Test bench characterization of the Precision Beam Position Monitor (PBPM) 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’s presently used in CTF3, aims to achieve a resolution of 100 nm in a 6 mm aperture. A dedicated test bench has been designed and constructed to fully characterize and optimize the PBPM. The present document describes the solution which was adopted for the test bench and reports the test bench results of the PBPM using the wire method.
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1 Introduction

The new Precision Beam Position Monitor (PBPM) for EUROTeV [1], has been manufactured and fully characterized in a dedicated test bench before installation in the machine for beam tests. Due to the challenging requirements of the PBPM, e.g. a time domain resolution of 100 nm and an accuracy of 10 µm in a bandwidth from 100 kHz to 30 MHz, the test bench is subjected to tight tolerances. The setup is thus optimized to damp the ground vibrations and minimize the mechanical deformations induced by thermal changes.

![Figure 1](image)

**Figure 1:** Section of the PBPM assembly. The main components and dimensions are indicated.

In Figure 1 a section of the PBPM is shown. The body, electrodes and the vacuum chamber are all connected to ground in both ends. For very low frequencies the image current runs through the body while at mid frequencies the reactance of the electrodes is smaller than the body reactance, and the image current will take this path. For frequencies above the band of interest (> 100MHz) the resistance of the ceramic coating (10 Ω) is lower than the electrode reactance, and will thus be the preferred path for the image current. In this way the the longitudinal impedance is limited for high frequencies.

Figure 2 shows a photo of the assembled PBPM.
Figure 2: Photo of the assembled PBPM.

Figure 3 sketches the electrodes of the PBPM and the way the differential and sum signals ($\Delta_{H,V}$ and $\Sigma$) are calculated. In this report, the test bench setup is presented and the results of the main parameters of the PBPM are analyzed and compared with the specifications.

$\Delta_H = H^+ - H^-$
$\Delta_V = V^+ - V^-$
$\Sigma = H^+ + H^- + V^+ + V^-$

Figure 3: Sketch of the electrodes and the output signals of the PBPM.
2 Test bench setup

The design of a test bench able to measure with sufficient reliability the features of the PBPM prototype is challenging. To verify the required accuracy and resolution, it is necessary to mount the test bench on a vibration damped table. The goal is to damp the vibrations above 5 Hz to less than 100 nm. Even if the pick-up and the measurement tools are well assembled, the presence of high frequency sources could excite mechanical modes and the structure could start vibrating and perturb the measurements. In the CLIC design study, all the supports are damped, actively pre-aligned [2] and finally aligned using the ballistic alignment method [3].

Depending on the type of measurement, two different setups have been developed: a thin wire for linearity and sensitivity measurements, and a 50 Ω wire setup for coupling impedance tests. Both methods are based on the well-known wire excitation method [4], where a central wire simulates the TEM mode of the beam. A further description of both setups is given in the following sections.

2.1 Linearity, sensitivity and electrical offset measurements

The test bench will be used to verify the position and intensity linearity, as well as the resolution. This can be done by exciting the PBPM with a wire and measure its response at several positions. The relative position of the wire must be known with high accuracy and the movement needs to have a resolution of 100 nm or less. The PBPM is attached to two linear precision micro movers (mounted perpendicularly) and a rotary motion system. This combination of motors provides the following performances:

- PBPM rotations of 180° around the mechanical axis (for offset measurement) with a resolution of 0.03 mrad.
- Linear step motions along the horizontal and vertical axes with a minimum step size of 100 nm over a range of 6 mm.
- Independent movements along the horizontal and vertical direction to verify the coupling between the planes.

A small wire of φ 0.1 mm was used for these measurements. A draft of the proposed scheme is pictured in Fig. 4.

The PBPM and the wire simulating the beam are mounted vertically. In this way, the bending of the wire due to the gravity is minimized. Figure 5 shows a comparison of the simulations of the effect of the gravity on a copper wire if this is placed vertically or horizontally. The diameter of the wire is bigger for these simulations φ 2.6 mm (50 Ω-setup) and the length is 300 mm. The vertical installation reduces the total deformation at the center of the wire by a factor of $10^4$.

To minimize the measurement errors due to the mechanical vibrations, it was decided to move the PBPM assembly instead of the wire. The misalignment between the mechanical and the electrical centers can be also measured in the test bench by the method outlined later and detailed in [5].
Figure 4: Scheme of the main components of the PBPM test bench.

Figure 5: Simulation, using the ANSYS code, of the deformation due to the gravity of a copper wire in vertical or horizontal position. The maximum deformation at the middle of the wire is marked for both situations.
Figure 6 shows the components of the test bench. The vibration level on the honeycomb table is monitored using a geophone. The micro movers (horizontal $x$, vertical $y$ and rotation, shown in red in the figure) and the signal monitoring is governed by a PC using LABVIEW. The room temperature is also monitored with a thermistor connected to a digital multimeter.

In order to verify the precision of the micro movers a Wire Position System (WPS) [6] has also been installed in the assembly, directly attached to the PBPM (Fig. 6).

![Figure 6: Pictures of the test bench: the PBPM which is attached to the motion stages, the wire which is supported by a frame attached to the honeycomb table. The main components and the degrees of freedom of the assembly are shown.](image)

2.2 Impedance measurements

The setup used for the sensitivity and linearity tests is not well adapted for high frequency analysis like the coupling impedance. For such a tests, another setup was designed (Fig. 7). Like for linearity measurements, it consists of a center wire which
simulates the TEM mode of the electron beam. However, in this case the diameter of the wire forms a 50 Ω coaxial line with the vacuum pipe of the PBPM. The impedance of the setup is then well matched with the external excitation, and wave reflections at high frequencies are minimized [7]. Unlike the linearity tests, here the wire is fixed and measurements are only possible at the center of the PBPM. In order to compute the coupling impedance two transmission measurements are necessary. One with a reference tube and another with the PBPM.

Figure 7: Picture of the setup to determine the coupling impedance of the PBPM up to high frequencies. The diameter of the excitation wire is chosen to form a 50 Ω transmission line with the PBPM.

3 Electronics

3.1 Signal generators

3.1.1 In frequency domain

To predict with precision how the PBPM will behave when excited by the beam, several measurements were carried out in the frequency domain. Properties like resolution, linearity and sensitivity of the PBPM are measured more easily with a sinusoidal wave of one single frequency component as excitation. The Hewlett Packard HP8753C network analyzer is used in the bench tests using a 10 MHz, 25dBm (80 mA), CW signal as wire excitation, and to measure the PBPM S-parameter responses.
3.1.2 In time domain

A pulse generator was used to drive a 5 V, 100 mA (50 Ω) signal to the wire simulating the beam excitation, and an oscilloscope was used to measure the PBPM response.

3.2 New head amplifier

To achieve the high requirements of beam position resolution of the PBPM, it was necessary to develop a new Low Noise Amplifier (LNA) with optimized CMRR within a bandwidth up to 30 MHz.

Figure 8 shows the ∆H,V and Σ frequency response, and the amplified CMRR obtained with the new electronics. Up to 85 dB of CMRR are achieved at 10 MHz, which is close to the specified requirements. Unfortunately such a high CMRR is difficult to control and, the vertical CMRR is ∼ 8 dB lower. The new electronics represents also an improvement in terms of equivalent input noise as listed in Tab. 1. The two difference amplifiers are based on the LT6402-20 difference amplifier from Linear Technologies. In order to obtain a 100 nm resolution over a ±0.5 mm range (no gain switching) a 13 bit (Effective Number Of Bits, ENOB) is needed. The gain difference of ∼ 26 dB between the delta and sigma channels gives ∆ = Σ at 600 µm for an electrode with a sensitivity of 12 mm. As shown later the sensitivity of a 3mm gap electrode is 11.88 mm.

Figure 8: Frequency response of the HE electronics: ∆H,V, ΣH,V channels, and the horizontal CMRR with amplification.
Table 1: Specifications of the new head electronics.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Noise (nV/Hz^{0.5})</th>
<th>Gain (dB)</th>
<th>BW</th>
<th>CMRR @ 10 MHz (dB)</th>
<th>Z_{in} (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ_{H}</td>
<td>2.3</td>
<td>35</td>
<td>500 Hz-20 MHz</td>
<td>85</td>
<td>50</td>
</tr>
<tr>
<td>Δ_{V}</td>
<td>2.3</td>
<td>35</td>
<td>500 Hz-20 MHz</td>
<td>78</td>
<td>50</td>
</tr>
<tr>
<td>Σ</td>
<td>63</td>
<td>8.5</td>
<td>300 Hz-40 MHz</td>
<td>–</td>
<td>50</td>
</tr>
</tbody>
</table>

### 3.3 CMRR

A high CMRR is essential since the magnitude of the common mode signal influences the performance of the PBPM. Any signal (e.g. common mode) added to the real difference signal will limit either the PBPM resolution or its accuracy. In fact, if the residual common mode signal is in quadrature phase with respect to the difference signal, the magnitude of the position signal can never become zero, and will thus limit the resolution. In the case of an in-phase common mode signal the magnitude will be zero at a certain distance from the mechanical center, and will result in an electrical offset which is in principle less critical, since the offsets can be measured using beam based alignment.

### 4 PBPM results

#### 4.1 Titanium coating

As explained in [1, 7], a thin resistive layer on the inside of the ceramics vacuum tube is necessary to limit the longitudinal impedance at the high frequency components. Magnetron sputtering techniques have been successfully applied to bigger ceramics tubes [7, 8].

![Figure 9: Vacuum assembly](image)

However, the coating showed out to be much more challenging than foreseen. 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 is achieved with an unusual high magnetic field 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 ceramics axis. A special coil was built based on simulations (Fig. 10) which took into account the magnetic properties of the KOVAR collars brazed on the ceramic.

![Simulation of magnetic field in presence of KOVAR collars.](image)

Figure 10: Simulation of magnetic field in presence of KOVAR collars. The rectangular shapes represents the KOVAR collars

Unfortunately, the exact magnetic properties of the finally used alloy were not known precisely enough. Measurements on the real object revealed that the magnetic field decreases by a factor of two at the ceramics collars, which led to less dense plasma at the collar regions and consequently a thinner coating thickness compared to the middle of the ceramic. Once the problem was understood, the solution chosen was to order new ceramics with non-magnetic stainless steel collars. Test coatings on ceramic half shells with stuck on stainless steel collars where coated (Fig. 11) but had bad reproducibility. The 6 mm ceramic tubes, with brazed on stainless steel collars, in the same configuration did not show either a satisfying uniform coating thickness. However, it has been possible to obtain an end-to-end DC resistance around 10-15 Ω. The quite different coating times needed to obtain these values confirms the non uniformly distributed plasma during coating.

A solution would be a new setup of the magnetic field. This involves building a new magnet, ordering new test tubes with stainless steel collars and running another series of tests. A possible solution is a setup where the magnetic field, and thus the plasma,
Figure 11: Coating of test ceramic with stainless steel collars

is concentrated at a small longitudinal distance of the ceramic tube. After a certain time the magnetic field (magnet) is moved in the longitudinal direction in order to coat another part of the tube. This procedure is then repeated in order to coat the whole tube.

4.2 Characterization of the test bench

The quality of the sensitivity measurements depends very much on the precision of the movement of the linear stages. In particular it is important that the axes of the movements of both linear stages are well aligned with the horizontal and vertical planes of the PBPM. As was already described, a WPS is directly attached to one of the reference planes of the PBPM. It can be used to crosscheck the readout from the linear stages and the position obtained with the PBPM.

Fig. 12 compares the readout from the horizontal linear stage, the WPS output signals and the PBPM ones, for a systematic movement of the horizontal stage in steps of 1 µm in the range ±1.5 mm. From the plot, it can be concluded:

- The WPS horizontal signal, the PBPM horizontal and the readout from the horizontal motor encoder are practically the same.

- There is a small angular misalignment between the horizontal axis of the motor and the WPS vertical axis.

It has to be noted that the temperature effect that could affect the quality of the WPS signals are not evaluated in these measurements. It is difficult to determine misalignment
between the axes of the micro movers and the horizontal and vertical planes of the PBPM and the WPS. But, from the plot in Fig. 12, it is estimated to be $< 10 \, \mu m$ over $\pm 1.5 \, mm$. The small discontinuity observed on the Horizontal PBPM signal in the center of the plot is due to a common mode signal which is in quadrature phase with the difference signal. This problem will be addressed later.

Figure 12: Correlation between the measurements of the WPS, the readout from the horizontal encoder of the linear stage and the differential signal from the PBPM for a movement in steps of 1 $\mu m$ along the horizontal direction.

A similar measurement was carried out with the vertical linear stage. As can be observed in Fig. 13, in this case the readout from the motor encoder and the PBPM did not agree. The cause of this disagreement was an error in the vertical linear stage readout for small movement steps (1 $\mu m$). Even though the readout from the motor asserted that the motor was moving properly, the actual movement did not correspond with the readout of the motor, as can be crosschecked by the values obtained from the PBPM and the WPS in the vertical directions. Furthermore, if the same measurement was repeated with larger steps (50 $\mu m$) (Fig. 14), the readouts from the motors, the PBPM and the WPS agreed. The micro mover was then shipped back to the manufacturer for reparation and the measurements presented hereafter were carried out with the repaired micro mover.

4.3 Frequency domain

4.3.1 Sensitivity and linearity

For a Beam Position Monitor (BPM), one of the most important parameters to evaluate is the variation of the output signal as function of the beam position, the so-called PBPM
Figure 13: Correlation between the measurements of the WPS, the readout from the vertical encoder of the linear stage and the differential signal from the PBPM for a movement in steps of 1 µm along the vertical direction.

Figure 14: Correlation between the measurements of the WPS, the readout from the encoders of the linear stage and the differential signal from the PBPM for a movement in steps of 50 µm along the vertical direction.
sensitivity (horizontal or vertical) $S_{x,y}$ defined as:

$$\frac{\Delta H,V}{\Sigma} = \frac{1}{S_{x,y}} r$$

where $r$ is the horizontal or vertical beam offset. For a circular PBPM $S_x = S_y$ which is the case of the PBPM. The sensitivity of the PBPM has units of length, but sometimes the inverse value $1/S_{x,y}$ is also referred as sensitivity. Normally, the sensitivity is a linear function of the beam offset around the electrical center of the PBPM, and a non-linear function near the walls of the vacuum chamber. In the range that the PBPM differential output is linearly proportional to the beam offset, the sensitivity can be represented by a real constant, as defined in Eq. 1. But outside a certain range the beam position signal is no longer linearly proportional to the beam displacement. The discrepancy between the measured value at a certain beam displacement and a linear fit, gives an evaluation of the linearity of the PBPM.

In the sensitivity and linearity tests of the PBPM, the beam excitation is substituted by a wire stretched inside the vacuum chamber. The measurement consists in moving the wire in certain steps along one direction (or diagonally) and to plot the PBPM response as function of the wire position. In these measurements, a network analyzer generates a sine wave excitation at a single frequency and measures the S-parameters for the differential and sum signals from the head electronics of the PBPM.

As can be observed in Fig. 15, the sensitivity of the PBPM increases for bigger distances $g$ between electrodes, from $S_x=16.08$ m for a gap of 1 mm, to $S_x=11.48$ mm for a gap of 5 mm. From these results, it was decided to choose the 3 mm gap electrode $S_x=11.88$ mm for use in the bench tests. The reason is that the sensitivity gain when the gap is increased from 3 to 4 mm is quite low in comparison to the gain between 2 and 3 mm.

The sensitivity of the PBPM responses is analyzed in Fig. 16. From the plots it is clear that the sensitivity ($S_x$) is non-linear in a certain distance around the center. Especially in the horizontal plane, in a range of several micro meters, the sensitivity tends toward zero. The reason is a common mode signal in quadrature phase, which inhibits the difference signal from going to zero. In the vertical plane the response is much better around the center. The residual signal does not come from the head electronics but from the PBPM itself. The magnitude of this signal changes every time the PBPM is dismantled and mounted again on the test bench. The source of this residual is not yet understood, but work is still under going in order to eliminate it. With a gain difference of 26.5 dB between $\Delta$ and $\Sigma$ channels, the measured sensitivity, after signal amplification in the head electronics, is $562 \mu$m, which corresponds to a PBPM sensitivity of 11.88 mm for a 3 mm gap electrode.

### 4.3.2 Linearity error

The analysis of the linearity error in the vertical plane, in a ±0.4 mm range, shows that the error is less than 1 %, (Fig. 17), that is, less than 5 $\mu$m error. In the presence of a residual common mode signal, as shown here in the horizontal plane, the error is 11 $\mu$m.
Figure 15: Measurements of the linearity for several sets of electrodes with wire movements along: \textit{top}) the horizontal axis, \textit{bottom}), the vertical axis, of the PBPM with linear stage steps of 2 µm.
Figure 16: Measurements of the magnitude of the linearity response along the horizontal plane of the PBPM with linear stage steps of 2 $\mu$m for the 3mm gap electrodes.

Figure 17: Linearity error of the PBPM in a $\pm 0.4$ mm range.
4.3.3 Frequency dependence

In Figure 18 measurements ($\Delta_H/\Sigma$) at several excitation frequencies are compared. The measurements were carried out using the set of electrodes with 3 mm gap. The horizontal movement of the linear stage was with 2 $\mu$m steps, the new head electronics was installed and a power of 10 dBm for the input sine wave signal. The magnitude of the transmission parameter for the $\Delta_H/\Sigma$ signal is plotted. As mentioned earlier, around the center of the PBPM, the signal do not reach zero, but a minimum, which seems to depend on frequency. The sensitivity ($S_x$) of the PBPM is increasing with frequency. The real sensitivity has been measured in time domain with a rectangular beam-like pulse as shown later.

![Figure 18: Measurements of the linearity response (linear stage steps of 2 $\mu$m) of the PBPM at different frequencies.](image)

4.3.4 Resolution

One of the most important parameters of the PBPM is the ability of detecting very small beam position variations (resolution), which will be used to stabilize the beam along the linear collider and enhance the luminosity in the collision point. In the PBPM, the resolution is limited basically by the thermal noise in the head electronics and around the electrical center also the CMMR is important. The expected resolutions for the test bench, ILC and CLIC are resumed in Tab. 2 together with their expected beam currents and measurement bandwidths. The resolutions are calculated using an electrode sensitivity of 12mm, the 2.3 nV amplifier equivalent input noise, a turns ratio of the current transformer of 30 and a secondary load of 25 $\Omega$. That is a coupling impedance of 0.833 $\Omega$ ($V_\Sigma = \frac{I_{\text{wire}}}{N} R_L$).


<table>
<thead>
<tr>
<th></th>
<th>Test bench</th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{rms}$ (A)</td>
<td>0.08</td>
<td>0.055</td>
<td>1.5</td>
</tr>
<tr>
<td>$V_{Sigma}$ (V)</td>
<td>0.067</td>
<td>0.046</td>
<td>1.25</td>
</tr>
<tr>
<td>$V_{Delta}$ (@0.1 , \mu m) (\mu V)</td>
<td>0.56</td>
<td>0.38</td>
<td>10.4</td>
</tr>
<tr>
<td>$V_{Noise}$ (\mu V)</td>
<td>0.12</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Resolution (nm)</td>
<td>20</td>
<td>3300</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 2: Comparison of beam parameters and expected resolution at the test bench (3kHz BW) and extrapolated resolution for ILC and CLIC (30MHz BW).

In figure 19 the output signal from the PBPM is monitored continuously for a certain period of time and the width (standard deviation) of the line is directly proportional to the resolution.

![Figure 19: Plot of the evolution of the readout of the WPS and the PBPM as function of time with the wire at the center position of the PBPM.](image)

Table 3 lists the main parameters used in the measurements. It also compares the experimental resolutions obtained in the measurements by calculating the standard deviation of the signals in the horizontal and vertical plane and then scaling to beam position using the PBPM sensitivity mentioned earlier (11.88 mm). If the value is scaled to the beam conditions at CLIC, with a much higher current (1.5 A) and a frequency bandwidth of 30 MHz, the expected PBPM resolution is 190 nm. Which is within a factor two of the expected resolution as calculated in 2.

A very intuitive and graphical way of estimating the resolution of the PBPM is to monitor the output signal of the PBPM for a systematic movement of the motors in
<table>
<thead>
<tr>
<th>Number of samples</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Electrodes gap</td>
<td>3 mm</td>
</tr>
<tr>
<td>Electrodes sensitivity</td>
<td>11.88 mm</td>
</tr>
<tr>
<td>Input power</td>
<td>25 dBm (80mA)</td>
</tr>
<tr>
<td>$\sigma_{H,V}$ (3 kHz bandwidth)</td>
<td>36 nm</td>
</tr>
<tr>
<td>$\sigma_{H,V}$ (30 MHz bandwidth)</td>
<td>3.6 µm</td>
</tr>
<tr>
<td>$\sigma_{H,V}$ (1.5A CLIC beam current)</td>
<td>190 nm</td>
</tr>
</tbody>
</table>

Table 3: List of the main parameters of the measurements, measured resolutions, and resolution to CLIC beam current.

small steps. The comparison between the positions measured with the PBPM, the encoders of the linear stages and the WPS gives a good idea about the quality of the measurement. Figure 20 represents the evolution of the output signals for a horizontal movement starting in the center of the PBPM. Some conclusions can be obtained from this plot:

- Due to the presence of a quadrature common mode signal, and measuring the magnitude of the differential signal, the sensitivity is smaller in the center of the PBPM in regions (left side of plot) ($< 5 \mu m$) from the electrical center.

- There is a small error between the WPS and the motor movement. It is believed that this is mainly due to mechanical assembly errors in the setup.

Another interesting measurement is to evaluate the resolution of the PBPM at several wire offsets. Against all expectations the resolution was observed to decrease with increasing wire position (Fig. 22). A reduction in the current passing through the wire significantly reduced this effect (Fig. 21). We believe that big wire offsets induce differential currents in the setup which causes the wire to vibrate. The amplitude of the vibration depends on the wire current.

### 4.3.5 Frequency bandwidth

An important parameter of the PBPM is the frequency response, mainly in the operation bandwidth (from 100 kHz to 30 MHz), but as well within all the beam frequency spectra. As explained in [1] and [7], the titanium layer acts as a high frequency filter of the high frequency beam components to limit the longitudinal impedance.

Figs. 23 and 24 compare the shape of the frequency response of the $\Delta$ and $\Sigma$-signals for different wire positions in the horizontal plane. For the $\Delta$-signals, the minimum power is obtained (as expected) in the electrical center of the PBPM. The signal amplitude increases with bigger wire positions. The $\Delta$ low frequency cutoff is estimated to 300 kHz, as expected from the electromagnetic simulations [1]. The high frequency ripple is due to an impedance mismatch of the setup. The sum signal has a low frequency cutoff
Figure 20: Measurement of the resolution of the PBPM at a single frequency ($f = 10$ MHz), with linear stage micro movements. The readout from the linear stage encoders, the WPS and the magnitude of the PBPM are plotted versus the time.

Figure 21: Plot of the resolution of the PBPM at different wire positions, with a wire excitation of 10dBm.
Figure 22: Plot of the resolution of the PBPM at different wire positions, with a wire excitation of 25dBm.

around 5 kHz, which is also in the range of the simulated values [1]. The discrepancy can be explained by the uncertainty in some of the material properties of the ferrite, e.g. the permeability. The high frequency cut off is estimated to ∼ 80 MHz, and is limited by the bandwidth of the electronics (current transformers and head amplifier), but is sufficient for the PBPM purposes.

Figure 23: Plot of the frequency response of the ∆-signal at several wire positions along the horizontal axis.

4.3.6 Absolute precision

The offset between the electrical center of the PBPM and the mechanical center of the assembly was evaluated using the technique described in [5]. With this technique, the electrical center is found at the position where the difference signal from the PBPM is
minimum. The PBPM is then rotated $180^\circ$, and a new electrical center is found. The difference between the two measured electrical centers is equal to twice the difference between the mechanical and electrical center. At first an offset of $50 \, \mu m$ was found. It was first believed that the reason of such a big offset was due to wobble and an imprecise misalignment of the PBPM on the rotational stage. Several attempts to improve this failed, and the suspicion that the individual alignment of the current transformers could influence the electrical offset was proven with the setup shown in Fig. 25. Here the lateral position of two opposite current transformers were slightly modified, and it was possible to obtain an electrical offset $< 1 \, \mu m$. The reason why the electrical offset depends on the current transformer position is not understood, but could be related to a capacitive coupling of the electrode to the secondary windings. But since the movement of the current transformers do not influence the magnitude of the out of phase common mode residual mentioned earlier, it is more likely to be related to asymmetrical leakage inductance in two opposite current transformers.

### 4.3.7 Influence of the environmental temperature

One of the most difficult parameters to control, affecting the precision of the measurements, is the mechanical deformation caused by the environmental temperature changes. As the test bench is constructed mainly with metals like aluminum, stainless steel or copper, with moderate dilatation coefficients, the effect of the temperature is small but still important for the required PBPM resolutions (100 nm). To minimize this problem, the PBPM has been placed in the middle of the support, where symmetry should cancel
out the geometrical variations related to temperature. That is not the case of the WPS and its wire. The position of the horizontal axis of the WPS is also in the center of the test bench structure, but the vertical plane is displaced with respect of the center of the test bench.

In the top plot of Fig. 26, the correlation between the temperature increase and the decrease in the vertical position readout of the WPS (which corresponds to the horizontal position of the PBPM) can be seen. In addition, bottom plot, a similar correlation between the temperature increase and the horizontal readout of the PBPM is found. Therefore, even if the PBPM was placed in the center of the table, a position drift due to temperature changes could be detected. This effect is in fact very small but still important for the resolution measurement, since the measurement of the standard variation will change if the average position change. Therefore, it can be concluded that the temperature is one of the limiting factors of the resolution measurement of the PBPM. The measurement should be done in a relatively short period with stable temperature.

**4.3.8 Influence of the ground vibration**

To evaluate the effect of the ground vibrations in the output signals from the PBPM, a comparison of the output signals, with the active damping system of the honeycomb table on and off, was carried out. Comparing the measurements in both situations (Figs. 19 and 27), no difference was noticed and the resolutions calculated were similar.
Figure 26: Plot of the evolution of the readouts of the linear stage encoders, the WPS and the thermistor for a resolution measurement in the center of the PBPM versus time. In the bottom right corner, correlation between the magnitude readout from the PBPM and the environmental temperature.

Figure 27: Plot of the evolution of the readouts of the linear stage encoders, the WPS and the PBPM as function of the time with the active vibration damping system disconnected.
4.3.9 Long term measurements

It is important to verify the stability of the PBPM output signals as function of time. Figure 28 plots the output signals during 14 h at several wire positions. The measurements show that the stability of the PBPM system is around 2 µm.

4.3.10 Longitudinal impedance

The ceramics of the PBPM has been coated to limit the longitudinal coupling impedance \( Z_{||} \) at high frequencies. In that way, the perturbations (wake fields) are minimized, as explained in [1, 7]. Due to the problems with the coating technique, the titanium layer on the internal ceramics surface was not totally homogeneous and the DC resistance was a bit higher than the design requirements, 14.6 Ω, instead of 10 Ω.

The longitudinal coupling impedance is measured using the wire method and calculated as:

\[
Z_{||} = -2Z_L \log \left( \frac{S_{21}}{S_{21R}} \right)
\]

with \( S_{21} \) the transmission S-parameter of the Device Under Test and \( S_{21R} \) the transmission of the reference tube. Figure 29 shows the calculated and measured longitudinal impedance in frequency domain. The real and imaginary parts of the measured longitudinal impedance fits very nicely the simulated ones, apart from a ringing above 2 GHz which is related to the setup. A small delay of 1 ps was added to the measurement in order to obtain a good fit.

4.4 Time domain

4.4.1 Electrodes comparison

During preliminary tests before the final assembly, the influence of the electrodes azimuthal angle (or gap \( g \) between electrodes) in the response of the monitor was studied. The measurements were carried out without head electronics and by directly coupling a pulse generator to one of the calibration channels. The output signals from electrodes with \( g =1 \) mm, 2 mm and 3 mm (Fig. 1) can be compared in Fig. 30. To evaluate the results, the differential time signals (\( \Delta(t) \)) were fitted using the following formula:

\[
\Delta(t) = (NI_0) \left( \frac{R_p}{R_c + R_p} \right) \left[ R_p \exp \left( -\frac{L_{\Delta}}{R_c + R_p} \right) + R_c \right]
\]

with \( N \) the number of windings of the current transformer, \( I_0 \) the value of the input pulse current, \( L_{\Delta} \) the electrode inductance, \( R_c \) the parasitic contact resistance, \( R_p \) the secondary load of the current transformer transformed to the primary. The results of the fittings are listed in Tab. 4. As was expected, the electrode inductance increases as the gap between the electrodes is bigger, since the electrodes are getting thinner. The
Figure 28: Plots of the position and phase long term (14 h) stability: top) horizontal channel with the wire with 50 µm horizontal offset, middle) vertical channel with the wire with 50 µm vertical offset and bottom) horizontal and vertical channel for a center wire.
same effect is observed both in the horizontal and the vertical planes. In the case of the Σ signal, as the inductance depends mostly on the ferrite around the electrodes, the value is almost constant and independent of the electrode shape. For these measurements, the secondary load was $R_s = 25 \, \Omega \, (R_p = 27.7 \, \text{m}\Omega)$. That means a low frequency cutoff around 150-200 kHz for the Δ signal and 3 kHz for the Σ signal.

Figure 30: Output Δ (left) and Σ (right) signals from the different set of electrodes without head amplifier.
Table 4: Calculated inductance of the $\Delta$ and $\Sigma$ signals with three different spacing between electrodes.

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>$L_{\Delta H}$ (nH)</th>
<th>$L_{\Delta V}$ (nH)</th>
<th>$L_{\Sigma}$ (µH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.45</td>
<td>21.96</td>
<td>1.41</td>
</tr>
<tr>
<td>2</td>
<td>22.73</td>
<td>23.3</td>
<td>1.39</td>
</tr>
<tr>
<td>3</td>
<td>26.4</td>
<td>24.96</td>
<td>1.39</td>
</tr>
</tbody>
</table>

### 4.4.2 Sensitivity and linearity

The sensitivity and linearity of the PBPM was also analyzed in time domain for a pulse excitation of 200 ns, 100 mA. In the measurement shown in Fig. 31, the $\Delta_{H,V}$ and $\Sigma$ signals were recorded and their ratio plotted for different horizontal wire positions. The sensitivity of the PBPM measure in time domain was evaluated to 11.92 mm, which is very close to the sensitivity of 11.88 mm measured in frequency domain. The linearity error is less than 1

![Figure 31: Horizontal and vertical linearity measurements with a pulse excitation.](image)

### 4.4.3 Resolution

In Fig. 32 the PBPM response is seen for four different wire positions. The estimated standard deviation with the measured sensitivity of 11.9 mm is 1.18 µm for a 200 mA, 200 ns pulse, which corresponds to 160 nm for the CLIC 1.5 A beam.

![Figure 32: PBPM response for four different wire positions.](image)
4.5 Summary of the measurements

Tables 5 and Tables 6 summarizes the time domain and frequency domain measurements.

<table>
<thead>
<tr>
<th>Electrode gap (mm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution bench (nm)</td>
<td>-</td>
<td>-</td>
<td>36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Resolution ILC (nm)</td>
<td>-</td>
<td>-</td>
<td>5200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Resolution CLIC (nm)</td>
<td>-</td>
<td>-</td>
<td>190</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Linearity error ±400 µm(%)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sensitivity PBPM (mm)</td>
<td>16.08</td>
<td>13.11</td>
<td>11.88</td>
<td>11.47</td>
<td>11.48</td>
</tr>
<tr>
<td>Δ low frequency cutoff (kHz)</td>
<td>-</td>
<td>-</td>
<td>300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Σ low frequency cutoff (kHz)</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>High frequency cutoff (MHz)</td>
<td>-</td>
<td>-</td>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24 h stability (µm)</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Longitudinal impedance, &gt; 5 GHz, (Ω)</td>
<td>-</td>
<td>-</td>
<td>14.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electrical offset (µm)</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Summary of the test bench measurements of the PBPM in frequency domain using a 10MHz, 25dBm, CW sine wave.

5 Influence of the quadrupoles magnetic field

In future linear colliders, the PBPM’s are foreseen to be directly attached to the quadrupoles. That means that the magnetic field, used by the quadrupoles to focus the beam, could also distort the PBPM causing a wrong response. However, for the existing BPM’s at
<table>
<thead>
<tr>
<th>Electrode gap (mm)</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution bench (nm)</td>
<td>1180</td>
</tr>
<tr>
<td>Resolution ILC (nm)</td>
<td>4250</td>
</tr>
<tr>
<td>Resolution CLIC (nm)</td>
<td>160</td>
</tr>
<tr>
<td>Linearity error ±400 µm(%)</td>
<td>1</td>
</tr>
<tr>
<td>Sensitivity PBPM (mm)</td>
<td>11.92</td>
</tr>
</tbody>
</table>

Table 6: Summary of the test bench measurements of the PBPM in time domain with a 100mA 200ns pulse.

CTF3 it has not been a problem. It seems that the ferrite surrounding the BPM (Σ signal) shields the current transformers, avoiding the saturation. Magneto static simulations with the expected magnetic field will be anyway suitable to confirm the proper magnetic shielding of the transformers under realistic circumstances. In addition, the influence of the ferrite on the quality of the quadrupole fields must be simulated.

6 Tests with beam in CTF3

Bench measurements are necessary to characterize the PBPM and to correct all the possible errors. Nevertheless, the only definitive confirmation of the correct functioning of the PBPM is the experience with real beam. In December 2007, three PBPMs were installed in the magnetic chicane of CTF3 (see Fig. 33). In this location, the beam has the properties detailed in Tab. 7, which are close to the foreseen CLIC main beam. The results of several beam tests carried out in 2008 are reported in EUROTeV-Report-2008-061.

<table>
<thead>
<tr>
<th>Beam current</th>
<th>1.5 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width</td>
<td>200ns</td>
</tr>
<tr>
<td>rms-Transverse beam size</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Beam angle</td>
<td>1.25 mrad (0.5 mm offset at 400 mm length)</td>
</tr>
<tr>
<td>Transversal position jitter</td>
<td>100 to 200 µm</td>
</tr>
</tbody>
</table>

Table 7: Main properties of the CTF3 beam at the entrance of the magnetic chicane.

7 Conclusions

The results of the PBPM test bench measurements confirms that it is possible to operate an inductive beam position monitor with the required precision, sensitivity, linearity and resolution of 160-190 nm has been measured. The sensitivity of the PBPM in the center depends on the CMRR of the electronics, or more precisely, on the magnitude of the common signal which is in quadrature phase with the real difference signal. Such common mode signal is originating from the PBPM itself (the contribution from the head
amplifier is much smaller), and is at present not understood. Every time the PBPM is dismantled and remounted on the test bench the magnitude of this residual signal in the electrical center of the PBPM changes. Investigations to understand the cause of this problem are under going. In the case where the average position of the whole beam pulse is demanded this is not a problem since the integrated error from a 90° off-phase signal (differentiated) is zero.

The accuracy of the position measurement depends on the electrical offset with respect to the mechanical center, or a mechanical reference plane. By adjusting the positions of the current transformers an electrical offset of 1 µm has been obtained. This is well within the specifications, but for a BPM to be manufactured in large quantity, this is not a practical solution, and a better solution must be found. The dedicated test bench, that has been designed and constructed, works according to the specifications. In addition, a new low noise head electronics, which complies with the required specifications, has been developed.

The main problem encountered was the deposition of a titanium layer on the inside of ceramics assembly. Magnetron sputtering technique, with a magnetic field of up to 0.3T, used to create a homogeneous plasma, showed out to be very difficult in the very small vacuum tube of 6mm diameter. Even though that end to end resistances around 10-15 Ω was obtained, the layer thickness along the ceramic tube was not uniform. A new solution having the plasma concentrated in a small sector of the tube is proposed. The location of the plasma can be controlled by an external magnet.

Beam tests will be carried out at the CTF3 chicane with 3 PBPM’s in order to evaluate the validity of the test bench results.
Acknowledgements

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References


