HOM filter design for double quarter wave crab cavity

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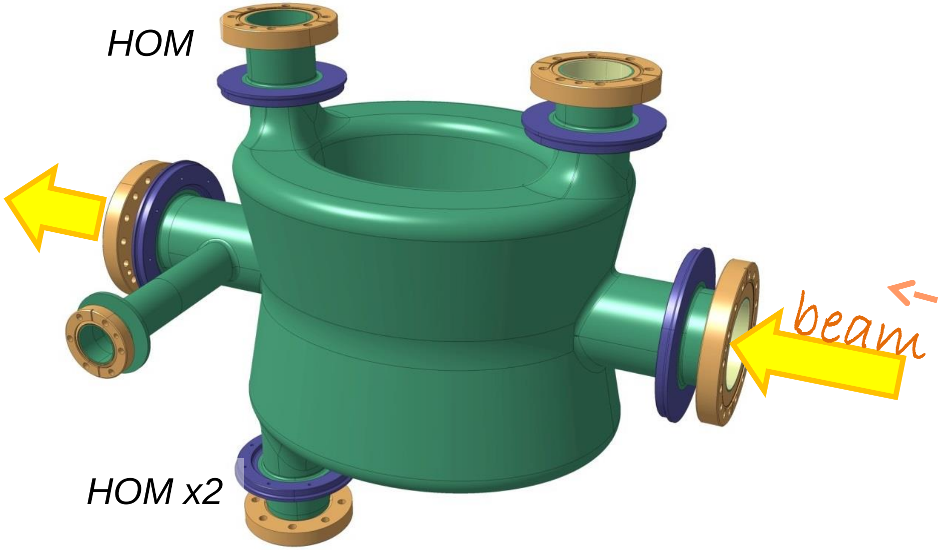
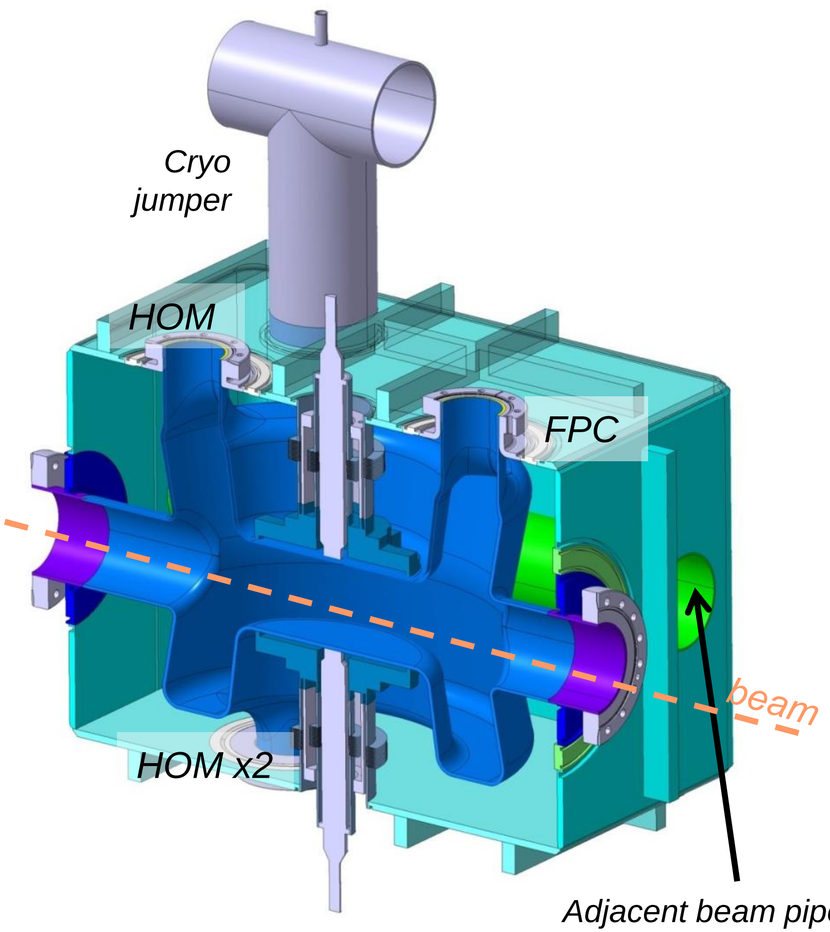
Work partly supported by the EU FP7 HiLumi LHC grant agreement No. 284404 and by the US DOE through Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the US LHC Accelerator Research Program (LARP). This research used resources of the National Energy Research Scientific Computing Center, which is supported by the US DOE under contract No. DE-AC02-05CH11231.

Outline

- SPS double quarter wave crab cavity
- Constraint in the HOM filter design
- Design of HOM filter
- Fundamental mode in HOM filter
- Multipacting
- HOM window
- Identify HOMs (Bead pulling of PoP cavity)
- Shunt impedance
- HOM power estimation
- Thermal analysis
- Tolerance study
- Summary

SPS double quarter wave





Constraint in the HOM filter design

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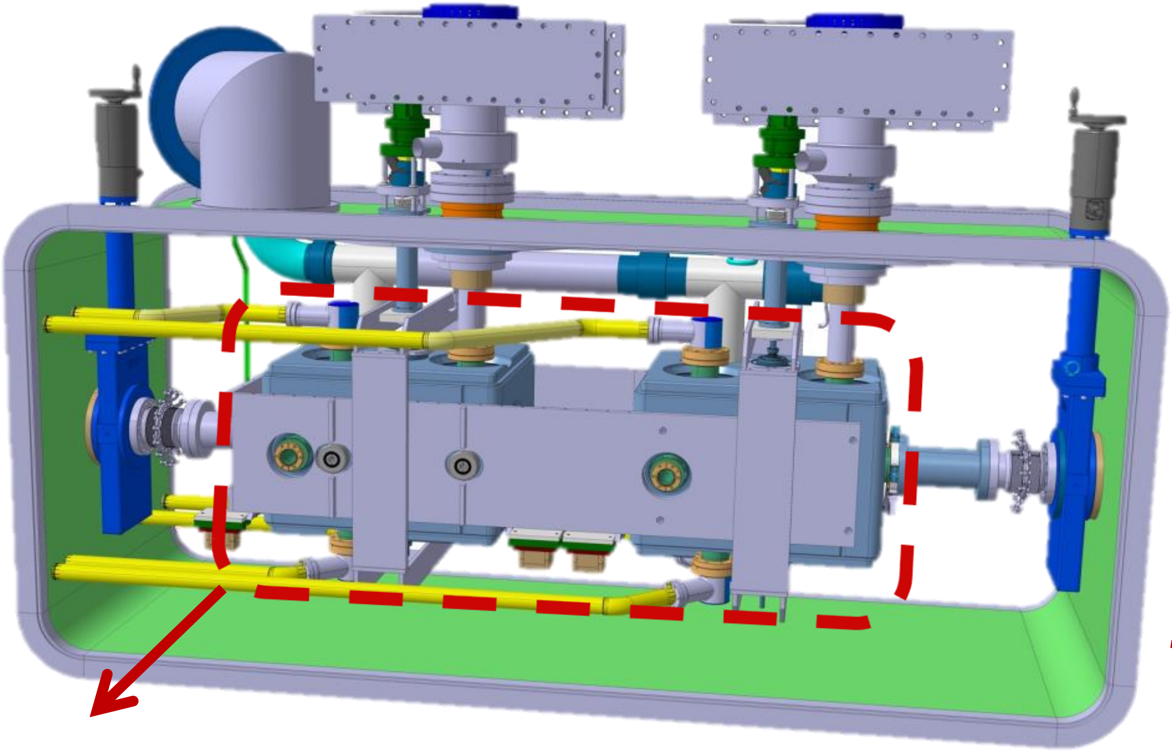
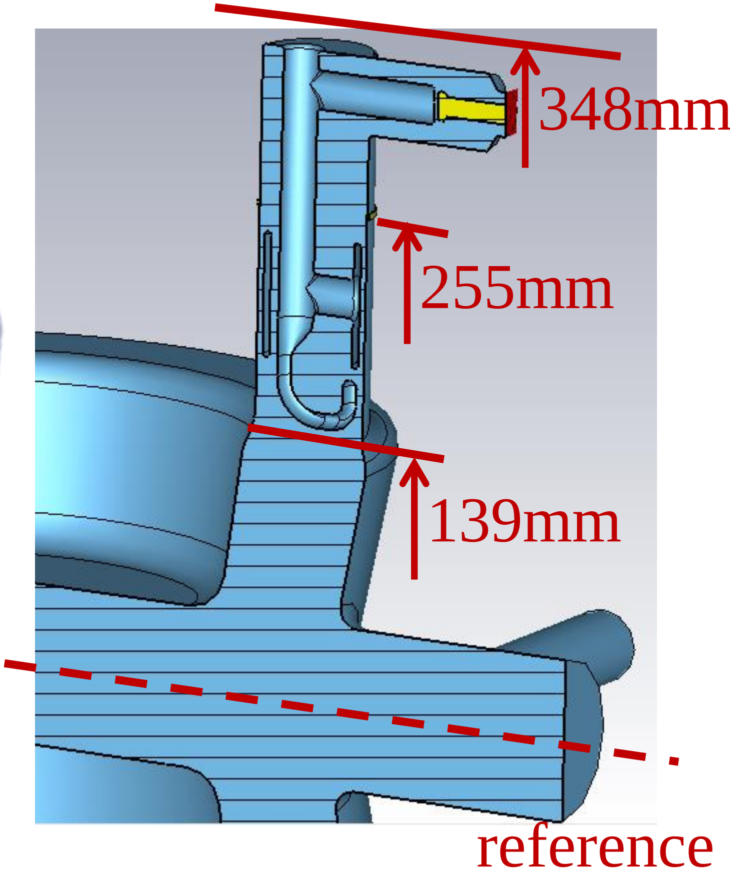
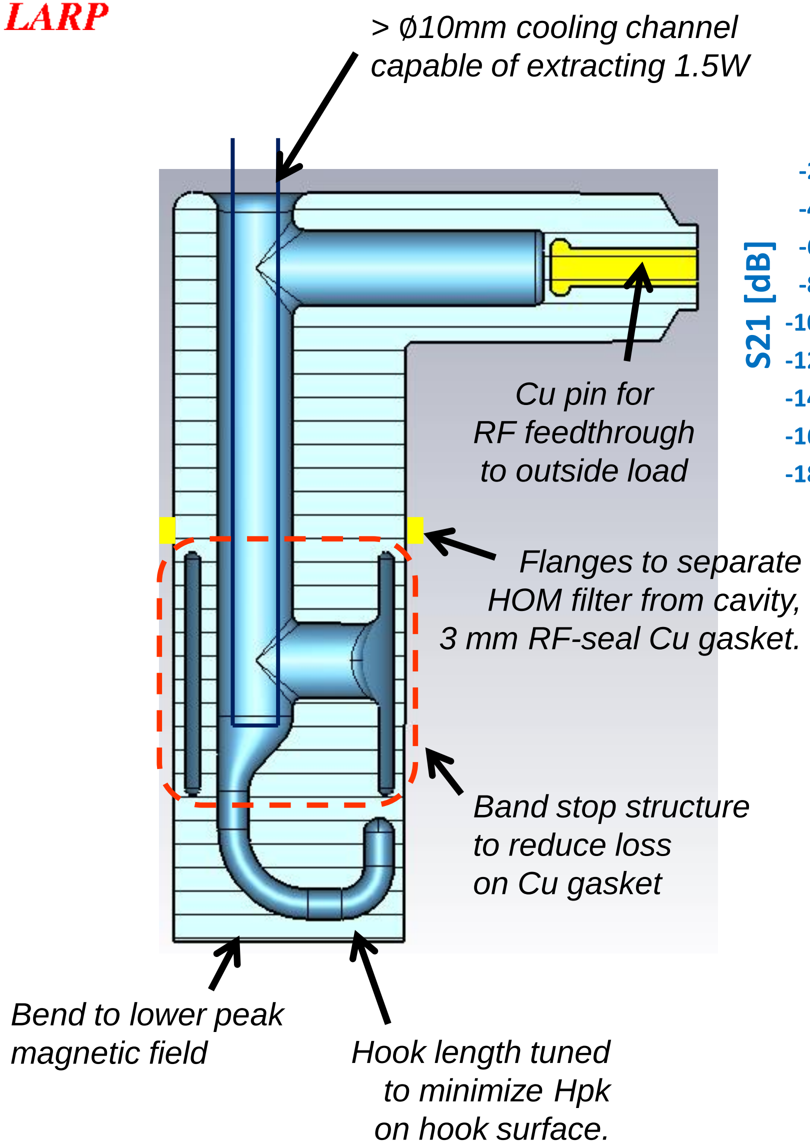
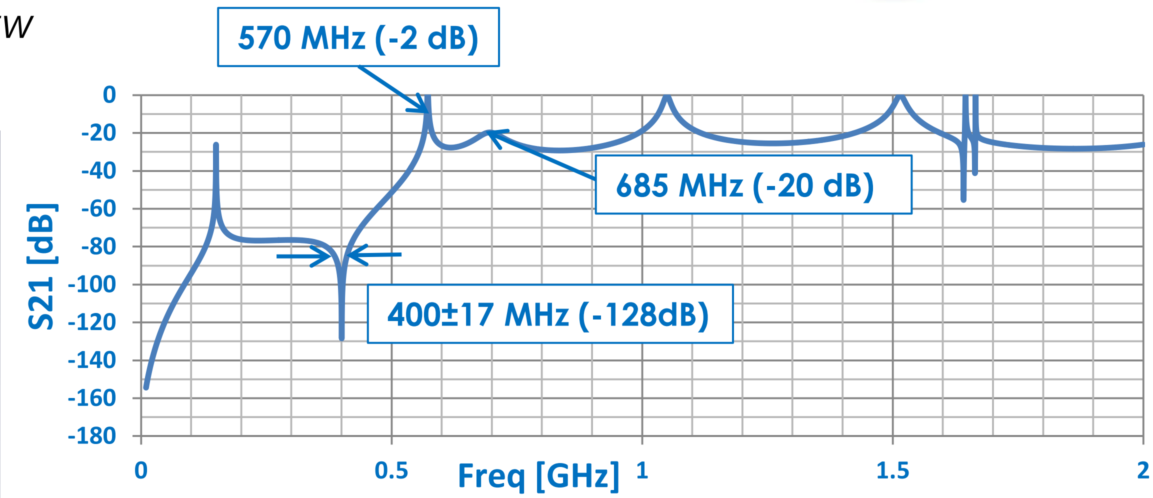


A liquid helium vessel for the HOM filter was not shown here



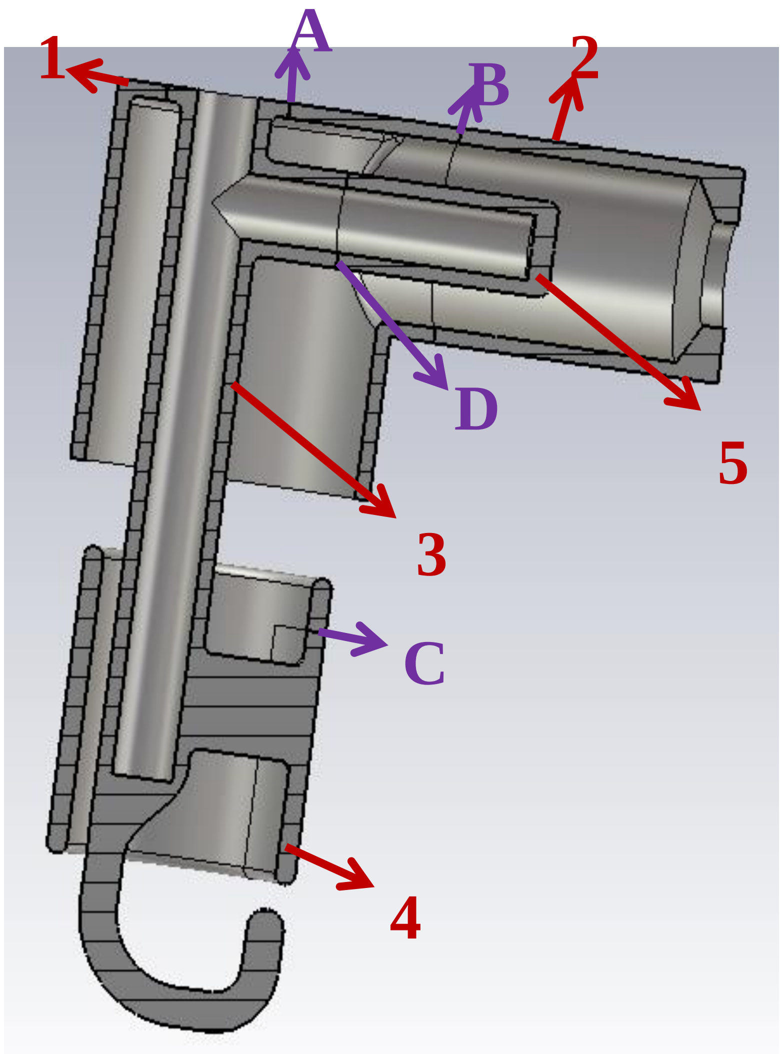
L-shape filter



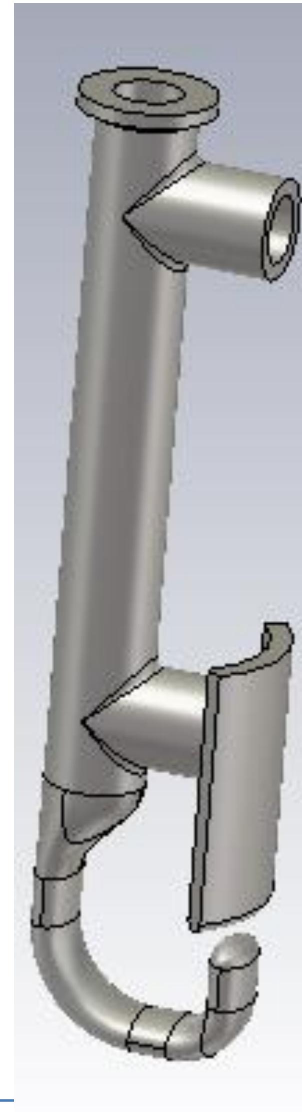


- **L shape to meet the space constraint.**
- **Band stop structure to reduce loss on Cu gasket.**
- **34MHz rejection band at 400MHz.**
- **Good passing band at freq > 570MHz (1st HOM).**

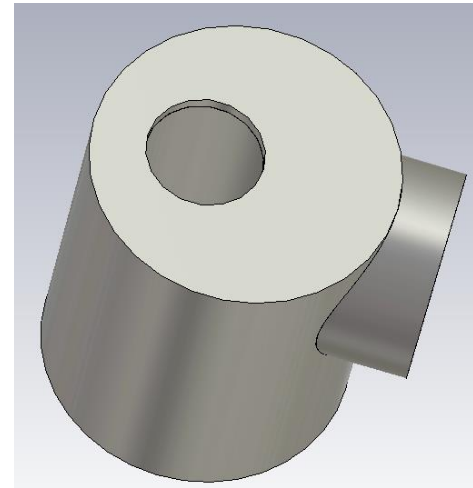
L-shape filter



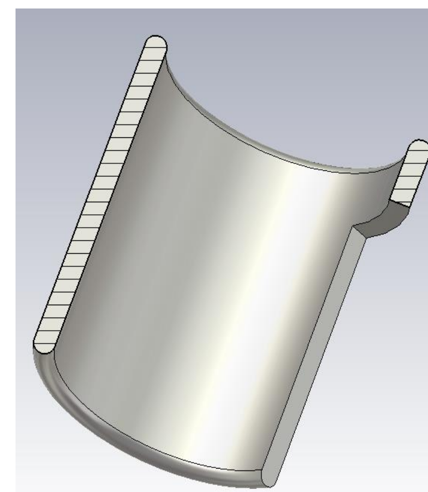
Piece 3



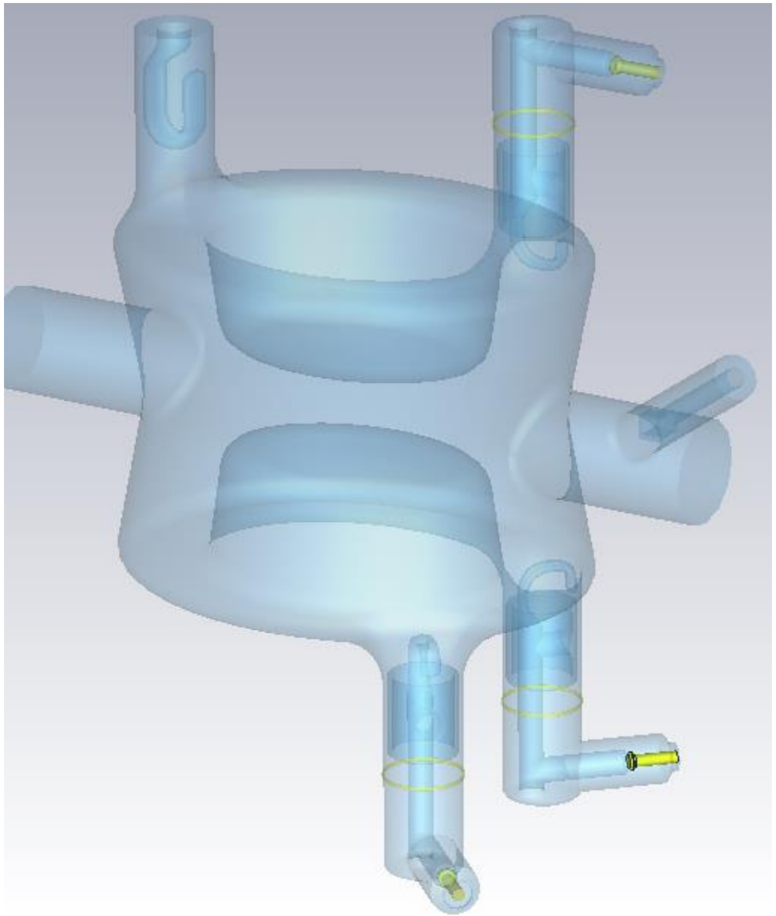
Piece 1



Piece 4

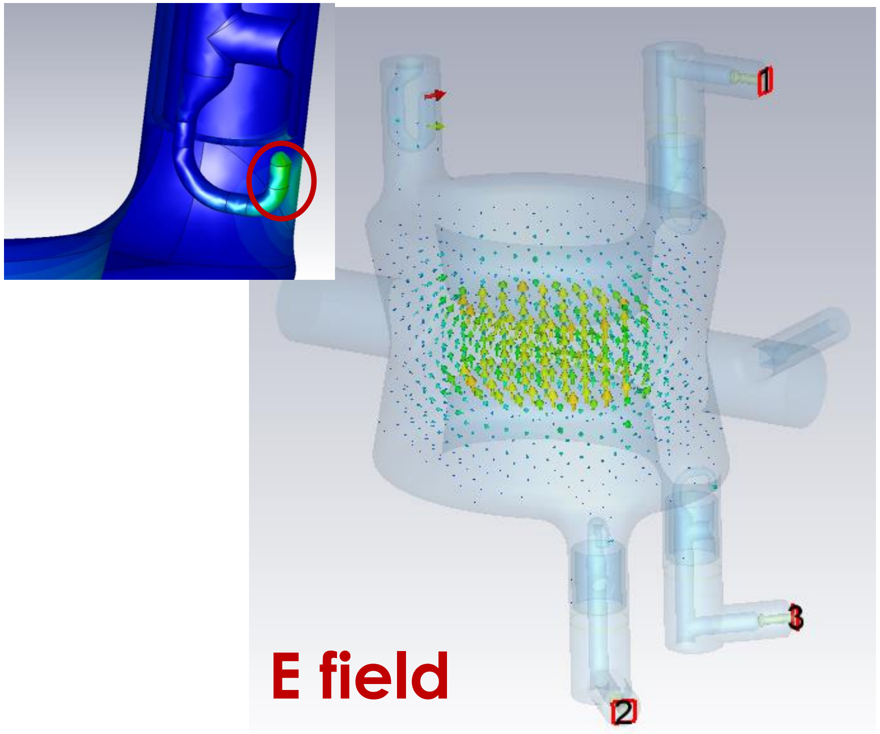


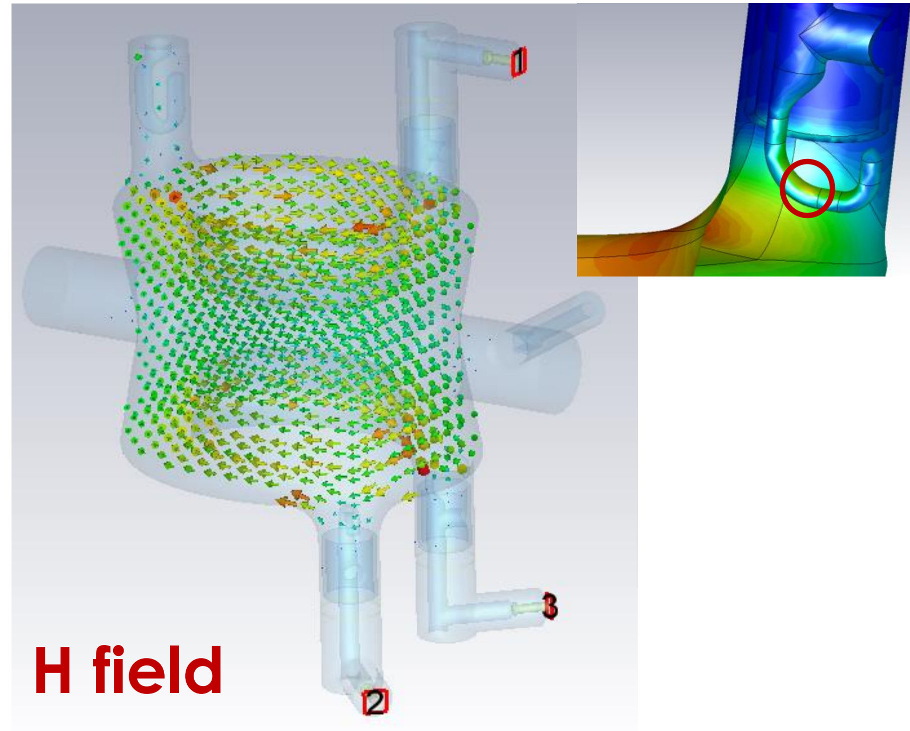
Filter integration



- 3 HOM filters per cavity, with two 60-degree away from the center to give ***clearance to the other beam pipe*** in horizontal kick scheme
- ***Symmetrical*** design to minimize multipolar components.
- 60 degree is chosen to provide more coupling to HOMs.
- ***Compact*** to fit into cryomodule.
- Longer RF cables can be easily attached to the L shape filter to ***reduce static heating***.

Filter at 400MHz

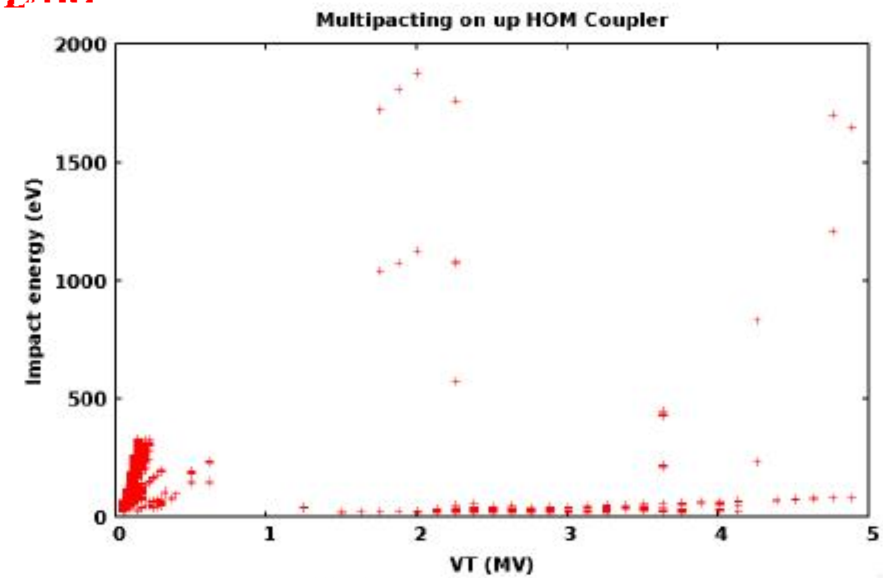


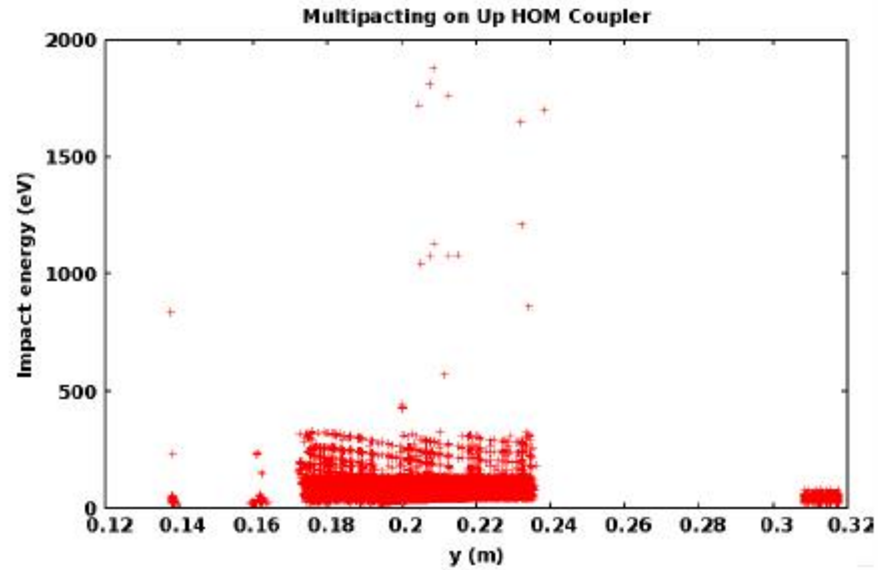


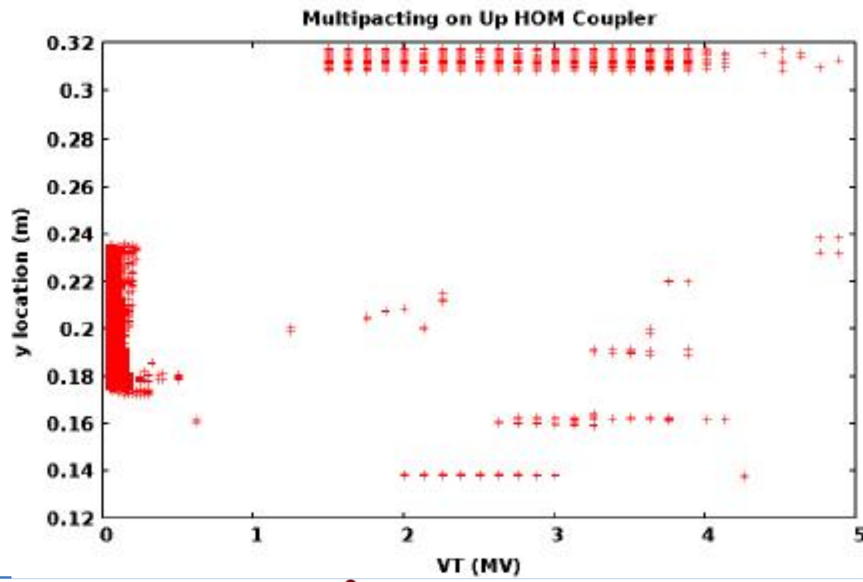
For 400MHz crabbing mode with V_t = 3.34MV:

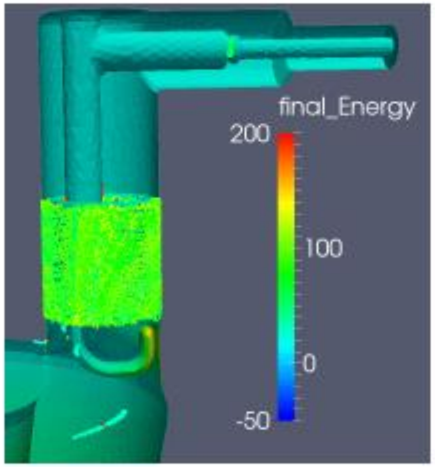
- **Peak E field on the hook: 19.3MV/m, on the cavity: 36.7MV/m.**
- **Peak H field on the hook: 61.3mT, on the cavity: 71.3mT.**
- **Coupling to 400MHz: 7.9x10^9, 1.1 W at each port to outside load.**
- **30mW dynamic loss per filter for 20nΩ resistance.**
- **7.8mW range RF loss on Cu gasket.**
- **10.8 μW range RF loss on Cu pin.**

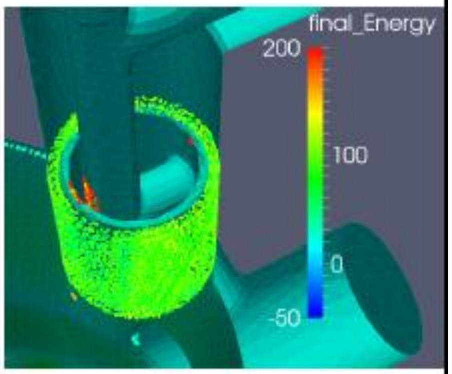
Multipacting: filter on top



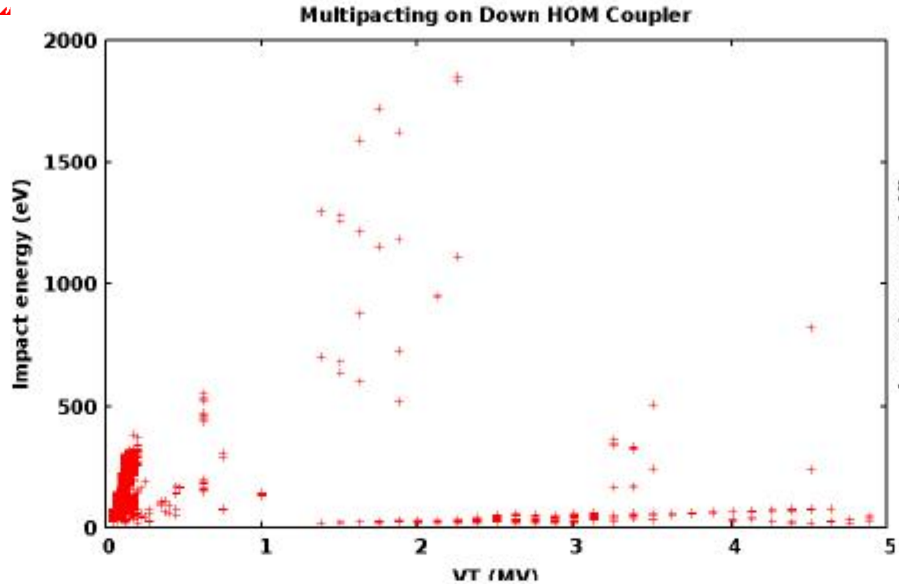


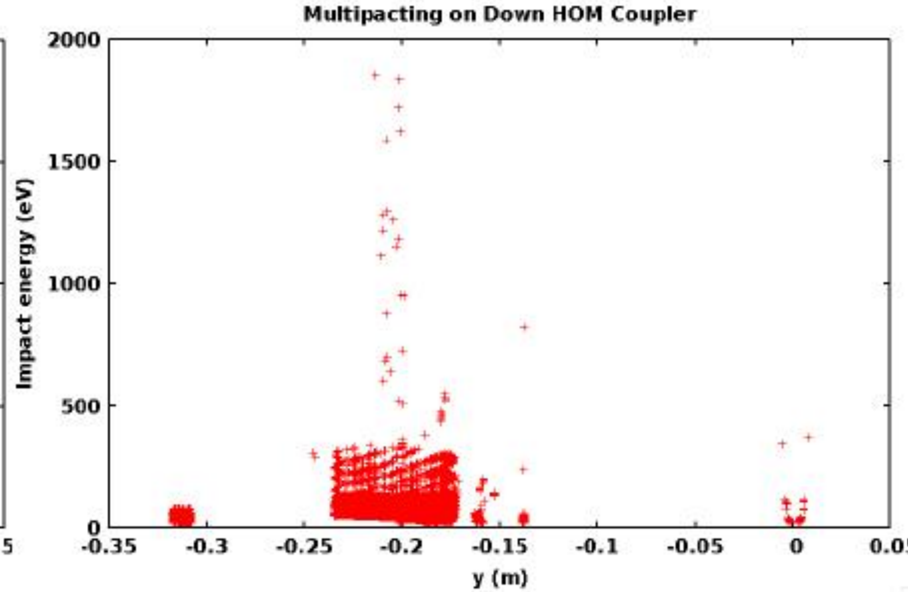


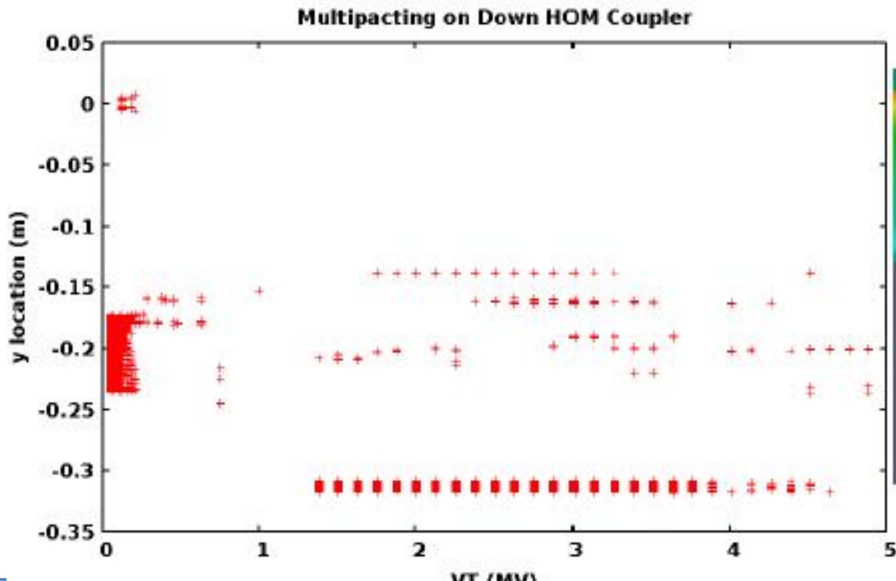


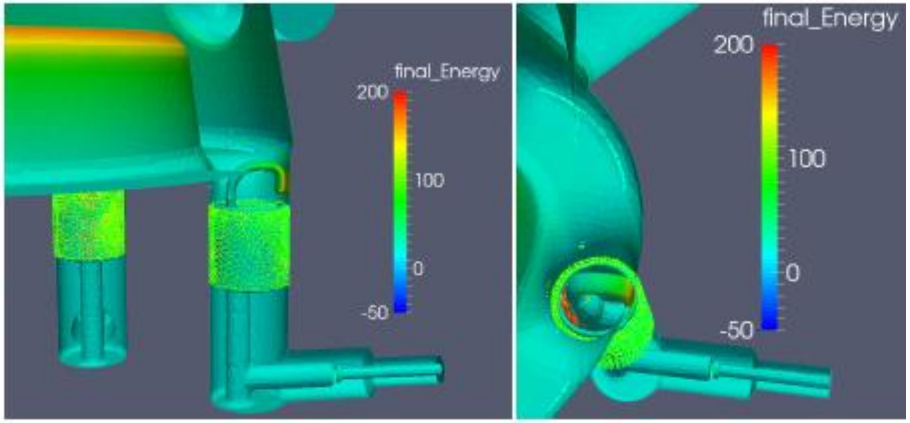


Multipacting: filter on bottom



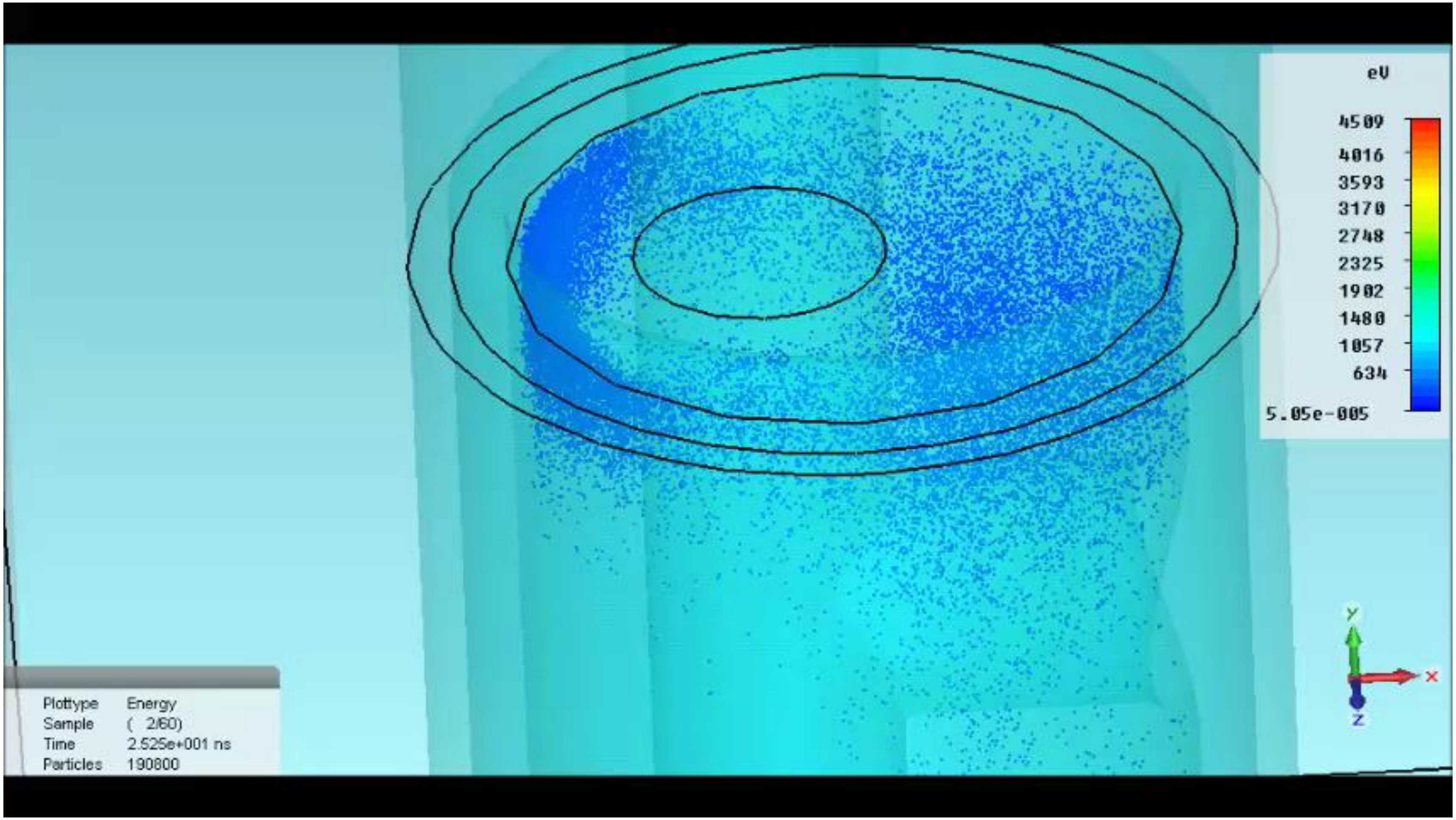






Multipacting

© Hall & Burt @Cockcroft



Multipacting

Multipacting with standard treated Nb at 0.3MV (BCP, EP, baking)

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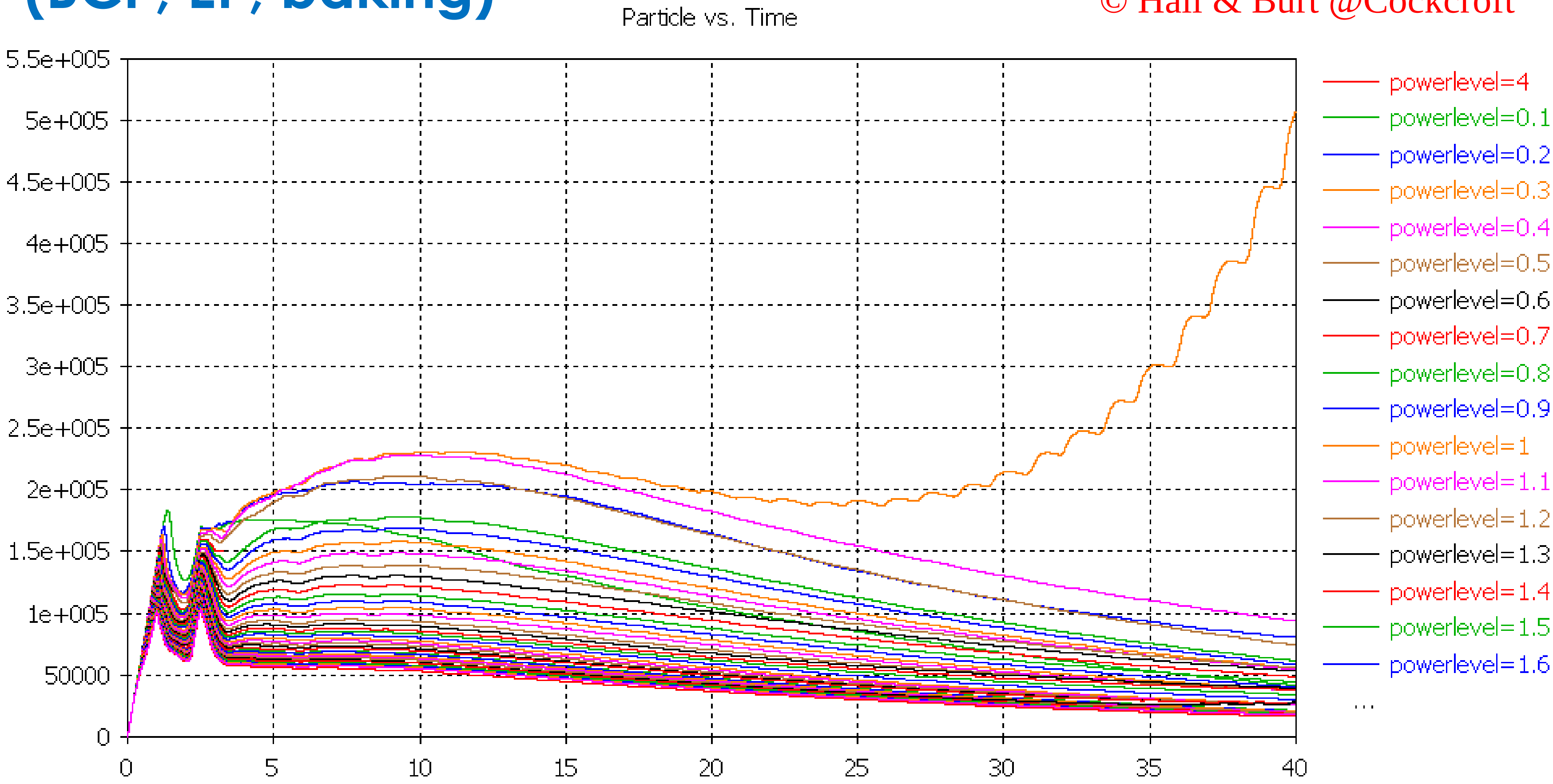

Multipacting

No multipacting for pure/Ar treated Nb (with lower SEY)

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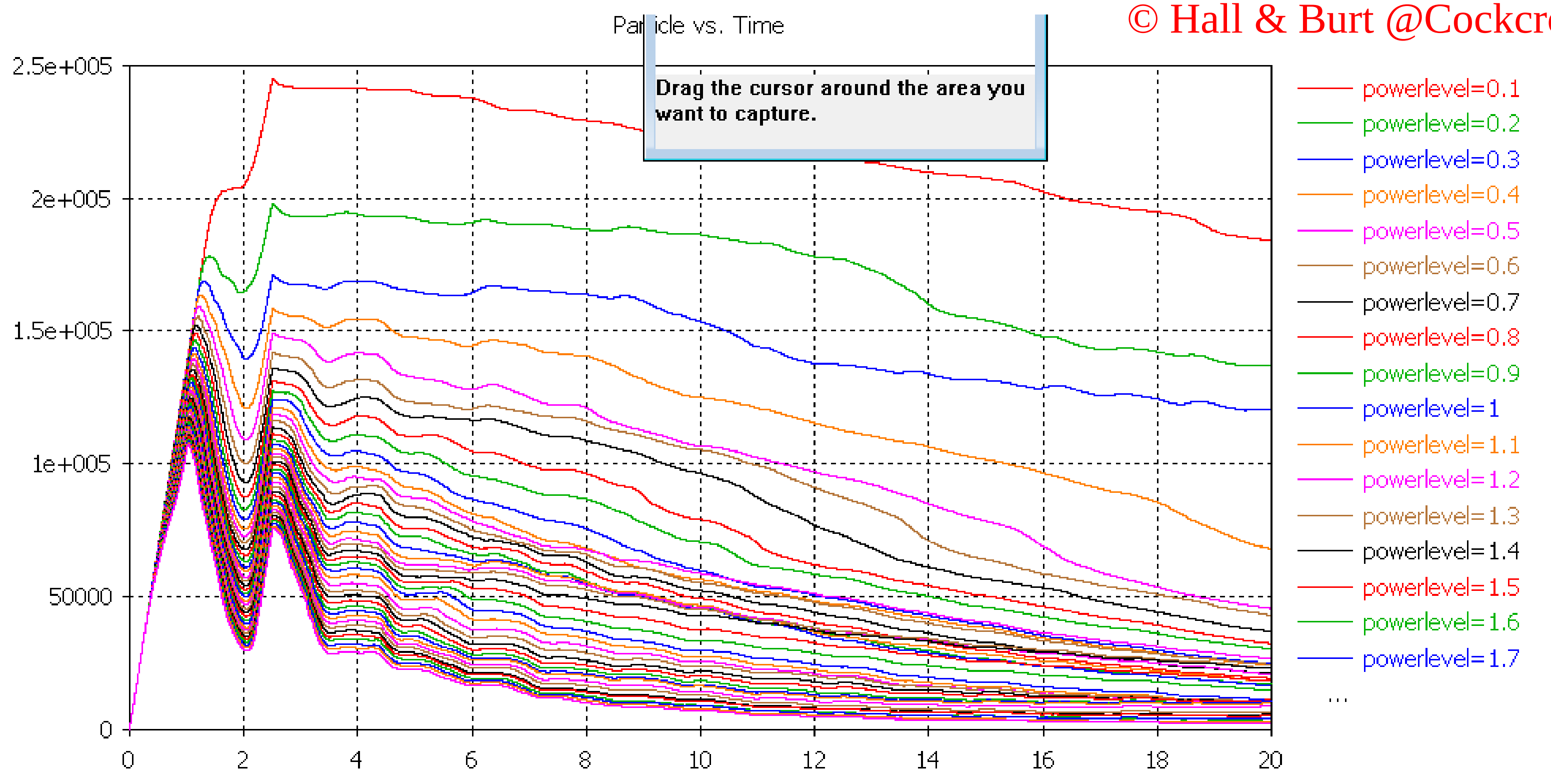

Multipacting is not a critical issue in this design
Continuous study to further suppress it by changing the EM field near the top blending

HOM window

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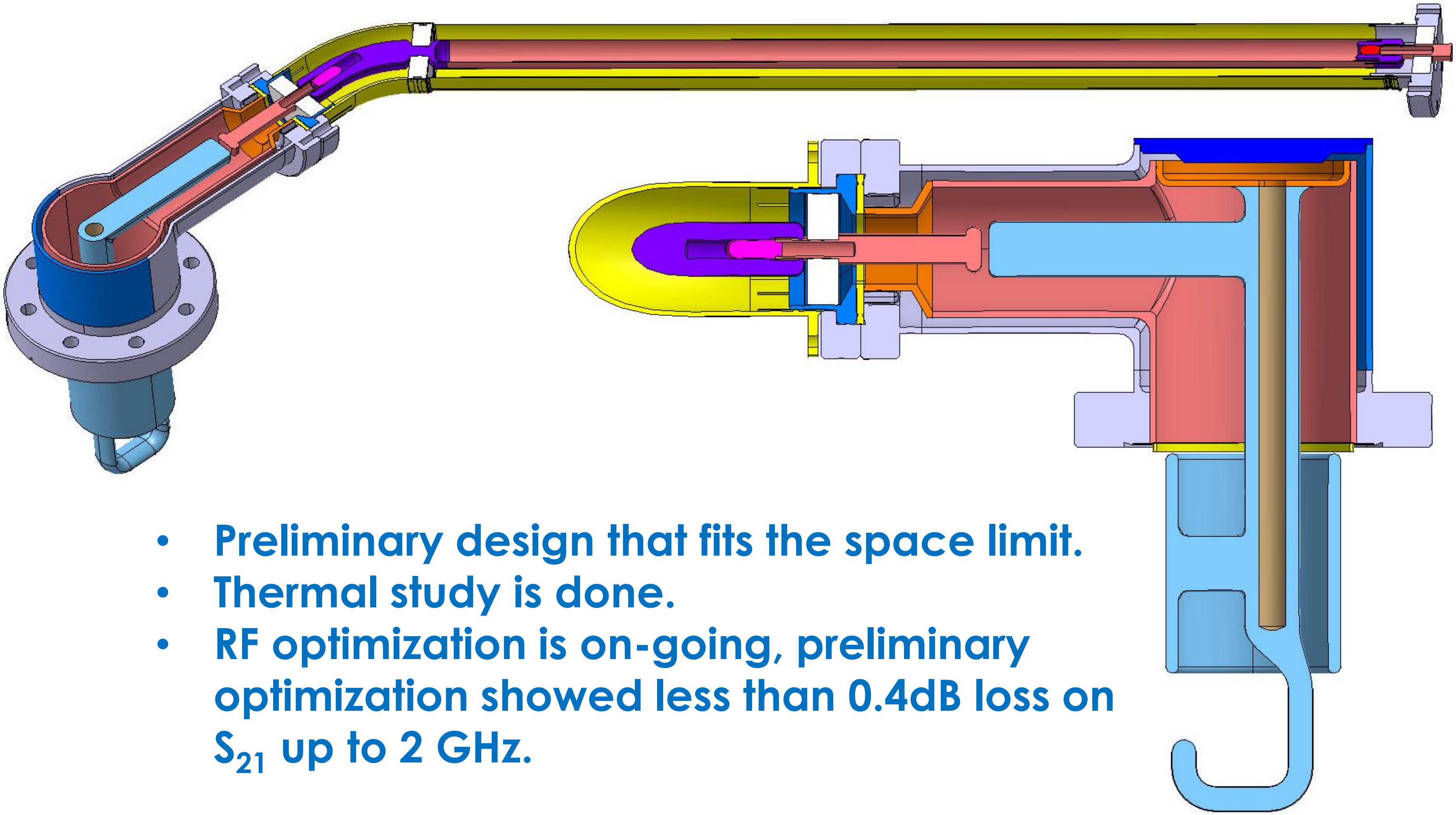
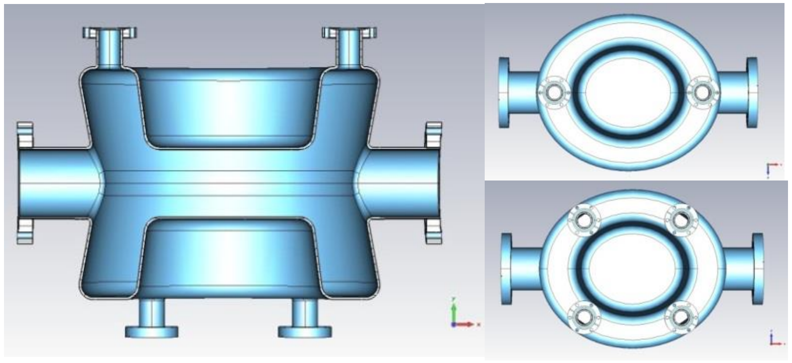
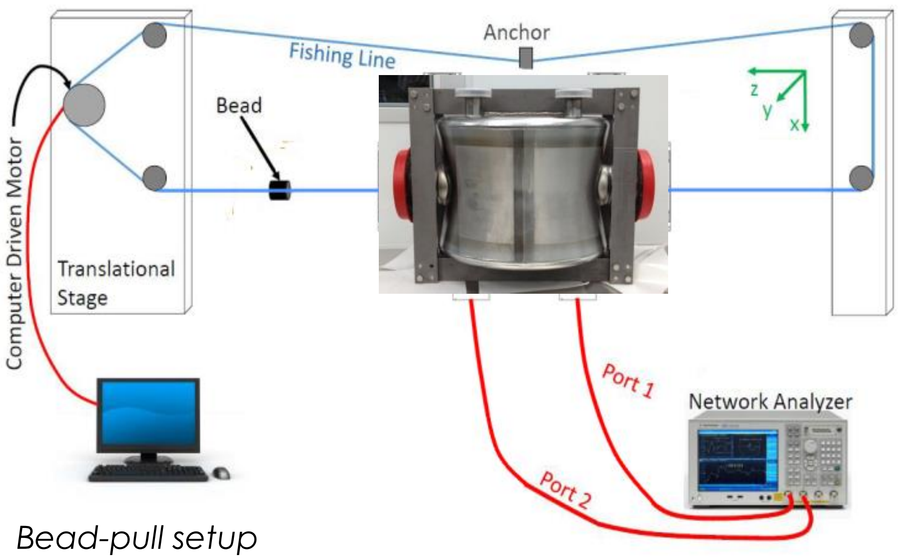


- Preliminary design that fits the space limit.
- Thermal study is done.
- RF optimization is on-going, preliminary optimization showed less than 0.4dB loss on S_{21} up to 2 GHz.

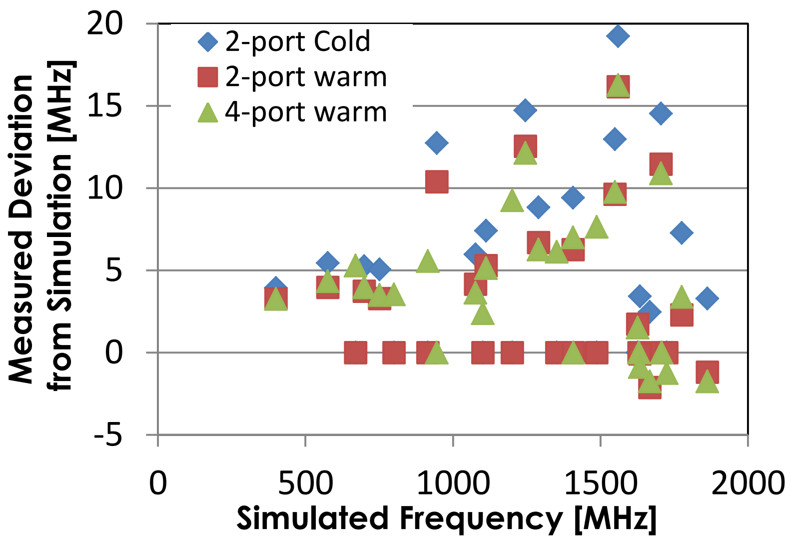
Identify HOMs: Bead Pulling



Proof-of-Principle (PoP)
Double-Quarter Wave Crab Cavity (DQWCC)

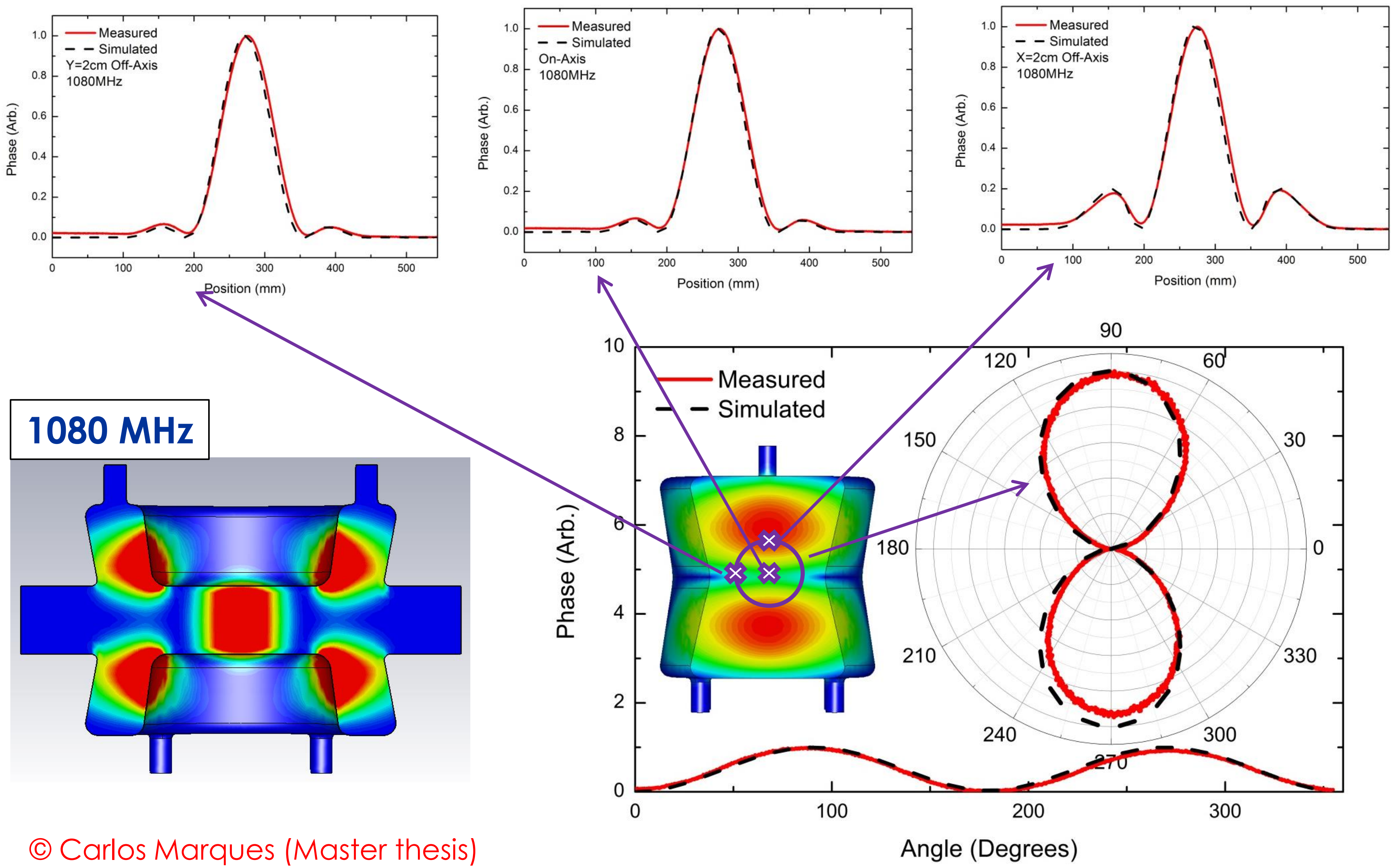


Bead-pull setup



- **Cavity prototype smaller than RF model cause frequencies shifting up.**
- **HOM frequencies deviated from designed values due to unspecified tolerances for PoP cavity.**

Identify HOMs : Bead Pulling (2)

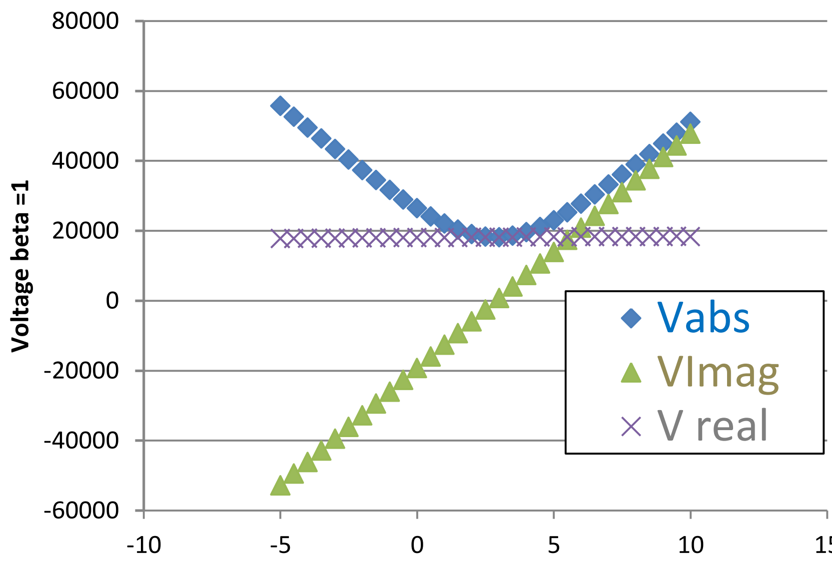


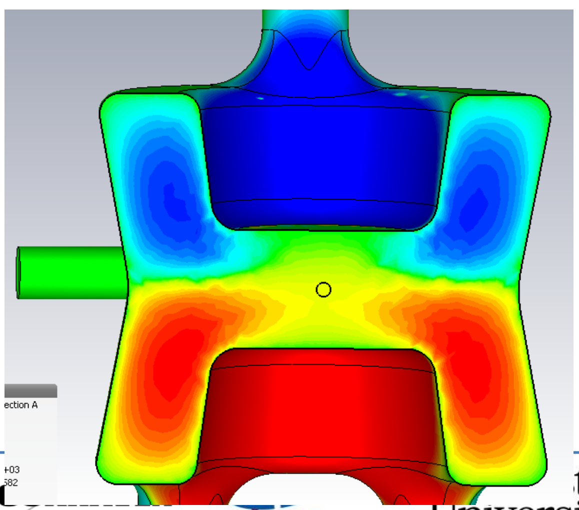
LARP

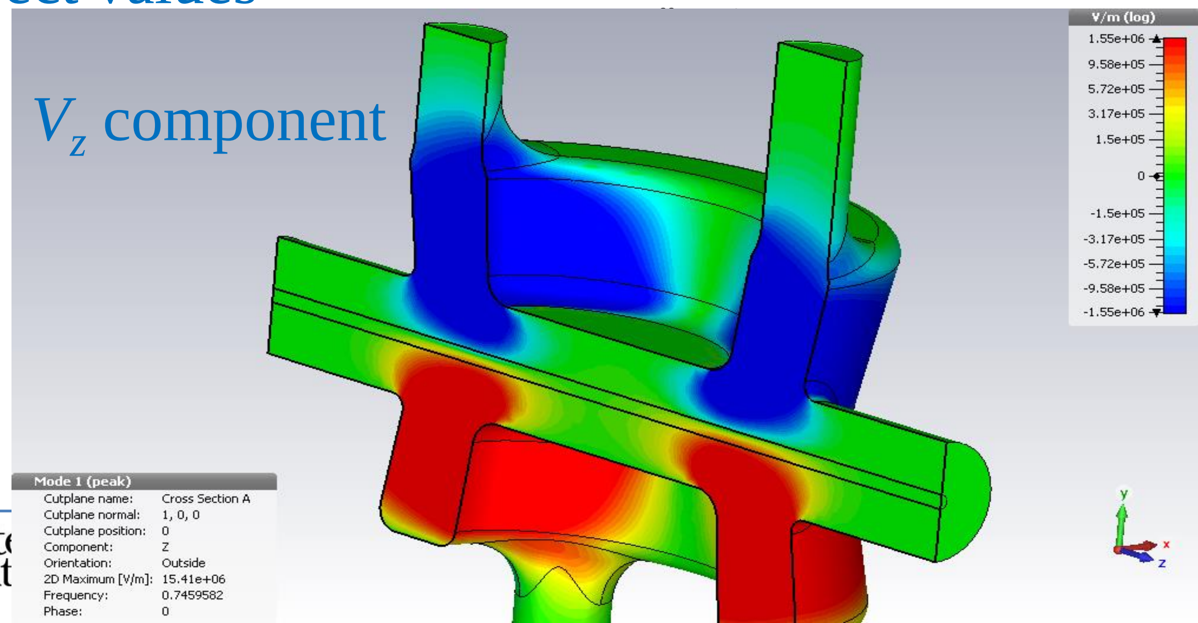
Shunt impedance

High Luminosity LHC

- V_z both monopole and dipole components.
- Out of phase: electrical minimum off centre, and non zero
- Components need to be split and recombined to get correct values







Shunt impedance

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$$V_z = \sqrt{(\boldsymbol{V}_z(0)Im)^2 + (\boldsymbol{V}_z(0)Re)^2}$$ keeps the same

$$V_{T_{\hat{r}}}/r = (\boldsymbol{V}_z(r) - \boldsymbol{V}_z(0))/r$$ changes to:

$$V_{T_{\hat{r}}}/r \approx \sqrt{\left(\frac{\boldsymbol{V}_z(r)Im - \boldsymbol{V}_z(0)Im}{(r)}\right)^2 + \left(\frac{\boldsymbol{V}_z(r)Re - \boldsymbol{V}_z(0)Re}{(r)}\right)^2}$$

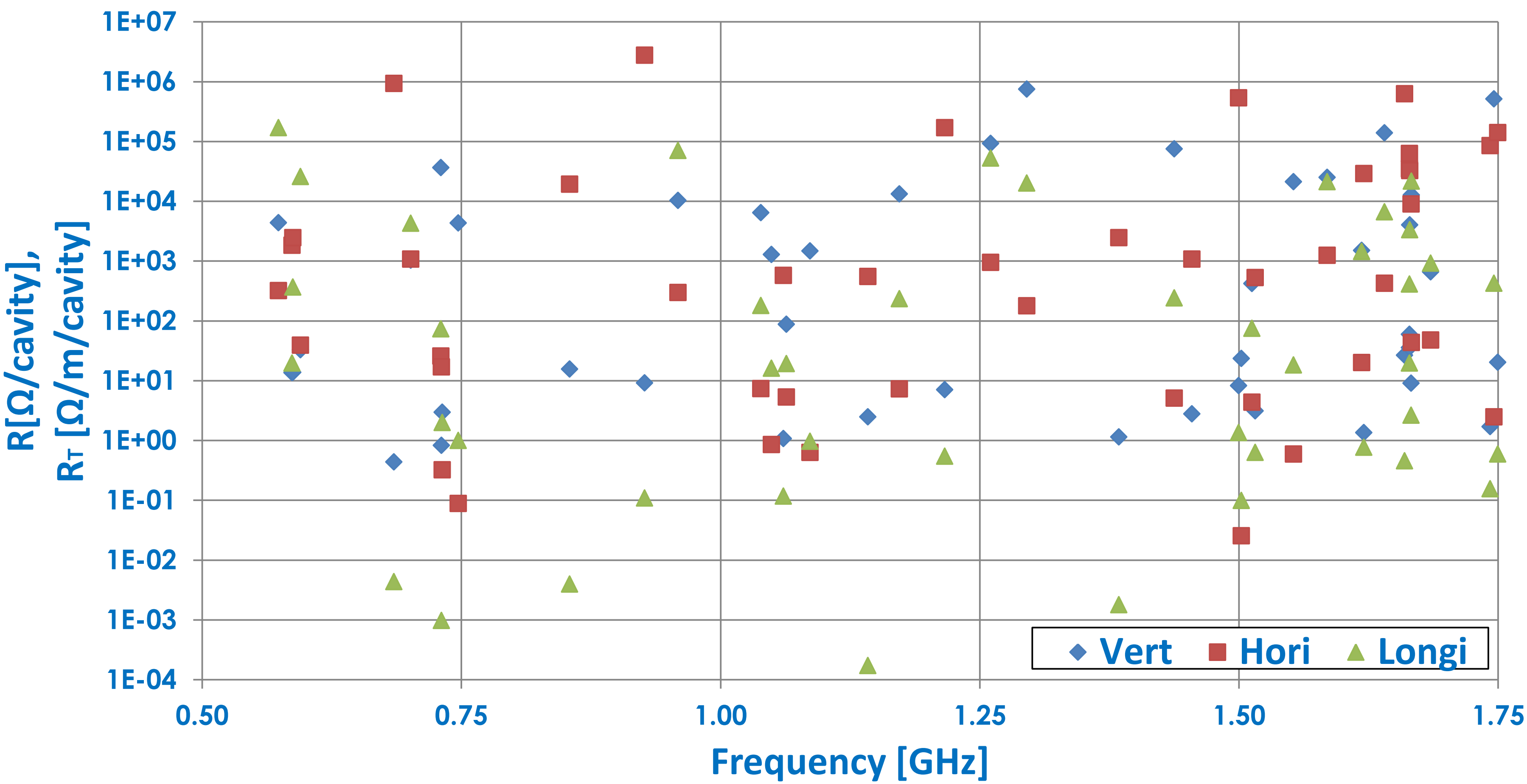
Position mm	On axis	-1 to 1	1 to 5	-1 to -5	5 to -5
RT/Q	0.08	347.6	10.7	0.49	28.27

@745MHz

Changes to

Positions mm	-5 to 0	5 to 0	10 to 5	-1 to 1
RT/Q	19.86	19.54	20.2	19.9

Shunt impedance



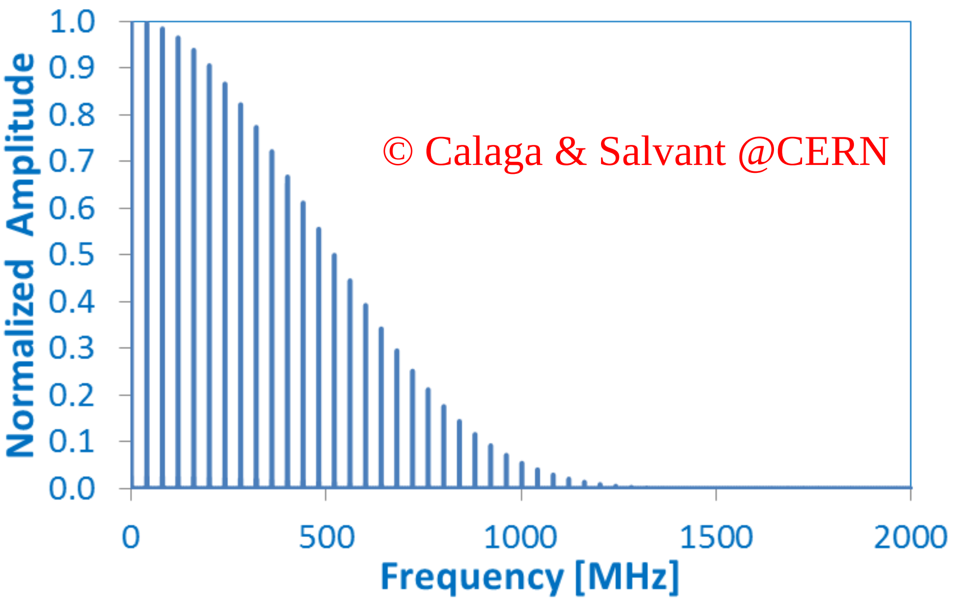
Higher than 10^5 (Ω for longitudinal, Ω/m for transverse):

0.574, 0.685, 0.927, 1.216, 1.296, 1.500, 1.660, 1.746, 1.750 GHz

HOM power estimation

	F (MHz)	573.8	594.9	685.1	927.0	959.1
	Mode Type	L	L	H	H	L
	Qext	4637	1270	1880	8602	7200
Impedance	Longitudinal [Ω/cavity]	170000	25800			70100
	Horizontal [Ω/m/cavity]			934000	2750000	
	Vertical [Ω/m/cavity]					
	HOM Power [Watt]	0.7	3.8	<0.1	<0.1	0.13
	Close to harmonic of 40.08MHz		15th			24th

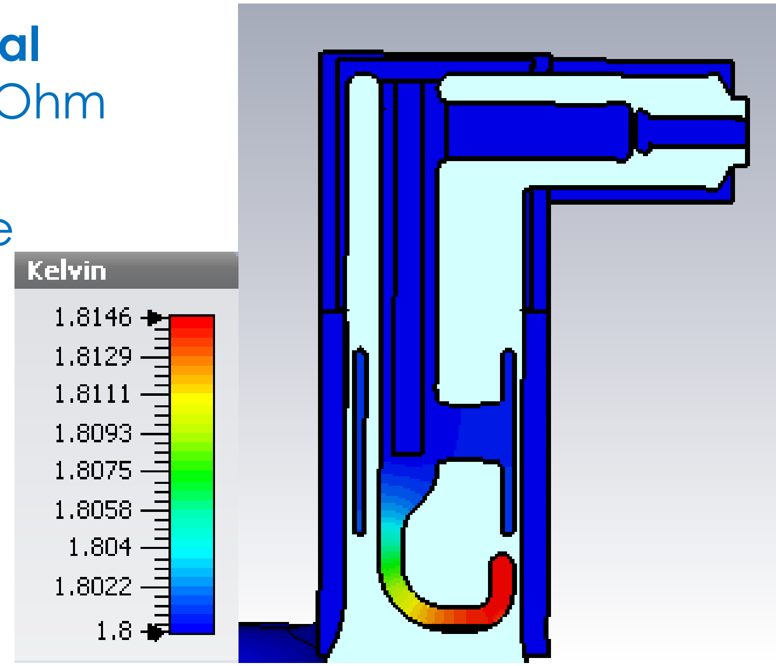
- Based on 25nS beam spectrum
- Power of transverse modes estimated based on 5mm offsets.
- HOM power is about 5.3 Watts per cavity

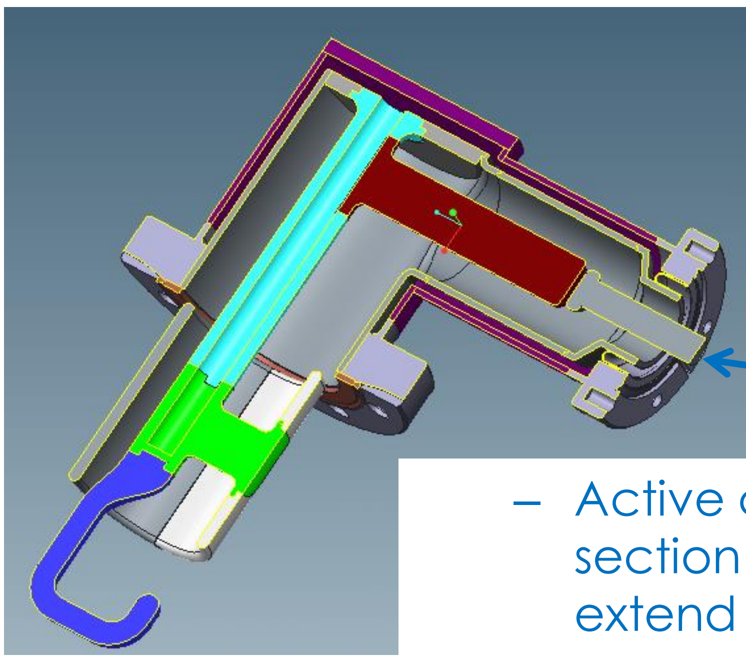


Thermal analysis

CERN and Cockcroft

- Assumes cavity operating **at nominal deflecting voltage** of 3 MV with 5 nOhm surface resistance.
- Assumes active cooling through the center cooling channel **at 1.8 K**

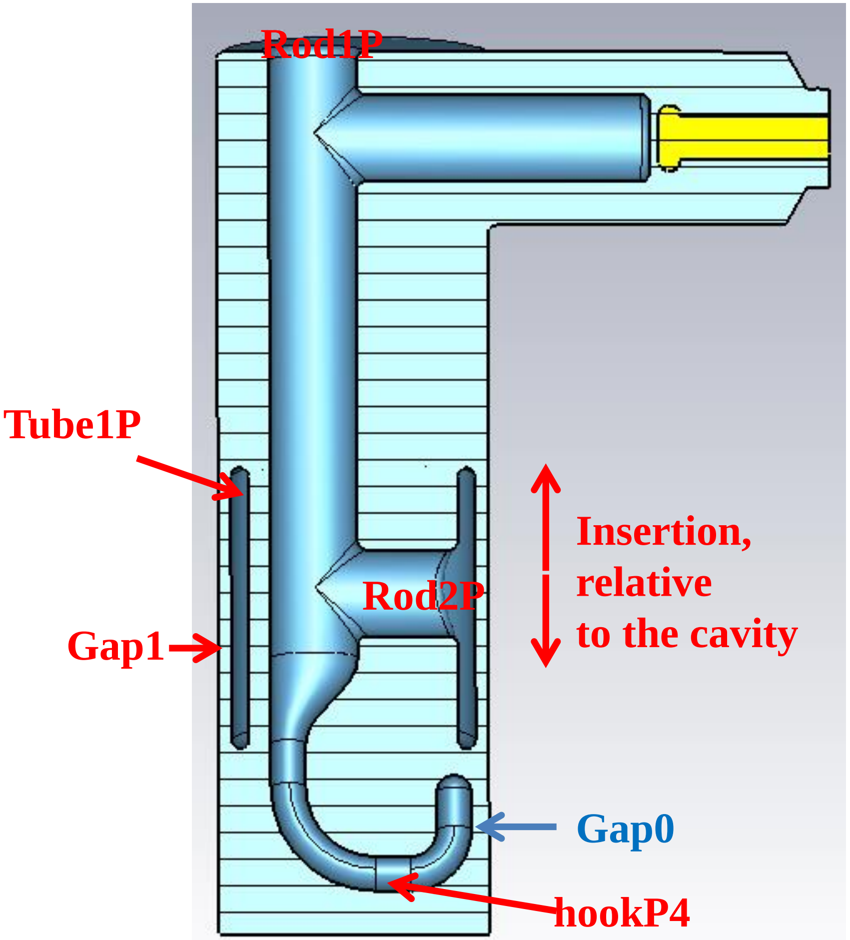




Feed-through to a coax cable to an outside load

- Active cooling will be applied in the straight section of the HOM hook, and it is possible to extend it till the end of the tip.
- Static loss from the cable is ~**0.5** Watt.

Tolerance study



Evaluated the impedances with the red numbers on the left varying in ±0.5mm range, with Gap1 shifting left/right with 0.5mm. (results shown in the next page)

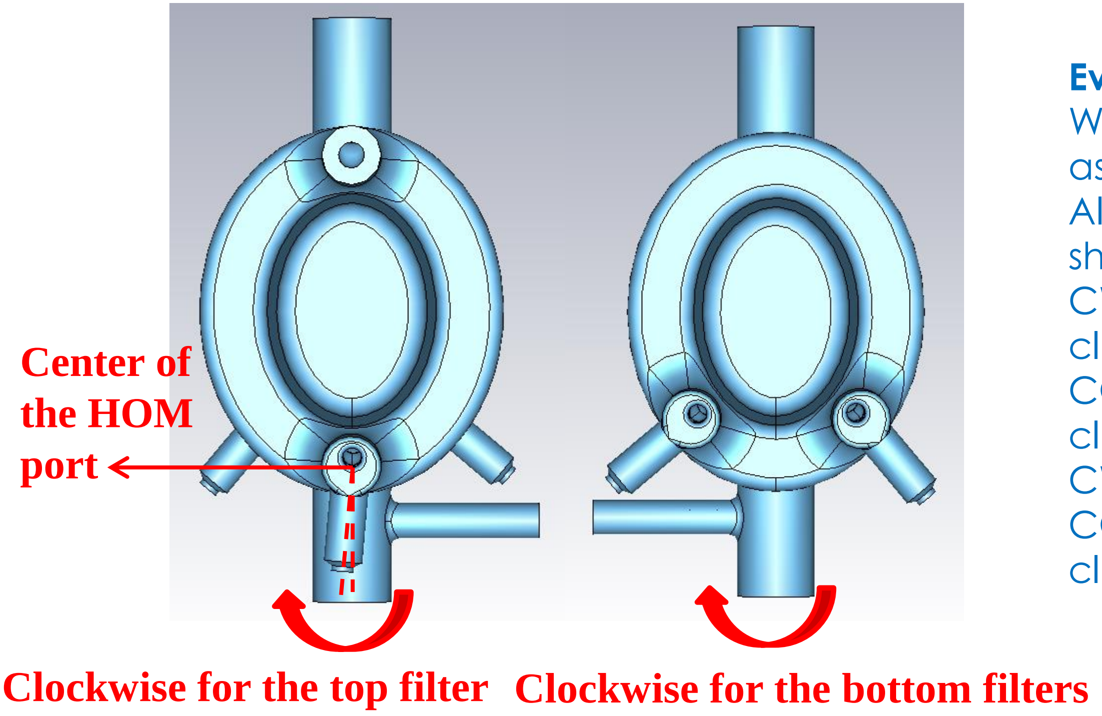
Results showed that within this range most of the impedances will not get enhanced significantly (ie: by a factor of 50%) **except the impedance of the first HOM** (reasonably high though)**.**

To meet ±0.5mm range,
all machining errors should be confined within ±0.1mm,
all assembling errors should be confined within ±0.3mm.

Additional confinement: During the final assembling to the cavity, a method should be developed to ensure Gap0 to be 4mm ±0.2mm (for two reasons: impedance change at 0.57G, and peak electric field on the hook)**.**

The impedances are not sensitive to the rotation of the HOM filter relative to the cavity (see the following page)**, however we still want to confine it within a reasonable degree (please advise).**

Tolerance and impedance



Evaluate

We use the model with gap0=3.5mm as a start

All filters rotate a certain degree, as shown in the pictures.

CW1: (all filters) rotate 1 degree in clockwise

CCW1: rotate 1 degree in counter clockwise

CW5: rotate 5 degree in clockwise

CCW5: rotate 5 degree in counter clockwise

Impedance table

For modes with impedance higher than 10^5 Ω or Ω/m.

L: longitudinal in Ω

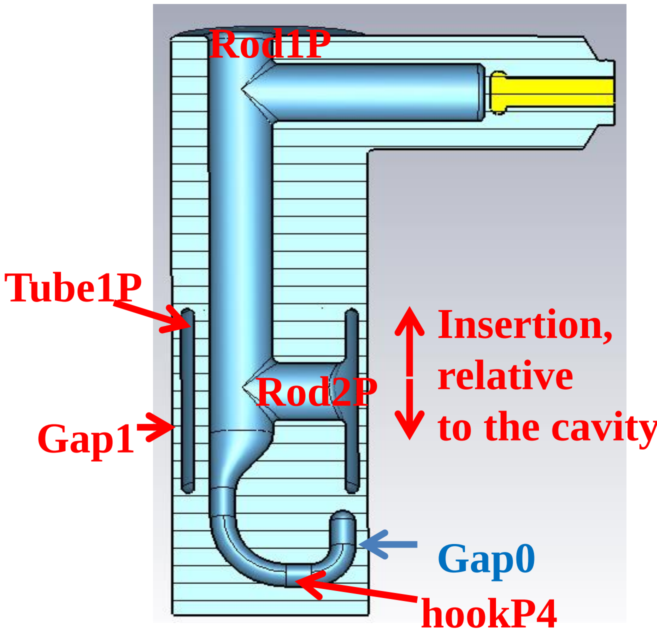
H: horizontal in Ω/m

V: vertical in Ω/m

T: transverse (a mix of longitudinal and vertical, the number showed here is the higher one of these two) in Ω/m

	Impedance table (circuit definition)					
freq [GHz]	Gap0 3.5 model	CW1	CCW1	CW5	CCW5	
0.6851649	1.04E+06	1.03E+06	1.09E+06	1.08E+06	1.07E+06	H
0.9269259	2.59E+06	2.75E+06	2.76E+06	2.78E+06	2.75E+06	H
1.2162745	1.79E+05	1.81E+05	1.67E+05	1.65E+05	1.62E+05	H
1.2955984	7.51E+05	7.55E+05	7.09E+05	7.15E+05	7.08E+05	V
1.4998569	1.04E+05	2.17E+05	2.26E+05	2.28E+05	2.24E+05	T
1.6598078	5.27E+05	1.16E+05	2.81E+05	4.84E+05	2.75E+05	H
1.7460401	5.62E+05	6.08E+05	5.84E+05	5.93E+05	5.81E+05	V
1.7497177	1.56E+05	1.71E+05	1.63E+05	1.63E+05	1.60E+05	H

Tolerance and impedance



Evaluate the red numbers in ±0.5mm range

Tube1P and Rod2P will not affect RF performance based on S21 calculation and they are not considered in this analysis.

The length of hookP4 is used to tune Gap0

For the ref model, Gap0=4mm, Gap1=3mm, Rod1P=-9mm (minus here means shifting left).

We focus on the modes with impedances higher than 10^5 (Ω for longitudinal, Ω/m for transverse).

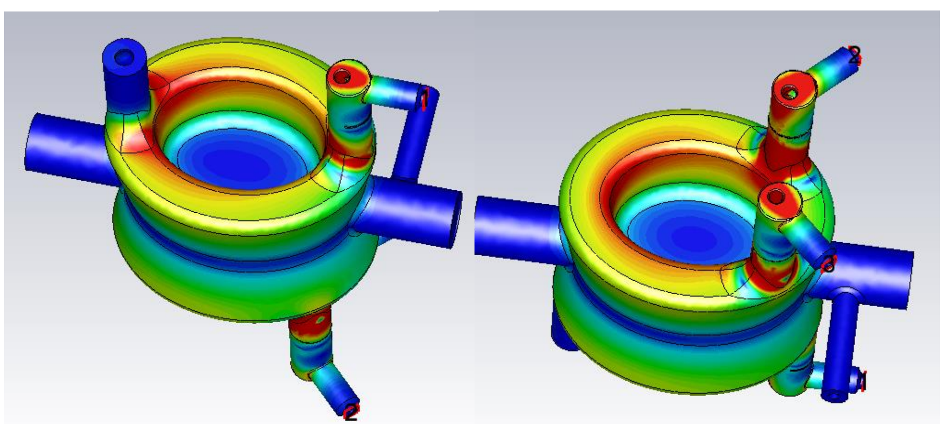
Impedance table were sent to CERN for evaluation.

			Impedance (circuit definition)							
Freq [GHz]	ref. model	Gap0 3.5	Gap0 4.5	Gap1 left0.5	Gap1 right0.5	Rod1P -8.5	Rod1P -9.5	0.5inner	0.5outter	Mode
0.573846	1.70E+05		3.69E+05	1.82E+05		2.89E+05	4.67E+05	1.17E+05	1.19E+05	L
0.685176	9.34E+05	1.04E+06	8.97E+05	7.79E+05	6.97E+05	1.07E+06	8.36E+05	7.15E+05	7.72E+05	H
0.926951	2.75E+06	2.59E+06	3.15E+06	3.22E+06	2.05E+06	3.77E+06	2.62E+06	2.48E+06	2.72E+06	H
1.216278	1.69E+05	1.79E+05	1.53E+05	1.45E+05	2.00E+05	1.47E+05	1.78E+05	1.65E+05	1.75E+05	H
1.295595	7.46E+05	7.51E+05	7.08E+05	6.81E+05	7.91E+05	7.11E+05	7.61E+05	6.98E+05	7.55E+05	V
1.499932	5.35E+05	1.04E+05	5.41E+05	6.07E+05		6.41E+05	1.20E+05	3.75E+05	4.27E+05	T
1.640505	1.39E+05	2.71E+05						1.57E+05	1.30E+05	T
1.659981	6.28E+05	5.27E+05	4.22E+05	2.77E+05	7.07E+05	2.31E+05	8.15E+05	6.18E+05	5.75E+05	H
1.746212	5.15E+05	5.62E+05	4.97E+05	5.11E+05	5.06E+05	5.02E+05	5.55E+05	5.02E+05	5.30E+05	V
1.749750	1.41E+05	1.56E+05	1.35E+05	1.42E+05	1.39E+05	1.41E+05	1.57E+05	1.36E+05	1.47E+05	H

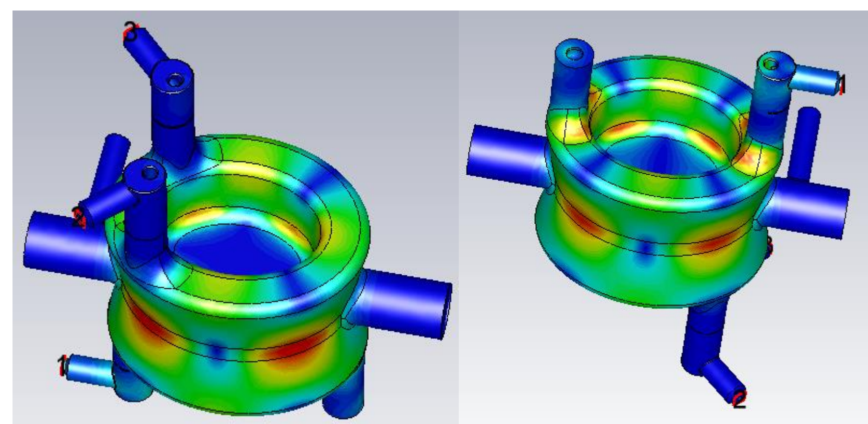
Tolerance and freq shift

	F (MHz)	573.8	594.9	685.1	927.0	959.1
	Mode Type	L	L	H	H	L
	Qext	4637	1270	1880	8602	7200
Impedance	Longitudinal [Ω/cavity]	170000	25800			70100
	Horizontal [Ω/m/cavity]			934000	2750000	
	Vertical [Ω/m/cavity]					
	HOM Power [Watt]	0.7	3.8	<0.1	<0.1	0.13
	±6 MHz HOM Power [Watt]	1.7	**535.7**	18.1	6.9	**221.0**
	Harmonic of 40MHz		15^{th}			24^{th}

594.9MHz H field



959.1MHz H field



Tolerance and freq shift

- In the study of the tolerances on HOM power, we focus on the two dangerous modes at 594.9MHz and 959.1MHz.
- The fabrication tolerances of the HOM filter and the cavity is confined in a reasonable range so that the total HOM power is <100Watt.
- However there are several modes at ~600MHz that might be dangerous, an additional constraint on Gap0 (4±0.2mm) is added for risk control.
- Q_{ext} of the crabbing will not decrease to less than 50%, the coupling to the crabbing mode will extract <2.2Watt power to the outside load for each filter.

Error in the HOM filter

	Q_{ext}	Impedance	Power [Watt]	Mode
Gap0 4.5				
0.5951258	691	182.8	0.12	H
0.5997148	751	9308.1	61.90	L
Rod1P+0.5				
0.597517	1375	21759.7	7.63	L
0.959304	10927	106660.7	0.12	L
Rod1P-0.5				
0.599114	705	260.9	1.48	H
0.599845	748	3084.5	25.60	H
0.603770	721	6188.6	15.45	L

Error in the cavity

Mode	594.9 MHz	959.1 MHz
Height change ±0.5mm	±0.52 MHz	±0.26 MHz
Waist change ±0.5mm		±0.10 MHz
	601.2 MHz	961.9 MHz

Tolerance and RF losses

Freq [MHz]	Power to the load outside [Watt]	Loss on Cu pins [mW]	Loss on Cu gaskets [mW]	Loss on Nb [mW]
573.85	1K	15.01	81.27	1.36
594.91	1K	11.55	35.79	0.46
685.18	1K	9.44	0.50	0.21
926.95	1K	2.18	0.90	0.07
959.08	1K	28.36	9.30	0.68
total:		66.53	127.76	2.79

Results are per cavity, with 3 HOM filters on each cavity.

Summary

- An **L-shape filter** with a band stop structure is designed for DQWCC.
- Peak electric/magnetic fields on filter **smaller** than on cavity.
- **Multipacting** simulations are cross-checked between CST MWS (UK) and ACE3P/TRACK3P (SLAC).
- Design of the HOM window is on-going.
- HOM modes are characterized using bead pulling system.
- **Methodolog**y for R/Q calculation has been established by UK team. Values cross checked by UK and BNL using CST MWS.
- Q_{ext} calculations of HOMs using two methods: eigenmode Q and S parameter Q.
- Thermal simulation of HOM the filter shows only **15 mK** temperature increase on the HOM hook.
- HOM filter is designed trying to meet the current impedance budget with HOM frequency up to 1.75 GHz. Impedance table were sent to CERN, together with the tolerance study.
- Estimated the **HOM power** and **RF losses**, together with the tolerance study.

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Thank you!