Cold cavity BPM R&D for the ILC Main Linac

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Clic Project Meeting #45, 19/03/2024

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Introduction

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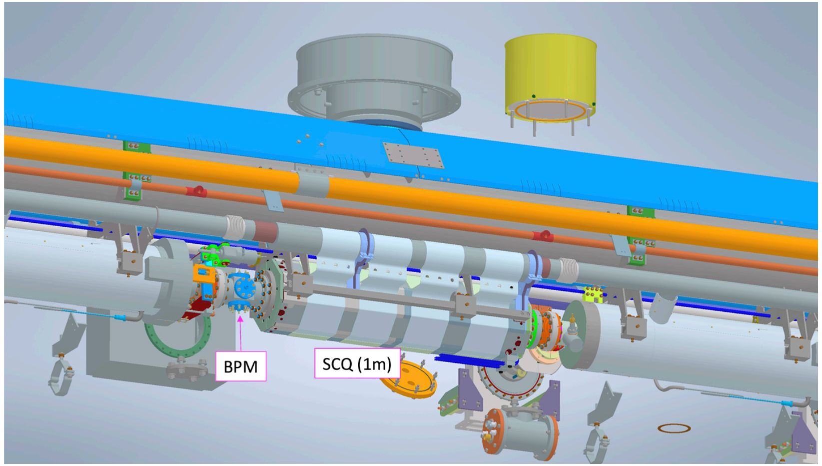
Development of a **re-entrant cBPM for the ILC Main Linac**

Measurement requirements:

- Spatial resolution < 1 μm
- Temporal resolution < 369 ns
- Dynamic range: 0-35 nm (offset) and 0.1-3.2 nC (bunch charge)

Mechanical requirements:

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



Project in collaboration with KEK and CIEMAT: development of the cryostat for BPM and SCQ

The designed BPM will initially be tested at ATF (Accelerator Test Facility) and at STF (Superconducting RF Test Facility) at KEK where:

- Temporal resolution has to be matched in order to perform bunch to bunch measurements at STF specially

Beam parameters	ATF2	STF	ILC
Beam energy (GeV)	1.3	0.5	250
Bunch charge (nC)	1.6	0.6	3.2
Bunch spacing (ns)	150	6.15	369
Bunch length (mm)	7	3	0.3

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

I. Project definition and objectives

I. Project definition and objectives

➡ **Modify an existing cBPM design to decrease the decay time τ**

❖ Modifications of the Claire Simone design to improve the temporal resolution τ (< 6 ns) → perform bunch to bunch measurements at STF

❖ Mechanical attachment and alignment between the BPM and the SC quadrupole magnet

❖ Evaluate possibility of extracting both monopole and dipole signal from the same output

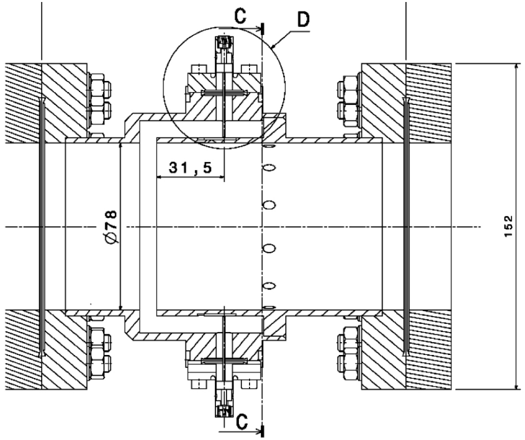
➡ **Buy a the cBPM from Claire Simone (Saclay)**

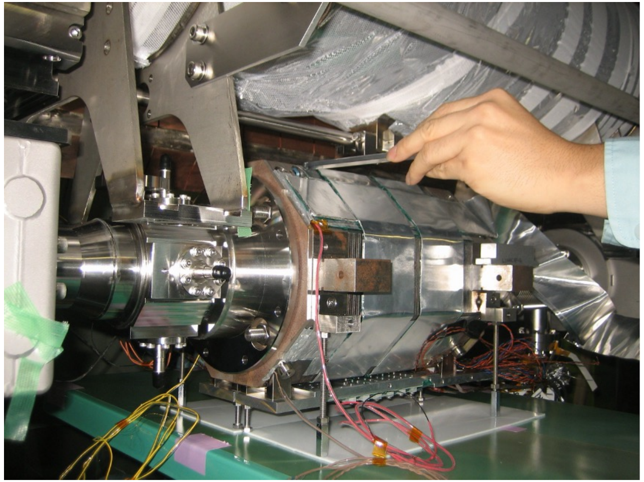
❖ Understand the cBPM behavior

❖ Develop electronics suited for this model

❖ Test the cavity and the electronics without beam at the RF laboratory: preparation of the set-up

❖ Test the cavity and the electronics with beam at ATF





C. Simon, N. Rouvière, N. Baboi, Performance of a reentrant cavity beam position monitor, DSM, CNRS, DESY
H. Hayano, Status of Re-entrant cavity-type Cold BPM R&D for ILC Main Linac, KEK

II. Cavity BPM Theory

A. Pillbox cavity BPM
B. Re-entrant cavity BPM

II. Cavity BPM Theory

A) Pillbox cavity BPM

➔ Working principle

EM modes can resonate inside a PEC cavity. Their energy oscillates between pure E and pure M.

Short bunches can excite several resonating modes in a cavity.
The beam couples with modes that have longitudinal E-field components: the TM modes.
Two particular modes are of interest:

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

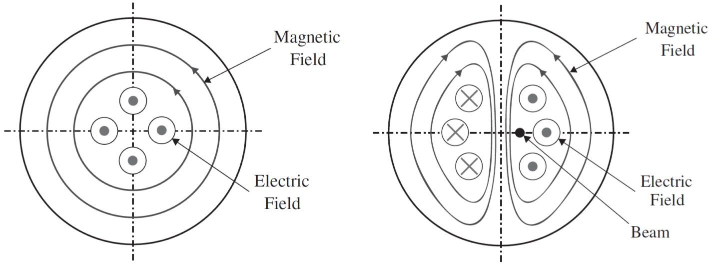


Figure: Transverse view of the modes

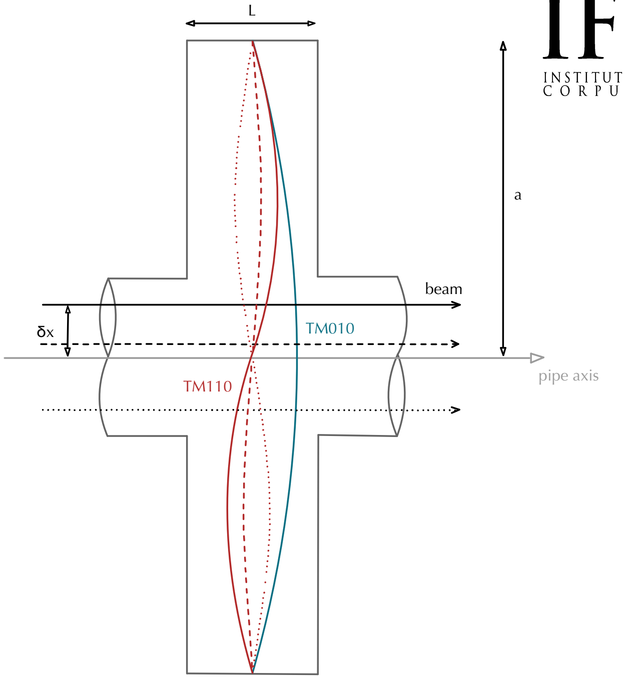


Figure: Representation of the E-fields induced in the cavity

The monopole mode is always excited by the beam since its maximum amplitude is on the beam axis.

An offset beam induces the dipole mode with:

$$V_{TM110} \propto I_{beam} \times \delta x$$

R. Lorenz, Cavity Beam Position Monitors, DESY
M. Viti, Resonant Cavities as Beam Position Monitor, DESY

II. Cavity BPM Theory

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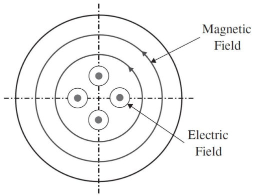
A) Pillbox cavity BPM

✦ Resonant modes

Field E_z:

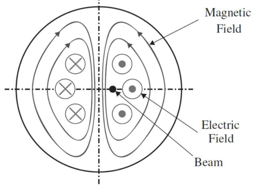
Monopole mode TM_{010}:

$$E_{z,010} = C_{010} J_0 \left(\frac{j_{01} r}{a} \right) e^{i\omega 010 t}$$



Dipole mode TM_{110}:

$$E_{z,110} = C_{110} J_1 \left(\frac{j_{11} r}{a} \right) \cos\phi \, e^{i\omega 110 t}$$



where C_{mnp} is the amplitude and $\omega_{mnp} = 2\pi f_{mnp}$ is the angular frequency of mode TM_{mnp}.

Resonance frequency of mode TM_{mnp} is:

$$f_{mnp} = \frac{c_0 k_{mnp}}{2\pi} \quad \text{where} \quad k_{mnp} = \sqrt{\left(\frac{j_{mn}}{a}\right)^2 + \left(\frac{p\pi}{L}\right)^2} \quad \Rightarrow \quad f_{010} = \frac{c_0 j_{01}}{2\pi a}, \quad f_{110} = \frac{c_0 j_{11}}{2\pi a}$$

where m, n, p are the node numbers, k_{mnp} is the wavenumber, a is the cavity radius, L is the length and j_{mn} is the nth zero of the mth Bessel function

- **(R/Q):** is defined as

$$\left[\frac{R}{Q_0}\right]_{mnp} = \frac{\left|\int \mathbf{E} ds\right|^2}{P_{wall}} \frac{P_{wall}}{\omega_{mnp} W_s} = \frac{\left|V_{mnp}\right|^2}{\omega_{mnp} W_s}$$

Used to evaluate the effect of the beam on the cavity and depends only on the cavity shape.

II. Cavity BPM Theory

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A) Pillbox cavity BPM

- **Fundamental theorem of beam loading:**

“the voltage induced by a charge traveling through a cavity is twice the effective voltage "seen" by the charge itself”

Voltage of a mode in the cavity excited by the beam:

$$V_{b\to m} = q\frac{\omega_{mnp}}{2}\left(\frac{R}{Q}\right)_{mnp}$$

- **Output signal V_{out} :**

Stored energy in the cavity:

$$W_s = \frac{V_{b\to m}^2}{\omega_{mnp}(R/Q)_{mnp}} = q^2\frac{\omega_{mnp}}{4}\left(\frac{R}{Q}\right)_{mnp}$$

since $\left(\frac{R}{Q}\right)_{mnp} = \frac{{V_{mnp}}^2}{\omega_{mnp}W_s}$

By definition of Q_{ext}, the output power is:

$$P_{out} = \frac{\omega_{mnp}W_s}{Q_{ext}} = \frac{q^2\omega_{mnp}^2}{4}\frac{1}{Q_{ext}}\left(\frac{R}{Q}\right)_{mnp}$$

since $Q_{ext} = \frac{\omega_{mnp}W_s}{P_{out}}$

Output voltage (with impedance Z) is:

$$V_{out,0} = \sqrt{ZP_{out}} = \frac{q\omega_{mnp}}{2}\sqrt{\frac{Z}{Q_{ext}}\left(\frac{R}{Q}\right)_{mnp}}$$

R. Lorenz, Cavity Beam Position Monitors, DESY
M. Viti, Resonant Cavities as Beam Position Monitor, DESY

A) Pillbox cavity BPM

- **R/Q for each mode:**

Cálculo de $\left(\frac{R}{Q}\right)_{mnp} = \frac{V_{mnp}{}^2}{\omega_{mnp} W_s}$ using $V_{mn0}(\delta x) = \int_0^L E_{z,mn0}(r,\phi)\, \mathrm{d}z$ and $W_{s,mn0} = \int_V \frac{1}{2}\varepsilon_0 \left|E_{z,mn0}\right|^2 dV$

Dipole mode: $\left[\frac{R}{Q}\right]_{110} \propto J_1\left(\frac{j_{11}r}{a}\right)^2 \cos^2\phi \simeq \left(\frac{j_{11}\delta x}{a}\right)^2$

$\Rightarrow [R/Q]_{110} \propto (\delta x)^2$ for small offsets δx

Monopole mode: $\left[\frac{R}{Q}\right]_{010} \propto J_0\left(\frac{j_{01}r}{a}\right)^2 \simeq$ constante

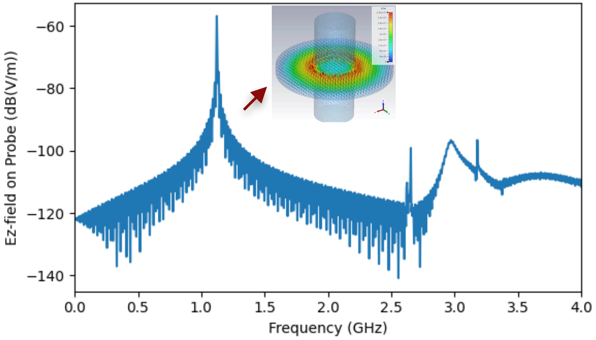
$\Rightarrow [R/Q]_{010} \propto$ constant

As $V_{out} \propto \sqrt{\left(\frac{R}{Q}\right)_{mnp}}$

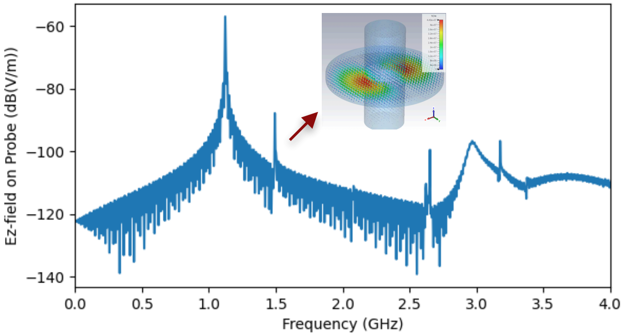
then $V_{out} \propto (\delta x)$ for the dipole

and $V_{out} \simeq$ constant for the monopole

- centered beam ($\delta x = 0$ mm)



- beam with offset ($\delta x = 0.5$ mm)



R. Lorenz, Cavity Beam Position Monitors, DESY
M. Viti, Resonant Cavities as Beam Position Monitor, DESY

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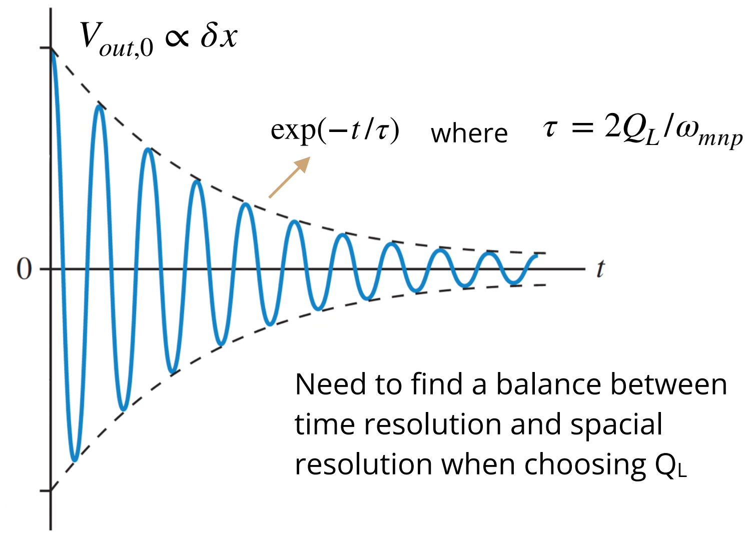
➔ Output signal

❖ on the time domain:

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

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



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

❖ on the frequency domain:

Contamination of the monopole signal at the dipole mode frequency

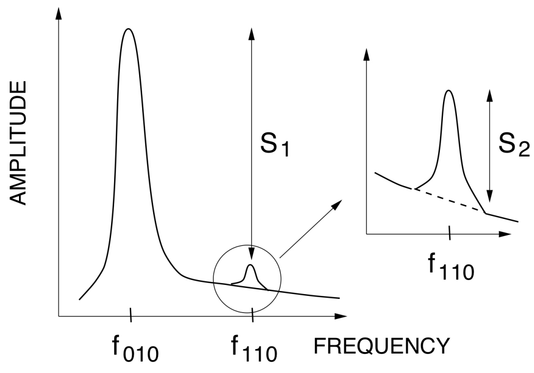


Figure: Common-mode contamination

When recovering the monopole signal, there is the need to suppress the monopole mode.

However the monopole signal has to be recovered in another way since it is needed for the intensity normalization (need of a reference cBPM)

❖ other considerations:

- Aperture of the cBPM has to be similar to the aperture of the beam pipe

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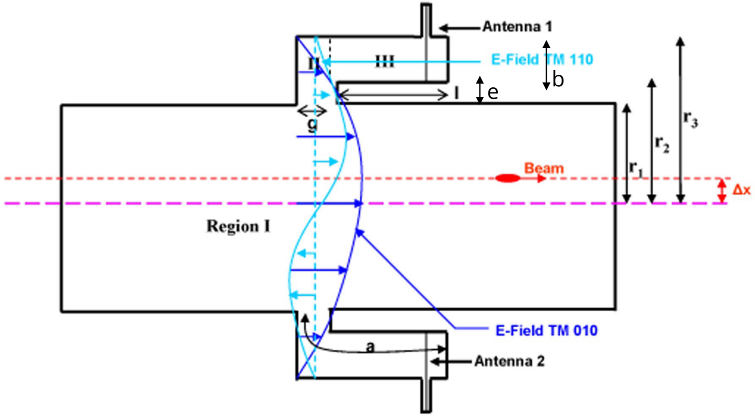
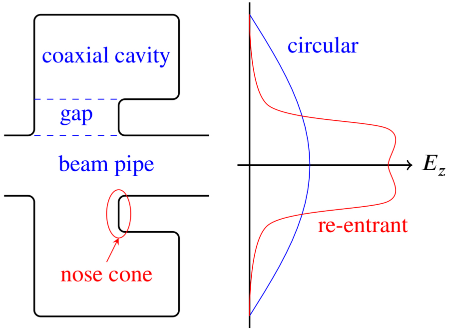
B) Re-entrant cavity BPM

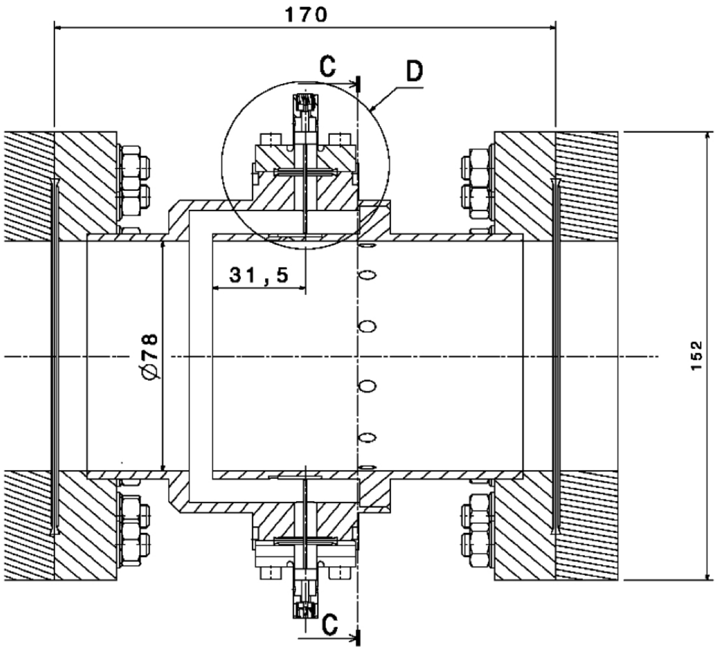
- **Geometry and modes:**





E field is concentrated on the *nose cone*
This structure increases the shunt impedance and therefore the sensitivity

Saclay: Simone - Re-entrant cavity BPM for DESY



Resonance frequencies: $f_{010} = 1.25$ GHz and $f_{110} = 1.72$ GHz

R. Bossart, High precision BPM using a re-entrant coaxial cavity, CERN
C. Simon, N. Louvière, N. Baboi, Performance of a reentrant cavity beam position monitor, DSM, CNRS, DESY

III. Ongoing work

A. CST Simulations
B. Parametric studies
C. BI-RME 3D

III. Ongoing work

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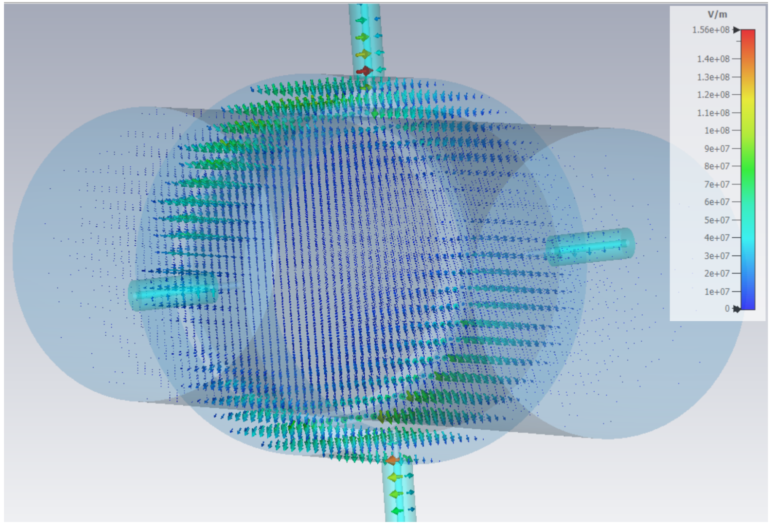
A) CST Simulations

- **Eigenmode study**

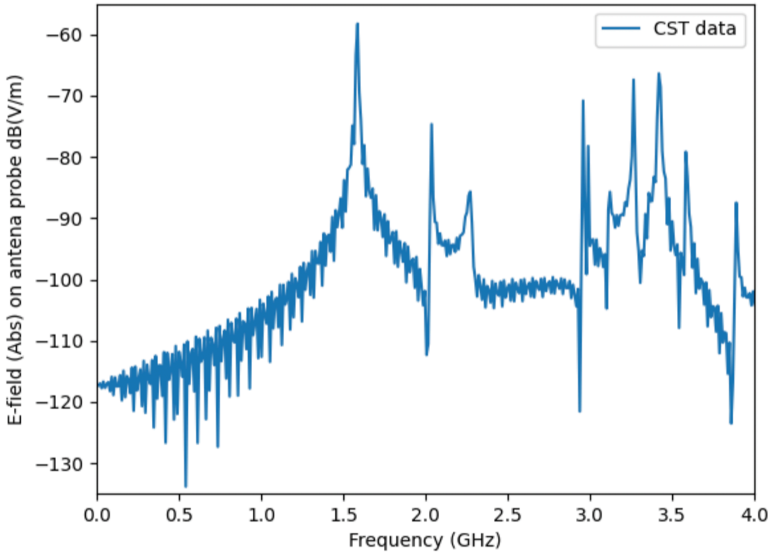
Evaluate the E and M fields distributions, coupling to antennas and the influence of geometrical parameters on the resonant frequency and quality factor Q_L



- **Wakefield study**

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

Beam offset: $\delta x = 1.0$ mm



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

III. Ongoing work

A) CST simulations

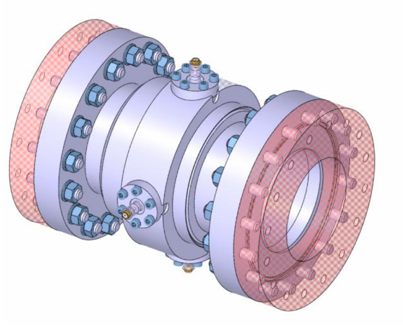


Fig. 8: Design of the new cavity BPM

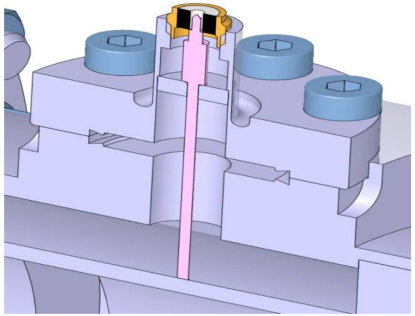
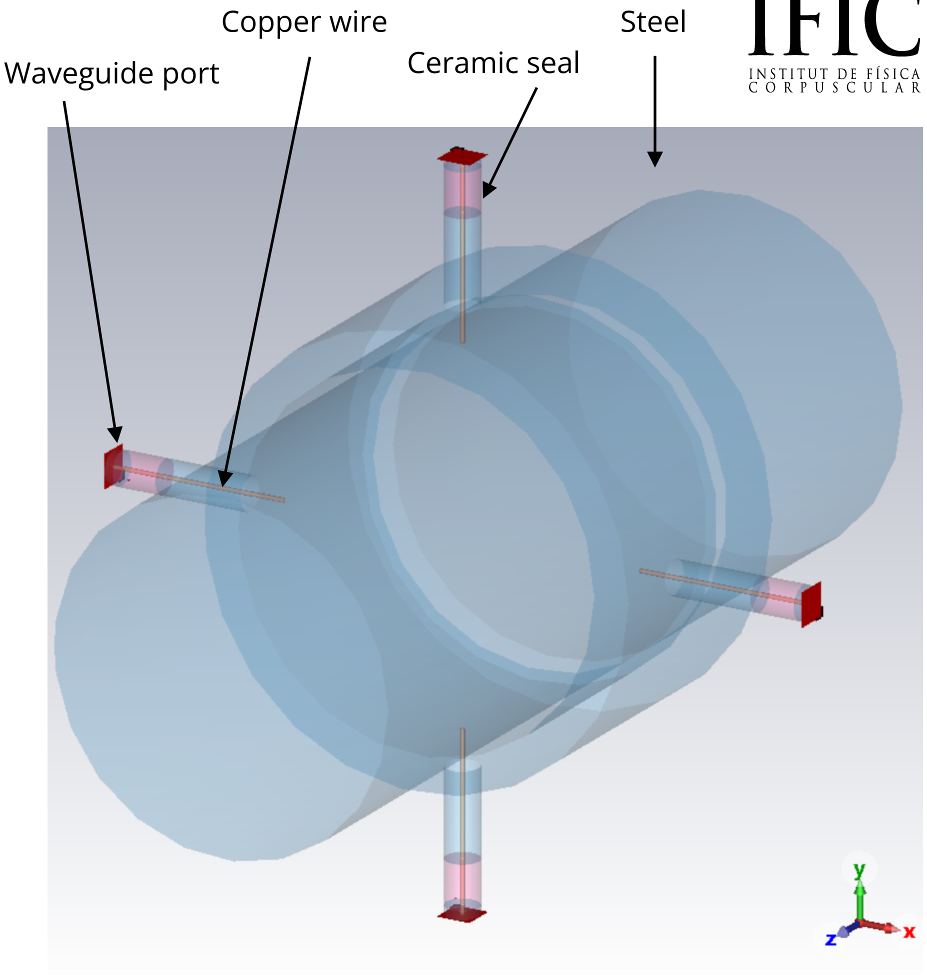


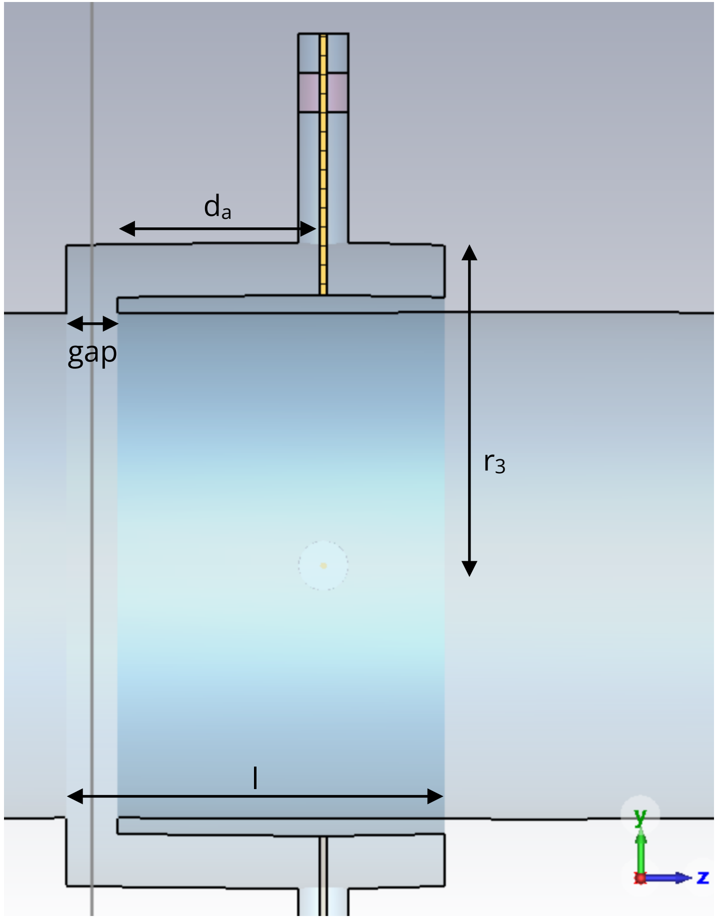
Fig. 9: Design of the new feedthrough

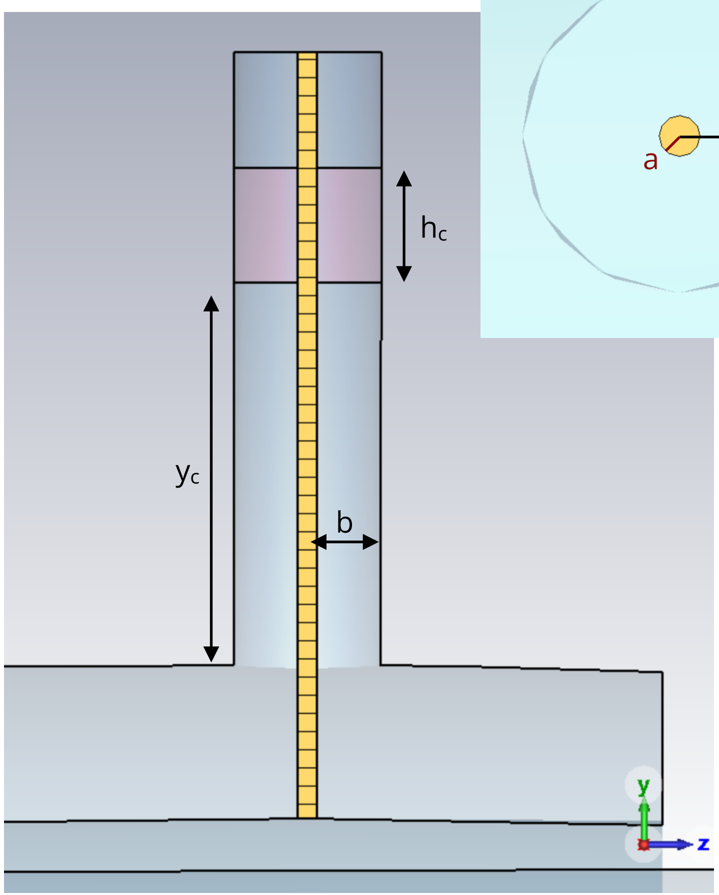
Mode	Frequency ω_{mnp} (GHz)	Loaded Q	Decay time (ns)	R/Q at 5 mm (Ω)
Bibliography				
Mode 1 TM_{010}	1.25	24	6.11	13
Mode 2 TM_{110}	1.72	51.4	9.51	0.25
CST Simulations				
Mode 1 TM_{010}	1.272	15.7	3.97	24.5
Mode 2 TM_{110}	1.728	57.9	11.07	0.46

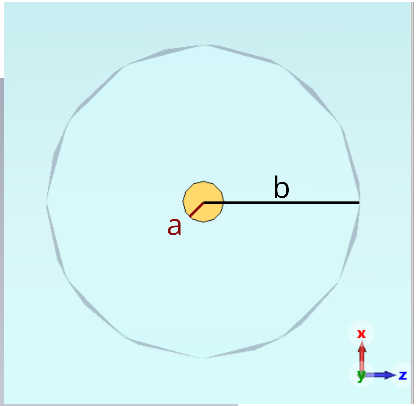


III. Ongoing work

A) CST Simulations







Parameter	Value (mm)
r_3	49.5
gap	8
l	50
d_a	31.5
a	0.5
b	3.85
y_c	20
h_c	10

III. Ongoing work

B) Parametric studies on CST

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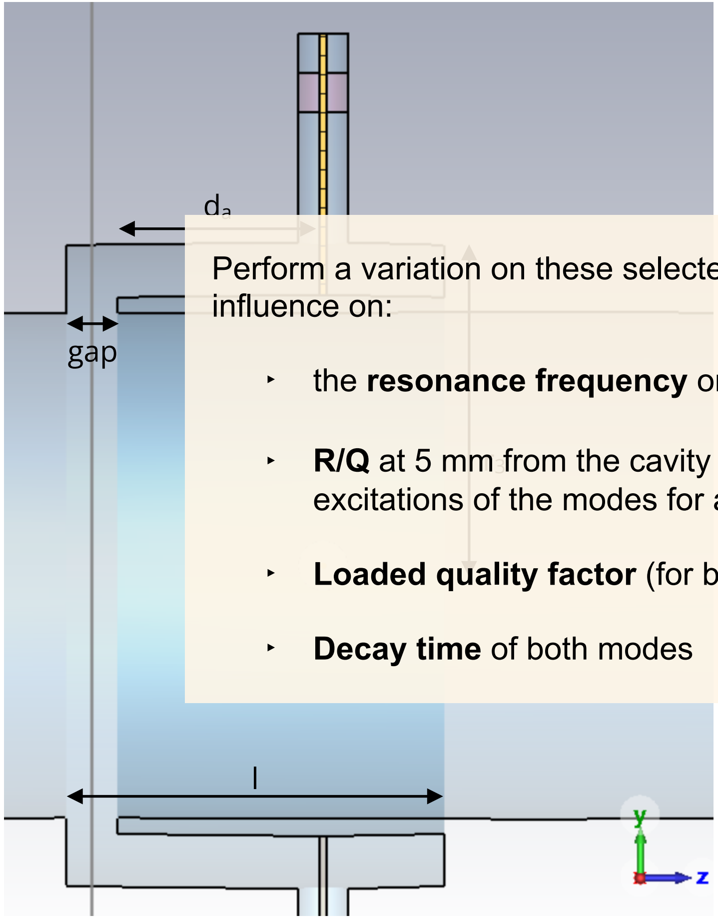
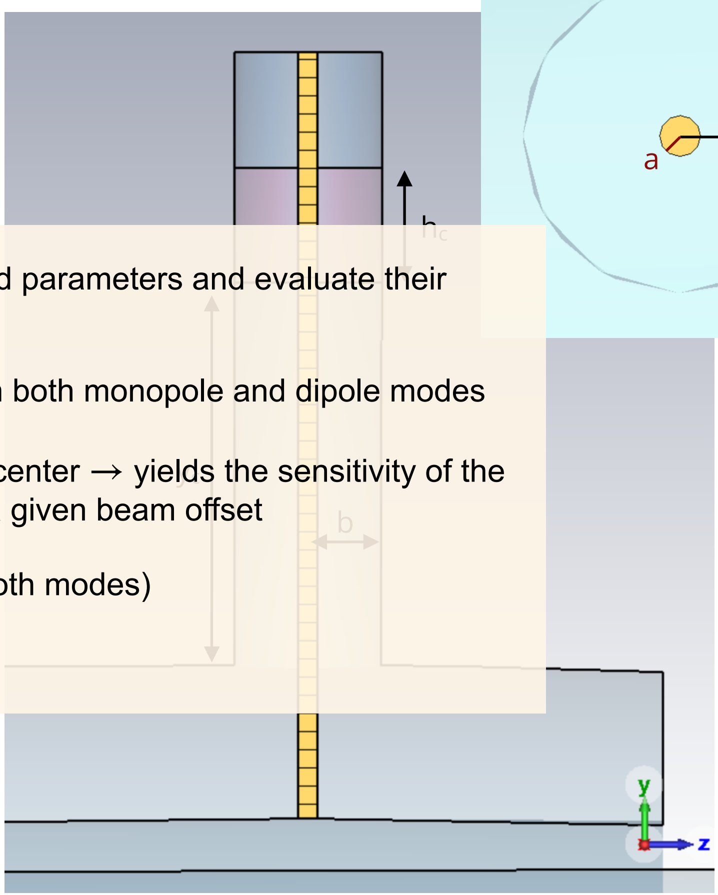
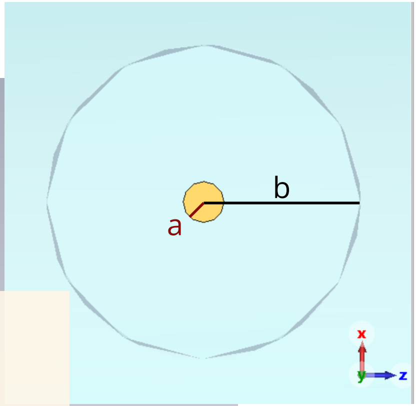






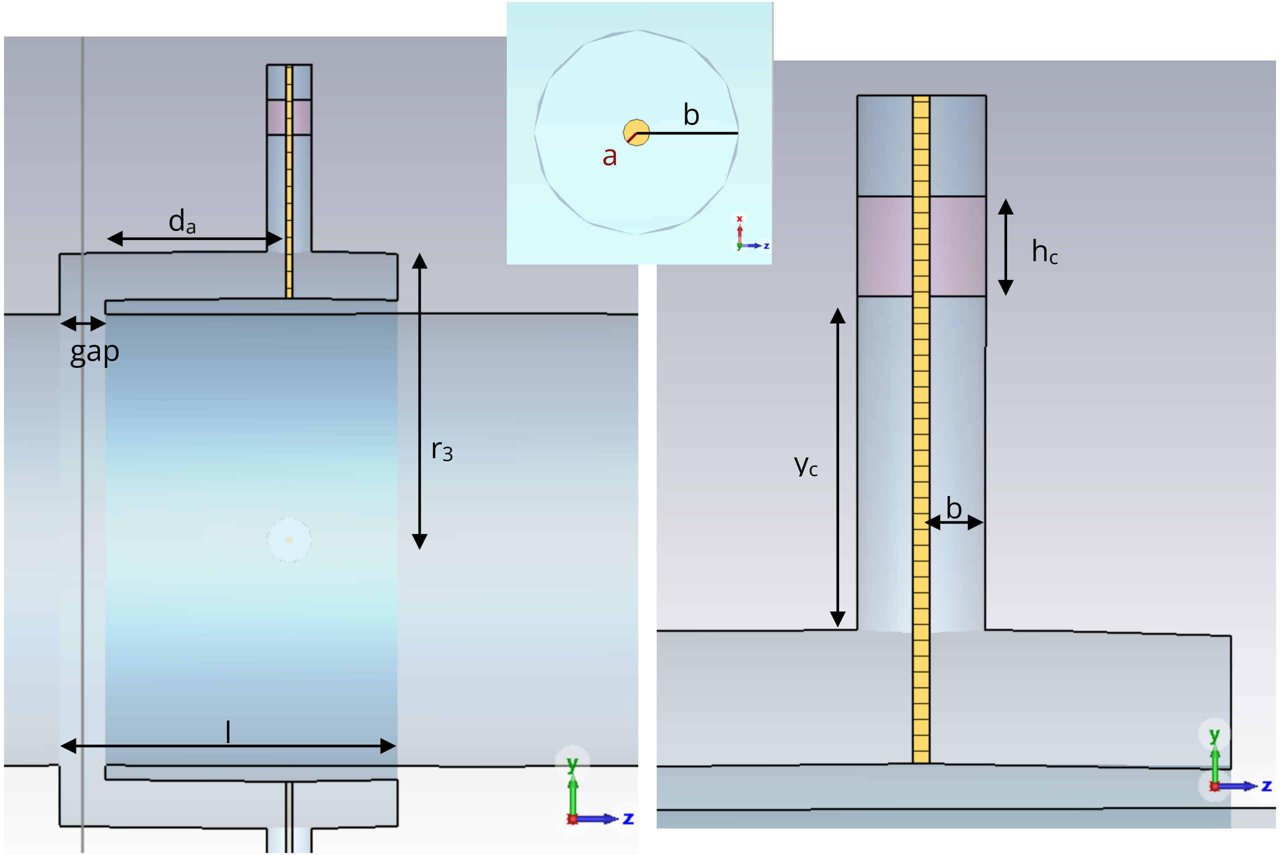
Perform a variation on these selected parameters and evaluate their influence on:

- the **resonance frequency** on both monopole and dipole modes
- **R/Q** at 5 mm from the cavity center → yields the sensitivity of the excitations of the modes for a given beam offset
- **Loaded quality factor** (for both modes)
- **Decay time** of both modes

Parameter	Value (mm)
r_3	49.5
gap	8
l	50
d_a	31.5
a	0.5
b	3.85
y_c	20
h_c	10

III. Ongoing work

B) Parametric studies on CST



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.

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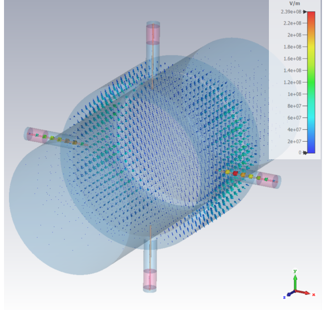


BI-RME 3D = Boundary Integral - Resonant Mode Expansion

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

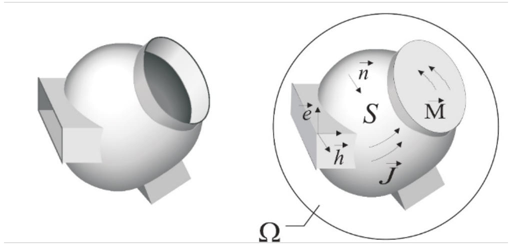
Method:

- The EM fields within a cavity can be expressed as a superposition of the full set of solenoidal and irrotational modes.
- The expressions of the electric and magnetic fields existing in the cavity excited by the time-harmonic electric $\vec{J}$ and magnetic $\vec{M}$ current densities are:

$$\vec{E}(\vec{r}) = \frac{\eta}{jk}\nabla\int_V g^e(\vec{r},\vec{r}\,')\,\nabla'\cdot\vec{J}(\vec{r}\,')\,dV' - jk\eta\int_V \vec{\mathbf{G}}^{\mathrm{A}}(\vec{r},\vec{r}\,')\cdot\vec{J}(\vec{r}\,')\,dV' - \int_S \nabla\times\vec{\mathbf{G}}^{\mathrm{F}}(\vec{r},\vec{r}\,')\cdot\vec{M}(\vec{r}\,')\,dS' + \frac{1}{2}\vec{n}\times\vec{M}$$

$$\vec{H}(\vec{r}) = \frac{1}{jk\eta}\nabla_s\int_S g^m(\vec{r},\vec{r}\,')\,\nabla'\cdot\vec{M}(\vec{r}\,')\,dS' - \frac{jk}{\eta}\int_S \vec{\mathbf{G}}^{\mathrm{F}}(\vec{r},\vec{r}\,')\cdot\vec{M}(\vec{r}\,')\,dS' + \int_V \nabla\times\vec{\mathbf{G}}^{\mathrm{A}}(\vec{r},\vec{r}\,')\cdot\vec{J}(\vec{r}\,')\,dV'$$

for a set of scalars and tensors of Green functions under the Coulomb gauge

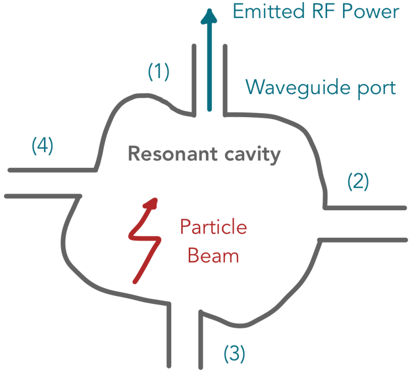


B. Gimeno, *Wide-band full-wave electromagnetic modal analysis of the coupling between dark-matter axions and microwave resonators, AITANA Seminar 2024*

III. Ongoing work

C) BI-RME 3D

A cavity BPM can be considered as a resonant cavity with 4 waveguide ports as outputs:



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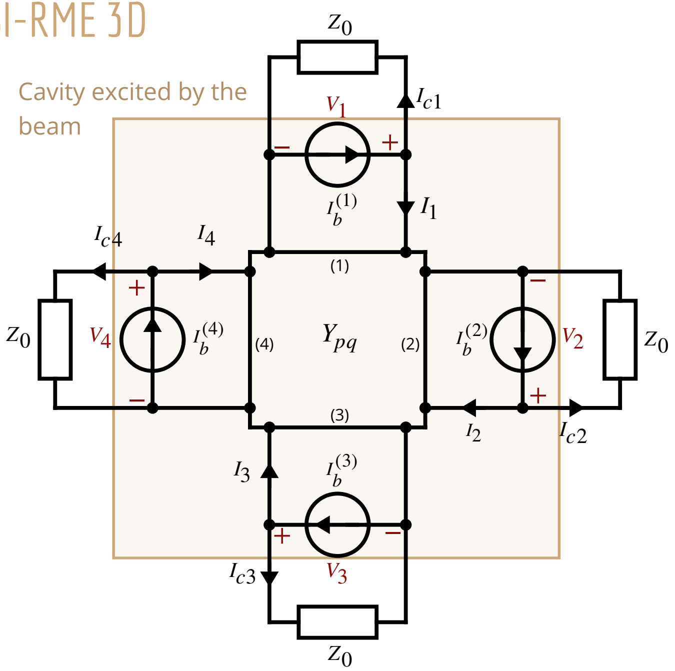


Variable definition:

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

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{pmatrix} \cdot \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix}$$

Input admittance of the cavity

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

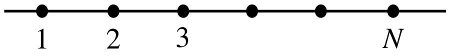
Coupling cavity-port

Coupling beam-cavity

Intensity generated by the beam leading to port (i)

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



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

IV. Future plans

III. Future plans

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New cBPM design

Crossed examination of parameters for a detailed optimization

Start developing cBPM design to fit
- measurement requirements: temporal resolution < 6.15 ns
- mechanical requirements: mechanical fit with the SC quadrupole

Performance estimation with BI-RME 3D

Saclay model

Acquire the cBPM model from C. Simone → summer/fall 2024

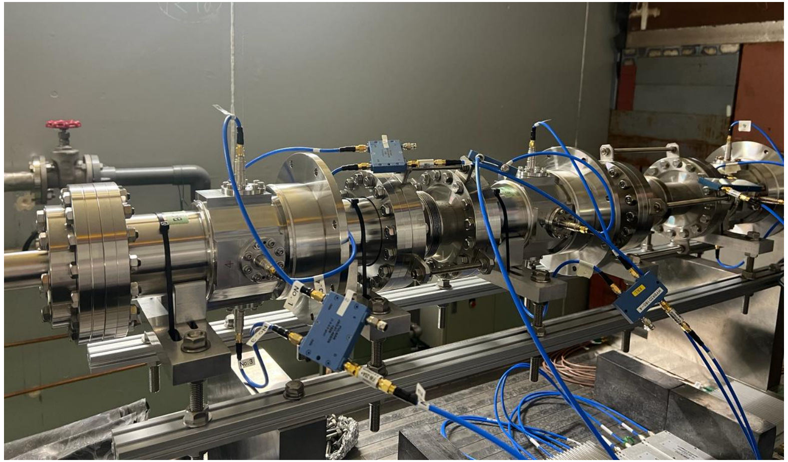
Start developing the electronics readout to test with this model
Possibility of collaboration with the RHUL / ELI + KEK (test their electronics)

Prepare set-up for cBPM at RF laboratory (IFIC)

Measurements at ATF and STF

Possibility to perform measurements at the end of 2024, provided that we receive the cBPM from Saclay and have the read-out system ready

Prepare setup and space that will be used at ATF



Thank you for your attention

laura.pedraza@ific.uv.es