CLIC Main Linac Cavity BPM

Snapshot of the work in progress

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(Manfred Wendt)

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CLIC Main Linac BPM Requirements

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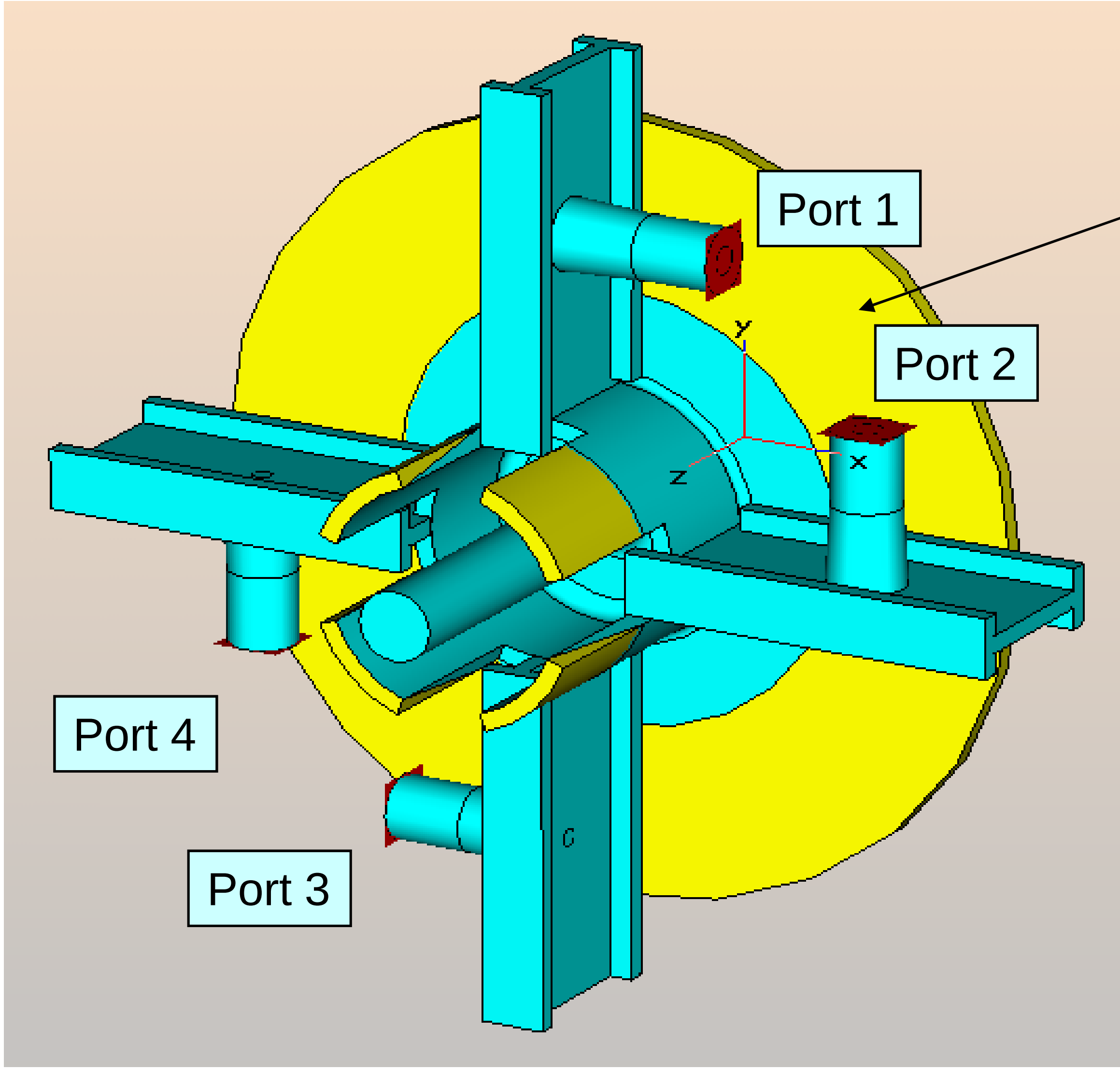
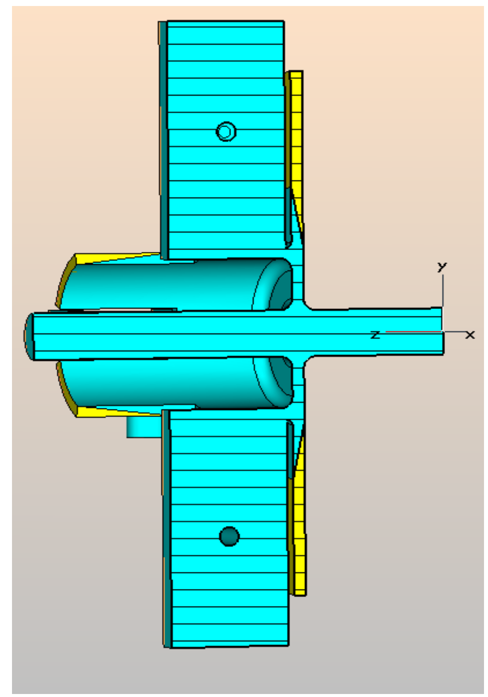
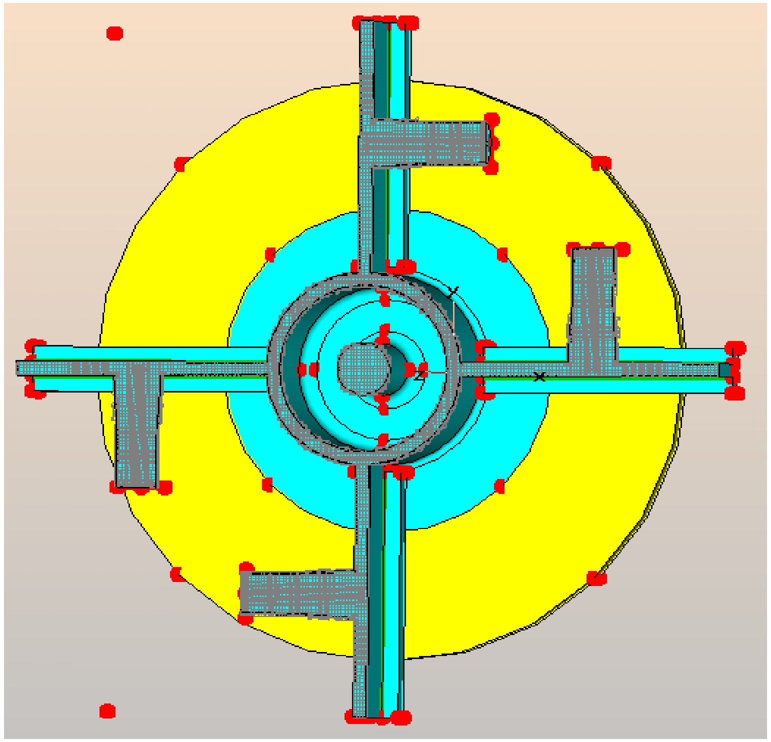
Parameter	Value
Charge / bunch	3.7×10^9
# of bunches	312
Bunch length	45-70 μm
Length of the bunch train	156 nsec
Bunch spacing	0.5 nsec
# of main linac BPMs	4176
Beam pipe diameter	8 mm
Real estate for BPM	65 mm
BPM accuracy	5 μm
BPM resolution	50 nm within a 200 μm range
BPM time resolution	10 – 50 nsec
BPM stability	100 nm
BPM system latency (for FB)	<5 msec

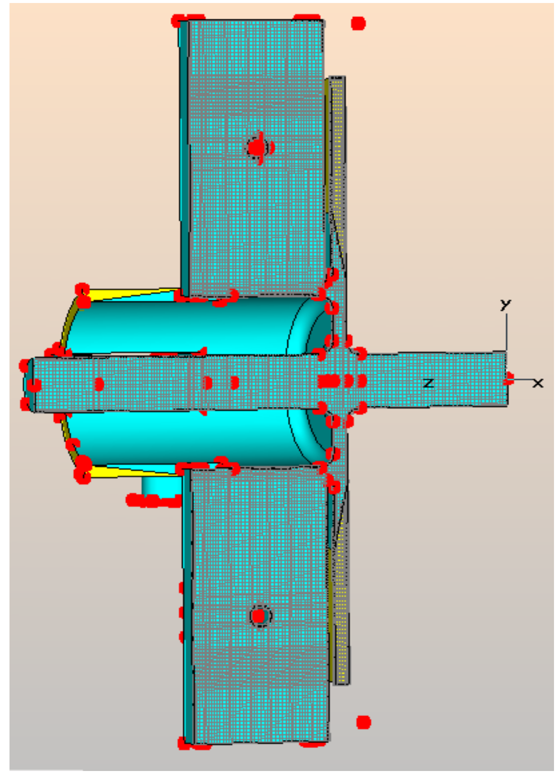
CLIC BPM as is. MWS model.



Absorber:
Epsilon = 1
Mue = 1
El. Tang = 1

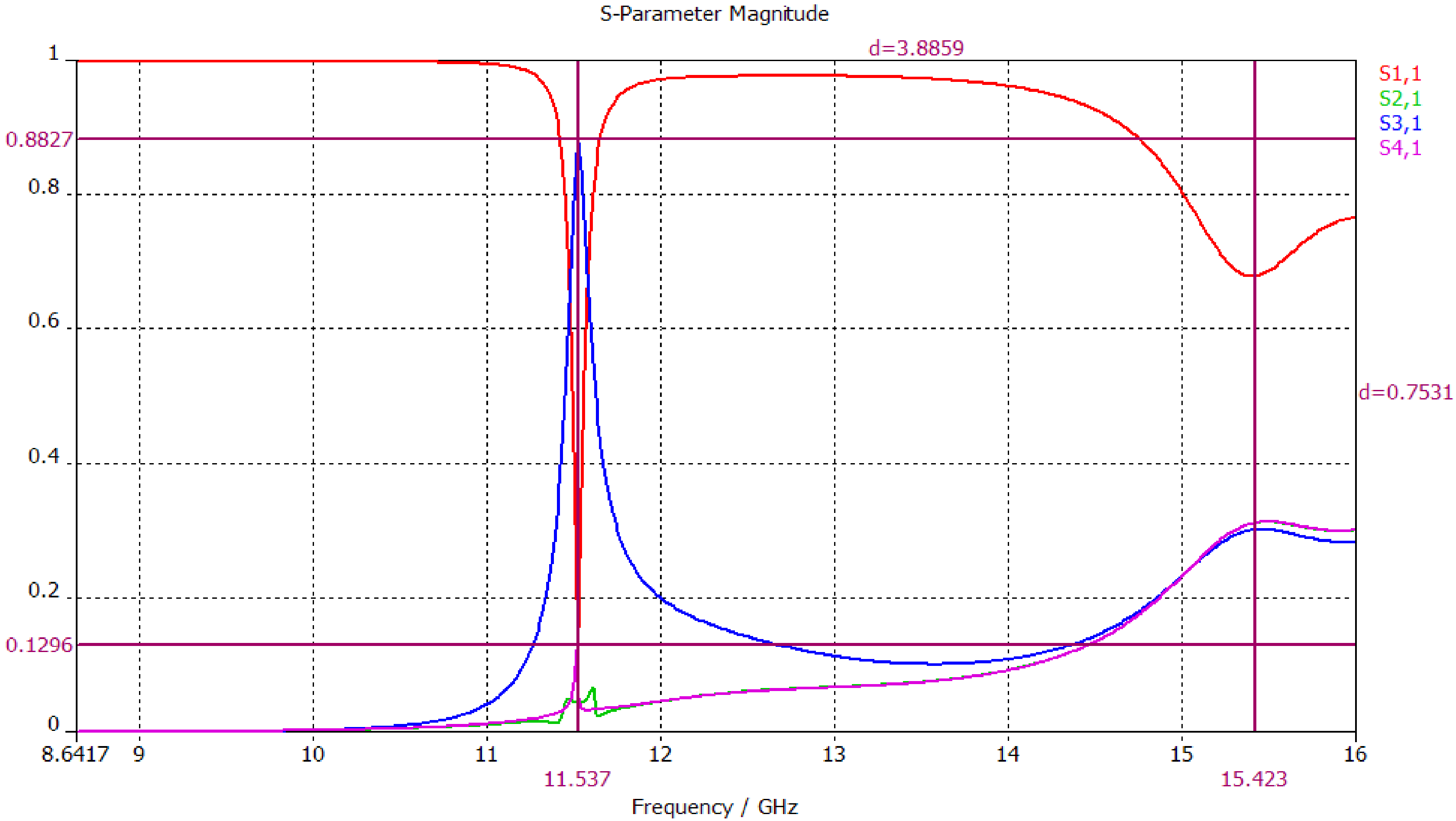




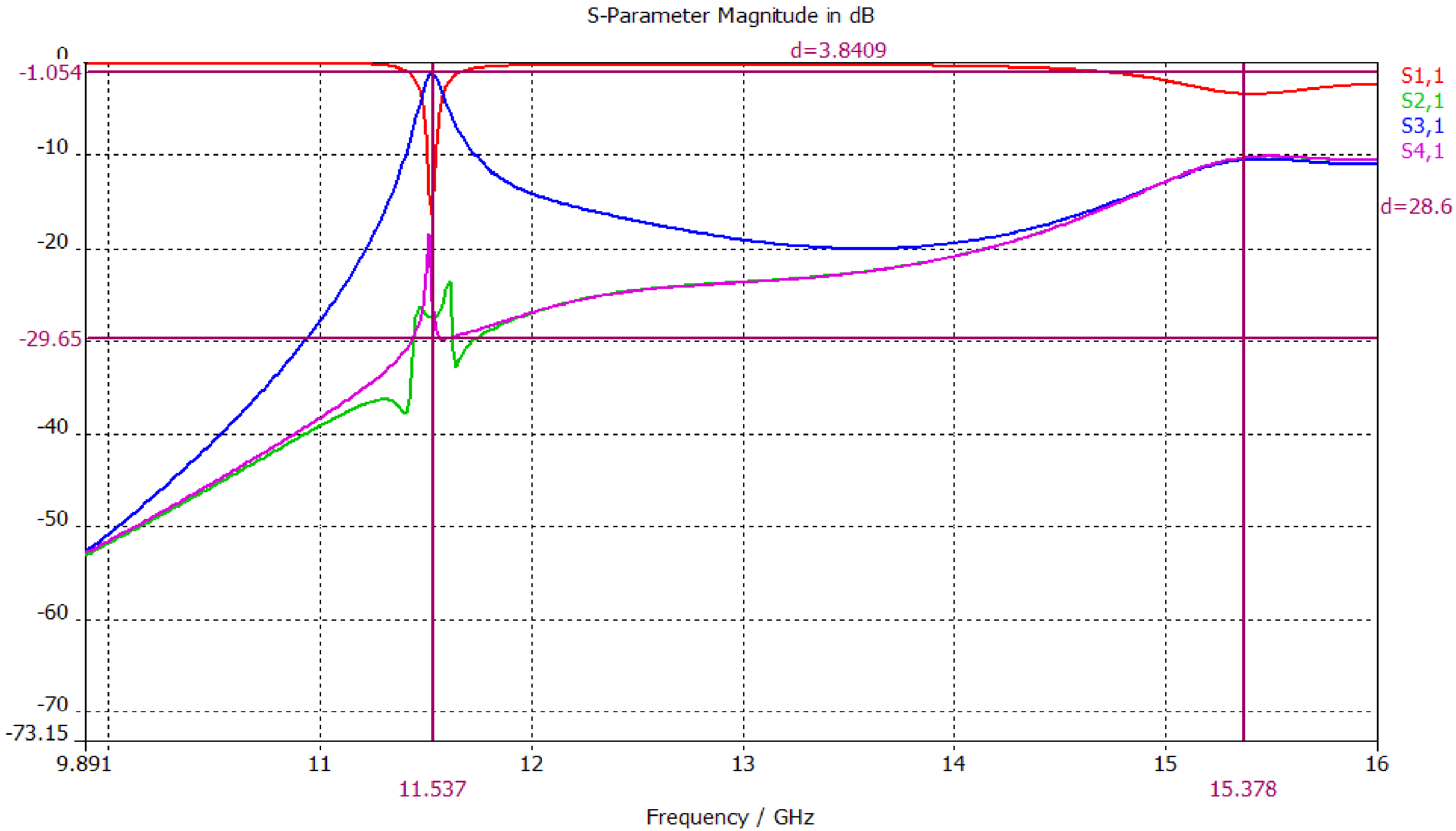


Meshcells – 1,227,331

Excitation through Port 1



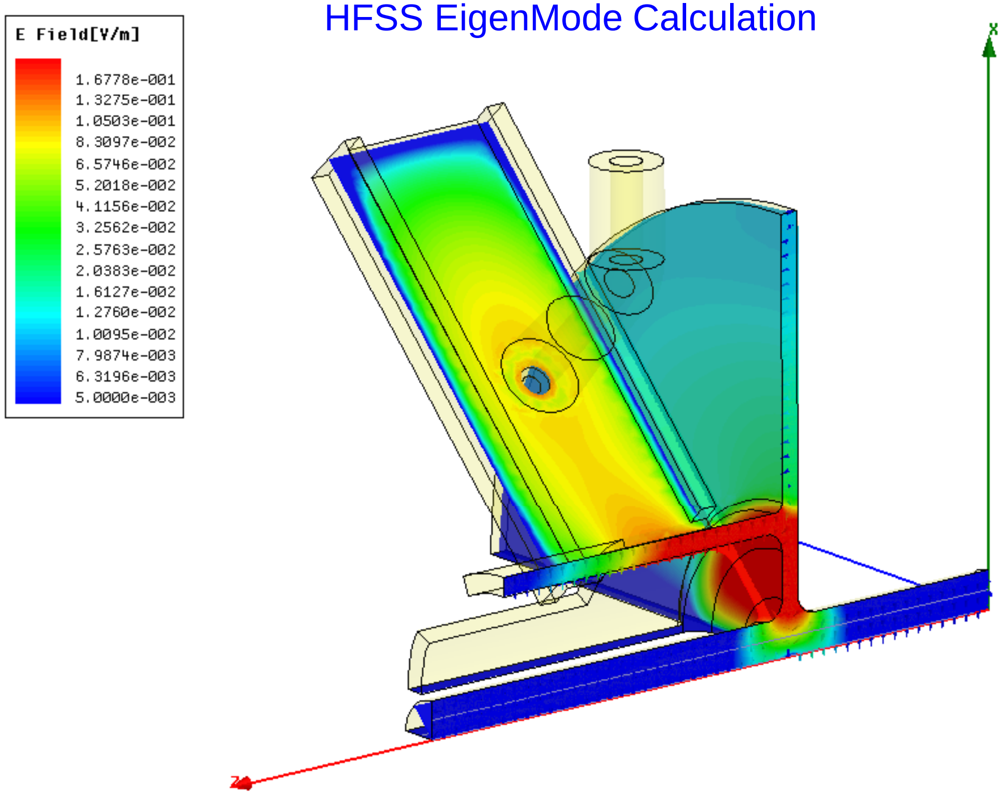
Excitation through Port 1



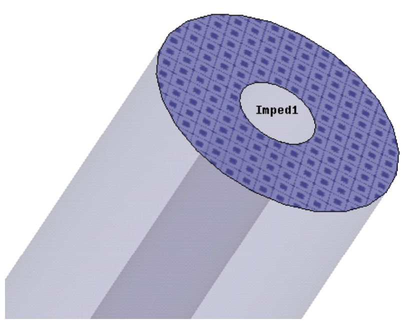
If smooth behavior of S31 and S21 is assumed, then isolation is 29 dB. Their actual behavior at 11.54 GHz needs to be simulated with higher accuracy

Operating Dipole TM_{11} mode

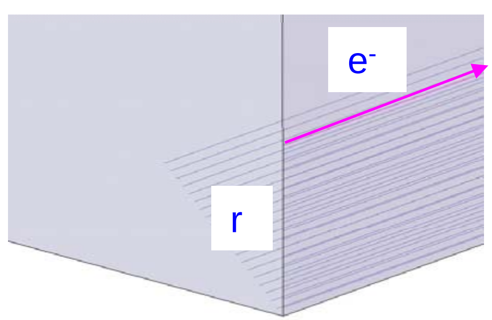
HFSS EigenMode Calculation



(I) Matched Impedance, P_coax



(II) Bunch trajectories



HFSS Data:

W - Stored Energy
P_coax - Exited RF Power
Ez - E-field along bunch path

Scale Factor:

$$k_{scale} = \frac{q_0}{q_{HFSS}} = q_0 * \frac{\left| \int_0^L Ez * e^{j\omega t} dz \right|}{2 * W}$$

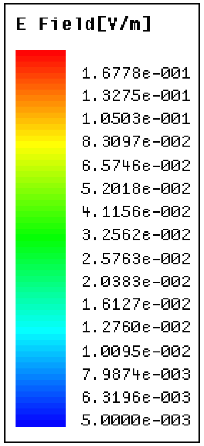
Output Power:

$$P_{TM11}(r) = P\_coax(r) * (k_{scale})^2$$

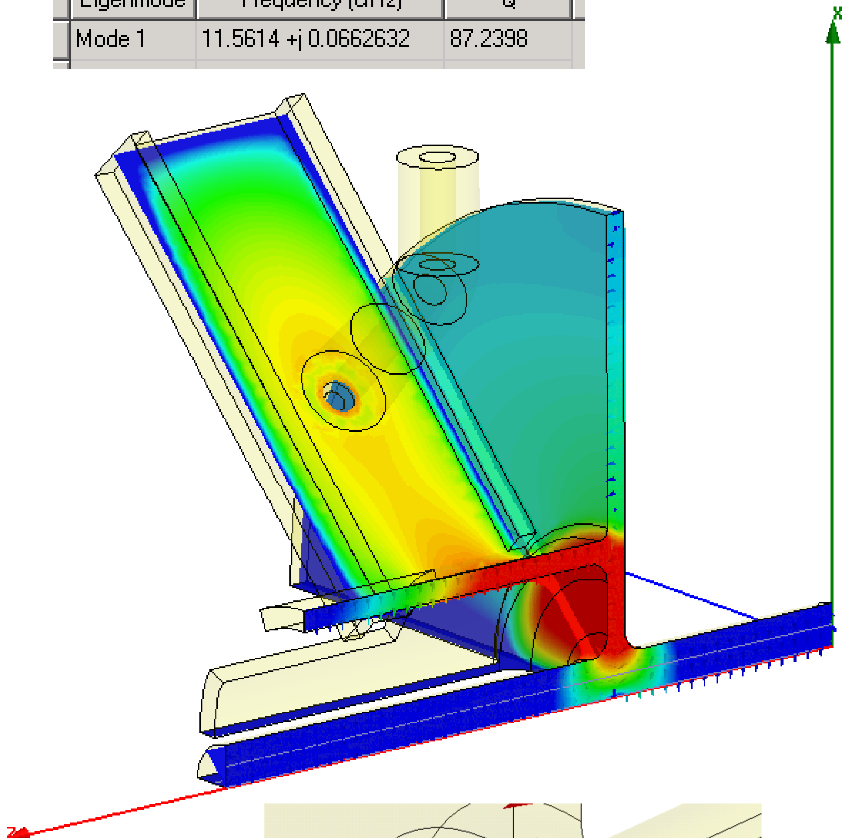
Estimated Sensitivity (q_0 = 1nQ):

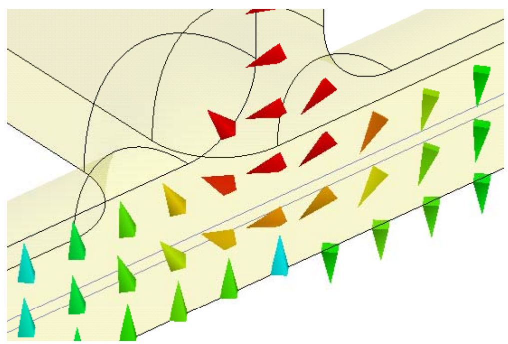
$$S = \frac{\sqrt{P_{TM11}(r) * 50[Ohm]}}{r}$$ V/nQ/mm

Operating Dipole TM_{11} mode



Eigenmode	Frequency (GHz)	Q
Mode 1	11.5614 +j 0.0662632	87.2398



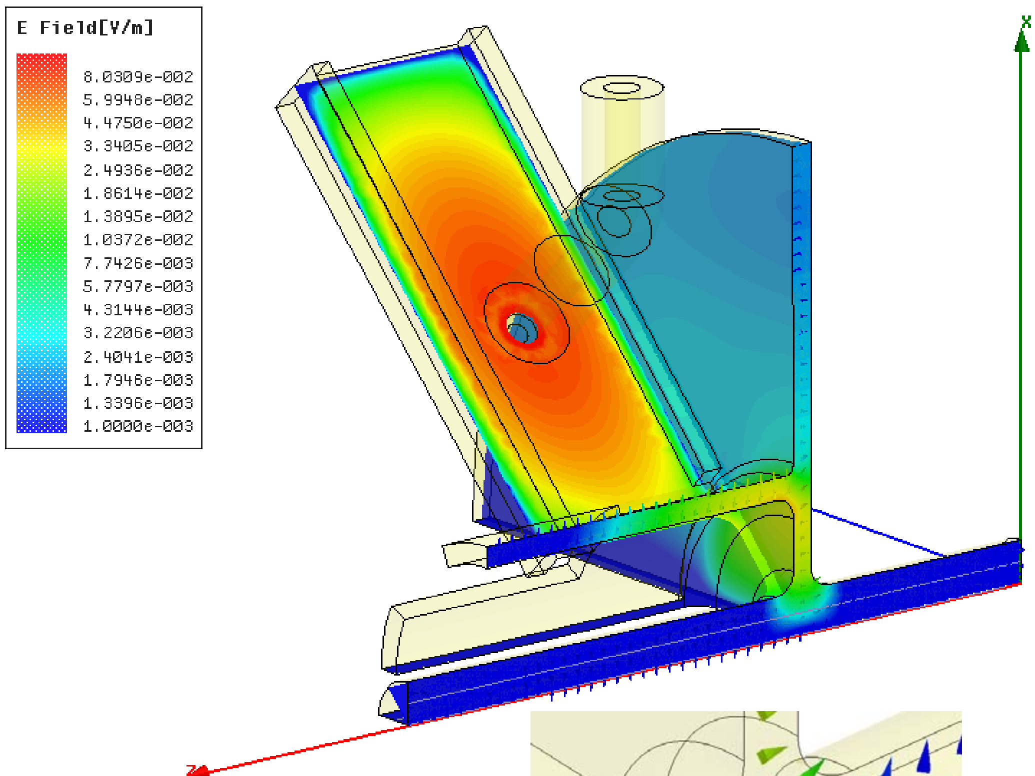


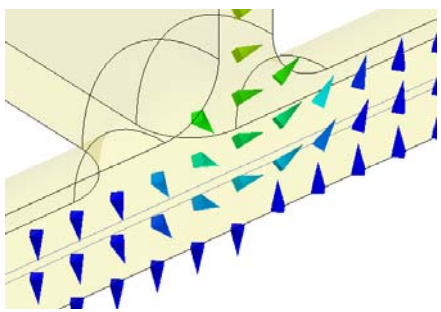
Frequency, [GHz]	11.561
Q, External	90
Test charge, [coulomb] (X=1mm, Y=0mm)	1E-9
R/Q, [Ohm/mm]	7
Output Voltage at T=0*, [V/nQ/mm]	100

Scl : 99.1020506703066
Scl : V_out
Scl : 7.12087848013592
Scl : RQx
Scl : 4.38821853836838E-011
Scl : P_coax
Scl : 5.77811461802102E-020
Scl : W_E
Scl : 242.308845238102
Scl : kz

* Normalized to 50 Ohm,

Mode 2	11.5617 +j 1.04267	5.56681





Frequency, [GHz]	11.561
Q, External	5
Test charge, [coulomb] (X=1mm, Y=0mm)	1E-9
R/Q, [Ohm/mm]	0.2
Output Voltage at T=0*, [V/nQ/mm]	70

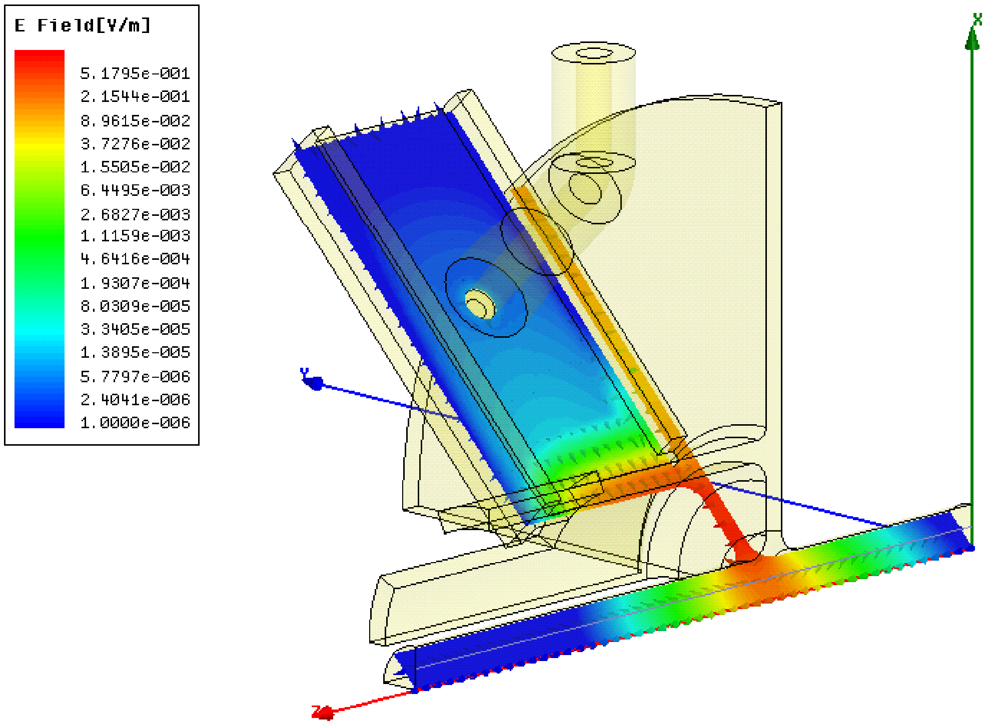
Scl : 68.2039050993727
Scl : V_out
Scl : 0.196639126319497
Scl : RQx
Scl : 8.48871316538816E-011
Scl : P_coax
Scl : 6.51682269613322E-021
Scl : W_E
Scl : 242.316087672475
Scl : kz

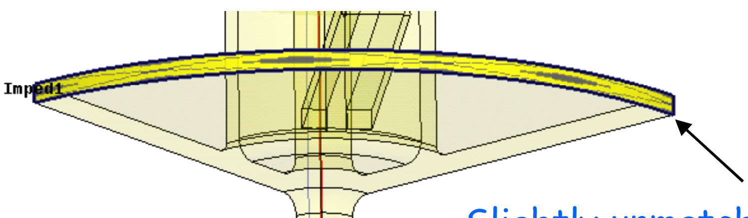
180 degree phase shift
Should we write V_out = - 70 V ?!

* Normalized to 50 Ohm,

Monopole TM_{01} mode N1

Eigenmode	Frequency (GHz)	Q
Mode 1	6.29809 +j 0.247543	12.7310





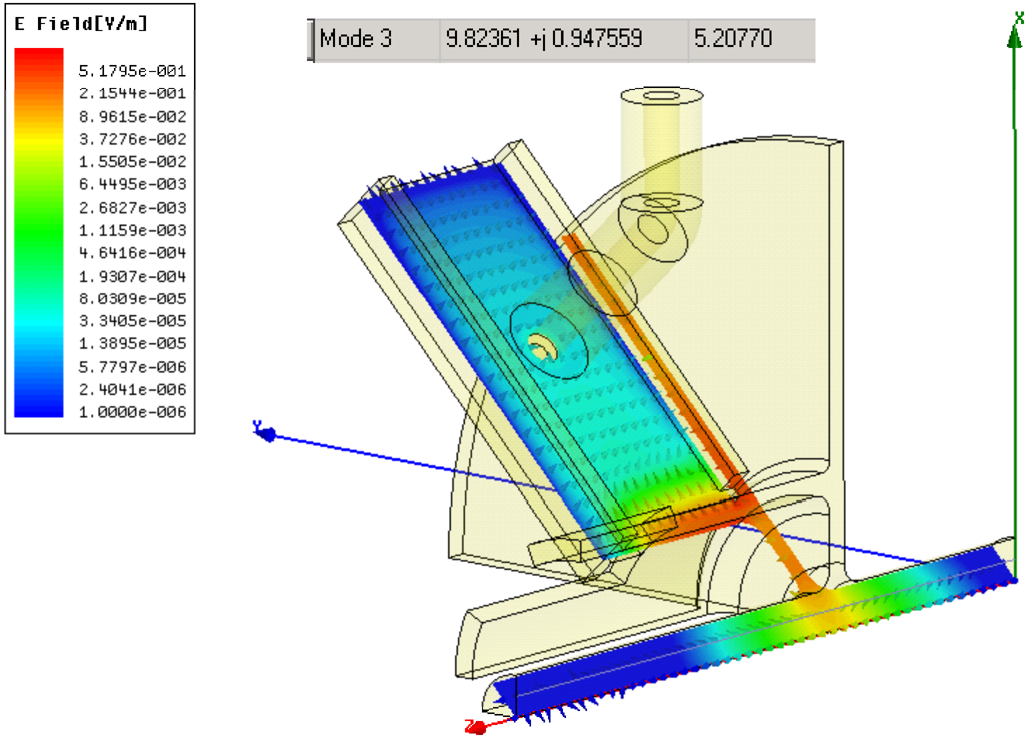
Slightly unmatched Impedance Boundary to get a reasonable Q-value

Frequency, [GHz]	6.3
Q, External	13
Test charge, [coulomb] (X=1mm, Y=0mm)	1E-9
R/Q, [Ohm/mm]	116
Output Voltage at T=0*, [V/nQ]	0.005

Scl : 0.00583225195204708
Scl : V_out
Scl : 116.506170433799
Scl : RQx
Scl : 4.4431979522073E-020
Scl : P_coax
Scl : 1.50556724182942E-019
Scl : W_E
Scl : 131.998429700892
Scl : kz

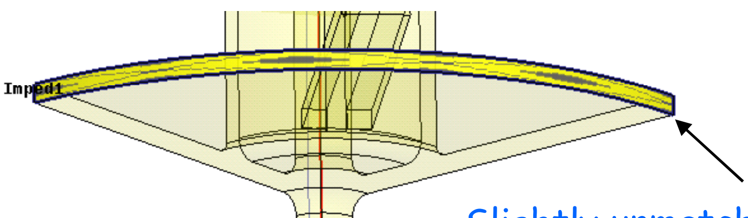
* Normalized to 50 Ohm,

Monopole TM_{01} mode N2



Frequency, [GHz]	9.8
Q, External	5
Test charge, [coulomb] (X=1mm, Y=0mm)	1E-9
R/Q, [Ohm/mm]	2
Output Voltage at T=0*, [V/nQ]	0.008

```
Scl : 0.00847005653556336
Scl : V_out
Scl : 2.06811403310181
Scl : RQx
Scl : 6.34105680622382E-018
Scl : P_coax
Scl : 2.82068189851649E-019
Scl : W_E
Scl : 205.888100817774
Scl : kz
```



Slightly unmatched Impedance Boundary to get a reasonable Q-value

* Normalized to 50 Ohm,

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✓ 1. General idea:
- low Q-factors
- monopole modes decoupling

✓ Cavity spectrum calculations:
- Frequency
- R/Q, Q
- TM11 output voltage

✓ BPM parameters:
- Cavity length
- Waveguide dimensions
- Coupling slot
- Coaxial transition

✓ 3. Parasitic signals:
- monopole modes
- quadruple modes

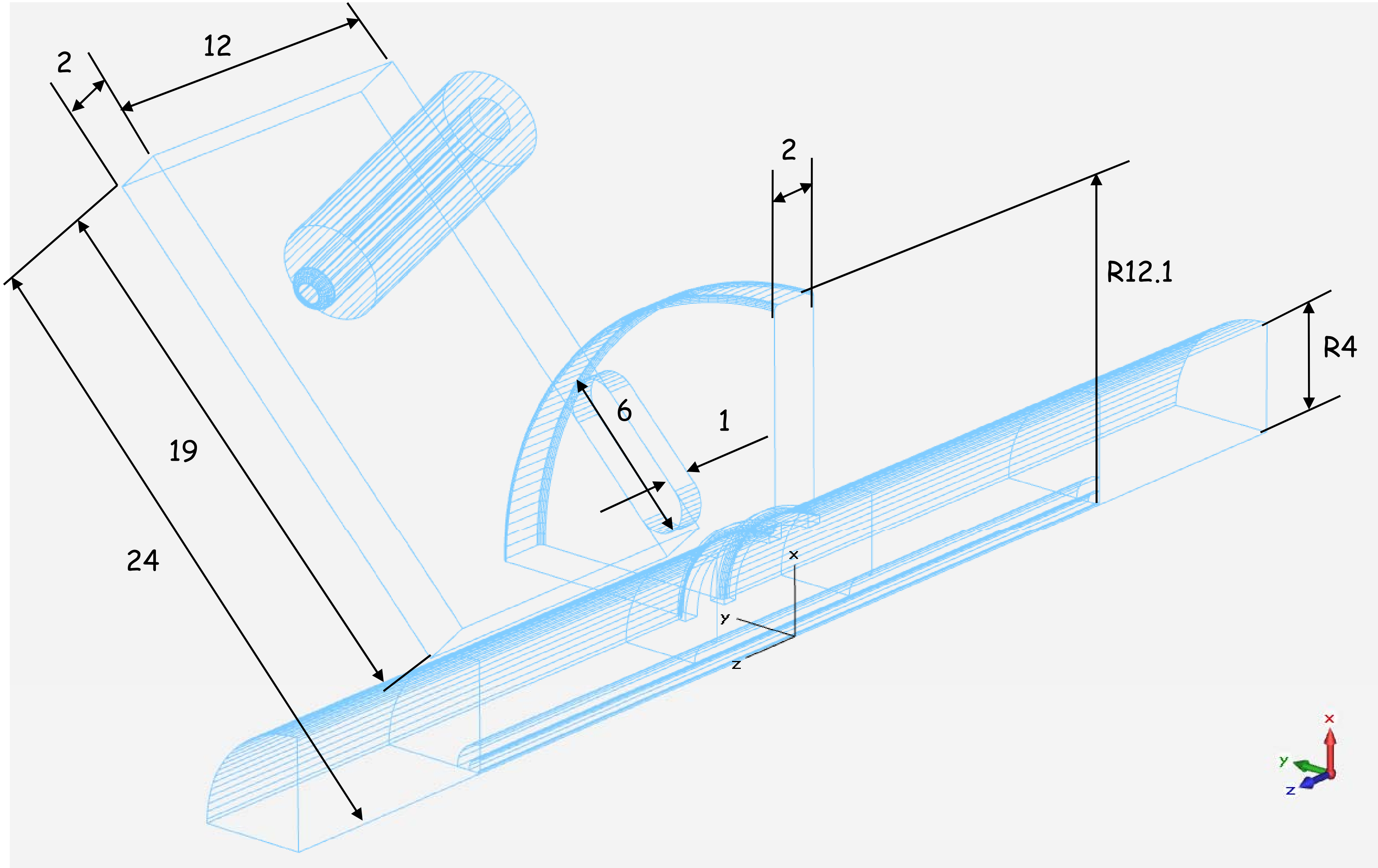
loop

loop

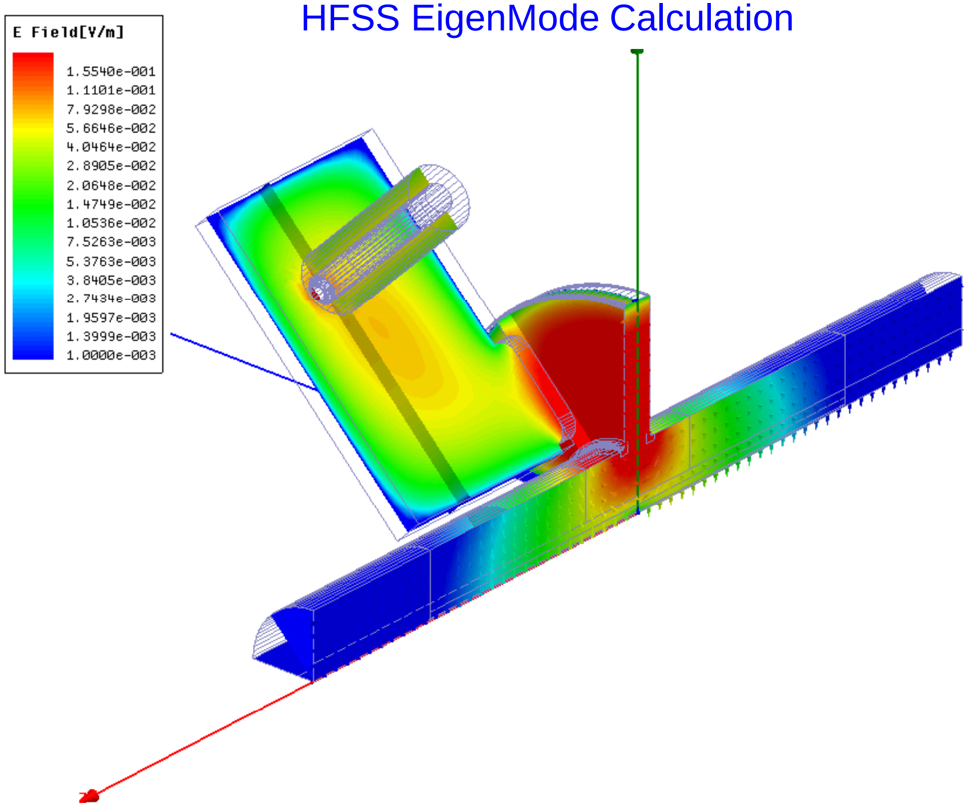
4. Cross coupling:
- waveguide tuning
- 2 ports vs 4 ports

5. Tolerances calculation:

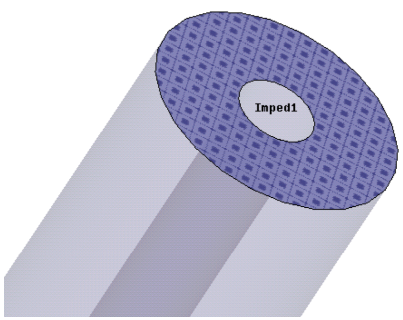
- coupling slots
- waveguide to cavity
- cavity to pipe


12
2
2
R12.1
R4
6
1
19
24
x
y
z
x
y
z

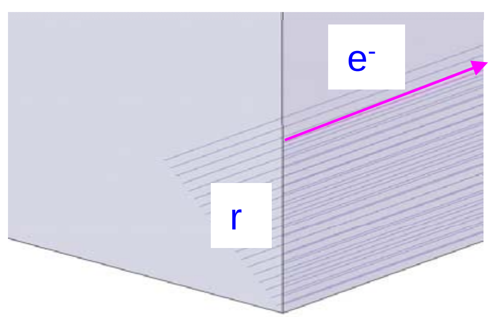
HFSS EigenMode Calculation



(I) Matched Impedance, P_coax



(II) Bunch trajectories



HFSS Data:

W - Stored Energy
P_coax - Exited RF Power
Ez - E-field along bunch path
g_{sym} - Symmetry coefficient

Scale Factor:

$$k_{scale} = \frac{q_0}{q_{HFSS}} = \frac{q_0}{g_{sym}} * \frac{\left| \int_0^L Ez * e^{j\varpi t} dz \right|}{2 * W}$$

Output Power:

$$P_{TM11}(r) = P\_coax(r) * (k_{scale})^2$$

Estimated Sensitivity (q_0 = 1nQ):

$$S = \frac{\sqrt{P_{TM11}(r) * 50[Ohm]}}{r} \quad \text{V/nQ/mm}$$

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Mode Type	Cavity length, [mm]	Freq.,[1] [GHz]	Qext	Qint[2]	Qtot	R/Q[3], [Ohm]	Output Voltage[3,4,5], [V/nC]
TM01	1	10.855	>1e10	210	210	23	< 0.001
	2	10.333	>1e10	210	360	45	< 0.001
	3	10.147	>1e10	520	520	65	< 0.001
TM11	1	14.006	300	240	140	1.7	11.5
	2	14.002	450	430	220	3	12
	3	13.996	620		310	4	12
TM21	1	18.194	75		64	0.033	-
	2	18.631	44		39	0.038	-
	3	18.821	35		32	0.04	-
TM02	1	25.730	>1e10	400	400	7.5	-
	2	24.234	>1e10	640	640	12	-
	3	23.344	>1e10	900	900	15	-

[1] - Cavity radius was tuned to keep TM11 mode frequency ~ 14 GHz
[2] - Stainless steel material was used
[3] - Dipole and quadruple modes values were normalized to 1mm off axis shift
[4] - Signals are from a single coaxial output at resonance frequency

BPM Cavity Modes

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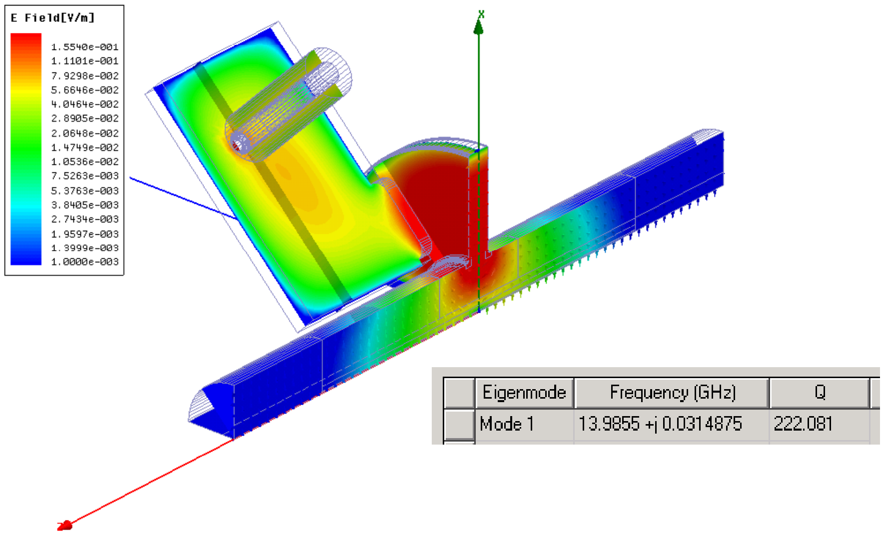
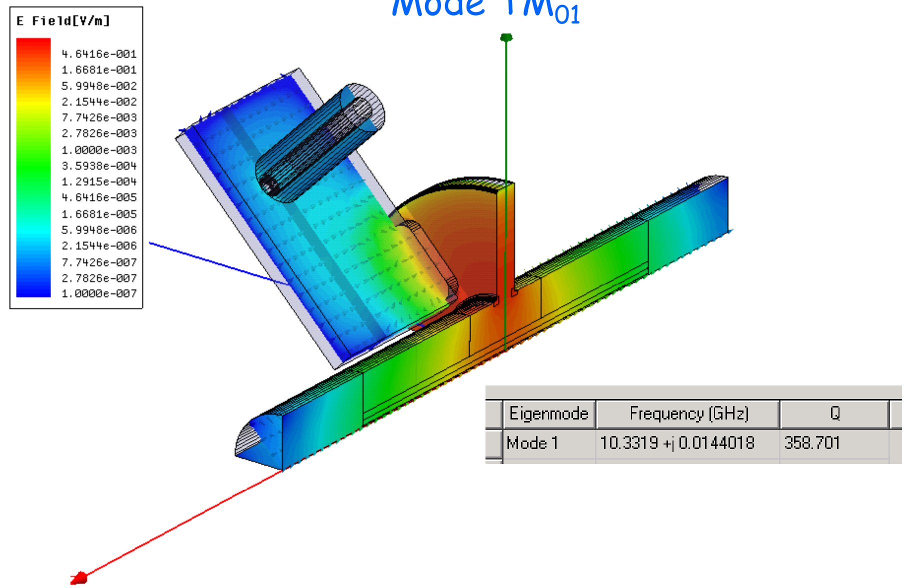
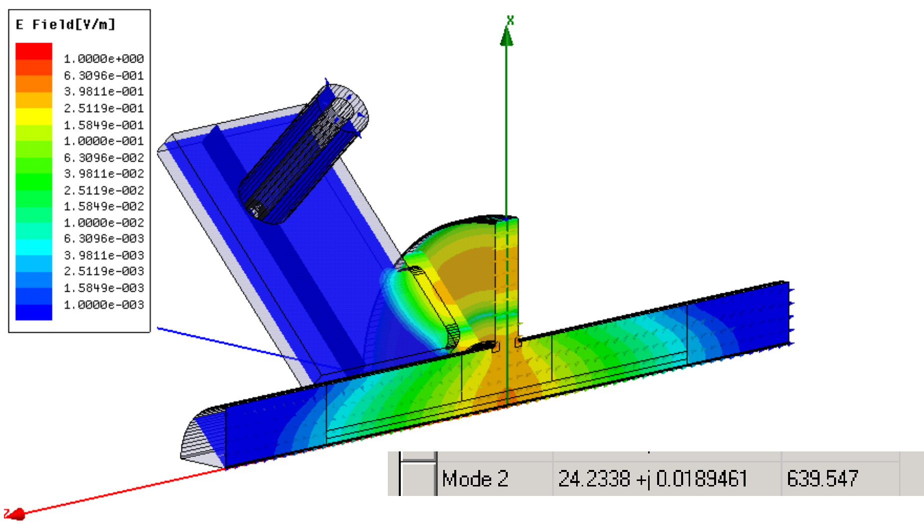
Mode TM_{11}



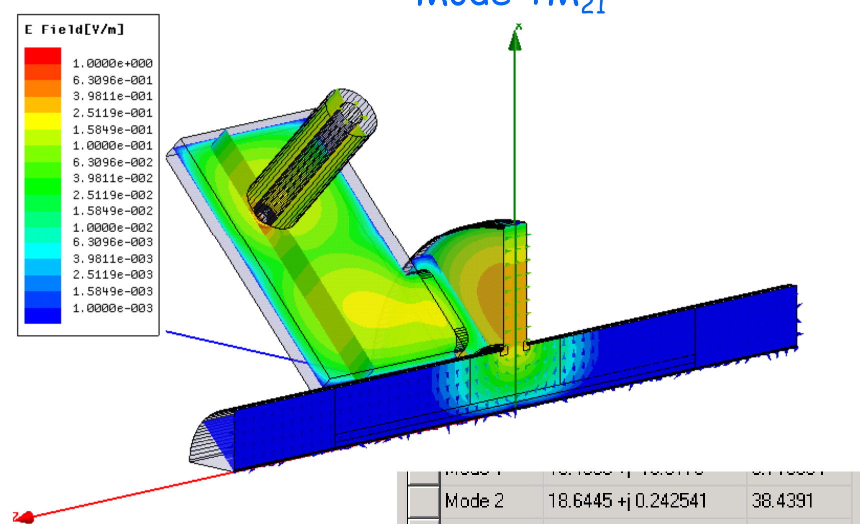
Mode TM_{01}



Mode TM_{02}



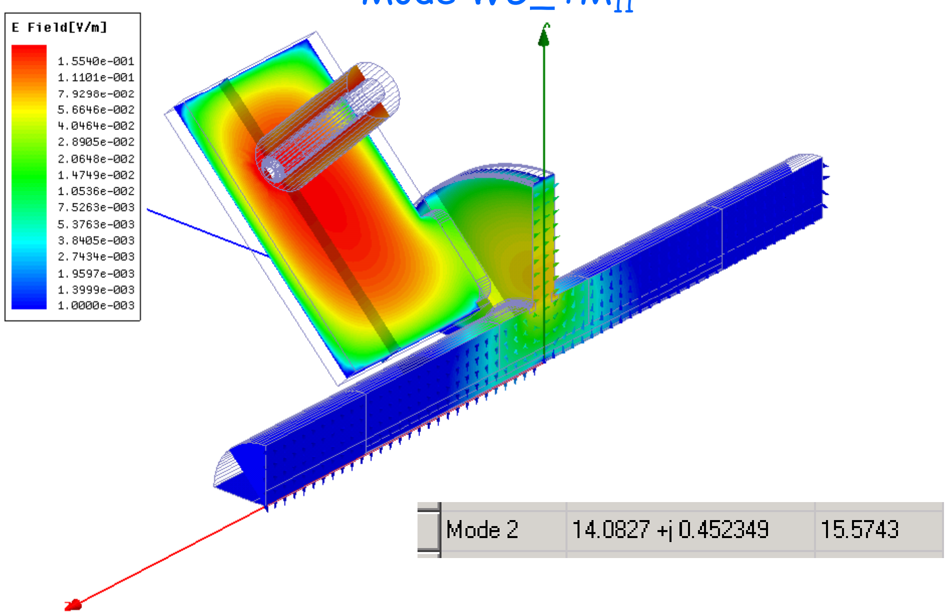
Mode TM_{21}



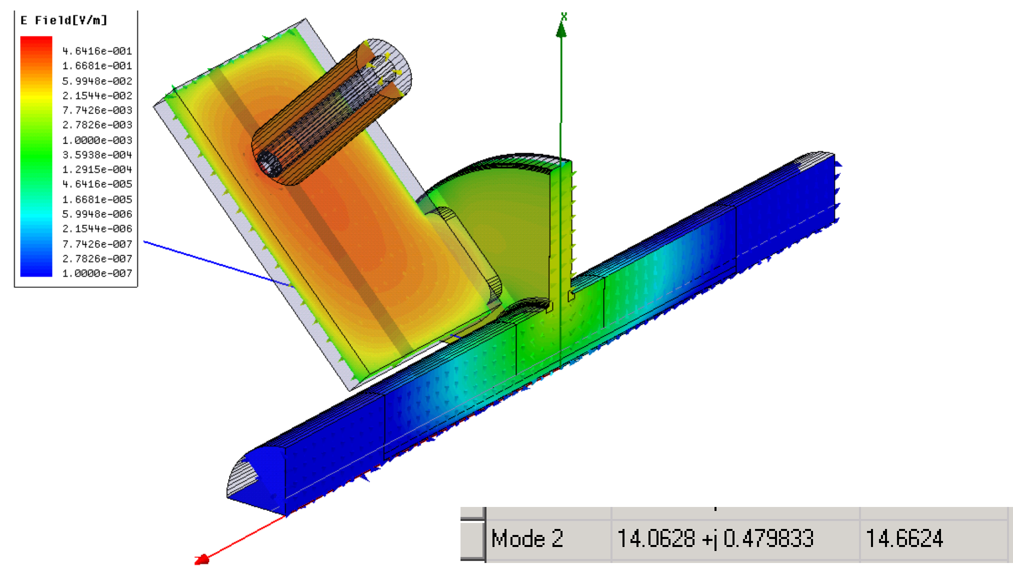
Mode Type[1]	Freq., [GHz]	Q[2]	R/Q[3], [Ohm/mm]	Output Voltage[3,4], [V/nC/mm]
WG_TM11	14.08	18	0.1	11
WG_TM21	14.06	18	1E-4	0.35
WG_TM11	19.0	12	4E-3	3.5
WG_TM21	19.2	18	0.01	5.8

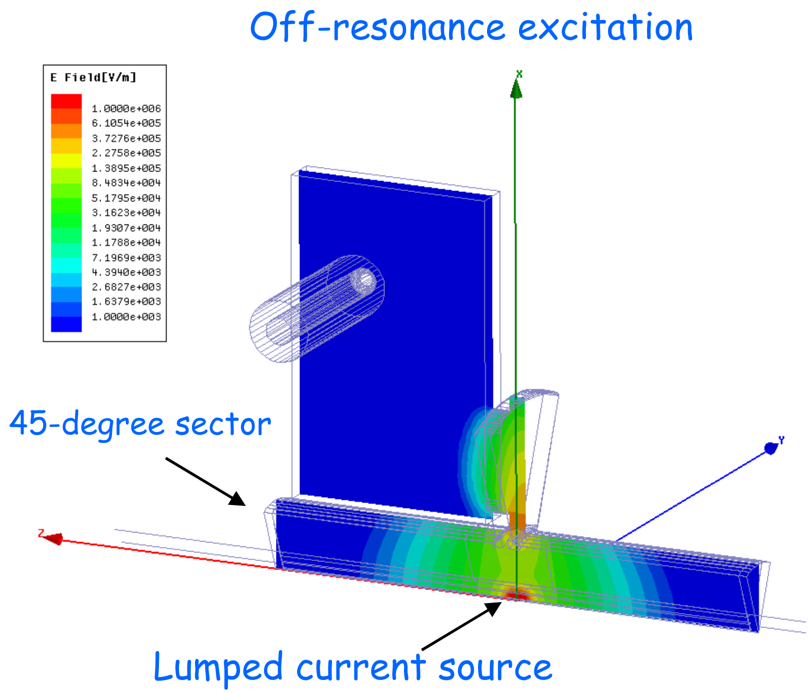
[1] - Mode exited in the cavity
[2] - Stainless steel material was used
[3] - Dipole and quadruple modes values were normalized to 1mm off axis shift
[4] - Signals are from a single coaxial output at resonance frequency

Mode WG_TM_{11}

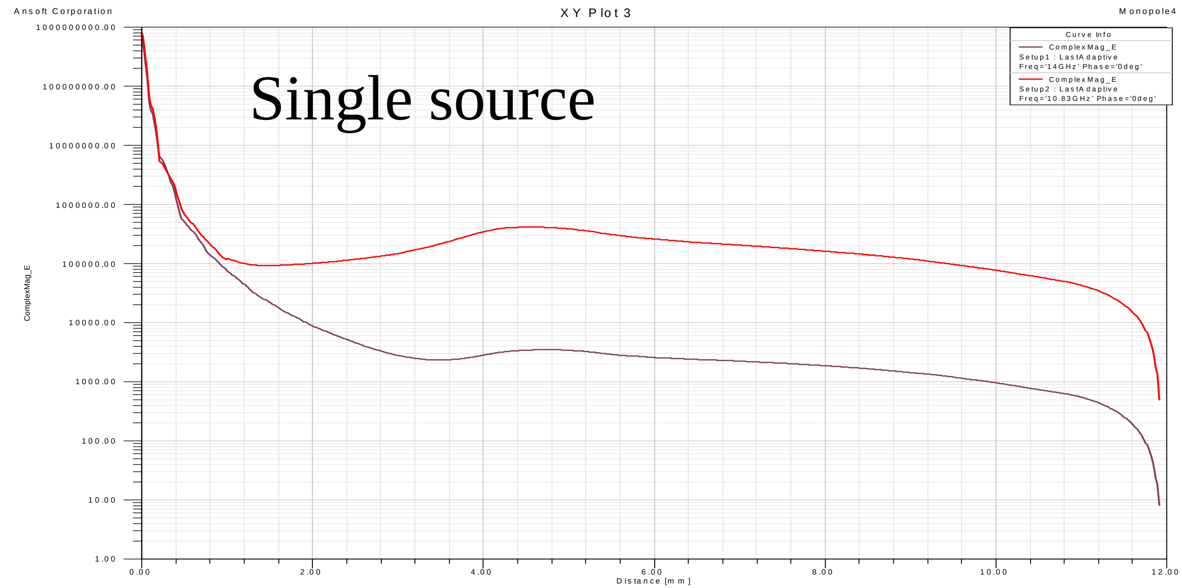


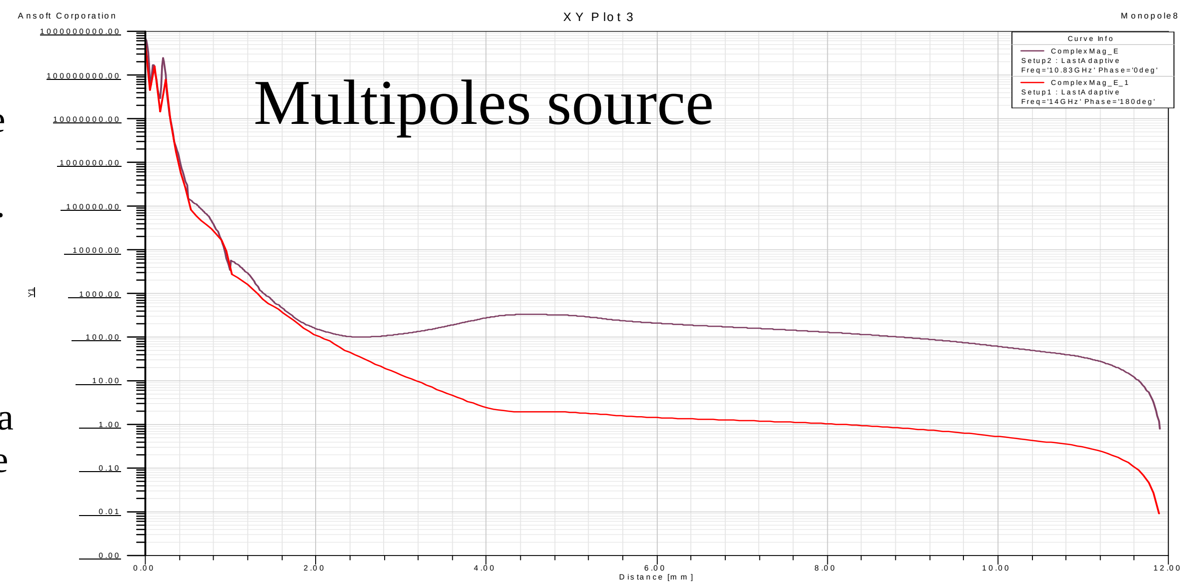
Mode WG_TM_{21}





E-field along cavity radius

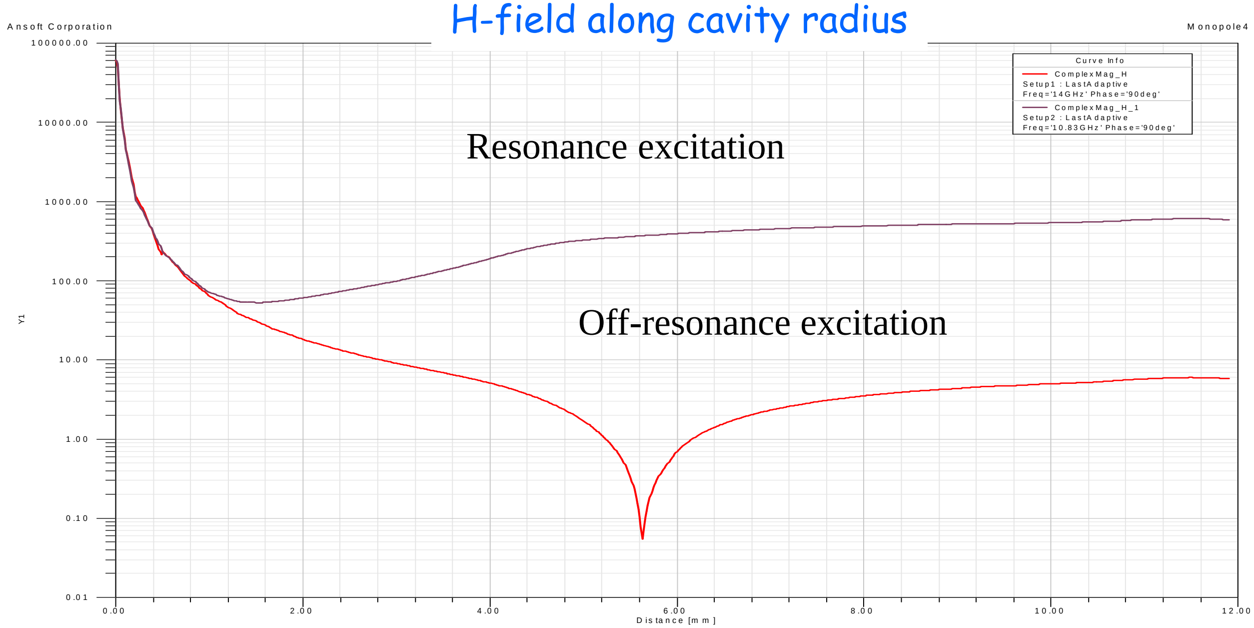




The static field component from current source is overlapped with the cavity mode itself and prevent the calculation of pure monopole mode output signal . One can try to use a mulitpole source in order to get quick radial damping but it doesn’t help because monopole mode amplitude damps as well.

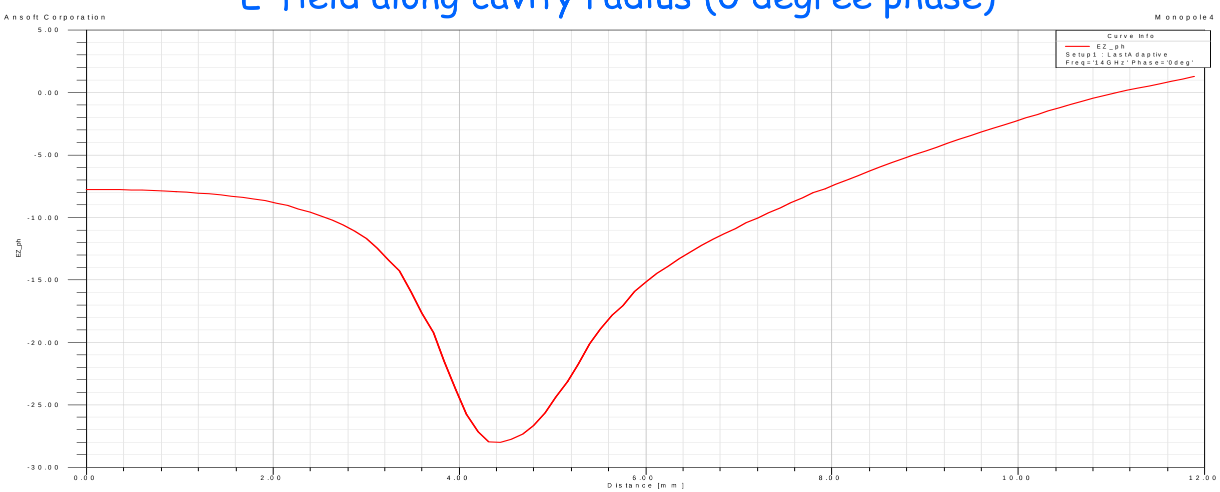
Nevertheless we see that the relation of output signals (on resonance and off-resonance) depends on a static component only and therefore there is no visible resonant coupling of monopole modes at 14 GHz observed.

H-field along cavity radius



We can estimate the monopole mode amplitude at 14 GHz by comparing the H-field component near the cavity radial side where static fields from the source are mostly damped. HFSS simulations show that off-resonance excitation gives us about 2 order in amplitude damping which is in a good agreement with resonance factor from a circuit theory :

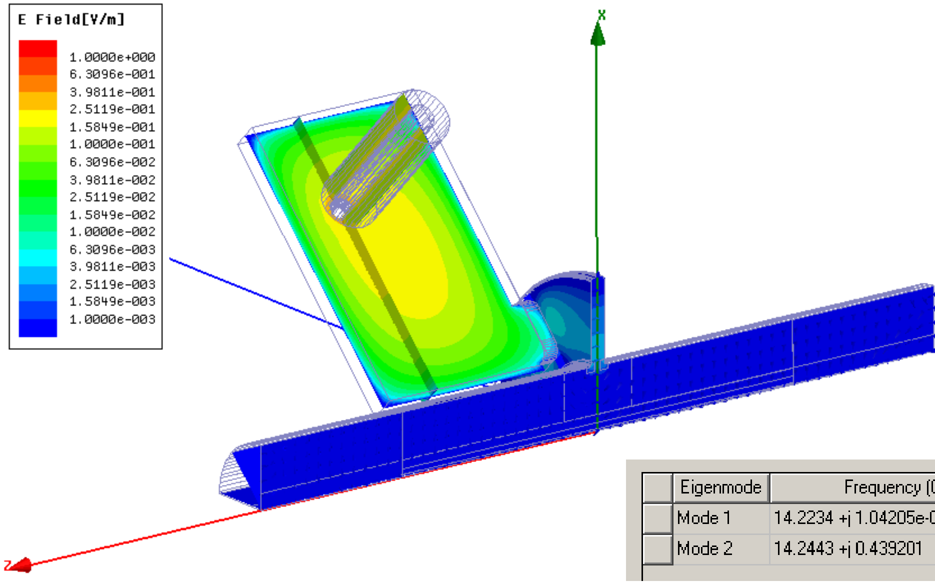
E-field along cavity radius (0 degree phase)



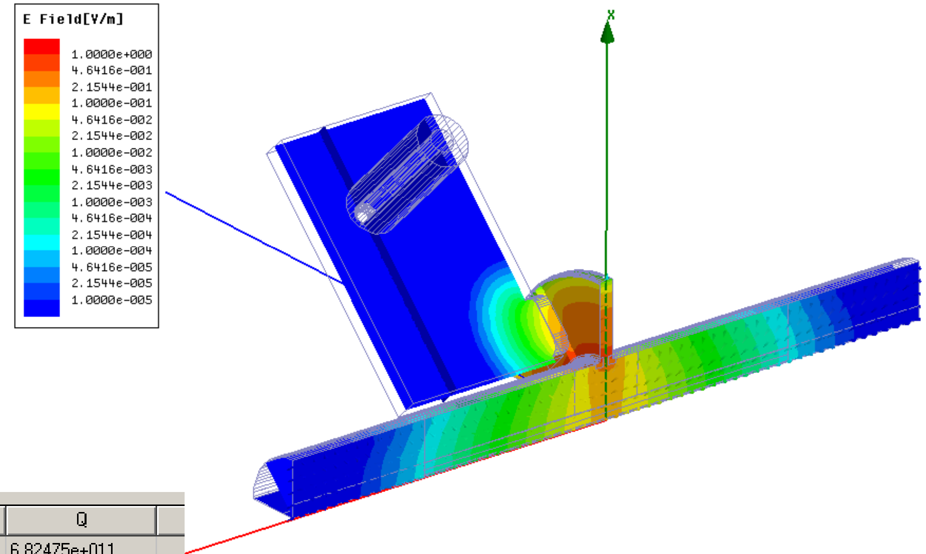
Far off-resonance excitation gives us about 90 degree phase shift (but not exactly !) Therefore at 0-degree phase we have no static field from the source but pure monopole modes only. The plotted profile of E-field along cavity radius belongs almost to first monopole TM01 mode. There is no visible TM02 mode component. One can say that TM02 mode is at least one order less and could be neglected.

Monopole Modes Signal at 14 GHz

Mode WG_TM_{21}



Mode TM_{01}



Eigenmode	Frequency (GHz)	Q
Mode 1	14.2234 +j 1.04205e-011	6.82475e+011
Mode 2	14.2443 +j 0.439201	16.2238

In order to check the monopole and waveguide mode decoupling we reduced cavity radius to bring TM01 frequency on 14 GHz. There is no monopole output signal amplification was observed again. One can see that waveguide resonance excites instead quadruple mode in the cavity. It could increase parasitic signal from the cavity quadruple mode (further analysis is needed).

Conclusions.

1. Because the cavity gap is small enough comparing to wavelength, modes R/Q's are almost linearly depends on a gap length.

2. The mode's output signals are proportional to R/Q divided to stored energy and therefore are roughly constant.

3. Low-Q resonance in a waveguide at 14 GHz (made to increase coupling for dipole TM11 mode) may affect on other modes as well because of their tails of a resonance curves. If we choose gap that gives us Q-internal as low as <250 then we can remove resonance coupling and make coaxial doorknob perfectly matched at 14 GHz. From the calculations we can see that requiring gap should be 2 mm or less in a case of cavity made of stainless steel.

4. The mechanical tolerances question is still open. If a narrow gap (like 1 mm will give us a problem than we can chose longer gap and lower Q-value by using lossy material inside a cavity.

5. The most dangerous parasitic mode is TM01 - because it is closer to working frequency and has lower Q value than TM02. The rough estimation shows that TM01 signal will be about 10 times larger than TM02. How it will limit BPM resolution needs to be check with further mechanical tolerances simulation.

6. The quadruple TM21 mode could potentially limit BPM dynamic range because of a good waveguide coupling and quadratic output signal dependence versus radius.