Double Quarter Wave (DQW)
For the ILC Crab Cavity Application

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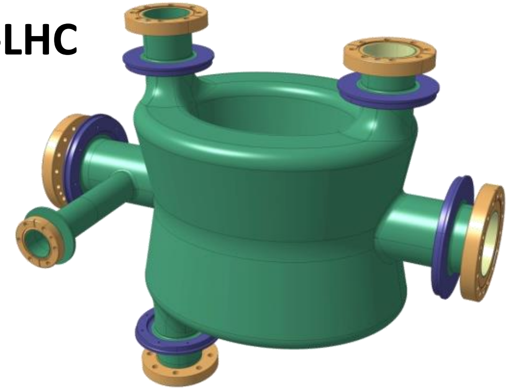
DQW Design Evolution

HL-LHC



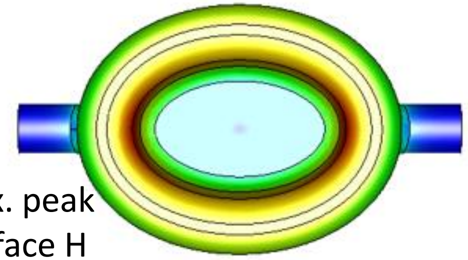
- 400 MHz, on-cell damping & FPC
- Cavity walls with **waist,** space
- Elliptical profile (H-field region)
- Coaxial couplers

EIC

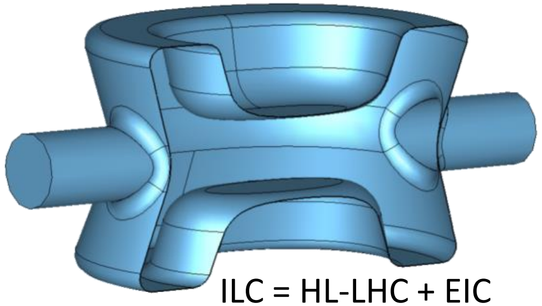
Space requirements →
Further reduce peak fields →

- 200-400 MHz, on cell-damping
- Flat cavity walls
- **Cassini-Oval** profile (H-field region)
- Waveguide and/or coaxial couplers

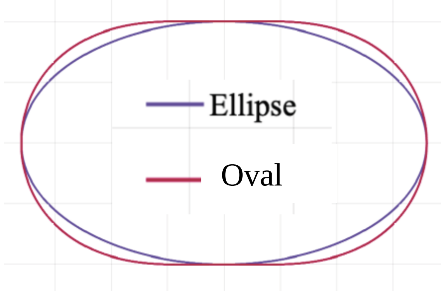
ILC



Max. peak surface H



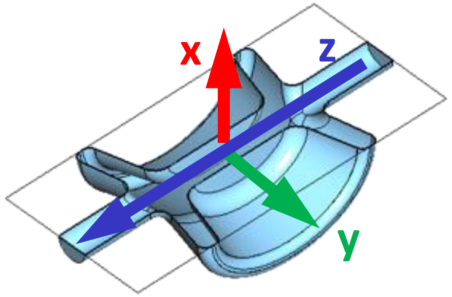
ILC = HL-LHC + EIC

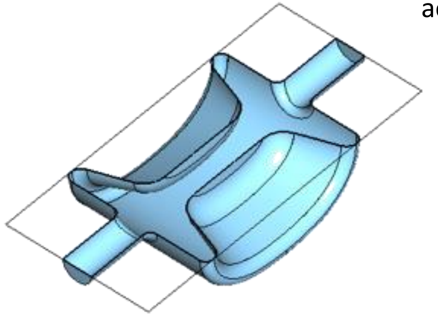


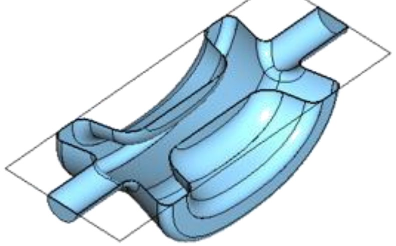
Design Comparison

Parameter	unit	LHC-type DQW (B05)	EIC-type DQW (A42)	LHC+EIC-type (C02)
Aperture, pole distance	[mm]	20	20	20
Profile		Elliptical + waist	Oval + straight walls	Oval + waist
Dimensions: L x W x H	[mm]	95 x 100 x 88	115 x 98 x 82	117 x 76 x 97
Rt/Q (circuit)	[Ω]	309	333	311
Geometric factor	[Ω]	80	82	97
E_{pk} at 1.86 MV	[MV/m]	50	56	55 ←
B_{pk} at 1.86 MV	[mT]	99	81	84 ←
First HOM (GHz)	[GHz]	1.74 (z)	1.98 (z)	2.18 (z) ←

Added advantages: broad inductive plate to accommodate ports, ease cleaning





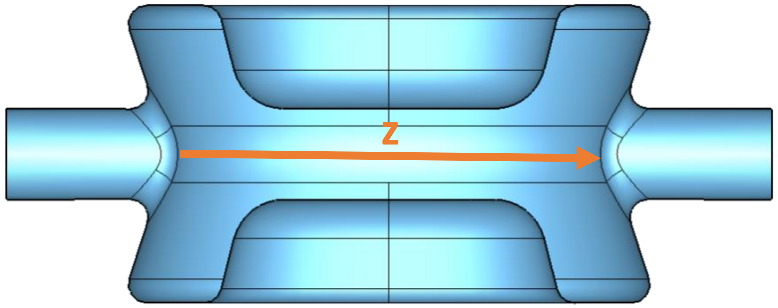


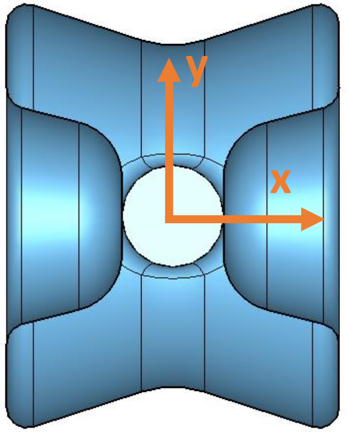
Aperture Study

Aperture	[mm]	30*	25* (Design)	20
Dimensions: L x W x H	[mm]	126 x 91 x 106	117 x 82 x 104	117 x 76 x 97
Circuit Rt/Q	[Ω]	153	211	311
Geometric factor	[Ω]	104	102	97
E_{pk} at 1.86 MV	MV/m	63	58	55
B_{pk} at 1.86 MV	MV/m	109	99	84
First HOM	GHz	1.84 (z)	2.00 (z)	2.18 (z)

* Peak fields may be further reduced with refined optimization

#cavities for 125 GeV (Total Vcc = 1.86 MV)	2	
#cavities for 500 GeV (Total Vcc = 7.4 MV)	6	



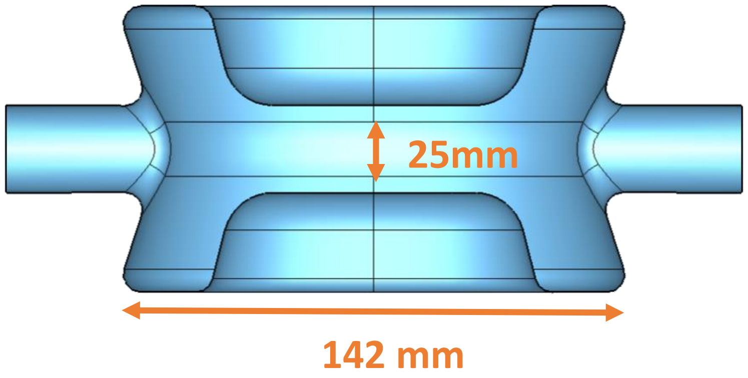


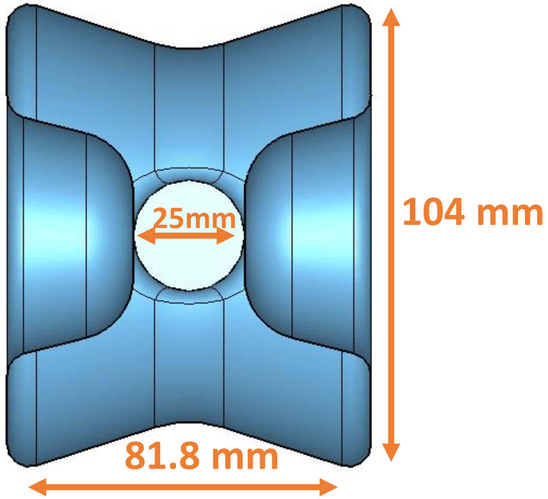
* with adopted max. allowable peak fields of 45 MV/m and 80 mT

DQW Parameters

Parameter	Unit	Value
Operating frequency	(GHz)	1.3
First long. HOM	(GHz)	2.00
First trans. HOM, vertical	(GHz)	2.21
Ep/Et*		3.60
Bp/Et*	(mT/MV/m)	6.14
G		102
Rt/Q (acc)	(Ω)	422
RtRs	(Ohm^2)	43044
Vt max per cavity	(MV)	1.44
Vt /cavity (125 GeV)	(MV)	0.93
No. cavities (125 GeV)		2
Extendability (500 GeV)		6
Number of cells		1

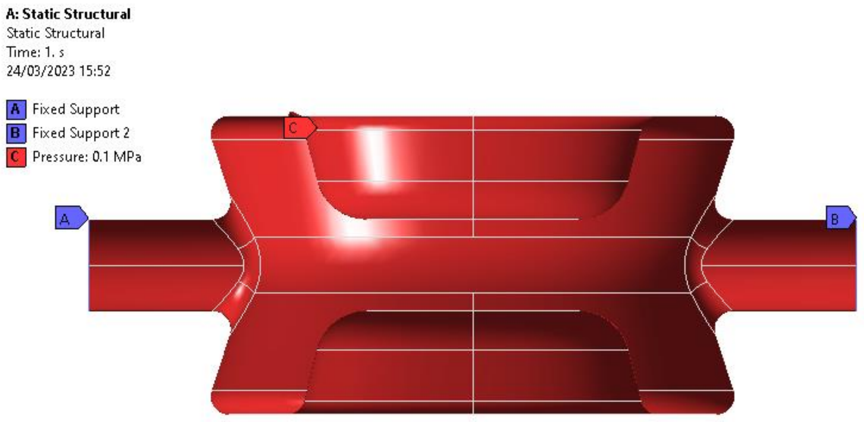
Parameter	Unit	Value
Cavity diameter	(mm)	104
Min. Aperture	(mm)	25
Flange-to-flange length	(mm)	~250
FPC Loaded Q		1×10^7
Loaded Bandwidth	(kHz)	0.13
Cavity input power	(kW)	0.3
Stored energy (at Vt operational)	(J)	0.25
HOM impedance		TBD
Loss and Kick Factors		TBD
Multipole Parameters		TBD
Max. Stress, Max. Press	Mpa, bar	42, 2.1
Nb per cavity	(kg)	15





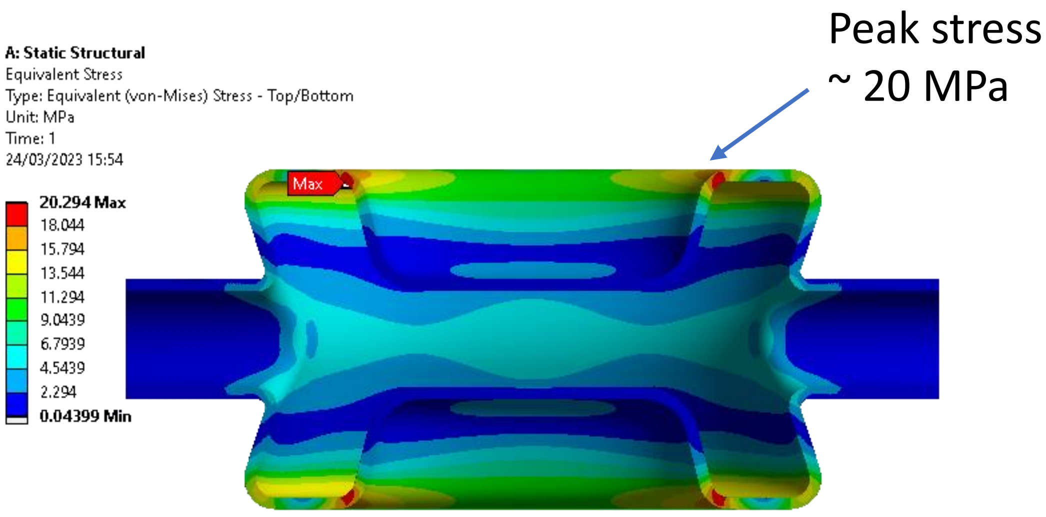
First Stress Analysis

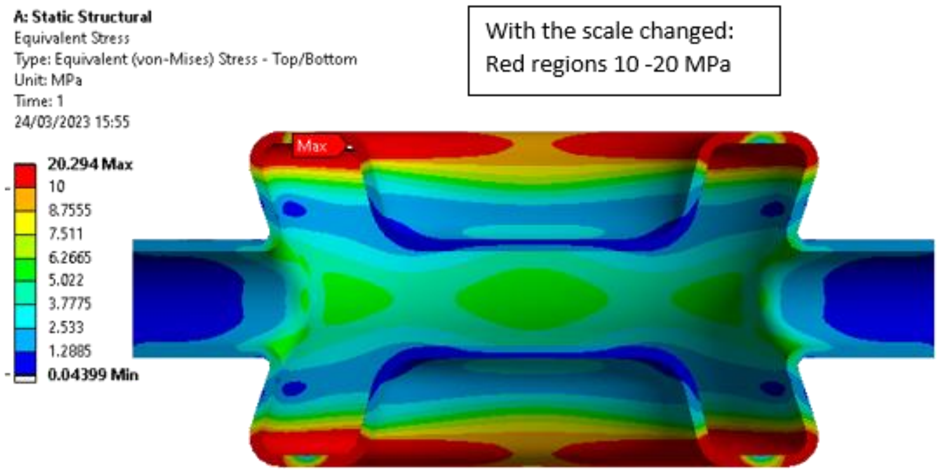
- Shell elements with a 3 mm thickness
- The external pressure of 1 bar
- Two fixed supports (on both cavity extremities)



Analysis is linear elastic, results can be scaled with pressures (assuming to stay in elastic domain).

A tuning frame to transfer the force symmetrically will be needed – similar to HL-LHC crab cavities

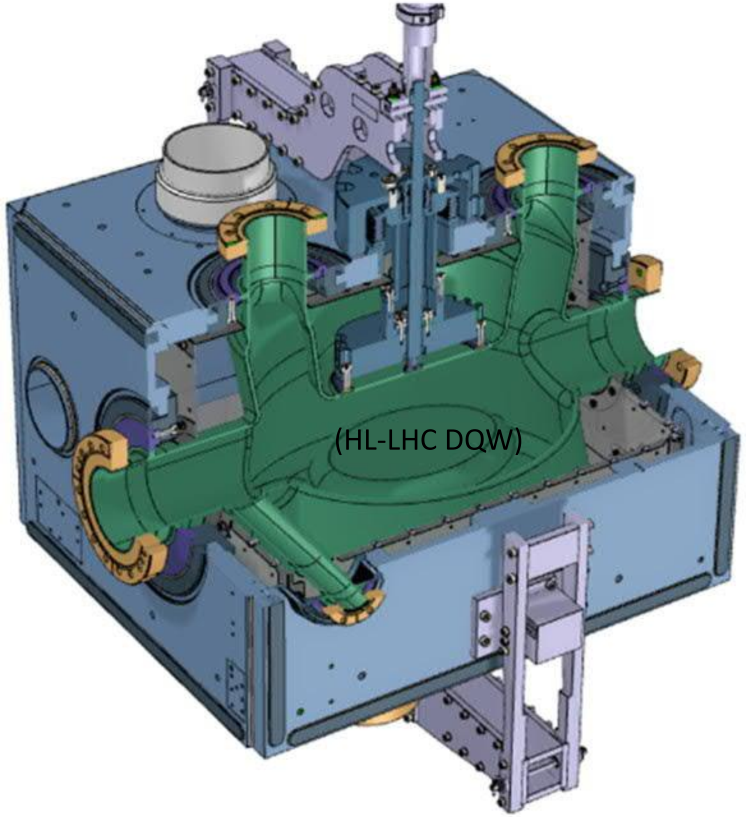




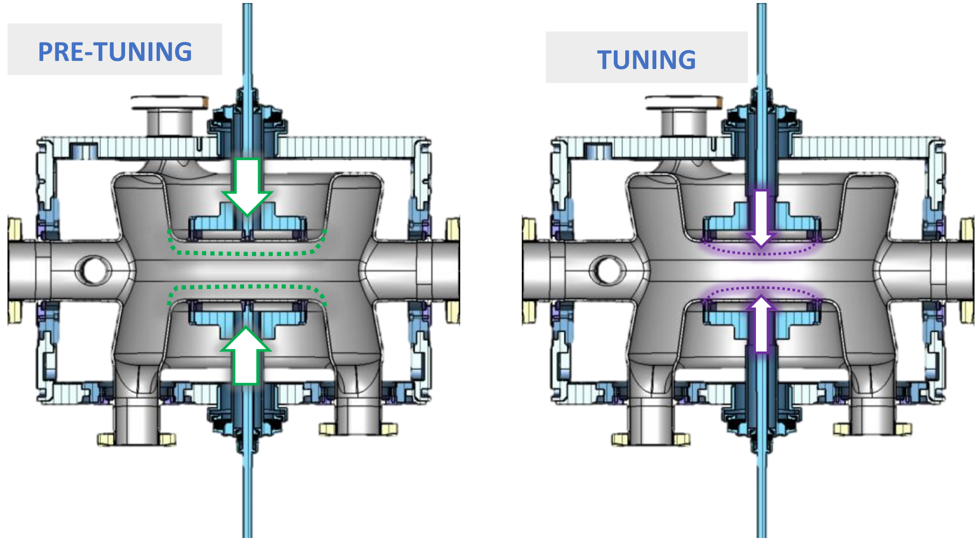
Courtesy: J. Swieszek

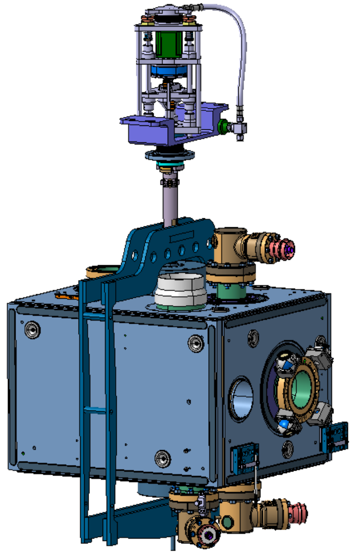
Frequency Tuner & He-Tank

Active & symmetric tuning using Ti-frame across the poles with actuation done at warm → push-pull tuning systems of both capacitive plates.



- Symmetric displacement of the poles to preserve field center
- Initial (asymmetric) pre-tuning and symmetric tuning



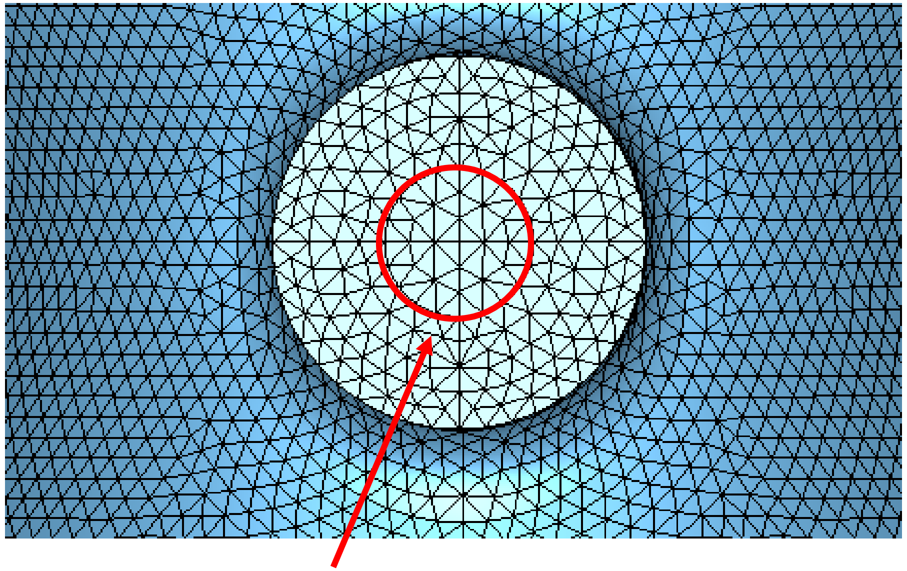


- Provides reinforcement to sensitive pole region by transferring the force symmetrically
- Further development requires He vessel design which can be similar concept as HL-LHC

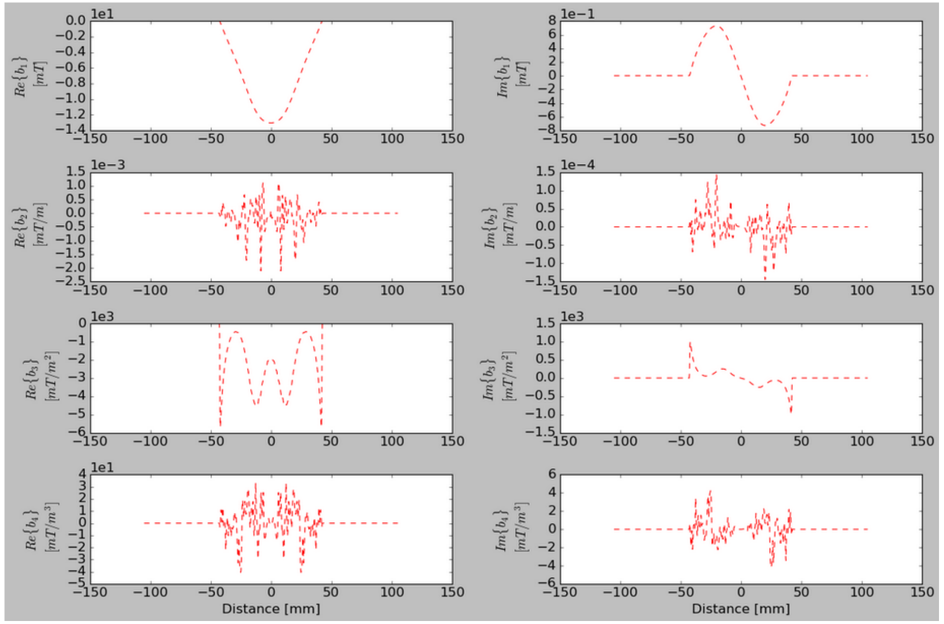
RF Multipoles

$$B_{\perp}^{(n)} = \frac{1}{qc} F_{\perp}^{(n)} = \frac{nj}{\omega} E_{acc}^{(n)} \qquad [Tm/m^n]$$

$$b_n = \int_0^L B_{\perp}^{(n)} \, \mathrm{d}z \in \mathbb{C} \qquad [Tm/m^{n-1}]$$



Radius = 5mm
(20% of aperture)



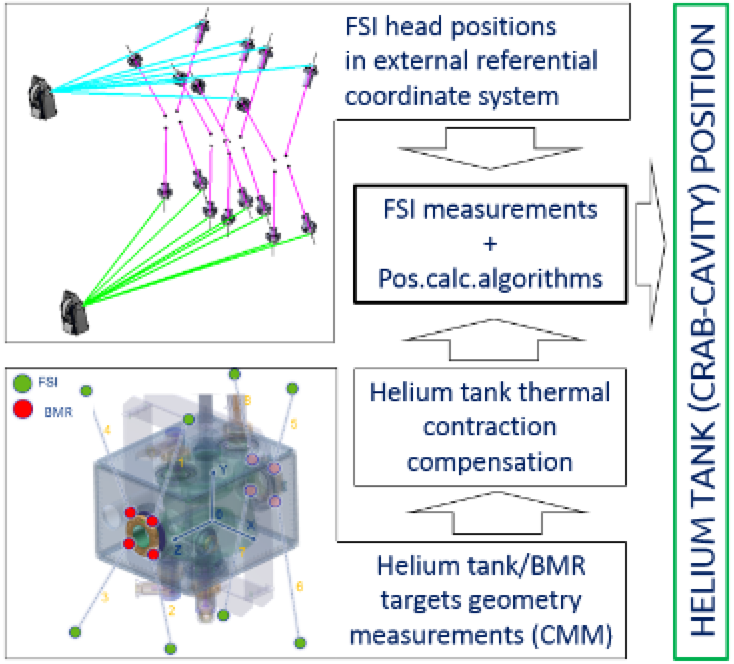
n	bn (normal)	an (skew)	bn (normal), PW	an (skew), PW
1	3.105714e+00	2.813182e-06	4.294989e+00	7.297858e-08
2	2.963073e-03	7.775165e-02	1.935741e-04	2.842546e-04
3	**8.726951e+02**	3.375818e-01	1.265596e+03	2.919143e-03
4	2.370459e+02	7.185031e+03	7.742965e+00	2.749502e+02
5	**1.425299e+07**	2.250545e+04	7.318126e+05	1.167657e+02

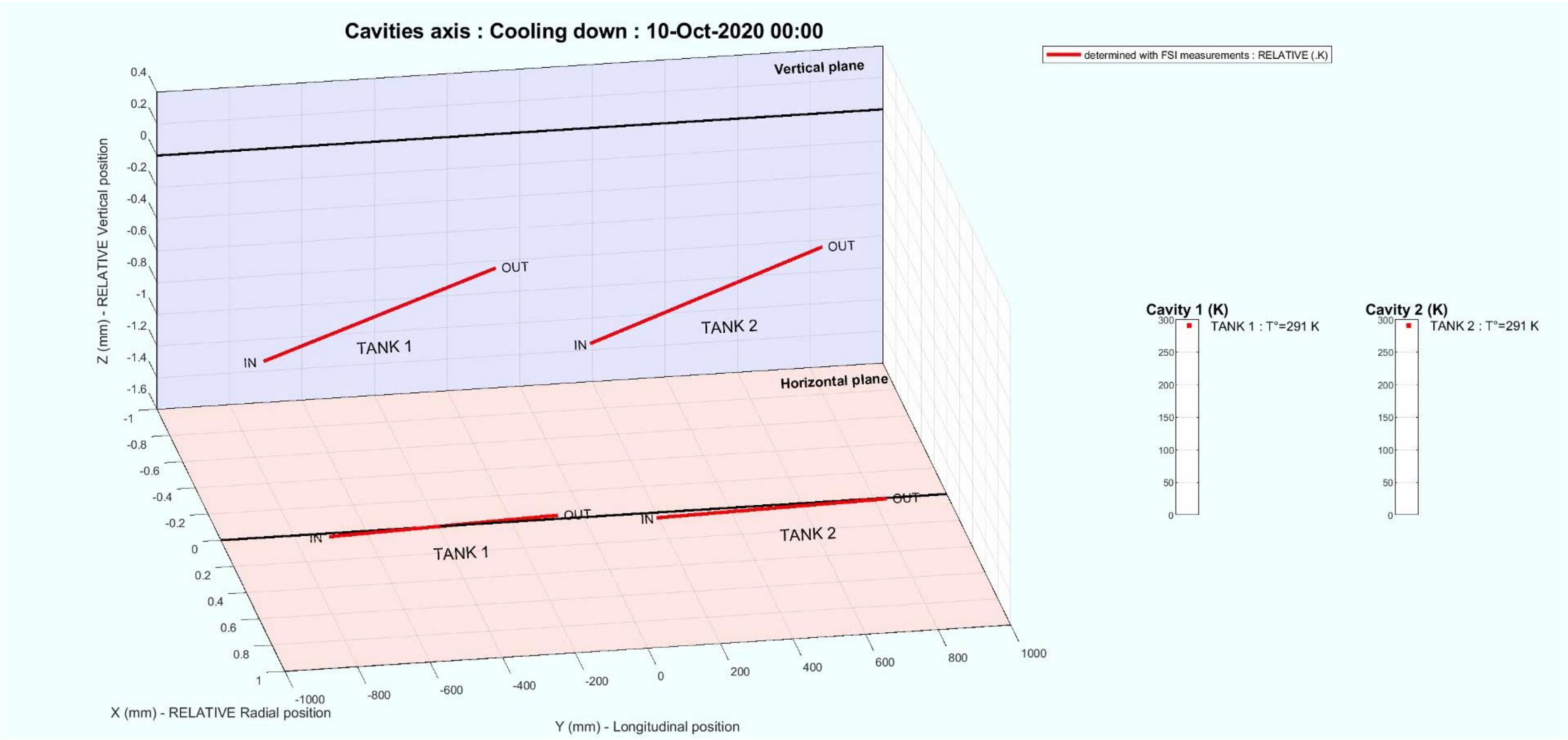
But, maybe this not relevant for ILC. Perhaps kicks are dominated by alignment & vibrations ?

* Recheck needed with more careful mesh

Alignment Monitoring, HL-LHC Example

3-point supporting system





Repeatability of several heat-up and cool down sequences : Below 20 μm

Courtesy: V. Rude et al.

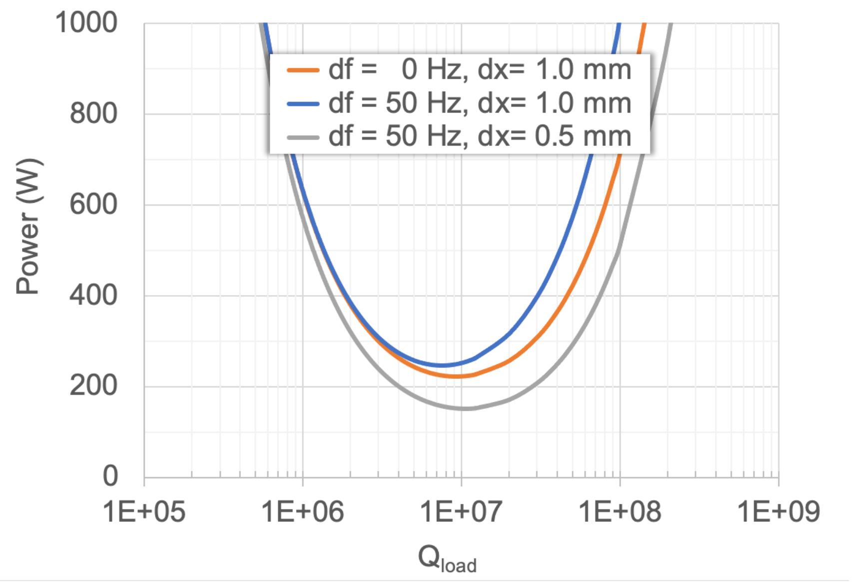
RF Power Requirements

Input power required including beam offset beam (y) & by detuning $(\Delta\omega)$:

$$P_g = \frac{1}{8}\frac{|\vec{V_\perp}|^2}{(R/Q)_\perp Q_{load}} \times \left\{\left[1 + \frac{2(R/Q)_\perp \kappa y Q_{load} * I_{b0} cos\varphi_b}{|\vec{V_\perp}|}\right]^2 + \left[2Q_L \frac{\Delta\omega}{\omega_0} + \frac{2(R/Q)_\perp \kappa y Q_{load} * I_{b0} sin\varphi_b}{|\vec{V_\perp}|}\right]^2\right\}$$

ILC CC Specs v11		125 GeV, 10 Hz upgrade	500 GeV
Frequency $\omega_0/2\pi$	[GHz]	1.3	1.3
Total $V_\perp$	[MV]	1.86	7.4
I_{b0}	[mA]	8.75	7.6
No. DQW cavities		2	5
$V_\perp$ per cavity	[MV]	0.93	1.48
DQW $R/Q_\perp$ (circuit)	[Ω]	211	211
Max. offset y	[mm]	0.5	0.5
Detuning $\Delta\omega/2\pi$	[Hz]	50	50

P vs Q_L for 125 GeV



Target Qe = 1e7, Bandwidth = 130 Hz
Power = 300 W

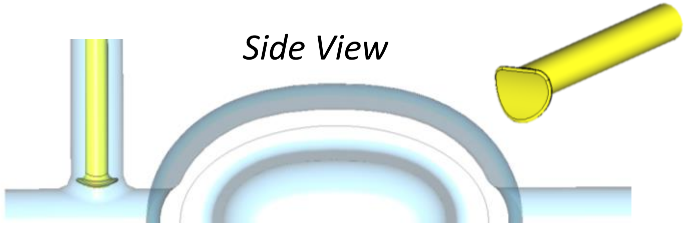
Fundamental Power Coupler

(1) Target Qe = 1e7 easily obtained by hook coupler (H) inserted in horizontal port opened at inductive plate (like LHC DQW). Low P_0 ~ 1.4 W (Vt = 0.93 MV, copper).

(2) Attempts to attain similar coupling levels with cone-like coupler (E) inserted in horizontal port at the beam pipe only provided Qe ~ 1e8.

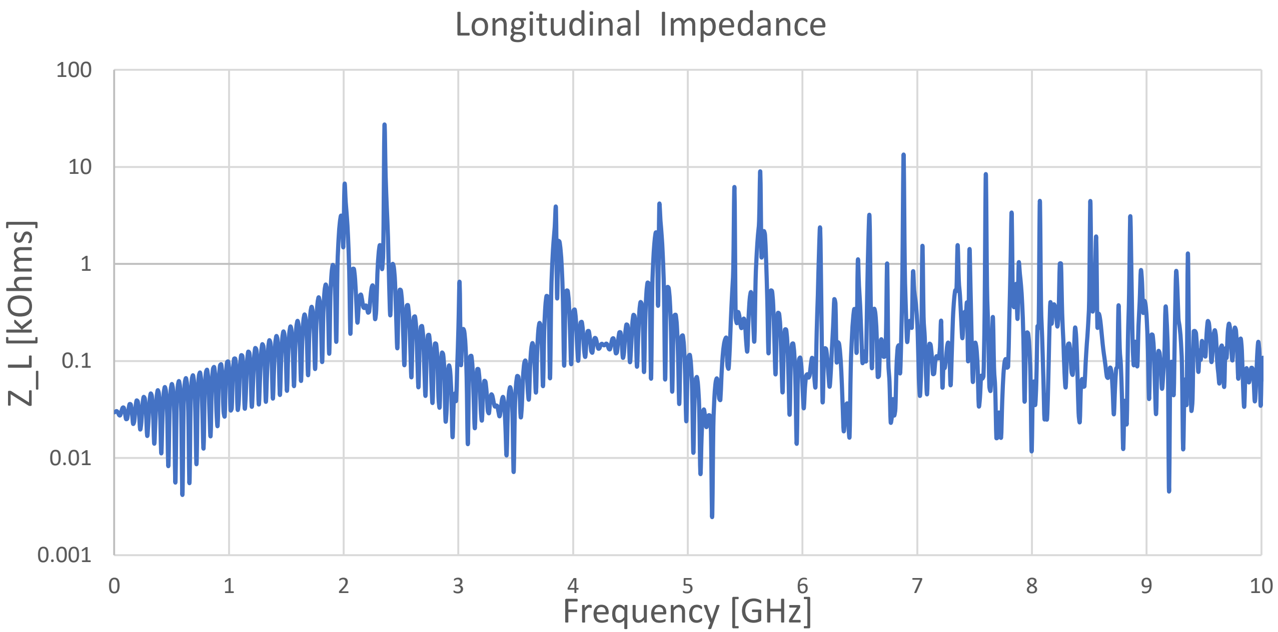
(3) A pringle-like coupler (E) provided similar results as option (2).

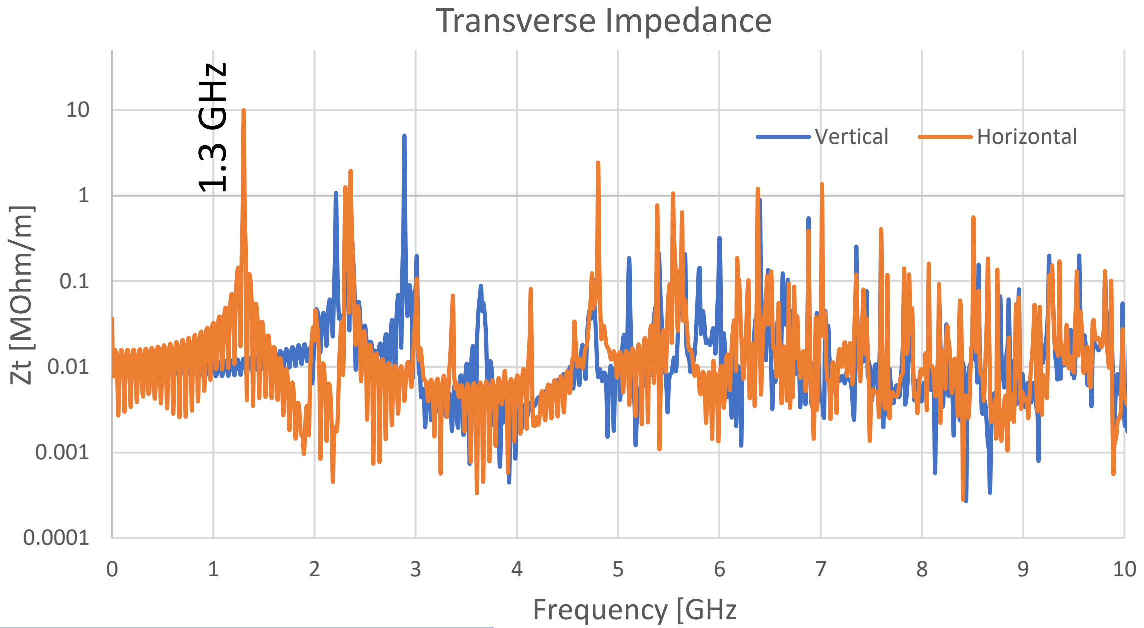
(4) Explored coupling levels offered by ice cream scoop coupler inserted in (preferable) vertical port at the beam pipe with insufficient Qe ~ 1e10. Further studies ongoing drawing from EIC DQW design experience.



All using 40 mm Ø tube for DN40 CF flange

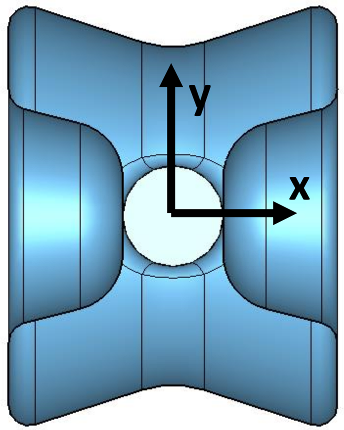
Mode Spectra, Bare Cavity





Impedance threshold [ILC CC Spec v13]	Total	Per cavity (6 cavities)
Zx (MΩ/m)	48.8	8.1
Zy (MΩ/m)	61.7	10.3
Zz	TBD	--

HOM #	Freq (GHz)	R/Q (circuit)	Type
(1)	2.00	43 Ω	Long. (z)
(2)	2.21	23 Ω/m	Vert. (x)
(3)	2.30	28 Ω/m	Hor. (y)
(4)	2.36	31 Ω	Long. (z)
(5)	2.89	26 Ω/m	Vert. (x)



Freq TE11 cutoff (25 mm diameter) = 7 GHz
Wake = 200m, not converged

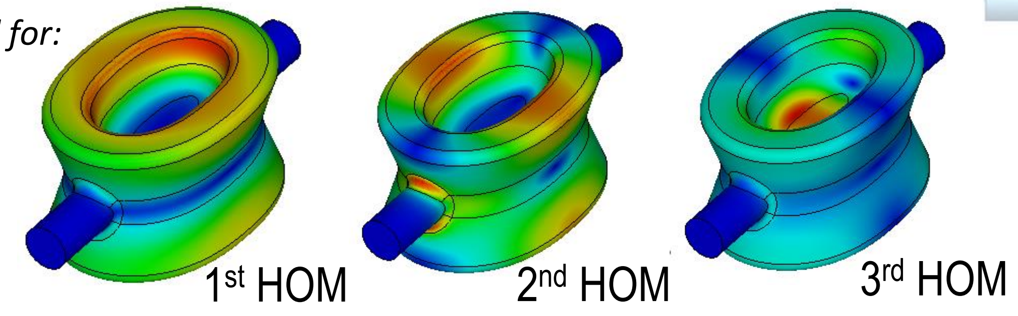
HOM Coupler

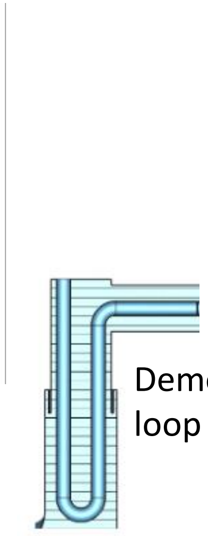
**Work in progress

(1) Install HOM couplers in horizontal ports opened at inductive plate (H-coupling like LHC DQW).

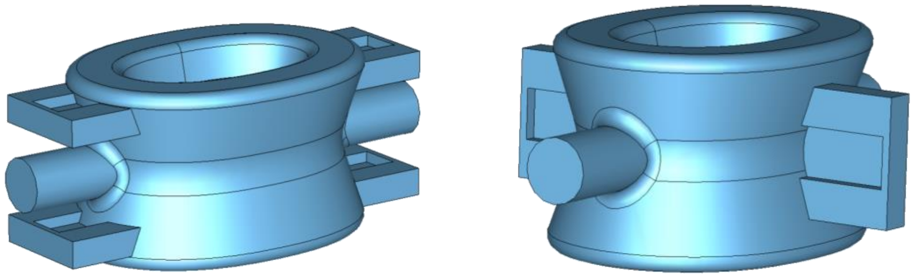
- Filter can be TESLA-like, HL-LHC like or even a demountable loop
- Will require 2-3 HOM couplers to extract all the required HOMs.

H-field for:





(2) Due to high frequency of the 1st HOM, a waveguide concept could be exploited [Rectangular WG with a ~ 75 mm has fc,TE10 = 2 GHz.]

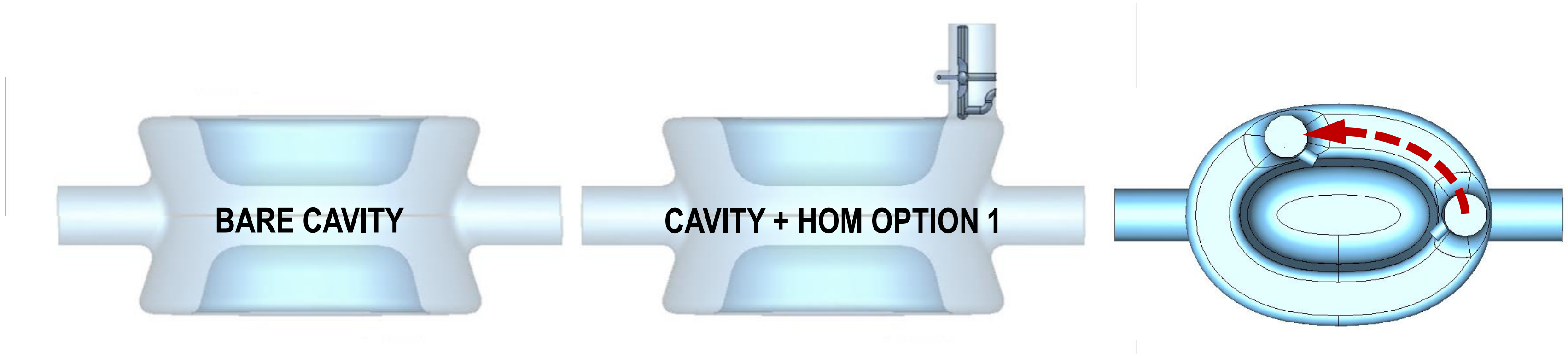


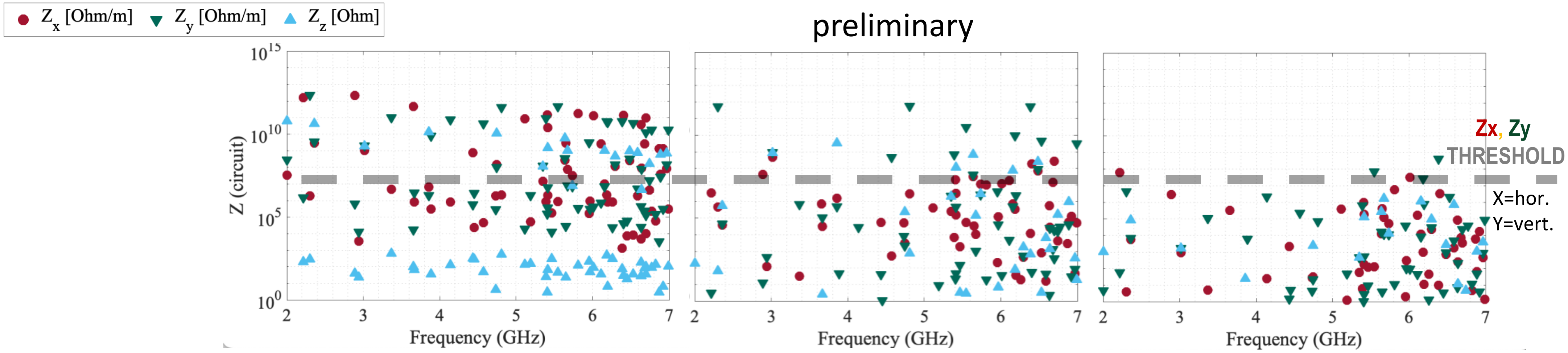
(3) A combination of options (1) and (2) is most likely the final option

HOM Coupler Option 1 - Coax

**Work in progress

- Almost all relevant modes have substantial magnetic field on the inductive region (top/bottom)
  - HL-LHC DQW uses 3-hook type HOM couplers on the inductive plate
- First results with single Tesla-type HOM coupler shows promising results. Studies to be followed up

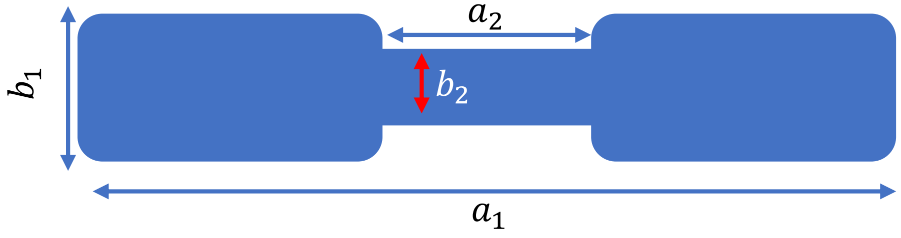




HOM Coupler Option 2 - RWG

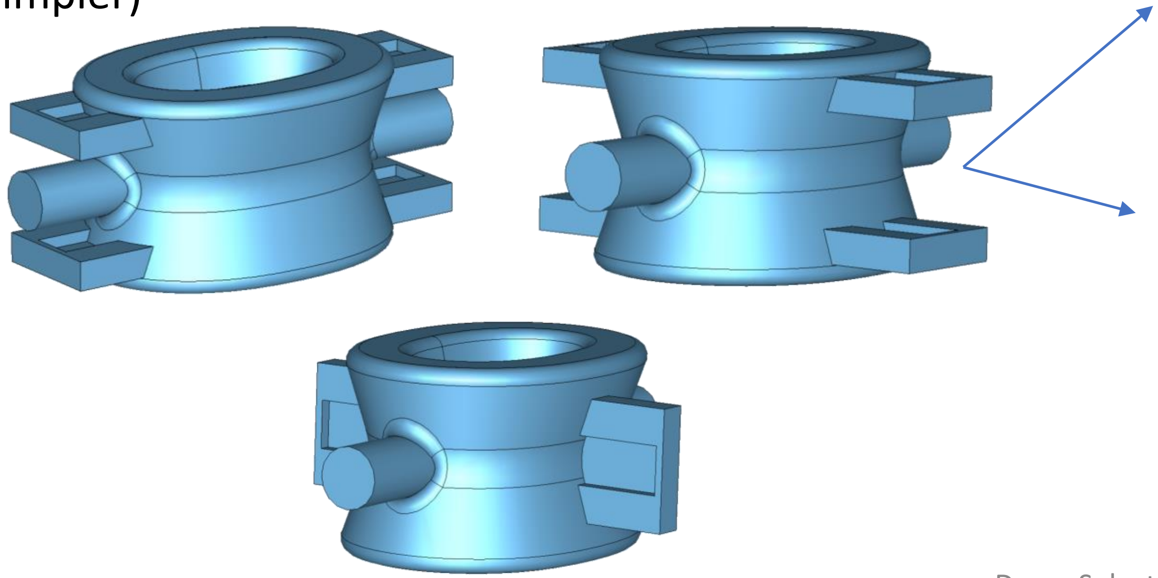
**Work in progress

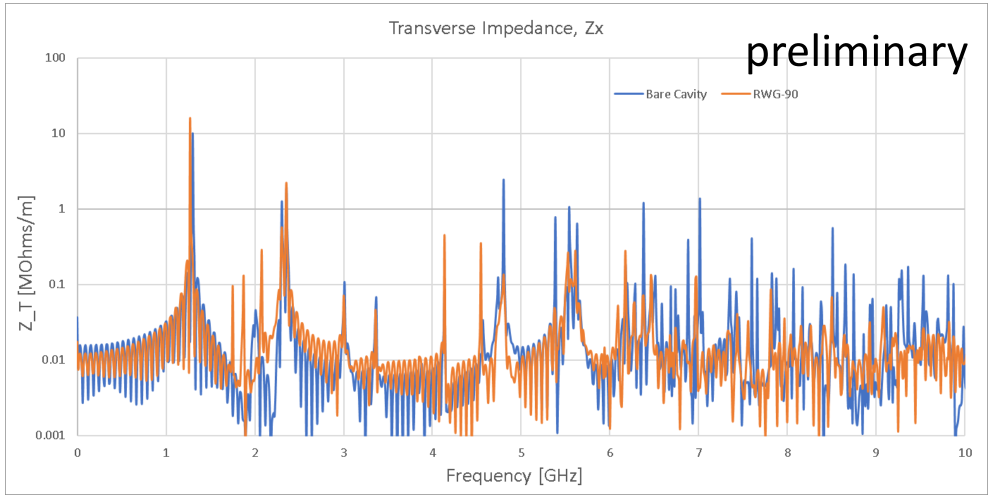
The high frequency of the HOM $\geq 2\ \mathrm{GHz}$ allows for the use of waveguide.
For example, we can start with WRD200 ($2 - 5\ \mathrm{GHz}$) – adapt the ridge geometry to make it smaller

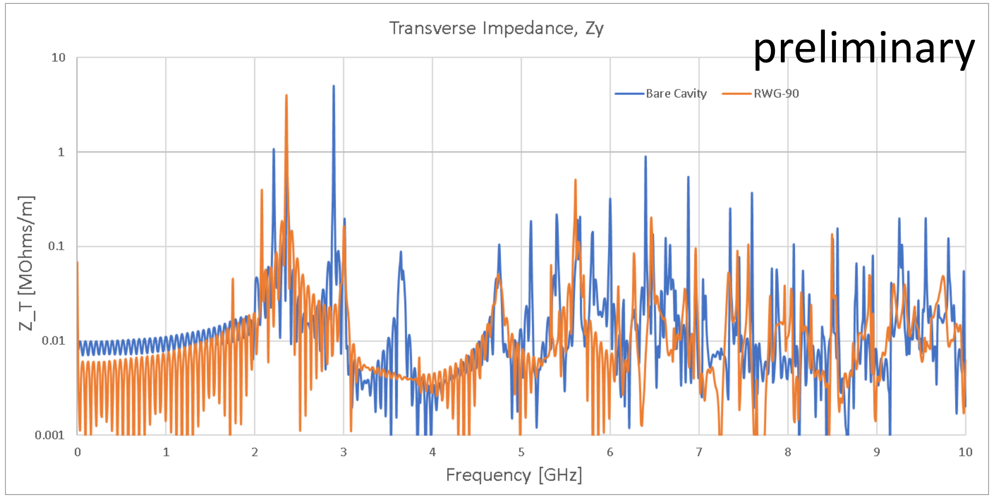


$a_1 = 65.8,\ a_2 = 16.5$
$b_1 = 30,\ b_2 = 13$

A first attempt (the final configuration will be much simpler)



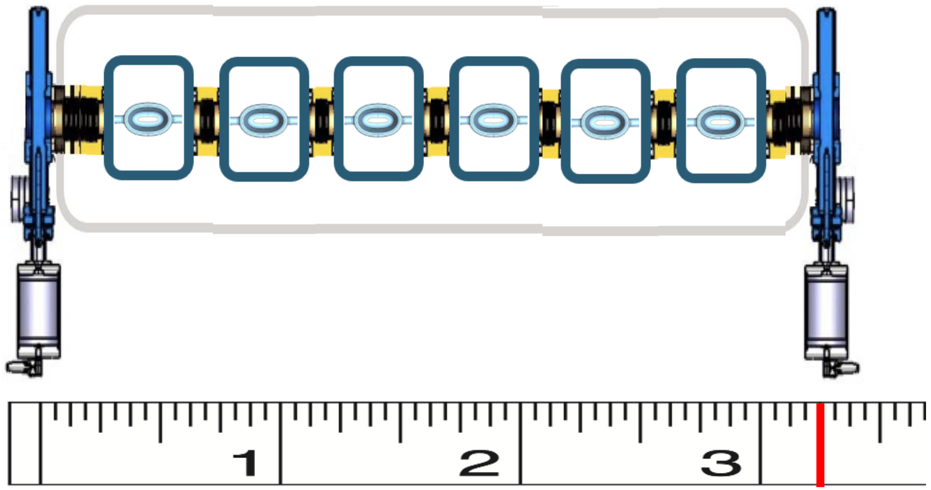




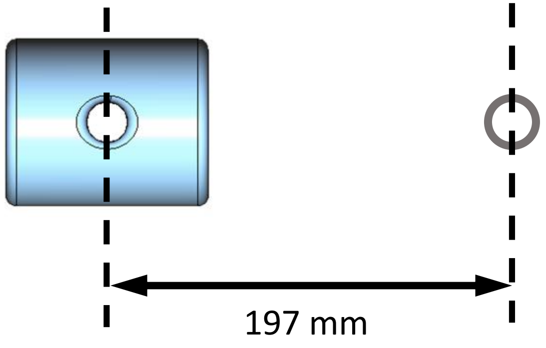
Scalability

- For 500 GeV option: 6 DQW cavities to provide 7.4 MV crabbing kick
- Length available of 3.25 m enough for crab cavities and transitions (cold-warm, gate valves, etc.)
- Sufficient clearance to 2nd beam pipe for coupler integration
- Top loading cryostat similar to HL-LHC has many salient features to exploit

Side view, 6 DQW in cryomodule



Front view, distance to 2nd beam pipe



Top Loading Concept, HL-LHC

Alignment check during a cryostating step (2017)

Precision alignment of cavities & components on alignment table and closure of beam vacuum in ISO4

Alignment followed through the assembly and then rest of the life cycle

Mounting and assembly of cryostat components done on lifting frame & access to key components until the final closure on the bottom part

Final Comments

- The DQW cavity is a very compact solution for the ILC crabbing system
  - 2 single-cell cavities provide 1.86 MV for the 125 GeV option
  - 6 single-cell cavities for the 500 GeV option

- Several concepts can be directly adapted from the recent developments of the of HL-LHC and EIC work.

- Cavity compactness lends itself to a machined cavity ingot (at least the main body and interfaces). Depending on the damping scheme, adapted welding/brazing operations will have to considered
  - First priority is to converge on HOM damping scheme
  - Second priority is to build a prototype for voltage demonstration
  - Engineering design and other details to follow