PRECISION BEAM POSITION MONITOR FOR EUROTEV*

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Abstract

In the framework of EUROTeV, a Precision Beam Position Monitor (PBPM) has been designed, manufactured and tested. The new PBPM, based on the inductive BPM presently used in the CERN CLIC Test Facility (CTF3), aims to achieve a resolution of 100 nm and an accuracy of 10 μm in a 6 mm aperture. A dedicated test bench has been designed and constructed to fully characterize and optimize the PBPM. This paper describes the final design, presents the test bench results and reports on the beam tests carried out in the CERN CTF3 Linac.

INTRODUCTION

The resolution and precise alignment of the BPM's are important parameters for future linear colliders since they affect the emittance growth of the beam. For example, for CLIC, the PBPM's will be in charge of monitoring the beam position along a 150 ns pulse to control the beam stability in the main beam LINAC. Minimum one BPM per quadrupole is foreseen for this task, i.e. 4200 BPM's in total.

28 European institutes participated in a Design Study (DS), within the frame work of EUROTeV, for a Linear Collider in the TeV energy range, ILC. Within the same context, the DS has also supported, in part, critical R&D for a possible multi-TeV facility i.e. CLIC. EUROTeV work package 5 (WP5) contains several different types of monitors, among others Beam Position Monitors (BPM). The deliverables for the PBPM as defined by EUROTeV are: to design and build a prototype [2]; to report on bench tests [4] and to report on beam tests [6].

DESIGN

Introduction

The PBPM is based on the pickups developed for CTF3 [1]. In this case, the aperture of the vacuum chamber is smaller, 6 mm, which leads to a more compact BPM. The position readout is based on the differential measurement of the image current flowing on four strip electrodes, located outside the vacuum chamber, each with a current transformer around one end. The transformers convert the image current of each electrode to voltages in a secondary 25 Ω load. The four voltages are then transformed to difference and sum signals in front-end electronics, from which beam positions are calculated. The pickup is calibrated with a pulsed current source using a single calibration turn on each current transformer. The design of the PBPM was optimized by the use of 3D electromagnetic microwave simulators. The geometry of the electrodes, the body and the ferrite was optimized in order to reach the required low frequency cut-off. The main parameters are listed in Tab. 1.

Mechanics

The pickup consists of a stainless steel vacuum chamber, of 6 mm diameter, with an insert made of alumina of 2 mm thickness and 51 mm long. The vacuum assembly is bypassed by four copper electrodes (Ø=13 mm), separated azimuthally by a gap of 3 mm. At one end the electrodes are connected to the vacuum chamber with a copper beryllium screw surrounded by the VITROVAC current transformer with μ≈50000. An external copper body shields the pickup against electromagnetic interference. A ferrite tube with μ≈100 fills the space between the electrodes and the body. On one end of the vacuum chamber bellows allow the correction of possible misalignments during manufacturing and installation. The external body has reference surfaces for the installation of alignment targets.

Vacuum Chamber

To minimize the effects of the pickup on the beam, the internal surface of the ceramics is coated with a titanium layer [1, 3]. Magnetron sputtering techniques have been successfully applied to bigger ceramic tubes, but here the plasma providing the ions for the sputtering process has to be maintained in a limited space between cathode and chamber walls (<3 mm space). For the coating of the PBPM ceramics chamber, this was achieved with an unusually high magnetic field of up to 0.3 T. The longitudinal thickness distribution of the coating depends on the magnetic field homogeneity, and in consequence the plasma density along the axis of the ceramic. A special coil was built based on simulations which took into account the magnetic properties of the KOVAR collars brazed on the ceramic. In practise, the plasma density and thus the coating thickness varied close to the Kovar collars. To overcome this issue, the design of the pickup was changed and stainless steel collars were welded to the ceramics. Finally, the resistive coating was controlled to obtain uniform values between 10-15 Ω. However, for a better control of the uniformity of the coating, the setup of the magnetic field should be optimized.

Table 1: Summary of Specifications of the PBPM

Ceramic diameter/ coating resistance	6 mm/ 14.6 Ω
Ceramic thickness	2 mm
Electrode length / diameter	50 mm / 13 mm
Length assembly / with bellow	70 mm / 95 mm
Gap between electrodes	3 mm
Transformer load / turns number	25 Ω / 30

Electronics

The current transformers are located inside the PBPM on a PCB which also contains the I/O terminals. The signals are then processed in a front-end amplifier near the accelerator and the difference and sum signals transmitted for processing to the control room. The difference and sum signals are constructed on the front-end amplifier using differential amplifiers LT6402-20. With straight difference over sum signal processing, the position resolution is limited by the Common Mode Rejection Ratio (CMRR) in the bandwidth of interest and the thermal noise of the electronics. The prototype amplifier constructed for the PBPM provides 80 dB CMRR @ 10MHz, and an equivalent input noise of 2.2 nV/$\sqrt{\text{Hz}}$. Around the center, any common mode signal in quadrature phase (capacitive coupling) with the position signal will reduce the sensitivity of the pickup to zero, in a region proportional to the magnitude of the common mode signal.

TEST BENCH MEASUREMENTS

Procedure and Hardware

A complete test bench setup was designed to characterize the pickup. The test bench is mounted on a honeycomb table with air cushion damping to minimize vibrations. The sensitivity, resolution and linearity were measured with the use of a thin 0.1 mm wire. In those tests the wire was displaced in the two orthogonal directions using micro-movers with 100 nm resolution. The measurement of the linearity, sensitivity and resolution of the pickups was controlled by Labview software. All parameters were measured both in frequency and time domain.

Linearity, Sensitivity and Resolution

For the frequency domain measurements the wire was excited by a network analyzer using a single frequency of 10 MHz and 25 dBm. The tuned filter of the receiver (3kHz BW) was used to measure magnitude and phase responses of the PBPM. The resolution measurements were then scaled to a 30 MHz bandwidth. In time domain a square pulse of 100 mA and 200 ns length was used to simulate the CLIC beam pulse, and the PBPM responses were measured by an oscilloscope having a bandwidth limitation of 25 MHz. The time and frequency domain resolution measurements agree. All measurement results are summarised in Tab. 2. Figure 1 shows a typical ±400 µm sensitivity scan in horizontal and vertical. The linearity error is below 2% in the worst case. The non-linearity in the centre is due to a quadrature common mode signal originating from the PBPM itself and not the front-end electronics. The source of this common mode signal is not yet understood.

Electrical Centre

To complete the characterization of the pickup, the offset of the electrical centre of the PBPM was measured with respect to the mechanical centre. For this measurement a precise rotary motor was used to find the discrepancy on the electrical centre position after 180º movements [4]. In the first tests the electrical offset was found to be very high ~50 µm. After failed attempts to optimize the wobble and alignment of the PBPM on the rotary stage, the reason turned out to be the misalignment of the current transformers to the centre of the electrode screws. Position dependent capacitive coupling between the screws and the windings is the most plausible explanation of this effect. By adjusting the position of the current transformers the electrical offsets, and thus the measured accuracy, was reduced to 1 µm.

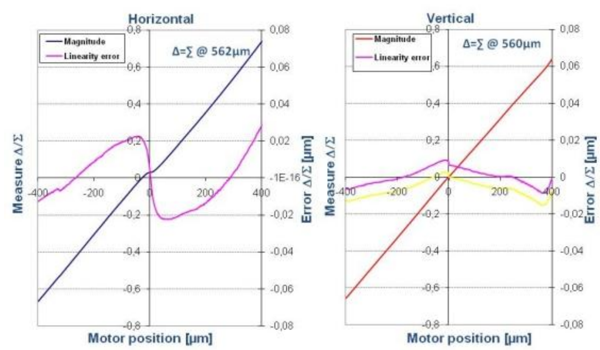

Figure 1: Phase corrected magnitude of Δ/Σ. Sensitivity and linearity error of the PBPM in a ±0.4 mm range.

Table 2: Summary of the test bench measurements of the PBPM in frequency domain using a 10MHz, 25 dBm, CW sine wave.

Resolution test bench	36 nm
Resolution CLIC	190 nm
Resolution ILC	5.2 µm
Linearity error (±400 µm)	1 %
Electrical offset	1 µm
Sensitivity	11.9 mm × Δ/Σ
Δ low frequency cutoff	300 kHz
Σ low frequency cutoff	5 kHz
High frequency cutoff	80 MHz
24H stability	2 µm

Longitudinal Impedance

To optimize the transmission of the setup at high frequencies, a 50 Ω coaxial setup was used. The matched setup was used for the measurement of the S-parameters of the PBPM and a reference test system. From those parameters the longitudinal impedance of the PBPM was calculated [5]. In addition, the longitudinal impedance of the PBPM was simulated using SPICE simulations with the geometrical parameters of the PBPM [3]. Figure 2 shows the comparison of the measured and simulated longitudinal impedance. The agreement is good up to 2-3 GHz, from where reflections in the setup dominate the measured response.

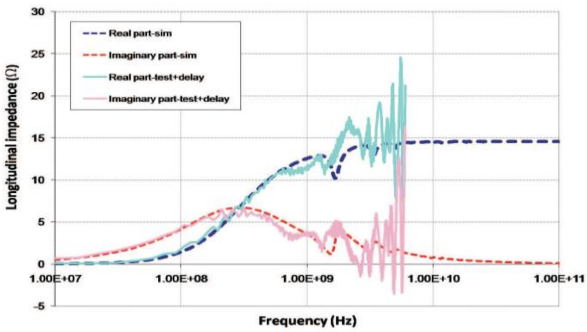

Figure 2: Plot of the measured and simulated longitudinal impedance of the PBPM with a coating of 14.6 Ω.

BEAM TESTS

To estimate the resolution of the PBPM with beam, a suitable location in the CERN CTF3 Linac was identified, in the straight part of the magnetic chicane used to optimise bunch lengths. This gave the possibility to leave the PBPMs in place, with a 6 mm aperture compared to the Linac 40 mm aperture, without disturbing normal operation.

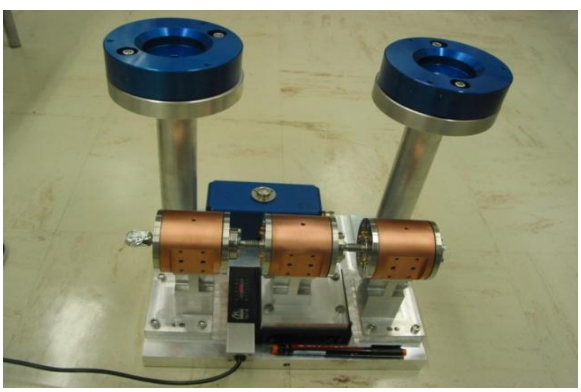

Figure 3: PBPM triplet for resolution measurement.

Beam Jitter

The jitter of the CTF3 beam is quite high compared to the resolution of the PBPM. It has been estimated to be in the order of 100-200 µm and consist of both position and angle jitter. It is possible to disentangle these by using three PBPM's [7], where the first and last PBPM's are used to calculate the expected position at the centre PBPM, by linear interpolation.. The calculated position and measured position, on PBPM2, can be shown in a correlation plot as:

$$\text{Graph (x,y)} = \left(\frac{Pos1 + Pos3}{2}, Pos2\right)$$

The width of the resulting line σ_{res} is proportional to the resolution σ_{PBPM}, as given by [6]:

$$\sigma_{PBPM} = \frac{\sigma_{res}}{\sqrt{1.5}}$$

Results

Three PBPM's were manufactured, tested and installed in CTF3. The setup includes an accelerometer which enables observation of vibrations, lead blocks for radiation shielding and alignment targets. After passage through the three PBPM's the beam was dumped on an iron block. After the initial beam tests a 40 mm diameter BPM was added before the dump in order to have an independent current measurement after the PBPM triplet. A photo of the three PBPM's before installation can be seen in Fig. 3.

Several beam tests were carried out during the year 2008 with the high resolution triplet installed in CTF3. First beam tests gave very poor transmission efficiencies, which was caused by the absence of titanium coating on the inside of the second and third PBPM. The high frequency components were no longer bypassed via the resistive layer and saturated the current transformers.

Three new vacuum assemblies with titanium coating were manufactured, and an equivalent CLIC beam (1.5 A, 150 ns) resolution of **650 nm** was measured in the horizontal plane. The vertical plane was perturbed by the beam losses (10%), and the measured resolution was measured as **1.9 µm**.

CONCLUSION

The inductive PBPM developed for EUROTeV has shown promising results. A 190 nm resolution has been measured on the test bench and 650 nm with beam. It is believed that beam losses are still limiting the measured resolution especially in the vertical plane, and it is therefore foreseen to continue the tests in order to obtain loss free transmission in all three PBPM's. The 10 µm absolute accuracy needed, is still not obtained for larger scale productions and a residual common mode signal, originating from the PBPM itself, reduces the sensitivity to zero in a region of a few micrometers around the center.

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