PRECISION BEAM POSITION MONITOR FOR EUROTEV

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Abstract

For future linear colliders (ILC, CLIC) a new Precision Beam Position Monitor (PBPM) has been designed within the framework of EUROTeV. The design goals are a resolution of 100nm and an overall precision of 10µm, in a circular vacuum chamber of 6mm in diameter. The required frequency bandwidth is 100kHz-30MHz. The PBPM is based on an inductive type BPM [2]. Beam positions are derived from the difference between the image currents created by the electron beam into four strip electrodes surrounding the vacuum ceramics insert. In this paper, the design of the PBPM is presented together with first bench measurements, where two micro movers and a rotational stage, installed on a vibration damped table, have been used to characterize the PBPM.

INTRODUCTION

28 European institutes are participating 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 will also support, 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 as defined by EUROTeV are: to design and build a prototype; to report on bench tests and to report on beam tests. The design and construction of the prototype PBPM is reported in [1]. The bench tests have started and preliminary results are reported in this paper. The complete results will be published soon in a EUROTeV report. Beam tests are foreseen for autumn 2007 in the CERN CLIC test facility (CTF3). Table 1 lists the beam parameters of ILC, CLIC and CTF3 at the Combiner Ring (CR) exit.

General Description

The inductive BPM which is based on a design developed for CTF3 [2], has a length of 95 mm (including the bellow) and a external diameter of 68mm and the diameter of the vacuum chamber is 6 mm for this first prototype. A schematic drawing can be seen in Fig. 2.

A ceramic insert forces the image current to pass through the four electrodes placed orthogonally to the horizontal and vertical planes. The position dependant image currents are guided through four current transformers, which transform the currents to voltages in an external resistive load. From these voltages, difference and sum signals are generated in the front end electronics, from which the beam positions are calculated. The sum signal can be used as a true current measurement since all of the image current in the frequency bandwidth of interest pass through the electrodes. A single calibration winding on the current transformers, enables calibration of position and current measurements.

Table 1: Beam Parameters

	CTF3 (CR)	ILC	CLIC
Energy	184 MeV	0.5-1 TeV	0.5-6 TeV
Pulse length	140ns	950us	207ns
Bunch spacing	67ps	300ns	667ps
Bunch length	1.67ps	1ps	0.1ps
Charges/bunch	$1.5 \cdot 10^{10}$	$2 \cdot 10^{10}$	$4 \cdot 10^{9}$
Nb. of bunches	2100	2820	310
$I_{average}$	35A	9.5mA	1.5A

MECHANICAL DESIGN

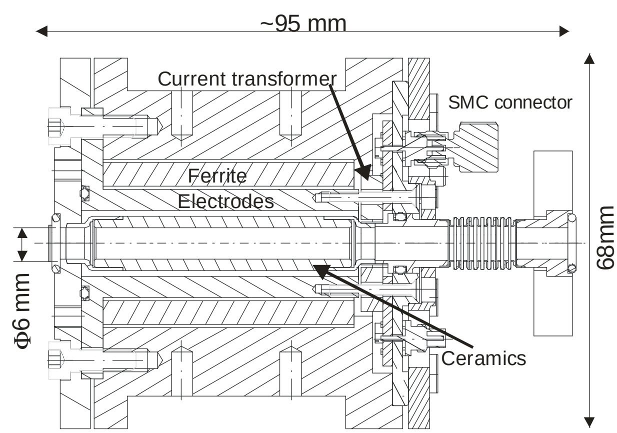

Figure 1: PBPM schematic.

Vacuum Assembly

The 6mm internal diameter vacuum assembly consists of a ceramic tube onto which 2 collars have been brazed. One end is electron beam welded directly into the bottom flange (Fig. 1). On the other end an intermediate piece, a bellow and a rotational DN16 flange are also electron beam welded to the ceramic assembly.

In order to minimize the longitudinal impedance above 100MHz, the inside of the ceramic tube must be coated with a resistive layer (5 Ω/□) [1,3]. At present titanium coating using the sputtering technique is being tested. A precise value of the overall resistance must be obtained, with good uniformity. Coatings inside dummy ceramic tubes could be obtained with the desired accuracy by a magnetron sputtering coating process, adapted to the very small diameter of the pieces. However coating inside the definitive pieces is at present hindered by the presence of the brazed collars which are made of a soft magnetic alloy which modifies the field lines of the magnetron system. To overcome this problem (without changing the collar material) a modification of the magnetron system has been designed and will soon be tested.

Electrodes

The electrodes are made of copper and they are machined in one single piece. The length of the strip electrodes is 51 mm, the inner diameter is 13mm and they are 3.5mm thick. Three sets of electrodes have been manufactured with electrode apertures of 60º, 70º and 80º, in order to measure the influence of electrode width on the linearity and sensitivity. The image currents are guided through the current transformers with the help of M2 beryllium copper screws, which are screwed into the end of the electrodes.

Current Transformers

Four small current transformers are used to transmit the image currents to the external circuit. VITROVAC cores W650 (6.6 mm of external diameter, 3.5 mm inside and 2 mm thickness) are used. These transformers have a large magnetic permeability ($\mu \approx 50000$) which produces a very good low frequency response. In addition, the small size of the transformers increases the high frequency response due to the capacitive coupling between the windings. A frequency bandwidth of 100Hz-100MHz, i.e. 6 decades, has been obtained, with 30 turns and 50Ω secondary load.

Ferrite

The ferrite which surrounds the electrodes in order to decrease the low frequency cut-off of the sum signal, is a cylindrical piece made by Ceramics Magnetics. The material is C2050 and has a magnetic permeability around 100, constant with the frequency band of the PBPM.

ELECTRONICS

PBPM

To minimize the noise effect and reflections in the PBPM, the four current transformers are mounted on a dedicated PCB installed close to the electrodes. Each current transformer incorporates a single calibration turn and a secondary winding of N=30 turns. The PCB also contains the connections for the beam and calibration signals. Two different low cutoff frequencies can be distinguished, one for the difference signal, $f_{L\Delta}$ and another for the sum signal, $f_{L\Sigma}$ [1].

$$f_{L\Delta} = \frac{1}{2 \cdot \pi \cdot L_{\Delta}} \left(\frac{R_S}{n^2} + R_C \right) \tag{1}$$

$$f_{L\Sigma} = \frac{1}{2 \cdot \pi \cdot L_{\Sigma}} \left(\frac{R_S}{n^2} + R_C \right) \tag{2}$$

where L_Δ is the inductance of a strip electrode, R_S is the secondary winding load of the transformer and R_C the parasitic connection resistances of the primary loop. The inductance L_Σ is calculated with the loops, filled with ferrite, made of the electrodes and the body walls.

Difference Amplifier

The required resolution of the pick-up, 100 nm, is limited by the Common Mode Ratio Rejection (CMRR) and thermal noise of the electronics. The required CMRR for the PBPM in the frequency range 100kHz - 30MHz can be identified as:

$$CMRR \geq 20 \cdot \log\left(\frac{6\text{mm}}{100\text{nm}}\right) = 95\text{dB} \tag{3}$$

The prototype differential amplifier developed for the PBPM has a CMRR of 80dB in the frequency range of interest. It is very difficult to measure CMRR in this range and especially the phase of the common mode (CM) signal. The part of the CM signal which is in phase (or anti phase) with the difference signal will not limit the resolution but only introduce an electrical offset. CM residuals with 90º phase shift with respect to the difference signal will reduce the amplitude sensitivity to zero in the electrical centre in a range $R \approx d/CMRR$ where d is the internal diameter of the strip electrodes, see figure 2. If a narrow bandwidth acquisition system is used (single frequency), measuring the real part of Δ/Σ eliminates this problem.

A total thermal noise (ΔV_{Noise}), coming from the secondary 50 Ω load and the active difference amplifier, of $3\text{nV}/\sqrt{\text{Hz}} = 16\mu\text{V}$ in a bandwidth of 30 MHz, will be superimposed to the beam pulse induced signals (V_B) and limit the resolution. With sufficient gain the ADC quantisation noise can be ignored and the maximum resolution is given by:

$$\Delta_H / V_{Noise} = k_{XY} \frac{\sqrt{2} \cdot \Delta V_{Noise}}{V_B} \tag{4}$$

Where k_{xy} are the transverse sensitivities ≈ 8mm. For a CLIC beam current of 1.5A and thus a V_P=2.5V the resolution due to thermal noise would be 72nm. In the case of ILC a Bessel filter is necessary to dilute in time the single 1ps bunch before sampling. After filtering a single bunch will generate a 60ns Gaussian pulse with $V_p \approx 160$ mV, which will result in a resolution of 1.1µm. Higher sampling rate and a filter with higher bandwidth will increase the resolution.

TEST BENCH MEASUREMENTS

System Description

To measure the linearity, resolution and long term stability of the PBPM system, two linear micro movers with a resolution of 100nm and a maximum displacement of 25mm have been mounted on a vibration damped table. On top of them a rotational stage is mounted in order to measure the relative offset between the electrical and mechanical centre using a 180º rotation. A Wire

Position System (reference) is attached to the PBPM in order to verify the movement of the motors. Temperature monitoring as well as vibration measurements using a geophone, are also part of the system. A fixed wire is stretched through the PBPM and terminated in 50Ω. The whole setup is screened with a Plexiglas box in order to avoid any wire movements due to air draft. Time domain measurements using a pulse generator and an oscilloscope and frequency domain measurements with a network analyzer have been carried out. In both cases a current of 100mA on the wire is supplied to simulate the beam and results are scaled to CLIC and ILC beam currents. Motor control and acquisition of measurements are done with the help of Labview programs.

Table 3: Frequency Domain Results

Linearity error [±500µm]	1%
Electrical offset	50µm
Sensitivity Δ=Σ (10 MHz, 3mm gap)	11.5mm
Meas. Resol. (100mA, 3kHz BW)	σ_H=28nm, σ_V=52nm
Resolution CLIC	σ_H=180nm, σ_V=350nm
Resolution ILC	σ_H=2.8um, σ_V=5.5µm
Bandwidth Δ	300kHz-80MHz
Bandwidth Σ	5kHz-80MHz

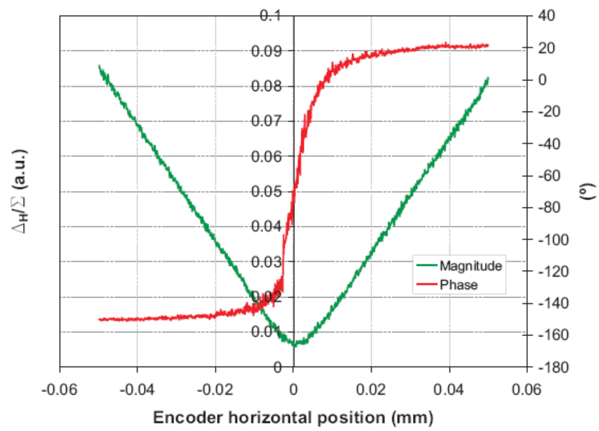

Figure 2: Sensitivity measurement in a ± 50µm range.

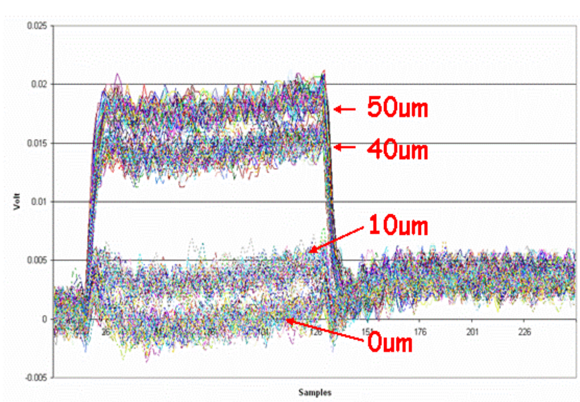

Figure 3: Resolution measurement in time domain.

Frequency Domain Measurements

All of the PBPM characteristics have been measured in frequency domain. For linearity, sensitivity, resolution and electrical offset a single frequency of 10MHz have been used. For the resolution measurements the results are then scaled to a 30MHz bandwidth. The results are resumed in table 3. Fig. 2 shows a ± 50µm sensitivity scan and clearly shows the zero sensitivity of the magnitude around the centre in a range of ± 1µm. In this range the phase could be used to estimate the position.

Resolution in Time Domain

Time domain measurements, using a 200ns 100mA pulse to simulate a CLIC type beam has been done in order to measure the resolution. In figure 3 the PBPM response is seen for 4 different wire positions. The estimated standard deviation of 100 measurements is 2.5µ for a 100mA current, which corresponds to 170nm for the CLIC 1.5A beam. This is in perfect agreement with the network analyser measurements.

CONCLUSION

A high resolution inductive BPM has been designed and preliminary tests have been made using an active damped high resolution test bench. Measurements made with a network analyser using a single frequency have been used to characterise the PBPM. The resolution has been verified in time domain using a pulse generator and an oscilloscope. The measured resolution for CLIC is different for the two planes (180nm/350nm) and is ~ 3-4 times bigger than calculated one. The reason for this is not yet understood. The front end electronics used in the tests had a CMRR of ~80dB and this must be further improved to increase the sensitivity in the centre. The relatively big electrical offset is due to lack of precision in the alignment of the PBPM on the rotational stage. Improvement of this will be studied.

REFERENCES

[1] I. Podadera, L. Søby, Design of a Precision Beam Position Monitor (PBPM) for EUROTeV. EUROTeV-Report-2007-008.

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[3] M. Gasior, Limiting high frequency Longitudinal impedance of an inductive pick-up by a thin metallic layer, EPAC'2004, Lucerne, Switzerland.