Beam Formation Studies on the CERN IS03b H⁻ Source

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Abstract. An H^- ion source is being operated at the new 160 MeV linear injector (Linac4) of the CERN accelerator complex. The source's plasma is of the Radio Frequency Inductively Coupled Plasma type (RF-ICP), without magnetic cusp and runs with Cs-loss compensation [1]. Vertical downward oriented filter- and electron dump-dipolar magnetic fields expand over the plasma chamber, beam-formation, beam-extraction and electron dump regions and generate horizontal asymmetry and beam angular deflection partially compensated by mechanical alignment of the front-end. The H^- beam is generated via volume and caesiated plasma surface modes, the latter inducing a radial asymmetry characterized by an increased current density close to the plasma electrode surface [2]. Asymmetries affecting the meniscus shape, or its current density have to be simulated via 3D Particle In Cell Monte Carlo (PIC-MC) solvers, such as the Orsay Negative Ion eXtraction code (ONIX) [3]. Validation of these simulations require dedicated measurements. This contribution describes experimental methods newly implemented at CERN's ion source test stand and initial results for Optical and Beam Emission Spectroscopy (OES, BES), emittance and beam profile measurements. In a later stage, the gathered data sets can be compared to source plasma parameters and extracted beam parameters from PIC-MC simulations, once coupled to the Ion Beam Simulation (IBSimu) [4] beam transport code. The experimental parameter space includes RF-power, density of neutrals, position of the RF coil and extraction field. Beams of H^-, D^- and protons were produced; examples of measured data are presented in this contribution.

1. Introduction

H^- sources for Linac4 are designed to generate a specified beam current within RFQ-acceptance. The beam optics is iteratively optimized with IBSimu runs of variable electrodes and co-extracted electron beam dump (e-dump) geometries, extraction field, and e-dump magnetic field. IBSimu simulates electron and ion beams, encompasses an electron impact energy density map essential for e-dump design and enables tracking of secondary electrons. The plasma parameters, the total ion and electron currents extracted through the meniscus input to IBSimu were used to design the IS03b H^- source operated at Linac4 and presented in figure 1.

RF-ICP heating of the plasma was simulated with the 2.5D PIC-MC code NINJA [5] and validated by optical emission spectroscopy (OES) and photometry [6,7]. However, high-resolution 3D PIC-MC simulation is mandatory to resolve the physics in the vicinity of the meniscus, plasma sheath and caesiated plasma electrode. Neutral Beam Injector (NBI) for fusion pioneering work [8,9] brought deep insight into the processes resulting from combined volume and plasma surface H^- ion production and identified halos and the negative potential well at the origin of the massive reduction of co-extracted electrons observed under Ceasiated Surface Plasma (CSP) production mode. Initial ONIX runs [10] on the Lina4 source illustrated the phase space differences between volume and surface emitted ions. When compared to NBI-sources applications, radial boundary conditions in ONIX must be modified to match single aperture conditions, furthermore, the larger plasma density of Linac4 sources (few 10^{18} m^{-3}) is challenging. Extension of ONIX to single aperture is required to simulate the Linac4 source, preliminary low-density results are presented in [11].

The dual-origin of H^- ions, the filter-field induced asymmetry and the expected radial variation of ion current-density along the meniscus are likely detrimental to beam properties, i.e. presence of beam halos. Beam formation studies around the meniscus region is the link between RF-ICP-plasma heating and beam transport that determines the beam properties (position and velocity). Ions and electrons extracted from ONIX simulations a few mm after the meniscus, will be injected into IBSimu and transported to beam diagnostics locations. This contribution presents experimental methods to refine plasma parameters input to ONIX, to complement the Linac4 test-stand slit-grid beam emittance diagnostics with a new 2D beam profile monitor and to measure BES based angular distribution [12]. Setups and illustrative examples of the results are presented in the following sections.

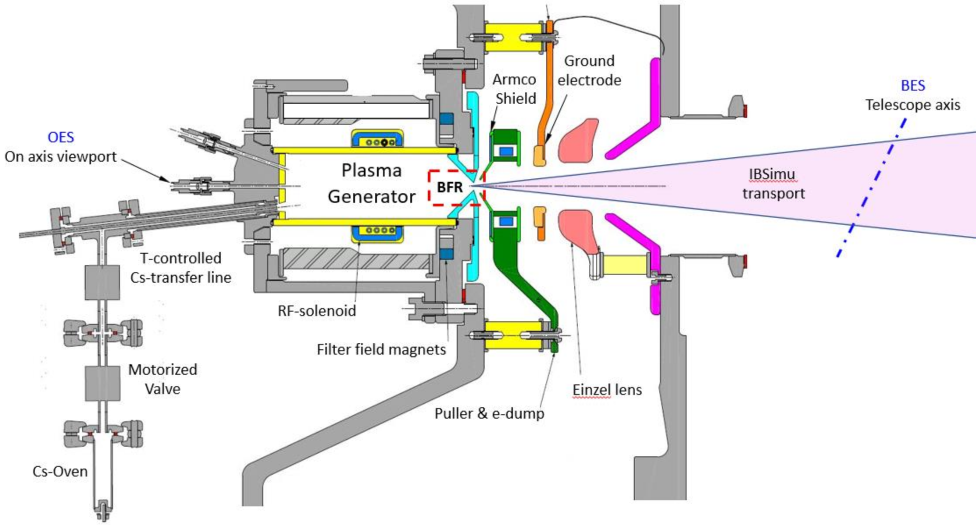

Figure 1. Layout of the Cusp free IS03b H^- source operated at Linac4. The beam formation region, the OES on-axis view port and the orientation of the BES telescope axis are indicated.

2. Plasma electrode prototype and Optical emission spectroscopy

A new plasma electrode (PE) geometry was produced (PE75) to provide simple metallic radial boundary conditions at the periphery of the beam formation region (BFR) of the ONIX simulation region. Black anodized (20 μm) Al-mockups of the prototype and standard plasma electrode (PE45) are produced and equipped with sets of mirrors and focusing lens to an optical fiber. The IS03 plasma chamber equipped with plasma electrode mockups can be operated without high voltage, the collisional radiative analysis of the light captured via this view port shall provide insight to plasma parameters, at the location of the meniscus. BFR-plasma will be compared to ONIX simulations with no extraction field. The new plasma electrode geometry and OES-mockups are presented in figure 2, the light is collected at 7 and 3.5 mm (PE75-mock-up) and 4 mm (PE45 mock-up) upstream from the PE-aperture.

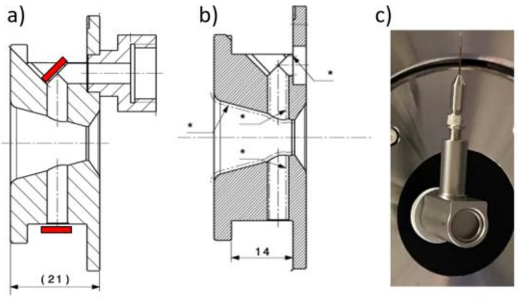

Figure 2. OES-mock-ups of the PE75 plasma electrode, 5 mm diameter view port are located: a) 7 mm and b) 3.4 mm upstream the plasma electrode aperture. Flat and 45 deg. mirrors illustrated in a) guide the plasma light to a lens focussing it onto an optical fibre c). The 20 µm black anodized surfaces are indicated with a star in b). The angle of the PE75 inner conus is 30 deg.

OES of the bulk plasma measured through the on-axis view ports of the plasma generator provides a reference point to previous work [5,6]. For each beam setting, 15 wavelength spectra are recorded to cover the Fulcher band (~200 H_2 molecular transition lines) and 4 atomic Balmer lines $H_{\alpha-\gamma}$. After noise subtraction, the spectra are corrected to account for the spectrometer calibration. The leakage of light from the bulk plasma to the beam formation detector amounts to approximately 1%.

3. Beam emission spectroscopy

A fraction of the H^- ions propagating through the space charge compensation gas is neutralized, the excited atoms maintain direction and velocity and, when observed in the laboratory's rest frame, the wavelength of its H_α transition is Doppler shifted according to its velocity and angle of observation. The H_α spectrum of the light collected from a telescope oriented vertically at an angle of 62˚-65˚ and pointing to the beam axis can therefore be converted into an angular distribution [12]. Due to our low duty factor, a few hours acquisition and a residual H_2 pressure of 2×10^{-2} Pa are necessary to obtain clean signals. The telescope viewing zone partially overlaps with the beam, extracting the BES signal from a simulated beam does not require any assumption, however, cylindrical symmetry is necessary to reconstruct a beam from an experimental BES angular distribution. BES angular distributions are presented in figure 3, effects of variating the extraction field (3.a) for a constant plasma heating power and of increasing beam intensity (3.b) under fixed extraction field on the beam angular distributions are shown, the difference between volume and CSP modes operated D^- is illustrated (3.c).

The beam halo is larger for the D^- cesiated surface production as a likely result of the fraction of the beam originating form the cesiated surface at the vicinity of the plasma electrode aperture, however this remains to be demonstrated via simulations of ONIX beam formation folded with IBSimu transport to the BES detection region.

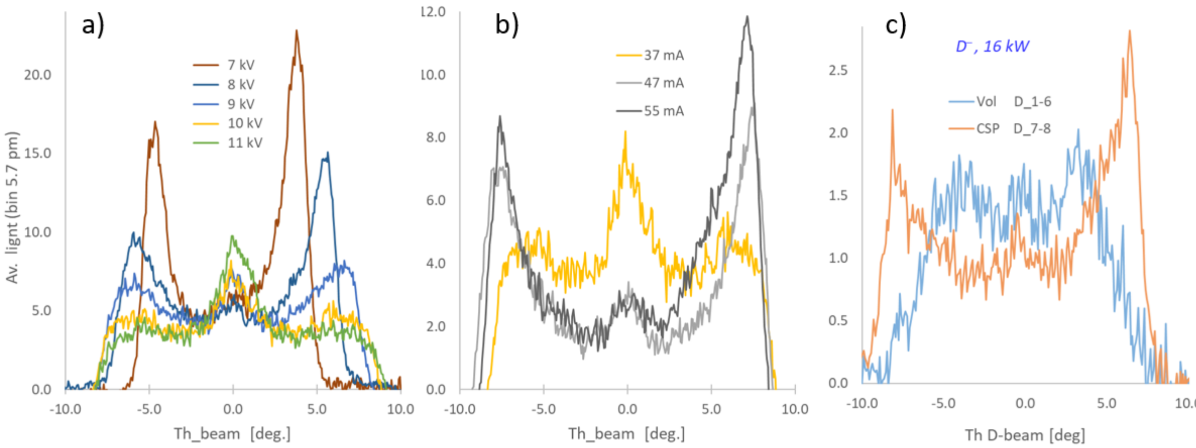

Figure 3. Beam emission spectroscopy angular distributions: a) CSP H^- beam at variable extraction field and b) CSP H^- beam at variable beam intensity, c) D^- beam in volume and CSP production modes.

4. Beam Emittance and profile

The Slit Grid emittance meter operated at the ion source test stand delivers velocities and positions integrated along parallel slit and wires. Assumptions on the beam profile are mandatory to reconstruct the beam phase space. The active surface 30×30 mm^2 is smaller than the beam and focusing is required to match the beam to the detector. The detection of positive charges on the wires is achieved with a bias voltage extracting secondary electrons, however, a negative signal is observed around each emittance measurement and neglected in the beam analysis. Operating the slit and wires in perpendicular orientation provides insight to the beam current density distribution, as the beam is converging, its image on the grids (located 200 mm downstream) is smaller than on the slit. Beam profile at the slit plane is reconstructed from two drift corrected scans of the horizontal (resp. vertical) slit across the beam monitored via vertical (resp. horizontal) grid. In figure 4 the profile of a 40 mA H^- beam is presented, the reconstructed picture is neither cylindrical nor axis symmetric, the observed shape cannot be extracted from emittance scans and shows a strong current density inhomogeneity. The larger radial current density is partially due to optics non-linearities, our long-term goal is to understand whether part of it originates from the beam formation process. Beam profiles can be compared to simulations. Future beam phase space reconstruction in view of beam transport (usually based on emittances) should account for the observed inhomogeneous current density.

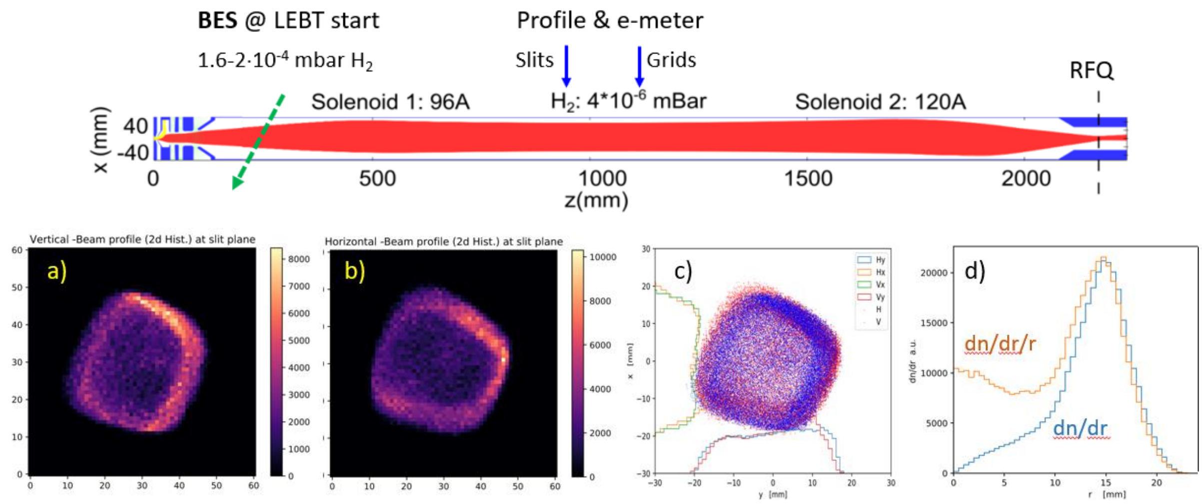

Figure 4. Beam simulation of Linac4's low energy beam transport section [13], the location of the BES telescope and of the slit-grid profile and emittance meter are indicated. H^- Beam profile at the slit plane measured via a) vertical- and b) horizontal-slits scans. c) scatter plots and projection histograms on horizontal and vertical axis and d) average radial beam current and current density distributions.

5. Conclusion and outlook

Volume and CSP production modes coexist in caesiated H^- sources. For permanent magnet filter field configuration, the plasma components' temperatures and densities, ion-current and ion to co-extracted electron ratio scale to the plasma RF-power; their contribution to the beam position and velocity distribution is complex and often reduced to a set of IBSimu parameters fitted to measurements. Furthermore, immediately after extraction through the meniscus, beam optics effects may be predominant at high current (i.e. non-linearities far from beam axis) and are difficult to disentangle from BFR induced asymmetries. Comparing volume and CSP production modes for identical plasma density is complexified, as co-extracted electrons drop by a factor around 20 while H^- beam intensity is doubled. Beam profile now provides a mean to cross check and possibly improve previous beam transport simulations. Plasma densities above 10^{18} m^{-3} are expected in Linac4 plasma generator and currently beyond reach of available superclusters. Simulation of the beam formation region without direct coupling to NINJA relies on complex OES calibration and production of dedicated prototypes for which radial boundary conditions are well defined.

BES shows a clear response to plasma and extraction field parameters, the low duty factor of the source implies multi-hours acquisition and, in the future, should be performed along horizontal and vertical axis to highlight asymmetries. Plasma electrode geometry will be developed to improve the match to ONIX's simulation domain. XRF based Cs-coverage measurement method is developed [14], a calibration down to 0.01 μg enables to measure Cs-coverage, averaged on the inner surface of the plasma electrode, down to sub monolayer thickness. An experimentally demanding correlation between H^- beam yield, electron suppression and Cs-coverage would provide insight to CSP core physics.

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