Compact Crabbing Systems for Particle Colliders

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Outline

- Crabbing cavities – History
  - KEK Crabbing Cavity
- TM_{110} class cavities
- New geometries
- RF tests on proofs-of-principle cavities
- Crabbing cavity R&D for LHC High Luminosity Upgrade
  - RF properties
  - HOM spectrum and HOM couplers
  - Multipacting analysis
- Proof-of-Principle Cavity Tests
- Engineering and Prototyping

Crabbing Concept

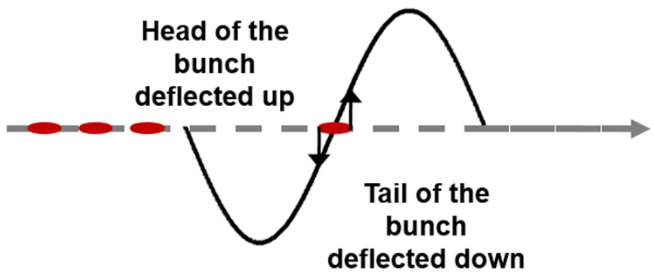
- Crab crossing – Proposed by R.B. Palmer

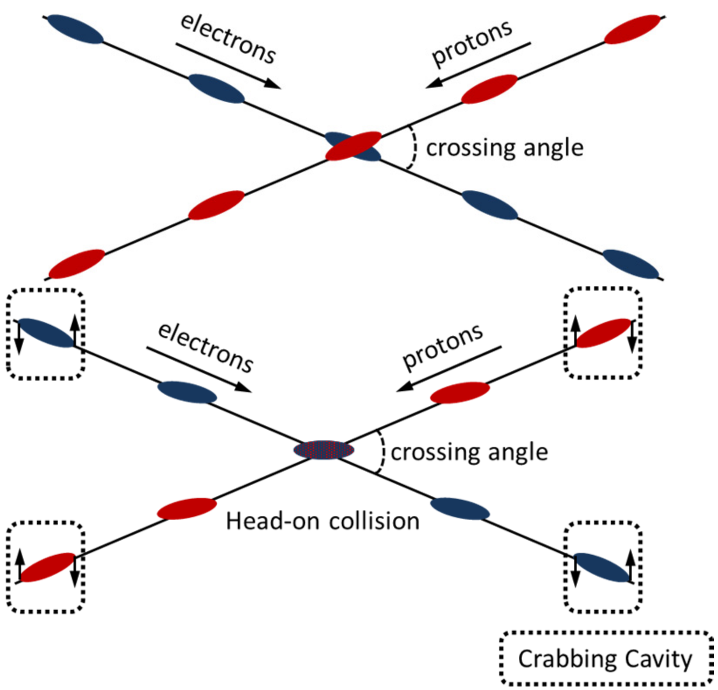
  R.B. Palmer, Energy scaling, crab crossing and the pair problem, SLAC-PUB-4707

- Crabbing cavities:
  - Luminosity management in linear or circular colliders with head on collision → Crab crossing

$$\mathcal{L} = \frac{N_1 N_2 f_c N_b}{4\pi\sigma_x\sigma_y}\frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x}\right)^2}}$$

  - Emittance exchange in beams
  - X-ray pulse compression
  - Beam diagnostics





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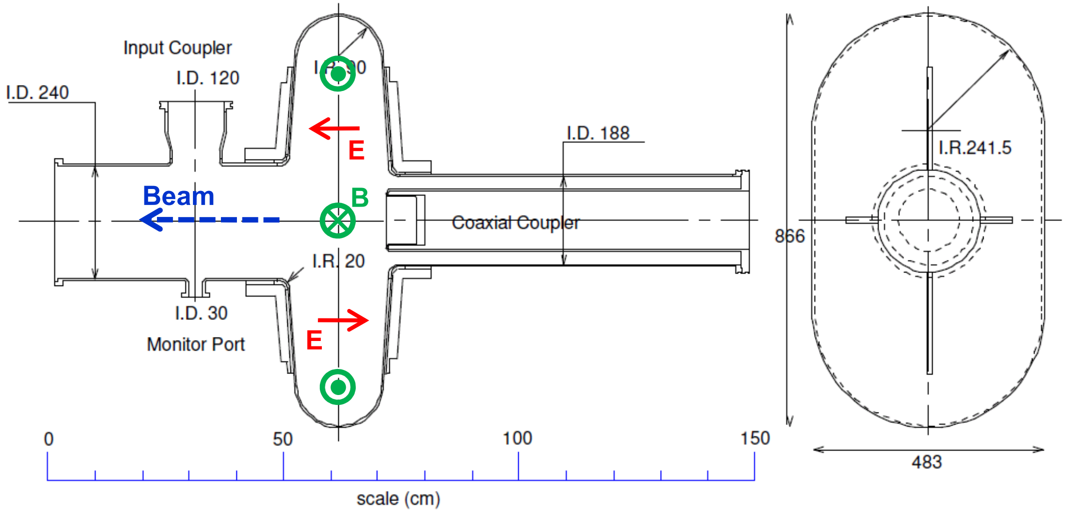
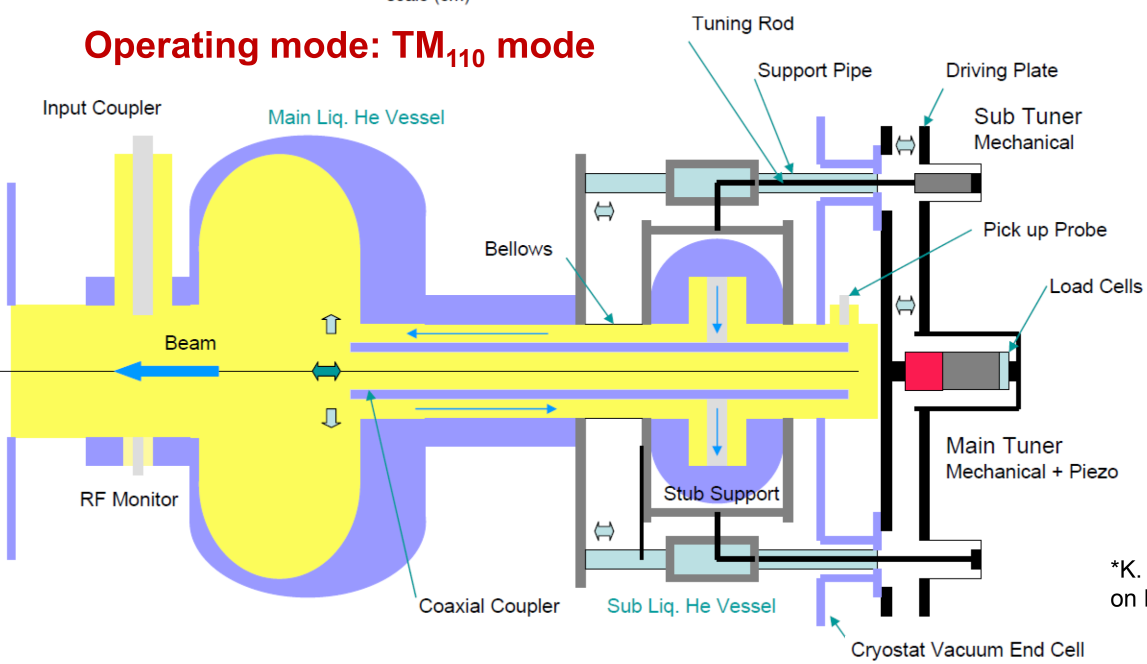
The 1st Superconducting Crabbing Cavity



Operating mode: TM_{110} mode



Complex HOM Damping Scheme

- Two crabbing cavities
  - High energy ring (HER)
  - Low energy ring (LER)

Properties of KEK Crabbing Cavity*

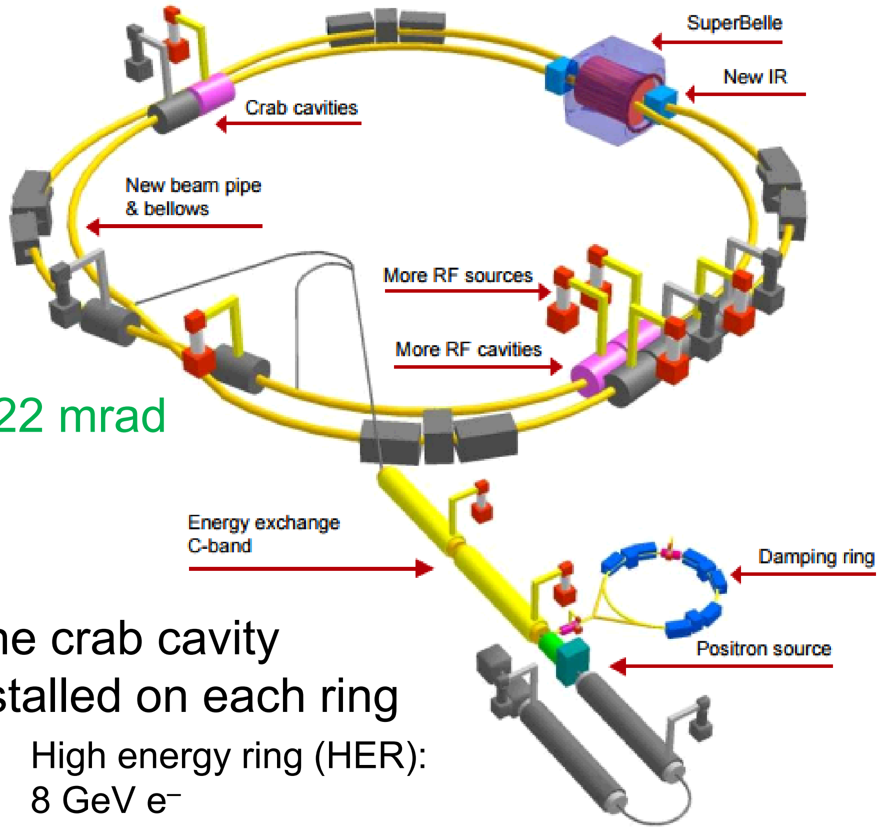
Frequency	508.9	MHz
LOM	410.0	MHz
Nearest HOMs	630.0, 650.0, 680.0	MHz
E_p^*	4.24	MV/m
B_p^*	12.23	mT
B_p^*/E_p^*	2.88	mT/(MV/m)
$[R/Q]_T$	48.9	Ω
Geometrical Factor (G)	227.0	Ω
$R_T R_S$	1.11×10^4	Ω^2
At $E_T^* = 1$ MV/m		

*K. Hosoyama *et. al.*, "Crab Cavity for KEKB", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

KEK Crabbing Cavity Performance

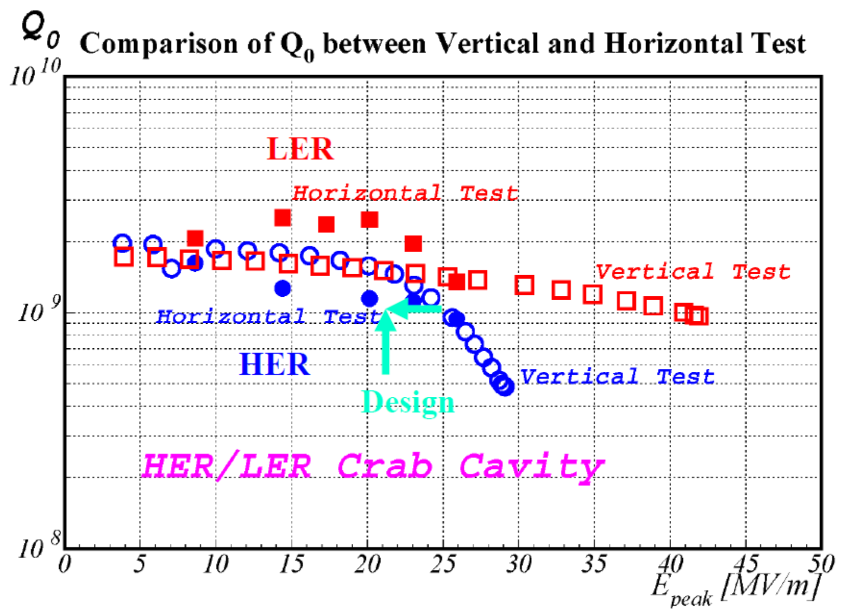
Crab cavity for HER

Crab cavity for LER



Global crabbing scheme → Crossing angle – 22 mrad

Peak luminosity achieved: 2.1×10^{34} /cm^2/s

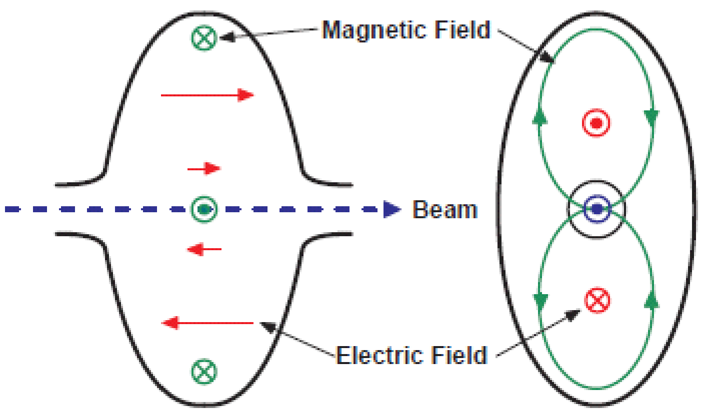


- One crab cavity installed on each ring
  - High energy ring (HER): 8 GeV e⁻
  - Low energy ring (LER): 3.5 GeV e⁺
- Crab cavities operated from 2007-2010
  - V_t = 1.5 MV for LER
  - V_t = 1.6 MV for HER

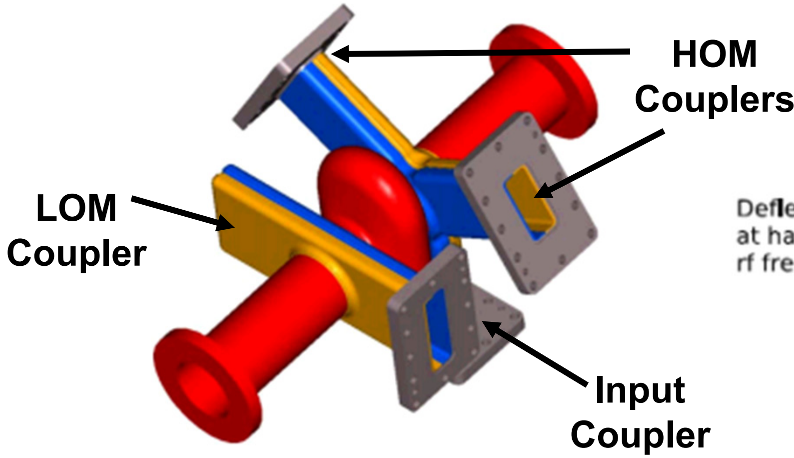
Features of TM_{110} Class Cavities

- Deflection mostly through interaction with magnetic field
- Presence of lower-order mode (TM_{010})
- TM_{110} mode is degenerate in cylindrical geometry
  - Squashed cross-section
- Large with respect to wavelength compared to new designs
  - Disadvantageous for low frequency
  - Advantageous for high frequency
  - Able to accommodate large apertures
- Few degrees of freedom in the design
  - Higher order multipole components
- Relatively low real estate gradient
  - Couplers on beam line

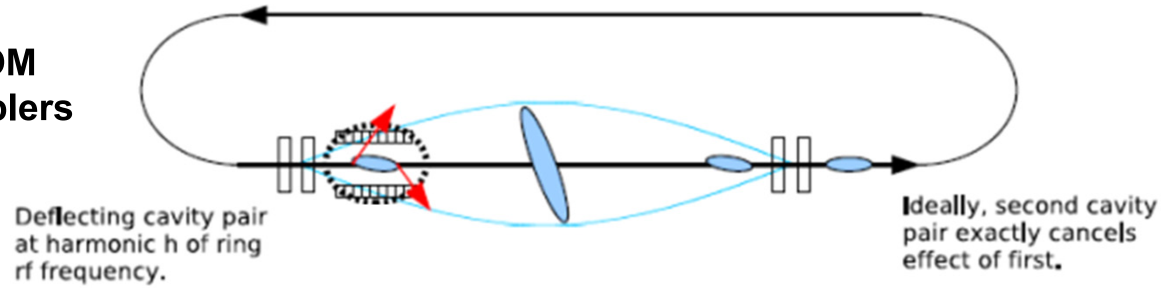
Squashed elliptical design

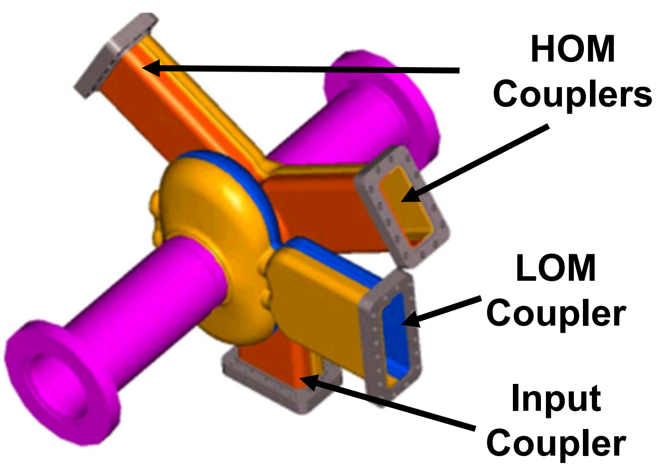


Crabbing Cavity for Short Pulse X-ray Project



Baseline Design (MARK I)





Alternate Design (MARK II)

Generate short x-ray pulses using crabbing cavities

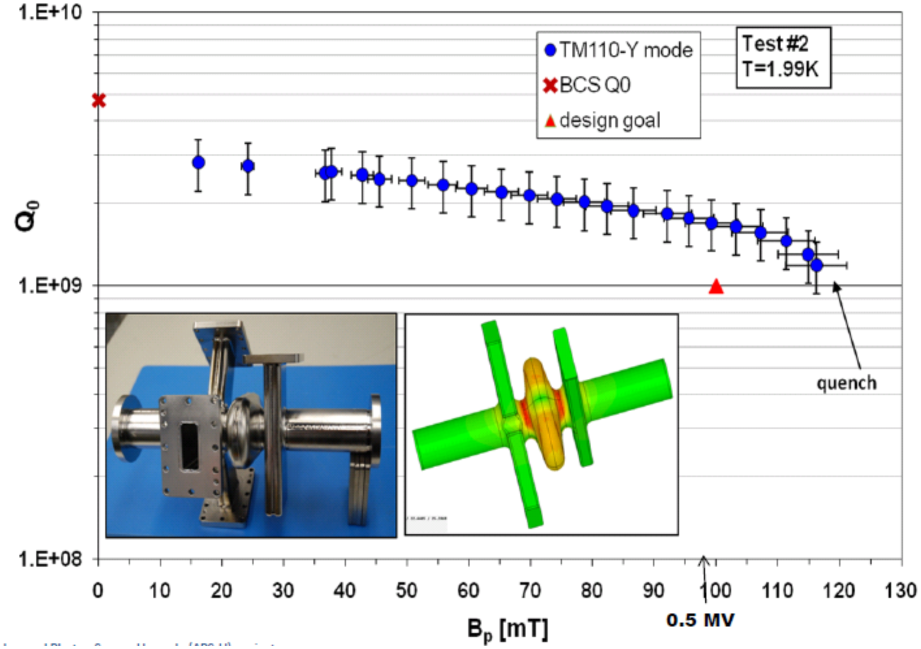
- Beam energy – 7 GeV
- Beam current – 202 mA

SPX Crabbing Cavity – RF Properties*

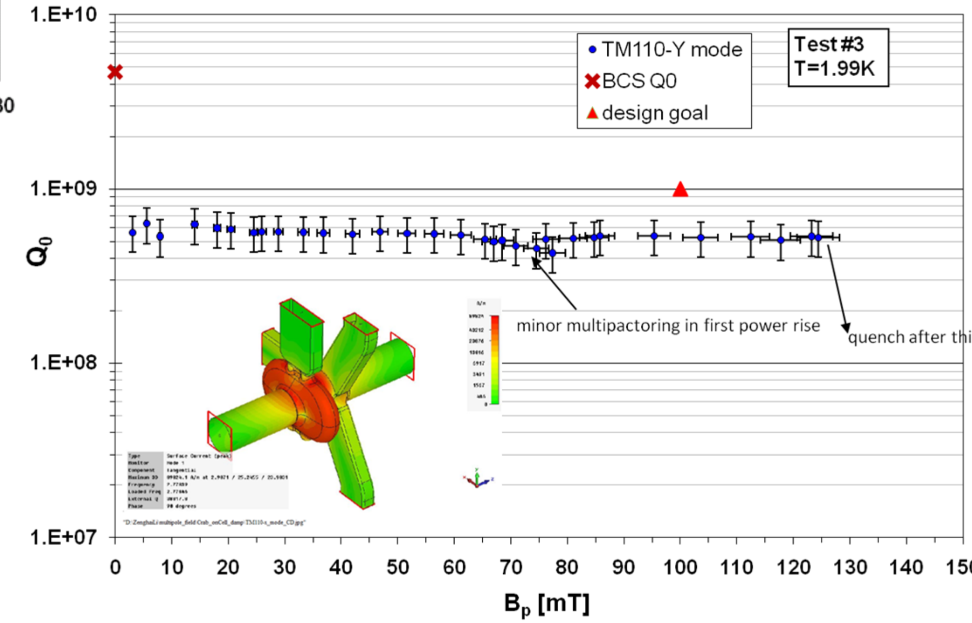
Parameter	Baseline Design	Alternate Design	Units
Frequency	2.815		GHz
Beam iris	25		mm
V_t	0.5		MV
B_t	98	100	mT
E_t	41	42	MV
$[R/Q]_t$	35.8	37.1	Ω
G	227.5	227.8	Ω
Material thickness	3 Nb Sheet	4 Nb Block	mm

*H. Wang, "SPX Crab Cavity Development and Testing Result", TTC Meeting, Nov, 2012
#J. Mammosser, "SPX Cryomodule Design", APS-U Lehman Review, May 2011

SPX Crabbing Cavity Performance



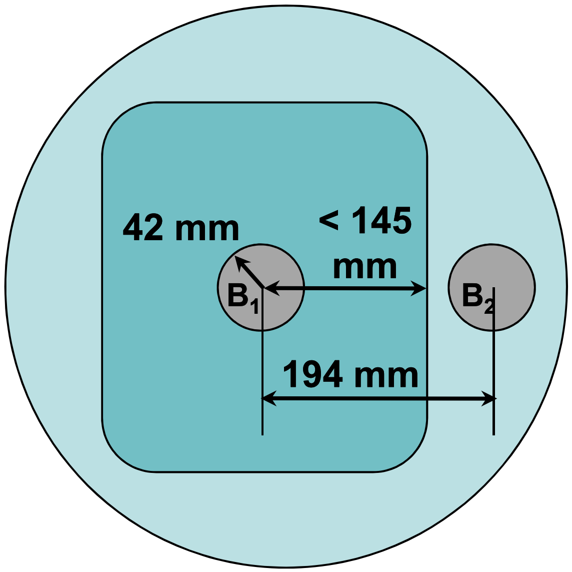
MARK I (Baseline Design)
Prototype Crabbing Cavity
Vertical Test at JLab

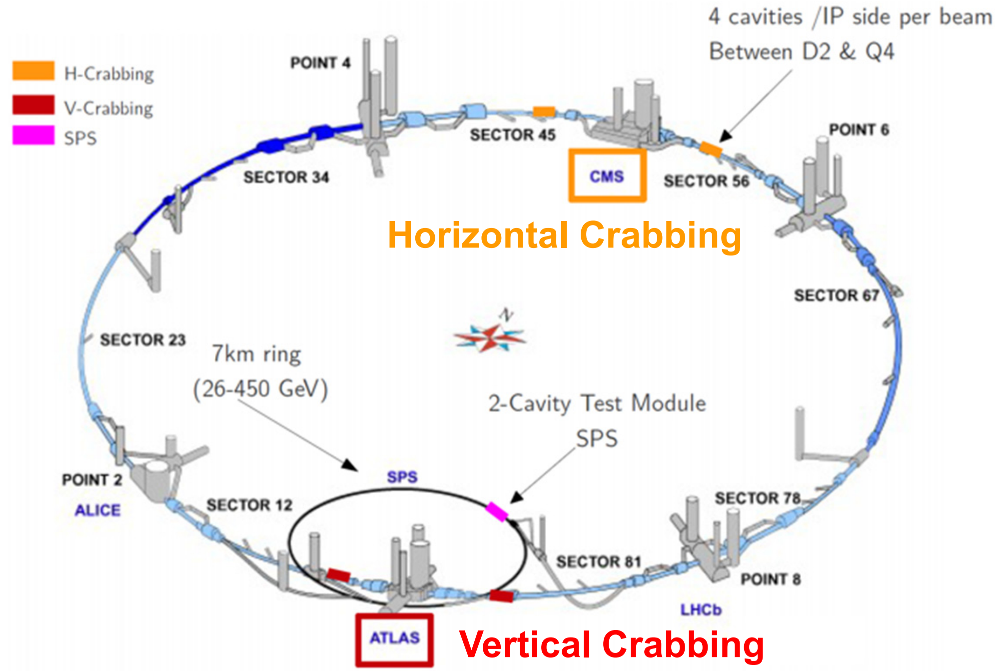


MARK II (Alternate Design)
Prototype Crabbing Cavity
Vertical Test at JLab

Applications in Need of Compact Crabbing Cavities

Crabbing cavities for LHC High Luminosity Upgrade





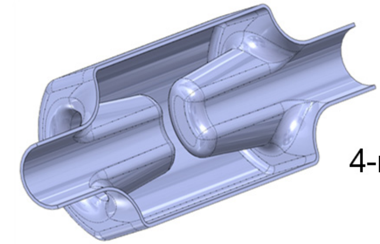
- Requires compact designs due to
  - Low operating frequency
  - Separation between beam pipes
- TM_{110} squashed elliptical geometries are not favorable
- Solution: Designs operating in TEM or TE-like modes

Specifications

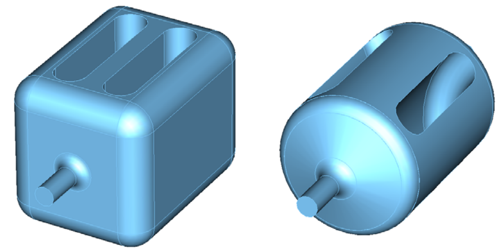
- Crossing angle: 0.59 mrad
- RF frequency (f_c) = 400.79 MHz
- Total transverse voltage (V_t) per beam per side = 13.4 MV
  - Total 16 crabbing cavities per type

New Geometries and Concepts

- Cavities operating in TEM-like modes
  - 4-rod cavity – Lancaster University, UK
    - 4 quarter-wave resonators (deflection from both E and H)
  - Parallel-bar cavity – ODU
    - 2 half-wave resonators (deflection from E)
    - Evolved into rf-dipole

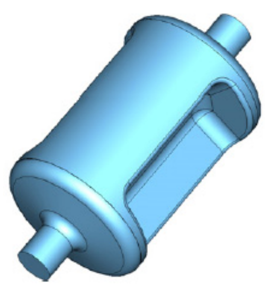


4-rod cavity

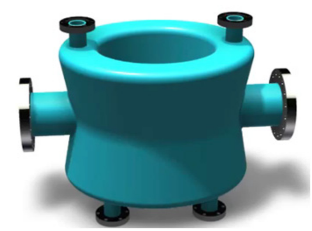


Parallel-bar cavities

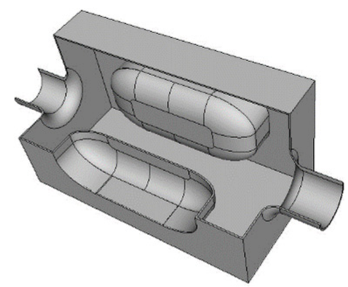
- Cavities operating in TE-like mode (cannot be pure TE)
  - RF-dipole – ODU
  - Double quarter-wave – BNL
  - Ridged waveguide – SLAC



RF-Dipole cavity



Double quarter-wave cavity

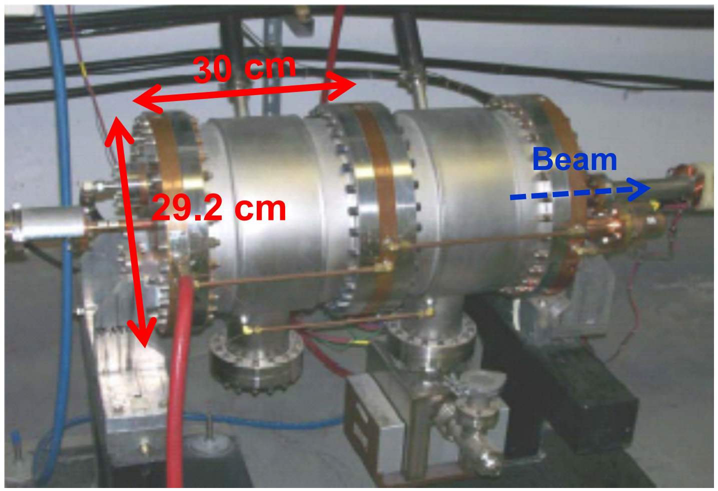


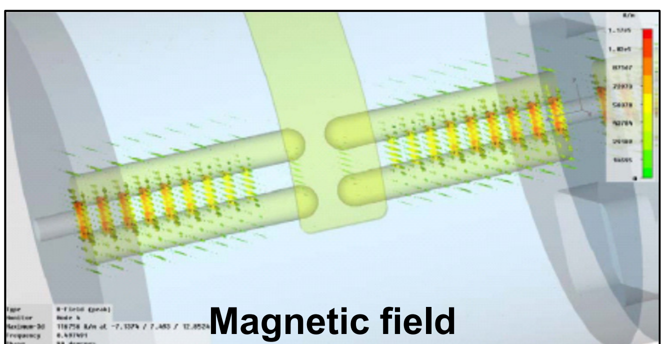
Ridged waveguide cavity

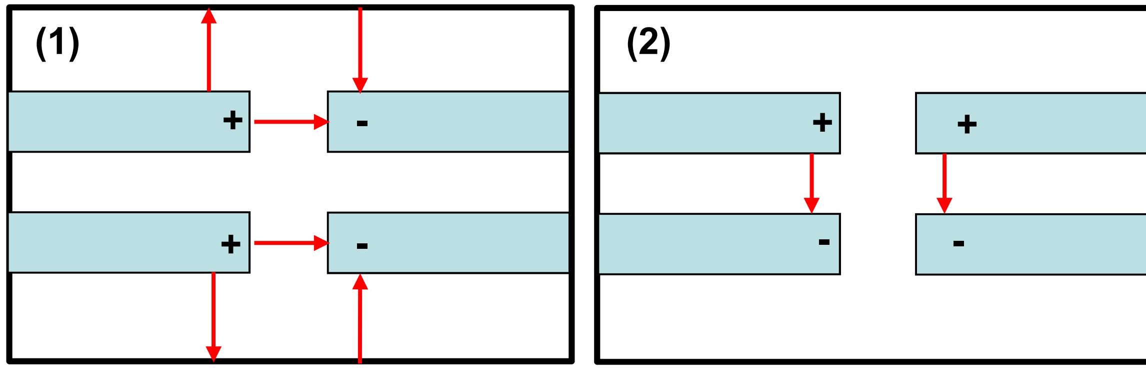
4-Rod Cavity Design

- 499 MHz normal conducting rf separator* at Jefferson Lab
- High shunt impedance

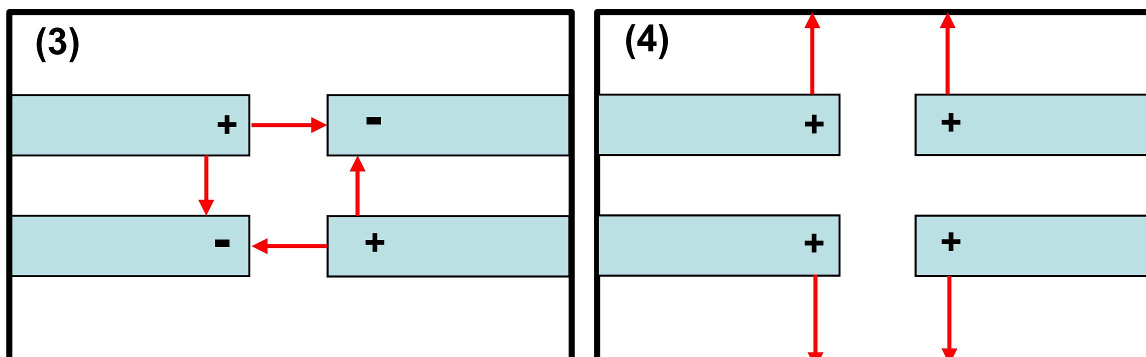
- Operates in a TEM-like mode
  - Uses both electric field and magnetic field
  - Deflecting mode is not the lowest mode







Accelerating lower order mode



Fundamental deflecting mode

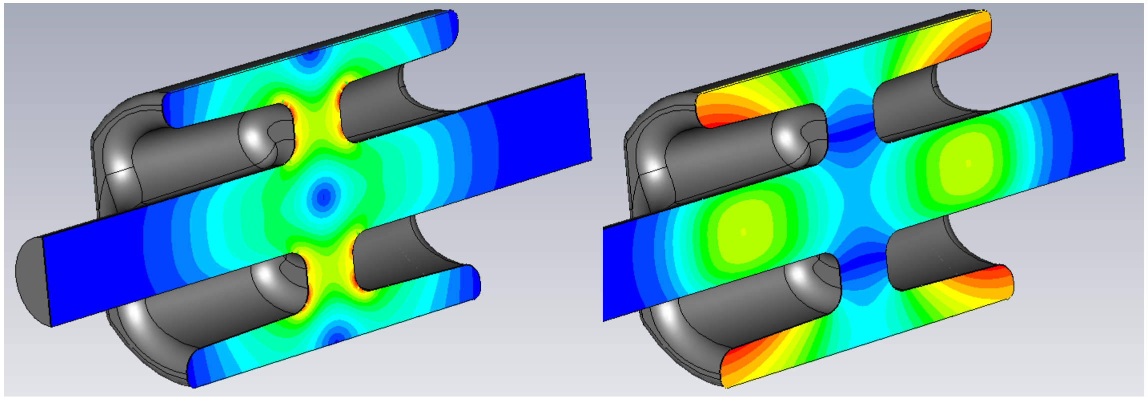
*C. Leemann and C.G. Yao, "A Highly Effective Deflecting Structure", Proc. of the 1990 LINAC, p.232-234, (1991)

4-Rod Crabbing Cavity (U. of Lancaster)

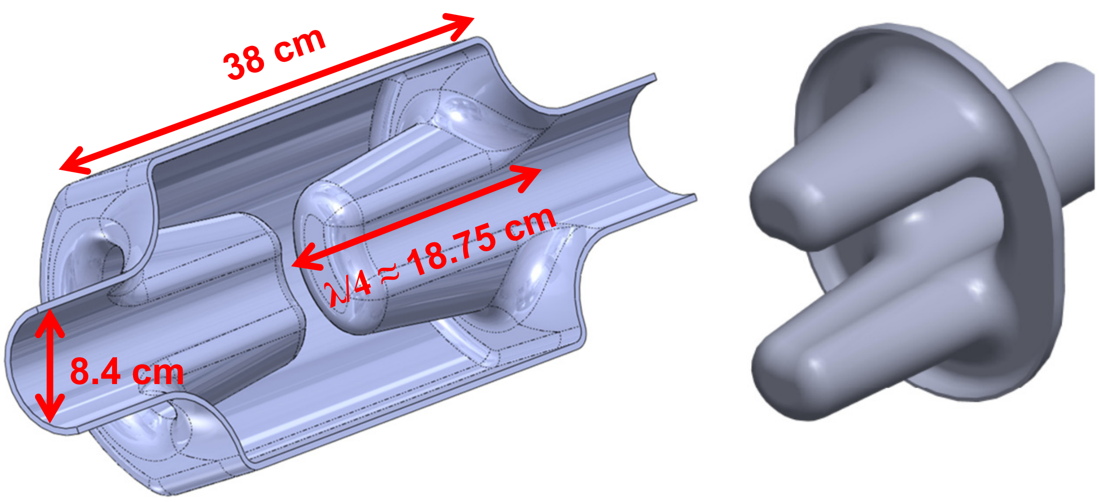
- 4-Rod crabbing cavity – University of Lancaster / Cockroft Institute
- Adapted from JLab normal conducting cavity

Frequency	400.0	MHz
LOM	375.2	MHz
Nearest HOMs	436.6, 452.1	MHz
E_p^*	4.0	MV/m
B_p^*	7.56	mT
B_p^*/E_p^*	1.89	mT/ (MV/m)
$[R/Q]_T$	915.0	Ω
Geometrical Factor (G)	62.8	Ω
$R_T R_S$	5.7×10^4	Ω^2
At $E_T^* = 1$ MV/m		

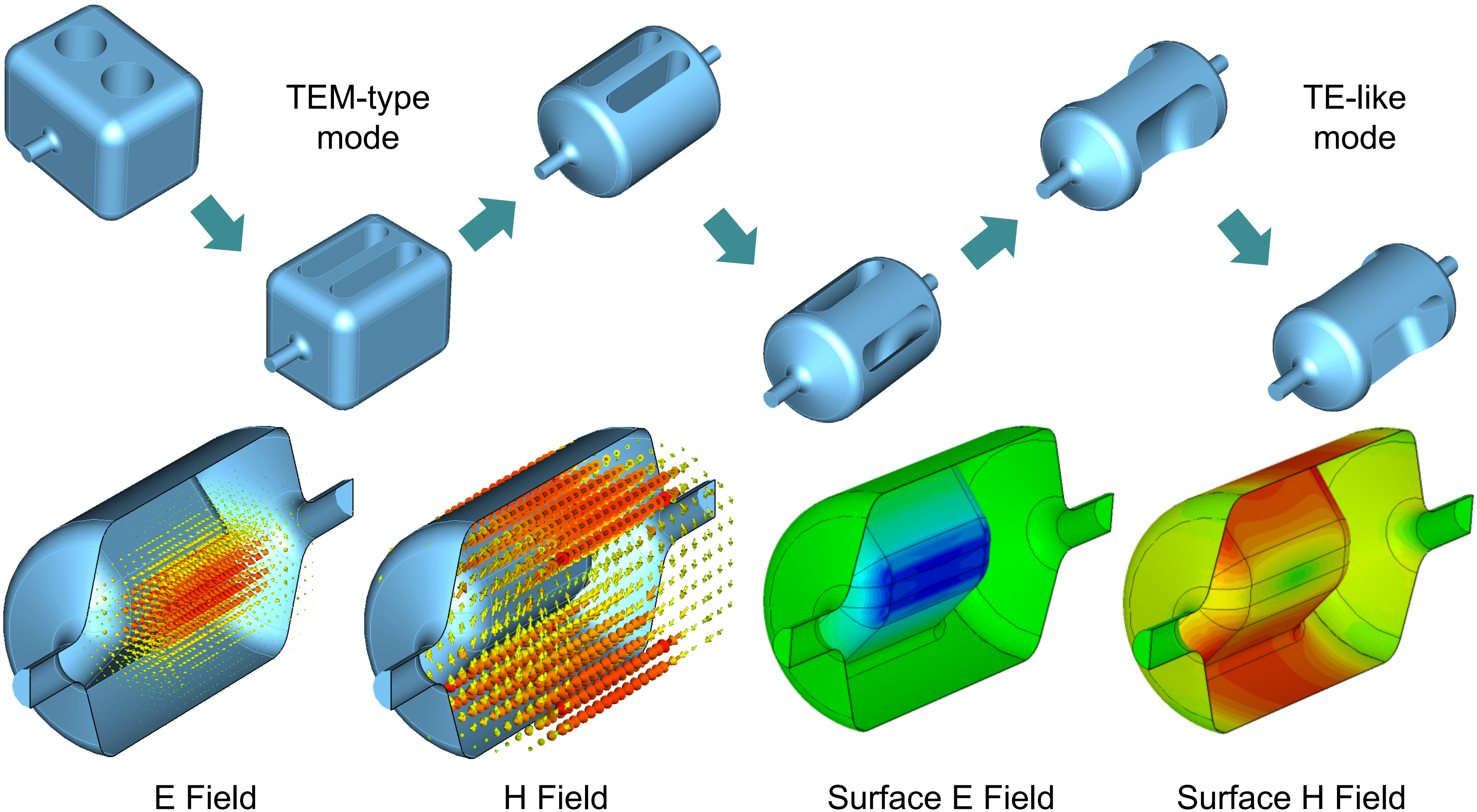
Courtesy: G. Burt (Lancaster University)



Magnetic Field **Electric Field**



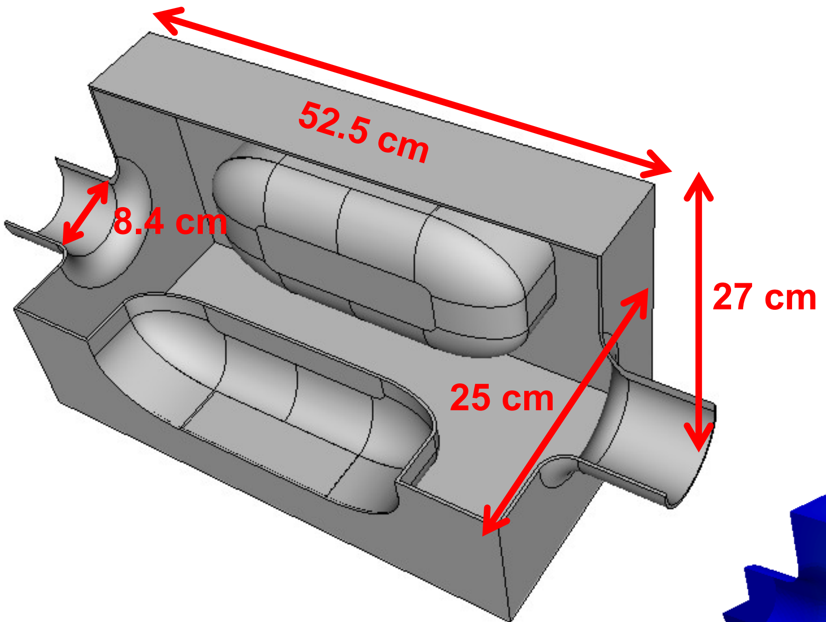
Parallel-Bar Cavity to RF-Dipole Cavity (ODU)



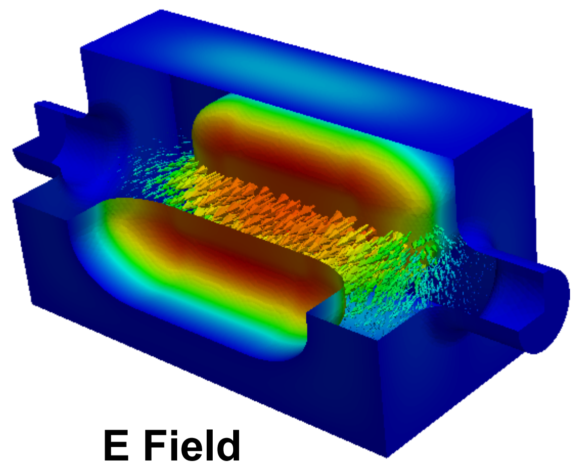
S. U De Silva and J. R. Delayen, “Design evolution and properties of superconducting parallel-bar rf-dipole deflecting and crabbing cavities, PRSTAB 16, 012004 (2013)
S. U. De Silva, PhD thesis, ODU 2014

Ridged Waveguide Cavity (SLAC)

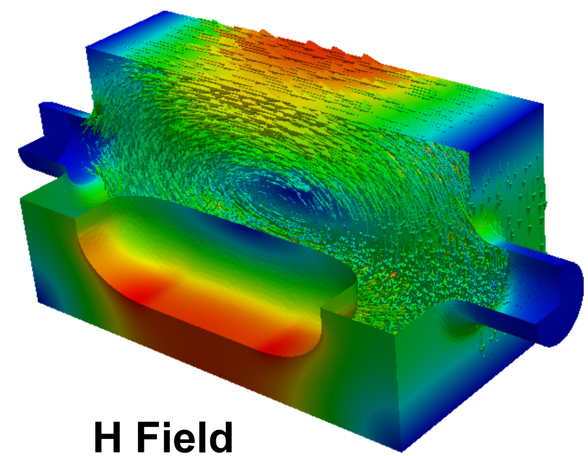
- 400 MHz Crabbing Cavity*
- Operating at a TE_{11}-like mode



Frequency	**400.0**	**MHz**
LOM	None	MHz
Nearest HOM	617.0	MHz
E_p^*	3.38	MV/m
B_p^*	7.05	mT
B_p^*/E_p^*	2.09	mT/(MV/m)
$[R/Q]_T$	330.0	Ω
At $E_T^* = 1$ MV/m		



E Field



H Field

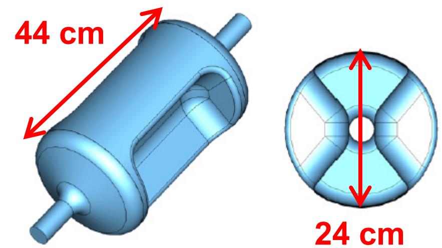
*Z. Li and L. Ge, "Compact Crab Cavity Design and Modeling Using Parallel Code ACE3P", LHC-CC11, (2011)

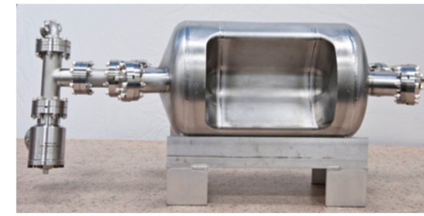
RF-Dipole Deflecting/Crabbing Cavities

Proof-of-principle cavities

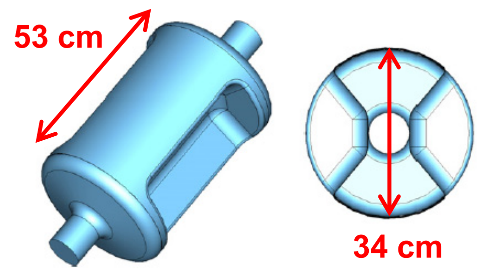
Frequency	499.0	400.0	750.0	MHz
Aperture Diameter (d)	40.0	84.0	60.0	mm
d/(λ/2)	0.133	0.224	0.3	
LOM	None	None	None	MHz
Nearest HOM	777.0	589.5	1062.5	MHz
E_p^*	2.86	3.9	4.29	MV/m
B_p^*	4.38	7.13	9.3	mT
B_p^*/E_p^*	1.53	1.83	2.16	mT/ (MV/m)
$[R/Q]_T$	982.5	287.2	125.0	Ω
Geometrical Factor (G)	105.9	138.7	136.0	Ω
$R_T R_S$	1.0×10^5	4.0×10^4	1.7×10^4	Ω^2
At E_T^* = *1* MV/m				

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

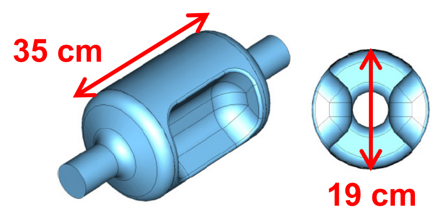




400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

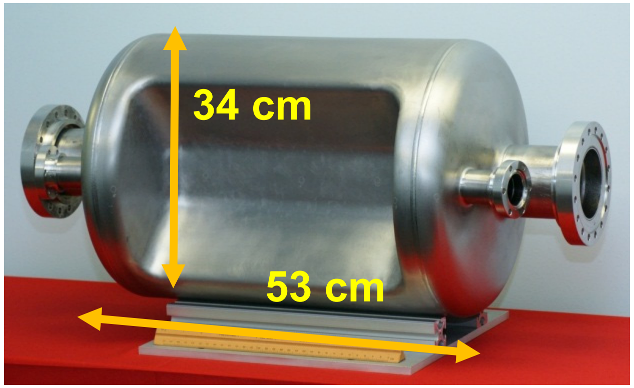


750 MHz Crabbing Cavity for MEIC at Jefferson Lab



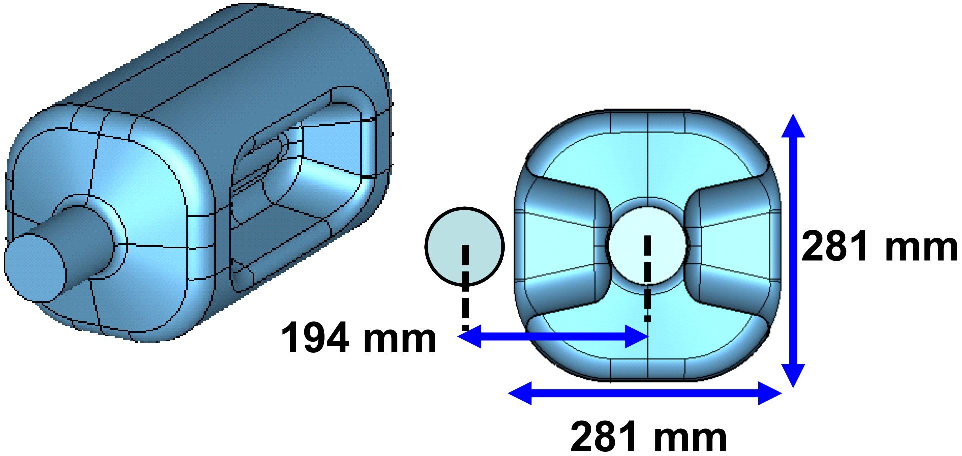
RF-Dipole Crabbing Cavity

Proof of Principle Cavity



	P-o-P Cavity	Prototype Cavity	
Frequency	**400**	**400**	**MHz**
1st HOM	590	633.5	MHz
V_t	3.4		MV
E_p	37	33	MV/m
B_p	64	57	mT
$[R/Q]_t$	287	430	Ω
G	141	107	Ω
R_tR_s	4.0×10^4	4.6×10^4	Ω^2

Prototype Cavity



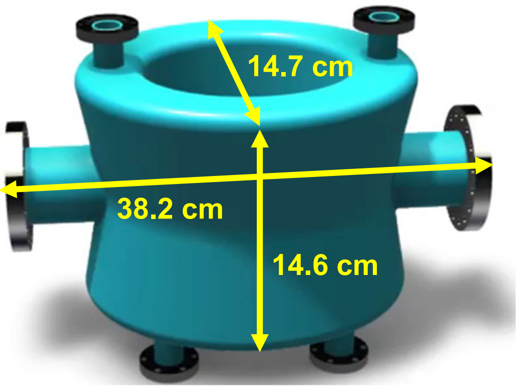
Prototype cavity

- Well separated HOMs
- Reduced surface electric and magnetic fields
- High shunt impedance
- Improved multipacting levels compared to P-o-P cavity
- Reduced multipole components

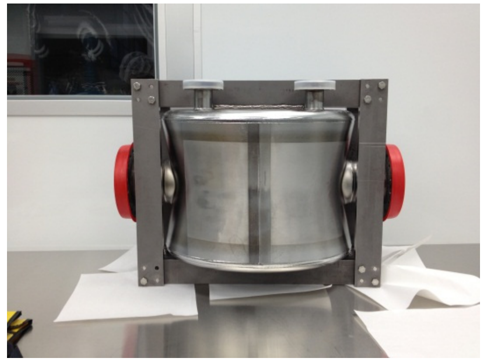
*S.U. De Silva and J.R. Delayen, PRAB 16, 012004 (2013)
#S.U. De Siva and J.R. Delayen, PRAB 16, 082001 (2013)

Double Quarter Wave Crabbing Cavity

Proof of Principle Cavity

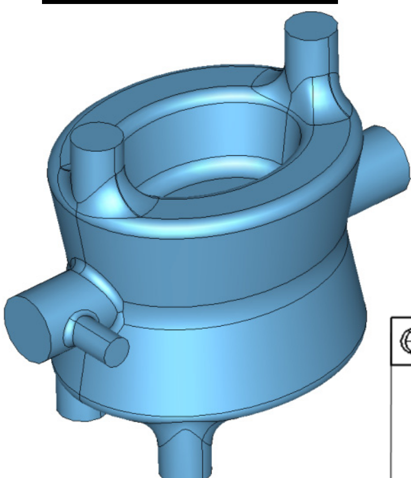


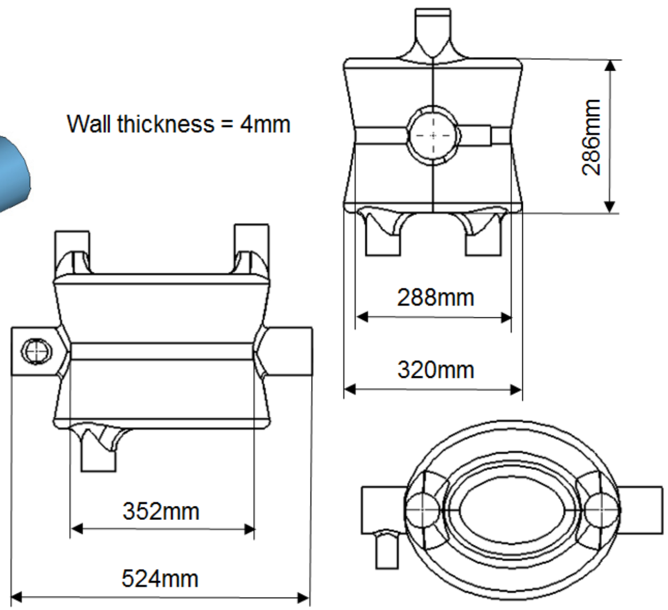
Courtesy: Q. Wu (BNL)

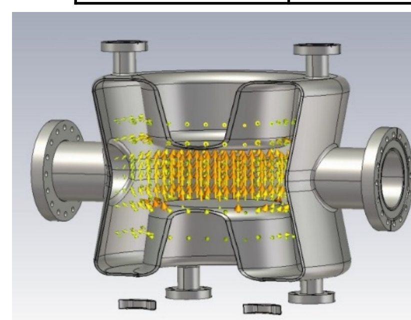


	P-o-P Cavity	Prototype Cavity	
Frequency	**400**	**400**	**MHz**
1st HOM	579	580	MHz
V_t	3.34		MV
E_p	49	40.7	MV/m
B_p	80	70.9	mT
$[R/Q]_t$	406	430	Ω
G	85	89	Ω
R_tR_s	3.45×10^4	3.83×10^4	Ω^2

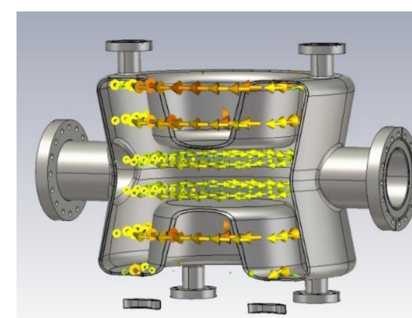
Prototype Cavity







Electric Field



Magnetic Field

B. Xiao et al, PRSTAB 18, 041004 (2015)

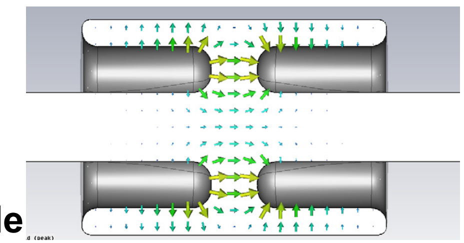
Dimension-Dependent Properties

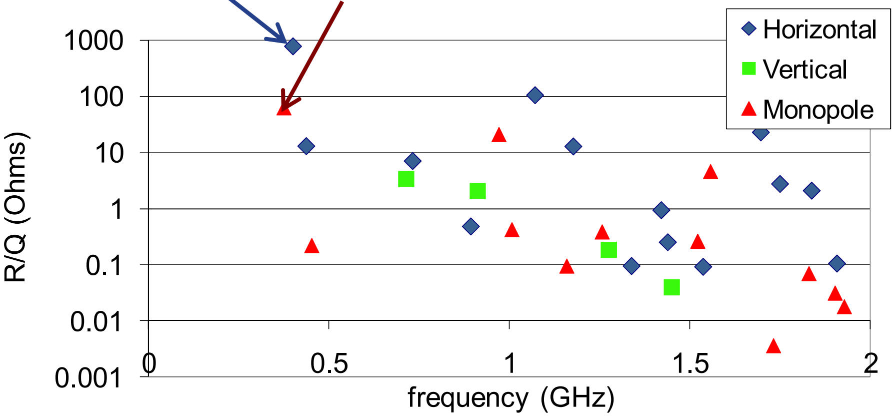
- 4-Rod – "TEM-like" cavities
  - Frequency governed by longitudinal dimension (~ $\lambda/2$)
  - Frequency independent of transverse dimension
    - Could accommodate very low frequencies with small transverse size
  - "Matched" particle velocity related to longitudinal dimension
    - Limited to high-velocity particles

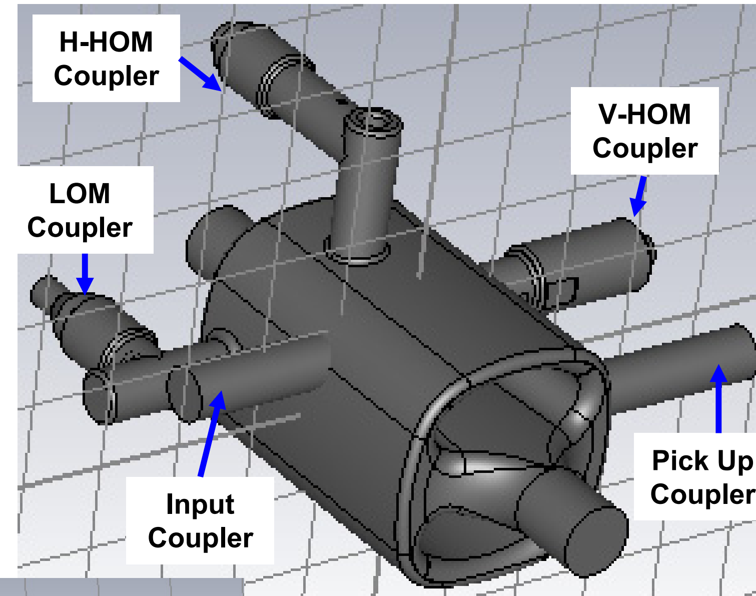
- Double Quarter-wave / Ridged-Waveguide / RF-Dipole – "TE-like" cavities
  - Frequency governed by transverse dimension (~ $\lambda/2$)
    - Transverse size is frequency-dependent
  - Frequency independent of longitudinal dimension
  - "Matched" particle velocity related to longitudinal dimension (~ $\beta\lambda/2$)
    - Could accommodate low-velocity particles

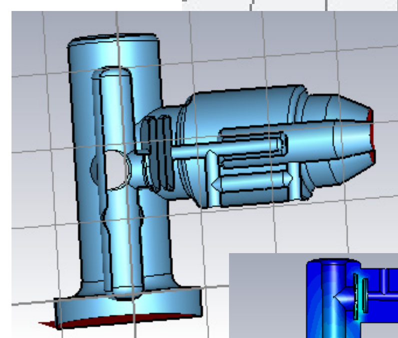
HOM Damping – "TEM-Like" Cavity

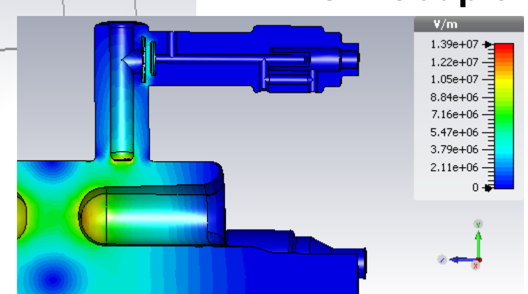
- "TEM-like" cavities (4-rod cavity)
  - 4 same-order modes
  - Accelerating mode lower in frequency than fundamental deflecting mode
  - Other modes in close proximity
  - Need for notch-filters

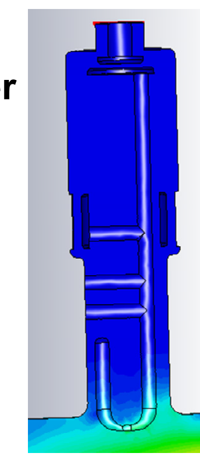








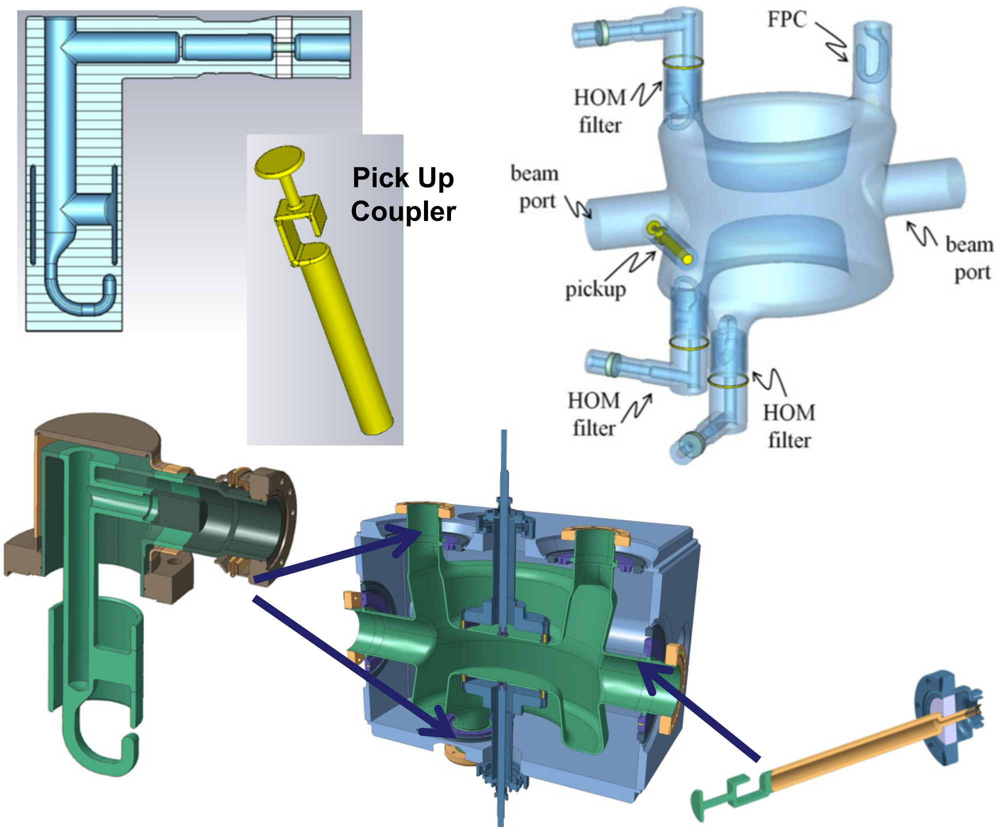


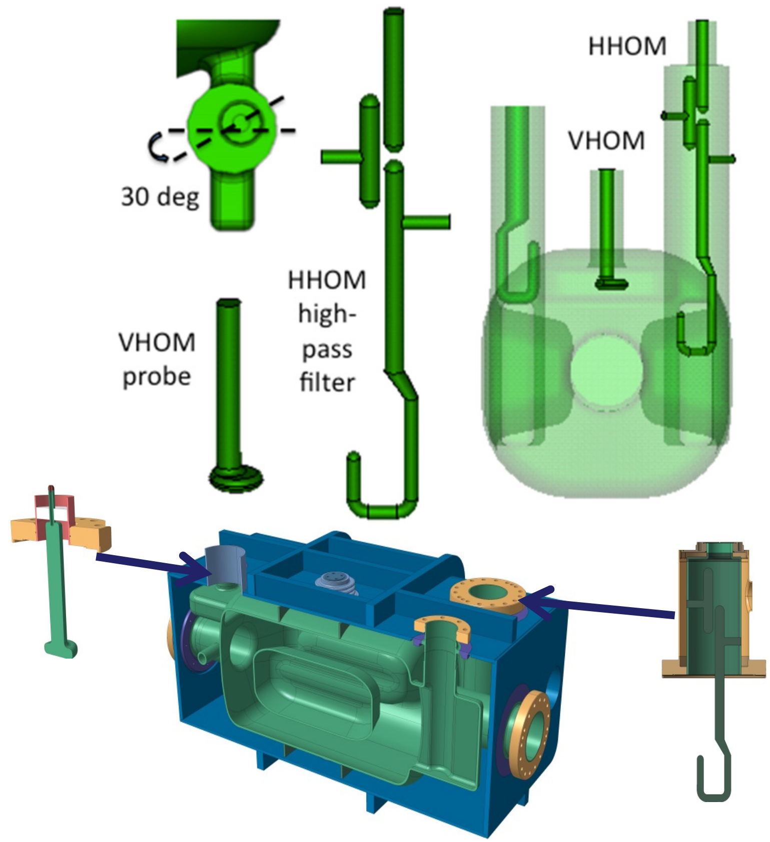


HOM Damping – "TE-Like" Cavities

- First HOM at 580 MHz
- 3 HOM couplers with filters
- Pick-up coupler provide damping for a specific HOM at 1.75 GHz

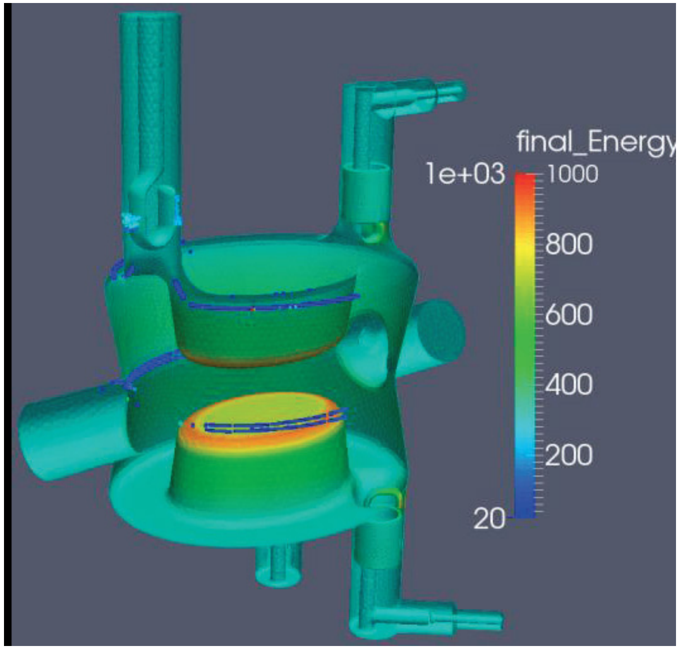
- First HOM at 633.5 MHz
- 1 HOM coupler with filter (HHOM)
- 1 HOM coupler without filter (VHOM)
  - Does not couple to the fundamental

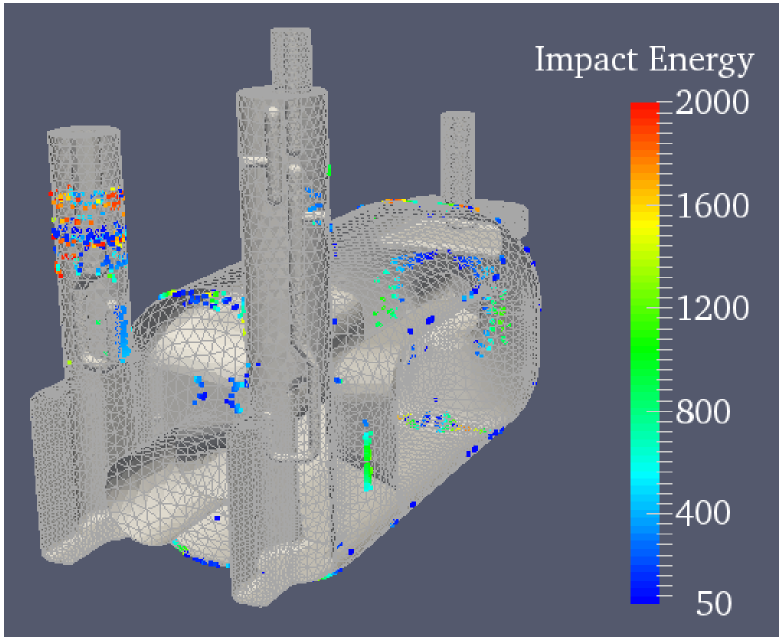




Multipacting Analysis

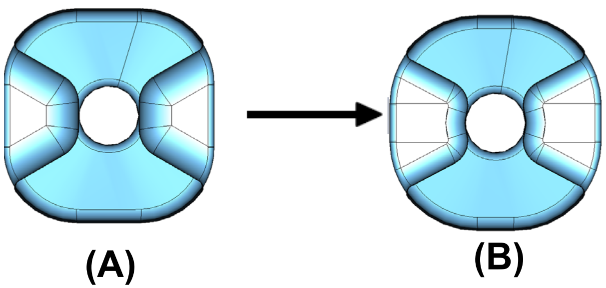
- Extensive simulations of multipacting have been performed using the SLAC ACE3P suite of codes
- Multipacting occurred in the proof-of-principle cavities where predicted, was easily processed, and did not reoccur

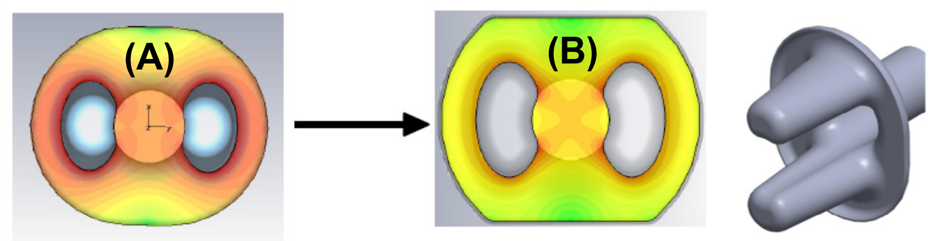


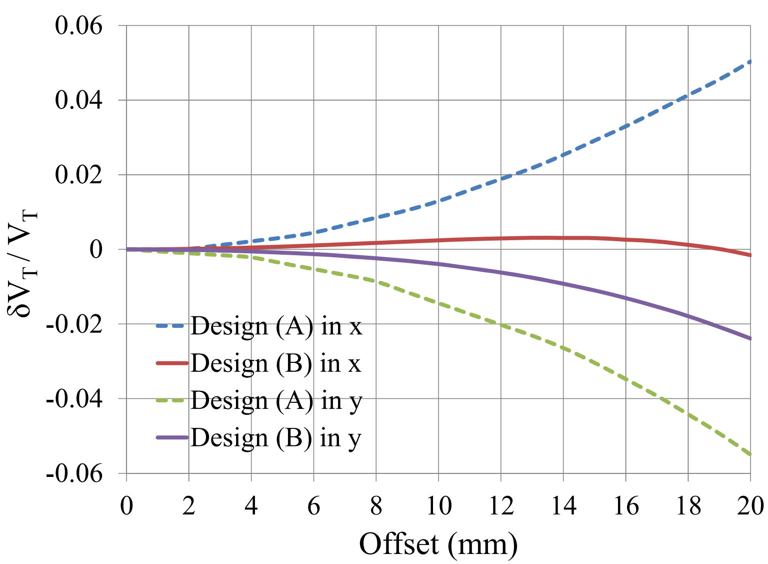


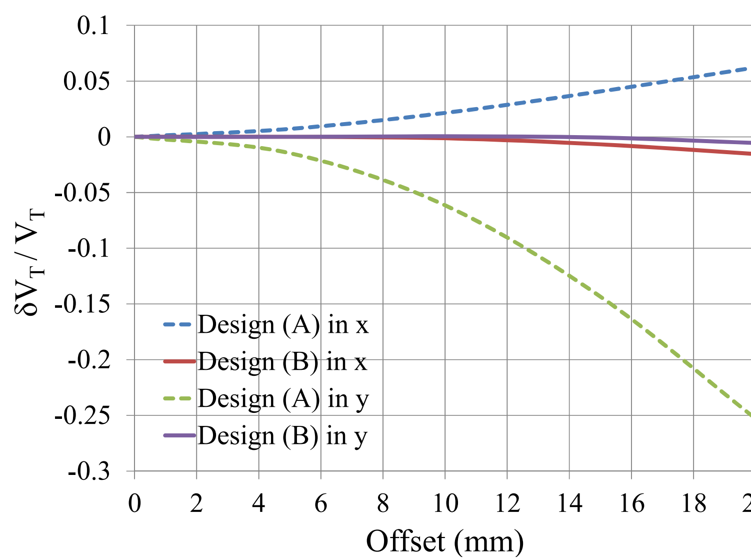
Multipole Components

- Shaping of the geometry near the beamline can be used to control the magnitude of the higher order multipoles
  - Involves trade-off with surface fields and shunt impedance



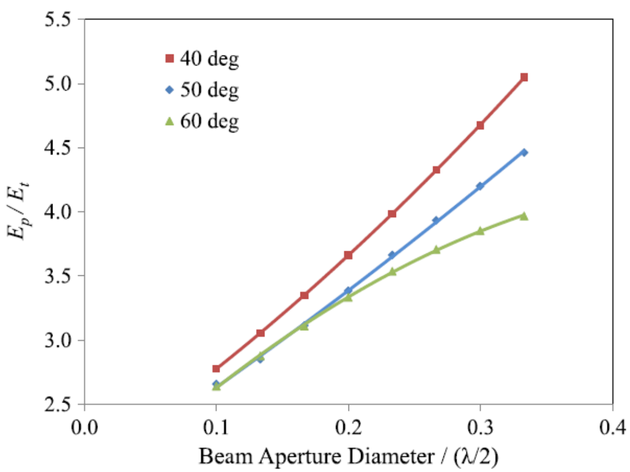


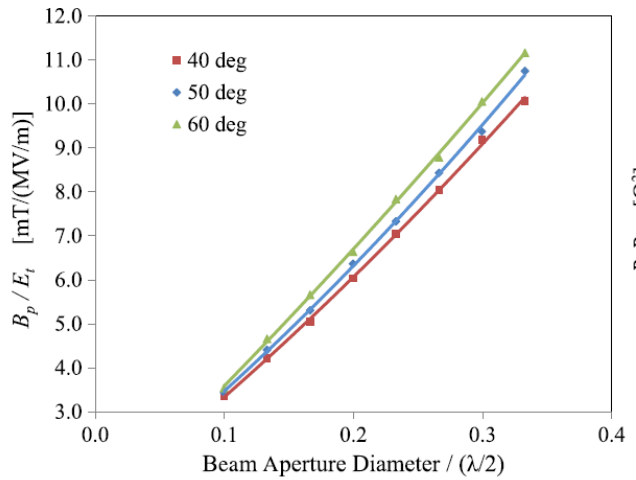


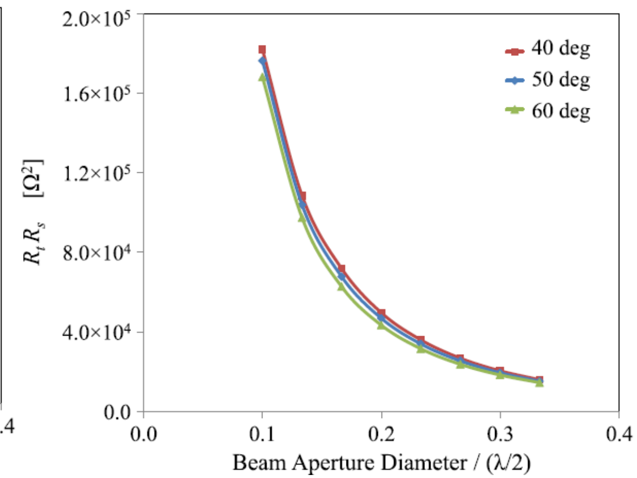


Influence of Beamline Aperture

- Electromagnetic properties of “TE” cavities are quite sensitive to beamline aperture (separation between the poles or rods)



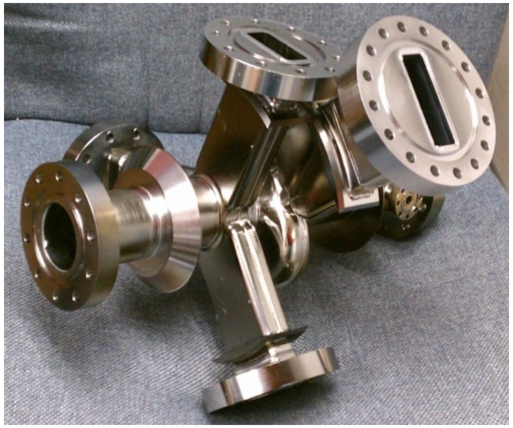




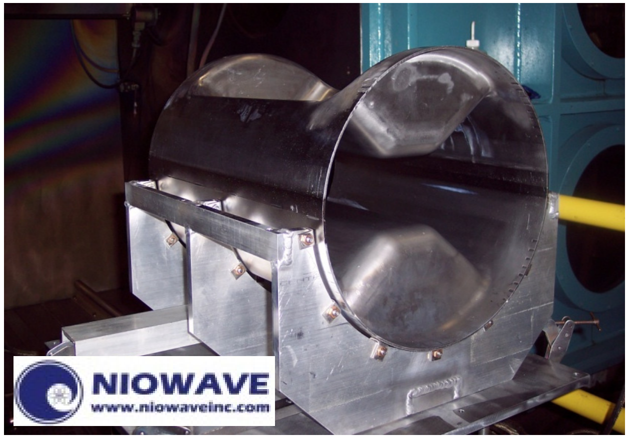
12 mm Electrode Gap

2.8 GHz crabbing cavities

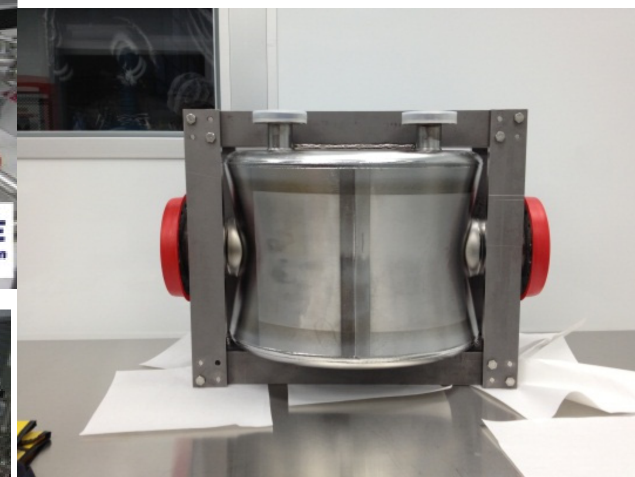
50 mm Aperture



400 MHz RF-Dipole Cavity Fabrication

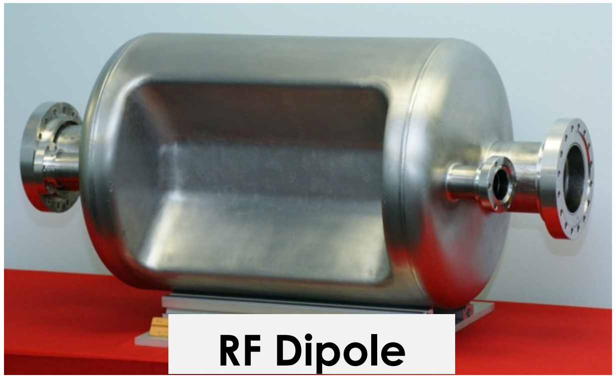


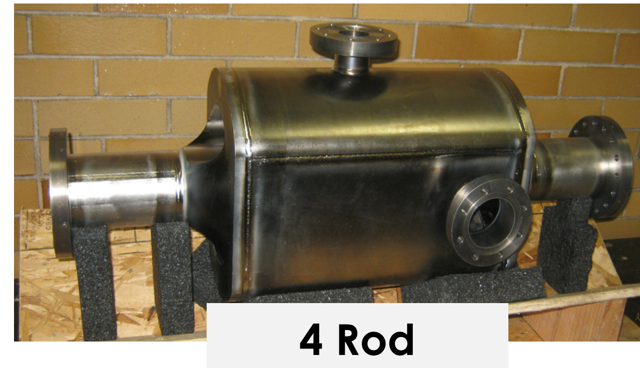
400 MHz Double Quarter-Wave Cavity Fabrication

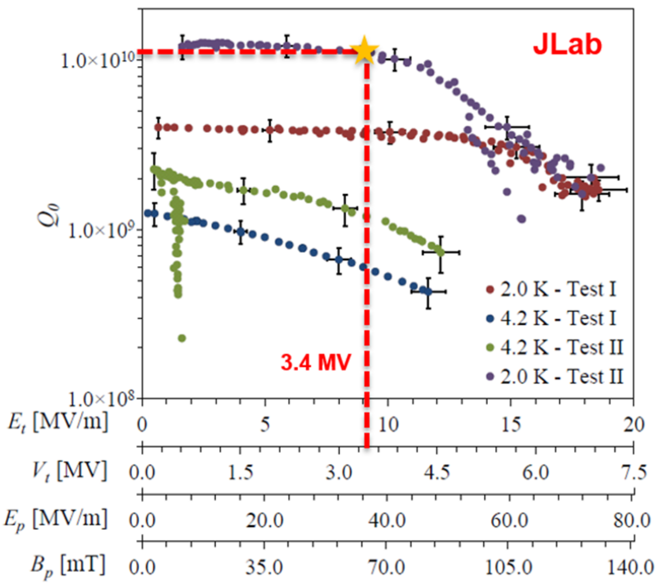


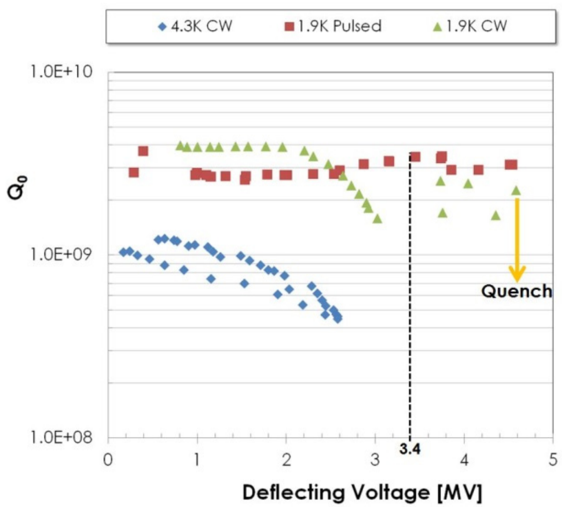
400 MHz 4-Rod Cavity Fabrication

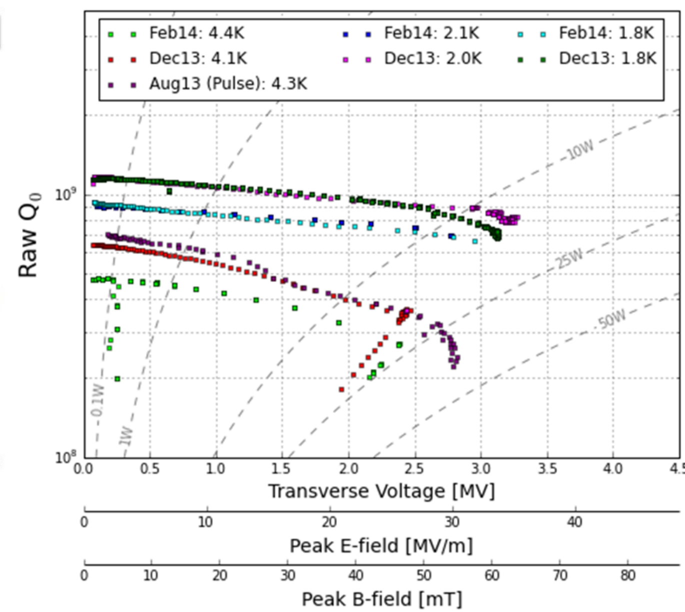
RF Tests of 400 MHz Proofs-of-Principle Cavities





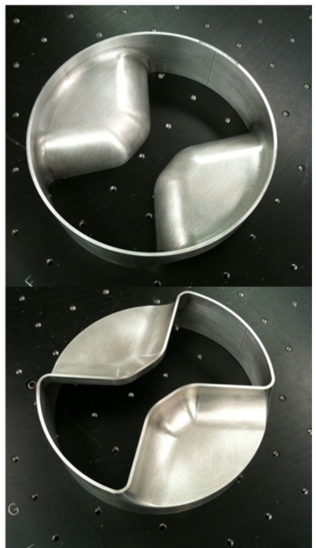


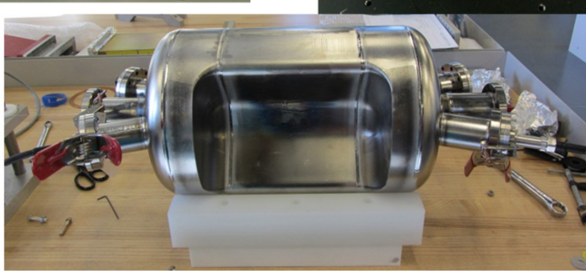
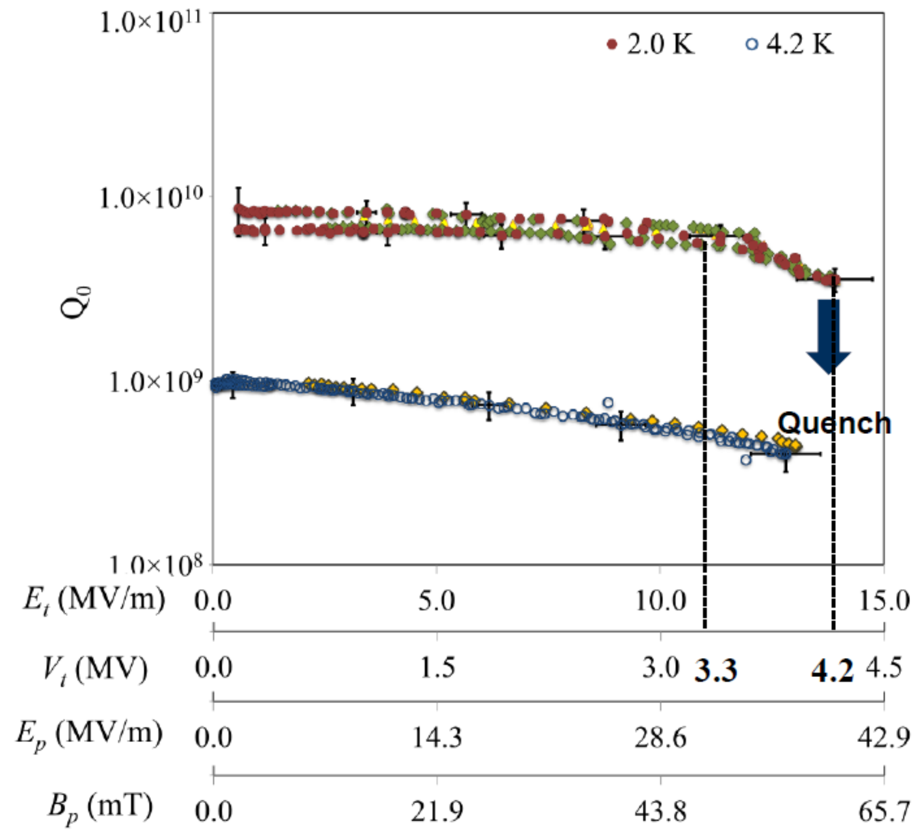




RF Test of 499 MHz Deflecting Cavity

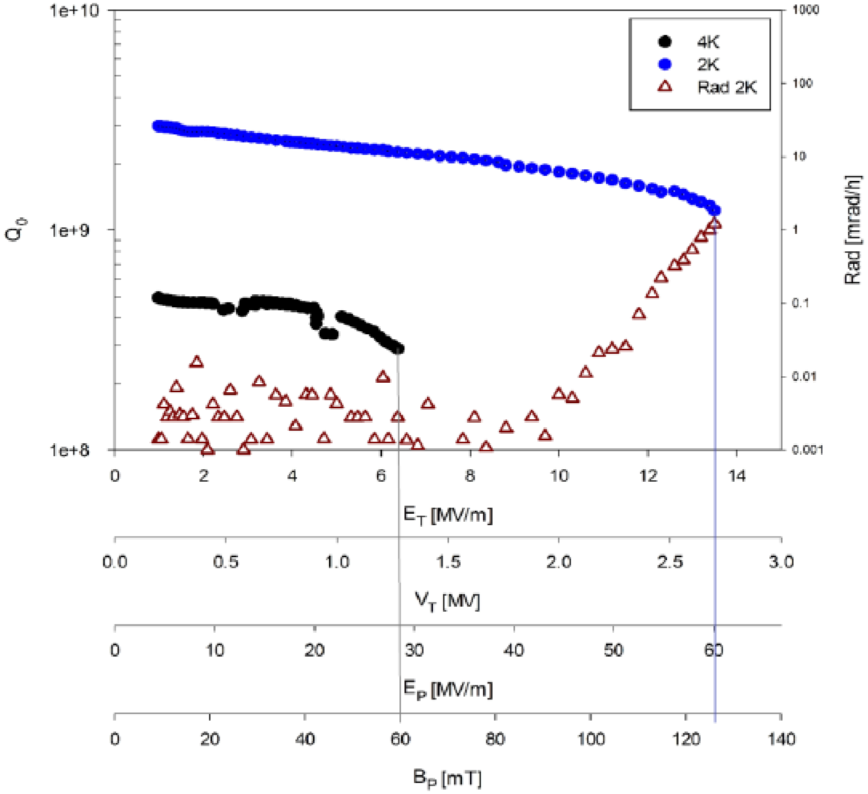
- Proof-of-principle cavity designed as the rf separator for Jefferson Lab 12 GeV upgrade
- Fabricated at Jefferson Lab – HyeKyoung Park (JLab)

RF Test of 750 MHz Crabbing Cavity

- Proof-of-principle cavity designed initial frequency for Jefferson Lab MEIC
- Dissertation – Alex Castilla (ODU)

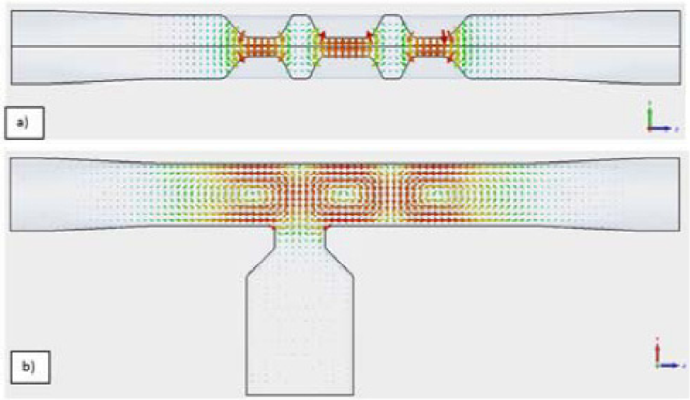


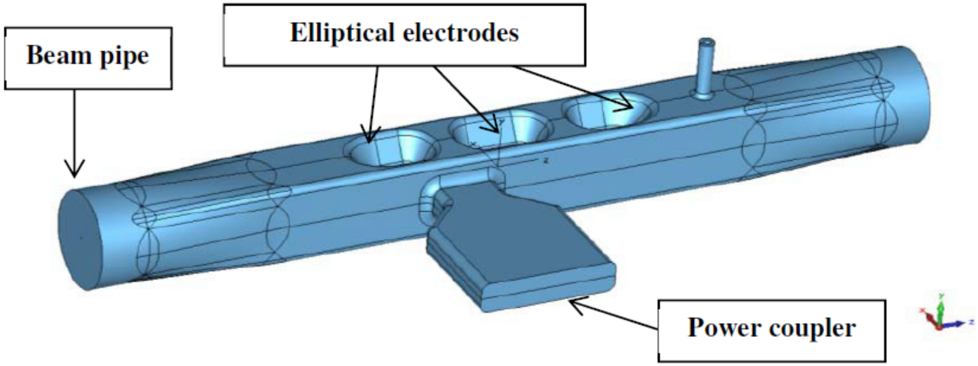
$$E_T = 13.5\ MV/m$$
$$V_T = 2.7\ MV$$
$$E_P = 60\ MV/m$$
$$B_P = 126\ mT$$

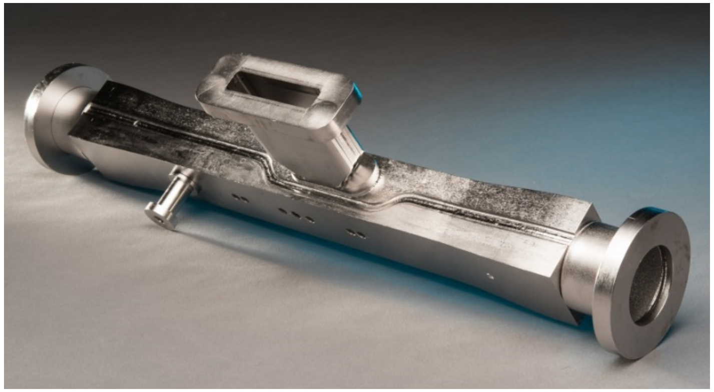
Multi-Cell Deflecting Cavity ANL/FNAL

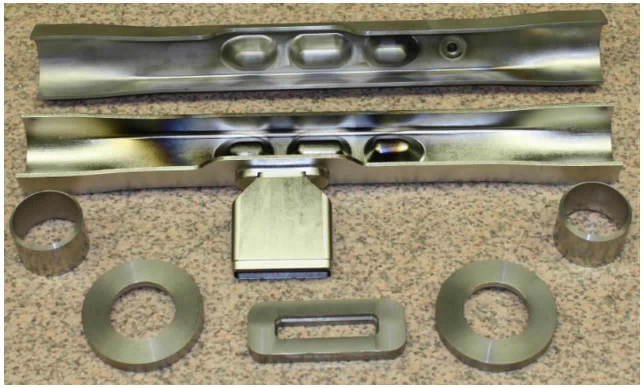
- A prototype superconducting (SC) cavity has been built to demonstrate the feasibility of this concept, QMiR (Quasi-waveguide Multi-cell Resonator)
- Deflecting electromagnetic mode trapped in a waveguide

Courtesy Zack Conway, ANL







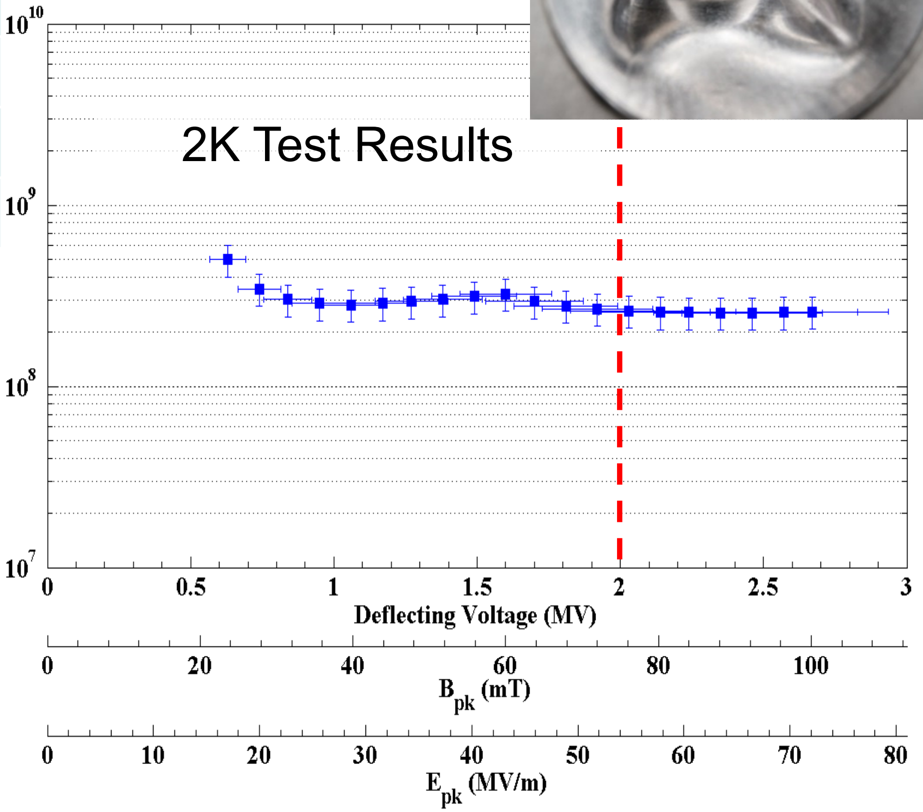


Multi-Cell Deflecting Cavity ANL/FNAL

Cavity Type	Deflecting
Frequencies	2815 (π), 2696 ($2\pi/3$), 2509 ($\pi/3$) MHz
Design Kick	2 MV
E_{peak}/V_{def}	27 m^{-1}
B_{peak}/V_{def}	37.5 mT/MV
G	130 Ω
$(R_{sh}/Q)_y$	1042 Ω

- A very high shunt impedance = 1 QMiR ~ 1000 Ω = Lower cryogenic load, lower cavity count and lower real-estate length requirements along a beam line
- The waveguide cut-off frequency allows for the propagation of all higher order mode power out via the beam pipes to room temperature loads. Eliminates complex HOM extraction couplers

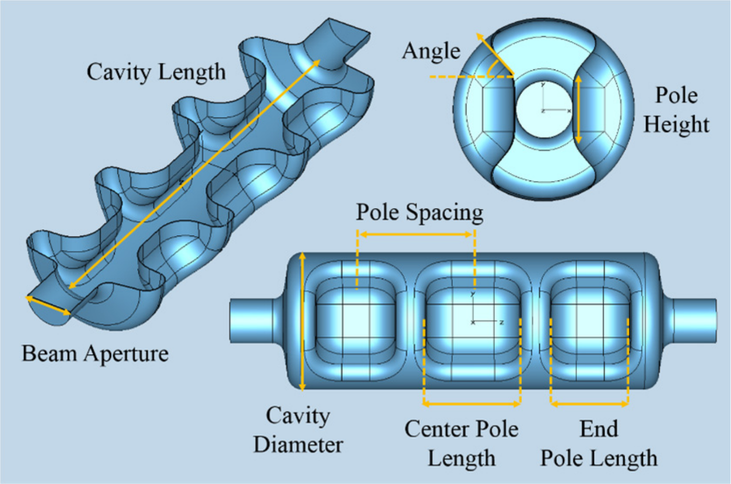
12 mm Electrode Gap

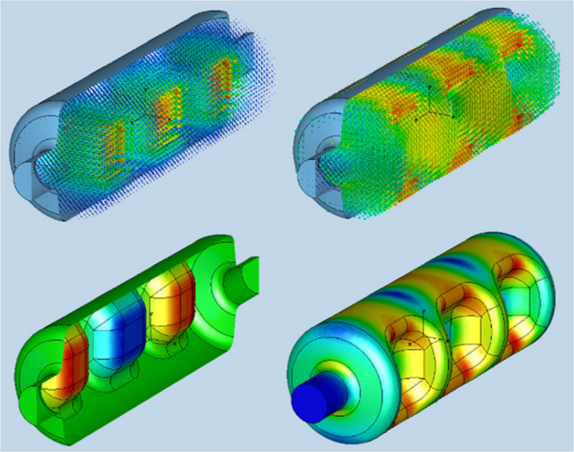


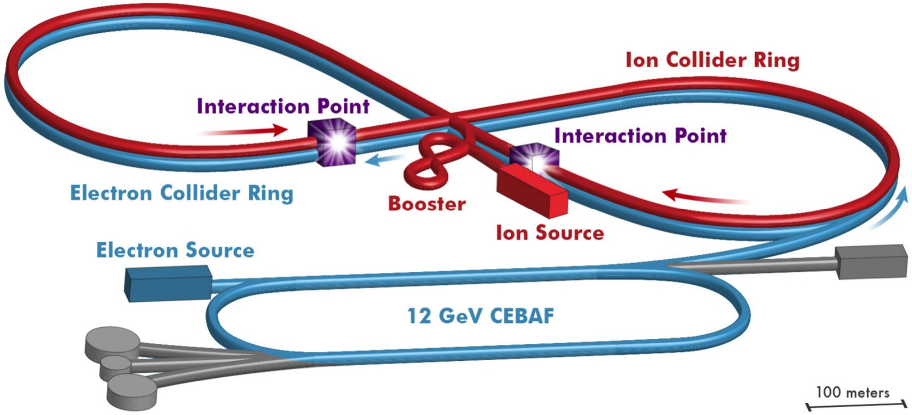
Courtesy Zack Conway, ANL

952.6 MHz Multi-Cell Cavity for JLEIC

- A 3-cell design for Jefferson Lab Electron-Ion Collider

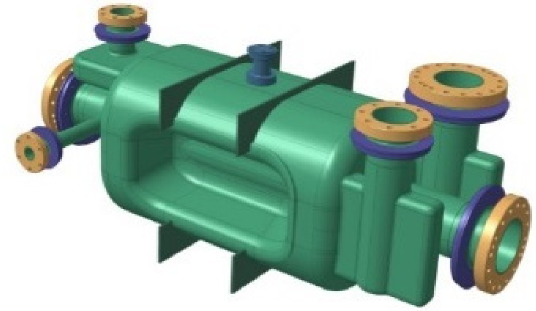




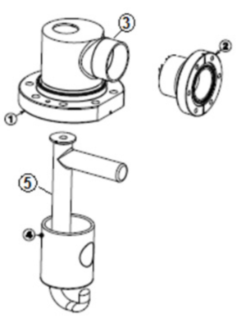


Frequency	952.6			MHz
Aperture	50	60	70	mm
LOM	790, 879	773, 870	757, 862	MHz
1st HOM	1409	1383	1335	MHz
V_t^*	0.157			MV
E_p^*	4.7	5.1	5.6	MV/m
B_p^*	8.7	10.0	11.4	mT
$[R/Q]_t$	494	323	219	Ω
G	161	170	179	Ω
R_tR_s	8.0×10^4	5.5×10^4	3.9×10^4	Ω^2
$^* E_t = 1$ MV/m				

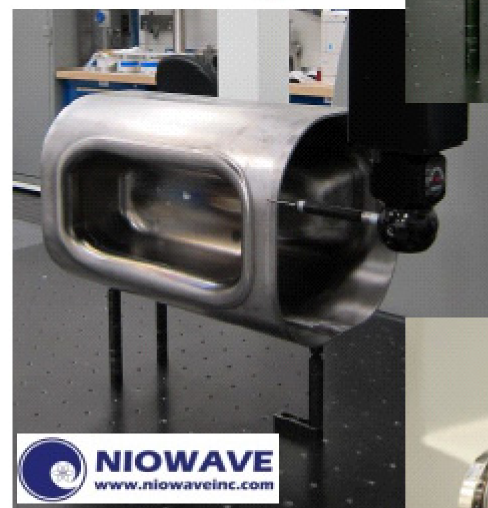
Cavity and HOM Couplers Fabrication

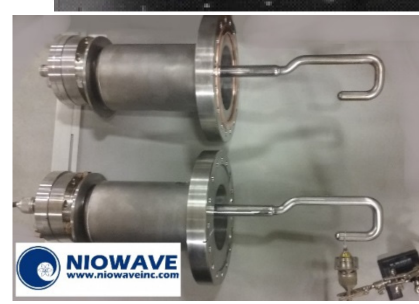


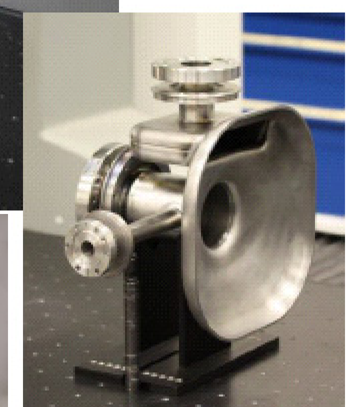
Fabrication at CERN



Fabrication at Niowave Inc.

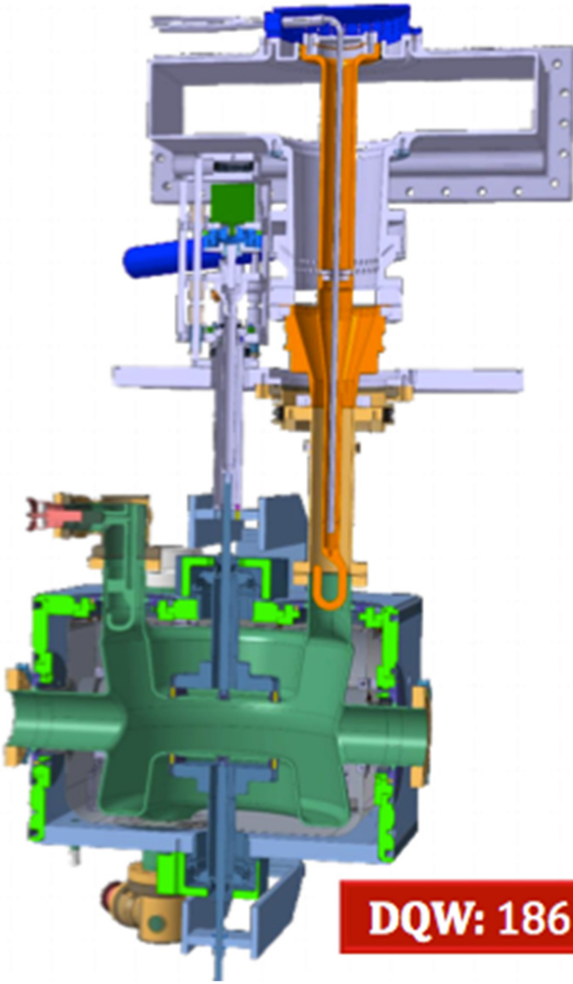


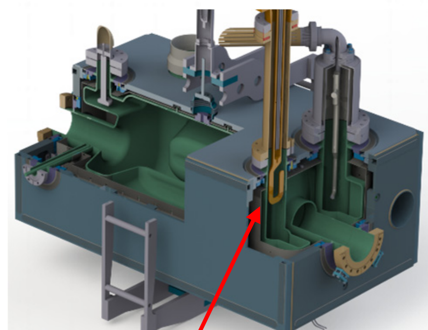




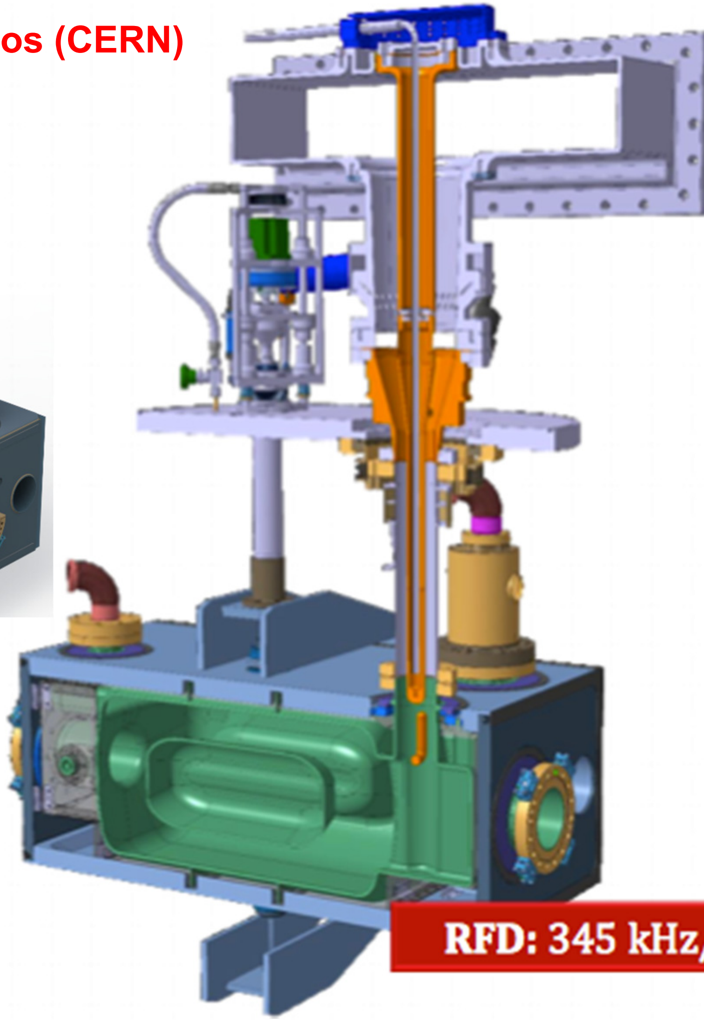
Tuner Engineering

Courtesy – Kurt Artoos (CERN)





Fundamental Power Coupler

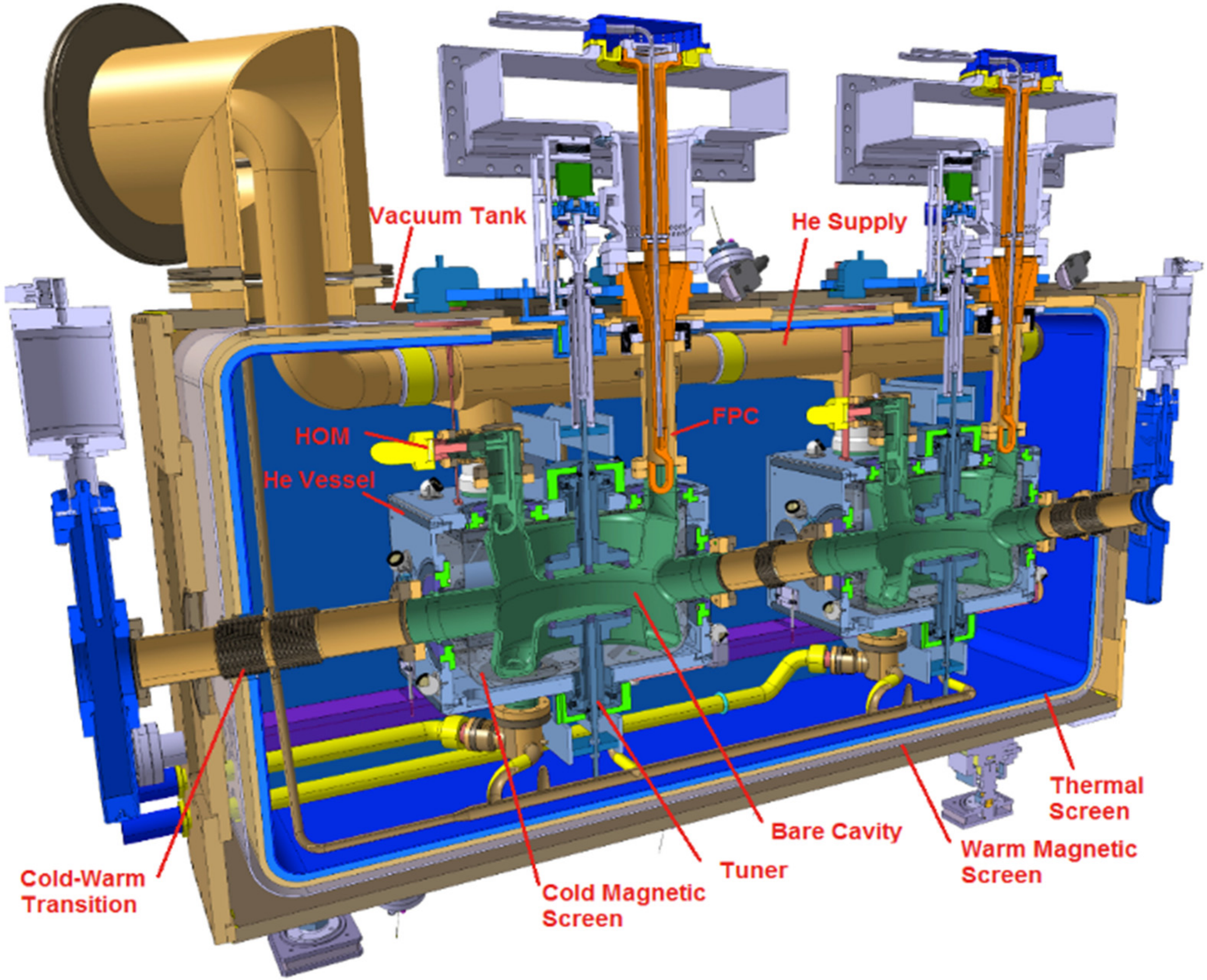


DQW: 186 kHz/mm

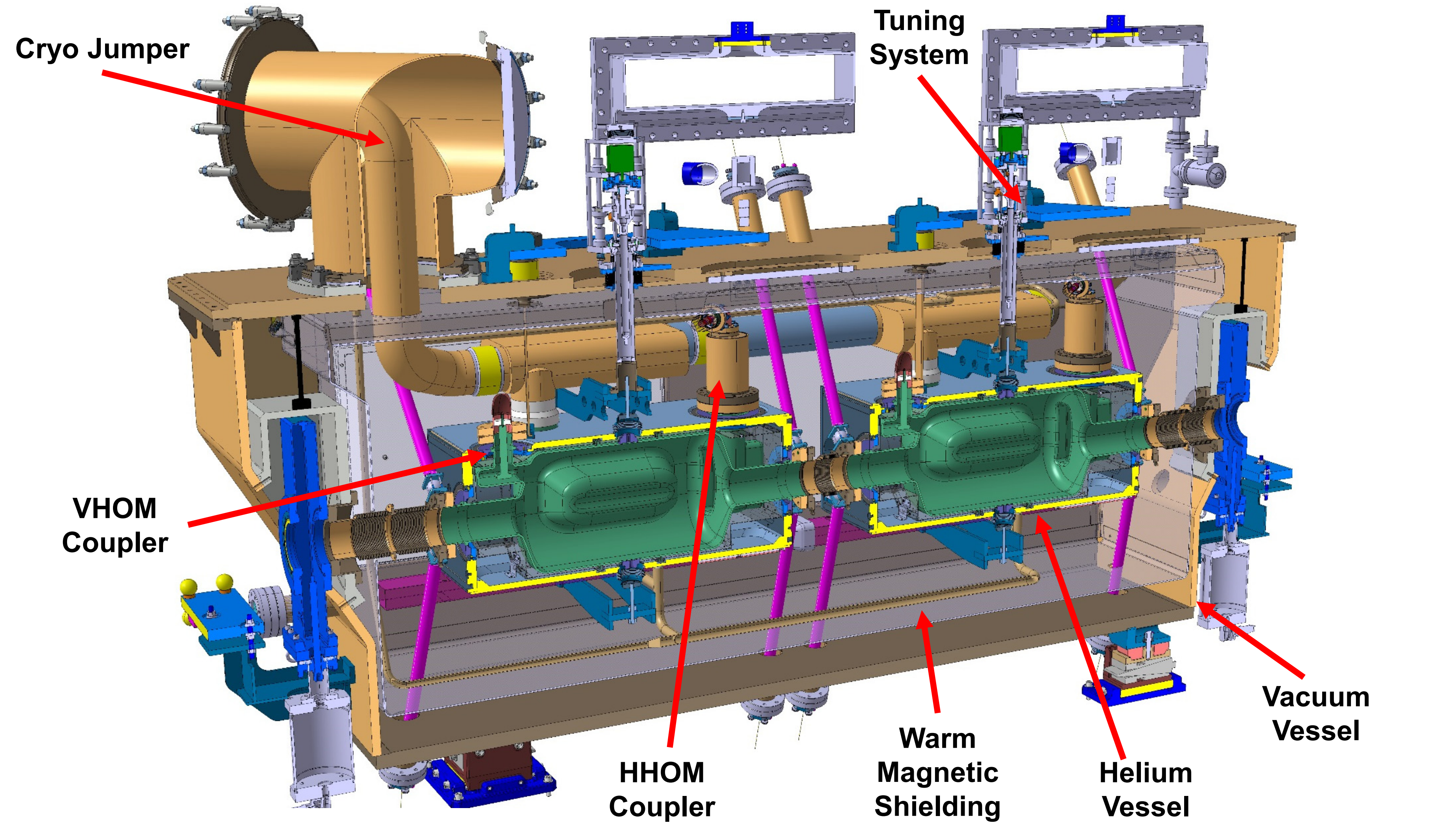
RFD: 345 kHz/mm

Tuner sensitivity with 0.5 mm deflection each side

Integration into Cryomodule for SPS (DQW)



Integration into Cryomodule for SPS (RFD)



Summary

- KEK crabbing cavity – First demonstration of successful implementation and operation of a superconducting crabbing cavity
- No crabbing cavity has been demonstrated on a machine with a proton beam
- Promising compact crabbing cavity designs
  - Concept has been successfully tested with Proof-of-Principle cavities
  - Improved prototype cavity designs for LHC High Luminosity Upgrade
- Prototype engineering and testing at SPS and LHC
  - First SPS cryomodule test is planned for 2018
  - Cavities, couplers, He vessel are under fabrication for SPS cryomodule
  - Cryomodule designing for LHC is ongoing
- Deflecting/crabbing mode cavities have wide range of applicability and are key for the success of a number of future accelerators for high-energy physics, nuclear physics and light sources

Acknowledgements

- ODU – Jean Delayen, HyeKyoung Park, Rocio Olave, Alex Castilla
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- CERN
  - Rama Calaga, Ofelia Capatina, Raphael Leuxe, Carlo Zanoni, Teddy Capelli and the team
  - Benoit Salvant, Nic Biancacci
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- LBNL – Alex Ratti