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PRELIMINARY SIMULATION OF CERN'S LINAC4 H^- SOURCE BEAM FORMATION

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Abstract

Linac4 is the new (H^-) linear injector of CERN's accelerator complex. This contribution describes the modelling activities required to get insight into H− beam formation processes and their impact on beam properties. The simulation region starts from a homogeneous hydrogen plasma, the plasma then expands through the magnetic filter field. H^- ions and electrons are electrostatically extracted through the meniscus (line of separation between the plasma and the extracted beam) and eventually accelerated. The physics is simulated via the 3D PIC-Monte Carlo code ONIX. This code, originally dedicated to ITER's neutral injector sources, has been modified to match single aperture sources. A new type of boundary condition is described, as well as the field distribution and geometry of the standard IS03 and a dedicated prototype of CERN's Linac4 H− source. A plasma electrode prototype designed to provide metallic boundary conditions was produced and tested. This plasma electrode geometry enables Optical Emission Spectroscopy in the region closest to the meniscus. A set of plasma parameters was chosen as input characterizing the plasma. Preliminary simulation results of beam formation region are presented.

INTRODUCTION

The IS03b H^- source is being operated on CERN's Linac4 injector to the Proton Synchrotron Booster (PSB) [1]. IS03b is of the Radio Frequency Inductively Coupled Plasma (RF-ICP) type and ensures reliable H^- beam intensities of 25 mA after the RFQ in pulses of 600 µs at a repetition rate of 0.8 Hz [2, 3].

IS03b is composed of a ceramic plasma chamber surrounded by an external five-turn RF coil. Hydrogen gas is supplied with a pulsed valve. The extraction system consists of five-electrodes. A detailed view of the IS03b ion source is shown in Fig. 1.

H^- ions are produced via "*volume*" (dissociative attachment of a low energy electron to an excited $H_2{}^v$ molecule) and "*plasma surface*" (re-emission as H^- ion of a proton or hydrogen atom produced in the plasma and impacting onto a low work function caesiated molybdenum surface) mechanisms [4-6]. The H^- ion produced on the caesium coated molybdenum Plasma Electrode (PE) induces a localized charge separation and builds a negative sheath which is at the origin of an order of magnitude reduction of co-extracted electrons. The beam formation in the IS03 source results from the convolution of volume and localized PE-surface ion production. An electric field generated by a puller-dump electrode of typically 2-3 kV/mm extracts H^- and electrons simultaneously and repels positively charged particles to build the so-called meniscus. The meniscus shape and H^- ion's energy distribution defines the initial properties of the beam to be propagated through beam optics components.

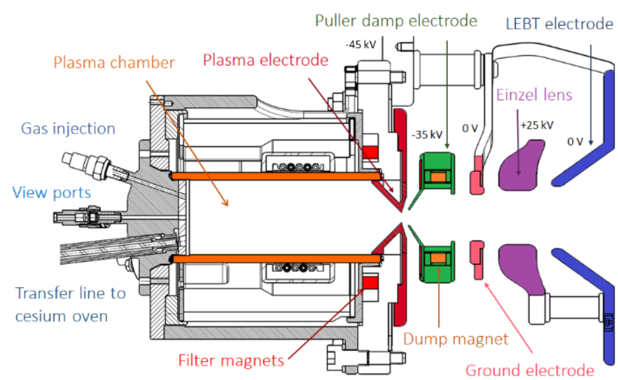

Figure 1: IS03b Linac4 H− ion source and extraction system. This source operates in volume and plasma surface H− production modes.

Co-extracted electrons are deflected by dipolar magnetic fields and dumped into the Puller-dump electrode, the filter and dump fields are generated by pairs of permanent magnets located around the PE and in the puller dump electrode. The filter field reduces the energy of electrons present in the beam formation region upstream of the PE-aperture down to typically tenth of eV energies, a crucial effect mandatory to preserve negative hydrogen ions required by the low (0.75 eV) binding energy of the second electron.

When operated with a high work function Mo PE, in volume production mode, the beam extracted reaches 30 mA for an electron to H^- ion current ratio (e/H) of 20. Caesiation of the PE enables surface H^- production mode yielding up to 70 mA H^- extracted current and e/H below 2. The final goal of the numerical simulations and associated experimental program is to gain insight into the initial beam properties resulting from these different modes of source operation.

After electron dumping, the beam is accelerated to 45 keV by the field between PE and a ground electrode and focused by an accelerating Einzel lens. Details of the plasma generator and operation under Cs-loss compensation can be found in references [3, 7].

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The stability and performance of the cusp free version of IS03 match today's CERN beams requirements. However, e-dumping at 10 kV induces emittance growth; to exploit the full potential of Linac4, a new extraction and beam optics are being studied. Initial beam properties downstream the meniscus provides insight to beam transport.

Negative ion beam formation and plasma in the vicinity of the PE extraction aperture have been simulated with the Orsay Negative Ion eXtraction code (ONIX) for fusion's neutral injectors sources [8-12] and preliminary investigation of previous Linac4 ion sources IS01 and IS02 [13]. We aim to simulate IS03b with the most up to date version of ONIX and, at a later stage, to compare its output to detailed Optical Emission Spectroscopy (OES) measurements of the plasma, beam emission spectroscopy, beam profiles and emittances.

SIMULATION MODEL

ONIX, a 3D Particle-in-Cell (PIC) Monte Carlo Collision (MCC) code developed by LPGP-Orsay for simulating the formation and extraction of H^- ions and co-extracted electrons in negative ion sources for ITER's Neutral Beam Injector (NBI). Currently the code is maintained by LPGP-Orsay and IPP Garching.

ONIX is an explicit 3D PIC model with a Monte-Carlo collision module (PIC-MCC). The code is self-consistent and parallelized using domain decomposition and the message passing interface (MPI).

To match accelerator H^- sources, ONIX has been modified and adapted. The originally implemented periodic boundary conditions of the simulation volume in directions orthogonal to the beam axis were replaced with non-periodic, *i.e.* single aperture. In this case, all plasma particles that strike the boundaries in y and z directions are reinjected in the "*bulk*" plasma, following certain rules. The extraction potential is applied to the right boundary of the simulation domain in a plane orthogonal to the beam axis. The remaining domain boundaries potential are assumed to be zero.

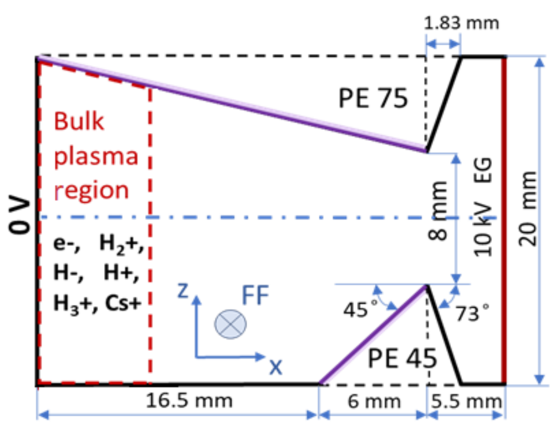

Figure 2: Schematic view of the simulation domains used in the ONIX code (x–z mid plane) for modelling beam formation of IS03b PE45 bottom and PE75 top. The filter field (FF) orientation is indicated. The PE bore diameter is 8 mm.

The simulation domain is 28×20×20 mm in x, y, z directions. The bulk plasma region is in the 0.5 to 8 mm interval. Sketches of the simulation region are shown in Fig. 2, the PE bore diameter is 8 mm. The aim of PE 75 (Fig. 2 - top) is to set radial metallic boundary conditions, a prototype was produced and is being tested.

The simulation is performed with the filter and dump magnetic fields calculated using the Opera 3D code [14,15]. The filter field in the y direction in the coordinate system used in the simulations. Fig. 3 shows the calculated magnetic field from the filter and dump magnets.

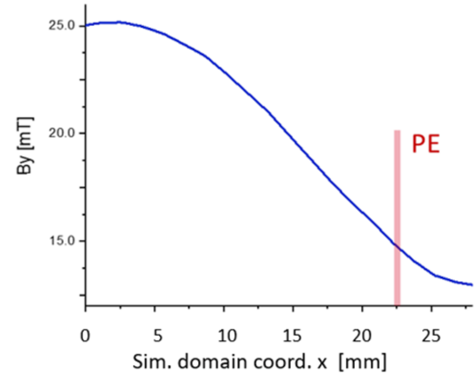

Figure 3: Magnetic field strength along beam-axis (x). The red line indicates the location of the plasma electrode (PE) aperture centred.

RESULTS AND DISCUSSION

The aim of the preliminary simulation presented in this paper is the verification of ONIX modified boundary conditions matching accelerator sources.

The simulation has been performed on a CERN cluster using 20 CPUs (total 360 cores), a meshing of 420×310×310 PIC nodes and a time step 5×10^{-12} s. The cell size is 6.5×10^{-5} m, slightly larger but close to the Debye length ($\lambda_D \approx 4.1 \times 10^{-5}$ m). These numerical parameters are sufficient for PIC stability requirements for a plasma density of 10^{16} m^{-3} in the bulk region. The bulk plasma composition and energy distributions were taken from previous measurements: 50% H^- (0.8 eV), 50% e (1 eV), 70% H^+(0.8 eV), 20% H_2^+ (0.1 eV), 10% H_3^+ (0.1 eV). All plasma species are tracked in 3D.

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 [16].

Simulation starts from a uniform initial distribution in the bulk plasma region and void in the remaining volume, with 5×10^5 macro particles per cell. The typical simulation for one condition takes 14 days on 20 CPUs representing 1.8 µs real time.

The self-consistent meniscus is formed in the vicinity of the plasma electrode aperture. In a first phase, the populations of the plasma migrate according to their energy to mass ratios. The meniscus stabilizes only once all plasma populations expanded into the beam formation region. The

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density maps of electrons and positive ions in the (*x*-*y*) and (*x*-*z*) planes of the simulation domain are shown in Fig. 4. The electron density decrease in the *x* direction is caused by the magnetic field. The electron 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 influence the distribution of the positive charged species.

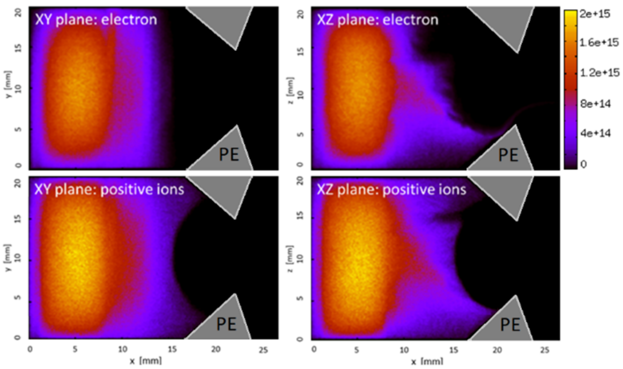

Figure 4: Density maps of electron (top) and positively charged particles (H+, H2+, H3+) (bottom) in the (x-y) (left) plane and (x-z) (right) plane where filter field generated asymmetry is clearly visible.

The particle is considered extracted when crossing the right boundary of the simulation domain. Fig. 5 shows the evolution of the H^- and co-extracted electron beam currents during simulation.

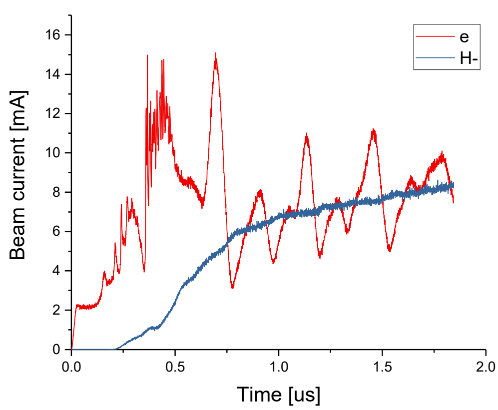

Figure 5: Time evolution of the extracted H- current (blue line) and co-extracted electron (red line) current for the IS03 PE45 system simulated with ONIX using a 10 kV extraction voltage. H− originates from volume and plasma surface production modes and e/H current ratio tends to 1.

Significant 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 after 0.7 µs. The value of both currents, for co-extracted electrons and H^-, is about 8 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 can be explained by 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.

CONCLUSION - OUTLOOK

A modified version of ONIX code with a single extraction aperture and non-periodic boundary conditions was written to model the Linac4 ion source in the extraction region and the beam formation. It was successfully tested on a subset of CERN's computing cluster using degraded plasma parameters. ONIX simulations demonstrated the self-consistent positive ion meniscus formation in the vicinity of the extraction aperture and will be applied to the IS03b beam formation studies. The main question to be addressed using this simulation technique is studying the different phase space distributions of the initial beam under volume or plasma surface production modes.

Simulation of higher plasma densities and different species energy distributions and proportions will be performed, requiring high performance computers. These initial conditions refinements rely on analysis from OES system installed around the plasma generator at the Linac4 ion source test stand [17].

The IS03 simulation results of ONIX (initial beam phase-space distribution) will be used as input parameters to beam transport simulations codes (*e.g.*, IBSimu) to the BES, beam profile and emittance locations in the Low Energy Beam Transport (LEBT) and directly compared to the diagnostics output.

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