COMMISSIONING OF THE CERN LINAC4 BPM SYSTEM WITH 50 MeV PROTON BEAMS

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Abstract

The new Linac4 at CERN will provide a 160 MeV H- ion beam for charge-exchange injection into the existing CERN accelerator complex. Shorted stripline pick-ups placed in the Linac intertank regions and the transfer lines will measure beam orbit, relative beam current, beam phase, and average beam energy via the time-of-flight between two pickups. A prototype Beam Position Monitor (BPM) system has been installed in the transfer line between the existing Linac2 and the Proton Synchrotron Booster (PSB) in order to study and review the complete acquisition chain. This paper presents measurements and performance of this BPM system operating with 50 MeV proton beams, and compares the results with laboratory measurements and electromagnetic simulations.

INTRODUCTION

The CERN Linac4 [1] represents the first upgrade of the LHC injector chain, and will replace the still in use 50MeV proton Linac2. The new Linac is an 80 m-long H^- accelerator, which will supply 400 µs pulses with a 40 mA average beam current after chopping. Its accelerating scheme is based on 352.2 MHz klystrons, generating 2.84 ns-spaced bunch trains, with nominal bunch population of 1.14×10^9 H^- ions.

The beam trajectory measurement system is based on shorted striplines pick-ups, offering the versatility to match the limited space constraints: 15 BPMs are foreseen between the Linac4 intertanks. The 160 MeV H^- beam will be sent to the Proton Synchrotron Booster (PSB) via a long transfer line, composed of a new 69 m-long section to be equipped with 10 BPMs, and joining the existing 108 m-long section. Figure 1 shows the layout of the upgraded accelerator configuration.

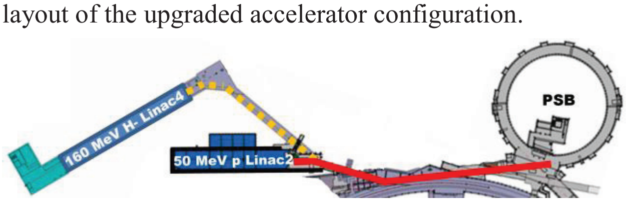

Figure 1: The new Linac4 and its transfer line (golden dashed line). The Linac2 and its present transfer line (solid red line) to the PSB.

The present 40-year-old beam trajectory measurement system of the Linac2 [2] will undergo an upgrade program, in view of keeping its compatibility with the new Linac4 standards. Prior to replacing all the 20 magnetic type BPMs, a prototype of the new BPM, based on a shorted stripline pickup has been installed in the transfer line to analyze the characteristics of this BPM system and its acquisition chain in detail.

PICK-UP DESIGN

The basic BPM model is cylindrical-shaped, with one pair of electrodes per plane, each electrode has a characteristic impedance 50 Ω and spans an azimuthal angle of 45°. Five different beam apertures (D) are required, ranging from 34 mm up to 140 mm in the different areas of the transfer lines. The prototype under test, shown in Figure 2, has the largest diameter, also its electrodes are 140 mm long. As part of the image current has to pass the body cavity having a diameter larger than that of the beam pipe, this perturbation yields trapped modes within the cavity [3]. The TM110 mode frequency $f_{110}=c/D$ (c being the light velocity) will be excited if the bunched beam energy bandwidth exceeds f_{110}. Hence for filtering the bunching frequency harmonics, and for mitigating spurious resonances, all electrode designs feature an added capacitance between electrode and body. Moreover, as the bunch length increases with beam energy, one expects an additional suppression of ~35 dB of the trapped modes in the transfer lines, assuming $\sigma_t > 1/2f_{110}$ for Gaussian beams.

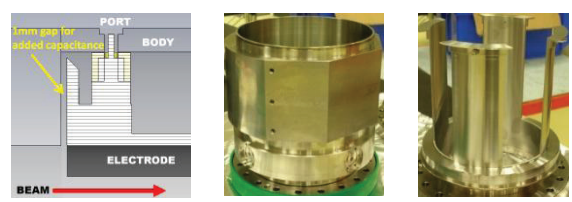

Figure 2: Left : principle of added capacitance. Middle: body. Right: electrodes with added capacitance.

Table 1: Comparison between simulations at β=1 and measurements at 352.2 MHz.

	Theory	H plane [rms]	V plane [rms]
Sensitivity[mm^{-1}]	0.01334	0.01307 *Std dev 1.3%*	0.01332 *Std dev: 0.16%*
Electrical offset [mm]	-	1.04 *Std dev 0.05*	0.35 *Std dev 0.16*
Sensitivity Error wrt theory [%]	-	2.02	0.15

The stretched wire technique is used for characterizing the response of the prototype pickup. The mechanical axis of the monitor is found with a precision of ±0.01 mm using an optical sensor. A 352.2 MHz signal supplied by a network analyzer, is applied to the wire grounded at the opposite end, hence building a standing wave. The wire was moved in steps of 0.2 mm, separately in each plane ranging ±10 mm. From the linear fit of the plot (Δ/Σ versus wire displacement we calculated BPM sensitivity and electrical offset. These values are close to the figures obtained by simulations of the test stand with CST Microwave Studio [4] (see Table 1).

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However, the BPM sensitivity also depends on the beam velocity, i.e. β and the frequency [5]. Therefore we computed the BPM sensitivities for non-relativistic beams with CST Particle Studio, using its "Particle In Cell" solver. The parameters used of the excitation source were: a 5 mm off-centered single bunch, Gaussian shaped (σ_t = 50 ps), populated with 4.63x10^9 protons, corresponding to 150 mA average current in Linac2. The beam energy was varied between 3 MeV and 5700 MeV; it should be noted that the bunch length depends on the beam velocity, and therefore on the relativistic β. For a given beam energy, the frequency domain signals from the impedance matched ports of the electrodes are used to compute the sensitivities for both Linac bunching frequencies. As Figure 3 shows, the overall sensitivity is better at the Linac2 RF frequency (202 MHz) than for 352 MHz, while for Linac4 energies (160 MeV and above), the dependence on energy and frequency becomes negligible.

ACQUISITION CHAIN

Details of the signal processing and acquisition system are presented in [3]. The BPM signals travel along ~150 m-long cables towards an analogue board, first passing a low-pass filter for selecting the first harmonic at 202 MHz. Both, filter and cable contribute to the mitigation of the spurious resonances quoted in the previous section. The filtered signal is down-converted using a local oscillator (LO). The 25 MHz intermediate frequency (IF) obtained is amplified, further band-pass filtered (10 MHz bandwidth), and feeds a commercial 16-bit-ADC for I/Q sampling [6] at four times the IF. All frequencies are phase-locked to the RF source of the Linac. The magnitude of each electrode signal is reconstructed by a software routine, grouping together I/Q pairs with $\pi/2$ phase shift. The parameters of interest: beam intensity, position, phase, and time-of-flight are derived based on the measured I/Q pairs of all electrodes. The position is deduced by computing the difference of the magnitudes between two opposing electrodes and normalization with the sum of all four electrode magnitudes.

At every machine cycle, a quick calibration was performed sequentially for each electrode channel. For a given channel, a CW 202 MHz sine wave signal was split into two parts. One part feeds directly the analogue module, and the other part travels through the coaxial cable towards the shorted stripline. From the signal reflected by each of the four electrodes, we corrected for the difference of the phases and amplitudes between the four cables, which connects the pickup and the electronics board (see Figure 4). The calibration coefficients can be stored and averaged to provide a set of "reference" scaling factors for phase and amplitude.

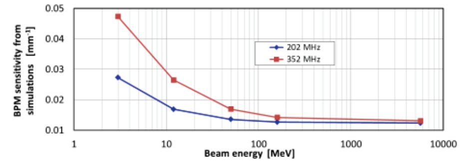

Figure 3: Energy and frequency effects on BPM sensitivity.

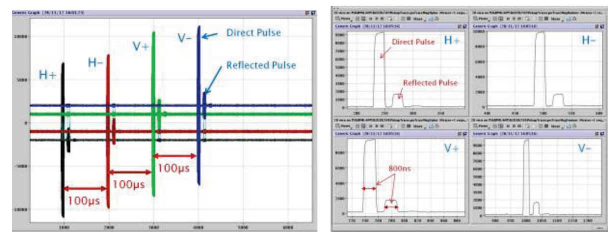

Figure 4: Calibration data: raw (left, added software offsets to ease display) and processed magnitudes (right).

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Intensity, Position, and Phase

After the 150m-long cables, the analogue signals, observed with an oscilloscope, feature a clean 202 MHz sine wave signal, AC coupled, with amplitude modulation related to the Linac pulse. Figure 5 Left compares the Linac2 pulse measured with the stripline BPM after I/Q signal processing, and with the fast Beam Current Transformer (BCT) located downstream. The pulse structure is split into three parts: the first part (head) lasts for 25 µs, followed by a "useful" part of the beam (here: 33.4 µs), and ends with the tail (starting 3 µs before the drop). Head and tail are both excluded from the region of interest, and dumped during the vertical distribution of the beam into the stack of four PSB rings. The stripline BPM can only provide qualitative information on the Linac pulse, as the beam intensity induced signal also depends on bunch length and on transverse beam size. Therefore the sum signal magnitude from the BPM has been scaled approximately to the BCT reading, just for comparison. A different time structure at the head of the beam pulse is observed between the two monitors, which might be caused by transients in the BPM electronics. Later along the pulse, both signals show the same response. Although investigations are on-going, this effect has not been observed during the recent commissioning phase of the Linac4, with the three BPMs mounted on the movable test bench characterizing the 3 MeV H$^-$ beam properties at the exit of the RFQ [7]. The beam positions and phase of another pulse are plotted in Figure 5 Middle and Right. In order to distinguish the four PSB rings for operations, the region-of-interest T1…T4 is individually set. Scalars positions by rings are calculated by averaging over the corresponding durations.

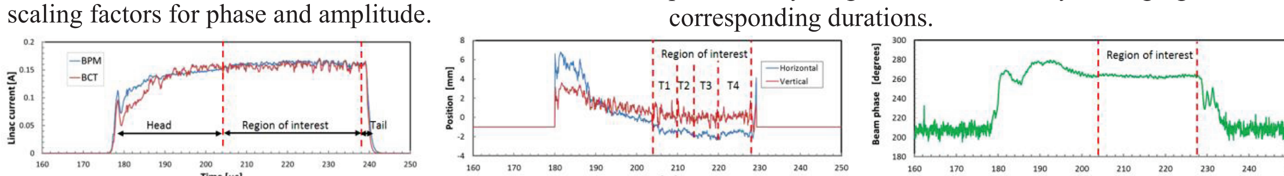

Figure 5: Linac2 beam parameters. *Left:* BPM and BCT readings. *Middle:* Beam positions. *Right*: Beam phase.

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Local Bump

A corrector magnet, located 6.5 m upstream of our prototype BPM, was used for deflecting the beam. The positions have been measured with the old magnetic BPM (UMA) before its removal, and later with the prototype. The beam conditions and Linac settings were kept as close as possible. The measurements are compared with optics simulations and presented in Figure 6. The new system fits very well with the predicted beam excursions, and is more consistent than the previous system (UMA) which has an unknown β-dependency.

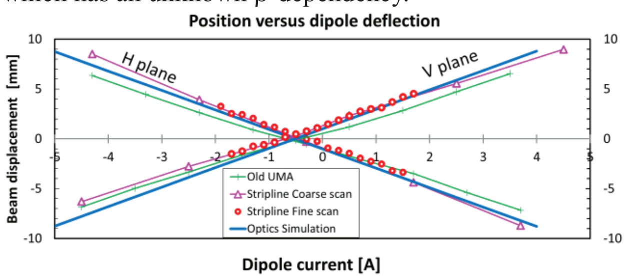

Figure 6: Positions measured with two systems, and compared with optics simulations.

Singular Value Decomposition Analysis

To understand resolution and performance of the prototype BPM under beam conditions, we used the singular value decomposition (SVD) method [8] to analyse and compare the acquired beam positions of all Linac2 BPMs. For a $p \times m$ matrix M (real or complex numbers), there exists a factorization in the form:

$$M=USV^T$$

where U (a $p\times p$ matrix) and V (a $m\times m$ matrix) are orthogonal matrices, and S is a diagonal $p \times m$ matrix with non-negative values. This over-constrained approach was applied to the position readings for a large number of low-intensity beam pulses ($p=485$ shots, Linac2 current = 50 mA), from all the monitors ($m=20$) in the transfer line, it does not rely on the knowledge of the machine optics. The SVD method decomposes the data with a correlation index, expressed in the values of the diagonal vector S. This allows to remove correlated beam effects (modes), e.g. betatron motion, cavity phase/energy errors, etc. from uncorrelated statistical noise of the BPMs, and thus get an estimate of the resolution of each BPM.

The normalized diagonal values of S, plotted in Figure 7 with decreasing order, gives the correlation level between U and V matrices, large values indicate strong, small values little correlation. We assume the first four modes of S account for correlated beam motion, while modes 5…20 are due to the uncorrelated BPM noise floor. Setting modes 1…4 to zero, and the re-computing of the decomposed BPM resolution is shown in Figure 8, where the abscissa corresponds to the BPM number, with the prototype BPM labelled #19. It shows a high resolution of 2.6 μm (horizontal) and 6.1 μm (vertical) for a low-intensity proton beam. The higher resolution of BPM#14 is consistent, as it is another improved prototype BPM with its own head amplifier, installed in 2005 [8].

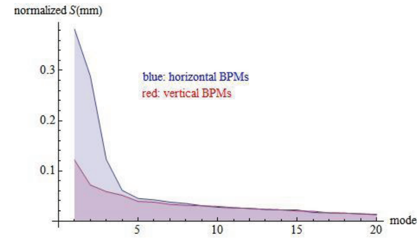

Figure 7: Diagonal values of the matrix S: 20 modes.

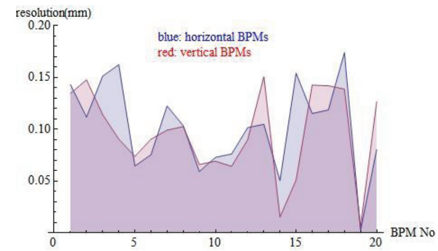

Figure 8: BPM resolution after SVD reducing the highest four modes to zero.

CONCLUSION AND OUTLOOK

A new prototype BPM system, as required by the Linac4 standards, has been successfully tested and commissioned with 50 MeV proton beams. It provides high-resolution, well-calibrated beam position measurements, in agreement with the machine optics. As the new BPM system does not require the use of a tunnel located head amplifier, electronics maintenance and tunnel access are minimized. The BPM is robust to beam losses or magnetic fields. Installation and commissioning into the 3 MeV/Linac4 test stand is underway [9]. Some teething issues are identified and have yet to be resolved. The upgrade of the new Linac4 transfer line is proceeding, the entire BPM system will be fully operational around Spring 2014.

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