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LINAC4: RELIABILITY RUN RESULTS AND SOURCE EXTRACTION STUDIES

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Abstract

Linac4, a 160 MeV, 352.2 MHz linear accelerator, has been fully commissioned and will take its place as injector to the CERN chain of accelerators during the long shutdown (LS2) in 2019-2020. In the past year, it has been providing beam during a test run to assess its reliability in view of the connection to the LHC proton injector chain. A target reliability of more than 90 % has been demonstrated during the accumulated nine months of run in 2017 and 2018.

The beam quality at 160 MeV is suitable for producing all beams for the CERN physics program of today. Nevertheless, the limited peak current of 30 mA might be a limitation for future high intensity programs. The bottleneck has been identified at the low energy end of the accelerator.

Meanwhile, beam extraction and low-energy beam transport studies are ongoing at a dedicated test stand with the goal to reach beam currents from the pre-injector up to 45 mA. We will present the status of the extraction modelling and possible solutions to reach higher beam currents from the RFQ along with results from the reliability run.

RELIABILITY AND BEAM QUALITY RUN

Linac4 was fully commissioned to 160 MeV in autumn 2016 with 60 % of the nominal current on the dump at the end of the linac [1]. The years 2017 and 2018 were dedicated to achieving the beam quality and reliability necessary for injection into the Proton Synchrotron Booster (PSB). The criteria were set such that the PSB will be able to provide its complete set of beams with pre-LS2 as well as the LIU target parameters. The two most extreme examples are the brightest beam namely 3.4×10^{12} protons per ring in an emittance of 1.7 µm and the highest intensity beam namely 9×10^{12} protons per ring in an emittance of 8 µm.

A peak current of 20 mA at the PSB, combined with an increase of the number of the injection turns to the maximum (150 turns per ring) is sufficient to achieve enough intensity to produce the mentioned beams [2] provided that the beam quality requirements given in Tab. 1 are met. The requested target reliability for the linac is more than 95 % [3], a very challenging value to meet for a brand-new accelerator.

The linac ran in its almost final configuration for a total of 8 months between 2017 and 2018. Important data has been gathered concerning its reliability, its weak points and the beam quality [3,4]. The most important achievement of the last run in 2018 was an overall availability of 94.1 % over 10 weeks. The peak beam current at the end of the Linac4 was routinely 25 mA which allows for 20 % losses in the transfer and capture into the PSB. The beam pulse flatness was achieved by using the chopper (at 3 MeV) to cut the rising edge of the beam, necessary due to the onset of space charge compensation after pre-chopping. This results in the need of a 850 µs beam from the source for a 600 µs beam at 3 MeV, achievable with the present source and RFQ.

The transmission from 3 MeV to 160 MeV is approaching 100 % with a beam of 25 mA, whereas the transmission of the pre-injector is 70 % to 80 % at best.

ION SOURCE EXTRACTION STUDIES

During 2017 and 2018, the extraction system of the ion source was investigated on the Linac4 test stand as a possible origin of the pre-injector performance limitation. This test stand is a copy of the Linac4 low-energy beam transport line with added diagnostics: the pre-chopper hardware between the two solenoids is replaced by a slit-grid emittance meter. Detailed information on the layout is given in [5].

Figure 1 shows the extraction system of the Linac4 ion source as modeled using IBsimu [6]. The beam is extracted through a bore, 6.5 mm in diameter, by the electric field generated by a dual-function puller-dump electrode. Any co-extracted electrons are deflected into a cup by the magnetic field produced by two permanent magnets housed within this electrode. The beam is then accelerated to its final energy of 45 keV. An einzel lens additionally focuses the beam to transport it to the first solenoid downstream. More informa-

Table 1: Target Beam Quality at the PSB Injection

Parameter	**Target value**
Intensity flatness along the pulse for pulse lengths < 180 µs	±2 %
Intensity flatness along the pulse for pulse lengths > 180 µs	±5 %
Horizontal/vertical position variation along the pulse	±1 mm
Horizontal/vertical injection angle error along the pulse	±0.4 mrad
Shot-by-shot current stability	±2 %
Transverse norm. rms emittances	< 0.4 mm mrad
Beam energy	160 MeV
Pulse to pulse energy spread	80 keV to 600 keV
Nominal chopper operation	65 % at 1 MHz
Energy painting	±0.8 MeV

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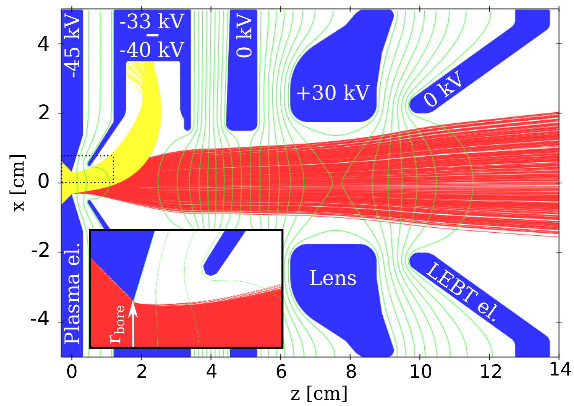

Figure 1: The present extraction system of the Linac4 ion source [7]. Both the source potential and the voltage on the lens are typically left at the given values, while the puller voltage can be chosen between 5 kV to 12 kV.

tion on the plasma generator can be found in references [8,9]. The design of the extraction is detailed in [7].

Advances in Extraction Modelling

We realized that an accurate solution of the equation describing the plasma in IBsimu is only possible when the Debye length of the plasma is resolved. A motivation for this is given in [10]. The Debye length λ_d in the plasma region for an H^- beam with a current of I_{H^-} and an electron to ion current ratio of k extracted from a bore with radius r_bore is

$$\lambda_\mathrm{d} = r_\mathrm{bore}\sqrt{\frac{\epsilon_0 \mathrm{k_b} T_\mathrm{p} \pi}{e}\left[I_{\mathrm{H}^-}\left(1+\sqrt{\frac{m_{\mathrm{e}^-}}{m_{\mathrm{H}^-}}}k\right)\right]^{-1}}\sqrt{\frac{2E_0}{m_{\mathrm{H}^-}}}.$$

As an example, for $r_\mathrm{bore} = 3.25$ mm and $I_{\mathrm{H}^-} = 30$ mA with no co-extracted electrons ($k = 0$), $\lambda_\mathrm{d} = 17.4\,\mu$m. The plasma model parameters were kept from the design studies [7]: initial particle energy $E_0 = 5$ eV and plasma temperature $T_\mathrm{p} = 1$ eV. A simulation in cylindrical coordinates indeed converges around this length, as seen in Fig. 2.

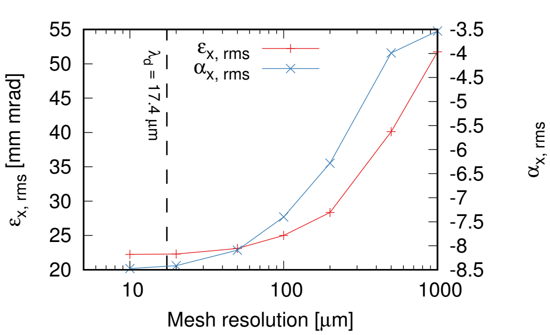

Figure 2: Beam emittance (un-normalized) and divergence of a 30 mA H^- beam after the extraction gap at different resolutions of the cylindrical grid.

Any simulation of the full extraction needs to be performed in three dimensions due to the influence of the filter and dump magnetic fields. Resolving the entire system with a grid of micrometer resolution is neither feasible nor necessary. We adopted a scheme calculating the electrical fields in the meniscus area, where the beam deflection is still negligible, on a 10 μm cylindrical grid and using a 500 μm three-dimensional mesh in the rest of the system. The improved resolution has a significant impact on the simulated emittance after the source, as seen for example in Fig. 3.

In the past, we observed that simulation and measurement results are consistent if the electron to ion ratio was much higher than the measured value [5]. Increasing the electron to ion ratio in the simulation leads to a higher charge density in the plasma region before the bore and consequently to a more convex plasma meniscus. Since a large error in the measurement of the ratio was deemed unlikely, we concluded that the plasma density used by the simulation must be inaccurate.

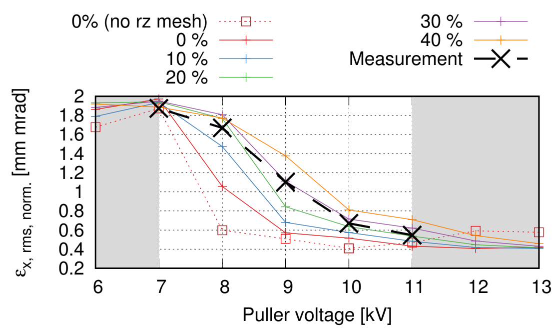

Figure 3: Comparison of rms emittances from simulation and measurement as a function of the electric field in the extraction gap. The extracted beam current is 50 mA. Percentages indicate the increase of density in the plasma region in the simulation.

A mechanism was implemented to increase the charge density by a given factor within the plasma region. This can be done by multiplying the density when the calculated potential is below a certain value. Figure 3 gives an example for the influence of this factor. A good agreement between measurement and simulation is found at an increase of 30 %. The same is the case for the emittances measured for different beam currents at constant extraction field, given in Fig. 4.

Both the smaller mesh size and the increased plasma density affect the simulation of the plasma meniscus position, shifting it into a more convex position. The beam is thus more divergent and the beam transport not well adapted. While the need for such a modification of the density is still unknown, the improved simulation explains the origin of the observed emittance values.

Sources of Emittance Growth

Figure 4 shows rms emittances as a function of the H^- current at constant puller voltage. The simulations were performed with the previously discussed 30 % density increase.

The beam after the extraction gap has a very low emittance. It is slightly larger at low beam currents due to nonlinear focusing caused by a concave plasma meniscus. Below

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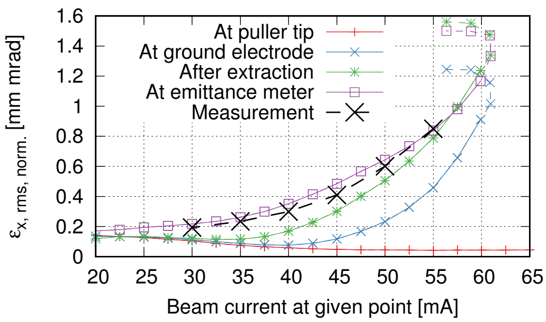

Figure 4: Emittance as a function of beam current at various points throughout the extraction. Puller voltage constant at 10 kV. Left to right in Fig. 1: after the tip of the puller electrode (z=10 mm), at the ground electrode (z=48 mm), after the system (z=14 cm) and at the position of the emittance meter (z=1.08 m). The electron to ion ratio was set to 2 in the simulation and between 2-3 for the measurement.

40 mA, the beam expands rather freely throughout the whole extraction and consequently, the large divergence at the entrance of the solenoid is the cause of most of the emittance growth downstream. Above 40 mA, most emittance growth is caused by aberration within the extraction. Around 50 mA, the beam fills the aperture of the second gap of the einzel lens almost entirely ($z =\sim 9$ cm in Fig. 1).

Due to the large aperture of the end-plate of the puller-dump ($z =\sim 3.2$ cm), the electric field extends far into the dump region. The resultant transverse field components help the beam transport, but cause significant emittance growth at high beam current. For 60 mA, the aberration at this point is responsible for 75 % of the observed emittance. In addition, above 60 mA, the beam is collimated at the plate and any further increase of extracted H^- current results in a decrease of current measured after the solenoid.

Several modifications to the extraction gap have been previously tested on non-cesiated sources [5] with the goal to shift the meniscus back into a more concave position: decreasing the extraction gap length to increase the field, increasing the transverse focusing by decreasing the angle of the plasma electrode towards the axis and increasing the diameter of the bore. Among these, the most effective at reducing the extracted emittance was the increase in bore diameter. Therefore, larger diameters up to 9 mm were tested on a cesiated source.

Measurement Results With Larger Bore Diameters

Figure 5 gives emittance measurement results for a source equipped with a 9 mm bore diameter, measured at a constant puller voltage of 9.5 kV, in comparison to the data also given in Fig. 4 for a diameter of 6.5 mm.

Just as expected from simulation, the rms emittances are significantly lower at higher H^- current. With the smaller diameter, using the highest possible puller voltage was always beneficial, independent of the beam current. With the larger bores, this is no longer the case. For currents below 40 mA, the measured emittances could be improved by lowering the puller voltage.

The emittance data was taken on two separate days: the day after the cesiation and one a week later. The electron to ion ratio was below 1 in both cases. During the cesiation, the pressure in the source is typically increased for stabilization. For the first measurement, the source was still operated at this larger pressure. This could be the reason for the deviation from simulation, since larger source pressures were previously already observed to have a negative impact on the emittance [11, Fig. 3b].

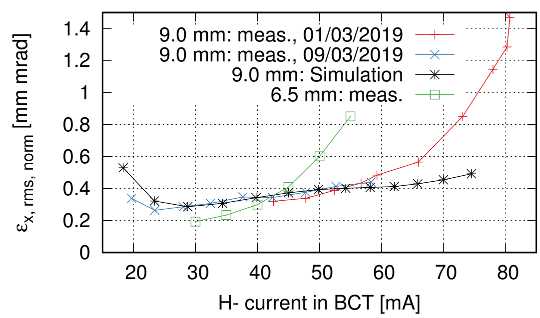

Figure 5: Emittance measurements on a source with 9 mm bore diameter in comparison to measurements with 6.5 mm. The puller voltage was reduced from 10 kV for the latter to 9.5 kV for the former to reduce beam losses in the solenoid.

With bore diameters above 7.5 mm, the simulation predicts beam losses to occur in the solenoid and, in extreme cases, at the LEBT electrode at the end of the extraction system. They appear since the focusing scheme of the extraction system is inefficient for the typically smaller beam extracted from the larger bore. These losses were observed in measurements: for some source settings, the solenoid strength required for beam matching is lower than the strength required for full transmission.

A new set of extraction electrodes has been designed for use with the larger bore diameter plasma electrodes, with decreased diameters for the puller end-plate, ground electrode and lens, which will be tested in the near future. These should ensure full transmission through the extraction and the first solenoid up to a given current limit, while keeping the emittance low.

SUMMARY AND OUTLOOK

Linac4 has been commissioned with a reduced current of 25 mA which is sufficient to produce all beams required after the second long shutdown of LHC. The source extraction has been investigated as possible bottleneck. Comparing emittance measurements with values calculated from simulations, we found aberrations from the electrostatic elements in the extraction system to be responsible for most of the emittance growth at high currents. An increase of the source bore diameter led to a significant decrease of the emittance. The present system will be iteratively improved while other systems are under investigation.

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