LINAC4: RELIABILITY RUN RESULTS AND SOURCE EXTRACTION STUDIES

CERN, Geneva, Switzerland

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.

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 $3.4 \times 10^{12}$ protons per ring in an emittance of 1.7 µm and the highest intensity beam namely $9 \times 10^{12}$ 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.

Table 1: Target Beam Quality at the PSB Injection

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

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 \( \lambda_d \) in the plasma region for an \( \text{H}^+ \) beam with a current of \( I_{\text{H}^+} \) and an electron to ion current ratio of \( k \) extracted from a bore with radius \( r_{\text{bore}} \) is

\[
\lambda_d = r_{\text{bore}} \sqrt{\frac{e_0 k_b T_p \pi}{e}} \left[ I_{\text{H}^+} \left( 1 + \sqrt{\frac{m_e}{m_{\text{H}^+} - k}} \right) \right]^{-1} \sqrt{\frac{2E_0}{m_{\text{H}^+}}}
\]

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

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 \( \text{H}^- \) 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 non-linear focusing caused by a concave plasma meniscus. Below
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].

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.
REFERENCES


