LAYOUT OF THE BPM SYSTEM FOR P-LINAC AT FAIR AND THE DIGITAL METHODS FOR BEAM POSITION AND PHASE MONITORING

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Abstract

At the planned Proton LINAC at the FAIR facility four-fold button Beam Position Monitor (BPM) will be installed at 14 locations along the LINAC. Four of these BPMs will be mounted only about 40 mm upstream of the CH cavities. The coupling of the rf accelerating field to those BPMs was numerically investigated. The properties of a digital I/Q demodulation scheme were characterized by detailed lab-based tests. The performance was investigated by a 80 μA Ca^{10+} beam at 1.4 MeV / u at GSI UNILAC for beam position and phase determination. The I/Q phase results were compared to a time-domain approach as well as successive FFT calculation. A significant deviation between the methods were observed and further investigations to understand the reason are ongoing.

INTRODUCTION

The proton LINAC at FAIR will provide the primary beam for the anti-proton production chain. It will serve as an injector for the existing synchrotron SIS18 delivering 35 mA of beam current within macro-pulse length of 36 μs and a typical bunch length of 150 ps. It is designed to accelerate the beam from 3 MeV to 70 MeV with an operating frequency of 325 MHz [1]. Beam Position Monitors (BPM) will be installed at 14 locations along the LINAC and they will serve as the main beam diagnostic tool, as schematically shown in Fig. 1. The BPM system will determine three beam quantities, the beam displacement with a spatial resolution of 0.1 mm, the mean beam energy and the relative beam current. The beam energy is recorded from the time-of-flight of bunches between two successive BPMs with an accuracy of 8.5 ps corresponding to a phase difference of 1° with respect to the accelerating frequency of 325 MHz. The relative beam current is determined for the sum signal of the four BPM plates. The basic layout for the BPM system and relevant calculations are described in [2].

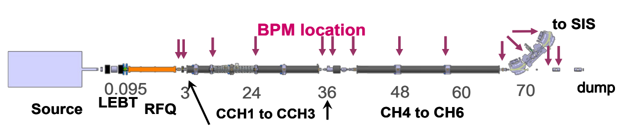

Figure 1: Layout of the proton LINAC including BPM locations.

SIMULATION OF RF COUPLING TO BPM

At four locations the BPMs will be an integral part of the inter-tank section between the CCH or CH cavities mounted within an evacuated housing as shown Fig. 2. A very precise model of the inter-tank section was created to simulate the realistic situation of rf field propagation from the cavity into the beam tube and the BPM's co-axial signal path [3]. The simulation gives the solution of the large-scale eigenvalue problem which has been handled with a parallel implementation of the Jacobi-Davidson algorithm [4] but requires a large amount of CPU time and memory.

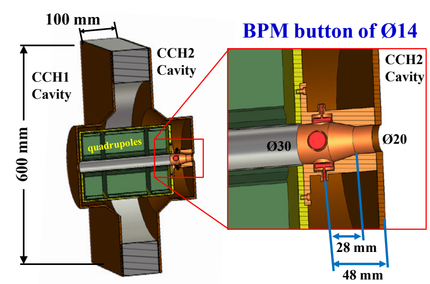

Figure 2: The technical layout of the inter-tank section.

As the BPM centre is only 48 mm apart from the upstream cavity boundary and assuming an electric field strength of $E_{z,peak} = 21.2\ MV/m$ in the first acceleration gap, the unintended rf coupling to the BPM pickup antennas (so called rf-leakage) was evaluated. It has been shown, that this exact solution can be approximated by a simple electro-static approach with an appropriate, static potential applied to the closest drift tube in the cavity.

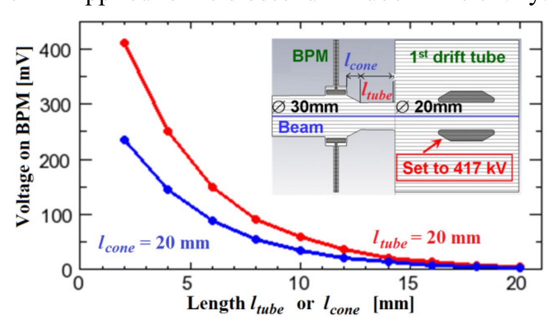

Figure 3: Shielding properties as a function of the length of the cone l_{cone} (red) for a fixed length of the tube or as a function of the cylindrical tube length l_{tube} (blue) for fixed cone length. For the electro-static solver the first drift tube is set to 417 kV.

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The shielding properties of a cone and a tube with reduced beam pipe diameter are depicted in Fig. 3 performed with the electro-static solver. A cone and a tube of 20 mm length respectively, are sufficient to reduce the rf pick-up signal below 5 mV amplitude. This value has to be compared to the signal voltage of ~ 1V for nominal beam current of 35 mA.

THE DIGITAL METHODS FOR BEAM POSITION AND PHASE MONITORING

A digital signal processing is foreseen for the transverse beam position and the phase monitoring, which could be realized by using the Libera SPH (**Libera S**ingle **P**ass **H**adron) electronic from the company Instrumentation Technologies [5]. In the Libera SPH, the phase measurement is performed with respect to an external master oscillator rf signal. The digital processing involves sampling and digital I/Q (in-phase and quadrature) down-conversion from each electrode. The amplitude and phase of the individual signal can be evaluated in the FPGA digital electronics. From these data the beam position (from the difference of the plates' amplitude) and mean energy (from the phase value compared to the accelerating frequency) can be extracted in a flexible manner with a selectable time resolution between 1 and 70 µs. The proton LINAC operates with an accelerating frequency of 325 MHz and the technique of under-sampling will be applied with a sampling rate of 117.440 MSa/s. In order to suppress the above discussed rf-leakage contribution a band-pass filter matched to the second harmonic (650.5 MHz) of the accelerating frequency is placed into the analoge chain. The limited spectral content is suitable for digitalization by a high resolution ADC (16 bit nominal).

Beam-Based Experiment at UNILAC

A beam-based experiment was conducted at GSI UNILAC with a Ca^{10+} beam at 1.4 MeV/u and a beam current of ~ 80 µA to test the performance of Libera SPH system. Since accelerating frequency of UNILAC is 108.4 MHz, Libera SPH electronics was customized to process the signals at the base frequency and its second harmonic. Most of the measurements were performed for the first harmonic. The beamline optical elements consist of a buncher for longitudinal focussing, quadrupole doublet for beam transverse focussing and dipole for horizontal position variation.

For the measurements, a single BPM capacitive pickup with four electrodes was used to detect the beam position and to act as a "Bunch arrival monitor" for phase determination. The purpose of these investigations was to characterize the dependence of beam arrival time on bunch shape. The Libera SPH digital processing system was evaluated and compared with a time-domain reading obtained by a 10 GSa/s oscilloscope (LeCroy Waverunner 6200A). The characteristics of the digital electronics were tested for sevn different settings of the buncher for longitudinal focusing resulting in different bunch shapes. Each individual shape was displayed and stored on the oscilloscope from the sum of the BPM signals by looking at the average over many macropulses. For the same beam parameters, the digital I/Q demodulation on the Libera SPH calculates the beam position the phase value compared to the accelerating frequency. Every data set corresponds to one macro-pulse and it is given in steps of 1 µs (correspond to 108 bunches) for 129 µs. Fig. 4 shows a typical example of Libera SPH data-set for pickup amplitudes and phase reading during one macro-pulse. The ratio of the difference over sum voltage between two opposite electrodes is used for beam position determiation.

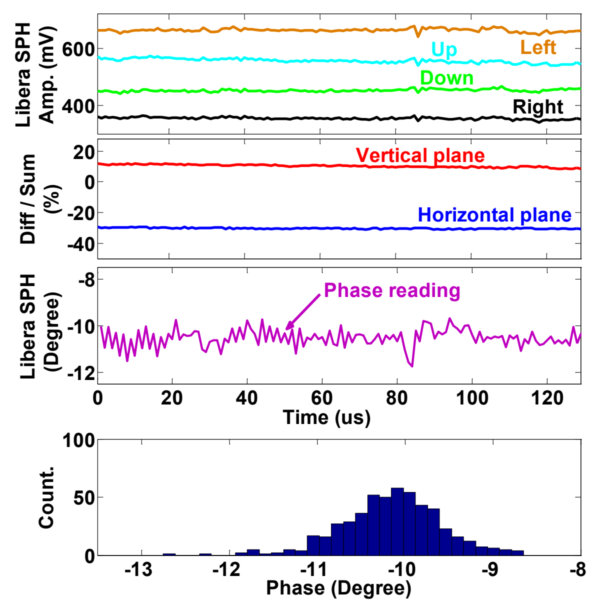

Figure 4: Single plate amplitude, position & phase reading within 1 µs time resolution during one macro-pulse. The botton figure is the histrogram of the phase reading.

The BPM signal was adapted by low noise, broad-band amplification of 44 dB to yield signal strengths such that 0.3 V < U_{peak} < 1.35 V depending on the bunch length. Each individual bunch curve recorded by the 10 GSa/s oscilloscope contains about 92 samples. The granularity was improved by the spline interpolation to increase the resolution of the original curve from 0.1 ns to 1.12 ps containing 2^{13} points. As a representation for the arrival time the zero crossing of each signal is chosen with respect to a reference shape as depicted in Fig.5.

For further investigations, the interpolated signal curve obtained from time-domain data for a single bunch was Fourier-transformed to verify with the time-domain reading and to compare with the frequency-domain results obtained by Libera SPH. Zero padding technique was used during Fourier transformation to further increase the

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resolution of the amplitude and phase spectrum. Additionally, a stream of bunches were stored the 1.5 ms for each bunch shape (~166 000 bunches). Due to a memory limitation only 30000 bunches were used for FFT calculations. Fig. 6 shows an example of the amplitude and phase spectrum for two shapes.

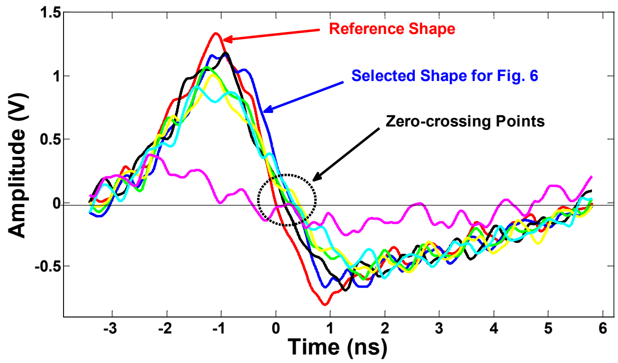

Figure 5: Time-domain recording of single bunches for different buncher amplitudes are depicted to determine the individual zero-crossing points.

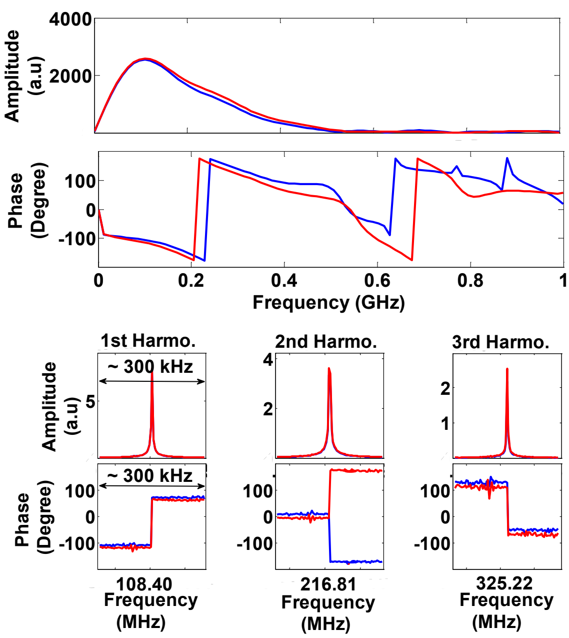

Figure 6: Amplitude and phase spectra for the reference shape (red) and the selected shape (blue) from Fig. 5. (up) from a single bunch, (down) from a stream of bunches (the amplitude spectrum nearly coincided).

Experimental Results

As shown in Fig. 7, the evaluated results showed some agreements between the Libera SPH phase readings and the time-domain measurements. In contradiction to the expectation, Libera SPH processed only large amplitude signals of $U_{peak} > 0.5$ V with a phase accuracy better than 1°. The measured resolution (noise) is actually much better than accuracy. However, the FFT calculations of the specified single bunch data and the bunch stream are better matched to the time-domain evaluation.

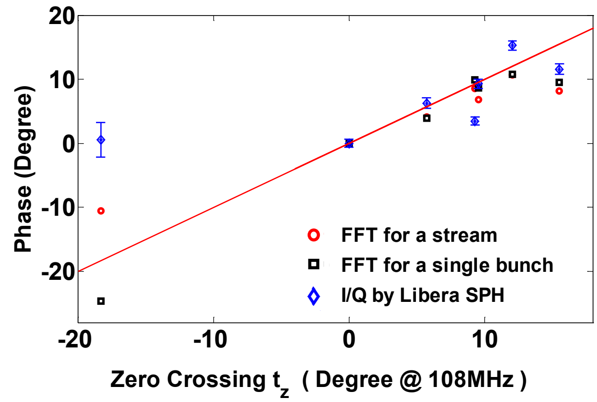

Figure 7: Time-domain data versus Libera SPH and FFT calculations for a single bunch and a stream of bunches.

CONCLUSION

Four-fold button BPMs are foreseen at 14 locations for the proton LINAC. To prevent for a significant rf-leakage, the distance to the rf cavity must be above 40 mm. An electro-static approach can be applied for the optimization of the required beam tube length and shape and gives comparable results with remarkable accuracy.

A beam-based measurement with 80 µA beam current of a Ca^{10+} ions accelerated by 108 MHz was performed using the proposed digital processing scheme. The tested Libera SPH digital electronics seem to be suited for beam position determination. However, a precise test for the beam position resolution has not been performed. For phase detection, a significant deviation between the different methods were observed. Therefore, further investigations and more detailed calculations are still required to understand the reasons of such large deviations between the results from the Libera SPH, the time-domain processing and the FFT analytic calculations.

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