Design and Studying Physical Properties of Cavity Beam Position Monitors for Electron Accelerators

DIPARTIMENTO DI FISICA

FISICA DEGLI ACCELERATORI

SAPIENZA
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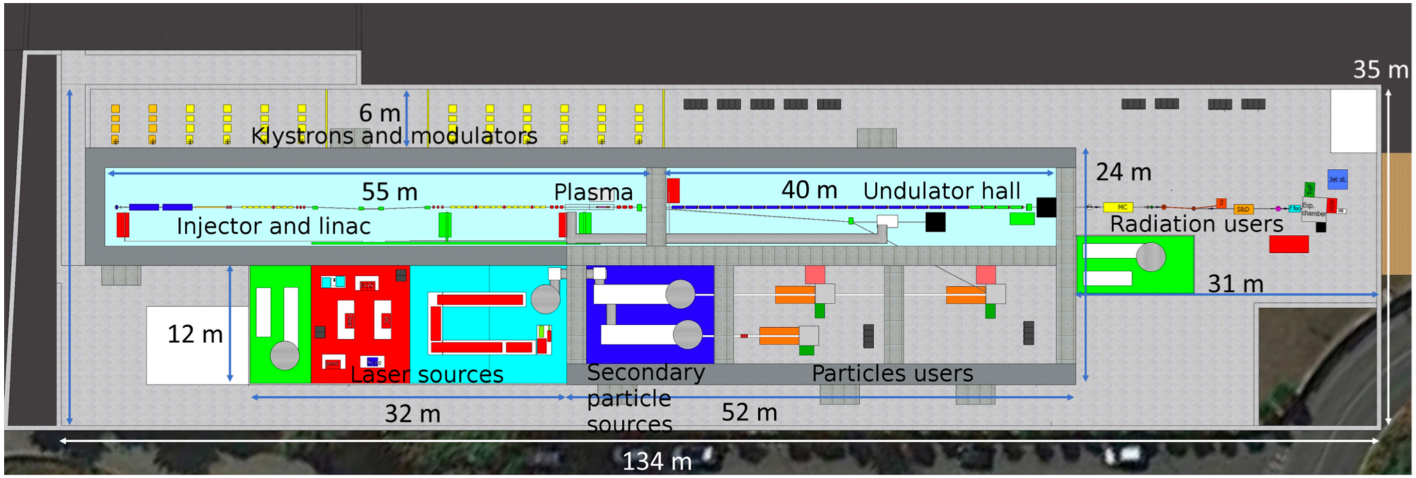
Outline

- Introduction
- EuPRAXIA@SPARC_LAB project and it’s requirements.
- Cavity BPM design process and strategy.
- Working principle and theory of Cavity Beam Position Monitors.
- Geometrical parameters for the monitor.
- Waveguide to coaxial transition.
- Proposal of cBPM prototype with one resonator.
- Dual-Resonator cBPM prototype.
- Sensitivity and theoretical resolution for dual-resonator cBPM.
- Mechanical implementation.
- Conclusions and Outlook.

Introduction

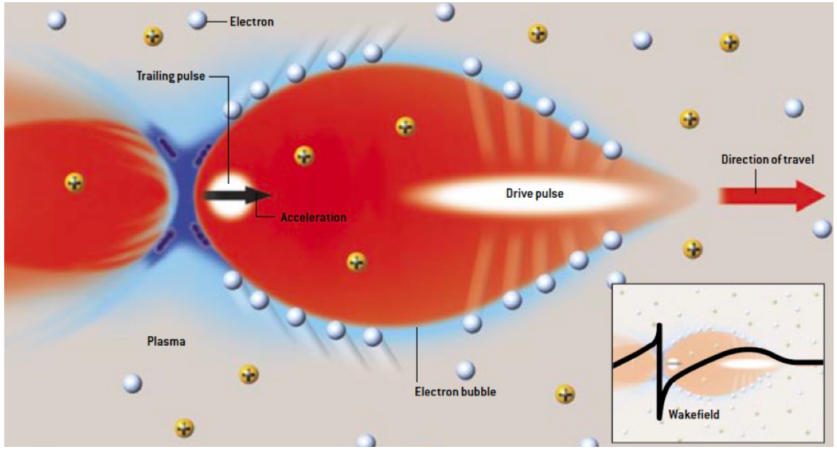
- We have designed a Cavity Beam Position Monitor for the EuPRAXIA@SPARC_LAB project.
- A particular set of parameters for the prototype were determined in order to fulfil the EuPRAXIA@SPARC_LAB requirements.
- Based on this set, simulations were performed with ANSYS HFSS for frequency domain calculations, using the wire technique, and CST for simulating the passing particle beam, to verify the goodness of the designs layout and optimise them.
- Sensitivity to the possible fabrication errors and performance degradation of the prototype have been studied.
- Theoretical resolution of the device was approximated with the upper limit for additional contribution in noise due to the mechanical tolerances.
- Mechanical implementation, based on the new clamping method, developed at LNF INFN, is proposed.
- Foreseen future tests.

EuPRAXIA@SPARC_LAB project and it's requirements



The layout of the EuPRAXIA@SPARC_LAB infrastructure.

The control of the charge and the trajectory at a few pC and few μm is mandatory in this machine, especially in the plasma interaction region. However, other kind of BPMs, such as stripline BPM, can be used only at the beginning of the accelerator, where the beam pipe is 40 mm. But starting from X band structures, the pipe size decreases. Also, one of the most important parameter was considered to be the length of the device.

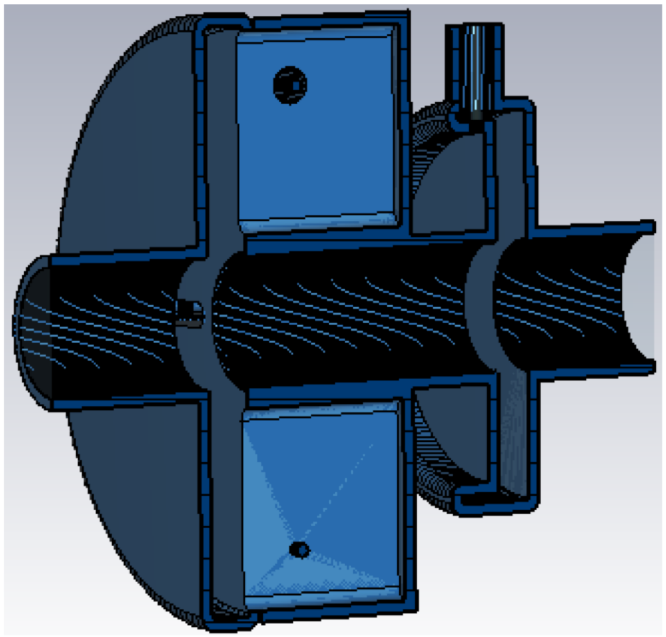


EuPRAXIA@SPARC_LAB project beam specifications.

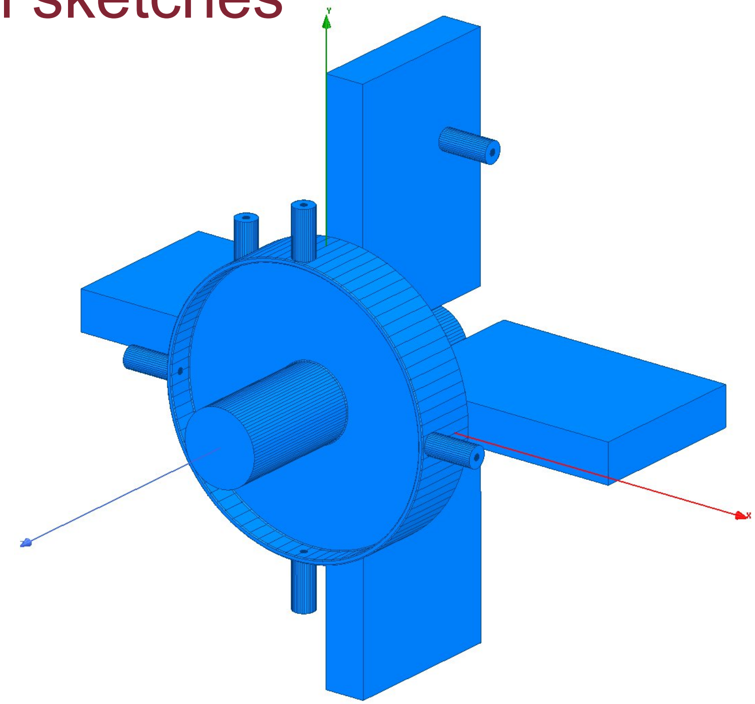
Parameter	Units	Full rf	LWFA	PWFA
Electron energy	GeV	1	1	1
Repetition rate	Hz	10	10	10
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch charge	pC	200	30	200(D)-30(W)
RMS Bunch Length	μ m (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.05	0.47	1.1
Slice Length	μm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.015	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13(0.8)	1.13(0.8)
Undulator Length	m	30	30	30
ρ (1D/3D)	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98(0.42)
Photon Energy	μJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	μm	200	145	10
Photon Brilliance per shot	(s mm2 mrad2 bw(0.1%)) $^{-1}$	1.4×10^{27}	1.7×10^{27}	0.8×10^{27}

EuPRAXIA@SPARC_LAB's beam parameters for plasma and conventional RF linac driven FEL.

Proposed cavity BPM design sketches



Sketch of dual-resonator cBPM



Sketch of single-resonator cBPM

Parameters	Values
Working frequency range	C band
Loaded quality factor Q_L	≈ 500
Sensitivity	≈ 5 V/nC/mm
Required resolution	$< 1\mu$m

Sensitivty of the device should be of the order of 5 V/nC/mm in order to provide <1 μm resolution.

Cavity BPM design process and strategy

General idea:
- loaded quality factor Q_L
- theoretical resolution

Cavity spectrum calculations:
- working frequency
- R/Q
- TM_{110} output voltage

cBPM parameters:
- design layout
- cavity length
- waveguide dimensions
- coaxial transition

Cross coupling:
- waveguide tuning
- 2 ports vs 4 ports

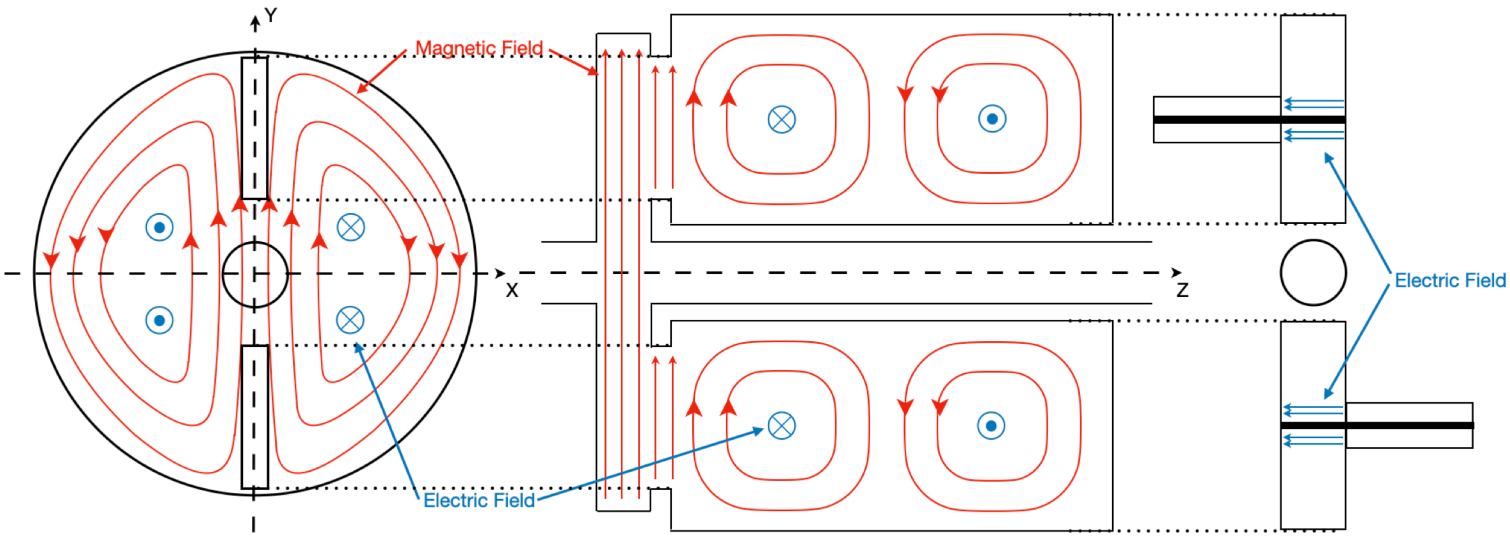
loop

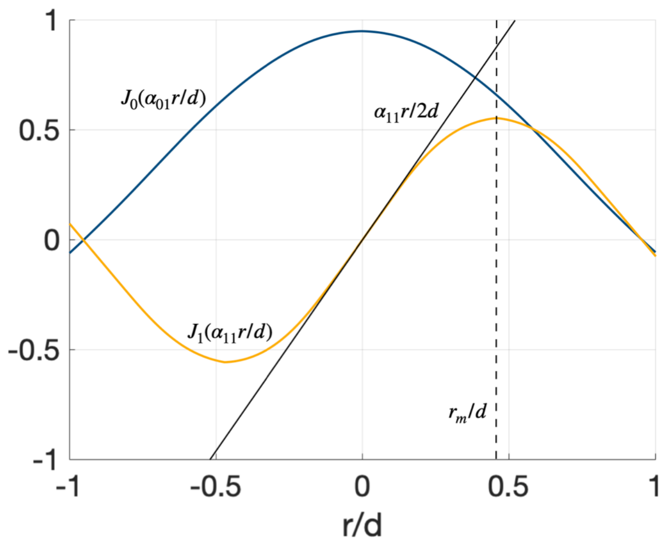
loop

Tolerances calculation:
- coupling slots or waveguide alignment to cavity
- coaxial coupler position

Parasitic signals:
- monopole modes
- quadruple modes

Working principle and theory of Cavity Beam Position Monitors.



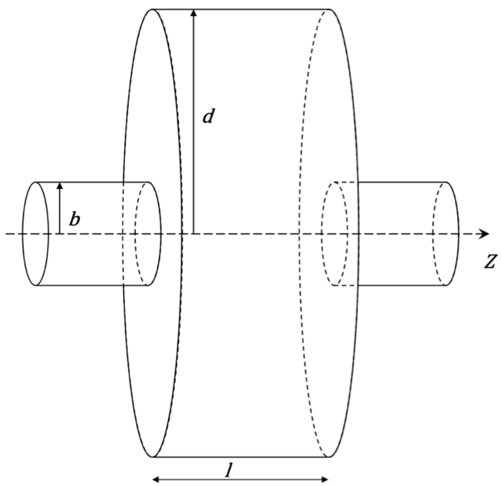


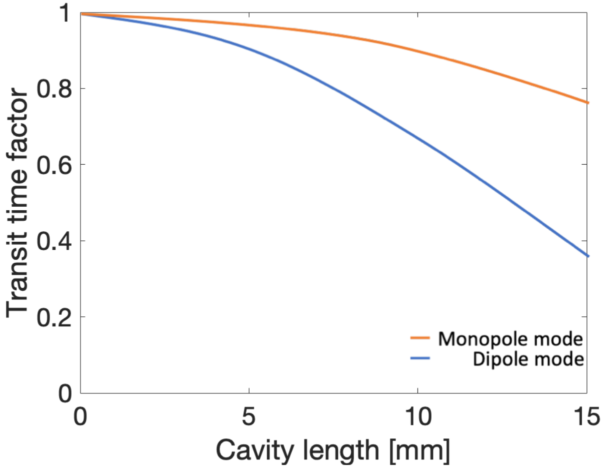
$$\frac{R}{Q}_{110} = \frac{V_{110}^2(r_m)}{2\omega_{110}W_{110}} = \frac{2Z_0 l J_{1max}^2 T_{tr}^2}{\pi\alpha_{11} d J_0^2(\alpha_{11})}$$

$$\mathrm{V}_{110}(\delta x) = \frac{q_b\omega_{110}}{2}\frac{J_1\left(\alpha_{11}\frac{\delta x}{d}\right)}{J_{1max}}\left(\frac{R}{Q}\right)_{110}$$

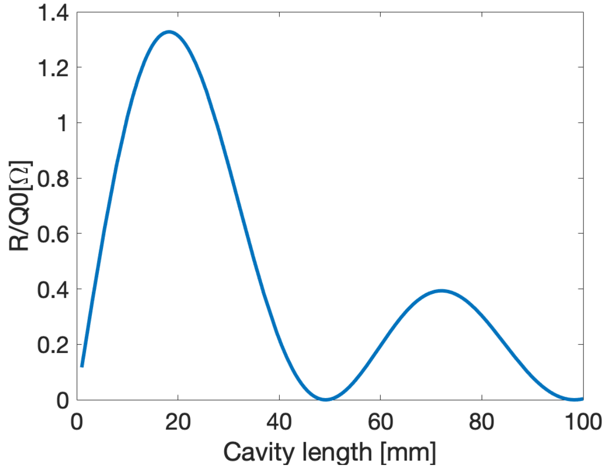
$$\mathrm{V}_{110}(\delta x) = \delta x \cdot q_b \frac{l T_{tr}^2}{d^3}\frac{Z_0 c\alpha_{11} J_{1max}}{2\pi J_0^2(\alpha_{11})}.$$

Geometrical parameters for the monitor.

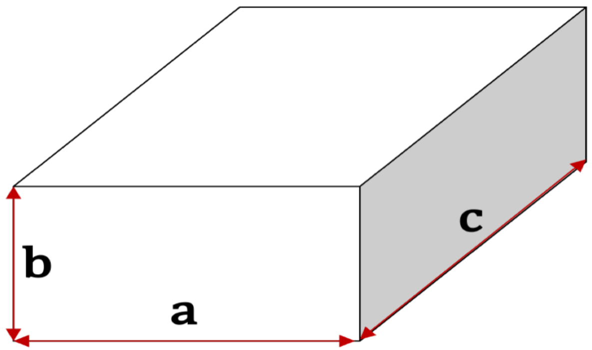




Transit time factor for the monopole and dipole modes of a pillbox cavity with different lengths.



Dependence of the shunt impedance on the cavity length.

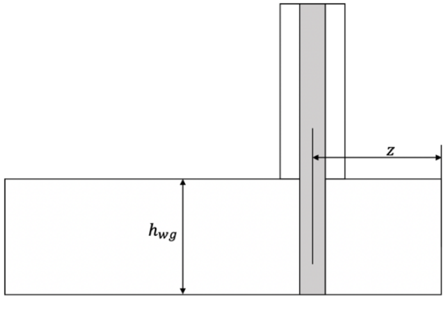


The width of waveguide (a) has to be chosen such, that its cut-off frequency is located between TM_010 and TM_110 cavity modes.

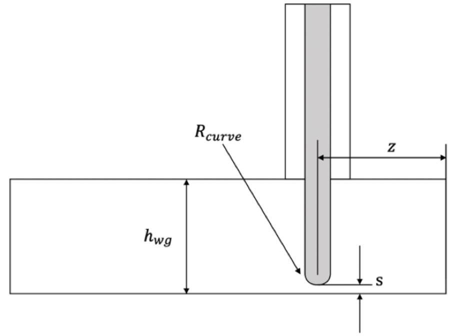
The monopole signal is exponentially decaying along the waveguide, therefore, it is better to have minimal height (b) (compromise has to be found between height and coaxial output transmission quality).

The length (c) has to be chosen in order to eliminate reflections.

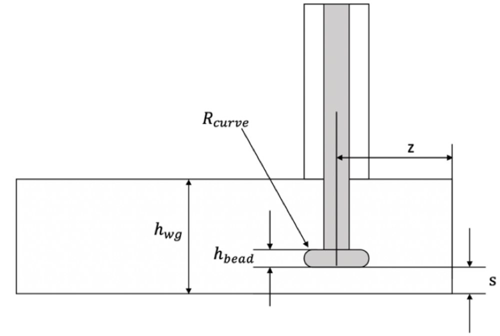
Waveguide to coaxial transition.



Sketch of the direct coupling



Sketch of the inductive coupling

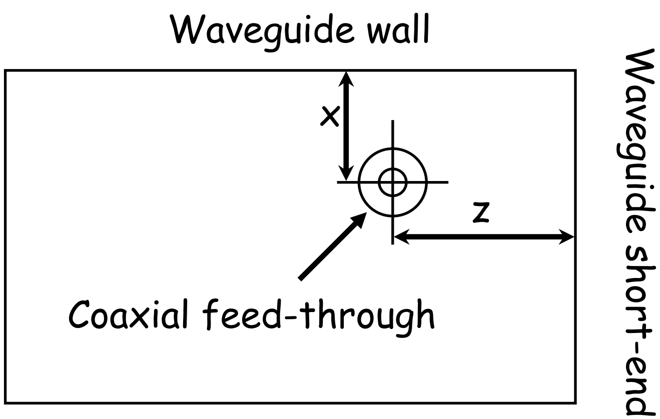


Sketch of the capacitive coupling

Different types of coupling were simulated for waveguide to coaxial transition substructure.

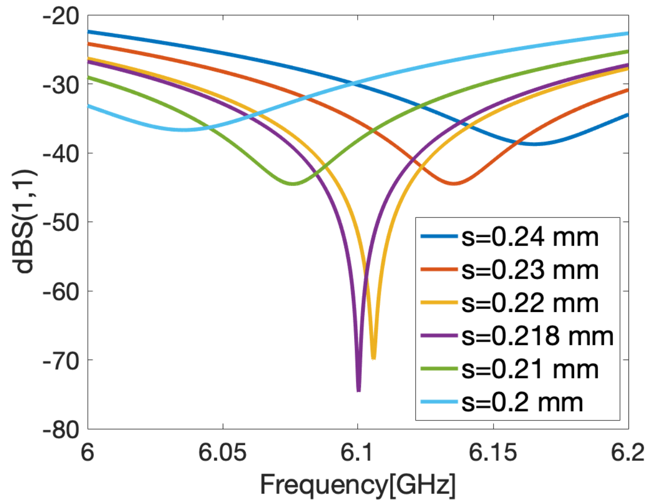
Dimmension	Value[mm] Inductive coupling	Capacitive coupling
Waveguide Length l $_{WG}$	33	33
Waveguide Width w $_{WG}$	48	48
Waveguide Height h $_{WG}$	8	8
Coaxial Position x	9.63	23.41(2)
Coaxial Position z	9.63	17.3
Bead Height h $_{bead}$	–	1.2
Antenna Curvature Radius R_{curve}	0.5	0.5
Whip and Bead Radius	0.635	1.3
Spacing between Antenna and Waveguide Wall s	0.21(8)	0.7

Dimension values for the inductive and capacitive couplings for 6.1 GHz.

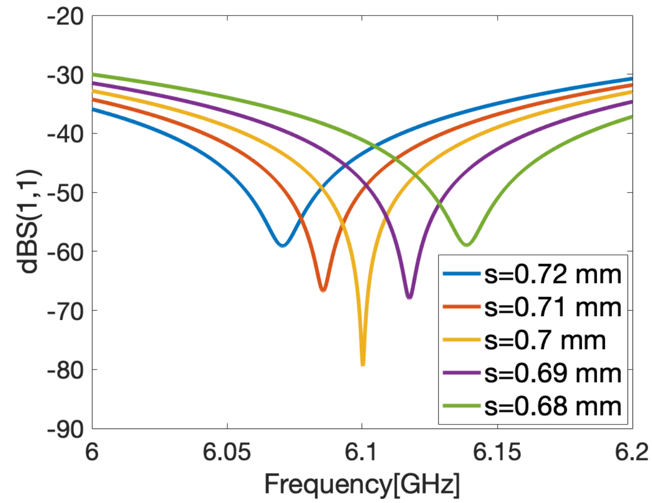


Exposition of how sufficient transition is achieved between the waveguide and coaxial antenna by changing the **x** and **z** parameters.

Reflection coefficients for waveguide to coaxial transition.

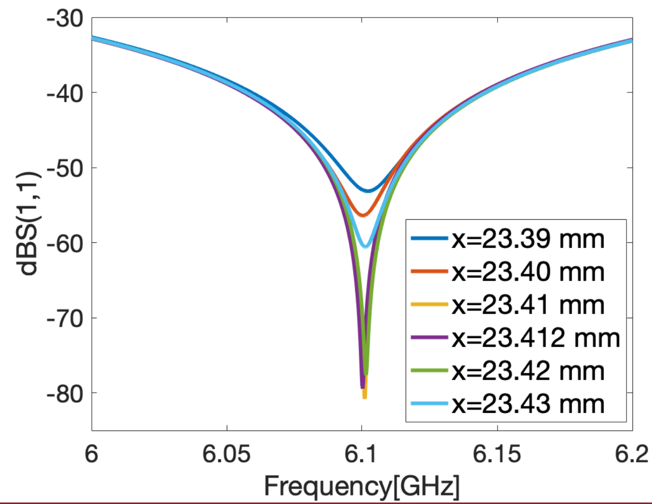


dB S(1,1) parameter dependence on the spacing variation between the antenna end and waveguide wall for inductive coupling.

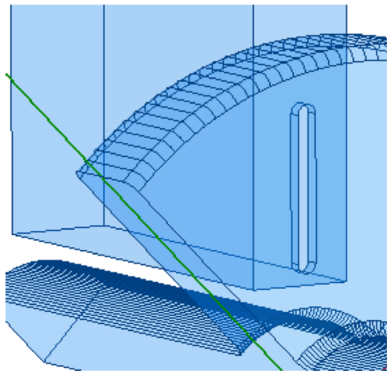


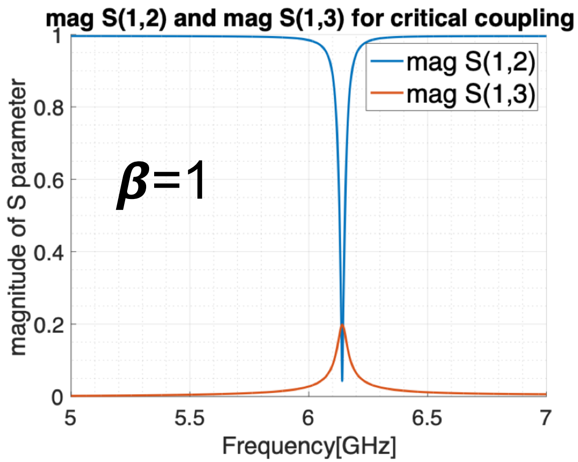
dB S(1,1) parameter dependence on the spacing variation of the bead end and waveguide wall.

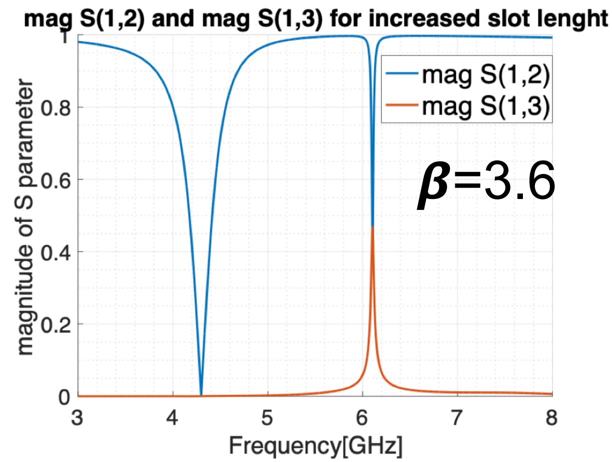
Different coupling methods were studied, using the whip antenna for inductive coupling and preforming capacitive coupling by whip antenna with a flat bead at the end of the inner conductor. In the capacitive coupling case, we have a little more freedom in terms of distance from the waveguide wall, Since the capacitance between two flat surfaces is proportional to their area and inversely proportional to their separation. Increasing the area of the bead should allow for a larger spacing between it and the waveguide wall.

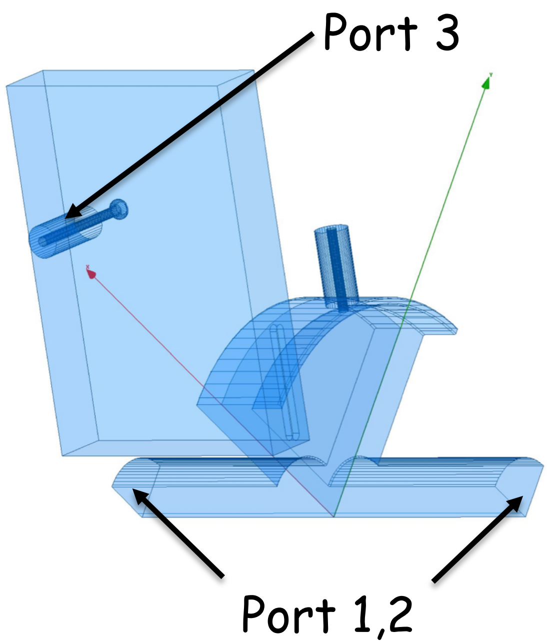


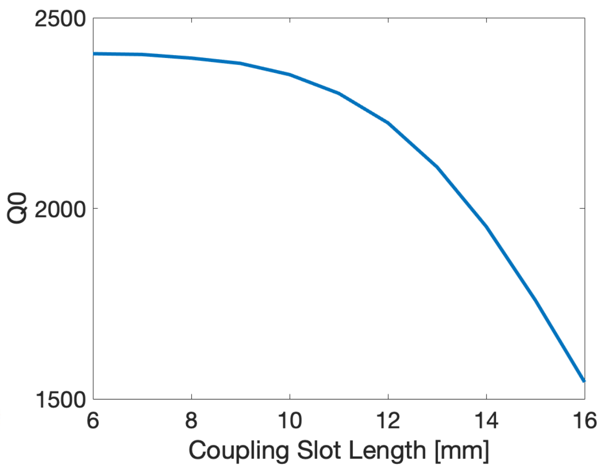
Proposal of cBPM protorype with one resonator.



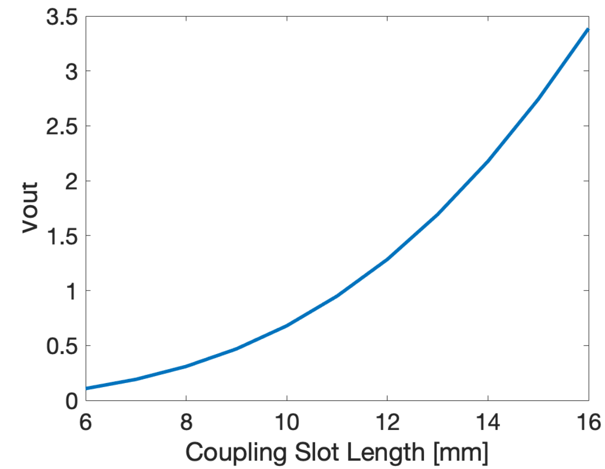








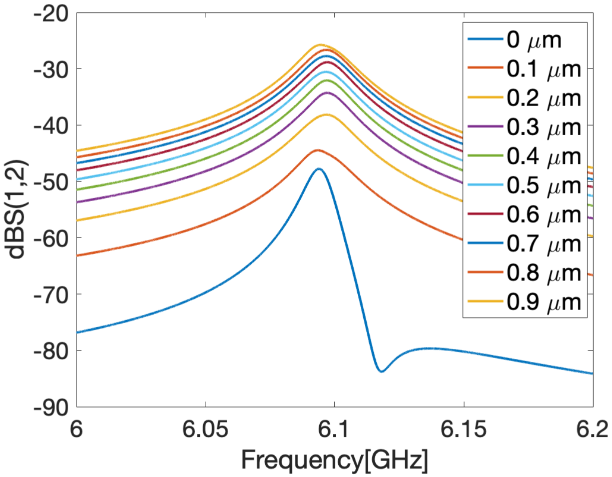
Q_0 dependence on the slot length variation.

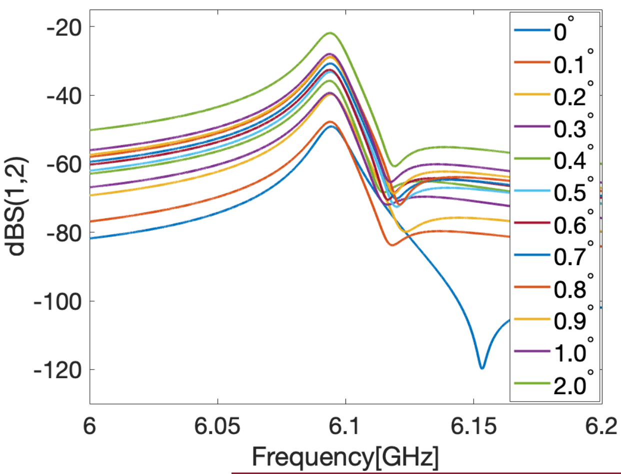


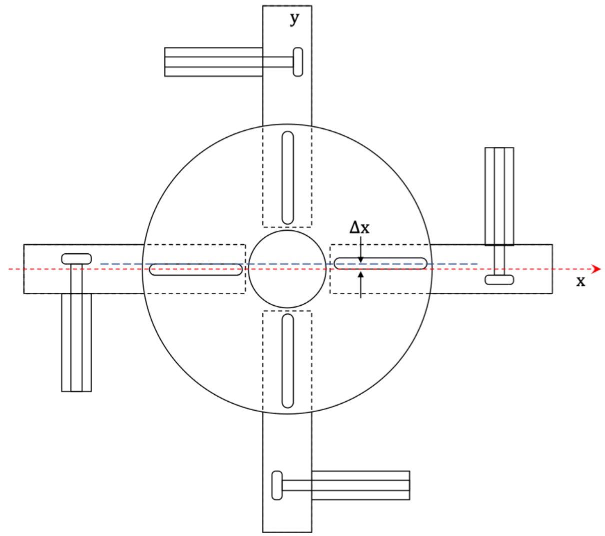
Slot length influence on the Vout.

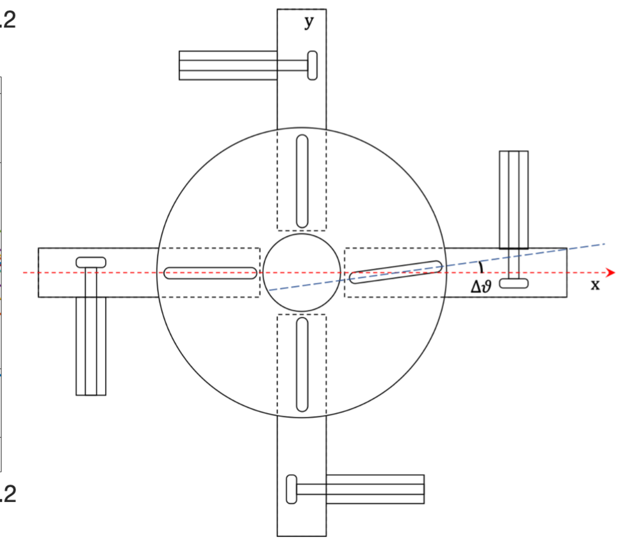
cBPM with one resonator studying mechanical tolerances

Dipole mode TM_{110} cross-coupling to orthogonal port as a function of coupling slot angle and position errors.

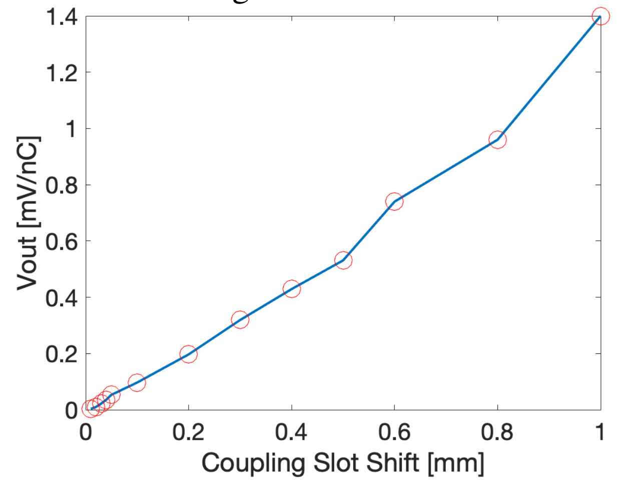


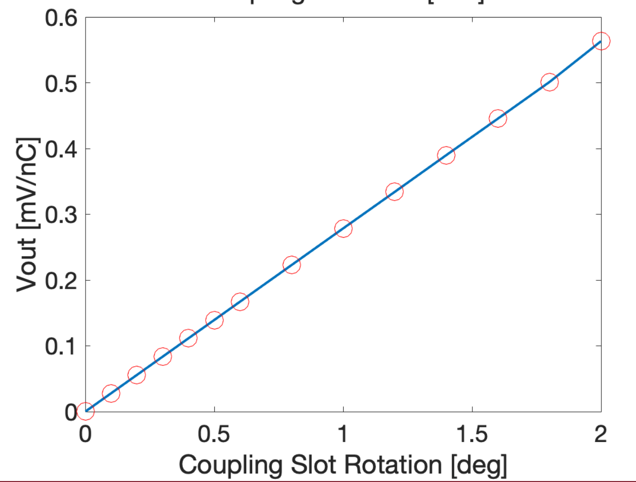




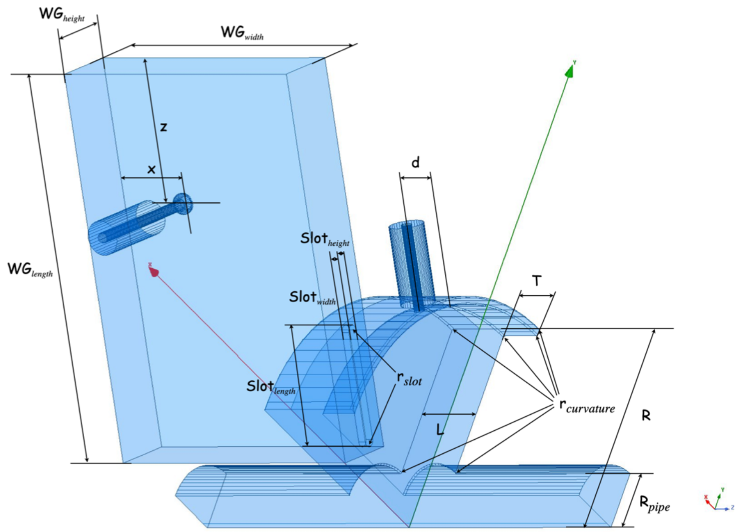


Simulated output signal contribution of TM_{010} mode generated by 1nC, 1 mm offset beam, as a function of coupling slot misalignments.





cBPM with one resonator RF and dimension values



A general sketch and indications of the dimensions for the cBPM prototype only with one resonator.

Dimmension	Value[mm]
Position Cavity Radius R	27.71
Position Cavity Length L	8
Waveguide Length WG $_{length}$	33
Waveguide Width WG $_{width}$	48
Waveguide Height WG $_{height}$	8
Coaxial Position x	9.58
Coaxial Position z	17.6
Separation of Monopole Coaxial Port d	2.4
Trench Length T	5
Trench Height h	1
Slot Length Slot $_{length}$	14
Slot Width Slot $_{width}$	1.5
Slot Height Slot $_{height}$	1
Slot Curvature Radius r_{slot}	0.75
Cavity Edge Curvatures $r_{curvature}$	0.2
Beampipe Radius R_{pipe}	7.5

Dimension values for the one resonator prototype cavity BPM

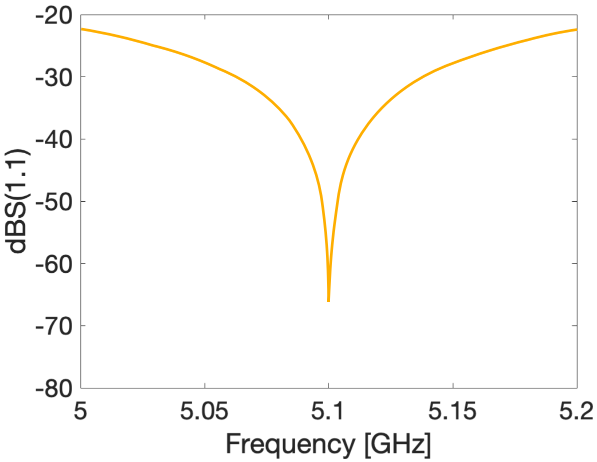
Parameter		Numerical calculation
	TM$_{010}$ as reference	TM$_{110}$
f_{GHz}	4.18	6.100
Q_0	2631	3075
Q_L	657	877
Damping time,τ ns	34.3	44.5
$\frac{R}{Q}$,Ohm	42	0.49
V_{out}	21 V/nC	3.02 $V/nC/mm$
Theoretical resolution	–	326 nm

The main characteristics of the one resonator cBPM prototype.

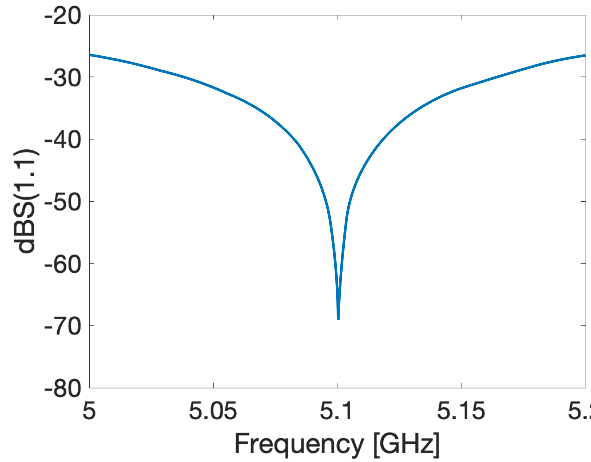
Dimmension	Q $_0$ Variation [%/mm]	Frequency shift [MHz/mm]
Cavity Radius R	2	-218
Cavity Length L	3	-33.9
Waveguide Length WG $_{length}$	-2.3	-0.2
Waveguide Width WG $_{width}$	-3.81	-0.3
Waveguide Height WG $_{height}$	-6.93	-0.6
Separation Coaxial Port d	20	1.6
Spacing s	8	0.1

Dimension tolerances to the 1mm change for the one resonator prototype.

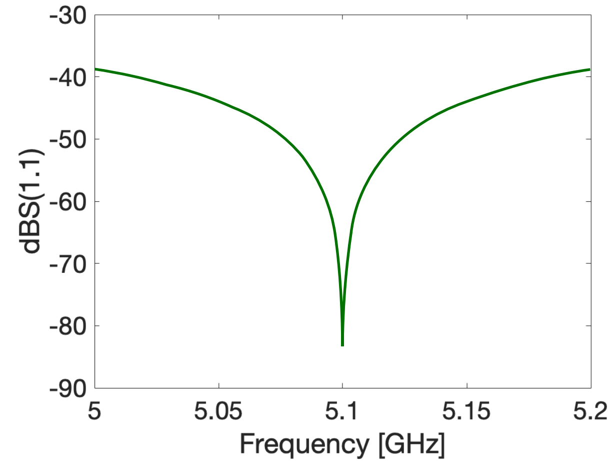
Waveguide to coaxial transition for dual-resonator cBPM.



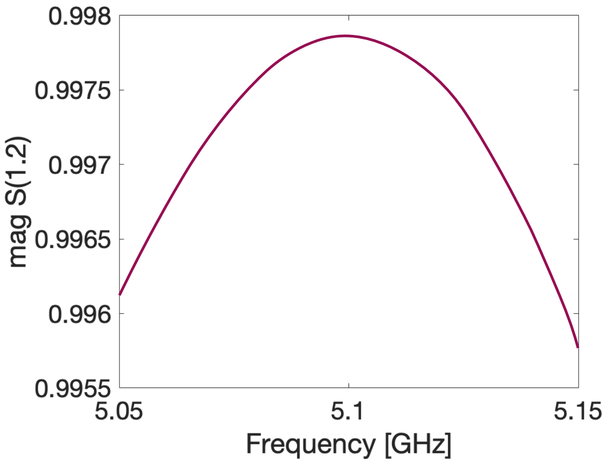
dB S(1,1) parameter for 5.1 GHz waveguide to coaxial transition for the direct coupling with whip antenna.



dB S(1,1) parameter for 5.1 GHz waveguide to coaxial transition for the inductive coupling with whip antenna.



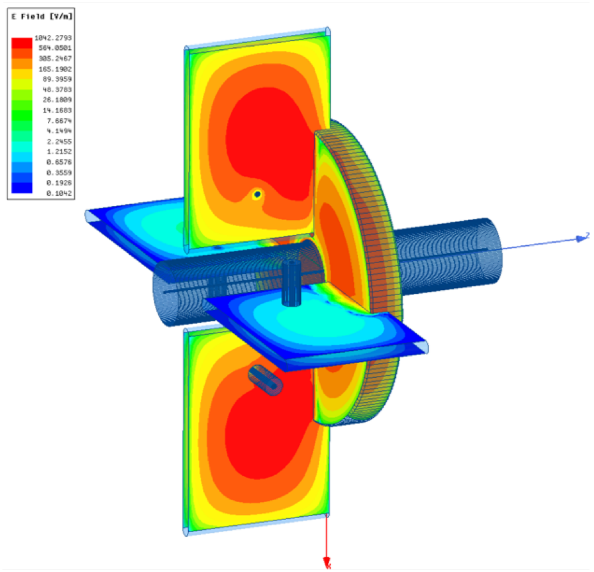
dB S(1,1) parameter for 5.1 GHz waveguide to coaxial transition for the capacitive coupling.

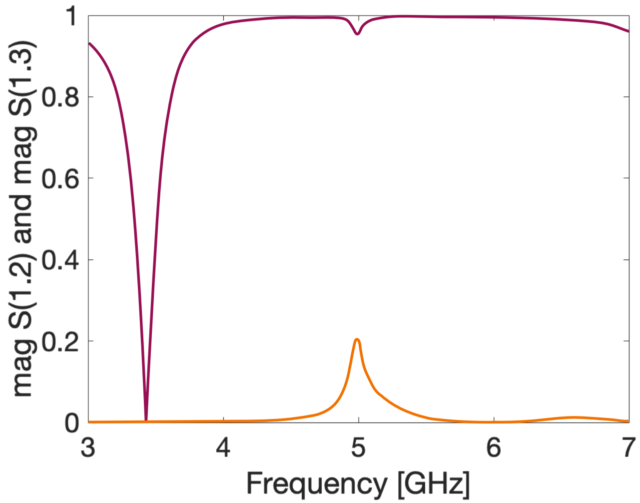


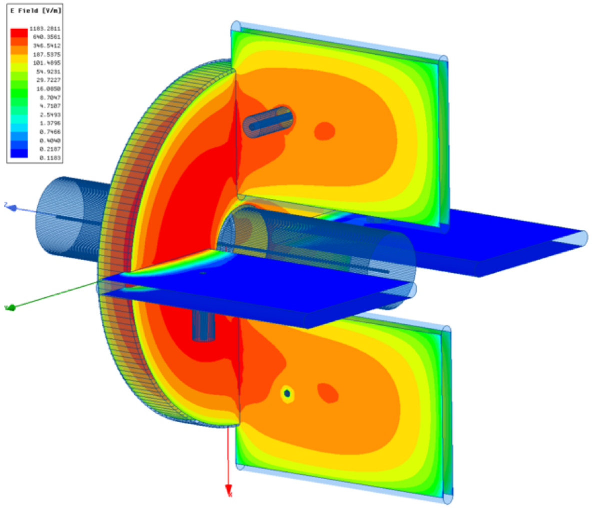
Mag S(1,2) parameter for 5.1 GHz waveguide to coaxial transition for the direct coupling case.

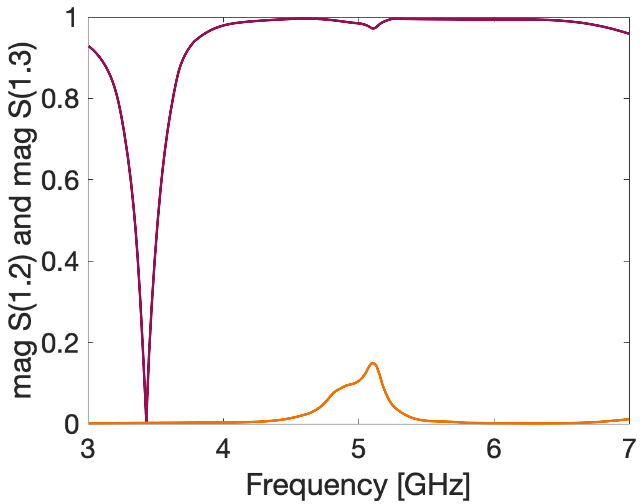
Dimmension	Value/mm		
	Direct coupling	Inductive coupling	Capacitive coupling
Whip Antenna Raduis	0.635	0.635	0.635
Bead Radius	–	–	1.8
Bead Height h $_{bead}$	–	–	1.2
Curvature Radius R $_{curve}$	–	0.5	0.2
Spacing s	0	0.151	1.969
Distance from the short-end$z$	19.5	58.8	21.74
Distance from the wall x	25	18.5	12.2
Waveguide height h $_{wg}$	3	8	6
Waveguide height w $_{wg}$	39	37	37
Waveguide height l $_{wg}$	57	90	57

Simualting position cavity with wire for dual-resonator cBPM.

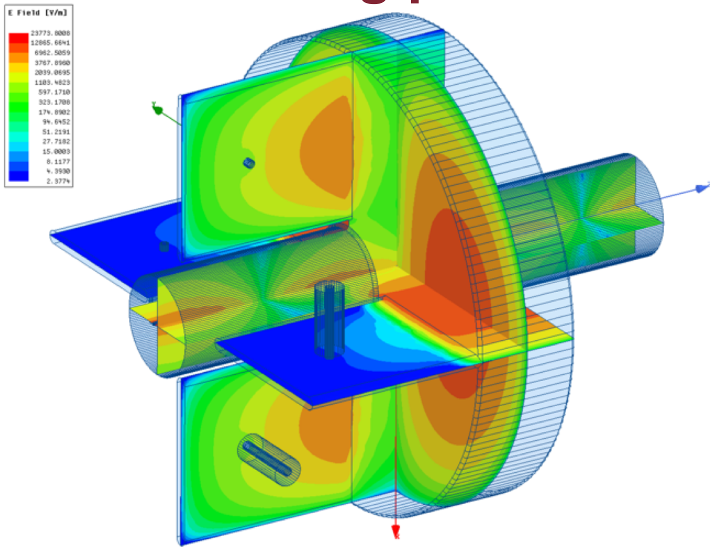


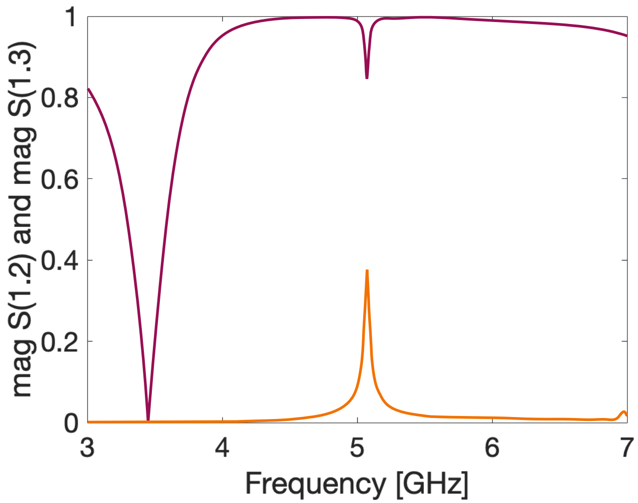


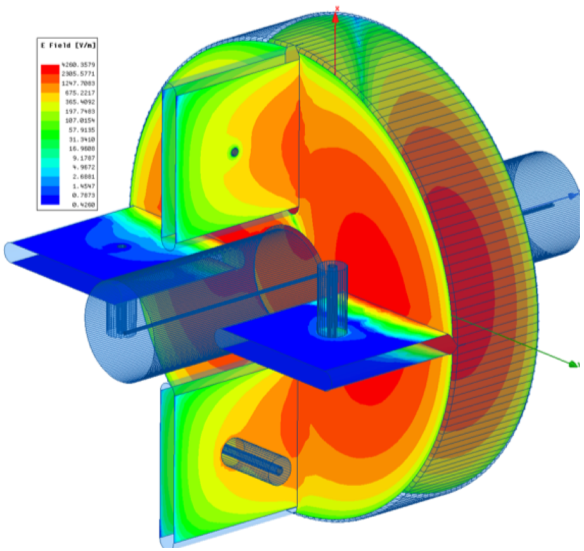


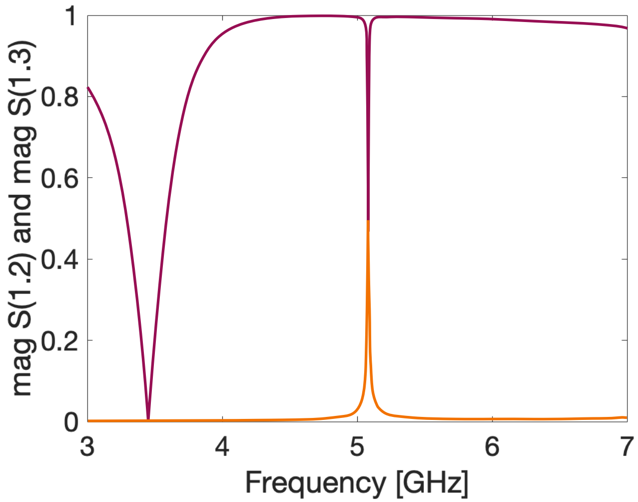


Simualting position cavity with wire for dual-resonator cBPM.

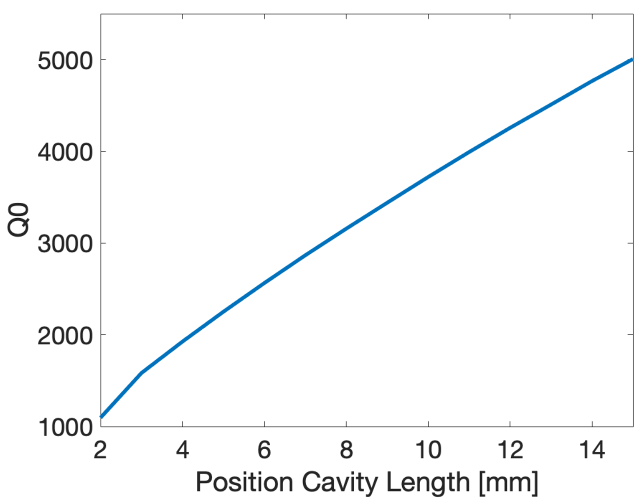




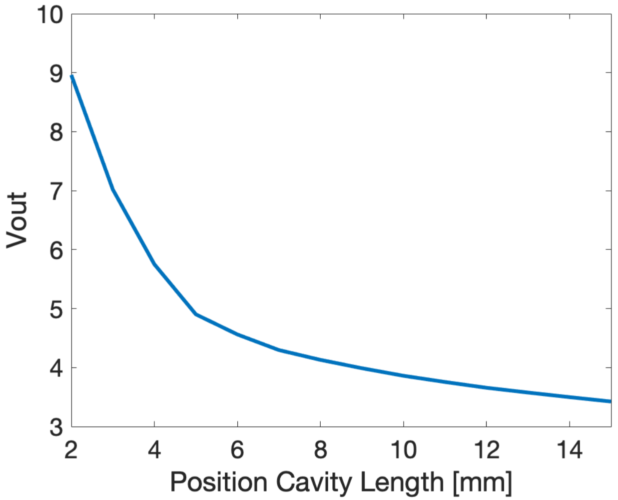




Optimizing position cavity length for dual-resonator cBPM.



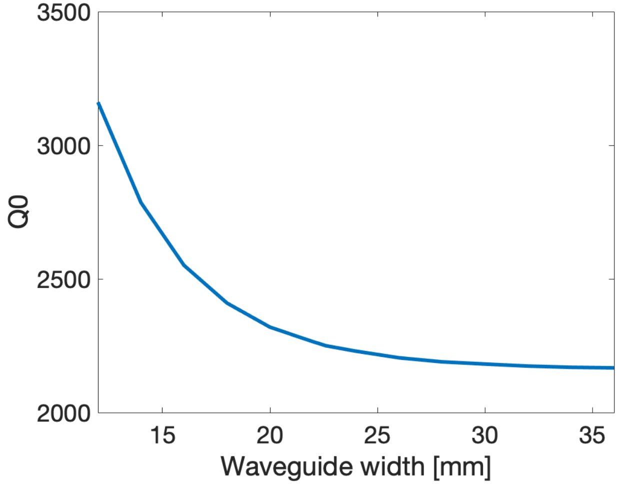
Q_0 dependence on the position cavity length variation.



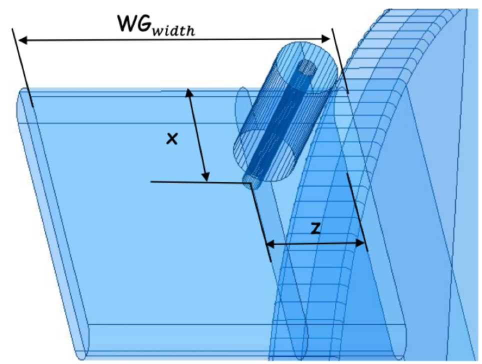
Output voltage V_{out} dependence on the position cavity length variation.

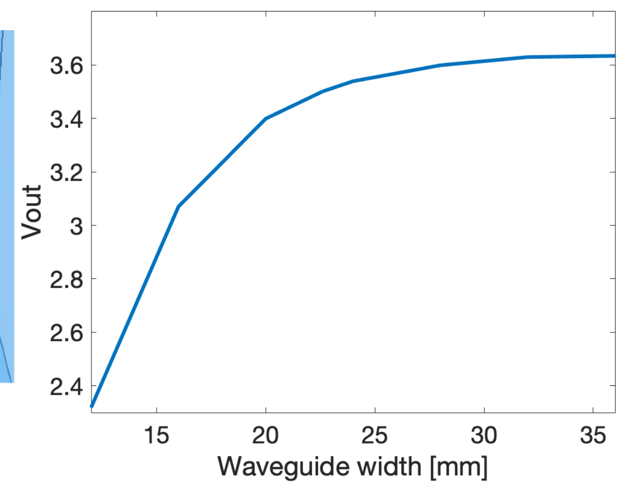
After the prototype conceptual design was obtained, separate parts still need to be tuned to match the required properties and deliver optimal performance. However, the cavity beam position monitor can be considered as a system, where one component/dimension variation causes changes to other parameters, one can still divide the whole system into separate parts and start the design process to unite them in one particular layout then.
To determine the optimum position cavity length, which will provide sufficient output voltage for the required spatial resolution, corresponding simulation and long enough decay time τ, the output voltage dependence on the position cavity length with quality factor was set up.

Optimizing WG and x,z dimensions for Dual-Resonator cBPM.

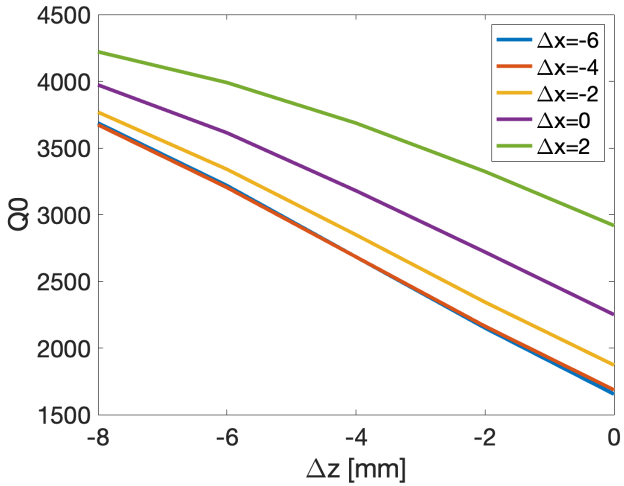


Q_0 dependence on the waveguide width variation.



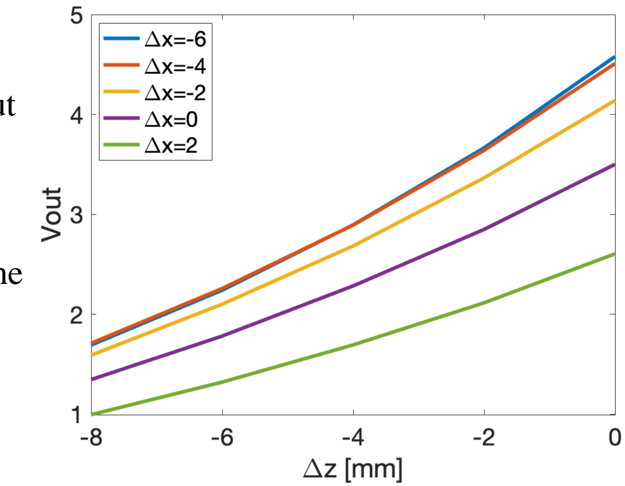


Vout dependence on the waveguide width variation.

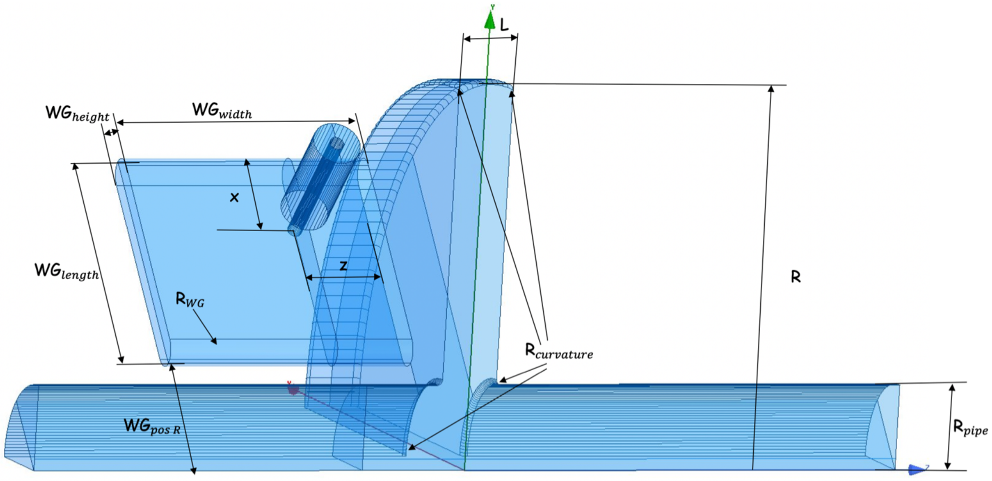


Coaxial feed-through position variation influence on the output voltage and quality factor.

The zero on the axis is the position where it is located in the original design



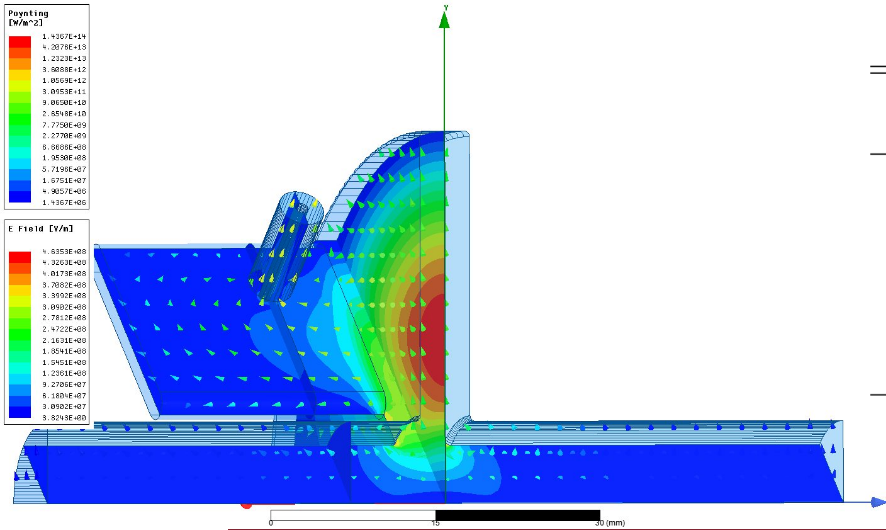
Position cavity's dimensional values and tolerances.



The 5.1 GHz prototype position cavity's optimised design.

Dimmension	Value[mm]
Position Cavity Radius R	34.07
Position Cavity Length L	5
Waveguide Length WG $_{length}$	21.57
Waveguide Width WG $_{width}$	22.6
Waveguide Height WG $_{height}$	3
Coaxial Position x	6.3
Coaxial Position z	7

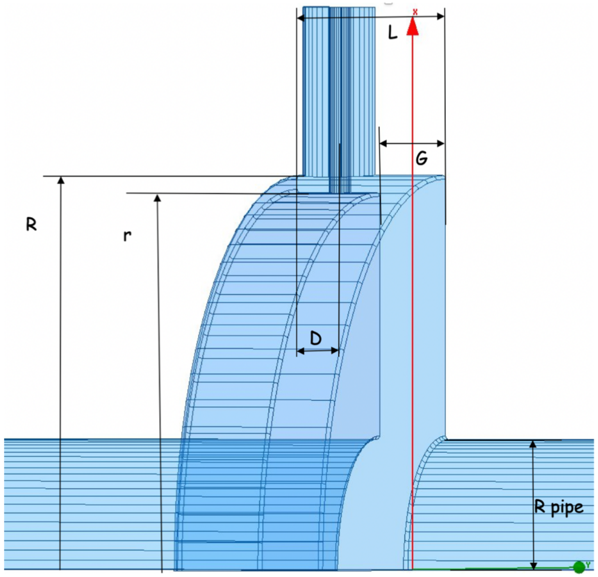
Dimension values for the 5.1GHz prototype position cavity.



Dimmension	Q $_0$ Variation [%/mm]	Frequency shift [MHz/mm]
Position Cavity Radius R	1	137.77
Position Cavity Length L	12	-28.06
Waveguide Length WG $_{length}$	-5	-4.2
Waveguide Width WG $_{width}$	-0.87	-0.12
Coaxial Position x	13	-0.48
Coaxial Position z	9	0.45

Dimension tolerances to the 1mm change for the 5.1GHz prototype position cavity.

Reference cavity's dimensional values and tolerances.

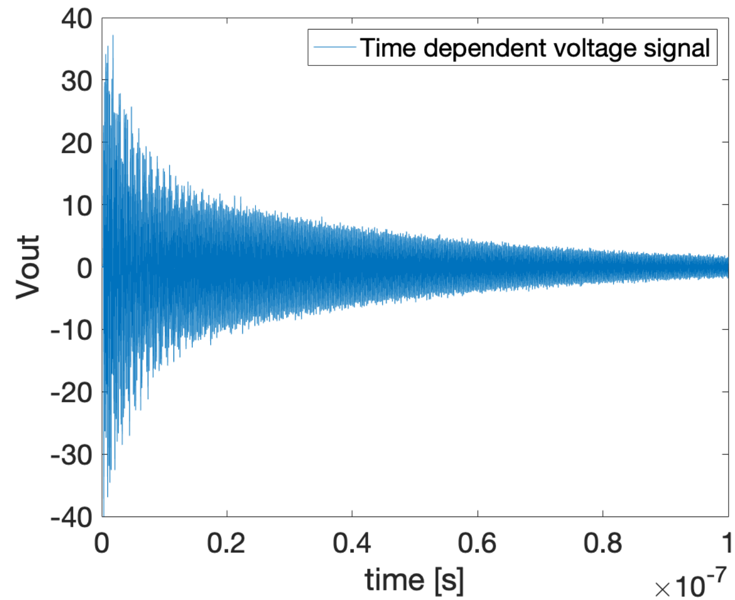


Schematic view of reference cavity with geometrical indications.

Dimmension	Value	Deviation, [MHz/1 mm]	Q variation [%/mm]
Reference Cavity Radius R	22.71	-221	5.6
Reference Cavity Length L	9	25.43	20
Trench Radius r	21.71	-315.38	-26
Reference Cacity Effective Length G	4	-175	-22
Distance between cavity wall and coaxial coupler D	2.6	3.5	-30

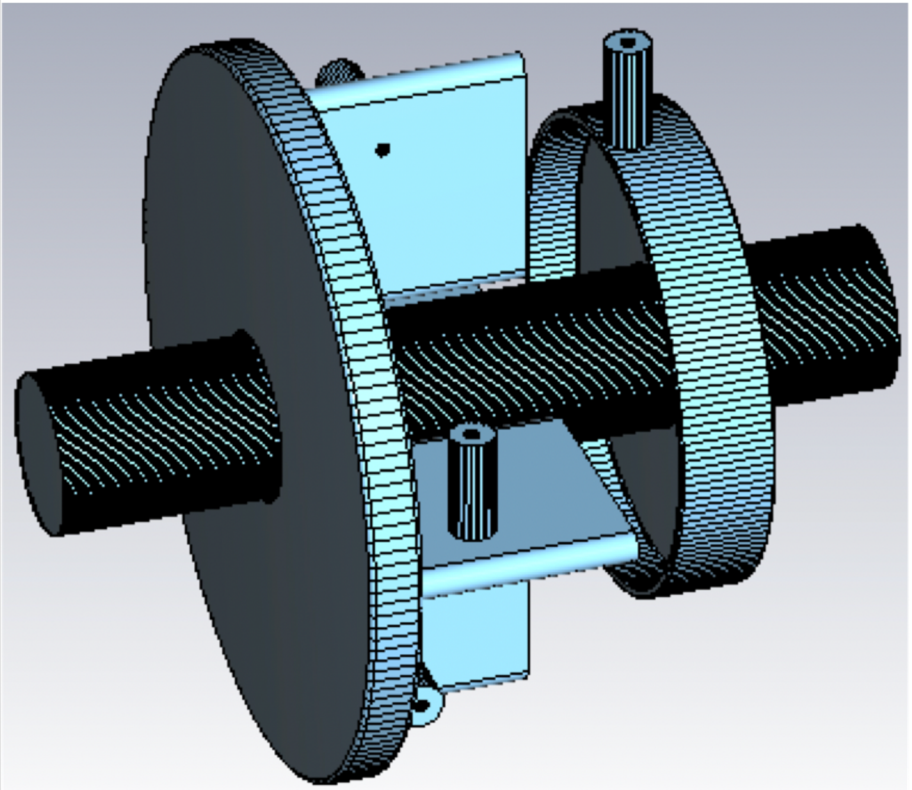
Dimensions and tolerances to 1 mm change for the 5.1GHz prototype reference cavity.

It consists of a particular pillbox where the antenna is inserted in the bulge. In general, the insertion depth of the antenna in the bulge determines the desired output signal level. In particular, the closer the antenna end is to the cavity wall, the higher the output signal amplitude becomes.

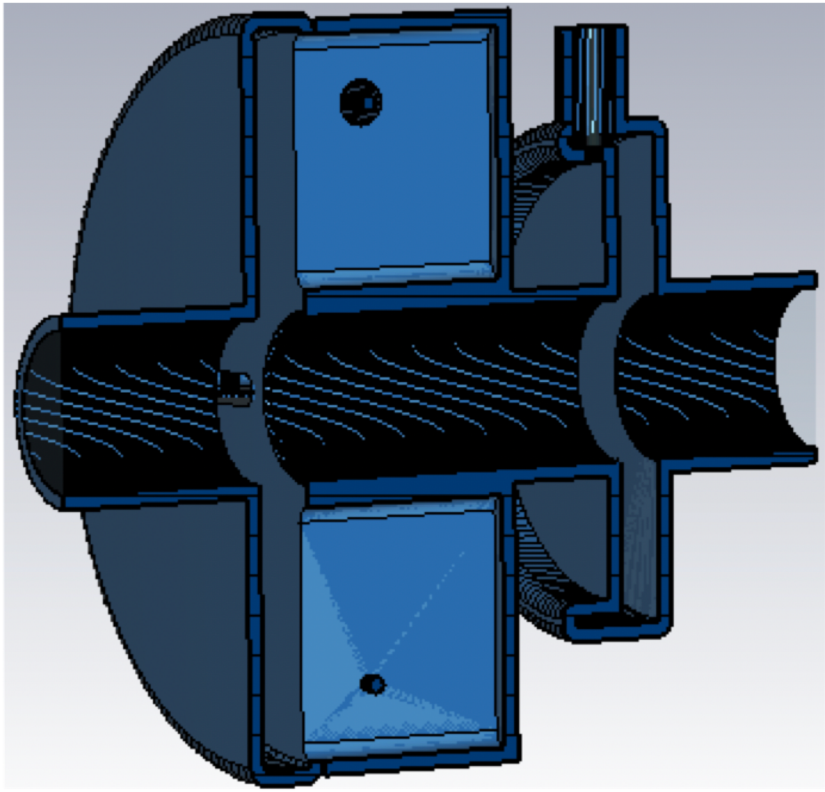


Output voltage signal coming out from the reference cavity with a 1 mm beam offset. Wakefield simulation.

Dual-Resonator cBPM full object analyze

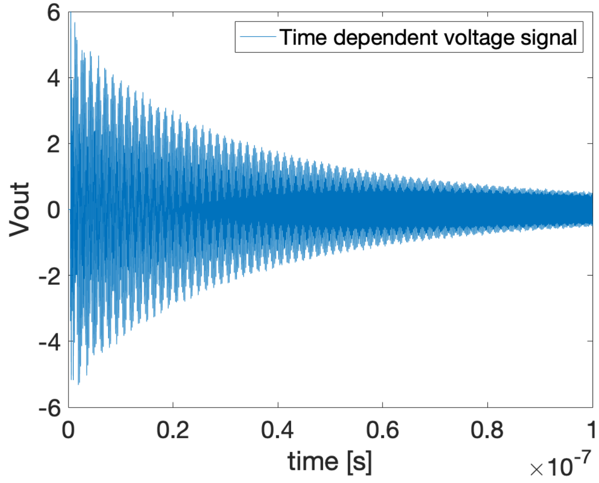


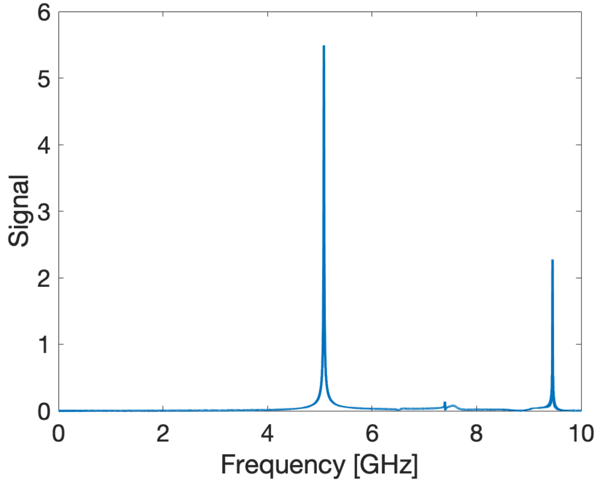
Cavity BPM pickup schematic view (shown: vacuum).



Cavity BPM pickup half-cut schematic view (shown: copper shell).

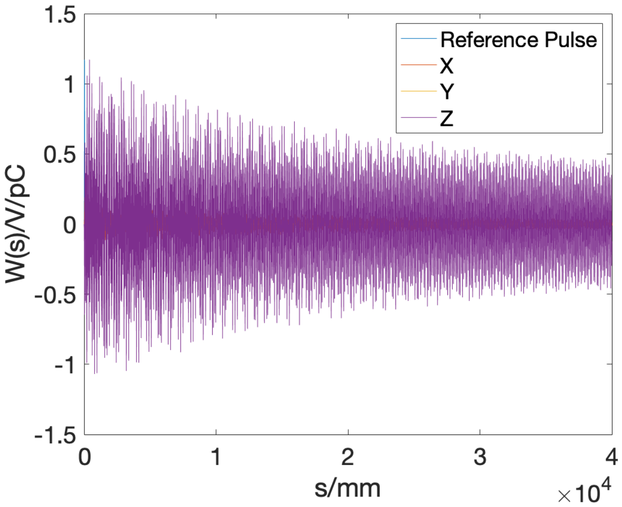
Dual-Resonator cBPM prototype wakefield simulations.

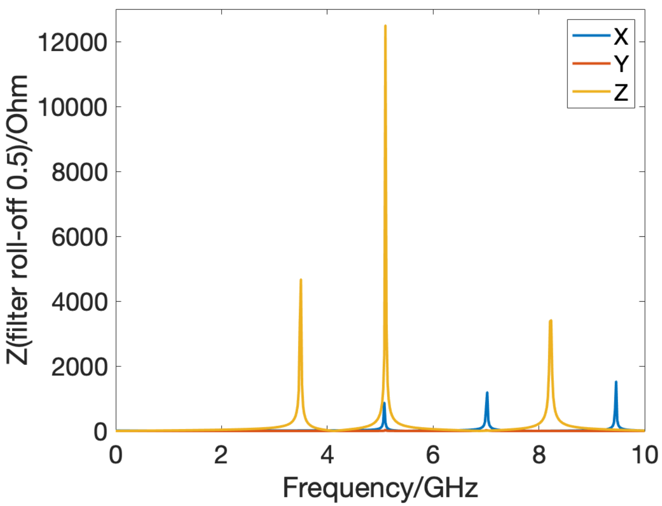




Output voltage signal coming out of one of the coaxial ports for position cavity.

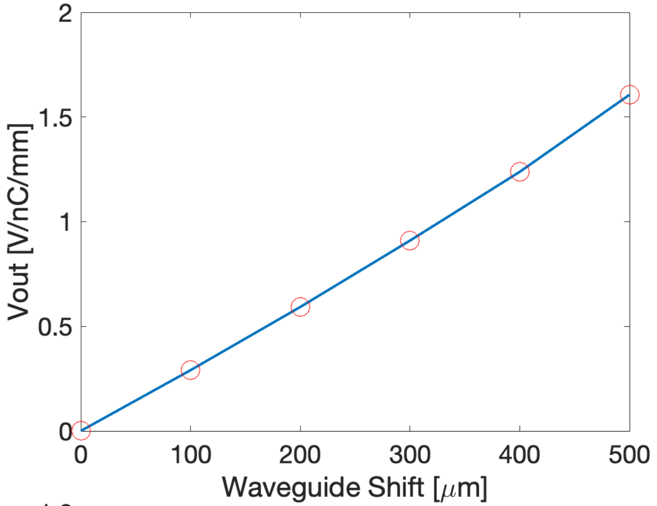
FFT of the signal coming out from the coaxial port.

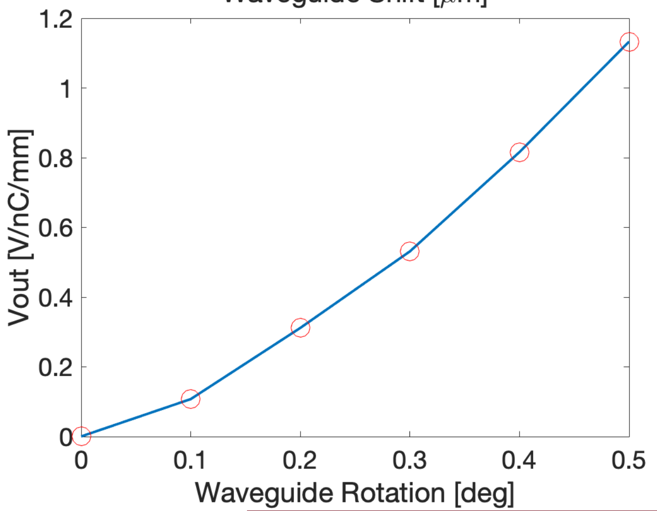


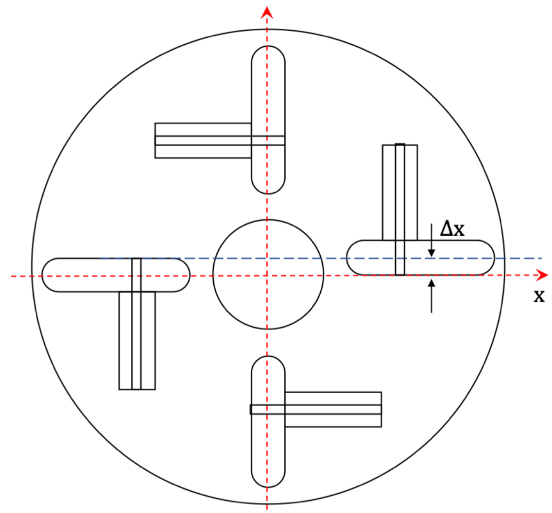


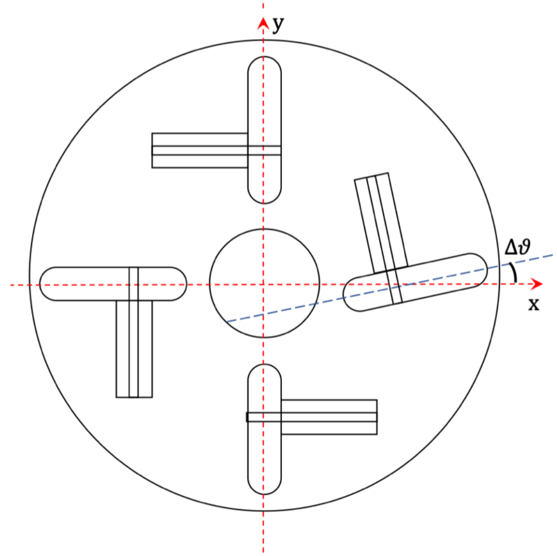
Sensitivity and mechanical tolerances of the monitor.

Dipole mode TM_{110} coupling to orthogonal port as a function of waveguide angle and position errors.

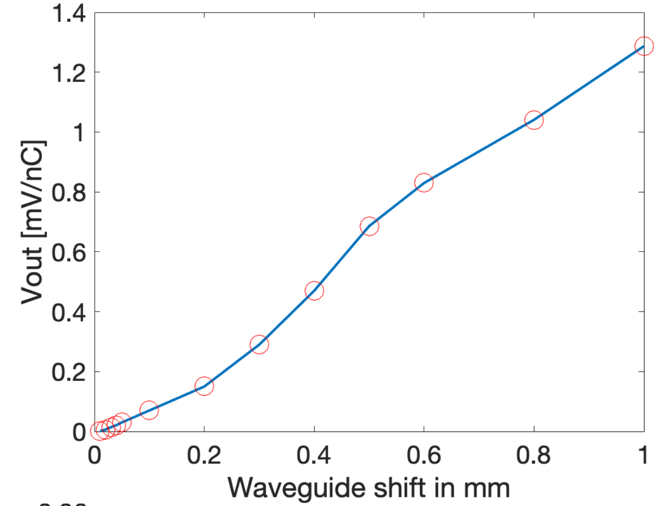


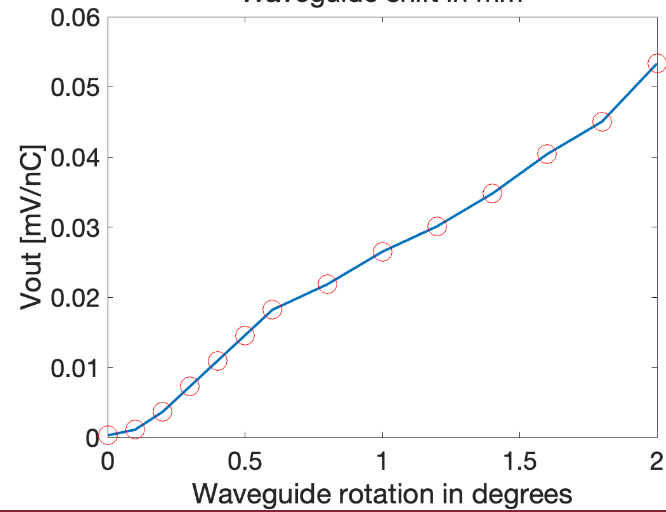






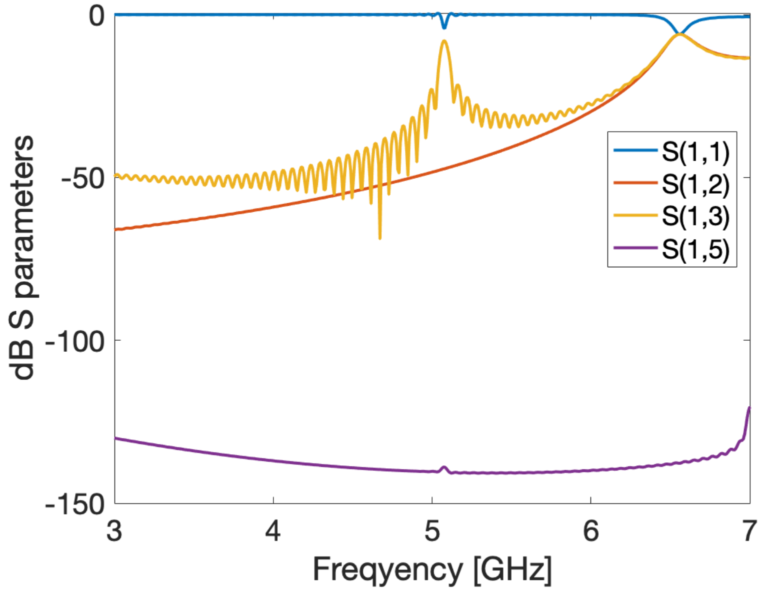
Simulated output signal, generated by 1nC, 1 mm offset beam, due to TM_{010} coupling as a function of waveguide misalignments.



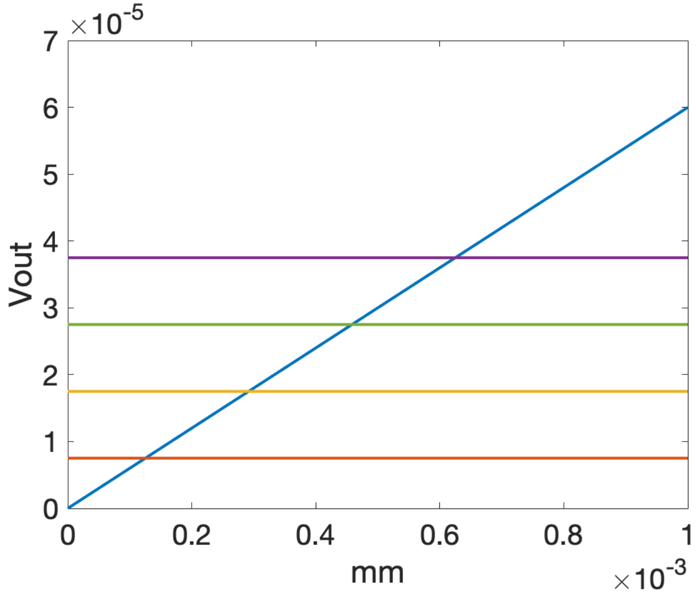


Sensitivity and theoretical res. for dual-resonator cBPM.

Parameter	Numerical calculation		
	TM_{010}	TM_{110}	Reference
f_{GHz}	3.419	5.100	5.100
Q_0	2800	2200	1400
Q_L	–	450	410
Damping time,τ ns		28.17	25.6
$\frac{R}{Q}$,Ohm	52	0.5	48
V_{out}	–	$4.9\ V/nC/mm$	$36\ V/nC$
angle/position signal ratio [deg/mm]	–	0.0163	–
Theoretical resolution	–	170 nm	–

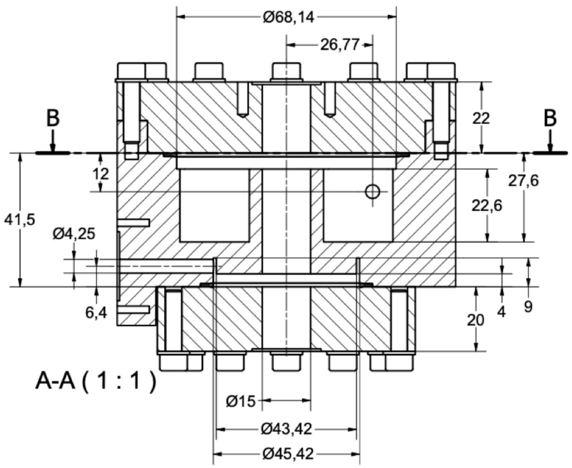


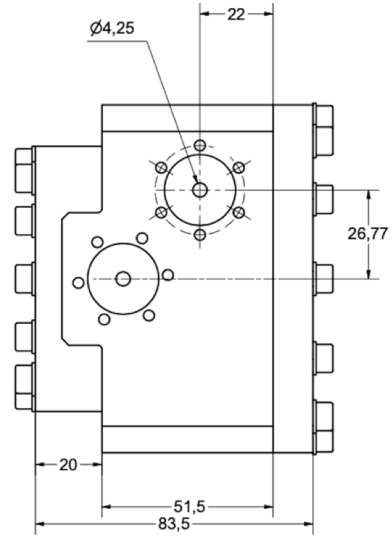
Position cavity ports cross-coupling and isolation between the position and reference cavities.

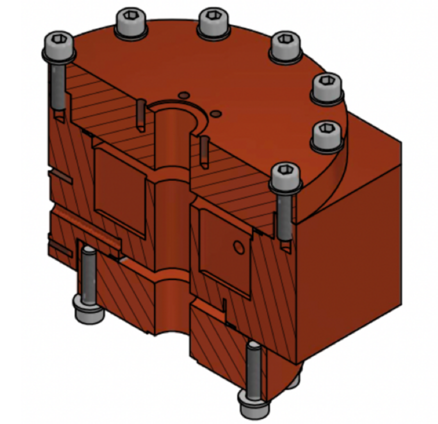


Thermal noise level.
Additional 10 μV contribution in total V_{out} due to fabrication errors.
Additional 20 μV contribution in total V_{out} due to fabrication errors.
Additional 30 μV contribution in total V_{out} due to fabrication errors.
Output voltage due to the beam offset in mm.

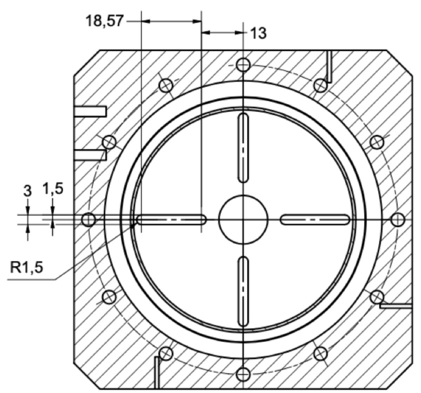
Mechanical implementation.



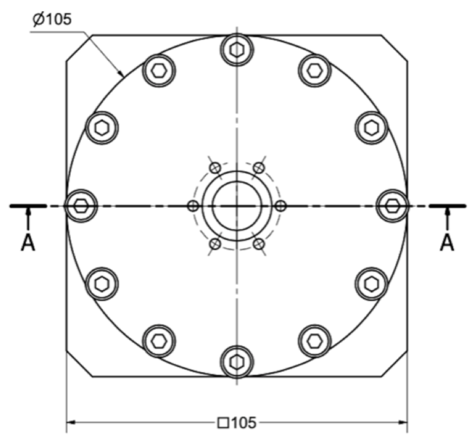


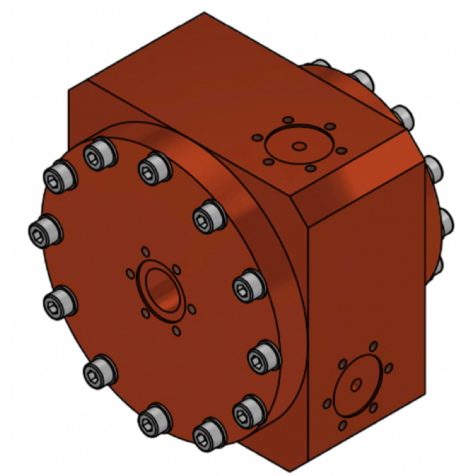


Longitudinal cut of the assembled prototype.



B-B (1 : 1)

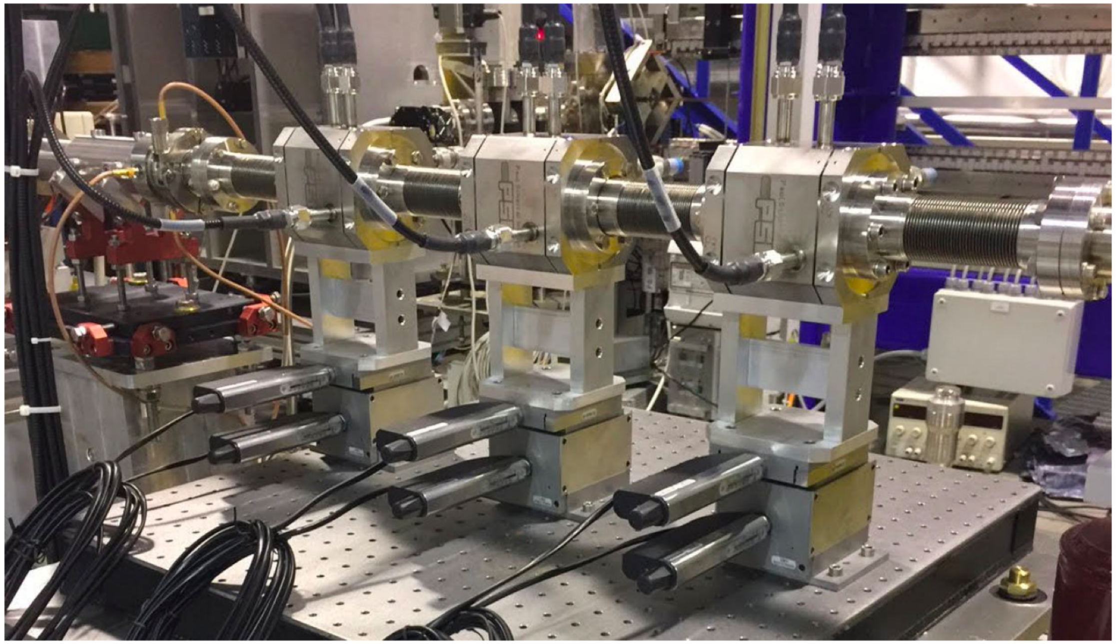




Assembled prototype.

The device is assembled from three parts, using the clamping method.

Outlook



Once the first prototypes will be fabricated, bench-top measurements and beam tests will be performed. Such a new test-bench for cBPMs at SPARC-LAB at INFN-LNF was designed and will be used in the prototype tests.
The test bench aims to perform measurements on the manufactured cBPMs. The main reason for these is to investigate further the prototype presented in this dissertation and their properties, dealing with the new challenges related to beam diagnostics for the EuPRAXIA.

Conclusions

- Cavity BPM **design process** and **strategy** for achieving the required specifications is described.
- Cavity beam position monitor prototype with **single resonator** is proposed as a possible solution, when the **longitudinal dimension** of the device has a critical importance.
- **Dual-resonator cavity BPM** prototype is proposed that is simpler from the mechanical point of view and has **looser mechanical tolerances.**
- **Sensitivity** and **theoretical resolution** for developed cBPM are evaluated.
- **Future tests**, once the monitor is manufactured, are determined.

Thank you!

References

[1] M. Ferrario - “EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF,” Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2018, issn: 01689002. doi: 10.1016/j.nima.2018.01.094.

[2] A. Cianchi - Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 909, 12 November 2018, Pages 350-354 Conceptual design of electron beam diagnostics for high brightness plasma accelerator.

[3] G. Franzini - Studies and Measurements on Cavity Beam Position Monitors for Novel Electron Linacs , Tesi dottorrato.

Appendix

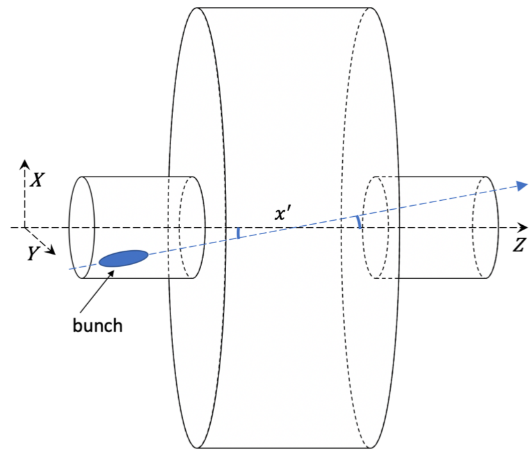
$$V_{out}^{total}(5.1\text{GHz}) = V_{110}^{out} + V_{110}^{angle} + V_{010}^{out} + V_N$$

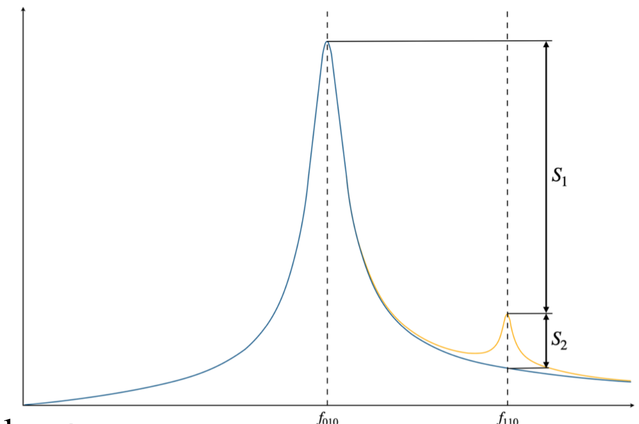
$$V_{110}^{out} = V_{110}^{angle} + V_{010}^{out} + V_N$$

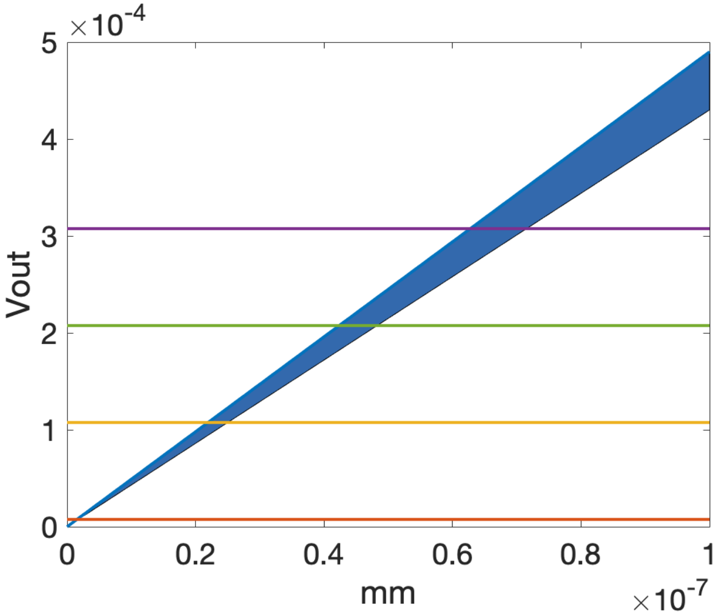
$$V_N = \sqrt{4kT\Delta f R N_F}$$

$$V_{110}^{out} = a \cdot \delta x$$

$$V_{110}(\delta x) = \delta x \cdot q_b \frac{l T_{tr}^2}{d^3} \frac{Z_0 c \alpha_{11} J_{1max}}{2\pi J_0^2(\alpha_{11})}.$$







- Thermal noise level.
- additional 100 μV contribution in total V_{out} due to fabrication errors.
- additional 200 μV contribution in total V_{out} due to fabrication errors.
- additional 300 μV contribution in total V_{out} due to fabrication errors.
- Prototype performance degradation due to the fabrication errors. Upper edge represents performance for ideally built cBPM.