Development of a new Beam Position Monitor for the FLASH and XFEL

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Introduction

❖ A re-entrant beam position monitor (BPM) is developed by the CEA/Saclay in collaboration with DESY in the European framework of CARE/SRF/WP11 program.

❖ Task of the CEA is the design, fabrication and full test of high resolution re-entrant BPM.

❖ System can be used in a clean environment, at cryogenic temperature.

❖ Mechanical and signal processing designs are a compromise to get:

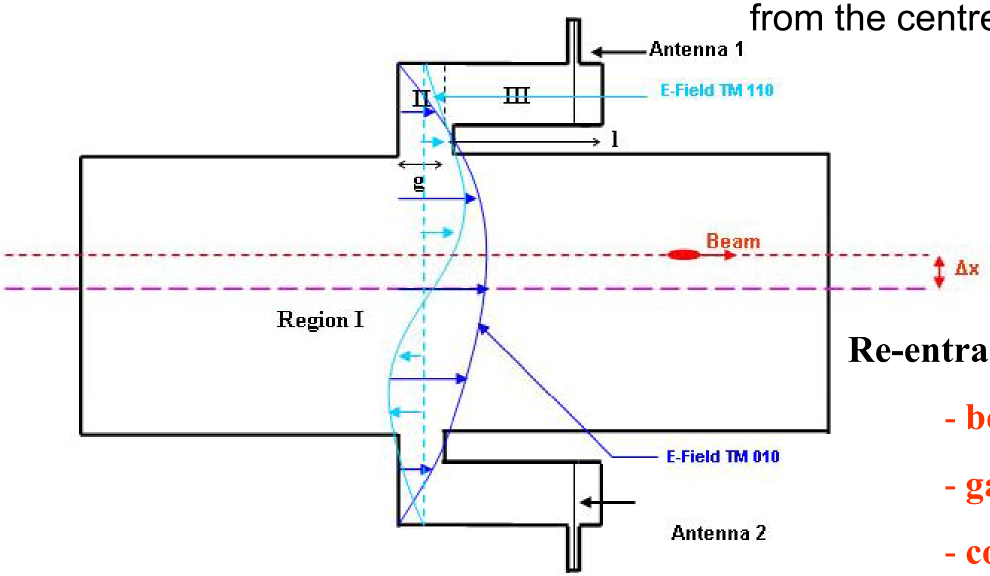
- high position resolution (better than 10 µm)
- possibility to perform bunch to bunch measurements for the X- FEL at DESY and the ILC.

Re-entrant Cavity BPM (1)

- Coaxial re-entrant cavity has been chosen for the beam orbit measurement because of its mechanical simplicity and excellent resolution (concept from CERN).

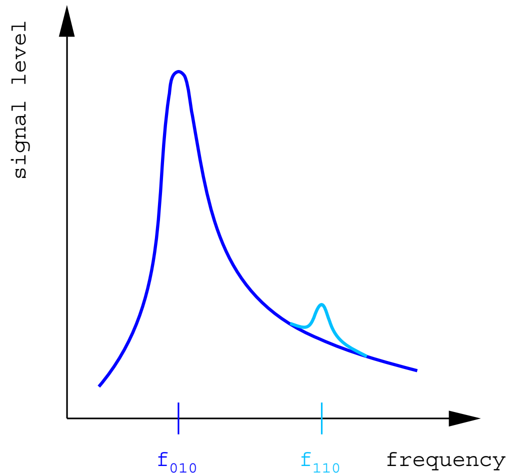
- The re-entrant BPM is composed of a mechanical structure with four orthogonal feedthroughs (or antennas).

- Passing through the cavity, the beam excites some electromagnetic fields (resonant modes)
  - two main modes : - monopole mode (proportional to beam intensity and does not depend on the beam position : normalization)
    - dipole mode (proportional to the distance of the beam from the centre axis of the monitor)



Re-entrant Cavity :

- **beam pipe (I),**
- **gap (II),**
- **coaxial cylinder (III)**



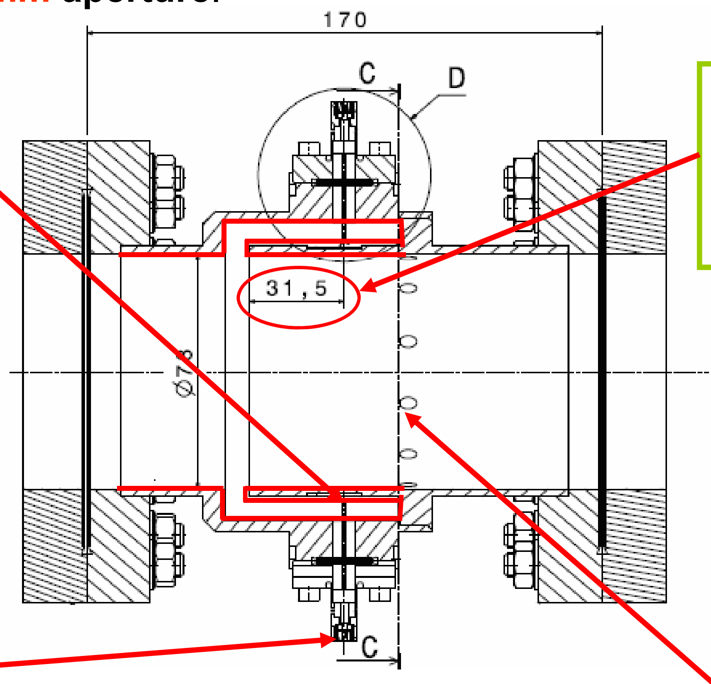
Re-entrant Cavity BPM (2)

- It is arranged around the beam tube and forms a coaxial line which is short circuited at one end.
- The cavity is fabricated with stainless steel as compact as possible :

170 mm length (minimized to satisfy the constraints imposed by the cryomodule)

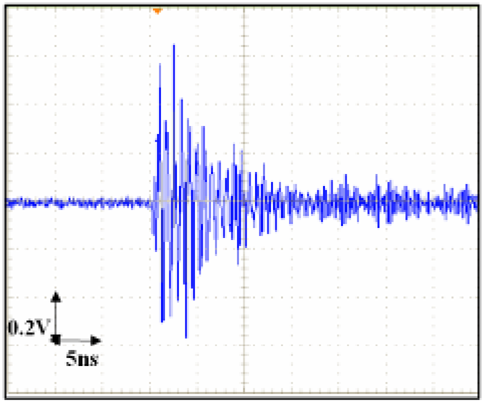
78 mm aperture.

Cu-Be RF contacts welded in the inner cylinder of the cavity to ensure electrical conduction.



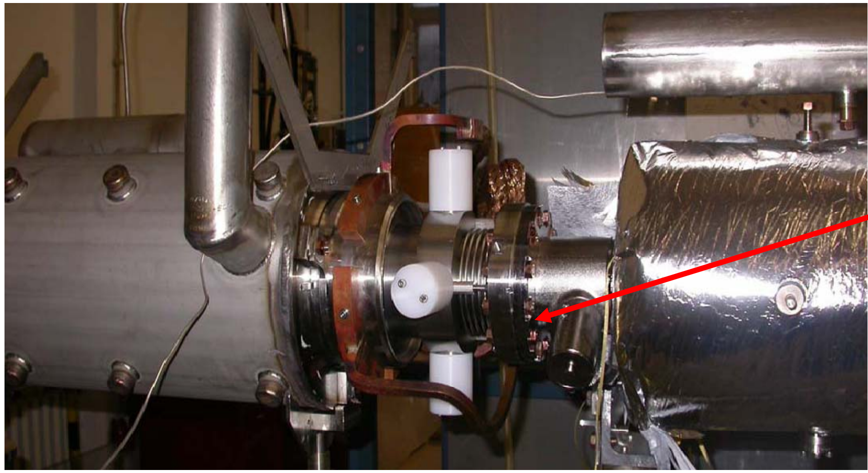
Feedthroughs are positioned in the re-entrant part to reduce the magnetic loop coupling and separate the main RF modes (monopole and dipole)

Twelve holes of 5 mm diameter drilled at the end of the re-entrant part for a more effective cleaning (Tests performed at DESY).



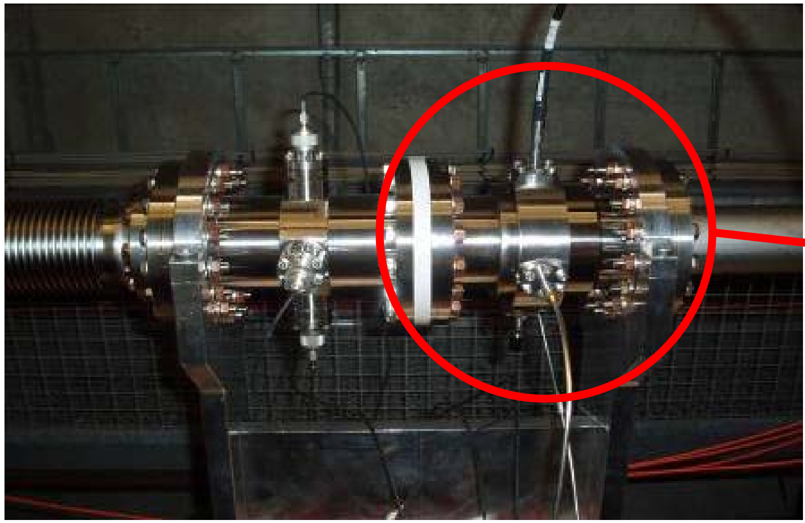
Signal from one pickup

Re-entrant Cavity BPM (3)



Re-entrant cavity BPM located at cryogenic temperature inside the cryomodule (ACC1).

Re-entrant cavity BPM installed in a warm section on the FLASH linac



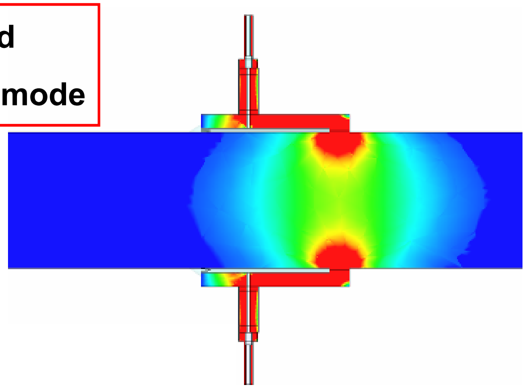
RF Characteristics of the BPM

- RF characteristics of the cavity: frequency, coupling and R/Q

Eigen modes	F (MHz)		Q_l		$(R/Q)_l$ (Ω) at 5 mm	$(R/Q)_l$ (Ω) at 10 mm
	Calculated with HFSS in eigen mode	Measured in the tunnel	Calculated with HFSS in eigen mode	Measured in the tunnel	Calculated	Calculated
Monopole mode	1250	1255	22.95	23.8	12.9	12.9
Dipole mode	1719	1724	50.96	59	0.27	1.15

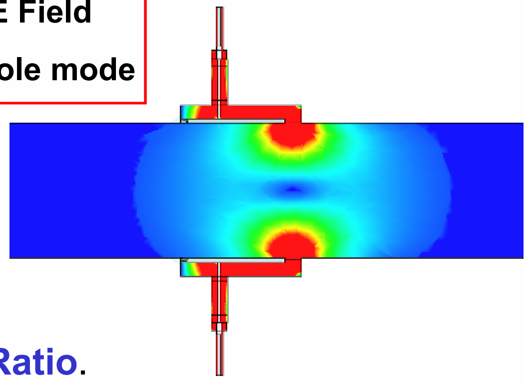
E Field

Monopole mode



E Field

Dipole mode



- With **Matlab and the HFSS calculator**, we computed **R/Q Ratio**.

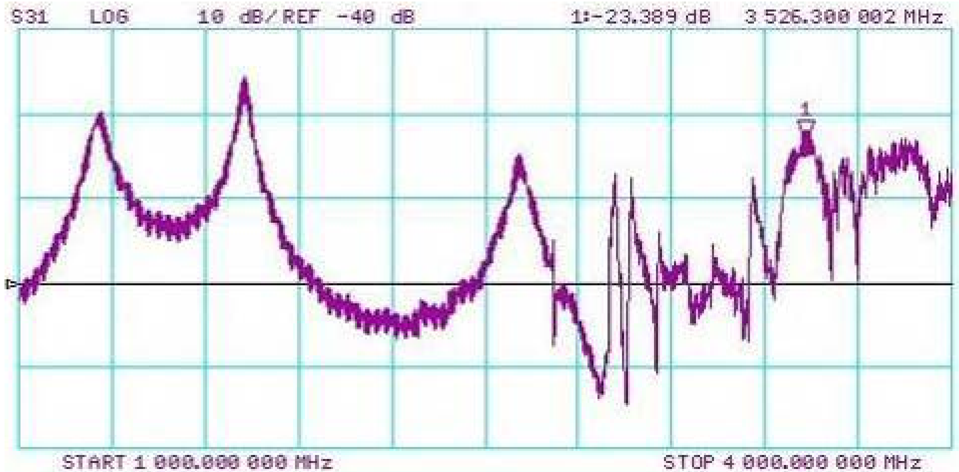
R: the Shunt impedance and Q: the quality factor

$$\frac{R}{Q} = \frac{V^2}{2 * \pi * f * W} \qquad V = \left| \int E(z) * e^{jkz} dz \right| \quad \text{and} \quad k=w/c$$

RF Measurements on the Cavity BPM

• The dipole mode orthogonal polarizations show slightly different eigenfrequencies; the relative difference is less than 2 per 1000.

• Frequencies and Q factor of modes existing in the cavity BPM were measured with network analyzer.



❖ First and second peaks are monopole and dipole modes.

❖ Others peaks are higher order modes which can propagate out of the cavity through the beam pipe. **Cut-off frequency of the beam pipe mode** TE11 is **2.25 GHz**.

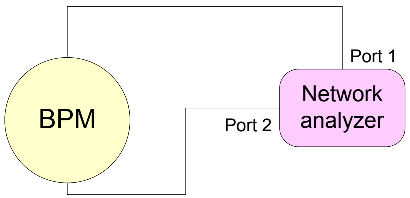
❖ 1.72 GHz band pass filter, used in the signal processing, has an attenuation around -70 dB at 3 GHz and around -60 dB at 4 GHz **=>** rejection of 'higher order modes'.

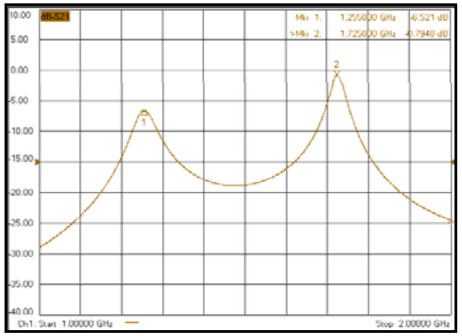
Cross Talk of the Cavity BPM

- **Due to tolerances in machining, welding and mounting, some small distortions of the cavity symmetry are generated**.

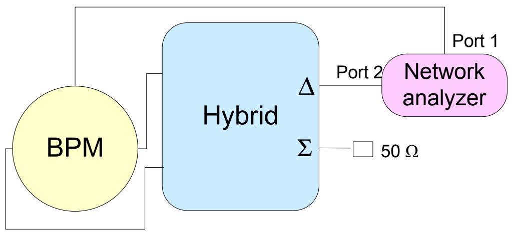
A beam displacement in the ‘x’ direction gives not only a reading in that direction but also a non zero reading in the orthogonal direction ‘y’.

This **asymmetry** is called **cross talk**.



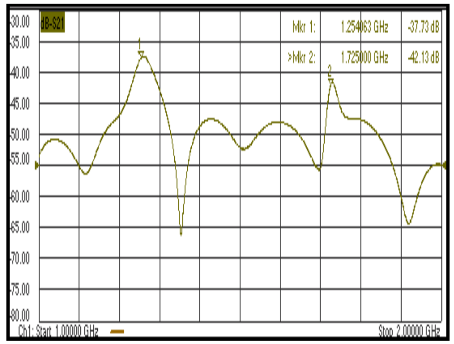


Monopole and dipole transmission measured by the network analyzer



Representation of the cross-talk measurement

Transmission of 2 antennas positioned at 90°



From those measurements, the **cross-talk isolation** value is estimated around 33 dB.

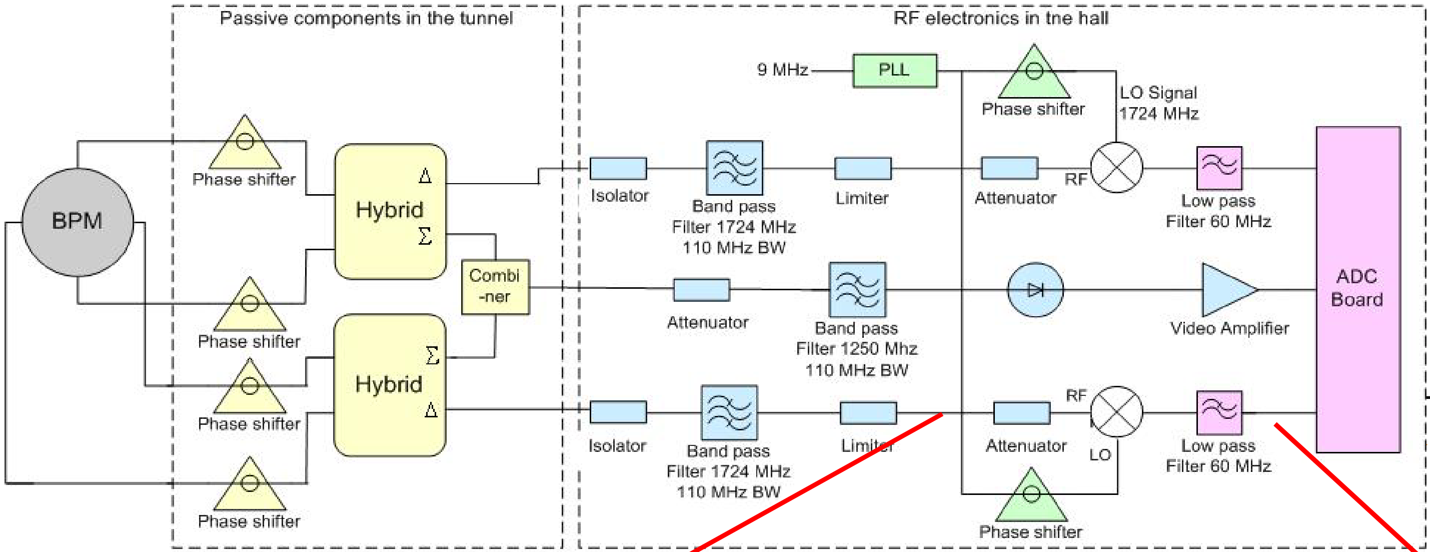
Signal Processing

➢ The rejection of the monopole mode, on the Δ channel, proceeds in **three steps** :

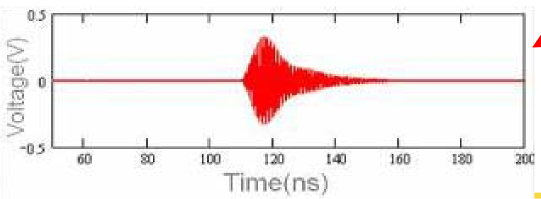
- a rejection based on a hybrid coupler having isolation higher than 20 dB in the range of 1 to 2 GHz.

- a frequency domain rejection with a band pass filter centered at the dipole mode frequency. Its bandwidth of 110 MHz also provides a noise reduction.

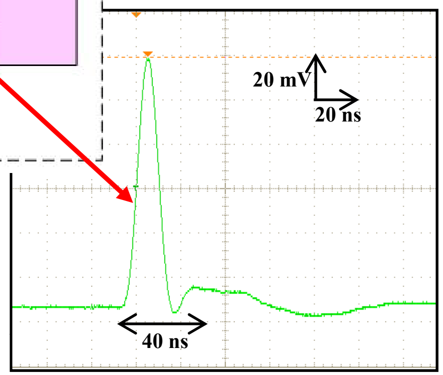
- a synchronous detection.



RF signal



IF signal behind Lowpass Filter on channel Δ



Resolution

❖ **Signal voltage determined by the beam's energy loss to the dipole mode.**

Dipole mode signal depends on frequency fi and external coupling Qi of this mode

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

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

Φ(t) = heaviside function, q = bunch charge, R0 = 50 Ω, (R/Q)i = coupling to the beam and ζi = 2 (dipole mode)

❖ **Noise** is determined by :

Thermal Noise : $P_{th} = k_b * T * BW$

kb = Boltzmann constant, BW (Hz) = Bandwidth, T (K) = Room Temperature.

Noise from signal processing channel : $P_n = NF * G * P_{th}.$

with $NF = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 * G_2} + \dots$

P_{th} = Thermal noise, NF=Total noise figure of the signal processing, Fi and Gi respectively the noise factor and the gain of component i.

Re-entrant Cavity installed at FLASH :

Δ Signal with 10 mm offset : 181 mV

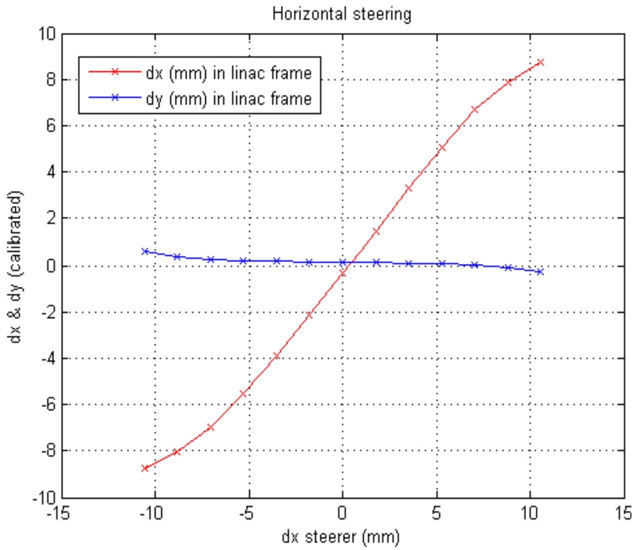
Noise: 6 μV (calculated)

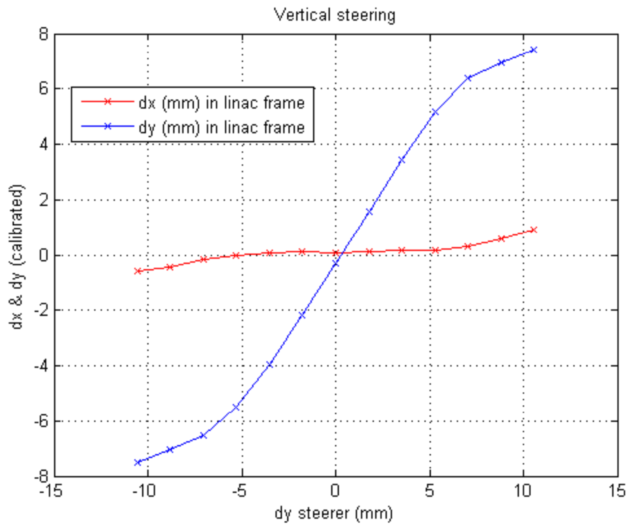
Environment Noise RMS: 66 μV (measured)

Beam tests on the BPM (1)

❖ To calibrate the BPM:

- Beam is moved with one steerer.
- Calculate for each steerer setting, the relative beam position in using a transfer matrix between steerer and BPM (magnets switched off to reduce errors and simplify calculation).
- Average of 500 points for each steerer setting.





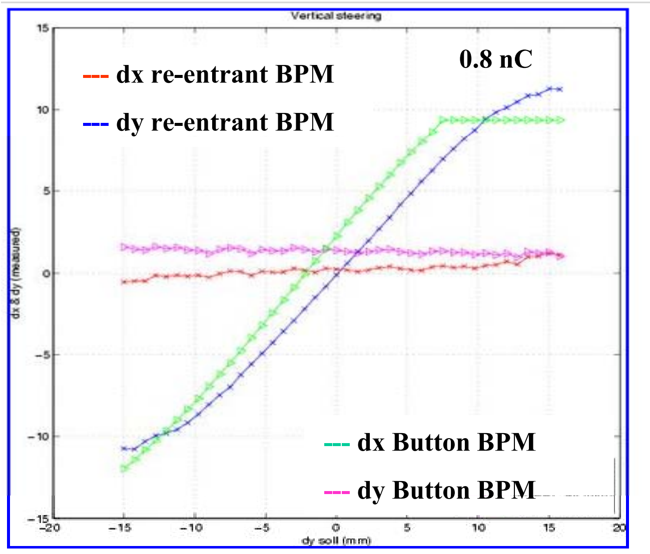
Calibration results from horizontal (left) and vertical (right) steering

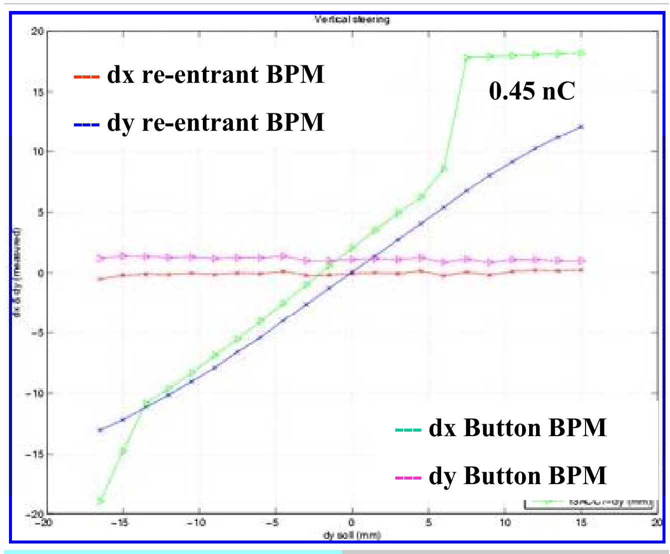
➡ **Good linearity in a range ± 5 mm**

➡ **RMS resolution: ~4 µm on the Y channel**
~8 µm on the X channel } **with 1 nC**

Beam tests on the BPM (2)

With an attenuator 6 dB on each channel





Good linearity : ± 10 mm @ 0.8 nC

± 15 mm @ 0.45 nC

Resolution measurement:

correlation of the reading of one BPM in one plane against the readings of all other BPMs in the same plane (using linear regression).

Charge	Resolution Re-entrant	Resolution Re-entrant+ 6 dB attenuator
1.0 nC	~ 4 µm	
0.8 nC		~ 12 µm
0.5 nC	~ 11.8 µm	~ 21 µm
0.2 nC	~ 30.1 µm	~ 55 µm

Time Resolution

➢ **Damping time** is given by using the following formula :

$$\tau = \frac{1}{\pi * BW}$$

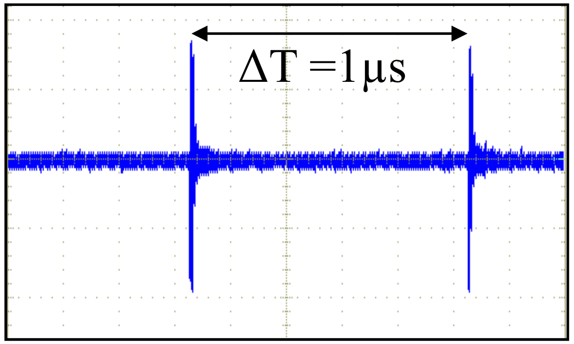
With $BW = \frac{f_d}{Q_{ld}}$

fd: dipole mode frequency
Q_ld: loaded quality factor for the dipole mode

➢ Considering the system (**cavity + signal processing**), the **time resolution** is determined, since the rising time to 95% of a cavity response corresponds to 3τ.

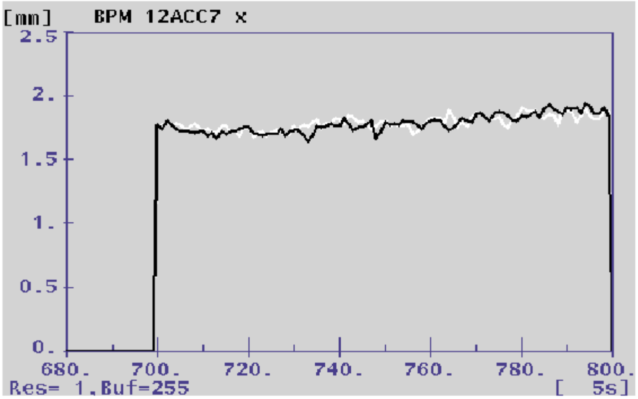
	Damping Time cavity only	Time resolution cavity + electronics
BPM	9.4 ns	40 ns

Time resolution for re-entrant BPM



RF signal measured at one pickup

100 bunches read by the re-entrant BPM



Possibility bunch to bunch measurements

Summary

❖ **High resolution re-entrant cavity BPM features:**

- **Effective in clean environment**
- **Operation at room and cryogenic temperature**
- **Large aperture of the beam pipe (78 mm)**
- **Position resolution around 4 µm measured with a measurement dynamic range around ± 5 mm**
- **Time resolution around 40 ns**
- **~ 20 BPMs will be installed in the XFEL cryomodules.**

❖ **This BPM appears as a good candidate for being installed in the ILC cryomodules.**

New Development of a re-entrant BPM

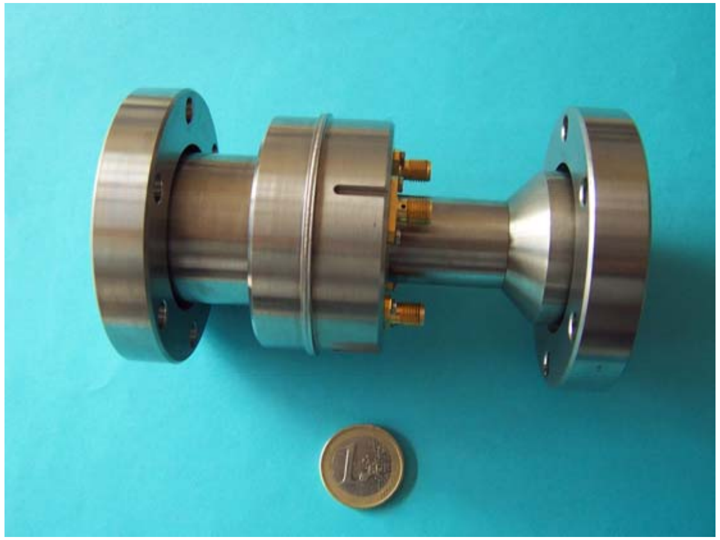
- BPM developed for the CTF3 probe beam CALIFES:

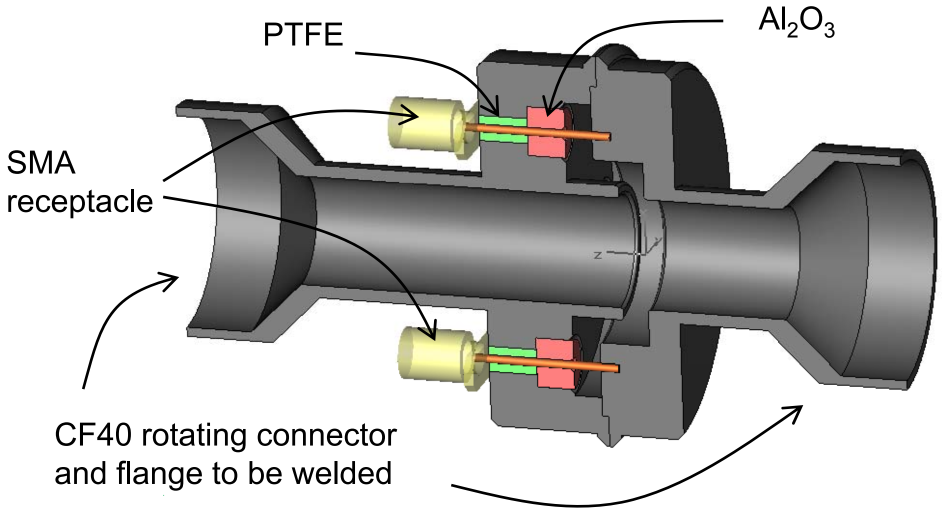
- designed with a large frequency separation between monopole and dipole modes, as well as a low loop exposure to the electric fields

- mechanical simplicity

- excellent resolution

- operated in single and multi-bunches modes





Acknowledgements

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Thank you for your attention

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