

## Space Charge Compensation in the Linac4 Low Energy Beam Transport Line with Negative Hydrogen Ions

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### Abstract

The space charge effect of low energy, unbunched ion beams can be compensated by the trapping of ions or electrons into the beam potential. This has been studied for the 45 keV negative hydrogen ion beam in the CERN Linac4 Low Energy Beam Transport (LEBT) using the package IBSimu<sup>1</sup>, which allows the space charge calculation of the particle trajectories. The results of the beam simulations will be compared to emittance measurements of an H<sup>-</sup> beam at the CERN Linac4 3 MeV test stand, where the injection of hydrogen gas directly into the beam transport region has been used to modify the space charge compensation degree.

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The space charge effect of low energy, unbunched ion beams can be compensated by the trapping of ions or electrons into the beam potential. This has been studied for the 45 keV negative hydrogen ion beam in the CERN Linac4 Low Energy Beam Transport (LEBT) using the package IBSimu<sup>1</sup>, which allows the space charge calculation of the particle trajectories. The results of the beam simulations will be compared to emittance measurements of an H<sup>-</sup> beam at the CERN Linac4 3 MeV test stand, where the injection of hydrogen gas directly into the beam transport region has been used to modify the space charge compensation degree.

## I. Introduction

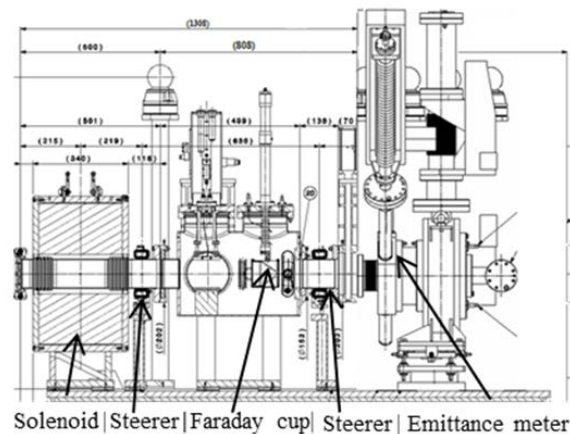
The LEBT of the Linac4 is the region between the ion source and the entrance of the RFQ. Its function is to transport the beam with an energy of 45 keV from the source, and with the help of two solenoids, match it to the 352 MHz Radio Frequency Quadrupole (RFQ). The space charge repulsion of the beam affects the beam's propagation. This is reduced by Space Charge Compensation (SCC) caused by the secondary particles created from ionization of the residual gas, a process that leads to a variation in the space charge forces in the beam as a function of time. In order to help control the SCC, the Linac4 LEBT is equipped with an independent gas injection system.

Measurements have been made at the 3 MeV H<sup>-</sup> beam test stand<sup>2</sup> using the first section of the Linac4 LEBT and a slit and grid emittance meter<sup>3</sup> at different H<sub>2</sub> pressures, and compared to simulations of the region including the SCC.

## II. Experimental setup

The experimental setup consists of one LEBT solenoid, Faraday cup, two steerer magnets for beam trajectory correction, emittance meter and the gas injection system. Relative to the LEBT entrance z=0 the solenoid entrance position is z=50 mm, the Faraday cup at z=876 mm and the emittance meter at z=1308 mm. The beam pipe has an aperture radius of 50 mm, the solenoid has a

maximum integrated magnetic field of 0.13 Tm. An integrated solenoid field of 0.089 Tm was used during the measurements. The ion source is a 2MHz DESY<sup>4</sup> volume production source with an extraction system designed<sup>5</sup> at CERN. It delivered a 14 mA H<sup>-</sup> beam with pulses of 400 μs spaced by 1.2 s. Measurements of the beam phase-space emittance were made as a function of the H<sub>2</sub> gas pressure in the LEBT, where the lowest achievable pressure was 5x10<sup>-7</sup> mbar and was increased to a pressure of 3x10<sup>-6</sup> mbar.



Solenoid | Steerer | Faraday cup | Steerer | Emittance meter

Figure 1 Experimental setup Layout. Beam travels from left to right.

## III. Simulation of the space charge compensation of the H<sup>-</sup> beam

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A compensation time, as given in Equation 1, is the average time that it takes for one beam particle to produce a secondary particle by interacting with the residual gas.

$$\tau = \frac{1}{v_{beam} \sigma N_{gas}} \quad (1)$$

Where  $N$  is the density,  $v_b$  is the speed of the beam particles and  $\sigma$  the cross section of the process  $H + H_2^0 \rightarrow H^- + H_2^+ + e$ . In our case, with a pressure of  $1 \times 10^{-6}$  mbar, the compensation time is approximately 450  $\mu$ s. This means that we need the whole beam pulse to allow the SCC conditions to establish.

The simulations have been performed using the IBSimu 3D code, which was used to track the primary H<sup>-</sup> beam through the magnetic field of the solenoid, and by using the resulting space charge map, create the electric potential distribution in the beam region. Secondary particles are created along the trajectories of the primary beam, and they are in turn tracked through the magnetic and electric fields. As in general, the electrons are expelled quickly from the beam, they were not included in the calculations<sup>6</sup> (early simulations confirmed this effect, and also require considerable more computation time for the light particles). For the same reason no emission of secondary electrons from the walls was included. The positive H<sub>2</sub><sup>+</sup> ions are trapped by the beam potential and are responsible for modification the dynamics of the beam. An isotropic distribution of gas was assumed.

The input beam to the LEBT region is taken from IBSimu simulations of the extraction system<sup>7</sup>. SCC has not been considered in these extraction simulations because of the presence of strong electric fields that pull out the compensating ions from the beam. The simulations of the 1.392 m LEBT experimental setup include the boundary conditions of the extraction system potential (which includes a positively biased Einzel lens) and the grounded emittance meter slit at the end of the simulation, along with a field map of the solenoid.

IBSimu is a Vlasov solver, which tracks particles through an electrical field distribution to produce a space charge map. The space charge map is then included in the electric field distribution, and the process is repeated iteratively. In addition to this procedure, at each iteration step, secondary ions are created randomly along the primary trajectories with a random energy around 1 eV. These secondaries are tracked for a given time step (typically 6  $\mu$ s in our case) and contribute to the space charge map. 10,000 input particles are used for the primary beam, and the number of secondary ions generated depends on the gas pressure being simulated (from 1,300 to 8,000 secondaries generated per iteration).

Secondaries that do not strike a surface within 6  $\mu$ s are retained for the next iteration, where also new secondary ions will be created. Energy transfer from the beam to the secondary ions through collisions is negligible<sup>8</sup> and is therefore omitted.

The simulated compensation time (Equation 1) is given by the time when the rate of particles created and leaving the system is the same. Using the derived compensation time from the simulations, we infer the gas density, and therefore pressure simulated from Equation 1.

IBSimu allows setting a macro current to the particles to quantify its space charge contribution. The final number of secondaries stored in the system is dependent on this macro current. This value then becomes a compromise between computing time and precision in the solution. The average number of secondaries after the compensation time was 80,000 particles.

#### IV. Simulation and measurement results

Comparison of a phase space image of the measured and simulated beam is shown in Fig 2, where both cases are taken for a  $5 \times 10^{-7}$  mbar pressure, in the first microseconds of the beam pulse where the SCC is negligible. The plots show some similarities, with a dense beam core having the same orientation and a low density halo that simulations show to be generated at the source extraction aperture. This gives confidence that the beam dynamics simulations with space charge are correct, before significant compensation occurs.

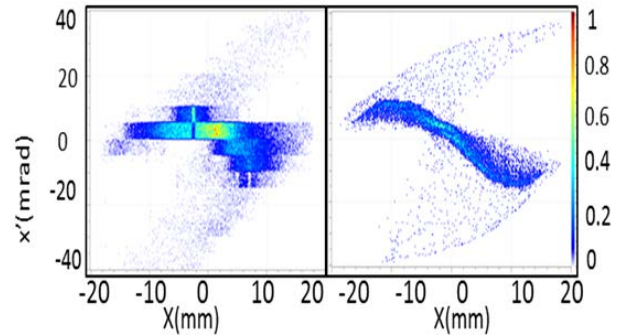


Figure 2 Emittance Measurement (Left) and Simulated (Right), colors represent the particle density (color online)

Comparison of the measured and simulated beam size is shown in Figure 3, as a function of time during the pulse, and for different gas pressures. These simulations show good agreement for the time when the SCC is effective, showing the same characteristic response time with the final beam size falling between 3 mm and 4.5 mm, depending on the pressure. The also measurements show a different final stabilized beam size for each pressure, varying in the slightly higher range of 4-5.5 mm, a

difference that could be explained by uncertainties in the experimental settings.

The emittance Measurement has shown that the lowest measured values occur at the beginning of the pulse, before SCC builds up. The simulations do not reproduce this behavior. However both converge to an emittance value close to 0.5  $\mu\text{m}\cdot\text{rad}$ (normalized 1 rms) to the end of the beam pulse.

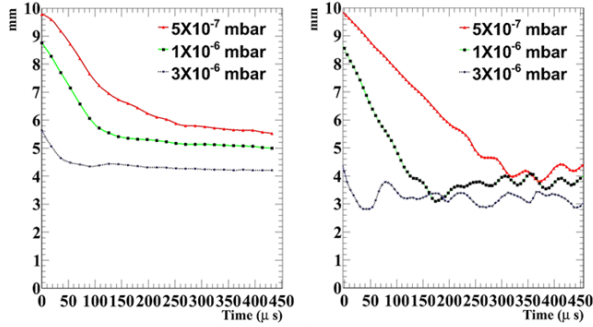


Figure 3 Beam size (1 rms) evolution in time, measurements (Left) and simulated (Right), for different beam line H<sub>2</sub> pressures.

The Figure 4 show at different times the evolution of the SCC fraction defined in equation 2 along the experimental setup in the center of the beam.

$$\Psi = 1 - \frac{\varphi_C(r=0, z)}{\varphi_N(r=0, z)} \quad (2)$$

$\varphi_C$  and  $\varphi_N$  are the compensated and non compensated potential. The SCC fraction is not homogenous along the experimental setup until it reaches a stable level of 80% at 450 $\mu\text{s}$ . During the stabilization phase we see that the SSC fraction grows more quickly around 1.2m, due to the beam waist which has the lowest overall potential in the beam.

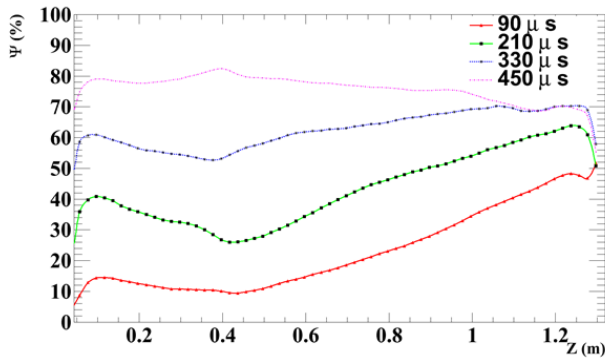


Figure 4 Simulation of the compensation degree at different times for a pressure of  $1 \times 10^{-6}$  mbar

## V. CONCLUSION AND OUTLOOK

The phase space and emittance of a 45 keV H<sup>-</sup> beam has been measured at different gas pressures, and the results have been compared to simulations including compensation of the beam space charge with secondary ions produced by beam-gas ionization. There is a reasonable match between the measurement and simulation.

The simulations show that up to  $3 \times 10^{-6}$  mbar the beam has reached a compensation factor of 80%, and does not go into an overcompensation regime that is predicted to happen at beam-line pressures of  $1 \times 10^{-5}$  mbar<sup>6</sup>.

The simulations show that the compensation factor increases more quickly in the region where the beam potential is strongest (by attracting secondary ions from other regions of the beam) but by the end of the beam pulse the factor is homogenous.

The measurements show an increase in beam emittance as a function of gas pressure, which is not reproduced by the simulations and requires further investigation.

In the next steps, the beam simulations should be propagated through the full LEPT. Measurements and simulations should also be performed with different injected gases (e.g. Kr and N<sub>2</sub>).

## ACKNOWLEDGMENT

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