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Cavity Beam Position Monitor for the ILC Main Linac: Status and Plans

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Introduction

Development of a **re-entrant cBPM for the ILC Main Linac**

Project in collaboration with KEK and CIEMAT: development of the cryostat for a BPM and a super-conducting quadrupole

Mechanical requirements:
- Mechanical fit of the BPM and the SC quadrupole magnet
- Cryogenic and UV conditions have to be met

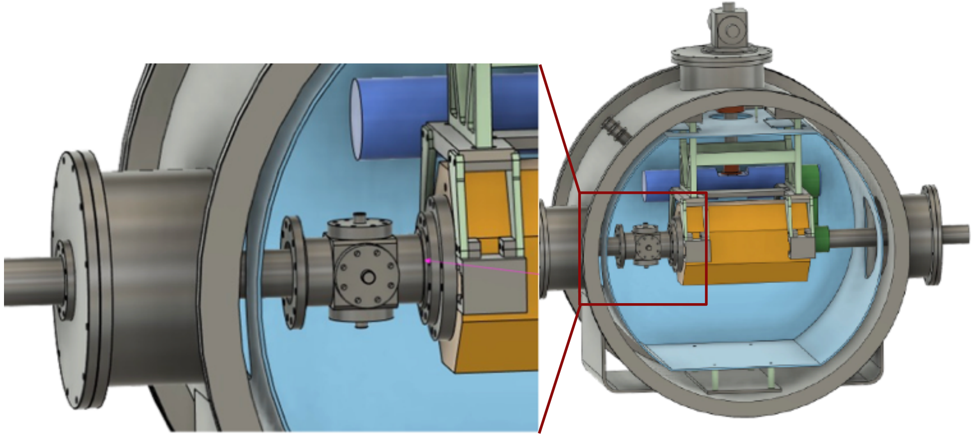


Figure: Cryostat accommodating BPM and SC quadrupole

Measurement requirements:
- Spatial resolution < 1 μm
- Temporal resolution < 369 ns

The designed BPM will initially be tested at ATF at warm and cryogenic conditions after installation of the test cryomodule.

Beam parameters	ATF	ILC
Bunch charge (nC)	1,6	3,2
Bunch spacing (ns)	150	369

Table: Relevant ATF and ILC parameters

M. Wendt, Cold Cavity BPM R&D for the ILC, FermiLab
Tomohiro Yamada, Test cryostat for BPM-SCQ, KEK

I. Resonant cavity Beam Position Monitor

A) Pillbox cavity BPM

➔ **Working principle**

Cavity BPMs are resonant systems crossed by the beam pipe. EM modes are induced on the cavity by the beam and their amplitude depends on the beam position.

Two modes in particular are of interest:

Monopole mode TM_{010} Dipole mode TM_{110}

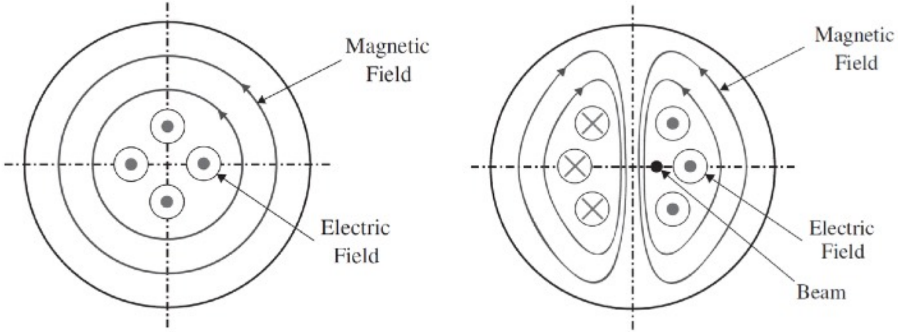


Figure: Cross-sectional view of the TM modes in a pillbox cavity

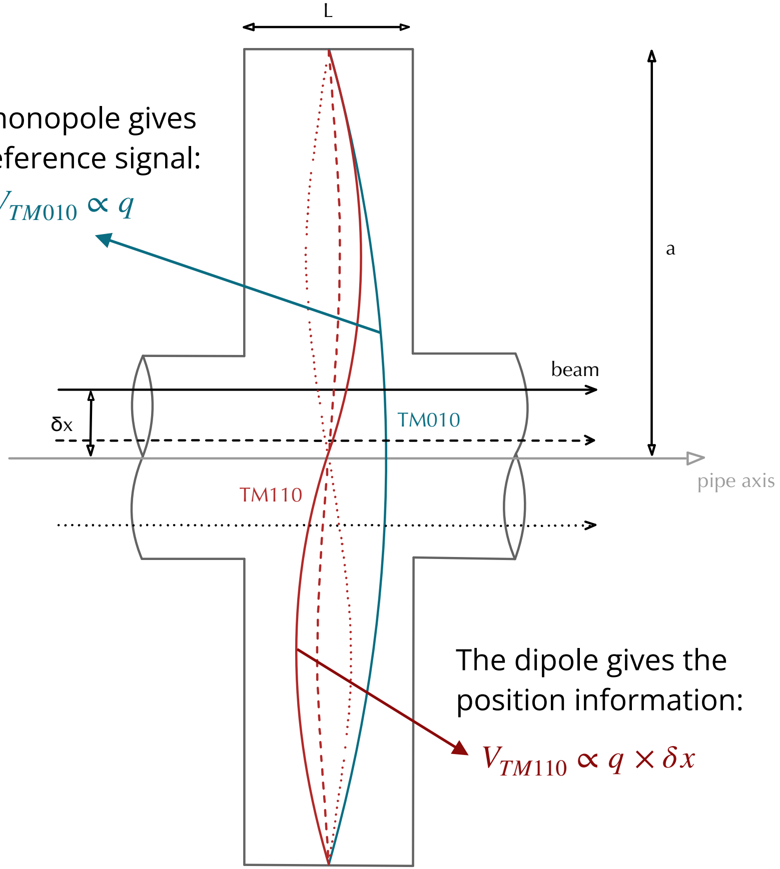


Figure: Representation of the E-fields induced in the cavity

I. Resonant cavity Beam Position Monitor

B) Re-entrant cavity BPM: a model from C. Simon - Saclay

The re-entrant cavity BPM

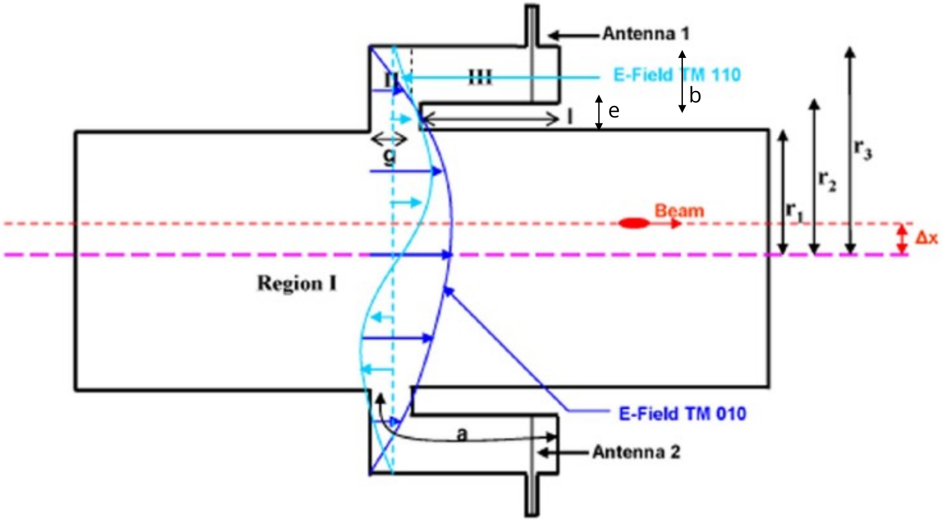


Figure: Scheme of the re-entrant cBPM

I. Beam pipe
II. Gap
III. Coaxial cylinder

Saclay: Simon - Re-entrant cavity BPM for X-FEL

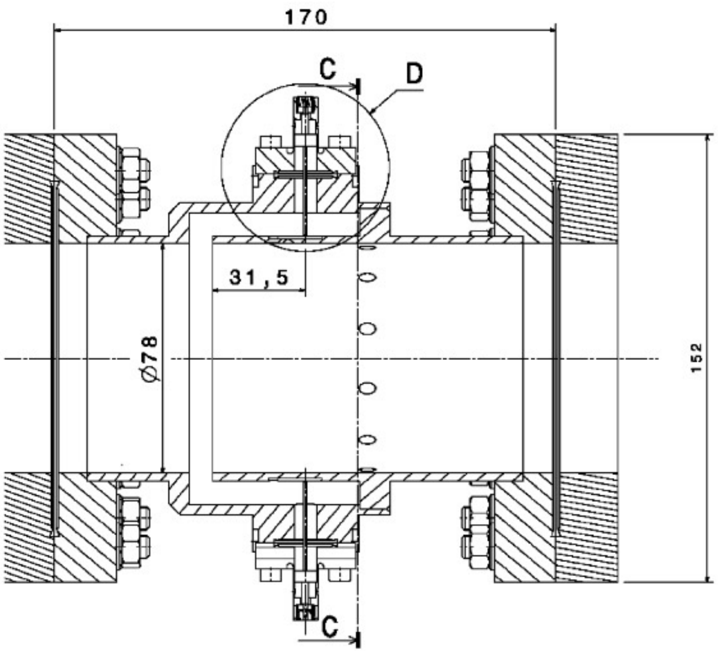


Figure: Design plans of cBPM from Saclay

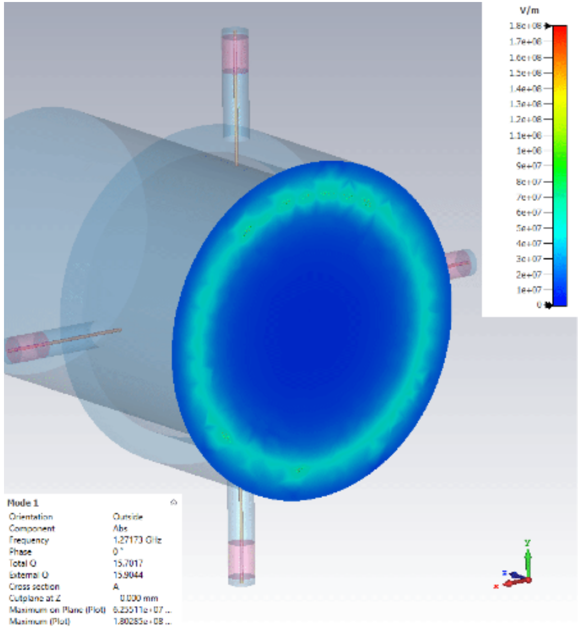
C. Simon, N. Rouvière, N. Baboi, Performance of a reentrant cavity beam position monitor, DSM, CNRS, DESY

I. Resonant Cavity BPM

B) Re-entrant cavity BPM: a model from C. Simon - Saclay

Monopole mode TM_{010}

$f_{010} = 1.25$ GHz

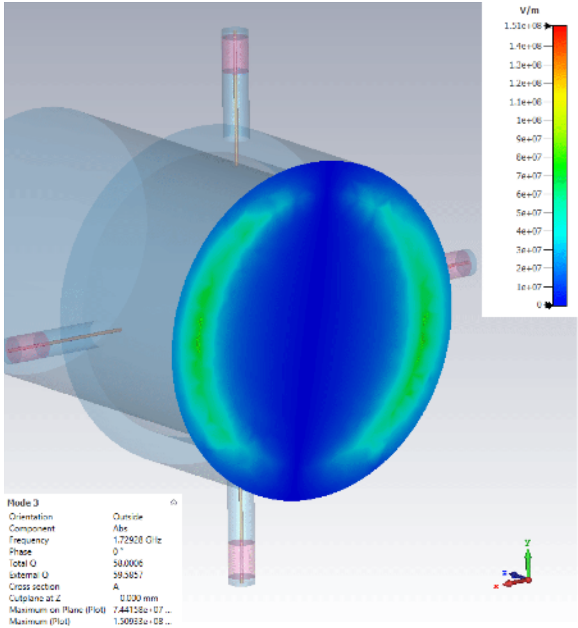


Yields reference signal

Dipole mode TM_{110}

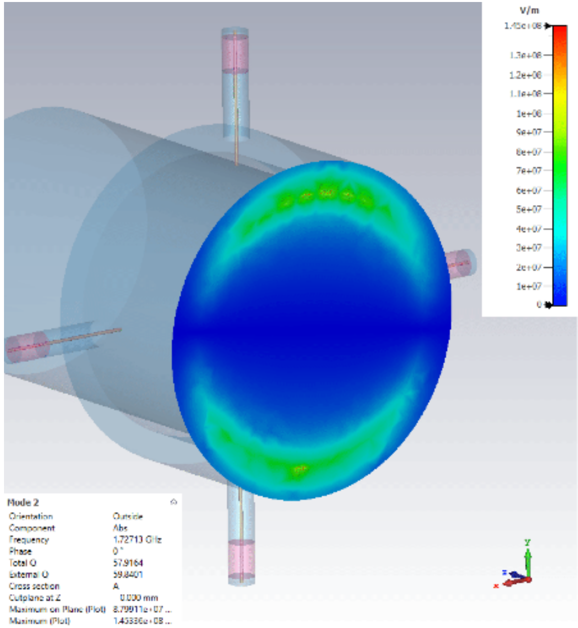
$f_{010} = 1.72$ GHz

degeneration on x



Yields position signal on x

degeneration on y

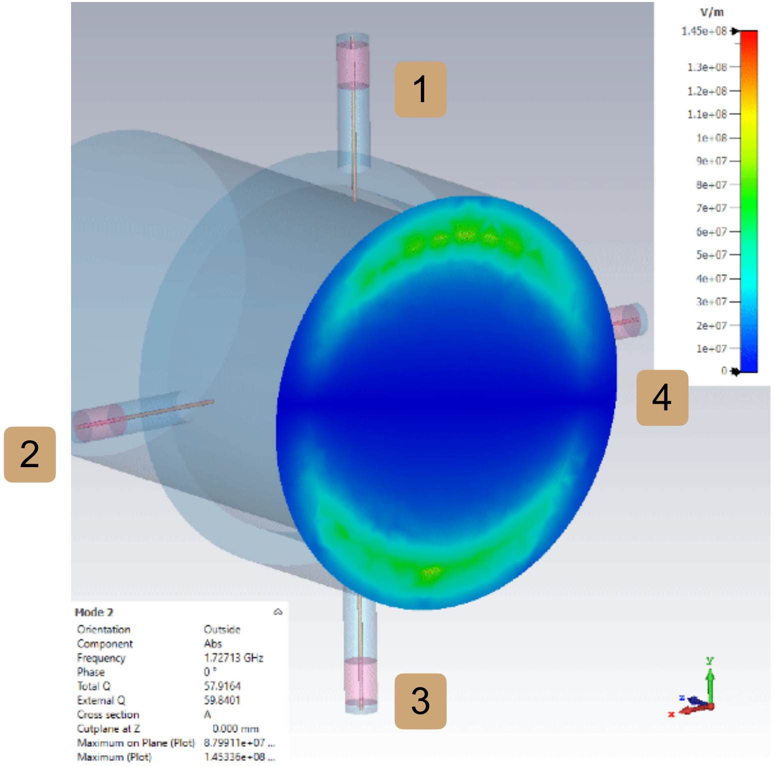


Yields position signal on y

CST Studio Suite, Charged Particle Simulation - Workflow & Solver Overview, 3DExperience

I. Resonant cavity Beam Position Monitor

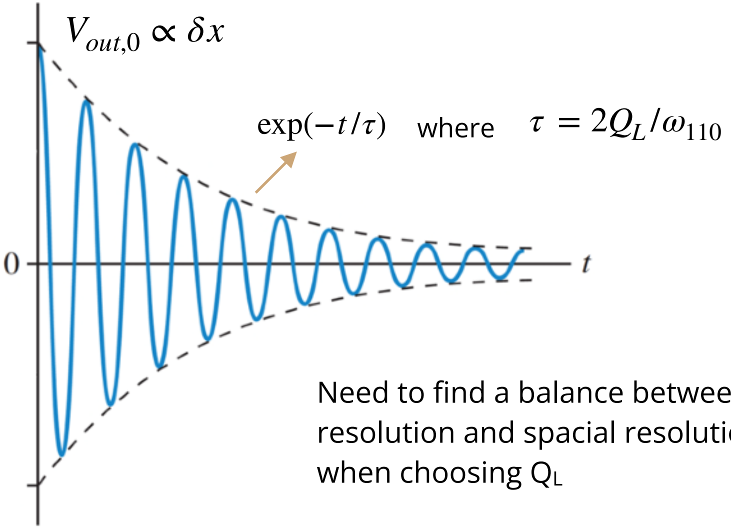
C) Signal extraction



➔ **Output signal on the time domain:**

The position signal oscillates at the dipole mode resonance frequency and decays exponentially with decay constant τ:

$$V_{position}(t) = V_{out,0}\sin(\omega_{110}t + \varphi)\exp(-t/\tau)$$



Need to find a balance between time resolution and spacial resolution when choosing Q_L

II. Project definition and objectives

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➡ **Modify an existing cBPM design to fit ILC demands and improve spacial resolution**

Challenges to overcome:

❖ Improve spacial resolution of the re-entrant cBPM (under 1 μm)

- Modification of the cBPM design to improve:
  - sensitivity of the modes
  - loaded quality factor
- Design of a read-out system that allows high resolution measurements

❖ Mechanical attachment and alignment with SC quadrupole

❖ cBPM and read-out system has to be suitable to perform measurements at ATF

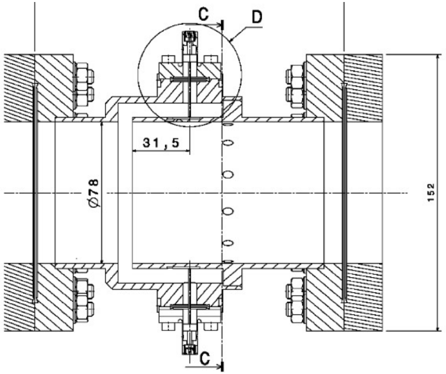


Figure: Design plans of cBPM from Saclay

	F (GHz)	Q	R/Q @10 mm
Monopole mode	1.25	24	13Ω
Dipole mode	1.72	51.4	1.11Ω
Resolution: around 4 μm			

C. Simon, WP11 (Beam diagnosis) The re-entrant BPM, CEA, Saclay, France
C. Simon, N. Rouvière, N. Baboi, Performance of a reentrant cavity beam position monitor, DSM, CNRS, DESY

III. Design studies of the cBPM

A) Geometry studies of the cBPM

- **Eigenmode solver in CST**

Evaluate the E and M fields distributions, coupling to antennas and the influence of geometrical parameters on the resonant frequency and quality factor Q_L

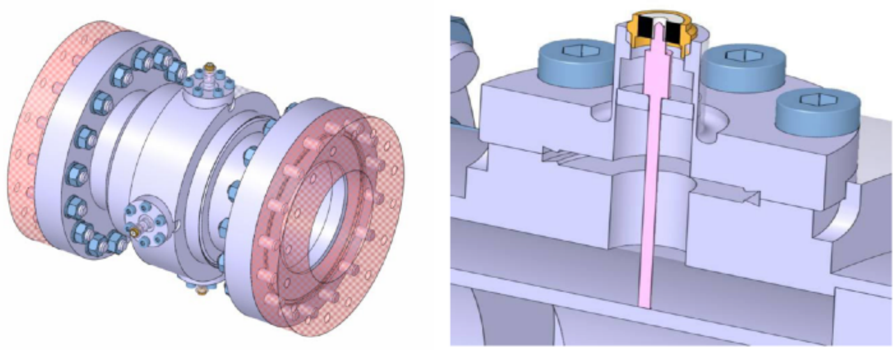
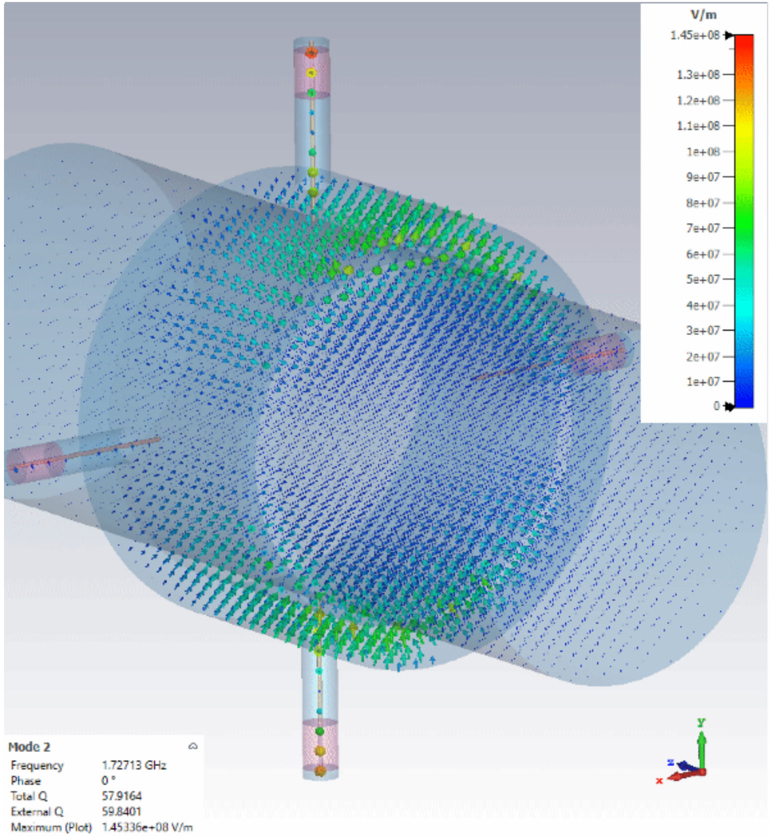


Figure: Design of cavity and feedthrough from cBPM from Saclay



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C. Simon, WP11 (Beam diagnosis) The re-entrant BPM, CEA, Saclay, France

III. Design studies of the cBPM

A) Geometry studies of the cBPM

- **Parametric study**

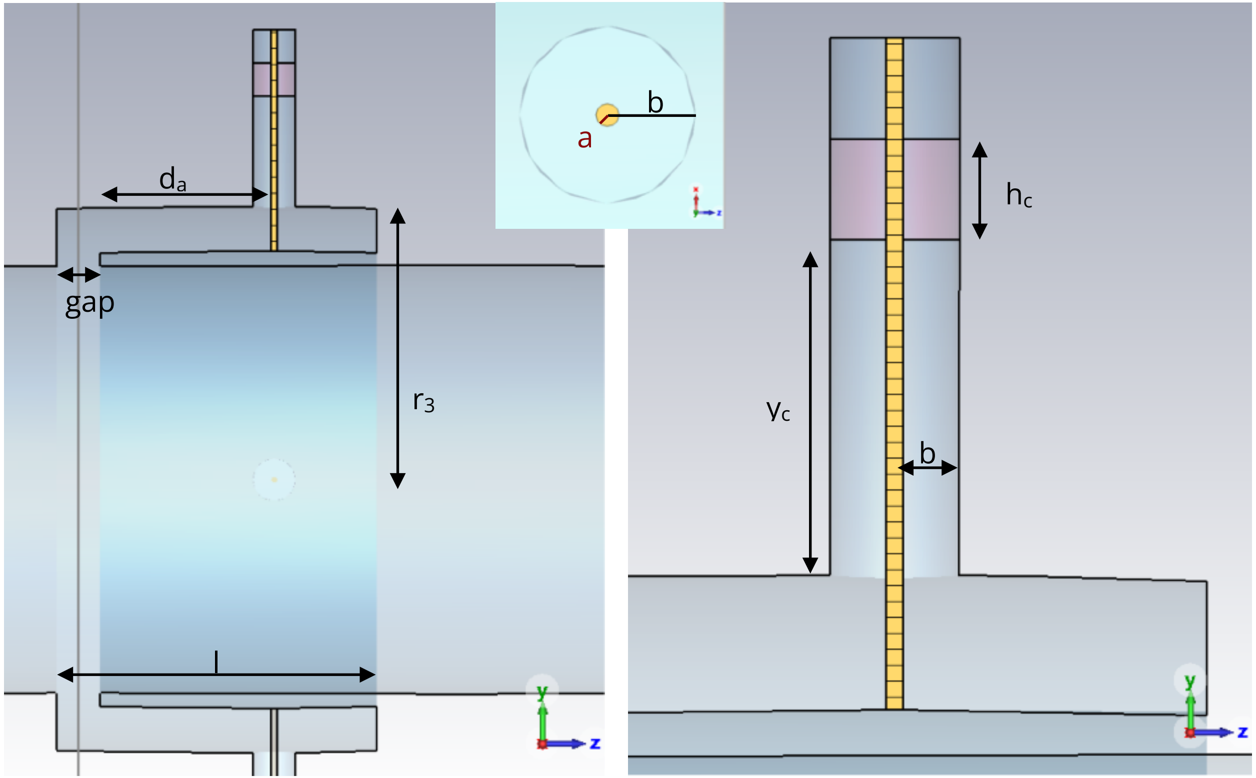

Figure: cBPM geometry dimensions

Preliminary conclusions:

Higher influence on **Q_L (dipole)** (and **τ**):

- ↘ when l ↗ (cavity length)
- ↗ when d_a ↗ (antenna distance)
- ↗ when h_c ↗ (thickness of seal)
- ↘ when a ↗ (radius of inner conductor) (but limited)

Higher influence on **R/Q (dipole)** (sensitivity):

- ↗ when r_3 ↗ (cavity aperture)
- ↘ when l ↗ (cavity length)

➡ Parameters usually affect al variables at the same time. Need of careful selection.

III. Design studies of the cBPM

B) Inclusion of a perturbation in the cBPM

- **Wakefield solver in CST**

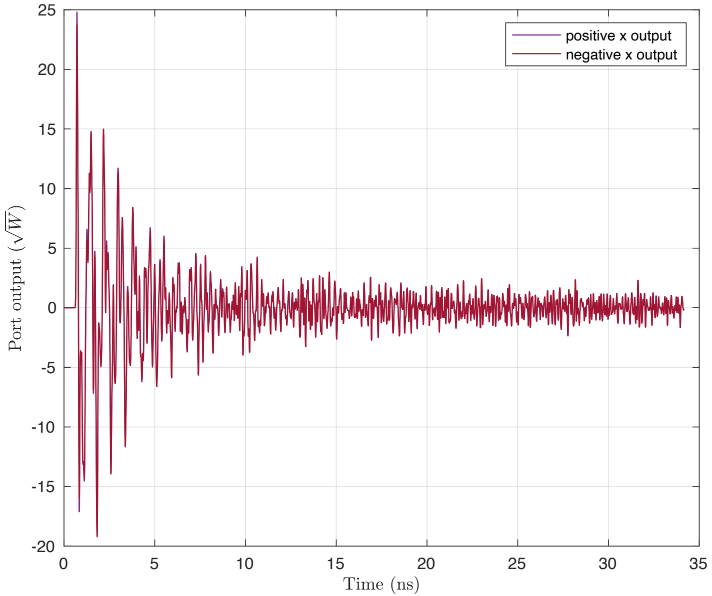

Figure: output signal from two oposite outputs on the wakefield simulation on CST

Evaluate the E and M fields under the presence of a beam and their response to different offsets

➡ Retrieve signal from the output ports and reconstruct beam dependence on the amplitude of the dipole mode

- **Signal processing in MATLAB**

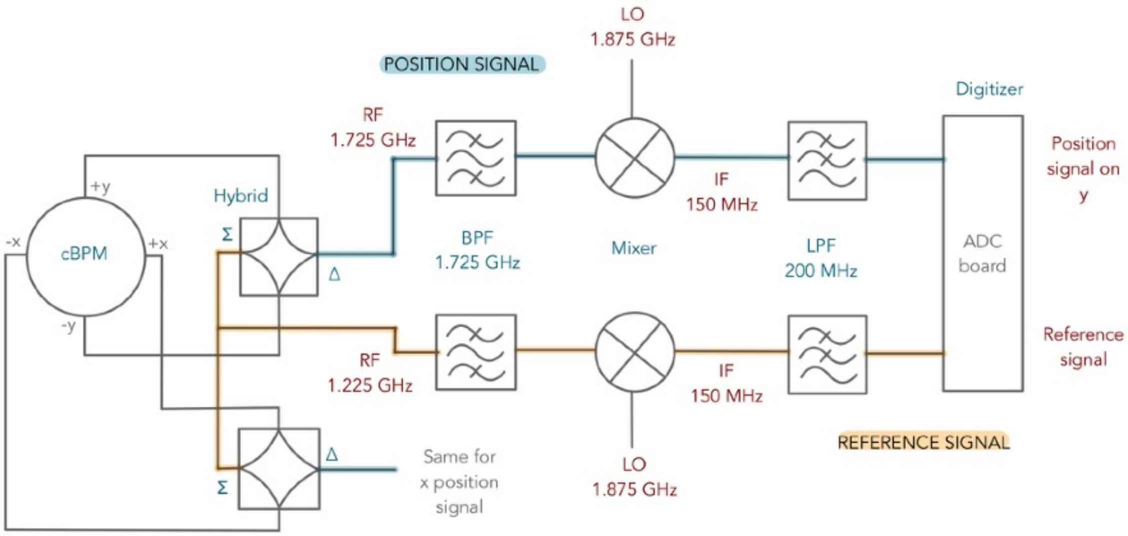

Figure: scheme of the provisional analog read-out system of the cBPM

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III. Design studies of the cBPM

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B) Inclusion of a perturbation in the cBPM

- **Signal processing in MATLAB**

❖ Extraction of information form both monopole and dipole modes from the same cavity.

❖ Hybrid coupler separates position and reference signal.

❖ The two signals are filtered at the dipole resonance frequency with BPF (butter-worth type)
  - filters leakage from hybrid
  - filters HOM

❖ Down-mixing of position and reference signal to 150 MHz

❖ Band-pass filter removes up-converted component and noise

❖ Digitizer of 600 MS/s

Retrieving maximum amplitude for range of offsets:

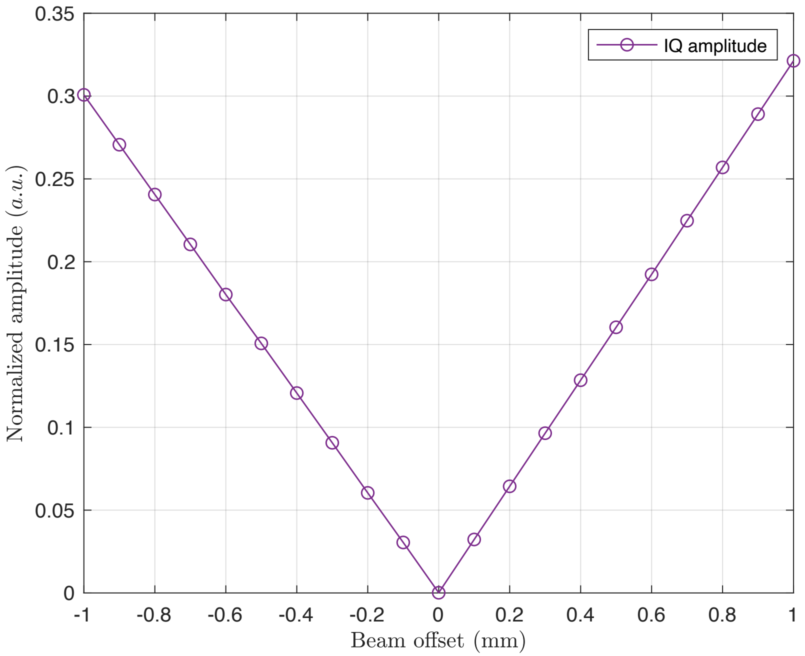

Figure: Position signal's amplitude dependence on δx

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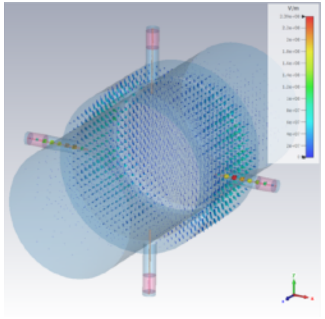
BI-RME 3D = Boundary Integral - Resonant Mode Expansion

Hybrid method that uses CST field results for a closed resonant cavity and allows to evaluate the RF power extracted at the output ports from the cavity when excited by a beam

➡ For a given operation frequency, the numerical method yields:

- power consumed by the cavity P_c and power delivered to the waveguides (ports) P_w
- output RF signal's amplitude and phase
- external and loaded quality factors



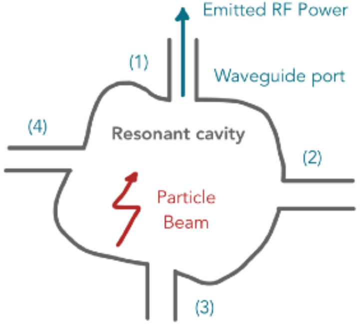
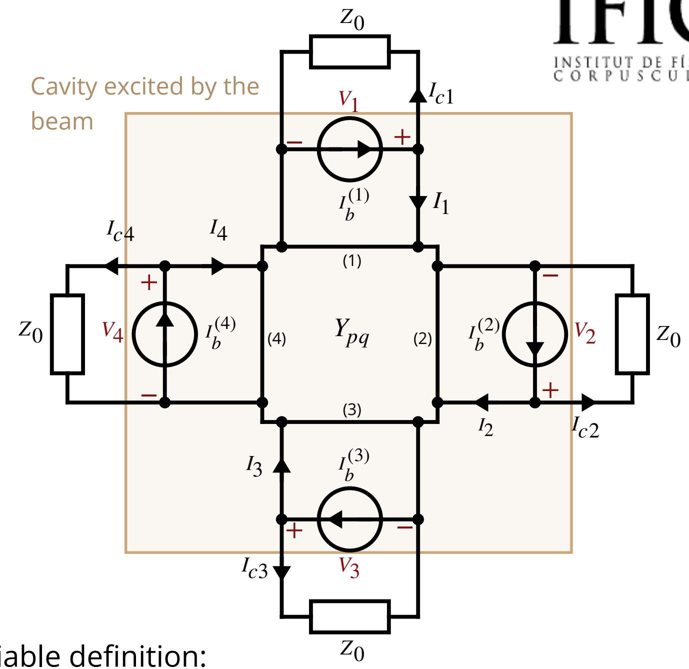


Figure: cBPM simulation in CST and representation for BIR-ME



Variable definition:

Z_0 impedance of coaxial output

V_i voltage at port (i)

$I_i = I_b^{(i)} - I_{ci}$ intensity at the cavity

$I_{ci} = V_i / Z_0$ intensity at the coaxial port

(Y_{pq}) is the Input admittance of the cavity

B. Gimeno, *Wide-band full-wave electromagnetic modal analysis of the coupling between dark-matter axions and microwave resonators, AITANA Seminar 2024*

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C) BIR-ME 3D method

Intensity generated by the beam leading to port (i)

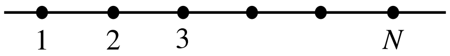
$$I_b^{(i)} = \sum_{m=1}^{3} \frac{\kappa_m}{k^2 - \kappa_m^2} \int_{S^{(i)}} \vec{H}_m \cdot \vec{h}_{TEM}^{(i)} dS \int_V \vec{E}_m \cdot \vec{J}_b dV$$

Coupling cavity-port (surface integral) — Coupling beam-cavity (volume integral)

where

$$\kappa_m \simeq k_m \left(1 - \frac{1}{2Q_m}\right) + j\frac{k_m}{2Q_m}$$ to consider Ohmic losses

$$\vec{J}_b = \sum_{n=1}^{N} q_n \delta(\vec{r} - \vec{r}_n{}')\vec{v}_n$$ is the beam current density



For a beam with a horizontal offset

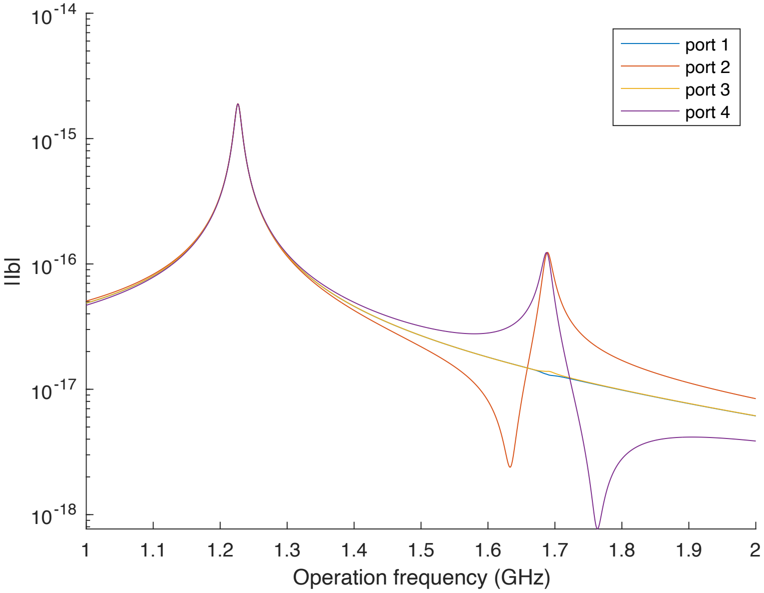


Figure 5: $|I_b^{(i)}|$ as a function of frequency for $\delta x = 5$ mm

B. Gimeno, *Wide-band full-wave electromagnetic modal analysis of the coupling between dark-matter axions and microwave resonators, AITANA Seminar 2024*

Conclusion

cBPM developed by C. Simon (Saclay) enables bunch-to-bunch measurements at ILC with a resolution on the order of micrometers.

Methods employed to enhance the spatial resolution and meet the Main Linac requirements:

- The Saclay design is under evaluation to enhance BPM sensitivity and spatial resolution
- Simulation of the read-out system in MATLAB to asses the influence of all components on the overall system performance
- BIR-ME 3D method estimates the cBPM output signal with careful definition of the beam.

A preliminary plan is underway to develop a prototype integrating the SCQ and BPM assembly into a test cryostat.

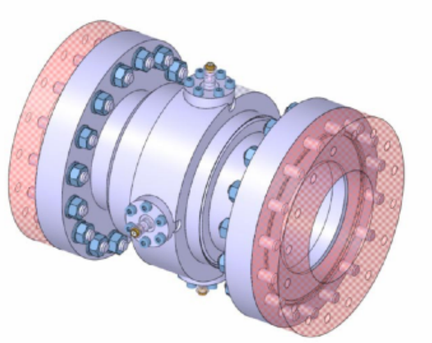


Figure: Design of cBPM from Saclay

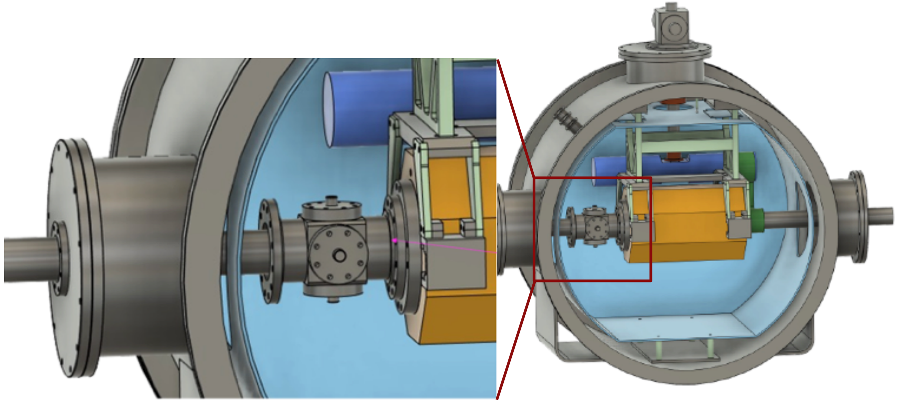


Figure: Cryostat accommodating BPM and SC quadrupole

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Thank you for your attention

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