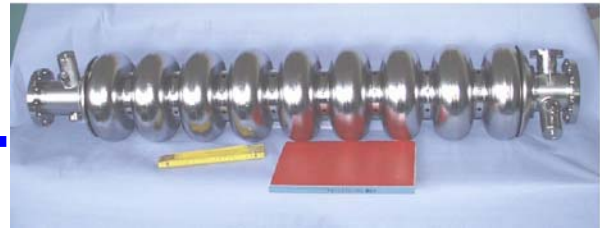SRF

HIGH RESOLUTION BPM FOR LINEAR COLLIDERS

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Abstract

The beam-based alignment and feedback systems, essential operations of the future colliders, use high resolution Beam Position Monitors (BPM). In the framework of the European CARE/SRF programme, the task of CEA/DSM/DAPNIA (Saclay) is the design, the fabrication and the beam test of a BPM in collaboration with DESY. This system can be used in a clean environment, at cryogenic or room temperature. It is composed of a radiofrequency re-entrant cavity with a beam pipe diameter of 78 mm and an analogue electronics having several signal processing steps to reject the monopole mode. The mechanics and signal processing design is a compromise to get a high position resolution (better than 1 µm) and the possibility to perform bunch to bunch measurements for the X-FEL at DESY and the ILC.

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INTRODUCTION

Two reentrant BPMs are installed on TESLA Test Facility (TTF2) at DESY. The first, operated at cryogenic temperature inside the cryomodule ACC1, in an environment where dust particle contamination has to be avoided, is not discussed here [1]. The second, installed on the linac outside a cryomodule for test, is developed by CEA in collaboration with DESY. The mechanics, RF characteristics and signal processing were designed to achieve a high resolution down to 1 μm and to allow bunch to bunch measurements for the X-Ray Free Electron Laser (X-FEL) and the International Linear Collider (ILC). This paper describes the model and the method of cavity BPM and signal processing simulation. The theoretical performances of this system and the first measurements on this reentrant cavity are presented.

CAVITY BPM DESCRIPTION

A reentrant BPM consists of a coaxial cavity arranged around the beam pipe [2]. The cavity is fabricated with stainless steel as compact as possible: 170 mm length, 78 mm aperture as illustrated in Fig. 1.
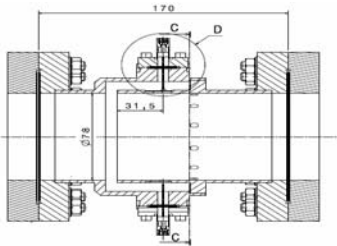

Figure 1: Drawing of the reentrant BPM.

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Passing through the cavity, the beam excites electromagnetic fields (resonant modes: monopole and dipole mainly). The dipole mode signal is proportional to beam offset contrary to the monopole mode which depends only on the beam intensity.

The signal processing uses a single stage downconversion before the Δ/Σ computation. The Δ and Σ signals are obtained from a passive 4-ports 180° hybrid. On the Δ channel, the rejection of the monopole mode proceeds in three steps [3].

SIMULATION

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. 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.

$$S_{pickup} = \Sigma S_i \qquad (1)$$

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

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 $\Phi(t)$ 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.

To simulate the signal processing, the transfer functions of different components are used. A description of the method is given for the Δ channel (Fig. 2).
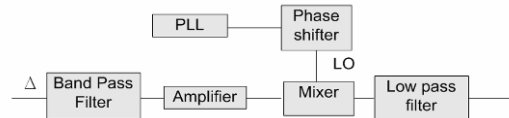

Figure 2: Δ channel signal processing

The transfer function of cables (H_c) takes into account the effect of attenuation and dispersion. The length of cables was chosen to be around 33 m. The model of the 180° hybrid couplers composing the signal processing is derived from measurements with a network analyzer: the transmission measurement from the port 1 to port Δ, as shown Fig. 3, gives the transfer function 'Hdiff1', the transmission from the port 2 to the port Δ gives 'Hdiff2'.

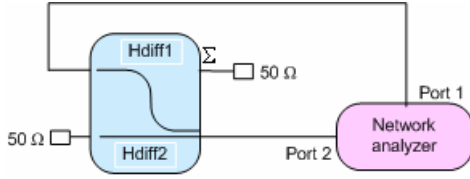The same measurements are made with the port Σ to determine 'Hsum1' and 'Hsum2'.

Figure 3: S parameters measurement of the hybrid 180°

The hybrid isolation is determined by the following relation:

$$I_{hybrid} = 20 * \log(|Hdiff1 + Hdiff2|) \qquad (3)$$

Those hybrid couplers have isolation higher than 20 dB in the pass-band of 1-2 GHz but are different in details especially outside the pass-band (Fig. 4).
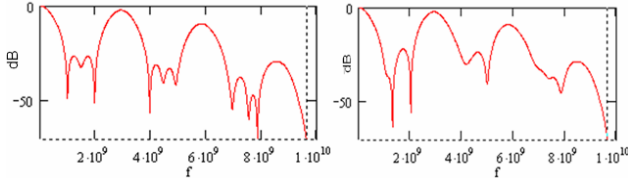

Figure 4: Isolation of two 180° hybrid items.

A local enhancement of the isolation can be obtained with adjusting of the phase and attenuation.

The Δ signal from the hybrid is given by the following relation:

$$T_\Delta = [((S_m - S_d).H_c.Hdiff1) + ((S_m + S_d).H_c.Hdiff2)] \qquad (4)$$

The band pass filter has a 110 MHz bandwidth centred at 1.72 GHz. Its transfer function is given by a CAD code. The filter output signal is the RF signal (Fig. 5a). The local oscillator (LO) signal is modelled by a sine wave at the dipole frequency with 1 Volt amplitude. 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 IF output signal (with monopole mode) (Fig 5b) is, then, sampled at the peak for a significant the beam offset around 1 mm.
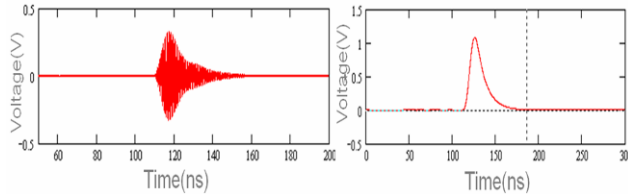

Figure 5: RF (a) and IF (b) signals from the Δ channel.

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 noise level is about $3.83 \cdot 10^{-4}$ V. The signal is given by the model (cavity+signal processing) simulation. The gain was adjusted to get an RF signal level around 0 dBm on the Δ channel with 100 µm beam offset. The Table 1

compares the offset and the resolution of the reentrant BPM regarding different isolations of hybrids at the dipole frequency and two different hybrids which isolation curves was given in Fig. 4 (left for hybrid '1' and right for hybrid '2').

|	Resolution (nm)	Offset (µm)
hybrid '1', isolation 40 dB	323	-1.5
hybrid '1', isolation 30 dB	330	0.6
hybrid '2', isolation 40 dB	350	-0.38
hybrid '2', isolation 30 dB	350	0.95

Table 1: Influence of hybrid isolation on the position resolution and offset.

The position resolution is better than 1 µm. The isolation of the hybrid does not affect the resolution but modifies the position offset. Moreover, the offset depends also on the isolation variation inside and outside the nominal pass-band of the hybrid coupler. The adaptation of amplifier gain for a 100 µm measurement dynamic range spoilt by a 2 factor the resolution in comparison with 10 µm range [3].

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.

RF MEASUREMENTS

In April 2006, the reentrant BPM was installed in a warm part on the machine TTF2 at DESY. After this mounting, the first RF measurements were carried out. Figures 6 and 7 represent the signal measured on one pickup with a 5 GHz bandwidth scope.
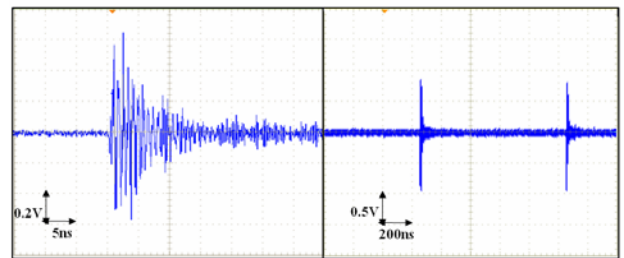
Figures 6 and 7: Signal on one pickup.

Figure 7 represents the same signal than the one in Fig. 6 but the time base is longer. It shows a clean separation between two bunches distant to 1 µs. No long range echo is observed, confirming the possibility for measurements in a multi-bunch mode.

To check the proper feethroughs mounting on the cavity, the RF characteristics and cross-talk were measured. The resonant cavity was, first, simulated with the software HFSS (Ansoft) to determine its modes and coupling [3] then, it was measured in laboratory and finally on the linac. The RF measurements, presented in Table 2, provide a comparison that gives information on

the sensitivity of the RF characteristics to the mechanical mounting and operating environments.

	F (GHz) measured		Q_{ext} measured	
	in lab.	on the linac	in lab.	on the linac
Monopole mode	1.254	1.255	22.74	23.8
Dipole mode	1.725	1.724	48.13	59

Table 2: BPM RF characteristics in test and final configuration.

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.

The crosstalk was measured to be around 33 dB instead of 41 dB measured in laboratory [3]. This difference could be explained by the fact that the BPM has a rotation/tilt (11.25 degrees) with a button BPM which is very close.

The reflexion measurement on each pick up gives nearly the same results with only ±0.07 dB. The four pickups mounted on the BPM are therefore quite identical.

Figure 8 shows the Fourier transform of a signal on the output of one pickup. The step around 3 GHz fits with the 2.94 GHz cut-off frequency of the beam pipe mode (TM_{01}). The modes, having a frequency above can propagate in the beam pipe. Conversely, the disturbances above the cut-off frequency from elsewhere can also propagate down to the BPM.
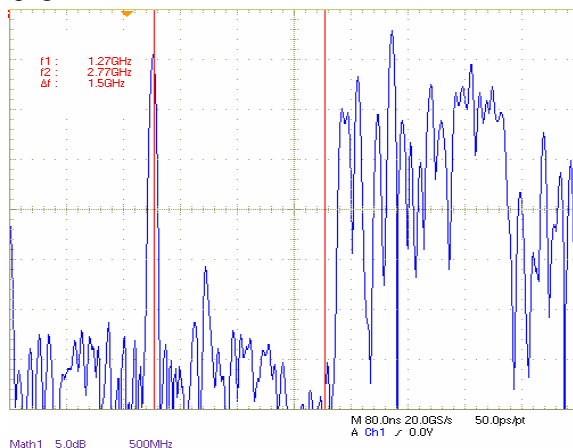

Figure 8: Pickup signal spectrum

The transmission measurement on the opposite antennae was completed in the 1 to 4 GHz range (Fig. 9). All peaks correspond to eigenmodes present in the reentrant cavity. The first and second peaks are the monopole and dipole modes, the others are higher order modes which can propagate out of the cavity through the beam pipe. All the 'higher order modes' are of monopole type, their eigenfrequency was determined with HFSS (Ansoft) and is between 3 GHz and 4 GHz (3 GHz, 3.24 GHz, 3.44 GHz, 3.58 GHz and 3.96 GHz). The 1.72 GHz band pass filter, used in the signal processing, was measured in laboratory and at 3 GHz, its attenuation

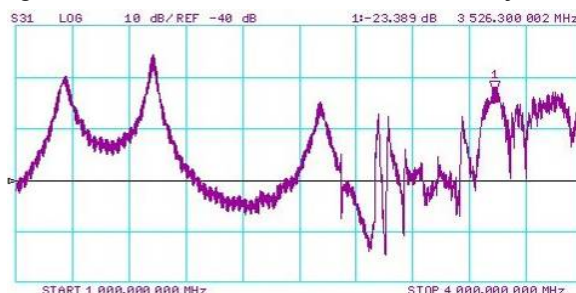is around -70 dB and around -60 dB at 4 GHz. These 'higher order modes' should be therefore well rejected.

Figure 9: Transmission measurement on the opposite antennas without beam

CONCLUSION

This BPM is designed to be used in a clean environment, at cryogenic or room temperature. Its main features are the small size of the RF cavity, a large aperture (78 mm) and an excellent linearity. The simulation results for the BPM system are very encouraging. The time resolution is lower than 50 ns and the theoretical resolution is around 0.35 μm. The preliminary measurements on the BPM show a very good agreement with the theoretical analysis. To get a better evaluation of noises, once all the electronics system is integrated, a noise measurement will be undertaken. Moreover, in August 2006, the BPM will be calibrated and the first tests with the beam will start at room temperature. This BPM appears as a good candidate for being installed in the XFEL and ILC cryomodules.

ACKNOWLEDGMENTS

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