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Modeling of Negative Ion RF Sources for ITER NBI: Current Status and Recent Achievements

D. Wünderlich, R. Gutser, S. Christ-Koch, U. Fantz, M. Berger, P. Franzen, M. Fröschle, B. Heinemann, W. Kraus, C. Martens, P. McNeely, R. Riedl, E. Speth

Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany

Introduction

For heating and current drive of future fusion devices neutral beam injection based on negative hydrogen ions is required. The ion source for ITER should deliver 40 A of deuterium ions with a current density of 200 A/m^2 at a source pressure of 0.3 Pa and an electron to ion ratio < 1. 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]. These ion sources are the base of the reference source for ITER NBI.

Modeling is a key issue to improve the understanding of the physics of the ion sources and thus enable a further optimization of the production and extraction of negative ions. Due to large differences of the relevant time and length scales, it is impossible to describe the ion source using one single code. Therefore at IPP several codes are developed and used which describe different important physical aspects. Fig. 1 represents a schematic overview of the ion source and the areas for which the available codes are utilized. In the following an overview of the current status of two of these codes will be given.

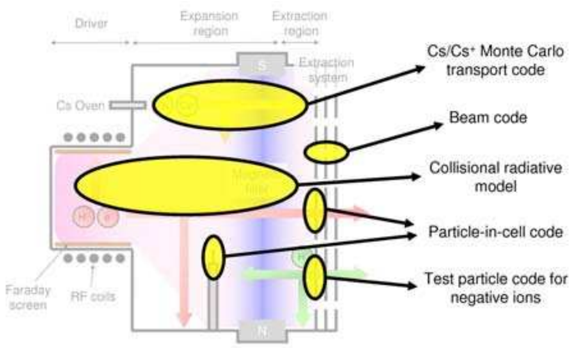

Figure 1: *Schematic overview of the IPP negative ion source. The ellipses indicate the areas for which the available codes are utilized.*

Laser-photo-detachment: 1d3v particle-in-cell code

The negative ion density in the plasma volume above the plasma grid is an important parameter for the characterization of the source efficiency. The laser-photo-detachment (LD) technique can be used to determine the relative ion density $n(H^-)/n_e$. At IPP this technique was applied for the first time to RF driven ion sources (f_{RF} = 1 MHz) with high negative ion densities ($n(H^-)/n_e$=O(1)) and the presence of magnetic fields (B<10 mT) [2].

The LD method is based on the detachment of weakly bounded electrons ($E_{binding}$=0.75 eV) by a laser pulse (Nd:YAG laser, λ=1064 nm). A Langmuir probe being present in the laser spot can be used to determine the transient increase of n_e and thus $n(H^-)/n_e$. The mobility of the detached electrons is significantly higher than the mobility of the negative ions. Fast electrons leaving the volume of the laser spot induce a potential well which confines electrons and negative ions and displaces positive ions. The time scale of recovery of the system to the initial condition is defined primarily by the transit time of the negative ions through the volume of the laser spot.

The physical background of LD was previously investigated by means of analytical methods [3,4] and PIC codes [5]. These PIC calculations are based on a 1d slab geometry and thus neglect the presence of a Langmuir probe. To overcome this restriction, a 1d3v cylindrical PIC code was developed. The grid cell size and the time step were chosen appropriately to resolve the Debye length ($\Delta x<0.3\cdot\lambda_D$) and plasma oscillations ($\Delta t<0.2\cdot\omega_p^{-1}$), respectively. The Courant criterion is fulfilled ($\Delta t< \Delta x/\overline{v}_e$), where $\overline{v}_e$ is the thermal velocity of the electrons.

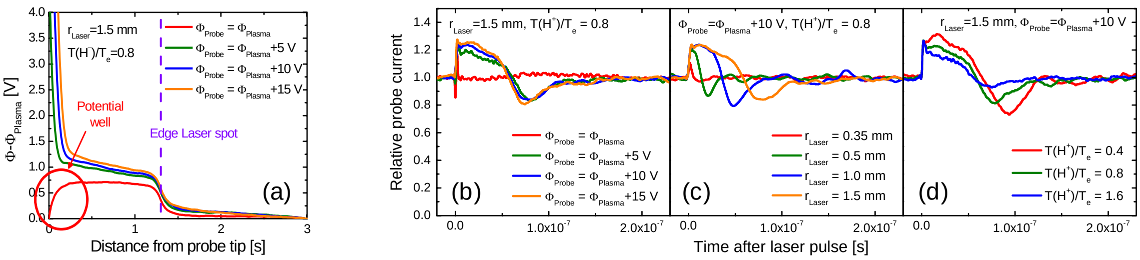

Figure 2: *Results of calculations with the PIC code on the LD process: (a) potential well caused by the high mobility of the created electrons, (b) influence of the potential well on the detachment signal, (c) dependence of the detachment signal on the laser radius, (d) overshoot of the detachment signal for cold positive ions.*

Fig. 2 presents results of calculations with this code for a small calculation domain (x=3 mm) and large probe radius (r_{Probe}=0.2 mm). The relative ion density was set to 0.25.

Fig. 2a shows the potential profile close to the probe $5\cdot10^{-9}$ s after the laser pulse for different probe potentials. The potential well can clearly be seen. The corresponding temporal evolution of the probe current is shown in fig. 2b. For low probe potentials ($\Phi_{Probe}=\Phi_{Plasma}$) the potential well shields electrons from the probe and no detachment signal is observed. For high probe potentials ($\Phi_{Probe}>\Phi_{Plasma}$+5 V) the detachment signal is almost independent of the probe potential. Hence the probe has to be used in the electron saturation branch.

Fig. 2c shows the dependence of the detachment signal on the radius of the laser spot. For small radii (r_{Laser}<1.0 mm) the probe current shows just a short peak which is not directly correlated to the negative ion density. When the laser radius is large enough ($r_{Laser}\geq$1.0 mm), a plateau appears which broadens with increasing laser radius. The relative height of this plateau represents the relative negative ion density $n(H^{-})/n_e = \Delta I/I$.

The shape of the detachment signal is affected by the positive ion temperature as can be seen in fig. 2d. The displacement of positive ions caused by the potential well temporarily decreases the total plasma density and thus the probe current. For high positive ion temperatures the recovery of the plasma density takes place on a faster time scale and the amplitude of the observed undershoot decreases.

These results perfectly reproduce the predictions made analytic calculations [3,4]. To speed-up the code and thus enable calculations for more relevant conditions (higher relative ion density, larger laser diameter, considering RF oscillations, presence of a magnetic field) the PIC code was parallelized using the Message Parsing Interface (MPI). First hard-scaling benchmarks on a Beowulf class cluster show that the code scales quite good with the number of processors.

Cs-dynamics: Monte Carlo transport code

In the IPP sources negative hydrogen ions are produced mainly by the surface effect on the walls. Due to their small survival length only ions produced on the surface of the plasma grid can reach the extraction system. A sufficiently low work function is provided by Cs evaporated from an oven attached to the back plate. Cs sticks at the surfaces and can be re-distributed by thermal desorption and sputtering processes. The time scale of the Cs redistribution determines the time scale of the ion source reaching high performance. In order to enhance the understanding of these processes, IPP started the development of a code for the behavior of Cs in negative ion sources. Such a model should consider both Cs and Cs^+ since in the plasma most Cs is ionized due to the tow threshold energy. The first steps were developing geometry routines and gathering the needed input data.

The recent version of the code calculates the Cs dynamics for an evacuated source, i.e. the number of collisions inside the volume is small. The trajectories of Cs are assumed to follow straight lines (molecular flow). Calculation of the desorption rate is based on a computational grid which covers the walls.

The desorption probabilities available in literature [6,7] are valid for high vacuum conditions ($p<10^{-9}$ mbar) and neglect the generation of compounds (CsOH, CsH, …) on the walls. These probabilities cannot be used for description of the actual ion sources ($p\approx 10^{-6}$ mbar). Thus, in collaboration with the University of Augsburg, an experimental campaign was carried out to determine Cs desorption probabilities for relevant conditions. Cs was evaporated into a small vacuum chamber using a Cs dispenser and the Cs coverage of a small sample surface was determined using a quartz micro balance. From the temporal evolution of the measured coverage the Cs desorption probability was deduced.

Fig. 3 shows the distribution of Cs on the walls calculated for an evacuated ion source using the measured desorption probabilities. The temperature of the walls was set to 50 °C, the temperature of the grid system to 150 °C. After five minutes the Cs is concentrated in the

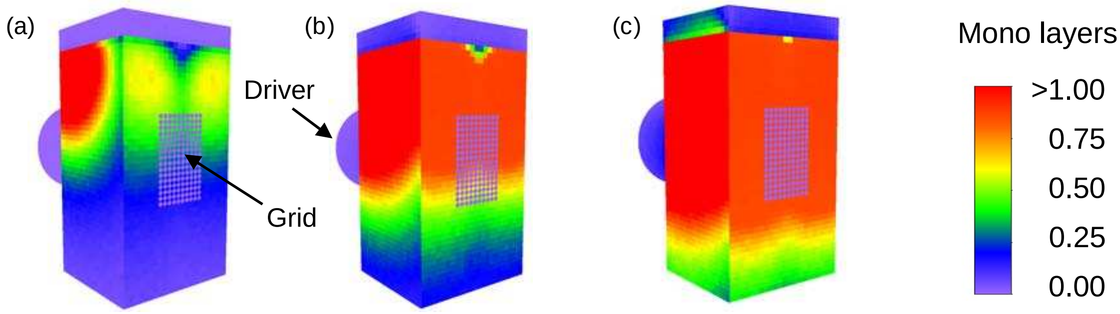

Figure 3: *Results of the MC code for the Cs dynamics inside the evacuated source: Cs coverage (in ML) of the walls after (a) five minutes, (b) 15 minutes and (c) 30 minutes.*

upper part of the source (vicinity of the oven). With increasing time re-distribution takes place and the Cs coverage of the walls gets more and more homogeneous.

In a next step plasma-Cs interactions will be implemented. This includes the influence of sputtering and an increased wall temperature on the desorption rate, ion dynamics and collisions.

Summary

At IPP several codes are developed to investigate important physical aspects of the negative ion sources. The current status of two of these codes have been presented in this paper: the cylindrical 1d3v PIC code for the laser-photo-detachment process reproduces predictions of analytic models and will be used for calculations considering a higher relative ion density, larger laser radius, RF oscillations and magnetic fields. The input data base for the Cs Monte-Carlo transport code was extended by measured desorption probabilities. First calculations were performed for an evacuated source chamber. In the next step the code will be extended with plasma-Cs interactions.

References

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