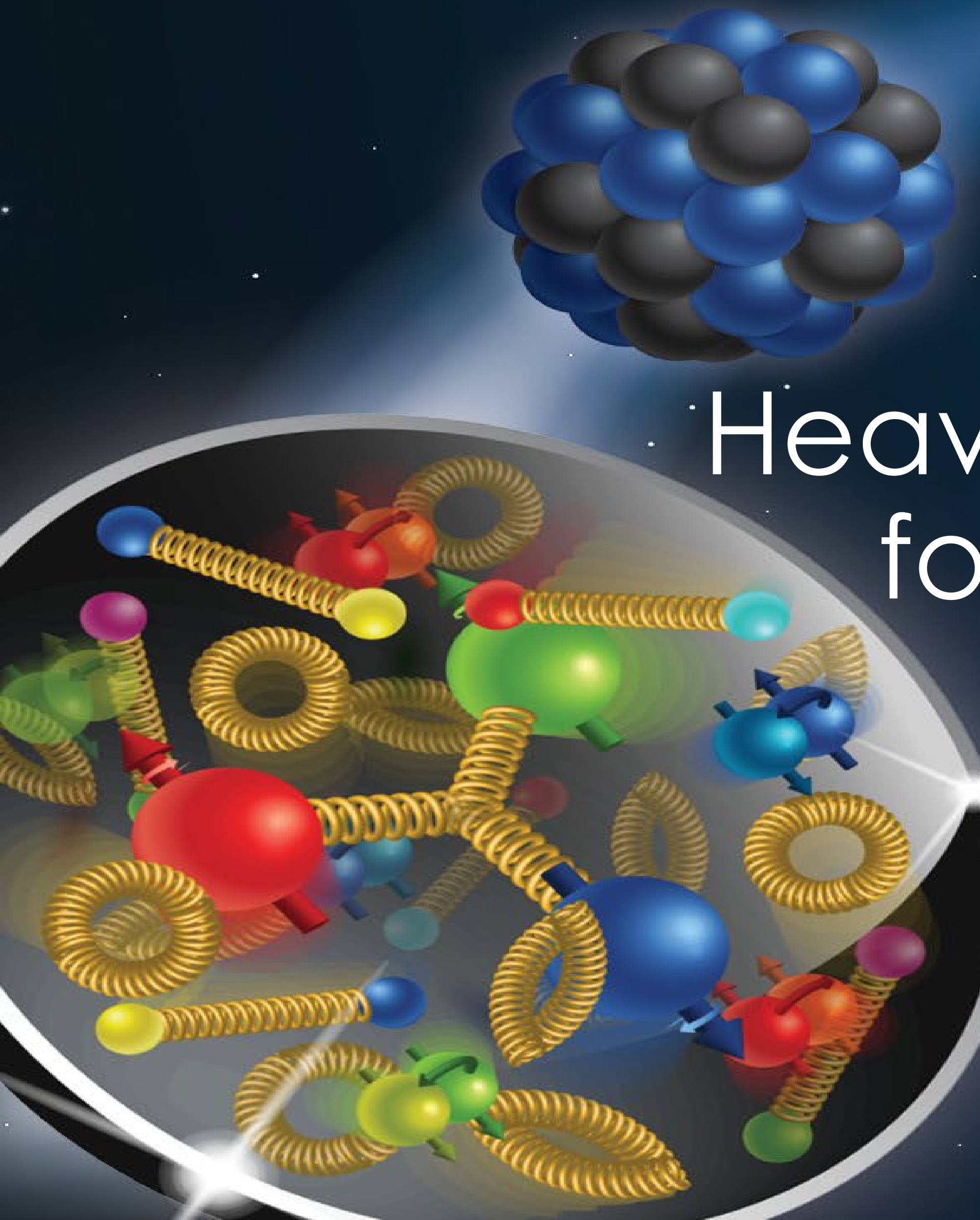
21st International Conference on Radio-Frequency Superconductivity (SRF 2023)



Heavily Damped Crab Cavities for High Luminosity Collisions

Binping Xiao

Jun 30 2023

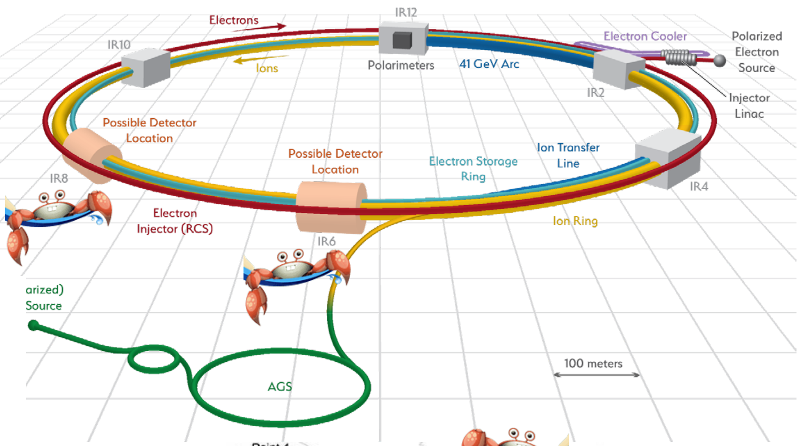
Electron-Ion Collider

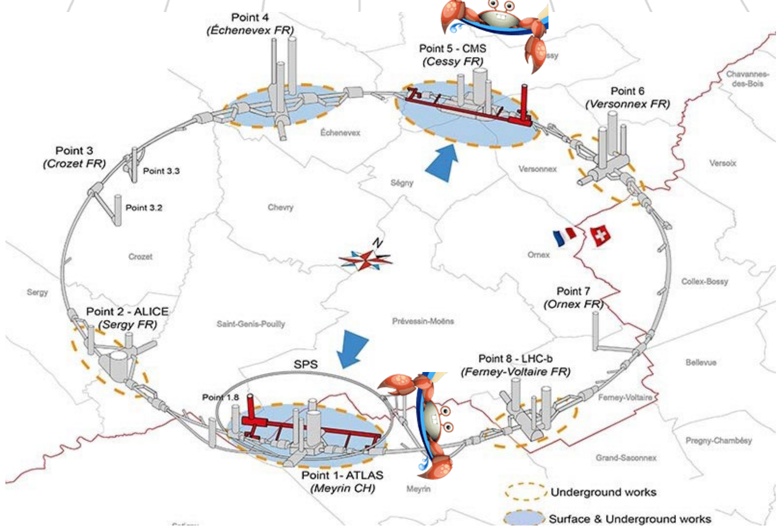
OLD DOMINION UNIVERSITY
SLAC NATIONAL ACCELERATOR LABORATORY
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

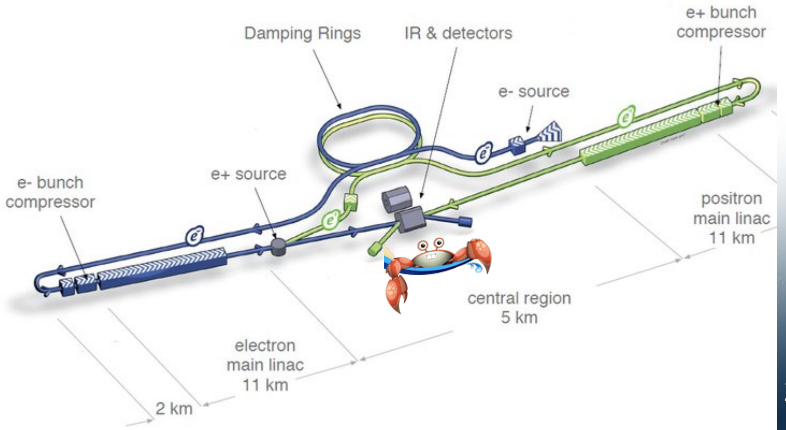
Outline

- Projects Comparison
  - EIC, HL-LHC & ILC
- EIC Crab Systems
  - 394MHz
    - WOW with beamline absorber or RFD with waveguides
  - 197MHz
    - DQW or RFD
    - Waveguide or coax absorbers
  - Control
    - Tuning
    - Multipoles
    - Noise and LLRF
- Summary

DQW: Double Quarter Wave
RFD: RF-Dipole
WOW: Wide Open Waveguide
HSR: Hadron Storage Ring
ESR: Electron Storage Ring







Project Comparison

	EIC	HL-LHC	ILC
Crossing angle [mrad]	25 for IP6 (baseline) 37.5 for IP8 (TBD)	0.590, two IPs, one vertical one horizontal	14
Frequency [MHz]	197 & 394 for HSR 394 for ESR	400, DQW (vertical) & RFD (horizontal)	1300/2600/3900
Voltage [MV]	33.83 from 197, -4.75 from 394 for HSR, 2.9 from 394 for ESR, per side for IP6, 50% more for IP8.	6.8 per IP per side as the baseline, upgradable to 12~13	1.845@1.3GHz, 250GeV 7.4@1.3GHz, 1TeV Inversely proportional to frequency
Space allocation - longitudinal	15m for HSR, 4.5m for ESR, per side for IP6, 50% more for IP8.	~3.5m	3.8m
Space allocation – transverse	1.0m for HSR, 0.7m for ESR, to adjacent wall	0.194m, to adjacent beampipe center	0.1967±0.0266m, to adjacent beampipe center

Damping Requirement

	EIC	HL-LHC	ILC
Longitudinal	316kΩ for hadron ring 26kΩ-GHz for electron ring	2.4MΩ	-
Horizontal	2.64MΩ/m for hadron ring 0.96MΩ/m for electron ring	1.5 MΩ/m	48.8MΩ/m for 250GeV 195.2MΩ/m for 1TeV
Vertical	13.2MΩ/m for hadron ring 0.96MΩ/m for electron ring*	1.5 MΩ/m	61.7MΩ/m for 250GeV 246.8MΩ/m for 1TeV

*This number could be higher if vertical beta function at crab cavity location can be confined.

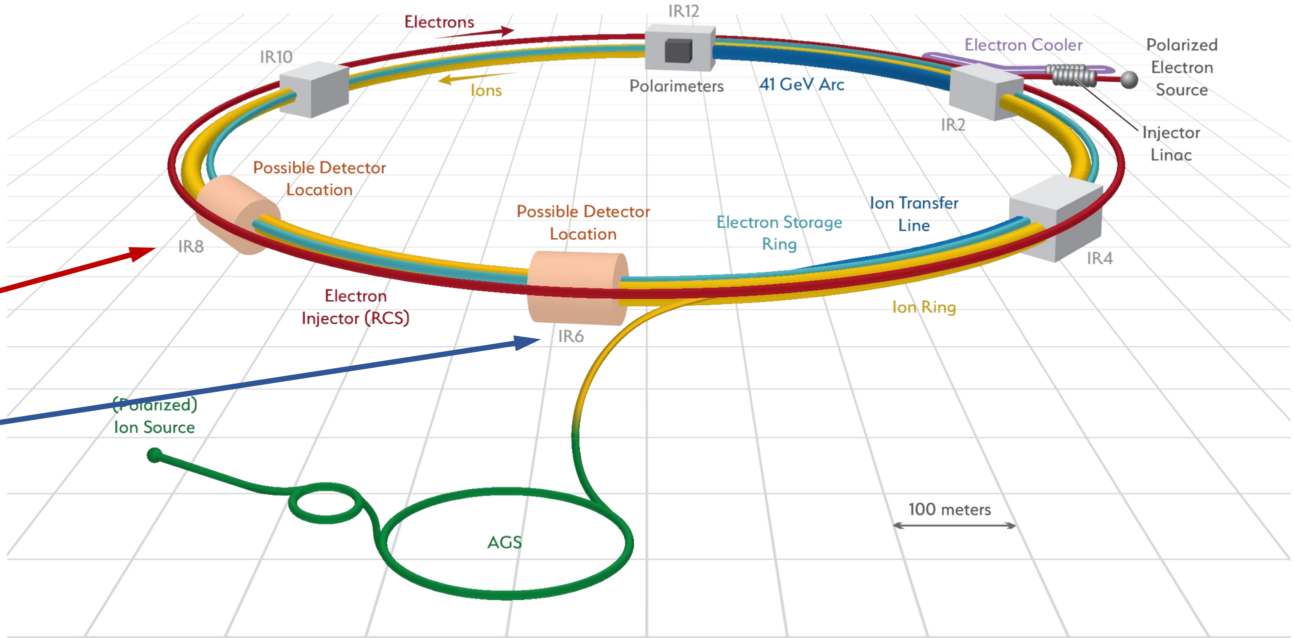
High-Luminosity Large Hadron Collider (HL-LHC): Technical design report
P. McIntosh, Crab Cavities for ILC, FRIBA04

EIC Crab Systems

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2*

*or 4/4 for redundancy

50% more

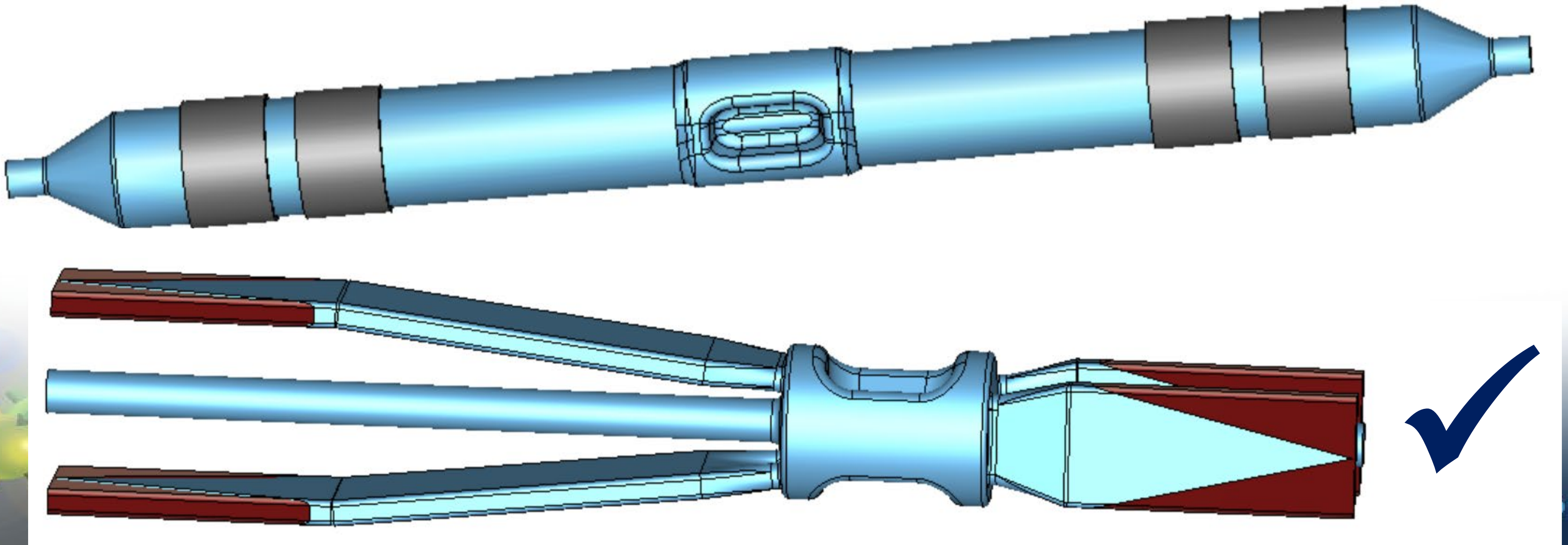


- Operating voltage per cavity: 8.5MV for 197MHz & 2.9MV for 394MHz.
- Designed specs: 11.5MV for 197MHz & 3.5MV for 394MHz, with Epk 45MV/m & Bpk 80mT.
- Impedance budget (per cavity): For 197MHz **10kΩ** longitudinal **0.132MΩ/m** horizontal **0.66MΩ/m** vertical & for 394MHz **3.25kΩ-GHz** longitudinal **0.12MΩ/m** transverse (with two 394MHz for ESR per IP per side, considering two IPs).
- And high HOM power per cavity, **a few kW** for hadron ring 197MHz and **~40kW** for electron ring 394MHz.

ESR 394MHz Crab Cavity

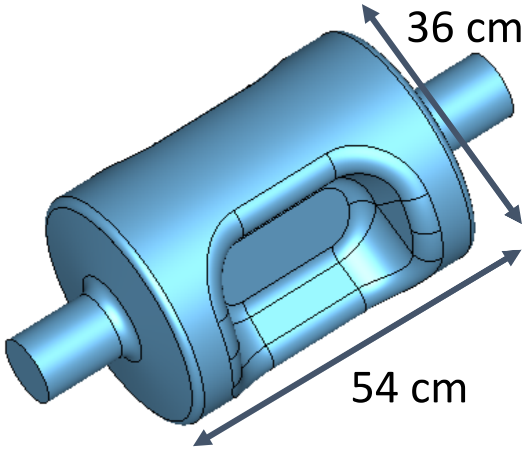
MOPMB054

- Wide Open Waveguide (WOW) type with beamline absorbers or RFD cavity with rectangular waveguide absorbers? HOM power (in 50kW range) is the major concern. The former produces >50% more HOM power than the later thus is not preferred.



ESR 394 MHz RFD Crab Cavity

- 394 MHz cavities will be installed on both HSR and ESR
  - 197 MHz crabbing system is the primary crabbing system at HSR
  - Second harmonic crabbing system operating at 394 MHz will be installed at HSR to linearize the kick for the 6-7 cm long proton bunches
  - Beam aperture = 100 mm from HSR
  - Damping specs from ESR
  - HOM power handling from ESR
- 394 MHz crab cavities will be designed as a single cavity cryomodule to be similar for both HSR and ESR



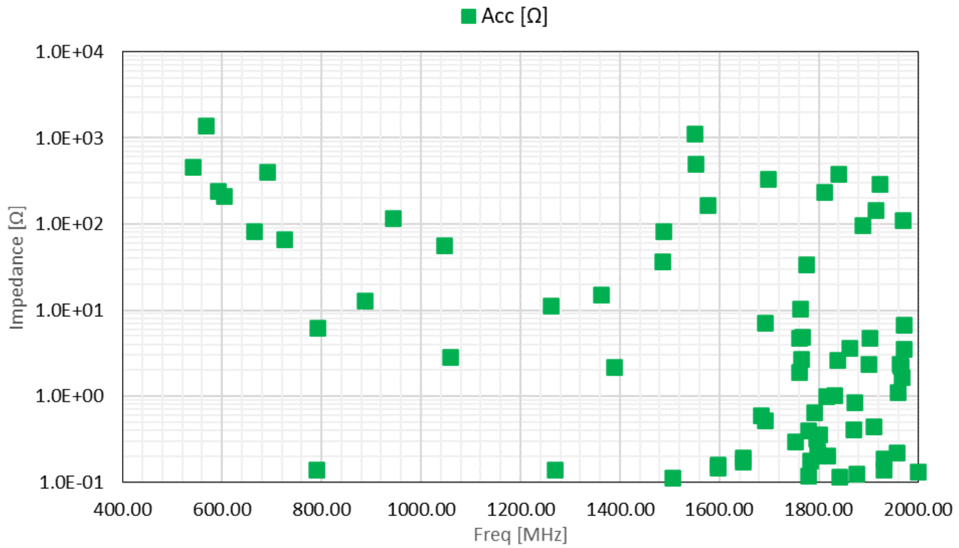
* $E_t = V_t/(\lambda/2)$

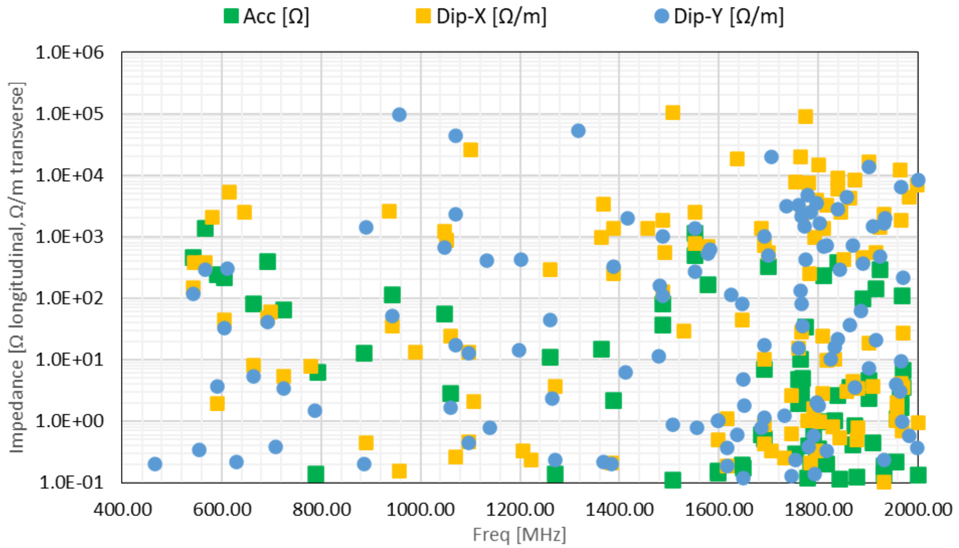
Property		
Operating frequency	394.0	
1st HOM [MHz]	537	
E_p/E_t^*	3.87	
B_p/E_t^* [mT/(MV/m)]	8.08	
B_p/E_p [mT/(MV/m)]	2.09	
G [Ω]	125.4	
R/Q [Ω]	308.6	
R_tR_s [Ω^2]	3.9×10^4	
Max V_t [MV] per cavity	2.9	
E_p [MV/m]	29.5	
B_p [mT]	61.56	
Total V_t [MV]	2.9	4.75
No. of cavities	1	2

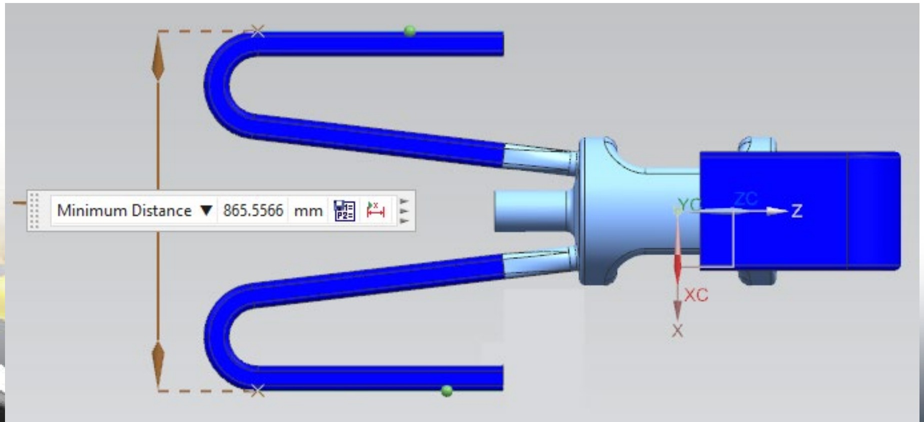
S. De Silva

HOM Damper Designs

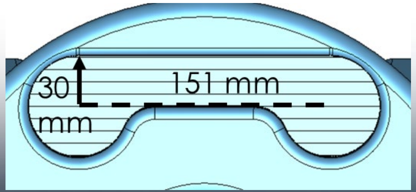
- HOMs are suppressed with 4 waveguide dampers
  - Tilted ridged waveguide allows more space between the beam pipe and waveguide for flanges
- With increased crossing angle at the second IP, number of cavities may need to be increased to 8
  - HOM dampers are designed with sufficient margin; will not exceed impedance thresholds
- HOM power for the 4 waveguide absorbers are 25.0 kW for modes below 2 GHz and 30.3 kW above 2 GHz
  - <12kW for each waveguide load
  - ~5kW each beampipe port
  - Further optimization going on to reduce HOM power







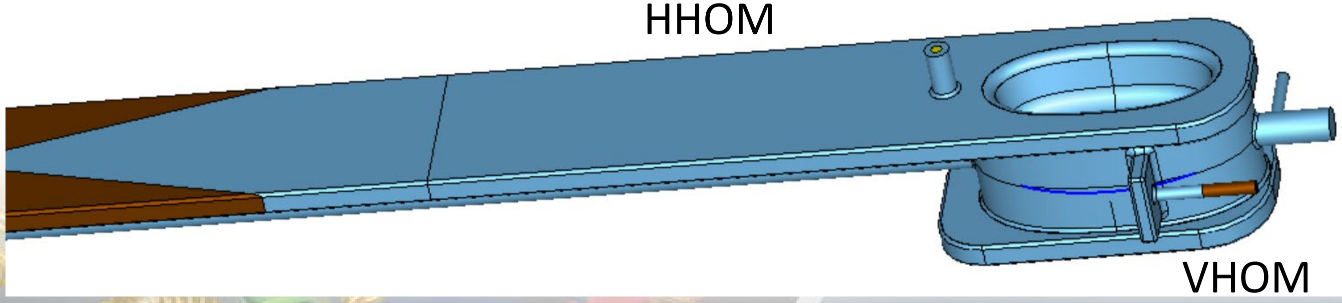
Single ridged waveguide cross section

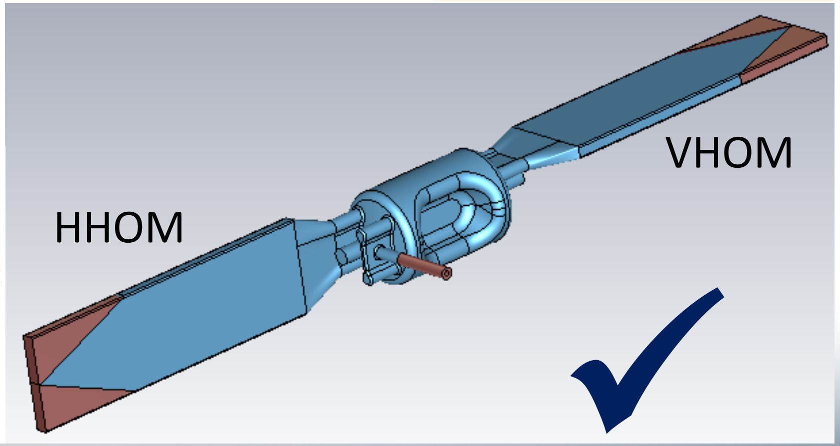


HSR 197MHz Crab Cavity

- DQW or RFD?
- RFD is preferred majorly because it is more mature in engineering design, and the shape is more favorable as a vacuum vessel.

S. De Silva

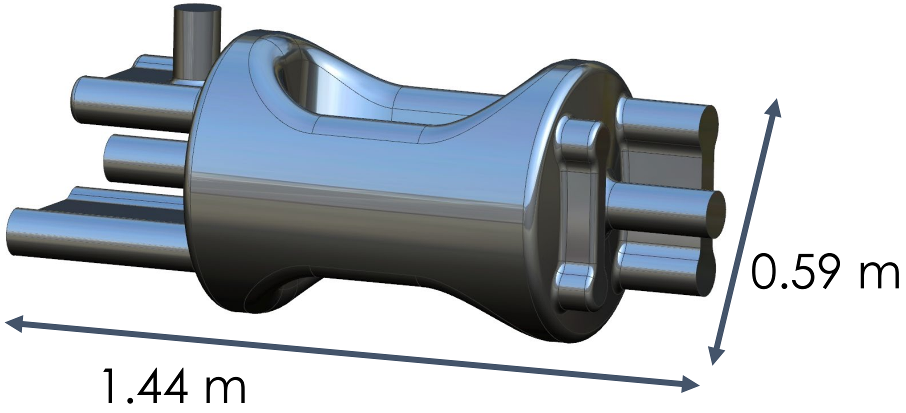




RF Properties

- Electromagnetic design requires to achieve:
  - Cavity peak surface fields of E_p < 45 MV/m and B_p < 80 mT at 11.5 MV
  - Bare cavity dimensions:
    - Cavity length ≤ 1.5 m
    - Cavity diameter (without couplers) ≤ 0.6 m
- Reasonable surface fields at nominal voltage of 8.5 MV

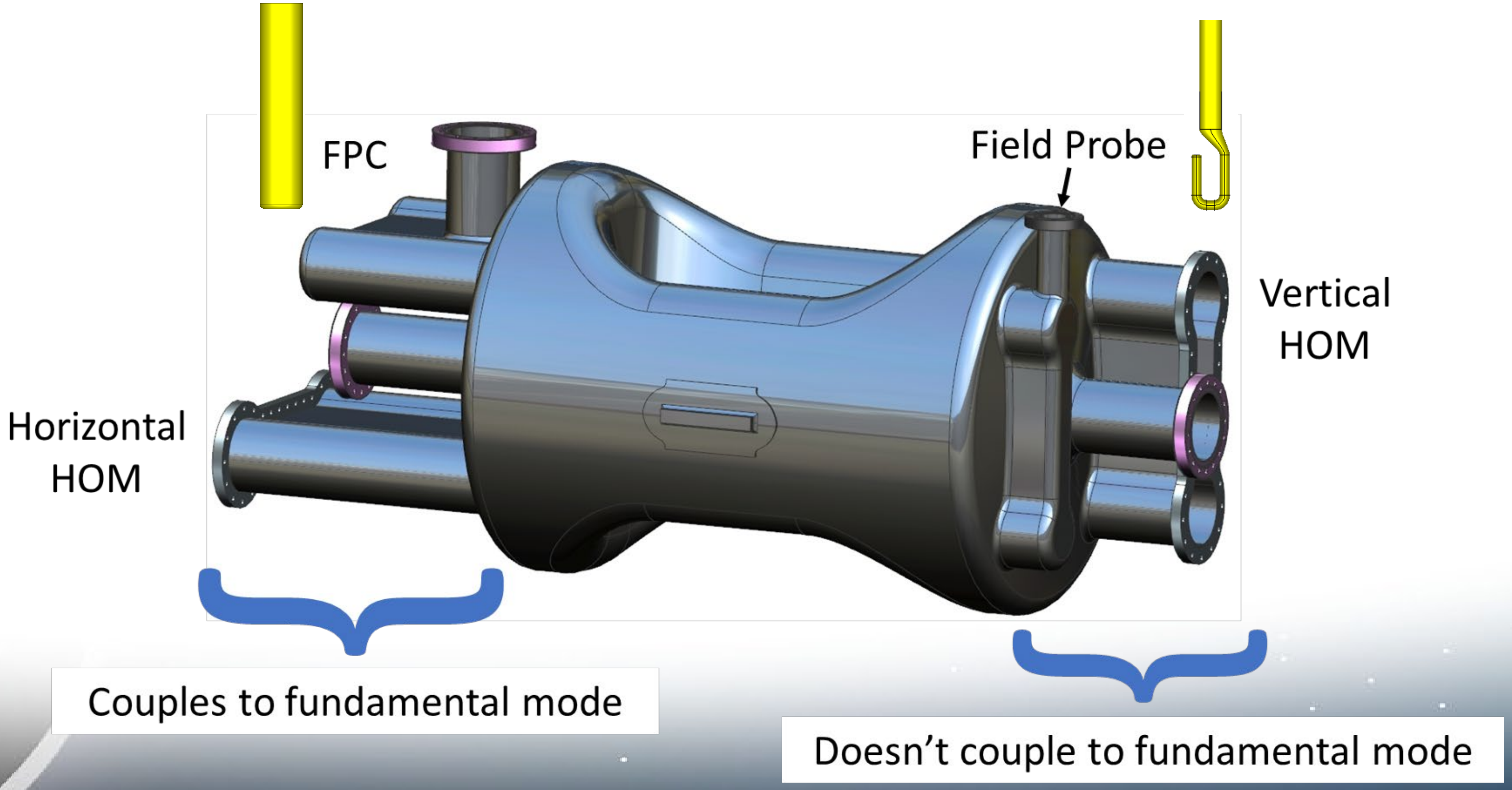
Dimension	Value
Cavity Length [mm] (iris-to-iris)	921.9
Cavity Length [mm] (flange-to-flange)	1435
Cavity Diameter [mm]	587.2
Pole Length [mm]	524
Angle [deg]	20



RF Property	Value	
V_t [MV]	8.5	11.5
E_p [MV/m]	32.3	43.7
B_p [mT]	58.1	78.6
Total V_t [MV]	34	
No. of cavities	4	3
Operating Temp. [K]	2.05	
Stored Energy [J]	50.3	92
R_s [Ω] (R_{BCS} = 0.4 nΩ)	15	
P_{diss} [W]	9.6	17.6
Q_0 (G = 97.2 Ω)	6.48×10^9	

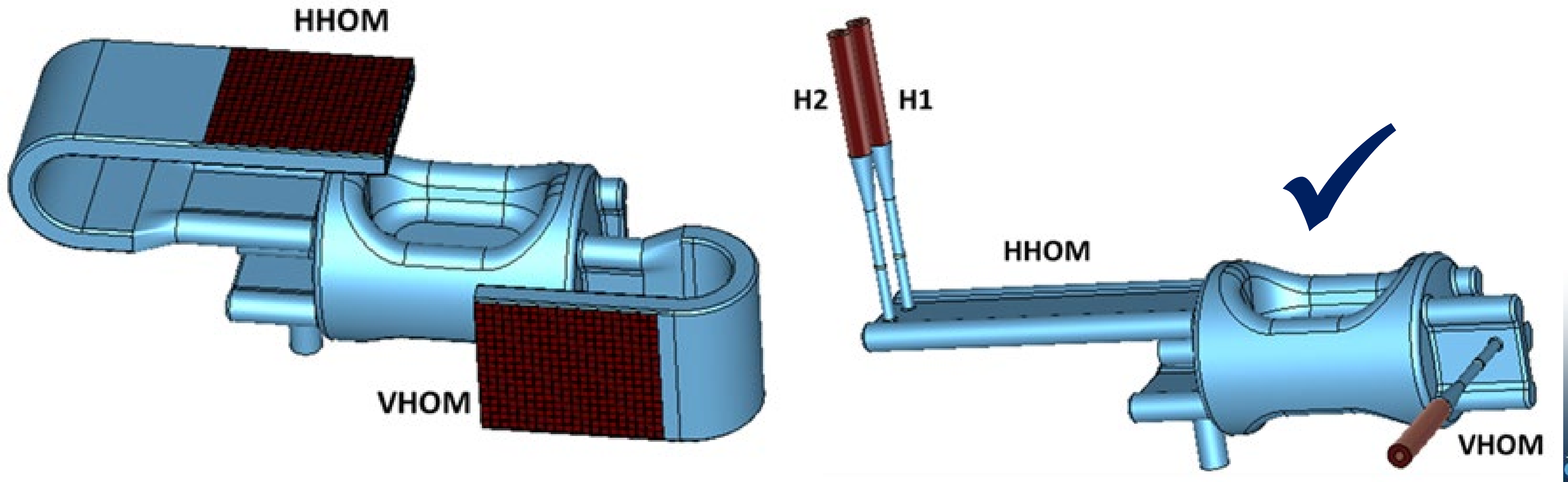
197 MHz Crab Cavity Design

- Bare cavity design: Frequency at 2.0 K – 196.643 MHz
- Cavity has two HOMs: Horizontal HOM (HHOM) coupler and Vertical HOM coupler (VHOM)
  - HHOM – Couples to horizontal dipole modes
  - VHOM – Couples to vertical dipole modes
- FPC – Coaxial antenna
- Field Probe – Hook coupler



Waveguide or coaxial absorber

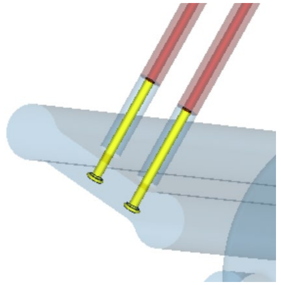
- Both meet the requirements.
- After comprehensive comparison on cost, manufacturability, engineering difficulties, maturity, further R&D effort needed, hardware readiness etc, coaxial design is chosen as the current baseline.

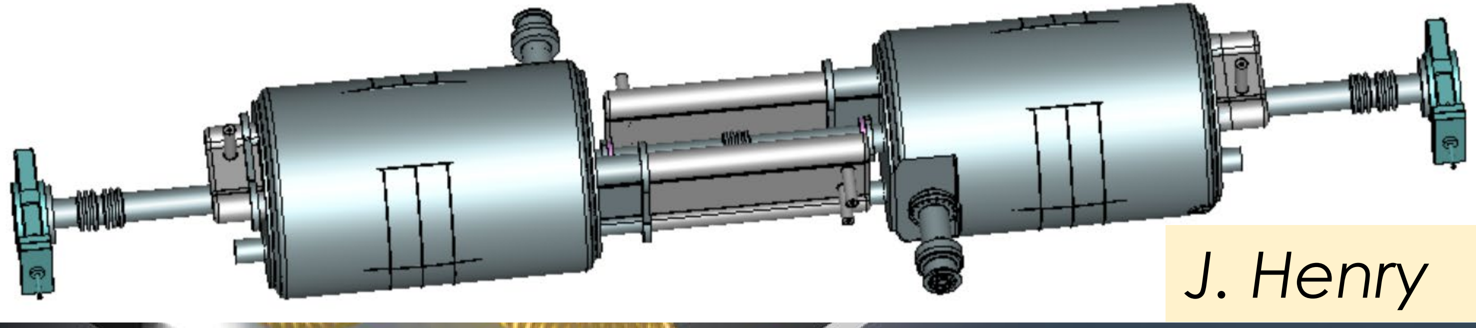


Coaxial HOM Couplers

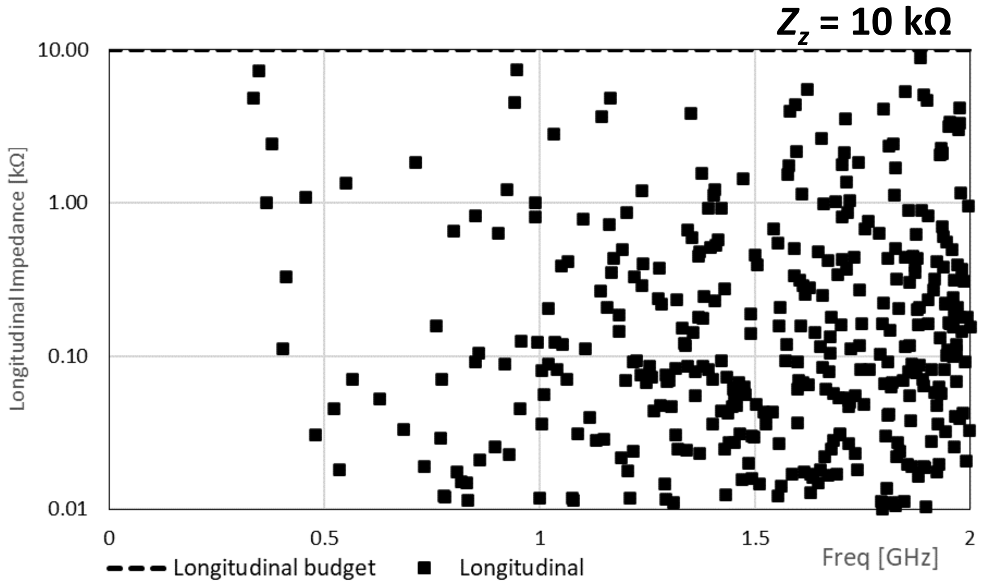
Impedances are in circuit definition and includes 0.5 factor

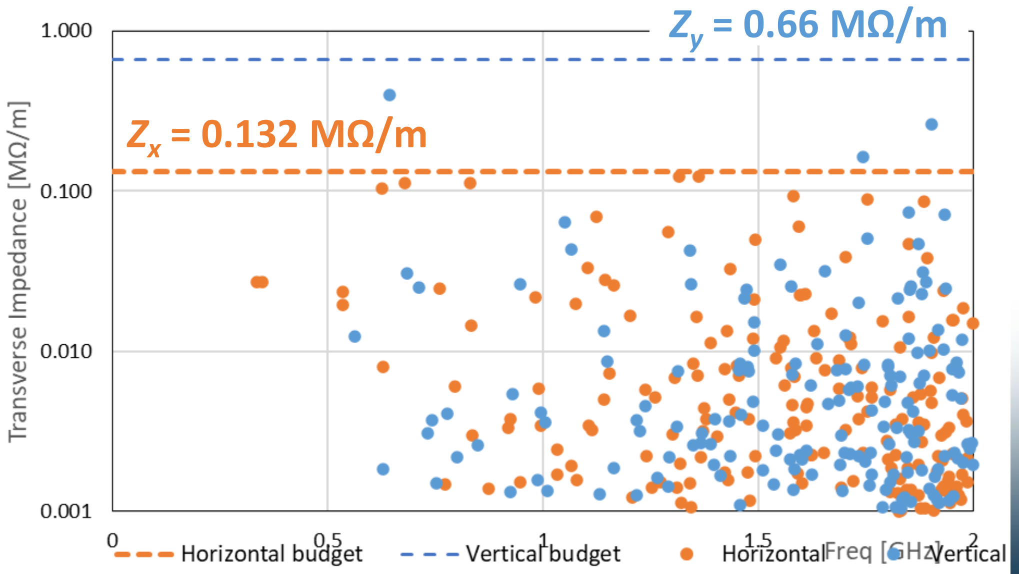
- Identical coaxial antennas in all the 3 couplers
- No more than 2.3kW each port
- Simulated with RF window designed for LHC Hi-Lumi crab cavities
- Simulated with coax absorbers with VSWR similar to the off-the-shelf product
- All longitudinal and dipole modes are well damped
- 2 cavities in 1 cryomodule.





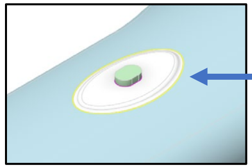
J. Henry



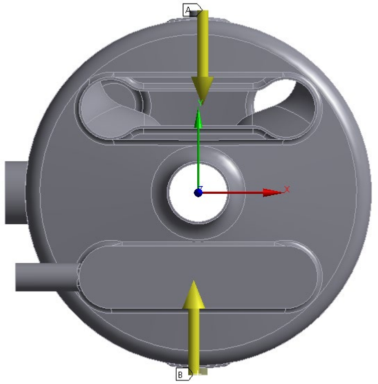


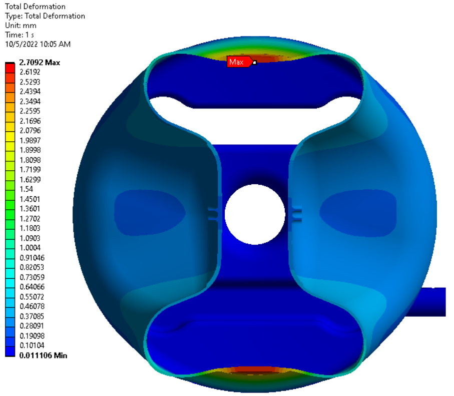
Tuner for 197 MHz Crab Cavity

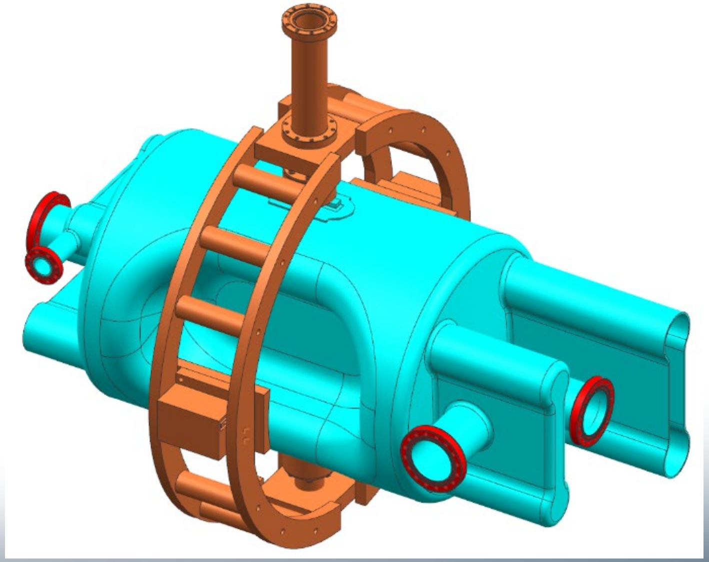
- Cavity body is comprised of 4 mm Nb with some regions thicker than 4 mm
- Stress analysis
  - For VTA test at 22 psi is within allowable stress of 6.3 ksi
- Tuning specs
  - Frequency range of acceptance: +/-25kHz
  - Resonant frequency in MHz during energy ramp Min 196.158 Max 197.050
  - Add $f_{rev}/2$ and acceptance: 196.643MHz ± 472kHz
- Tuning analysis - Tuning in the magnetic field region
  - Δf = ± 682.3 kHz
  - Tuning sensitivity = 126.4 kHz/mm for a total 5.4 mm displacement
  - 2.7 mm push/pull tuning limit at allowable stress
  - 7400 lb force on each tuner pad (2740 lb/mm)
  - Scissor jack tuner (in orange)



Tuner plate and adapter







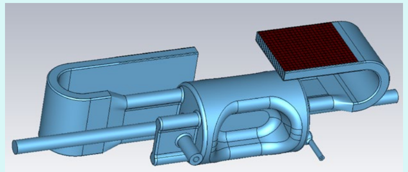
M. Marchlik

Multipole Components

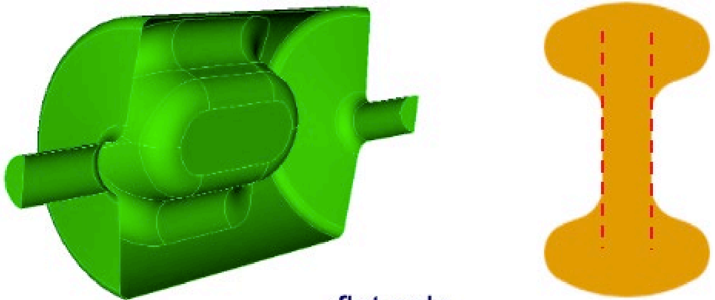
- Specs at 10MV:
  - $b_2 \leq 2.05$ mT
  - $b_3 \leq 69.8$ mT/m
  - $b_4 \leq 1360$ mT/m^2
  - $b_5 \leq 85300$ mT/m^3
- Specs are still preliminary as we need to add 394MHz crab into the study, include the 2nd IP, use realistic errors for magnets etc.
- We know how to meet the specs
  - Capacitive plates (poles) need to be curved
  - Error analyses need to be done
- Prototype with flat poles and first article will be curved poles, and only poles will be different in these two designs.
- Poles machined from ingot Nb to ensure the accuracy so that multipole components will not be compromised.

Q. Wu, MOPL041, IPAC 2023
Z. Li, TUPTB068

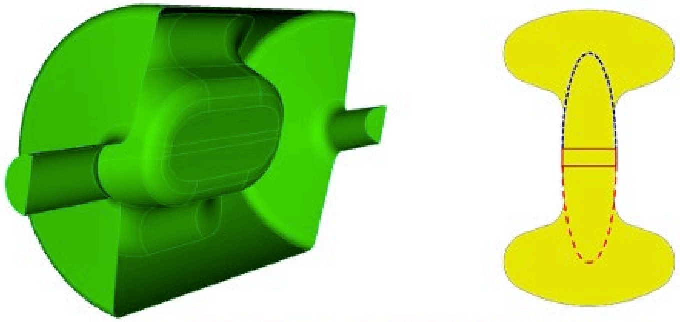
3D Model



$b_1\ [mT \cdot m]$	85.70
$b_2\ [mT]$	0.19
$b_3\ [mT/m]$	1342.72
$b_4\ [mT/m^2]$	3.35
$b_5\ [mT/m^3]$	71760.90
$b_6\ [mT/m^4]$	2186.21



flat pole



curved pole to minimize b3 and b5

Crab Cavity Noise

Linear theory of crab cavity noise: *P. Baudrenghien and T. Mastoridis*, [*Phys. Rev. Accel. Beams* **18**, *101001 (2015)*]

Bunch length

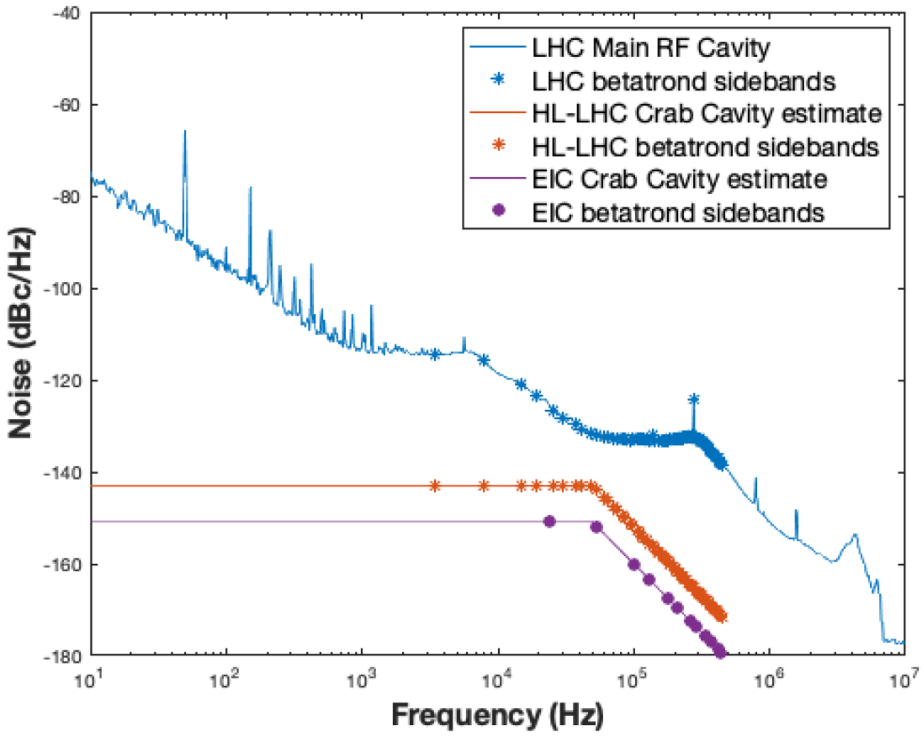
Phase noise

$$\frac{d\epsilon_x}{dt} = \beta_{cc}\left(\frac{eV_o f_{\mathrm{rev}}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi) \sum_{k=-\infty}^{\infty} S_{\Delta\phi}[(k \pm \bar{\nu}_b) f_{\mathrm{rev}}]$$

Amplitude noise

$$\frac{d\epsilon_x}{dt} = \beta_{cc}\left(\frac{eV_o f_{\mathrm{rev}}}{2E_b}\right)^2 C_{\Delta A}(\sigma_\phi) \sum_{k=-\infty}^{\infty} S_{\Delta A}[(k \pm \bar{\nu}_b \pm \bar{\nu}_s) f_{\mathrm{rev}}]$$

Crossing angle and beta*



Estimated tolerance for HL-LHC (<1%/hr emittance growth) and Hadron beam for EIC (Emittance growth comparable to IBS)

	$\sigma_{\Delta\phi}$(urad)	$\sigma_{\Delta A}$(1e-6)
HL-LHC	8.2	13.3
EIC 41 GeV Proton	3.1	10.1
EIC 100 GeV Proton	2.7	9.4
EIC 275 GeV Proton	1.8	7.1

Tighter requirement on the crab cavity noise (a factor of 2~7 lower), both phase noise and amplitude noise, compared with HL-LHC.
Feedback system with small-error pickup (TBD).

T. Mastoridis, P. Fuller, P. Mahvi, Y. Matsumura, MOYD3, in the proceedings of NAPAC 2022, Albuquerque, NM

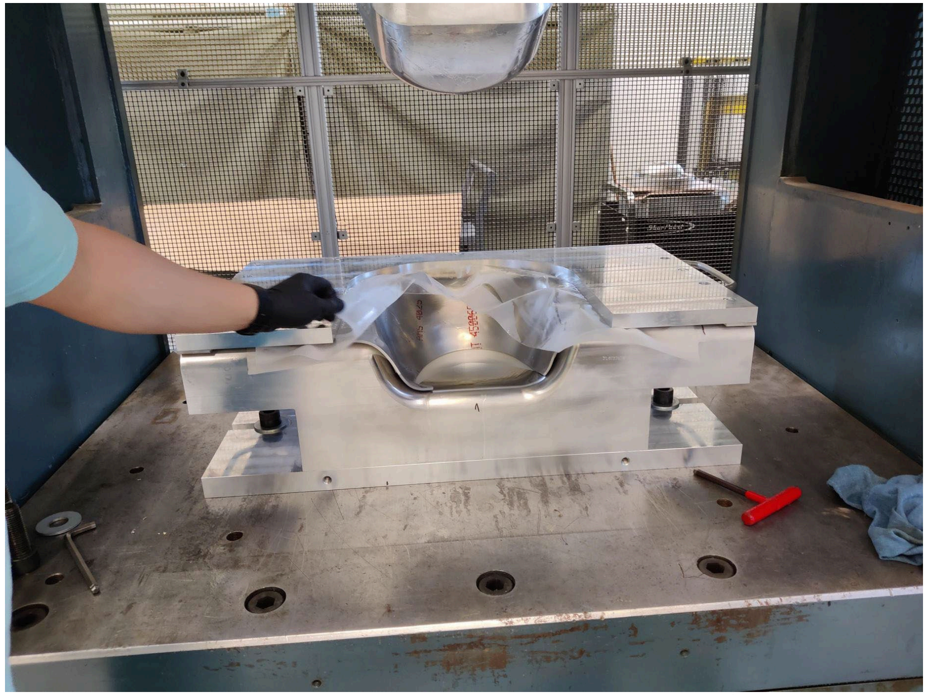
Crab Cavity Feedback System

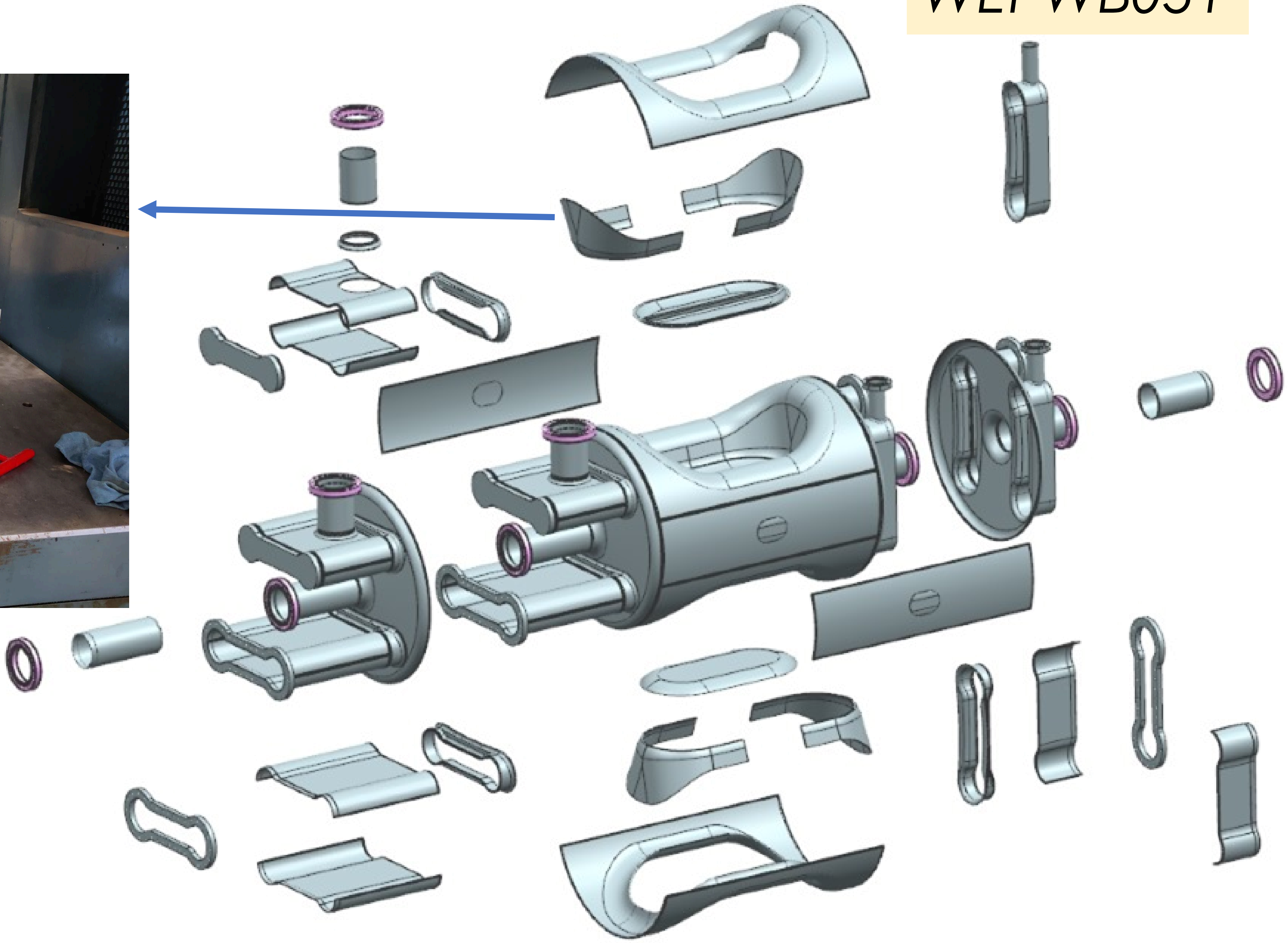
- The fundamental mode of the crab cavity has a large transverse impedance and the beta functions at the cavity are large.
- Plan to keep fixed resonant frequency with wideband feedback on with zero voltage setpoint during injection and ramping.
  - High gain feedback: FPC Qext at1.75E6, effective Q ~300, a ~6000 gain.
  - Short feedback delay at ~380 nS.
- Recent study by Themis showed it is possible to lower the requirement to 1400 gain with 1μS delay, still challenging but much better.
- Requirement on high gain contradicts with the noise control requirement.
- Plan to place the amplifiers right on top of (and outside) the tunnel to minimize the delay.

M. Blaskiewicz, Instabilities Driven by the Fundamental Crabbing Mode, BNL Tech Note BNL-222221-2021-TECH
M. Blaskiewicz, EIC MAC Review, July 15, 2022

First Stamp!

N. Huque
WEPWB051





Summary

- Specs and consequences
  - Large crabbing angle → high crabbing voltage
  - Tight impedance budget → on-cell damper
  - High current short bunch → high HOM power
  - Tight space
  - Tight multipoles → pole shape
  - Tight in noise and feedback system
- Designs
  - To provide higher crabbing voltage, elongated DQW is not mechanically suitable, thus RFD is chosen.
  - On-cell waveguide ports to provide better damping
    - 197MHz: waveguide to coaxial design to avoid large waveguide damper; 2 cavities in 1 cryomodule to save longitudinal space.
    - 394MHz: waveguide damper (preliminary); WOW type causes higher HOM power thus is not preferred.
  - Curved pole (machine from ingot Nb) for multipoles specs.
  - High gain low delay loop
    - Amplifier on top of tunnel for low delay
  - Noise control
    - Feedback with good pickup.

Acknowledgement

- BNL – B. Xiao, Q. Wu, M. Blaskiewicz, W. Xu, J. Fite, D. Holmes, K. Smith, Z. Conway, J. C. Brutus, S. Verdu-Andres, A. Zaltsman, D. Xu, Y. Luo, Y. Hao, S. Berg, G. Narayan, F. Severino, K. Mernick, K. Hamdi, and many more
- ODU – S. De Silva, J. Delayen
- JLAB – A. Castilla-Loeza, N. Huque, M. Marchlik, J. Henry, R. Fernandes, N. Joshi, J. Matalevich, R. Rimmer, E. Daly, T. Satogata, J. Guo, H. Wang, S. Wang, H. Huang, G. Bamunuvita, and many more
- SLAC – Z. Li
- Cal Poly - Themis Mastoridis
- TRIUMF – R. Laxdal, P. Kolb, Z. Yao