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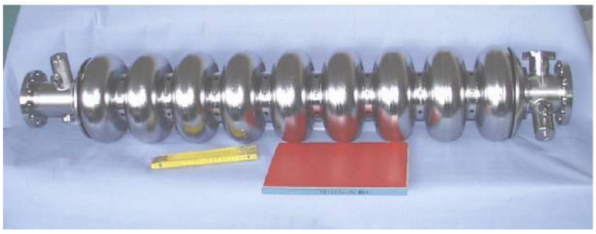


WP11 (Beam diagnostics)
The Re-entrant BPM

S.Chel, G Congretel, M. Jablonka, M. Luong, C. Magne, C. Simon
CEA, Saclay, France

Abstract

This report presents a re-entrant beam position monitor (BPM), developed at Saclay, in the framework of CARE/SRF. It gives the mechanical and RF characteristics of this system. The re-entrant BPM is used for the beam-based alignment and feedback systems, which are essential for the operation of the future colliders. This system can be operated at cryogenic or room temperature and is being tested at DESY. The simulations predict a good resolution (around 1 µm) and a high time resolution (around 10 ns).

Introduction

In the framework of CARE/SRF, the task of CEA is the design, the fabrication and the full test of high resolutions re-entrant BPM in collaboration with DESY.

A BPM is a device that determines the beam position in accelerators. The re-entrant BPM is composed of a RF cavity with four feedthroughs, an analogue and digital electronics to calibrate the system and interface to the control system. This BPM combines high resolutions (“position” resolution and time resolution) with wideband response. It is specially designed for the very high intensity short bunches of collider linacs and for beam-based alignment and feedback systems which are essential for the operation of the future colliders.

An existing re-entrant BPM has already operated at 2K inside the capture cavity cryostat (ACC1) on the TESLA Test Facility 2 (TTF2). The Figure 1 shows this unit before insertion into the cryomodule.

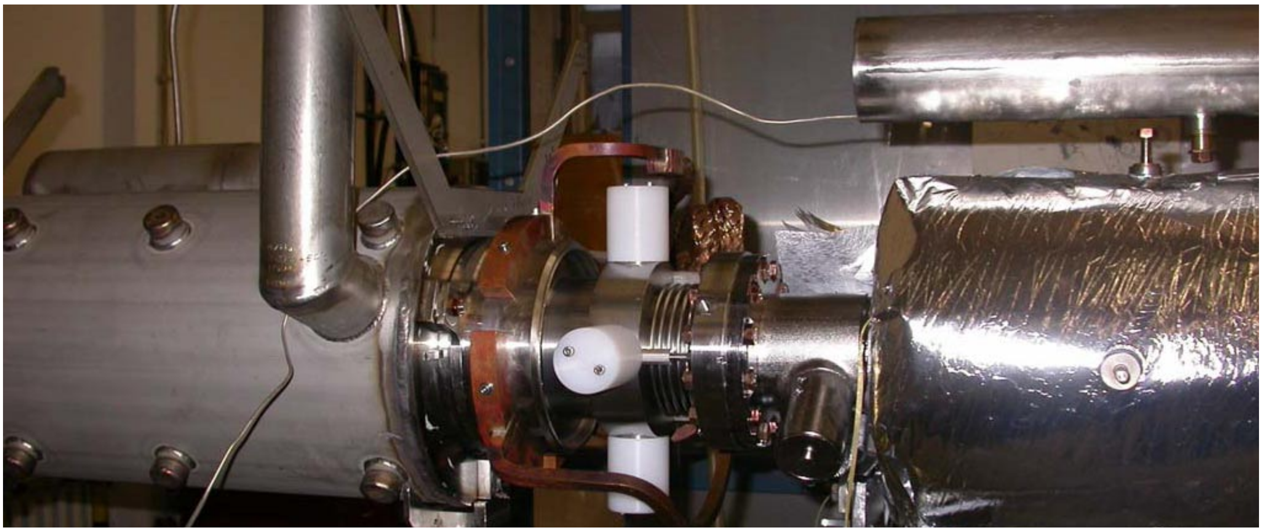


Fig. 1: BPM insert before installation inside tunnel, adjacent to the accelerating cavity. Four feedthroughs are protected by plastic cylinders during mounting.

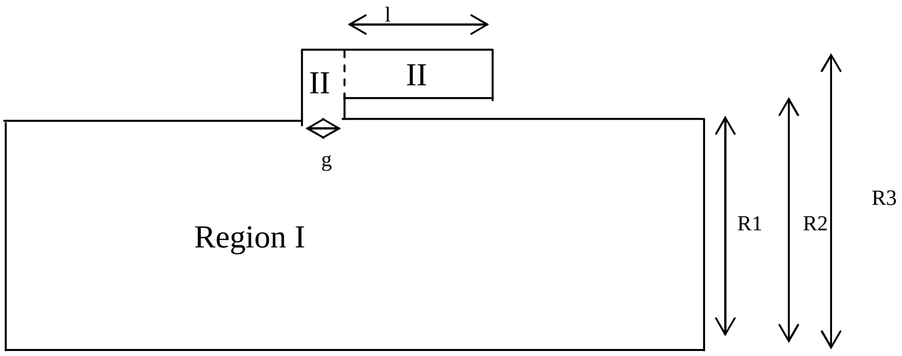
Some tests of the BPM in ACC1 were made at room temperature and showed that the resolution was around 10 µm ([2]). Measurements with the TTF2 beam showed that a “blind” zone existed in a radius of about 50µm around the axis, due to poor rejection of the common mode, as confirmed by simulations. The new development will fix this problem, and improve the resolution to 1 µm which is necessary for TESLA.

A new design and new electronics are presented to have some higher resolutions and work at cryogenic and room temperatures. They will be tested at DESY in Hamburg. With this new system the time resolution should be around 10 ns, and the resolution (minimum position difference than can be resolved - rms value) is expected around 1 µm.

BPM in ACC1

Design of the BPM in ACC1

The re-entrant coaxial cavity is arranged around the beam tube and forms a coaxial line which is short circuited at the downstream end. It consists in three distinct regions: beam tube (I), gap (II), coaxial cylinder (III) (Fig. 2).



l	50 mm
g	8 mm
R1	39 mm
R2	41.5 mm
R3	49.5 mm

Fig. 2: Geometry of the re-entrant cavity.

As the Figure 2 shows, the beam pipe radius is 39 mm and the gap (g) of the re-entrant cavity is 8 mm. This cavity has a small size and a cylindrical symmetry which allows a high precision of the machining. This BPM is composed of a mechanical structure with four orthogonal feedthroughs. The fixing of the antenna tips to the inner diameter of the cavity over coupled the cavity.

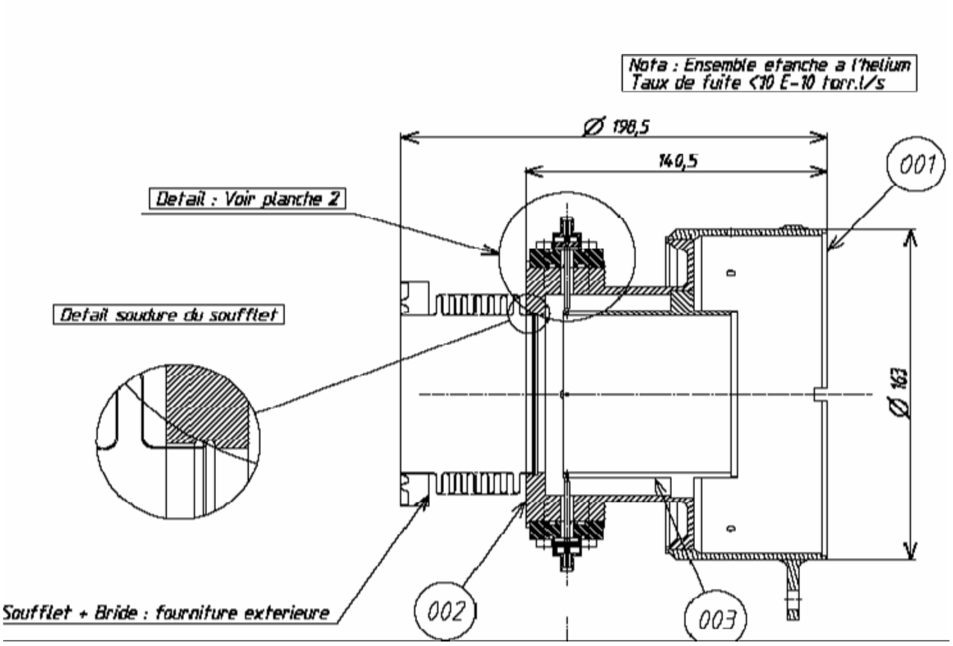


Fig.3: Drawing of the re-entrant cavity in ACC1 on TTF2

Passing through this cavity, the beam excites electro-magnetic fields (resonant modes), which are coupled by four feedthroughs to the outside: two of them determine the x position and two others the y-position. The signal voltage of the monopole mode is proportional to beam intensity and does not depend on the beam position. The dipole mode voltage is proportional to the intensity and to the distance of the beam from the centre axis of the monitor. All modes of the cavity which have an eigen frequency higher than the beam pipe TE11 mode cut off frequency (2.25 GHz) are damped, so their contribution is negligible and the linearity of the measurement is ensured.

Before determining the performances of the system, the time resolution and the resolution, the RF characteristics of this cavity have to be analysed. The cavity, which is in ACC1, was simulated with HFSS (Ansoft Corporation) and the RF characteristics of this cavity are given by the Table 1.

	BPM in ACC1			
	F (GHz)	**Q_l**	**R/Q** at 5mm of the center of the cavity	**R/Q** at 10mm of the cavity
Monopole mode	1.58	2.15	20.2 Ω	20.4 Ω
Dipole mode	2.01	4.11	0.53 Ω	2.2 Ω
Quadrupole mode	2.25	0.97	0.01 Ω	0.015 Ω
Parasitic dipole mode	2.30	1	0.3 Ω	1 Ω
Parasitic monopole mode	2.34	1.02	3.7 Ω	4.1 Ω

Tab. 1: RF characteristics of the cavity in ACC1

Q is determined by HFSS with matched feedthroughs in eigen solver mode. With Matlab and the HFSS calculator, we computed R/Q ratio (R: the Shunt impedance and Q: quality factor). It’s determined by:

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

with $V = \left|\int E(z)*e^{jkz}\,dz\right|$ where k= w/c

and W: the stored energy in the mode $W = \left|\frac{\varepsilon_0}{2}\iiint \left|E*E^*\right| d\tau\right.$

The simulation showed:

- The re-entrant cavity has two monopole modes and two dipole modes. When the cavity without feedthroughs is simulated with HFSS, only one monopole mode and one dipole mode exist. A simulation of one feedthrough, in driven mode, showed that a resonant mode exists in feedthroughs (Fig.4). The minimum standing wave is found around 1.3 GHz. The parasitic modes can be a combination of this resonant mode (1.3 GHz) with the first monopole and dipole modes.

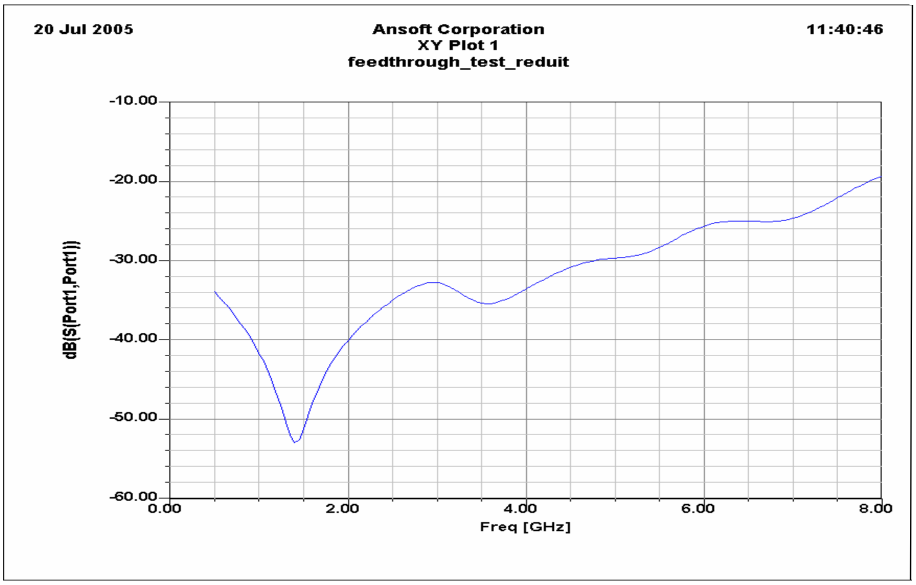


Fig. 4: S11 of one feedthrough simulated with HFSS in driven mode

- The coupling is very high, the first monopole and dipole modes have respectively a quality factor Q =2 and Q=4. The signals are spread out in spectrum, the distinguishing of the monopole and dipole mode is not easy and the monopole signal is not, efficiently, rejected.

Signal processing for the BPM in ACC1

The four pickups catch the signal of the displaced beam, then this signal is transferred to electronics to detect it. Signals detecting electronics extracts the beam position (displacement) and delivers this information to the acquisition board. The chosen measurement frequency, for the signal processing, is 650 MHz because it is a multiple of the repetition bunch frequency (216.66 MHz) on the first TTF injector. It is defined by a Bessel bandpass filter.

The signal processing of the re-entrant BPM in ACC1, is composed of a 180° hybrid junction, which is connected to each pair of opposite antennae with 33 m of semi-rigid cables. It yields the sum and the difference of RF voltages proportional to the beam current and position. These RF signals are then filtered, amplified and demodulated with a synchronous detection. The sum signal is used as a local oscillator signal for the mixer. The acquisition is done either by standard COMET boards of the TTF control system, or by dedicated boards for the other applications. Two boxes compose the electronics of the BPM in ACC1: the calibration box (Figure 5) and the synchronous detection box (Figure 6).

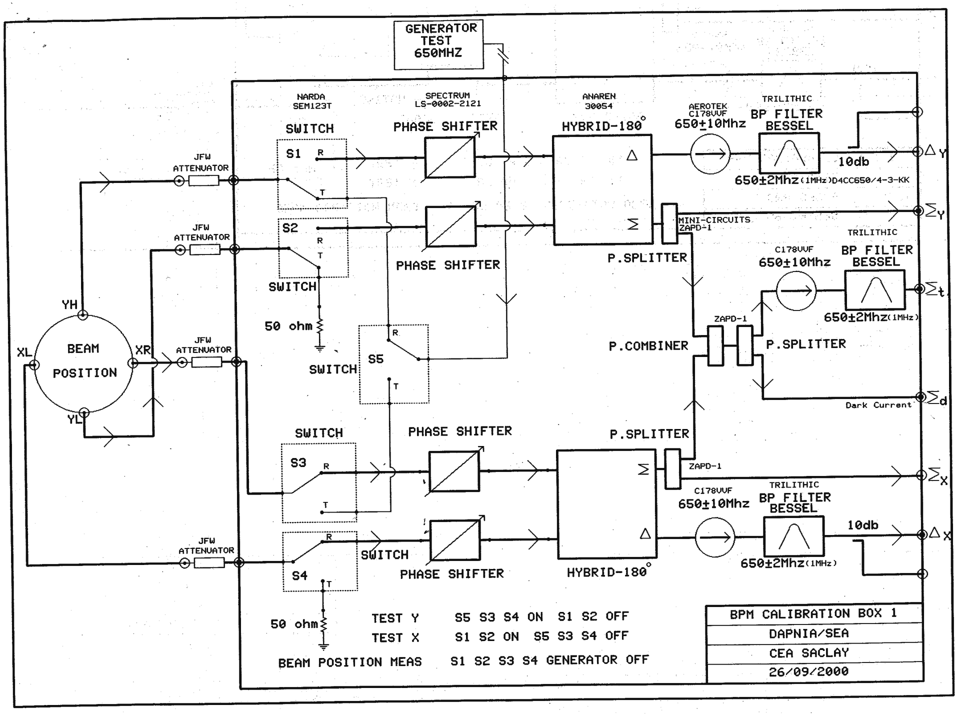


Fig.5: Calibration box of the BPM in ACC1

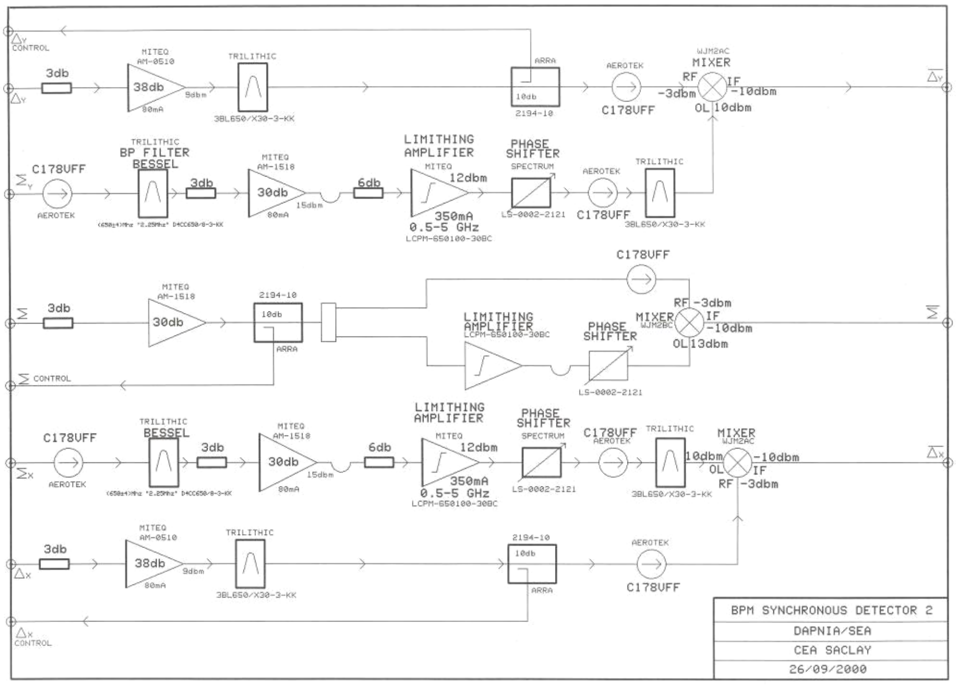


Fig.6: Synchronous detection box of the BPM in ACC1

To assess the performances of system, the model (cavity+signal processing) was elaborated with Mathcad. The model for the re-entrant cavity is a resonant R L C circuit; the impulse response of the monopole and dipole modes depends on R/Q, Q, and f. The transfer functions of different electronics elements are used and combined to have the plots of the output voltage (after detection) as a function of the position of the beam (Fig. 7).

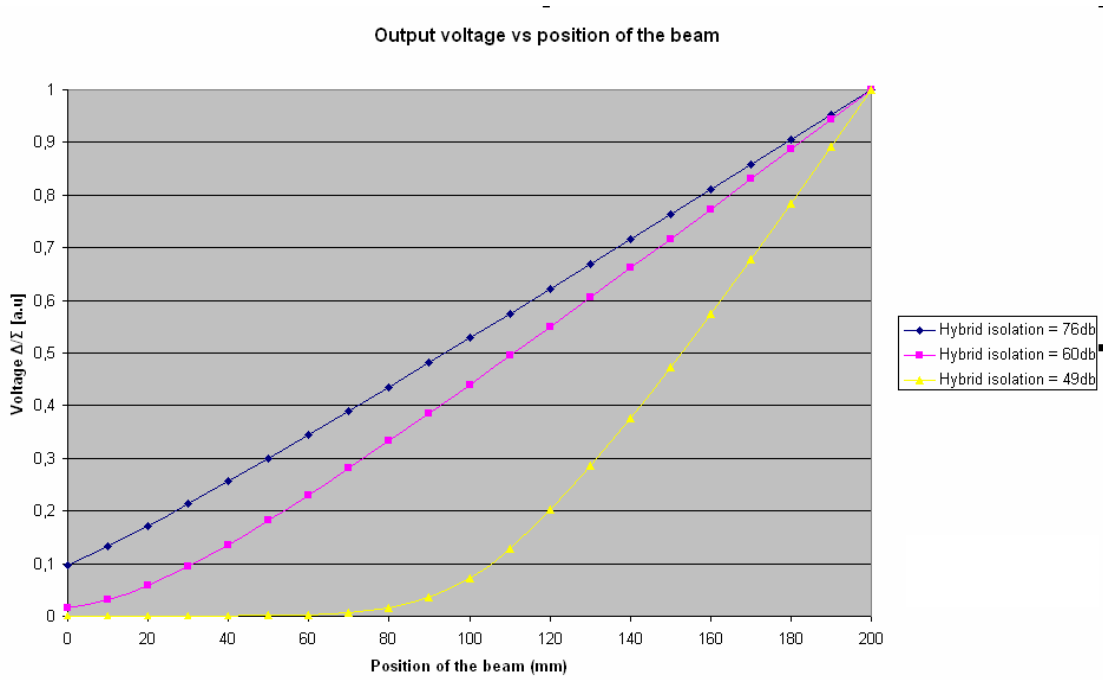


Fig. 7: Output voltage (after detection) vs position of the beam

In these simulations, we detect the maximum of the Δ and Σ signals and therefore the same sampling point in time isn't used. We note that the limit for high resolution comes from the isolation between the Σ and Δ channels of the hybrid coupler. Indeed, the monopole signal is still important at the measurement frequency (f=650 MHz). The "blind" zone is around 40µm for an isolation of 60 dB and 100 µm for an isolation of 49 dB. An isolation of 76 dB will be difficult to obtain during the calibration of the BPM system. That is why another part of the activity has been to start designing a new version of the beam position monitor to obtain a high resolution around 1 µm.

New BPM

New design of the BPM cavity

The mechanical structure for this new BPM is quite similar to the BPM in ACC1 (Fig. 8). It should have an overall length of 170 mm. Just the gasket changed: it will be a conflat gasket. This prototype will be used for warm tests with beam in TTF2 and to validate the fabrication process: brazing, heat treatment, cleaning and dust free mounting. A second prototype will have DESY-type flanges to be mounted inside a cryomodule.

The position and the design of feedthroughs changed (Fig. 9). Indeed, a critical point was the feedthrough fragility, 50% of the feedthroughs had to be rejected. With the new design, the feedthroughs are simpler and more robust. Moreover, this new design has no resonant mode. To have a higher Q and therefore a longer signal in time, the feedthroughs moved from 31.5 mm in the re-entrant part. With this moving, the distinguishing of the monopole and dipole signals is clearer and the rejection of the monopole signal is better.

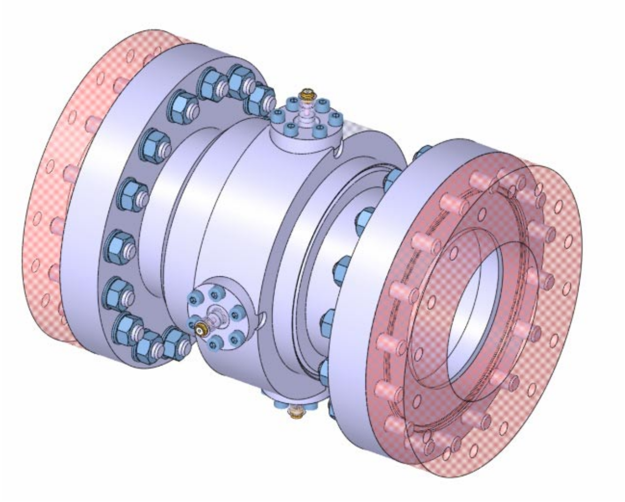


Fig. 8: Design of the new cavity BPM

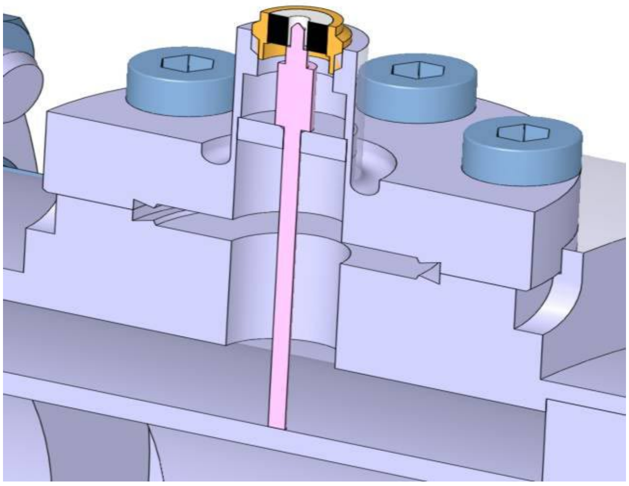


Fig. 9: Design of the new feedthrough

One of the biggest problems on the cavity in ACC1 was the cleaning. As the BPM is designed to be used in a clean environment and at the cryogenic temperatures, twelve holes of 5 mm diameter were drilled at the end of the re-entrant part. A simulation was carried out to check that the RF characteristics of the re-entrant cavity do not change. Cleaning tests were successfully preformed at DESY and validated the system for the cleaning.

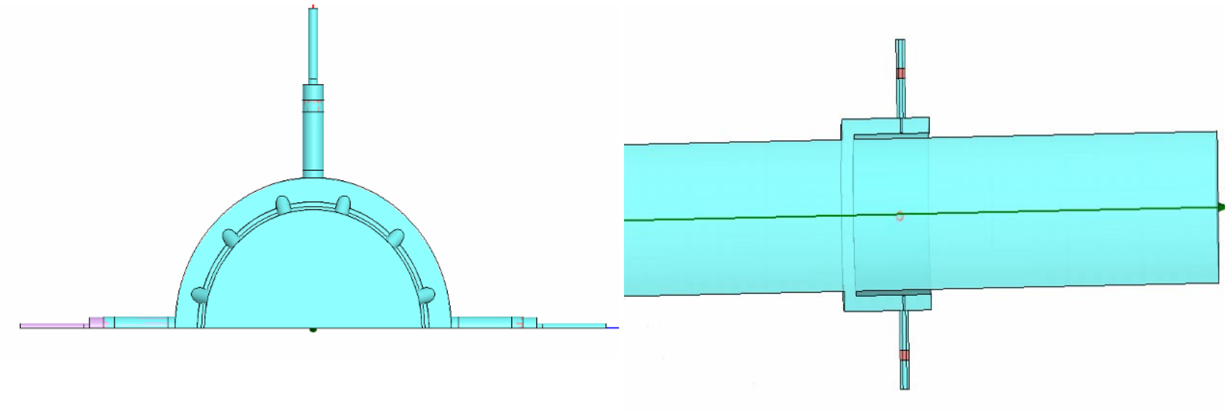


Fig. 10: New design of the re-entrant cavity used for HFSS.

The simulation, with HFSS, of the new design (Fig. 10) gives the RF characteristics (Tab. 2).

	New BPM			
	F (GHz)	Q	R/Q at 5mm of the center of cavity	R/Q at 10mm of the center of cavity
Monopole Mode	1.25	24	13 Ω	13 Ω
Dipole Mode	1.72	51.4	0.25 Ω	1.11 Ω

Tab. 2: RF characteristics of new BPM

The choice of resonant mode frequencies was determined according to the 180° junction hybrid available on the market. The resolution around 1 µm but also the mechanical feasibility of the structure determined the quality factors, Q, of the monopole and dipole modes. They are not able either to be too high to keep a time resolution around 10 ns or too low to have a centuring accuracy better than 1 µm.

One of the most important parameters for a BPM is the time resolution also called damping time. It is defined by the bandwidth of the BPM:

$$\tau_{110} = \frac{1}{\pi * BW} \quad \text{with} \quad BW = \frac{f_{110}}{Q_{l110}}$$

f_{110}: frequency of the dipole mode
Q_{l110}: loaded quality factor for the dipole mode

The time resolution is 9.5 ns for the new re-entrant BPM. It is lower than the separation between bunches on TTF2. The bunch to bunch measurement is therefore possible.

Signal processing of the new BPM

The signal processing of the new re-entrant BPM is composed of a 180° hybrid junction, which is connected to each pair of opposite antennae with 33 m of semi-rigid cables. The rejection of the monopole mode proceeds in three steps. One is made by the new hybrid coupler, which has more than 25 dB of isolation in the band 1-2 GHz, the second with the pass band filter and the third with the synchronous detection. On the Δ channel, the monopole signal is rejected and on the Σ channel, it is the dipole signal. The noise is limited by the bandpass filters. The one on the Δ channel has to have the center frequency of the dipole mode and the one on the Σ channel the center frequency of the monopole mode. To perform the synchronous detection, the signals must be amplified. The 9 MHz reference signal, from the control system on TTF2, combined with some PLLs generates some signals at the monopole and dipole modes frequencies. These ones are used as local oscillators for the mixers. Some phase shifters, controlled by the digital electronics, adjust the PLL signals, which have to be in phase with the signals coming from the hybrid. The digital electronics, also, makes the sampling, the calibration of the system and the control-command interface. The signal on the Σ channel is used in order to normalize the Δ signal, which determines the position of the beam. This normalization is, also, made by a digital electronics. The schematic of the new electronics is shown figure 11.

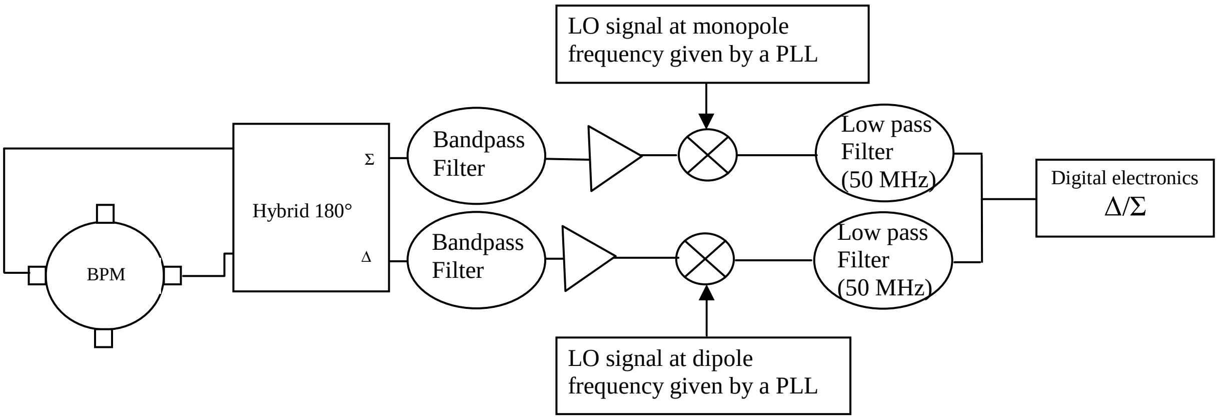


Fig. 11: Electronics of the new system

To assess the performances of this new system, the model (cavity+signal processing) was simulated with Mathcad. The output voltage vs position of the beam of the new system is plotted figure 12.

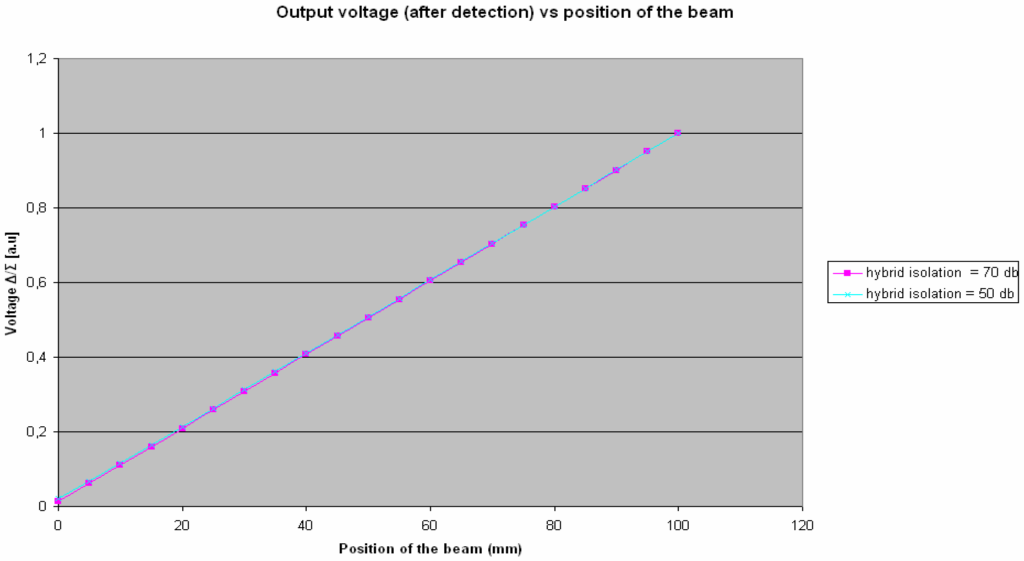


Fig.12: Output voltage (after detection) vs position of the beam

In the simulation, with this new design of BPM, the Pearson coefficient is of 1 and the centering accuracy is 0.5 µm. We note that the isolation between the Σ and Δ channels of the hybrid coupler has an influence which is less important than the first system. Indeed, the rejection of the monopole signal is determined by 3 parameters:

- The isolation of the hybrid is more than 25 dB in band 1-2 Ghz. It can be optimized at the frequency of the dipole mode with attenuators and phase shifters to have an isolation around 50 dB.
- The bandpass filter, on the delta channel, which rejects the monopole mode.
- And the synchronous detection, on the delta channel at the frequency of the dipole mode.

The chosen amplifiers are with a low noise because the resolution depends on the noise.

With the Mathcad model, the influence of the length of cables on the resolution can be studied. For different lengths of cables, the output voltage vs the position of the beam was plotted (Fig. 13).

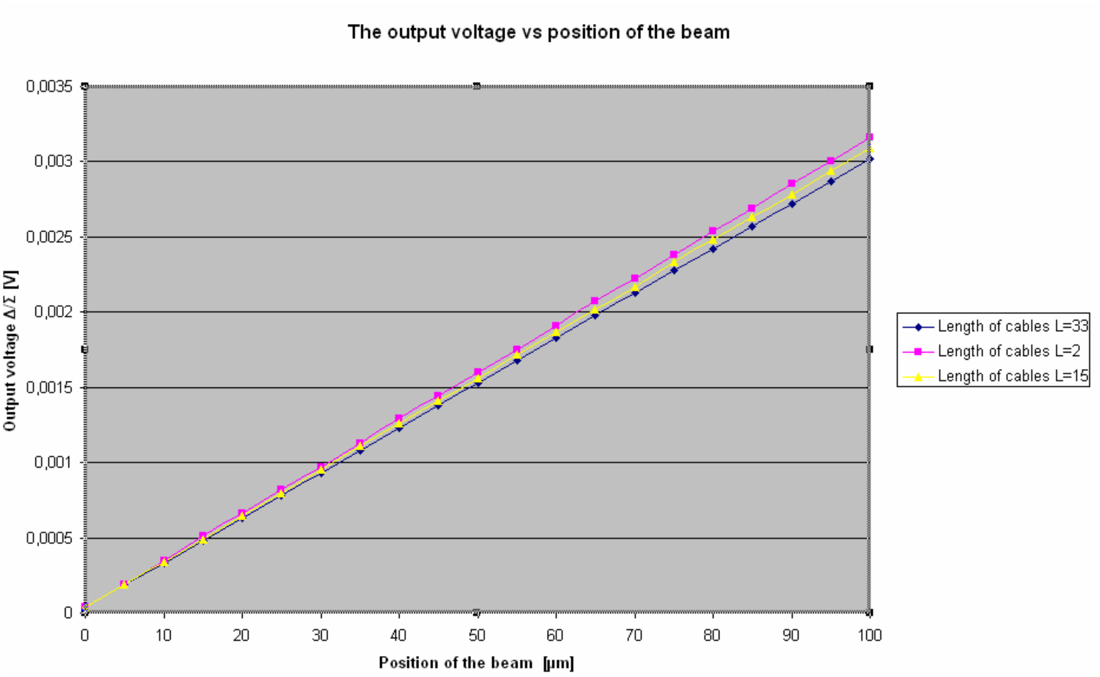


Fig. 13 Output voltage vs position of the beam for different length of cables

We note that the length of cables influences the slope of the characteristic plot (Fig. 11) and the resolution consequently. The influence is tiny. Indeed, the difference between a 2 m cable and 33 m cable is around 5%. The electronics could be outside but close to the tunnel to reduce the length of cables because putting the electronics in the tunnel generates a problem for the access during the calibration or maintenance. With this new system, a resolution around 1 µm should be reached.

Future planning:

This preliminary analysis predicts that a good resolution (around 1 µm) and a high temporal resolution (around 10 ns) are possible for the re-entrant BPM.

The status and planning about the re-entrant BPM are the next:

- Design and mechanical drawings of the BPM cavity are ready.
- Design of the RF electronics and signal processing are made.
- Signal processing board will be fabricated for December 2005.
- A BPM cavity will be fabricated at the end of 2005.
- Tests on the electronics will be made at the beginning of 2006.
- Preliminary tests on this new BPM to verify RF characteristics of the cavity and validate the fabrication process: brazing, heat treatment, cleaning and dust free mounting, will be made at the beginning of 2006.

Acknowledgements

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