*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.149 (2007)*

Modeling of a Negative Ion RF Source for ITER NBI

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Introduction

For heating and current drive of future fusion devices neutral beam injection based on negative hydrogen ions is required. The ion source used for ITER should deliver 40 A of deuterium ions with an accelerated current density of 200 A/m^2. At IPP Garching RF driven ion sources are under development, which have already fulfilled the physical parameters of these requirements on a small scale and for short pulses [1].

In contrast to positive ion sources in which the process of creating and extracting ions is relatively simple, the physics of negative ion sources is far more complicated: production of H^- happens mainly by the surface effect which is optimized by covering the surfaces with a thin Cs layer. Since the ions can be destroyed easily, their survival length is in the range of a few cm and thus just ions produced at the surface of the plasma grid are of relevance for the extraction. To minimize the destruction of H^- in this region, a magnetic filter is applied which reflects hot electrons and thus reduces the electron temperature. To reduce the amount of co-extracted electrons, the plasma grid can be biased, i.e. a potential with respect to the walls is applied to the grid.

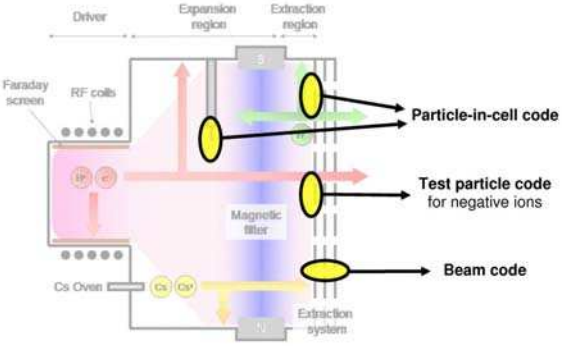

Figure 1: *Schematic overview of the IPP negative ion source. The ellipses indicate the areas for which the three codes have been utilized.*

Comparing results from modeling with measurements opens the possibility of enhancing the understanding of the relevant physics. A model for which the applicability to a certain parameter range has been proven may be used for predicting results of parameter changes in a wider range. For describing physical aspects correctly, a model needs to resolve the typical length scales and time scales of all relevant processes. This means that a model for describing the IPP negative ion sources as a whole needs to consider a length scale of 1 m (but resolving λ_D, i.e 10^{-5} m) and a time scale of 10^3 s (but resolving ω_P^{-1}, i.e. 10^{-11} s). Such a model would require a non available amount of CPU time and memory. Thus at IPP several codes are being developed, each of them describing an important physical aspect of the negative ion source. Three of these codes will be briefly described in this article. The codes use - as far as possible - the geometry and fields (magnetic and electric) present in the IPP RF ion sources.

Particle-in-cell code

A 1d PIC code for a three component plasma (e, H^+, H^-) was developed and applied to investigate the basic physics of plasma-wall (or plasma-beam) transitions in negative ion sources. The code uses the LU decomposition technique for solving Poissons equation. The Leap Frog scheme is applied for the calculation of the particle trajectories. Either half-bounded or fully bounded calculation domains are feasible. Particles are injected at a source plane which can be set by the user to any position inside the domain (including the domain walls). Negative ions are generated either by volume production (at the source plane) or surface production (when positive ions hit one of the walls).

Adding negative ions to two component plasmas changes the plasma potential since electrons and negative ions do not have the same mass. Volume production may result in the formation of a double sheath when the ratio of T_e to $T(H^-)$ is larger than 12.2 [2]. Concerning this effect the PIC code is in very good agreement with the literature. For surface production the potential is decreased uniformly with increasing H^- density (about 0.5 V for T_e=2 eV, $n_e=3\cdot10^{17}$ m^{-3}, $n(H^-)=10^{17}$ m^{-3}, profiles are plotted in fig. 2a).

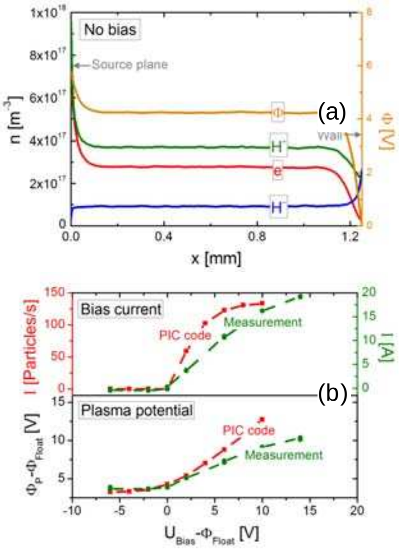

Figure 2: *Results of the 1d PIC code: profiles of particle densities and potential without bias voltage (a), comparison of calculated and measured plasma potential and bias current (b).*

To investigate the influence of biasing on the plasma a fully bounded model was used and the particle source for electrons and positive ions was set to the centre of the domain. Negative ions are produced by the surface effect and removed from the calculation when they cross the source plane (i.e. reach the plasma volume). The two boundaries were set to different potentials to represent biasing. The input parameters (particle densities, temperatures) correspond to measured values.

In fig. 2b calculated values of plasma potential and bias current for a variation of the bias potential are compared with measurements. A quite good qualitative agreement is found: for highly negative bias voltages the bias current is both in experiment and model restricted to zero. For highly positive bias voltages the plasma potential is directly proportional to the bias voltage. In the intermediate region an increase of the bias voltage decreases the potential drop at the sheath. The number of electrons with sufficient energy to traverse the sheath increases and thus the electron current grid rises. Discrepancies of model and experiment are due to the application of a 1d domain which does not reproduce the 3d geometry of the real plasma grid.

Test particle code for negative ions

Currently at IPP the construction of a half-size-ITER NBI test facility with extraction system is planned. The extraction geometry of the new testbed (called ELISE) should follow the current plannings for ITER NBI but incorporating experiences made with the LAG extraction system used in the small IPP ion sources. While for ITER an aperture diameter of 14 mm is foreseen, the LAG system uses $\text{ø}_{\text{apert.}}$=8 mm. Both extraction geometries are presented schematically in fig. 3a. Concerning the magnetic filter field, for ITER NBI a combination of permanent magnets with a current flowing in the plasma grid (PG current) is foreseen while in the small IPP ion sources just permanent magnets are being used. The effects of changes in geometry and magnetic configuration are critically examined by extensive modeling efforts and - as far as possible - measurements.

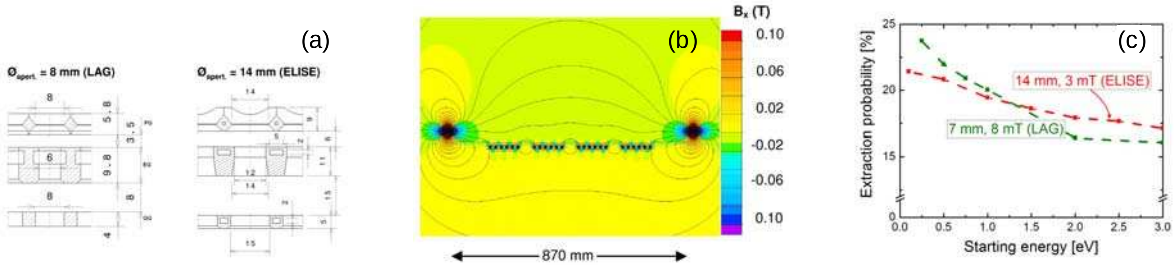

Figure 3: *Input and results of the test particle code: extraction geometries of ELISE and the LAG system (a), possible magnetic field configuration of ELISE (b), dependency of* H^- *extraction probability on the starting energy for the two different extraction geometries (c).*

In fig. 3b a possible magnetic field configuration of ELISE is presented: two permanent magnets (3 cm × 2 cm) combined with 4 kA PG current and electron deflection magnets embedded into the second grid. This data was used as input for the IPP test particle code [3] to calculate the trajectories of negative ions produced on the surface of the plasma grid. The ions are either extracted, destroyed by collisions or hit the surface of the grid. The dependence of the extraction probability on the starting energy (representing the sheath acceleration of the ions) is shown in fig. 3c and compared with the results for the LAG system. Maximum extraction probability is obtained for low starting energies (or high magnetic fields) due to a small gyro radius of the ions. Although the magnetic field in ELISE is significantly lower compared to the LAG system (≈3 mT instead of ≈8 mT) comparable extraction probabilities for both extraction geometries are obtained. This can be explained by geometrical effects (larger aperture size) which compensate the decrease of the extraction probability caused by the lower magnetic field.

Beam code

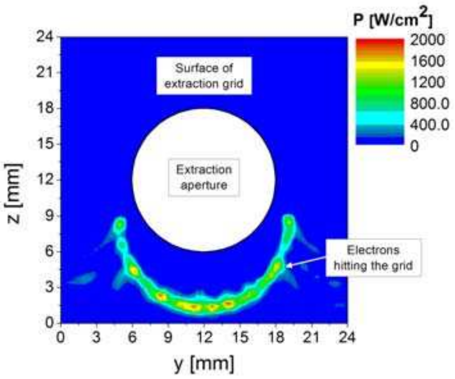

Figure 4: *Power load distribution on the surface of the ELISE extraction grid* $Ø_{apert.}=14$ *mm,* $j_e=j(H^-)=200\ A/m^2$, $U_{extr.}=9.6\ kV$.

The commercial beam code KOBRA 3d [4] was used to calculate the properties of the extracted beam. Points of interest are the size and divergence of the ion beam as well as the trajectories of the co-extracted electrons. These electrons are prevented from being fully accelerated by deflection magnets embedded into the extraction grid. The electrons hit the surface of the extraction grid and may damage the grid structure. The influence of the deflection field on the ion beam is negligible due to the much higher mass of the ions. For supporting the construction of ELISE an external module for KOBRA 3d was developed which calculates the power load deposited by the electrons onto the extraction grid. The module was verified by comparing results calculated for the LAG system with melting traces observed after a campaign with insufficient cooling. In fig. 4 a result of this module for typical parameters of ELISE is shown.

Summary

At IPP several codes are developed to investigate important physical aspects of the negative ion sources. First results of these codes have been presented in this paper: a 1d PIC code has been applied improve the basic understanding of biasing which is used in the experiment to minimize the amount of co-extracted electrons. Calculation and measurement are in good agreement. The construction process of the new test facility ELISE was supported by extensive calculations: the H^- extraction probability for the new extraction system has been calculated using the IPP test particle. An external module for Kobra 3d has been used to calculate trajectories of co-extracted electrons and the power deposited by the electrons on the extraction grid. This data is used to optimize the cooling system of the grid.

References

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