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In collaboration with SLAC, LAPP and IFIC, a first prototype of a stripline Beam Position Monitor (BPM) for the CLIC Drive Beam and its associated readout electronics has been successfully tested in the CLIC Test Facility linac (CTF3) at CERN. In addition, a modified prototype with downstream terminated striplines is under development to improve the suppression of unwanted RF signal interference. This paper presents the results of the beam tests, and the most relevant aspects for the modified stripline BPM design and its expected improvements.

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STATUS OF THE STRIPLINE BEAM POSITION MONITOR DEVELOPMENT FOR THE CLIC DRIVE BEAM*

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In collaboration with SLAC, LAPP and IFIC, a first prototype of a stripline Beam Position Monitor (BPM) for the CLIC Drive Beam and its associated readout electronics has been successfully tested in the CLIC Test Facility linac (CTF3) at CERN. In addition, a modified prototype with downstream terminated striplines is under development to improve the suppression of unwanted RF signal interference. This paper presents the results of the beam tests, and the most relevant aspects for the modified stripline BPM design and its expected improvements.

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. RF power, required to accelerate a high energy luminosity beam is extracted from a high current Drive Beam (DB), whose decelerator requires 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 accuracy requirements are demanding (20 μm). 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 the signal processing at the 12 GHz bunching frequency. Also wakefields, and hence the longitudinal impedance, should be kept low. The first proposed solution was a compact, downstream shortened stripline BPM utilizing a low-frequency (<40 MHz) signal processing scheme operating in the accelerator tunnel. The system has been recently tested with beam in the CLIC Test Facility 3 (CTF3), in presence of low and high power interfering 12 GHz RF signals from the PETS. In parallel, a second prototype stripline BPM, with improved notch-filtering properties at 12GHz, has been developed.

BEAM TESTS ON A PROTOTYPE BPM

Following a comprehensive laboratory characterization [3][4], a stripline BPM prototype with short-circuited electrodes at their downstream end has been tested under realistic beam conditions in CTF3. The BPM pickup was installed in the Test Beam Line (TBL) in close proximity to a de-accelerating structure, to study the immunity to high power RF pulse (Fig. 1). The beam tests have been performed in two configurations: with 6 MW and 60 MW of PETS power at 12 GHz, running a beam current of 10 A and 22 A, respectively.

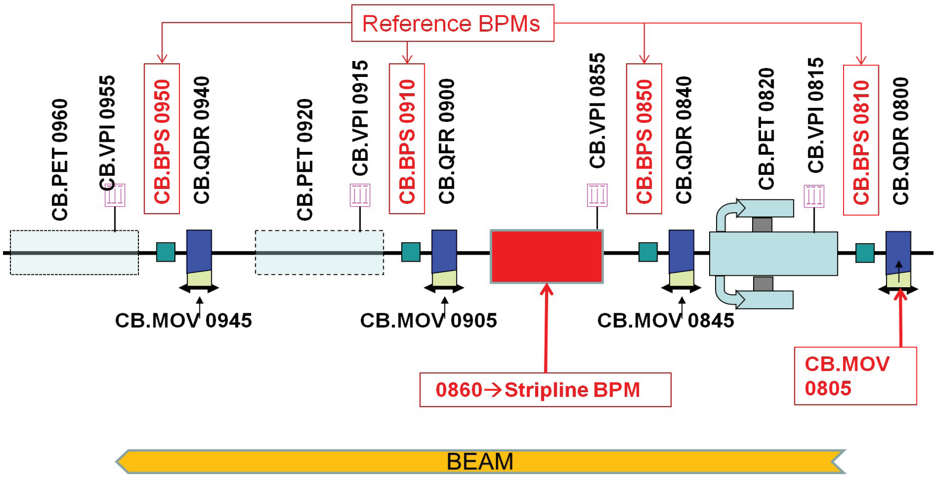

Figure 1: Layout of TBL girders n° 8 and 9 showing the test setup.

For both configurations, the performance of the acquisition electronics, located in a shielded area behind

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the beam dump was satisfactory, as the expected waveforms [3] were obtained (Fig. 2).

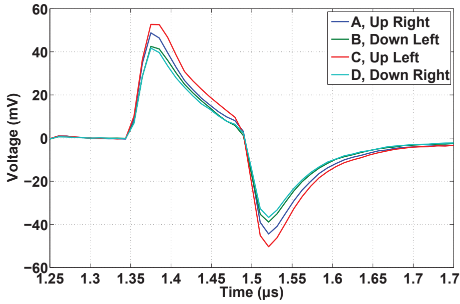

Figure 2: Output signals of the electronics for a centred beam (beam pulse: 140 ns, PETS RF power: 60 MW).

Linearity and Sensitivity

In this first beam test, the stripline BPM was installed into the beam-line at location 0860 – under a 45^0 rotation, to account for synchrotron radiation issues in some arc areas of the final design of the CLIC drive beam-line. Figure 3 gives an idea of the expected position sensitivity and linearity, based on a 2D electrostatic analysis in the horizontal plane. It calculates to $d(\Delta/\Sigma)/dx|_{x=0}=101.8\ m^{-1}$ at the centre, but varies to more than 10% for beam displacements >±3 mm.

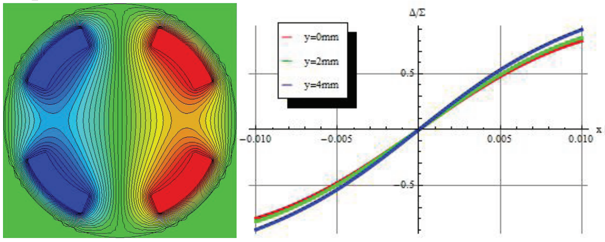

Figure 3: Horizontal position characteristic (equipotentials of Δ/Σ) of the stripline BPM, in a 45^0 rotated installation.

Some brief tests on sensitivity and linearity on the entire BPM system, i.e. stripline BPM and read-out electronics, have been made using a stretched wire setup [4], and now with beam as well. The wire, respectively the beam, has been moved in a ±5 mm range, horizontally and vertically. The beam movement was realized by physical movements of a preceding quadrupole (QDR0800), while crosschecking the beam displacement by recording the beam positions of the neighbouring BPMs, BPS0850 and BPS0910. Table 1 summarizes the results based on linear fits to obtain the sensitivity, the electrical offset (EOS), the linearity error and the nonlinearity contribution to the overall precision, giving the uncertainty in the position measurements. However, it has to be mentioned that these results are not taking the effect of the quadrupole at position 0900 into account, which may explain the discrepancy between calculated and measured sensitivity, particularly in the vertical plane.

The beam measurements have been performed for two different settings of the PETS RF power, 6 MW (BEAM 6) and 60 MW (BEAM 60). Despite the general issue on the vertical sensitivity, for both PETS settings the measured BPM parameters are very similar, indicating only little from the effect of the PETS RF power on the beam position measurement. Figures 4 and 5 display the measured data along with linear fits, showing the change in the electrical offset (EOS) for the two power settings. The data also indicates a tilt between quadrupole QDR0800 and our BPM in the order of 5 mrad for the horizontal plane and 7 mrad for the vertical plane.

Table 1: Linearity and Sensitivity Parameters

Parameter	BEAM 6	BEAM 60
V sensitivity S_V (m^{-1})	72.4±1.8	75.3±0.6
H sensitivity S_H (m^{-1})	98.1±1.7	94.2±1.4
V offset EOS_V (mm)	-1.76±0.07	-1.91±0.02
H offset EOS_H (mm)	0.24±0.05	0.46±0.04
V RMS lin. error (µm)	250.42	92.73
H RMS lin. error (µm)	182.87	120.00
I_{beam} (A)	10	22
t_{pulse} (ns)	240	140

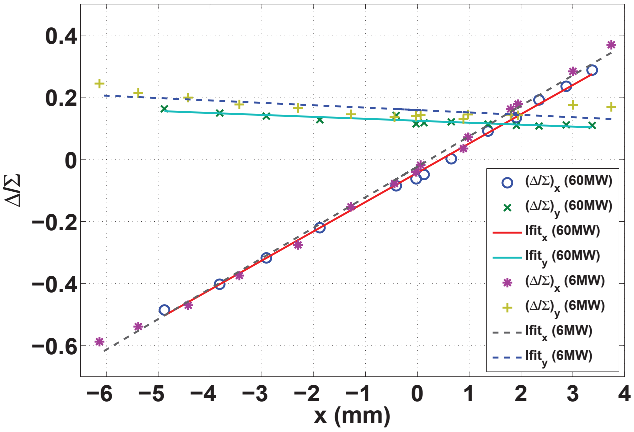

Figure 4: Dependency of the difference-over-sum ratio on the beam displacement in the horizontal plane for PETS RF power values of 6 MW (dashed lines) and 60 MW (solid lines).

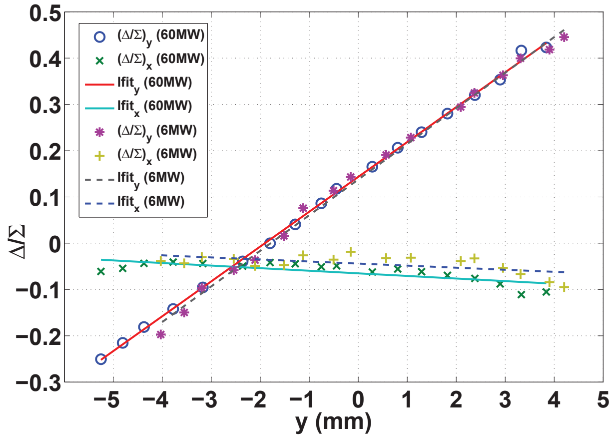

Figure 5: Dependency of the difference-over-sum ratio on the beam displacement in the vertical plane for PETS RF power values of 6 MW (dashed lines) and 60 MW (solid lines).

Resolution

Currently the prototype electronics have not been integrated into the control and timing system of CTF3, so we were unable to synchronise shot-by-shot data to the other 16 BPMs in the beam-line, thus to entangle beam motion from the residual noise systematics of the BPM. Simply analysing the RMS value of 85 consecutive beam shots gives an upper resolution limit of 43.3 µm and 54.9 µm for the horizontal and vertical planes, respectively. These values are consistent with the analysis of the neighbouring BPMs: BPS0850, 64.2 µm (H) and 80.9 µm (V), and BPS0910, 73.3 µm (H) and 66.9 µm (V).

MODIFIED STRIPLINE BPM DESIGN

The first 4-port stripline BPM prototype, as presented in the previous section, is not providing the expected transfer response of an ideal stripline BPM. The discrepancy is particularly large at high frequencies, also due to geometry constraints as described in [4], and as a result this BPM with short-circuited stripline electrodes at their downstream end provides insufficient filtering at the 12 GHz CLIC DB beam harmonics. In order to improve this issue, a modified version with downstream terminated electrodes, thus 8 ports, has been developed. It provides an improved suppression of unwanted 12 GHz RF signals, while offering a loop-thru calibration with test signals using the downstream ports.

The impulse response of an ideal stripline BPM (Fig. 6) is a pair of pulses of opposed polarity delayed $2l/c_0$, where l is the electrode length and c_0 is the speed of light in vacuum. In the frequency domain, the transfer response will be given by (1):

$$H(\omega) = je^{-j\frac{\omega l}{c_0}} \sin\left(\frac{\omega l}{c_0}\right) \qquad (1)$$

The minima (notches) of its magnitude will be located at multiples of $c_0/2l$ and its maxima at odd multiples of $c_0/4l$, as shown in Fig. 6.

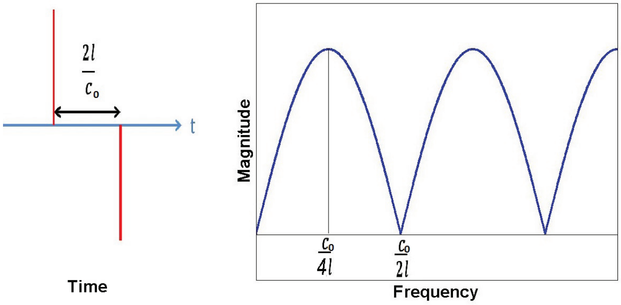

Figure 6: Stripline BPM impulse response (left) and transfer function (right).

In this approach we tried to optimize the geometry within the given real estate to achieve a decent transfer response, i.e. an effective notch filter effect at 12 GHz. This was achieved by optimizing the physical length of the electrode such that the 3rd notch of the stripline pick-up transfer response hits this frequency. This solution seemed to be the best compromise, as optimizing on the 1st or 2nd notch results in a quite short physical length of the electrode, having a similar dimension as the beam pipe diameter, which causes unwanted resonances [4].

Operating the BPM with a stripline length of l=37.5 mm in the CTF drive beam with a bunching period of 83.33 ps results in a time delay of 3x83.33 ps = 250 ps between the direct and the reflected BPM signals The ideal response to a multi-bunch train will then only show the first and last triplets of bunches, the signals from all other bunches in-between will cancel, assuming the notch filter effect is perfect and precisely tuned to 12 GHz (Fig. 7). Table 2 compares the relevant design parameters and dimensions for this new prototype and the initial design.

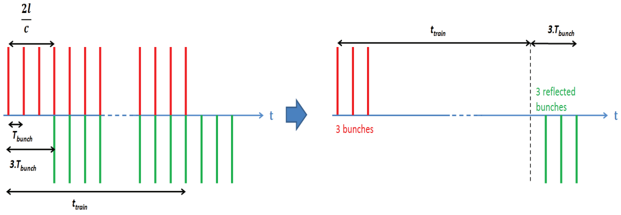

Figure 7: Multi-bunch train response of the modified prototype.

Table 2: CLIC Drive Beam Stripline BPM Parameters

Parameter	**Shortened BPM**	**Terminated BPM**
Stripline length	25 mm	37.5 mm
Angular coverage	12.5 % (45°)	5.55 % (20°)
Electrode thickness	3.1 mm	1 mm
Outer radius	17 mm	13.54 mm
Ch. Impedance	37 Ω	50 Ω
Duct aperture	23 mm	23 mm
Resolution	2 µm	2 µm
Accuracy	20 µm	20 µm
Temporal resolution	10 ns	10 ns

The signal processing scheme from the first design (operating at baseband frequencies, ranging from 4 to 40 MHz, to stay well separated from the microwave PETS frequency), can be reused with minor adjustments in the attenuation and gain stages of the readout electronics. A thorough description of the acquisition system and further details of the design can be found in [3] and [4].

Geometry Considerations

Similarly as in the first prototype [1], it is necessary to damp a strong resonance peak of the transverse wake impedance observed in EM simulations around 12 GHz. A ring of SiC has been placed at each end of the striplines, separated from their rounded end by a narrow gap (Fig. 8, right). However, while successfully damping higher order modes (HOMs), the dielectric ring also increases the electrical length the stripline electrodes, thus shifts the notches to lower frequencies. Therefore, to obtain the desired frequency behaviour with electrodes of 37.5 mm physical length, the distance between the upstream and downstream port pins was reduced to 36.6 mm, which compensated the lengthening effect of the SiC dampers.

As Figure 8 shows, the stripline electrodes of the terminated design are less wide (20^0 vs. 45^0 coverage) to ensure a TEM-like field propagation, which reduces

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unwanted spurious resonances and results in an improved transfer response (see Fig. 11). Evidently, the coupling of these narrow striplines to the beam is reduced by ~8 dB, which is not an issue as of the high beam current in the drive beam.

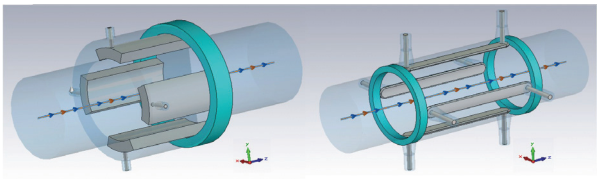

Figure 8: Initial (left) and modified (right) stripline BPM prototypes for CLIC DB.

A conical transition between electrode and coaxial feedthrough was included in the new BPM design (Fig. 9). This improved the return loss without altering the frequency response. While changes in the radius of the cone base causes a slight frequency shift in the transfer function, the appropriate height of the cone allows to optimize for the best 50 Ω impedance matching compromise, i.e. minimize the reflections in a Time Domain Reflectometry (TDR) as shown in Fig. 10.

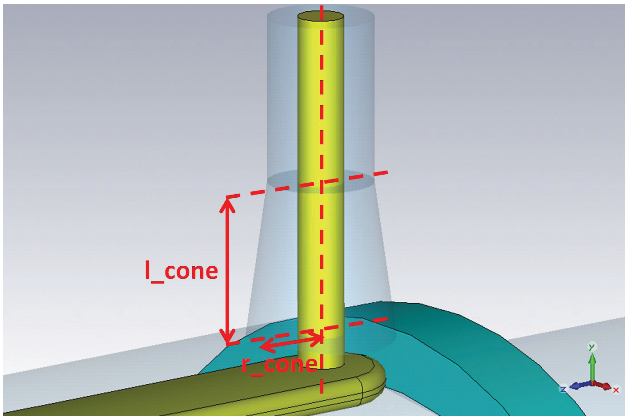

Figure 9: Transition region to the coaxial feedthrough.

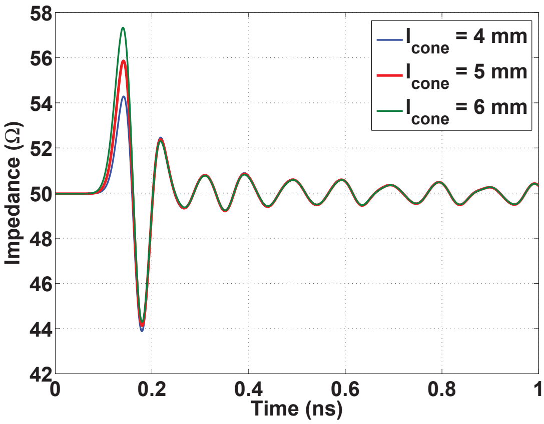

Figure 10: Effect of the conical transition height in the impedance matching.

In contrast to the prototype with shortened electrodes, the frequency response of the modified pick-up (Fig. 11) resembles that of an ideal stripline BPM up to higher frequencies (~8 GHz). An unavoidable resonance appears around 10 GHz, which seems to be caused by the TM_{01} waveguide mode of the vacuum chamber [4]. However, a substantial notch effect at 12 GHz is still present, and should improve the suppression to the PETS high power RF fields.

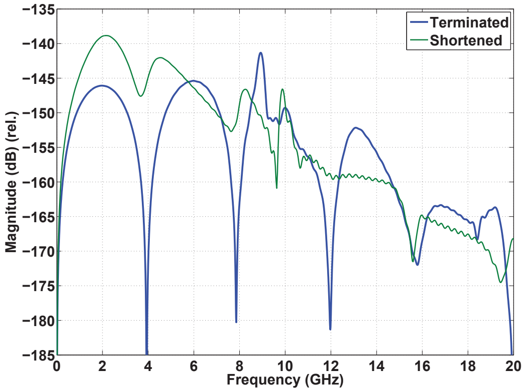

Figure 11: Shortened (green) and terminated (blue) Drive Beam Stripline BPM Frequency Response.

CONCLUSIONS

A first stripline BPM prototype with downstream terminated electrodes and its acquisition electronics have performed satisfactorily during the beam tests at CTF3, providing the expected output signals and levels and the foreseen radiation-hardness. In the presence of high power RF interferences from the PETS, a small effect in the offset was observed, which seems to be caused by insufficient suppression of 12 GHz CLIC RF fields. This problem has been addressed by the development of a new stripline prototype with improved notch filter effect at 12 GHz, providing also the possibility of loop-thru calibration via the downstream ports.

The performance of both prototypes will be tested under beam conditions at CTF3, and compared to EM simulations of a coaxial cavity BPM.

ACKNOWLEDGMENT

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