A magnetized Einzel lens electron dump for the Linac4 H⁻ ion source

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Linac4 is a 160 MeV linear accelerator which will inject negative hydrogen ions (H⁻) into CERN's Proton Synchrotron Booster, a required upgrade to improve the beam brightness in the LHC injector chain. A volume production RF ion source, based on the design of the DESY RF source was implemented, but showed considerable electron dump ablation during operation at 45 keV beam energy. To reduce the electron beam power density in the dump, a magnetized Einzel lens is designed that reduces the beam energy to 10 keV before permanent magnets dump the electrons on a tungsten surface. Presented in this paper are simulations of the design using IBSimu, the tunable range of parameters depending on the extracted H⁻ and electron current, as well as details of the implementation, the choice of pulsed power converters and the electrode alignment system. In addition, simulations of proton extraction from this source will be shown.

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Abstract. Linac4 is a 160 MeV linear accelerator which will inject negative hydrogen ions (H^-) into CERN's Proton Synchrotron Booster, a required upgrade to improve the beam brightness in the LHC injector chain. A volume production RF ion source, based on the design of the DESY RF source was implemented, but showed considerable electron dump ablation during operation at 45 keV beam energy. To reduce the electron beam power density in the dump, a magnetized Einzel lens is designed that reduces the beam energy to 10 keV before permanent magnets dump the electrons on a tungsten surface. Presented in this paper are simulations of the design using IBSimu, the tunable range of parameters depending on the extracted H^- and electron current, as well as details of the implementation, the choice of pulsed power converters and the electrode alignment system. In addition, simulations of proton extraction from this source will be shown.

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INTRODUCTION

A prototype of a new ion source for Linac4 has been constructed at CERN and is ready for commissioning [1]. The initial design based on the non-caesiated, 2 MHz DESY H^- volume source [2] has undergone major modifications of the plasma generator and extraction system to meet Linac4 requirements. The specification for the Linac4 ion source is a pulsed H^- beam of 500 μs , 45 keV beam energy, 80 mA beam current with a normalized rms emittance of 0.25 mm mrad at a repetition rate of 2 Hz. The goal has proven to be challenging when it comes to the requirements of beam current, emittance and extraction voltage.

In 2009, an H^- beam of 23 mA with an energy of 35 keV and 0.26 mm mrad emittance was demonstrated from the non-caesiated source as reported in [3] and [4]. However, when the extraction voltage was increased to 45 kV in 2010, ablation of the electron dump caused frequent high voltage breakdowns between the plasma generator and the puller, making it impossible to operate the source. In 2011, two new extraction systems were proposed to ensure that the co-extracted electrons would be dumped in a controlled manner and that the high current beam would be transported to the two solenoid Low Energy Beam Transport (LEBT) with low emittance and beam loss. Both systems were designed and optimized with the simulation code IBSimu. A decision was made to construct a new extraction system where the electrons are dumped in a magnetized Einzel lens, lowering the electron beam energy in the dump and at the same

time focusing the H^- beam [5]. The source will in addition use pulsed high voltage power supplies to avoid breakdowns occurring in between beam pulses and to reduce damage from sparks with the $2\ \mu\text{F}$ capacitively backed DC high voltage system that was previously used. The first prototype of the ion source is designed to produce a beam of 20-30 mA for the commissioning of the LEBT, Radio Frequency Quadrupole (RFQ) and beam chopping system.

During the upgrade of the negative ion source, the plasma generator and extraction system was operated with inverted polarity to provide a proton beam (with $\sim 10\%$ fractions of H_2^+ and H_3^+) at 45 keV for commissioning of the LEBT.

SIMULATION AND DESIGN OF EXTRACTION SYSTEM

During the commissioning of the ion source, different parameters (e.g. H_2 gas pressure, RF-power) that will affect the plasma properties and beam formation will be iteratively tuned in order to optimize the extracted H^- and electron currents and the beam emittance. Thus, the extraction system is designed to be flexible and the optics of the system is tunable *in-situ* for the optimum transmission of the negative ion beam. This choice of design makes the extraction system complex, however at this stage of the development, the adaptability of the system is required for systematic studies of the ion source.

The new extraction system, shown in Fig. 1, has a design based on simulations with IBSimu, a general-purpose three-dimensional (3D) simulation code for charged particle optics with space charge [6]. The ion source uses a multiple electrode extraction system for transporting the beam to a two solenoid LEBT. The puller accelerates the beam from the source before the beam enters a magnetized Einzel lens where the electrons are dumped. A second Einzel lens is implemented for H^- beam transport and beam optics tuning into the LEBT. The effect of each of the electrodes is described in the following sections. The geometry for the simulation has been imported to IBSimu as a DXF file and the magnetic field for the electron dump has been calculated with Vector Fields OPERA/TOSCA [7].

Initial conditions for simulation

For all simulations described in this paper, a set of plasma parameters which previously have shown good agreement between simulations and measurements [5], has been chosen and kept constant. The most important are the transverse temperature ($T_t = 0.5\ \text{eV}$) and the initial energy ($E_0 = 5.0\ \text{eV}$) of ions and electrons. The simulations use a rectangular mesh with a step size of 0.5 mm. The simulated beam current of H^- and electrons has been distributed over 30,000 particle trajectories for each specie, starting from a plane inside a defined plasma volume. Approximately one third of these trajectories exit the plasma generator and are tracked through the extraction system. The parameter space of H^- currents and electron to H^- (e/H^-) current ratios have been selected based on measurement results from the 35 keV commissioning of the Linac4 ion source made in 2009 [3]. The H^- current has been varied from 10 to 30 mA and the e/H^- ratio from 20 to 60. The potentials of the plasma generator at -45 kV, the magne-

FIGURE 1. Simulation of the extraction system of the Linac4 ion source. The electron beam in yellow (light grey) is deviated and dumped in the magnetized Einzel lens. The H^- beam in red (dark grey) is focused by two Einzel lenses and transported to the LEBT.

tized Einzel lens at -35 kV, and the grounded electrode and LEBT at 0 V have been kept constant in all simulations.

Puller electrode

The puller electrode provides the first stage of acceleration of the H^- beam and has, in addition, two tuning possibilities: (1) A variable voltage to give the best matched electrical field for the plasma meniscus. (2) The possibility to tilt and move for correcting the misalignment of the H^- beam caused by the magnetic field in the electron dump.

Plasma meniscus tuning

When extracting a beam from a plasma, the process of beam formation will vary with the properties of the plasma, i.e. plasma density, electron and ion temperature and electron to ion ratio. In Fig. 2, three simulated cases of beam extraction are illustrated. All simulations use an extraction voltage of -30 kV, giving a beam energy of 15 keV. Only the H^- beam current density has been varied while the e/H^- ratio has been fixed to 50. Case (a) shows an extraction of a 5 mA H^- beam, which with the strong electrical field gives an over-focused beam. In (b), the beam current is 20 mA and shows the ideal case where the plasma meniscus is slightly convex giving a close to parallel beam. In case (c), the beam current is 50 mA, and here the beam is divergent and part of it is even lost on the puller.

FIGURE 2. Illustration of beam extraction from under-dense, matched density and over-dense plasmas. (a) 5 mA H^- : Over-focused beam, (b) 20 mA H^- : Matched puller voltage to beam current density, (c) 50 mA H^- : Divergent beam. All three cases use an e/H^- ratio of 50 and an extraction potential of 15 kV.

A set of simulations was made to visualize the effect of the puller voltage on the beam properties of the Linac4 ion source, notably the H^- beam emittance and the efficiency of the H^- transmission and electron dumping. The H^- transmission efficiency is defined as the fraction of H^- ions that reaches the LEBT entry. Likewise, the electron dumping efficiency is the fraction of electrons being dumped inside the tungsten dump in the magnetized Einzel lens. Electrons dumped on the side walls of magnetized Einzel lens are not included in the calculation. Figure 3 shows a case where the beam parameters vary as a function of the puller voltage with a constant H^- current of 20 mA and an e/H^- ratio of 40. These conditions give an optimum puller voltage of -28 kV for minimum emittance and maximum transmission efficiency.

FIGURE 3. Emittance, H^- transmission and electron dumping as a function of the puller voltage. H^- current is 20 mA and e/H^- ratio is 40.

Assuming that the beam size and emittance mainly is defined by the shape of the plasma meniscus and the beam acceleration until the electron dump, the data set can be expanded to take into account the different extracted beam currents. It is then possible to visualize a voltage range within where one should work for optimal beam optics depending on the total space charge equivalent H^- current extracted from the source:

$$I_{tot H^- eqv} = I_{H^-} + I_e \sqrt{\frac{m_e}{m_{H^-}}}, \quad (1)$$

where I_{H^-} and I_e represents the extracted H^- and electron current and m_e and m_{H^-} the mass of electrons and H^- respectively. Figure 4 shows the H^- transmission efficiency and the horizontal emittance of the H^- beam as a function of the puller voltage and $I_{tot H^- eqv}$. The plots show that the highest H^- transmission efficiency and lowest emittance is obtained with the same matching of puller voltage to extracted beam current.

FIGURE 4. (a) H^- transmission efficiency and (b) horizontal emittance as a function of the voltage on the puller and the total space charge equivalent H^- current.

H^- beam steering

For compensating the offset of the beam induced by the electron dump magnetic field, the puller can be tilted and moved in the horizontal plane parallel to the electron dump direction. Shown in Fig. 5 is the impact of the puller tilt and offset on the position of the beam at the LEBT entry. The H^- beam current has been kept constant at 30 mA and the e/H^- ratio to 50 with a puller voltage of -20 kV. The two contour lines show under which conditions the beam is located centrally on axis and parallel to it. The plot shows that the beam position and angle are very sensitive to the offset of the puller (5.3 mm/mm and 10 mrad/mm respectively), however, the variation is less dependent of the puller tilt

(0.16 mm/deg and 0.12 mrad/deg respectively). The two zero lines converge to a value of puller tilt and offset giving an average zero position and angle of the beam at the entry of the LEBT. In this case, the optimum value of tilt is -5° and the offset is 0.85 mm, however this could vary for different beam currents and puller voltages.

FIGURE 5. Optimum tilt and offset of the puller electrode.

Einzel electron dump

The second electrode of the extraction system is a magnetized Einzel lens, focusing the H^- beam and dumping the electrons with a magnetic dipole field, illustrated in Fig. 6 (a). The H^- beam will also be deviated from the beam axis by this field and should be corrected. A second magnet dipole may be used, however, it has not been implemented in the present design, making the electrode shorter and reducing the emittance growth at low energy (10 keV). Due to the compact design and high magnetic field, a small fraction of the electrons ($< 1\%$) could return back to the puller, as is visible in Fig. 1. The quantity depends on the beam current and the extraction system tuning, however, this situation is acceptable compared to the risk of having electrons being transported through the electrode and follow the H^- beam or hit the grounded electrode with an energy of 45 keV. A correction of the H^- beam misalignment is still possible by applying an offset and/or tilt to the puller as previously described.

Electron beam power density

As reported in [5], the electron dumping at 45 keV beam energy caused sublimation of the dump material resulting in high voltage breakdowns in the source. The simulation of that extraction configuration showed a peak electron beam power density of 3.0 kW/mm^2

in the cup. Transient thermal simulations made with ANSYS have shown that a pulsed power density above 1 kW/mm^2 for a $500 \mu\text{s}$ beam pulse is sufficient for sublimating a graphite surface, the material used in the DESY source. For a tungsten surface, the accepted power density is approximately a factor 2 higher, however, this is still not sufficient for avoiding thermally induced damage. In addition to changing the material, the electron beam energy in the dump thus was reduced from 45 keV to 10 keV and the dump has been designed to spread the beam over a larger surface in the dump. The electron beam power density was calculated for all surfaces of the new dump design and was shown to be always one order of magnitude below the critical power density for tungsten. Figure 6 (b) shows that even for highest electron currents extracted, the dumped electron beam power density is acceptable.

FIGURE 6. (a) Cross-section of the electron dump. (b) Maximum power density in the electron dump as a function of the voltage on the puller and the total space charge equivalent H^- current.

Due to the low duty factor (2 Hz, 0.5 ms), no active cooling of the dump is implemented. Instead, the heat from the electron beam is evacuated by thermal radiation and conduction through a copper leg and a Shapal ceramic insulator to the stainless steel source body. The average heat distribution in the dump was studied by an ANSYS steady state thermal simulation showing that the temperature increases from room temperature to 57°C for a beam pulse length of $600 \mu\text{s}$.

Einzel lens

The purpose of the second Einzel lens is to transport the H^- beam to the LEBT keeping the beam size small and avoiding excessive emittance growth. The power supply for the lens is bipolar with a maximum voltage of 50 kV. A negative bias decelerates the beam and is a good method for keeping the beam size small. It causes, however, space

charge induced emittance growth due to the low ion velocity inside the lens. A positive bias is preferable since the emittance is kept low, but the voltage needs to be higher to avoid particles hitting the beam pipe. Figure 7 demonstrates the improved emittance of the accelerating lens. Optimization of the positive bias Einzel lens geometry is pending.

FIGURE 7. Emittance and beam size as function of Einzel lens voltage. H^- beam current is 30 mA, e/H^- is 50 and puller voltage is -20 kV.

Proton simulation

During the commissioning of the volume source, the H^- current is limited below 30 mA. In order to test the LEBT and RFQ in a higher space charge regime, the source will run in proton mode by reversing the polarity of the high voltage systems. Figure 8 shows that it is possible to run the ion source with a proton beam of 80 mA being extracted through the same geometry as for the H^- beam.

FIGURE 8. 80 mA proton extraction with inverted polarities on the electrodes. (a) Proton particle density plot. (b) Phase space plot at the simulation end.

DETAILS OF IMPLEMENTATION

Figure 9 shows a cut of the 3D model of the new plasma generator and extraction system for the Linac4 ion source with the beam travelling from bottom right to top left. The design of the extraction system was based on the geometry that was found to give the best results in the IBSimu simulations. At the exit of the plasma chamber sits the molybdenum plasma electrode with an aperture of 6.5 mm diameter. The puller is also made of molybdenum with an aperture of 8.0 mm diameter and is located at a distance of 7.0 mm from the plasma generator. It gives the first stage of acceleration up to 25 keV. The body of the magnetized Einzel lens is built of ARMCO, magnetic steel, to confine the magnetic dipole field within the electrode. The dipole is made from a pair of SmCo permanent magnets which are nickel and then copper coated to prevent reaction of the micro-structure of the magnets under low pressure of hydrogen [8]. The electron dump target is made of tungsten for minimizing the ablation by the electron beam. The tungsten dump is brazed to a copper arm held on a Shapal insulator for heat evacuation by conduction.

The final acceleration stage to 45 keV is made by the grounded electrode. Between the grounded electrode and the LEBT entry, a > 150 mm gap provides space for the high voltage insulators and vacuum pumping. A second Einzel lens that can be biased either positively or negatively is used to keep the beam size small for minimum particle loss. The voltages for the plasma generator, the puller and the magnetized Einzel dump will be pulsed, whereas a DC voltage will be used for the Einzel lens.

FIGURE 9. Cross-section of the Linac4 plasma generator and extraction system.

CONCLUSION AND OUTLOOK

A new extraction system has been designed and built for the Linac4 H^- ion source. It is a flexible system well suited for the ion source and LEBT commissioning where systematic studies of the different source parameters will be made in order to optimize the extracted beam current and its emittance.

In parallel with the upgrade of the plasma generator and extraction system, an effort is started to caesiate the collar electrode near the extraction hole of the plasma chamber to meet the final requirement of beam current [1]. The caesiation will lower the work function of the collar surface and increase the surface production rate of H^- ions. The higher population of H^- in the plasma will also help to reduce the ratio of co-extracted electrons, which again will reduce the electron beam impact on the electron dump. A lower emittance of the H^- beam is expected due to less space charge from the electrons.

Future possible upgrades of the extraction system include:

- Motorization of the puller tilt and offset for *in-situ* tuning. For the first prototype, the extraction system has to be dismantled to manually move the position of the puller.
- An increase of the extraction voltage of the puller. The 25 kV power supply for the puller is biased relative to the source body, however, by connecting it to ground instead, it is possible to increase the extraction voltage up to 70 kV provided the insulation is improved.
- Optimization of the dipole field in the magnetized Einzel lens in order to collect all electrons inside the electron dump with a maximum spread of the electron beam.
- Optimization of the shape of the second Einzel lens to achieve better focusing.
- A reduction the overall length of the extraction system for minimum emittance growth.

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