LONGITUDINAL BEAM PROFILE MEASUREMENTS IN LINAC4 COMMISSIONING

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Abstract

Linac4, the future 160 MeV H- injector to the CERN Proton Synchrotron Booster, is presently under construction at CERN as a central step of the planned upgrade of the LHC injectors. The Linac front-end, composed of a 45 keV ion source, a Low Energy Beam Transport (LEBT), a 352.2 MHz Radio Frequency Quadrupole (RFQ) and a Medium Energy Beam Transport (MEBT) housing a beam chopper, has been installed and commissioned. Precise measurements of the longitudinal micro bunch profiles of ion beams were possible with the help of a Bunch Shape Monitor (BSM) developed at INR Moscow. These were crucial for the successful commissioning of the three RF buncher cavities mounted along the MEBT and well complemented with higher precision the information provided in parallel by spectrometer measurements.

INTRODUCTION

Linac4 commissioning started in 2013 and is progressing in stages of increasing beam energy with the aim of reaching the final 160 MeV at the end of 2015 [1]. The accelerator front-end, composed of a temporary ion source, LEBT, RFQ and MEBT line was first commissioned on a dedicated test stand at the start of 2013 [2] before being moved to its final location in the underground tunnel in summer 2013. A 10-12 mA H- beam was used for the measurements detailed below.

Longitudinal beam measurements were taken on a moveable temporary test bench installed downstream of the machine (see Fig.1). On the straight arm of the bench there are three pick-ups (BPMs) for beam position and Time-Of-Flight-based energy measurements and a Feschenko/Bunch Shape Monitor (BSM), all to be later used permanently as in-line diagnostics devices. Validation of their performance during commissioning at low energy was done with the aid of a spectrometer line branching off after the BSM and ending in a harp monitor. This was used in particular during calibration of the RF structures for measuring the beam average energy and energy spread. The precise beam longitudinal characterisation thus obtained was instrumental to a full validation of the RFQ performance and of a correct beam injection in the DTL.

DIAGNOSTICS

The positioning and separation between BPMs was chosen to ensure a resolution of ~0.1% in the average energy measurements at 3 and 12 MeV. The spectrometer arm, formed by a 28.5° bending magnet and downstream

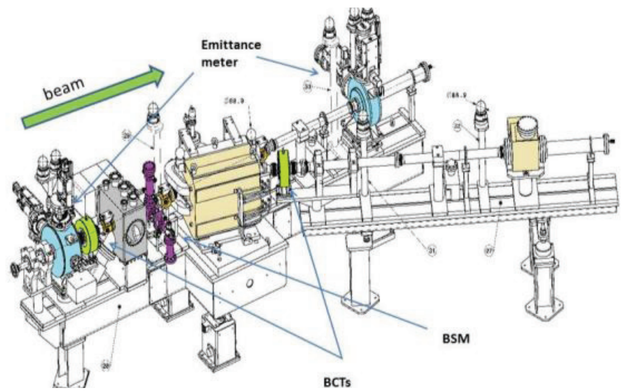

Figure 1: Test bench drawing.

Secondary Emission Monitor (SEM) grid (at ~3 m distance) has a momentum resolution of ~0.1%. The BSM installed at Linac4 was developed and built at INR Troitsk (Russia) [3]. As shown in Fig. 2, it consists of a 100 µm thick Tungsten wire which is inserted into the beam. Secondary electrons, created through the interaction of the primary beam with the wire, are accelerated away by a 9kV applied wire polarization. A fraction of the electrons travels through a slit to a deflector, to which an RF voltage of the same frequency as the bunch structure is applied. The electron beam is then steered and focused and finally amplified by an electron multiplier. The time structure of the secondary electrons being virtually identical to that of the primary H- beam, it is possible to measure the longitudinal intensity distribution by scanning through the beam pulse while changing the phase delays on the deflector. The BSM can characterize the full 400 µs pulse with a phase resolution of 1° covering the full phase range (180° at 352 MHz). The background due to stripped electrons is less than 1% of the total secondary emission from H- and the phase scan will provide one measurement point per beam pulse.

Figure 2: Photograph of the Bunch Shape monitor.

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During commissioning at 3 and 12 MeV, the BSM was mounted on the diagnostics test bench at a distance of 4.9m from the RFQ exit plane and 4.4m, 2.9m and 1.6m respectively from the three buncher cavities of the chopper line (at least one of them needing to be powered for the beam to be sufficiently bunched for measurements).

BUNCHERS CALIBRATION

Calibration of the three MEBT buncher cavities (BU1, BU2, and BU3) was carried out by combining information and measurements from the spectrometer line and the BSM.

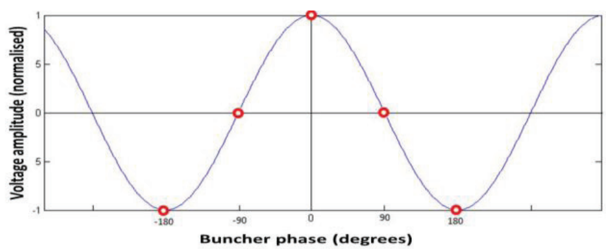

Figure 3: RF cardinal points of a buncher cavity.

For each cavity the four main RF points are shown in Fig.3: the accelerating phase at 0º, the decelerating phases at ±180º and the bunching and debunching phases at -90º and 90º respectively. These are determined for each individual cavity at a time by varying the RF phase and recording the corresponding shift in the beam centroid position on the harp monitor at the end of the spectrometer line (with the B field set at the value which would center the nominal 3MeV beam on the detector).

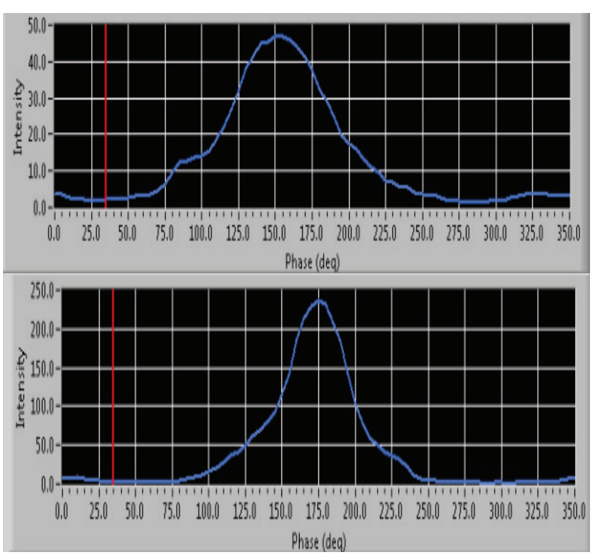

Figure 4: BSM beam profiles with BU3 set on the debunching (top) and bunching (bottom) phase.

The buncher phases for the maximum acceleration and deceleration were found using the spectrometer line. The BSM was then used to discriminate between the ±90º phases through measurements of the beam longitudinal phase spread (larger in the case of the debunching phase, as is shown by the trace at the top of Fig.4 when compared to the bottom one). The buncher amplitude was also calibrated individually for each cavity by recording on the spectrometer line the current values that need to be applied to the bending magnet to re-center the beam on the harp monitor after changing the cavity phase from bunching to accelerating and to decelerating settings respectively. Based on the relation $\Delta B/B = \Delta p/p$, the calibrated voltage of the cavity is the one that gives the best agreement between the $\Delta B/B$ measurements obtained at different cavity voltages, and the analytical calculation of $\Delta p/p$ for nominal settings, as shown in Table 1.

Table 1: Amplitude calibration of BU2 yields a value of ~3050mV at the RF probe.

Amplitude	ΔB/Bo	Δp/p (analytic)	Δp/p (simulation)
2000 mV	1.65%		
3000 mV	2.41%		
3100 mV	2.80%	2.6%	2.6%
3200 mV	3.00%		
3700 mV	3.30%		

LONGITUDINAL BEAM EMITTANCE

The longitudinal beam emittance was indirectly measured at the 3 MeV test stand using longitudinal profiles taken at the BSM. The procedure is very similar to the three gradients method used for transverse emittance reconstruction. Several BSM profiles were measured while varying the amplitude on BU2, with BU1 on its nominal setting and BU3 off and detuned. The RF phases of the first two cavities were set on their bunching values. The variation in the longitudinal phase spread of the beam as a function of the cavity voltage applied to BU2 is shown in Fig.5. Measurements (in blue) show a very good agreement with simulation results obtained from tracking to the BSM location (with operational machine settings) an ideal beam distribution (in red).

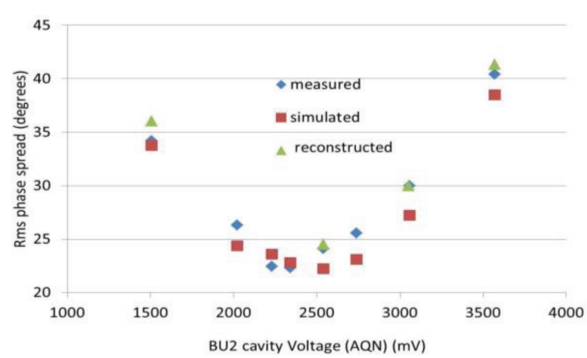

Figure 5: RMS bunch phase spread for different BU2 voltages.

The reconstruction of the longitudinal parameters is based on two steps: finding an initial estimate of emittance and

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Twiss parameters with the conventional matrix inversion technique (only correct in the assumption of system linearity), and then fine tuning this guess by tracking with space charge and comparing with data until convergence is reached [4]. The green points in Fig.5 are the results of tracking a reconstructed beam obtained from a Monte-Carlo-style repopulation of transverse emittance measurements at the RFQ output, with the longitudinal parameters thus tuned for best agreement with the data.

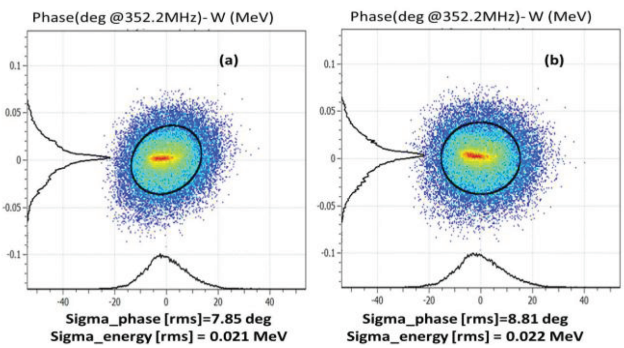

Figure 6: Expected (left) and reconstructed (right) longitudinal beam distribution at the RFQ output.

Fig.6 shows how the reconstructed beam (right) compares in the longitudinal phase space to a simulation of the beam (left) at the RFQ exit, calculated with PARMTEQ [5]. The impressive agreement between the two is a direct confirmation of both the strength of the reconstruction technique and of the instrumentation performance.

TRANSVERSE PROFILES WITH BSM

One observation made during commissioning was that the transverse position of the BSM wire, in case of misalignment with the beam axis, can influence the quality of the longitudinal beam profile measurements. Several beam profile measurements were thus taken on the 3 MeV beam at the MEBT output for different BSM horizontal wire positions (scanning from -10mm to 3mm in steps of 1 mm), within a specific pulse length window where the signal showed better stability. The RMS phase

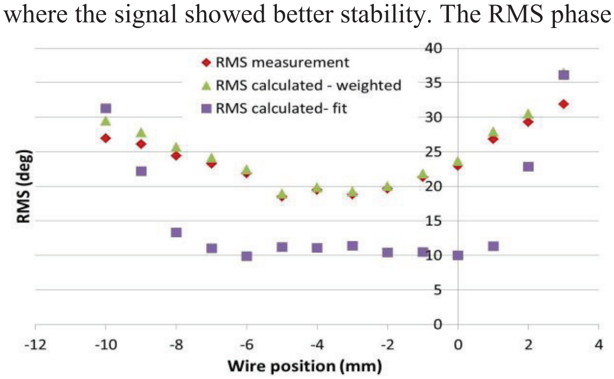

Figure 7: RMS phase spread for different BSM wire horizontal positions.

spread was then calculated for the profiles obtained at a specific time slot in the pulse using both a weighted method and a Gaussian fit (see Fig.7).

The minimum phase spread occurs at the BSM wire position that coincides with the centre of the beam, where the signal is maximum (~ -3mm); away from this position the signal picked up on the wire is lower and the corresponding RMS bunch length is larger. Gaussian fitting is also shown to underestimate the RMS width of the longitudinal profile. Incidentally this study then also showed the possibility of using the BSM as a horizontal wire scanner, albeit over a more limited range, by recording the signal strength as a function of the wire position. Fig.8 shows the comparison between the BSM signal strength (in blue), and the horizontal beam profile obtained from simulations after tracking to the BSM location the beam distribution measured by the emittance meter and backtracked to the RFQ output plane.

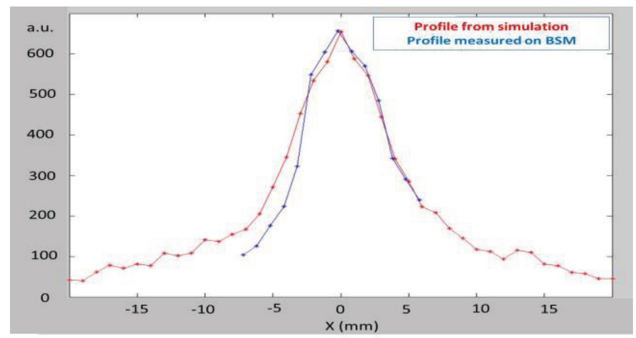

Figure 8: BSM measurement of transverse beam profile.

CONCLUSIONS

Longitudinal beam commissioning of the 3 MeV Linac4 frontend was successfully completed. The impressive consistency of the measurements obtained with different instrumentation devices and the excellent comparison of these to simulation results provide full validation of both the performance of diagnostics and RF structures on one side, and of the reconstruction and modelling methods employed on the other. Beam specifications and dynamics have been verified to be in accordance with expectations, thus building up confidence in the follow-up of the Linac4 commissioning and operation.

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