Beam Position Monitors using a reentrant cavity

C. Simon, M. Luong, D. Bogard, J. Novo, S. Chel,O. Napoly,
D. Roudier *CEA/Saclay/IRFU*
N. Rouvière, J-P Prestel *IPN/Orsay*
Nicoleta Baboi, Dirk Noelle, Nils Mildner *DESY*

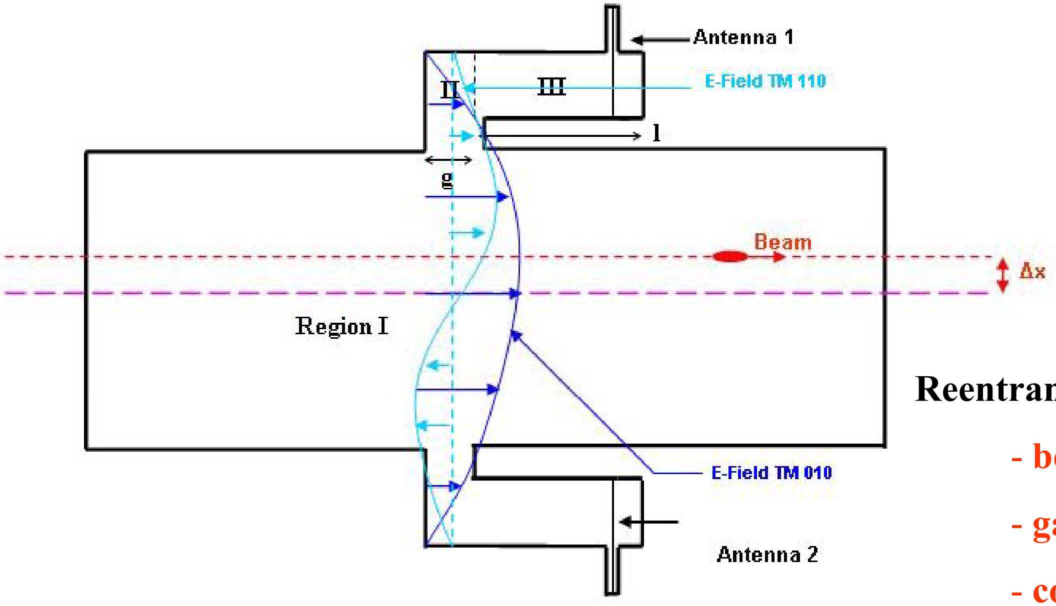
CLIC Meeting – 14-17 October 2008

Reentrant Cavity BPM

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

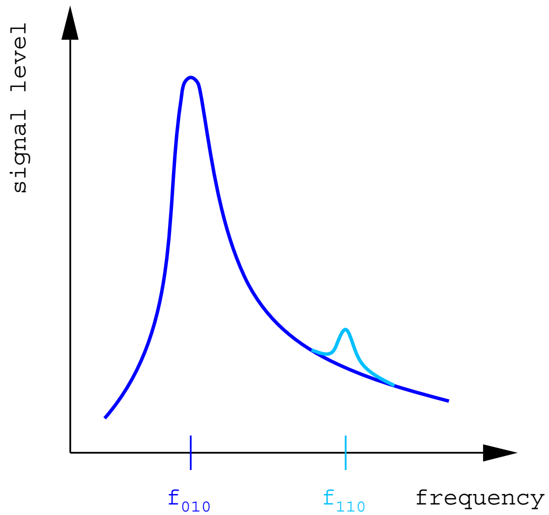
- It is arranged around the beam tube and forms a coaxial line which is short circuited at one end (concept from R. Bossart).

- 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)



Reentrant Cavity :

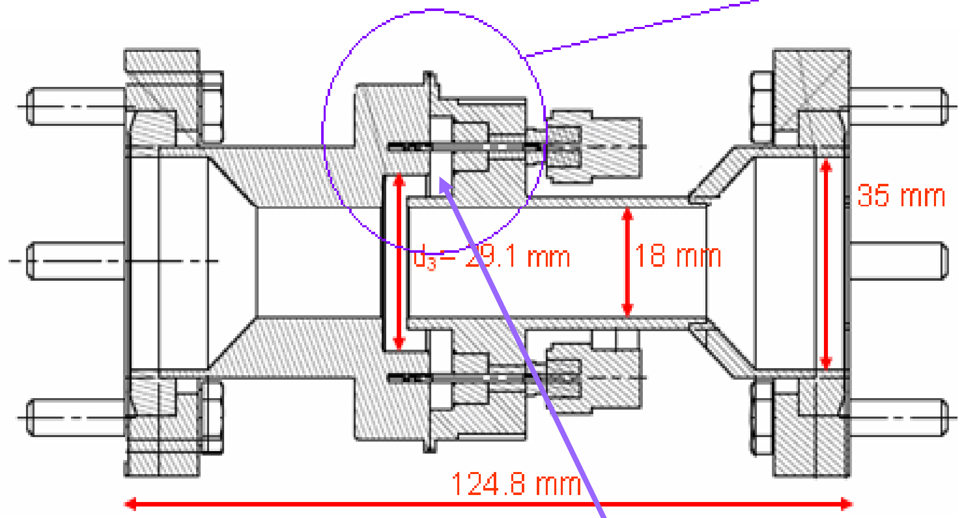
- **beam pipe (I),**
- **gap (II),**
- **coaxial cylinder (III)**

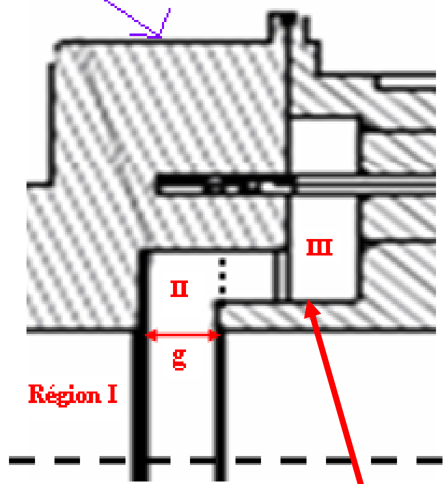


Reentrant Cavity BPM at CALIFES (1)

- Cavity BPM is designed for the **CTF3 probe beam (CALIFES)**
- It is operated in single and multi-bunches modes
- The cavity is fabricated with titanium and is as compact as possible :

~125 mm length and 18 mm aperture
4 mm gap





Reentrant Part

Bent coaxial cylinder designed to have:

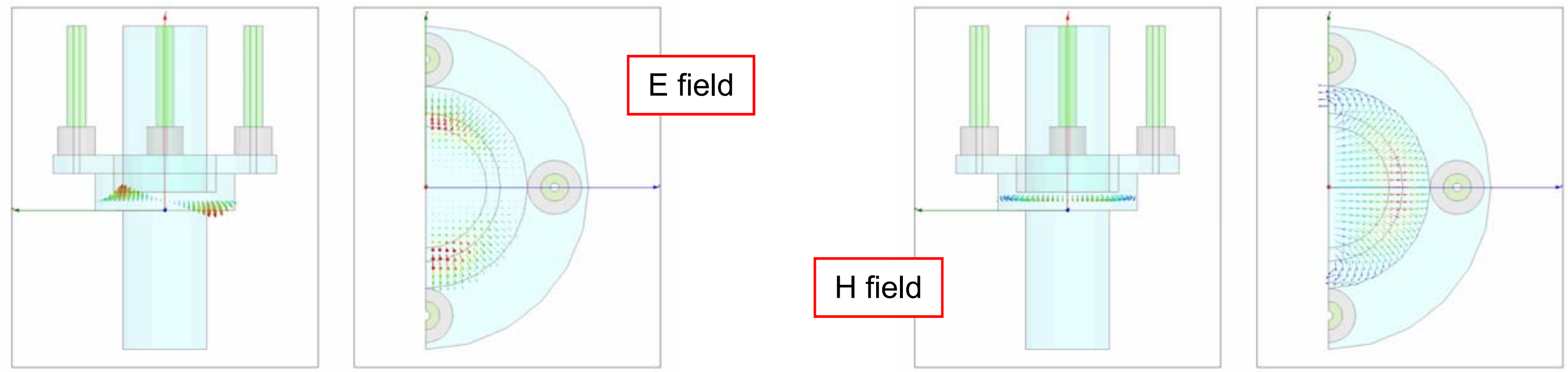
- a large frequency separation between monopole and dipole modes

- a low loop exposure to the electric fields

RF Characteristics

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

Eigen modes	F (MHz)		Q_l		(R/Q) (Ω)	(R/Q) (Ω)
	Calculated with HFSS in eigen mode	Measured in the CLEX	Calculated with HFSS in eigen mode	Measured in the CLEX	Calculated Offset 5 mm	Calculated Offset 10 mm
Monopole mode	3991	3988	24	26.76	22.3	22.2
Dipole mode	5985	5983	43	50.21	1.1	7



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

This asymmetry is called cross talk and the isolation is evaluated > 26 dB.

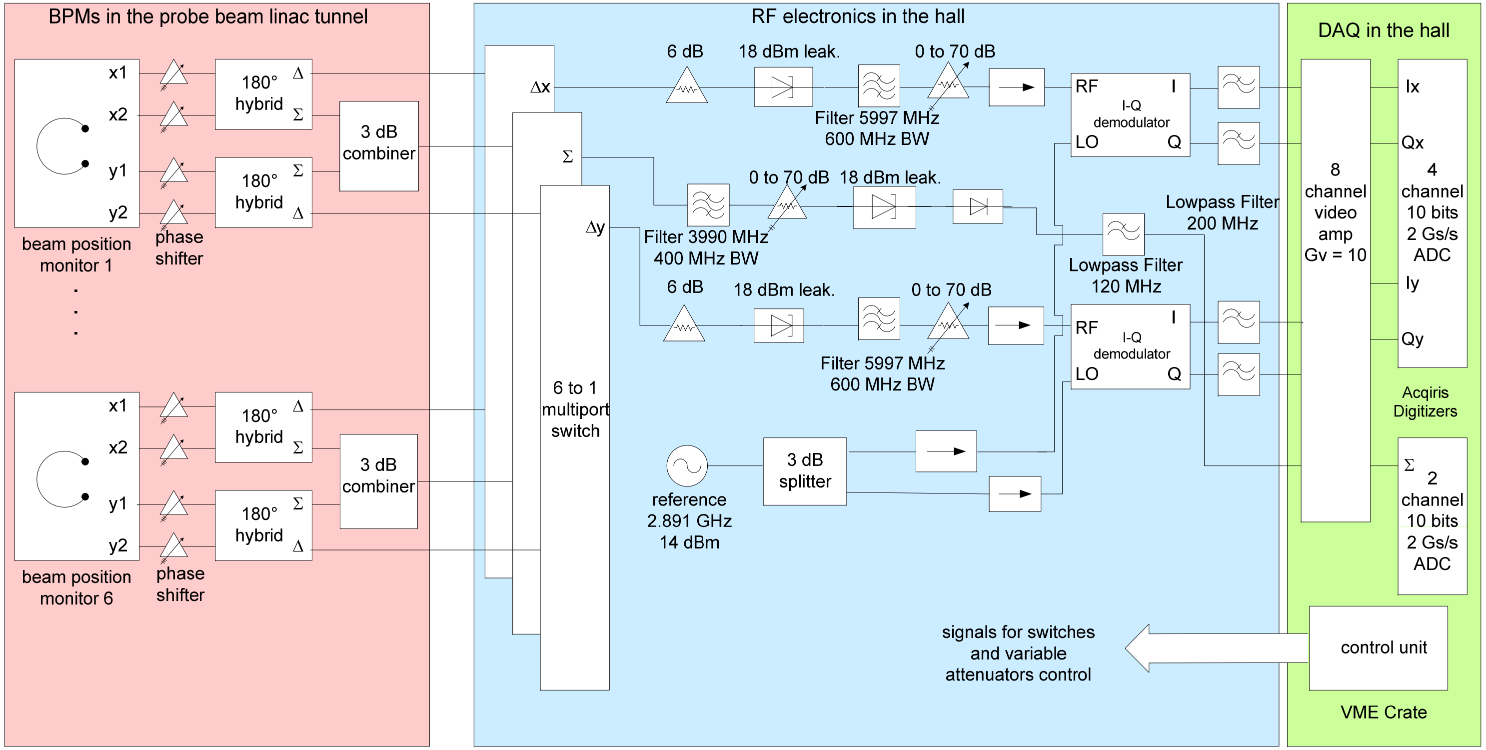
Signal Processing - CALIFES BPM

➢ 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 18 dB in the range of 2 to 8 GHz.

- a frequency domain rejection with a band pass filter centered at the dipole mode frequency. Its bandwidth of 600 MHz also provides a noise reduction.

- a synchronous detection carried out with an I/Q demodulator.

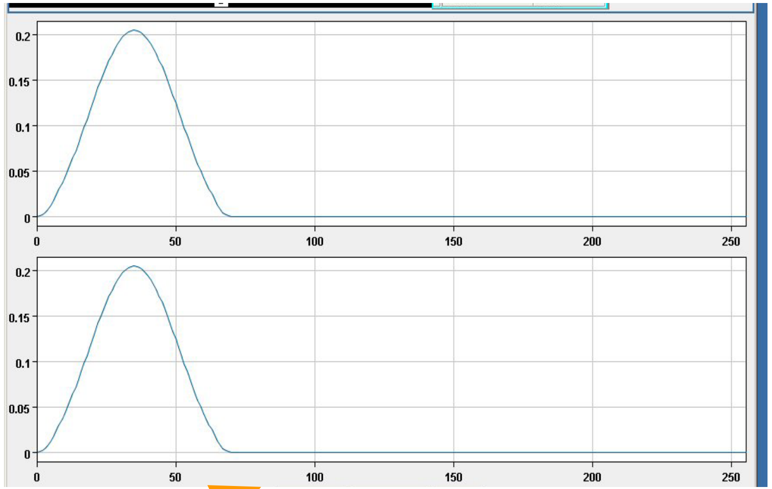


Control Command of BPMs

1/Sampling with acqiris boards and readout signals on OASIS

6 BPMs implemented

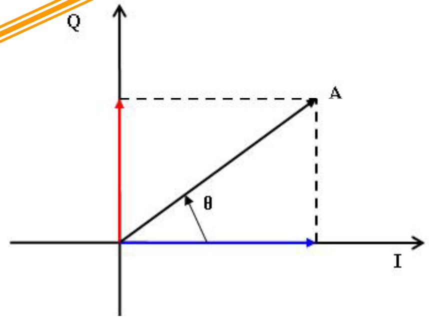
3/Results sent on graphic windows under JAVA



2/Signal processing:
Digital Down Conversion
+
Frame change

Beam position:

$$P = I\cos\theta + Q\sin\theta$$

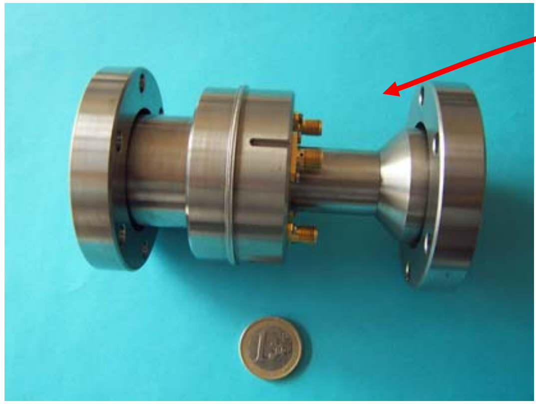


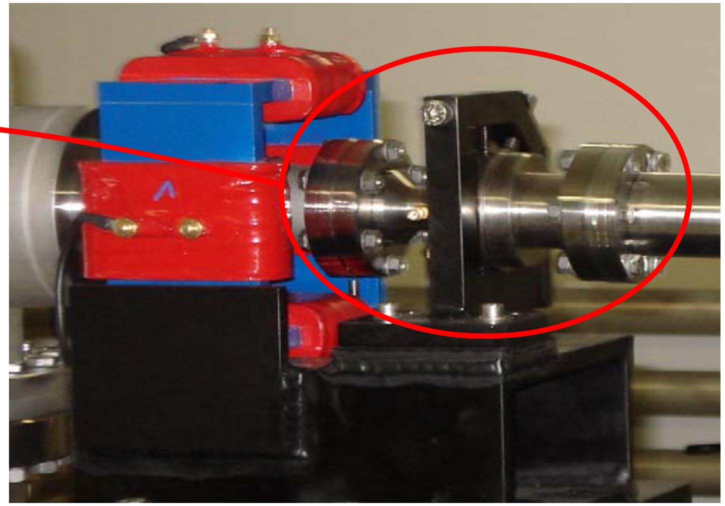
$$\cos(\theta) := \frac{I}{A} \qquad \sin(\theta) := \frac{Q}{A}$$

$$A := \sqrt{I^2 + Q^2}$$

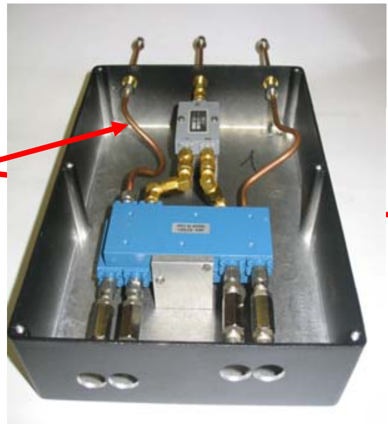
Reentrant Cavity BPM at CALIFES (2)

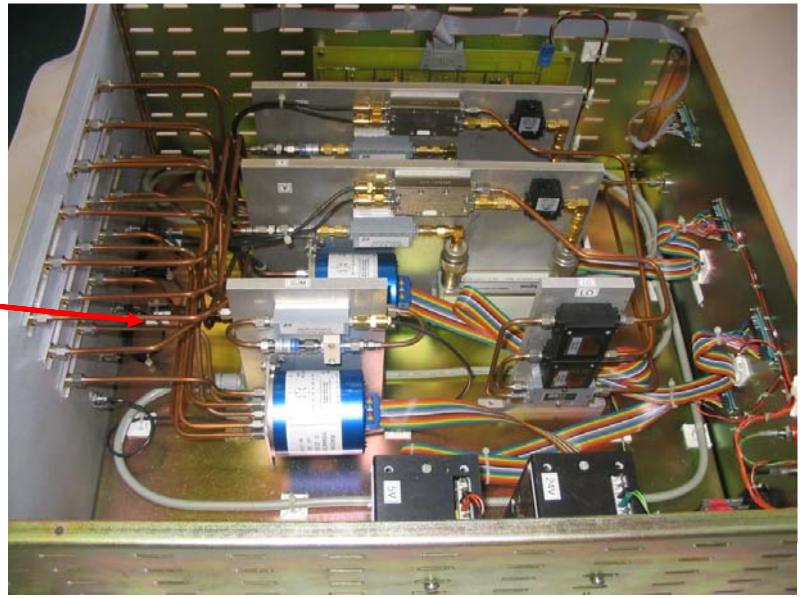
6 BPMs are installed on the CTF3 probe beam





Signal processing electronics of the re-entrant BPM





Simulations - CALIFES BPM (1)

❖ **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

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

single bunch

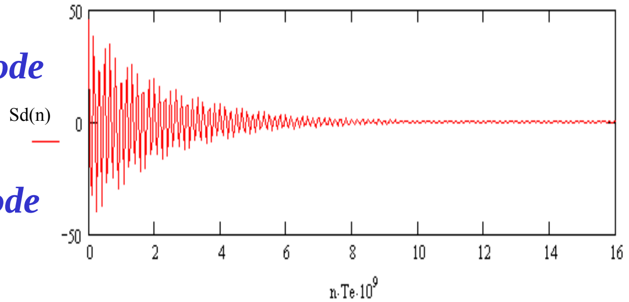
$$a_i = \omega_i \sqrt{1 - \frac{1}{4Q_i^2}} \qquad V_i = \sqrt{\frac{\omega_i^2 (R/Q)_i q^2 R_o}{\zeta_i Q_i}}$$

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

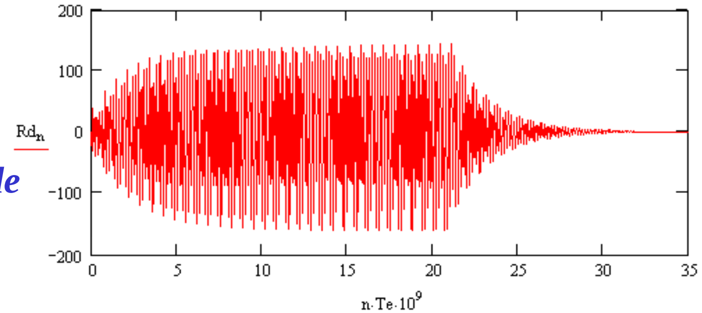
$$Rd_n := \sum_{I=0}^{32} \text{Phi}(n\cdot Te)\cdot\left[Vod\cdot e^{-2\cdot\pi\cdot Fd1\cdot\frac{n\cdot Te}{2\cdot Qd1}}\cdot\left(\cos(ad1\cdot n\cdot Te) - 2\cdot\pi\cdot Fd1\cdot\frac{\sin(ad1\cdot n\cdot Te)}{2\cdot Qd1\cdot ad1}\right)\right]$$

32 bunches

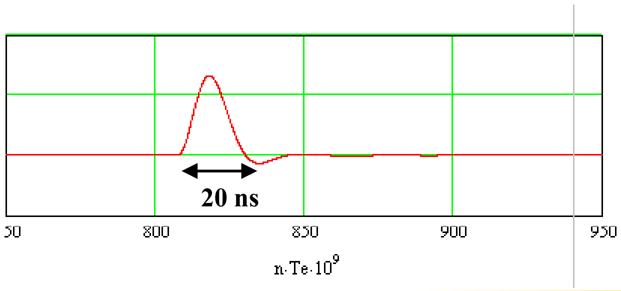
Dipole mode signal in single bunch mode



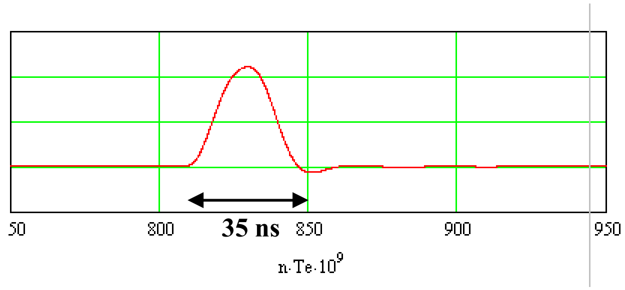
Dipole mode signal in 32 bunches mode



Signal in single bunch mode behind DDC



Signal in 32 bunches mode behind DDC



Simulations - CALIFES BPM (2)

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

Pth = 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 at CALIFES

Environment Noise RMS: 66 µV (measured at FLASH)

Δ signal (gain adjusted to get an RF signal ~ 0 dBm, simulated in single bunch)

with 5 mm offset : 590 mV (simulated), **Noise:** 0.5 mV (calculated) ➡ **Resolution :** 3.2 µm (simulated)

with 0.1 mm offset : 555 mV (simulated), **Noise:** 0.1 mV (calculated) ➡ **Resolution :** 100 nm (simulated)

Reentrant Cavity BPM at FLASH (1)

• The cavity is fabricated with stainless steel as compact as possible :

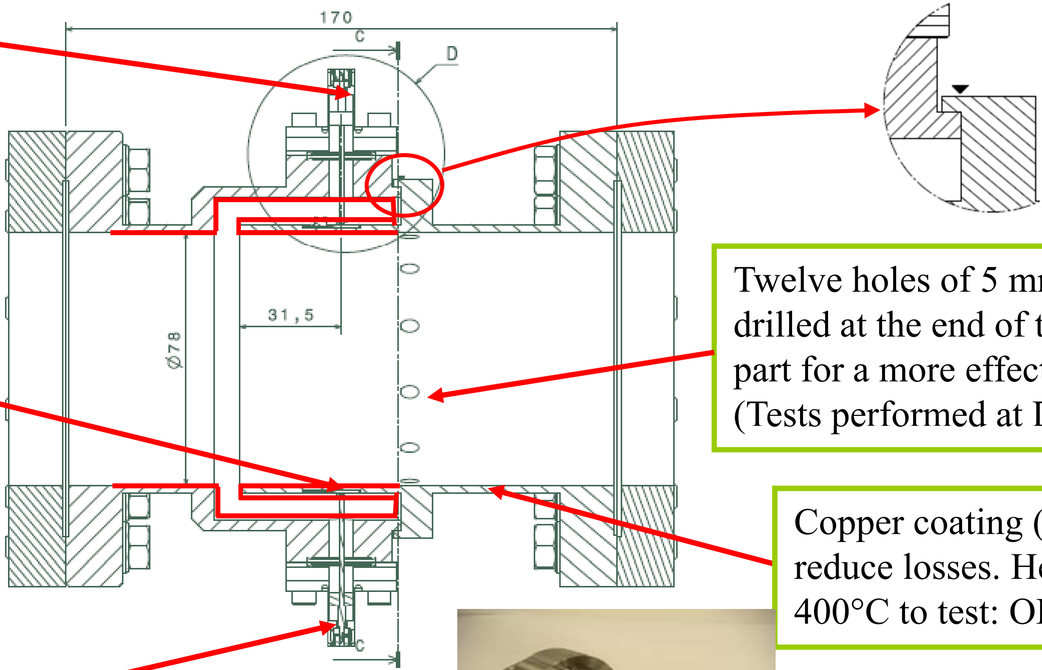
170 mm length (minimized to satisfy the constraints imposed by the cryomodule)

78 mm aperture.

• For the XFEL, mechanical design improved to respect tolerances of the BPM : Roll Angle **3 mrad**, Transverse displacement **0.2 mm**

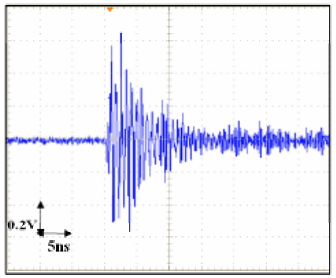
Cryogenics tests at 4 K on feedthroughs is OK

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



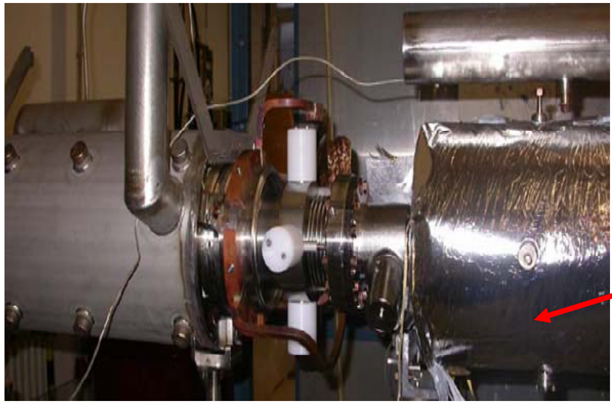
Twelve holes of 5 mm diameter drilled at the end of the re-entrant part for a more effective cleaning (Tests performed at DESY).

Copper coating (depth: 12 µm) to reduce losses. Heat treatment at 400°C to test: OK



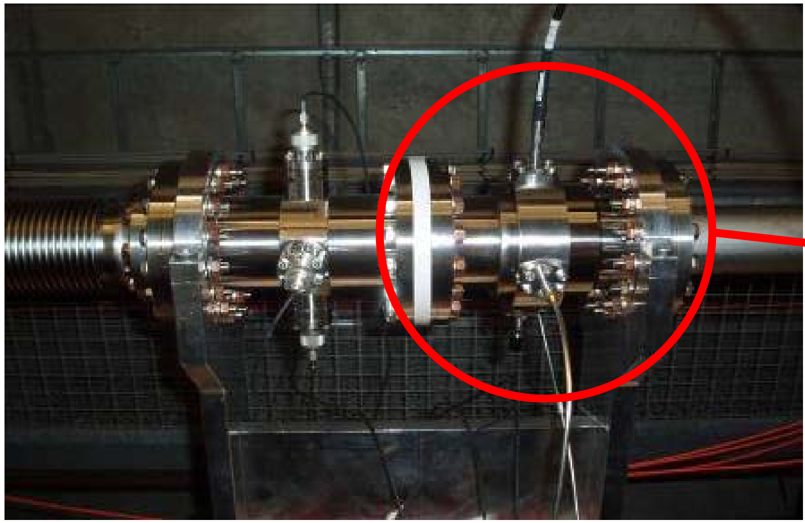
Signal from one pickup

Reentrant Cavity BPM at FLASH (2)



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



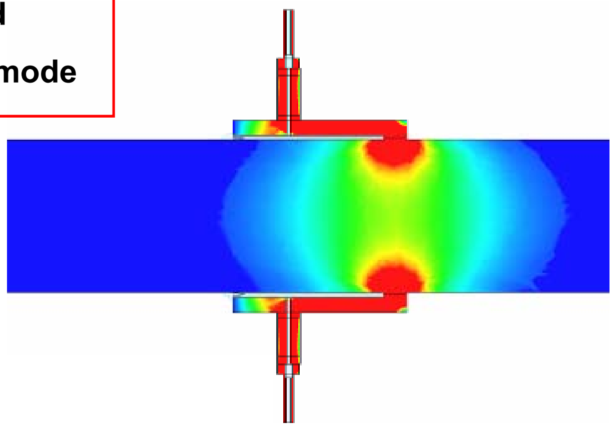
RF characteristics of the reentrant BPM at FLASH

- 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

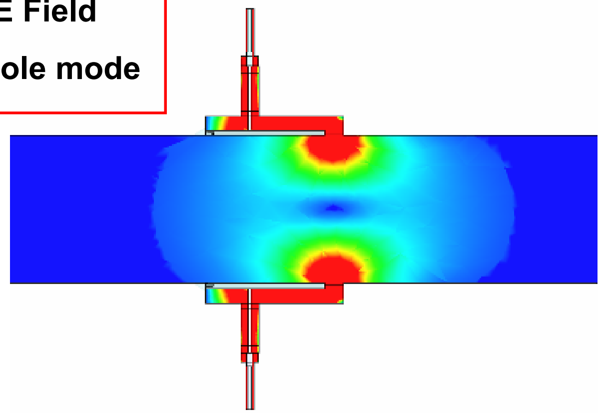
E Field

Monopole mode



E Field

Dipole mode



The cross talk isolation is evaluated around 33 dB.

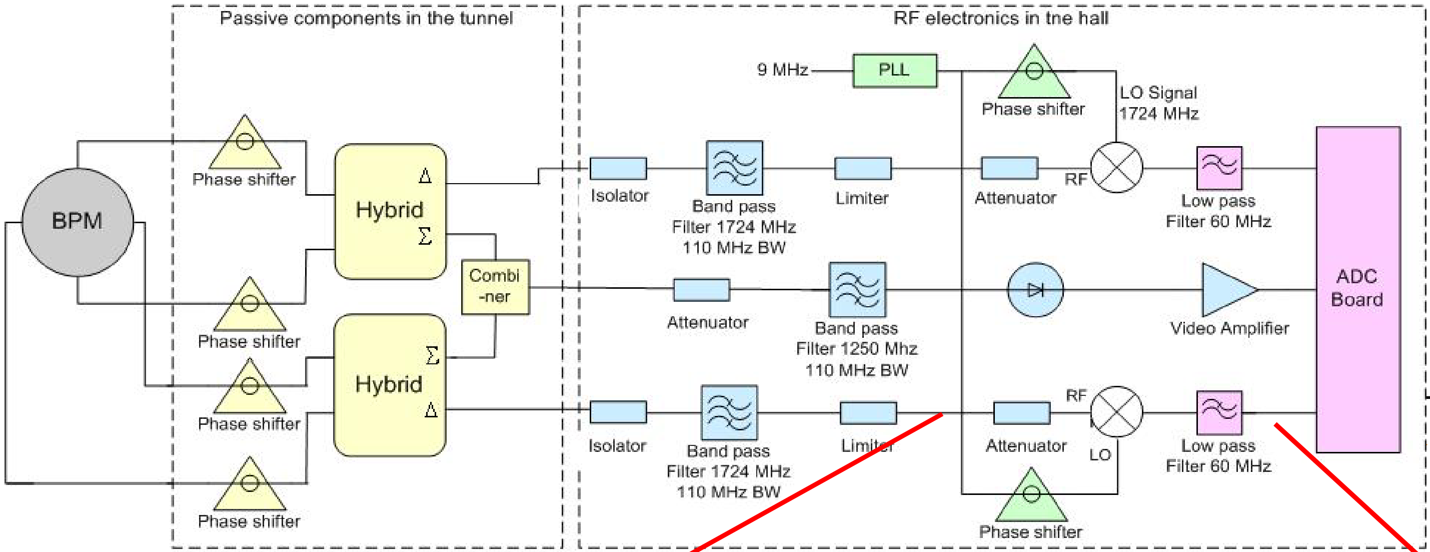
Common mode rejection

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

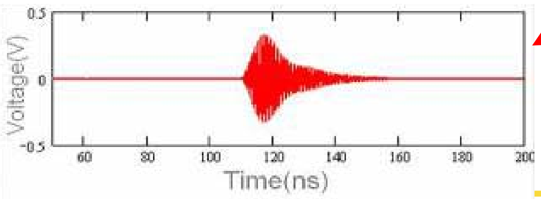
  - a rejection based on a hybrid coupler having isolation higher than 20 dB in the range of 1 to 2 GHz.

  - 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.

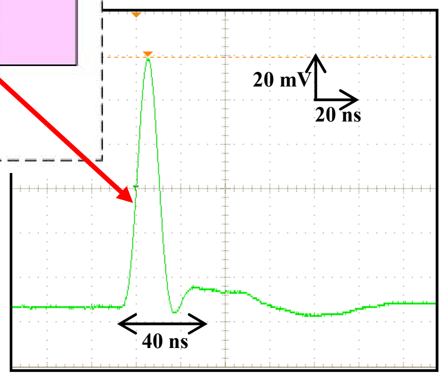
  - a synchronous detection.



RF signal



IF signal behind Lowpass Filter on channel Δ



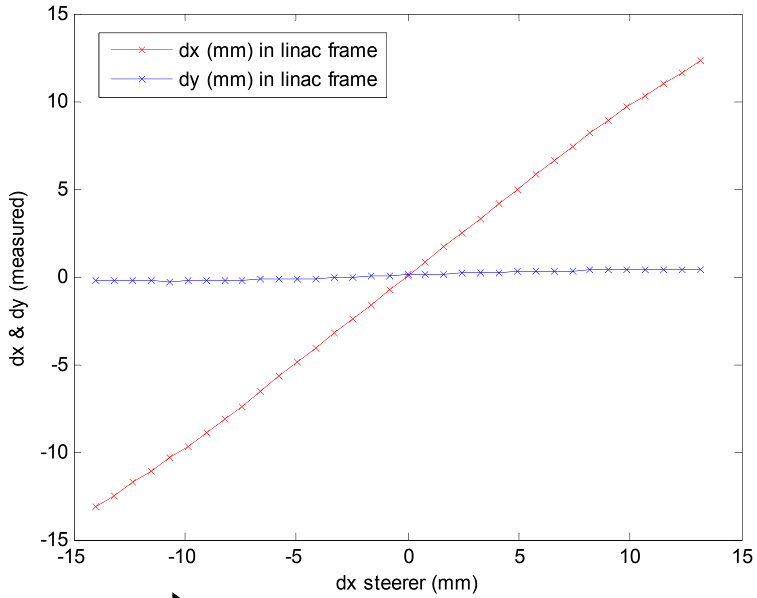
Beam tests at FLASH

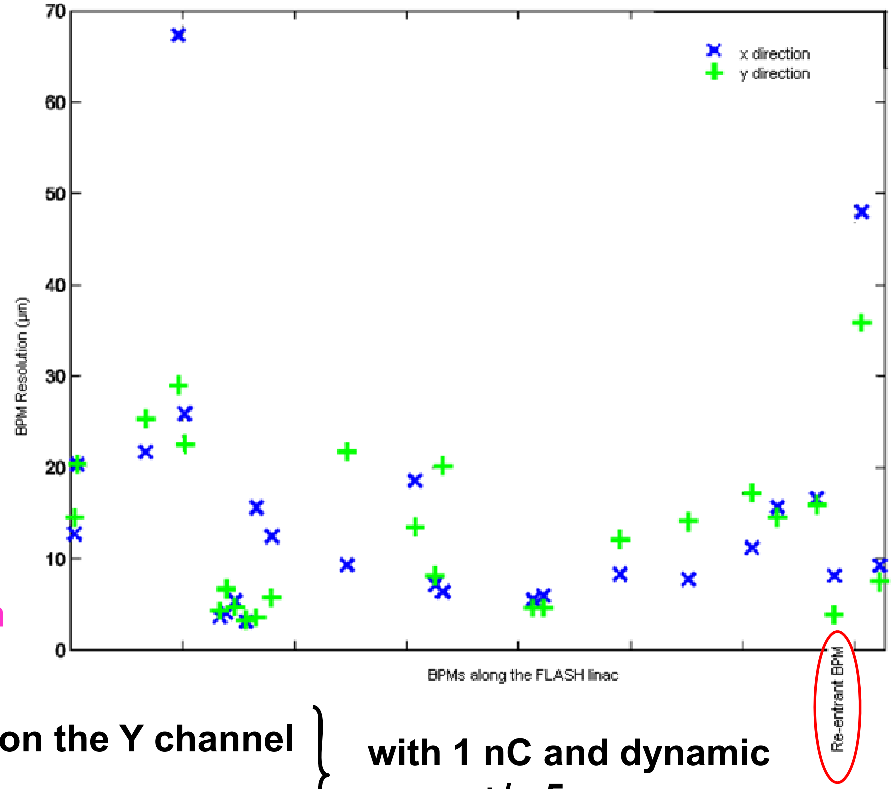
❖ **To calibrate the BPM:**

• 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).

❖ **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).





➡ **Good linearity in a range ± 12 mm**

➡ **RMS resolution: ~4 µm on the Y channel**
~8 µm on the X channel
} **with 1 nC and dynamic range +/- 5 mm**

Simulation of the Resolution

- **Simulation of the Resolution of the reentrant cavity BPM installed at FLASH**

Re-entrant Cavity installed at FLASH with cable length = 75 m :

Δ signal with 10 mm offset (dynamic range +/- 10 mm) : 181 mV

Δ signal with 1 mm offset : 181 mV

Noise: 6 μV (calculated)

Environment Noise RMS: 66 μV (measured)

Resolution : **3.64 μm** (simulated)

Offset due to monopole mode **: -0.624 mV** (simulated)

Measured Resolution ~ simulated resolution

Re-entrant Cavity with cable length = 75 m and an amplifier (G = 18 dB and NF = 3.8 dB) :

Δ signal with 1 mm offset (dynamic range +/- 1 mm): 149 mV

Noise: 6 μV (calculated)

Environment Noise RMS: 66 μV (measured)

Resolution : **0.45 μm** (simulated)

Offset due to monopole mode : **-4.37 mV** (simulated)

More work is needed to obtain < 1μm resolution

Time Resolution

- **Damping time** is given by using the following formula : $\tau = \dfrac{1}{\pi * BW}$

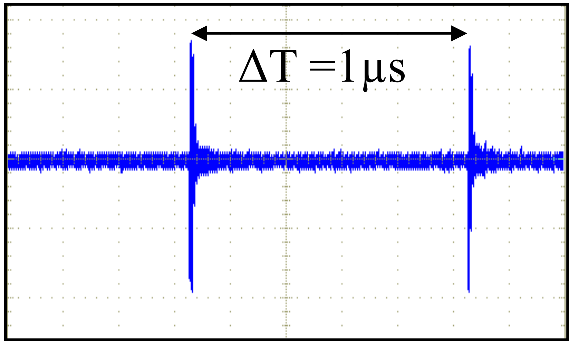
With $BW = \dfrac{f_d}{Q_{ld}}$

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.

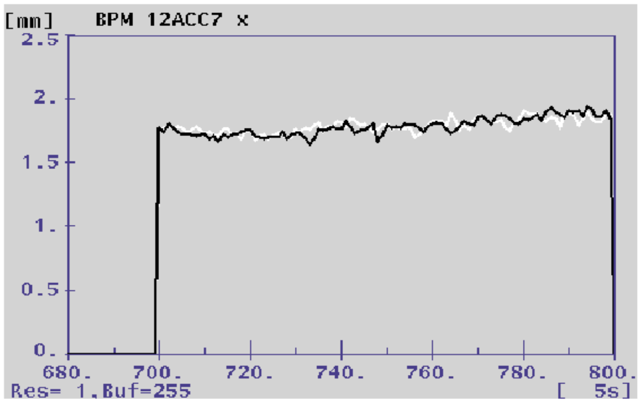
	Damping Time cavity only	Time resolution cavity + electronics
BPM	9.4 ns	40 ns

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

Irfu cea saclay

Summary

❖ **Reentrant cavity BPM at CALIFES:**

- **Operated in single and multi-bunches**
- **Single bunch resolution potential < 1 µm**
- **Beam test soon**

❖ **Reentrant cavity BPM at FLASH:**

- **Operation at room and cryogenic temperature, effective in clean environment**
- **Large aperture of the beam pipe (78 mm)**
- **Position resolution ~4 µm measured with a measurement dynamic range around ± 5 mm**
- **Bunch to bunch measurements (time resolution ~40 ns)**

- **30 reentrant cavity BPMs will be installed in the XFEL cryomodules**

  - Prototype installed in an XFEL cryomodule in January 2009

  - PCB of the RF front-end Electronics designed to reduce the electronics cost

Acknowledgements

Thanks to my colleagues from DESY, CERN and CEA :

Pascal Contrepois
Stéphane Deghaye
Mick Draper
Wilfrid Farabolini,
Patrick Girardot
Francis Harrrault
Pierre-Alain Leroy
Olivier Napoly
Fabienne Orsini
Anastasiya Radeva
Lars Soby

Thank you for your attention