BEAM POSITION MONITOR SYSTEM FOR THE CERN LINAC4

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Abstract

The new LINAC4 will provide 160 MeV H^- ion beams for charge-exchange and proton injection into the CERN accelerator complex. Among a wide variety of beam diagnostics devices, shorted stripline pick-ups will measure the absolute beam position, the relative and absolute beam current, and the average beam energy via the time-of-flight between two monitors. This paper describes the beam position monitor (BPM) with its electronic acquisition chain to be implemented on the movable test bench for beam characterization up to 12 MeV.

INTRODUCTION

The Linac4 [1] is an 80 m-long machine which will supply 400 µs pulses with 40 mA average beam current after chopping. Its accelerating scheme is based on 352.2 MHz LEP klystrons, generating 2.84 ns-spaced bunch trains, with nominal bunch population of 1.14×10^9 H^- ions. The machine layout is shown in Figure 1.

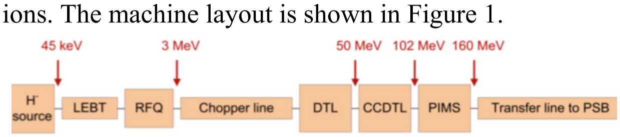

Figure 1: Linac4 schematic layout.

Shorted striplines pick-ups offer the versatility to match the limited space constraints, and exhibit interesting characteristics like good linearity and sensitivity: 15 BPMs will be integrated into the Linac4 between the DTL and the PIMS modules, whilst 27 others will be spread along the 175m-long transfer line. At the early commissioning phase of the machine, a movable test bench [2] is foreseen for characterizing the 3 MeV H^- beam properties at the exit of the RFQ and of the chopper line, but also at the exit of the first DTL tank where the beam energy reaches 12 MeV. Three BPMs will be used here for measuring:

- the absolute beam position,
- the relative beam intensity between BPMs.
- the mean energy via time-of-flight between BPMs.

Some expected beam parameters at the BPM locations and their specifications are listed in Table 1. In addition to this, there is a large spread of cylindrical beam apertures in the machine: 34 mm and 39 mm for the Linac4, 100 mm for the transfer line, and 67 mm for the movable test bench, which necessitates multiple designs. This paper focuses on the development of the 67 mm-aperture-BPM and its associated electronic acquisition chain.

PICK-UP DESIGN

The signal processing is based on down mixing of the first bunch harmonic of 352.2 MHz. In order to relax the filter requirements it is important to obtain a clean beam signal. The basic BPM model is cylindrical with one pair of electrodes per plane, each electrode of characteristic impedance 50Ω, having an azimuthal angle of 45°. Space restriction imposes 60 mm-long electrodes.

Table 1: Movable Test Bench Data: Beam Parameters at BPM Locations and their Specifications

	3 MeV	12 MeV
RMS bunch length [ps]	157-777	50-145
RMS bunch length [°]	20-98.5	6.4 – 18.4
Peak / Av. current [mA]	7 – 80 / 4 – 40	
BPM resolution / accuracy [mm]	0.1 / 0.3	
Phase/Energy resolution	1° / 1 per mille	
Intensity	1% of peak current	

Low-Beta Beam Effects

The software tool CST Particle Studio [3] has been extensively used for studying the monitor's interaction with low-β beams, where its "Particle In Cell" solver takes into account the space charge effects.

The frequency response of the pick-up was obtained by a run with a single nominal intensity bunch, gaussian-shaped, travelling along the BPM axis. The relativistic β span was 0.0797 up to 0.99, while the rms bunch length was kept constant and short at 50 ps (see Figure 2). The theoretical transfer function for relativistic beams, e.g. found in [4], and derived for shorted striplines gives an optimum response of 1.25GHz for 60 mm-long electrodes, which is confirmed in the green curve. With β = 0.0797 (resp. 0.16), this length is optimised for 178 MHz (resp. 330 MHz).

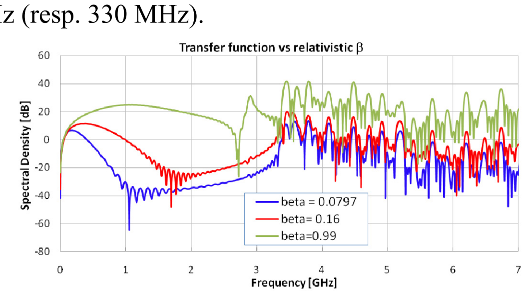

Figure 2: BPM transfer function for different beam velocities.

Figure 3 plots the time signals versus the bunch length σ_t at 12 MeV (β = 0.16). It shows that the Lorentz contraction effect is still weak: the interaction time Δt of the beam within the BPM is much larger than σ_t. Furthermore Δt remains constant with increasing σ_t. Consequently, the output time signal does not reflect the real physical bunch duration. However as expected the peak voltage is proportional to the charge density.

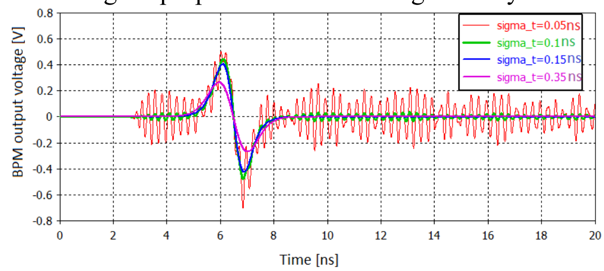

Figure 3: BPM output signals from a run with a 12 MeV-single bunch. The 1σ bunch length span is 0.05-0.35 ns.

High Frequency Noise and its Mitigation

The spectra and voltages above clearly show the development of high frequency (HF) resonances, even at very low β. Unlike simulation results quoted in [5], they are not related to improper matching of the wave fields at the port boundaries. A detailed analysis shows that they occur between the electrode-body gap and in the output ports. The excitation of these modes decreases as the bunch length increases.

These resonances cause serious concerns as the longitudinal bunch length, starting from the DTL throughout the Linac4, should stay in the range [2.5°-5°] (rms, i.e. 20-40 ps). The idea for mitigating the HF noise, which is getting worse with multi-bunch beams, consists in creating a capacitive effect between the electrode and the beam pipe: it would behave as a low-pass filter without affecting the fundamental harmonic. An increase of the electrode thickness at the port end yield this effect, as depicted in Figure 4 Left.

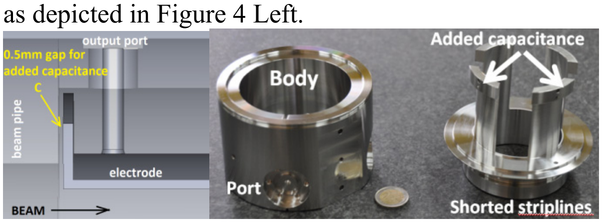

Figure 4: Left: Principle of added capacitance. Right: Body and electrodes with added capacitance before electron welding.

A comparison between three electrode models is proposed below: the basic stripline, and two electrode designs with 4 pF and 9pF added capacitance per electrode respectively. The simulations are performed with a series of ten gaussian bunches crossing the monitor at 12 MeV, having 50 ps bunch length (1σ). According to the results in Figure 5 the last model with 9pF provides an optimum filtering efficiency. The cut–off frequency of this first order filter with a 50Ω load is then 354 MHz. Most resonances are attenuated by ~20 dB, as shown in Figure 5b. The remaining higher frequencies are expected to be dissipated in the transmission cables before reaching the front-end electronics, where additional filters are also implemented.

The real monitor is made of two main parts assembled by electron bombardment welding. The capacitance location is shown (Figure 4 right).

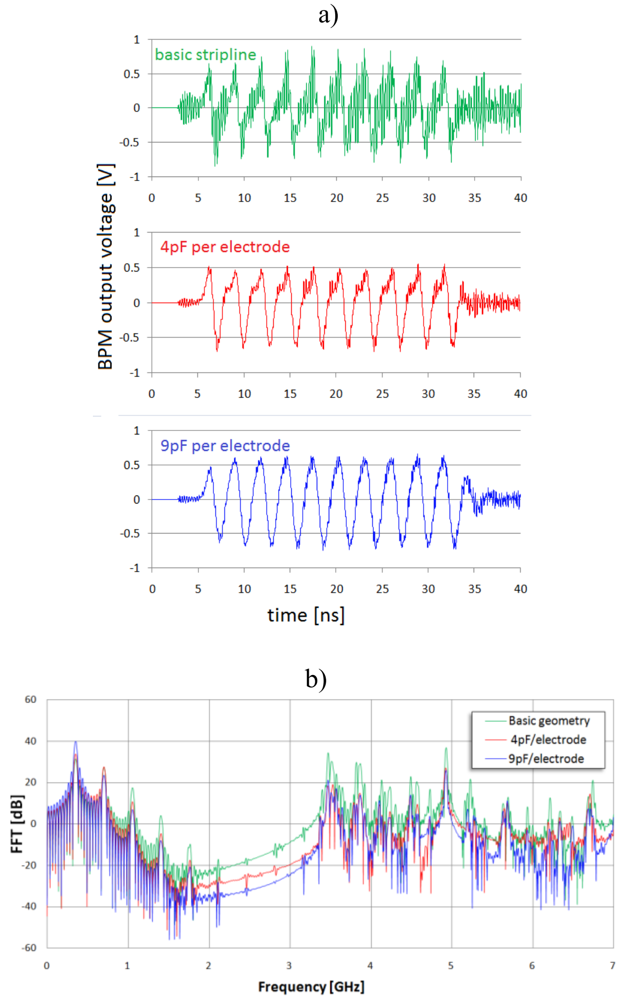

Figure 5: Simulation of between three BPM models: a) output voltages, b) spectra versus capacitance.

Position Sensitivity Versus Energy

The position sensitivity is computed with an off-centered beam at different βs. Processing the first harmonic peak gives the theoretical sensitivity at 352MHz as a function of beam energy (see Figure 6). These sensitivities will be applied for the movable test bench BPMs. In [6] a theoretical estimate of stripline sensitivity for low-β beams was proposed and is consistent with our simulations.

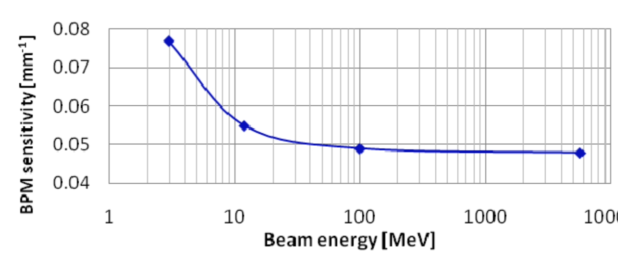

Figure 6: Estimated sensitivity at 352MHz as a function of beam energy.

PROCESSING WITH I/Q SAMPLING

Position, Intensity and Phase Measurement

The I/Q method [7] as represented in Figure 7, consists of down-mixing the first harmonic signal from the BPM with a Local Oscillator (LO). The intermediate frequency (IF) obtained is then sampled at four times the IF so as to acquire I/Q data 90° apart, giving the relative phase $\phi_{IF}=\phi_{BPM} - \phi_{LO}$ and the magnitude M for each electrode.

The position is then deduced by computing the difference of the magnitude between two opposing electrodes and normalisation with their sum. The beam intensity is proportional to the magnitude sum of all electrodes.

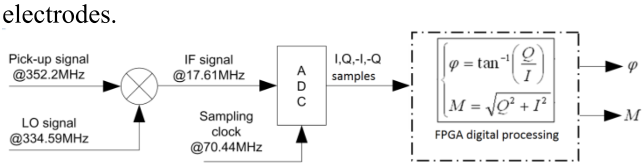

Figure 7: I/Q acquisition principle.

TOF Measurement

The LO signal is distributed towards all the down-mixers with a phase jitter of 300 fs. The relative longitudinal phase advance between two BPMs is obtained by difference $(\phi_{BPM2} - \phi_{BPM1})$ given by the ϕ_{IF} measurements. But one only gets the non-integer part of this difference. The average beam energy is computed after integration of the integer part, knowing the theoretical phase advance between the two monitors.

FRONT END ELECTRONICS

The Electronic Board

A-four-channel front end electronic board handles the electrode signals of a single BPM (see Figure 8). Each channel has an input stage filter, followed by a switch system for calibration. The signal is then down-mixed and amplified. As the first commissioning phase will start with only 4-10% of the nominal intensity, the board features also variable gains thanks to switchable attenuators in steps of 1dB, up to 32dB.

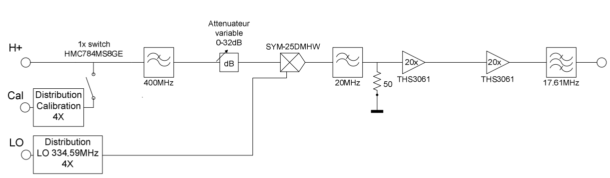

Figure 8: Electronic bloc diagram.

Calibration Procedures

The front end software and an onboard FPGA control the switch and the attenuator during the calibration procedure. There are three different calibration methods:

- With direct injection of a 352.2MHz sine wave signal into the analog input of each channel, the phase and amplitude differences between the four channels can be corrected for.
- From the signal reflected by each of the four electrodes, one can correct the difference of the phase shift between the four cables and the electronic board. We can also compare and correct the phase difference (non-integer part) between two BPMs, the integer part being irrelevant.
- The electrode coupling method [8] is used to measure the electrical offsets: the ratio of the coupling together with the acquisition gain between the adjacent electrodes (V+ and V-) by the H+ electrode gives the calibration offset for the vertical plane here (see Figure 9).

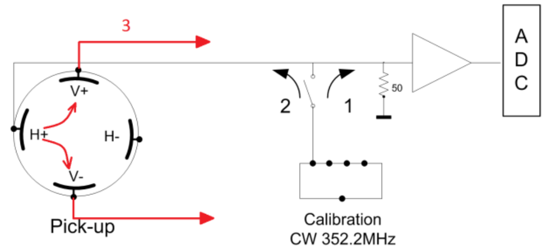

Figure 9: Calibration scheme.

CONCLUSION AND OUTLOOK

The design of the BPMs for the movable test bench has been optimized for operation with low-beta beams and short bunches. An automated and motorised test bench is under construction for characterising by the wire technique the five monitors that have been manufactured.

The analogue board will undergo a series of standard tests: bandwidth, gain, noise, stability, linearity, cross-talk between channels, and resolution. It is foreseen to sample and process its out-coming analog signals with an FPGA-based board (FMC) developed at CERN. This would result in a faster processing speed and ease data handling by the front end software. The first bench tests are foreseen for June 2011, and beam tests end of 2011.

ACKNOWLEDGEMENTS

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