LINAC4 BEAM CHARACTERISATION BEFORE INJECTION INTO THE CERN PS BOOSTER

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Abstract

Construction work for the new CERN linear accelerator, Linac4, started in October 2008. Linac4 will replace the existing Linac2 and provide an H⁻ beam at 160 MeV (as opposed to the present 50 MeV proton beam) for injection into the CERN PS Booster (PSB). The charge-exchange H⁻ injection combined with the higher beam energy will allow for an increase in beam brightness required for reaching the ultimate LHC luminosity. Commissioning of Linac4 is planned for the last quarter of 2012 and of the transfer line to the PSB for the third quarter of 2013. Appropriate beam instrumentation is foreseen to provide transverse and longitudinal beam characterisation at the exit of Linac4 and in two dedicated measurement lines located before injection into the PSB. A description of the diagnostics set and the upgrade of the measurement lines for Linac4 commissioning and operation is presented.

INTRODUCTION

Linac4 will be the first accelerator built in the framework of the LHC injector chain renovation program and will replace the current proton linac, Linac2, operational since 1978. Besides some maintenance issues of Linac2, one main aim of Linac4 is to enable the production of the ultimate LHC beam with $1.7 \cdot 10^{11}$ protons per LHC bunch at transverse normalised rms emittances $\epsilon^*_{rms} < 3.5\,\pi$ mm mrad. This translates to an intensity I $= 2.4 \cdot 10^{12}$ protons per bunch in the PSB including $\sim 15\%$ transmission losses and to $\epsilon^*_{rms} = 2.5\,\pi$ mm mrad. The reliable production of this high-brilliance beam with Linac2 is out of reach due to dominant space charge forces and related tune shifts at PSB injection. The increase of injection energy from 50 to 160 MeV will double the relativistic factor $\beta\gamma^2$ at PSB injection and should thus allow to double the brightness I$/\epsilon^*$ through a reduction of incoherent tune shift [1]. Additionally, the H⁻ charge exchange injection will minimise transverse emittance blow-up by transverse painting of the PSB acceptance and reduce injection losses unavoidable for the current conventional multi-turn injection.

LAYOUT FROM LINAC4 TO PSB

The diagnostic tools to be installed in Linac4 have been described in [2]. Linac4 will be commissioned stand-alone (in parallel to Linac2 operation) using the Linac4 dump line. After ~ 3 m from the Linac4 exit a horizontal bending magnet either lets the beam pass straight to the dump (Linac4 dump ~ 6 m downstream) or sends it to the new transfer line in the direction of Linac2. This 69 m long new transfer line (TL) connects to the existing Linac2 transfer line to PSB at another horizontal bending magnet. A level adaptation through two vertical bendings is unavoidable. Further on, the Linac4 beam will follow the existing Linac2 TL until PSB injection.

DIAGNOSTICS AT THE EXIT OF LINAC4

At the end of Linac4, a sufficient selection of diagnostic instruments has to be provided for commissioning and continuous beam parameter surveillance. A Secondary Emission Monitor (SEM) grid will measure the transverse beam profile at the exit of Linac4. Two Beam Current Transformers (BCT) will be used to determine the beam intensity, one at the end of Linac4 and the second one in the Linac4 dump line for statistics purposes. The transformers are automatically calibrated with a calibration pulse generated shortly before the beam pulse. The Linac4 pulses (max. 400 μs length) must be measured with 100 ns resolution (10 MHz sampling frequency) and a precision of around 1%. Two pickups (PU) behind steerer dipoles will measure beam position and angle. Beam loss monitors (BLM) will be placed at suitable locations.
In addition, it is planned to install a laser profile monitor in this region, developed within the framework of the US accelerator project for the LHC (APL). The primary aim is to measure transverse beam profiles and sizes within one linac pulse sweeping a laser beam across the ion beam. Another goal is to obtain an emittance measurement by combining profile data with measurements of the angular distribution of the neutral H^0 beam emerging from the laser 'slit'. These angular distributions have to be observed downstream of the horizontal bending magnet in a neutral beam detector, as a separation of the H^0 from the remaining H⁻ beam is required. The deployment of a laser profile monitor system would be important to gain experience at CERN in view of a future operation of the Superconducting Proton Linac (SPL; under design), where intercepting diagnostics are excluded due to the high repetition rate.

Longitudinal Diagnostics

To determine the longitudinal bunch profile of the Linac4 beam, a Bunch Shape Monitor (BSM) will be installed at the exit of Linac4. The measurement principle consists of a coherent transformation of the longitudinal beam structure into a transverse distribution of a secondary electron beam

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through radio-frequency scanning [3]. Typical phase resolutions are around 1°. Subsequent Linac4 pulses have to be sampled to obtain the complete longitudinal bunch profile.

Transverse Emittance Measurement

To obtain high brilliance beams in the PSB it is essential to measure the transverse beam emittance at Linac4 exit and close to PSB injection to understand potential emittance growth along the line. The simulated emittance growth along the TL is shown in Fig. 1. Currently a method using three SEM grids in the straight line between Linac4 exit and dump is under study. This method allows to calculate the emittance from the three measured profiles in case vertical and horizontal plane are decoupled and transfer matrices between the monitors are linear (and in general also if the dispersion function is known) [4]. Non-linear space charge forces could undermine this method.
First calculations were compared to a simulation code including space charge forces and indicate that this method could possibly be used, but the available parameter space still has to be fully explored to determine the systematic errors. In addition it has to be considered that part of the H^- beam will get stripped passing through the SEM grid. This means that no magnets should be used between the monitors, but this should in principle improve the situation through a reduction of space charge repulsion.

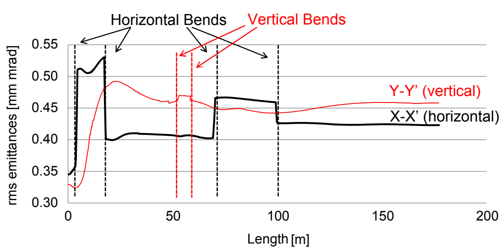

Figure 1: Simulated evolution of the horizontal and vertical emittance along the TL.

DIAGNOSTICS IN THE TRANSFER LINES

Beam Instrumentation Along the Transfer Line

Along the 177 m long TL between the exit of Linac4 and the injection into the PSB, the beam is surveyed with various instruments. Table 1 refers to the instruments between the first horizontal bending after the Linac4 exit until the PSB charge-exchange injection foil.

Table 1: Number of Beam Diagnostics Instruments Along the Linac4 to PSB TL

Instrument	BCT	PU	SEM grid	Screen	BLM
New TL	6	10	4	1	5
Existing TL	9	17	-	9	6

The only instruments that have to be replaced in the existing TL for operation with Linac4 are PUs and BLMs. BLMs will be placed at aperture limitations, in high dispersion and high loss regions as well as close to sensitive equipment. A couple of BLMs will be reserved for flexible installation. It should be mentioned that the upgrade of the PSB diagnostics for Linac4 operation is not treated here.

The beam ellipses (xx′, yy′, xy, $E\phi$ planes) at the end of the TL are shown in Fig. 2 for a certain matching scenario together with the output beam parameters in Tab. 2.

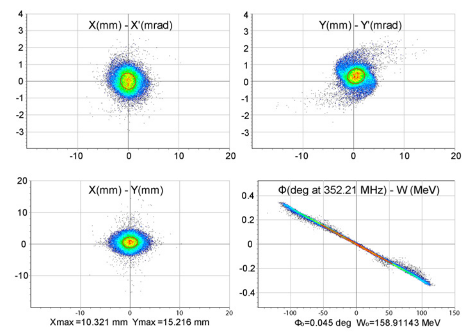

Figure 2: Beam ellipses at the PSB injection point.

Table 2: Beam Parameters at the TL Exit in Transverse and Longitudinal Phase Space; β in mm/mrad (H/V) and deg/MeV (Z), ϵ in π mm mrad (H/V) and deg MeV (Z)

	α	β	ϵ_{rms}	D [m]	D′ [rad]
H	0.077	3.112	0.422	-1.457	0.010
V	-0.040	3.818	0.458	0.001	0.299
Z	20.415	6904.7	0.433		

The Measurement Lines

At the end of the transfer line the H^- beam can optionally be deflected into two existing measurement lines to either measure the beam energy or the transverse emittances. Preliminary studies for their operation with the higher energetic Linac4 beam are presented. It should be noted that these lines must stay functional to characterise the Linac3 ion beam needed for LHC ion operation.

Measurement of Beam Energy In Fig. 3 the key elements of this line are shown as they are presently installed for the Linac2 beam. It consists of a collimator slit (vertical aperture d=2.2 mm) to select a beam slice. This slice is transferred via a spectrometer magnet of bending radius r with edge angle focusing vertically upwards to a SEM grid recording the electrical signal. This detector consists of 20 readout wires with a spacing of 3.6 mm. It is rotatable and the wire spacing is effectively reduced to 1.8 mm.

As a starting point for the upgrade studies the geometry of the line was not changed, but the kinematic factors of Linac4 were used to elaborate the parameters to

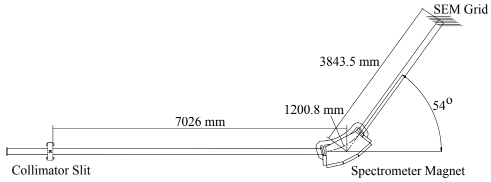

Figure 3: Schematic setup of the energy measurement line.

be modified. The input energy distribution at the entrance point of the measurement line has a mean value of $E_{kin} = 159.401$ MeV and a spread of $\sigma_E = 144$ keV. The dependence of the energy resolution on slit aperture d and bending radius r is given in linear approximation and with a first assumption of a magnification factor of -1 by

$$dE_{kin} = mc^2(\gamma - \frac{1}{\gamma})\frac{d}{4r} \qquad (1)$$

(m: particle mass, γ: relativistic factor). With the information mentioned above one can plot the correlation between the position of the particles on the SEM grid and their energy values (Fig. 4). The energy resolution normalised by the slit width dE_{kin}/d and given r yields 62 keV/mm. Then it is evident that a slit width of 2.2 mm is too large because the energy resolution would almost be equivalent to the energy spread of the beam. This number also suggests an effective spacing between adjacent SEM grid wires of at least 1 mm to be able to resolve energy shifts of about $0.5 \cdot \sigma_E$, reflected by appropriate position binning of Fig. 4.

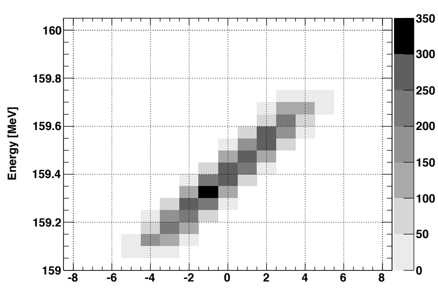

Figure 4: Correlation between the energy of a particle and its position at the SEM grid (correlation factor C≈96%). The position binning follows the requirement that energy values differing by approximately $0.5 \cdot \sigma_E$ can be resolved.

The mean energy of each measurement is determined by a second order polynomial fit to the projection on the x-axis between the half maximum values and provides an absolute energy value because of the known line optics.

It is foreseen to modulate the Linac4 energy by ± 1 MeV to paint the longitudinal PSB acceptance [5]. To take account of this energy shift, the SEM grid must extend to ± 13 mm to cover the extreme values within the energy range (see Fig. 5). Sampling the entire shape of the distribution requires in addition ± 5 mm on each side of the central position (see Fig. 4).

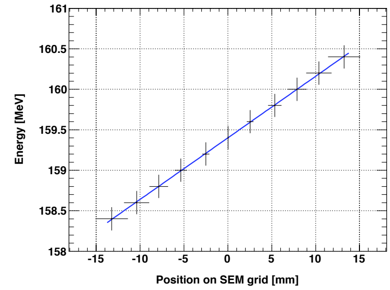

Figure 5: Energy calibration curve, showing a linear dependence between the central fitted value of the distribution on the SEM grid and the dedicated beam energy.

Apart from changes in the optics to achieve the desired energy resolution, the feasibility of the LBS line upgrade relies critically on positive design solutions for slit and beam dump, which will have to withstand a higher beam power impact. The results of these studies could potentially change the layout and/or strategy considerably.

Measurements of Transverse Emittance Two procedures to measure the transverse emittances are presently studied. The first method is based on phase space scanning by sampling parts of a beam pulse with a slit and measuring its image after a drift distance on a SEM grid [6]. The second method is based on the calculation of the emittance values after measuring three subsequent beam profiles [4].

CONCLUSIONS

An overview has been given on the different beam diagnostic instruments that will be deployed to characterise the beam out of Linac4 and before PSB injection. Along the 177 m of transfer line the beam positions, emittance growth and beam losses have to be steadily controlled. Calculations for the upgrade of the spectrometer measurement line have been presented and show its feasibility.

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