Modeling transport and extraction of negative ions (H-) for injection in ITER

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The future experimental reactor ITER will include two main heating systems: radio-frequency and neutral-beam injection. The second should provide 32 MW through two beam injectors, each one providing 16 A @ 1 MeV neutral Deuterium. High energy D^- ions are stripped of their extra-electron by collision with gas molecules in the so-called neutralizer. Fully 3D Particle-in-Cell numerical modeling of the negative ion extraction from the source was performed for each injector sub-system: ion generation, acceleration and neutralization. An overview of the most relevant results obtained is presented. These results get an insight into the mechanism of extraction of negative ions, the geometry and expected extracted current of the beams produced, the transport of these beams and the role of the plasmas created in the accelerator and in the neutralization region.

1. Introduction

In a thermonuclear fusion reactor, the plasma fuel must be heated up to tens of keV in order to trigger exothermic fusion reactions. In a Tokamak, the plasma is ohmically heated during the start up of the configuration by inductive coupling. Beyond temperatures of few keV, Ohmic heating becomes inefficient and other heating mechanisms must be introduced to reach thermonuclear temperatures. The future experimental reactor ITER will include two main heating systems: radio-frequency and neutral-beam injection. The second method should provide a power of 32 MW through two beam injectors, each one providing 16 A at 1 MeV neutral Deuterium (charged particles are not able to penetrate to the Tokamak core due to deflection caused by the toroidal magnetic field) [1].

In a neutral beam injector (NBI) charged particles are accelerated to the nominal energy and then neutralized by collision with a rarefied gas. As the effective neutralization of positive charged particles is not feasible at 1 MeV, the injector must work with negative ions. The injector is then composed by a negative ion source, a 1 MV electrostatic accelerator and a gas neutralizer, where the extra electron of D- is stripped by collision with gas molecules (figure 1). Charged particles remaining in the beam after the neutralizer are deflected in an electrostatic Residual Ion Dump (RID).

Several physical aspects regarding the operation of the injector are still open, as the origin of the extracted negative ions (volume vs surface production), the geometry of the extracted beam and its transport through the accelerator, the role of the plasma created by ionization of the target gas used to ensure neutralization, etc.

We present here a selection of our results obtained in recent years in the 3D numerical modeling of the negative ion extraction from the source, their acceleration followed by their neutralization. These results reveal the beam formation and transport and give an overview of the expected operation of the injector.

2. Negative ion extraction

ITER specification requires 1 MeV beam energy which can be obtained with a significant yield (~ 50 %) only by stripping of negative ions, because the cross section of electron attachment on protons becomes negligibly at such high energy. The

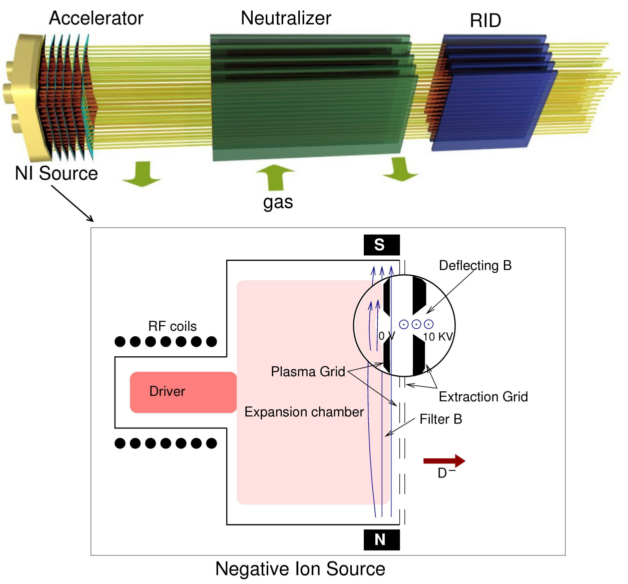

Figure 1: Schematic representation of the ITER neutral beam injector (top). Detailed view of the negative ion source (bottom).

construction of a negative ion source fulfilling the ITER requirements, especially in terms of NI extracted current (40 A), is a challenging issue. Besides the problem of creating enough amounts of negative ions, the highest efficiency of the extraction system is required. However, the higher the extracting field, the larger the co-extracted electron current is, affecting the operation of the accelerator.

In the source hydrogen (deuterium) plasma is created by radio-frequency inductively coupled coils [2] (see figure 1, bottom panel). The plasma diffuses into the expansion chamber where it becomes relatively homogeneous. To enhance the negative ion yields, Cs atoms, that act as electron donors, are used in most of the sources. Ions are extracted through an array of 1280 apertures in the plasma grid. As the survival length of the negative ions is just few centimeters into the plasma source [3], only NI created close to this plasma grid can be extracted. To limit the co-extraction of the electrons from the plasma, externally generated complex (3D) magnetic fields are used close to each extraction aperture.

The misbalance of the plasma neutrality induced by the negative charged particles extracted from it induces the formation of a concave equipotential surface in front of each aperture. This is called 'meniscus' and its shape impacts the NI convergence and can induce significant beam aberrations. A special designed code, called ONIX, was developed to address this topics[4]. The code is an electrostatic fully three-dimensional Particle-in-Cell Monte Carlo simulation domain includes only a single extraction aperture of the plasma grid, with periodical boundary conditions in the transverse planan infinite array of extraction apertures is actually modelled).

The present knowledge of the physics of the NI production by the interaction of the neutral molecules with the Cs covered surface is limited. So, a parametric study was performed for different values of negative ion emission rate from the PG surface. We found that for the range of reasonable values of this emission rate, the contribution to the extracted current of negative ions created at the surface is much higher than that of negative ions created in the volume. Experimental evidence of this fact has been reported in several works [6].

A saturation of the extracted current with the rate of negative ion emission from the surface has been found [7]. There exists an optimum emission rate for which the negative ion current is the largest (see figure 2). For larger emission rates than this optimum, the extracted current becomes smaller. This saturation is caused by the formation of a double layer close to the plasma grid surface. For too large emission rates, negative charge close to this surface produced the inversion of the electric field, that push negative ions back to the surface, preventing their extraction.

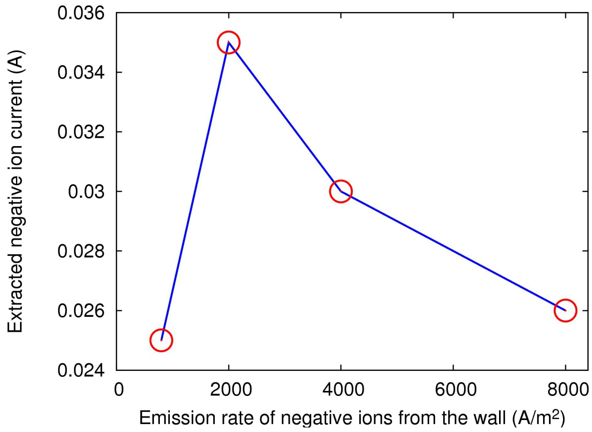

Figure 2: extracted negative ion current as a function of the rate of negative ion creation from the surface.

The saturation mechanism is illustrated in figure 3, showing the position of negative ions created at the surface of the plasma grid coming from PIC simulations. The top panel corresponds to a very low NI surface emission rate value (10 A/m^2), whereas bottom panel correspond to a high value (6000 A/m^2). The particle coulour indicates the initial position of the particle along the extraction axis. For the lowest emission rate, the double layer is not formed, and all the negative ions are extracted independently of their original position. For high emission rates, the double layer appears on the source side of the extraction aperture, and only ions (in yellow) coming from a small region of the aperture on the accelerator side are effectively extracted. The others are pushed back to the surface.

3. Beam transport in the neutralizer and the RID

The neutralizer is a crucial element for the final NBI performance, because the beam transport taking place there will determine ultimately the beam properties at the Tokamak chamber entrance, as no further optical correction can be introduced once that the particles become neutrals. In addition of the conversion to neutrals, the neutralizer plays a role in the screening of the spatial charge of the beam. Indeed, the gas filling the neutralizer is ionized by collision with the beam particles, creating a dilute and cold plasma. This plasma is expected to efficiently screen the beam spatial charge, preventing the radial expansion of the beam due to Coulomb repulsion. Moreover, some plasma positive ions mainly created by double stripping of NI can be guided backward by the electrostatic field in the free space between the neutralizer and the accelerator. As soon as they reached the last accelerating grid, they will be attracted by the local field leakage of the neighboring grid aperture. These ions will be accelerated in the opposite direction than the NI and they can disturb the accelerating field and even damage the back wall of the plasma source.

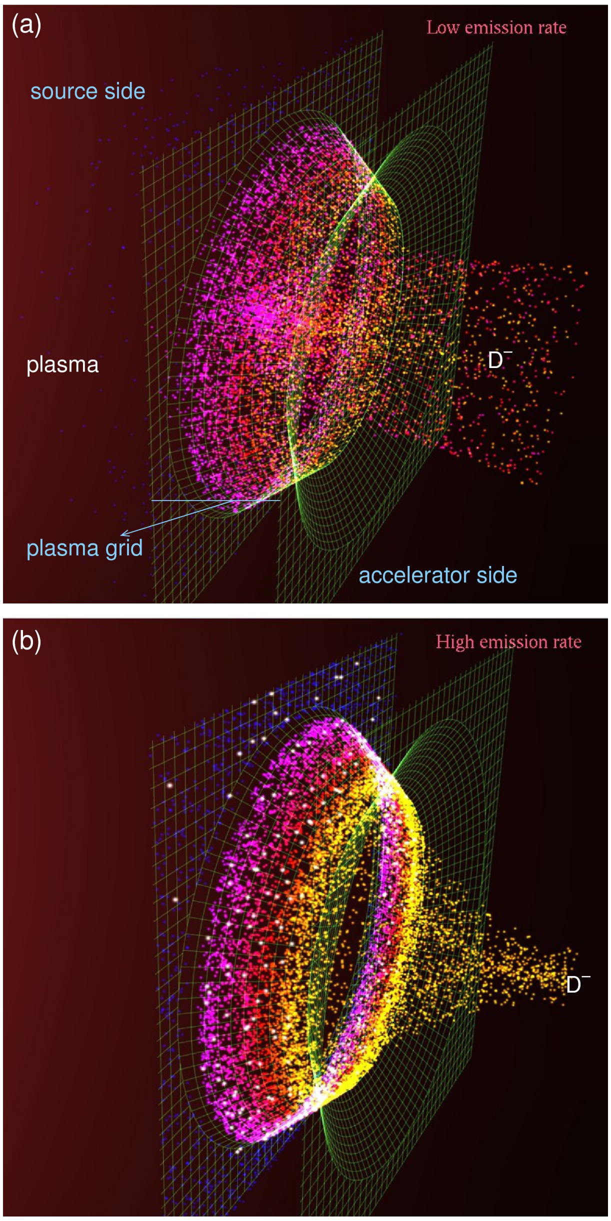

Figure 3: Screenshots of the negative ion extraction for a low (top) and a high emission rate (bottom) from the surface.

Quantitative assessment of on this current is needed to evaluate the accelerator performance.

To carry out a self-consistent modeling of the beam propagation from the accelerator exit to the injector exit plus the plasma behaviour we developed a tri-dimensional Particle-in-Cell Monte Carlo Collision code called OBI-3 (Orsay Beam Injector 3d)[8].

We show in figure 4 results obtained with OBI-3 code for an array of ideal beamlets. This figure shows the density of beam particles (D^-, D^+ and D^0) in the midplane for an early and a later time (respectively 1 µs and 15 µs). The beamlets are composed of monoenergetic 1 MeV D^- ions with zero emittance. In the first µs after switching on the beam, the plasma density is much lower than the beam one, and the beam diverges due to Coulomb repulsion. The beam particles repeal each other and very few of them can cross the system, most of them being deflected towards the walls.

After some µs, the secondary plasma density has build up enough to provide a good screening of the beam spatial charge. At t=15 µs (figure 4, bottom pannel) the plasma screening is indeed efficient enough to ensure a quasi-ballistic transport. The effect of the presence of the plasma sheath over the beam particles trajectories is small. Beam ions do not cross the electrostatic sheaths created in front of each one of the neutralizer plates. The transport is therefore quasi-ballistic up to the RID entrance.

The code also provides quantitative information about the distribution of ions created in the device by beam-gas interaction, which are back accelerated towards the plasma source by the longitudinal plasma potential drop. The current of positive plasma D_2^+ ions passing through the apertures of the last accelerating grid is relatively low (0.5 % of the current of negative ion leaving the accelerator). There is a leakage of positive ions leaving the RID, which represents a current close to 1 % of the negative ion current coming from the accelerator.

Simulations show the absence of arc formation between the plates of the RID for the largest value of secondary electron emission tested (7 electrons/ion). This indicates a safe operation of the electrostatic RID.

We also explored the transport for beamlets with more realistic geometrical properties. The input parameters from the beamlets were taken from Particle-in-Cell calculation including the extraction of ions from the source and their transport in the accelerator [9]. The beamlet divergence at the accelerator exit is relatively high, roughly 8 mrad RMS. The high divergence results in a significant

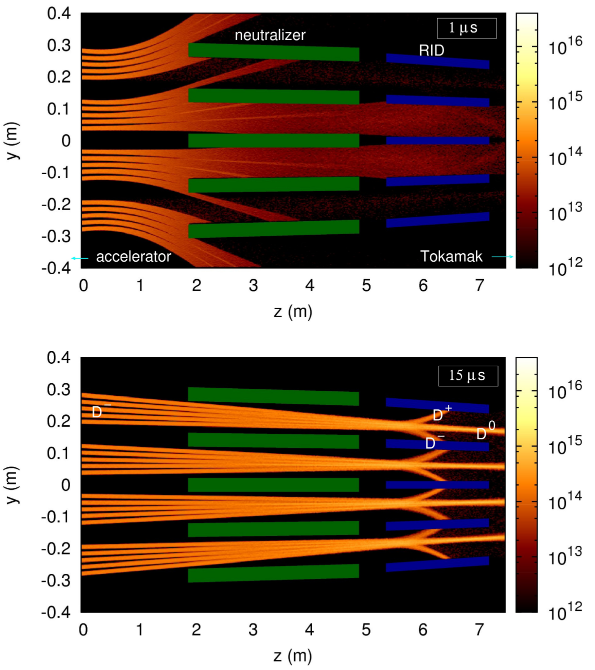

Figure 4: Spatial distribution of beam particles for selected times.

fraction of beam particles hitting the walls of the neutraliser. The current of D^0 at the exit of the RID is roughly 25% of the current of D^- leaving the accelerator, less than a half of expected value for the ideal beam (56 %). This result demonstrates the importance of the NI extraction and beam shaping system as well as the acceleration over the performance of the injector.

To summarize, the numerical modelling represents a very powerful and interesting approach to represent the 3D formation and transport of charged particles in the NBI. This realistic models allowed to tackle some interesting phenomena such as meniscus formation, electron co-extracted current, power load on the accelerator grids, beam neutralization in the neutralizer and the efficient and safe operation of the RID. Further work will be devoted to study the aberrations and beam halo, and to other designs for the future neutralizers.

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