

BEAM TESTS OF A PROTOTYPE STRIPLINE BEAM POSITION MONITORING SYSTEM FOR THE DRIVE BEAM OF THE CLIC TWO-BEAM MODULE AT CTF3*

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Abstract

In collaboration with LAPP and IFIC, two units of a prototype stripline beam position monitor (BPM) for the CLIC drive-beam (DB), and its associated readout electronics have been successfully installed and tested in the Two-Beam-Module (TBM) at the CLIC Test Facility 3 (CTF3) at CERN. This paper gives a short overview of the BPM system and presents the performance measured under different Drive Beam configurations.

INTRODUCTION

CLIC, a Compact electron-positron Linear Collider proposed to probe high energy physics (HEP) in the TeV energy scale, is based on a two-beam scheme. The RF power required to accelerate the high energy beam is extracted from a high current drive-beam decelerator, equipped with more than 40000 quadrupoles, each holding a BPM. These BPMs face several challenges, as they will be operated in close proximity to the Power Extraction and Transfer Structures (PETS), while the required resolution of 2 μm and accuracy of 20 μm in a beam pipe of 23 mm diameter are demanding. They have to be compact, inexpensive, and operate below the waveguide (WG) cut-off frequency of the beam pipe to ensure purity of the position signals, which rules out a signal processing at a (sub) harmonic of the 12 GHz bunching frequency. Wakefields, and hence the longitudinal impedance, should also be kept low. The presented solution consists out of a stripline BPM with downstream terminated electrodes and a signal processing scheme operating at frequencies <80 MHz, which is located in the accelerator tunnel. It was recently tested with beam in the CLIC Test Facility 3 (CTF3), in the presence of low and high power 12 GHz RF signals from the PETS.

SYSTEM DESIGN

Stripline Pick-up

The CLIC DB stripline BPM pickup is a compact design and fits into the quadrupole vacuum chamber. Each of the four electrodes spans an angular coverage of 20°, having a characteristic impedance of 50 Ω and a physical electrode length of $L=37.5$ mm. Due to the proximity of 12 GHz high

power accelerating structures (PETS), L was chosen to utilize the notch in the transfer function ($nc/2L$, $n=3$, where c is the speed of light in vacuum) at 12 GHz, which is also the bunch frequency. Therefore, in the time domain, the idealized response to a multi-bunch train would return only the first and last triplets of bunches, with all other bunches in-between cancelling (Fig. 1).

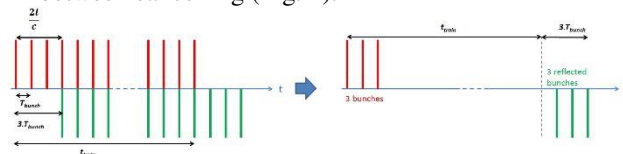


Figure 1: Idealized multi-bunch train response of the stripline BPM prototype.

The signal processing is performed at baseband, between 8 and 80 MHz, to be as far as possible from the fundamental PETS frequency of 12 GHz, which can propagate through the DB line as this is above the 7.6 GHz cut-off frequency of the 23 mm beam pipe. The position signal for a full multi-bunch train is estimated in a stripline BPM as $x=(r/2)\Delta/\Sigma$, r being the pipe radius, and Δ and Σ the difference and sum of opposite electrode signals. Further details of the pick-up design are given in [1].

Readout Electronics

A passive, analog pulse shaping network, basically an integrating-lowpass filter, performs the required manipulation of the electrode signals, since the pulse triplet signals at the BPM ports (Fig. 1) are too intense and short when stimulated by a 240 ns long train of 10 ps long bunches to be digitized directly. The pre-processed electrode signals need to give signals proportional to the beam position and intensity during the passage of a multi-bunch train and have a sufficient bandwidth to resolve the beam position not only of individual bunch trains, but even within the bunch train. A combination of filters was found through simulations for the optimal shaping of the signal, and consists of an 8 MHz 1st order low-pass filter, a 40 MHz 1st order low-pass filter, and a 70 MHz 2nd order low-pass filter. A block diagram of the BPM readout chain is shown in Fig. 2.

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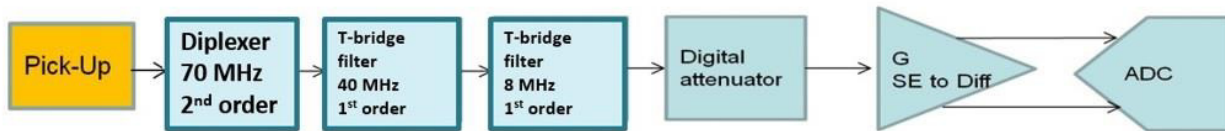


Figure 2: Block diagram of the analog readout electronics for the stripline BPM prototype (one channel)

To ensure good impedance matching, the 2nd-order filter was implemented as a diplexer with the other filters as T-bridge structures. A gain stage, implemented in the feedback loop of the Analog-to-Digital-Converter (ADC) driving amplifier stage, combined with a controllable digital attenuator, allows the readout signals to be adapted for different beam intensities and bunch structures [2] to the full-scale range of the ADC.

All four BPM signals are further processed digitally, applying a deconvolution of the theoretical impulse response of the full system, BPM and readout chain, with the acquired multi-bunch train response, and averaging the signal samples. The beam position is then computed by applying $x=(r/2)\Delta/\Sigma$.

Calibration

The read-out system includes a calibration test signal based on digital signal synthesis and a digital-to-analog converter (DAC), with two operating modes: white noise or pulse train. The selected calibration signal is converted to the analog domain and fed into the stripline electrodes through the downstream ports (Fig. 3).

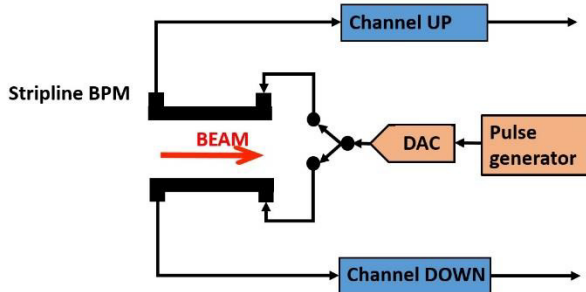


Figure 3: Loop-through calibration process for the vertical plane.

Based on a preliminary calibration with pulse trains the position sensitivity around the origin is 163.2 m⁻¹ (Vertical) and 153.0 m⁻¹ (Horizontal) for the first prototype and 161.7 m⁻¹ (Vertical) and 152.5 m⁻¹ (Horizontal) for the second. These values are consistent with the result obtained by electromagnetic simulation (Fig. 4) of 155.3 m⁻¹. The small differences between simulated and observed values can be explained through the tolerances in the analog signal processing section of the BPM.

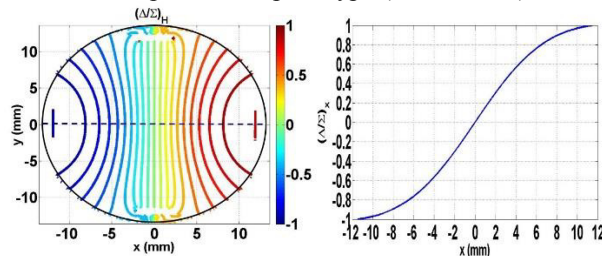


Figure 4: Horizontal position characteristics (equipotentials of Δ/Σ) of the stripline BPM.

BEAM TESTS ON BPM PROTOTYPES

Following their assembly and characterization in the laboratory, both stripline BPM prototypes were installed and tested under realistic beam conditions in CTF3. The BPM pickups are located in the DB line of the CLIC TBM at locations 0645 and 0685, each one in close proximity to a decelerating structure to study their immunity to high power RF pulses. The tests were carried out for two different PETS RF power configurations: 2.4 MW and 40 MW. Fig. 5 shows the waveforms of four raw BPM electrode signals acquired by the read-out electronics, which is located in a shielded area behind the beam dump.

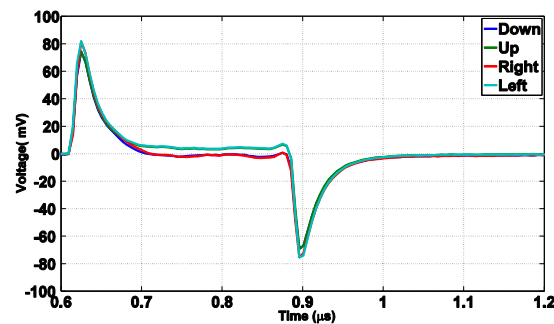


Figure 5: Output signals of BPM 0645 for a centred beam (beam pulse: 240 ns, PETS power: 40 MW)

Influence of Extracted PETS RF Power

The influence of the extracted PETS RF power at 12 GHz on the measured beam position was studied by analysing the trajectory along the DB line of the TBM for several positions of the beam, in the presence of low (2.4 MW) and high (40 MW) RF power. Figures 6 displays the variation in the measured position for the horizontal and vertical plane when moving from 2.4 MW (low power) to 40 MW (high power) PETS operation. The stripline BPM

prototypes (#5 and #6) performed very well in the horizontal plane, giving the lowest error of all BPMs, with similar results in the vertical plane.

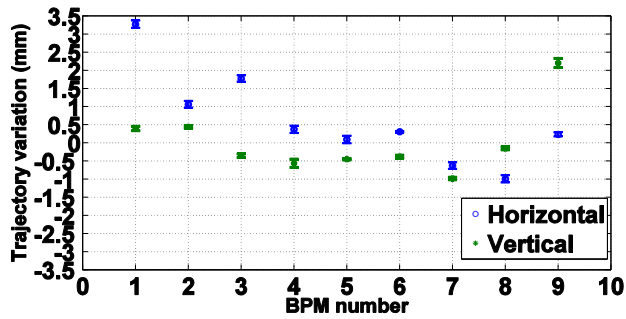


Figure 6: Variation of the horizontal (blue) and vertical (green) trajectories in the DB line of the TBM when increasing in extracted PETS power from 2.4 MW to 40 MW for a centred beam.

Singular Value Decomposition Analysis

To estimate the resolution of the prototype BPM, a singular value decomposition (SVD) [3] method was applied to disentangle the correlated beam motion from the uncorrelated noise of the BPM system. The beam position measured by all BPMs along the DB line of the TBM was acquired simultaneously on a shot by shot basis, to give position values in a $p \times m$ matrix B , where m is the number of monitors and p the number of shots. The SVD method factorizes B as:

$$B=USV^T$$

, where U (a $p \times p$ matrix) and V (an $m \times m$ matrix) are orthogonal matrices, and S is a $p \times m$ matrix with non-negative values in the diagonal. This over-constrained approach was applied to the position readings for a large number of high intensity beam pulses ($p=999$ shots, beam current = 22 A), from all the monitors ($m=9$) in the DB line of the TBM, and does not require the knowledge of the machine optics. The SVD method decomposes the data to obtain a correlation index between the temporal eigenvectors (U) and the spatial eigenvectors (V), and expresses the correlation in the values of the diagonal matrix S . This allows correlated beam effects to be removed, e.g. betatron motion, cavity phase/energy errors, jitter, etc., from the uncorrelated statistical noise of the BPMs, and thus to estimate of the resolution of each BPM.

The normalized diagonal values of S , plotted in Fig. 7 with decreasing order, give the correlation level between the U and V matrices. Large values indicate strong correlation while small values show little correlation. The first five eigenvalues of S are assumed to account for systematic, correlated beam effects, while higher order eigenvalues 6...9 are assumed to be due to the uncorrelated BPM noise floor. Setting modes 1...5 to zero, and re-computing the position data matrix gives an upper bound on the resolution limit, see Fig. 8. Here the abscissa corresponds to the BPM number, with the prototype BPMs under test labelled #5 and #6, reporting a position resolution of 1.4 μm (horizontal) and 0.5 μm (vertical) for BPM#5; 2.4 μm (horizontal) and 2.5 μm (vertical); for BPM#6. Considering the 1/3

ratio between the horizontal and the vertical β at the location of BPM#5 (1/1 at the location of BPM#6), and taking the known limitations of the SVD method into consideration, it is safe to report that the resolution of the stripline BPMs is substantially better than that of the other BPMs in the beam-line, in the range of $\sim 2 \mu\text{m}$, and would therefore satisfy the CLIC DB BPM requirement.

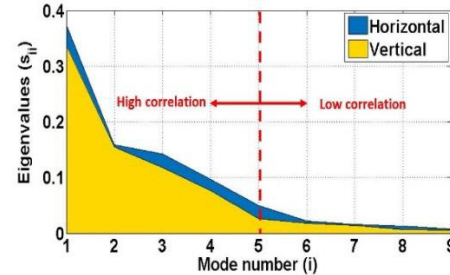


Figure 7: Diagonal values of the matrix S : 9 modes.

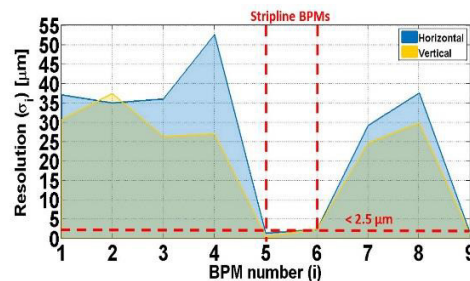


Figure 8: BPM resolution upper bounds after disregarding the five highest SVD eigenmodes.

CONCLUSIONS

The CLIC DB stripline BPM prototypes with downstream terminated electrodes and their acquisition electronics were successfully calibrated and tested with beam at CTF3. The beam studies demonstrated, that the BPMs are almost insensitive to an extracted PETS power increase from 2.4 MW to 40 MW, although this behaviour needs to be confirmed with higher power values. The resolution of the BPM system was estimated under realistic beam conditions, and meets the requirement for the DB line of 2 μm .

ACKNOWLEDGEMENT

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