Superconducting Twin Axis Cavity for ERL Applications

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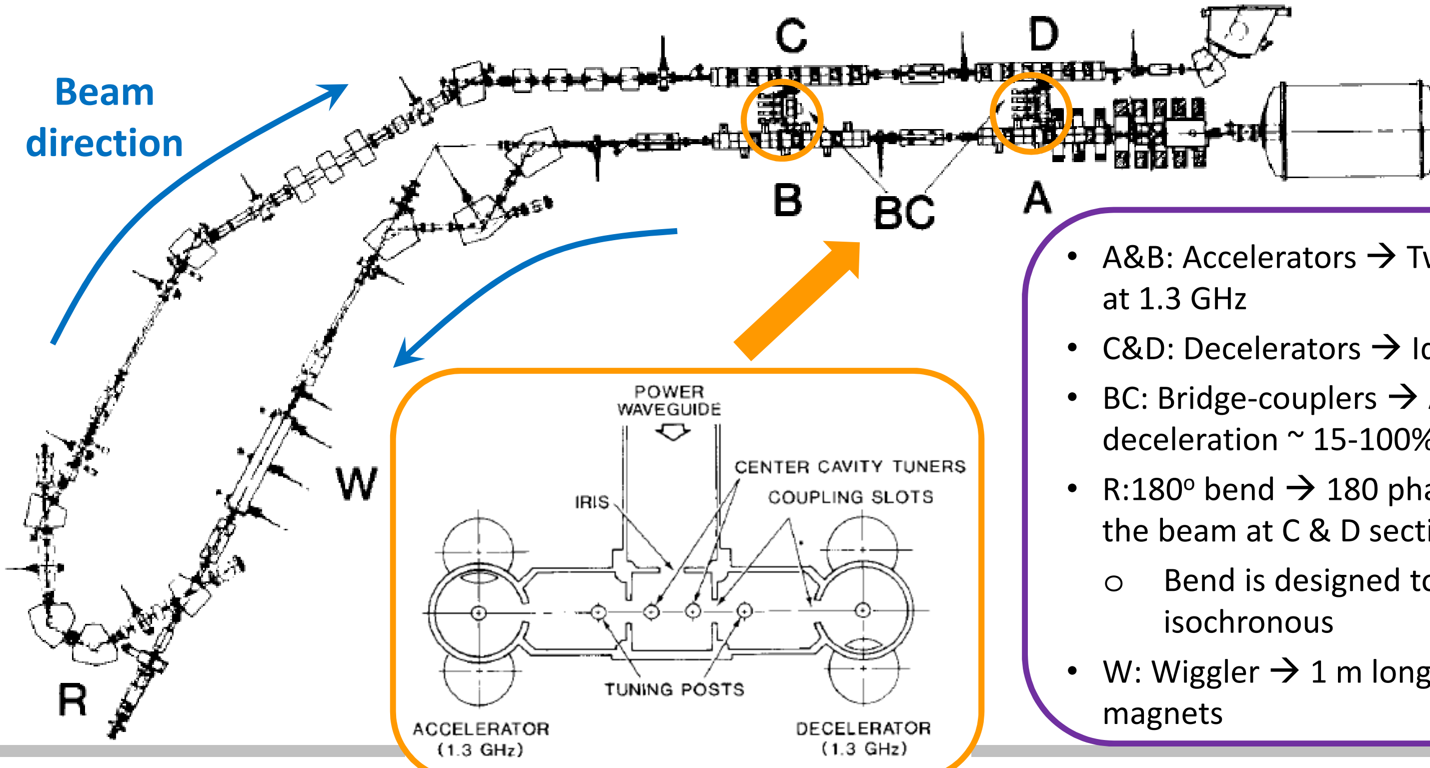
Outline

- Past proposals and motivation
  - A recent one as well
- Design process of Twin axis cavity (Suba at ODU CAS)
  - Design evolution and rf properties
  - HOM properties and wakefield analysis
  - Multipacting analysis
  - Higher order multipole analysis
- Fabrication process
- Post-fab processing of Twin axis cavity
- RF performance
- Lessons learned
- Summary

Past Demonstration

- Energy Recovery in the Los Alamos FEL (1987)*
- A proof-of-principle demonstration of energy recovery with bridge-couplers between two linacs
- Bridge coupler consists of 3 tuned cavities and operates in a TM_{110} mode
- Successful energy recovery with deceleration up to 3.5 MeV

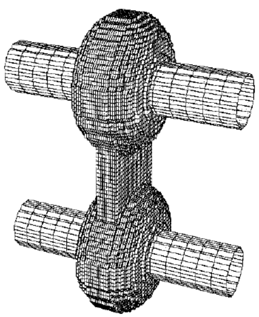


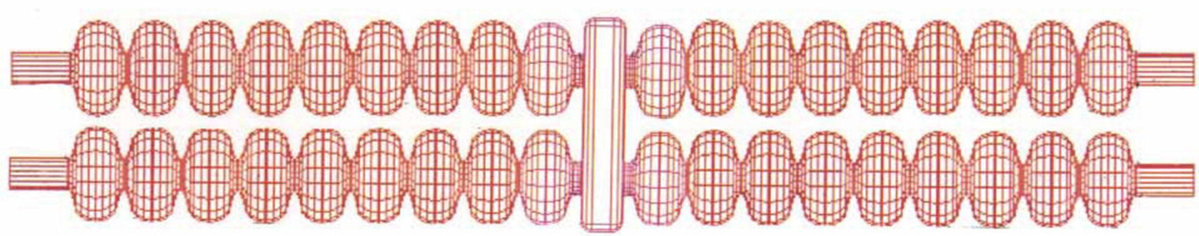
- A&B: Accelerators → Two 10 MeV sections operating at 1.3 GHz
- C&D: Decelerators → Identical to A & B
- BC: Bridge-couplers → Adjustable over a range of deceleration ~ 15-100%
- R:180° bend → 180 phase offset allows to decelerate the beam at C & D sections
  - Bend is designed to be achromatic and isochronous
- W: Wiggler → 1 m long section with permanent magnets

** D. W. Feldman, et. al., NIM A 259 (1987) 26.*

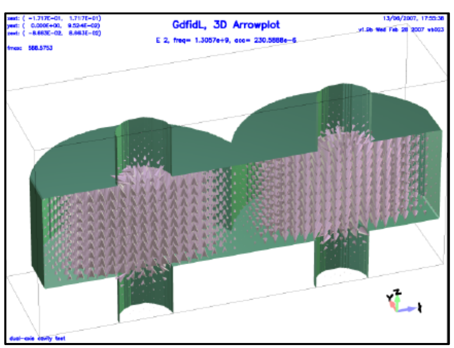
Past Proposals

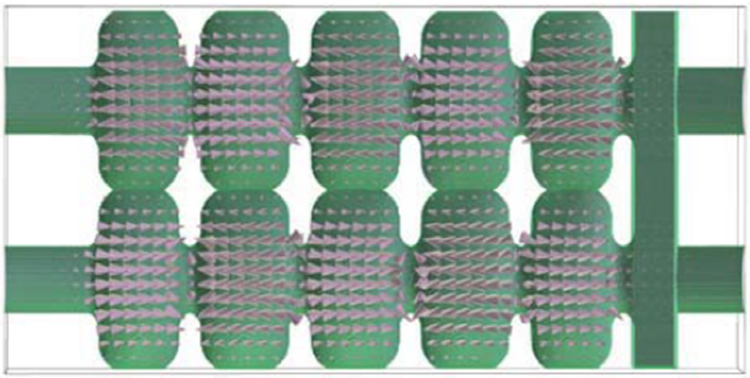
- Multi-beam accelerating structure by Noguchi and Kako at KEK (2003)
  - Multicell with one coupled cell proposed to avoid transverse kick by HOM.





- Dual axis cavity by Wang, Noonan, Lewellen at ANL (2007)





Beyond Concept – KEK Multibeam Cavity

From left E. Kako, T. Shishido, and S. Noguchi
March 2005

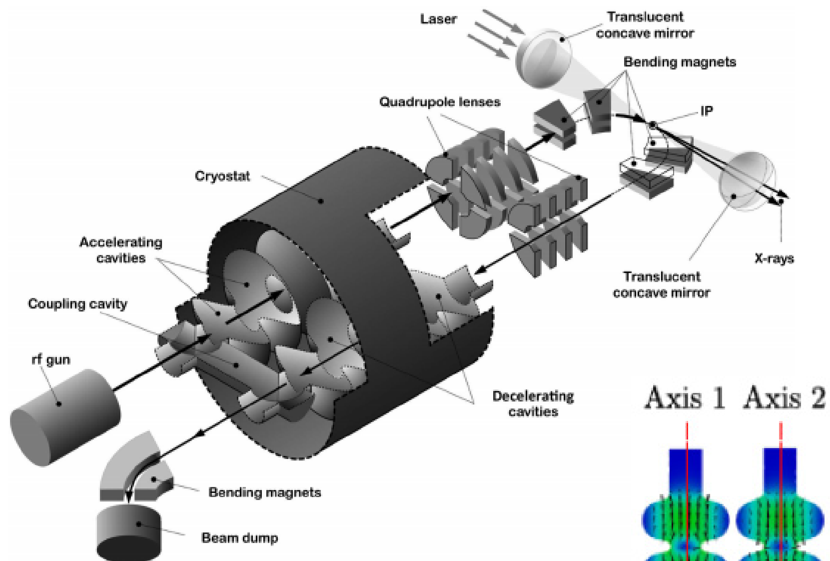
Photos courtesy of Eiji Kako

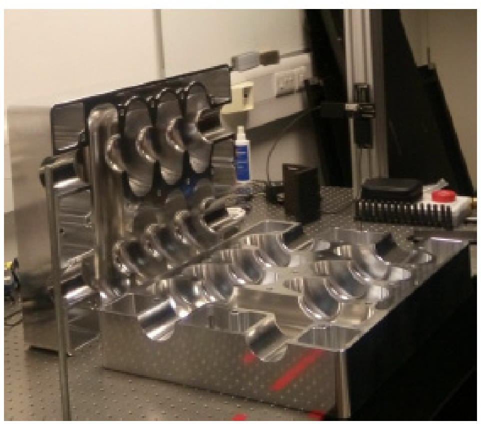
Recent Proposal – JAI/Cockcroft

- Asymmetric dual-axis ERL (AERL)*
  - Designed and developed by John Adams Institute at Oxford university
- Cavity for ultra high flux compact source of THz and x-ray
- Allows high beam current operation
  - Have different HOM frequencies between two axes with different cell shapes in the two multi-cell structures

Asymmetric dual axis energy recovery linac for ultrahigh flux sources of coherent x-ray and THz radiation: Investigations towards its ultimate performance

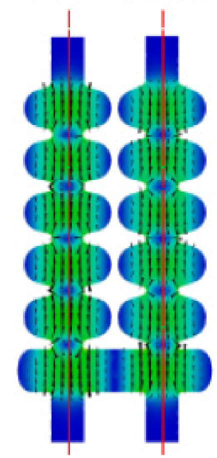
R. Ainsworth,[1] G. Burt,[2] I. V. Konoplev,[1] and A. Seryi[1]
[1]*John Adams Institute at University of Oxford, OX1 3RH, Oxford, United Kingdom*
[2]*Cockcroft Institute, Lancaster University, LA1 4YW, Lancaster, United Kingdom*
(Received 20 July 2015; revised manuscript received 3 June 2016; published 19 August 2016)





7-cell Al cavity

11-cell Cu cavity parts



E Field plot of 1.3 GHz operating mode

* R. Ainsworth, et. al., Phys. Rev. Accel. Beams **19**, 083502 (2016).
I.V. Konoplev, et. al., Phys. Rev. Accel. Beams **20**, 103501 (2017).

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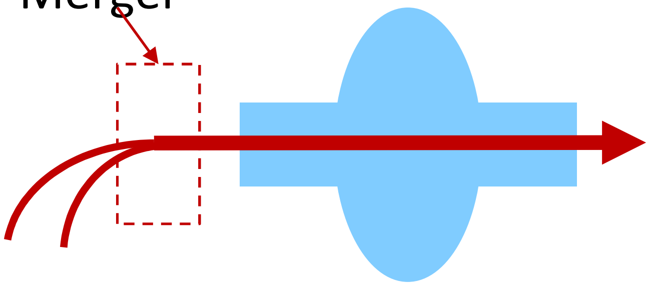
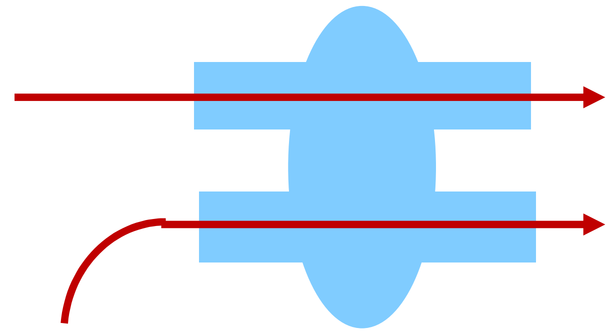
Motivations

Two beams in single line

Merger



Two beams in separate line



- Merging degrades low energy injection beam emittance
- Sum of accelerating beam and decelerating beam increases total beam current in the cavity which causes beam instability
- Optics become complicated with different energy level beams

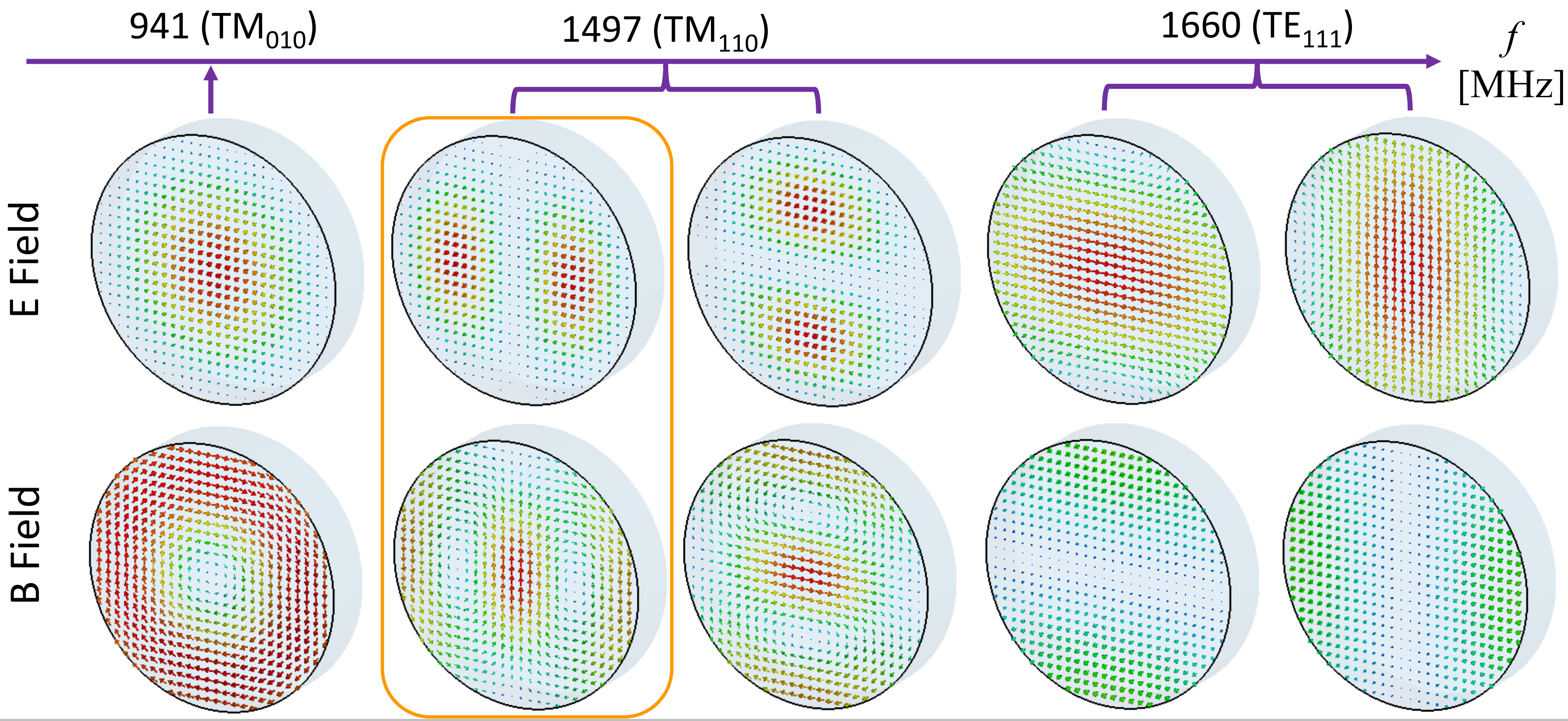
- Preserves low energy injection beam emittance
- Given equal instability threshold, machine can operate higher beam current
- Optics less complicated

Design Goals of Twin Axis Cavity

- *A multi-beam cavity with good electromagnetic properties and good rf performance*
- Frequency: Chosen to be CEBAF operating frequency – 1497 MHz
- Similar to any superconducting rf cavity:
  - Low peak surface field ratios (Low E_p/E_{acc} and B_p/E_{acc})
  - High $R_{sh}R_s$ = [R/Q]×G to reduce cryogenic losses
  - Wide separation between operating mode and LOM/HOM
  - Low or no multipacting levels up to operating gradient
- In addition:
  - Optimize the shape to symmetrize the electric fields along two beam axes
  - Maximize the separation between two beam pipes
  - Reduce higher order multipole components (Especially dipole component)
- Manufacturing:
  - Cavity shape compatible with the existing cavity processing facility, especially cleaning.

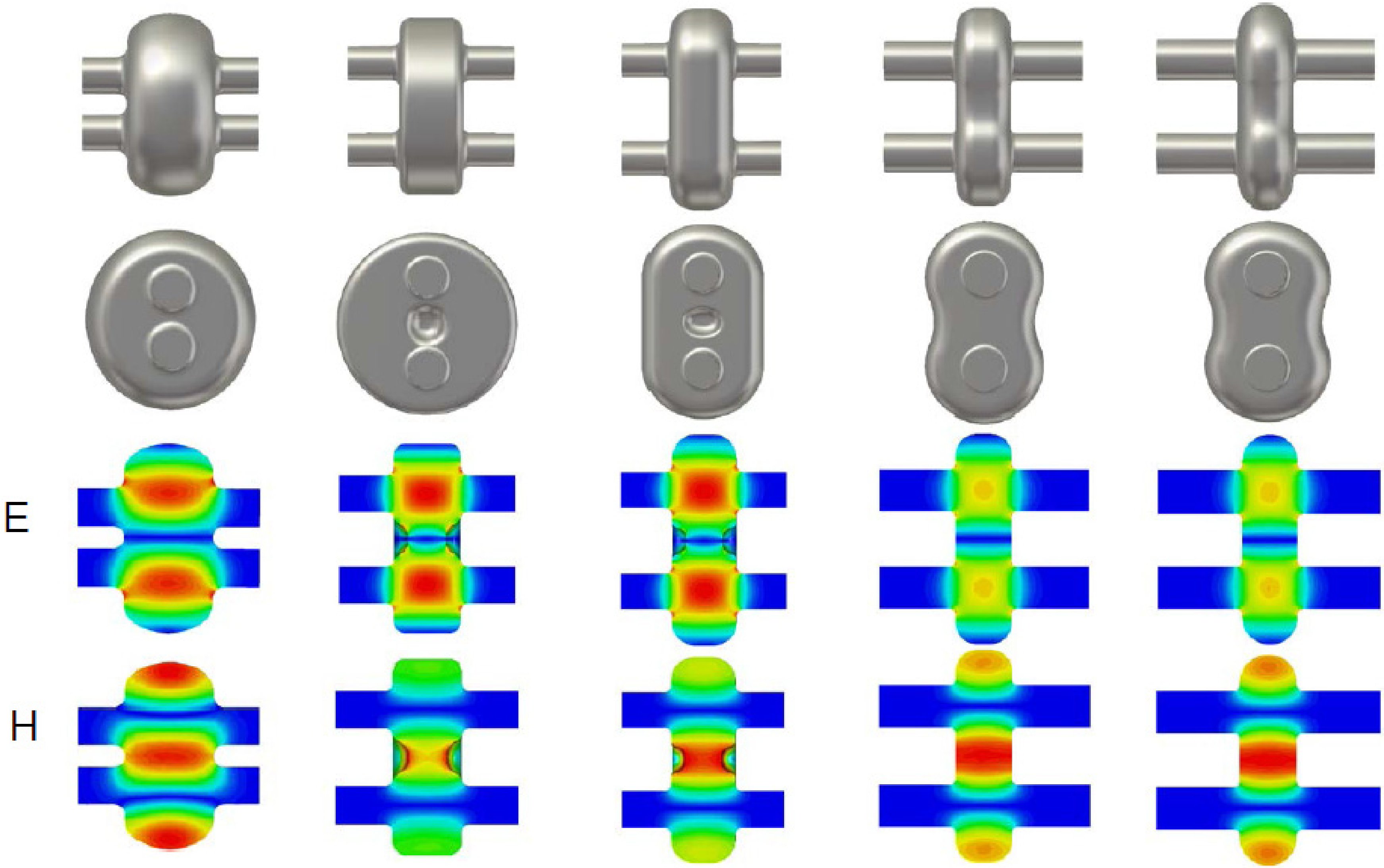
Electromagnetic Mode of Twin Axis Cavity

- Operates in TM_{110} mode
- Has a lower order mode (TM_{010})
- Needs to separate the other polarization of TM_{110} mode



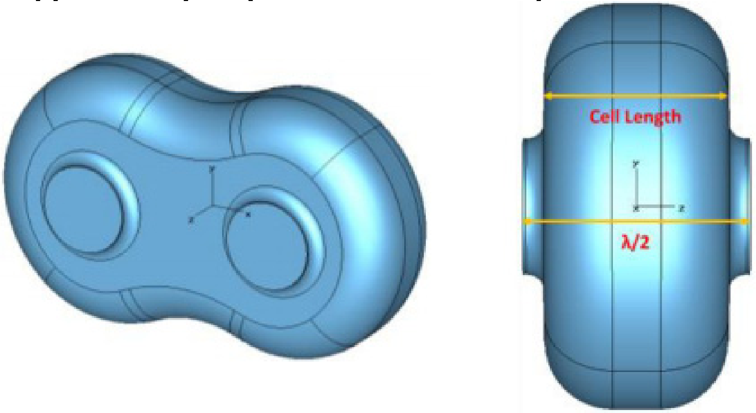
Subashini De Silva/ODU CAS

Design Evolution

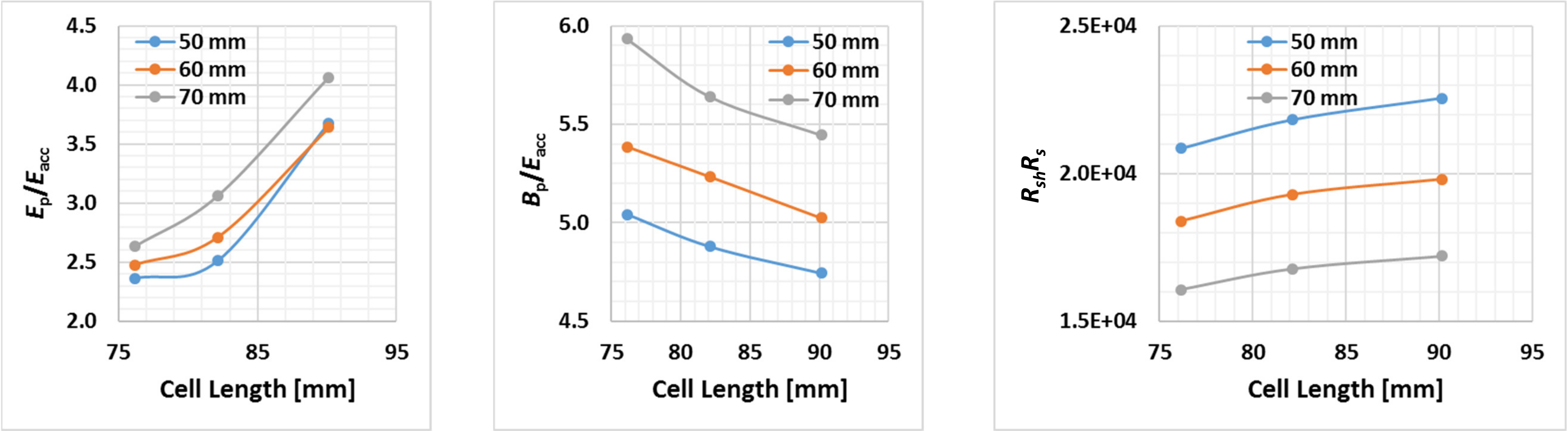


Design Optimization

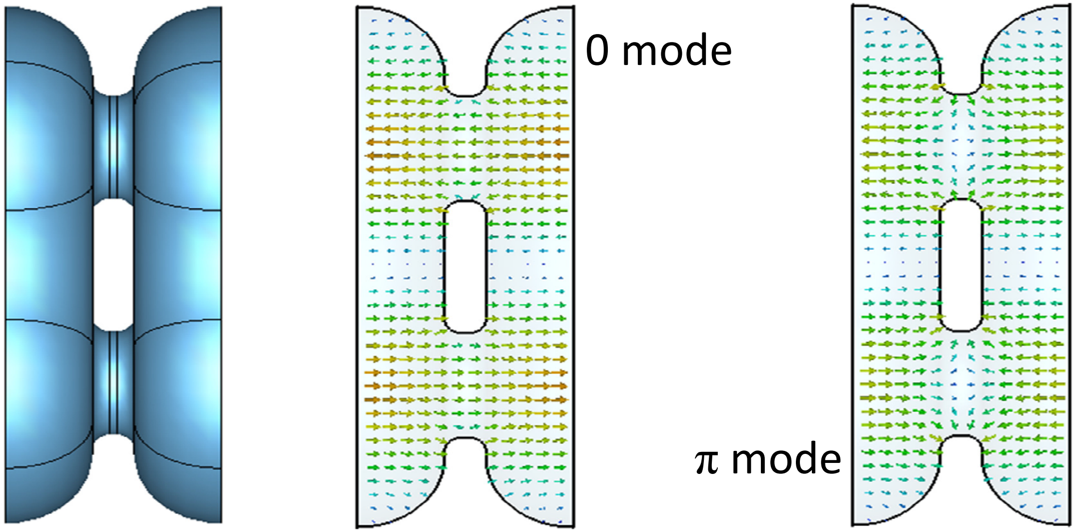
- Single cell cavity optimized to be adapted to a multi-cell cavity
- Fixed iris-to-iris length = $\lambda/2$ (100.131 mm)

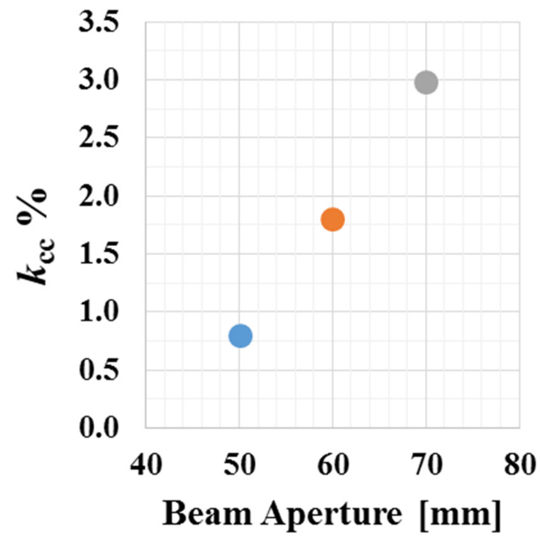


- Optimization of cell length with varying beam aperture



Cell–to–Cell Coupling

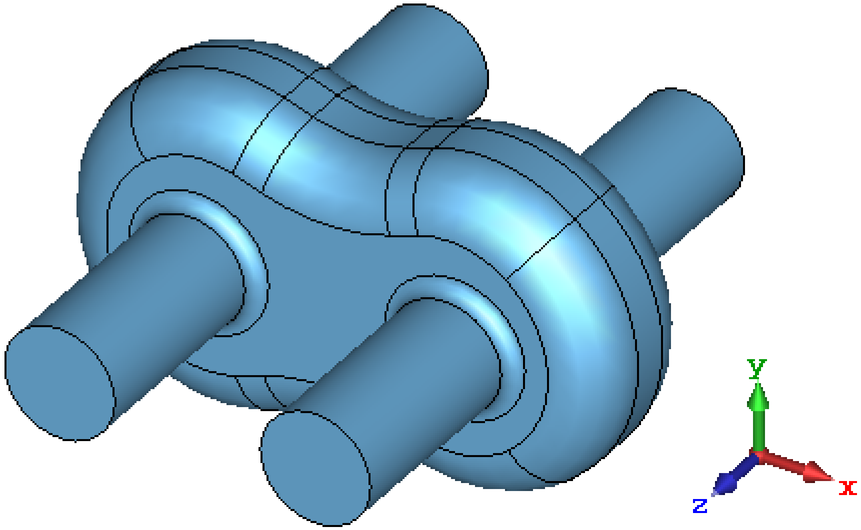


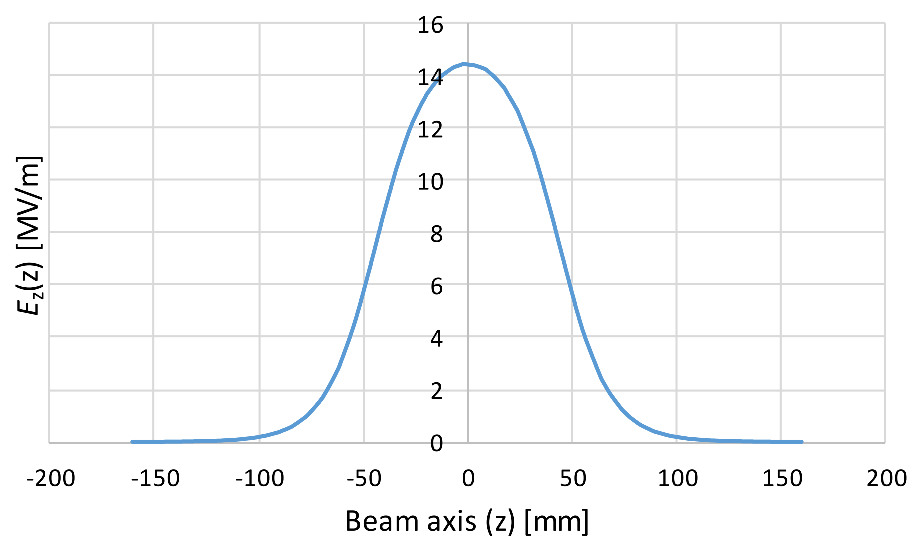


$$k_{cc} = 2\frac{\omega_\pi - \omega_0}{\omega_\pi + \omega_0}$$

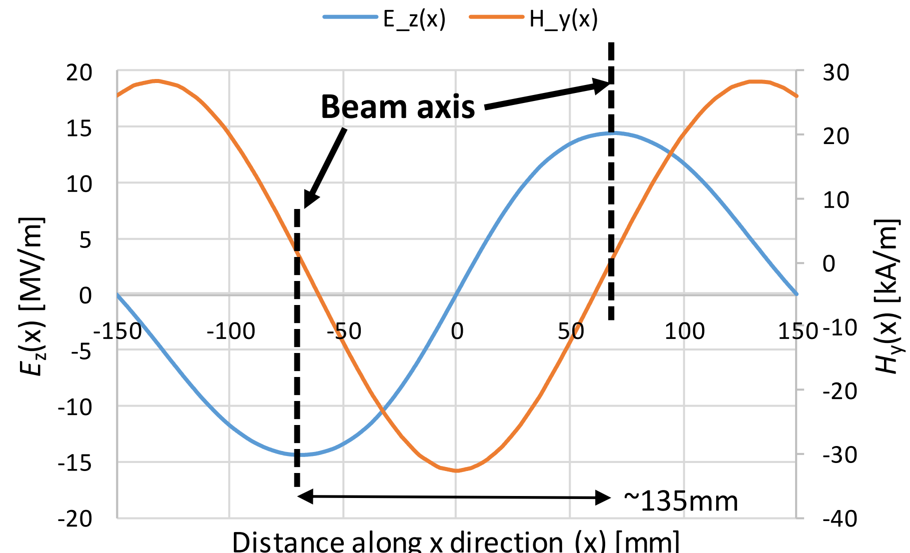
- Cavity beam aperture was selected to match the coupling coefficient of CEBAF 1497 MHz cavities
  - k_{cc} of CEBAF 7-cell 1497 MHz cavity is 1.55%
- A similar k_{cc} (1.80%) was chosen for the twin axis cavity and a 60 mm beam aperture was selected
- Based on HOM requirements a larger beam aperture may be required for end-cells

Separation of Two Beam Pipes



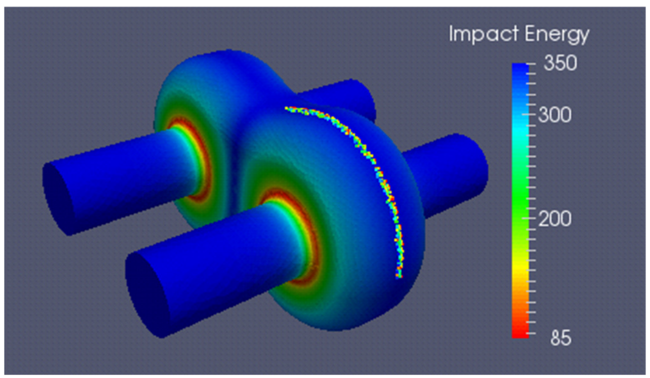


- Position of beam pipe is determined to maximize the longitudinal electric along the axis
- Beam pipe position is adjusted to cancel transverse kick due to E_x and Hy components.

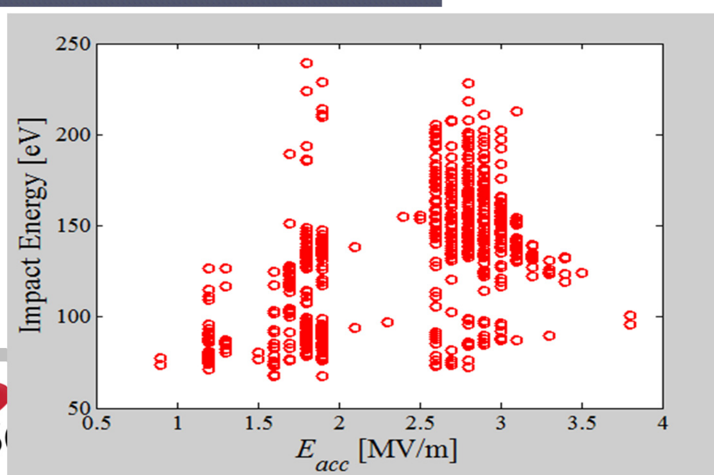


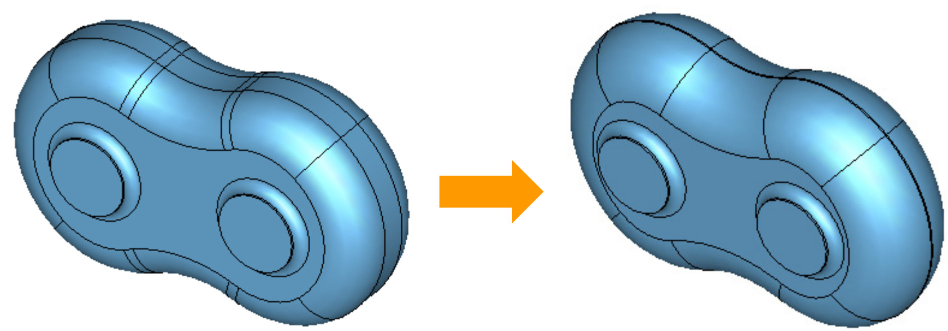
Multipacting Analysis

- Expected operating field of twin axis cavity is E_{acc} = 15 MV/m
- Multipacting analysis performed using Track3P in SLAC ACE3P Suite
  - Resonant particles traced up to a gradient of E_{acc} = 16 MV/m (E_p = 39 MV/m & B_p = 88 mT)
  - For an impact energy range of 50-2000 eV
- Resonant trajectories surviving after 50 rf cycles are seen at the equator below 4 MV/m with impact energies of 85 – 350 eV



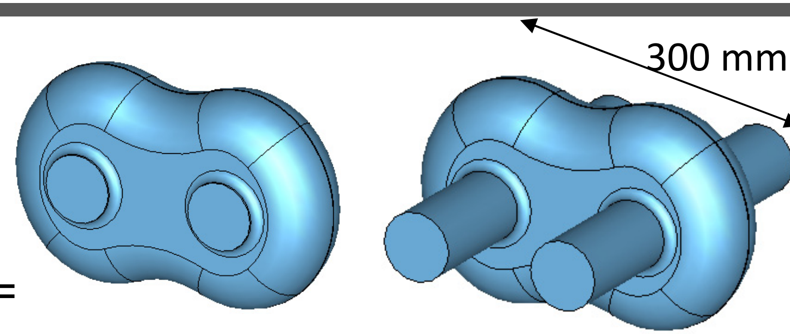
- Curvature at the equator was increased in the final design (30 mm → 40 mm)
- Multipacting barriers below 4 MV/m disappeared



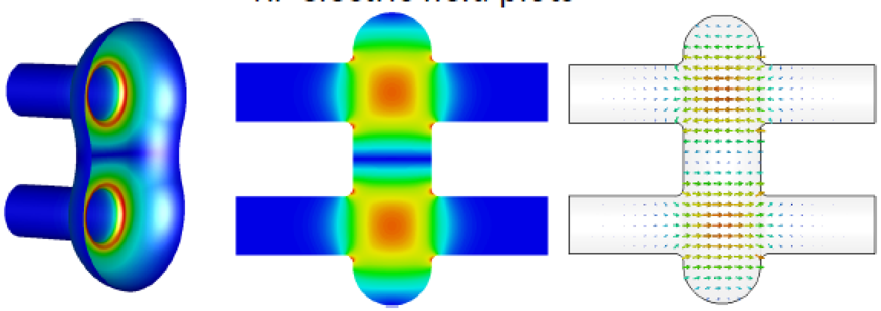


Final RF Design

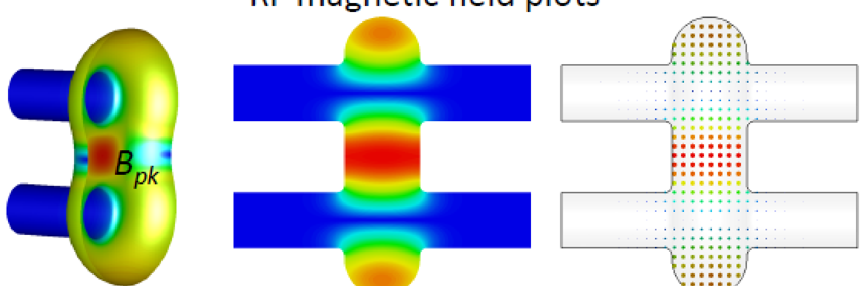
- Frequency without beam pipes is 1497 MHz
- Frequency with beam pipes is 1483.3 MHz
- Beam axis separation – 135.44 mm
- Operating gradient goal – E_p = 15 MV/m (E_p = MV/m & B_p = 82 mT)



RF electric field plots



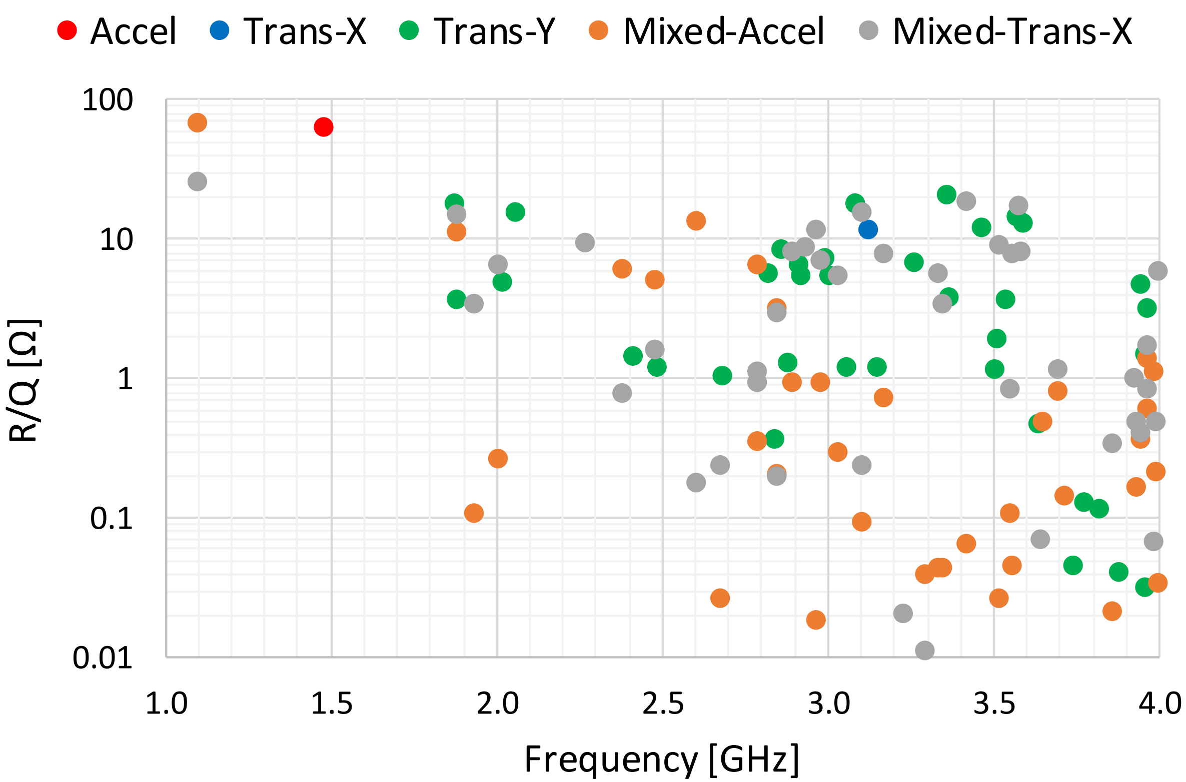
RF magnetic field plots



RF Properties	
E_p/E_{acc}	2.42
B_p/E_{acc} [mT/(MV/m)]	5.49
$[R/Q]$ [Ω]	60.7
G [Ω]	318
R_tR_s [Ω^2]	1.9×10^4
LOM [MHz]	1103
1st HOM [MHz]	1806
Beam aperture [mm]	60
k_{cc} [%]	1.80

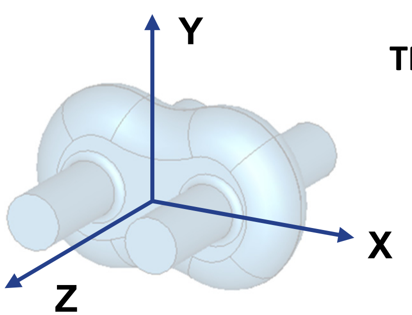
HOM Properties

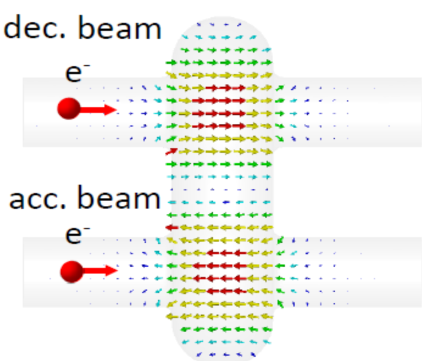
- Has a lower order mode: 1103 MHz
- LOM and operating mode has similar R/Q
- Due to the cavity shape there are mixed modes with both longitudinal and transverse R/Q

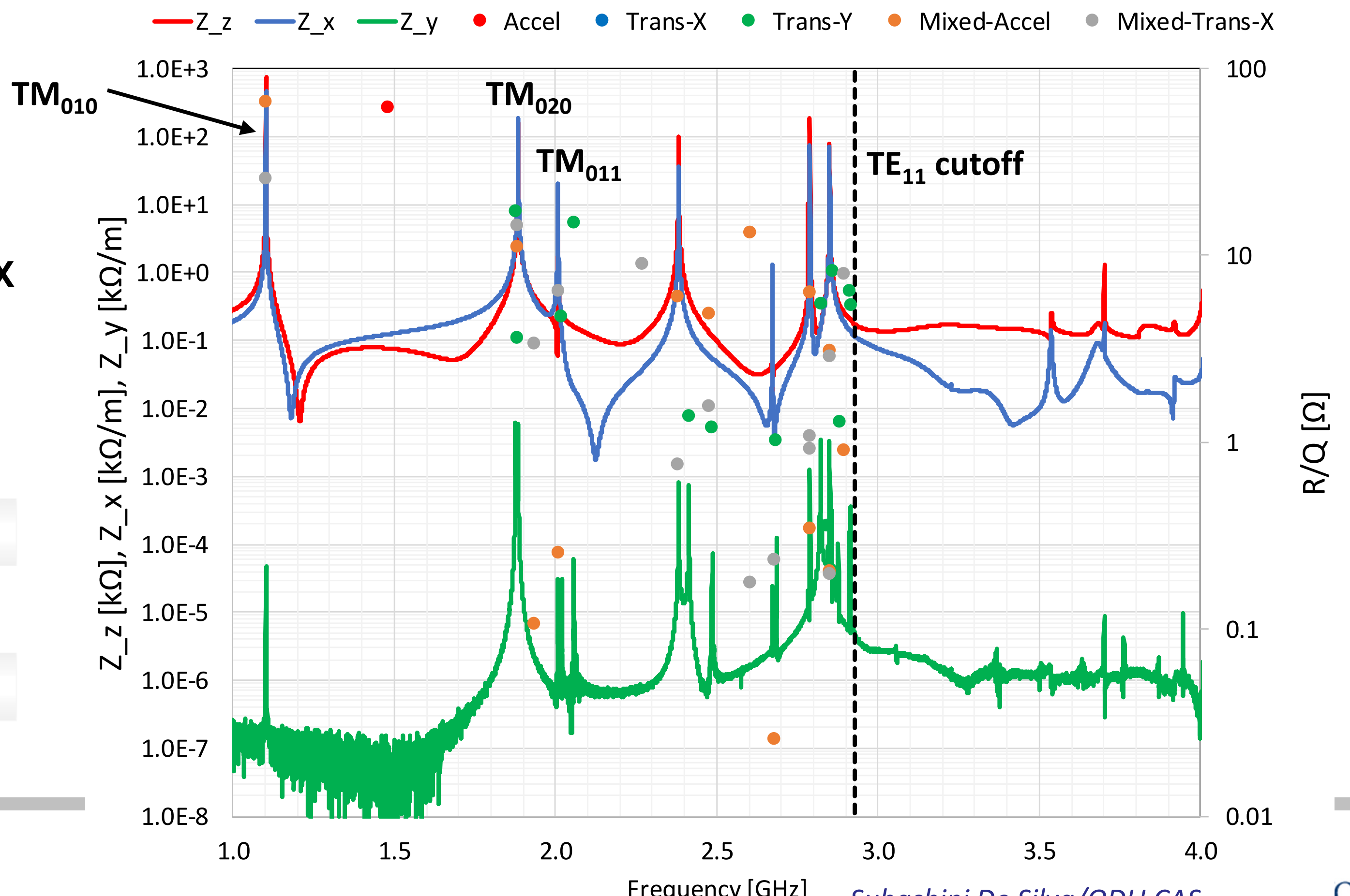


Wakefield Analysis

- Wakefield analysis of the bare cavity with two bunches passing through beam axis centers in same direction (energy recovery mode)
- Simulated bunch properties: σ_z = 25 mm with a 1 km long wake
- No HOM couplers (undamped impedances) → unresolved amplitude

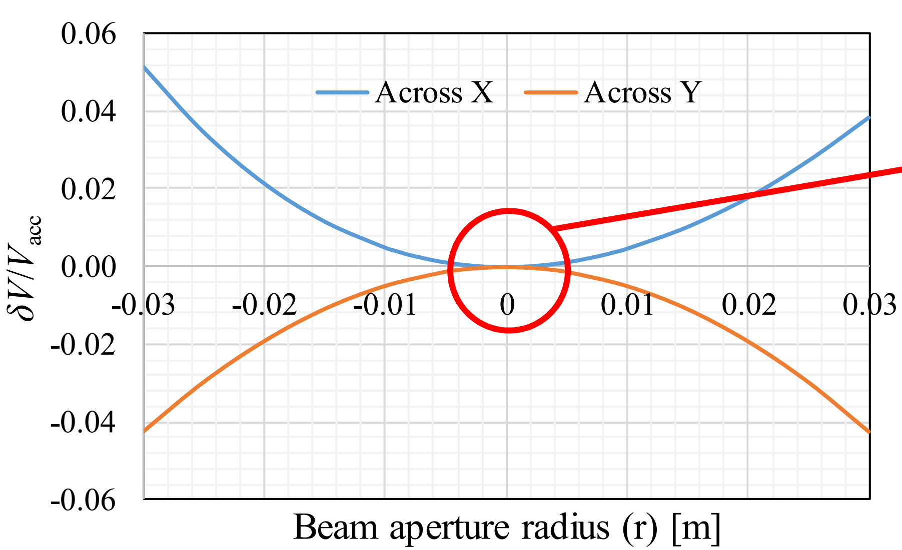


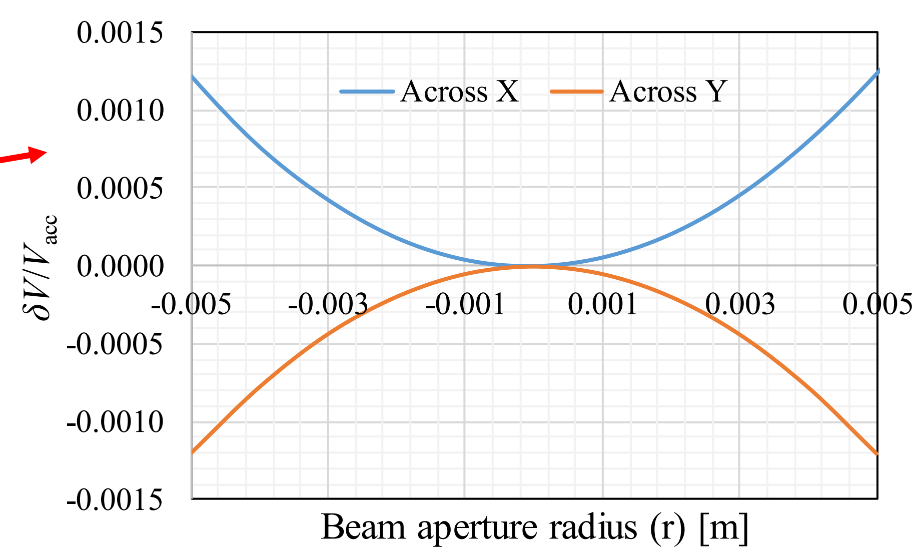




Field Non-Uniformity

- Field non-uniformity across beam apertures evaluated with normalized accelerating voltage
- Field variation across horizontal plane is not symmetric
  - Some higher order multipole component is present in the field
- Field variation across vertical plane is symmetric
- At smaller radii (r_0 < 5mm) field is symmetric in both horizontal vertical planes





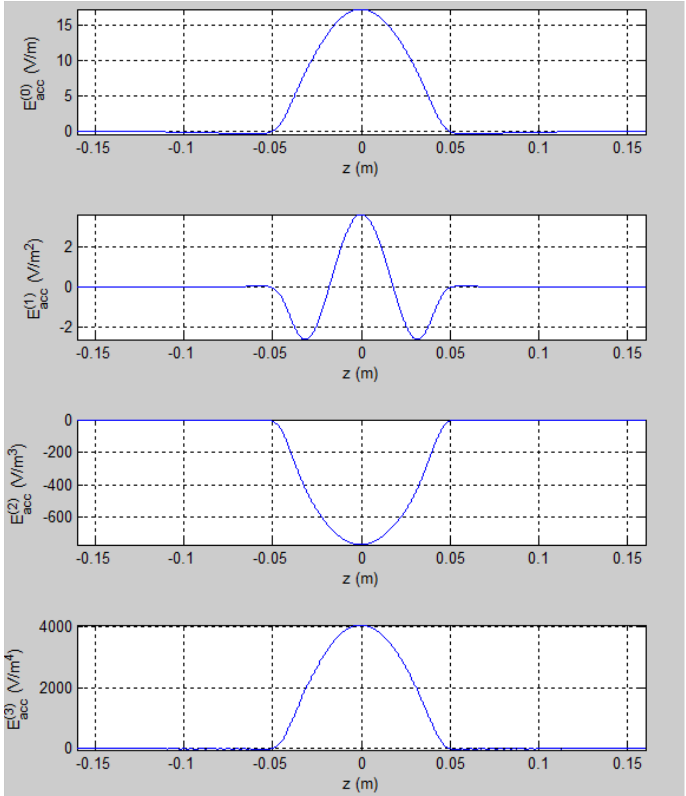
Multipole Analysis

- Time dependent higher order multipole components for an rf cavity can be evaluated following similar method used for magnets

$$E_{acc}^{(n)}(z,t) = E_z^{(n)}(z)e^{j\omega t} = \frac{1}{r^n}\int_0^{2\pi} E_z(r,\phi,z)\left[\boxed{\cos(n\phi)} + \cancelto{0}{j\,\boxed{\sin(n\phi)}}\right]e^{j\omega t}\mathrm{d}\phi$$

Normal components

Skew components



- Using Lorentz force or Panofsky-Wenzel theorem

$$\Delta p_t^{(n)}(z) = \frac{1}{c}r^{n-1}\int_{-\infty}^{+\infty} F_t^{(n)}(z)\mathrm{d}z$$

$$\Delta p_t^{(n)}(z) = -j\frac{q}{\omega}\int_{-\infty}^{+\infty} \nabla_t E_z^{(n)}(z)e^{j\omega t}\mathrm{d}z$$

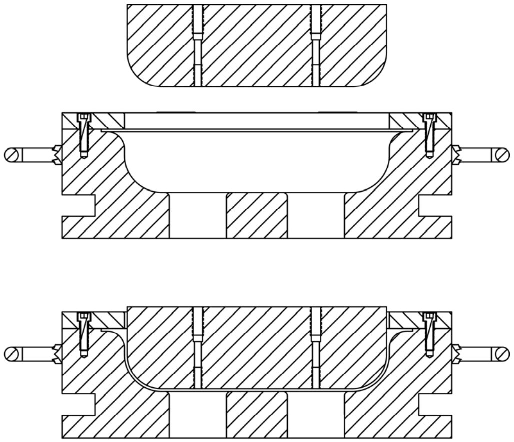
$$A_z^{(n)} + jB_z^{(n)} = \frac{1}{qc}F_t^{(n)}(z) \quad [\mathrm{T/m^{n-1}}]$$

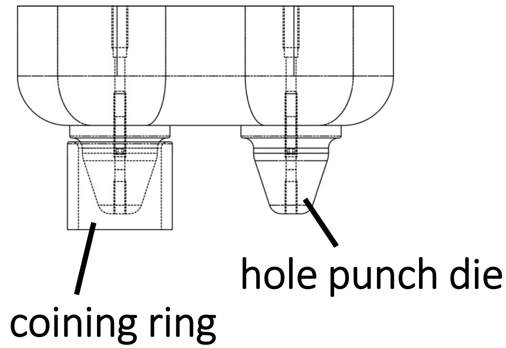
$$a_n + jb_n = \int_{-\infty}^{+\infty}\left[A_z^{(n)} + jB_z^{(n)}\right]\mathrm{d}z \quad [\mathrm{T/m^{n-2}}]$$

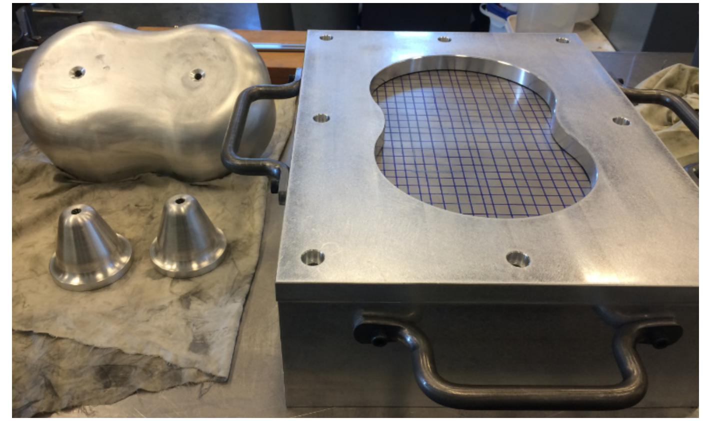
Multipole Components	
V_{acc} [MV]	1.0
V_t [V]	-228.6
b_1 [mT]	-0.00076
b_2 [mT m]	-10.3
b_3 [mT m^2]	76.4
b_4 [mT m^3]	-717.6
b_5 [mT m^4]	6535.7

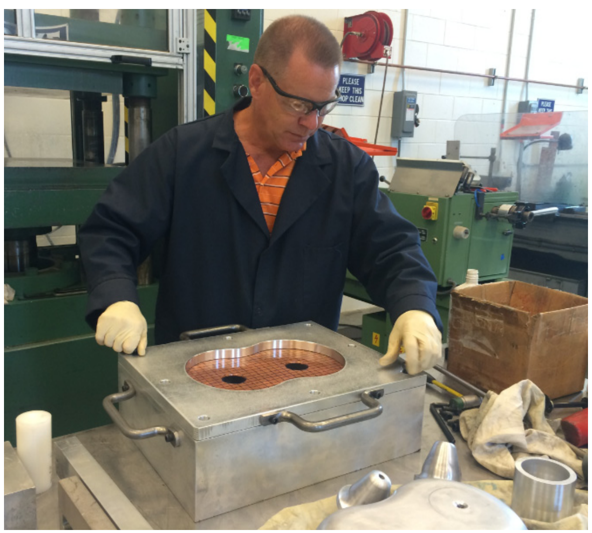
Deep-Drawing of Half Cells

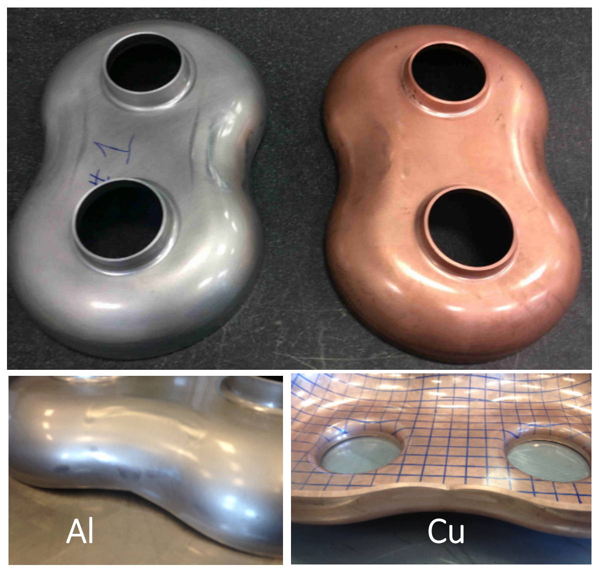
- Deep-drawing study done with Al and Cu discs (1/8” = 3.175 mm thick material)

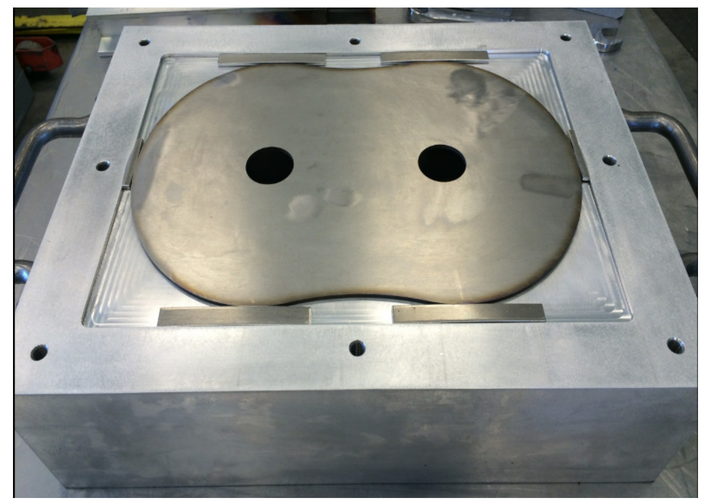






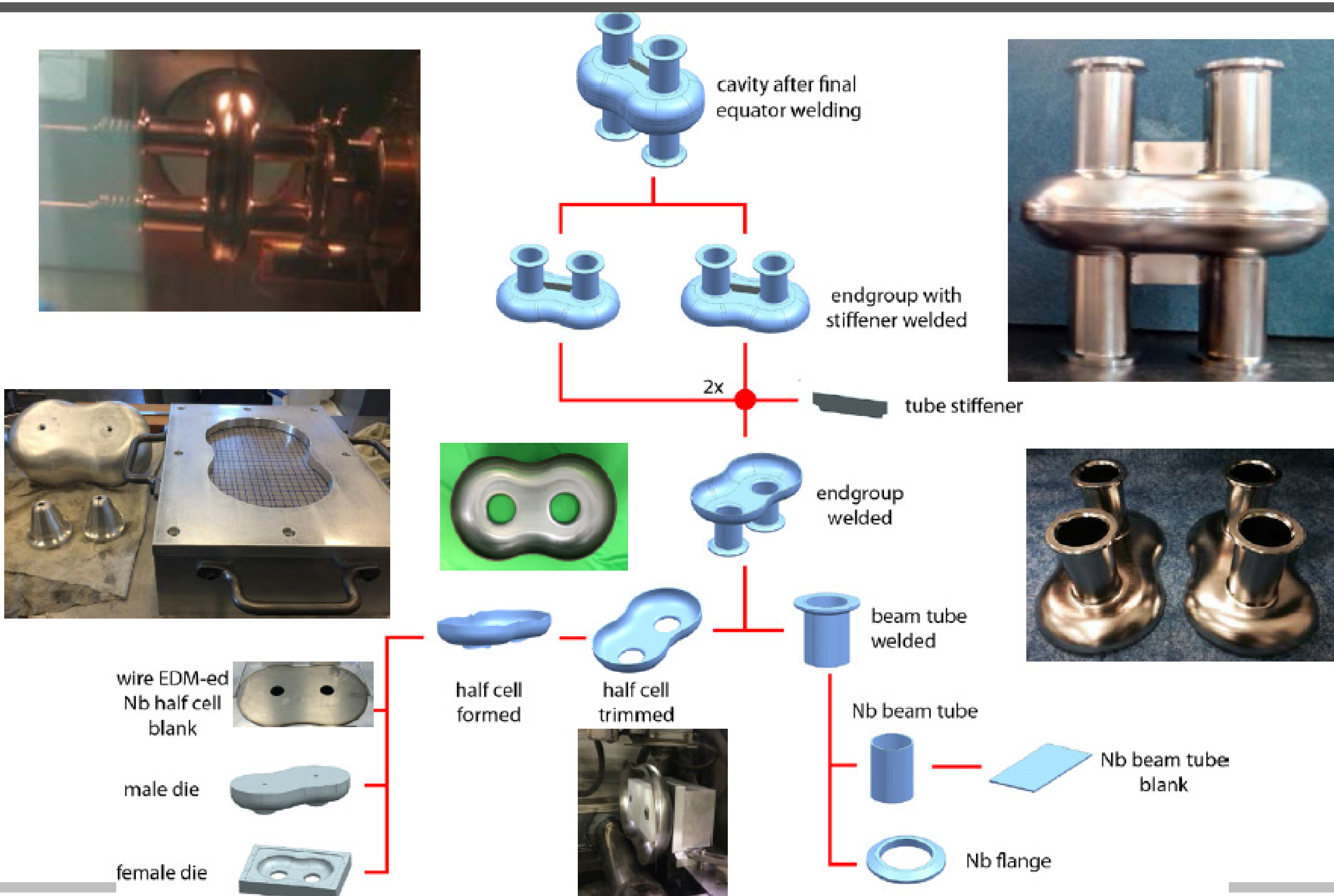






Final Nb blank shape (wire EDMed)

Cavity Fabrication



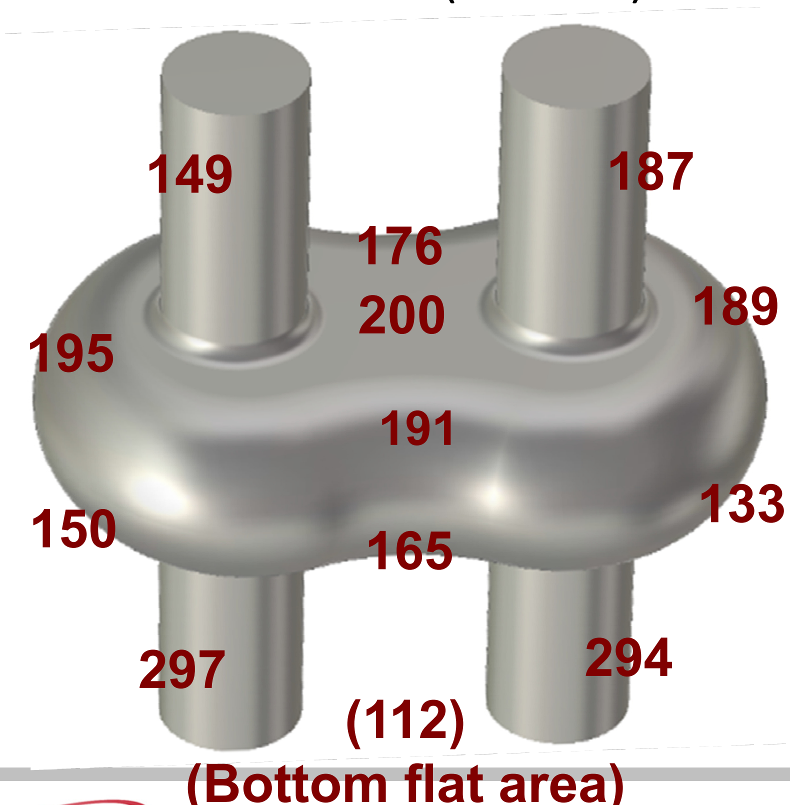
Cavity Processing

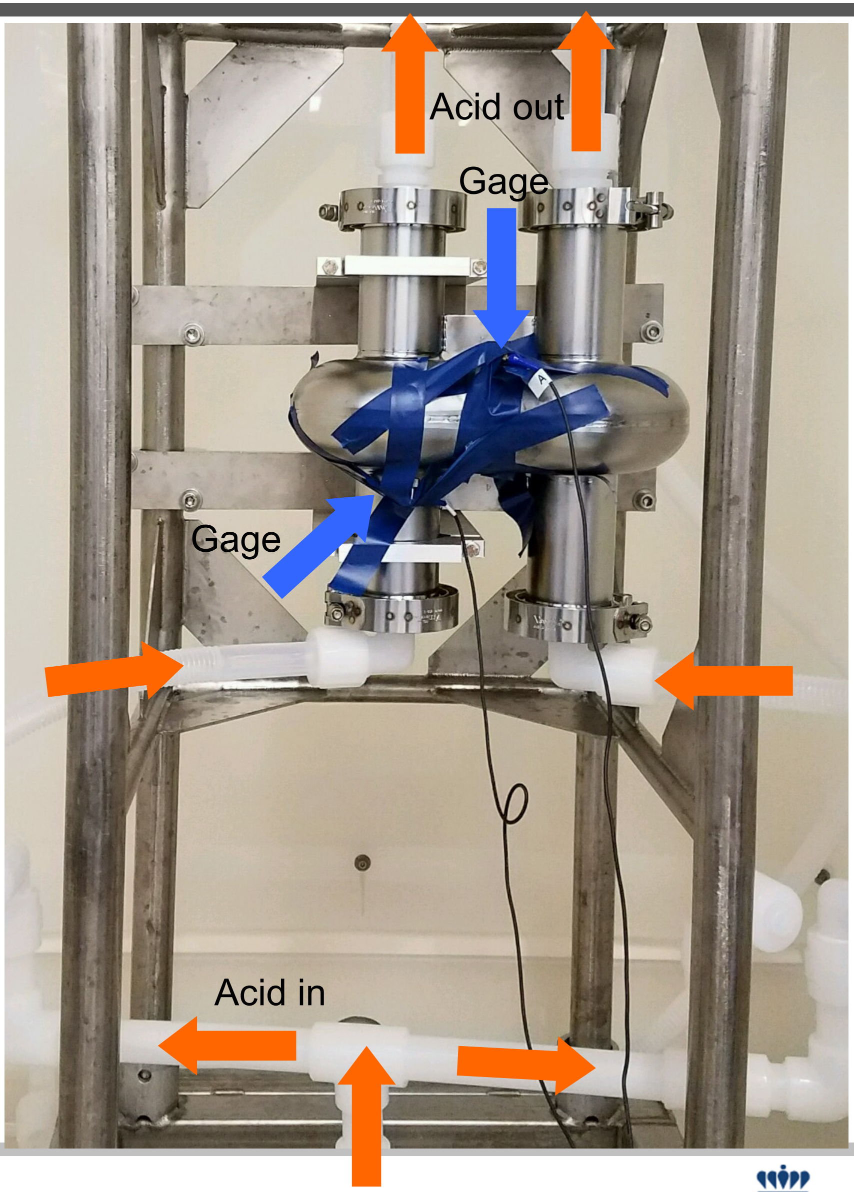
- Bulk BCP of 200 micron
- Heat treatment (degassing) 800 C 3 hours
- Light BCP of 25 micron
- High pressure rinse
- Clean room assembly
- Low temperature bake 120 C 12 hours
- RF test at 2 K

All processing used the elliptical cavity equipment.

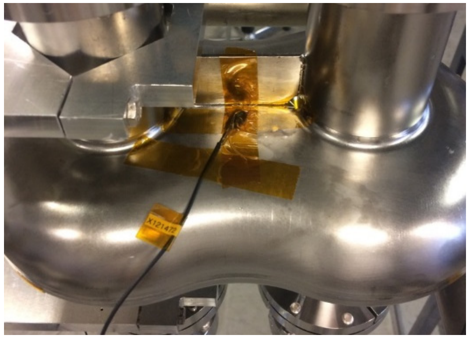
BCP Removal

- One step removal (no cavity flip) at production cabinet.
- Removal monitored by in-situ thickness gage
- Removal results (microns)

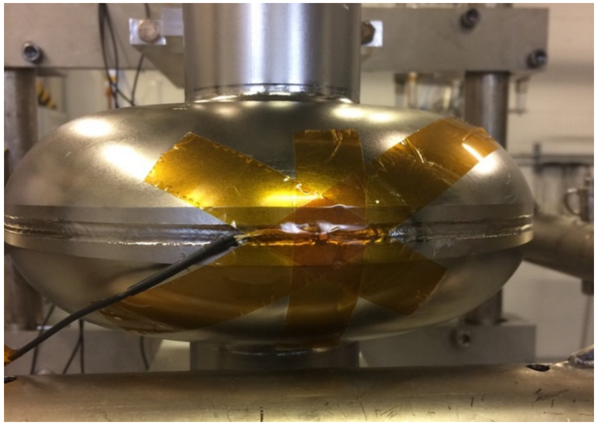


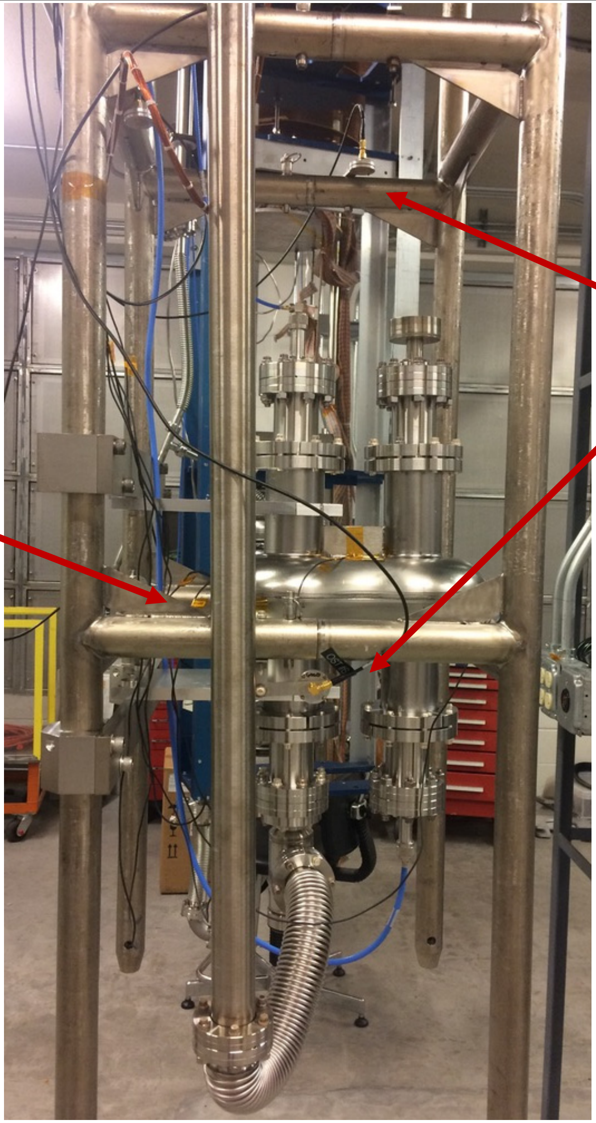


Instrumentation

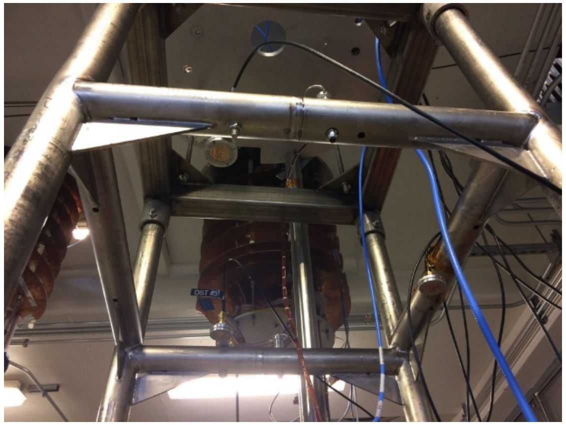


4 Cernox sensors
around the cavity



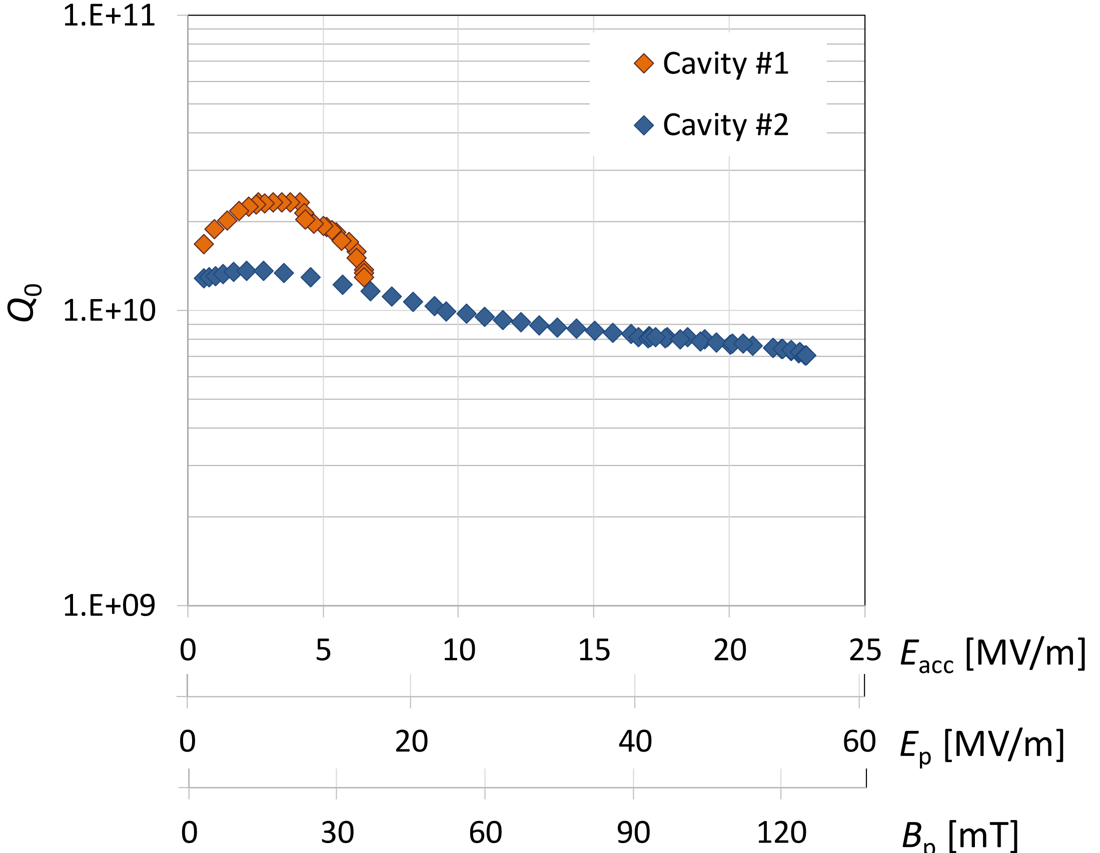


OST sensors 3 on top
3 around the cavity



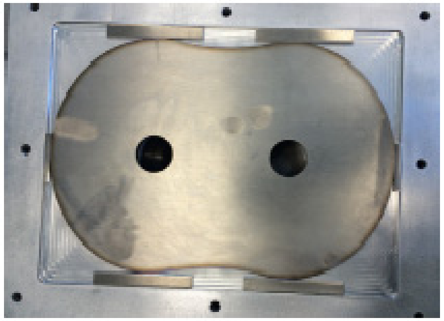
RF Test Results

- Cavity 1:
  - Low field Q_0 of 2.3×10^{10}
  - Cavity quenched at 6.5 MV/m
  - Weld defect seems to be the limiting factor according to OST measurements
- Cavity 2:
  - Low field Q_0 of 1.3×10^{10}
  - Achieved an accelerating gradient of 23 MV/m (E_p = 56 MV/m & B_p = 126 mT)
  - No multipacting levels were observed during the test
  - Given minimal surface treatment (BCP only, no EP) cavity reached high Q_0
- Cernox and OST data indicate the quench location at the weld defect area for cavity #1.



Lessons Learned - I

- Blank study – one iteration was enough to determine final blank shape
- Half cell shape (flat surface between beam pipes) allows minimal trimming fixture
- Spring back was surprisingly uniform in spite of non-axisymmetric perimeter
- Material thickening at equator was not uniform
  - Made weld joint machining complicated and contributed to weld problem



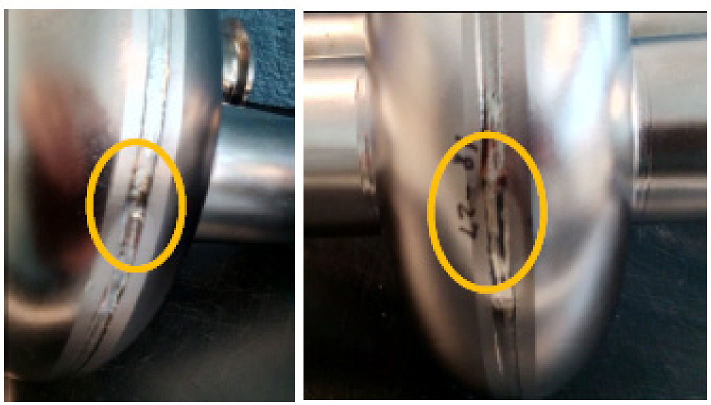
Final Nb blank

1st stage forming

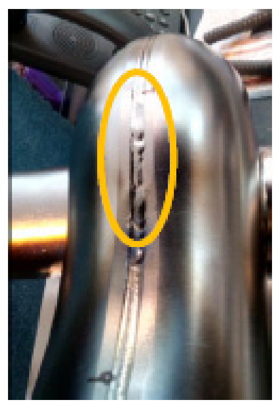
EDM trimming

Lessons Learned - II

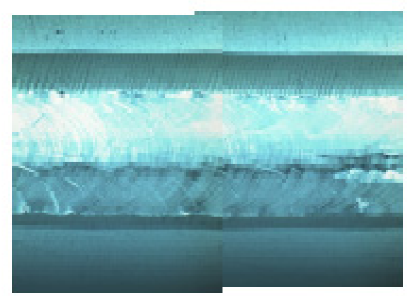
- Final equator welding was eventful!!
- Old EBW machine – manual control, hard to keep the constant ebw energy on the weld path. Newer machines have capability to work with CAD.
- Non uniform weld joint thickness did not help
- Excessive weld beam current left a couple of melt-through holes which were patched later
- 2nd prototype was prepared more carefully to have uniform thickness all around the perimeter → Improved but still had same issues



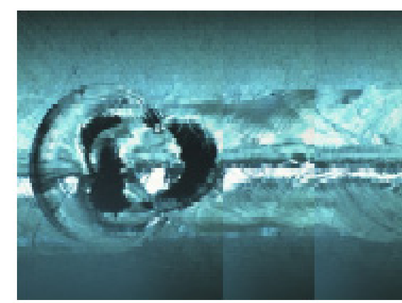
1st prototype



2nd prototype



Clean weld seam



Patched area

Summary

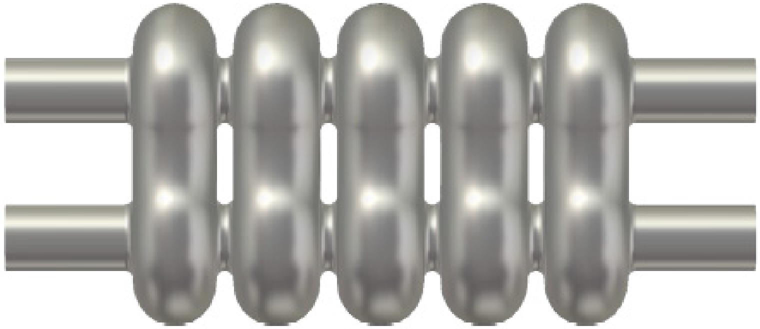
- Twin axis cavity proved:
  - Reasonable rf properties
  - No multipacting
  - Low higher order multipole components
  - Well separated LOM and HOMs
  - Fabrication and cavity processing within current technology
  - Excellent performance given minimal surface treatment (no EP) and no equipment was optimized for the twin axis cavity.

- Twin axis cavity would provide efficient energy transfer in two beam line energy recovery linacs.

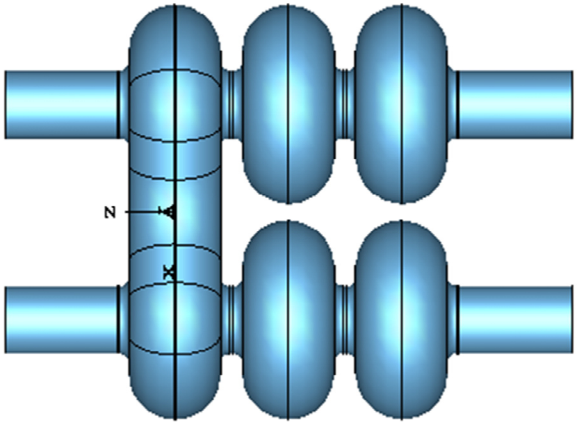
- Compared to the same cell ERLs this will allow stable energy recovery in higher current at the cost of increased cryogenic consumption.

More to be Learned

- HOM damping
- Tuning scheme
- More study is needed for the applicability of these two concepts.



vs.



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  - Subashini De Silva, Jean Delayen – ODU CAS
  - Frank Marhauser, Andrew Hutton – Jefferson Lab

- Work involved many others:
  - JLab machine shop in tooling/cavity fabrication
  - SRF Institute in cavity fabrication, processing, and test