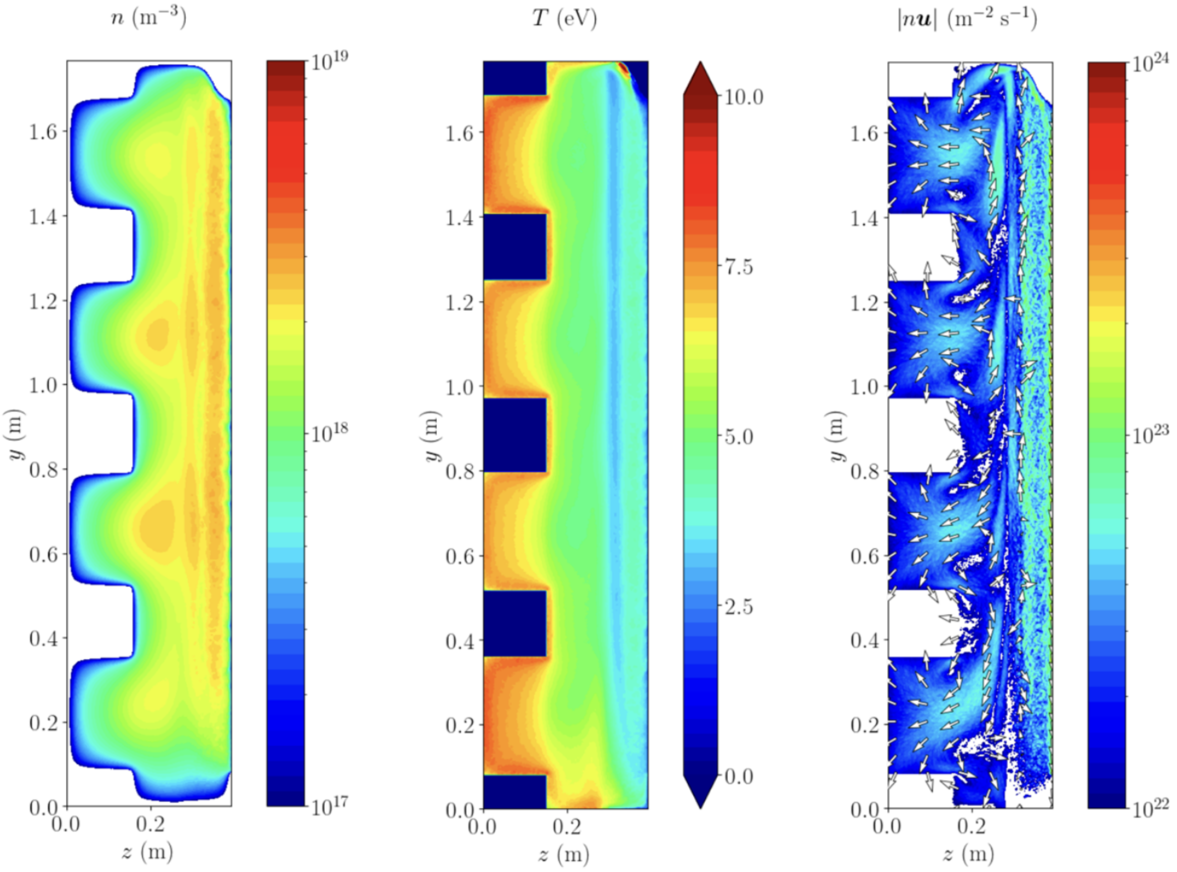

(a)

(b)

Fig. 1: SPIDER negative ion source prototype (a), simulation box (b).

The basic physical processes of a low temperature plasma occurring inside the SPIDER negative ion source were investigated by means of the numerical code PICCOLO (PIC COde for LOw temperature plasma) that uses the Particle-in-Cell method with Monte Carlo collisions (PIC/MCC) to model the kinetics of electrons and ions inside a negative ion source in a self-consistent electrostatic field. In detail, the Poisson equation is solved at each time step δt. Charged particles are moved between t and δt according to the Lorentz force $q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$, where $\mathbf{E}$ is the self-consistent electric field [2] and $\mathbf{B}$ is the imposed magnetic filter field. The two-dimensional simulation domain is shown in Fig.1(b). The field lines of the magnetic filter are perpendicular to the simulation plane. The configuration of the magnetic filter corresponds to a Gaussian profile, given by $B_x(z) = B_0\ exp\left[-(z-z_0)^2/(2L_z^2)\right]$, where $B_0 = 7\ mT$, $z_0 = 36\ cm$, and $L_z = 3.9\ cm$. An initial density of $5 \cdot 10^{18}$ $particles/m^3$ is imposed for the electrons and ions inside the drivers. In order to reproduce the large size of the source, a scaling technique is used consisting of artificially increasing the value of the vacuum permittivity in the Poisson equation by a factor $f_s = \epsilon_0^{'}/\epsilon_0$, where ϵ_0 is vacuum permittivity and $\epsilon_0^{'}$ its scaled value used in the simulation. With the aim of decreasing the computational cost, a hybrid OpenMP/MPI parallelization approach was also used. Some of the electrons are randomly heated in the driver region by subjecting them to a prescribed power of $100\ kW$ at a frequency of $4\ MHz$. A new velocity is assigned to the heated electrons [3] by sampling it from a Maxwellian distribution with a temperature equal to the heating temperature $T_h = \frac{2}{3}\left[< E_k >_h + P_{abs}/\left(eN_{eh}\nu_h\right)\right]$, where $< E_k >_h$ is the computed electron average energy in eV, P_{abs} is the absorbed power, ν_h is the heating frequency, and N_{eh} is the number of electrons to be heated. The heated electrons distribute the absorbed energy to heavier ions and neutrals by means of elastic and inelastic collisions. Various test simulations were carried out with different parameters such as density and scaling factors. In these tests only atomic hydrogen gas at a pressure of 0.3 Pa was considered, while negative ions and molecular positive ions were neglected. Fig.2 shows some quantities relating to the electrons, such as density, temperature and flux, in the case of $f_s = 2.25 \cdot 10^4$. Furthermore, the time step is equal to $4 \cdot 10^{-11}\ s$ and the number of simulated time steps is $5 \cdot 10^6$. The numbers of grid nodes chosen for the PIC mesh along the three directions were 3 (along the fake periodic x direction), 1765 (along the y direction) and 389 (along the z direction perpendicular to the Plasma Grid plate). The map in Fig.2 (a) shows the behaviour of electron density while Fig.2 (b) shows that electron temperature. The electron flux map shows a complex structure due to the magnetic filter field. Electron transport is governed by the diamagnetic and $\mathbf{E} \times \mathbf{B}$ drifts leading to a Hall current. It causes important top-bottom dishomogeneities in the plasma characteristics along the extraction region on the left.

The *scaled* PIC-MCC code is able to provide a very useful insight of the physical phenomena that occur within SPIDER. In the next phase of the study, molecular collisions will be implemented that will allow obtaining 2D maps of the physical quantities of interest and highlighting the physics of the SPIDER negative ion source [4].



(a) (b) (c)

Fig. 2: Density (a) and temperature (b) maps of electrons, arrow map of electron flux (c).

Acknowledgments - Work carried out in the frame of project NEFERTARI - CUP B53C22003070006, funded by the European Union under the National Recovery and Resilience Plan (NRRP) - NextGenerationEU. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

[1] F. Taccogna, G. Fubiani and P. Minelli, *In: Bacal, M. (eds) Physics and Applications of Hydrogen Negative Ion Sources. Springer Series on Atomic, Optical, and Plasma Physics* **124** Springer.
[2] F. Taccogna and P. Minelli, *New J. Phys.* **19** (2017) 015012.
[3] G. Fubiani, L. Garrigues, G. Hagelaar, N. Kohen and J.P. Boeuf, *New J. Phys.* **19** (2017) 015002.
[4] F. Taccogna, F. Cichocki and P. Minelli, *Front. Phys.* **10** (2022) 10:1006994.