Diagnostic Lines for the 160 MeV H⁻ Linac4 at CERN

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Abstract

Linac4 will be the new linear accelerator of the CERN accelerator chain delivering H^- ions at 160 MeV from 2016. The increased injection energy compared to the 50 MeV of its predecessor Linac2, combined with a H^- charge-exchange injection, will pave the way to reach ultimate goals for the LHC luminosity.
Extensive commissioning of Linac4 is planned for the coming years. For this purpose, the beam will be studied after the exit of Linac4 in a straight line ending at the Linac4 dump, equipped with various beam instruments.
An almost 180 m long transfer line will guide the beam to the charge-exchange injection point at the entry of the Proton Synchrotron Booster (PSB). About 50 m upstream of this point, two measurement lines will be upgraded to perform transverse emittance measurements as well as energy and energy spread measurements of the Linac4 beam.
A detailed description of the beam measurement principles and setups at these three Linac4 diagnostics lines related to distinct Linac4 commissioning phases will be given.

INTRODUCTION

Linac4, the new injector at CERN for proton fixed-target physics and the LHC experiments, is currently under construction. It consists of a H^- source at 45 keV extraction energy, Low-Energy Beam Transfer (LEBT), an RFQ, a Medium Energy Beam Transfer (MEBT) at 3 MeV comprising a chopper for clean injection into the PSB. The MEBT is followed by the accelerating structures DTL, CCDTL and PIMS with respective final energies of 50, 102 and 160 MeV [1]. The beam at the exit of Linac4 will have a kinetic energy of about 160 MeV and a maximum pulse length of 0.4 ms. The nominal current of the micro-bunches that are defined by the RF frequency of 352.2 MHz is expected to reach 65 mA, whereas the current averaged over the macro-pulse will be around 40 mA after the chopper.

Six distinct commissioning phases are foreseen focusing on different parts of Linac4 and the transfer lines to the PSB [2]: Starting with the commissioning of the H^- source, RFQ and chopper line, it will continue with DTL tank 1, DTL tanks 2 and 3, the CCDTL, the PIMS and finally the transfer lines. The commissioning phases are in line with the installation progress of Linac4, a commonly applied approach comparable to the commissioning stages of the J-PARC [3] or the SNS linac [4]. Phases 1 and 2 will make use of a dedicated (re-)movable diagnostics bench to be connected at the end of the structures [5]. For phases 3 and 4 it is planned to design another bench adapted to the higher energies.
This paper will give a description of the diagnostic lines available for commissioning of the completed Linac4 (after the PIMS) and its transfer lines. These diagnostic lines represent a permanent installation and will mainly serve to monitor the performance of Linac4 during operation for the CERN accelerator complex for the coming decades, expected to start in 2016.

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DIAGNOSTIC LINES FOR LINAC4

Providing adequate beam instrumentation along the machine and transfer lines, essential for commissioning and flawless operation, has always been of concern for the Linac4 project [6]. In the straight prolongation of Linac4, terminated with the Linac4 dump, the Linac4 beam will be characterized longitudinally and transversely.
The transfer to the PSB comprises two parts: the new transfer line 'L4T' ($\approx$70 m long) guides the beam with 2 horizontal bending magnets towards the existing Linac2 tunnel, where it connects after level adaptation (2 vertical bendings) via a horizontal dipole. About 60 m further downstream, a horizontal bending magnet can optionally deviate the beam to two additional measurement lines, the so-called 'LBE' line for transverse emittance measurements or the spectrometer 'LBS' line. In case of no deflection, the beam continues $\approx$50 m more to the PSB injection point, the H^- charge-exchange injection foil.
Beam instrumentation along the transfer lines comprises beam current transformers (BCTs), view screens, secondary emission monitor (SEM) grids, beam position (BPMs) and beam loss monitors (BLMs). The three above-mentioned measurement lines will be described in more detail in the following sections.

Linac4 Dump/Measurement Line

For Linac4 commissioning, the Linac4 dump line will be used. Table 1 lists the beam instrumentation to be installed in the $\approx$10 m long line and its functionality.

Transverse Emittance Measurement One handle to maximize the luminosity for LHC collisions is the minimization of the transverse beam emittance. Emittance growth control along the full CERN accelerator chain is therefore essential. The simulated transverse emittance evolution along the Linac4-to-PSB transfer lines is given in Fig. 1. Transverse emittances at Linac4 exit are around 0.3 mm mrad; at PSB injection the values in the horizon-

Table 1: Beam diagnostic instruments available between Linac4 exit and Linac4 dump.

#	Instrument	Measurement Function
2	BCTs	Intensity, matching, statistics
2	BLMs	Loss control
2	SEM grids (H+V)	Profile, matching, position
2	BPMs	Steering, intensity, phase, ToF
1	Long. BPM	Longitudinal bunch profile, phase spread (rf tuning)
3	View screens	Transverse emittance

tal plane will increase only slightly, whereas for the vertical plane a value around 0.4 mm mrad is expected for a dispersion-matched optics of the transfer line with respect to the PSB.

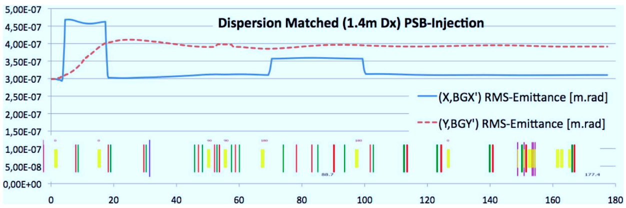

Figure 1: Simulated evolution of the horizontal (solid line) and vertical (dashed line) emittance along the Linac4-to-PSB transfer lines. Abrupt emittance changes are visible at the location of bending magnets.

It is foreseen to use the Three-Monitor-Method to determine the emittance [7]. The method is based on the propagation of the beam ellipse in phase-space along the line. The ellipse is sampled at a minimum of three positions, where through the precise measurement of the beam width and the knowledge of the transfer matrix the emittance can be determined by solving a linear equation system. With the help of a pair of quadrupoles the ellipse evolution is modified to be able to measure before, close to and behind a beam waist (see Fig. 2).
It has been studied in detail [8] whether this method would still be applicable due to non-linear space charge or variations of the input Twiss parameters. It was shown that it should be possible to measure the emittance in both planes with an error not exceeding 5% under the requisite of appropriate resolutions for the rms beam size measurements (200/50/200 μm), which seems to be feasible with scintillation screens read out with appropriate cameras. Nevertheless, in order to obtain the emittance at the Linac4 exit, the measured value will have to be corrected due to emittance growth mainly in the start of the line (depending also on the beam intensity). During commissioning, in case Twiss input parameters should deviate too much from the nominal values, an iterative method should be used.
In addition, the measurement with the three screens needs to be done sequentially due to multiple scattering and charge stripping of the H^- . The pulse length of Linac4 will most probably have to be reduced to a forth due to thermal considerations for the scintillation screens.

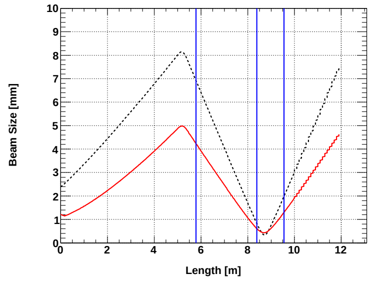

Figure 2: Variation of beam sizes along the Linac4 dump line (horizontal/vertical measurement: dotted/solid line). The three screen positions are marked with vertical lines.

Emittance Line LBE

The existing LBE line (for Linac2 50 MeV proton and Linac3 ion emittance measurements) has to be upgraded to allow transverse emittance measurements of the 160 MeV H^- during Linac4 and transfer line commissioning and later during standard operation. For this purpose, the field gradient of the already installed quadrupoles has to be increased, cooling needs to be revised, three scintillating screens with cameras and a beam dump to be installed. In case the Linac3 ion measurements will continue in the LBE line, a special optics has to be applied to be able to use the common part of the injection line without modifications, and the two LBE-line quadrupole power supplies need to be bipolar.
Also here, it is planned to apply the Three-Monitor-Method to calculate the emittance. Fig. 3 shows the dependence of the error on the emittance determination depending on the resolution for the beam size measurement. A maximum reconstruction error of the order of 1% has been simulated for beam size measurement resolutions of 200/50/200 μm. Systematic errors like beam size fit errors, errors on quadrupole field gradients and monitor positions as well as variations in the longitudinal and transverse beam input parameters have been studied in detail and could show the robustness of the method.

Spectrometer Line LBS

An upgrade of the LBS line is planned to allow for the measurement of mean energy and energy spread of Linac4, whilst keeping the line operational for Linac3 ions. This is also of special interest to evaluate the longitudinal painting process where the energy of Linac4 will be varied by ± 1 MeV with the last 2 PIMS modules to populate the PSB buckets more homogeneously [9].
The measurement relies on a vertical slit reducing the emittance in this plane, a spectrometer magnet to vertically sort the particles according to their energy and a SEM grid installed at a local minimum of the vertical beta function to

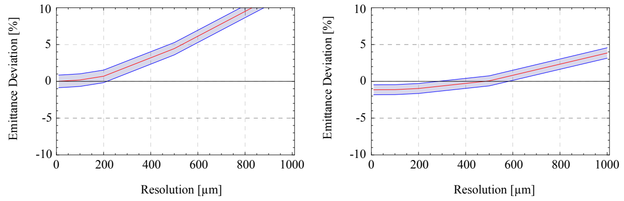

Figure 3: Deviation of the reconstructed emittance referred to its reference value at monitor 1 versus different (common) resolutions of the beam size measurement (left: horizontal plane, right: vertical plane). The central line indicates the nominal reconstructed value determined from the fitted beam sizes, while the error band shows the maximum deviations from the nominal value if the fitted beam sizes are systematically varied by their fit parameter error.

detect the beam signal [10]. All these elements will have to be renewed and a beam dump added for Linac4 operation. In this way a correlation is created between particle energy and position (see Fig. 4). The position on the SEM grid defines the mean energy, whereas the width of the distribution is a measure for the energy spread. The relative energy

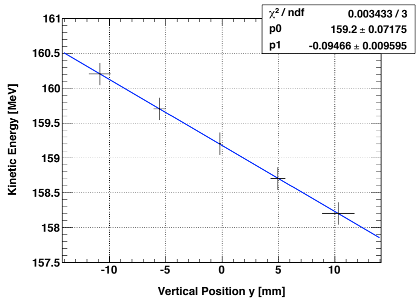

Figure 4: This plot shows the linear correlation between the fitted vertical beam position and the kinetic energy, covering the energy variations for longitudinal painting.

spread dT/T is given by the following equation, where the particular line setup allows for neglecting the second term:

$$\frac{dT}{T} = \frac{1+\gamma}{\gamma}\,\frac{1}{D}\sqrt{\sigma^2_{\mathrm{meas.}} - (\epsilon_{\mathrm{V}} \cdot \beta_{\mathrm{V}})^2} \qquad (1)$$

After fitting the distribution, the resulting energy spread will be underestimated by only about -1.7% compared to its nominal value of 160.6 keV for the Linac4 beam.

To assess the systematic uncertainty, element alignment errors of 1 mm, fabrication errors of the spectrometer edge angles of $\pm 0.5°$, B-field errors of $\pm 0.1\%$, and a variation of 50 μm on the slit width have been studied. For the absolute energy measurement, the error is dominated by the error on the knowledge of the spectrometer B-field value and is on the per mille level. The error on the energy spread measurement amounts to $<$9%. The determining factor is the intrinsic error due to the finite width of the slit ($\pm$13-14 keV).

CONCLUSIONS

For the commissioning of Linac4 and later to permanently monitor its performance during standard operation it will be possible to measure intensity, position, beam loss and longitudinal as well as transverse beam characteristics. In the Linac4 dump line and in two dedicated measurement lines located close to the PSB injection point it will be possible to determine transverse emittances, energy and energy spread, essential for emittance budget control and to optimize Linac4 RF settings and energy painting. Systematic studies have been performed to propose a suitable optics design and to evaluate various error sources. The simulations indicate that the goal of a transverse emittance measurement within 10% accuracy can be obtained. The mean energy can be determined at per mille level, and the relative error on the energy spread determination is less than 9%. This is sufficiently accurate for mean energy measurements and to resolve the nominal energy spread of 160.6 keV.

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