Charla Técnica:
Design of a high resolution Cavity BPM for the ILC main Linac

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I. Intro - Resonant Cavity-BPMs

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BPMs are EM beam pickups to determine the beam's horizontal and vertical offset.

➔ **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.

The beam couples with modes that have longitudinal E-field components: the TM modes.
Two modes in particular are of interest:

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

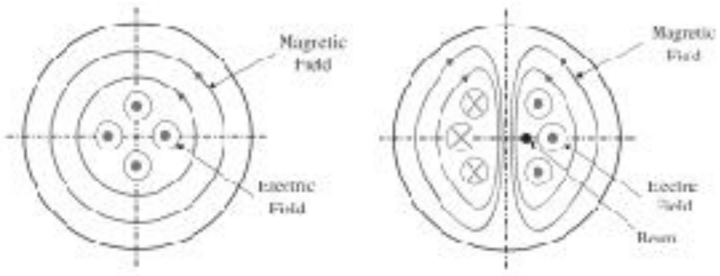


Figure: Cross-sectional view of the TM modes in a pillbox cavity

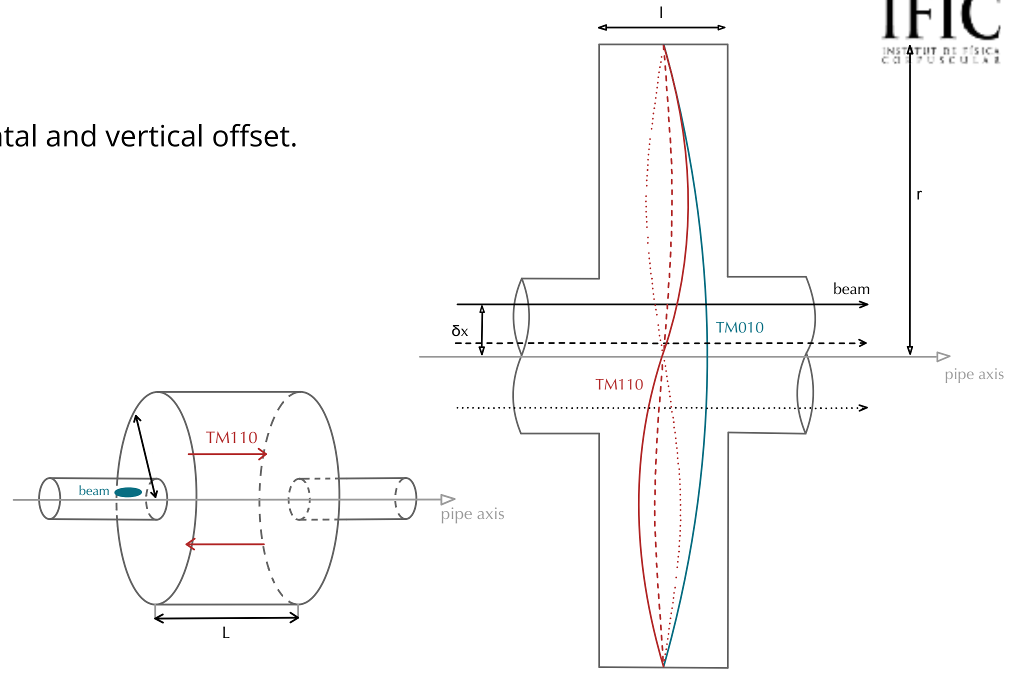


Figure: Representation of the E-fields induced in the cavity

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

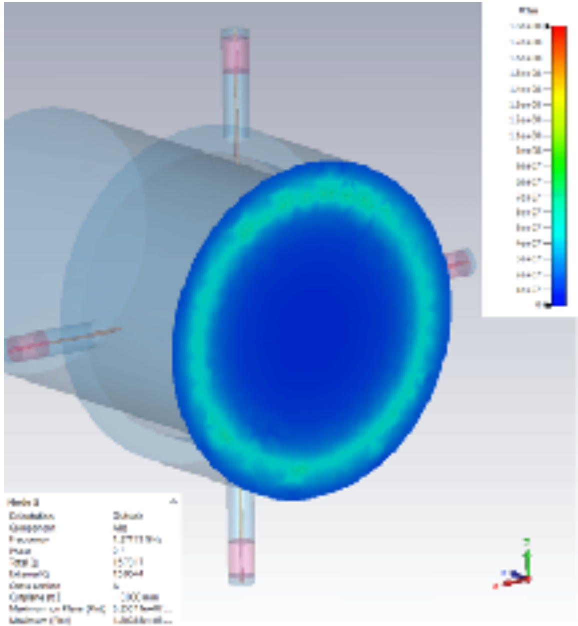
A shifted beam induces the dipole mode with:

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

I. Intro - Resonant Cavity-BPMs

Monopole mode TM_{010}

$f_{010} = 1.25$ GHz

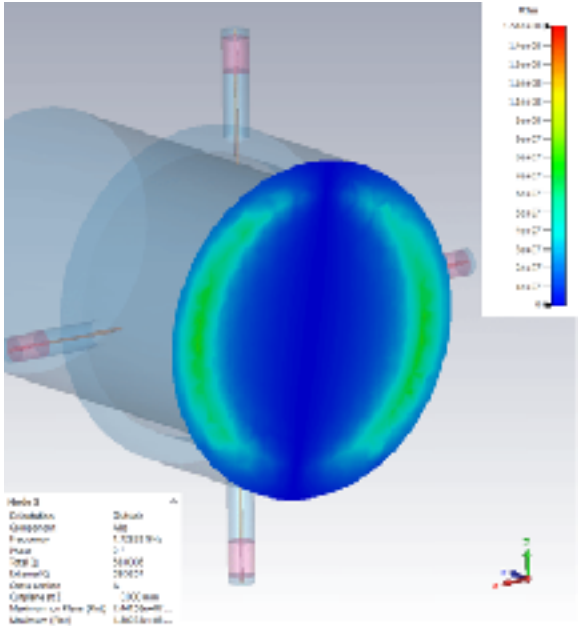


Yields reference signal

Dipole mode TM_{110}

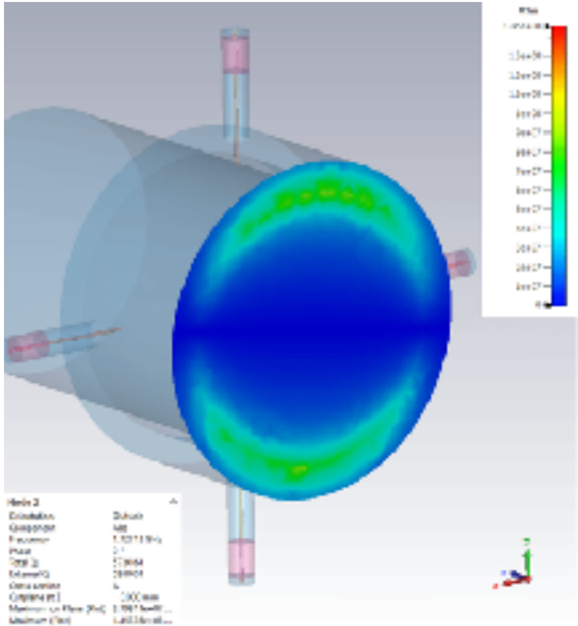
$f_{010} = 1.72$ GHz

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

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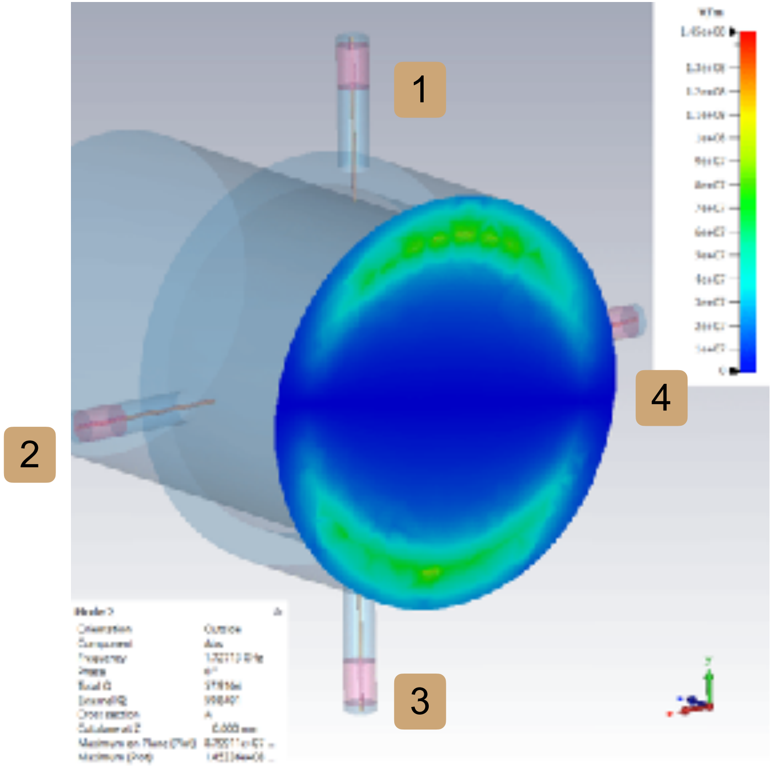
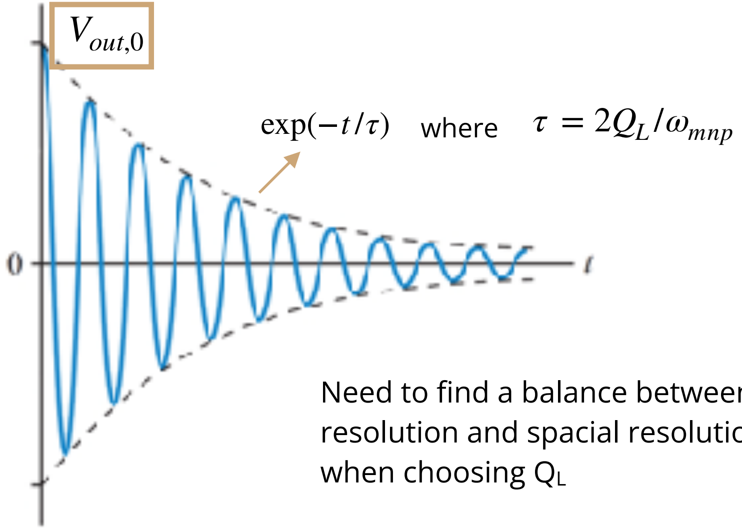


➔ **Output signal on the time domain:**

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

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



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

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Each mode output signal can be represented as: $V_{out}(t) = V_{out,0}\sin(\omega_{mnp}t + \varphi)\exp(-t/\tau)$

where

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

<u>Dipole</u>

$\Rightarrow [R/Q]_{110} \propto (\delta x)^2$ para pequeños desplazamientos δx

<u>Monopole</u>

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

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

entonces $V_{out} \propto (\delta x)$ para el modo TM_{110}

↓

Señal de posición

$V_{out} \simeq$ constante para el modo TM_{010}

↓

Señal de referencia

II. Saclay model and simulation on CST

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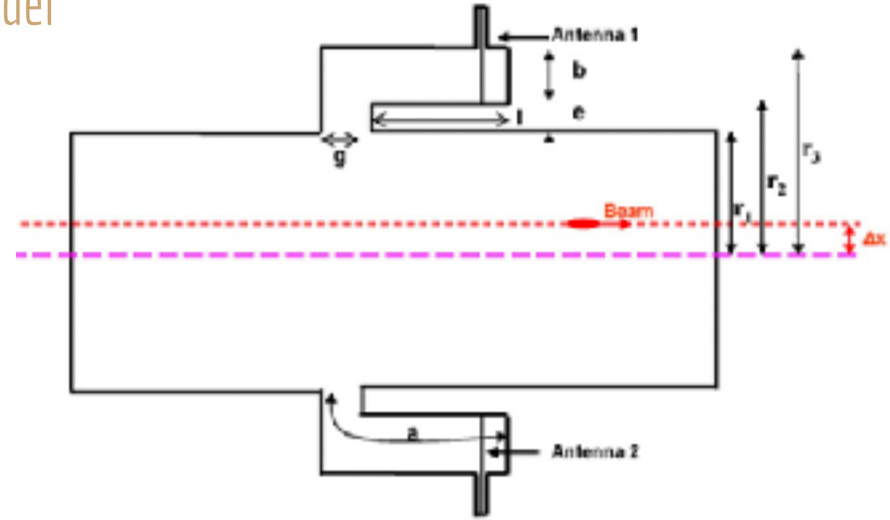
A. Saclay model



l	50 mm
g	8 mm
b	8 mm
e	2.5 mm
a=l+g/2+b/2+e	60.5 mm
r_1	39 mm
r_2	41.5 mm
r_3	49.5 mm

FIG. 4. (Color) Sketch of the reentrant BPM.

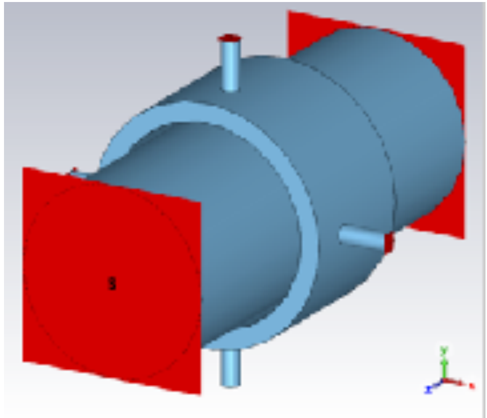
TABLE I. The rf characteristics of the new reentrant cavity BPM.

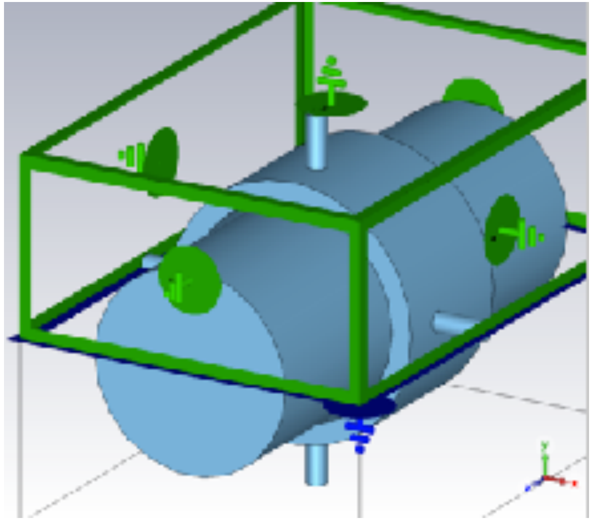
Eigenmodes	F (MHz)	F (MHz)	Q_l	Q_l	R/Q (Ω) 5 mm offset	R/Q (Ω) 10 mm offset
	Calculated	Measured	Calculated	Measured	Calculated	Calculated
Monopole mode	1250	1255	22.95	23.8	12.9	12.9
Dipole mode	1719	1724	50.96	59	0.27	1.15

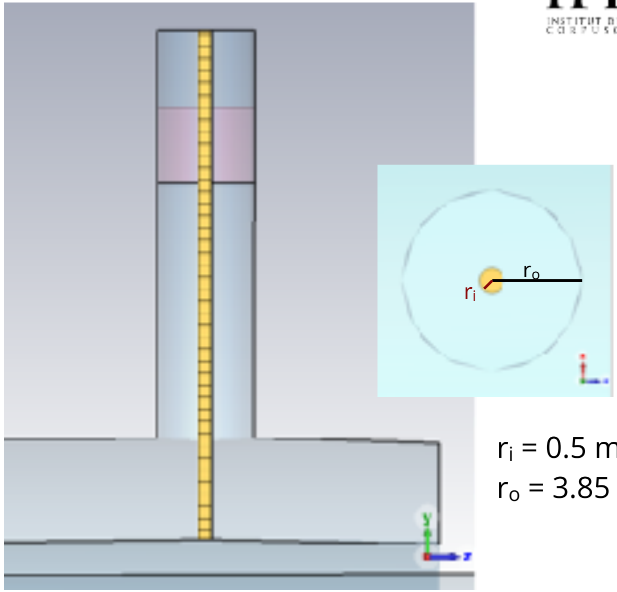
C. Simon, N. Rouvière, N. Baboi, Performance of a reentrant cavity beam position monitor, DSM, CNRS, DESY

II. Saclay model and simulation on CST

A. Saclay model







r_i = 0.5 mm
r_o = 3.85 mm

Mode	Monopole						Dipole					
Characteristic	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{11} (dB)	S_{12} (dB)	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{11} (dB)	S_{12} (dB)
Saclay (Biblio)	1,255	23,8	12,9	12,9	-	-	1,724	59	0,27	1,15	-	-33
Saclay (CST simulation)	1,273	15,71	23,9	24,0	-5,9	-6,14	1,729	58	0,56	2,29	-25,9	-24,8

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

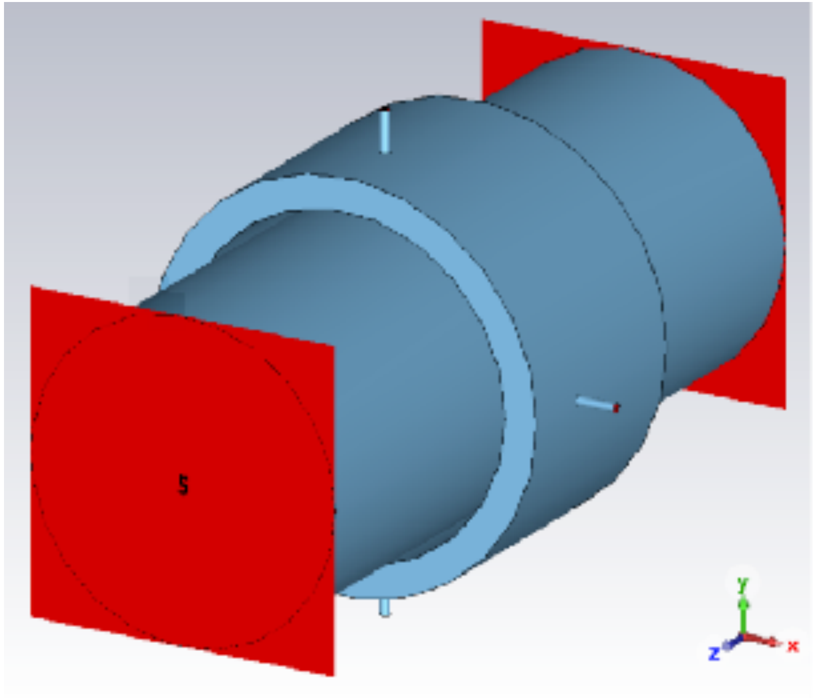
II. Saclay model and simulation on CST

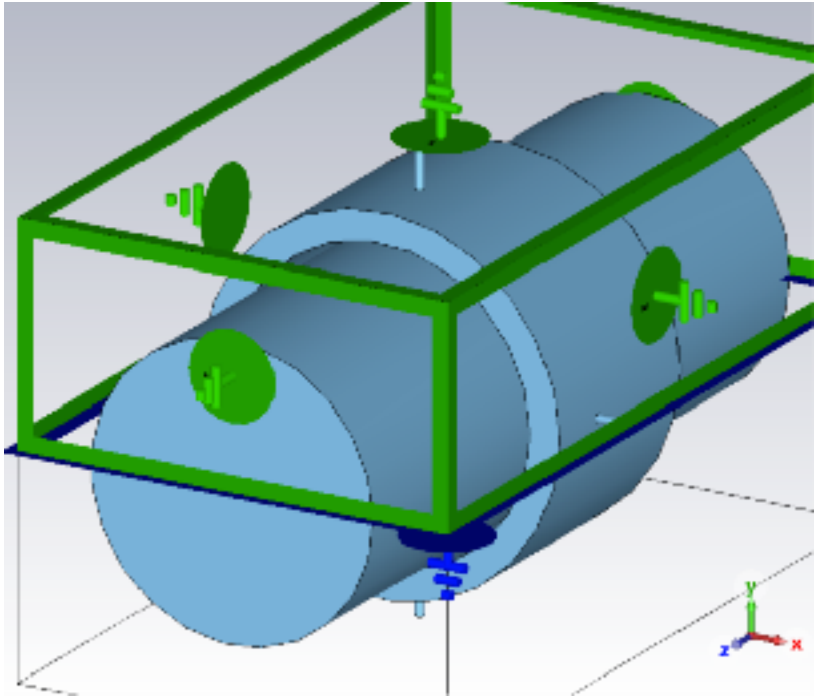
B. Our model in CST

Conector coaxial: 15310-03-W (ri = 0.5 mm, ro = 1.1512 mm)

Boundary material:
Steel with electric. cond. = 1.33×10^6 S/m

Magnetic wall on plane XZ → to observe the degeneration of dipole mode along the x axis





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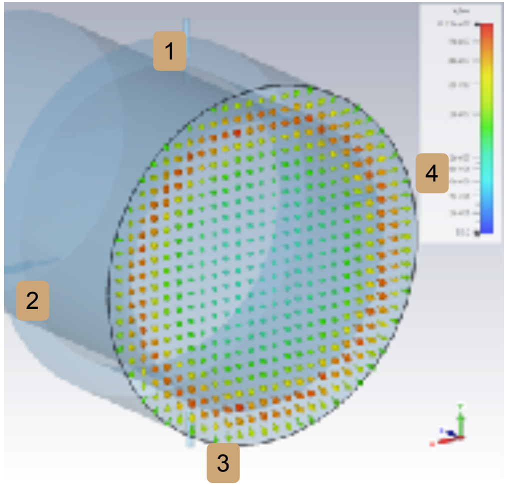
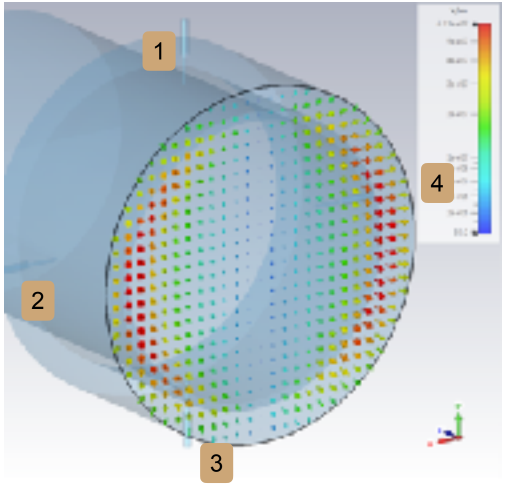
B. Our model in CST

Eigenmode solver





Mode	Monopole						Dipole					
Characteristic	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm			Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm		
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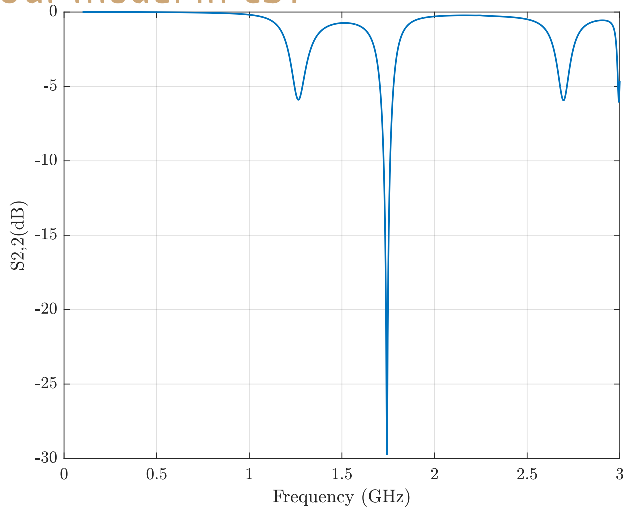
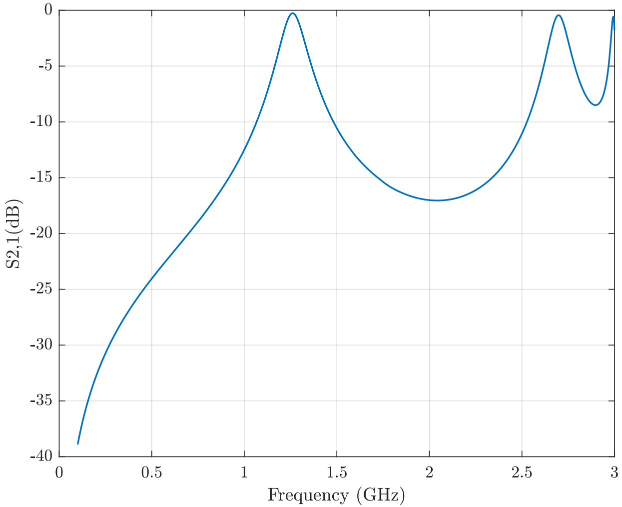
Saclay (CST simulation)	1,273	15,71	23,9	24,0			1,729	58	0,56	2,29		
Our BPM (CST simulation)	1,265	9,03	42,87	41,61			1,749	16,93	1,02	3,85		

II. Saclay model and simulation on CST

B. Our model in CST

Frequency domain solver





Mode	Monopole						Dipole					
Characteristic	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)
Saclay (Biblio)	1,255	23,8	12,9	12,9	-	-	1,724	59	0,27	1,15	-	-33
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Our BPM (CST simulation)	1,265	9,03	42,87	41,61	-5,89	-0,26	1,749	16,93	1,02	3,85	-29,34	-15,29

III. Parametric studies on CST Studio Suite

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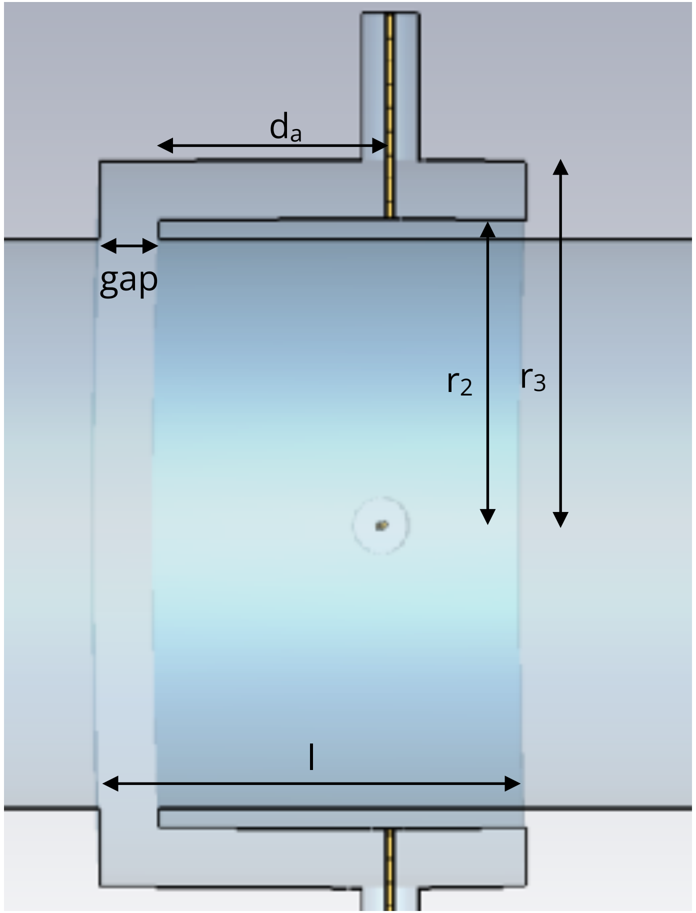

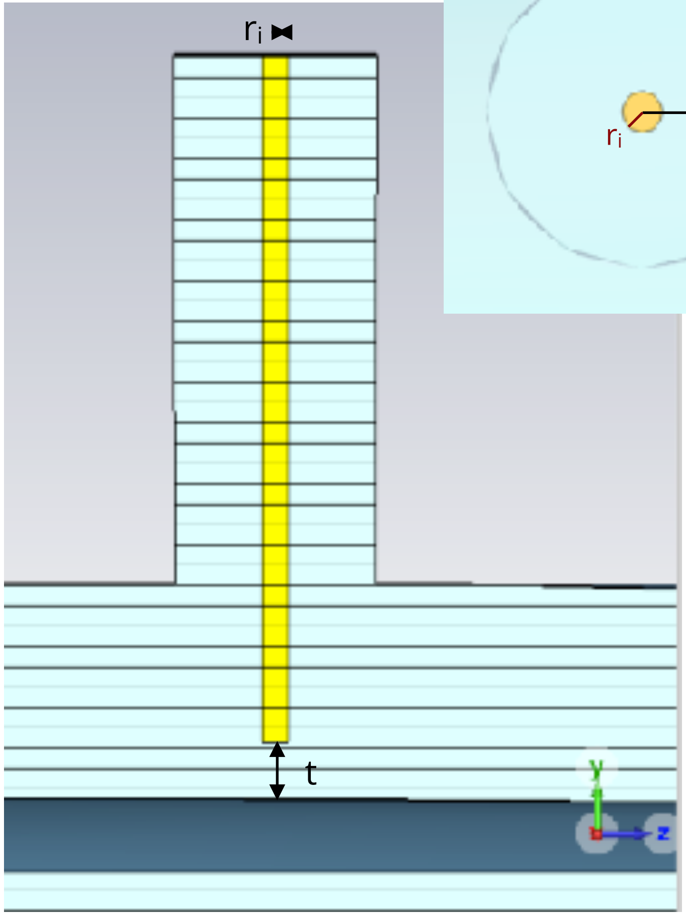

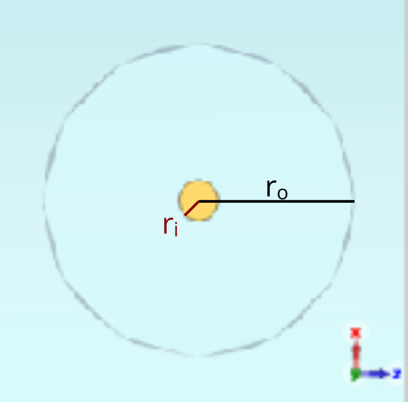

Parameter	Value (mm)
r_3	49,5
r_2	41,5
gap	8
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

III. Parametric studies on CST Studio Suite

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- **Resonance frequency** f_m**:** $f_{monop} < 1.3$ GHz $\quad 1.6 < f_{dip} < 1.8$ GHz

- **Loaded quality factor** Q_L**:** $\tau < 100$ ns $\Rightarrow Q_L < 100$ ns $\times \pi f_m$ (ATF bunch spacing of 150 ns)

- $(R/Q)_m$**:** $(R/Q)_{monop} =$ constante $\Rightarrow (R/Q)_{monop,\delta x} = (R/Q)_{monop,x_0}$ $\quad (R/Q)_{dip} \propto \delta x \Rightarrow (R/Q)_{dip} = (R/Q)_{dip,x_0} \times \frac{\delta x}{x_0}$

  tratar de llevar $(R/Q)_{monop}$ al mismo nivel de $(R/Q)_{dip}$ $\quad$ maximizar $(R/Q)_{dip}$

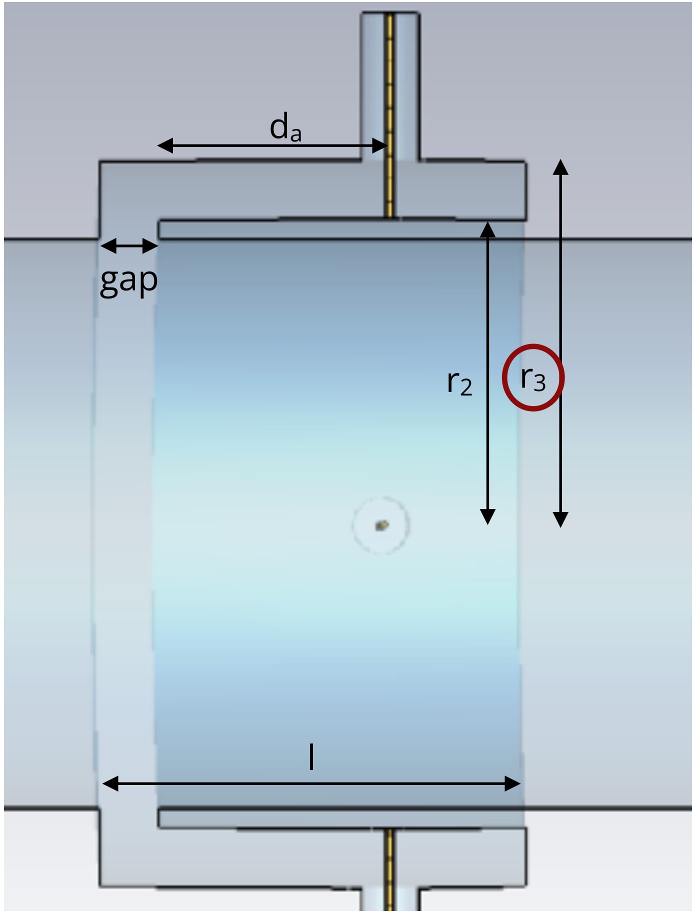
- **Output power** P_{out}**:**

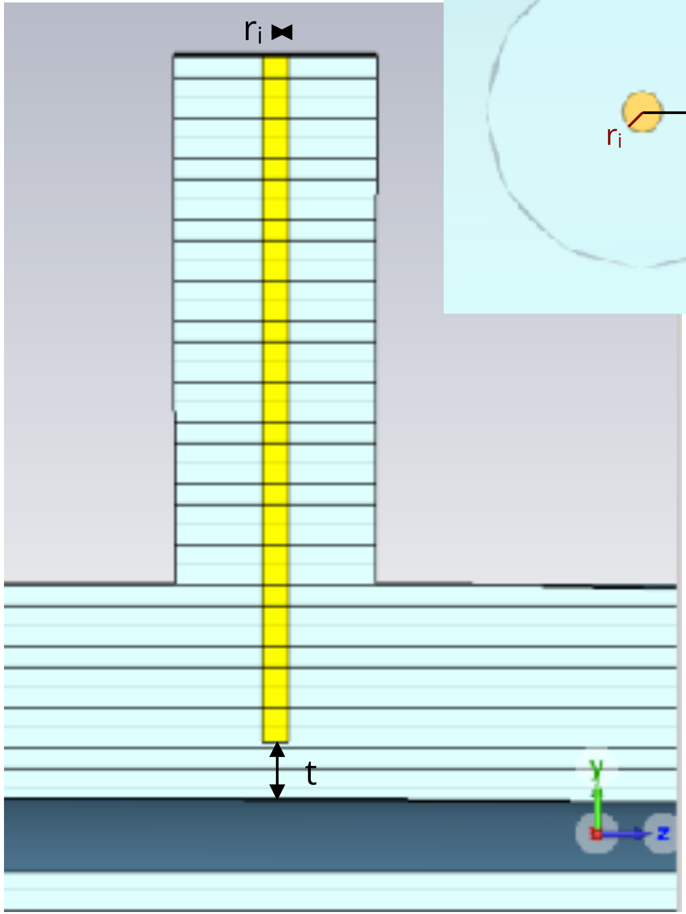
$$P_{out,m} = \frac{q^2\omega_m^2}{4Q_{ext}}\left(\frac{R}{Q}\right)_m \exp\left[-\frac{\omega_m^2\sigma_z^2}{c^2}\right] \Rightarrow P_{out,monop} = \frac{q^2\omega_m^2}{4Q_{ext}}\left(\frac{R}{Q}\right)_{m,x_0} \exp\left[-\frac{\omega_m^2\sigma_z^2}{c^2}\right]$$

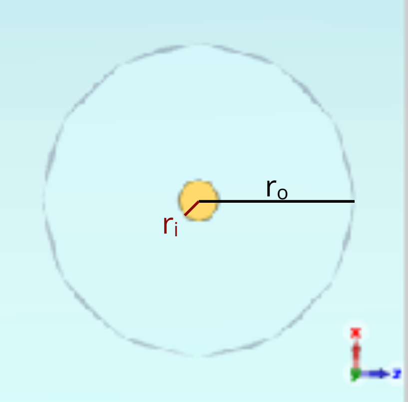
$$P_{out,dip} = \frac{q^2\omega_d^2}{4Q_{ext}}\left(\frac{R}{Q}\right)_{d,x_0}\left(\frac{\delta x}{x_0}\right)^2 \exp\left[-\frac{\omega_d^2\sigma_z^2}{c^2}\right]$$

- **S-parameters** S_{22} **and** S_{21}**:** evaluation at f_{monop} and f_{dip} $\quad |S_{21}(f_{dip})| < -33$ dB

III. Parametric studies on CST Studio Suite







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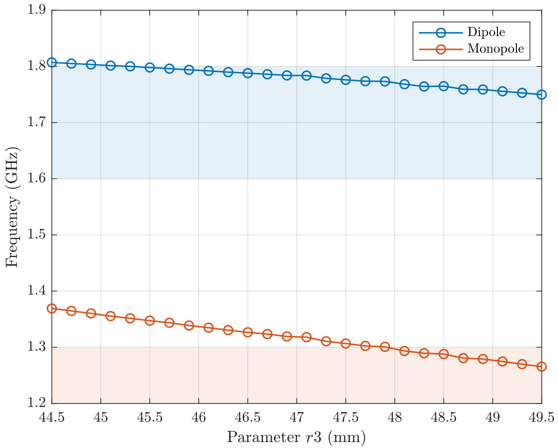
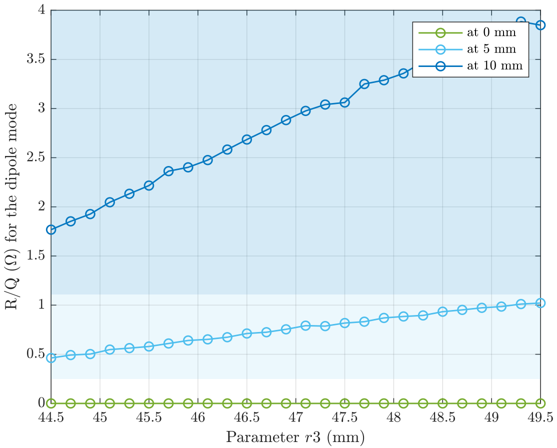
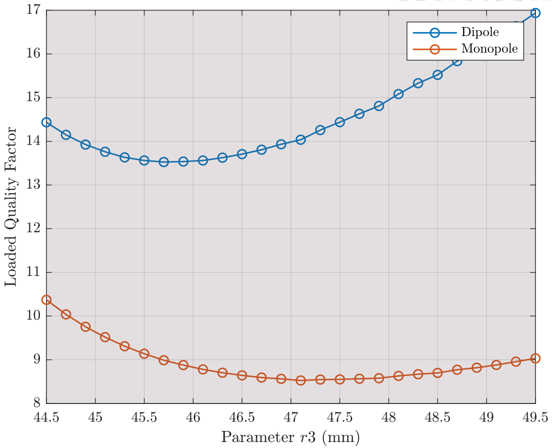
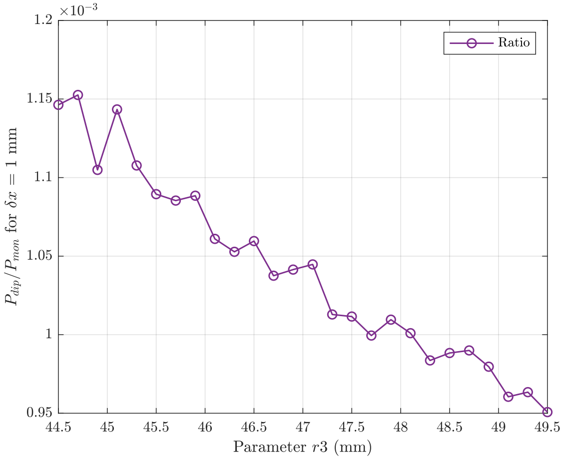
III. Parametric study

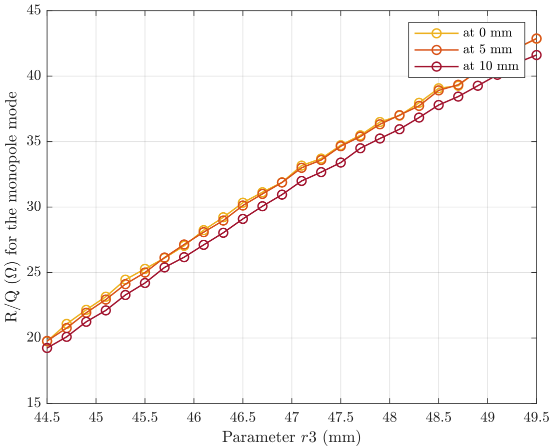
A. Coaxial cylinder outer radius r_3

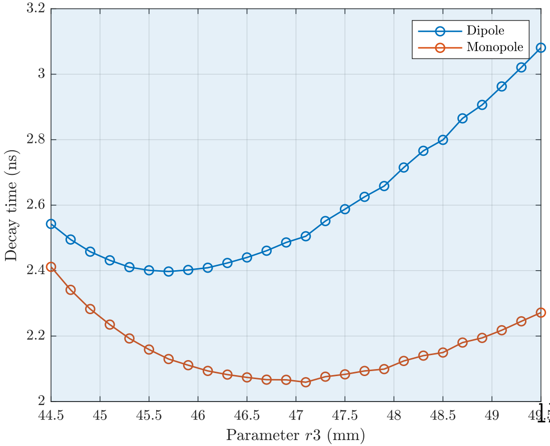












III. Parametric study A. Coaxial cylinder outer radius r_3

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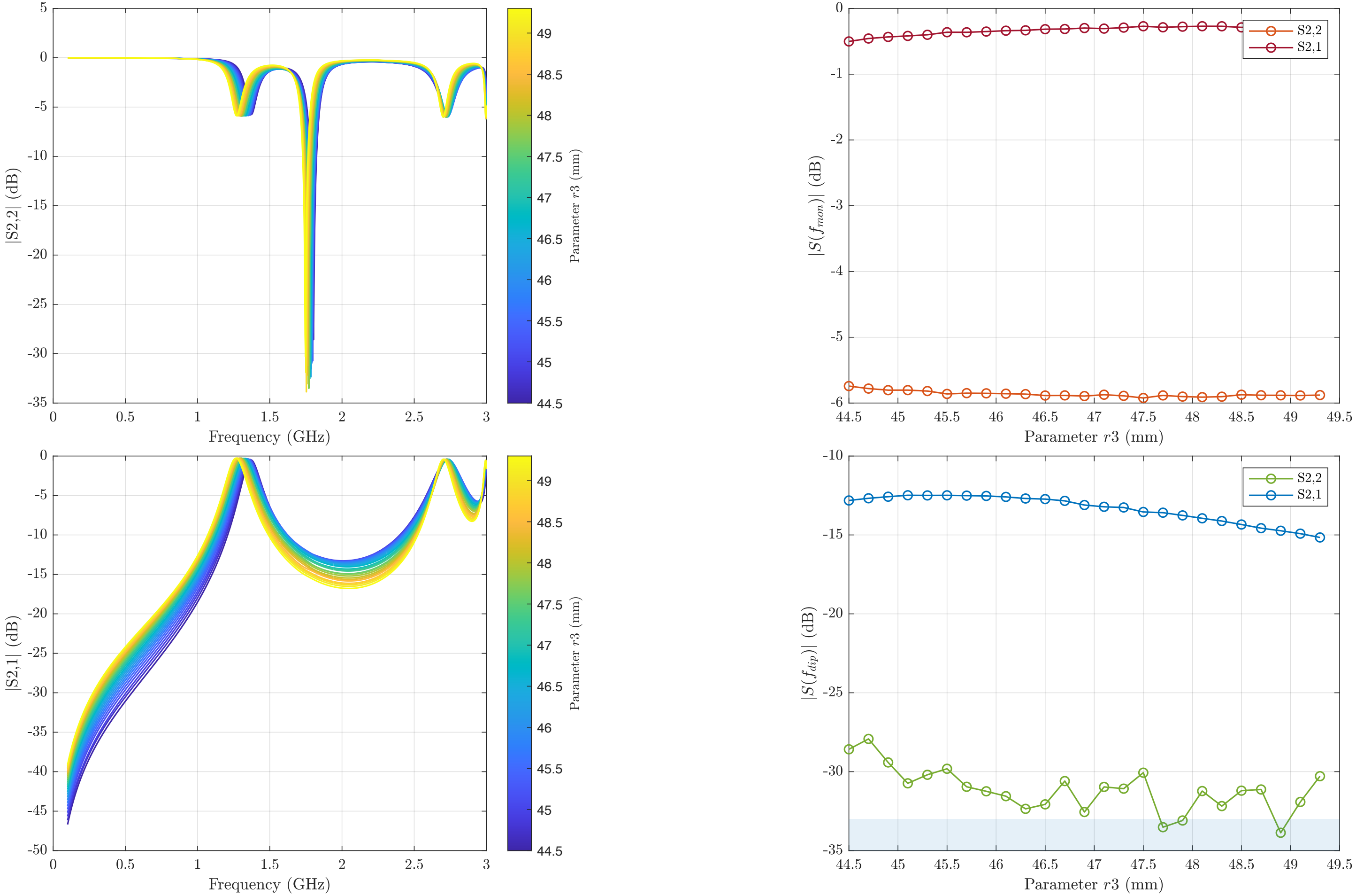
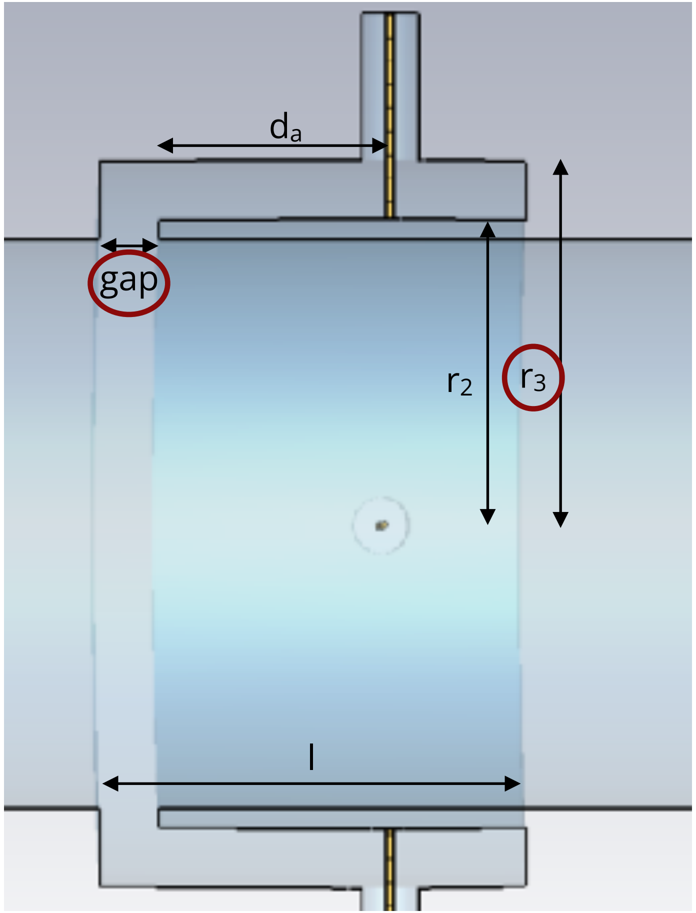
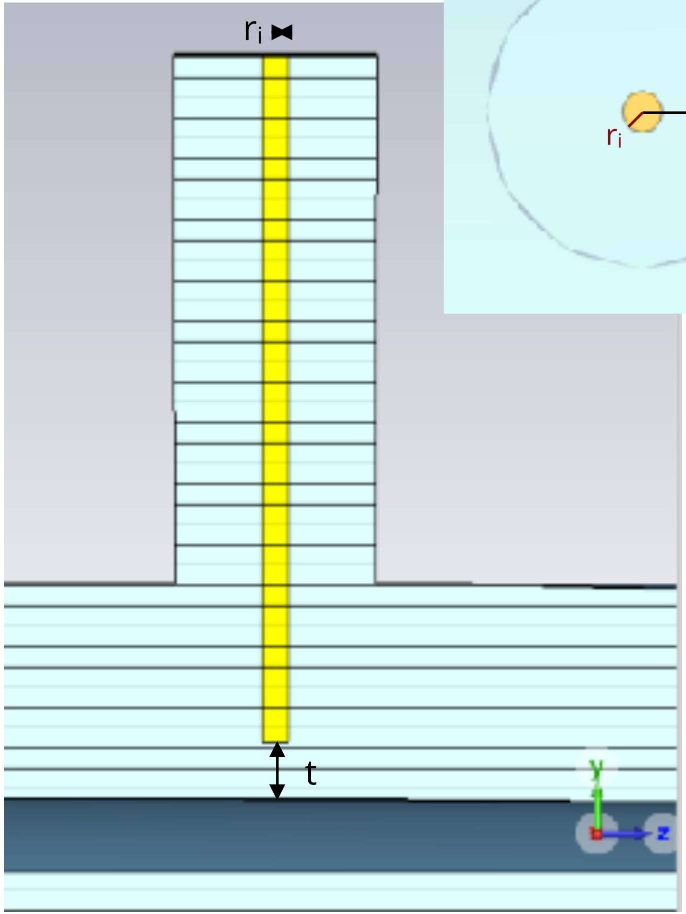
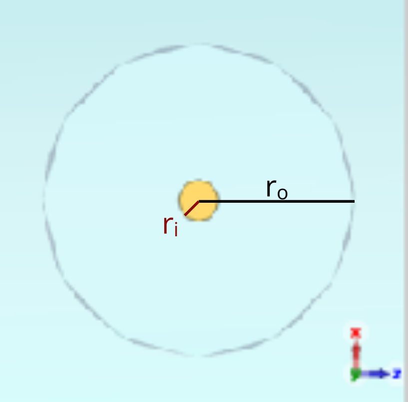


III. Parametric studies on CST Studio Suite







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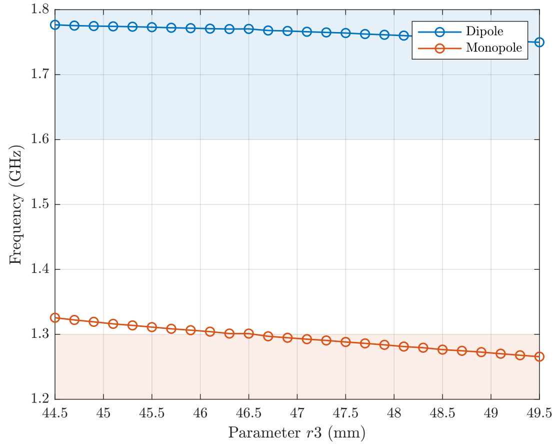
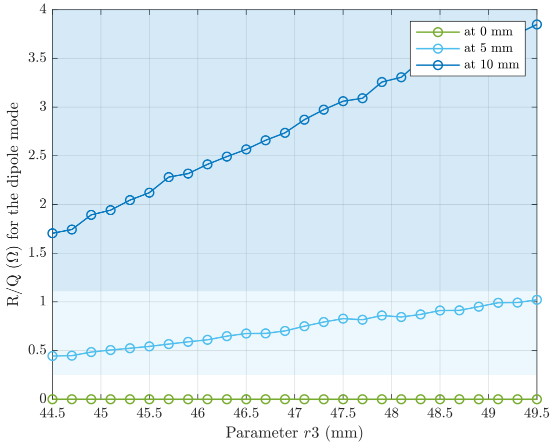
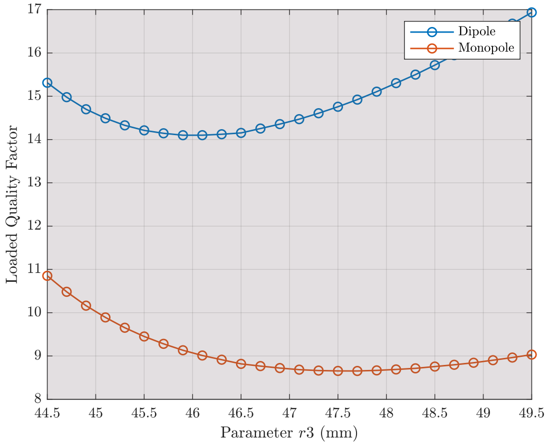
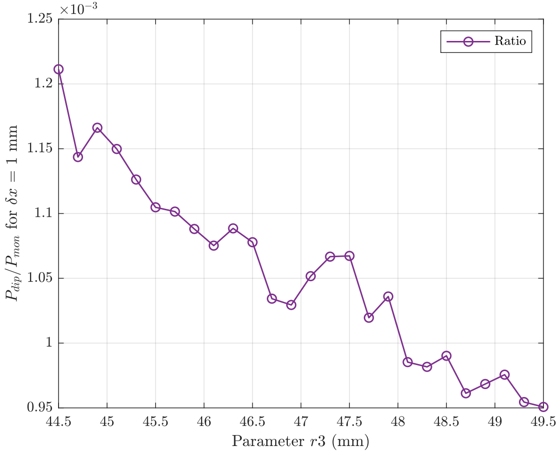
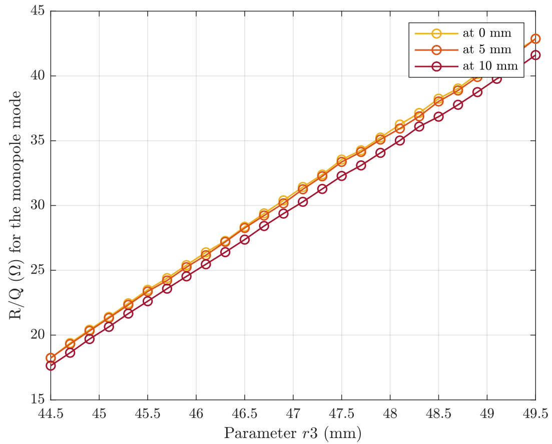
III. Parametric study B. Radius r3 and Gap g

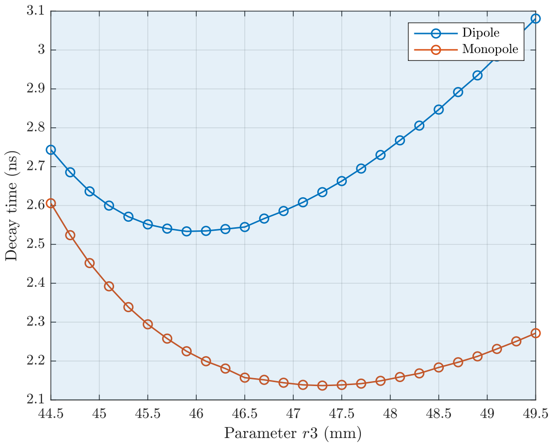




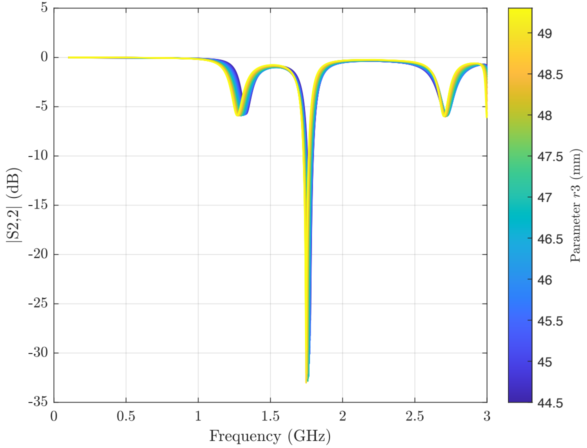


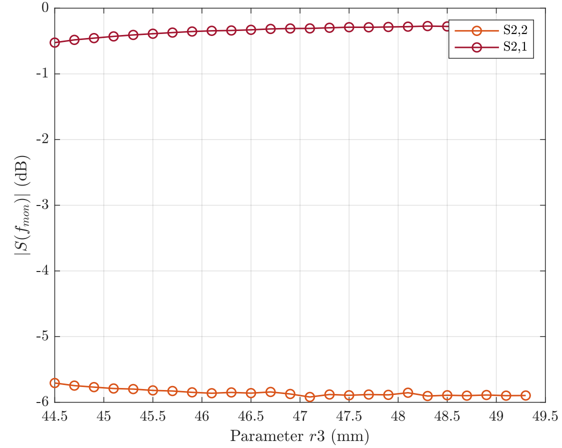


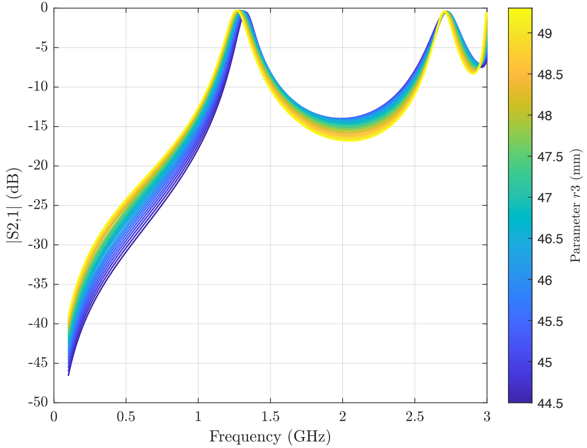


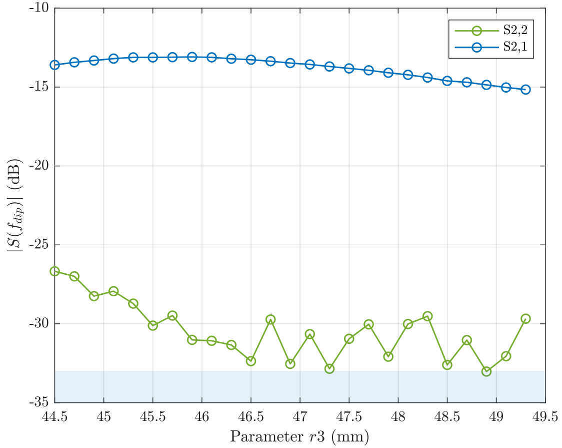


III. Parametric study B. Radius r3 and Gap g





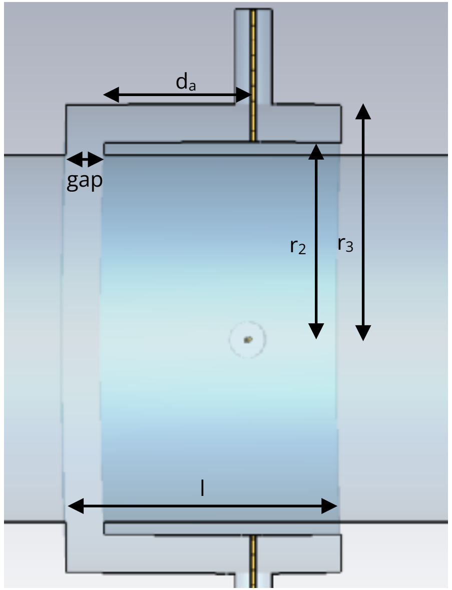




III. Parametric studies on CST Studio Suite

Length of the inner conductor of the antenna: 6,8 mm

Comparison between
- r3 = 48 mm and g = 8 mm
- r3 = 48 mm and g = r3-r2 = 6,5 mm

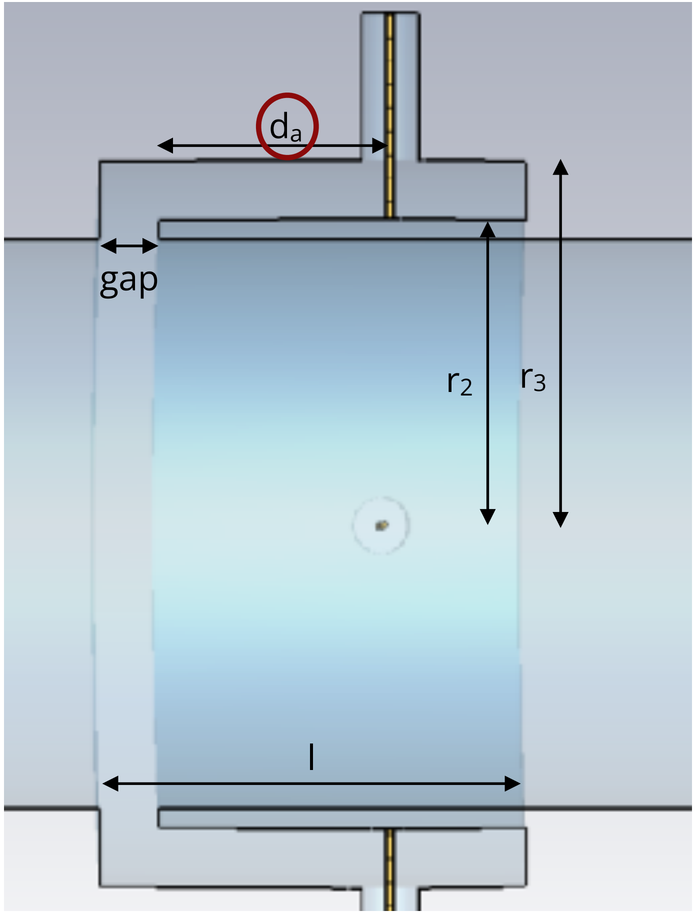


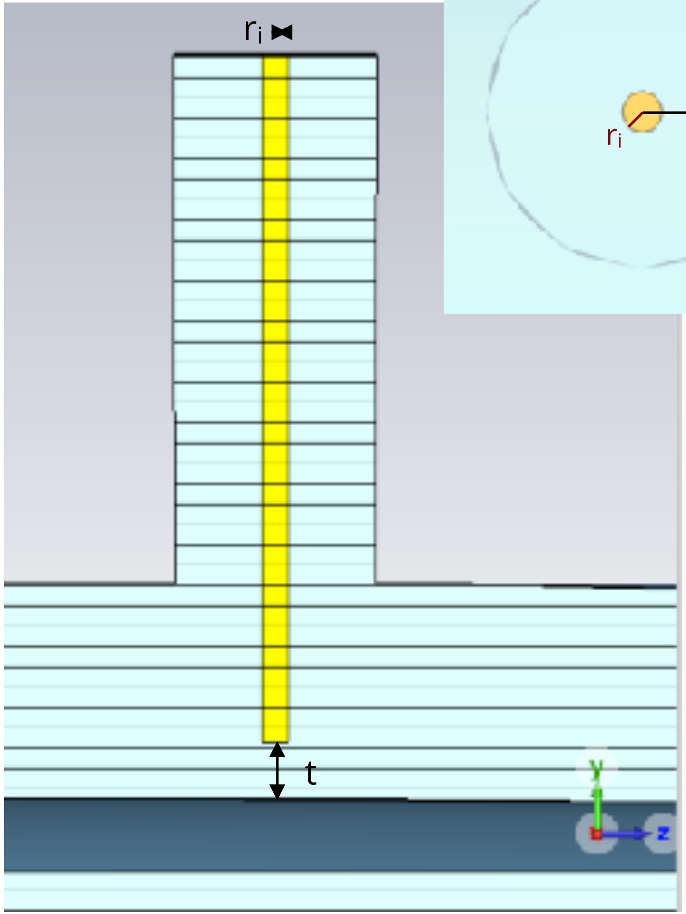
Base values:

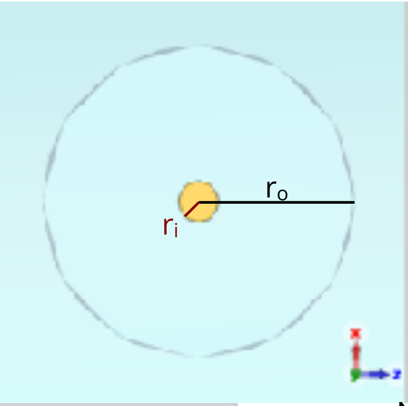
Parameter	Value (mm)
r_3	49,5
r_2	41,5
gap	8
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

Mode	Monopole						Dipole					
Characteristic	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)
Our BPM (CST simulation)	1,265	9,03	42,87	41,61	-5,89	-0,26	1,749	16,93	1,02	3,85	-29,34	-15,29
r3 = 48	1,3	8,65	37	36	-5,9	-0,25	1,77	14,9	0,9	3,3	-32	-14
r3 = 48 and g = r3-r2	1,282	8,67	35,5	34,5	-5,85	-0,29	1,76	15,2	0,84	3,25	-31,5	-14

III. Parametric studies on CST Studio Suite



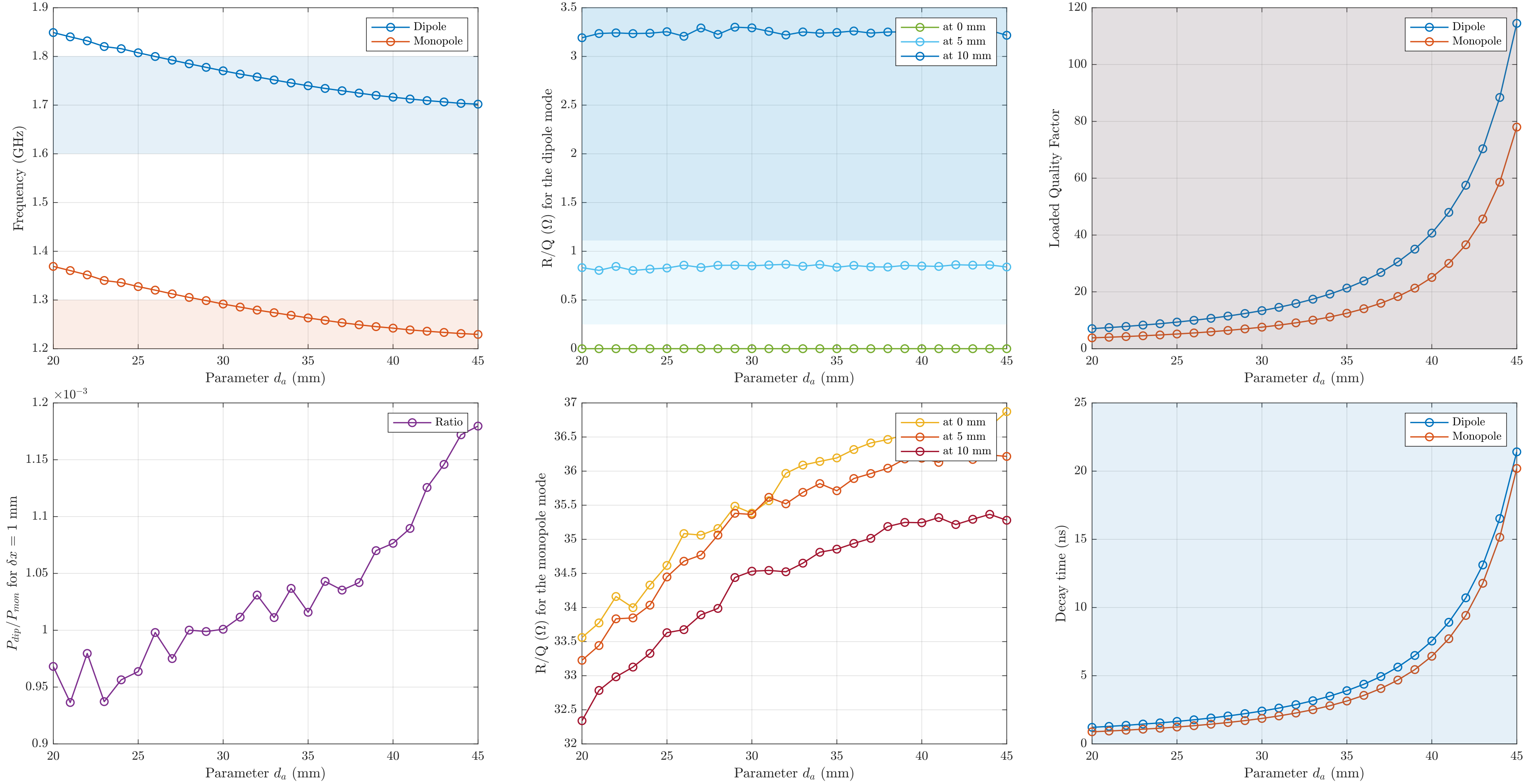




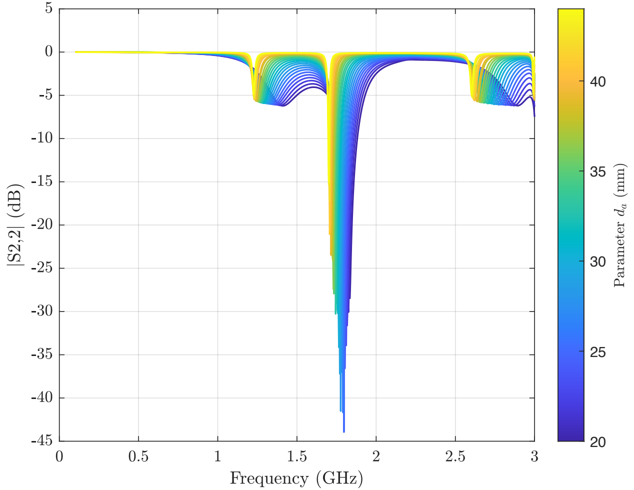
New parameters

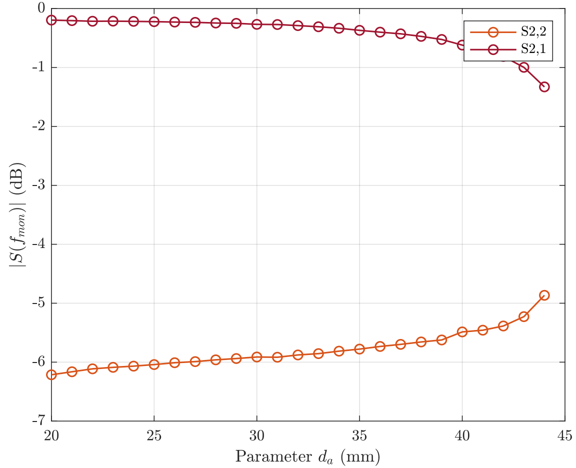
Parameter	Value (mm)
r_3	48
r_2	41,5
gap	6,5
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

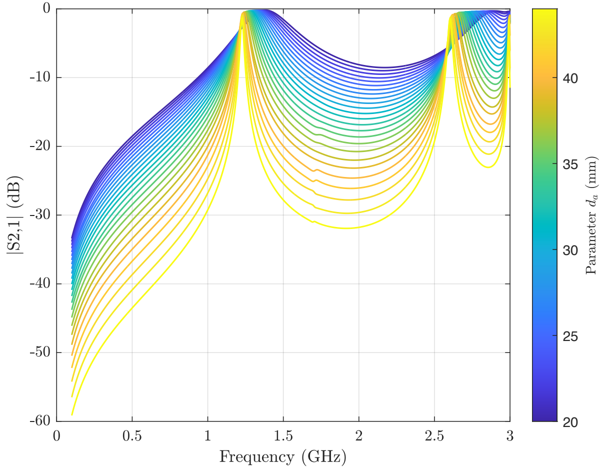
III. Parametric study C. Antenna distance d_a

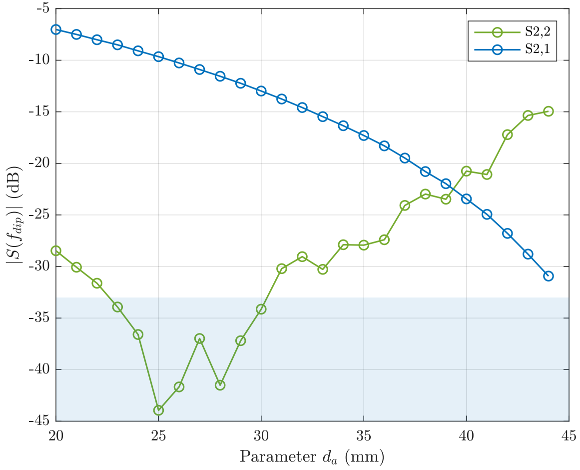


III. Parametric study C. Antenna distance d_a

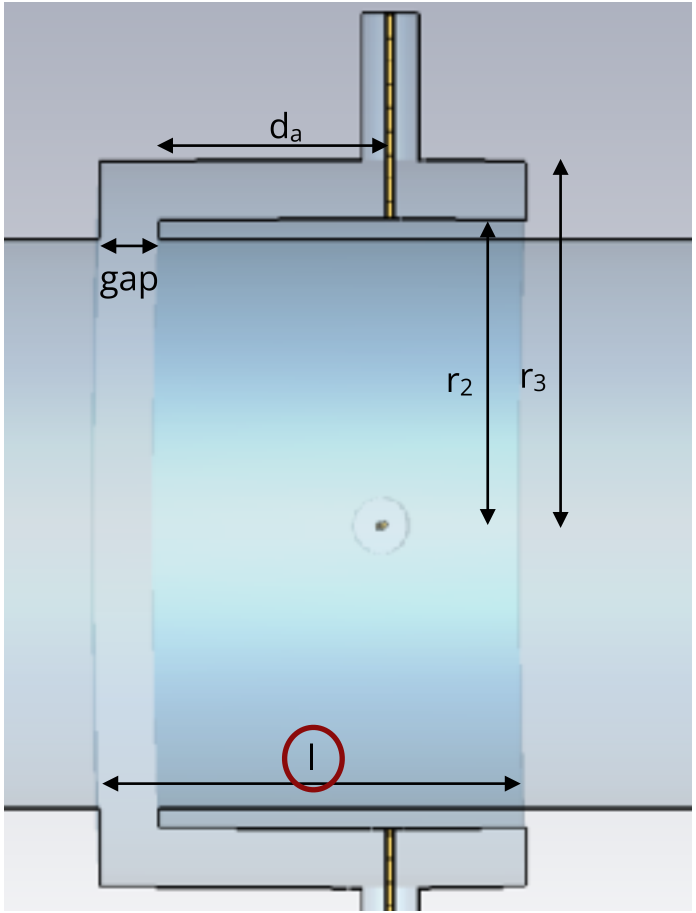


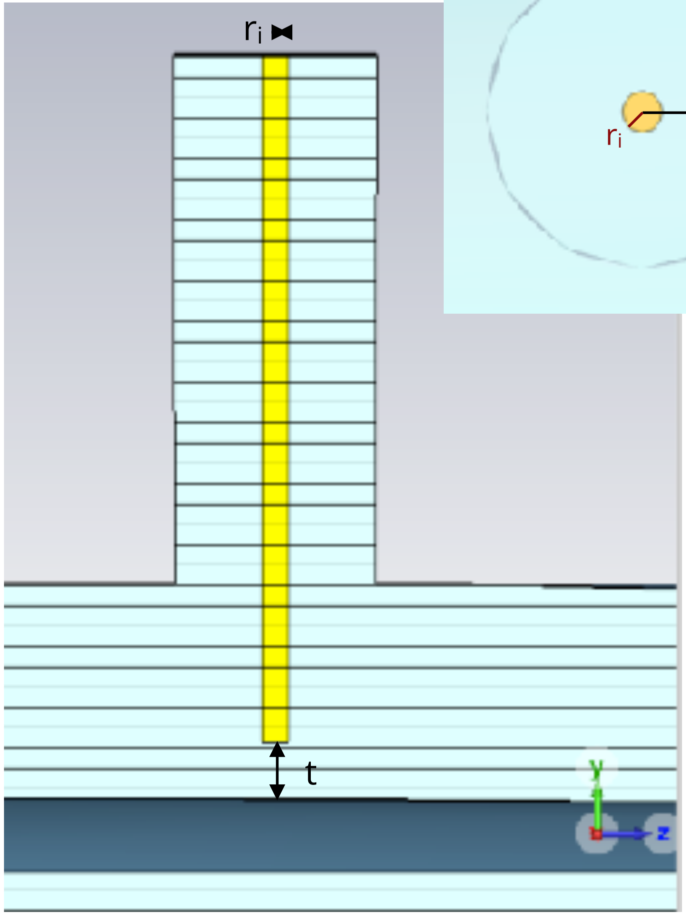


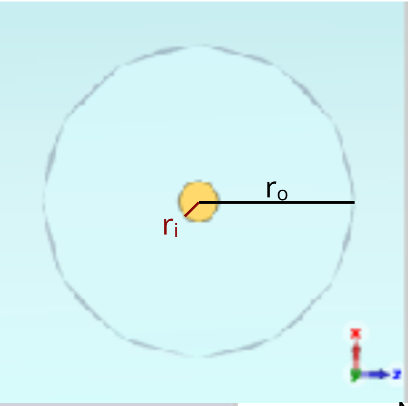




III. Parametric studies on CST Studio Suite



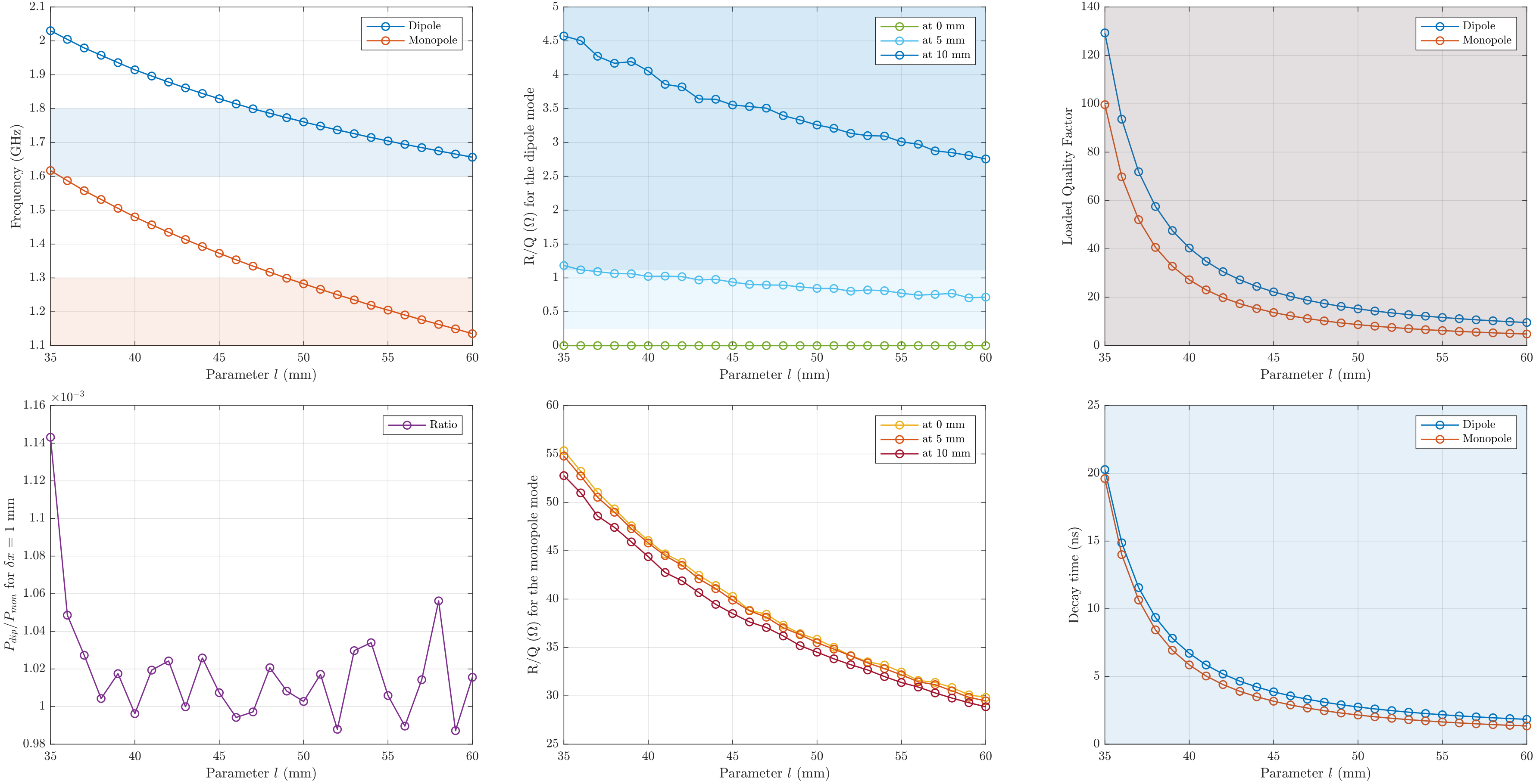




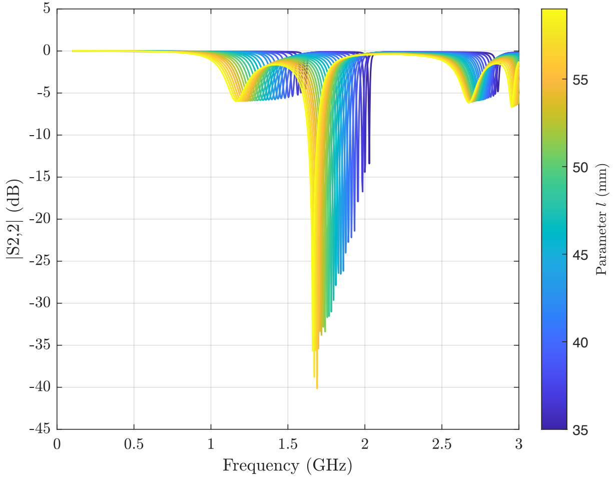
New parameters

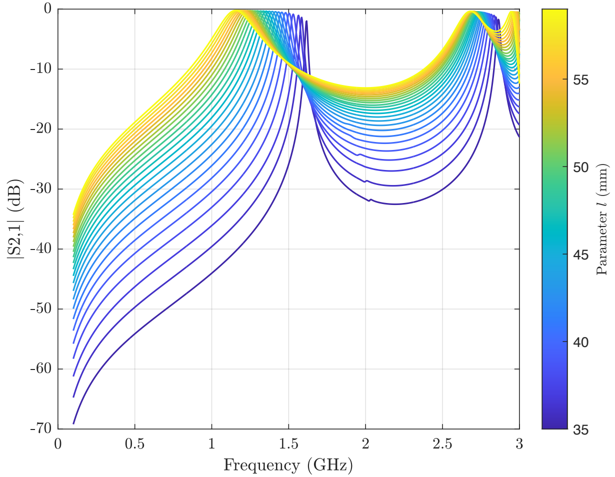
Parameter	Value (mm)
r_3	48
r_2	41,5
gap	6,5
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

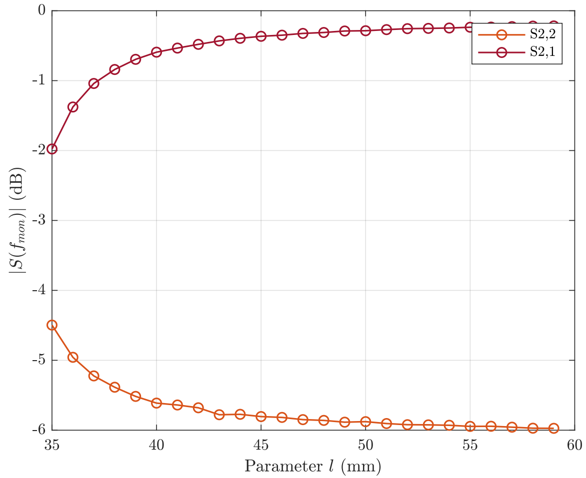
III. Parametric study D. Cavity length l

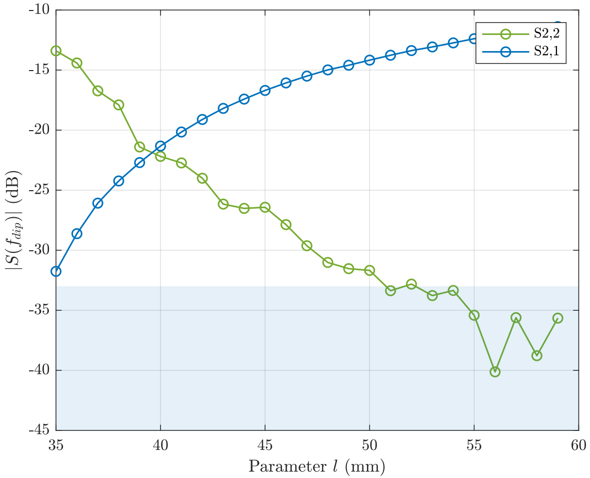


III. Parametric study D. Cavity length l

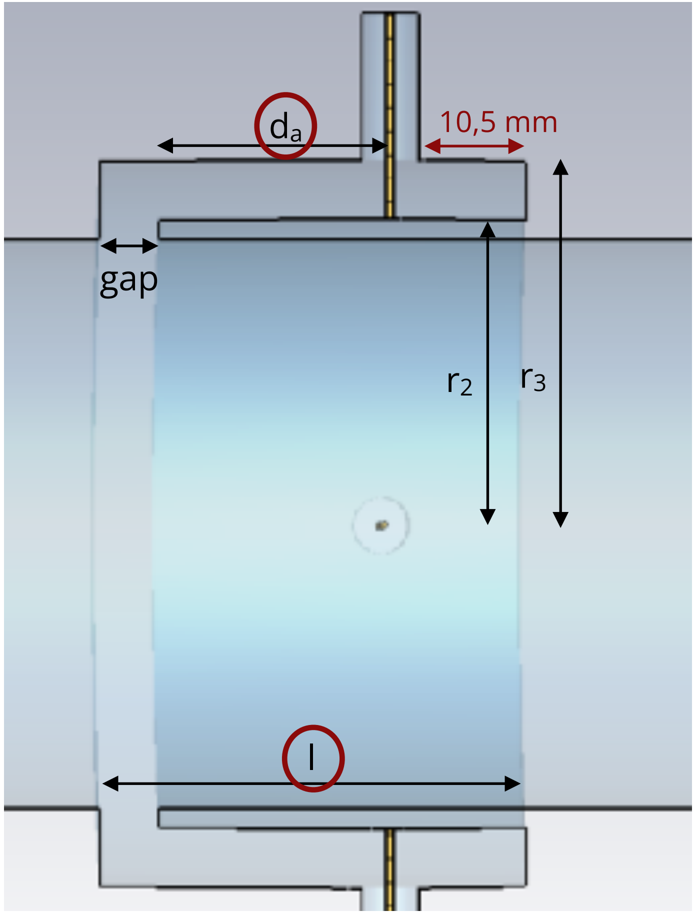


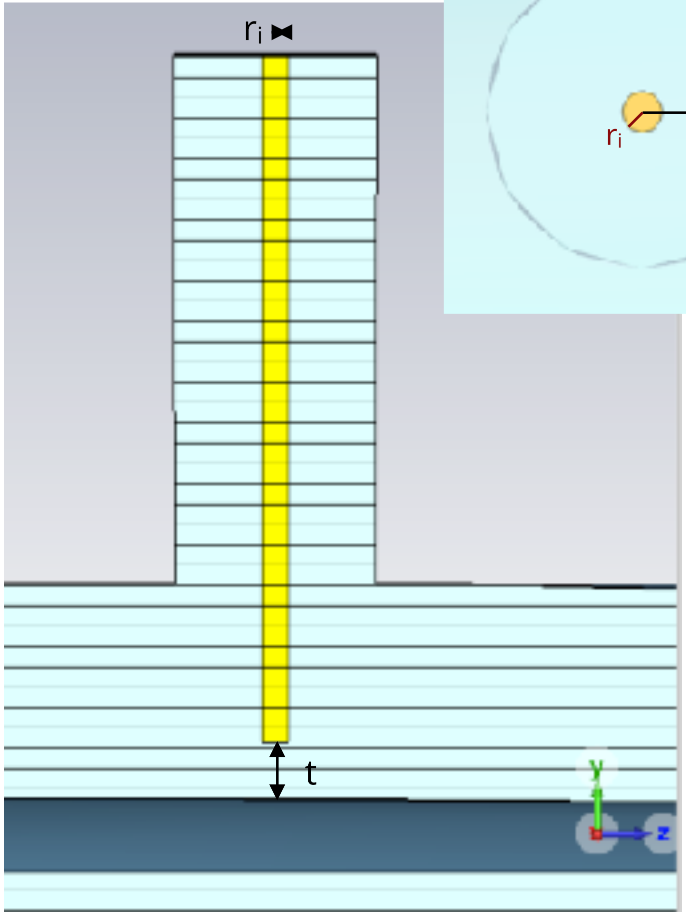


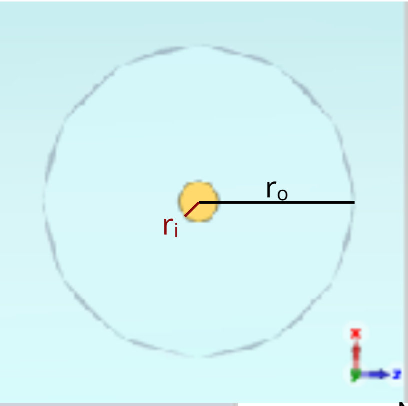




III. Parametric studies on CST Studio Suite







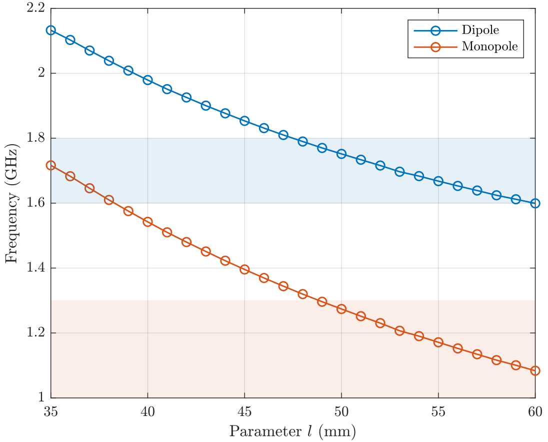
New parameters

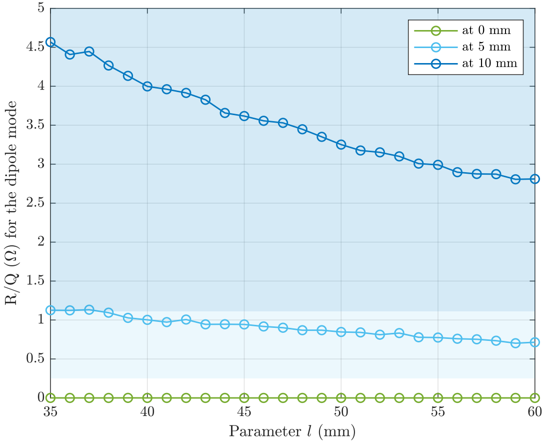
Parameter	Value (mm)
r_3	48
r_2	41,5
gap	6,5
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

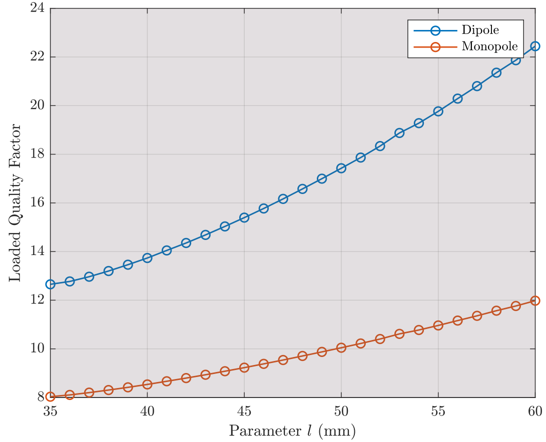
III. Parametric study

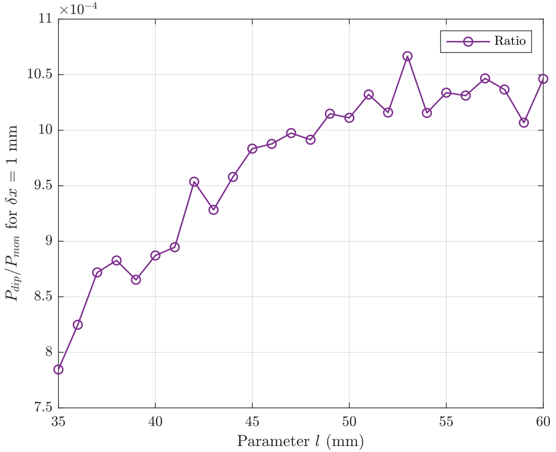
E. Cavity length l and $d_a = l - g - 10{,}5$

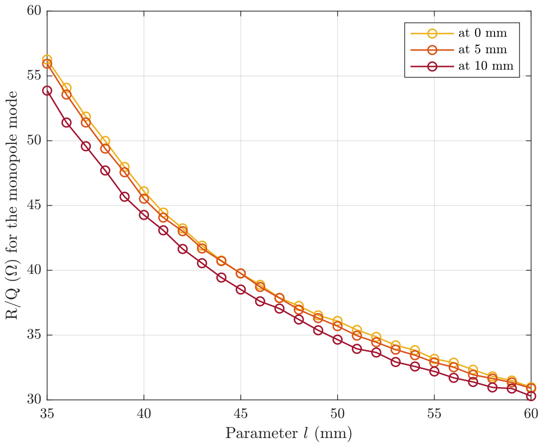
IFIC

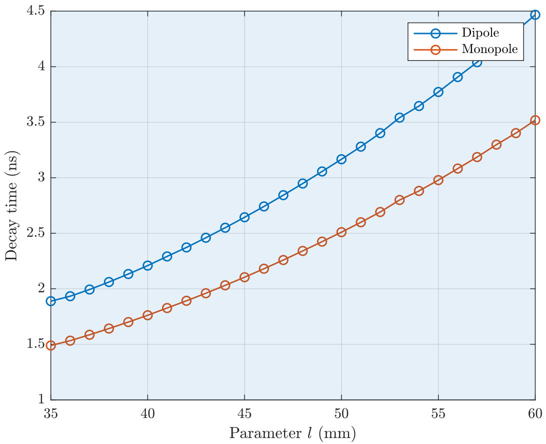






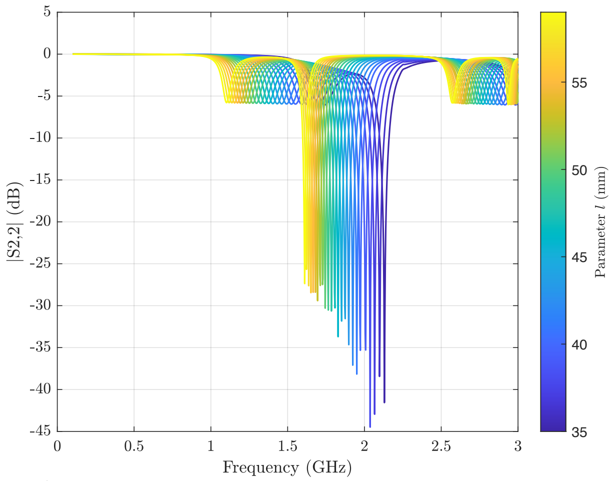


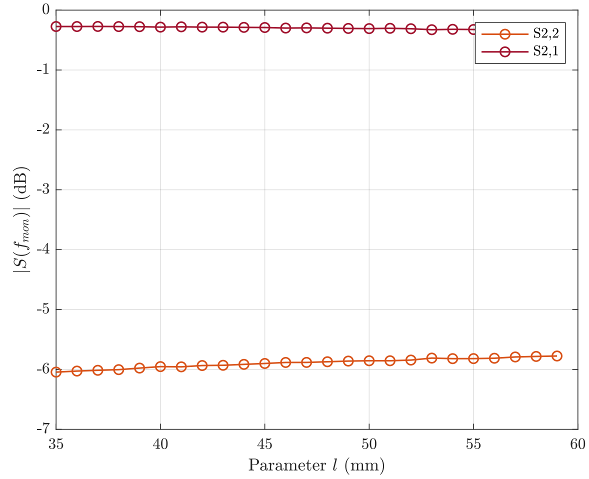


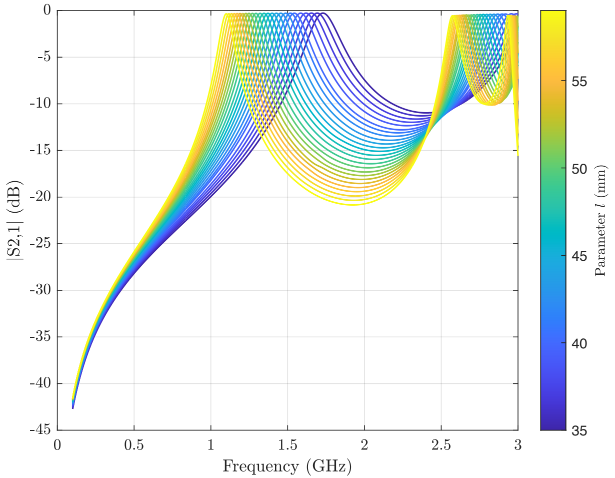


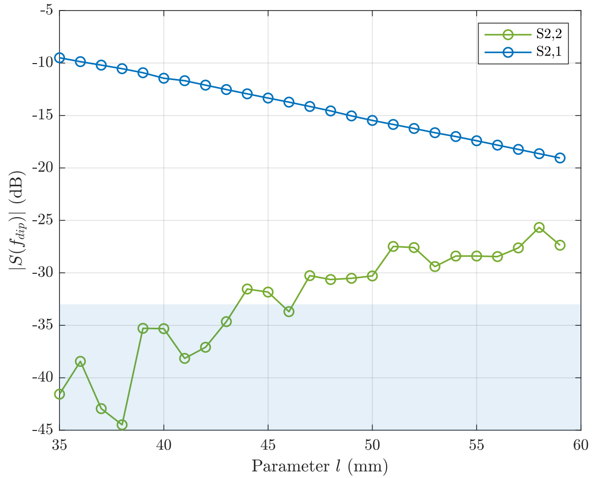
III. Parametric study

E. Cavity length l and $d_a = l - g - 10{,}5$

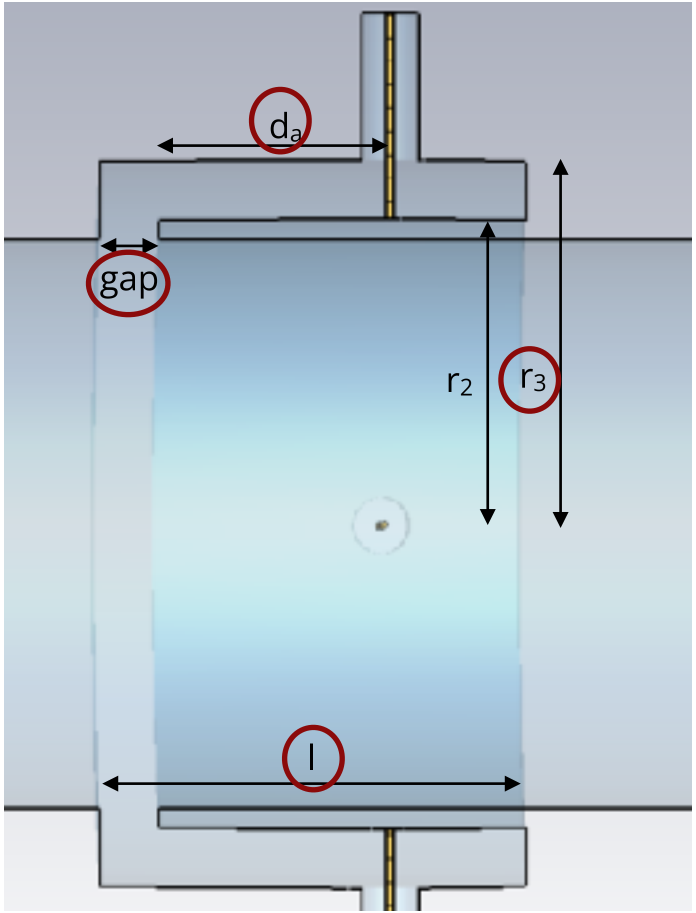


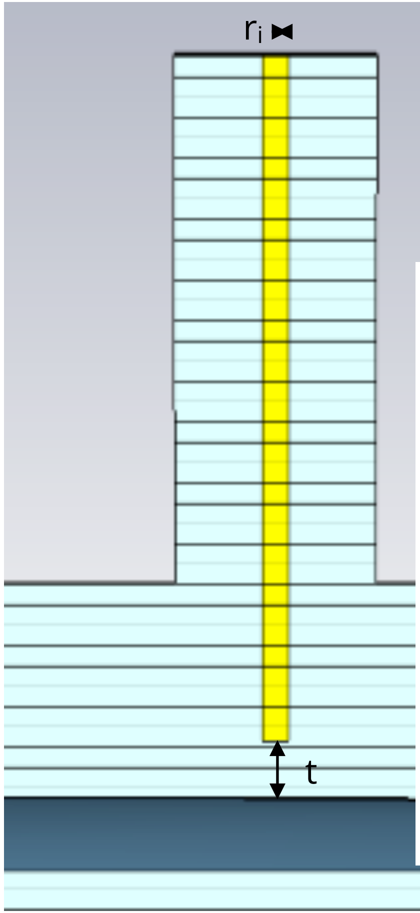


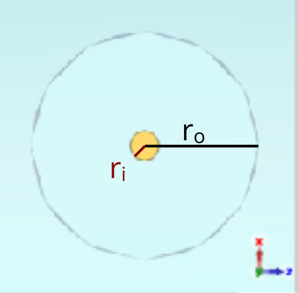




III. Parametric studies on CST Studio Suite







Old parameters

Parameter	Value (mm)
r_3	49
r_2	41,5
gap	8
l	50
d_a	31,5
r_i	0,5
r_o	1,1512
t	0

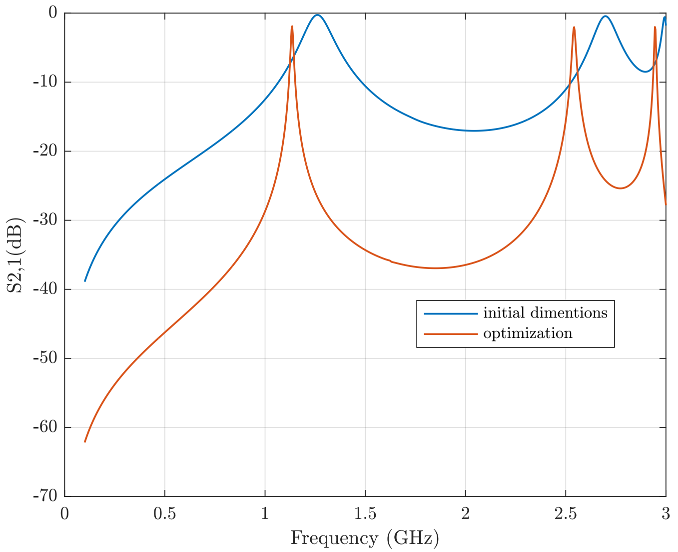
New parameters

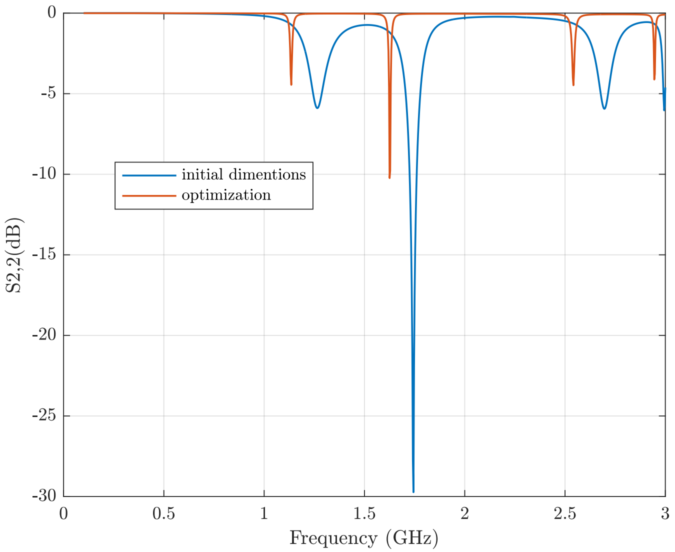
Parameter	Value (mm)
r_3	48
r_2	41,5
gap	6,5
l	55
d_a	50
r_i	0,5
r_o	1,1512
t	0

III. Parametric studies on CST Studio Suite

Try of optimization with: $r_3 = 48,\ g = 6.5,\ l = 55,\ d_a = 50$ mm

Mode	Monopole							Dipole						
Characteristic	Freq (GHz)	Q_L	τ (ns)	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)	Freq (GHz)	Q_L	τ (ns)	R/Q (Ω) @ 5 mm	R/Q (Ω) @ 10 mm	S_{22} (dB)	S_{21} (dB)
Initial BPM	1,265	9,03	2.3	42,8	41,6	-5,9	-0,26	1,749	16,9	3.1	1,02	3,85	-29,3	-15,2
Optimization	1,136	85,2	23.8	33,7	33,0	-4,5	-2,11	1,628	128,8	25.2	0,76	3,02	-10,2	-35,9





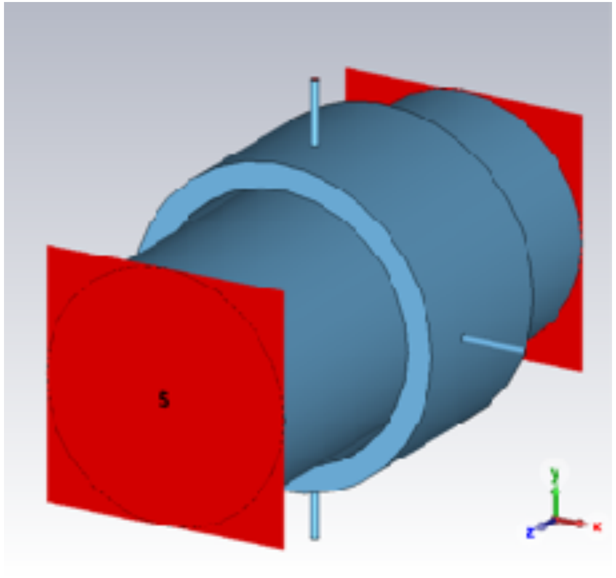
IV. VNA measurements in the lab

IV. VNA measurements

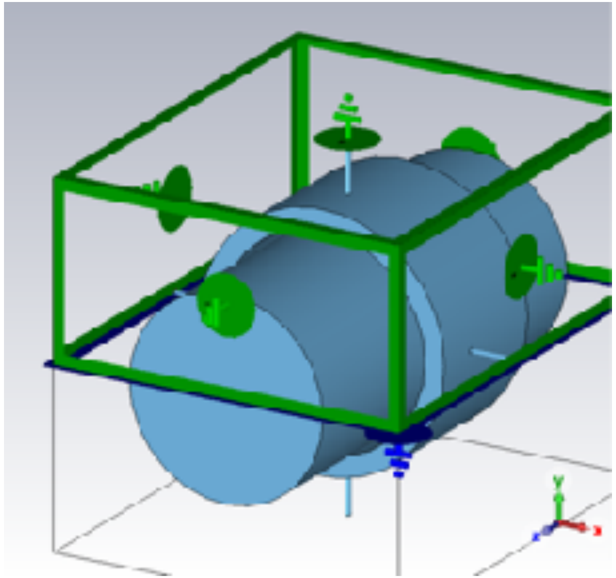
CST simulation comparison for VNA measurements

Simulations for cBPM with:

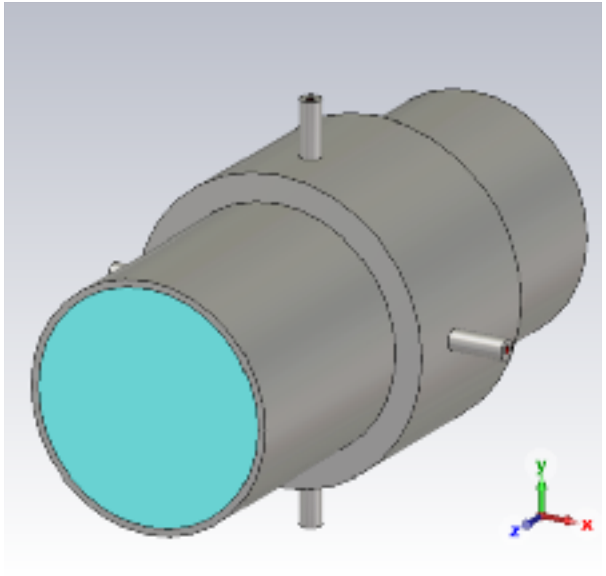
<u>waveguide port on the pipe</u>
(infinite)



<u>electric wall on pipe termination</u>
(short circuit)



<u>open</u>
(nothing on pipe termination)



IV. VNA measurements

CST simulation comparison for VNA measurements

Simulations for cBPM with: - waveguide port on the pipe (infinite)

- electric wall on pipe termination (short circuit)
- open (nothing on pipe termination)

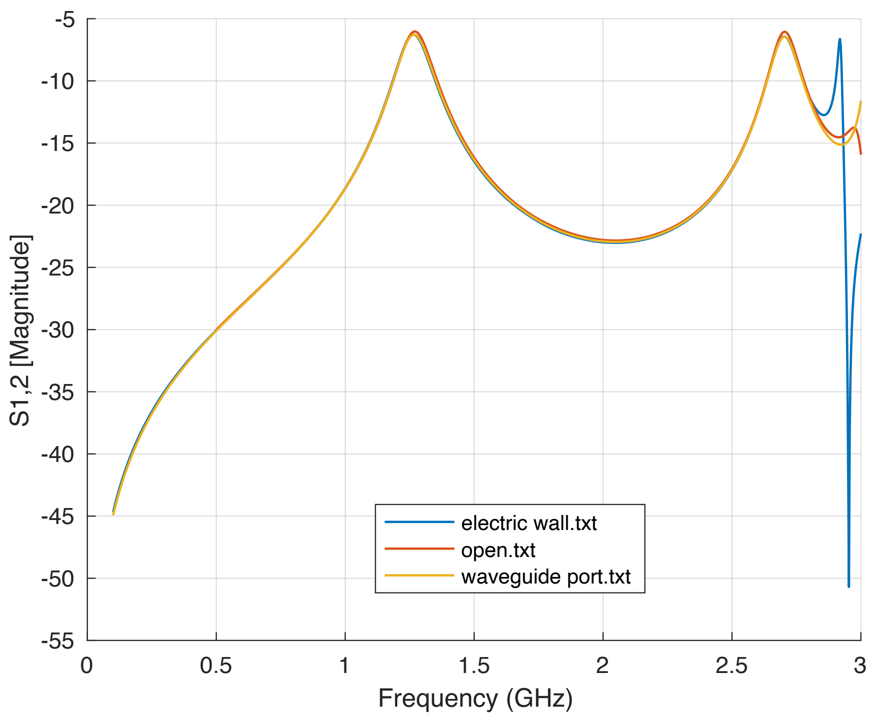
	Frequency (GHz)		Loaded Quality Factor		$S_{2,2}$ (dB)		$S_{2,1}$ (dB)	
	f_m	f_d	Q_m	Q_d	$S_{2,2}(f_m)$	$S_{2,2}(f_d)$	$S_{2,1}(f_m)$	$S_{2,1}(f_d)$
Waveguide port at pipe	1.262	1.746	9	17	-5.89	-29.34	-0.26	-15.29
Electric wall at pipe end	1.261	1.749	9	16	-5.9	-29	-0.27	-16
Open (no wall or extension)	1.267	1.752	9	17	-6.04	-33	-0.01	-15.11

IV. VNA measurements

CST simulation comparison for VNA measurements

Simulations for cBPM with:
- waveguide port on the pipe (infinite)
- electric wall on pipe termination (short circuit)
- open (nothing on pipe termination)

S1,2 (dB)



S2,2 (dB)