HIGH RESOLUTION RE-ENTRANT BPM FOR LINEAR COLLIDERS

C. Simon[#], S. Chel, M. Luong, O. Napoly, J. Novo, D. Roudier, CEA-Saclay, Gif sur Yvette, France
N. Baboi, D. Noelle, N. Mildner, DESY, D-22603 Hamburg, Germany
N. Rouvière, CNRS-IN2P3-IPN, Orsay, France

Abstract

A high resolution beam position monitor (BPM) is necessary for the beam-based alignment systems of high energy and low emittance electron linacs. Two monitors with a large aperture (78 mm) are installed in the FLASH linac at DESY: one inside a cryomodule and the other at room temperature in a clean environment. The mechanical and signal processing designs of this BPM were determined to get a high position resolution and the possibility to perform bunch to bunch measurements. Methodology, simulations and experimental results will be discussed in this paper.

INTRODUCTION

A BPM based on a radio-frequency re-entrant cavity is developed in the framework of the European CARE/SRF programme, in a close collaboration between DESY and CEA/Saclay. A first prototype of a re-entrant BPM installed inside a cryomodule in the FLASH linac has already delivered measurements [1]. A second system is installed at room temperature to confirm the theoretical analysis. The RF simulations carried out with the software HFSS and the development of a Mathcad model determined the mechanical design and signal processing of this BPM.

CAVITY BPM

Mechanical design

The re-entrant cavity BPM is composed of a mechanical structure with four orthogonal feedthroughs. It is arranged around the beam tube and forms a coaxial line which is short-circuited at one end [2]. The cavity (Fig. 1) is fabricated with stainless steel, its aperture has a diameter of 78 mm and its length of 170 mm is minimized to satisfy the constraints imposed by the cryomodule.

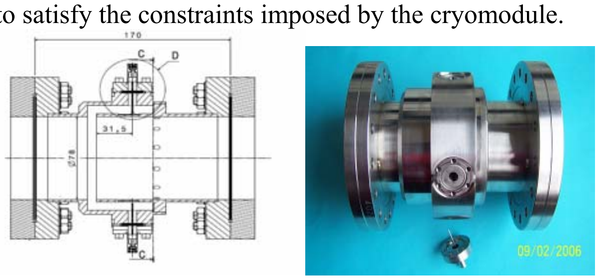

Figure 1: Re-entrant cavity BPM installed in the FLASH linac.

Twelve holes of 5 mm diameter were drilled at the end of the re-entrant part for a more effective cleaning. The position of feedthroughs was determined by simulations with the software HFSS, to reduce the magnetic loop coupling and separate the main RF modes (monopole and dipole modes). Several cryogenic and vacuum tests were, successfully, applied to feedthroughs. For each antenna, a CuBe RF contact is welded in the inner cylinder of the cavity to ensure electrical conduction between the feedthrough and the cavity, providing a magnetic coupling loop.

RF characteristics of the cavity BPM

The resonant cavity was, first, simulated with the software HFSS (Ansoft) in eigen solver mode to determine its frequencies and coupling. The simulations were carried out with HFSS on a half of the cavity. The electrical and magnetic fields are high in the re-entrant part. With Matlab and the HFSS calculator, the R/Q ratio was computed in using the following equation (R: the Shunt impedance and Q: quality factor).

$$\frac{R}{Q} = \frac{V^2}{2 * \pi * f * W} \tag{1}$$

With $V = \left| \int E(z) * e^{jkz} dz \right|$ and $W = \frac{\varepsilon_0}{2} \iiint \left| E * E^* \right| d\tau$

where k= w/c and W is the stored energy in the mode. Q factors were determined by HFSS with matched feedthroughs in eigen solver mode. The RF measurements, presented in Table 1, compare some computed quantities to measured values. The frequencies and coupling measurements of the main RF modes (monopole and dipole modes) were carried out to check the proper mounting of feedthrough on the cavity. The difference on Q factors can be explained by the boundary conditions which are not the same during the measurements in laboratory and in the tunnel.

Due to the finite tolerances in machining, welding and mounting, some small distortions of cavity symmetry are generated. The dipole mode orthogonal polarizations show slightly different eigenfrequencies; the relative difference was measured and is, however, less than 2 per 1000. Furthermore, a displacement of the beam in the 'x' direction gives not only a reading in that direction but also a non zero reading in the orthogonal direction 'y'. This asymmetry is called cross talk. Cross-talk isolation measurements are performed on the cavity with a network analyzer [3]. The crosstalk was measured in the FLASH tunnel to be around 33 dB instead of 41 dB measured in laboratory. This difference is not yet understood but it may be explained by the fact that the BPM has a rotation/tilt (11.25 degrees) with a button BPM which is very close.

Eigen modes	F (MHz)			Q_{ext}			R/Q_l (Ω) at 5 mm	R/Q_l (Ω) at 10 mm
	Calculated	Measured in lab.	Measured in the tunnel	Calculated	Measured in lab.	Measured in the tunnel		
Monopole mode	1250	1254	1255	22.95	22.74	23.8	12.9	12.9
Dipole mode	1719	1725	1724	50.96	48.13	59	0.27	1.15

Table 1: RF characteristics of the re-entrant BPM.

The transmission measurement on two opposite antennas was completed in the 1 to 4 GHz range (Fig. 2).

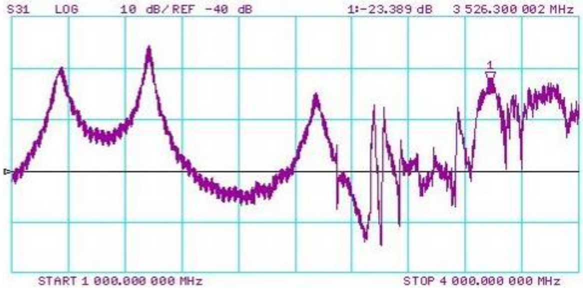

Figure 2: Transmission measurement on the opposite antennas without beam

The first and second peaks are the monopole and dipole modes. Others peaks are higher order modes which can propagate out of the cavity through the beam pipe. Those 'higher order modes' should be well rejected by a 1.72 GHz band pass filter used in the signal processing. This filter was measured in laboratory, at 3 GHz, its attenuation is around -70 dB and around -60 dB at 4 GHz.

SIMULATION

Mathcad Model

To assess the performance of the system, a model (cavity+signal processing) is elaborated with a Mathcad code based on Fourier transforms. The simulation covers a span from 0 to 20 GHz. Each mode of the cavity is modelled as a resonant RLC circuit. The delivered time domain signal is therefore determined by the RF characteristics of each mode (Equation 3). The single bunch response of the cavity depends on frequency w_i and external coupling Q_i of the modes. The signal from a pickup is the sum of all resonant modes excited by the beam.

$$S_{pickup} = \Sigma S_i \qquad (2)$$

$$S_i = \Phi(t)\left[V_i \exp\left(-\frac{w_i.t}{2.Q_i}\right)\left(\cos\left(a_i.t - \frac{w_i.\sin(a_i.t)}{2.Q_i.a_i}\right)\right)\right] \qquad (3)$$

With $a_i = w_i\sqrt{1-\frac{1}{4Q_i^2}}$ and $V_i = \sqrt{\frac{w_i^2.(R/Q)_i.q^2.R_o}{\zeta_i.Q_i}}$

where Φ(t) is the heaviside function, q the bunch charge, R_0 the 50 Ω cable impedance, R/Q_i defines the coupling to the beam and $\zeta_i = 4$ if it is a monopole mode or $\zeta_i = 2$ if it is a dipole mode.

The signal processing uses a single stage down-conversion to obtain Δ/Σ and is shown in Fig 3.

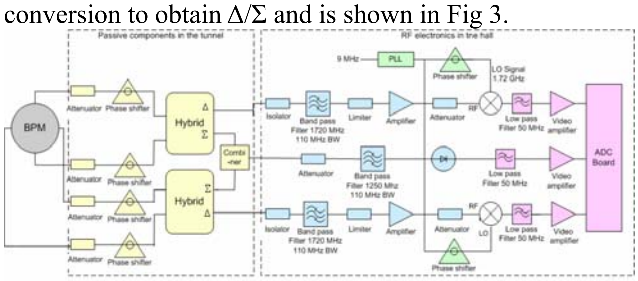

Figure 3: RF signal processing electronics

As the signal from the monopole mode does not depend on the beam position, the rejection of the monopole mode is necessary and is carried out in three steps [3].

To simulate the signal processing, the transfer functions of different components are used.

The model of the 180° hybrid couplers composing the signal processing is derived from the network analyzer measurements [4]. Its isolation is higher than 20 dB in the band 1-2 GHz. A local enhancement of the isolation can be obtained with adjusting of the phase and attenuation to have a better rejection of the monopole mode. The transfer function of cables (H_c) takes into account the effect of attenuation and dispersion. The "sum" signal peak power was measured around 36 dBm and the "sum" peak power simulated with the Mathcad model is around 34 dBm. Those values are close, the Mathcad model can be, therefore, validated.

The band pass filter with a 110 MHz bandwidth centred at 1.72 GHz provides a monopole mode rejection and a noise reduction. Its transfer function is given by a CAD code. The local oscillator (LO) signal is modelled by a sine wave at the dipole frequency with 1 Volt amplitude. To carry out the synchronous detection, a phase shift is added to put in phase the LO signal and the RF signal (without monopole mode) from the Δ channel. Follows a 50 MHz lowpass filter, which the transfer function is given by the same CAD code. The output signal of the signal processing (Fig 4) is, then, sampled at the peak for a significant beam offset, around 1 mm.

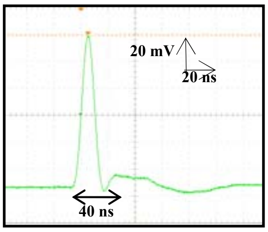

Figure 4: Output signal from the Δ channel.

Results

The position resolution is the rms value related to the minimum position difference that can be statistically resolved. The noise is determined by the thermal noise and the noise from signal processing channel [3]. The signal is given by the model (cavity+signal processing). The gain was adjusted to get an RF signal level around 0 dBm on the Δ channel with 100 μm beam offset. The noise level is about 0.4 mV. In using those parameters, the position resolution is around 350 nm [4].

One of the most important parameters for a BPM is the time resolution. It is usually identified to the damping time which is around 9.5 ns for the re-entrant cavity. Nevertheless, considering the whole system, the time resolution is around 40 ns [3], since the rising time to 95% of a cavity response corresponds to 3τ.

FIRST BEAM TESTS

Summer 2006, the two subsystems, composing the signal processing, were installed and calibrated. The adjustment of phase shifters allows having a high common mode rejection (30 dB at the monopole mode frequency). The synchronous and direct detectors, as well as amplifiers and limiters for protection were adjusted to have a linearity range around +/- 10 mm.

After the electronics calibration, the first tests with beam were carried out. The aim of this first calibration was to know the measurement dynamic range and no to have a high resolution. As the re-entrant BPM is mounted with a tilt angle of 11.25° with respect to the horizontal direction, a frame rotation change, done by software, was necessary. Figure 5 shows that the re-entrant BPM has, on the X and Y channels, a good linearity in a range 15 mm but there is an asymmetry and the linearity is better for a positive deviation. This effect is not yet well understood.

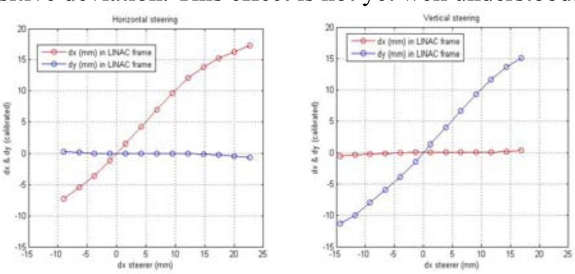

Figure 5: Calibration results in LINAC frame from horizontal (left) and vertical (right) steering

The standard deviation of the calibrated position measurement (fig. 6) was plotted for the horizontal and vertical steering.

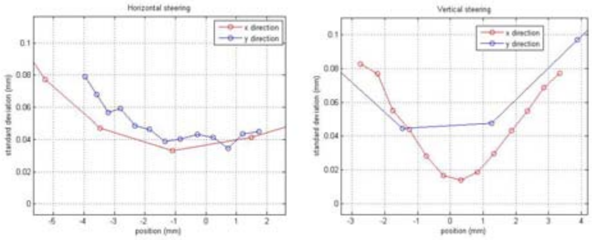

Figure 6: Standard deviation of the position measurement (calibrated)

The raw RMS resolution of the system directly measured by the standard deviation of the readings from the re-entrant BPM can reach 20 μm on the X channel and around 40 μm on the Y channel, at the BPM centre. But those results depend on the beam jitter, too. With simulations, the resolution of this system was determined around 15 μm.

OUTLOOK

For the next beam measurements, the resolution will be studied. The mixer used in the electronics will be replaced by a new one which accepts a high power RF input (around 17 dBm instead of 0 dBm). Some attenuators will be removed to change the gain and improve the resolution. Table 2 shows the re-entrant BPM simulations with the new mixer and 10 mm beam offset.

Table 2: Resolution estimated with the new mixer and 10 mm beam offset.

	Resolution (μm)
75m cables and RF signal level around 12 dBm on the Δ channel	1.3
33m cables and RF signal level around 17 dBm on the Δ channel	0.7

With this layout, the resolution of the re-entrant BPM should be around 1 μm with a measurement dynamics range around +/- 10 mm.

CONCLUSION

This BPM is designed to be used in a clean environment, at cryogenic or room temperature. Its main features are a large aperture (78 mm) and an excellent linearity. The time resolution is around 40 ns and the theoretical resolution is around 1 μm with a measurement dynamics range better than +/- 5 mm. The preliminary measurements on the BPM show a very good agreement with the theoretical analysis. This BPM appears as a good candidate for being installed in the XFEL and ILC cryomodules.

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REFERENCES

[1] C. Magne, et al, "Reentrant cavity BPM for linear colliders", BIW2000R.

[2] R. Bossart, "High precision beam position monitor using a re-entrant coaxial cavity" Processings of LINAC94, KEK, (1994).

[3] C. Simon, et al., "High Resolution BPM for linear collider", BIW 2006.

[4] C. Simon, et al., "High Resolution BPM for linear collider", EPAC 2006.