# ILC Racetrack Crab Design

Prof Graeme Burt, Lancaster University / Cockcroft Institute

Thanks to Nik Templeton and James Bourne, STFC

# ILC Crab Cavity Collaboration Team (c. 2008)

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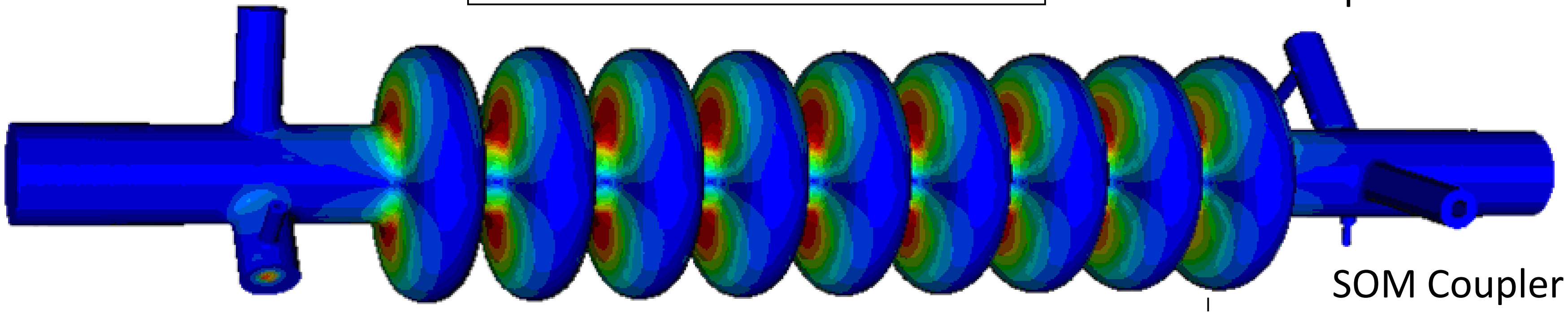
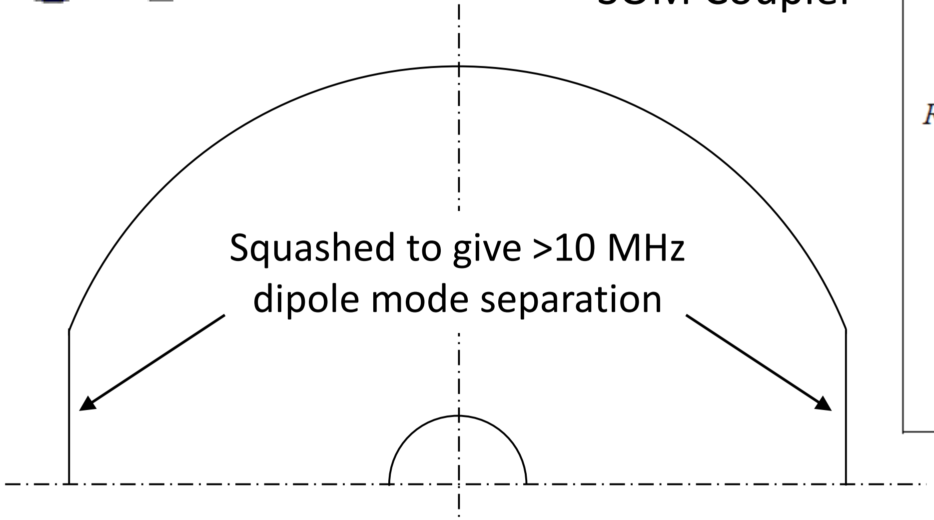
# ILC-CC Design

Based on the FNAL CKM Cavity



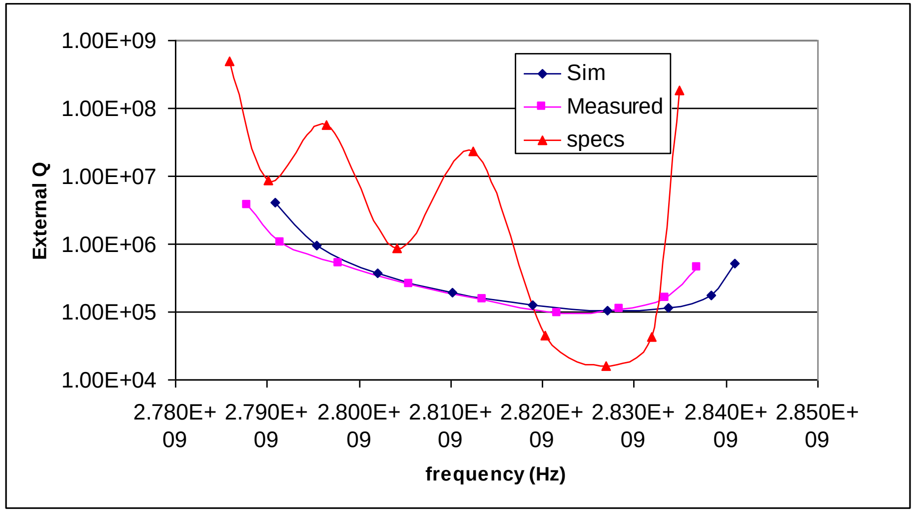

| At 5MV/m $P_{\perp}$: | |
|---|---|
| $B_{MAX}$ | 73 mT |
| $E_{MAX}$<br>$U$ | 16.6 MV/m<br>0.25 J |
| $Q$ (Nb, room temp) | 4780 |
| $\left(\frac{R}{Q}\right)' = \frac{1}{2}\frac{\lvert V_{\perp}(r)\rvert^2}{\omega U}\left(\frac{c}{\omega r}\right)^2$ | 235 Ω |
| $G = Q \times R_{SURF}$ | 225Ω |
| $R_{BCS}$(best measurement) @ 1.8K | 30nΩ |
| $R_0$(best measurement) | 40nΩ |
| $Q$ @ 70nΩ1.8K | $3.2 \times 10^9$ |
| Surface power @ 70nΩ | 1.9 W |

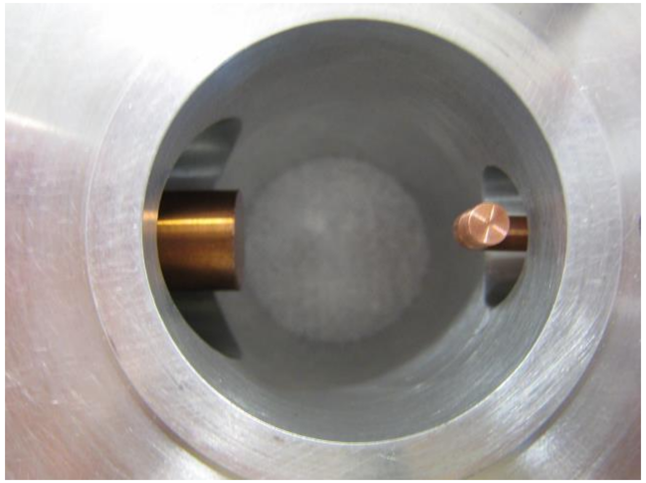
Beam-pipe radius = 18mm
Cavity iris radius = 15mm
Equator Radius = 47.37mm

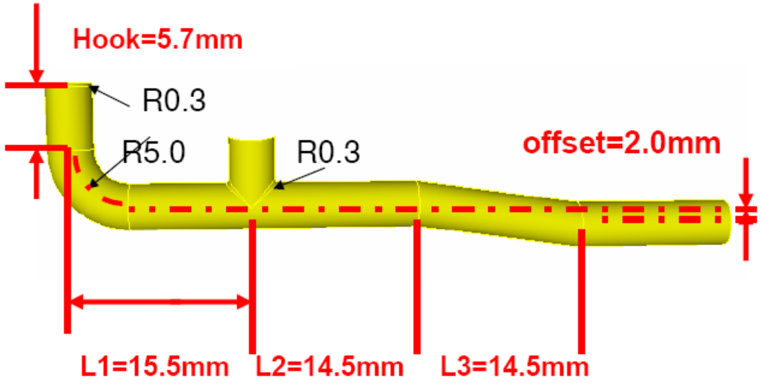



**In hindsight it may have been better to develop a racetrack solution with a larger polarisation separation. It would be prudent to revisit this**.

# Lower Order Mode Coupler



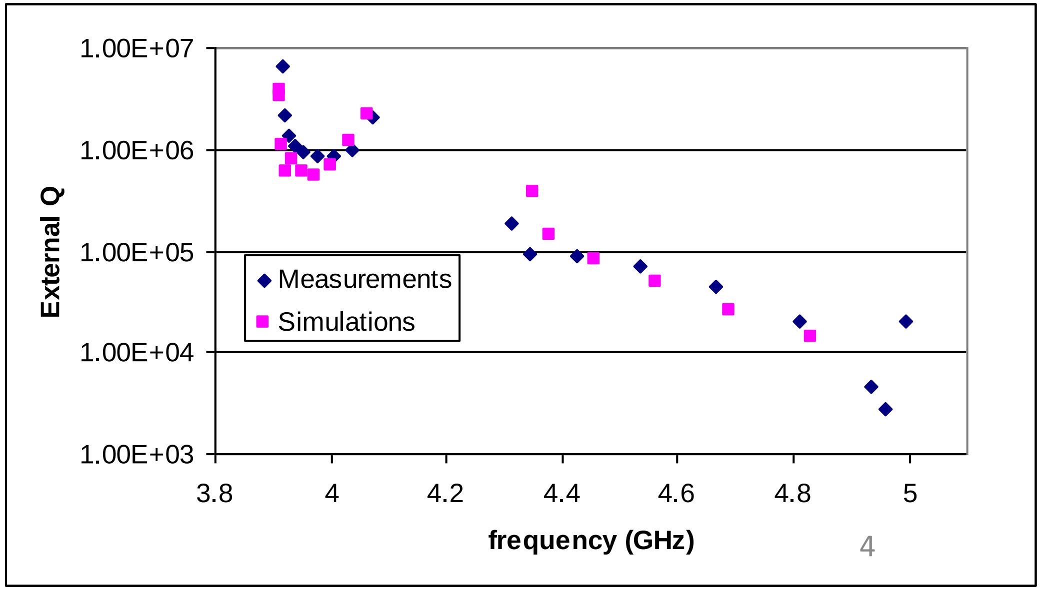






Hook type LOM coupler designed by FNAL/Lancaster and improved by SLAC

No filter, uses polarisation to avoid coupling to the crabbing mode

The LOM coupler prototype was found to give good agreement with both MWS and Omega3P simulations.



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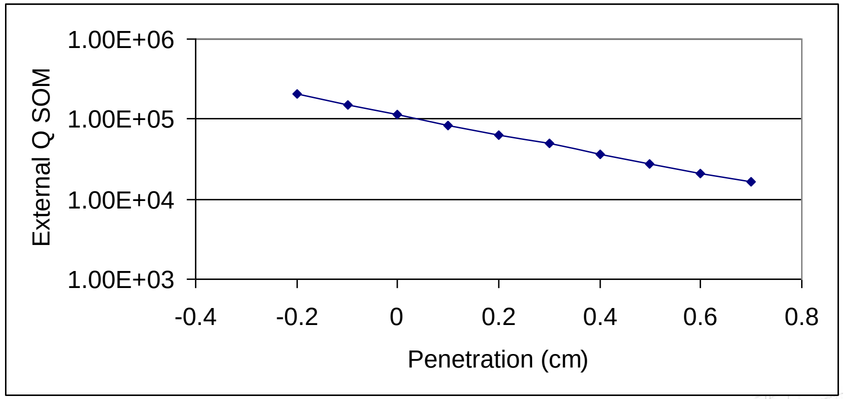
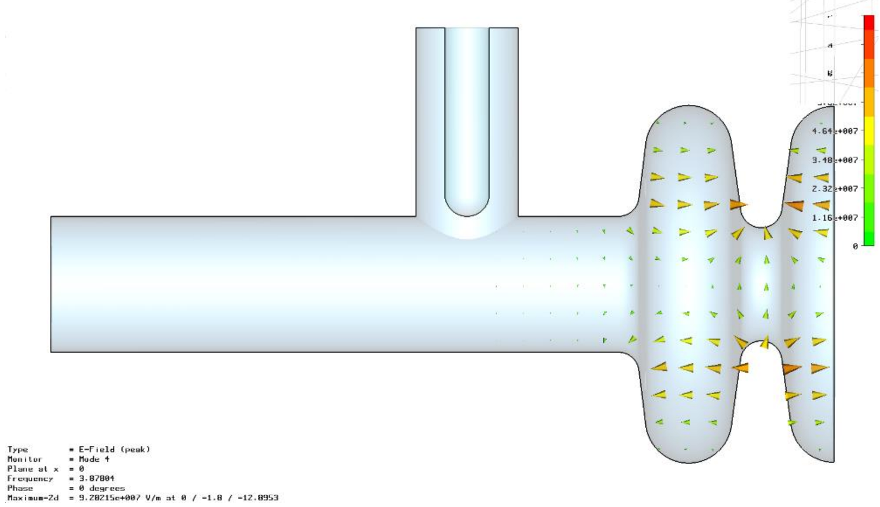
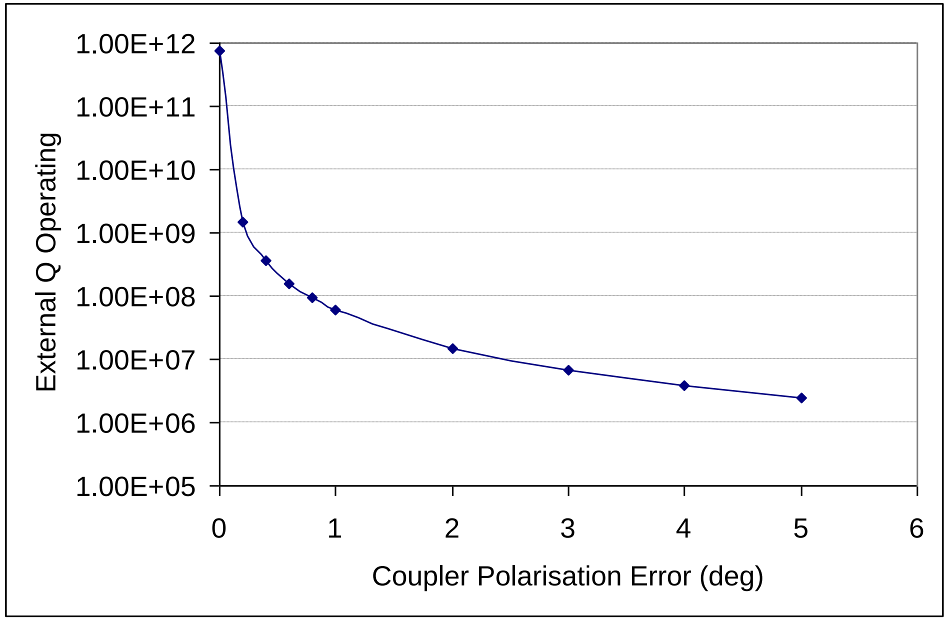
# Cockcroft SOM Coupler design

The SOM coupler is currently a simple coaxial structure.



The problem is that as we decrease the SOM external Q we make the coupler susceptible to damping the operating mode.



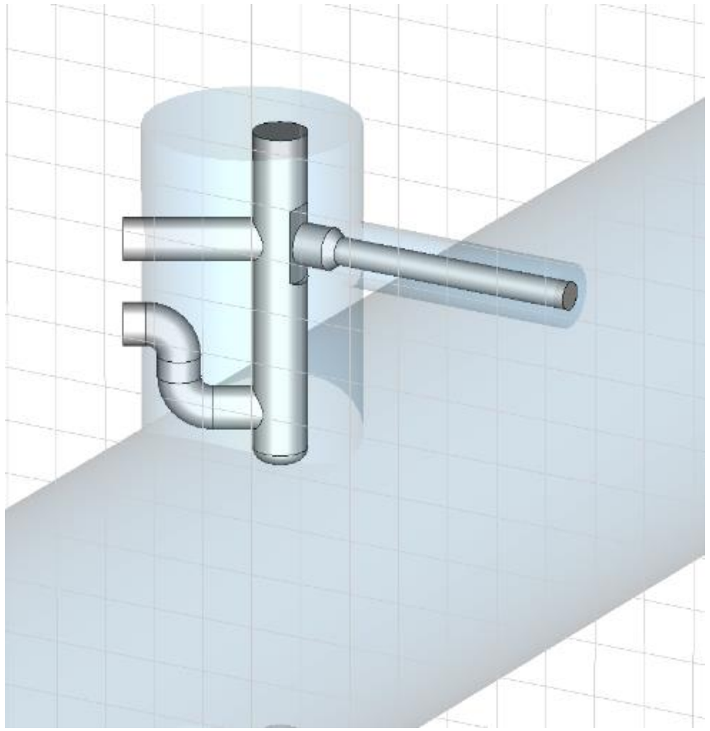

Assuming 10 Watts mean power flow in the coupler, and we meet the SOM damping spec then we need to align the coupler to within 1.4 degrees.

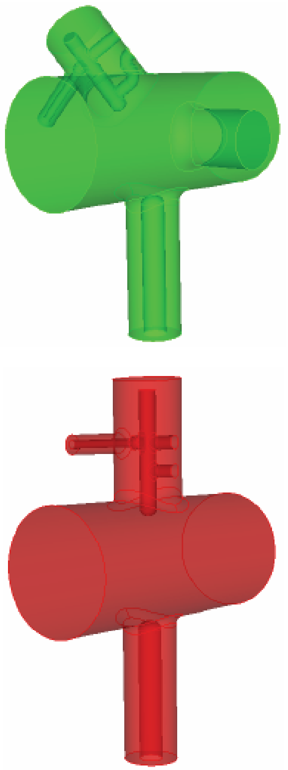
May be better to use a racetrack cell shape to separate the vertical and horizontal mode in frequency and use a filter

# HOM Coupler

The original HOM coupler was based on the EU-XFEL 3rd harmonic HOM coupler that's slightly modified.

SLAC redesigned the coupler but did not check all modes just the first two passbands.





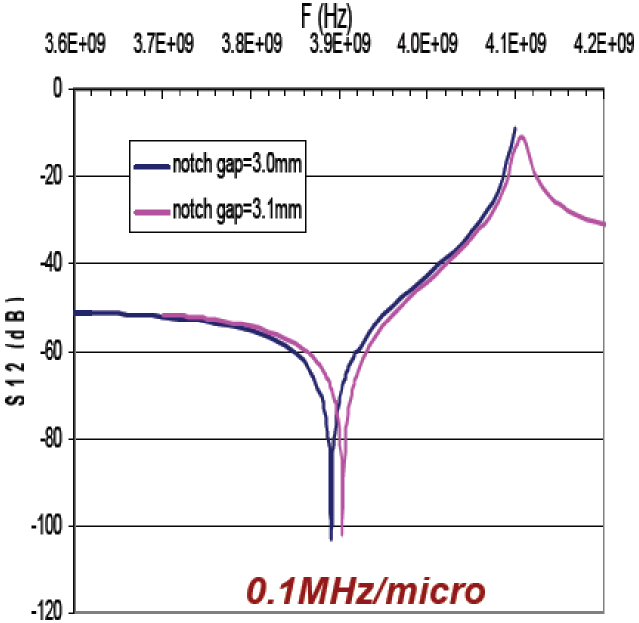
***FNAL DESIGN***

***loop coupling:***

**Reduce Notch Gap Sensitivity**

***SLAC DESIGN***

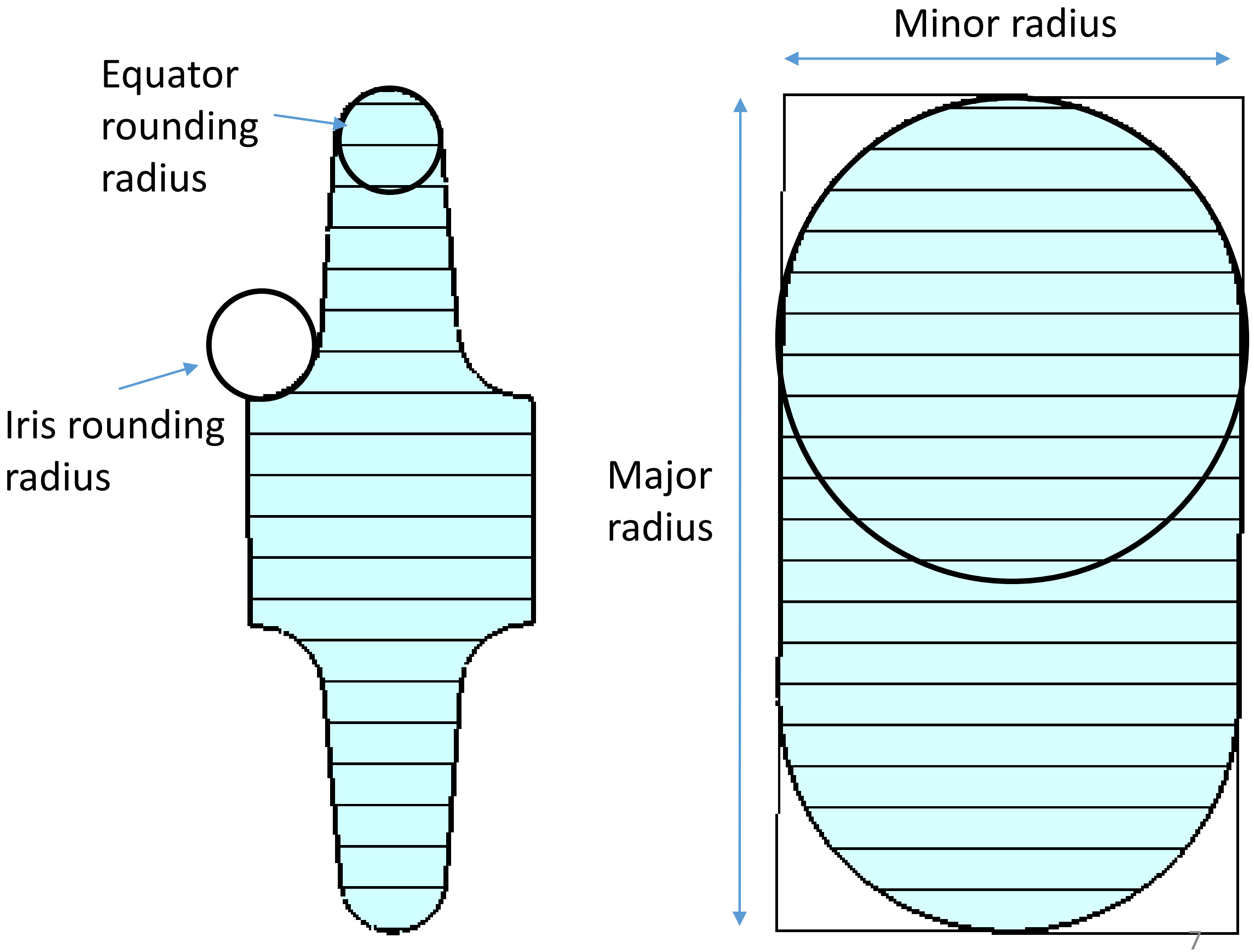
***probe coupling***



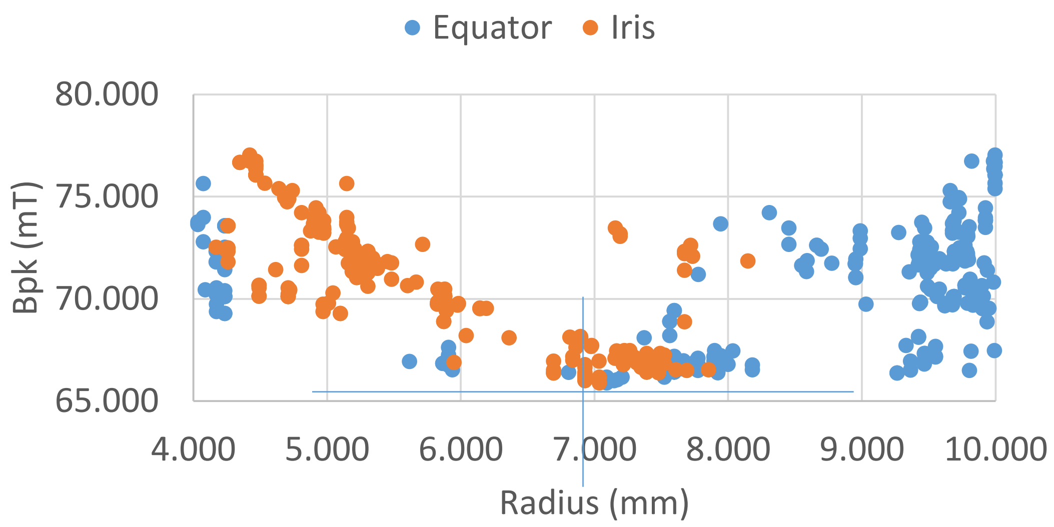

***~TESLA(0.13MHz/micro)***

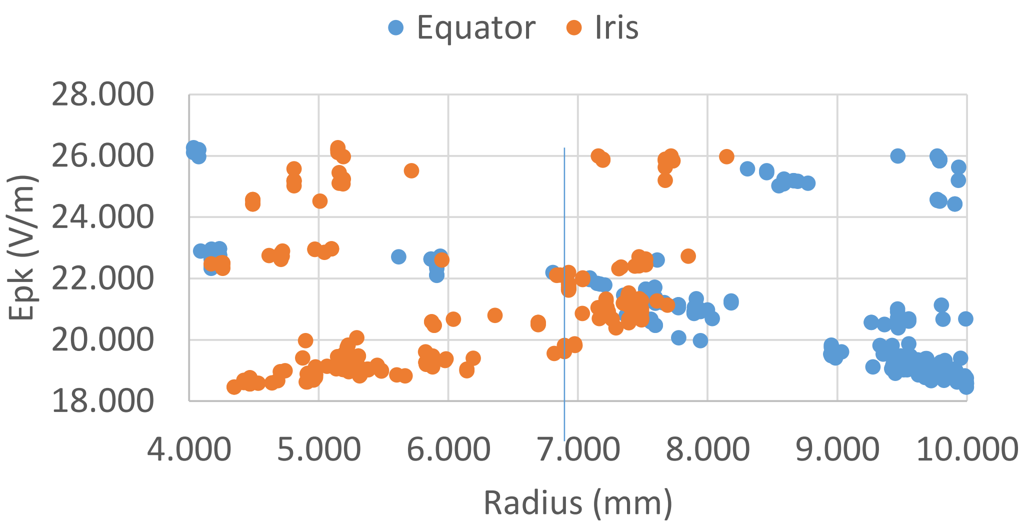
# Re-optimizing the ILC crab

- In the original design the SOM separation is only 10 MHz which caused issues it would be good to separate them more.
- 250 GeV ILC requires a 3-cell cavity @ 5.3 MV/m, or 2x2-cells at @4.2 MV/m

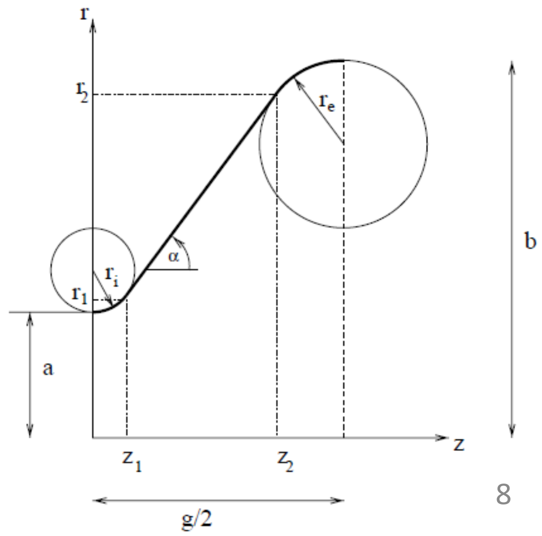


# Cell Optimisation (curvature radii)

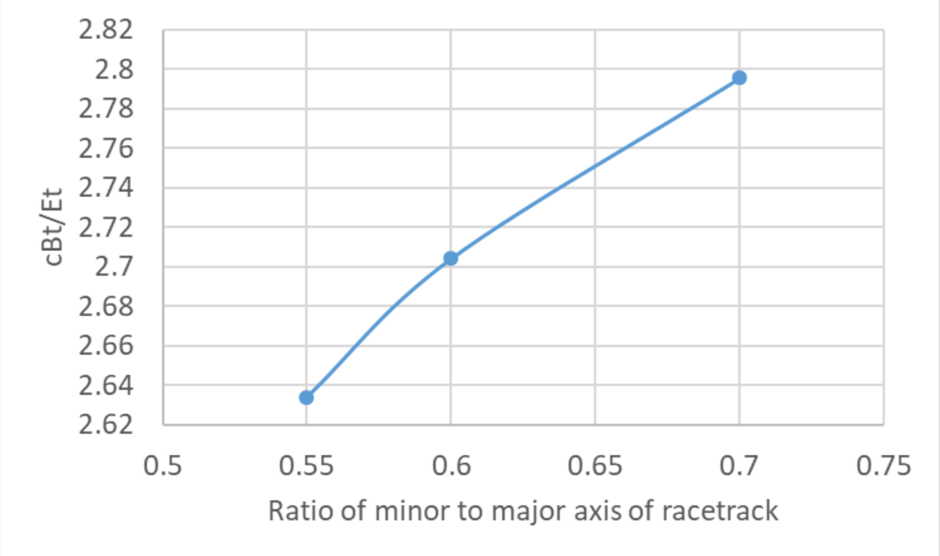


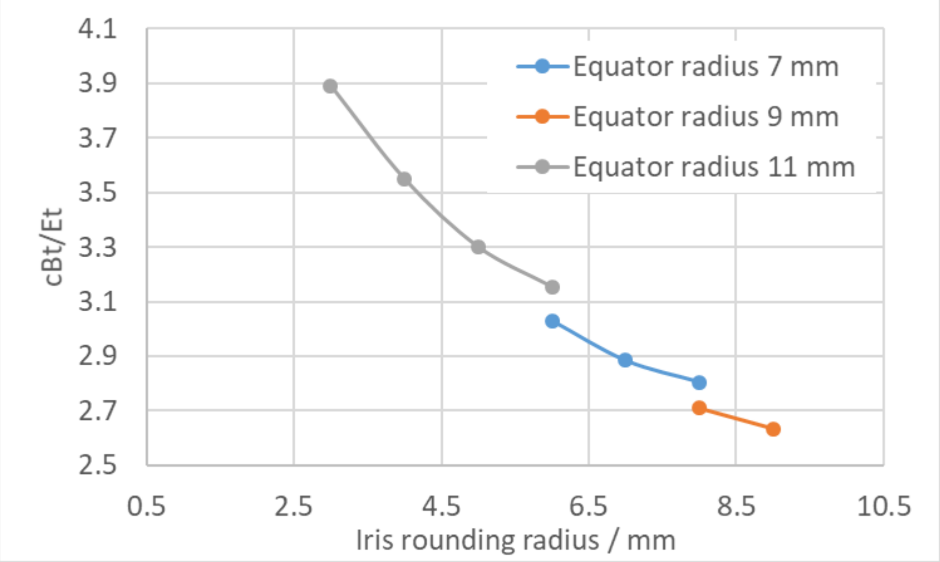




- Epk is minimised for a large rounding radius on the equator and small iris
- Bpk is minimised for iris rounding around 7 mm
- We have aimed for minimising Bpk as Epk is fairly conservative
- Note that having such a large iris rounding and hence thickness implies a smaller equator and hence cell length



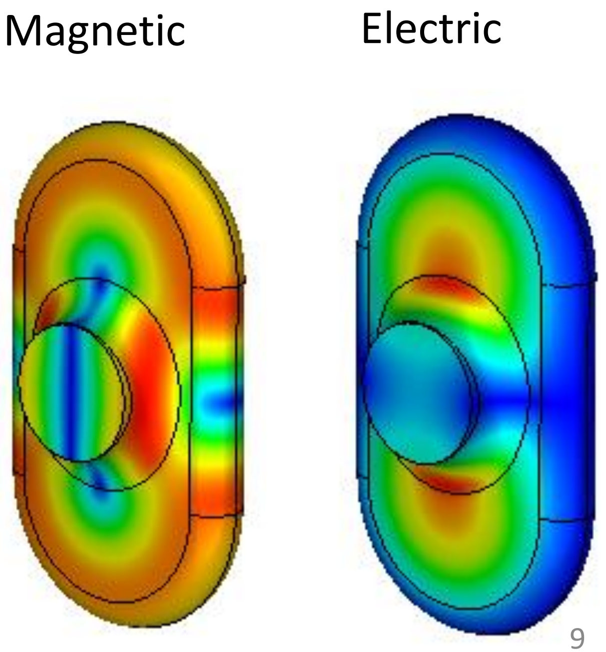
# Improved geometry




- The surface magnetic field decreases as the ratio of minor to major axis decreases (below 0.5 its starts to increase but with our aperture this is not an allowed geometry anyway)
- The surface electric field is too low to worry about

- It appears we want a small equator radius and a large equator radius (ie short cavity with a thick iris)



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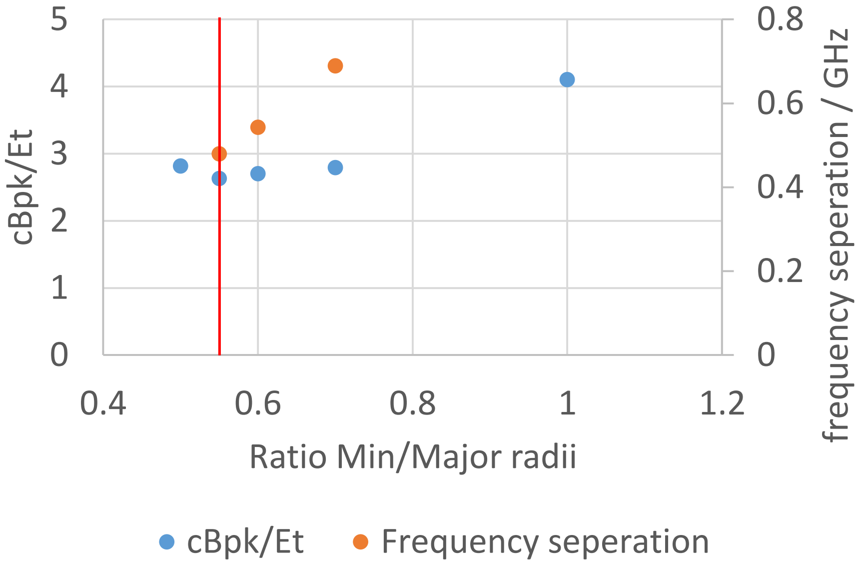
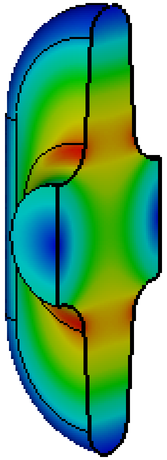
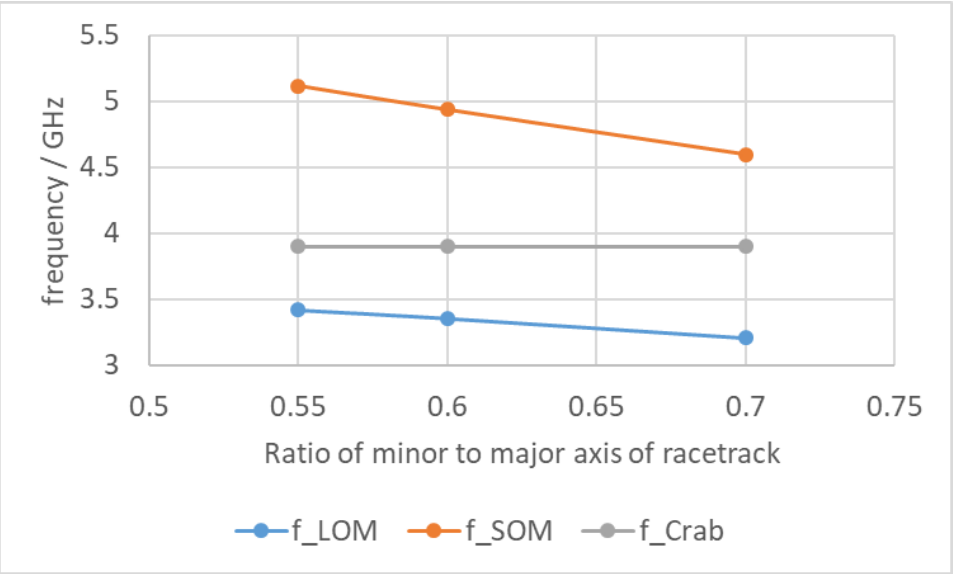
# Varying the ellipticity to tune the LOM/SOM

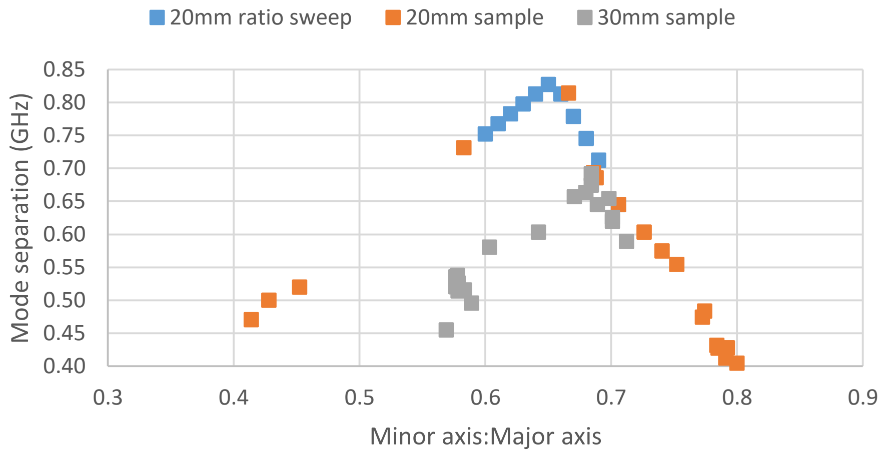
- Making the cavity elliptical pushes the other polarization of the dipole mode to higher frequencies
- One issue with making the cavity highly elliptical is the lower order mode moves closer to the crabbing mode
- Ideally LOM and SOM spacing equal
- Making more elliptical also drops Bpk until it gets close to the aperture hence **0.55 chosen as optimum**



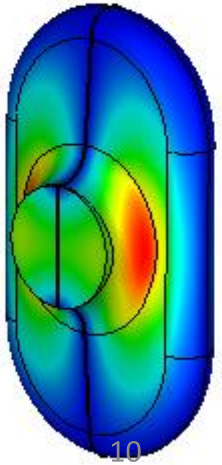

Lower order mode (LOM)






Same order mode (SOM)



# Figure 8 & Elliptical Cavity

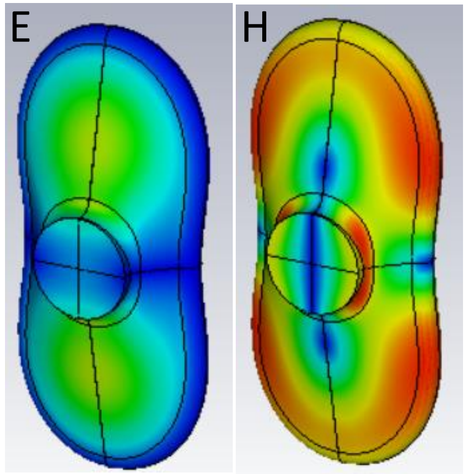
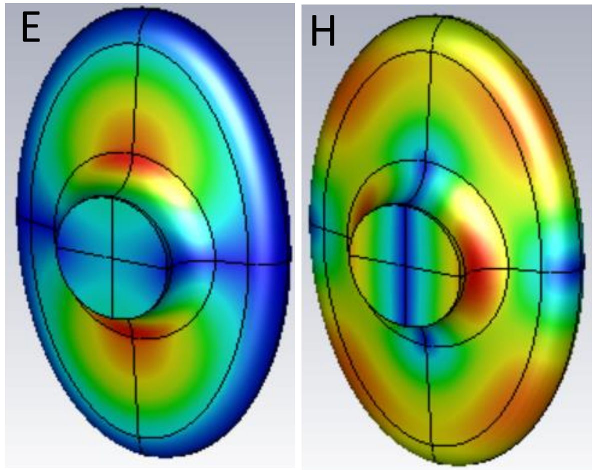
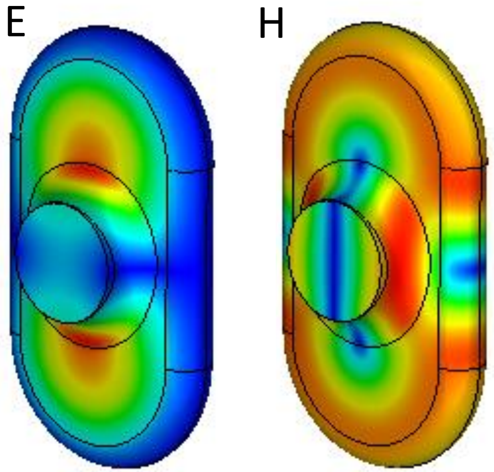



Figure 8



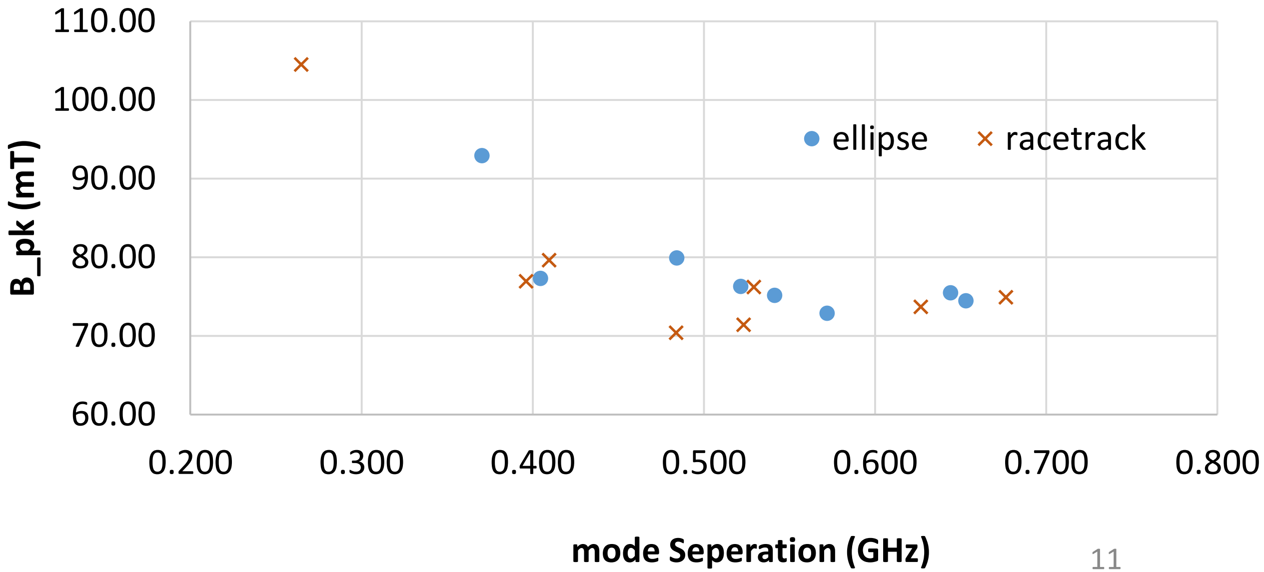

Elliptical




Racetrack

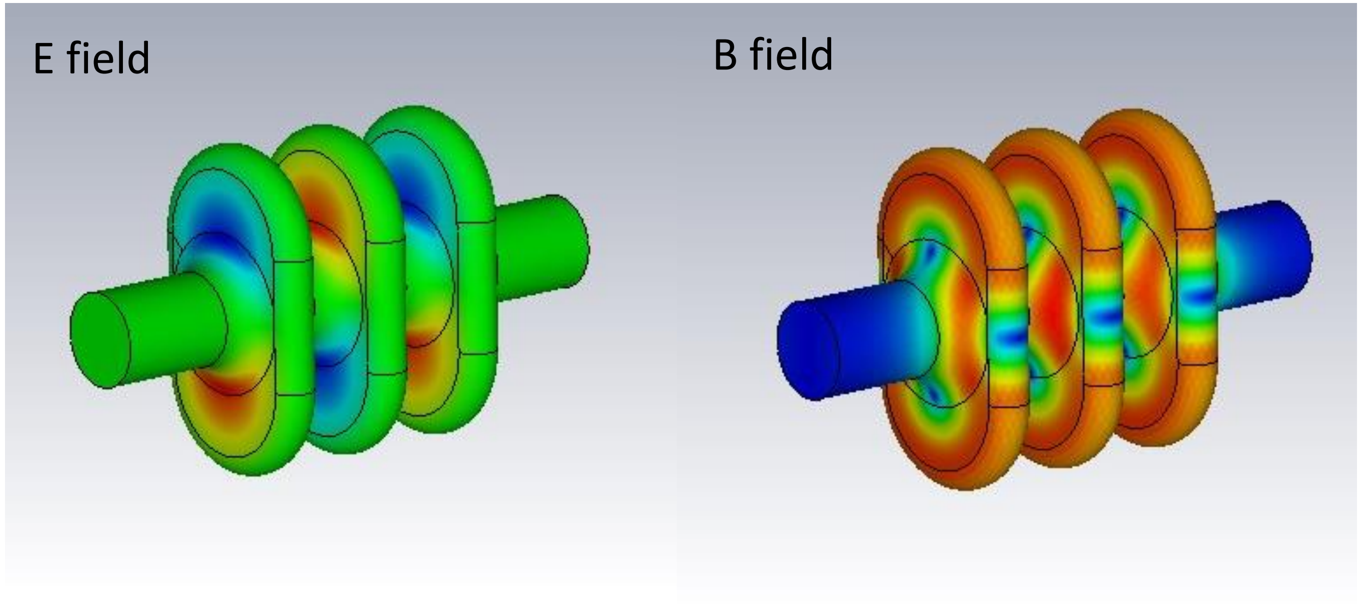
Other geometries were investigated but didn't prove to be as effective as a racetrack cavity.

- Figure 8 had enhanced B field
- Elliptical had poor mode seperation



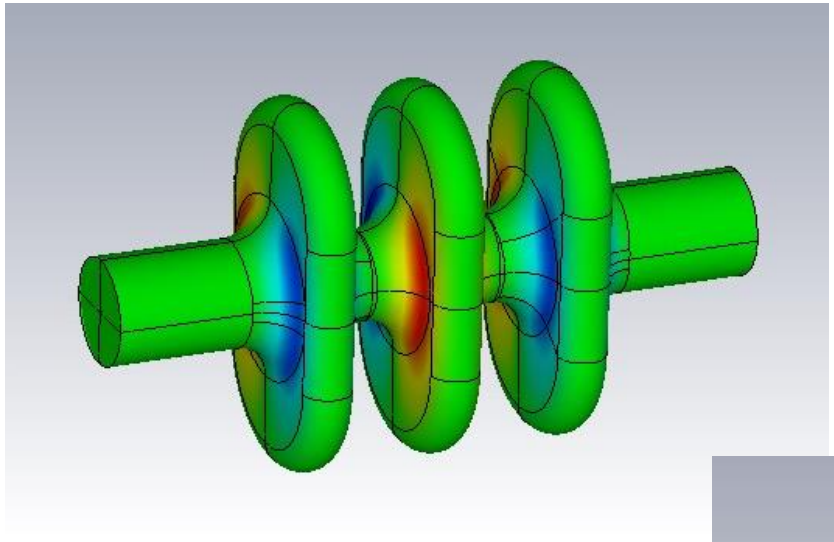
# Initial 3 cell cavity design

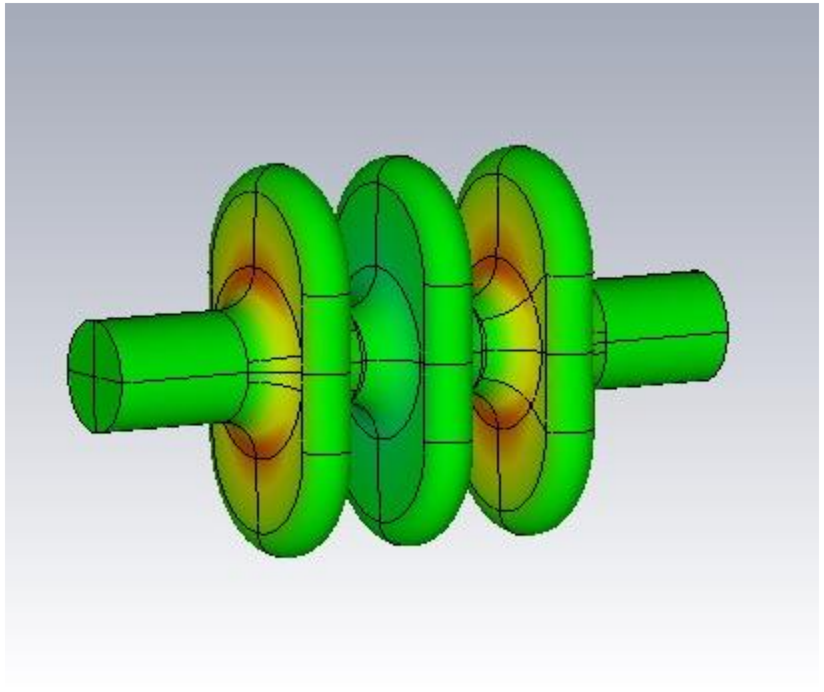
- End cells initially had lower peak magnetic field
- Larger beampipes were used on the end cells to aid damping
- Iris was increased until the peak magnetic field was the same on all iris (iris radii 18 mm and 12.5 mm)



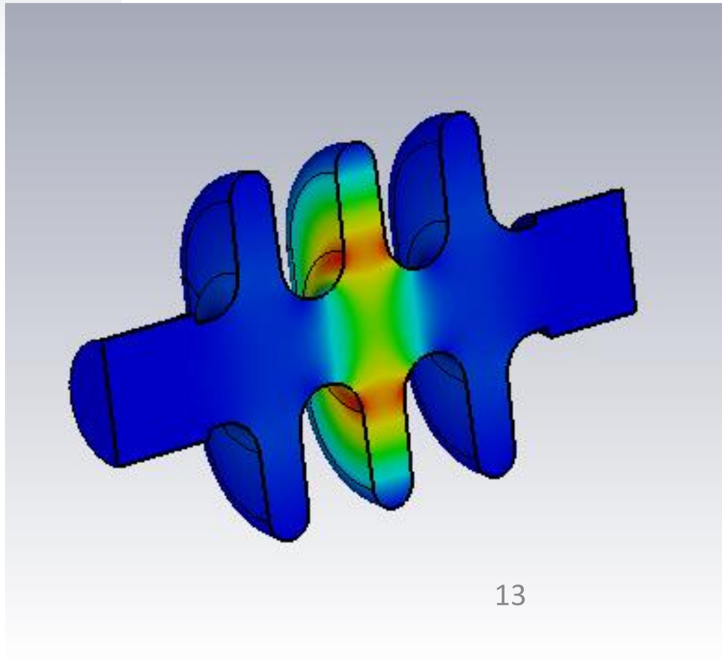
# Same order and lower order modes

- Highest impedance SOM is the pi mode at 5.07 GHz, Rt/Q is only 50 Ohms/m due to frequency not being synchronous.

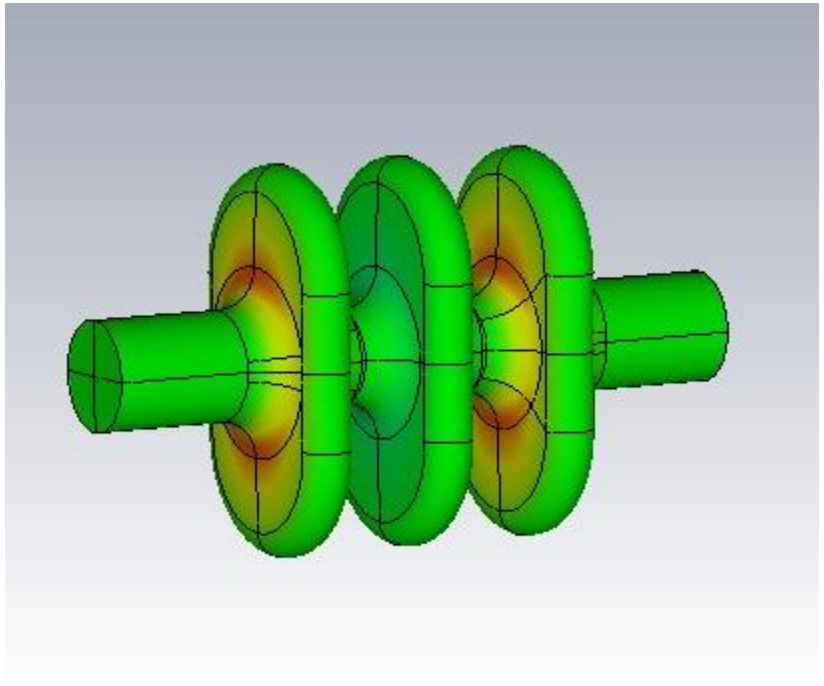




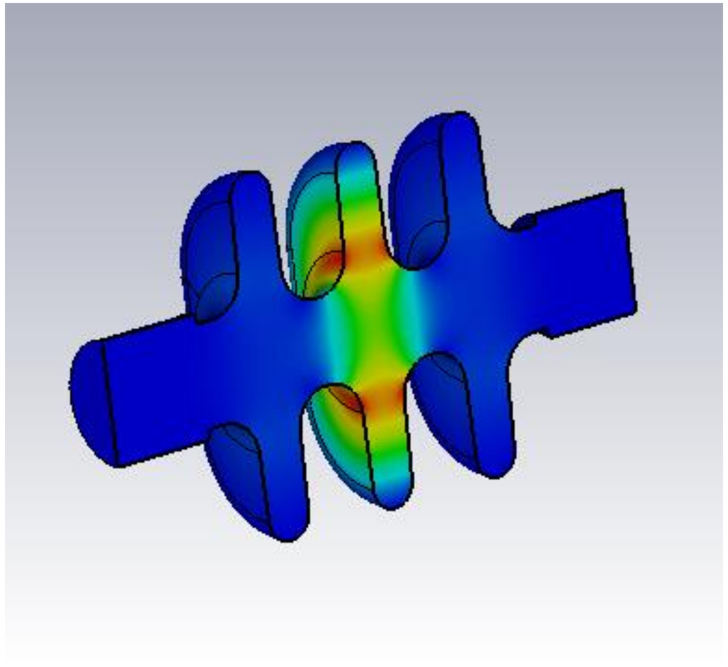
- Highest impedance LOM is the pi/2 mode at 3.32 GHz, R/Q is only 134 Ohms



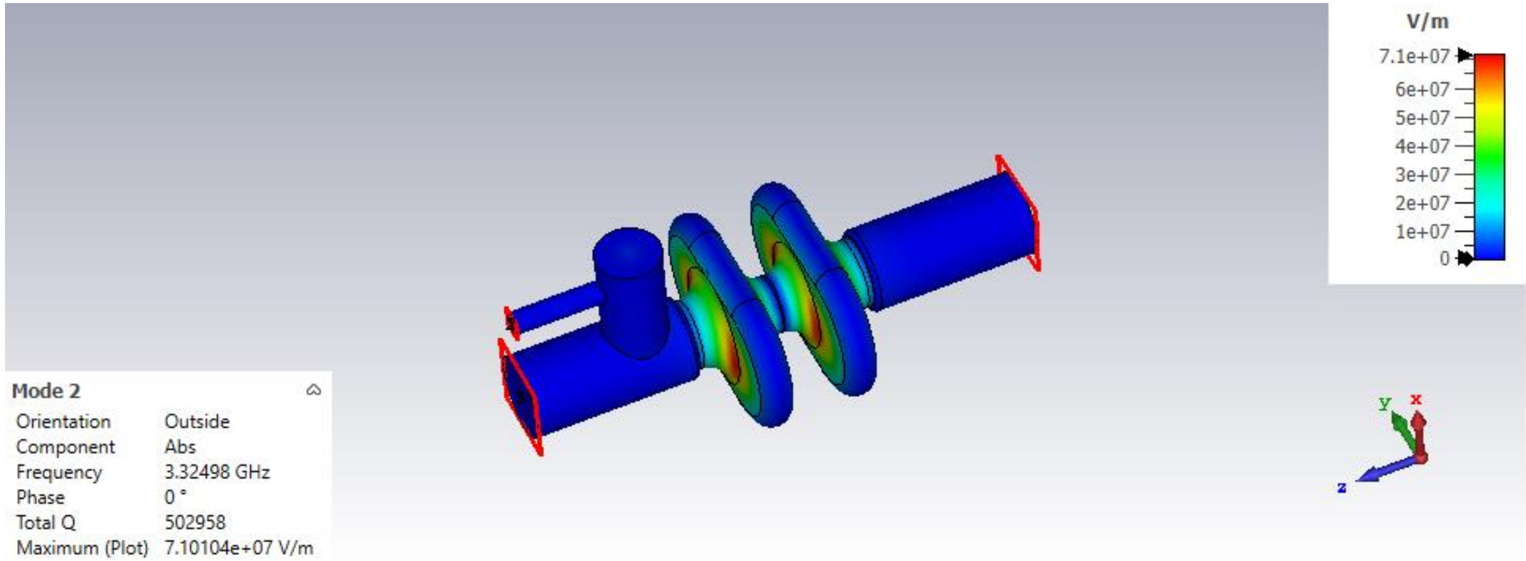
# Trapped lower order modes



- Trapped mode in the centre cell may be difficult to damp so may be a larger issue
- Its caused by the racetrack geometry, as can be seen the fields are away from the iris reducing the cell-to-cell coupling
- Solutions:
  - Less elliptical design
  - Larger aperture
  - Elliptical aperture
  - On-cell damping
  - 2 cell design

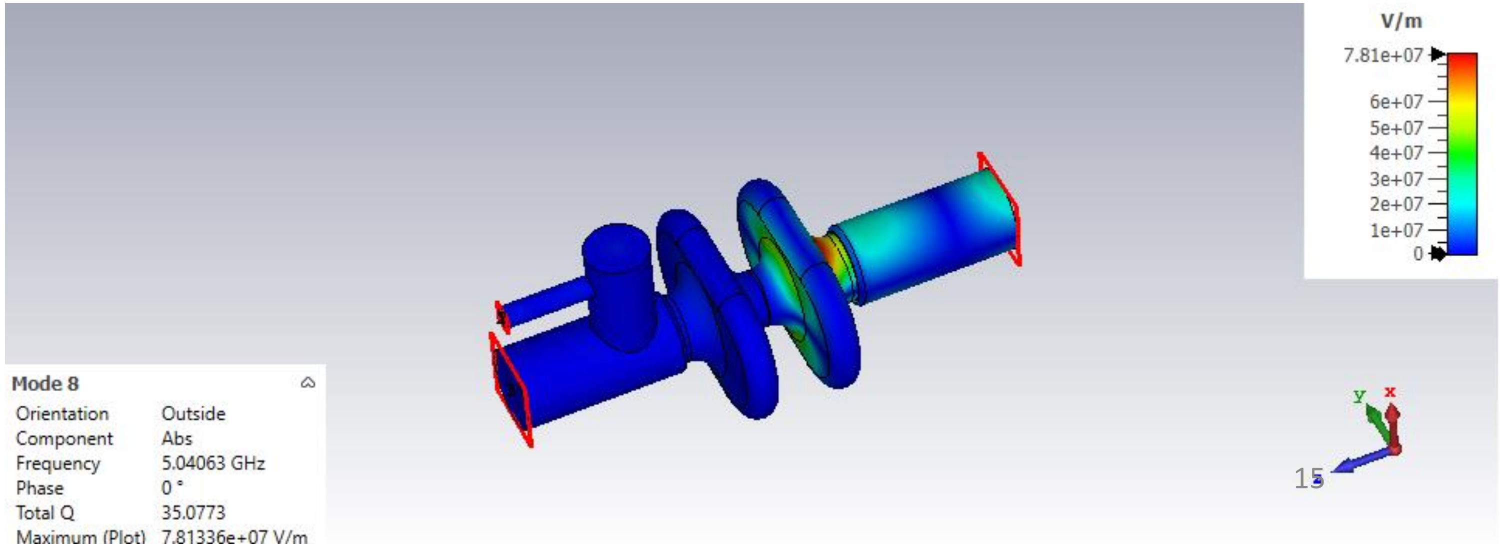


# Option 1: 2 cell cavity



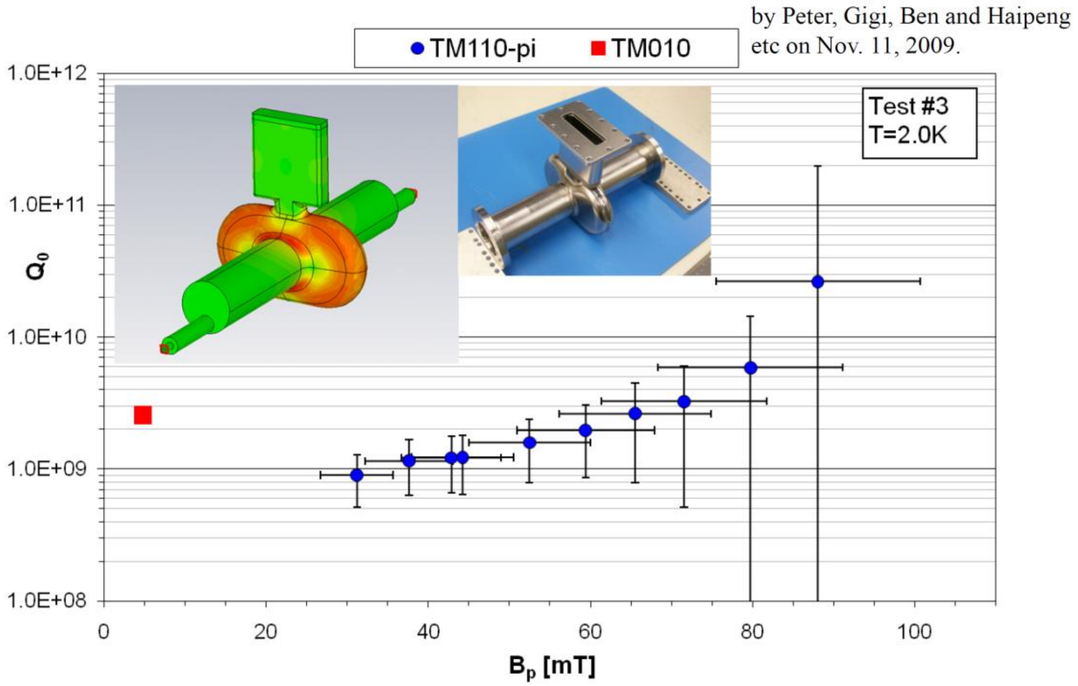

- A 2 cell cavity has no trapped mode
- However the gradient required is much higher unless we use two cavities

- LOM Q factor goes to 500,000
- SOM Q is 35-100 so not an issue.



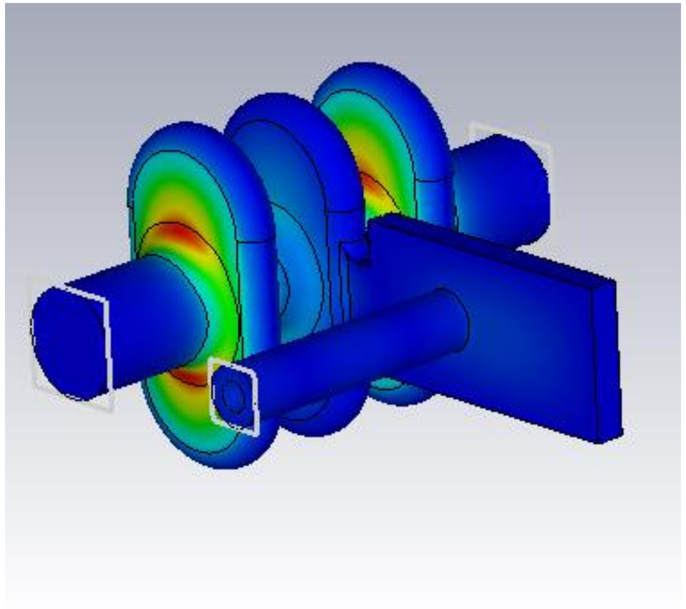
# Option 2: Waveguide damping

Jlab developed an on-cell waveguide for SPX, provides better LOM damping



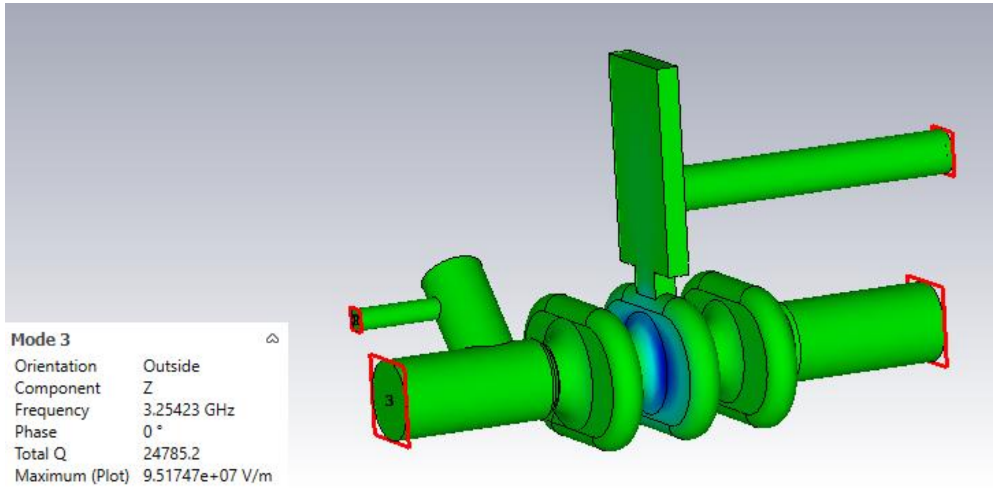

Considering a waveguide section with a coax coupled to it to minimize size and heat leak. Coax can be positioned to prevent coupling to the crabbing mode.

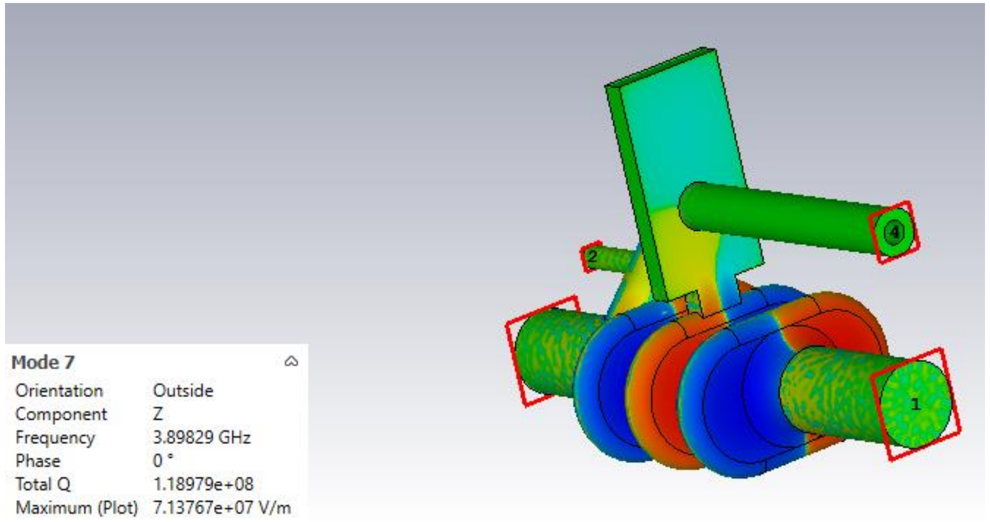
Good damping overall except one mode, unfortunately the highest impedance mode.



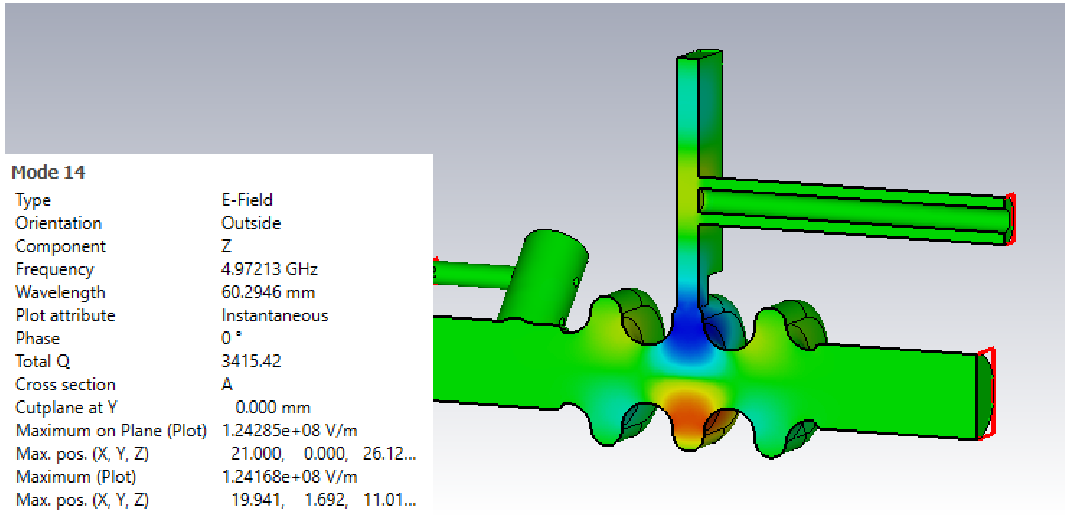
- Waveguide damper does damp the pi and 0 modes well but doesn’t damp the pi/2 modes but these will be damped strongly by a coax damper in the beampipes.

# Waveguide damper with coax antenna

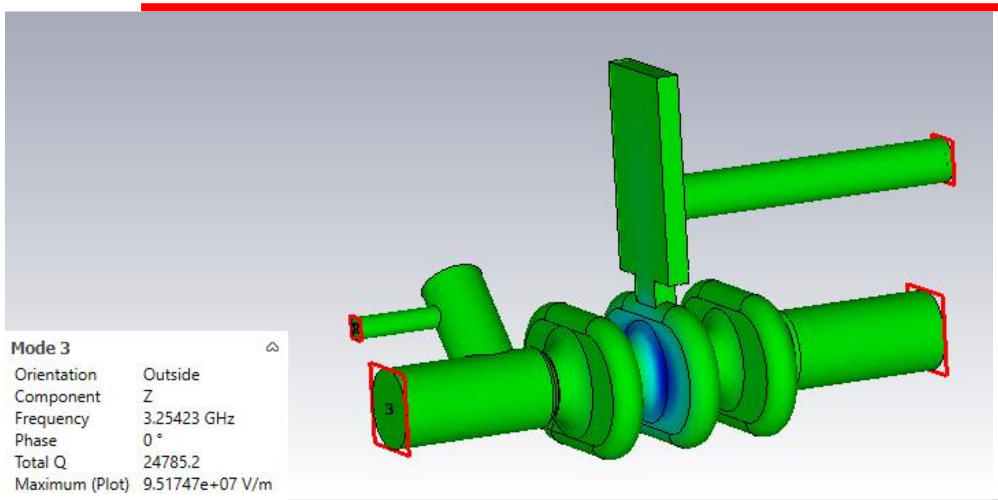


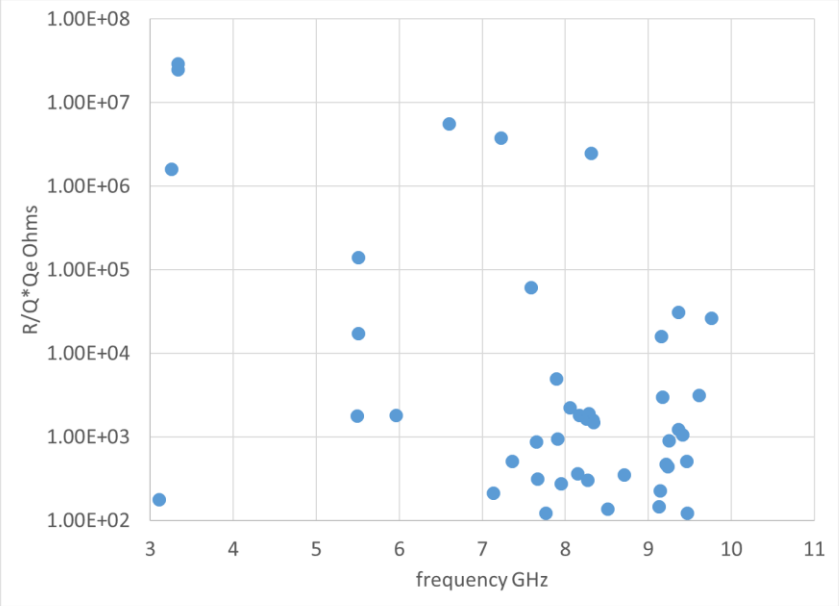



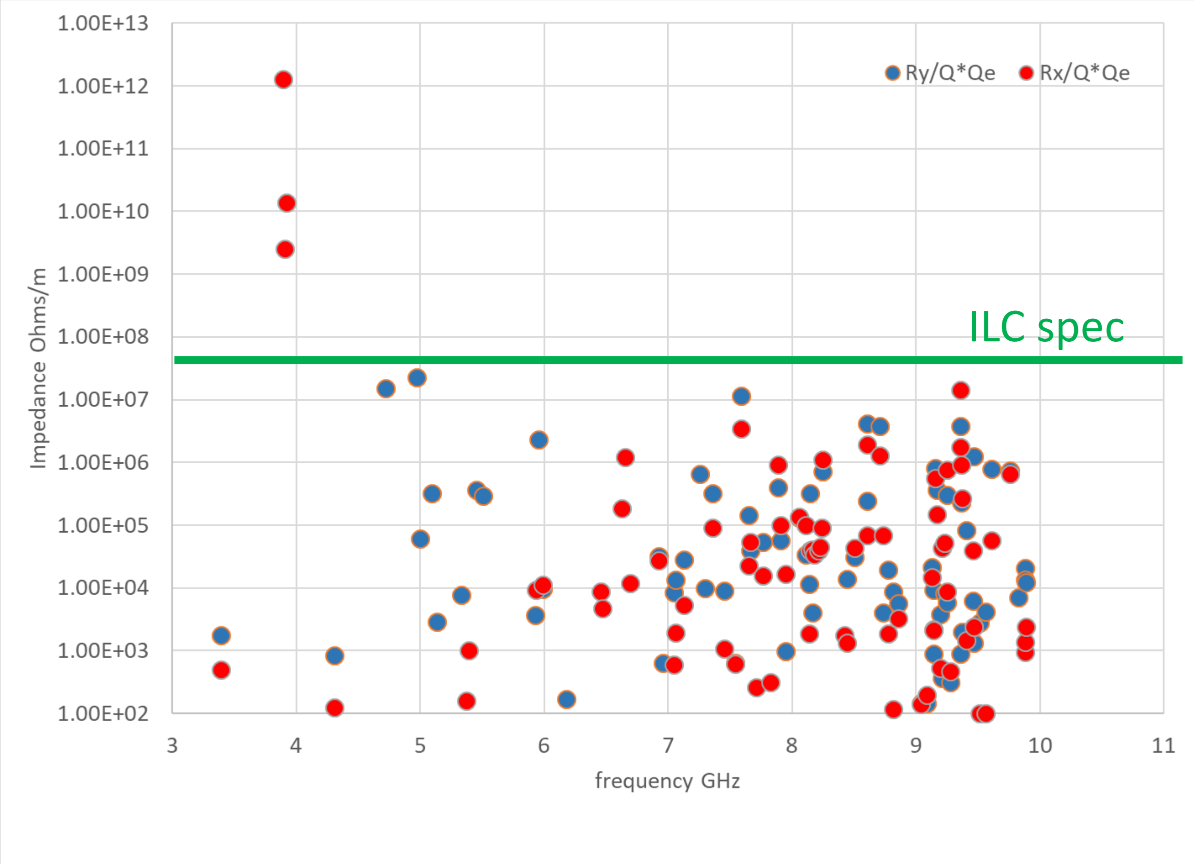

- Waveguide has a coax antenna positioned at the field null in the waveguide at 3.9 GHz but field maxima at 3 and 5 GHz to damp LOM and SOM
- LOM Q is 25,000 and SOM Q is 3,500



# Impedance for waveguide damped 3 cell

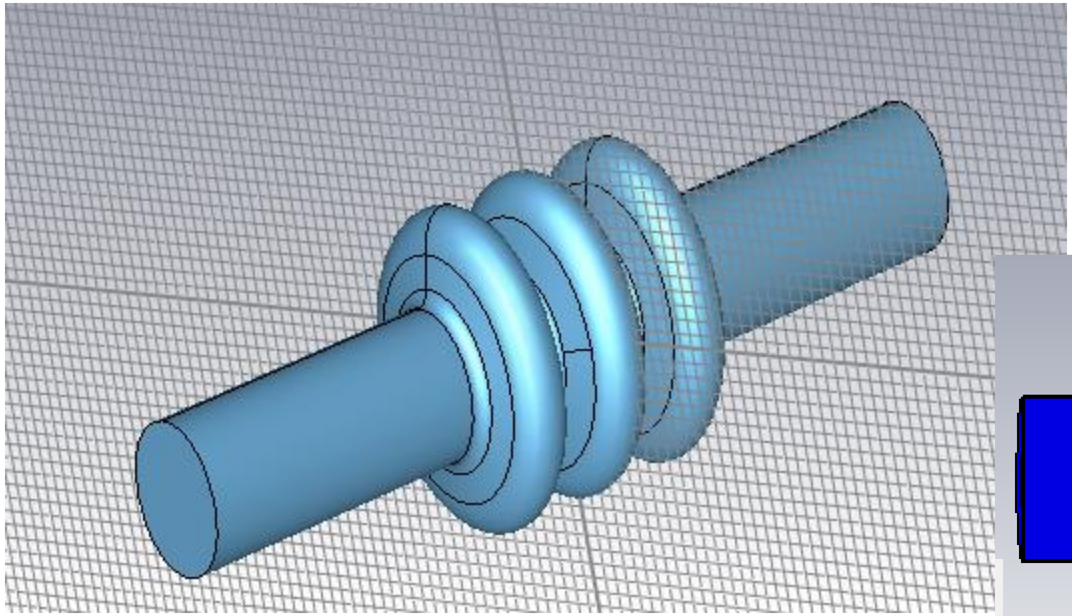


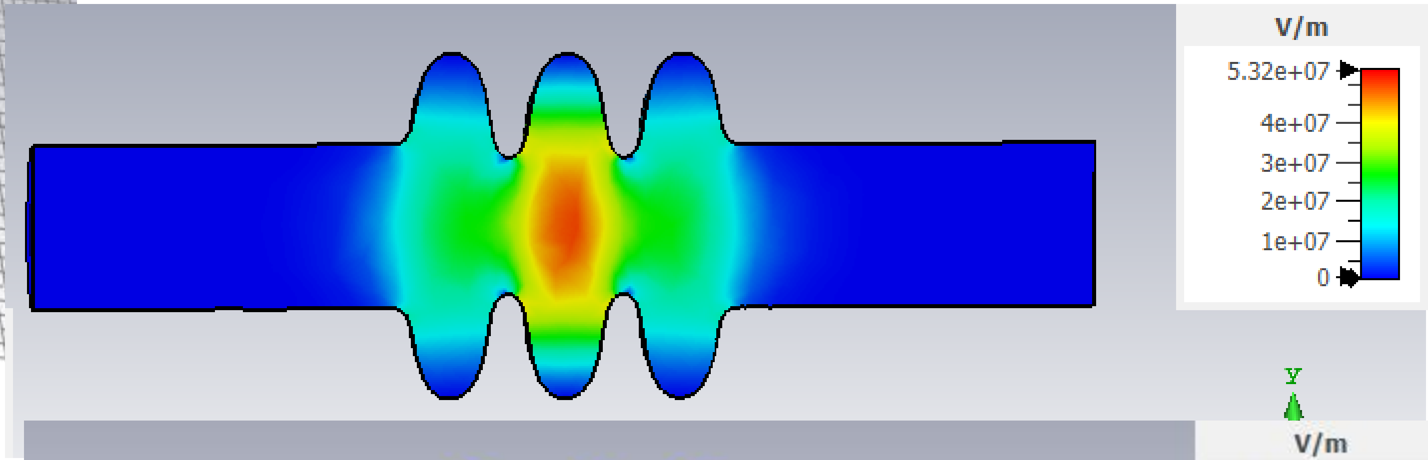



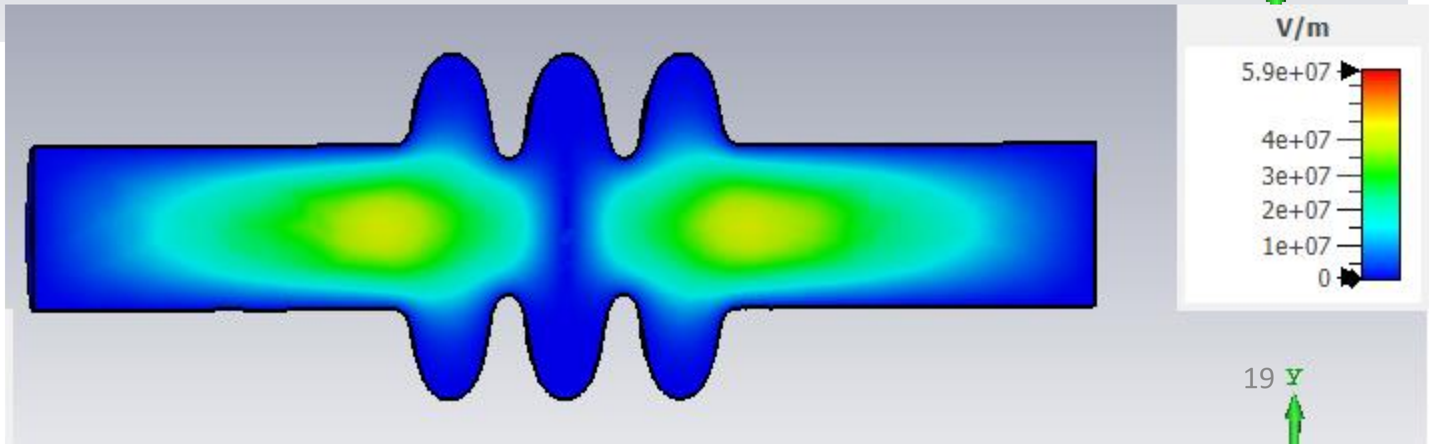

- The long. Impedance has no spec, the transverse impedance meets the spec except the other modes in the crabbing passband
- The FPC may well damp these

# Option 3: Elliptical Aperture



- An elliptical aperture means there is more coupling between the LOM and SOM in each cell.

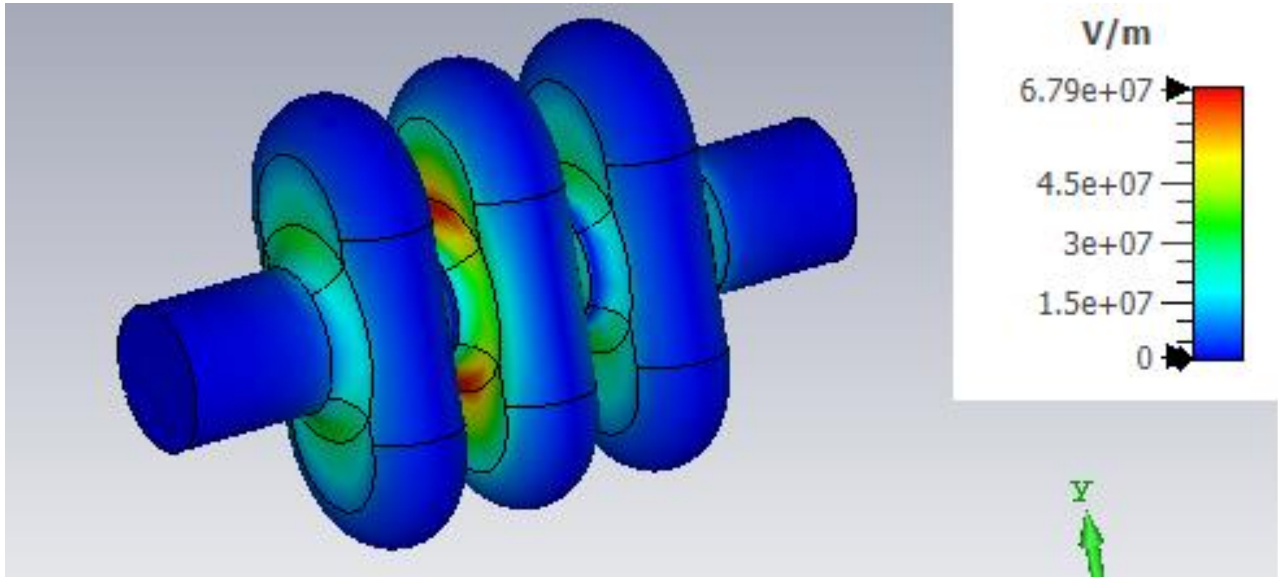


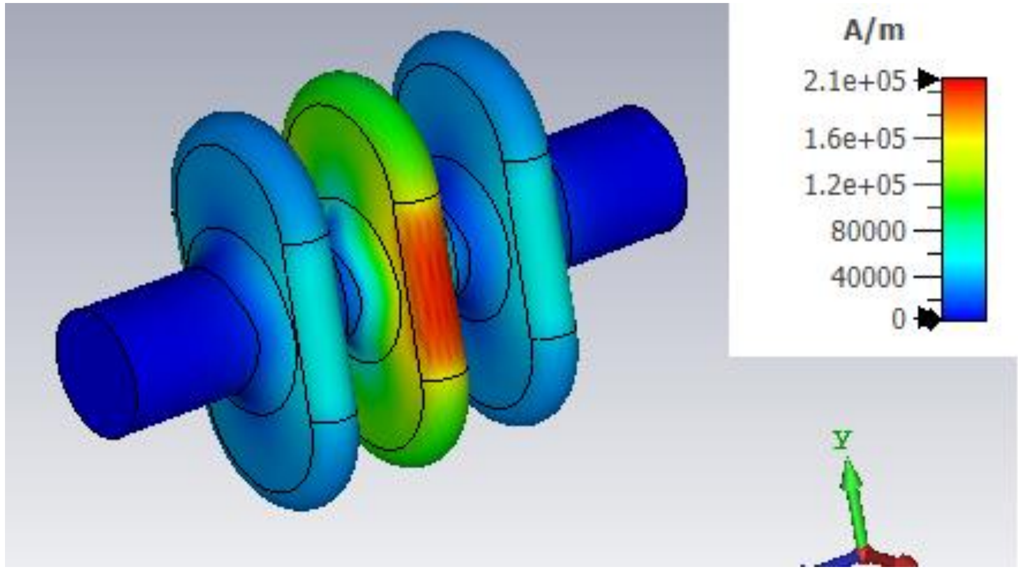




- LOM is at 3 GHz and has field in all cells now
- SOM actually moves down in frequency not up to 3.3 GHz but beampipe cutoff now 3.4 GHz in vertical plane

# Option 4: Larger aperture/ thinner aperture

- 30 mm aperture allows some field in the end cells, which might be OK.
- 35 mm might be better but starts to impact peak fields/ maximum ellipticity



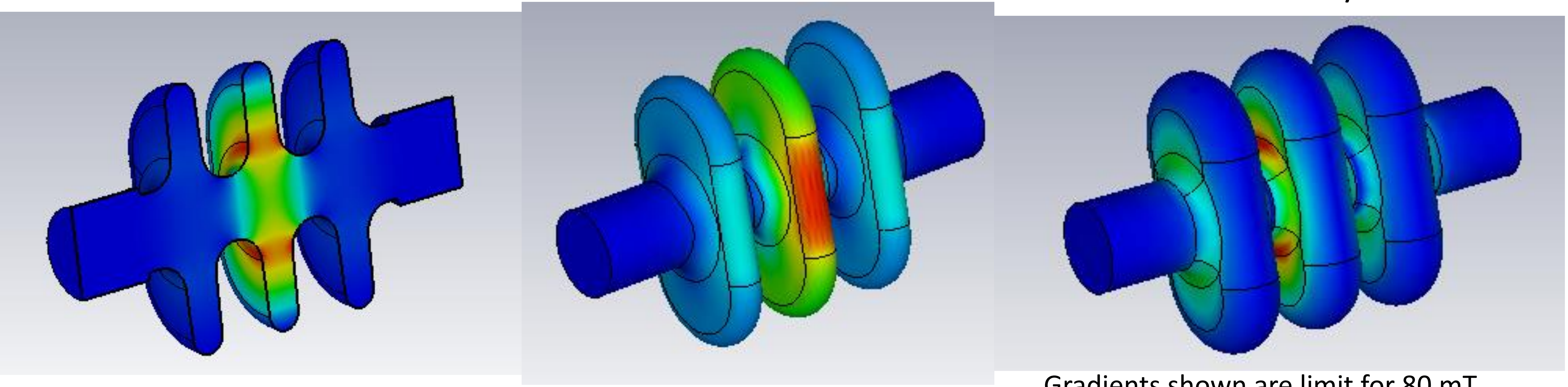




- We had a thick iris as this gave the lowest peak fields but using a thinner iris increases cell coupling
- Peak fields were well below limits (80 mT at 7.2 MV/m)

# Design evolution: **Option 4 selected**

Original design → Larger iris → Thinner iris

Original design 9.5 MV/m | Thinner iris 7.2 MV/m



Gradients shown are limit for 80 mT

Aperture size = 30 mm, increasing to 40 mm
Cavity major/min radii = 55.7 / 30.6 mm
Ration major/min axis = 0.55

LOM freq= 3.3 GHz
SOM freq= 5.0 GHz

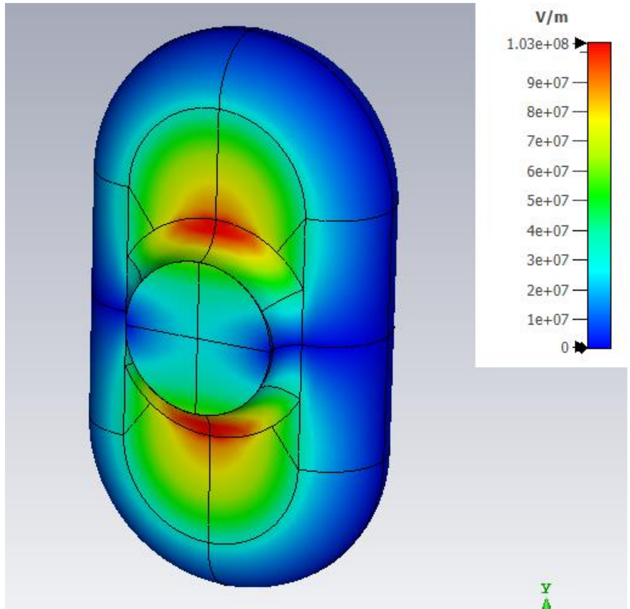
# Final mid-cell and 3 cell

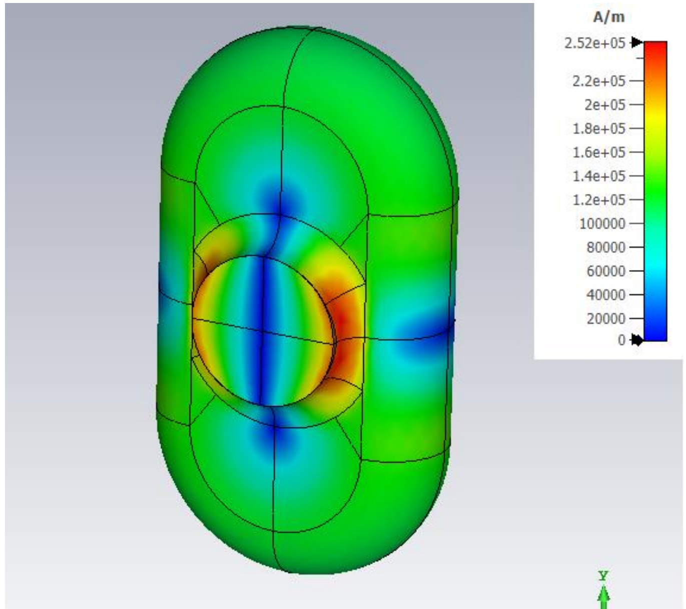
## Mid-cell

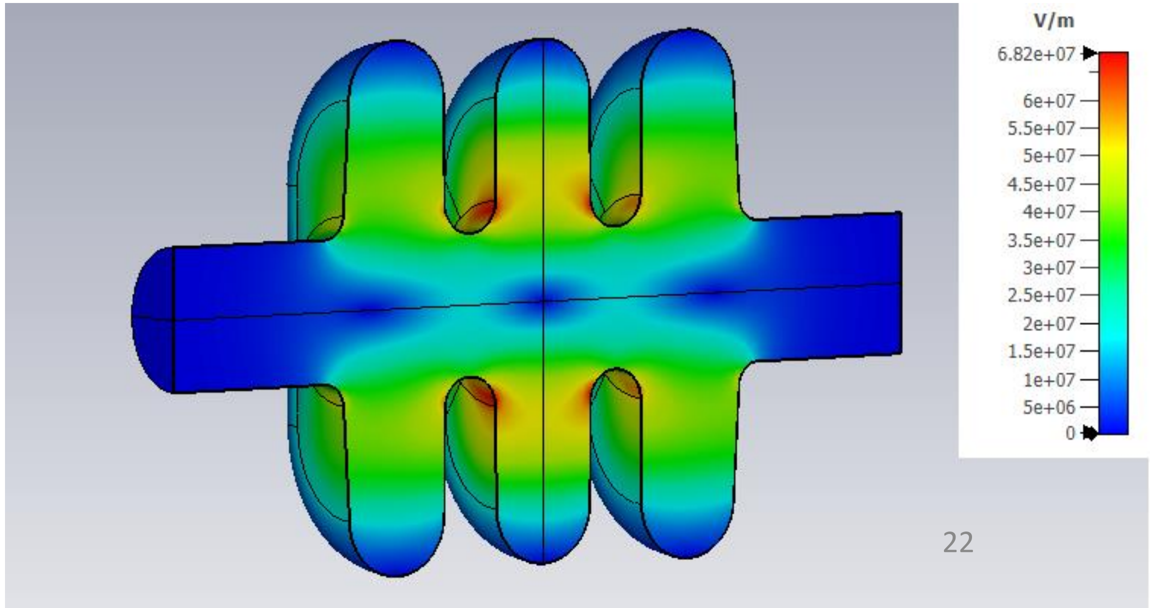
| | | |
|---|---|---|
| Required $E_t$* | 5.00 | MV/m |
| $E_{pk}$ operational | 18.20 | MV/m |
| $B_{pk}$ operational | 56.10 | mT |
| $B_{pk}/E_{pk}$ | 3.08 | |
| $R_t/Q$ | 48.00 | Ohms |
| G | 202.00 | |

## 3 cell

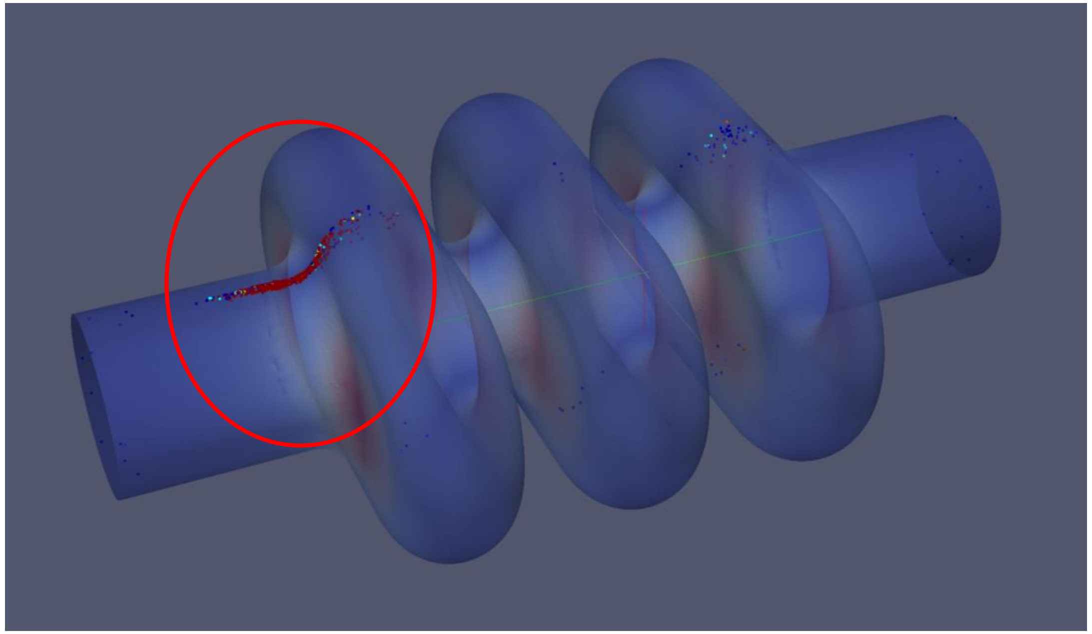
| | | |
|---|---|---|
| Required $E_t$* | 5.3 | MV/m |
| $E_{pk}$ operational | 22.5 | MV/m |
| $B_{pk}$ operational | 66.6 | mT |
| $B_{pk}/E_{pk}$ | 2.96 | |
| $R_t/Q$ | 140.00 | Ohms |
| G | 207.00 | |



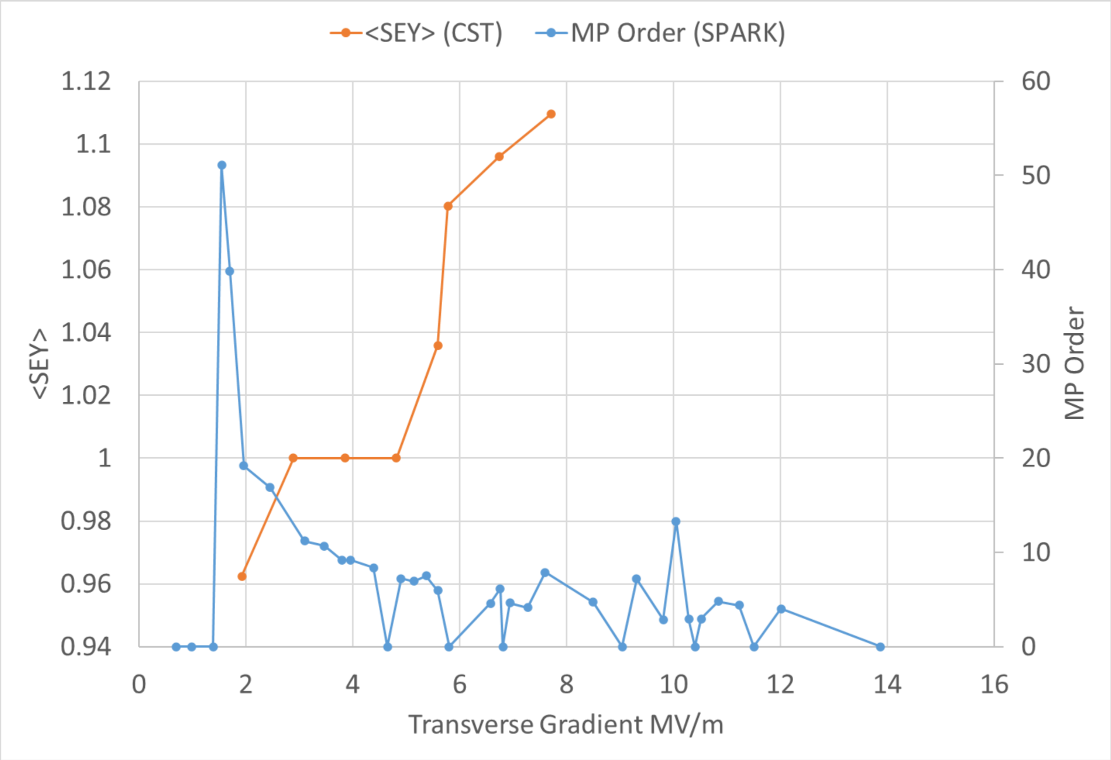



# Multipactor

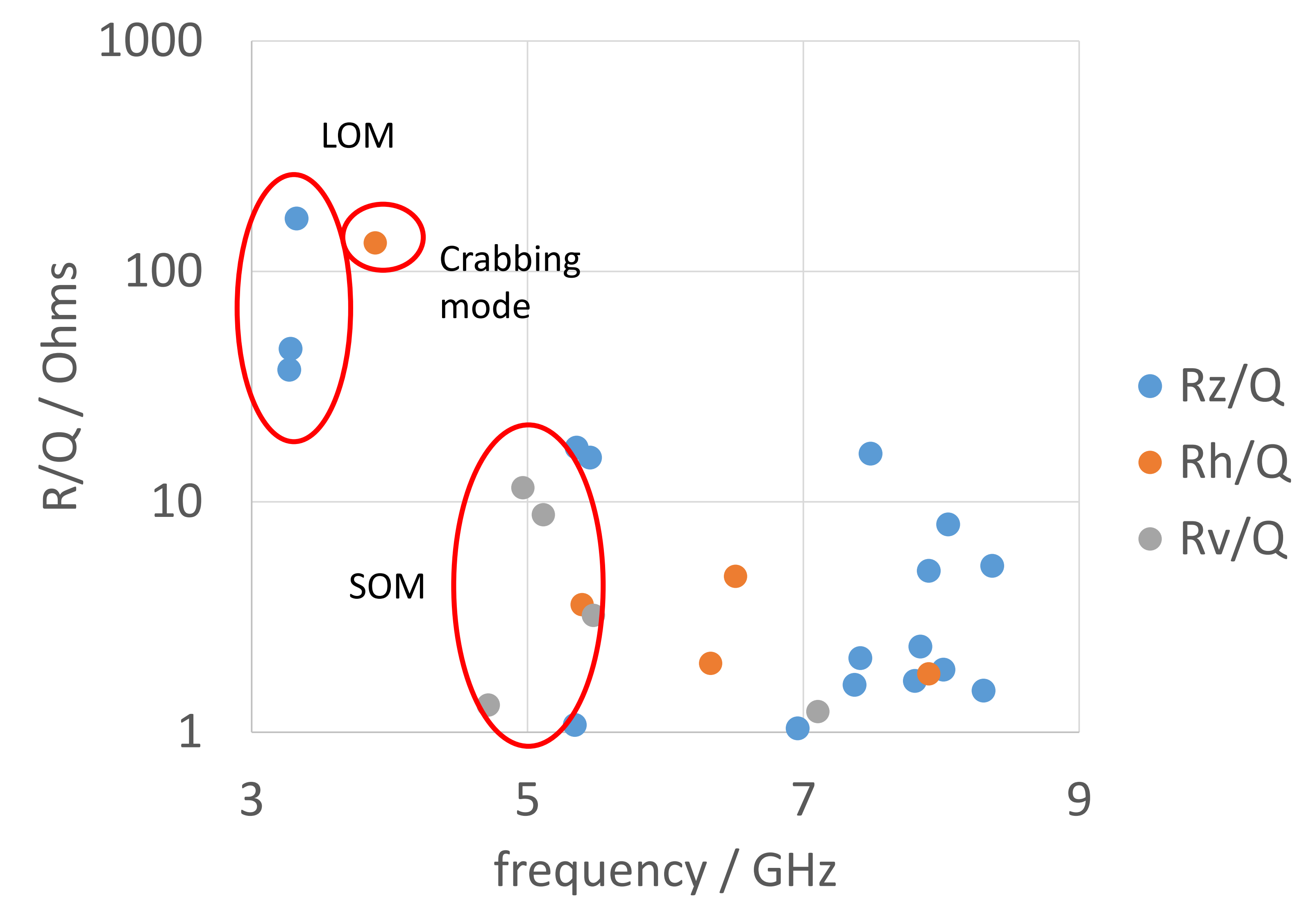


- Mid cell multipactor is up at 8 MV/m nothing seen below this
- Original elliptical design and smaller aperture design had no multipactor so clearly scope to move this
- The end cell has very low peak fields so design can prioritise multipactor suppression

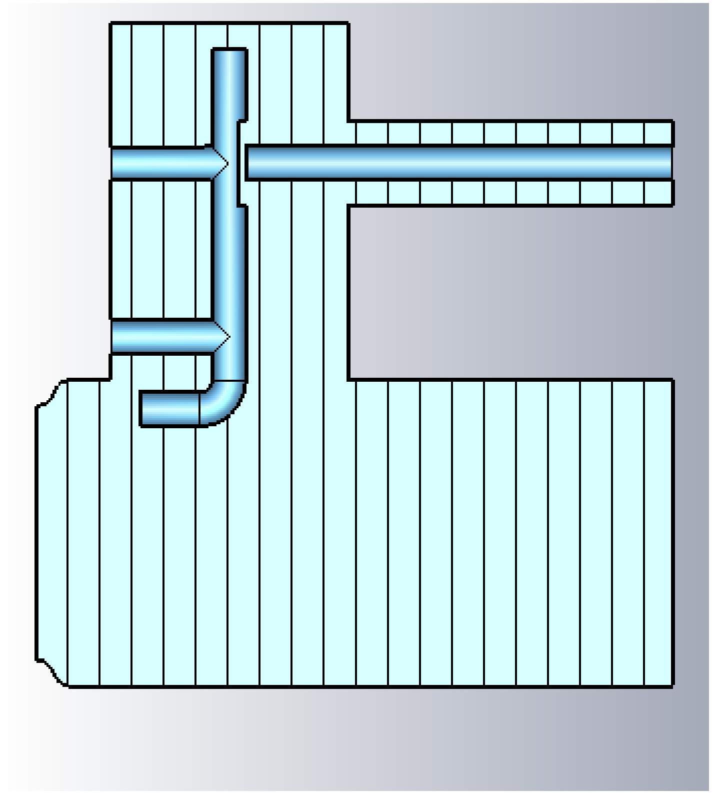
- Higher order (4th – 6th), slow-growing multipactor band found at 5.6 MV/m on minor axis iris of the end cell
- No growth below 5.6 MV/m in CST
- Multipactor is only on the end cell iris not the middle iris.



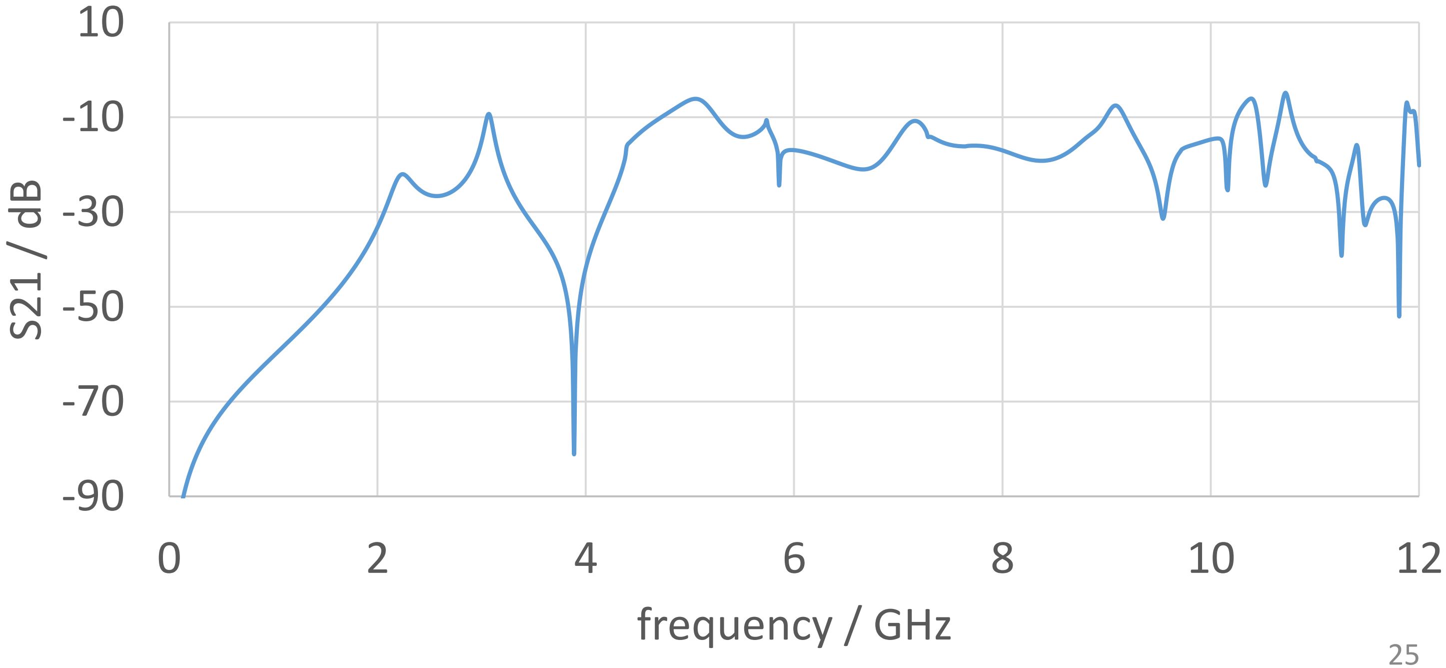
# Mode spectrum



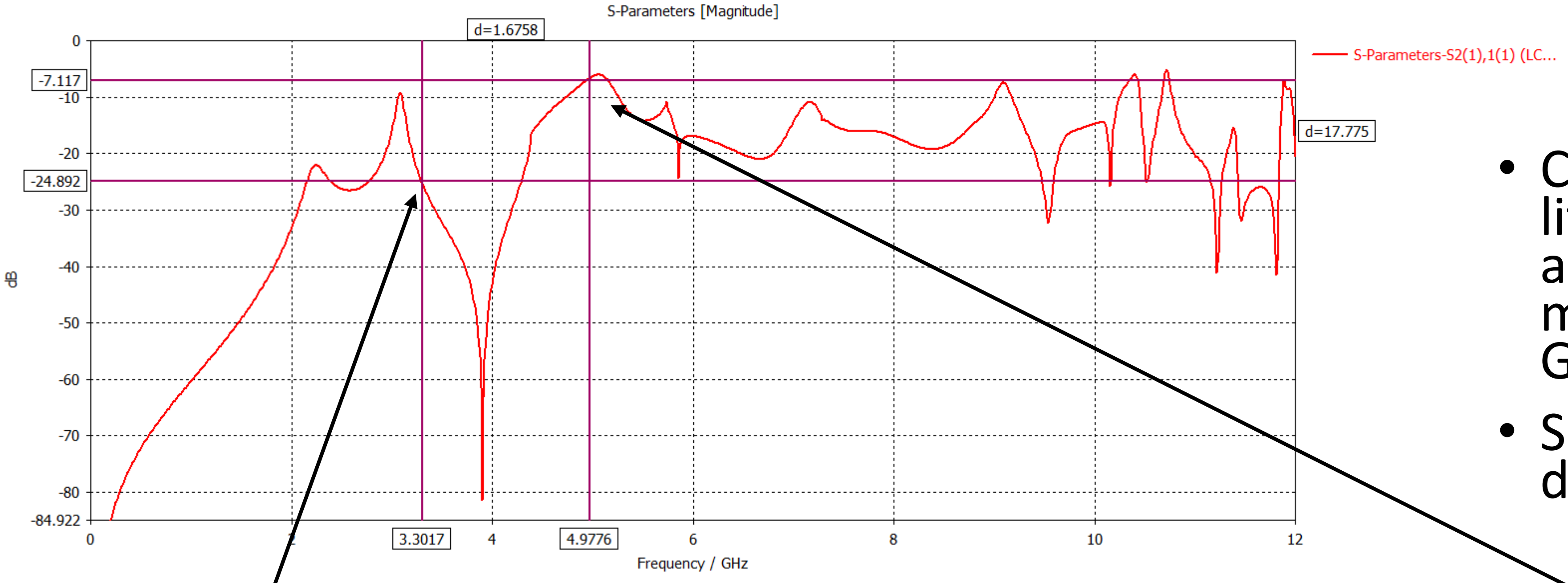
# HOM coupler design



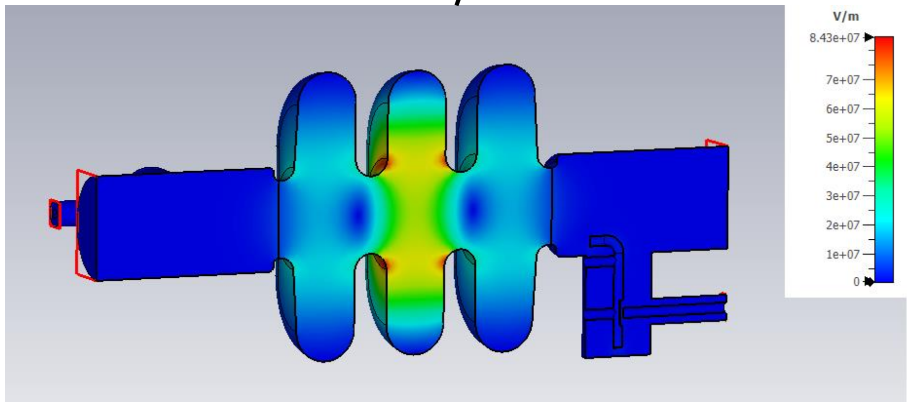
- Modified version of old ILC HOM coupler, similar to ILC main linac coupler
- Designed to have larger transmission at the LOM and SOM frequencies while filtering 3.9 GHz

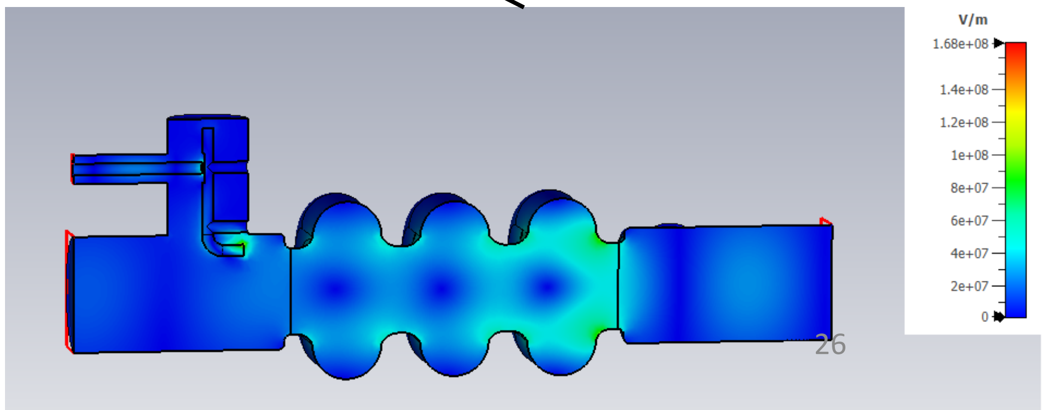


# Coax Coupler at key modes



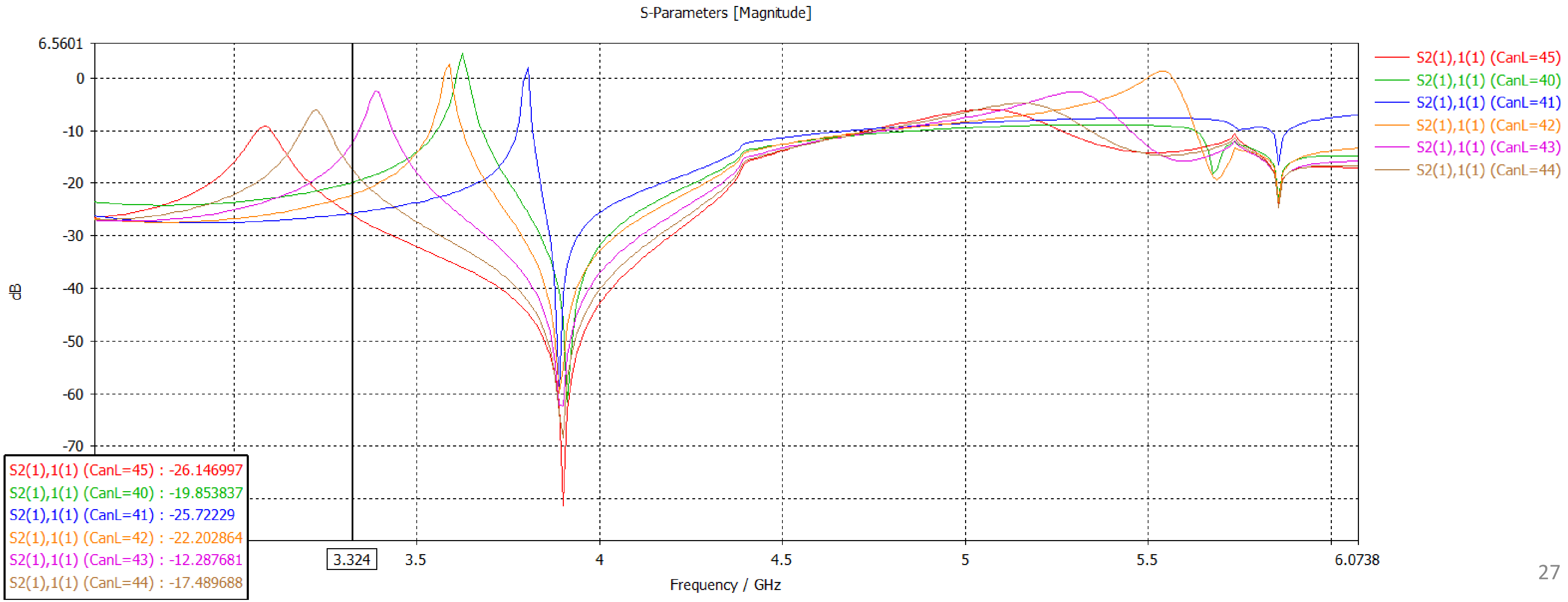

- Could do with a little optimization around the LOM to move peak to 3.3 GHz
- SOM is well damped



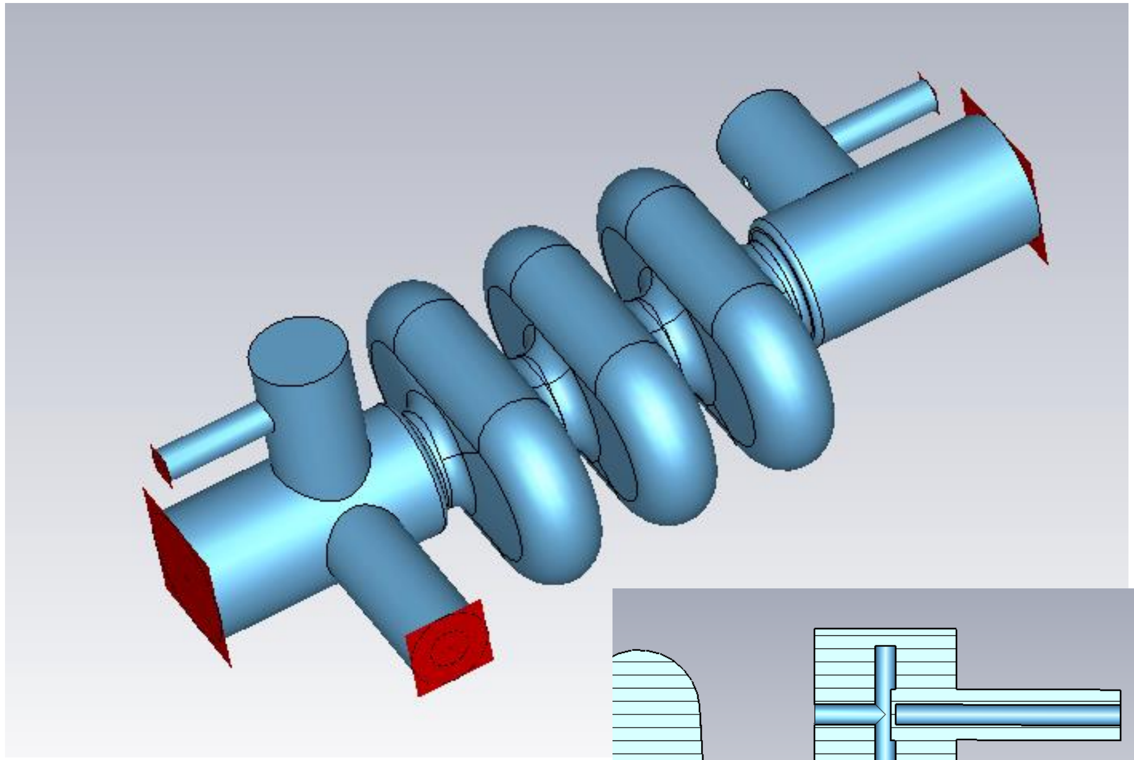
# Improved HOM design

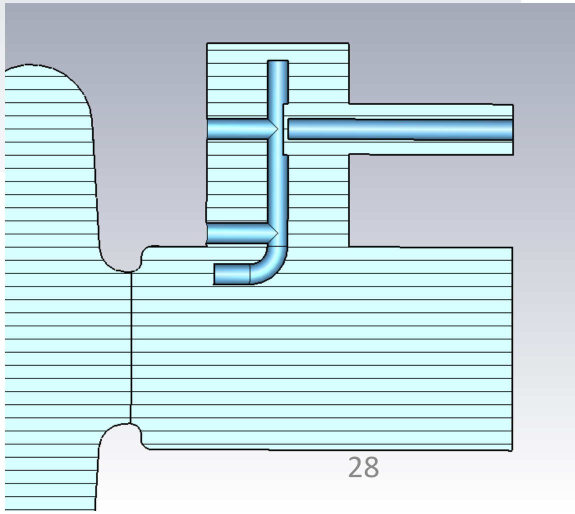
- Making the HOM can 2.5 mm shorter shows strong damping on the LOM at 3.3 GHz but impedance calculations were done with old design



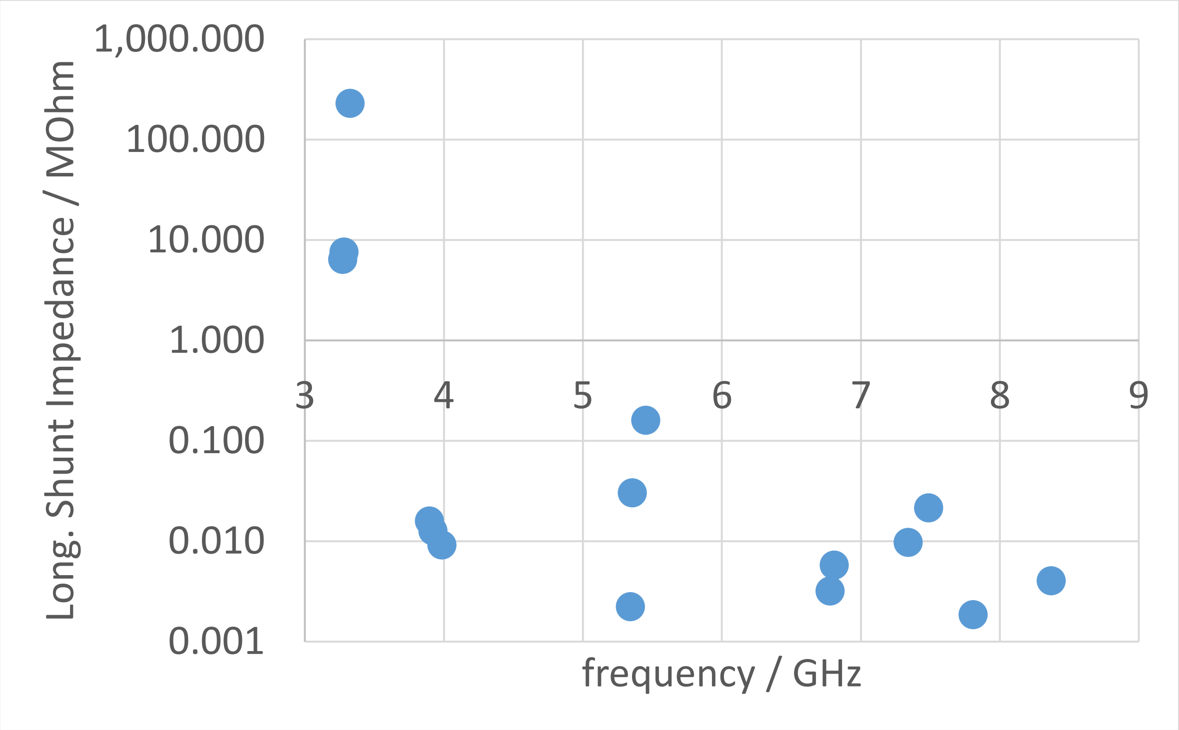
# HOM coupler configuration

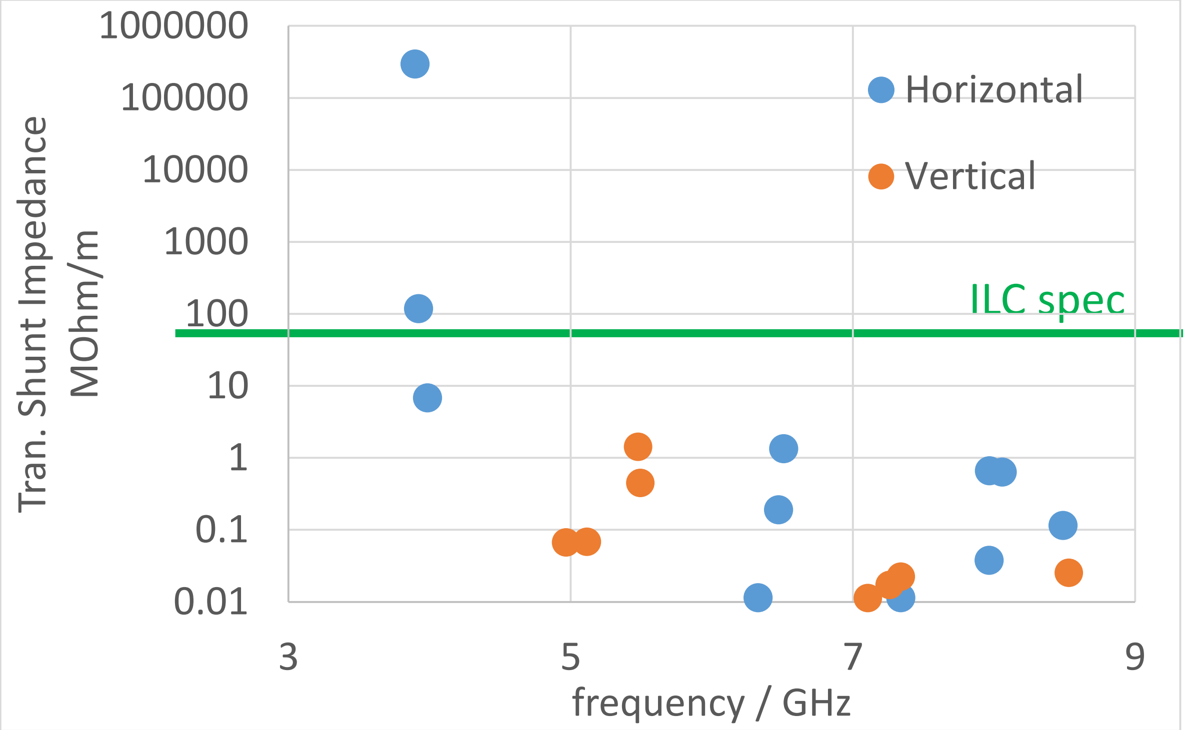
- The beampipe expands to 20 mm radius to push the cutoff frequency of the TM01 mode down
- This has negligible effect of RF performance
- Use two identical coaxial HOM couplers
- HOM protrudes into the beampipe but still respects 25 mm clearance





# Impedance for coax damped 3 cell

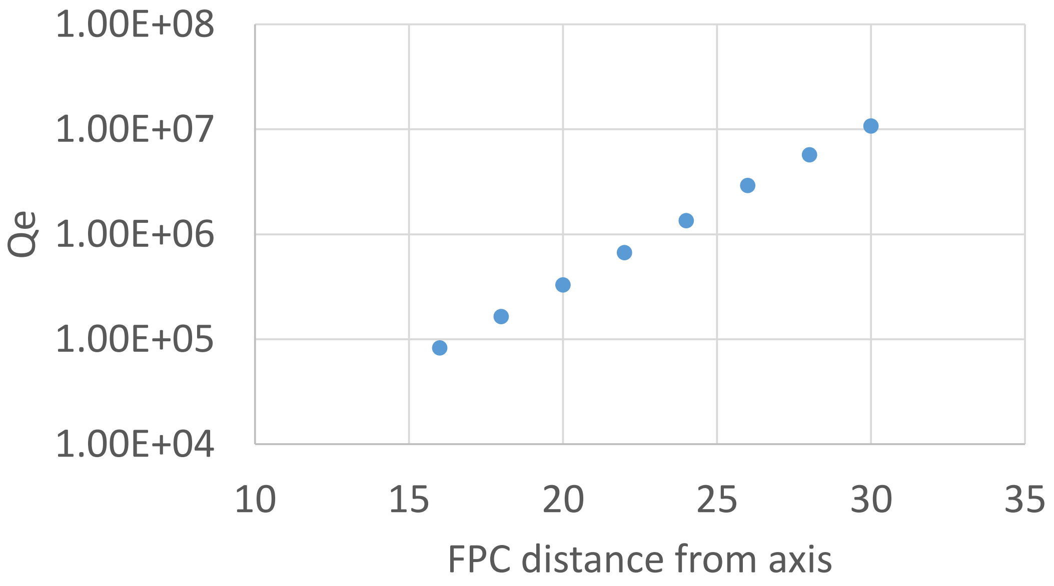


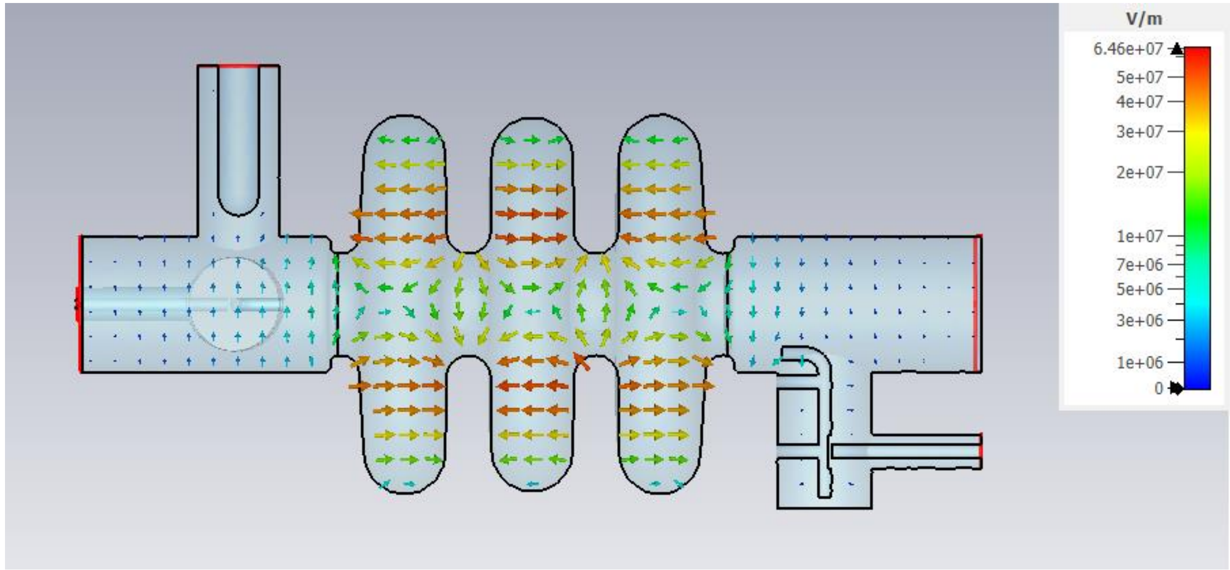




- The long. Impedance has no spec, Q achieved is around $2x10^5$
- The transverse impedance meets the spec except the other modes in the crabbing passband
- The FPC will likely damp these

# Fundamental power coupler

- Required QL is $10^7$ as the beam power at 0.5 mm is 200 watts.
- FPC is 30 mm off axis (10 mm from the beampipe) or could shift further from the cavity

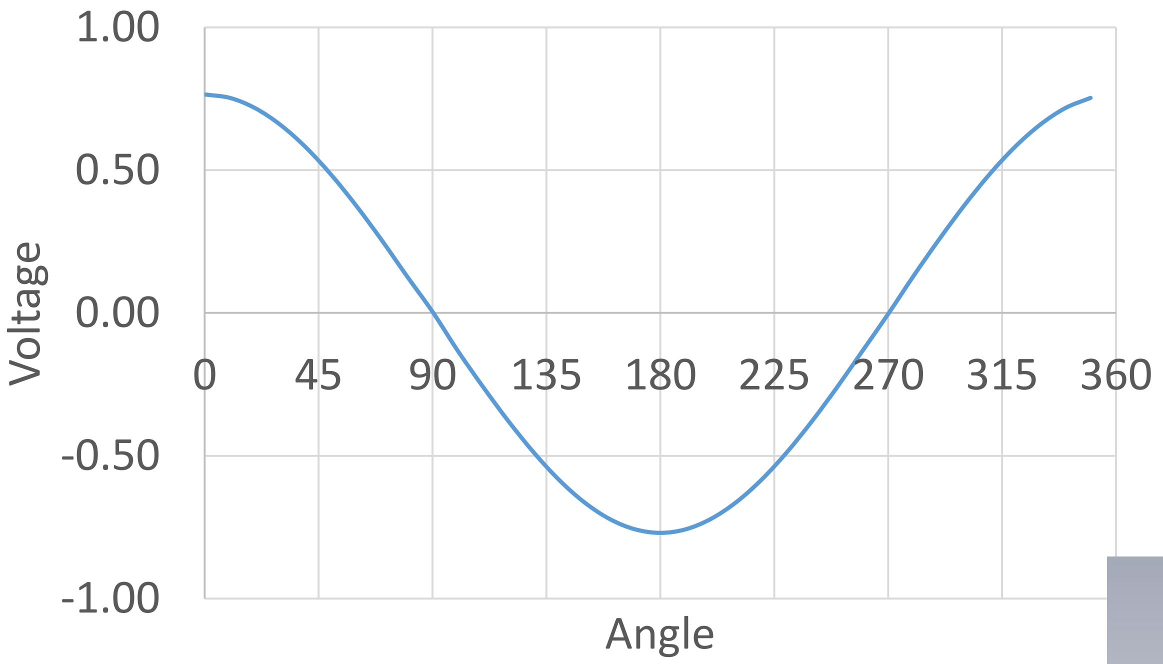


Lancaster University

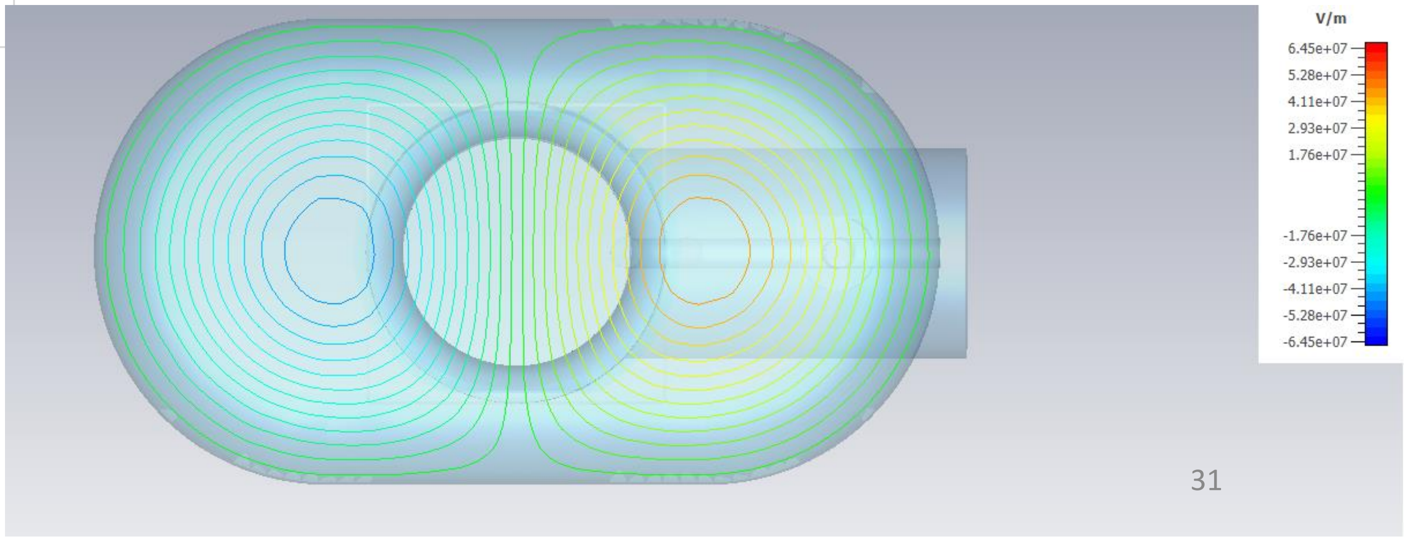
Science and Technology Facilities Council

# Multipole with couplers

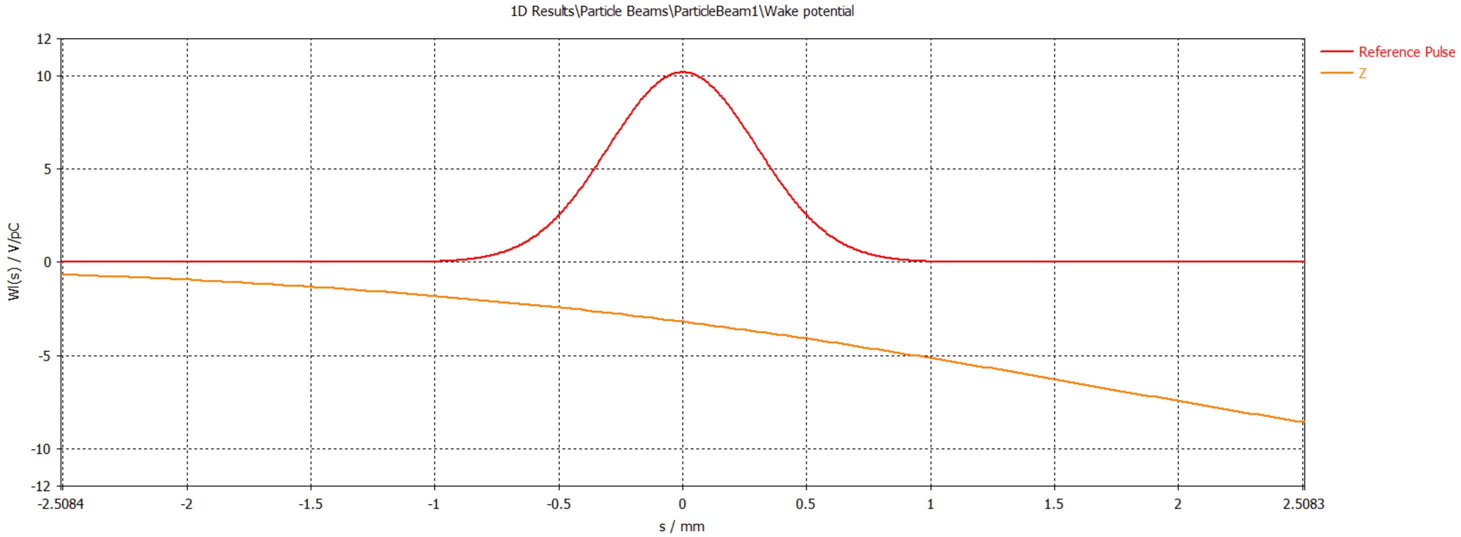



- At 5 MV/m the longitudinal voltage on axis is 570 V
- The multipoles at 5 mm normalized to b1 are shown in the table (up to b3):

| | |
|---|---|
| b1 | 1 |
| b2 | 0.102346 |
| b3 | 251.7836 |



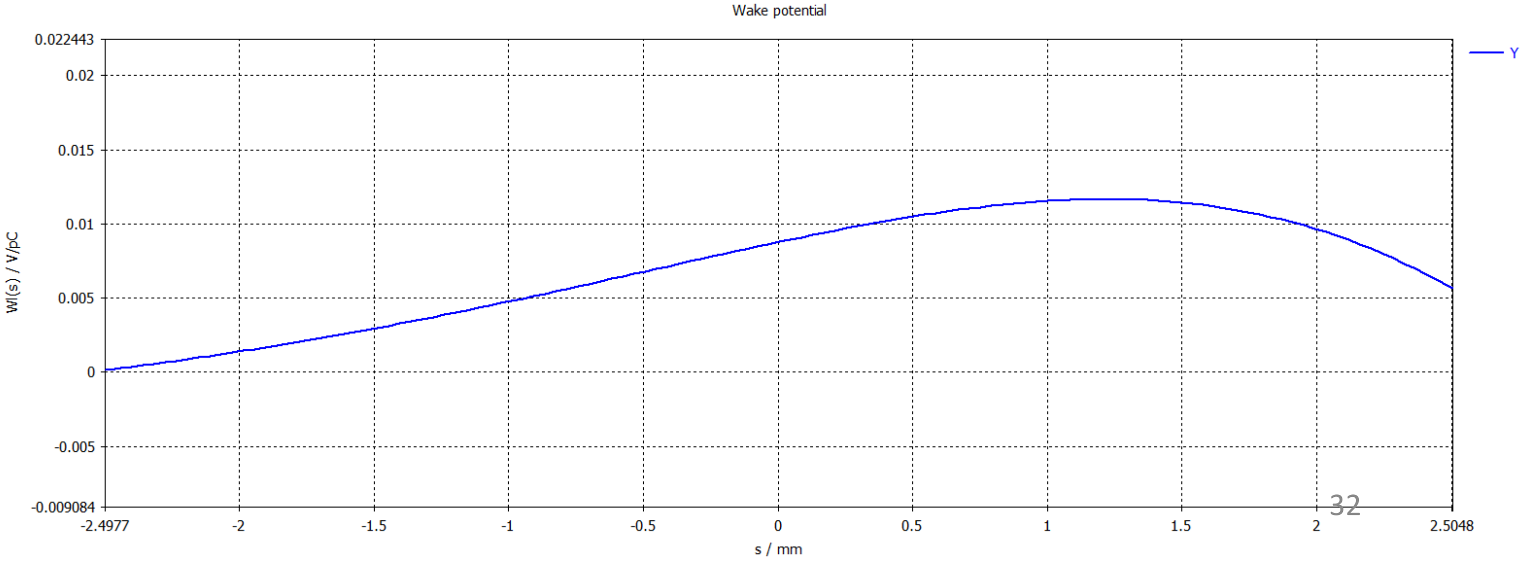
# Short range Wake




- The short range wake has been calculated for a 0.3 mm long bunch.
- The transverse voltage was calculated with a 1 mm offset
- Both long. and trans. Wakes are very small

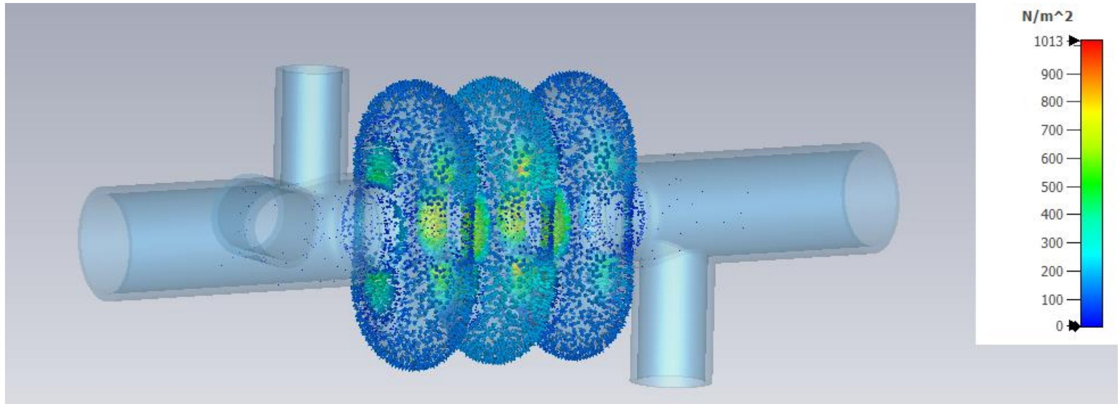
Loss factor= 3.2 V/pC

Kick factor = 16 V/pC/m

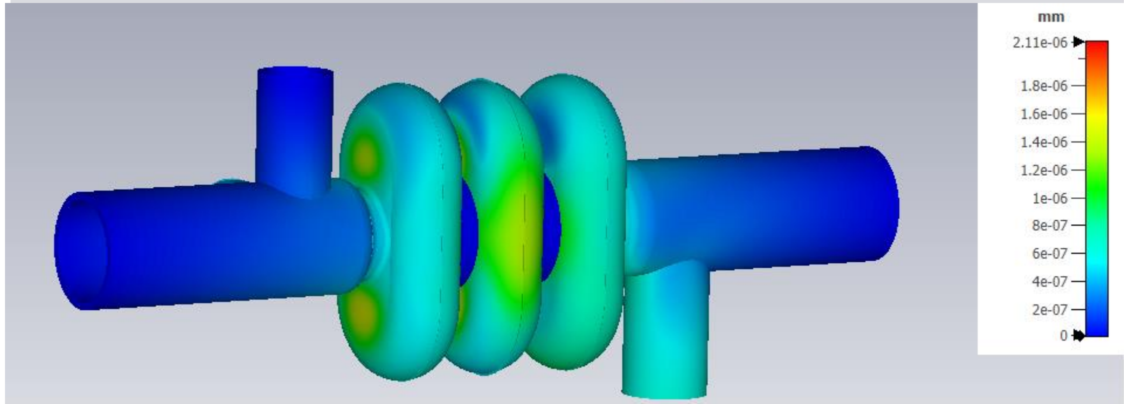


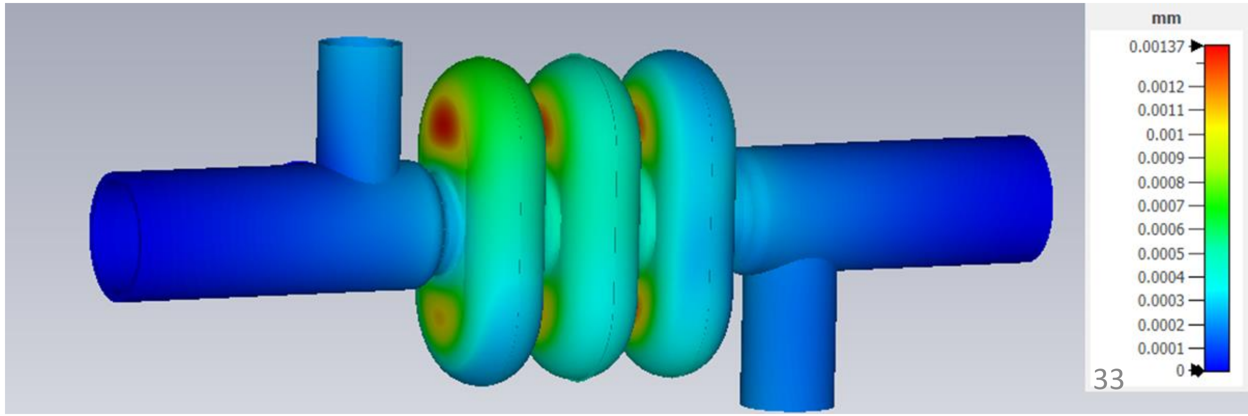
# Lorentz force and pressure deformation

- Lorentz force is 1.0 kN/m^2 at 5 MV/m gradient which is fairly small
- Equivalent to a 4 nm change in the cavity length (for 3 mm thick walls) which is 120 Hz,




- The frequency shift due to a 1 bar pressure difference is 90 kHz hence the pressure sensitivity is 90 Hz/mbar
- Max Stress is 5.4 MPa



# UK ILC Crab Cavity Cryo Design

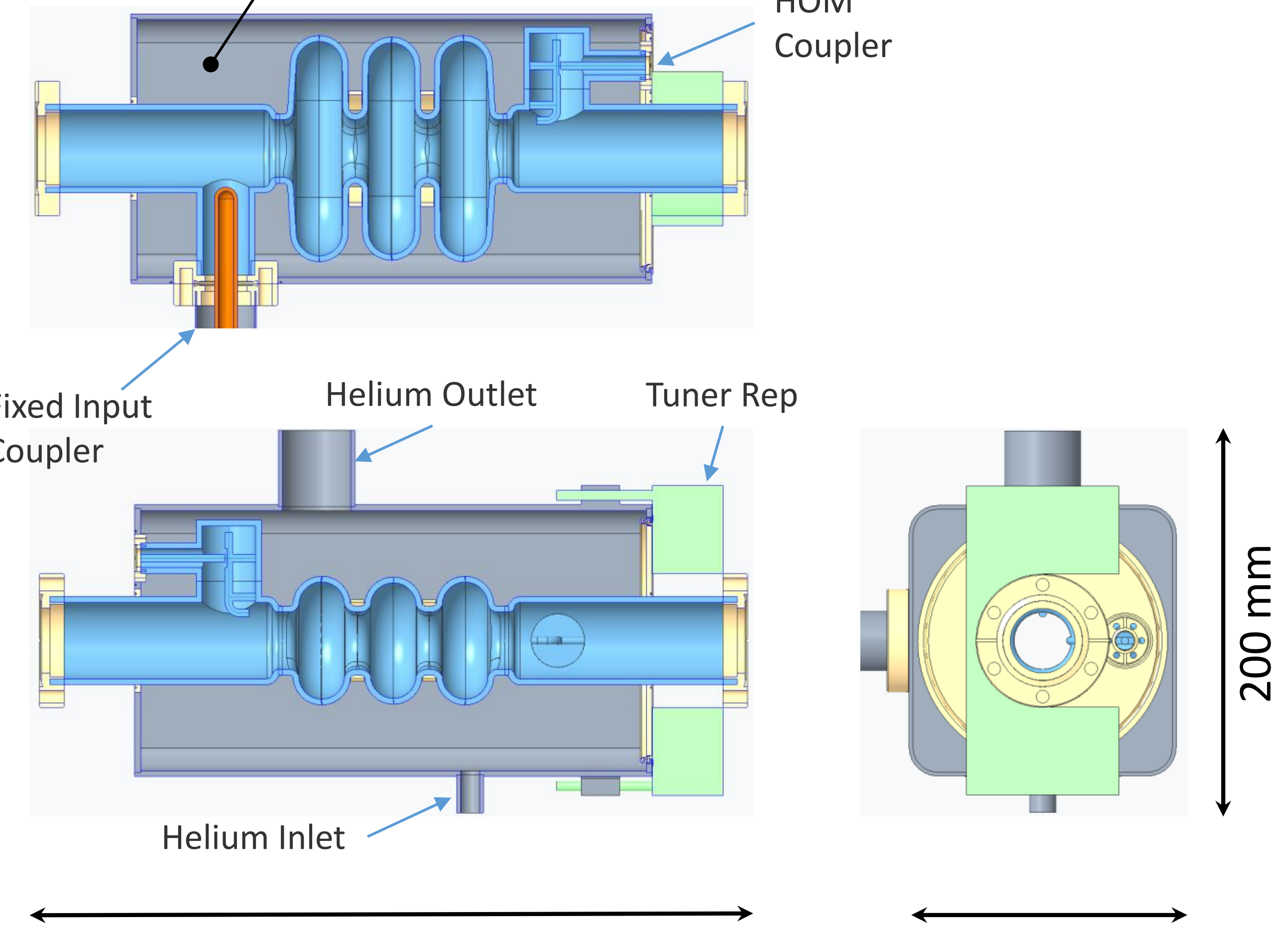
James Bourne & Niklas Templeton

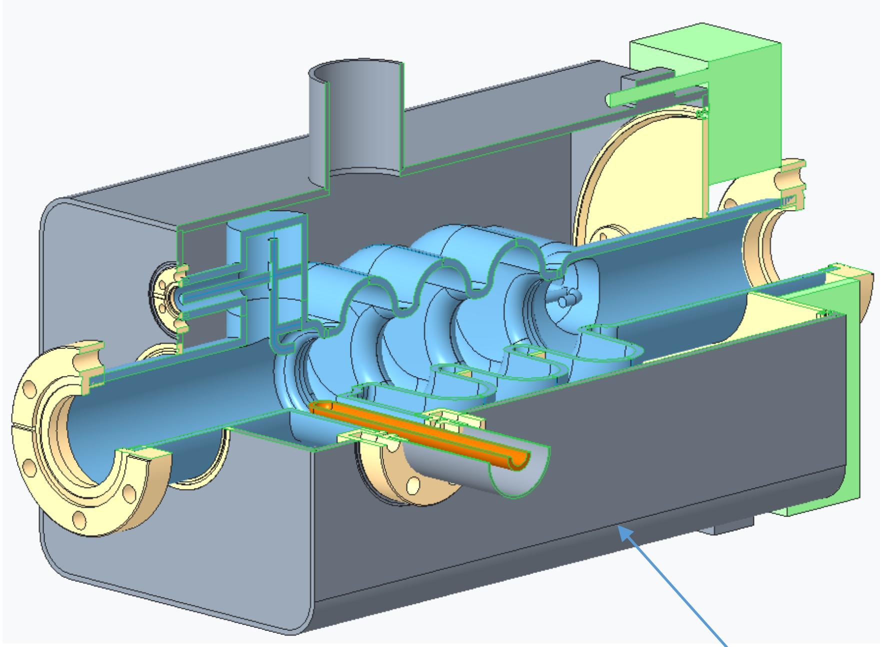
Lancaster University

UKRI Science and Technology Facilities Council

# UK ILC 3.9GHz Racetrack Crab Cavity

Helium Tank Internal Volume 4.3 litres (PED Category I)



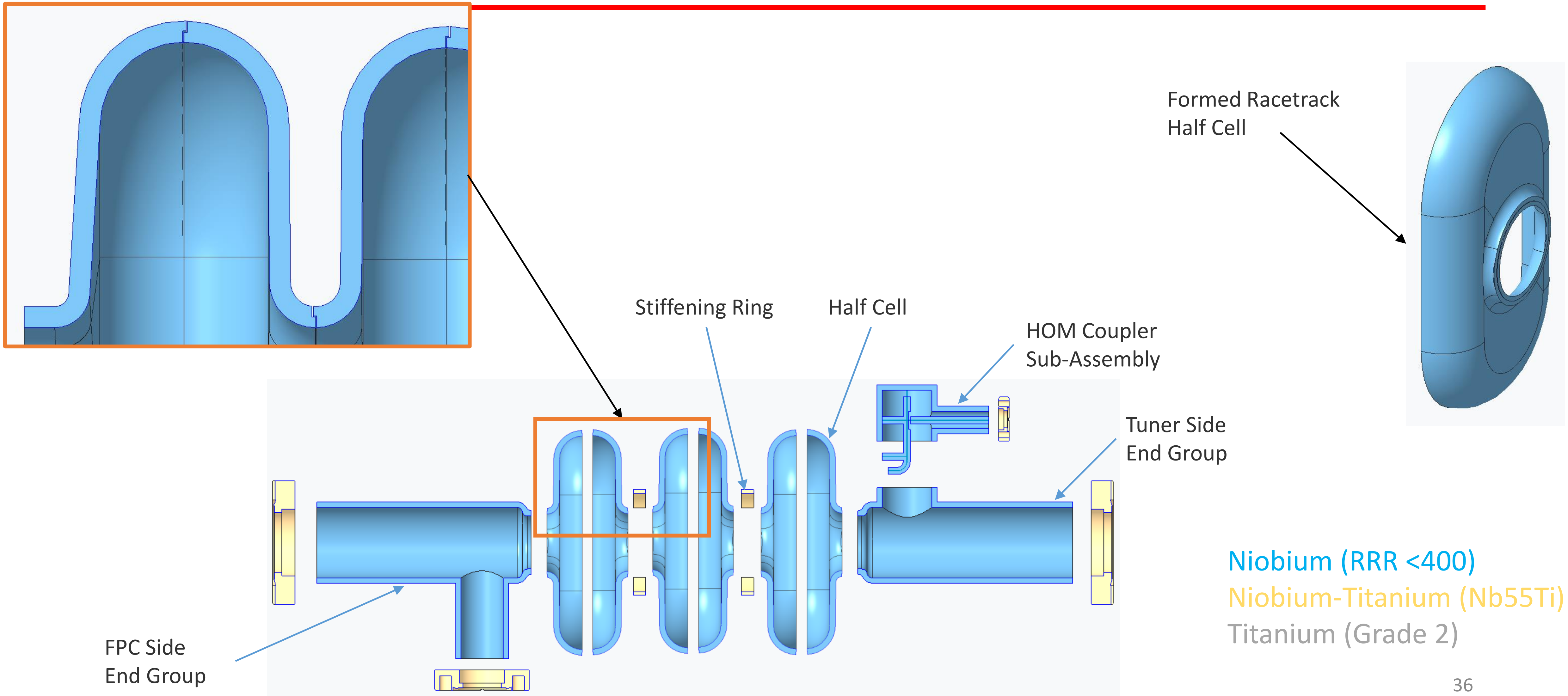




Niobium (RRR <400)

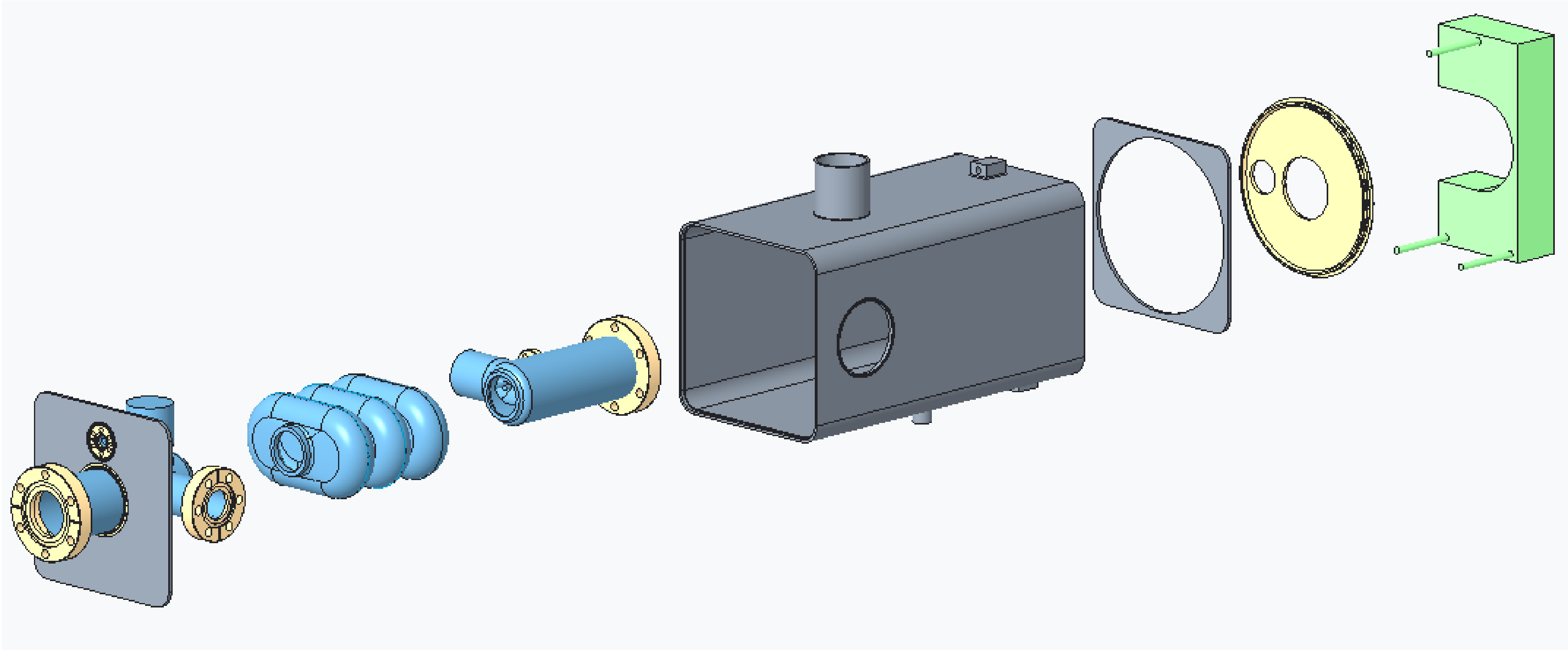
Niobium-Titanium (Nb55Ti)

Titanium (Grade 2)

# UK ILC 3.9GHz Racetrack Crab Cavity – Fabrication



# UK ILC 3.9GHz Racetrack Crab Cavity - Assembly



Niobium (RRR <400)
Niobium-Titanium (Nb55Ti)
Titanium (Grade 2)

# 1 Cavity Cryomodule Schematic

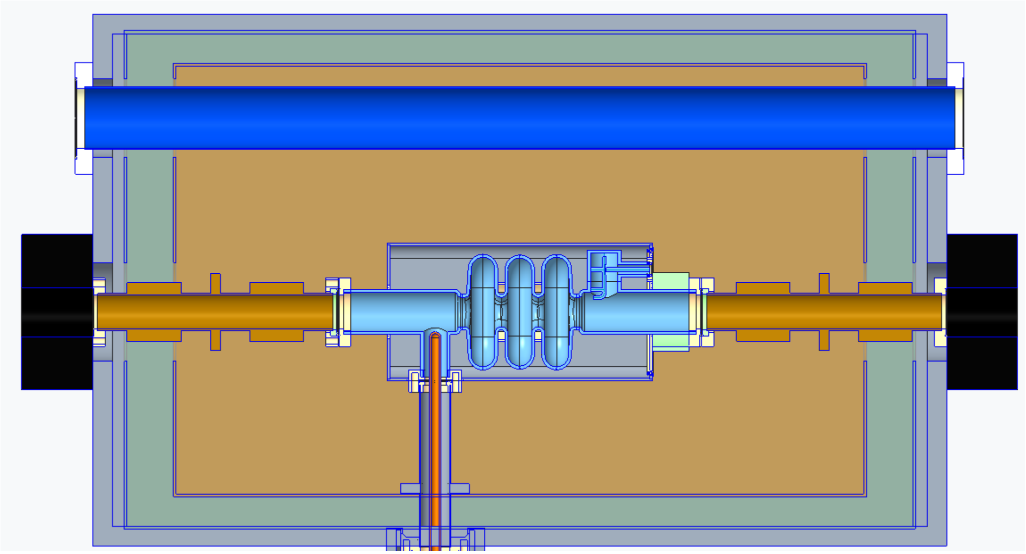
Could try to squeeze down to 950 mm to have 4 individual cryomodules in the 3.8 m installation length.

Outer Vacuum Chamber

Warm Magnetic Shield

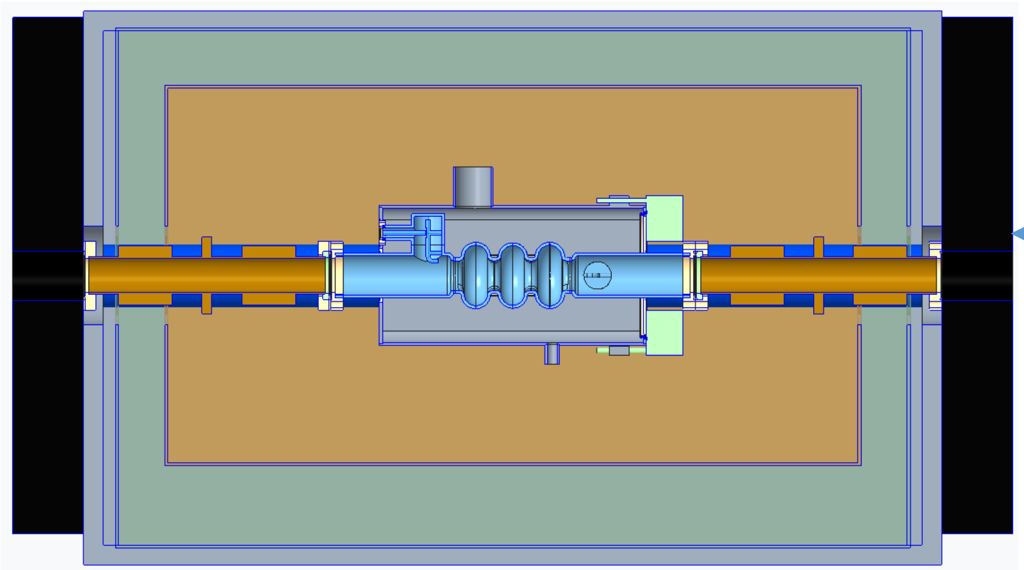
Thermal Screen

**Total Length: 1014 mm**



Top View

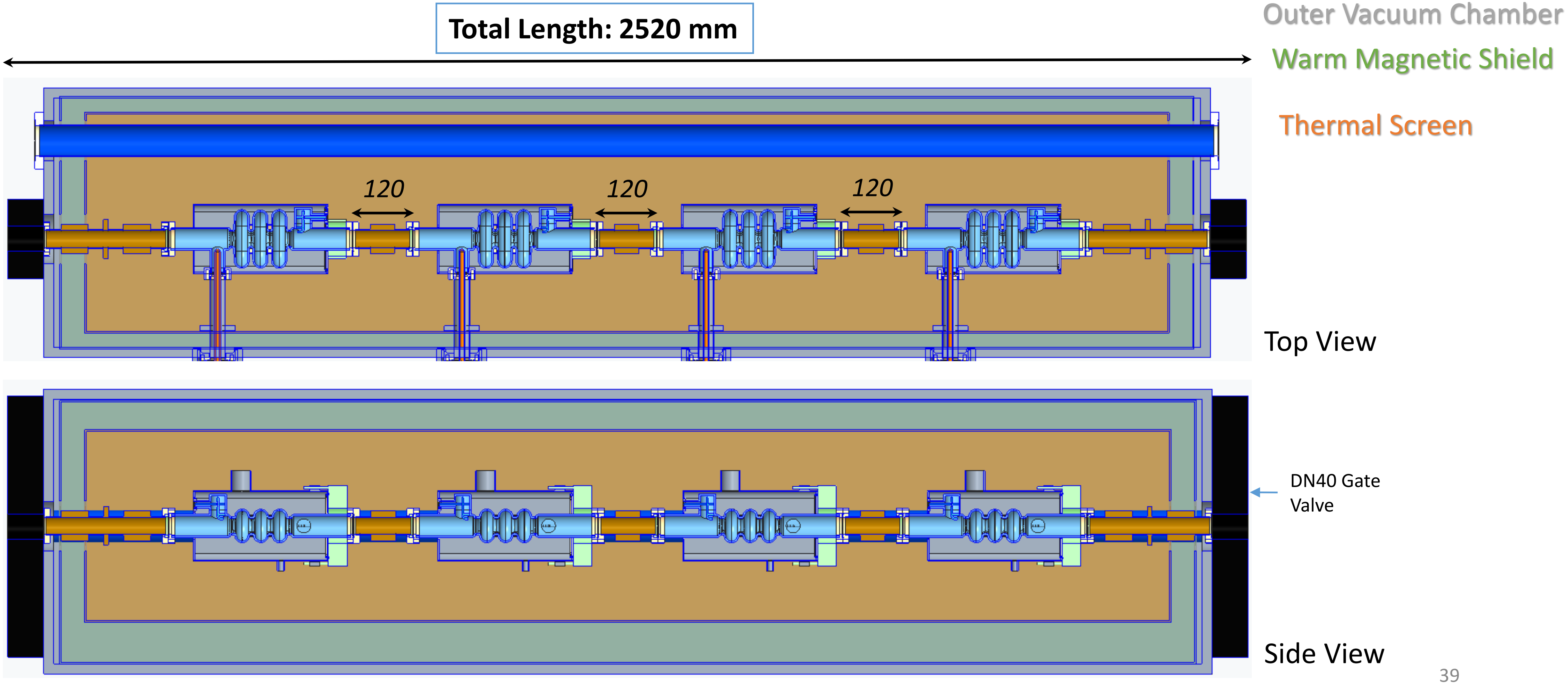
**Total Length: 1014 mm**



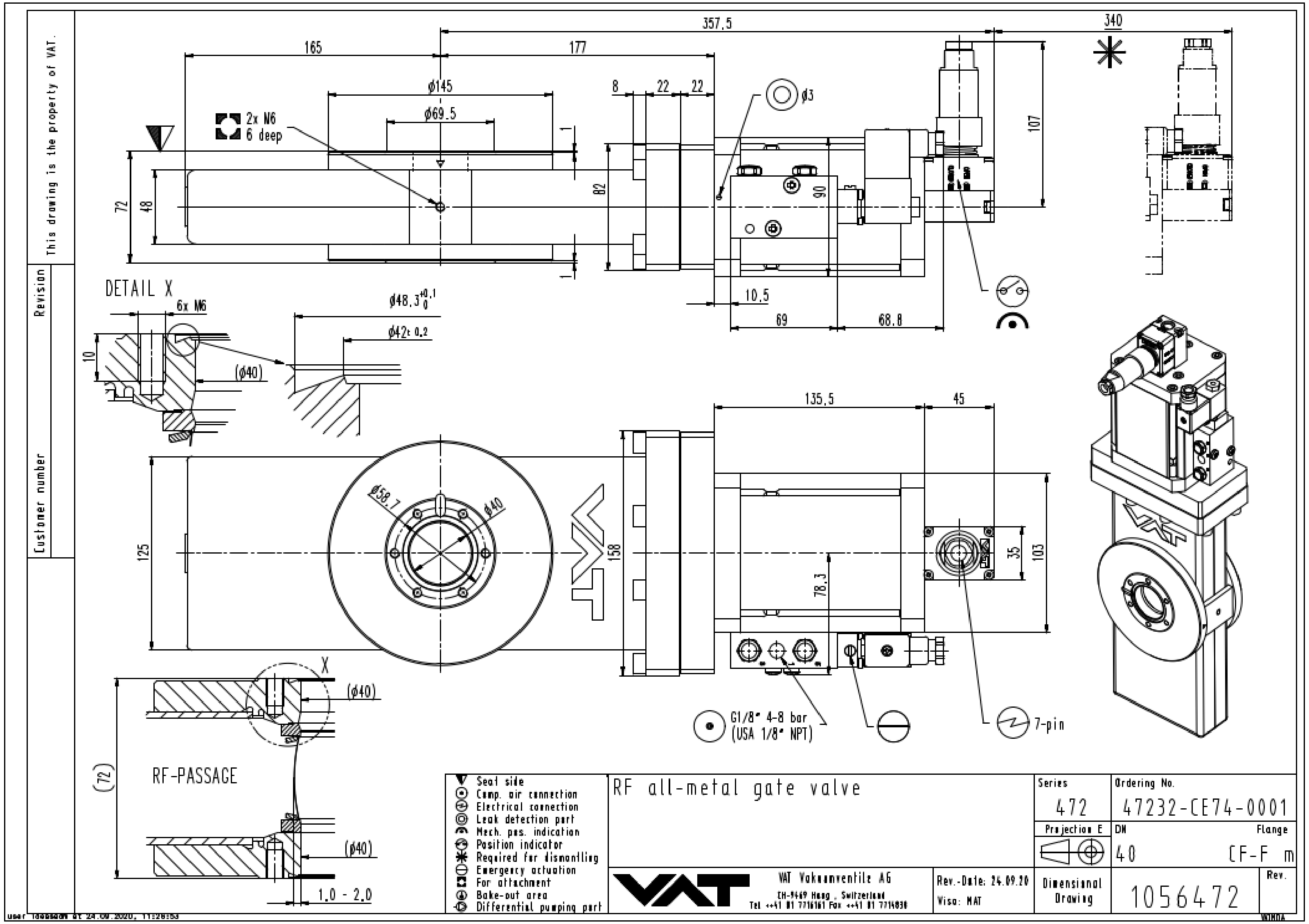
DN40 Gate Valve

Side View

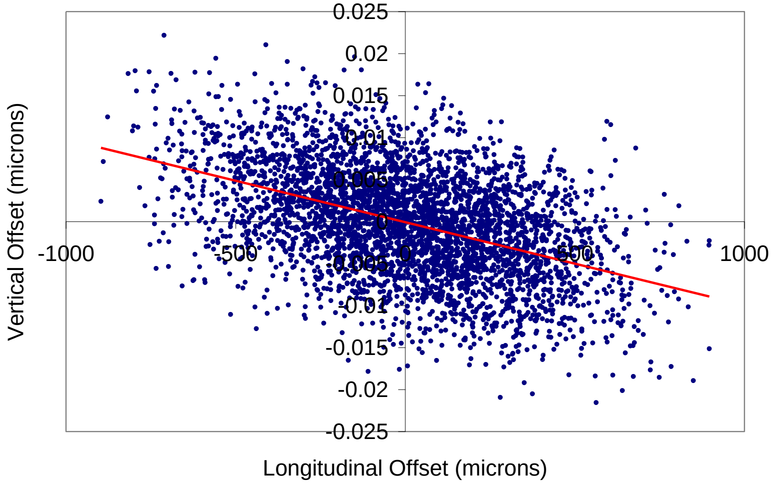
# 4 Cavity Cryomodule Schematic



# DN40 Gate Valves – 523 x 125 x 72

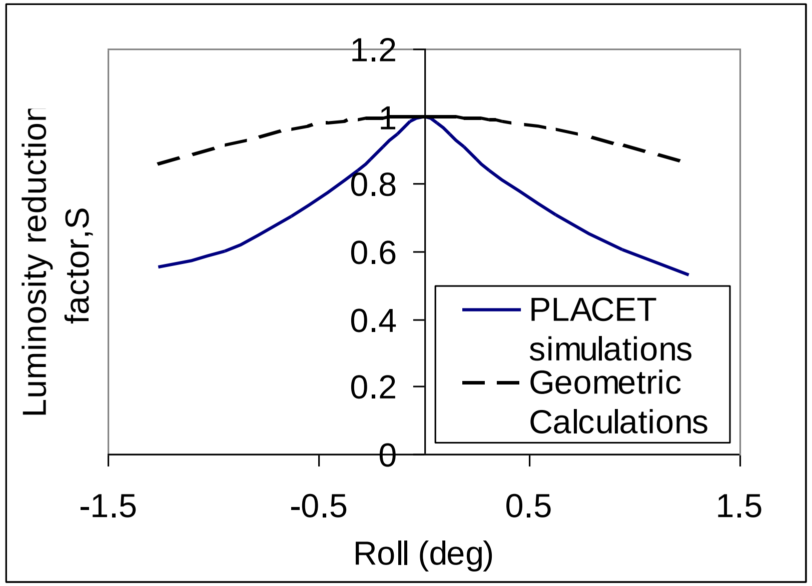


# Cavity Alignment (Anti-crabbing)

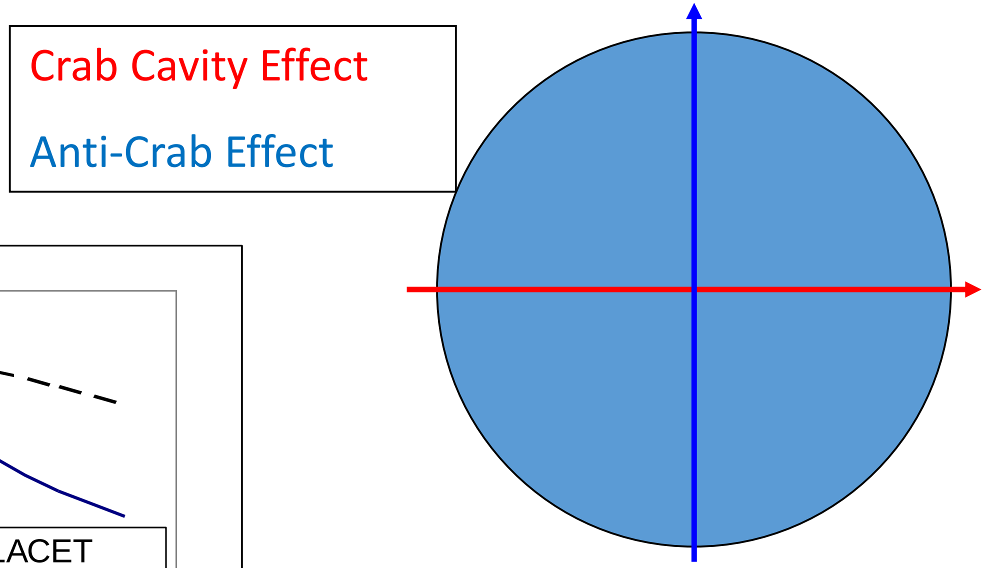



If the cavity has a roll misalignment it will cause a small crossing angle in the vertical plane.

This will significantly reduce the luminosity



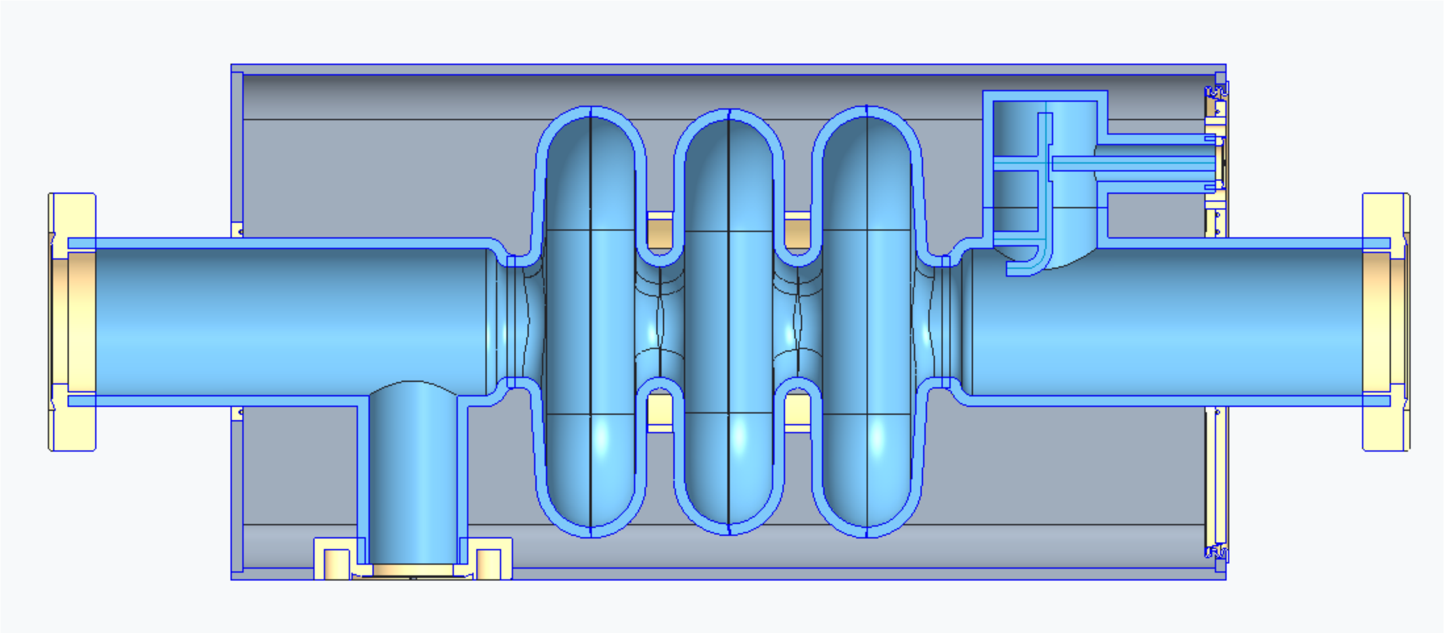

**<u>Either need active alignment or space for an extra cavity!</u>**




Adding a single cell crab cavity in the vertical (rather than horizontal) plane can correct for vertical crabbing and offsets due to cavity misalignment, wakefields or other sources of error such as x-y coupling.

# Volume within Helium Tank

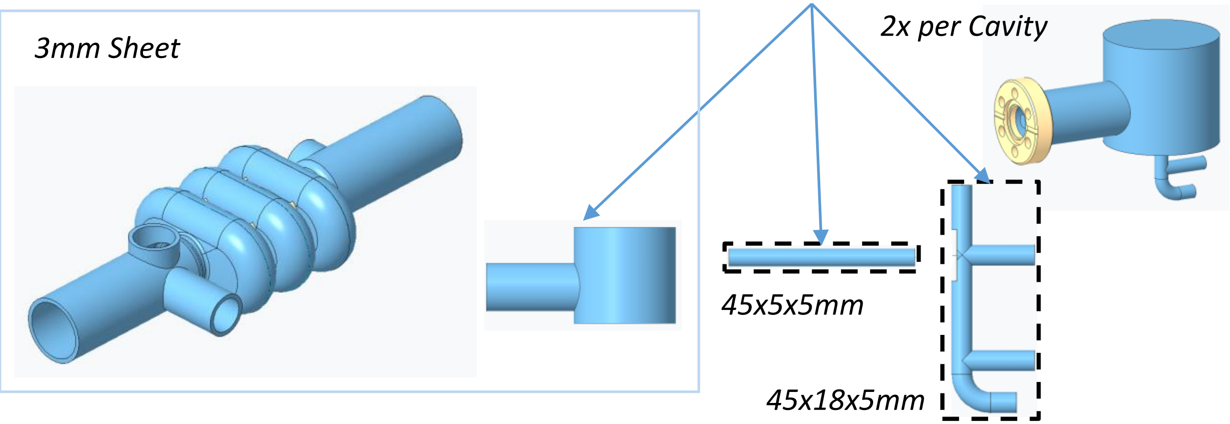
- Helium Tank: 5036080mm3
- Total Volume: 5036080-790119.5 = 4245960.5mm3 → 4.25 litres
- PED Category I



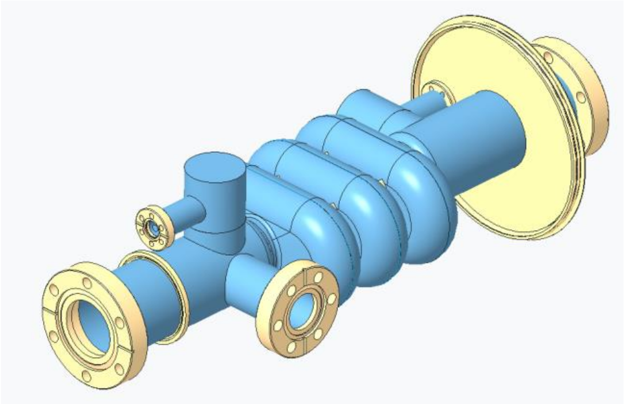
# Niobium Bill Of Materials

| Bare Cavities & HOM Housing | Nb RRR 400 - Sheet | | | | Nb RRR 400 - Billet | | | |
|---|---|---|---|---|---|---|---|---|
| | t (mm) | w (mm) | l (mm) | *(kg)* | t (mm) | w (mm) | l (mm) | *(kg)* |
| 1 | 3 | 200 | 550 | *2.8* | 5 | 45 | 46 | *0.1* |
| 4 | 3 | 200 | 2200 | *11.2* | 5 | 45 | 184 | *0.4* |

*Includes ~10% waste material*




# NbTi Bill Of Materials



| Flanges, Stiffening Rings & Bellows | Nb55Ti - Sheet | | | | Nb55Ti - Billet | | | |
|---|---|---|---|---|---|---|---|---|
| | t (mm) | w (mm) | l (mm) | *(kg)* | t (mm) | w (mm) | l (mm) | *(kg)* |
| 1 | 3 | 150 | 300 | *0.8* | 50 | 75 | 75 | *1.6* |
| 4 | 3 | 150 | 1200 | *3.2* | 50 | 75 | 300 | *6.4* |

*Includes ~10% waste material*

# Comparison to specification

| Parameter | Elliptical/Racetrack |
|---|---|
| Operating frequency | 3.9 |
| SOM | 5 |
| 1st Longitudinal HOM | 3.3 |
| 1st Transverse HOM | 4.7 |
| $E_p/E_t^*$ | 4.24 |
| $B_p/E_t^*$ | 12.6 |
| $B_p/E_p$ (including ports) | 2.96 |
| G | 207 |
| R/Q (accelerator definition per cavity) | 140 |
| $R_tR_s$ | $2.9\times10^4$ |
| $V_t$ max per cavity | 0.716 |
| $V_t$ operational per cavity (125 GeV) | 0.615 |
| $E_p$ operational | 22.5 |
| $B_{p\ operaytional}$ | 66.6 |
| Total No. of cavities (125 GeV beam) | 1 |
| Extendability (500 GeV beam) | Use 4 cavities |
| Vt max/Vt operational | 1.16 |

| | |
|---|---|
| Flange-flange Cavity Length | 370 |
| Number of cells | 3 |
| Cavity Diameter (RF model ID largest transverse horizontal dimension closest to 2nd beam-pipe) | 111.4 |
| Minimum Aperture | 25 |
| FPC $Q_L$ | $1.0\times10^7$ |
| Loaded Bandwidth | 390 |
| Cavity Input Power | 0.22 |
| Longitudinal Loss Factor kz | 3.2 |
| Horizontal Kick Factor $k_x$ | 16 |
| Vertical Kick Factor $k_y$ | 16 |
| Stored Energy W (at Vt operational) | 0.1 |
| HOM impedance (Longitudinal) | 230 |
| HOM impedance (Transverse) H | 1.3 |
| HOM impedance (Transverse) V | 1.4 |
| First 3 multipole pararameters | 1, 0.1, 250 |
| Nb material quantity (Kg) per cavity prototype | 2.9 |
| Nb material sheet/ingot | Sheet for main body, billet for HOM couplers |
| Maximum stresses, max pressure at RT (weakest)? | 5.4 |

# Conclusions

- Using a racetrack geometry gives improved separation to the same-order mode and minimizes the peak magnetic fields
- A 3 cell cavity with coax HOM dampers meets the ILC impedance specification
- There is a small amount of multipactor in the endcell at the operating gradient but, it appears possible to move this to higher voltages
- The cavity is small and a lower voltage is needed at 3.9 GHz making the cryomodule significantly cheaper and easier