CERN's Linac4 Cesiated surface H^- Source

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Abstract. Linac4 cesiated surface H^- sources are routinely operated for the commissioning of the CERN's Linac4 and on an ion source test stand. Stable current of 40-50 mA are achieved but the transmission through the LEBT of 80% was below expectations and triggered additional beam simulation and characterization. The H^- beam profile is not Gaussian and emittance measurements are larger than simulation. The status of ongoing development work is described; 36 mA H^- and 20 mA D^- beams were produced with a 5.5 mm aperture cesiated surface ion source. The emittances measured at the test stand are presented. During a preliminary test, the Linac4 proton source delivered a total beam intensity of 70 mA (p, $H2^+$, $H3^+$).

INTRODUCTION

CERN's Linac4 [1] is being commissioned in stages; the 50 MeV (October 2015) and 105 MeV (June 2016) were successfully completed [2], the installation is completed and the commissioning at the 160 MeV nominal energy is scheduled in September-October 2016. A fraction of the H^- beam will then be delivered to the so called "half sector test" to study half of the injection chicane, and steer the design of critical components (i.e. stripper, H^0/H^- diagnostics and dump) of the H^- charge exchange injection into the PS-booster [3]. A reliability run is scheduled in 2017 and connection to CERN's accelerator chain during LHC's maintenance and upgrade shut down (2018-19).

The H^- ion source (IS03a) described in [4] was successfully operated during the 50 and 105 MeV commissioning runs and provided reliably H^- beam intensities of 40 to 50 mA. However, the transmission through the Low Energy Beam Transport (LEBT) section and through the RFQ were below expectation pointing to an H^- beam emittance larger than originally simulated [5]. The extraction optics and co-extraction electron dumping geometries were optimized and a newly designed set of electrodes (IS03b) produced and tested. The preliminary emittance and profile measurements of IS03b H^- beams under various settings are presented.

During the 12 month integrated operation, the IS03a prototype required monthly cesiation; regular tuning of the plasma parameters is mandatory in view of the slow but constant evolution of the Cs-coverage that leads to an increase of the co-extracted electron current. The operator's tuning skills were translated in a set of independent algorithms and programmed operations sequences at the top level of accelerator controls, monitoring and logging [6]. The so-called "Autopilot" software package is a major asset to the source stability and absolutely necessary to meet the 99% required beam availability; key information is derived from the H^- pulse shape; therefore, the Beam Current Transformer (BCT) of the Linac4 LEBT illustrated in figure 1 was moved before the pre-chopper to ensure availability of the entire H^- pulse shape.

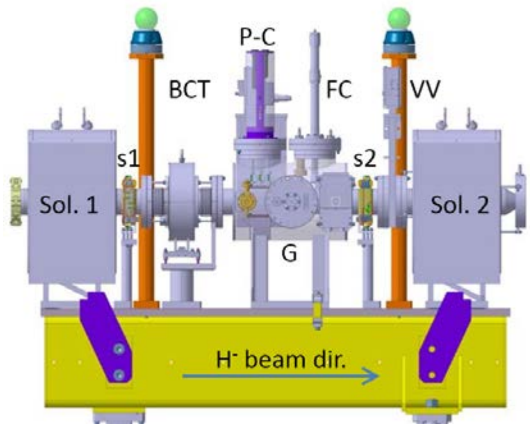

FIGURE 1. Scheme of the Linac4 LEBT: the beam current transformer (BCT) is located before the diagnostics box that encompasses the pre-chopper (P-C), horizontal and vertical grids (G) and a Faraday cup (FC). The matching solenoids (sol. 1,2), steerer magnets (s1,s2) and sector valve (VV) are indicated.

Simulation of the Linac4 H^- source, plasma at nominal operation parameters were achieved [7] and shall provide detailed plasma boundary condition including the H^0 and proton fluxes impacting on the cesiated plasma electrode. Plasma parameters,H^0- and p-fluxes are key input to Particle In Cell (PIC) H^- beam formation simulation [8] that are deemed essential towards further beam extraction improvements. A preliminary study of the extraction from the Linac4 H^- source was done via 2D PIC simulation [9]. Simulations of the inductively coupled plasma reproduced the trend of E to H transition measured via optical emission photometry (OEP) with and without magnetic cusp [10]. Plasma ignition measurement are regularly performed via OEP and will be the topic of a future publication. The simulated plasma parameters match those measured via optical emission spectroscopy (OES) and analyzed using collisional radiative modelling [11, 12]. The relation between the plasma parameters and the impedance induced into the RF-amplifier circuit was investigated [13].

The Linac4 ion source test stand is dedicated to investigation of space charge compensation, measurement of beam profiles and improvement of emittance.

H^- SOURCE PERFORMANCE DURING COMMISSIONING OF LINAC4

The IS03a H^- source was successfully operated during 1 year with regular 5 mg cesiations at typically one month interval. This successfully achieved stability is an encouraging sign in view of the desired maintenance free 12 month operation period. The Cs-valve is motorized and opened once the Cs-delivery temperatures are reached, the ion and co-extracted current are monitored during cesiation, and the strong reduction of the co-extracted electron to H^- ion ratio (*e/H*) indicates the effective start of the reduction of the work function of the plasma electrode surface.

The IS03a plasma electrode was initially implanted with a Cs layer (5, 10, 15 keV energy Cs^+ ions), the conditioning was faster than usual but the initial reduction the e/H ratio did not compare to a standard cesiation and lasted of the order of 1-2 weeks. The ion source conditioning procedure is steadily improved for each prototype (globally reduced form weeks to days) this first test therefore cannot lead to numeric comparison.

The duration of the linac4 H^- pulse was prolonged from 0.4 to 0.6 ms; the increase of the injection allows operation at a lower H^- beam peak intensity. After plasma ignition, the H^- beam intensity rises during approximately 0.25 ms before reaching the desired 40 mA current as illustrated in figure 2, this delay is associated to the plasma formation process. The LEBT space charge compensation (SCC) process also has a time constant of the order of 0.25 ms, it is illustrated in figure 2 on a beam pulse for which the low intensity beam period corresponding to the ignition and ramp up phases were chopped. A transmission through the RFQ measured as the ratio of the BCTs located in the LEBT and immediately after the RFQ show that the transmission of 80% anticipated for this beam is only reached after 0.35 ms. Optimization of the LEBT pressure may reduce the SCC time constant.

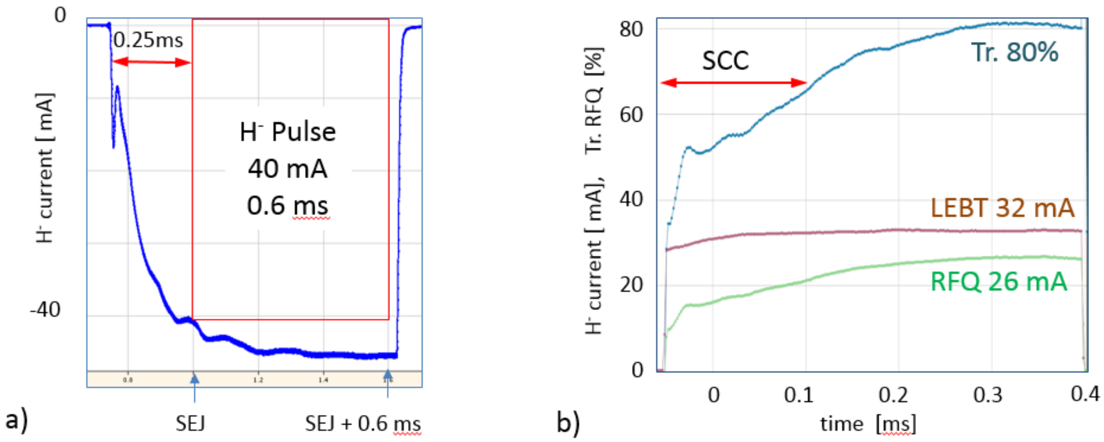

FIGURE 2. Linac4 IS03a H^- operation: a) H^- current pulse shape, the Linac4 extraction timing (SEJ) is indicated, a 40 mA and 0.6 ms H^- pulse is shown. b) Transmission of an IS03a H^- pulse through the RFQ, the pulse's head and tail are chopped in the LEBT. The current before and after the RFQ are measured with beam current transformers. The onset of the Space Charge Compensation (SCC) process is indicated.

As a result of a conservative risk analysis, the cesiation procedure demands a separation of the RFQ from the source vacuum sectors for the duration of the Cs-delivery. An automatized sequence controls the temperature profile and the opening/closing the Cs-valve. At the end of operation period of one year, the ion source components are cleaned in ultra-pure water, a measurement method based on Energy-Dispersive X-Ray Spectroscopy (EDXRF) analysis of a dried concentrate of the rinsing water was developed to characterize Cs-contamination and demonstrated a detection limit of 0.05 µg. After one year operation, the IS03a components directly facing the plasma generator were analyzed; the quantity above detection limit were found on the ARMCO® iron magnetic shield (1 µg), the puller electrode (12 µg) and the plasma electrode (124 µg).

IS03 H^- SOURCES

The IS03a prototype operated under nominal LEBT optics showed losses in the first half of the LEBT and also a transmission through the RFQ of 80%. The beam emittance was larger than predicted and exceeded the RFQ acceptance; refining the simulation optimized the beam optics. New prototypes illustrated in figure 3 were produced. The beam divergence induced losses in the LEBT. The beam divergence was limited by the maximum voltage of the cw Einzel lens, its feed through was improved and the cw HV-supply replaced by a 50 kV pulsed high voltage unit. The IBsimu [14] software was used to design the extraction optics; the simulation domain was split in three regions covering the extraction and electron dump (1) the Einzel lens and insertion into the LEBT (2) and the LEBT (3). The expected emittance calculated at the end of the LEBT for a 40 mA beam intensity (e/H = 3) was ε_{rms} = 0.34 $\pi\cdot$mm$\cdot$mrad. The electron dump was optimized to reduce leakage of co-extracted electrons and the production of secondary electrons on the e-dump. The ion source front end is tilted (1°) in the horizontal plane to partially compensate for the deflection of the H^- beam induced by the filter and dump field.

Two versions of the IS03 prototype ion source (IS03b and IS03c) were produced with the aim to test the sensitivity to small design changes. The standard 5 turn RF solenoid was enlarged also to improve the 3D printing aspect of its production process. IS03b disposes of a floating plasma electrode that can be biased at ±60V, its plasma electrode aperture diameter is 5.5 mm and the plasma generator is driven by a 5 turn RF-solenoid composed of 4 mm copper tube distributed over 31mm. The plasma electrode of IS03c is connected to the flange and therefore kept at the potential of the plasma chamber, the diameter of plasma electrode hole is 6.5 mm and the width of the antenna solenoid 26.5 mm. the plasma electrode of IS03c can be equipped with a heating system. The characteristics of the slightly different IS03 prototypes are summarized in table 1.

TABLE 1. IS03 prototypes: the features of the RF-heating solenoid, plasma electrode, electron dump and Einzel lens are given.

Parameter	IS03a	IS03b	IS03c
5 turn RF-solenoid:			
- Length	26.5 mm	31.0 mm	26.5 mm
- Distance to PE	31-52 mm	36-72 mm	31-52 mm
Plasma electrode:			
- Chamfer angle	45°, 72.5°	45°, 73°	45°, 73°
- Aperture diameter	6.5 mm	5.5 mm	6.5mm
- Option	Heating	Bias ± 60 V	Heating
- B-shield	Armco 1-2 mm		
Puller - Electron dump:			
- Chamfer angle	40°	58°	58°
- B-shield		Armco 1 mm	Armco 1 mm
Einzel lens:			
- Max. voltage	31 kV	45 kV	45 kV

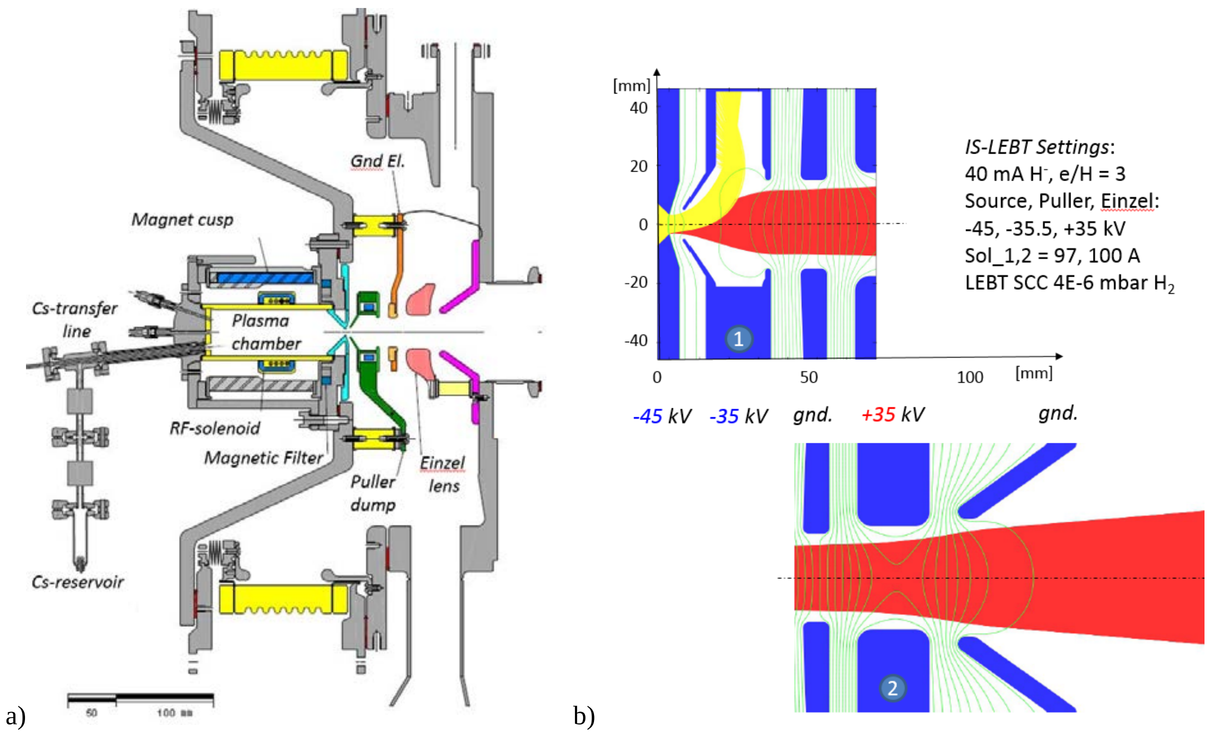

FIGURE 3. Linac4 IS03b H^- ion source: a) layout: the plasma generator, Cs-injection, the puller-dump, ground electrode and accelerating Einzel lens are indicated and b) two of the three IBSimu electron and H^- ion simulation that lead to the optics design are show: (1) extraction and e-dumping region and (2) Einzel lens. The simulation's input voltages and currents are indicated.

H^- BEAM CHARACTERIZATION

The Linac4 ion source test stand is illustrated in figure 4, the first section is identical to the one installed in Linac4 and encompasses a solenoid, a horizontal and vertical magnetic steerer and a beam current transformer. After a vacuum valve, the beam diagnostics encompasses a slit-grid emittance meter and the Linac4 beam diagnostics box equipped with profile measurement grids, a Faraday cup and the injection of the gas mandatory for space charge compensation. In the diagnostics box, space is reserved for the pre-chopper tests.

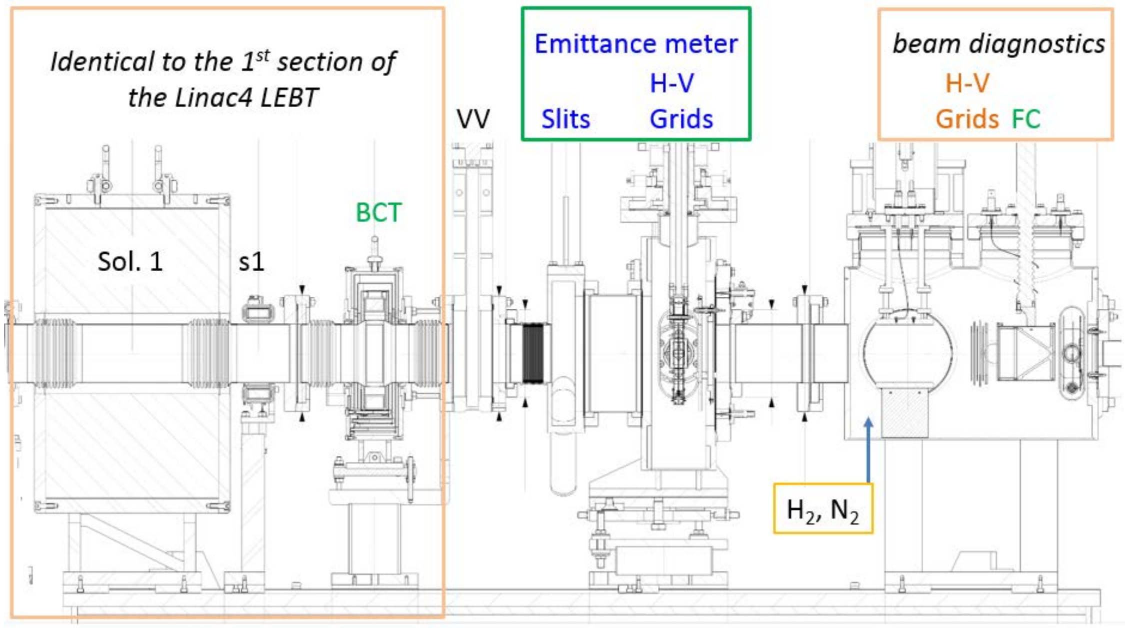

FIGURE 4. Layout of the Linac4 H^- ion source test stand: the first section is identical to the one installed in Linac4 and encompasses a solenoid (sol. 1), horizontal and vertical steerer (s1) and a beam current transformer. After a vacuum valve, the beam diagnostics section contains a slit-grid emittance meter and the Linac4 LEBT beam diagnostics box equipped with grids, a Faraday cup and the injection of the gas mandatory for space charge compensation.

The emittance meter is a slit grid system [15, 16], the grid consist of 40 gold plated tungsten grid wires of 40 μm diameter separated by 0.75 mm. The slit is machined in a 1 mm stainless steel plate, its width is 0.1 mm. the distance between slit and horizontal (vertical) grids is 200 mm. At plasma ignition, a short but intense electron burst is extracted and dumped, the plasma heats up and reaches stability after typically 0.25 ms, this period also corresponds to the typical time constant needed to establish space charge compensation in the LEBT. The acquisition time step is set to 6 μs to cover the 1 ms duration of the pulse. As an illustration, emittances of beams delivered by the IS03b prototype measured at the Linac4 ion source test stand are presented in figure 5 as a function of beam intensities (from 21 to 29 mA) corresponding to RF-power transmitted to the plasma of 36 to 48 kW. The Space charge compensation gas is hydrogen (5-7 × 10^{-6} mbar H_2) and the e/H ratios range from 3 (36 kW) to 4 (48 kW RF-power). The time profile of the beam intensity of the 27 mA H^- pulse is indicated to illustrate the plasma ignition and beam intensity buildup phases. Horizontal and Vertical plane emittance plots (averaged form 0 to 0.4 ms after SEJ) of an H^- pulse (SCC pressure in the LEBT: 6 × 10^{-6} mbar N_2) are shown.

For the IS03 extraction geometry and field distribution, an emittance at RFQ entrance of $\varepsilon_{\text{norm, RMS}}$ = 0.34 π·mm·mrad is obtained from IBSimu simulation for a 40 mA H^- beam intensity with an e/H of 3. Emittances were measured for a set of RF-power, LEBT gas density and extraction field. We observe that hydrogen pressure in the LEBT of typically 5-10 × 10^{-6} mbar H_2 minimizes the emittance and that the emittance grows with RF-power or beam intensity. A beam intensity of 36 mA intensity can be extracted from IS03b and loss free transported through the LEBT. An emittance of $\varepsilon_{\text{norm, RMS}}$ = 0.25 π·mm·mrad corresponding to the source specification is measured for an H^-

beam intensity of up to 25 mA. At 30 mA, the measured emittance is larger than the value expected from the simulation of 40 mA beam.

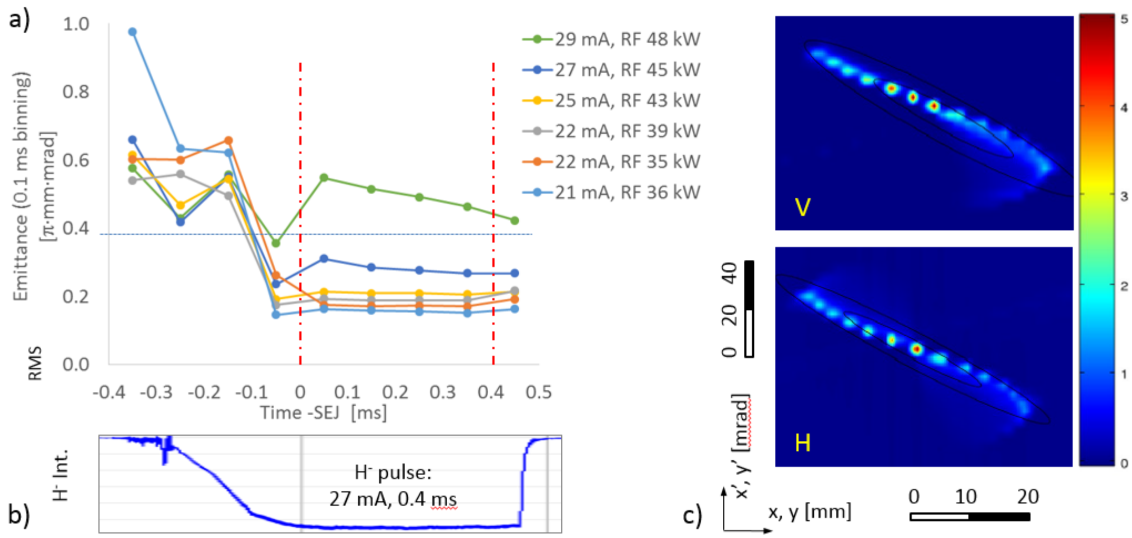

FIGURE 5. (a) IS03b emittance measurement performed at the Linac4 ion source test stand, the beam intensity and RF-power transmitted to the beam are indicated. The Space charge compensation gas is hydrogen (5-7 × 10^{-6} mbar H_2) and the e/H ratio ranged from 3 at 36 kW to 4 at 48 kW RF-power. The time profile of the beam intensity of the 27 mA H^- pulse is indicated. (c) Horizontal and Vertical plane emittances (averaged from 0 to 0.4 ms after SEJ) of an H^- pulse (SCC pressure in the LEBT: 6 × 10^{-6} mbar N_2).

Simulation and measurement of non-Gaussian beam distribution were reported in plasma cesiated surface sources for fusion [17]. In previous ONIX beam formation simulation of the IS02 prototype [8], the distinction can be made between H^- ion generated in the volume and on cesiated surface, preliminary results indicate rather different distributions. Vertical and horizontal beam profiles of a beamlet passing through the emittance meter slit were measured with the emittance meter grids and hint towards non-Gaussian profiles. However, at 45 keV, H^- ions absorbed on the grid-wires induce a negative signal while secondary electrons produce a positive signal. Our beam profile results are provisory as the impact of space charge conditions on the effective Secondary Emission Yield (SEY) requires further investigation.

D^- BEAM CHARACTERIZATION

The IS03b prototype was operated for the first time with Deuterium. The only modifications to the test stand setup were to scale the field of the LEBT solenoid magnet and to anticipate the D_2 injection timing by $\sqrt{2}$. During this test of a few hours duration, a beam of 11 mA was obtained before cesiation with an electron to D^- ion ratio (e/D) of 34 (more than double of our volume mode e/H ratio) and an emittance of $\varepsilon_{\text{norm, RMS}} = 0.4$ π·mm·mrad. After cesiation, a beam of 20 mA intensity was produced with an e/D of 2 and $\varepsilon_{\text{norm, RMS}} = 0.3$ π·mm·mrad. Doubling of e/D took only 30 minutes while for e/H, it is a matter of few hours followed by a slow growth of typically 0.3 electron/ion per day of operation. This hints towards a much more dynamic process impacting the work function of the cesiated Mo-surface. In order to keep a low work function during D^- beam operation (i.e. emittance measurements), the Cs-oven has to be kept at moderate temperature to constantly deliver a low flux of atomic Cesium.

PRELIMINARY RESULTS OF THE IS03 PROTON SOURCE

In the unlikely event of a major failure of the 50 MeV Linac2, Linac4 could be operated at 50MeV, deliver up to 80 mA protons and act as spare proton injector to the PS-booster. A Linac4 proton source is being developed, the layout of the IS03p prototype is shown in figure 6. Most of the components are those of the IS03 plasma generator mounted without dipole filter-field and with a stainless steel plasma electrode. The extraction optics was simulated with IBSimu, the beam is accelerated in 3 stages; the plasma generator potential is +45 kV, the puller +35 kV and the Einzel lens up to -43 kV. For the preliminary tests, it was mounted on the front end equipped with the IS03b Einzel lens that is optimized for H^- beam production, this assembly shown in figure 6b was not simulated but a short test could indicate whereas exchanging the Einzel lens is necessary for short proton beam validation tests in Linac4. The test condition were hampered by a fault in the puller electrode converter, therefore, the puller electrode was left floating for the duration of the tests. The proton beam required a solenoidal field of 120 % nominal to be transported through the LEBT to the grid and Faraday cup diagnostics. A pulse of 0.7 ms duration and (p, H_2^+, H_3^+) total beam intensity of 70 mA was produced. Reaching nominal intensity (80 mA protons) and emittance ($\varepsilon_{\text{norm, RMS}}$ = 0.25 π·mm·mrad) requires further testing.

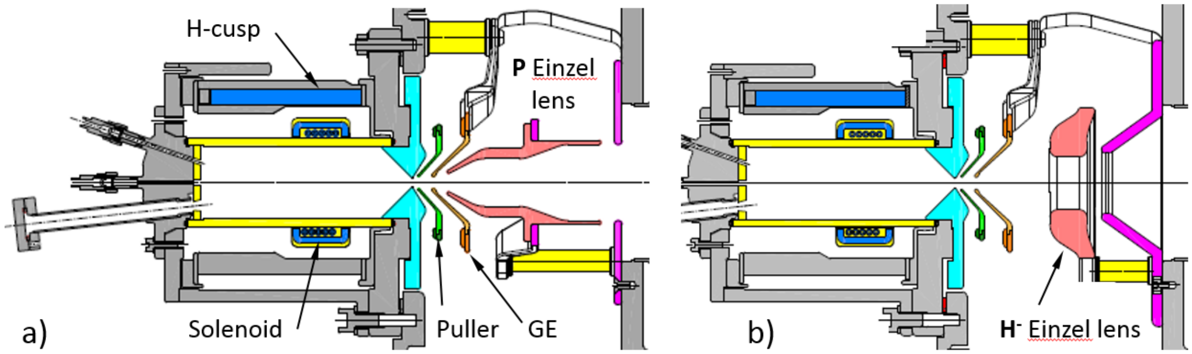

FIGURE 6. (a) Layout of IS03p plasma generator and extraction optics. The Halbach offset octupole, RF-solenoid antenna, puller electrode, ground electrode (GE) and Einzel lens are indicated. (b) IS03p plasma generator assembly with its puller and ground electrode mounted on the ion source frontend equipped with the IS03b H^- Einzel lens.

CONCLUSION AND OUTLOOK

The IS03a plasma cesiated Mo-surface prototype delivered H^- pulses of 0.4 to 0.6 ms duration and 40-50 mA intensity at a repetition rate of 0.8 Hz. It was operated reliably during 11 months with monthly cesiation of typically 5 mg. Hours or days interruption of the plasma is detrimental to the beam quality and increases the co-extracted electrons current, the beam is back to nominal within 2 hours. An operation software “Autopilot” drastically reduces the operator workload.

The plasma cesiated surface IS03b features an increased filter field strength, a larger solenoid antenna and new beam dump and Einzel lens design. The maximum beam intensity is 36 mA with no losses in the LEBT. The emittance specification of $\varepsilon_{\text{norm, RMS}}$ = 0.25 π·mm·mrad corresponds to an H^- beam intensity of up to 25 mA. At 30 mA intensity, the emittance is already larger than the value expected from simulation for the nominal 40 mA. A preliminary beam profile measurement hints towards the presence of beam halo. The RF-power, filter field strength, antenna coil geometry and position are the parameters impacting the plasma parameters that determine beam intensity. The first implicit 2.5D PIC RF-plasma heating simulation shall be followed by a parameter study to optimize the plasma generator engineering. H^- ions originating from the surface are deemed to cause the halo and sets our highest priority to 3D PIC simulation of the beam formation process providing access to emittance figures independent form assumptions on the meniscus current density. The plasma electrode geometry will be derived from the simulation’s emittance minimum but also from test on plasma electrode geometries.

Deuterium beams were produced in volume (11 mA) and plasma cesiated surface (20 mA) modes, during these preliminary tests, we could observe a very dynamic behavior of the effective work function of the Cesiated Molybdenum plasma electrode, a constant Cs-flow proved necessary to stabilize the beam parameters.

A Proton beam was produced with the IS03p prototype; although 70 mA (p, H_2^+, H_3^+) total beam intensity was extracted with a floating puller electrode, it is likely that a higher flux passes the plasma extraction hole and that its diameter has to be reduced.

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