Simulation of Beam Formation in the CERN Negative Ion Source for the Linac4 Accelerator

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Abstract. Linac4 is the negative hydrogen ion (H^-) injector of the CERN accelerator complex. Modelling of the beam formation is essential for optimizing the current and emittance of the H^- ion source. We exploited the 3D PIC-Monte Carlo ONIX (Orsay Negative Ion eXtraction) code for studying H^- beam formation processes in caesiated negative ion sources. The various geometries of the IS03 prototypes have been implemented into ONIX. The code, designed for neutral injector multi-aperture sources for fusion has been adapted to match the single-aperture extraction region of the Linac4 H^- source. A plasma electrode designed to ensure radial metallic boundary conditions was produced and tested. The simulation results of the beam formation region at low plasma density to validate the functionality of the modified ONIX version are presented.

1. Introduction

The Radio Frequency Inductively Coupled Plasma (RF-ICP) H^- source prototype (IS03b) is being operated on CERN's Linac4 [1-3]. This caesiated molybdenum-surface plasma source produces H^- through the volume and surface production mechanisms [4–6]. Details of the plasma generator and operation under Cs-loss compensation can be found in reference [7].

The initial formation of the beam determines the design of the required beam optics. The properties of the ion beams after their extraction from the ion source strongly affect ion losses during the beam transport in Low Energy Beam Transport Lines (LEBT) and efficiency of particle injection into accelerators. Modelling the beam phase space around the meniscus region (positions and velocities of each ion and electron) shall provide proper input to beam transport engineering, minimization of emittance growth and beam losses. The current densities, shape and the position of the meniscus are key parameters for the beam formation.

The physics of the meniscus is complex due to the presence of surface produced negative ions and the three-dimensional magnetic field topology. The magnetic field in the beam extraction system is formed to deflect and dump the co-extracted electrons into the puller-dump electrode. The filter and dump fields are generated by pairs of permanent dipole magnets located around the plasma and puller-dump electrodes (PE, PD). The filter field strength has to ensure a low electron energy in the beam formation region upstream of the PE aperture with minimal influence on H^- trajectories. Therefore, simulations of the self-consistent plasma in beam formation region are mandatory to understand the processes of negative ion extraction.

2. Simulation model

Negative ion beam formation and plasma in the vicinity of the PE extraction aperture have been simulated with the ONIX code [8-11], used to the modelling of the extraction of negative hydrogen ions and co-extracted electrons in negative ion multi-aperture sources for ITER's Neutral Beam Injector (NBI). ONIX has been modified and adapted to match extraction region of the Linac4 H^- source [12].

Boundary conditions of the simulation volume in directions orthogonal to the beam axis were assumed non-periodic in order to define the single-aperture extraction region of the Linac4 H^- source. In this case, all plasma particles that strike the boundaries in y and z directions and left side wall are reinjected in the "bulk" plasma, following certain rules. Sketches of the simulation region are shown in figure 1. Standard plasma electrode (PE45) and a new plasma electrode geometry (PE75) have been implemented to the code. PE75 was produced to provide simple metallic radial boundary conditions at the periphery of the beam formation region of the ONIX simulation region. The extraction potential of 10 kV is applied to the right boundary of the domain, the remaining domain boundary potentials are assumed to be zero. The initial bulk plasma covers the first 8 mm of the simulation domain, the bulk plasma composition and energy distributions were taken from previous measurements [13].

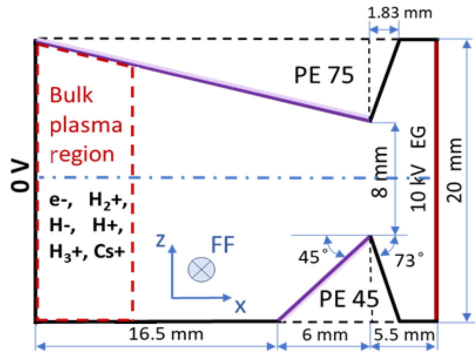

Figure 1. Schematic view of the simulation domains used in the ONIX code (x–z mid plane) for modelling beam formation of IS03b PE45 bottom and PE75 top. The filter field (FF) orientation is indicated. The bore diameter of PE is 8 mm.

3. Result and discussions

The simulation has been performed on a CERN cluster using 20 CPUs (total 360 cores) with a meshing of 420×310×310 PIC nodes and a time step 5×10^{-12} s. The cell size is 65 μm, slightly larger than the Debye length ($\lambda_D \approx 41$ μm). These numerical parameters are sufficient for PIC stability requirements for a plasma density of 10^{16} m^{-3} in the bulk region. The H^- plasma surface production mode has been simulated assuming a constant homogenous H^- emission rate of 550 Am^{-2} from the caesiated Mo-plasma electrode surface. This yield was theoretically estimated for the fusion negative ion sources [14].

3.1. Simulation of PE45

In the initial state, the particles are uniformly distributed in the bulk plasma region. The plasma expands into the simulated domain due to the extraction potential, the populations of the plasma migrate according to their energy to mass ratios. The self-consistent meniscus is formed in the vicinity of the plasma electrode aperture. The meniscus stabilizes only once all plasma populations expanded into the beam formation region. The meniscus position and the depth of its curvature play an important role for the beam formation since they define the velocity and angle of trajectory of each extracted particle. The density maps of electrons, positive ions and H^- in the (x-y) and (x-z) planes of the PE45 simulation domain are shown in figure 2, after steady state was reached. The electron density decrease in the x direction is caused by the magnetic field. The H^- density distribution is different in the (x-y) and (x-z) planes. The reason is that the filter field is predominant in the y direction and limits the electron flow, that influences the distribution of the positive charged species.

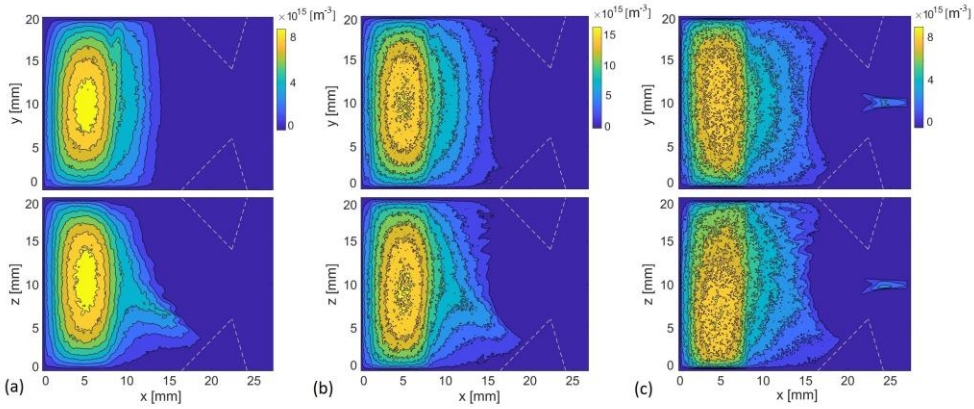

Figure 2. Density maps of electrons (a), positively charged particles (H^+, H^{2+}, H^{3+}) (b) and H^- (c) in the (x-y) (top) plane and (x-z) (bottom) plane where filter field generated asymmetry is clearly visible.

The particle is considered extracted when crossing the right boundary of the simulation domain. Figure 3a shows the evolution of the H^- and co-extracted electron beam currents during simulation. Rapid increase of electron current is observed at the beginning of the simulation. After this transitory phase, the electron and H^- currents stabilize, and the system evolves asymptotically towards a quasi-steady state. The value of both currents, for co-extracted electrons and H^-, is about 9 mA. The H^- current includes volume and surface production modes. The e/H current ratio is about 1, that corresponds to typical values for a well-caesiated source. The current is significantly lower than the experimental values, this is due to the low plasma density used as input for simulations to fulfil the stability criteria. The extracted H^- and co-extracted electron currents calculated for reduced plasma densities, provide the first microscopic information on the kinetics of plasma species and the beam formation in this type of plasma source.

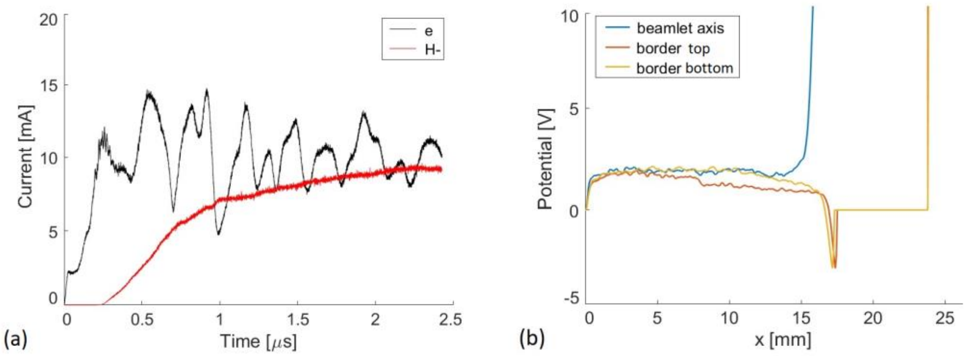

Figure 3. Time evolution of the extracted H^- current (red line) and co-extracted electron (black line) current for the PE45 system using an extraction voltage of 10 kV and a magnetic field of 11 mT (a); potential profile along the simulation domain (b).

The potential along the plasma region has an almost constant value of about 2 V, which is in agreement with the sheath potential expected for a plasma with the electron temperature of 1 eV [13]. Close to the meniscus the potential increases due to the applied extraction potential of 10 kV. The electrostatic potential profile along a beamlet axis and close to the border of the calculation domain is shown in figure 3b. The plasma density drastically drops close to the PE aperture and Debye length condition is completely fulfilled in the region of the plasma sheath including the meniscus. The depth of the plasma sheath is about 2 V near the PE aperture.

The influence of the magnetic field strength on the extracted current was considered additionally, see figure 4. The co-extracted electron current increases significantly with reducing of magnetic field, while the value of the proton yield remains unchanged. This demonstrates that the magnetic field of 11–13 mT meets the requirements for reducing the co-extracted electron current in the experiment.

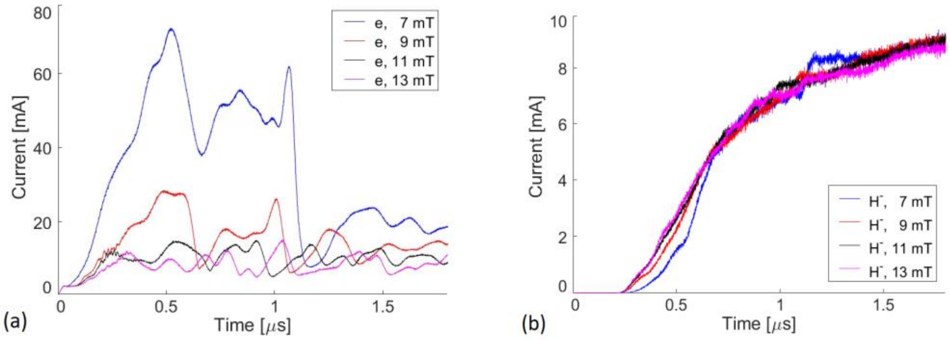

Figure 4. Time evolution of co-extracted electron (a) and the extracted H^- (b) current for the PE45 system simulated with different magnetic field.

The density profiles of electrons, negative and positive ions along a beamline and H^- profile at extraction aperture depend on their production origin in x-y and x-z plane are shown in figure 5. The simulation indicates that the majority of extracted H^- are created at the conical part of the PE. At the same time, it is observed that the production of H^- from the surface of PE is uniform, while the particles from the bulk plasma region are strongly influenced by the magnetic field. This distribution of H^- extracted from simulation domain indicates the appearance of a halo around the main beam.

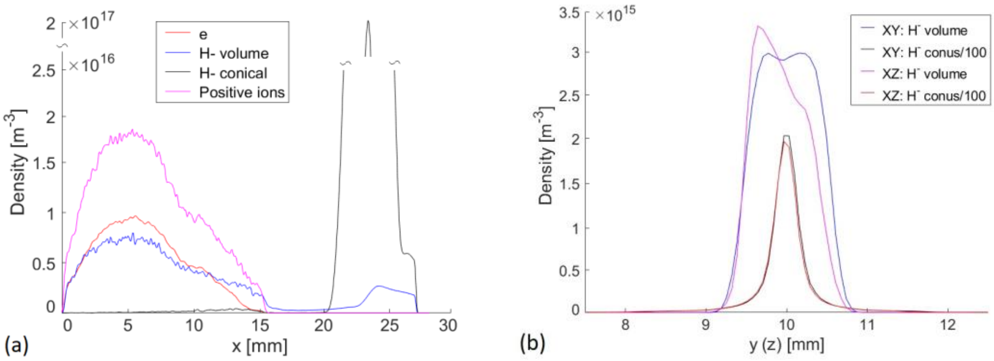

Figure 5. Density profile of electrons, negative and positive ions along a beamline (a) and H^- profile at extraction aperture (b).

3.2. Simulation of PE75

Similar simulations were carried out for the PE75 with the same settings. For this case, a significant decrease in H^- current was observed, see figure 6. The value of H^- current is about 4.5 mA, that is two times lower than for PE45 geometry. The e/H current ratio is below 1.

Comparative analysis of the density of positive and negative charged particles was performed with and without an applied extraction potential, see figure 7. The non-uniform density profiles of positive and negative ion are observed at extraction potential of 10 kV, but with significant lower impact of magnetic field on the meniscus. The negative ions produced in the surface of the plasma electrode are transported more uniformly due to the large emission surface over the entire domain. For the simulation without the applied voltage, the density distribution of the particles is completely different. Negative particles remain in the emission area (figure 7d), while positive particles are more evenly distributed over the entire domain (figure 7c).

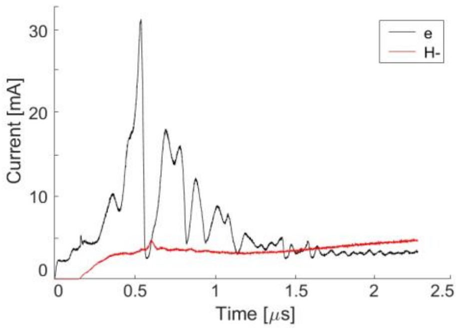

Figure 6. Time evolution of the extracted H^- and co-extracted electron current for the PE75 system.

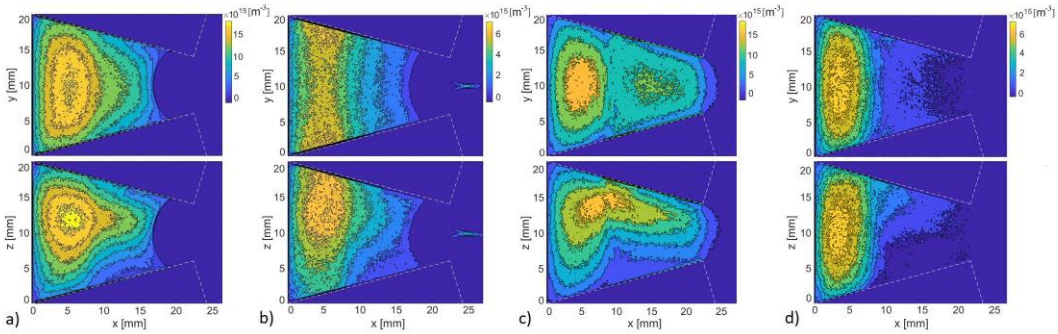

Figure 7. Density maps of positively charged particles (H^+, H^{2+}, H^{3+}) and H^- using an extraction voltage of 10 kV (a – b) and 0 V (c – d) in the (x-y) (top) plane and (x-z) (bottom)

4. Conclusion outlook

A modified version of ONIX code with a single extraction aperture and non-periodic boundary conditions to model the beam formation region of the Linac4 ion source was successfully tested on a CERN's computing cluster using low plasma density. The non-uniform profile of the current density was observed in the simulations of two type of plasma electrodes due to the influence of the magnetic field. As a result, the meniscus shape is strongly curved and the beam extracted from the peripheral region is uniform, that could lead to the formation of so-called beam halo. Relying on the demonstrated result, simulation of higher plasma densities with different species energy distributions and proportions are planned to be performed with initial conditions refinements base on analysis from OES system installed around the plasma generator at the Linac4 ion source test stand [13].

References

[1] Arnaudon L et al 2006 Linac4 Technical Design Report Rep. CERN-AB-2006-084 ABP/RF
[2] Lettry J et al 2017 AIP Conf. Proc. 1869 030002
[3] Noll D et al 2019 Proc. Conf. IPAC19 (Melbourne, Australia) 1090-1093
[4] Bacal M, Hatayama A and Peters J 2005 Volume production negative hydrogen ion sources IEEE Trans. Plasma Sci. 33 1845-1871
[5] Bel'chenko, Yu Dimov, G Dudnikov V and Ivanov A 1973 Dokl. Akad. Nauk SSSR 213 1283
[6] Bacal M and Wada M 2015 Appl. Phys. Rev. 2 021305
[7] Lettry J et al 2018 AIP Conf. Proc. 2052 050008
[8] Mochalskyy S et al 2013 AIP Conf. Proc. 1515 31-40
[9] Mochalskyy S, Lettry J and Minea T 2016 New Journal Phys. 18 085011
[10] Revel A et al 2017 J. Appl. Phys. 122 103302
[11] Wünderlich D et al 2021 Journal of Applied Physics 130, 053303
[12] Vnuchenko A et al 2021 Proc. Conf. IPAC21 (Brazil, South America)
[13] Briefi S, Fink D, Mattei S, Lettry J and Fantz U 2016 Rev. Sci. Instrum. 87 02B104
[14] Wünderlich D, Gutser R and Fantz U 2009 Plasma Sources Sci. Technol. 18 045031