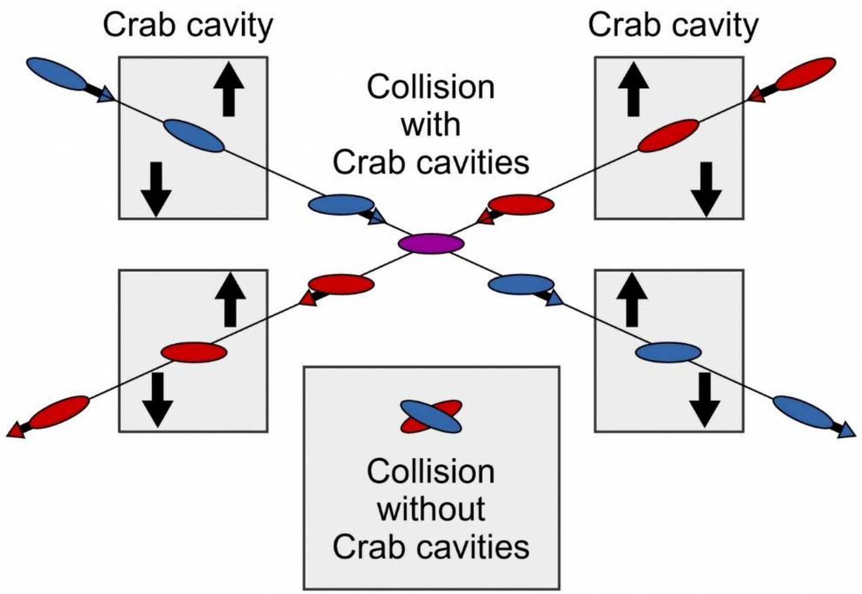
WG2 SRF: WP3 Crab Cavities

Design Review Workshop #3 – 21/10/22

Peter McIntosh

UKRI-STFC Daresbury Laboratory

1st November 2022



Science and Technology Facilities Council

Agenda for WP3 Design Review #3 (GMT)

Friday 21st October 2022			
13:30	Introduction and Remit for the Workshop	Peter McIntosh (STFC)	5 min
13:35	Specification Review	Peter McIntosh (STFC)	15 min
Cavity Design Updates			
13:50	Elliptical/Racetrack	Graeme Burt (Lancaster University)	15 + 5 min
14:10	RF Dipole (RFD)	Suba De Silva/Jean Delayen (ODU/JLab)	15 + 5 min
14:30	Double Quarter Wave (DQW)	Silvia Verdu Andres (CERN)	15 + 5 min
14:50	Wide Open Waveguide (WOW)	Binping Xiao (BNL)	15 + 5 min
15:10	Quasi-waveguide Multicell Resonator (QMiR)	Andrei Lunin (FNAL)	15 + 5 min
15:30	Next Stage CC Preparations	Peter McIntosh (STFC)/K Yamamoto (KEK)/A Yamamoto (KEK)	30 min
16:00	Meeting close		

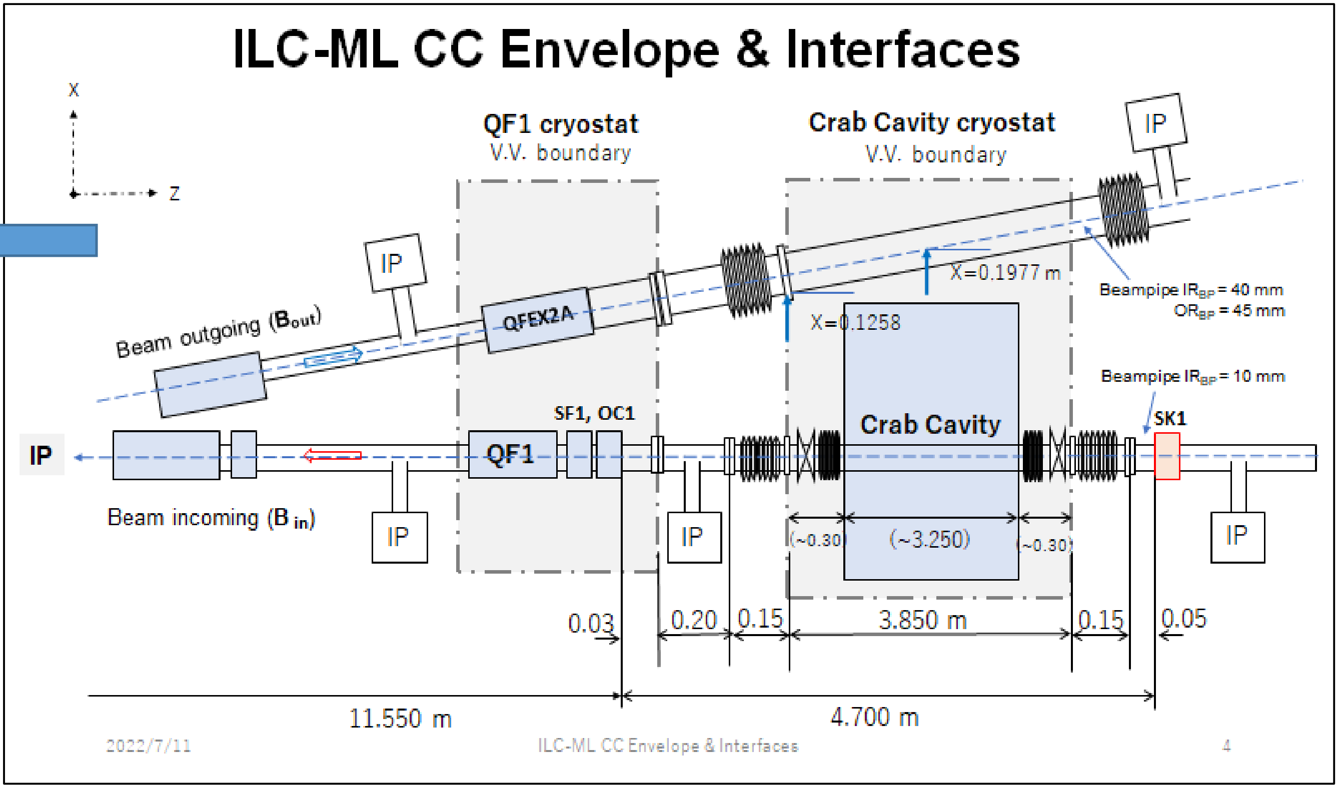
Scope Design Review #3

- Assess and compare CC EM designs, not likely finally optimised:
  - Cavity,
  - HOMs,
  - Couplers,
  - Multipacting,
  - Tuning.
- Clarifying next steps to 'head towards' a down-selection process:
  - All EM design aspects complete, including pressure stability and fabrication assessment.
  - Down-select 2 optimum CC designs for future prototype development (external review).
- Final CC down-selection, post-prototype validation at ~18-months later.

As proposed at Design Review #1 – Dec 21

Specifications Update (v14)

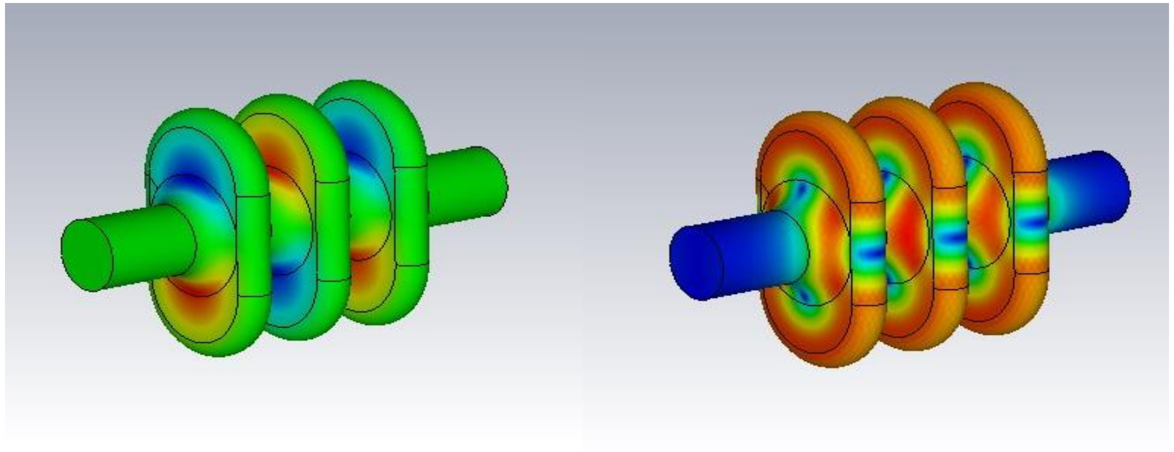
Parameter	Post-TDR Specification		10Hz Upgrade[1,2]	1 TeV CoM Spec [2]		
Beam Energy (GeV) e-	125			500		
Crossing Angle (mrad)	14					
Installation site (m from IP)	14					
RF Repetition Rate (Hz)	5		10	4		
Number of bunches	1312		2625	2450		
Bunch Train Length (ms)	727		961	897		
Bunch Spacing (ns)	554		366			
Beam current (mA)	5.8		8.75	7.6		
Operating Temp (K)	2					
Cryomodule installation length (m)	3.8 (incorporating gate valves)					
Horizontal beam-pipe separation (m)	0.1967 (centre) ±0.0266 (each end of installation length)					
Cavity Frequency (GHz)	3.9	2.6	1.3	3.9	2.6	1.3
Total Kick Voltage (MV)	0.615	0.923	1.845	2.5	3.7	7.4
Max Ep (MV/m)	45			45		
Max Bp (mT)	80			80		
Amplitude regulation/cavity (% rms)	3.5 (for 2% luminosity drop)					
Relative RF Phase Jitter (deg rms)	0.069					
Timing Jitter (fs rms)	49 (for 2% luminosity drop)					
Max Detuning (kHz)	240	170	100 - 180	240	170	100 - 180
Longitudinal impedance threshold (Ohm)	Cavity wakefield dependent					
Trasverse impedance threshold (MOhm/m) (X,Y)	48.8, 61.7					
Cavity field rotation tolerance/cavity (mrad rms)	5.2 (for 2% luminosity drop)					
Beam tilt tolerance (H and V) (mrad rms and urad rms)	0.35, 7.4 (for 2% luminosity drop)					
Minimum CC beam-pipe aperture size (mm)	>25 (same as FD magnets)					
Minimum Exraction beam-pipe aperture size (mm)	20					
Beam size at CC location (X, Y,Z) (mm,um,um)	0.97, 66, 300					
Beta function at CC location (X, Y) (m,m)	23200, 15400					
CC System operation	assume CW-mode operation					



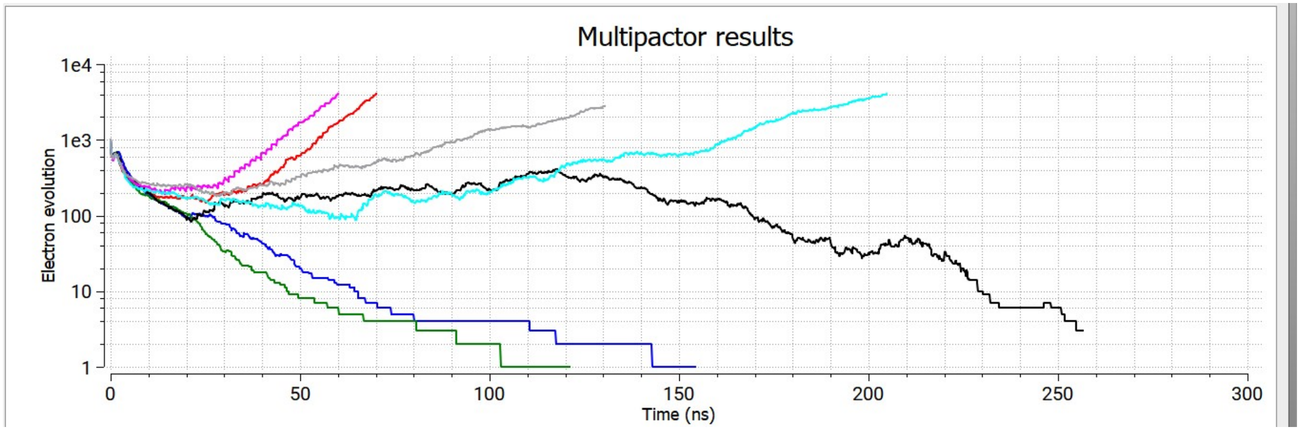
A Yamamoto/T Okugi – 19/7

Further clarify longitudinal impedance specification – Both Short/Long-range

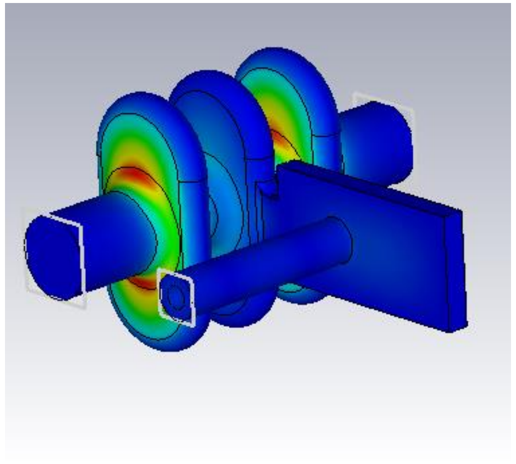
Elliptical/Racetrack 3.9 GHz
G Burt (Lancaster U)



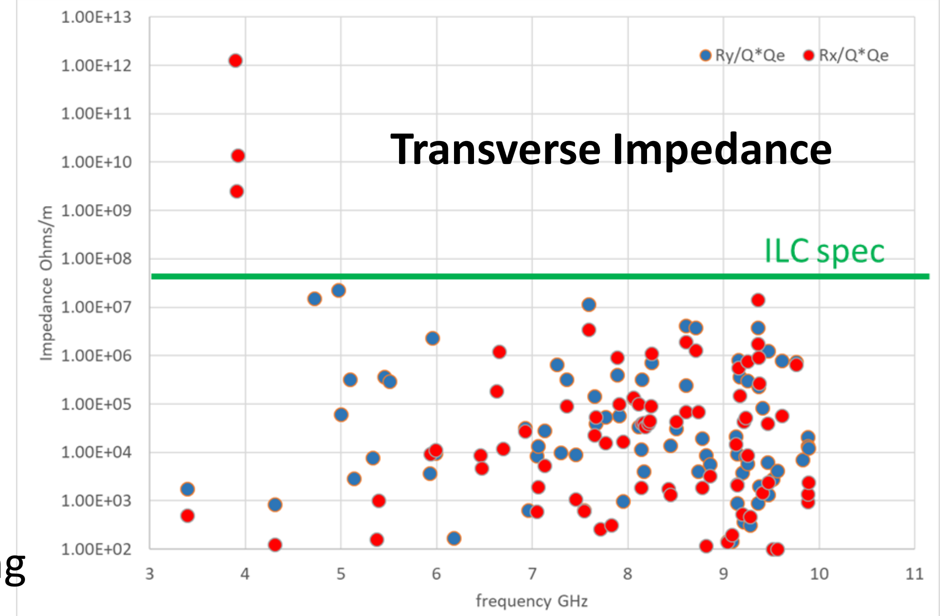
- Multipactor limit identified @ 7.15 MV/m (narrowband) on minor axis iris.



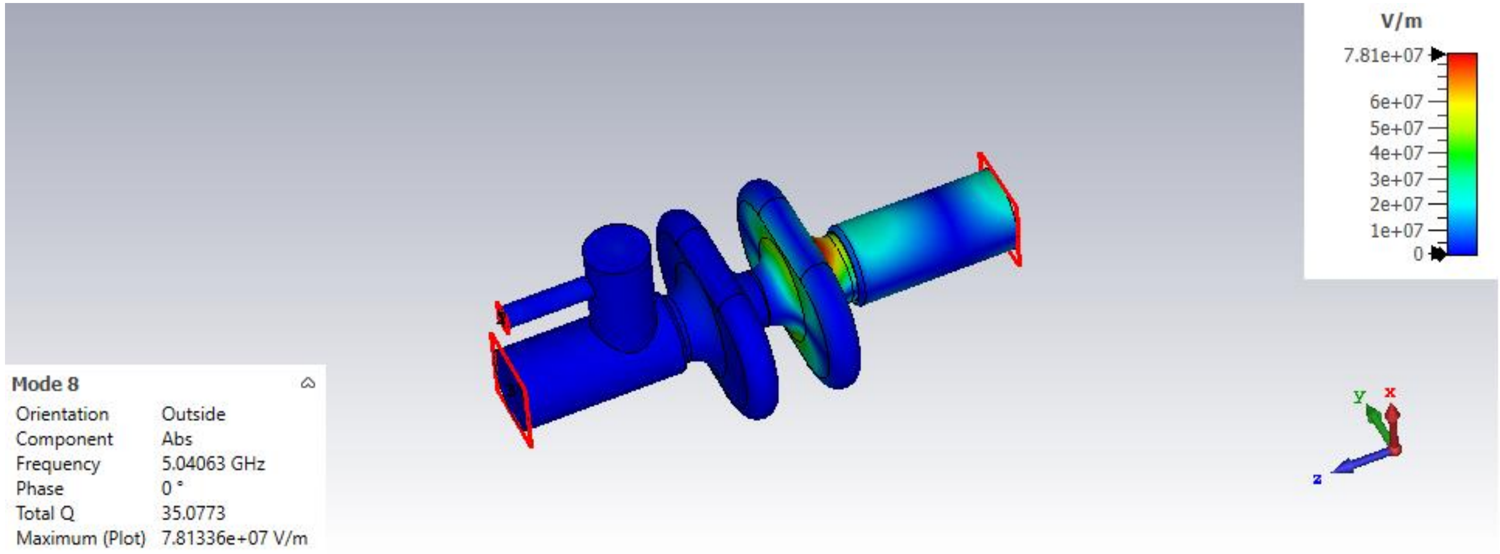
- 25 mm central beam-pipe, with 30 mm for end-cells to aid HOM damping.
- Expect to achieve 9.7 MV/m at 80 mT with R_t/Q=132 Ohms.
- 250 GeV ILC requires 1 x 3-cell cavity @ 5 MV/m to achieve 0.615 MV.
- 1 TeV ILC requires 4 x 3 cells @ 5.5 MV/m to achieve 2.5 MV.



Trapped Mode extraction using on-cell waveguide extraction



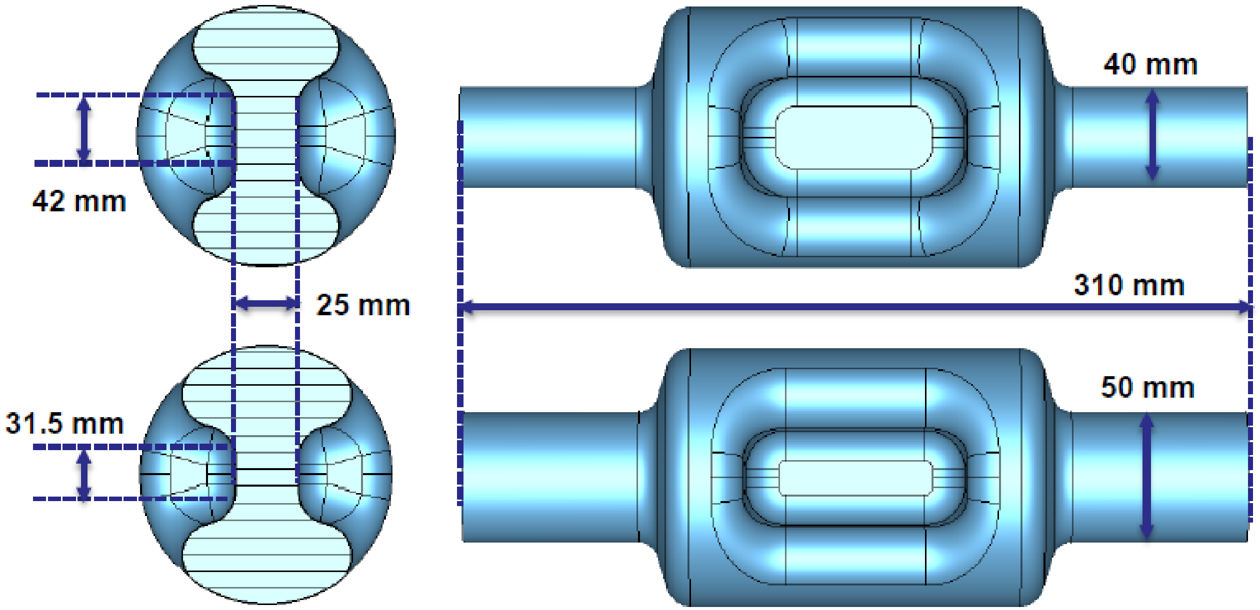
Elliptical/Racetrack 3.9 GHz
G Burt (Lancaster U)



- A 2-cell cavity has no trapped modes - on-cell damping is therefore not required – simpler to manufacture:
  - Expect an increase in both LOM and SOM Qe.
- Would change the ILC application expectations:
  - 250 GeV – 2 x 2-cell cavities @ 4.2 MV/m
  - 1 TeV – 5 x 2-cell cavities @ 6.5 MV/m

RF Dipole 1.3 GHz
S De Silva/J Delayen (Jlab/ODU)

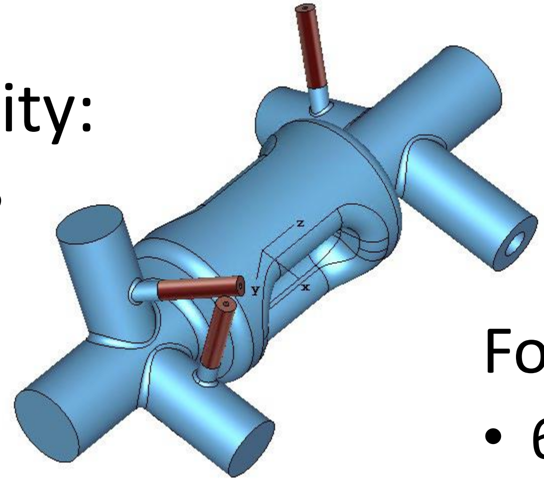
- Pole separation – 25 mm
- Beam aperture increased – 40 mm → 50 mm
  - Large beam aperture allows better HOM extraction
- Optimized the pole shape (pole height and length):
  - To maintain maximum achievable V_t at 1.35 MV
  - While maintaining peak surface field requirements of $E_p < 45$ MV/m and $B_p < 80$ mT



Property	1-cell	1-cell-new
Operating frequency [GHz]	1.3	1.3
1st HOM [GHz]	2.142	2.089
E_p/E_t^*	3.83	3.76
B_p/E_t^* [mT/(MV/m)]	6.84	6.80
B_p/E_p [mT/(MV/m)]	1.79	1.80
G [Ω]	129.9	129.54
R/Q [Ω] (V^2/P)	444.8	440.4
R_tR_s [Ω^2] (V^2/P)	5.78×10^4	5.70×10^4
*Reference length $V/E_t = \lambda/2$ [mm]	115.3	115.3
V_t [MV]	**1.35**	**1.35**
E_p [MV/m]	44.8	44.2
B_p [mT]	80.1	79.6
Pole separation [mm]	25	
Beam aperture [mm]	**40**	**50**
Cavity Length [mm] (flange-to-flange)	310	310
Cavity Diameter [mm]	100.3	99.4
Pole Length [mm]	80	85
Pole Height [mm]	42	31.5
Angle [deg]	22.5	22.5

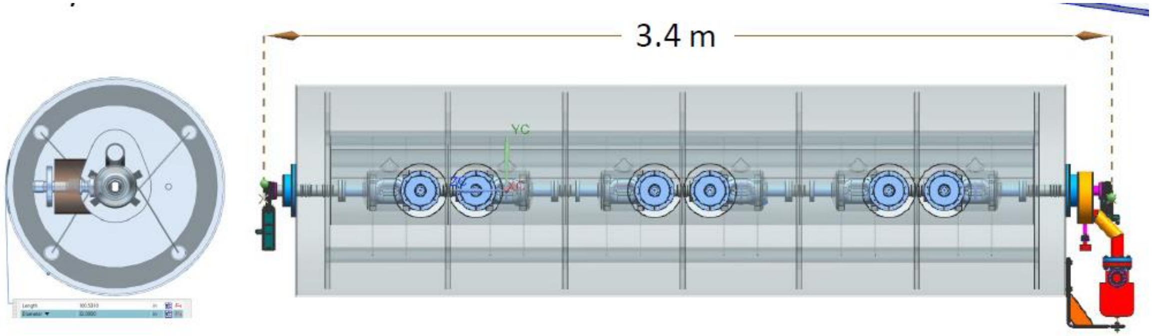
Machined from Nb ingots, 2.5 mm thick walls - ~ 40 kg Nb material

RF Dipole 1.3 GHz
S De Silva/J Delayen (Jlab/ODU)



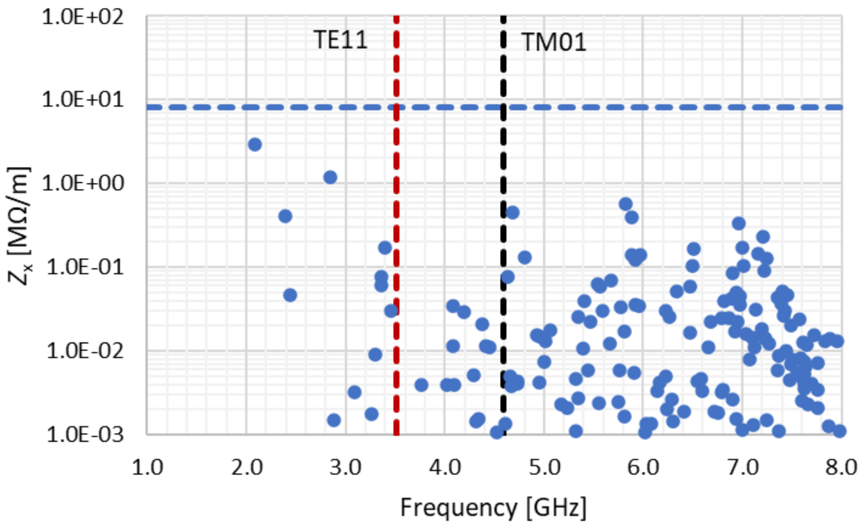
Impedance threshold/cavity:

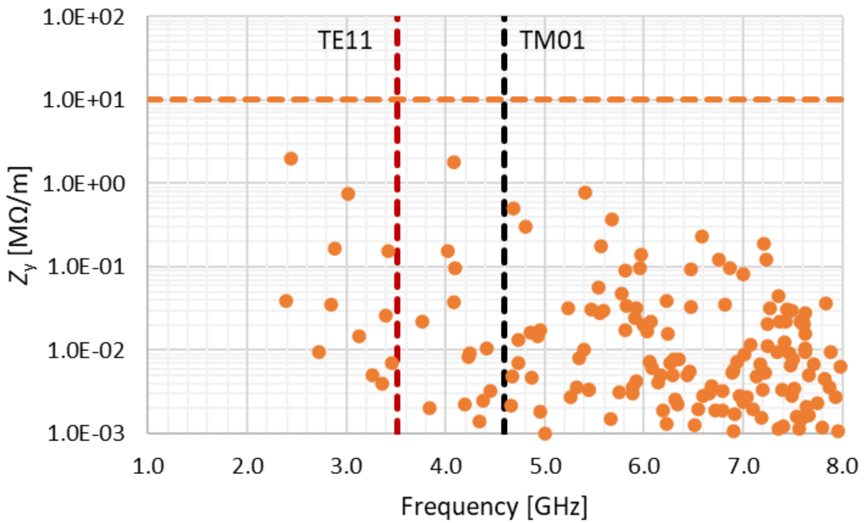
- Zx= 8.13 MΩ/m & Zy= 10.28 MΩ/m (6 cav).
- Well damped HOMs (with margin).



For 1 TeV – cryomodule to fit within 3.8 m:

- 6 cavities for single CM.
- Incl 2nd exhaust 20 mm beam pipe.





Total achievable – 8.1 MV (1.24 MV Vt per cavity).

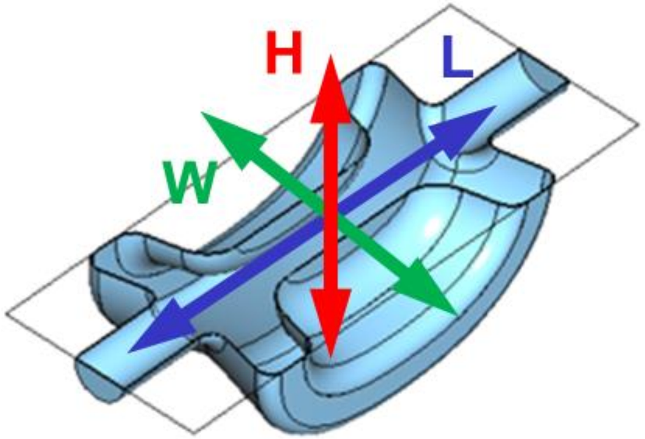
- ~10% extra margin

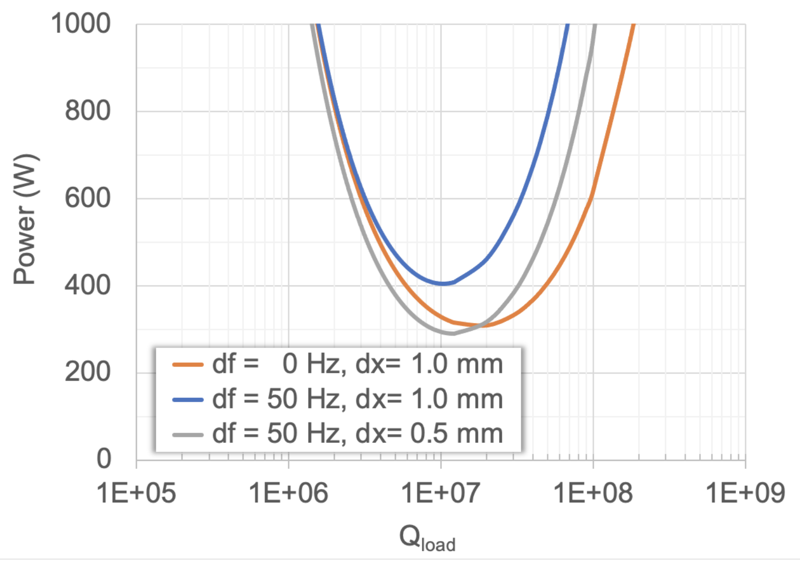
Design concept follows JLab C100 cryomodule.

Double Quarter Wave 1.3 GHz
S Andres Verdu (BNL)

- 25 mm pole-separation, with 40 mm beam-pipe.
- Both Tesla-type and waveguide HOM couplers being explored.
- Qe = 1e7, with 130 Hz bandwidth and 300 W power requirement.
- Various FPC options under study: Hook, Coax (cone and profiled).

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 $R/Q_\perp$ (Ω, circuit)	211	211
Max. offset y (mm)	**0.5**	**0.5**
Detuning $\Delta\omega/2\pi$ (Hz)	**50**	**50**

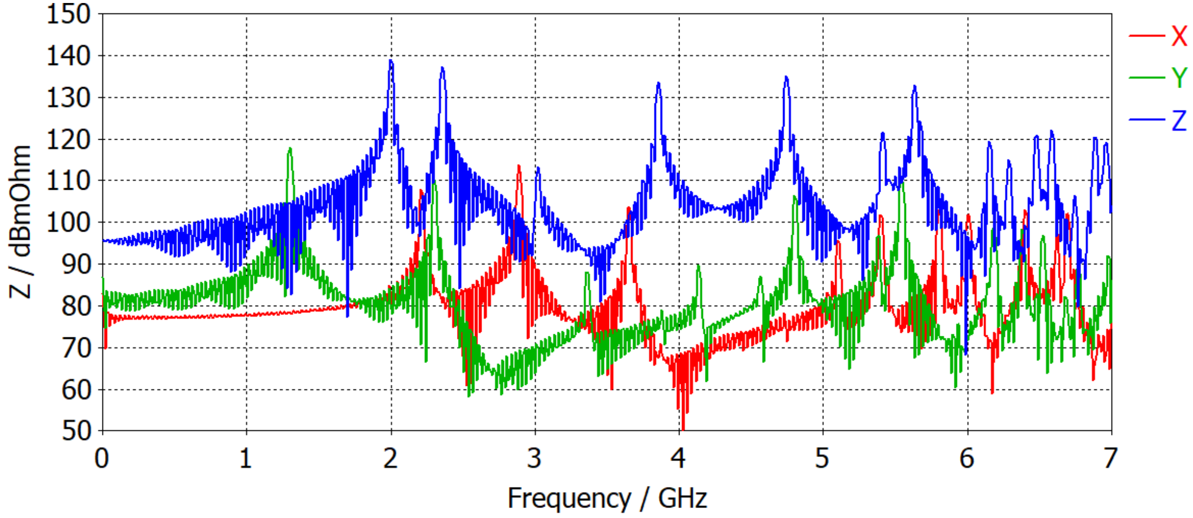




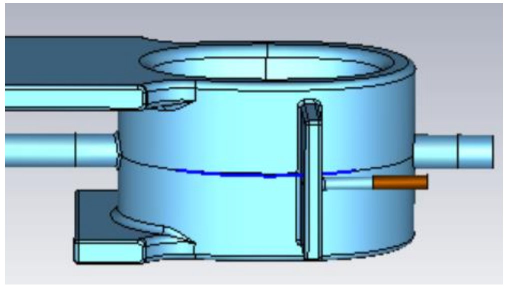
Double Quarter Wave 1.3 GHz
S Andres Verdu (BNL)

- ~3 orders magnitude HOM damping required.

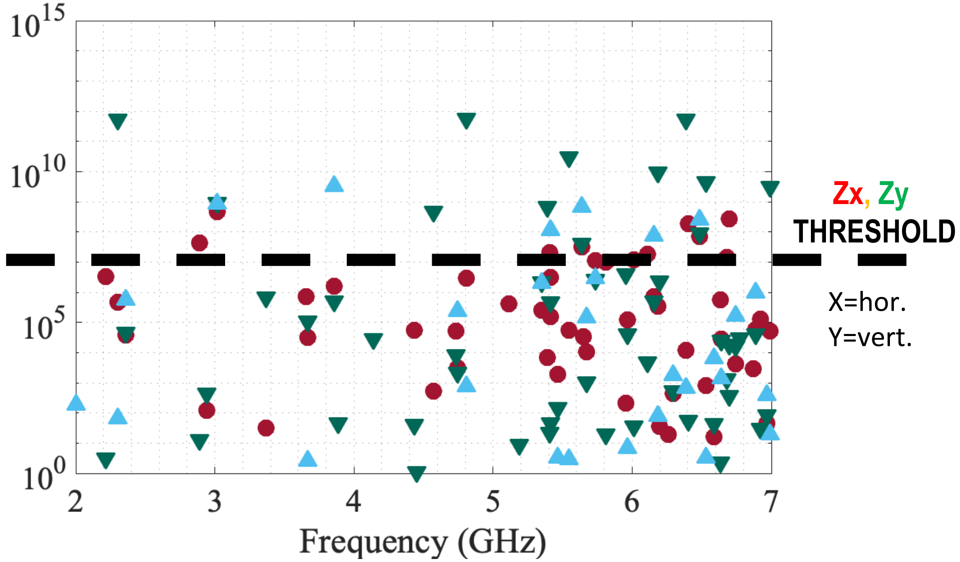
Freq TE11 cutoff (25 mm diameter) = 7 GHz



- Combination of both hook and waveguide HOM dampers anticipated.

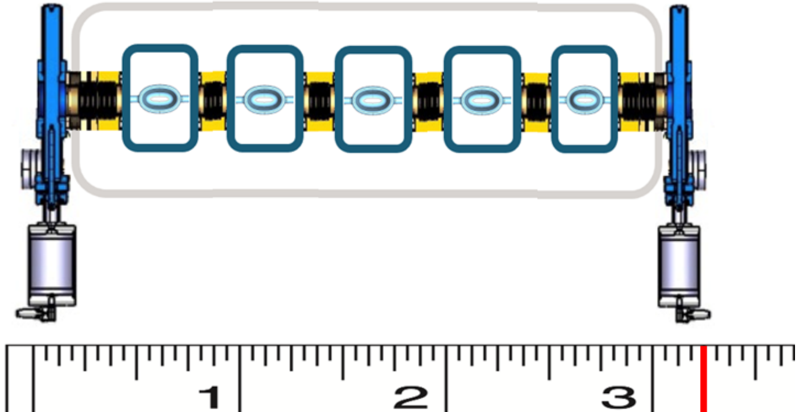


- Promising results using single Tesla-type coupler.



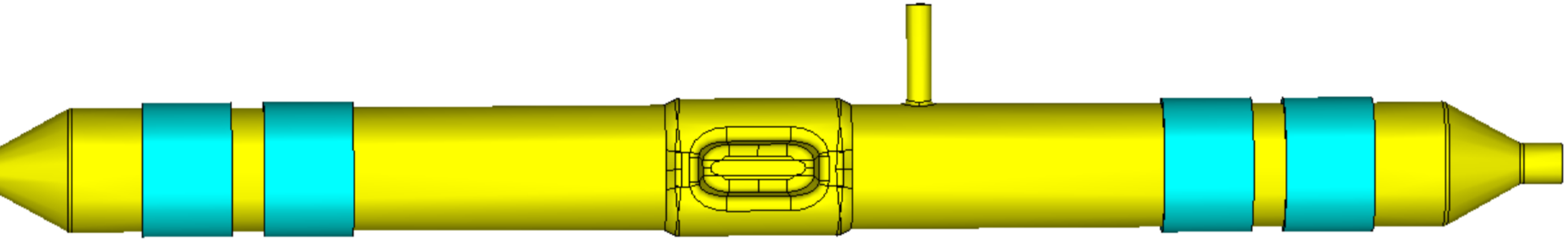
- CM easily fits within 3.8 m envelope.

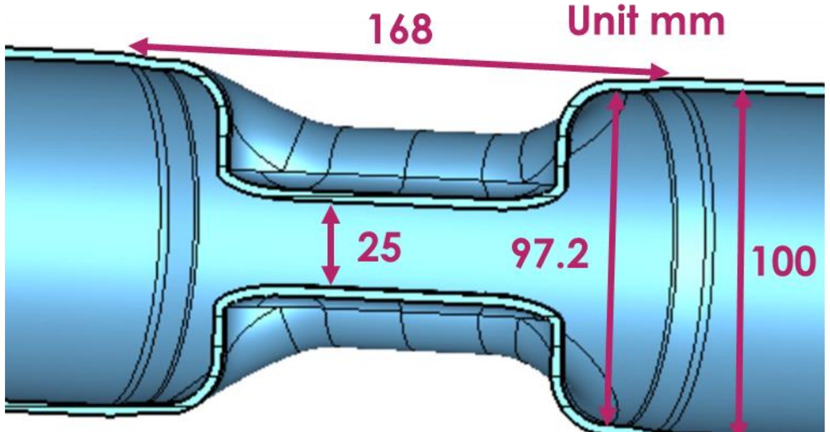
Side view, 5 DQW in cryomodule

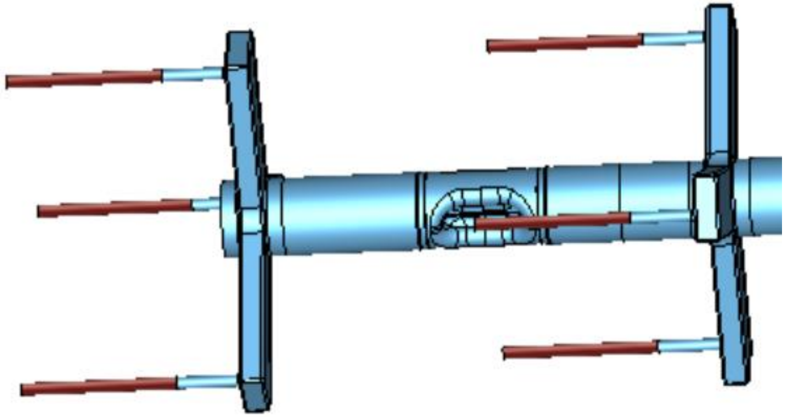


Wide Open Waveguide 1.3 GHz
B Xiao (BNL)

- 25 mm pole-separation, with 100 mm beam-pipe.
- HOM waveguides preferred to Beam Line Absorber – shorter structure.
- SOM can also attenuate in waveguides.
- First transverse HOM at ~1.8GHz, first longitudinal HOM at ~2.3GHz.



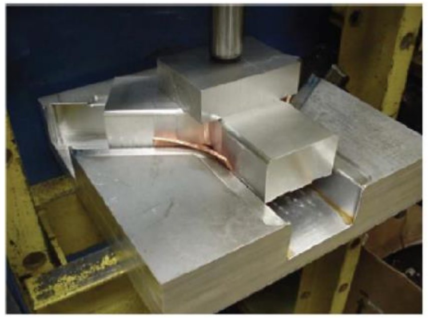


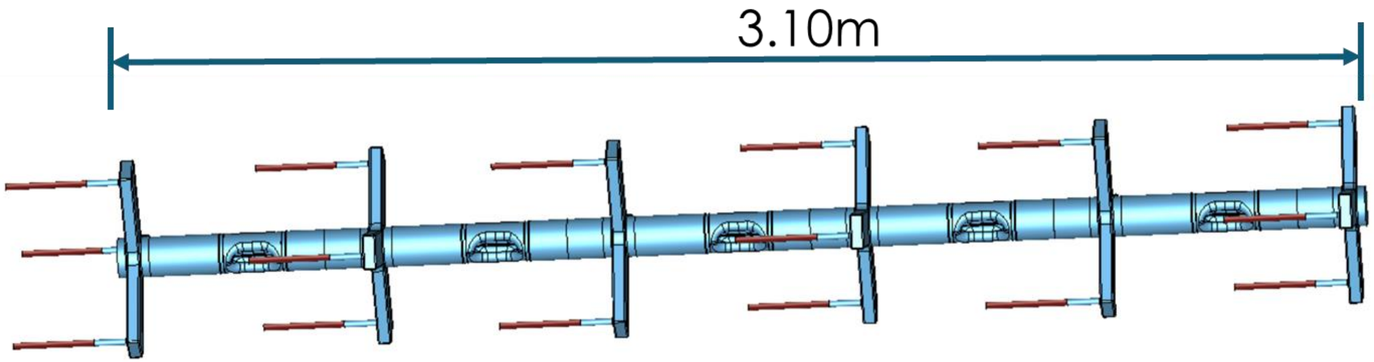


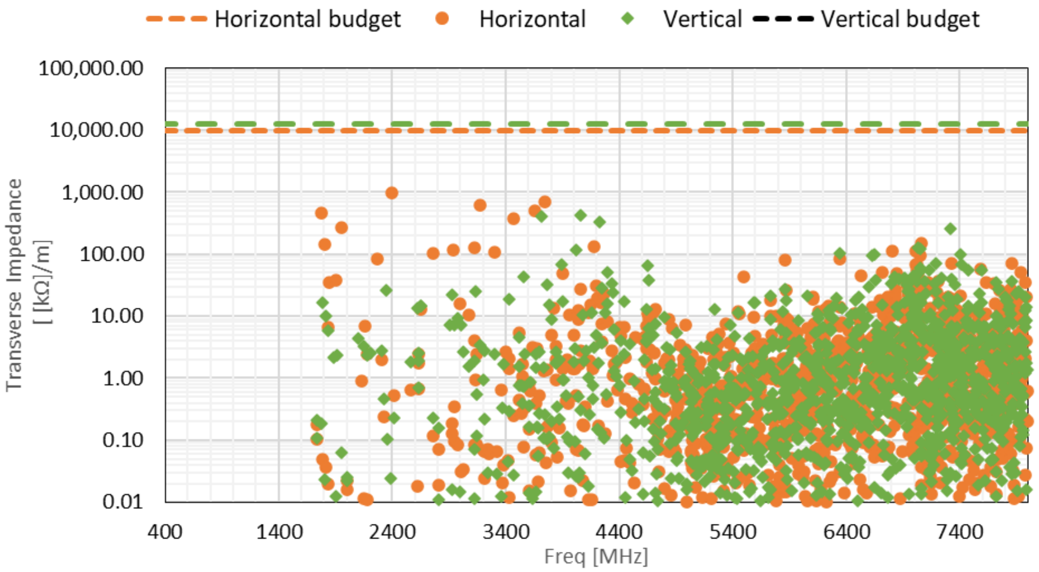
Property	Value
Operating frequency [GHz]	1.300
1st longitudinal HOM [GHz]	2.299
1st transverse HOM [GHz]	1.765
E_p/E_t with $E_t=V_t/(\lambda/2)$	3.24
B_p/E_t [mT/(MV/m)]	5.75
B_p/E_p [mT/(MV/m)]	1.77
G [Ω]	130.9
R/Q [Ω]	454.3
R_tR_s [Ω^2]	59446

Wide Open Waveguide 1.3 GHz
B Xiao (BNL)

- **1.845 MV for 125 GeV case and 7.4 MV for 500 GeV required.**
- 2 cavities for 125GeV (1.48MV/cavity) or 5 cavities for 500 GeV.
- Considering to electrically short 1 WG to reduce the number of coax on each circular pipe from 3 to 2 (re: Jlab ERL-FEL scheme).
- FPC Qe = 3 x 10^6, requires 850 W RF power.

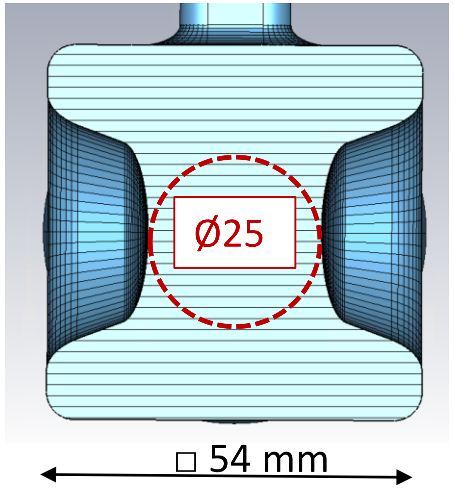




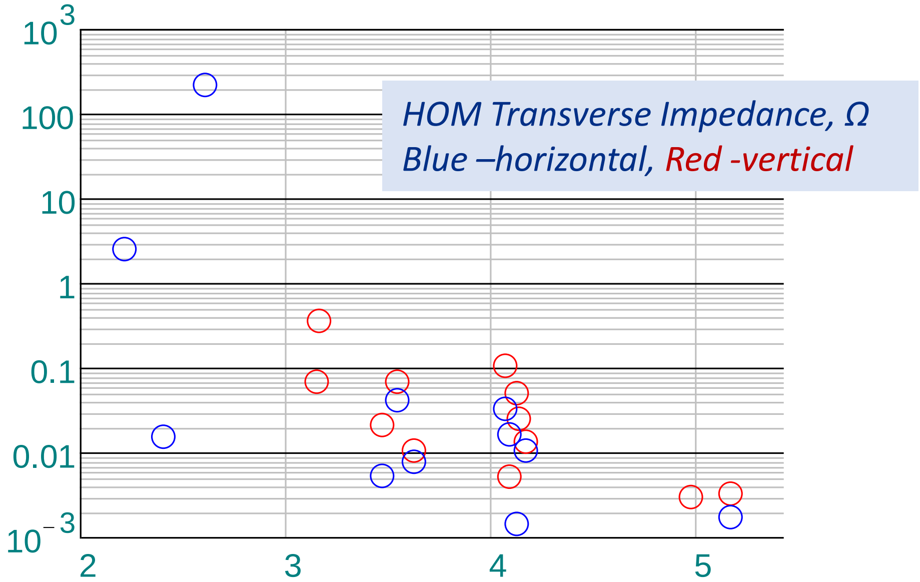


Quasi-waveguide Multicell Resonator 2.6 GHz
A Lunin/S Yakovlev (FNAL)

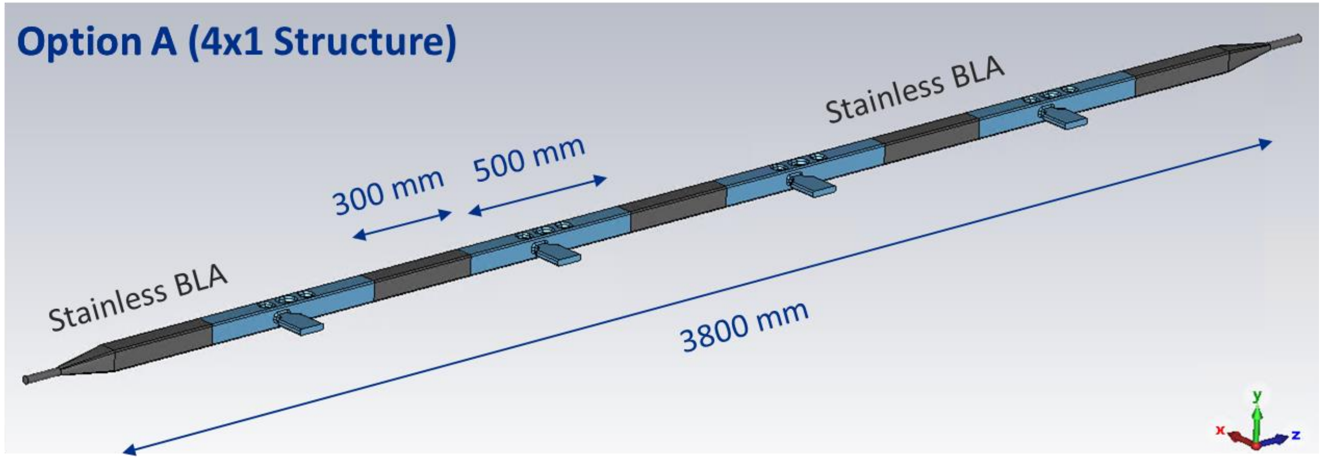
ILC Crab Cavity Aperture Limit: Ø25 mm

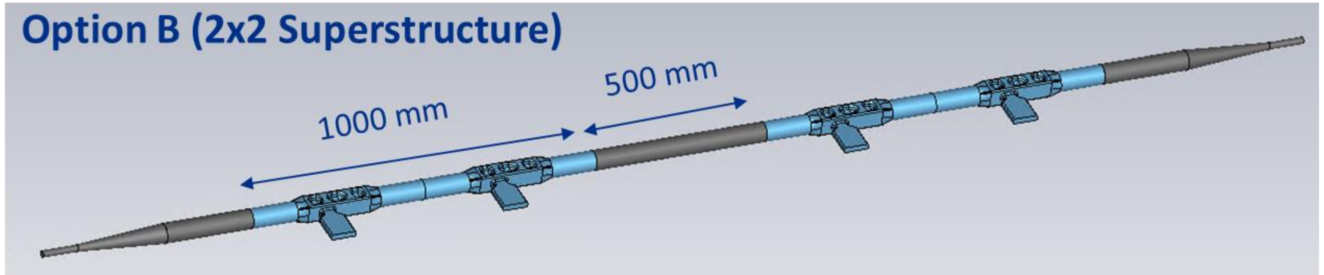


Freq	2600 MHz
V_{kick}	0.92 MV
$(R/Q)_t$	225 Ω
G-factor	130
W_{STORED}	0.24 J
Length	< 500 mm



- SOM strongly coupled with WG-port, Qext < $5x10^3$
- HOM spectrum is sparse and loaded to a beam pipe
- 4 QMiR cavities can provide Vt ~ 4 MV for 1 TeV option

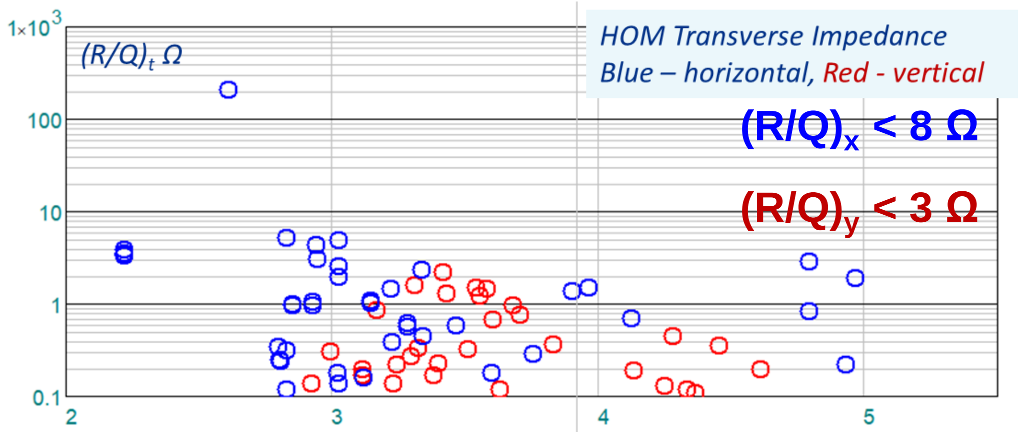


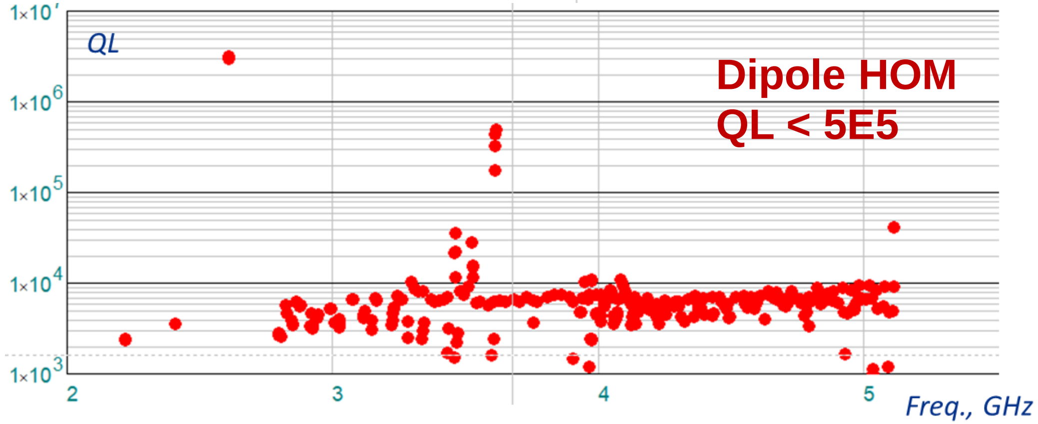


- Two options are considered, a chain of 1x4 and 2x2 cavities
- Simple stainless-steel inserts to damp HOMs
- Ceramic BLA can be a backup if needed.

Quasi-waveguide Multicell Resonator 2.6 GHz
A Lunin/S Yakovlev (FNAL)

Option B



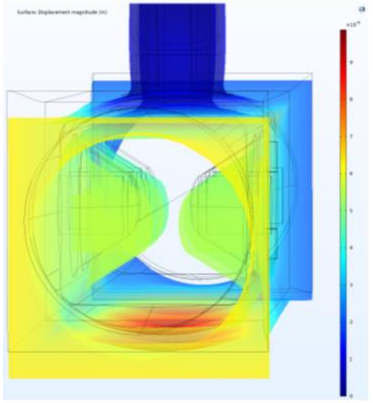


For max beam offset $x_0 < 1$ mm and $\Delta f < 1$ kHz (LFD, microphonics)

- Beam OFF: $P_{min} \approx 940$ W, Optimal Coupling: $Q_L \approx 1\times10^6$
- Beam ON & Microphonics: $P_{max} \approx 1500$ W

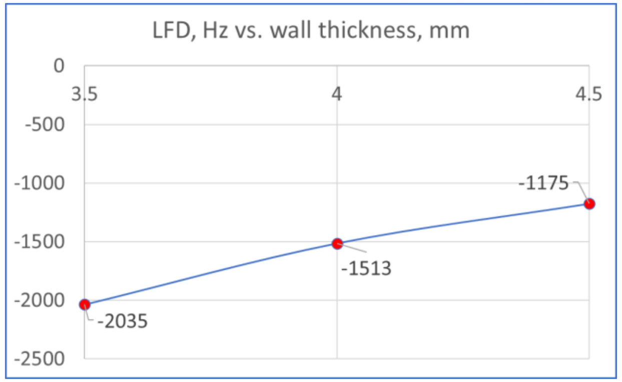
Required RF power from the generator (overhead 100%):

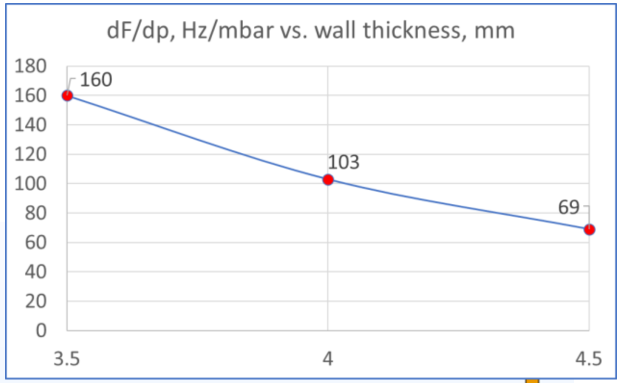
P_{gen} < 3 kW (FPC design is ongoing)



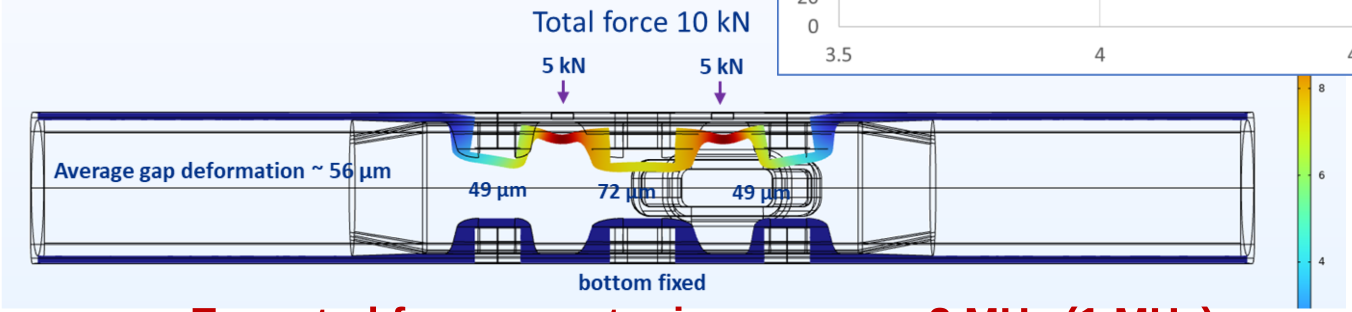
Deformation due to LFD

LFD < 1.5 kHz
dF/dP < 150 Hz



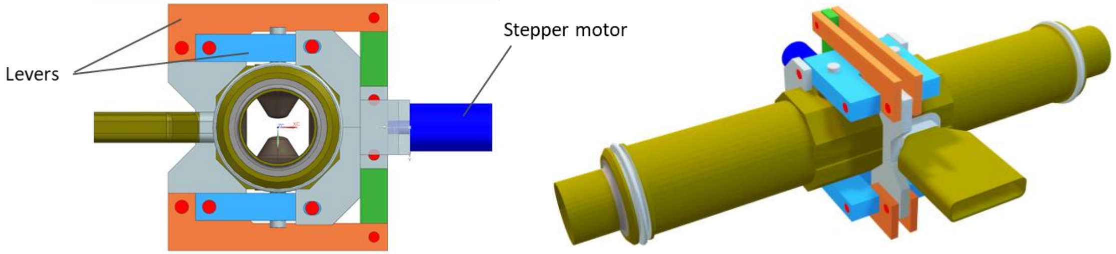


Wall thickness 4 mm, Δf ~ -1.936 MHz



Expected frequency tuning range: ~ 2 MHz (1 MHz)

Compact double 2-lever frequency tuner



Crab Cavity Parameters

Parameter	Elliptical/Racetrack	RFD	DQW	WOW	QMIR	Units	Nomenclature
Operating frequency	3.9	1.3	1.3	1.3	2.6	GHz	
SOM						GHz	
1st Longitudinal HOM						GHz	
1st Transverse HOM						GHz	
E_p/E_t^*							E_t - clarify eqtn (JD)
B_p/E_t^*						mT/(MV/m)	
B_p/E_p						mT/(MV/m)	
G						Ω	
R/Q						Ω	
R_tR_s						Ω^2	Assumptions for Rs
V_t per cavity						MV	
E_p						MV/m	
B_p						mT	
Total V_t						MV	
Total No. of cavities							
Active Cavity Length						mm	
Flange-flange Cavity Length							
Number of cells							
Cavity Diameter						mm	
Minimum Aperture						mm	
FPC Q_L							List assumptions used
Bandwidth						kHz	
Cavity Input Power						kW	
Horizontal Kick Factor k_x						V/pC	
Vertical Kick Factor k_y						V/pC/m	
Stored Energy W						J	Assume E_t 1 MV/m
HOM impedance (Longitudinal)						MΩ	
HOM impedance (Transverse)						MΩ/m	
First 3 multipole pararameters							

Design teams to converge on consistent parameters

Next Stage WP3 CC Preparations

For a future down-selection process:

- Agree the criteria to develop for each of the CC designs:
  - Cavity
  - Couplers (input and HOM)
  - Pressure stability and tuning
  - Multipacting
  - Fabrication **(Sheet/Ingot/Mixed, Nb material required, readiness detail)**
  - Anything else **(level of design detail expected (bare/dressed)**
- **WP3 meeting proposed to review and agree criteria in Nov/Dec.**

- What's left to complete for each of the design options currently?
- What are the expected timescales to complete – try and agree/set today?
- What alignment is needed with ILC IDT processes – timescales likely? **(Spring 2023?)**
- Context for a proposed down-selection review:
  - **Terms of reference to be developed/agreed.**
  - **Specialist membership – who defines/invites?**
  - **IDT output anticipated and when?**

(From WP3 Design Review #3 discussions)

MANY THANKS

Questions?

Science and Technology Facilities Council