Three-Dimensional Particle-in-Cell Model of the Extraction Region in the Negative Ion Source for ITER

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The radio- frequency negative ion source developed at IPP-Garching [1] has been chosen [2] by the ITER board as the new reference source for the ITER NBI system, due to the fact that it is potentially able to fulfil all ITER requirements. Experiments [3] have shown that the extracted ion current density increases by one order of magnitude when Cs is introduced into the source. This enhancement is attributed to the surface production of negative ions by neutral and positive ion conversion on the low work function caesiated surface surrounding the extraction apertures. For this reason the extractor region of the plasma source system is crucial for optimizing the extracted current (increase of negative ion and reduction of co-extracted electron currents). The extractor region consists of two grids: the plasma grid (PG) and the extraction grid (EG) which is positively biased. To suppress the undesirable co-extracted electron beam, a complex magnetic configuration is installed in the source (magnetic filter) and in the extraction (electron deflection field) regions of the negative ion source. The importance of having a self-consistent model of the extractor is due to the fact that different mechanisms responsible for the negative ion extraction are linked and combined such that they cannot be considered as free parameters and changed independently . For this reason, the sheath potential drop, the electric field penetration from EG, the potential well (formed to reflect back the negative ion flow emitted from the cesiated surface, which would otherwise be unbalanced) attached to PG and the surface-produced H^- starting energy are all self-consisted calculated in the Particle-in-Cell (PIC) model [4] presented here. The simulation domain consists of a box that includes one single aperture of PG (Fig. 1.a); the axial coordinate z normal to the aperture starts in the plasma source region (at z=-15 mm) and ends at the EG (z=5.5 mm) while the PG lies between z=0 and z=2 mm; periodic conditions along the boundary planes in *x* and *y* are imposed. The size in z has been chosen in order to be sufficient to analyze the effect of plasma parameters and EG field penetration in the source region. Moreover, the extraction probability of a negative ion produced farther than 20 mm from PG goes to zero [5]. The two fixed, non-homogeneous magnetic fields are directed along x and y with Gaussian profiles $B = B_{max} e^{-(z-z_{max})^2/2\sigma^2}$.

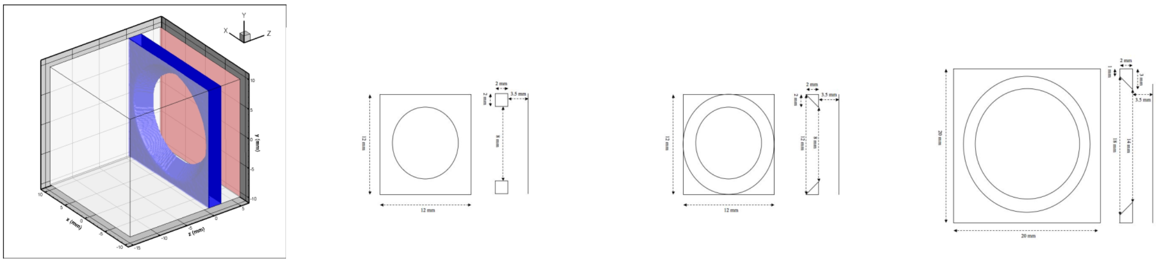

Fig. 1 – Sketch of the simulation domain and cross-sectional view of the three different PG simulated: flat and 45° chamfered LAG and 45° chamfered CEA grids.

Charged particles (e and H_x^+) are self-consistently followed while neutral particles are not: the axial profiles of H atoms and $H_2(v)$ molecules are kept fixed as calculated (uniformity is considered along the x and y coordinates) in previous models [6]. Moreover, an additional number of H^- ions are launched from the PG surface according to ion Γ_+ and neutral Γ_0 flow $\Gamma_{H-} = \Gamma_+ Y_+ + \Gamma_0 Y_0$ where Y is the H^- yield by ion/neutral conversion [7]. The neutral conversion mechanism is the dominant one: the neutral flux can be ten times larger than the ion flux towards the wall [8] giving to a negative ion current produced at PG of J_{H-}=660 Am^{-2} (less than 2% of this value derives by ion conversion). Different bulk collisions are implemented using Monte Carlo Collision (MCC) technique. All the parameters used in the present model are reported in Table 1.

Table 1. Main physical parameters used as input data in the present PIC model.

Plasma density $n_e/n_{H+}/n_{H2+}/n_{H3+}/n_{H-}$	2.7/1.8/0.9/0.3/0.3 x10^{17} m^{-3}
Plasma temperature $T_e/T_{H+}/T_{H2+}/T_{H3+}/T_{H-}$	2/1.2/0.1/0.1/0.1 eV
Gas Density n_H/n_{H2}	1/0.2 x10^{19} m^{-3}
Gas Temperature T_H/T_{H2}	0.8/0.1 eV
Magnetic field	Filter field B_y: B_{max}=7mT; z_{max}=-18mm; σ=12.2 mm Electron deflection field B_x: B_{max}=30mT; z_{max}=5.5 mm; σ=5.5 mm
PG bias/ EG bias	15 V / 9 kV
H^- surface conversion yield Y_0/Y_+ on Cs-Mo surface	Ref. [7]

Typical runs are performed using 10^8 macroparticles and 160x160x164 grid points, with a performance of 0.1 μs by day using 16 CPU at the time step $\Delta t = 1x10^{-11}$ s. Steady state results are obtained after about 2 μs. The current density are computed at EG plane. In this work we have focused our attention to study the effect of shape and size of PG aperture keeping all the others parameters (plasma source parameters and magnetic fields map) the same. In particular, three different grids have been simulated (see Fig. 1.b): flat and 45° chamfered LAG grids and 45° chamfered CEA grid [9-11]. All the most important output quantities computed are reported in Table 2.

Table 2. Characteristics and output results computed for the different PG simulated.

	Flat LAG	Chamfered LAG	Chamfered CEA
Production area P(mm^2)	93.76	119.77	287.76
Extraction area E(mm^2)	50.24	50.24	153.86
Co-extracted electron current density J_e (Am^{-2})	56	35	187
Negative ion current density extracted J_{H-} (Am^{-2})	123	320	240
Extracted negative ion population (from Volume / from Surface)	0.37 / 0.63	0.16 / 0.874	0.25 / 0.75
Extraction probability of volume-produced H^-	33 %	30 %	52%
Extraction probability of surface-produced H^-	6.4 %	26%	11%

The comparison between the first two cases shows the importance of PG inclination, which allows a better penetration of the EG field inside the source region. The virtual cathode completely disappears downstream of the conical region while its depth reaches 30 V for a distance farther than 1.4 mm from the inner hole (Fig. 2). In the flat version of LAG, the EG field penetration is limited to only a thinner region around the aperture. This reduces the active extraction area to a very small part of the production area: only 6.4% of negative ions produced on the surface are extracted, while this percentage increases reaching 26% with the chamfered version. Moreover, all the surface-produced ions extracted comes from the chamfered part. In both cases, the volume-produced H^- contribution to the extracted density current never exceeds 50 Am^{-2}. It should be noted that the inclination does not change the rate of negative ion produced on the surface $\Gamma_{H-}P$; in fact the increasing of the geometrical area for a 45° chamfered is cancelled by the decreasing of the neutral flow impacting the PG leading to a total cancellation of the dependence from the inclination angle. Therefore, the increase of extracted negative ion current density is totally due to the enhanced extraction probability of surface-produced negative ions due to the collapse of the virtual cathode by a better EG field penetration in the source region. Finally, comparing the two different chamfered configuration, a better extraction ion current density was obtained by the LAG system characterized by a low extraction to production area ratio (0.42 against 0.53 of CEA system) and a very small flat part (0.26% of the total production area against the 0.51% of the CEA system). This leads to a reduction of extraction probability of surface-produced negative ions for CEA system: 11%. It seems that the LAG system has a better ratio between production and extraction area which offers a better extracted current density. On the other hand, the CEA system allows a better extraction of volume-produced negative ions (more than 50 % against 30% of LAG system) due to a larger meniscus able to capture negative ions from a larger volume.

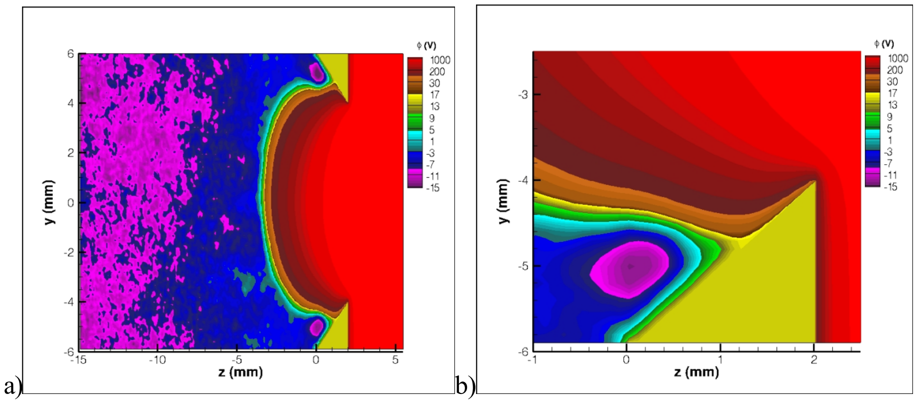

Fig. 2 – a) Electric potential in the plane x=0 for 45° chamfered LAG system and b) zoomed view close to PG.

The effect of a chamfered PG with different ratio of production to extraction surface has been investigated by means of a 3D PIC model. The best performances have been detected for the 45° chamfered LAG system due to a better penetration of the EG field allowing the collapse of the virtual cathode attached to the surface emitting negative ions.

References

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