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AN EFFICIENT H^-/ D^- EXTRACTION IN NEUTRAL BEAM INJECTION (NBI) ION SOURCES

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Abstract

The negative ion source development has reached performances close to those required by the ITER project; see for example the test facilities ELISE and SPIDER [1,2,3]. The main residual problem seems to be the great amount of co-extracted electrons in the top part of the source. The introduction of a magnetic filter to remove the electrons from the extraction zone of the source causes **E**x**B** particle drifts (or shifts) which move both ions and electrons towards the top (or bottom depending on the B direction); in the top part, the electron concentration and extracted current increase and that limits the extracted ion number. In this contribution, as a possible solution, the application of a Planar Ion Funnel (PIF) extraction electric field configuration [4] on the source exit is proposed. The electric field line shape of PIF configuration, not only should change the relative directions between the magnetic filter **B** and the extraction electric field **E** in such a way to prevents the **E**x**B** electrons (e^-) drifts toward the source extraction, but also should give a more efficient H^-/D^- extraction. Preliminary simulations of D^- and e^- trajectories are presented to confirm the efficiency of the PIF ion extraction system.

INTRODUCTION

The world project for the nuclear fusion power production, ITER, is in construction at Cadarache, France. It will use Neutral Beam Injections (NBI) to reach the plasma temperature needed for nuclear fusion ignition. ITER should have two NBI with negative ion sources D^- (H^-) capable of provide ion currents of 40 A at 1 MeV (or 46 A at 0.87 MeV for H^-). To develop suitable ion sources a facility with large ion extraction, ELISE, has been realized at IPP Garching [1]. For efficient negative ions extraction (D^- /H^-) it is very important to avoid, or at least limit as most as possible, the e^- co-extraction. In ELISE a magnetic filter (B_F) field on the ion source extraction region is used for that purpose. B_F is produced, essentially, by applying an electric current flowing vertically on the Plasma Grid (PG), the grided plate from which the negative ions are extracted [5]. To further improve the ion extraction, a proper polarization is given also on PG and/or on a Biased Plate (BP) which is present in the source before PG. In ref. [3], however, experimental test carried out on the ELISE facility presented results where the number of electrons co-extracted with the H-/D- from the top part of the source is significantly bigger than that co-extracted from the bottom part. That important asymmetry caused of reducing the extracted ion current to avoid discharge in the extraction region. It seems that one of the main limitations to reach the ITER source performance be due to this asymmetry [1,2]. The top/bottom asymmetry can be ascribed to the presence of perpendicular electric (the source polarization) and magnetic (the filter) fields which causes the **E**x**B** particle drifts in the source extraction region. The reducing the vertical plasma drift, then, should be a very promising action for symmetrizing the top/bottom electrons co-extraction. In ref. [2] different techniques have been tried to modify **E** and **B** field lines to reduces the top/bottom asymmetry. To modify the electrostatic potential close to the PG some potential rods have been proposed and tested in ELISE [1]. The potential rods are water-cooled vertical plates made of nickel-coated copper placed in between the aperture groups. The rods shift the PG potential and the plasma potential close to the PG upwards by a few volts. The total co-extracted electron current and the top/bottom ratio are reduced to smaller values. The effect of the rods, however, is not sufficient for fully symmetrizing the co-extracted electrons in deuterium at high P_{RF}. Alternative methods to the potential rods have been also investigated to obtain better results. For example, different polarization of BP with respect to PG and source have been tried but with still unsatisfactory results [3].

To better understand the asymmetric top/bottom e^- extraction in the ITER type sources, a study of the charged particle trajectories in the source extraction region has been carried out by using SIMION code [5]. In those simulations has been assumed that the whole extraction region is placed in the source plasma sheet in front of PG. The plasma sheet depth is given by $d=\lambda_D(V_{app}/kT_e)$ (in our conditions few mm) with λ_D the Debye length [2]. Charged particles starting from that region feel the extraction electric field (with reduced 'self-shielding plasma effect') and then SIMION simulation (with no plasma effect) can be used to follow the ion and electron trajectories during their extraction. The simulation results presented in ref. [5] show as electron **E**x**B** drifts can be reduced by the polarization of BP and PG in such a way that the extracting field in the region before PG could be reduced. A similar effect can be obtained by using the Planar Ion Funnel (PIF) electrode configuration proposed as ion extraction system for the sources in mass spectrometer applications [6]. In this paper the **E**x**B** particle drifts simulation with PIF electrode configuration applied to a scaled SIMION model of MaMuG type source extraction system is presented, and the results discussed.

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***ExB* Particle Drift Simulations**

The motion of a charged particle in electric and magnetic fields in a plasma forms a cycloid with a drift motion along the **Ex****B** vector direction. The **E**x**B** particle drifts can be expected in extraction region of the negative ion source since the **E** field, used for extraction, and the **B** field used as e- filter, are each other perpendicular. Being **E**x**B** direction perpendicular to the extraction direction it should, in principle, not favour e^- co-extractions. The e- flow direction, however, can be tilted towards **E** if frequent collisions with neutral atoms and/or molecules are present in the plasma [7] increasing so possible e^- co-extractions. A detailed study of negative particle trajectories in the ion source extraction region in presence of extracting (**E**) and filter (**B**) fields presented in ref. [5] have shown that e^- co-extraction is possible. In that ref. a possible solution has been indicated by using a more complex extraction field, that is the PIF electrode configuration proposed in ref. [4]. In the PIF configuration, in fact, the **E** field lines could be locally deviated from the extraction axis and the e^- **E**x**B** drifts could change direction moving also towards the back part of the source.

A rough SIMION 3D model of a multiaperture ITER style source type in rectangular geometry is here proposed to study D^- and e^- trajectories starting from the source plasma sheet region. The model used for simulations is shown in Fig. 1a), unfortunately, the volume that could be considered for simulation was limited by SIMION calculation capability. A rectangular geometry model with only 4 extraction holes could be used. In the model, the PIF electrodes are put on the Bias Plate (BP), not visible in 1a). They have a squared shaped, instead of the original ring shaped, nested each other from the smallest to the greatest. In the model are also used a Plasma Grid (PG), an Extraction Grid and an Accelerating grid (AG) like in ITER type source. In the simulation of Fig. 1, however, no PIF electrode configuration has been applied and BP has been kept to a unique potential value. Simulation results show that, in these conditions, the electrons drift toward the top source (positive y axis) as it is better shown in 1b) where xy, xz and yz projections are shown. The e^- drifts favour, in this case, their co-extraction in the top part of the source. In the simulation of Fig. 1, the particles starting positions considered are in plasma sheet (that is, roughly, at x ≥ 26 mm) and in y,z plane, formed a circumference with d=50 mm. In this way also the particle trajectories far from the exit holes, but the same in plasma sheet, have been considered.

The PIF extraction system has been applied to the model and to the same charged particles of Fig. 1. The simulation results of this case are presented in Fig. 2. The PIF electrodes voltages of BP, as first step, have been put to the same values of the voltages used in the cylindrical source simulated in ref. [3]. The value of the smallest electrode frame was, -80 V the next larger, -100 V, and so on, -120 V, -160 V, -200 V, -300 V, -400 V (which, in general, was also the potential of the source). The simulation results presented in Fig. 2 do not show e^- co-extractions. Furthermore, in Fig. 2b), it can be noted that the projection of the trajectories on the yz plane show that the e- still drift toward the top of the source but, dislike the case shown in 1b), they stop and change direction well before of reaching the plane limit.

It seems that, in Fig. 2, although the e- drifts toward the top part are still present, the most part of their drifts are curved and spread on the source back. Furthermore, the ions extracted through the holes present a higher density because of the PIF electrodes effect on the ions discussed in [3].

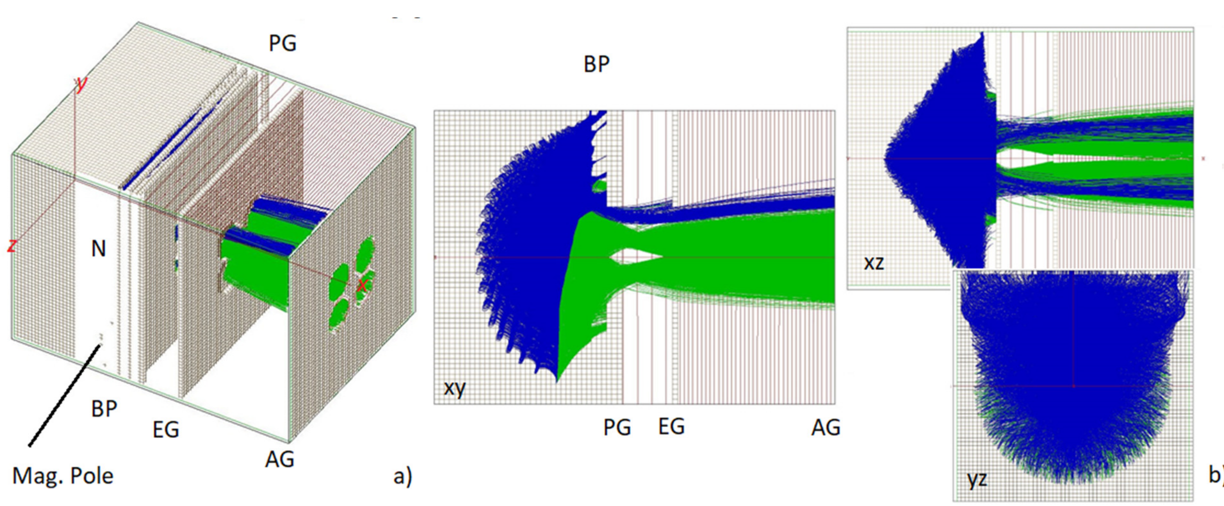

Figure 1: D^- (green) and e^- (blue) trajectory simulations without PIF electrodes: a) source ITER type 3D SIMION model with filter magnet (north pole, N, indicated), BP, PG (not visible in the ion extraction region), EG and AG; b) charged particle trajectory projection on the xy, xz zy planes. The D^- and e^- starting position along x is 27 mm.

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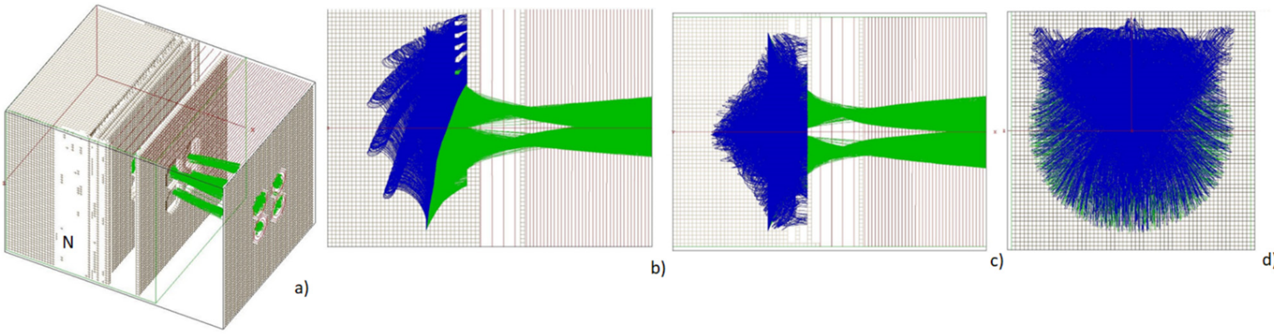

Figure 2: D^- (green) and e^- (blue) trajectory simulations with PIF electrodes: a) source ITER type 3D SIMION model with filter magnet; b) charged particle trajectory projection on xy, plane; c) trajectory projection on xz; d) trajectory projection on zy plane. The D^- and e^- starting position in x is 27 mm as in Fig. 1.

Note that the trajectory simulations shown in Fig. 1 and 2 have been carried out with particles starting from x=27 mm in the plasma sheet (the BP is placed at x=30 mm). What about particles starting for x >27 mm (then still on the plasma sheet but very close to the BP with its extraction window (given by the smallest electrode frame) for the same filter field, B_F = 6 mT. The simulations for those conditions presented in Fig. 3, show that a fraction of co-extracted e^- are noted also when PIF electrodes are used. In fact, for x>27 mm the starting e^- are too close to the source exit to benefit of the PIF configuration and avoid the co-extraction. An increase of the magnetic filter can be considered, however, to prevent the co-extraction. In Fig. 3, in fact, the case with starting particles at x=28 mm is given. In Fig. 3a) and 3b) there are the simulation results for PIF configuration. In 3b) the e^- co-extraction has been removed by using a field of 10 mT. In 3c), with no PIF configuration, the e^- co-extraction on the top part of the source remain also after the increase of B_F.

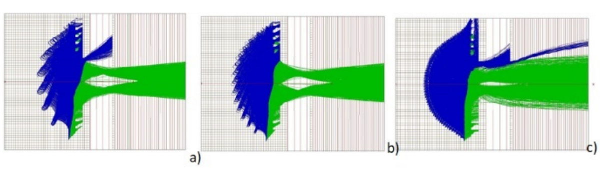

Figure 3: Trajectory simulations for starting x=28 mm: a) with BF=6 mT; b) with BF=10 mT; c) with BF=10 mT but no PIF electrodes.

Since the magnetic filter field used in the experimental test was, in general, ≤ 6 mT and then 10 mT is a high value capable to deflect sensitively also D^-, a new configuration of PIF electrodes to remove the e^- co-extraction with a lower B_F value has been looked for by modifying the geometric progression ratio r used in the above PIF voltage values. A ratio of 1.5 (instead of 1.2) but with PIF lowest voltage value of -20 V (instead of -80 V) has been tried. The new potential values of the PIF electrodes were then: -20 V; -30 V; -45 V; -70 V; -100 V; -150 V -300 V. The B_F reduction also allowed the reduction of V_{EG} at about 800 V and V_{AG}= 20 kV (instead of the old values of 2.8 kV and 26 kV). The simulation results obtained with the new PIF potential values with a lower filter field (6 mT,) were like those obtained with 10 mT.

Simulations for different Source Polarization (SP) with respect to BP and PG have been carried out to eliminate e^- co-extraction without PIF electrodes as done in ref [2]. The results of those simulation have shown that proper polarization can reduces the extraction field and then e^- co-extraction. However, in that case, the e^- **E**x**B** drifts continue toward the top part of the source with an increasing tilt toward the extraction side. The presence of further extracting holes in the source top part (as in ITER), then, would favour e^- co-extractions from upper holes.

CONCLUSION

To avoid the e^- co-extraction from ITER type negative ion sources a magnetic filter (B_F) is applied just before the extraction region, on the Plasma Grid (PG). In the extraction region, then, the charged particles have a common drift motion towards **E**x**B** direction [8-11]. An asymmetric top/bottom e^- co-extraction observed in the experiments [1,2] seems confirm that effect. The top/bottom e^- co-extraction asymmetry can be increased, decreased, and sometime removed by proper electric and magnetic field line shapes. SIMION simulation has shown that a particular Electrode system, called Planar Ion Funnel (PIF) configuration, can extract ions more efficiently and without e^- co-extraction. Trajectories simulations for the same particles without PIF electrodes, on the other hand, have shown the permanence of a large amount of e^- top/bottom asymmetry co-extraction. An experimental test to confirm that PIF extraction system can remove the e^- coextraction is in arrangement.

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