First Ideas on Measuring Beam Energy and Energy Spread of the 160 MeV Linac4 H- beam with Detached Electrons

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Summary

This note describes first simulation studies on an alternative method for energy measurements with a 160 MeV Linac4 H- beam.

Electrons are detached from H- ions by interactions with rest gas atoms in the beam pipe. The resulting electron current is measured as a function of a variable electric voltage, which can be applied to retard or stop the electrons. The question is addressed which maximum step width of this retarding voltage can be selected to still precisely determine the Linac4 beam energy and energy spread.

1. Introduction

The experimental method presented in this note is to measure beam energy and energy spread of the 160 MeV Linac4 H- beam. It could be must be considered as a potential alternative to measurements within the LBS line [1]. The concept is based on measuring the energy distribution of electrons being detached from H- ions by interactions with the rest gas atoms inside the beam pipe. The physical point of view exploits that H- ions and electrons travel at the same velocity, so that even after detachment the electron energy is correlated to the beam energy. Kinematic calculations reveal that Linac4 beam energy and electron energy scale according to the ratio of the H- mass M and the electron mass m, i.e. M/m ≈ 1838. Hence, the expected mean electron energy is about 86.6 keV (with $E_{Linac4} = 159.2$ MeV), while the energy spread is about 46.2 eV (with $\sigma_{E,Linac4} \approx 85$ keV).

This approach has already been established and its feasibility has been proven at the BNL linear accelerator [2]. As Table 1 shows the main beam parameters of the CERN Linac4 are very similar to the BNL Linac.

<table>
<thead>
<tr>
<th></th>
<th>BNL Linac</th>
<th>CERN Linac4</th>
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<tbody>
<tr>
<td>Ion Species</td>
<td>H⁻</td>
<td>H⁻</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>200 MeV</td>
<td>160 MeV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>30 mA</td>
<td>40 mA</td>
</tr>
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</table>

Table 1: Main parameters for the BNL Linac and CERN Linac4.

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Therefore, it is assumed that this concept could be adapted to Linac4, which motivates the following closer investigations. However, this note only summarizes first ideas and is far from proposing a concept for a technical implementation.

2. Potential Experimental Set-Up (generic)

Figure 1 illustrates a potential experimental set-up of this approach. The H⁺ ions interact within the beam pipe with rest gas atoms so that electrons are detached. The electrons are deflected into an analysis line, which is perpendicular to the main beam pipe in this example. Further downstream they fly through an electric field. The field vector is variable in strength and directed such that electrons are decelerated or stopped (retarding field, retarding voltage). Those electrons passing the region will be collected by a detector, e.g. a Faraday cup.

![Figure 1: Sketch of a potential experimental set-up to measure the Linac4 energy with detached electrons.](image)

A further advantage of this method is that only a fraction of about \(0.8 \cdot 10^{-6}\) of all H⁺ ions interacts with the rest gas, which allows for recycling the H⁺ beam\(^1\). However, this requires a correction of the distortion on the beam due to the bending magnet, which deflects the electrons into the analysis section.

3. Measurement Principle

Electrons are stopped within in the field region if its electric potential exceeds the kinetic energy of the particles. Hence, measuring the transmitted electron current as a function of the retarding voltage enables to calculate the Linac4 energy parameters from measured electron quantities.

Figure 2 shows a simulation of such an electron signal. The step-like shape of the signal (y-axis) reflects that no/all particles are stopped if the retarding voltages (x-axis) are too low/high compared to the electron energy (left/right part of the plot). In between there is a transition zone where only fractions of the particles are stopped. This is indicated by the steady decrease of the transmitted signal towards increasing retarding voltage.

A differentiation of this signal delivers an electron energy distribution (Figure 3), from which the quantities mean electron energy and electron energy spread can be derived (maybe after applying a signal fit). Due to the kinematic correlation between the Linac4 H⁺ ions and the electrons a re-scaling of the electron parameters gives Linac4 beam energy and energy spread.

\(^1\) The estimation on the electron current is assessed in chapter 6. in more detail.
Files with kinematic information on about 90’000 H- ions served as input data-set for the simulations. The data have been extracted from simulations of the transfer line between Linac4 and the PS Booster at the location of the bending magnet LTB.BHZ40. This is motivated by the fact that the regular energy measurement of the Linac4 beam is to be performed in the LBS line, which starts at this magnet.²

4. Measurement Precision

As the electron signal is recorded as integrated signal several Linac4 pulses are needed to scan the minimally required voltage range. It is evident that finer voltage steps allow for a better measurement precision, while on the other hand the measurement time increases due to measuring more pulses. Therefore, a crucial parameter of this method is the voltage step width. The following results focus on the question what maximum value can be afforded without losing too much measurement precision.

For that reason the input values for mean energy and energy spread are compared to the reconstructed values assuming varying voltage steps. As step width values between 0.01 and 0.3 kV have been selected. Figure 4 and Figure 5 depict the results as relative deviations versus voltage step width.

In general, it can be stated that the measurement precision becomes worse if the step width of the retarding voltage increases. Nevertheless, the absolute increase in precision for the mean energy

² Data-sets and transfer line lattice have been kindly provided by L. Hein (BE-ABP).
energy is always below 0.25%. Hence, even the largest step widths deliver acceptable results for mean energy measurements.

A contrary tendency can be observed for the energy spread. Only if the voltage steps are comparable to or lower than the electron energy spread the relative deviation remains below 10%, the value on which it has been agreed on as reference for an acceptable measurement [3].

Concerning the fluctuations beyond 0.17 kV it must be noted that in this region the differential histogram comprises only two bins differing from zero. Thus, although the result suffers significantly from statistical fluctuations because of binning effects it is nevertheless qualitatively evident that the energy distributions is scanned with a too large step width of the retarding voltage to obtain a sufficiently precise result.

Finally, it must be noted that two data-sets differing in dispersion values are presently investigated for the transfer line simulations. Both have also been considered for this note, but no significant differences concerning energy measurements have been found.

5. Conclusions

In order to obtain precise results for Linac4 energy spread measurements the electron energy spectrum must be scanned in steps of about 0.04 – 0.05 kV, corresponding to about 2 steps per $\sigma_{E, \text{electron}}$. This implies that approximately 10 – 20 Linac4 pulses are required to measure the entire energy distribution. Measurements of the mean energy do not impose more stringent constraints.

6. Outlook

This note summarizes the outcome of a preliminary study. The following main aspects remain to be addressed.

a) Electron Current and Detector Sensitivity

Given a rest gas pressure of about $10^{-8}$ mbar (LBS line conditions), a cross section of about $3 \cdot 10^{18}$ cm$^2$/atom for interactions between H- ions and rest gas atoms [4], and an interaction length of 100 cm, from which electrons are deflected into the analysis line, the expected maximum integrated electron current will be approximately 3 nA. This seems to be well beyond the sensitivity of Faraday cups (a few tenths of pA [5]), but does not take into account any efficiency or signal distortion. Therefore, it could be useful to artificially worsen the vacuum conditions with a gas injection system to increase the electron signal.

In addition, it should be verified that the signal shape as shown in Figure 2 can still be smoothly enough scanned. This mainly concerns the region where the retarding voltage is approaching the value of stopping all electrons.

b) Detector Readout

It must be discussed if and how a time-resolved readout of the detector can be implemented to ensure a measurement of beam energy shifts like the longitudinal energy painting within one Linac4 pulse.

c) Bunched versus Un-bunched Beam

Further studies are required to verify that also bunched beams can be measured. In a bunched beam electromagnetic forces between the particles in a bunch do not cancel and shift the beam energies such that the energy spread is artificially blown up. At the BNL linear accelerator this effect is compensated using correction factors from simulations of this effect [6].
This correction is less important for measurements close to the PS Booster injection where the beam is largely un-bunched. However, the proposed concept could also be interesting to be installed in the Linac4 diagnostic line behind the Linac4 exit, where the beam is still bunched.

7. References


   http://cern.ch/carli/PSBwithLinac4/Meeting11_03_11/Minutes11_03_11.html

