1.3GHz Wide-Open-Waveguide (WOW) type crab cavity for ILC

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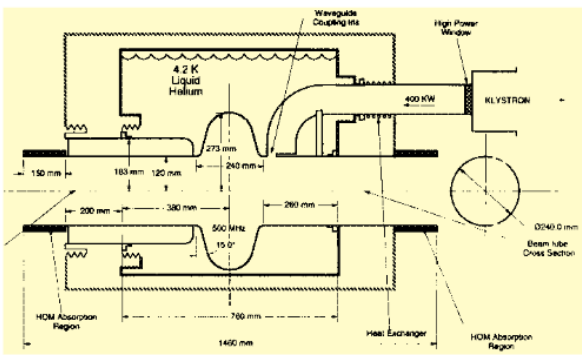
ILC Crab Cavity Down-selection Review
Apr 2023, KEK, Japan

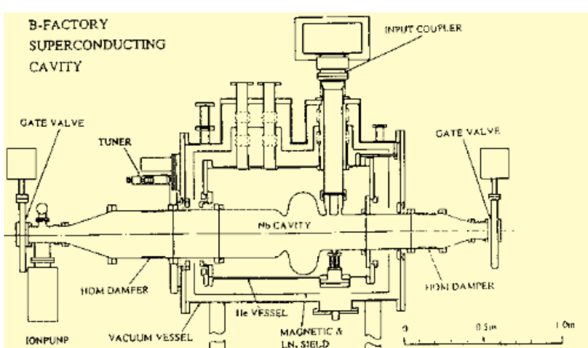
Outline

- Introduction and requirements
- Cavity
- HOM
- FPC
- Multipoles and multipacting
- Pressure stability and tuning
- Fabrication consideration
- Cryomodule (preliminary)

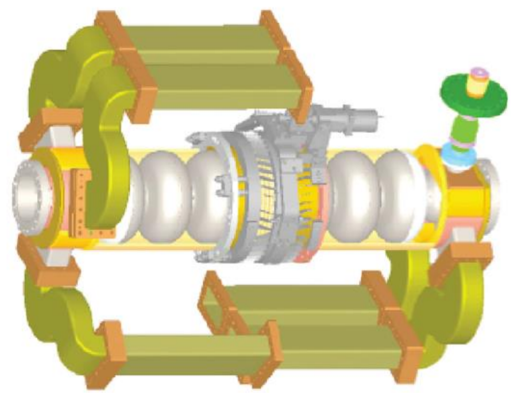
WOW for accelerating cavities

- Trapped fundamental mode in the cavity, no Lower Order Modes (LOMs).
- All Higher Order Modes (HOMs) leak out through beampipe and get absorbed.
- Widely used in accelerating cavities.

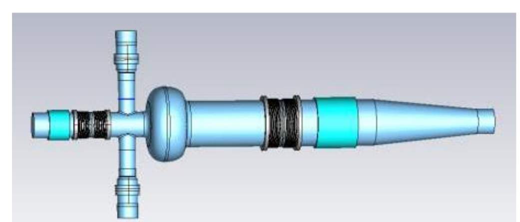




CESR-III & KEK-B single-cell



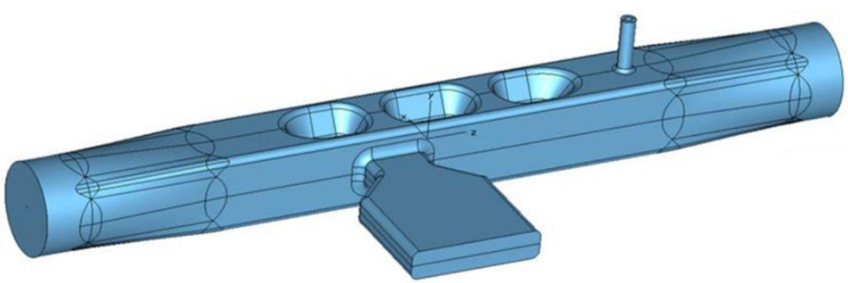
bERLinPro 7-cell

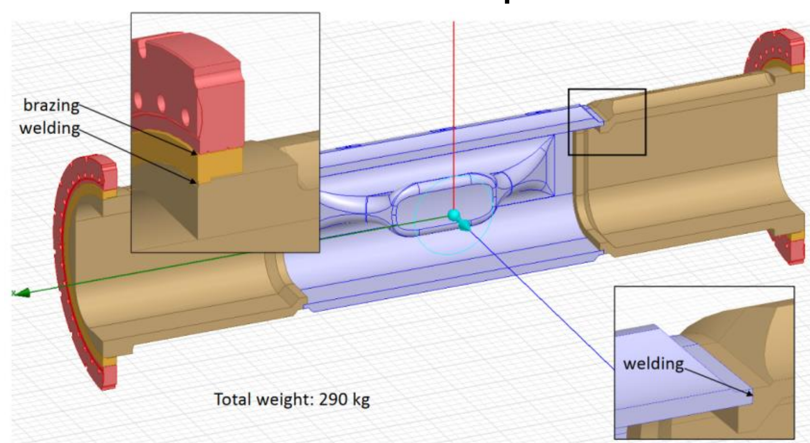


EIC single-cell from Jiquan Guo

WOW for crab cavities

- WOW type crab cavity was proposed back in 2014 in HOMSC meeting by Fermi Lab colleagues (Quasi-waveguide Multicell Resonator: QMiR) – details in next talk.
- CERN colleagues proposed WOW type crab cavity for LHC & FCC in 2015.
- EIC proposed to use WOW+RFD as a backup solution for 394MHz crab cavity.





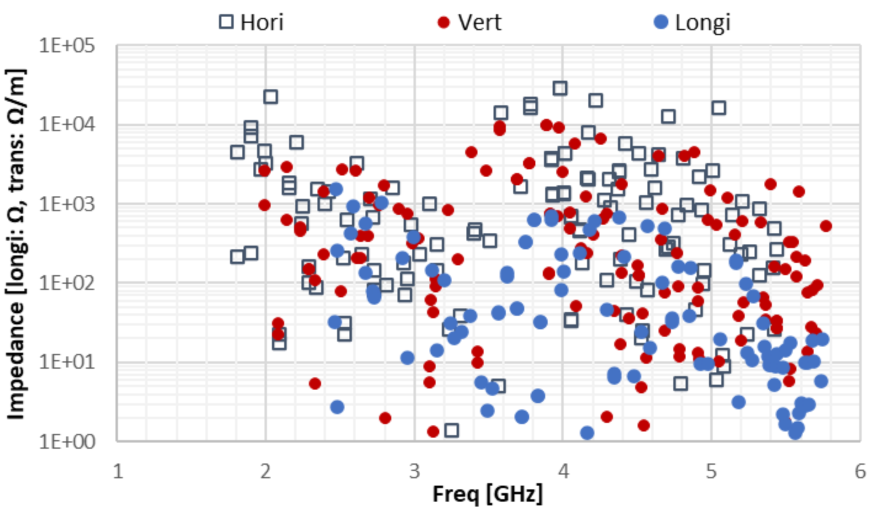
https://indico.fnal.gov/event/7942/contributions/104178/attachments/68128/81727/HOM_Free_Deflecting_Cavity.pdf
https://inspirehep.net/files/40359296b280f1cdd0a2b1cb94e33785

EIC WOW type

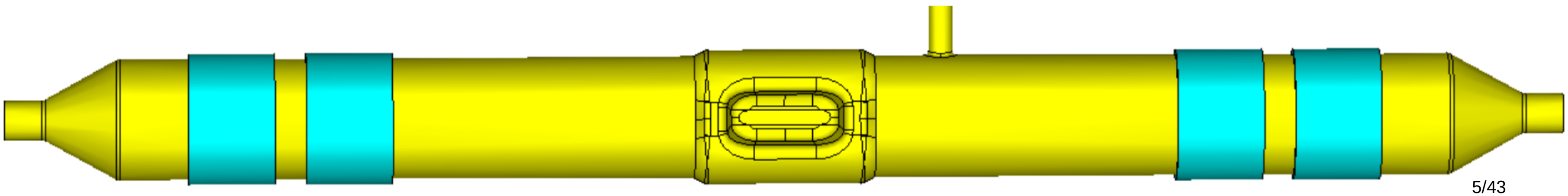
BNL/SLAC joint effort

(Scaled to 1.3GHz)

- Two SiC absorbers on each side.
- 30.3mm gap & 94mm pipe.
- Vt: 1.27MV, Epk: 50.4MV/m, Bpk: 80.0mT. Can be improved.
- Max imped, longitudinal: 1.5e3Ω, transverse: 2.9e4Ω/m.



- Needs 6 cavities for 7.4MV, total 4.74m.
- Possible to use one absorber on each side, and adjacent cavities can share absorber.
- Further optimization to lower the peak fields (less cavity number)



Specs and requirements

- 14mrad crossing angle.
- 1.3GHz with 1.845MV kick voltage (7.4MV for 1TeV).
- Minimum cavity aperture size 25mm.
- 3.8m long with gate valves, 0.1967m +/- 0.0266m horizontal beam-pipe separation.
- Max peak surface E field 45MV/m, B field 80mT.
- Total transverse impedance threshold for 250GeV: 48.8 MΩ/m horizontal, 61.7 MΩ/m Vertical. For 1TeV they are 4 times higher.
- Max detuning 180kHz.
- CW operation at 2K temperature.

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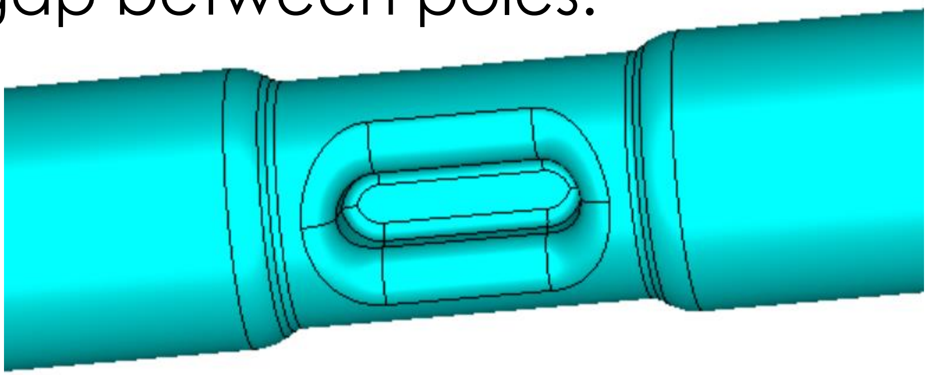
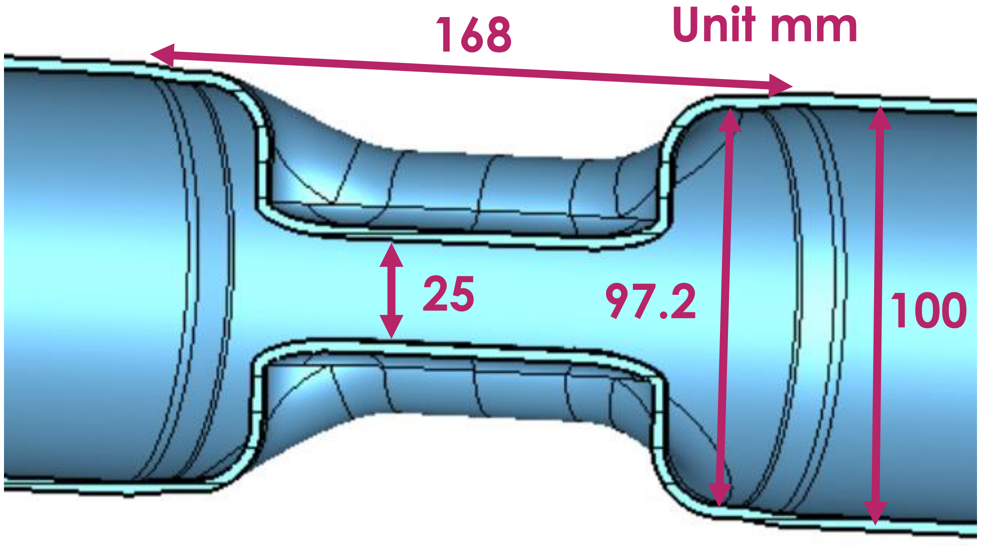
Cavity design considerations

- RFD is a better choice for WOW type while comparing with Double Quarter Wave (DQW).
- First transverse HOM at ~1.8GHz, first longitudinal HOM at ~2.3GHz.
- Choose 100mm ID WOW
  - with cutoff frequencies at 1.758GHz for TE_{11} and 2.297GHz for TM_{01}.
  - It is a good size for possible gate valves, no need for tapering, keep the possibility to use smaller valves though.
  - it is also the beampipe size for EIC crab cavities.
- 25mm gap between poles.



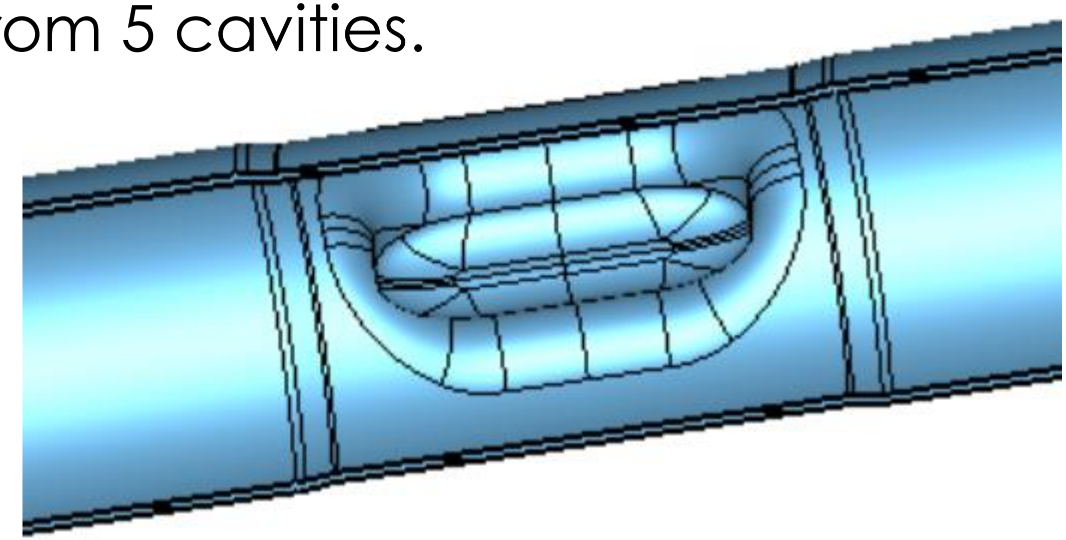
Cavity parameters

Property	Value
Operating frequency [GHz]	1.300
1st longitudinal HOM [GHz]	2.299
1st transverse HOM [GHz]	1.765
E_p/E_t with $E_t=V_t/(\lambda/2)$	3.24
B_p/E_t [mT/(MV/m)]	5.75
B_p/E_p [mT/(MV/m)]	1.77
G [Ω]	130.9
R/Q [Ω]	454.3
R_tR_s [Ω^2]	59446



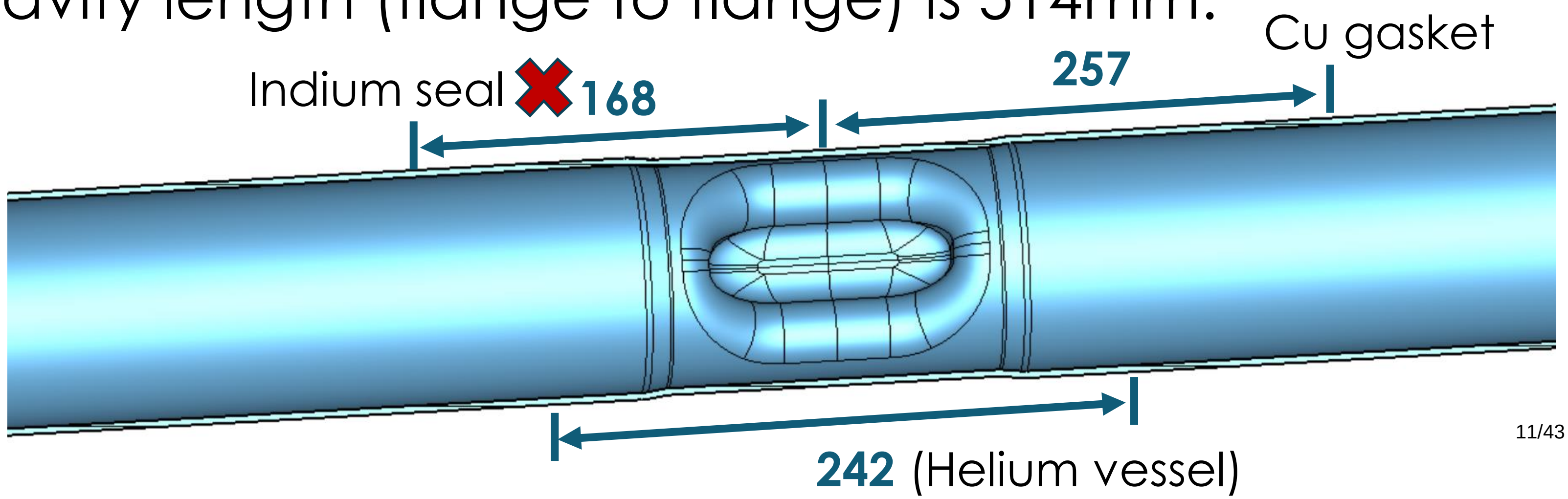
Peak fields

- Needs 1.845MV for 250GeV case and 7.4MV for 1TeV case.
- 5 cavities for 1TeV, meaning 1.48MV per cavity, corresponding to 41.6MV/m E_{pk} and 73.8mT B_{pk}.
- With this we need 2 cavities for 250GeV.
- With 45MV/m E_{pk} and 80mT B_{pk}, cavity could operate at 1.60MV, with a total of 3.2MV from 2 cavities, and 8.0MV from 5 cavities.



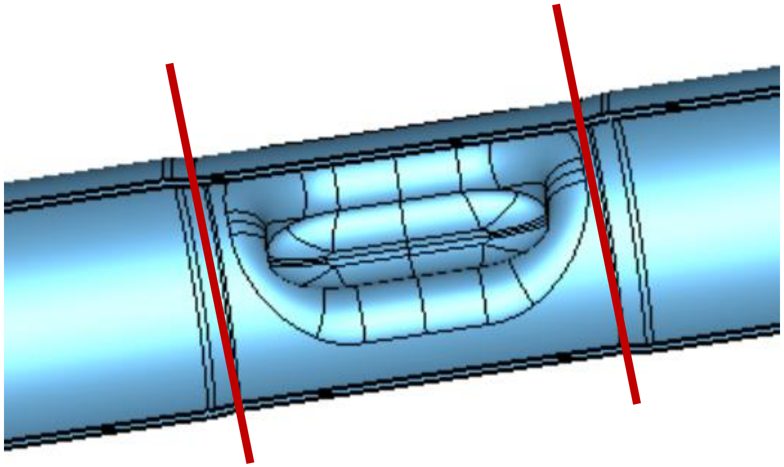
Interfaces

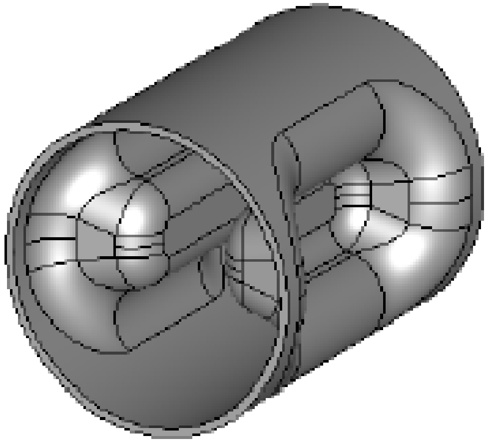
- Cavity helium vessel is placed at 8mT magnetic field Under nominal voltage (1.48MV is used here). Length of helium vessel can be as short as 242mm.
- Indium seal is placed at 2.5mT, located at 168mm from cavity center. (Indium seal is used in EIC 197MHz)
- Cu gasket is placed at 220A/m (~0.28mT), located at 257mm from cavity center.
- We will use Cu gasket. Indium seal is NOT used.
- Cavity length (flange to flange) is 514mm.



Further optimization

- It is an RFD cavity, possible to work together with ODU/JLab colleagues towards ONE bare cavity + tuner design.
- End-group will be different, different HOM damping, different FPC (window could be the same), different helium vessel.





Center part of the design: left, WOW type; right, RFD (Suba).

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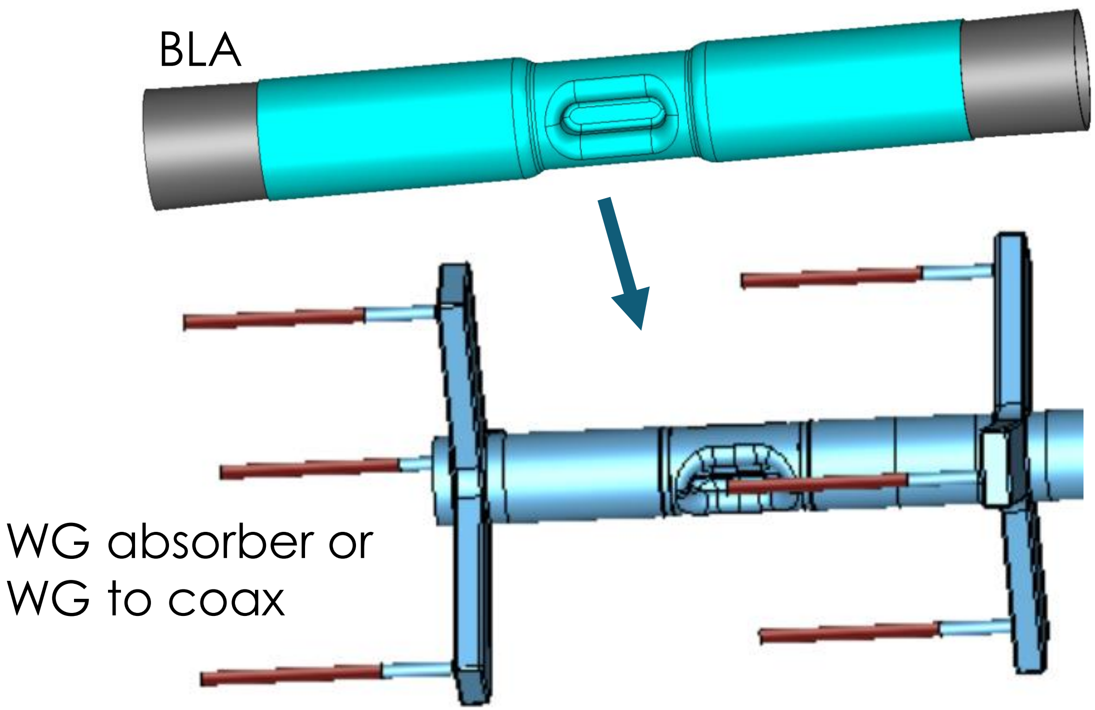
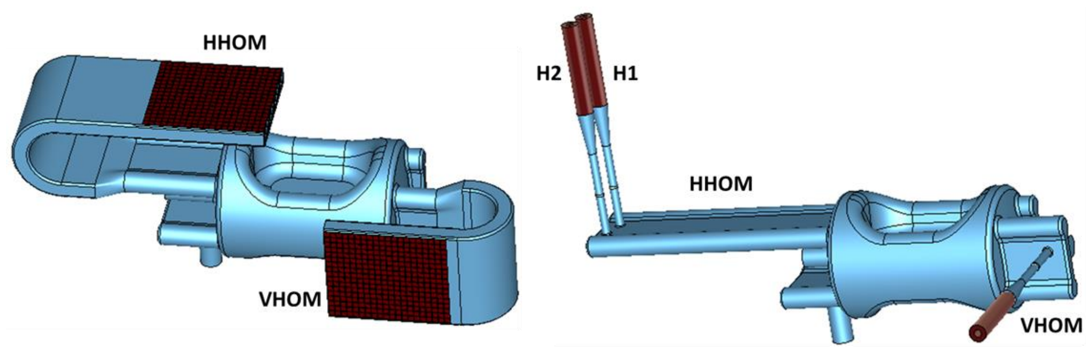
BLA or WG

- RFD cavity shape, with WOW and ~~beam line absorbers (BLA) or~~ Nb waveguide (WG) on both sides.
  - Fundamental mode can attenuate in WG.
  - With WG the total length can be shorter while comparing with BLA.
  - While both are detachable from cavity.



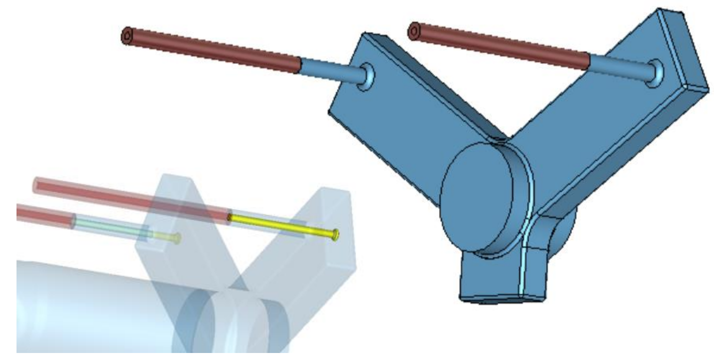
WG or coax absorbers?

- EIC 197MHz design faced the same issue.
- Coax (absorber) design was chosen over WG design:
  - WG absorbers require further R&D while coax absorbers are commercially available.
  - WG absorbers are large while considering the limited longitudinal and transverse space.
  - WG absorber design/fabrication is complex/expensive while comparing with the coax design.
  - Both designs meet the scope with reasonable margin.
  - WG design can handle higher power, while in ILC the average power is low.
  - Mechanical support for the WG loads adds to the design complexity including shipping and transportation.



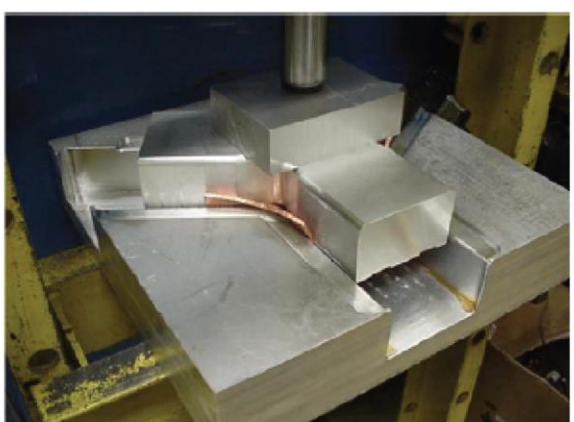
EIC 197MHz RFD design with WG (left) and coaxial (right) HOM dampers

Waveguide to coax transition



- Similar study for both 197MHz and 394MHz EIC crab cavities.
- 86mm x 32mm rectangular WG to coax (port ID 16.2mm, mini-conflat), 3 WGs evenly distributed on circular pipe.
- Simple identical Cu E-probes are used.
- To save space, we can add a few corrugations on the circular pipe so that we do not need bellows between cavities (DESY,BNL 56MHz).
- 3 (or 2, see picture on top) coax on each damper unit.
- Similar to JLab ERL-FEL damper.

Courtesy: Bob Rimmer

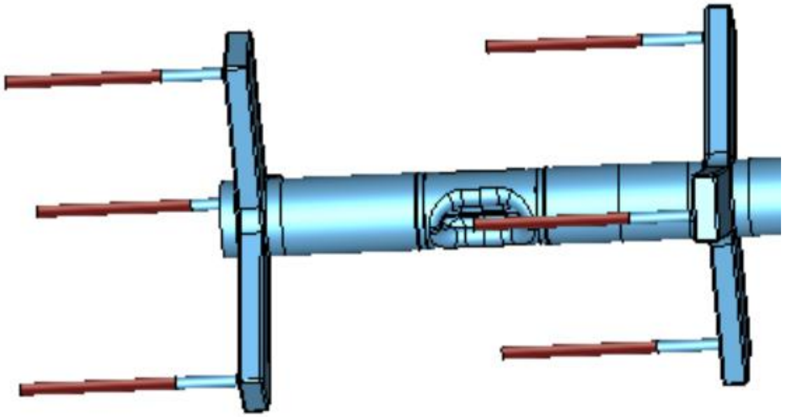


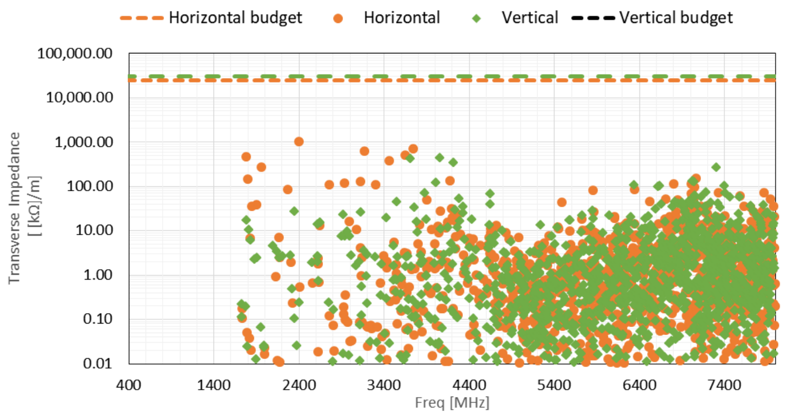
Fundamental loss on HOM absorber

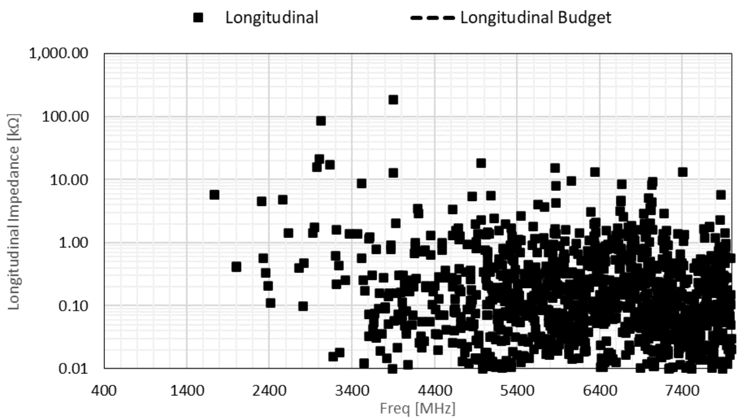
- At 1.48MV, the RF loss of the fundamental mode on each HOM absorber needs to be <0.1W since it is possible to use 4K thermal anchor to cool down the absorber.
  - FYI, for EIC, 100W fundamental power is allowed to be dissipated on each HOM absorber.
- With 454.3Ω R/Q. the Q should be >4.8e10.
- Waveguide 0.245m long from the beam center.
- 0.1W each on two of the absorbers, and 0.024W each on the other two, total 0.25W.

Impedances

- First round of simulation with one damper unit on each side, beampipes are with electrical boundary condition.
- Max horizontal impedance 0.99MΩ/m, max vertical impedance 0.43MΩ/m, 4% of the budget (24.4MΩ/m horizontal and 30.8MΩ/m vertical), all numbers are per cavity.
- Max longitudinal impedance 186kΩ per cavity, further optimization can be done if needed.

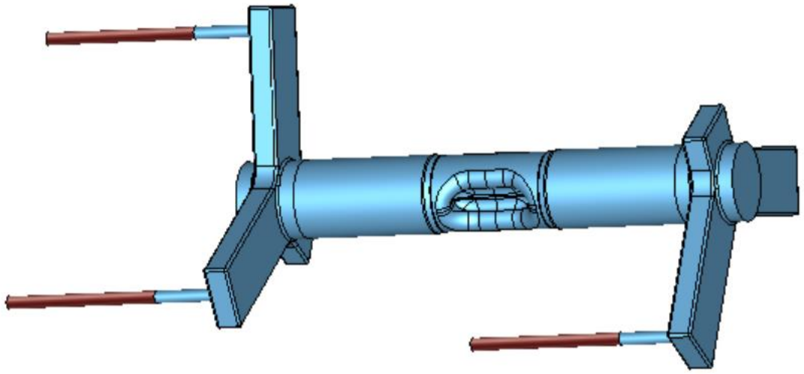


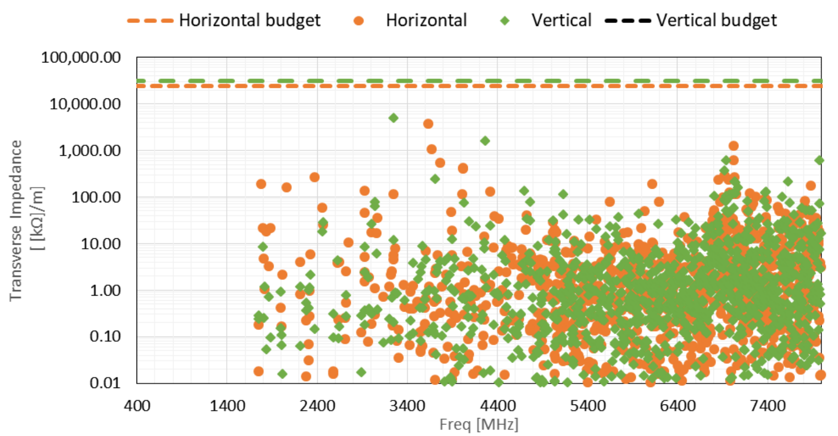


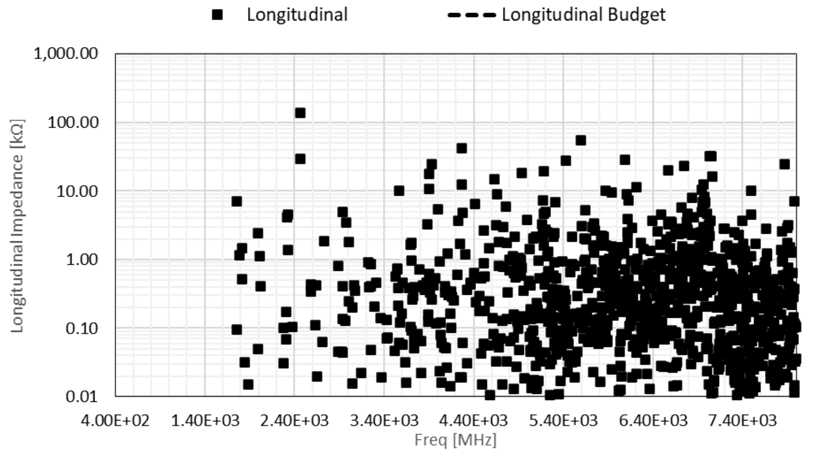


Impedances (2)

- Two coax absorbers on each damper unit.
- Max longitudinal impedance 139kΩ per cavity.
- Max horizontal impedance 3.65MΩ/m and max vertical impedance 4.87MΩ/m, 16% of the impedance budget.
- Further optimization can be done if needed.
- Simulation on full structure (5 cavities with 6 damper units) with open boundary on beampipe will follow.

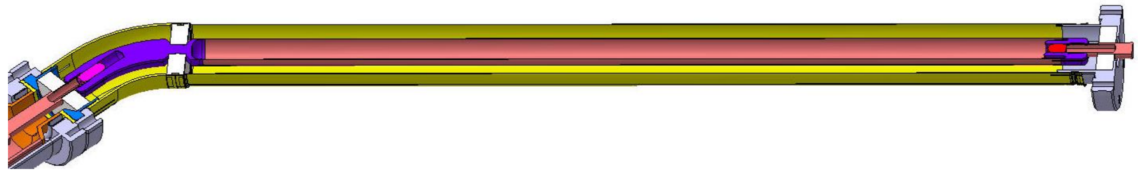






HOM power

- For a mA pulsed machine, the HOM power is low.
- (Maximum) beam current 8.75mA, RF repetition rate 10Hz, bunch train length 961μs.
- 2.71V/pC longitudinal loss factor up to 8GHz.
- The HOM power is calculated to be ~1W per cavity.
- Power handling of 1W per coax absorber would be enough.
- Modes higher than 8GHz propagates outside the cryomodule.



HOM damper

- LHC (also possible for EIC) uses an HOM window (cavity side) + a coax cable + an HOM window (cryomodule side) + coax damper outside cryomodule, see picture on top.
- Our design can be simple, an RF feedthrough/HOM window with welded Cu pin as the HOM probe, and a gas helium cooled coax damper. They should be able to handle reasonable frequency span (10GHz range) and low power (1W).
- Commercially available RF feedthrough & coax load (pictures below) can be used.
- Convert commercially available conventional (bottom middle) or water-cooled coax load (bottom right, need to make sure it works for up to 10GHz.) to gas helium cooled?




Commercially available RF feedthrough & coax load from MDC, Kurt J Lesker & Bird RF.

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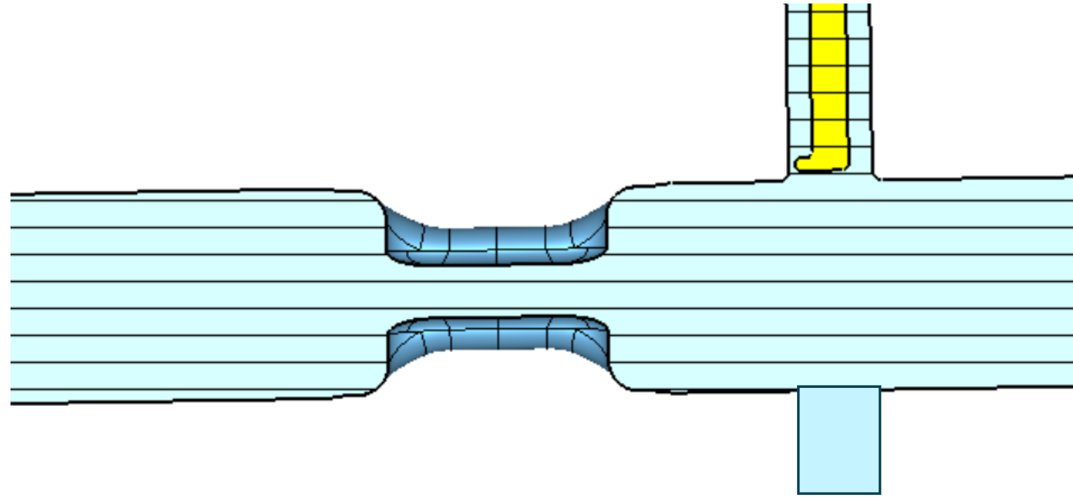
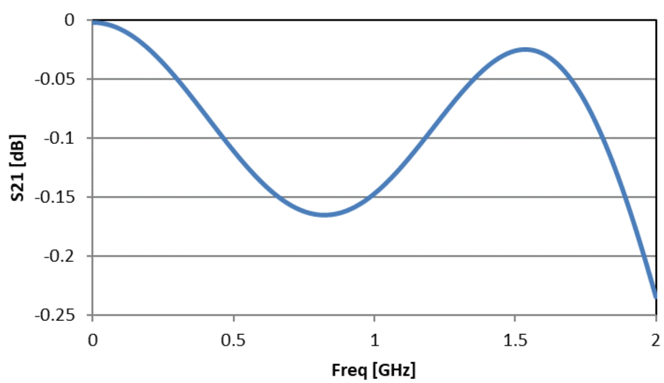
FPC

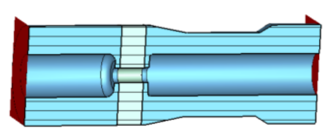


- Horizontal E-probe FPC outside the helium vessel.
- 3e6 coupling and 850W power for 1TeV at 1.48MV with 0.5mm offset, 200Hz frequency shift and 10mA peak current.
- 1e7 coupling and 160W input power for 250GeV at 0.9225MV with 0.5mm offset and 50Hz frequency shift.
- Less than 2W power dissipation on the inner rod, conduction cooling is enough, coax to waveguide transition or quarter wave stub for water/gas cooling is not needed, which leads to a simple design.
- Dummy port opposite to FPC to balance the field, possible to serve as the pumping port.

FPC Window

- Coax window for 40mm port can be used.
- I propose to use the same as LHC DQW HOM window.
- It was tested at CERN in October 2017 (Eric Montesinos):
  - Ok: 16 kW pulsed 100 microseconds at 10 Hz with SW all phases (equivalent to 64 kW, but only with 100 microseconds every 100 milliseconds, i.e. 1/1000 average power), more than that some contact started to burn.
  - Ok: 3 kW CW TW during 4 hours
  - Ok: 4 kW CW TW during 1 hour
  - Not OK: 4 kW CW TW after 1 hour and 30 minutes





S21 of the LHC Window

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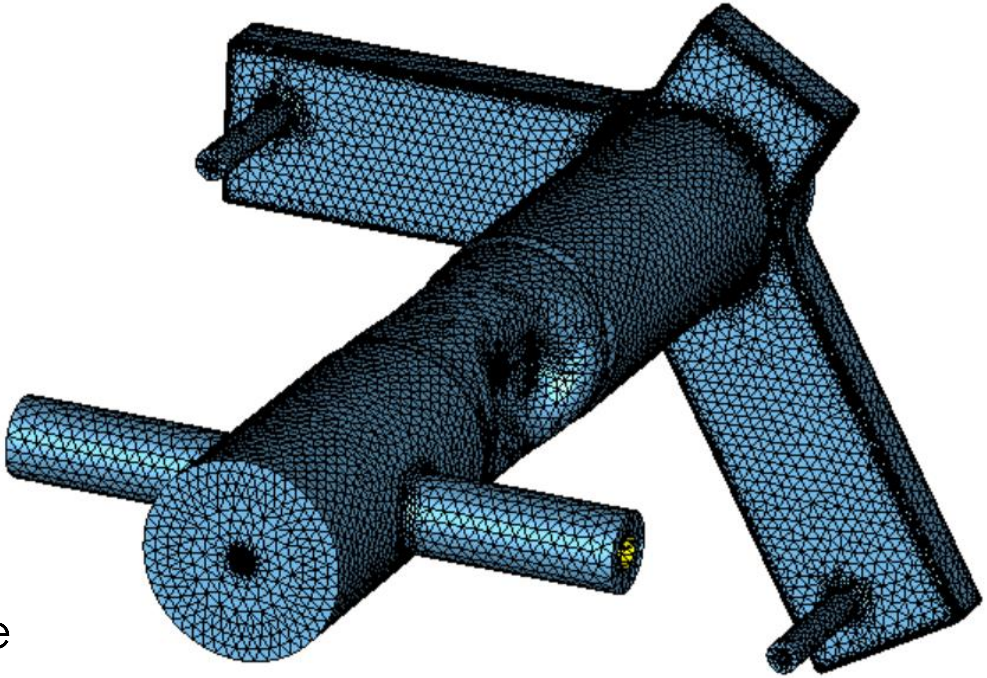
Multipoles

- Higher order multipole components for cavity with FPC, vacuum port and HOM damper
- Requires a finer mesh along the beam center, total mesh ~1M

	1.3GHz WOW	Unit
V_t	**1.0**	MV
b_1	3.32	mT m
b_2	-5.78×10^{-3}	mT
b_3	4.20×10^{3}	mT/m
b_4	87.5	mT/m^2
b_5	-8.46×10^{6}	mT/m^3
b_6	-7.93×10^{6}	mT/m^4
V_{acc}	8.62	V

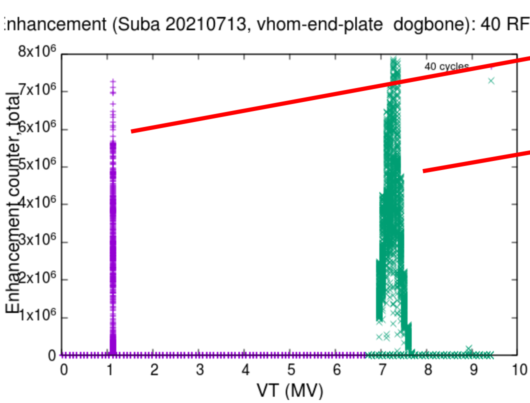


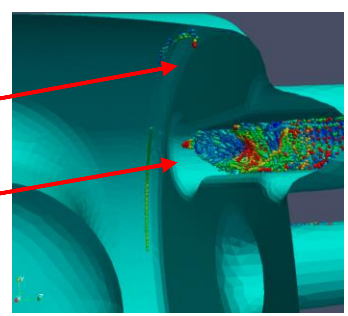
Thanks to Suba for providing the codes for multipoles calculation.

Multipacting

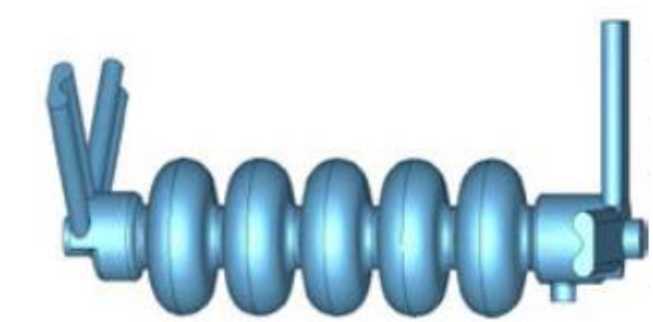
During the design we consider the following for multipacting suppression:

- Based on the LHC and EIC experience, in RFD multipacting happens on the endplates (between endplate and cavity, and between endplate and waveguide). WOW type does not have endplate thus multipacting is not a concern on the cavity body.
- Fundamental mode decays to a level that Cu gasket can be used on the damper units, rectangular WG should be okay, and we do not need ridged WG for multipacting suppression.
- Only <0.1W power leaks out of the coaxial line, field on Cu pins are also low.





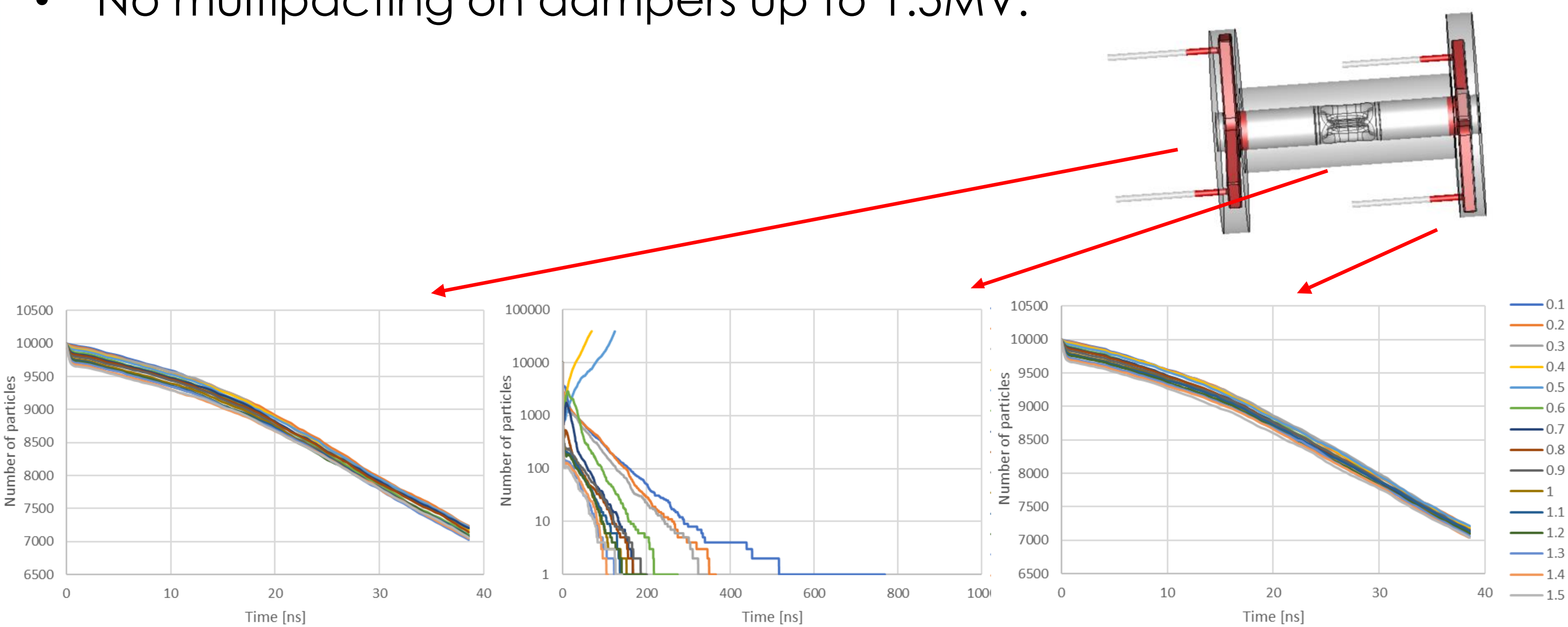
Multipacting in EIC 197MHz (Zenghai Li)



647MHz eRHIC 5-cell with single ridged WG (Wencan Xu)

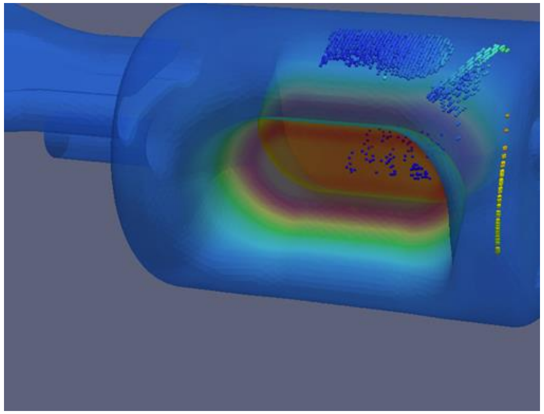
Multipacting

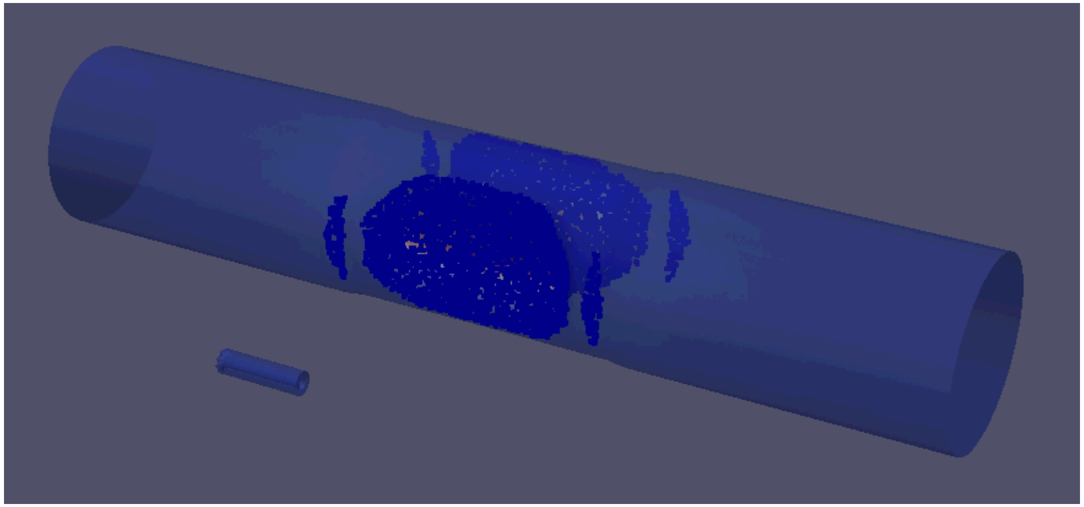
- Spark3D was used.
- Cross-checked using CST particle-in-cell.
- Damper units (Cu & Nb) and cavity (Nb) were simulated.
- No multipacting on dampers up to 1.5MV.

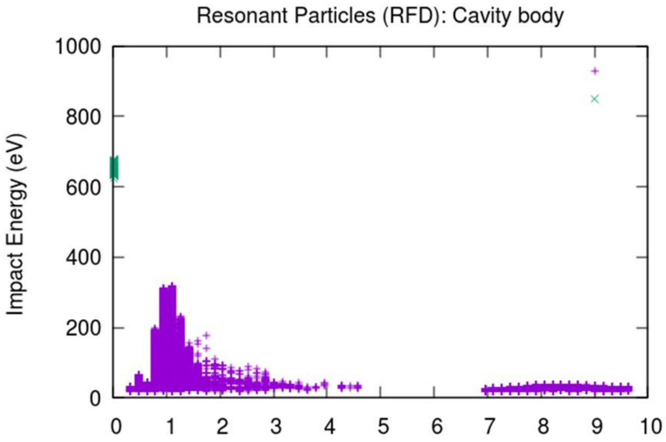


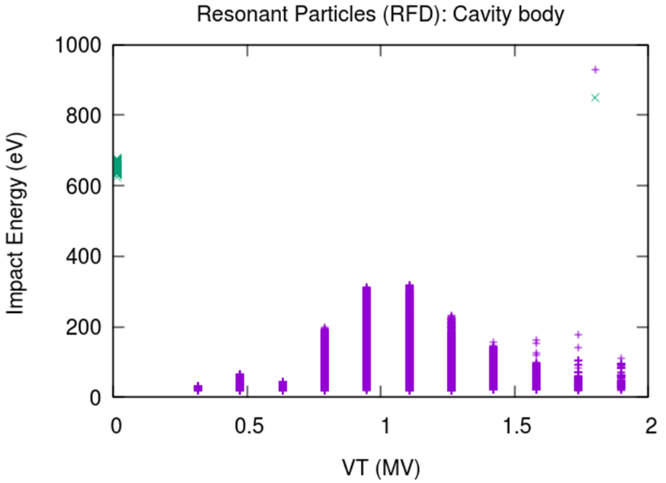
Multipacting

- Multipacting on cavity body at 0.4~0.5MV
- 4^{th} order
- Also exist in LHC & EIC designs, can be conditioned away.









Movie of multipacting in ILC (left)
Multipacting in EIC 197MHz (right, Zenghai Li)

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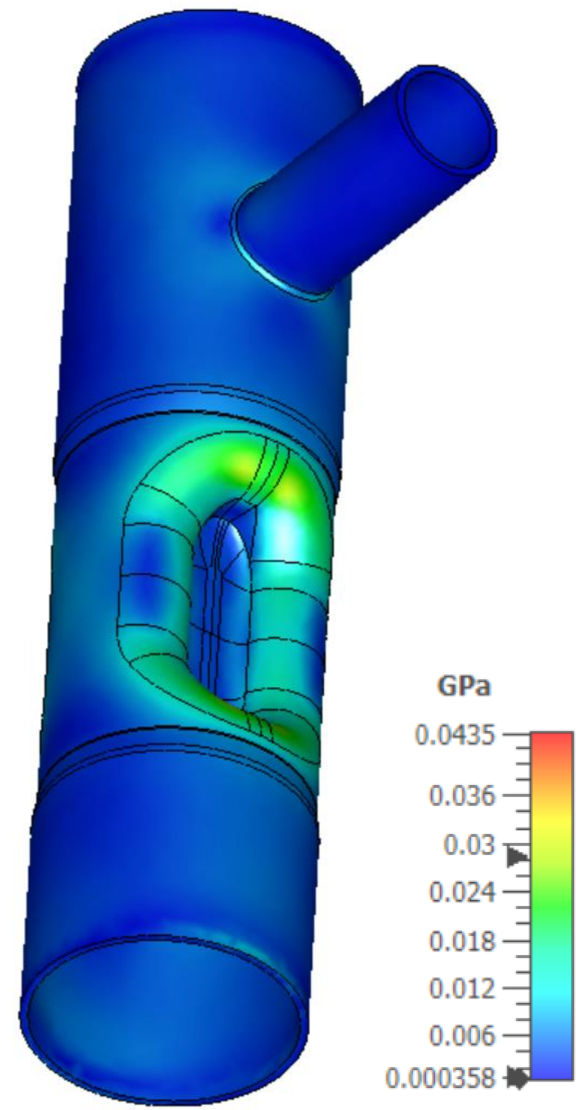
Stress analysis

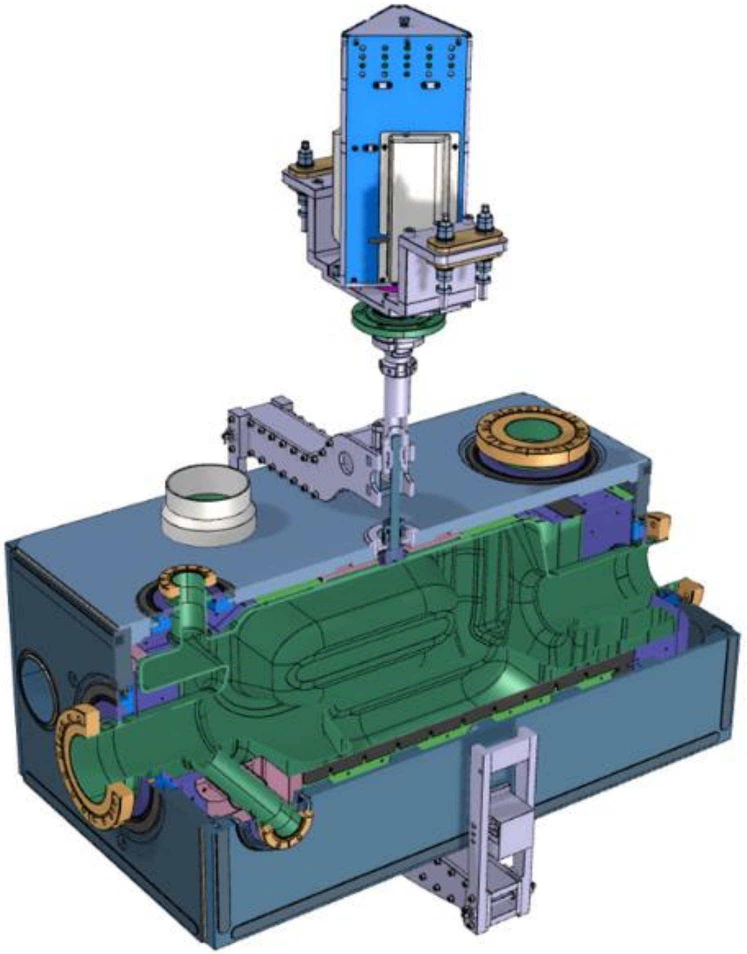
- Analysis at 2.2 atm external pressure
- Nb material properties at room temperature
    - Young's modulus 82.7 GPa
    - Poisson's ratio 0.38
- Cavity thickness at 3 mm.
- Boundary conditions: Cavity constrained at beam pipes and FPC
- Allowable stress < 43.5 MPa

- Maximum stress 28MPa
- No stiffener needed



Tuner

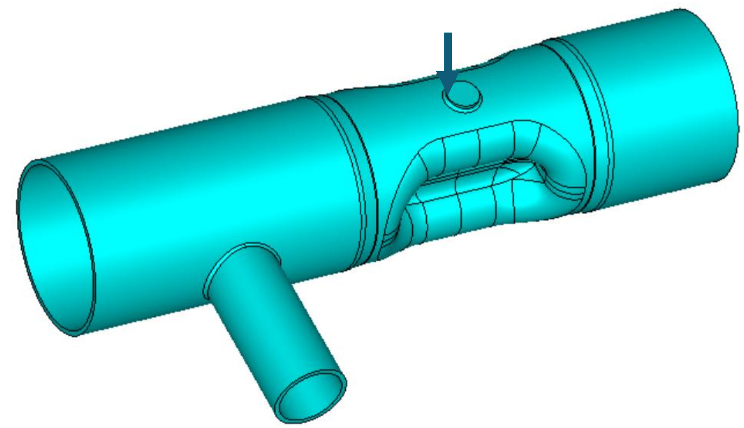
- Tuner will be similar to the LHC RFD cavity, with scissor jack tuner applying force symmetrically to the top and bottom (vertically) of the cavity.

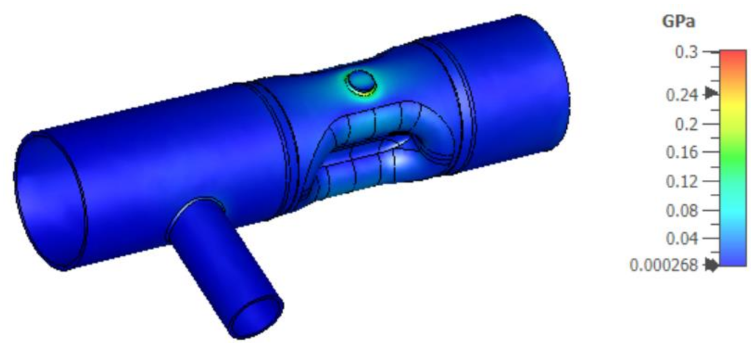


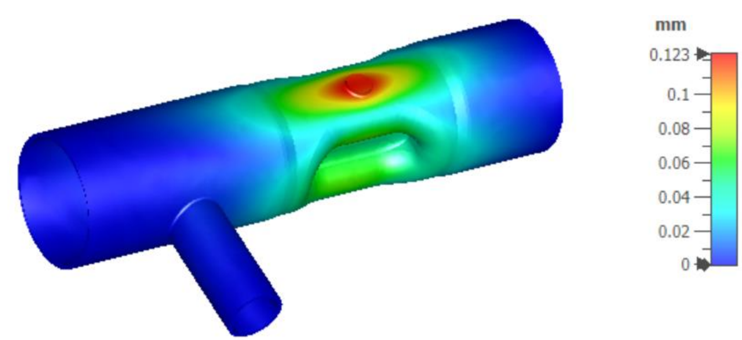
Tuning analysis

- Nb material properties at cryo temperature
  - Young's modulus 123 GPa
  - Poisson's ratio 0.38
- Cavity thickness at 3 mm.
- Boundary conditions: Cavity constrained at beam pipes and FPC
- Allowable stress < 0.3 Gpa

- Force 2.5 kN on each side (8MPa on a 20mm diameter disk)
- Maximum stress 0.24 GPa
- Displacement 0.12 mm each side
- Tuning sensitivity 10.2 MHz/mm
- Tuning range 2.5 MHz
- Detune requirement at 180kHz, 18µm with 370N force.







Pressure sensitivity

- Nb material properties at cryo temperature
  - Young's modulus 123 GPa
  - Poisson's ratio 0.38
- Cavity thickness at 3 mm.
- Boundary conditions: Cavity constrained at beam pipes, FPC.
- Allowable stress < 0.3 Gpa

- Apply 1mBar
- Displacement 2.3e-5 mm on the pole each side
- Pressure sensitivity 725Hz/mBar
- Pressure sensitivity 308Hz/mBar with tuner fixed.
- Stiffener can be added in case further improvement is required.

Lorentz force detuning

- Nb material properties at cryo temperature
  - Young's modulus 123 GPa
  - Poisson's ratio 0.38
- Cavity thickness at 3 mm.
- Boundary conditions: Cavity constrained at beam pipes, FPC.

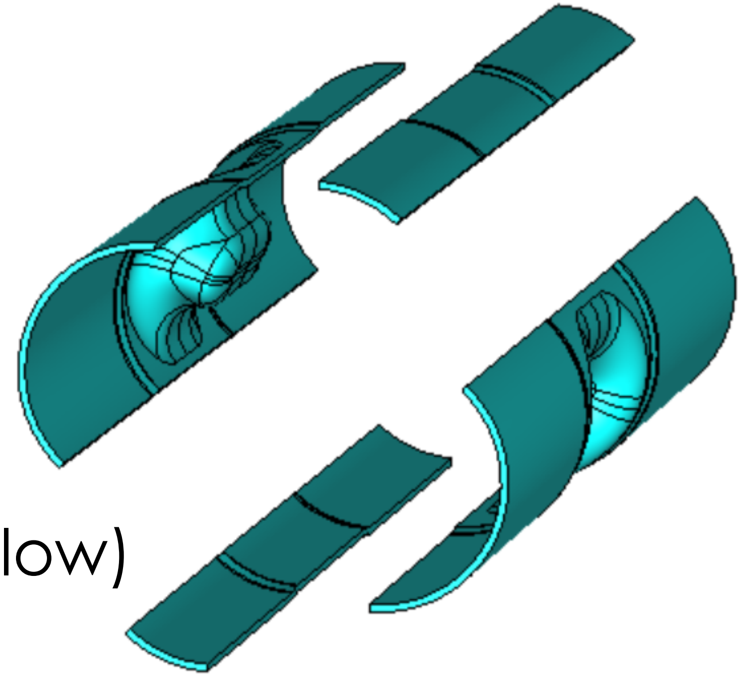
- Lorentz force detuning -1.51kHz/MV^2.
- At 1.48MV, it is -3.31kHz.
- Much smaller than detune requirement at 180kHz, can be compensated by tuner.

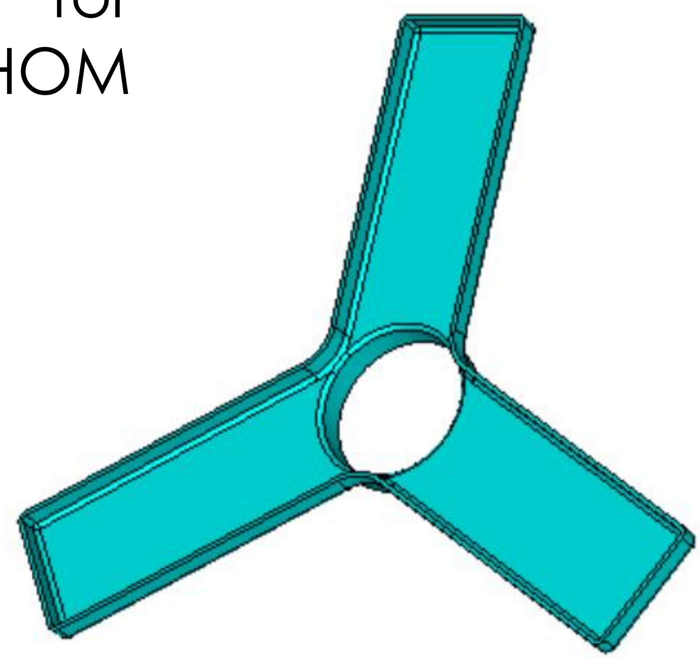
Outline

- Introduction and requirements
- Cavity
- HOM
- FPC
- Multipoles and multipacting
- Pressure stability and tuning
- Fabrication consideration
- Cryomodule (preliminary)

Fabrication

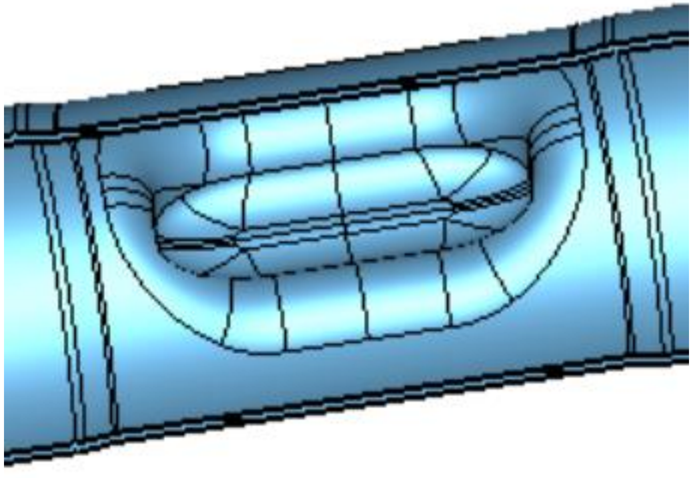
- Three dies:
  - One for cavity
  - One for damper unit
  - One for corrugations (bellow) on the circular pipe
- Then holes will be added for FPC/vacuum ports and HOM coax ports





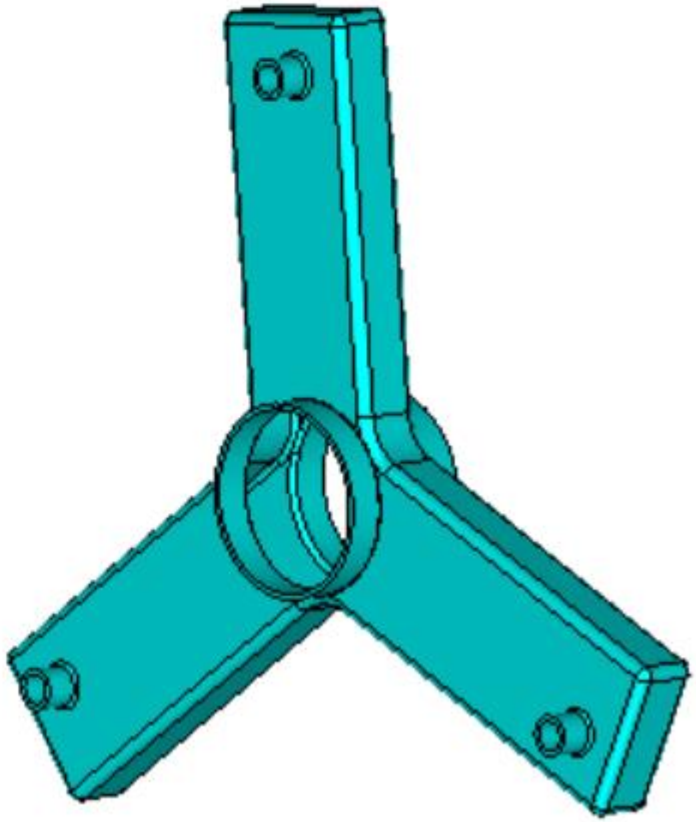
Fabrication - alternative

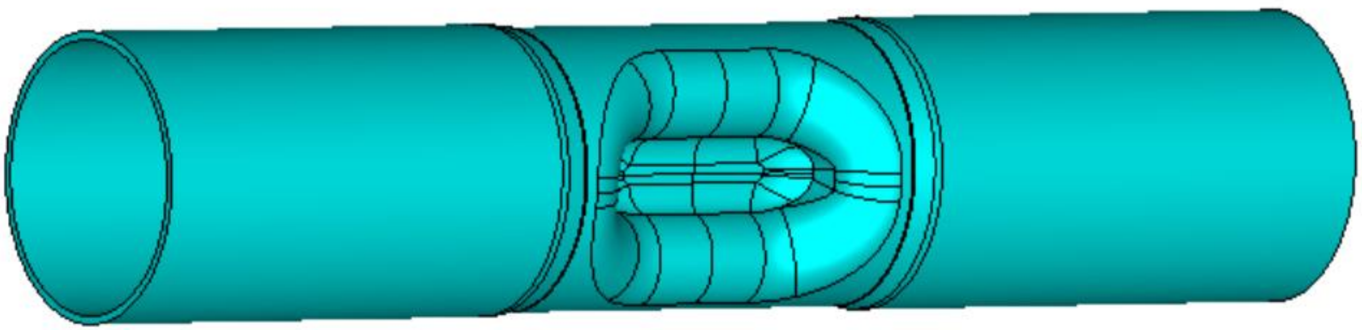
- Cavity can be machined from ingot if cavity fabrication errors are critical (HOM spectrum/peak fields/multipoles etc).



Total weight

- 3mm sheet
- Cavity 4.4kg
- Damper unit 4.7kg
- For 250GeV, 2 cavities + 3 damper units, total 22.9kg
- For 1TeV, 5 cavities + 6 damper units, total 50.2kg
- Based on 3 coax absorbers per damper unit, with 2 coax design it will be less.





Outline

- Introduction and requirements
- Cavity
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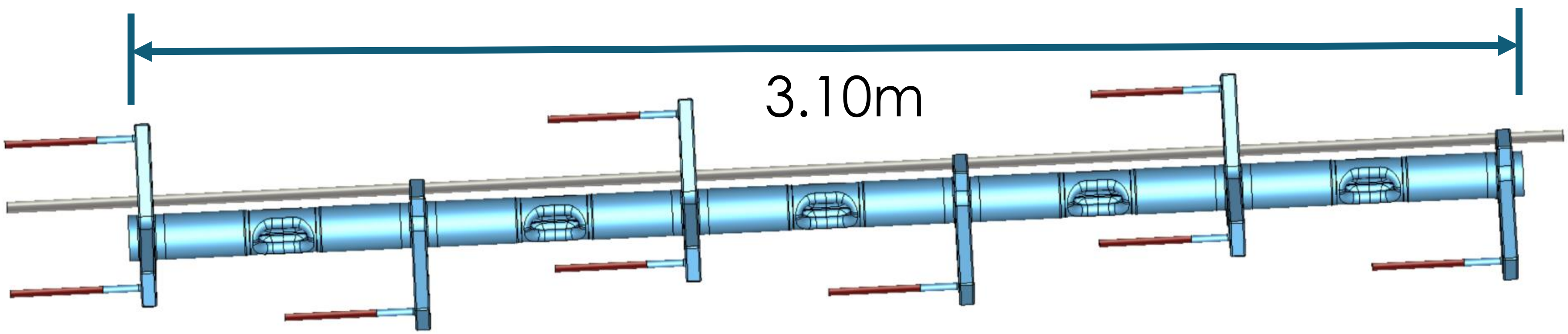
- FPC
- Multipoles and multipacting
- Pressure stability and tuning
- Fabrication consideration
- Cryomodule (preliminary)

Cavity string (estimation)

- One cryomodule with 5 cavities and 6 damper units.
- Simple design with single cell cavities and damper units between cavities.
- Total length can be 3.10m.
- Space reserved for cold-warm bellows and two valves, and tapers if needed.
- Space reserved for adjacent beampipe (pic below).
- 2 cavities for 250GeV and 5 cavities for 1TeV.



Summary

- WOW + RFD is a good candidate for ILC.
- Simple (robust) cavity design, with FPC/PU/HOM damper all outside the helium vessel.
- Simple cavity with large opening ease the surface treatment towards better RF performance.
- Demountable HOM units that connect to the cavity beampipe.
- Total length can be managed within 3.8m.
- Finished cavity + HOM design.
- Meet all specs with reasonable margin.
- More effort on ancillaries (FPC/PU, HOM damper, RF window, amplifier, tuner, vessel, etc.) is needed.
- Could be a good joint effort.

Thank you!