SRF2015
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RF Superconductivity
Whistler Conference Centre
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RECENT DEVELOPMENTS IN SUPERCONDUCTING DEFLECTING-MODE CAVITIES

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Outline

- A bit of history
- TM_{110} –class cavities
- New geometries and concepts
  - "TEM-like" cavities
  - "TE-like" cavities
  - Their properties
    - Dependence of frequency and velocity on external dimensions
    - Lower- and higher-order modes and couplers
    - Multipacting
    - Multipoles
    - Beamline aperture
- Proofs-of-principle demonstrations and results
- Design and engineering of prototypes

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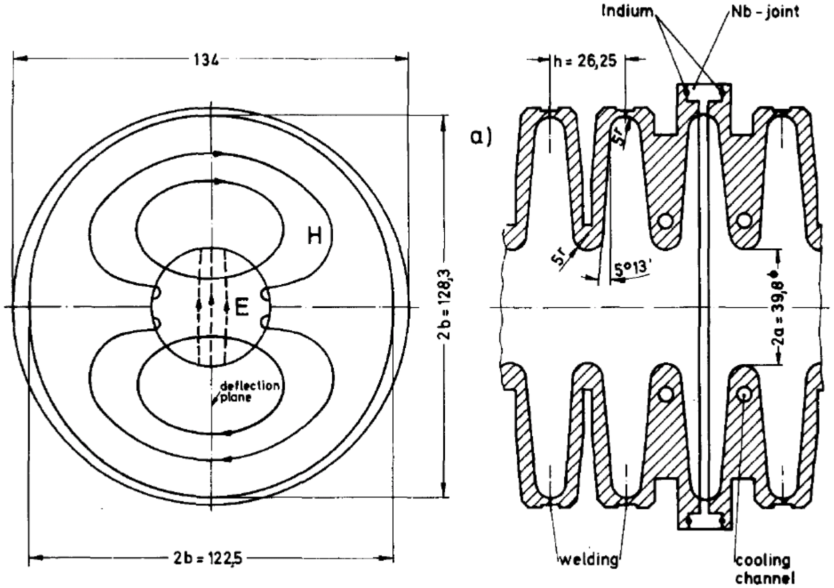
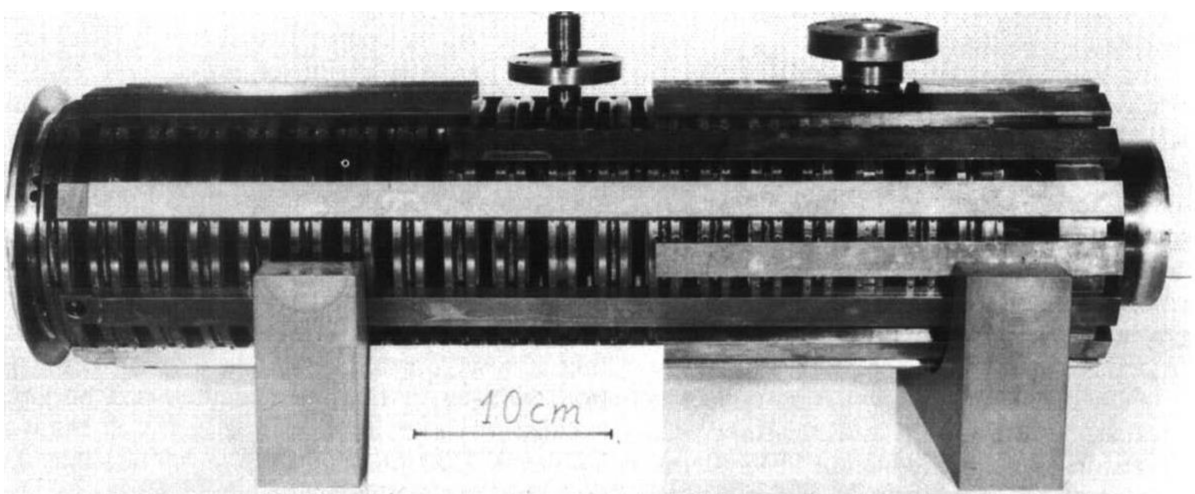
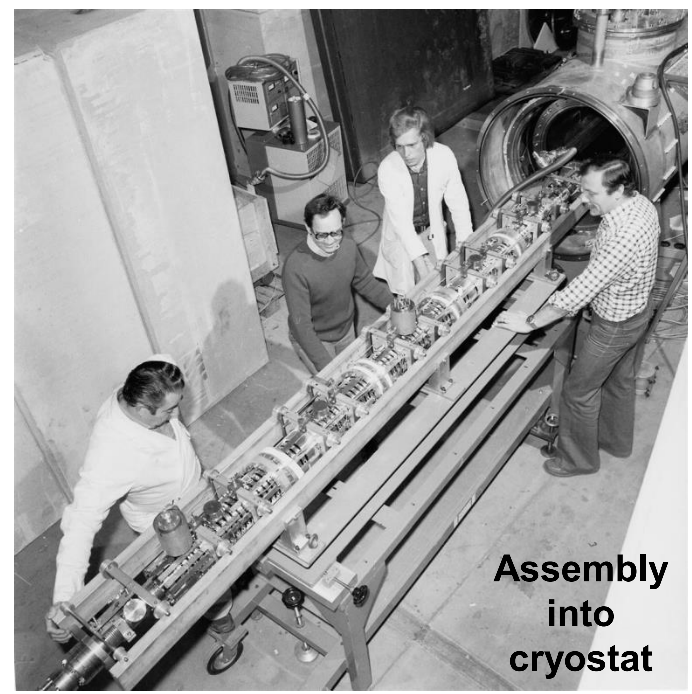
The 1st Superconducting RF Deflecting Cavity



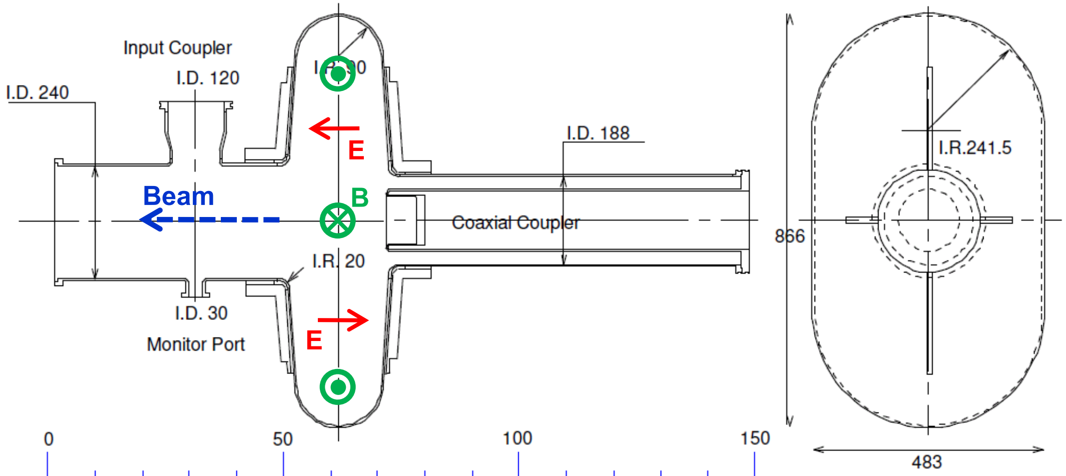
2.865 GHz Karlsruhe/CERN RF Separator*

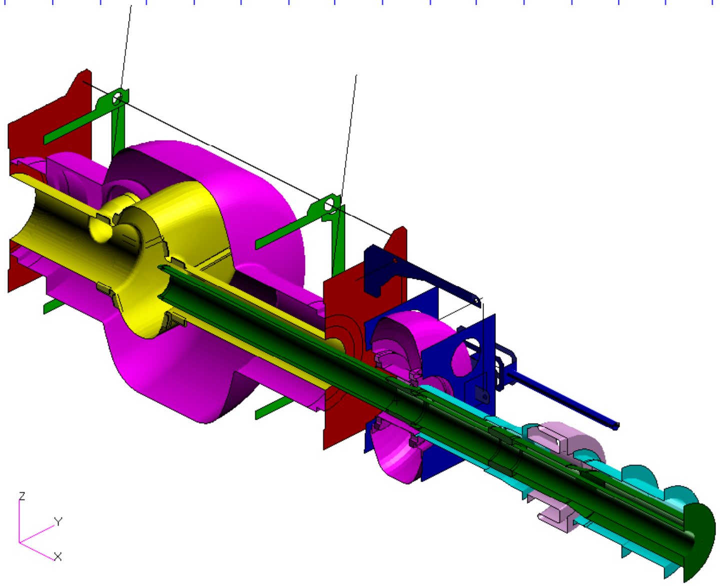
- Designed 1970, operated 1977-1981
- 104 cells
- At IHEP since 1998
- Operating mode: bi-periodic TM_{110} mode





The 1st Superconducting Crabbing Cavity





Complex HOM Damping Scheme

KEK Crabbing Cavity*

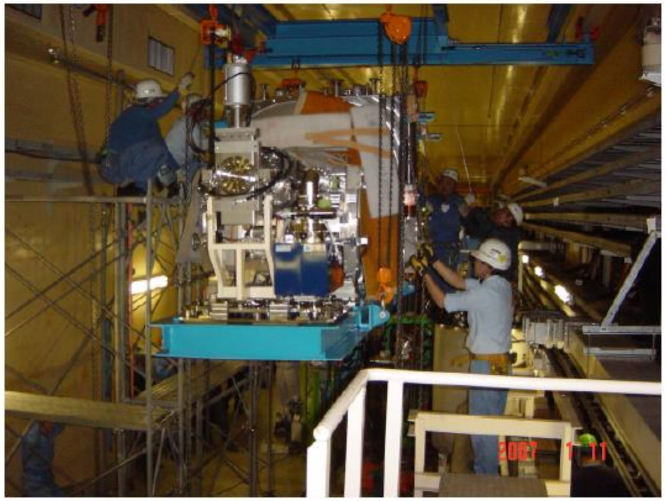
Frequency	**508.9**	**MHz**
LOM	410.0	MHz
Nearest HOMs	630.0, 650.0, 680.0	MHz
E_p^*	4.24	MV/m
B_p^*	12.23	mT
B_p^*/E_p^*	2.88	mT/(MV/m)
$[R/Q]_T$	48.9	Ω
Geometrical Factor (G)	227.0	Ω
$R_T R_S$	1.11×10^4	Ω^2
At $E_T^* = 1$ MV/m		

- Operating mode: TM_{110} mode
- Required transverse deflection: 1.44 MV
- Operation: 2007-2010

Some History (KEK)

Installation of Crab Cavities
for HER Jan. 8, 2007,
for LER Jan. 11, 2007

Crab Cavity for HER



Carrying the Crab cavity using crane track

Cool-down of Crab Cavities
Jan. 29 , 2007
Beam Operation Start
Feb. 13

Crab Cavity for LER

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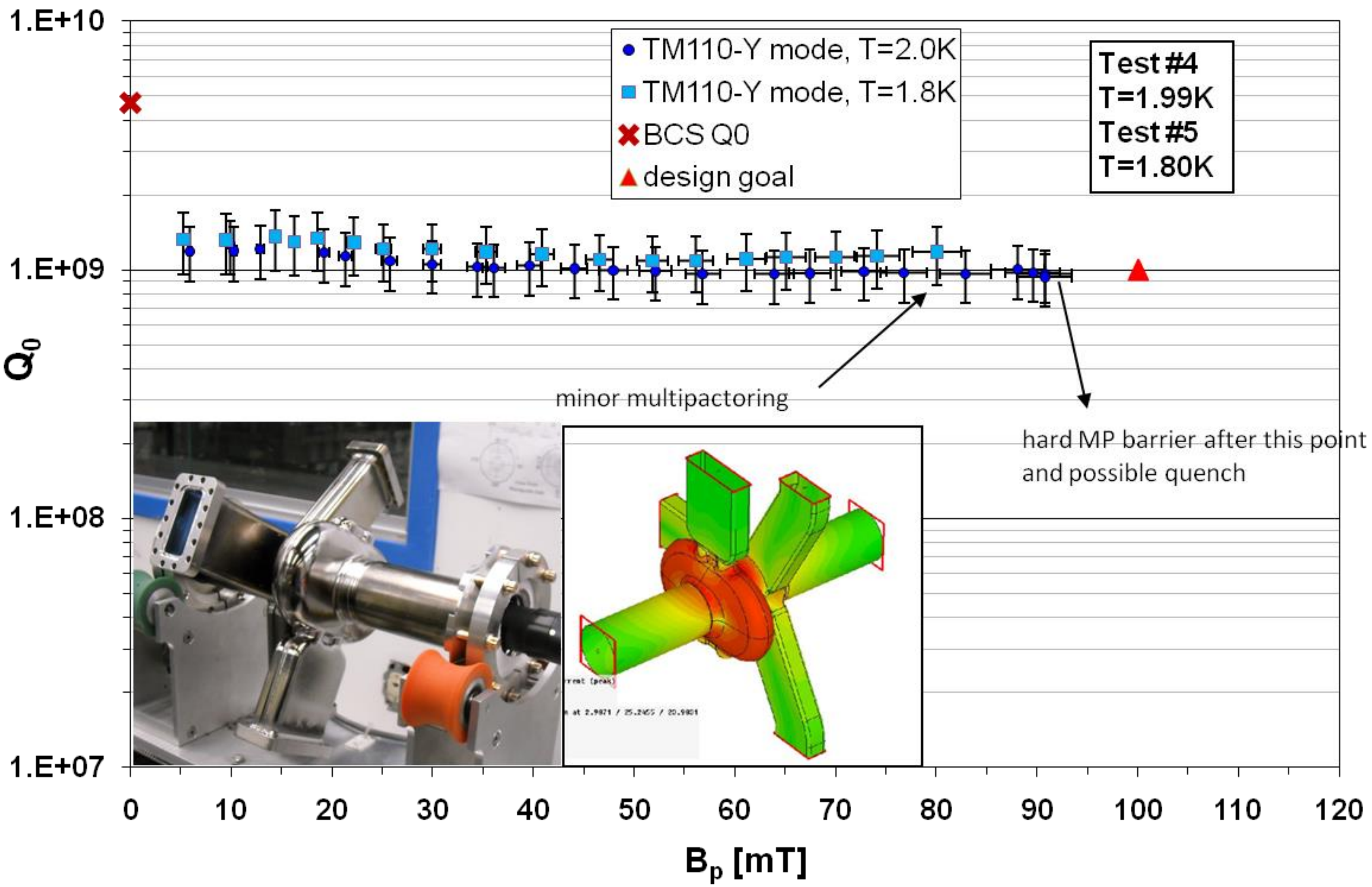
Features of TM_{110} Deflecting/Crabbing Cavities

- Deflection mostly through interaction with H-field
- Presence of lower-order mode (TM_{010})
- TM_{110} mode would be 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
  - Multipoles
- Relatively low real estate gradient
  - Couplers on beam line

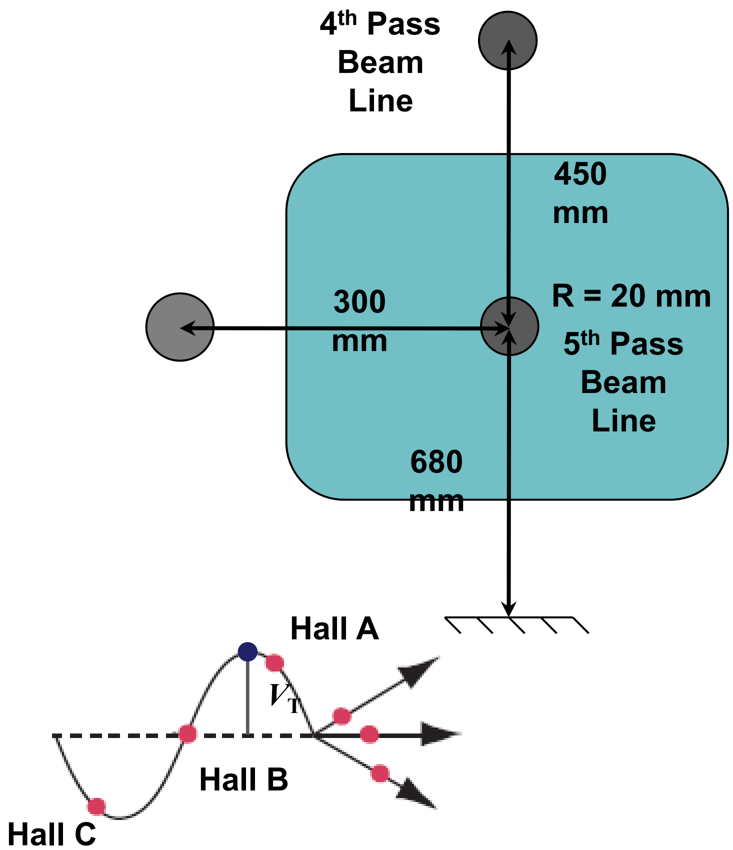
JLab/ANL 2.8 GHz TM_{110} Cavity

"Alternate" Prototype Crab Cavity (CC-A2 for SPX Project) Vertical Test at JLab

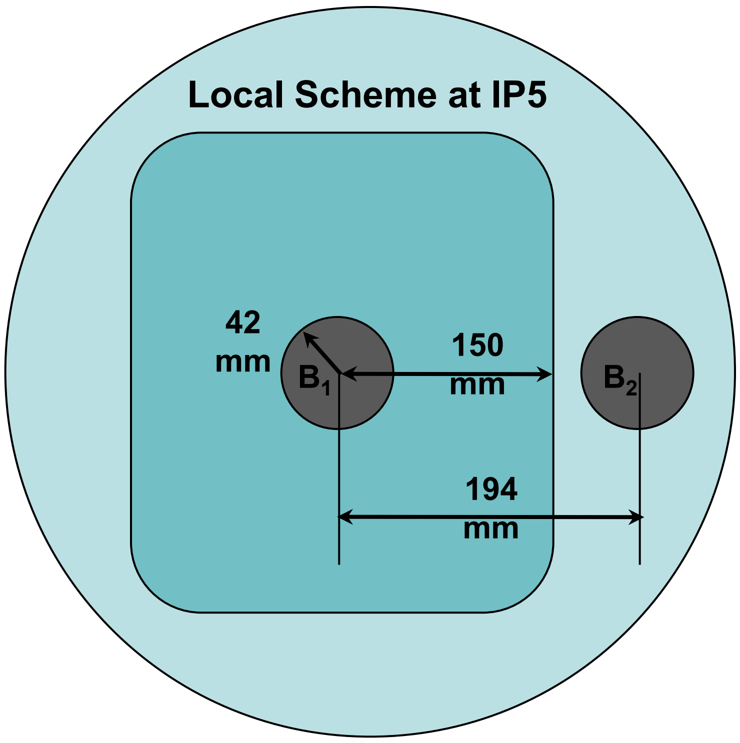


Dimensional Constraints

499 MHz Deflecting Cavity for JLab Upgrade



400 MHz Crabbing Cavity for LHC



Global scheme :
Separation between beam pipes – 420 mm

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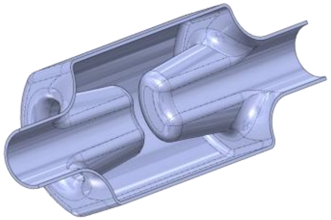
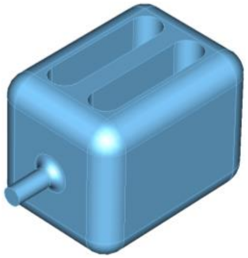
New Geometries and Concepts

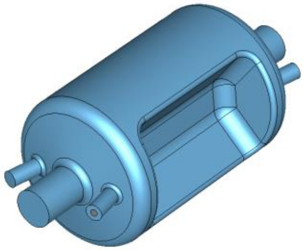
- Cavities operating in "TEM-like" modes
  - 4-rod cavity
    - 4 quarter-wave resonators (deflection from both E and H)

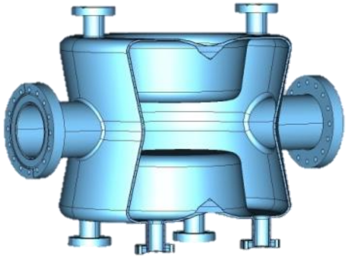


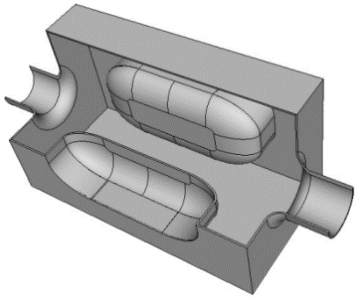
  - Parallel-bar
    - 2 half-wave resonators (deflection from E)
    - Evolved into rf-dipole



- Cavities operating in "TE-like" mode (cannot be pure TE)
  - Rf-dipole
  - Double quarter-wave
  - Ridged waveguide



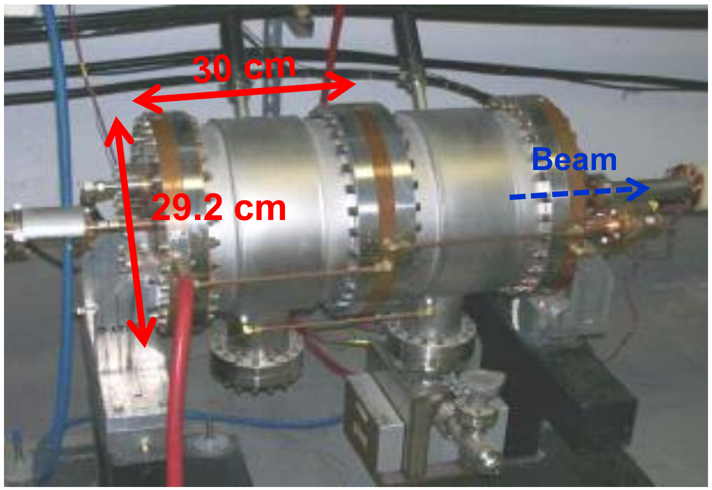


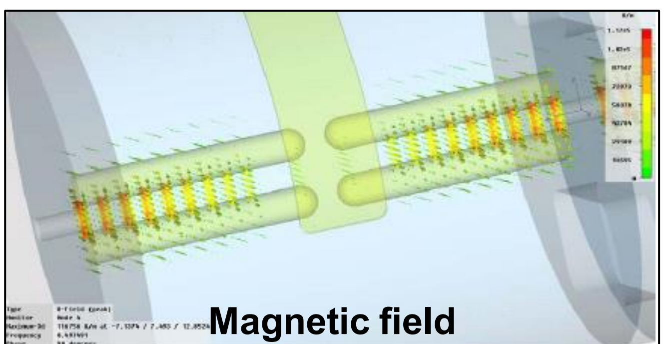


4-Rod Cavity

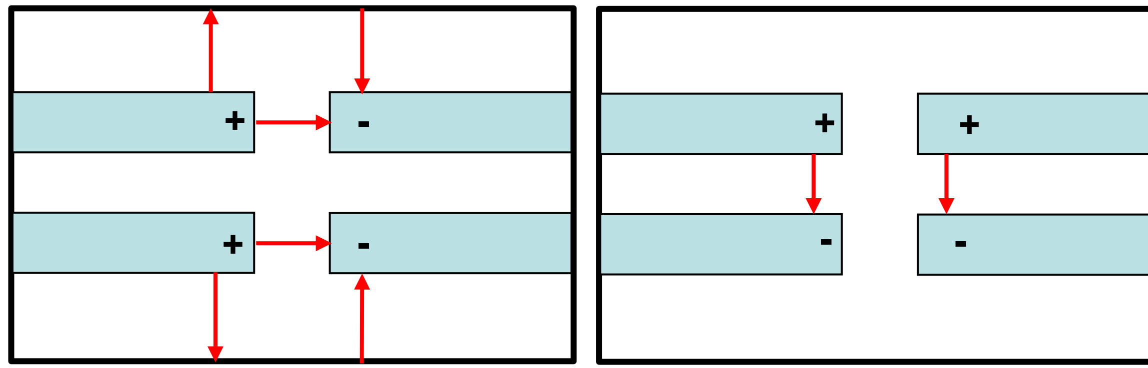
- 499 MHz normal conducting rf separator* at Jefferson Lab
- High shunt impedance

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

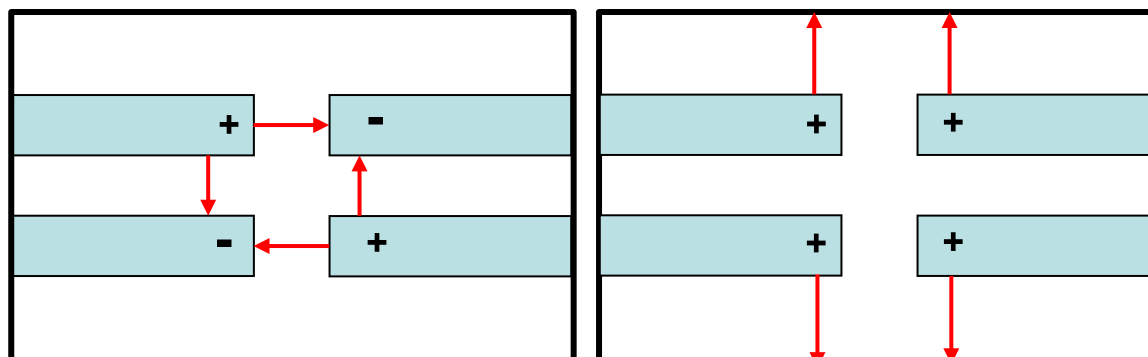




Magnetic field



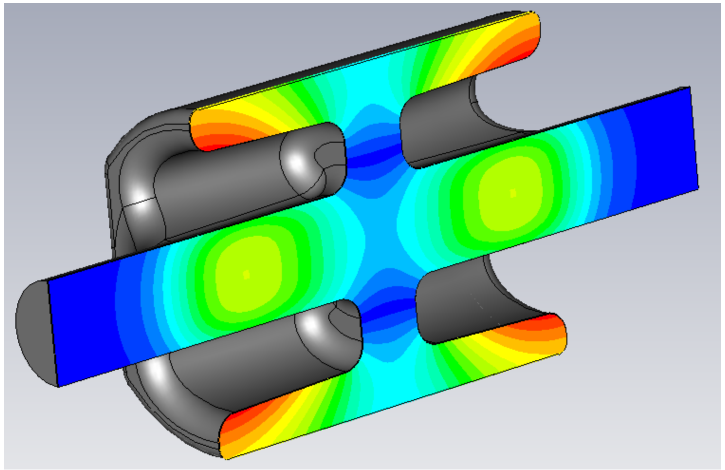
Accelerating lower order mode



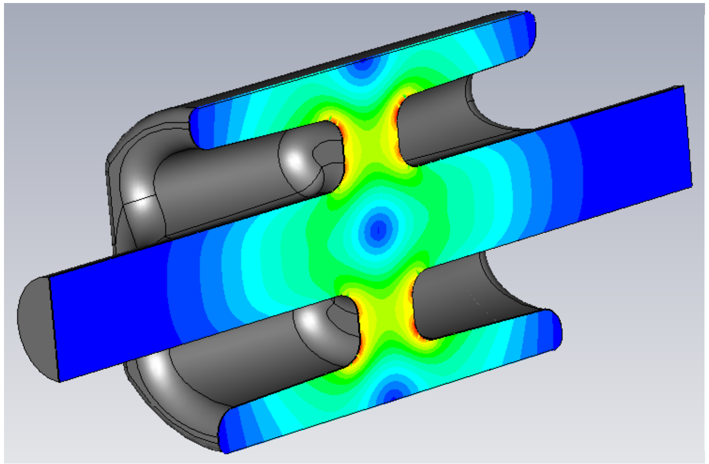
Fundamental deflecting mode

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

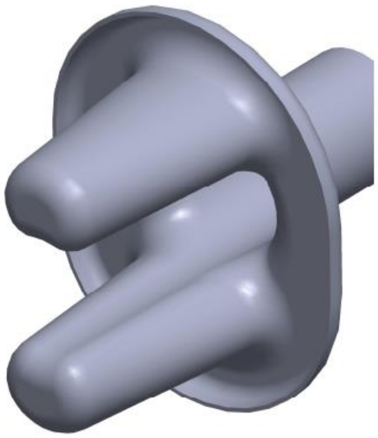
4-Rod Cavity (U. Lancaster/JLab)

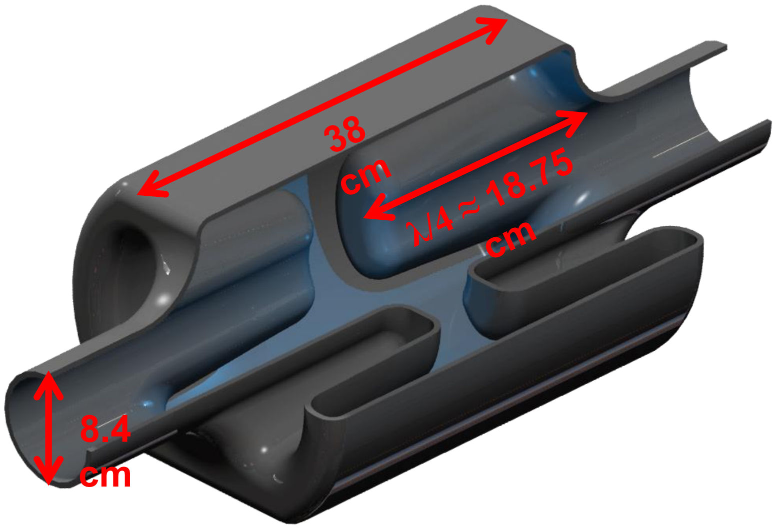


Magnetic Field



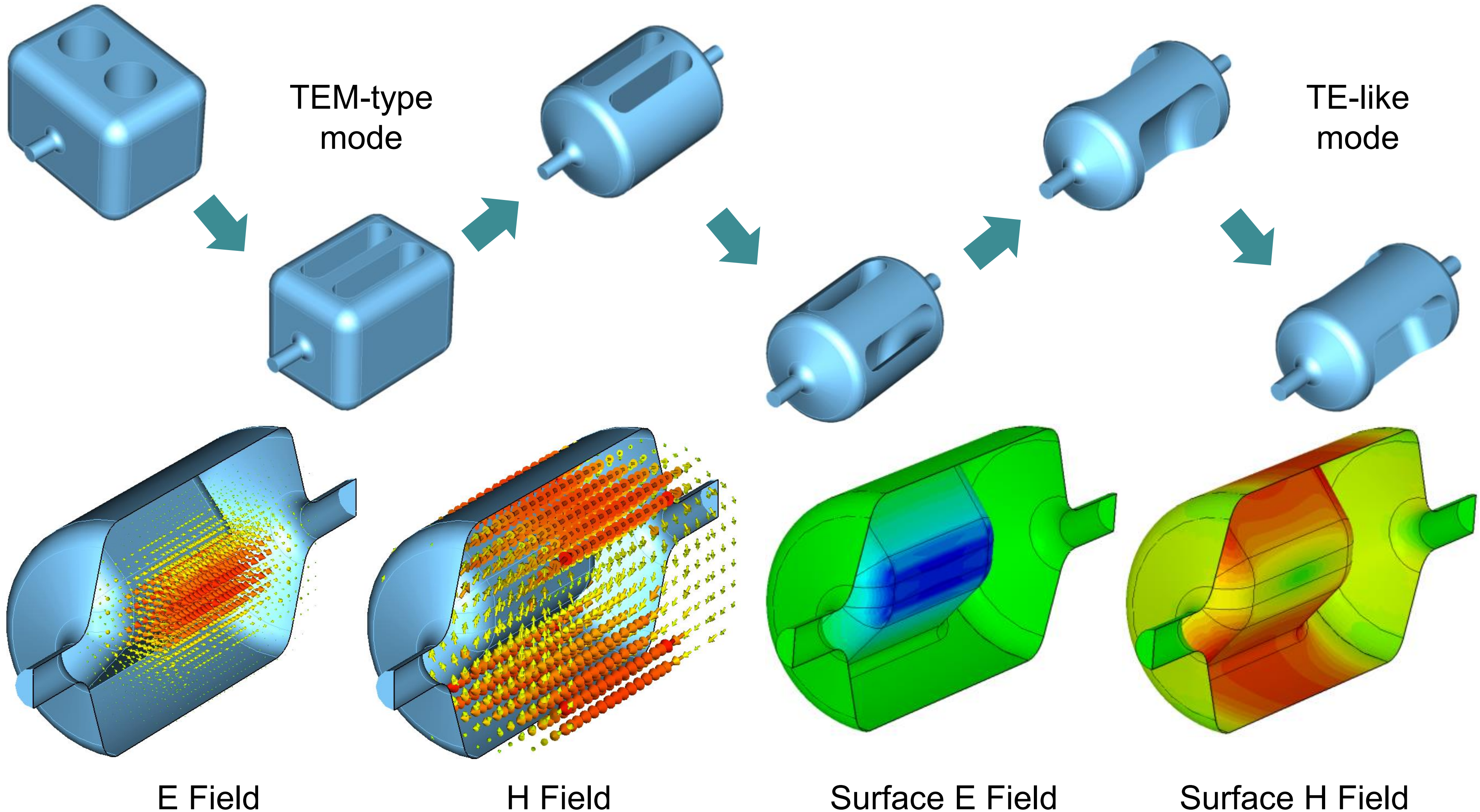
Electric Field





Emax @3MV	32.0 MV/m
Bmax @3MV	60.5 mT
Transverse R/Q	764.6 Ohms

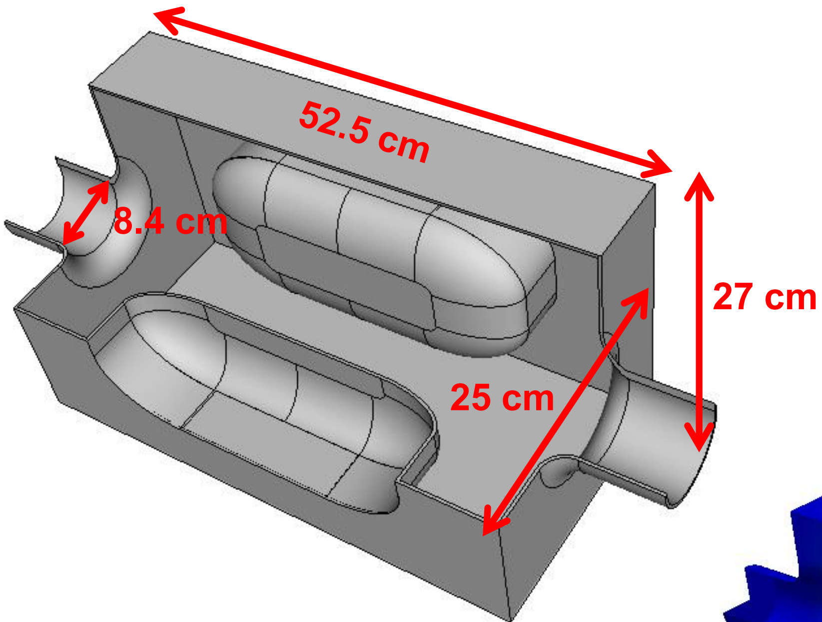
Parallel-Bar Cavity to RF-Dipole Cavity (ODU)



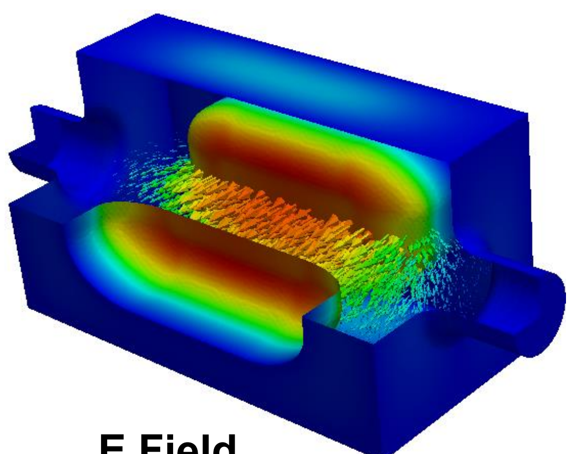
S. U De Silva and J. R. Delayen, “Design evolution and properties of superconducting parallel-bar rf-dipole deflecting and crabbing cavities, PRSTAB 16, 012004 (2013)
S. U. De Silva, PhD thesis, ODU 2014

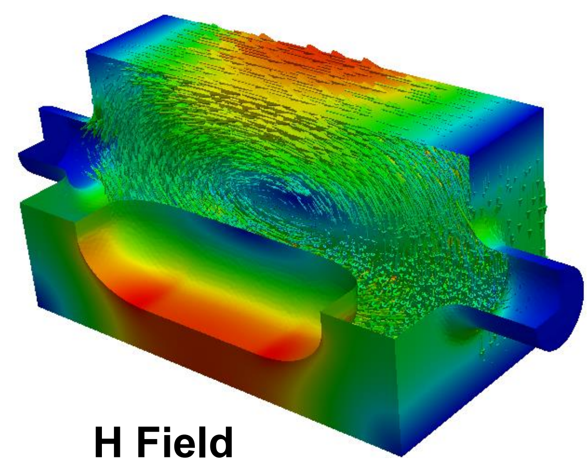
Ridged Waveguide Cavity (SLAC)

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



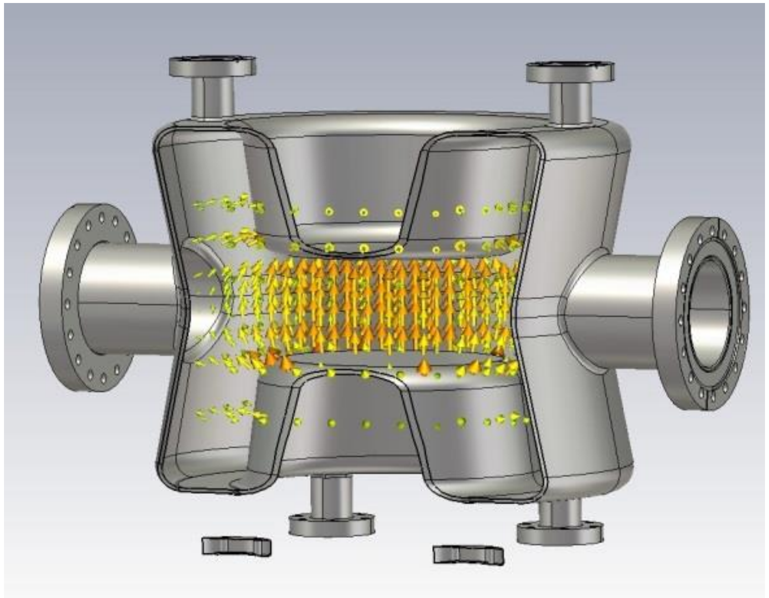
Frequency	400.0	MHz
LOM	None	MHz
Nearest HOM	617.0	MHz
E_p^*	3.38	MV/m
B_p^*	7.05	mT
B_p^*/E_p^*	2.09	mT/(MV/m)
$[R/Q]_T$	330.0	Ω
At $E_T^* = 1$ MV/m		

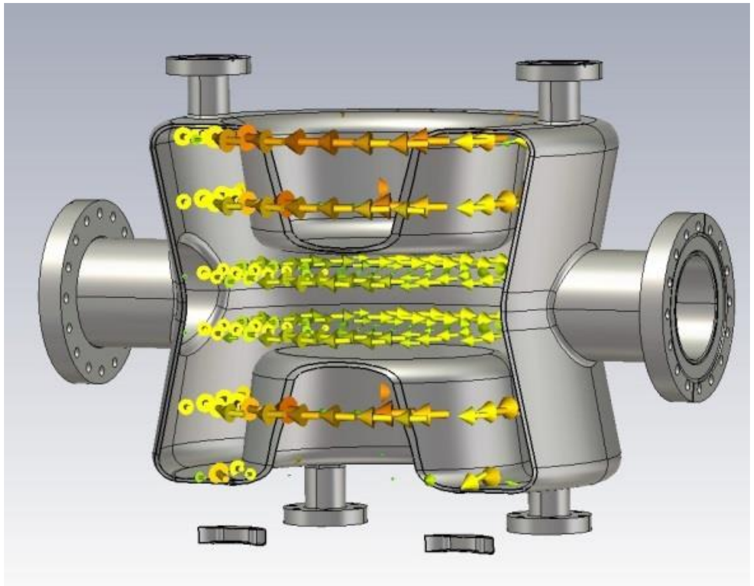

E Field


H Field

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

Double Quarter-wave (BNL)





Electric field (left) and magnetic field (right) of the fundamental mode.

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

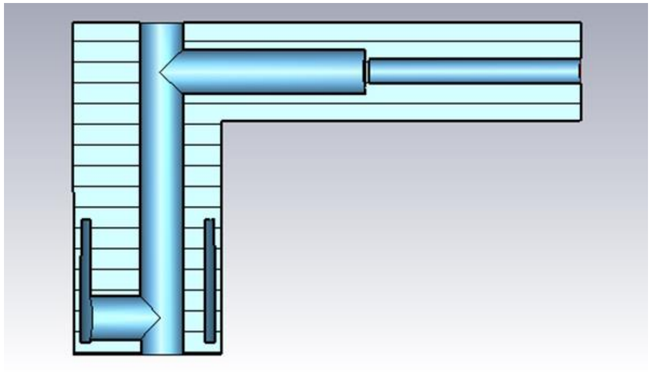
Dimension-dependent Properties

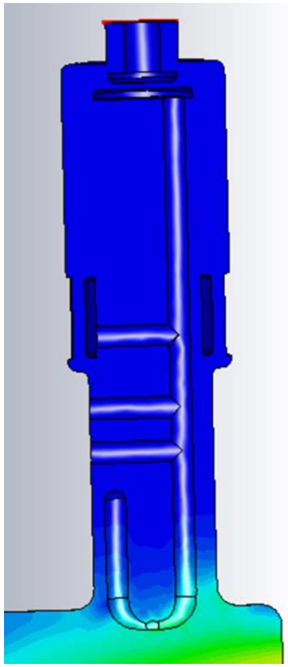
- 4-Rod
  - Frequency governed by longitudinal dimension (~ λ/2)
  - Frequency independent of transverse dimension
    - Could accommodate very low frequencies with small transverse size
  - "Matched" particle velocity related to longitudinal dimension
    - Limited to high-velocity particles

- Parallel-bar, "TE-like" cavities
  - Frequency governed by transverse dimension (~ λ/2)
    - Transverse size is frequency-dependent
  - Frequency independent of longitudinal dimension
  - "Matched" particle velocity related to longitudinal dimension (~ βλ/2)
    - Could accommodate low-velocity particles

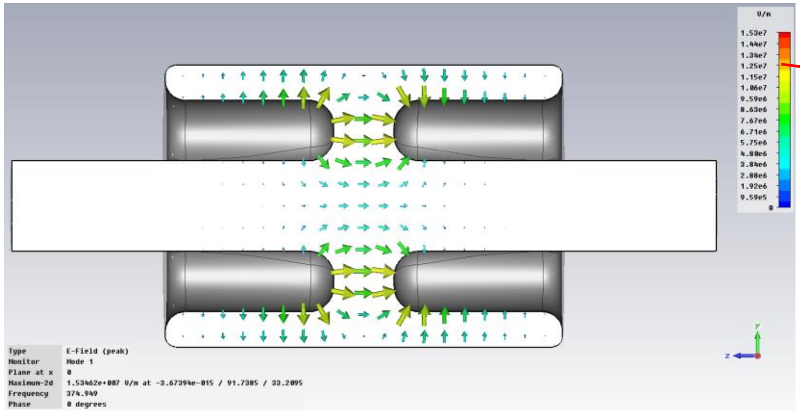
HOM Damping

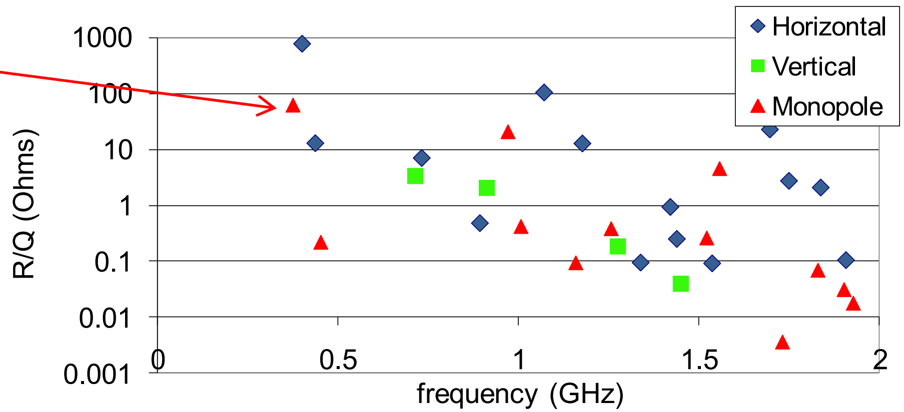
- "TEM-like" cavities (4-rod)
  - 4 same-order modes
  - Accelerating mode lower in frequency than fundamental deflecting mode
  - Other modes in close proximity
  - Need for notch-filters





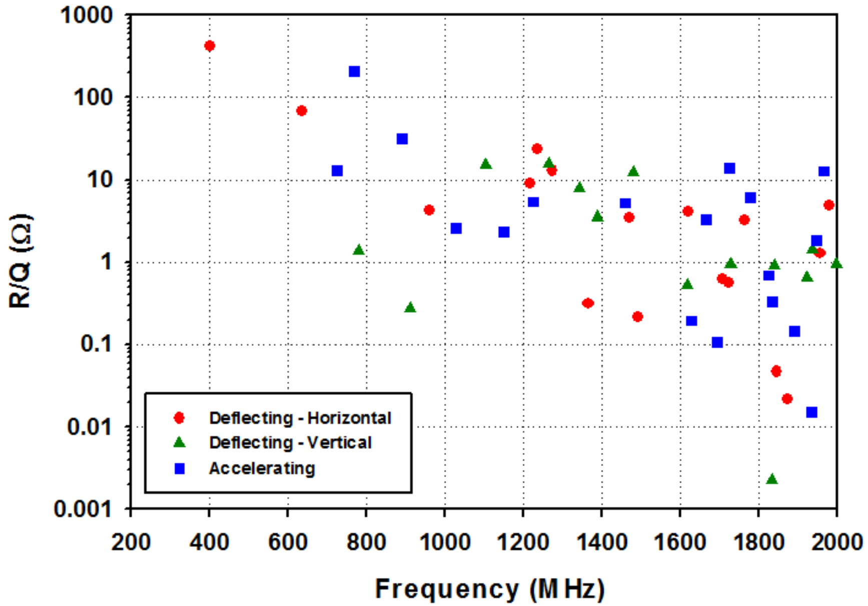
SOM Monopole

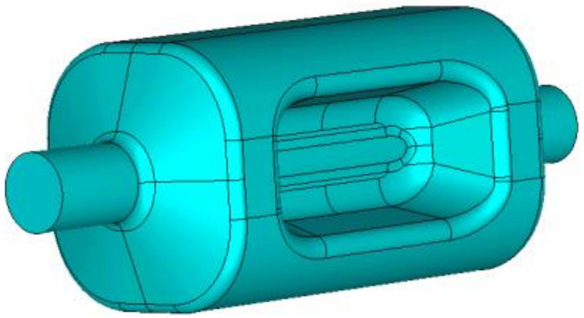




HOM Damping

- "TE-like" cavities (RFD and DQW)
  - No lower-order mode
  - Frequency of first HOM is about 1.5 that of fundamental deflecting mode

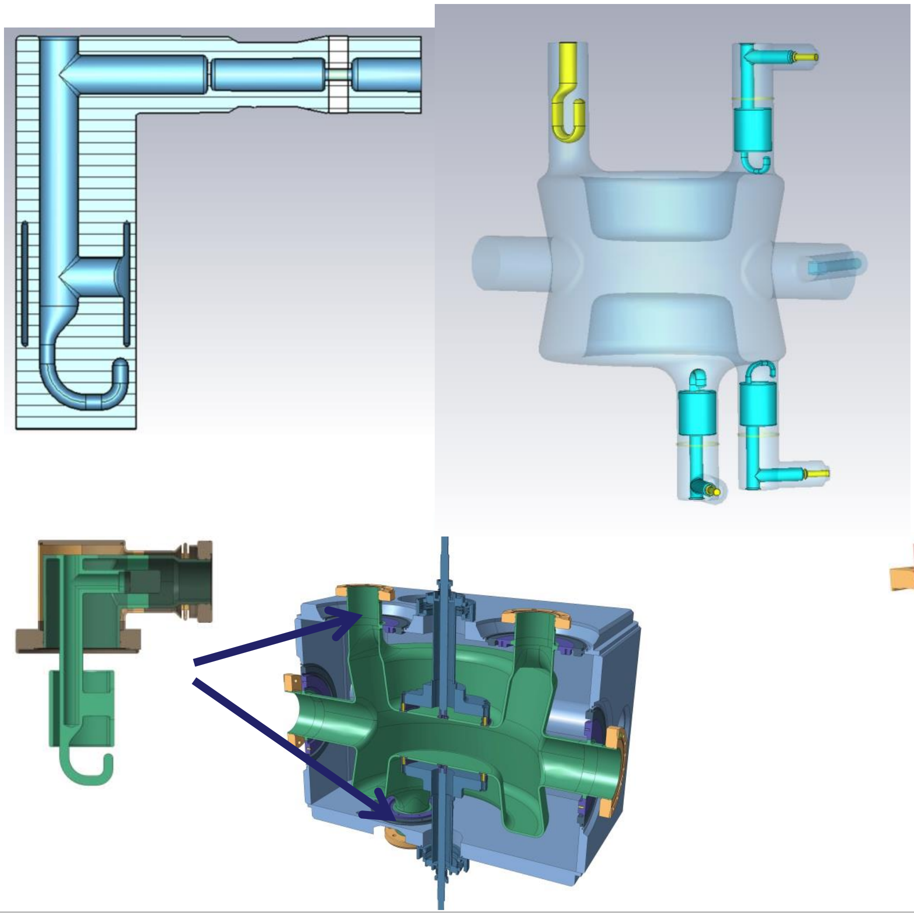




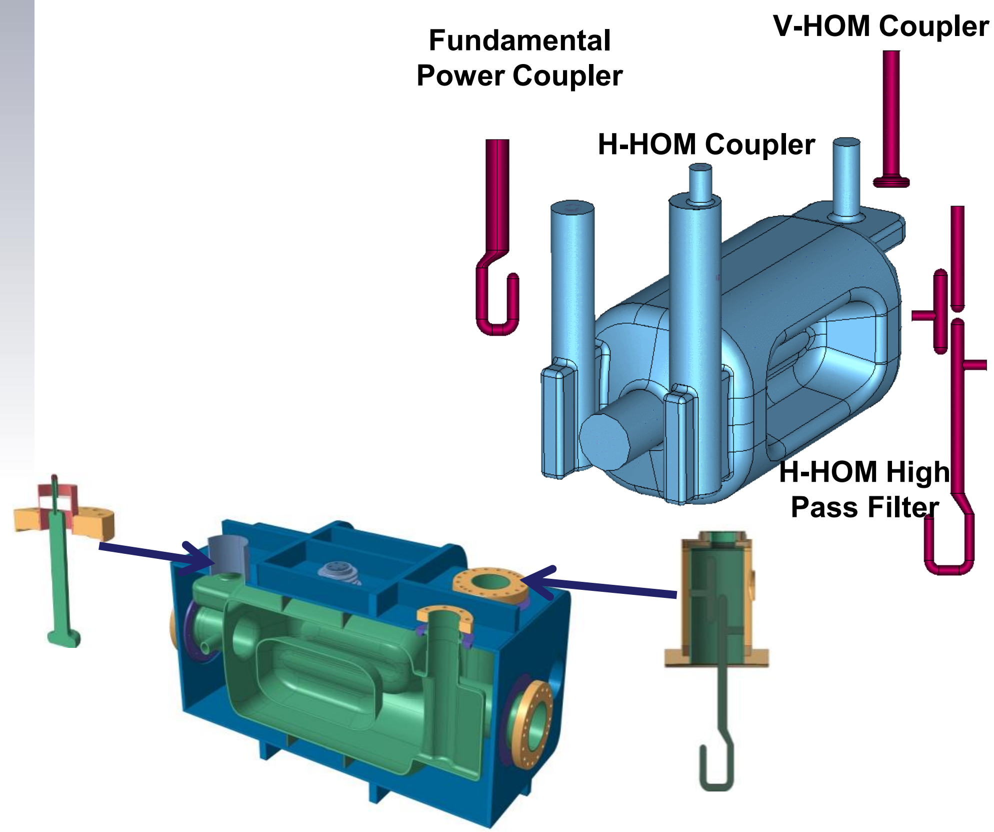
Nearest cavity mode
~230 MHz away

HOM Damping for “TE-like ”400MHz Cavities

- First HOM at 570 MHz
- 3 HOM couplers with filters

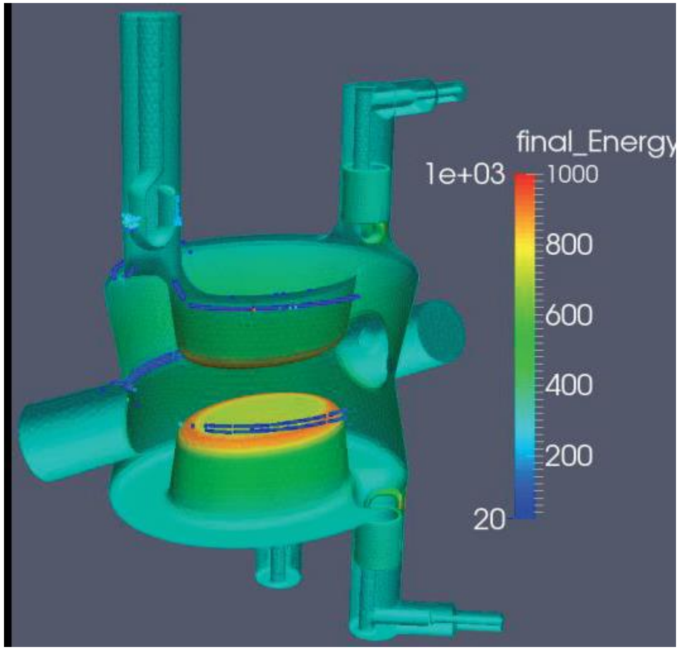


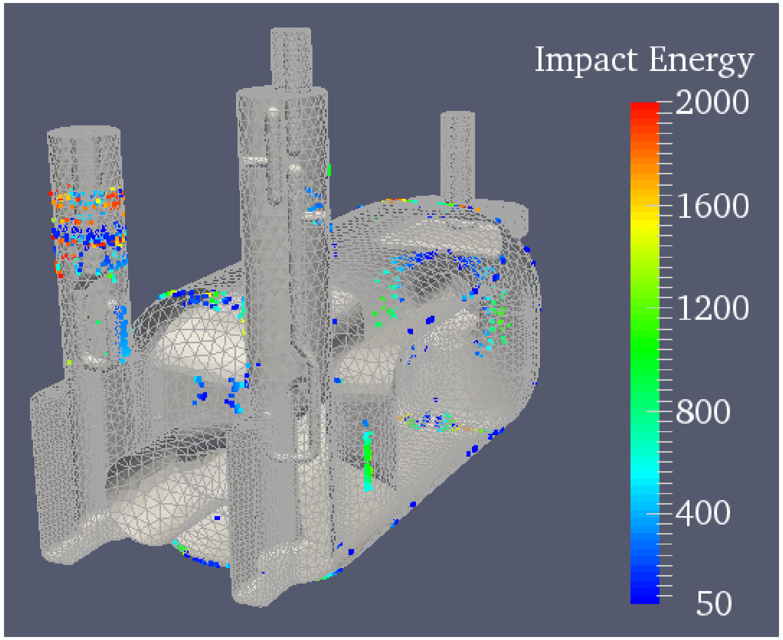
- First HOM at 630 MHz
- 1 HOM coupler with filter
- 1 HOM coupler without filter
  - Does not couple to the fundamental



Multipacting

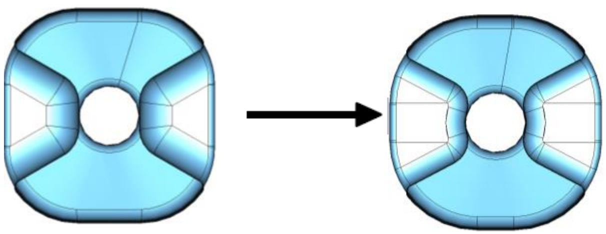
- Extensive simulations of multipacting have been performed using the SLAC ACE3P suite of codes
- Multipacting occurred in the proof-of-principle cavities where predicted, was easily processed, and did not reoccur



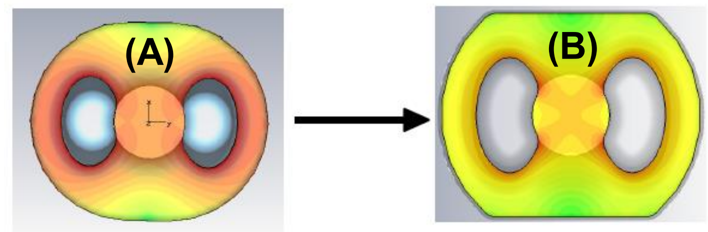


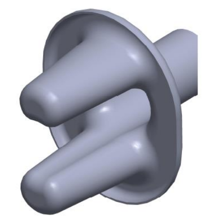
Multipole Components

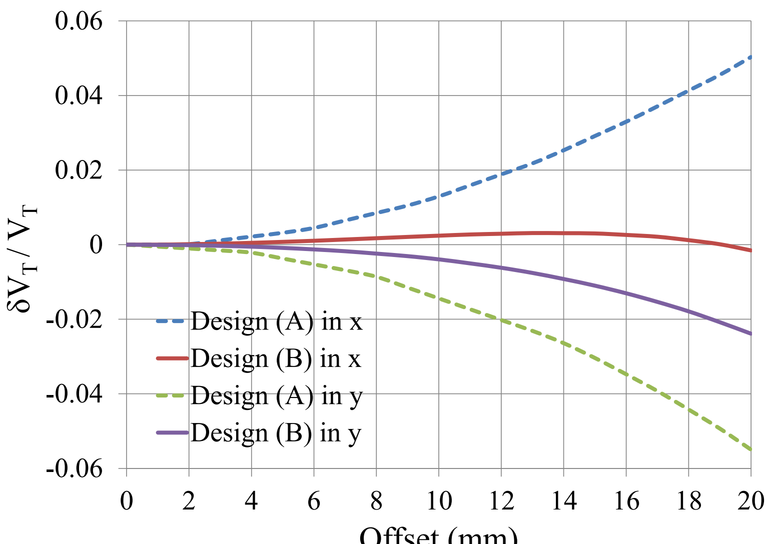
- Shaping of the geometry near the beamline can be used to control the magnitude of the multipoles
  - Involves trade-off with surface fields and shunt impedance

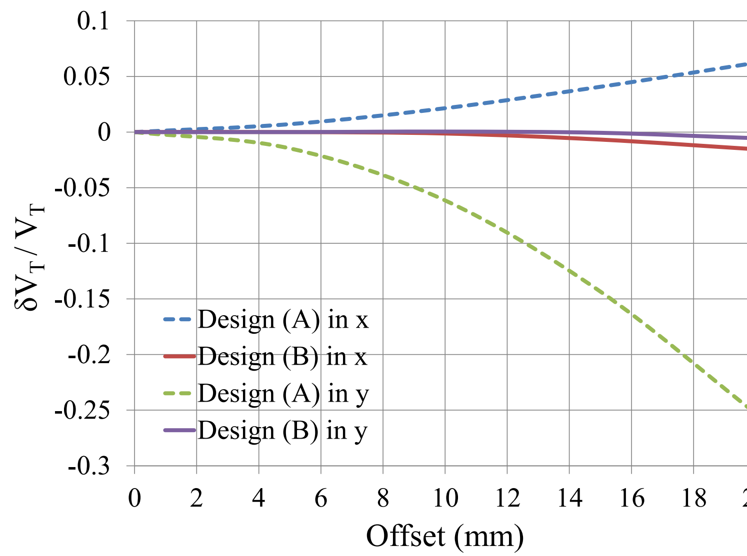


(A) (B)



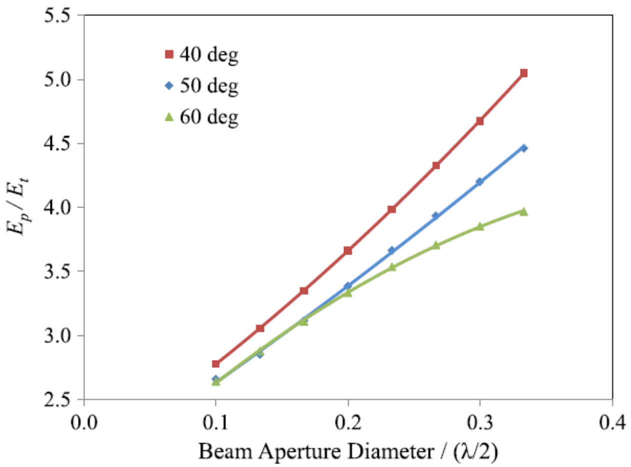


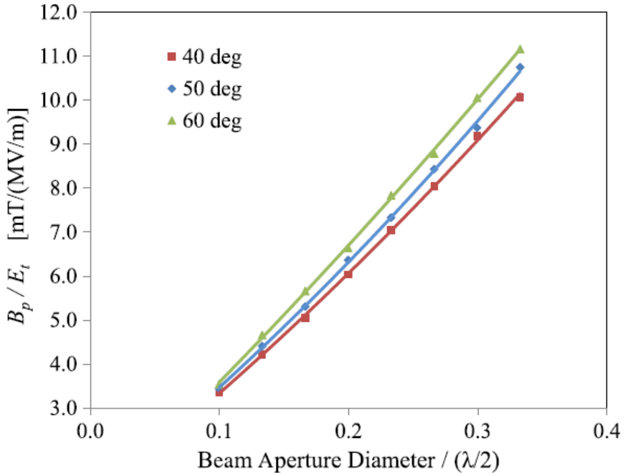


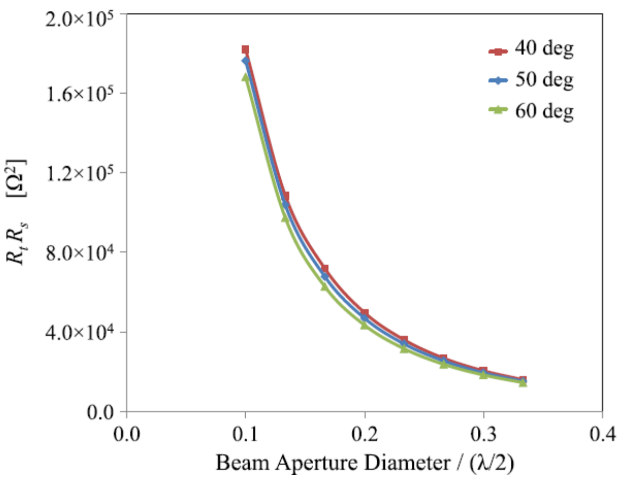


Influence of Beamline Aperture

- 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

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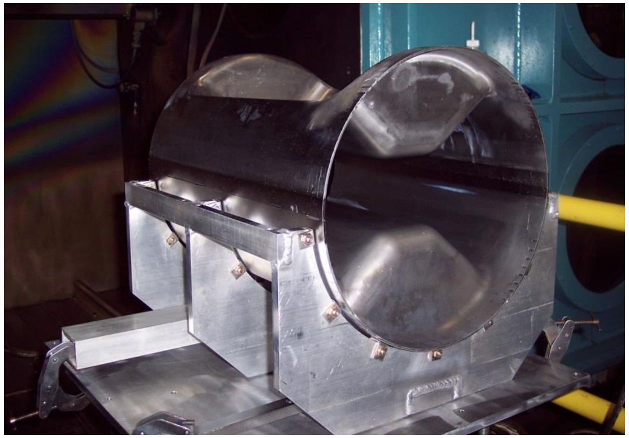
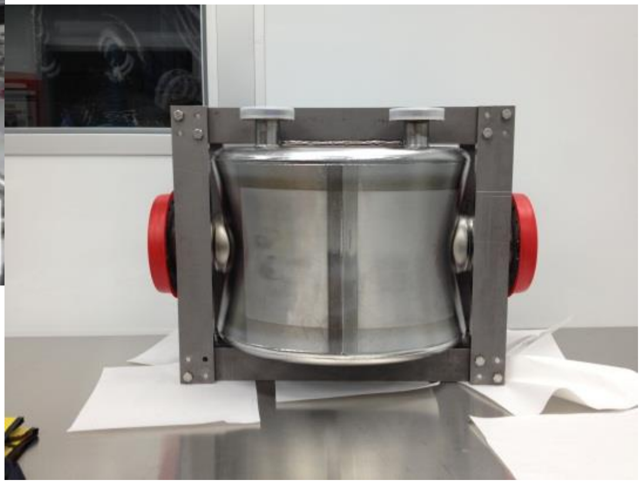
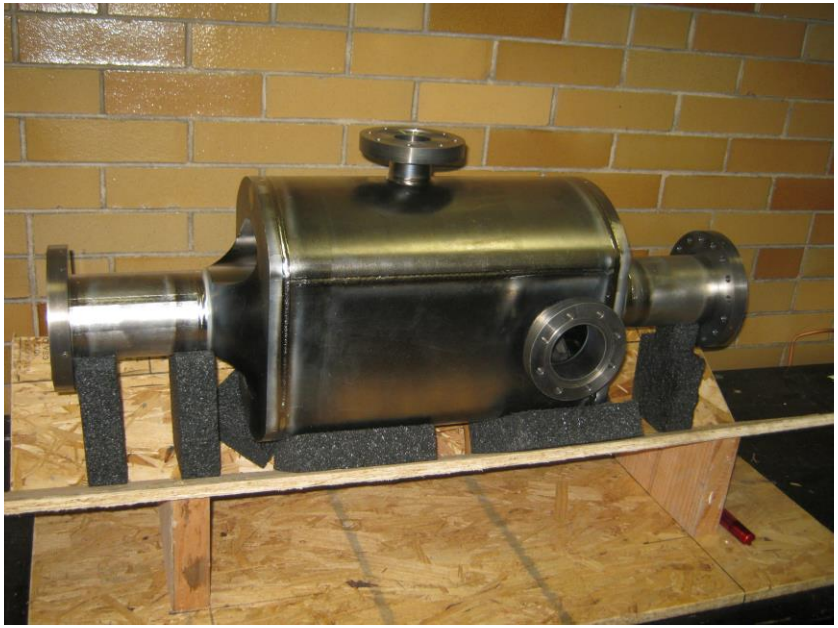
400 MHz RF-Dipole Cavity Fabrication



400 MHz Double Quarter-wave Cavity Fabrication

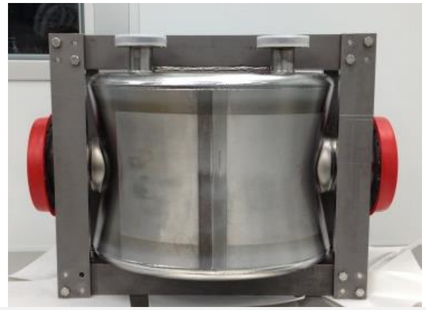


400 MHz 4-Rod Cavity Fabrication



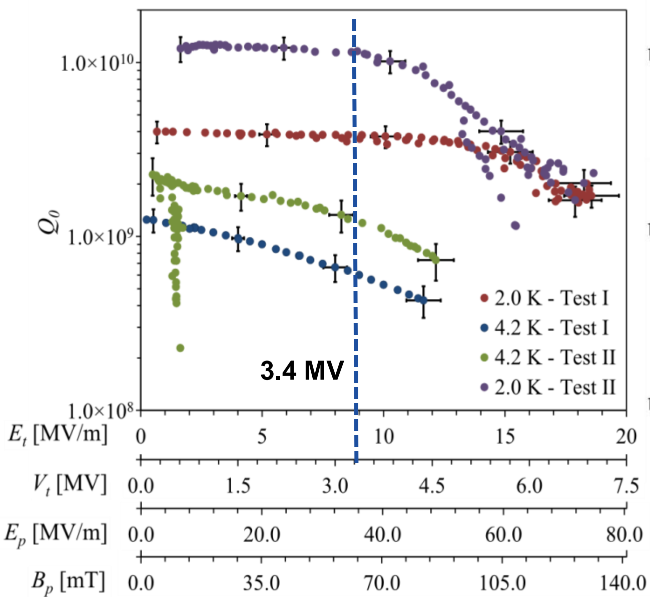
Cryogenic Tests of 400 MHz Proofs-of-Principle

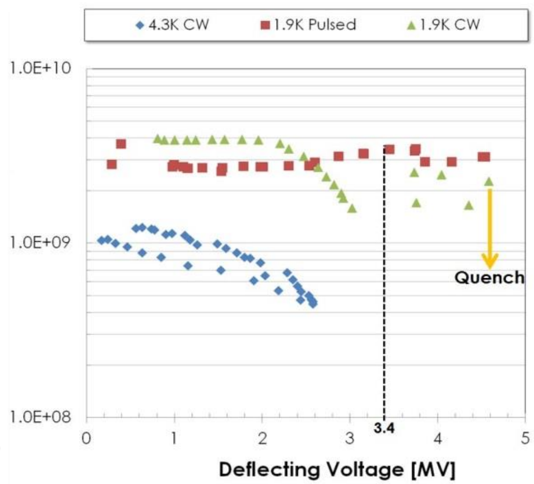
RF Dipole

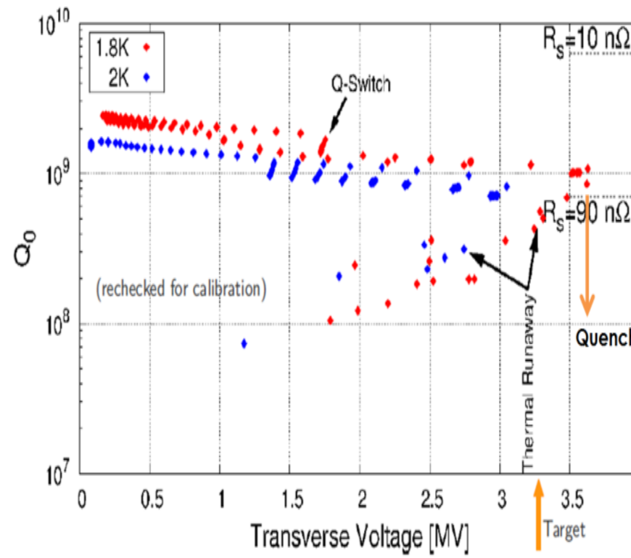


Double Quarter Wave

4 Rod

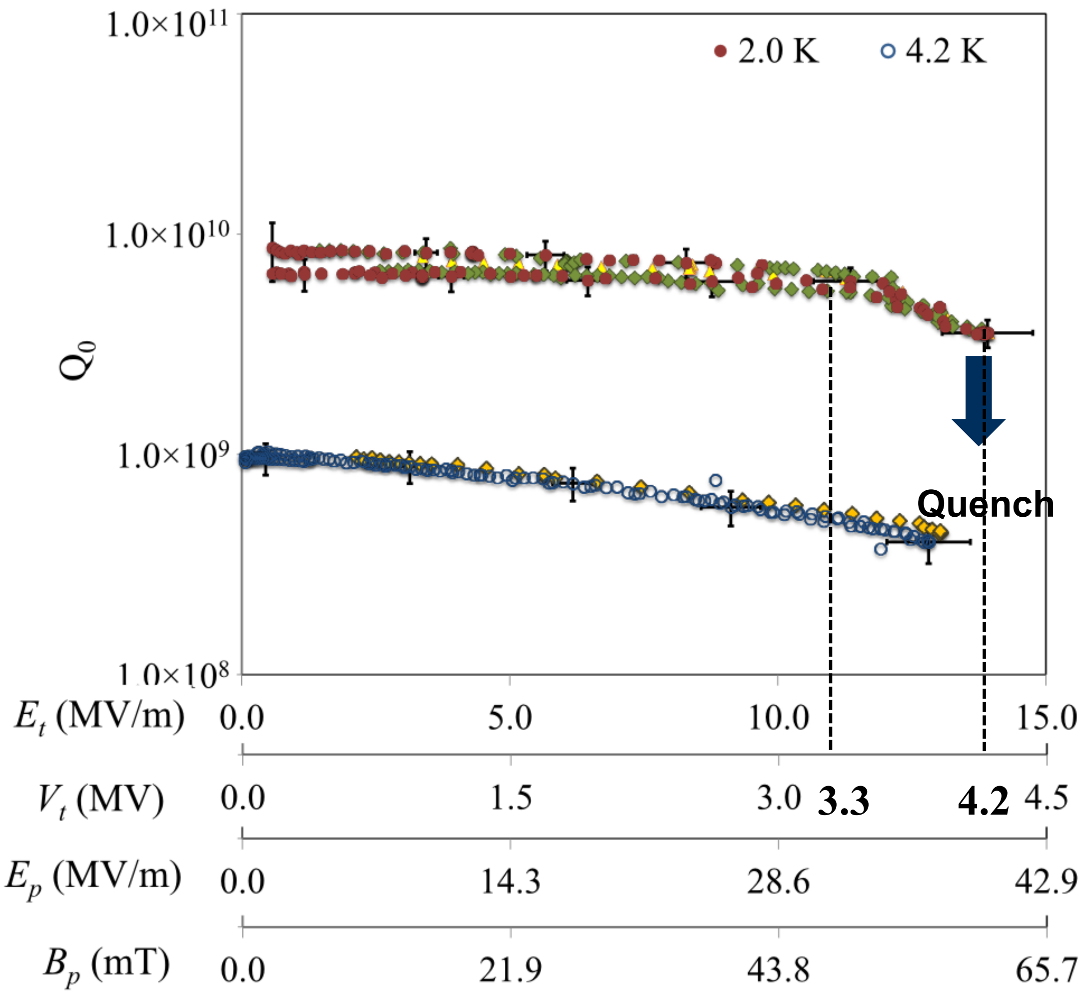






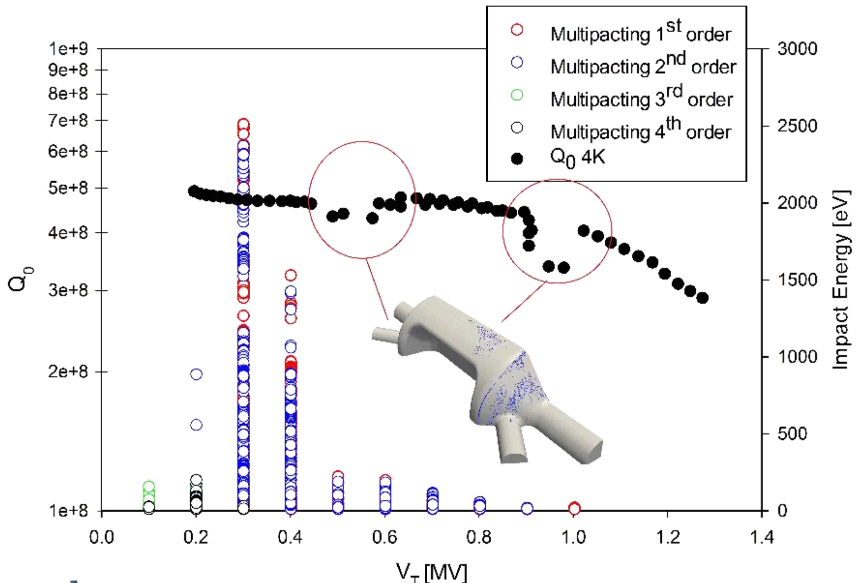
499 MHz Deflecting Cavity

Frequency	499.0	MHz
Aperture Diameter (d)	40.0	mm
Nearest HOM	777.0	MHz
E_p^*	2.86	MV/m
B_p^*	4.38	mT
B_p^*/E_p^*	1.53	mT/ (MV/m)
$[R/Q]_T$	982.5	Ω
Geometrical Factor (G)	105.9	Ω
$R_T R_S$	1.0×10^5	Ω^2
At $E_T^* = 1$ MV/m		

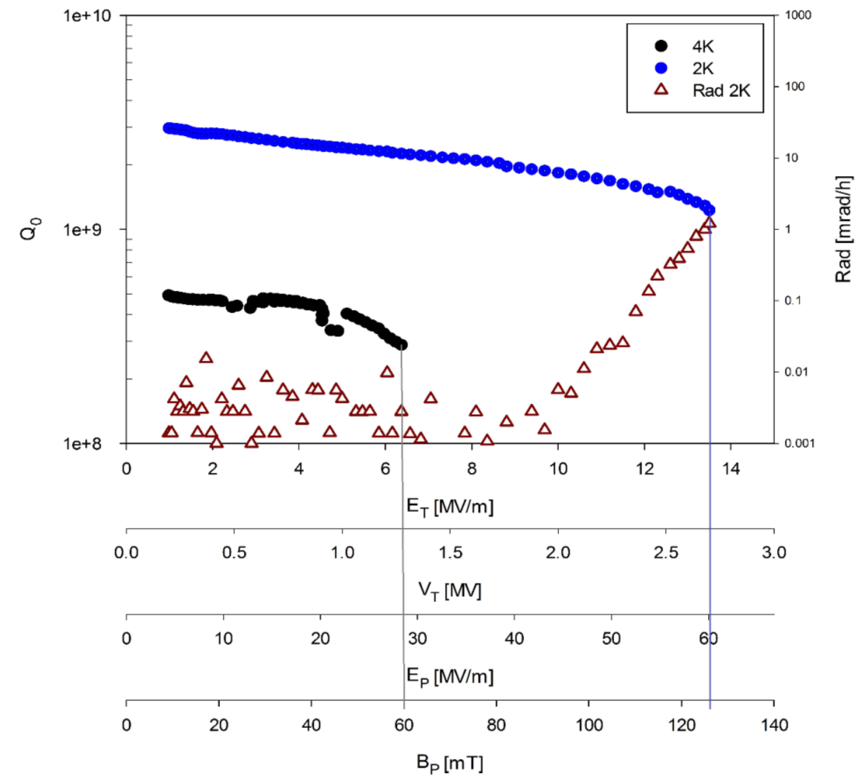


750 MHz Crabbing Cavity

Multipacting



Cryogenic Tests



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

Multi-cell Deflecting Cavity ANL/FNAL

- Deflecting cavities for the manipulation of the 4D phase space of beams are being investigated by a collaboration of ANL-APS/PHY and FNAL. Evolution of design from S.U. De Silva and J.R. Delayen, PRST-AB, 16, 012004 (2013). Applications:
  - Short Pulse X-ray Generation: A. Zholents et al, NIM A, 425 (1999) 385-389 and A. Zholents, NIM A, 798 (2015) 111-116.
  - High Resolution Streak Cameras.

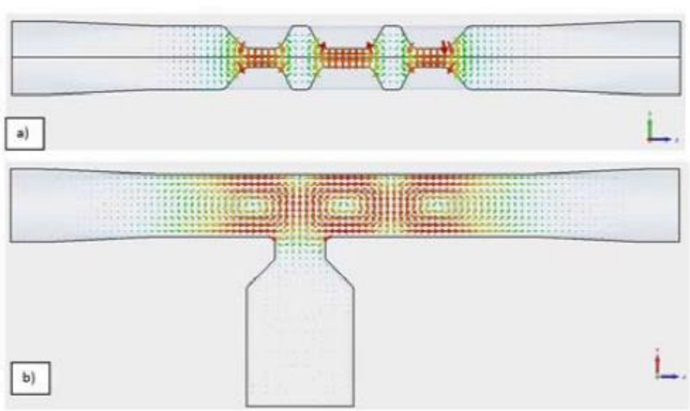
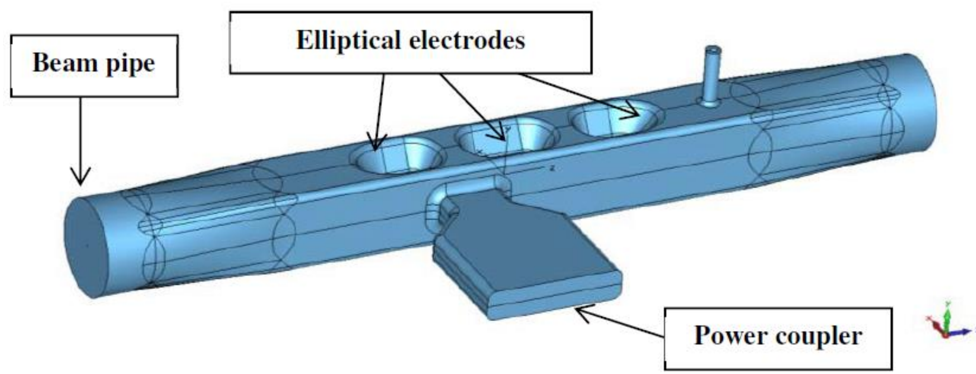


Figure 3: Vector electric (a) and magnetic (b) fields of the 2815 MHz operating dipole mode.



Courtesy Zack Conway, ANL

Multi-cell Deflecting Cavity ANL/FNAL

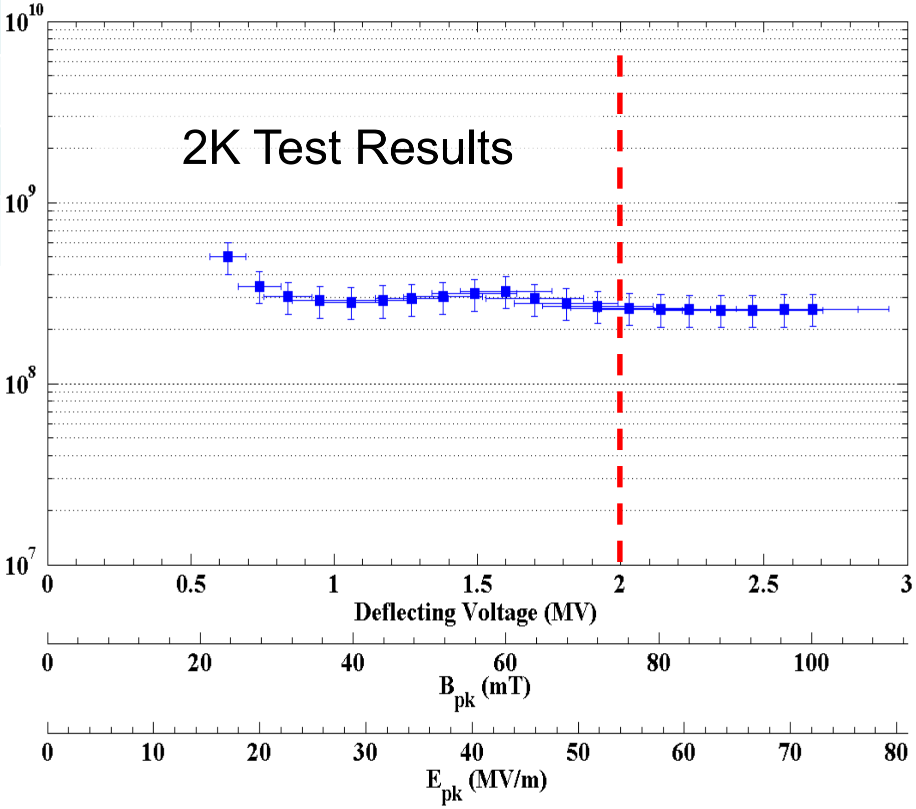
- A prototype superconducting (SC) cavity has been built to demonstrate the feasibility of this concept, QMiR (Quasi-waveguide Multi-cell Resonator):
  - The deflecting electromagnetic mode trapped in a waveguide.
  - A very high shunt impedance = 1 QMiR ~ 1000 $\Omega =$ Lower cryogenic load, lower 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.

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

12 mm Electrode Gap

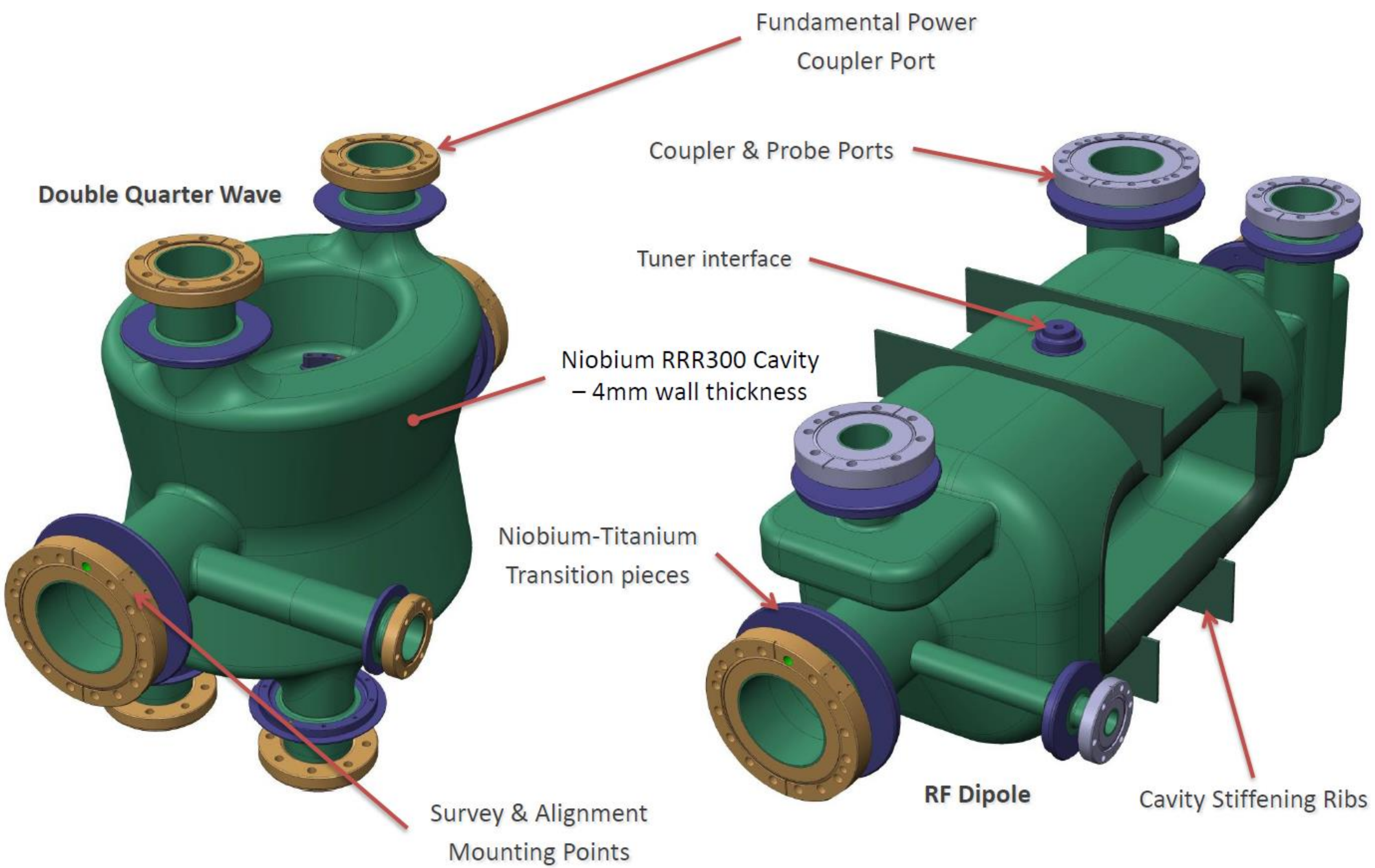


Courtesy Zack Conway, ANL

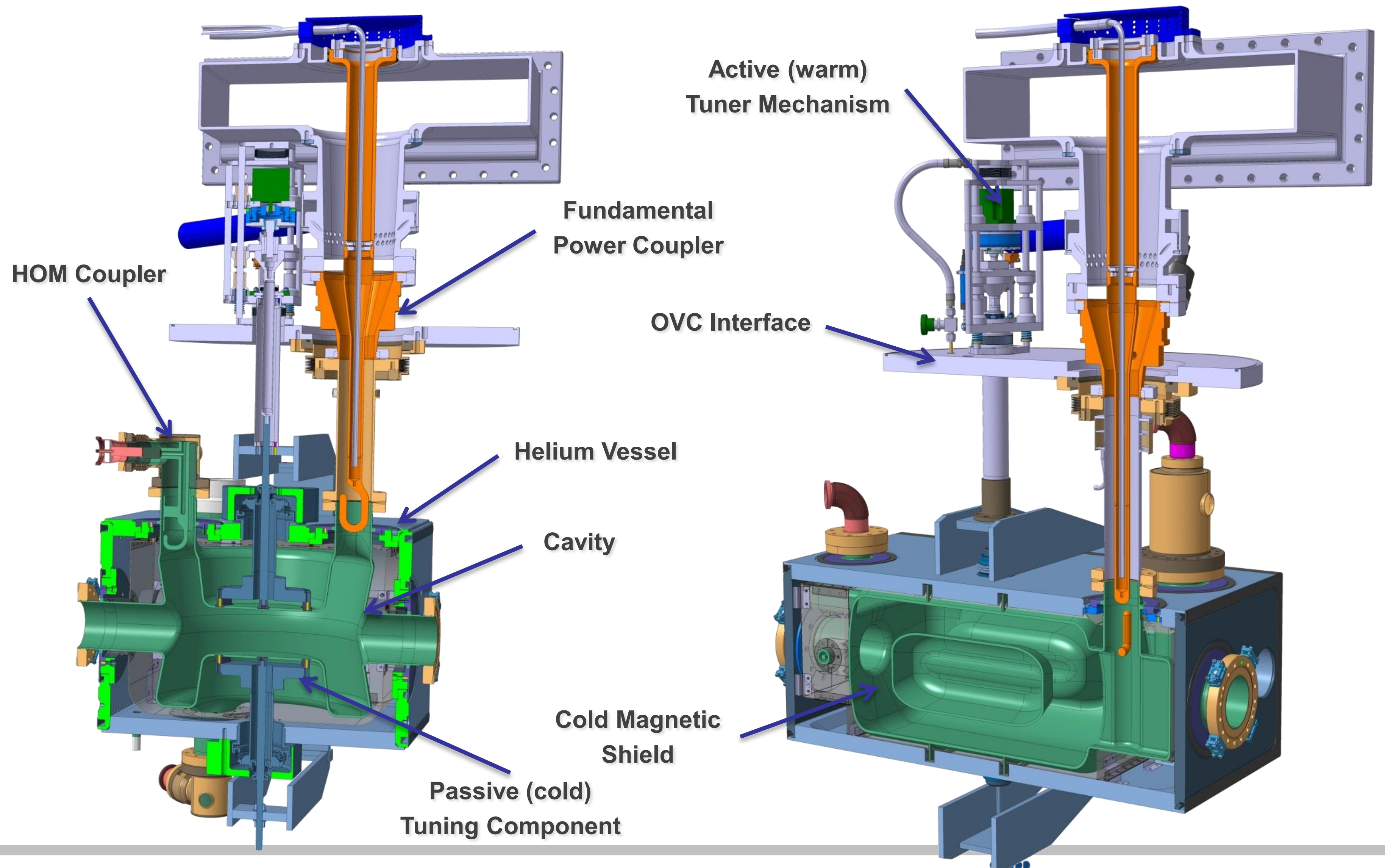
Outline

- A bit of history
- TM_{110} –class cavities
- New geometries and concepts
  - "TEM-like" cavities
  - "TE-like" cavities
  - Their properties
    - Dependence of frequency and velocity on external dimensions
    - Lower- and higher-order modes and couplers
    - Multipacting
    - Multipoles
    - Beamline aperture
- Proofs-of-principle demonstrations and results
- Design and engineering of prototypes

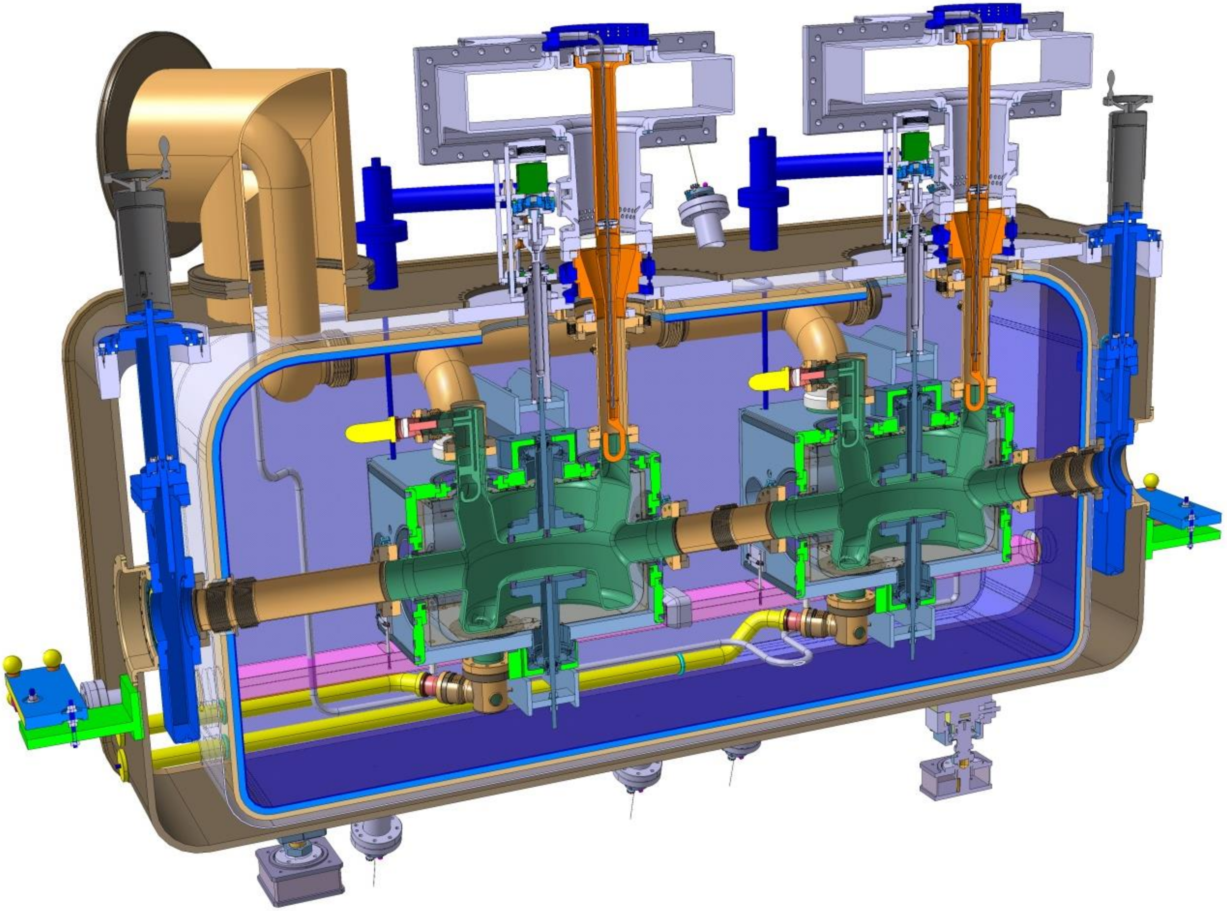
Cavity Designs for LHC Crabbing System



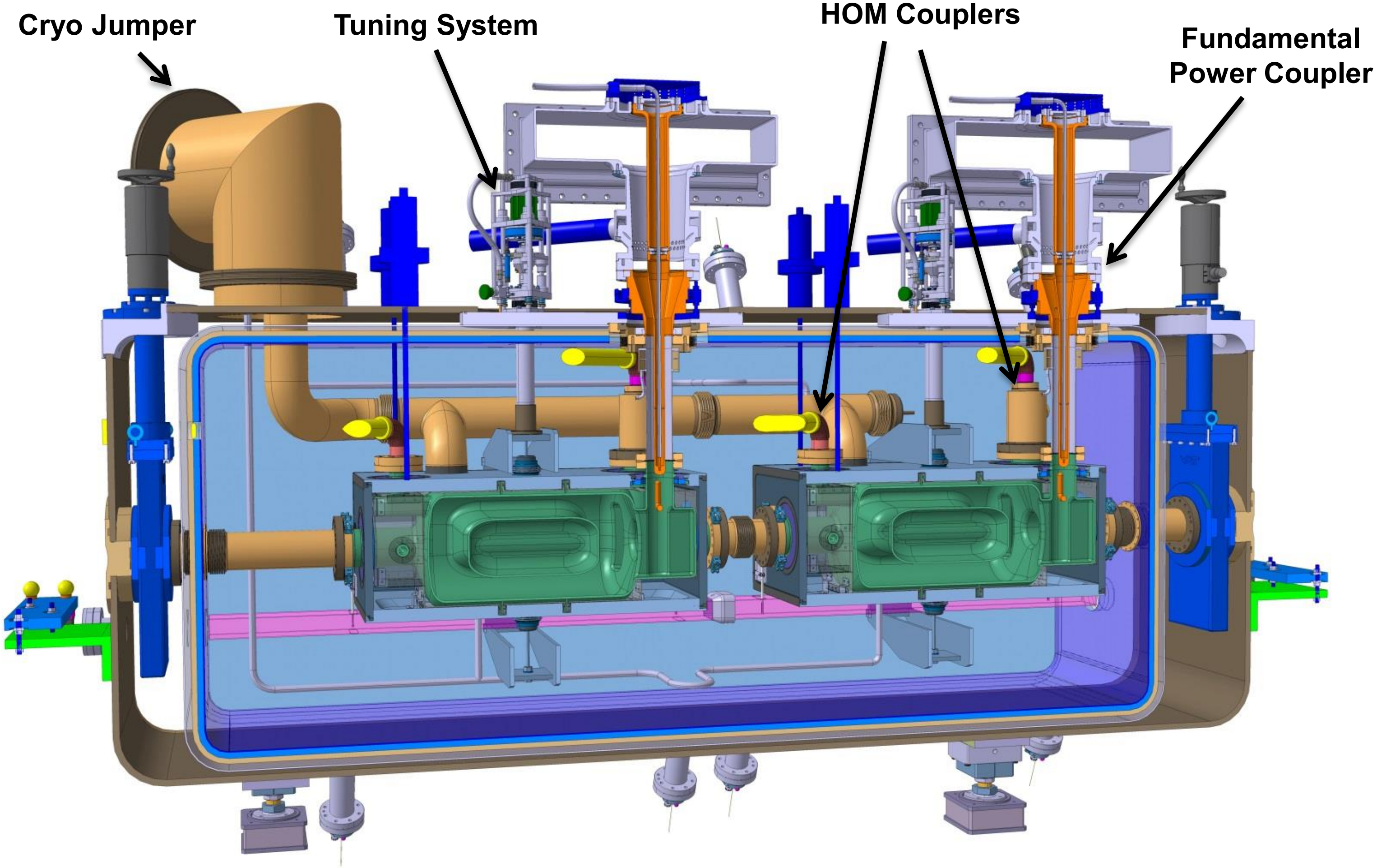
Cavity Engineering for LHC Crabbing System



Integration into Cryomodule for SPS (DWQ)



Integration into Cryomodule for SPS (RFD)



Parting Thoughts

- Faced with demanding challenges from the accelerator community for compact deflecting-mode cavities, the international SRF community has responded with its usual level of innovation and ingenuity
- Proof-of-principle cavities have been developed and tested
  - Requirements have been met and sometimes greatly exceeded
  - Behaviors in cryogenic tests matched predictions from simulation tools
  - New designs offer flexibility to meet specific requirements
  - New designs ease damping of HOMs but it remains a challenge
- Prototype cavities and cryomodules to be tested with high-current beams are being engineered
- Deflecting-mode SRF 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.

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