Superconducting Half Wave Resonator Design and Research

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Outline

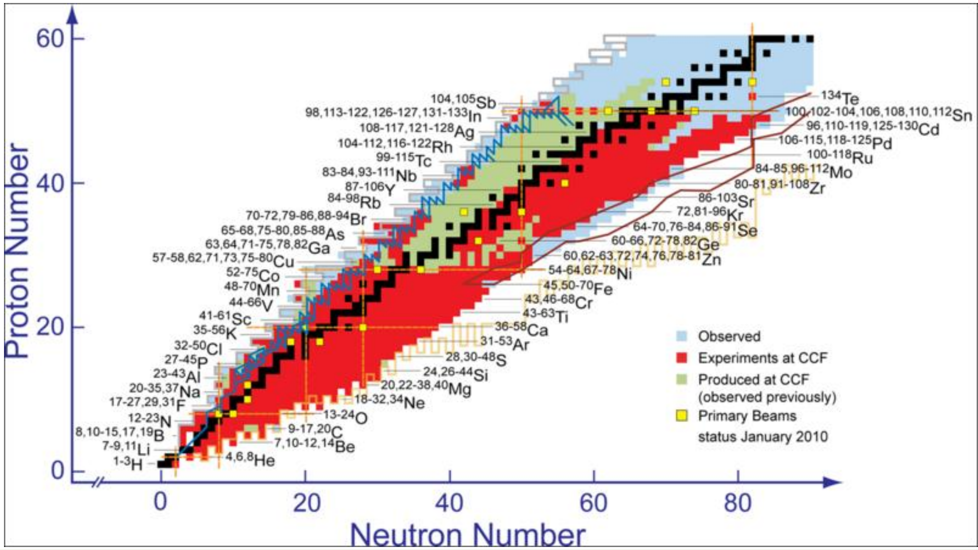
- Design Motivation
  - Facility for Rare Isotope Beams (FRIB)
- Cavity Theory
  - Low Beta Superconducting Cavities
  - Resonator Figures of Merit
- Existing Knowledge Base
  - Ongoing prototyping and testing of Half Wave Resonators at Michigan State University
- Detailed Design of a Half Wave Resonator
  - Electromagnetic Design/Optimization
  - Coupled Electromagnetic & Mechanical Simulations

The Facility for Rare Isotope Beams

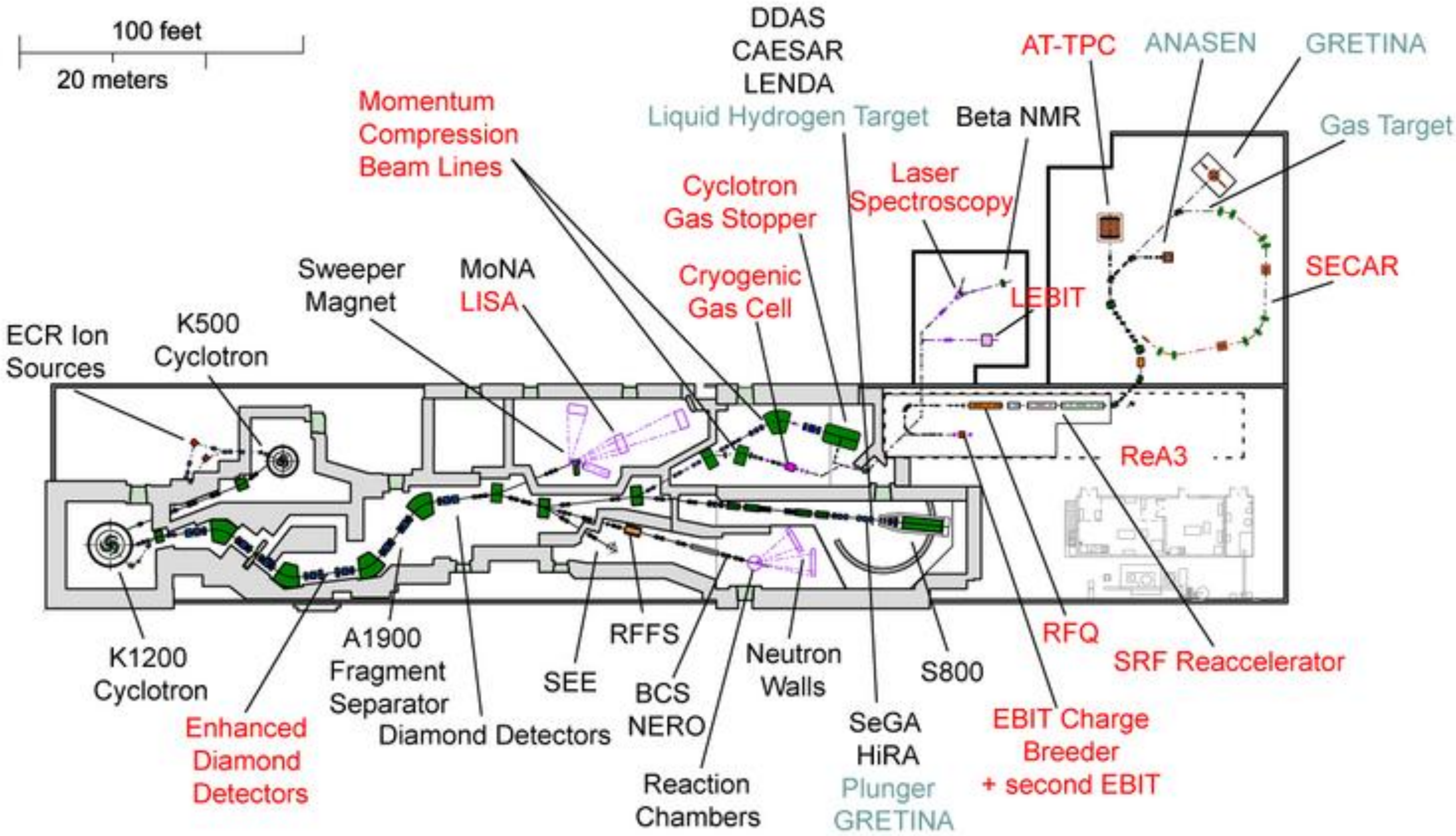
A Brief Overview

National Superconducting Cyclotron Laboratory (NSCL)

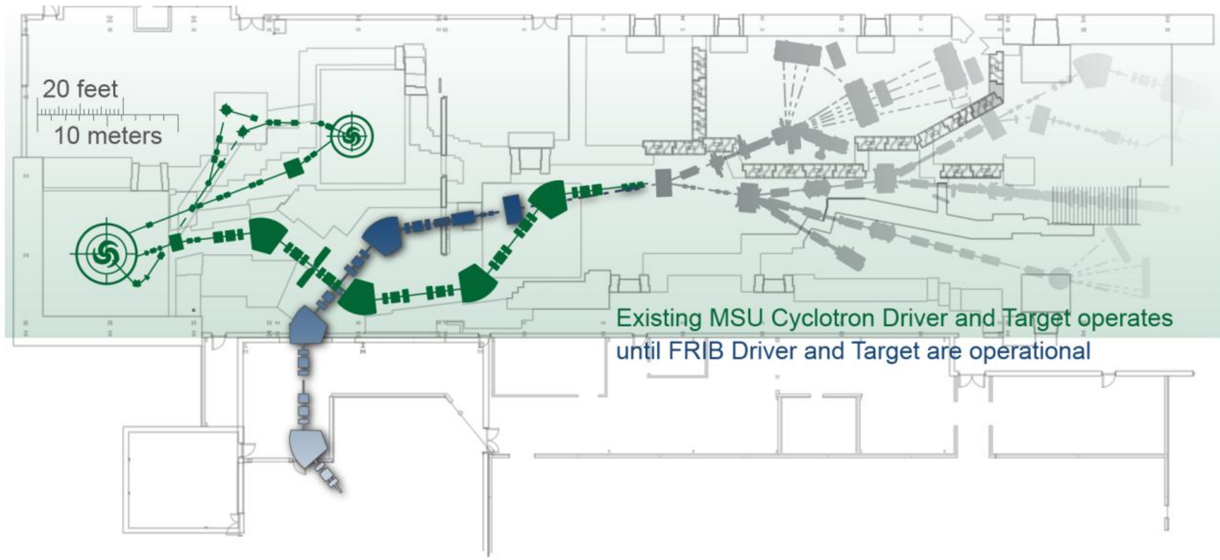
- World-Leading Nuclear Physics
  - 10% of US Nuclear Ph.D.s
  - #1 US Physics Graduate Program for Nuclear Physics (US News and World Report, 2010)
  - ~400 employees on the campus of Michigan State University operated by the National Science Foundation
  - International User community of over 700
  - Capable of producing up to 170 MeV/u rare isotope beams through thin target nuclear fragmentation

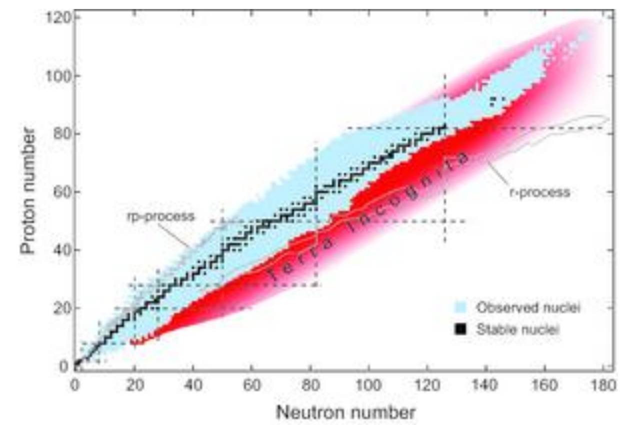


NSCL Facilities



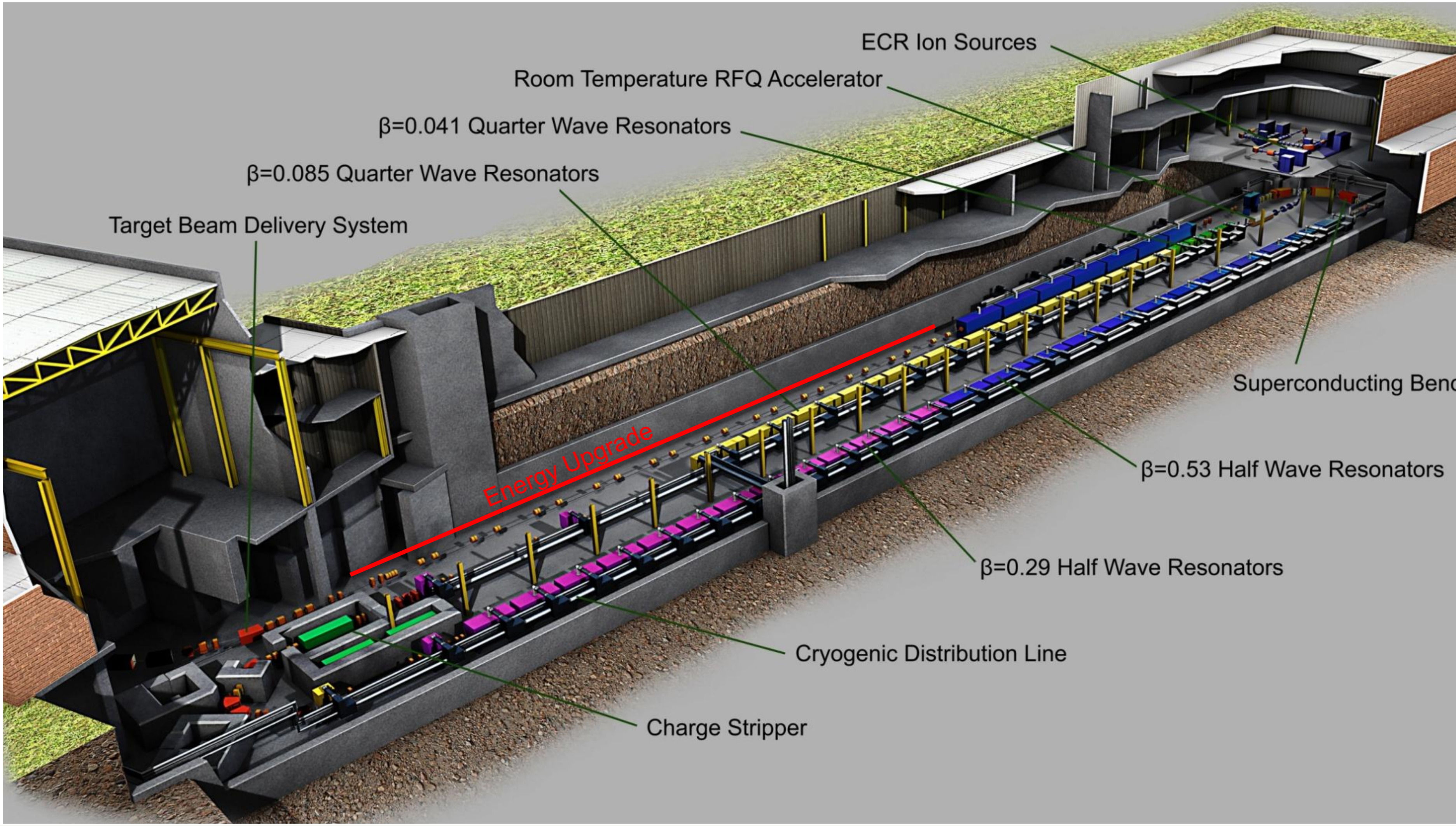
FRIB as the Future





- FRIB is a superconducting driver linear accelerator that will replace the Coupled Cyclotron Facility (CCF)
  - Primary beam power upgrade from 1-2 [kW] to 400 [kW]
  - Maximum Energy upgrade from 160 to 200 (400) [MeV/u] for Uranium
- Integrates into the existing CCF experimental program
  - Secondary beams injected directly into reconfigured A1900 fragment separator for use by existing and expanding scientific program

FRIB Driver Linac

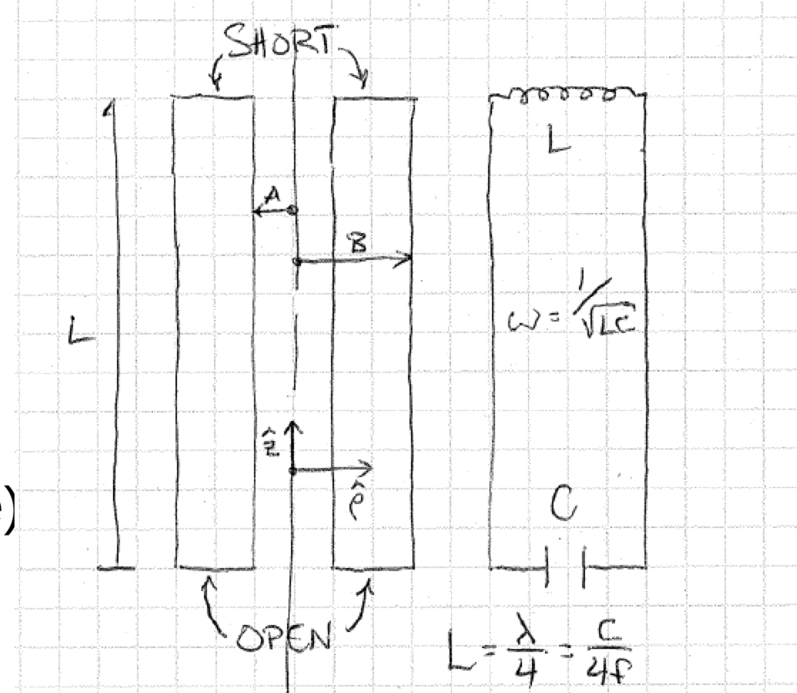


Low Beta Superconducting Resonators

A Introduction to Quarter Wave and Half Wave Resonators and their Figures of Merit

Quarter Wave Resonators

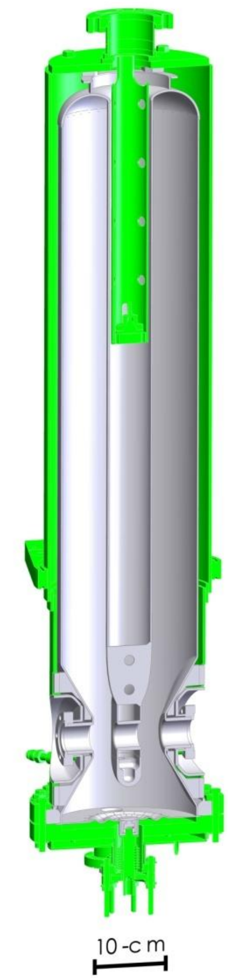
- Coaxial Resonator
  - Effective open and short termination
- Low Frequency Structure
  - Allows for efficient acceleration of low beta beams
- Accelerating Field
  - Two gap structure (Pi-Mode like)
- Steering
  - Asymmetric design leads to slight beam steering
- Open end for access/processing
  - Open end for cavity processing and inspection



$$\frac{\lambda\beta_{opt}}{2} = A + B$$

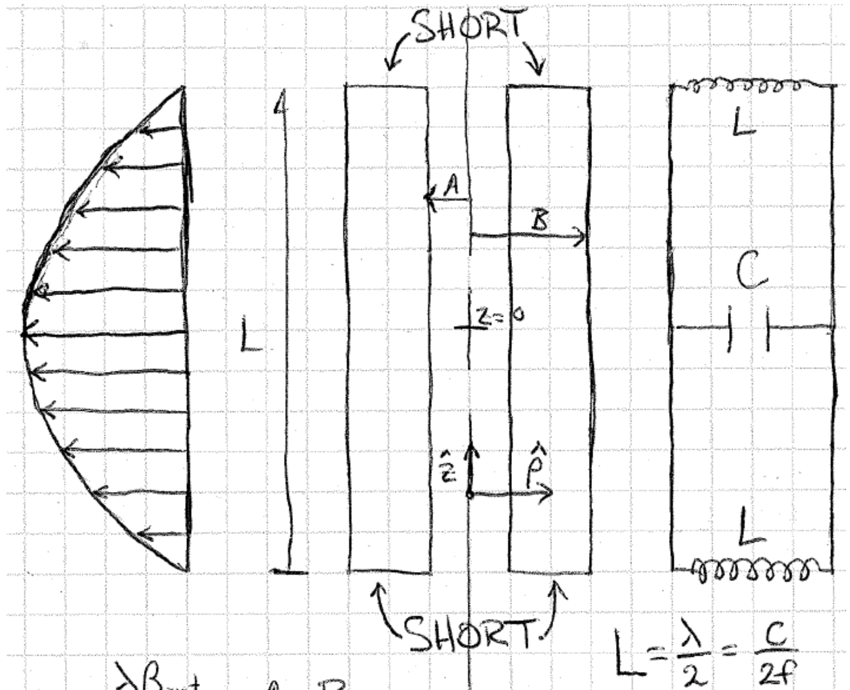
$$\vec{E}(\rho,\phi,z) = \frac{E_0 A}{\rho}\cos\left(\frac{\pi z}{2L}\right) e^{i\omega t}\,\hat{\rho}$$

$$\vec{B}(\rho,\phi,z) = \frac{E_0 A}{c\rho}\sin\left(\frac{\pi z}{2L}\right) e^{i(\omega t+\pi/2)}\,\hat{\phi}$$



Half Wave Resonators

- Coaxial Resonator
  - Two effective short terminations
- Higher Frequency Structure than QWR
- Accelerating Field
  - Two gap structure (Pi-Mode like)
- HWR v. QWR
  - Higher optimum beta
  - No beam steering
  - Double the losses
  - No easy access

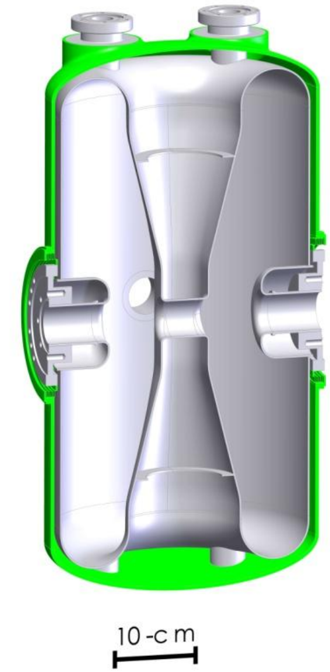


$$L = \frac{\lambda}{2} = \frac{c}{2f}$$

$$\frac{\lambda \beta_{opt}}{2} = A + B$$

$$\vec{E}(\rho,\phi,z,t) = \frac{E_0 A}{\rho} \cos\left(\frac{\pi z}{2L}\right) e^{i\omega t}\, \hat{\rho}$$

$$\vec{B}(\rho,\phi,z,t) = \frac{E_0 A}{c\rho} \sin\left(\frac{\pi z}{2L}\right) e^{i(\omega t + \pi/2)}\, \hat{\phi}$$

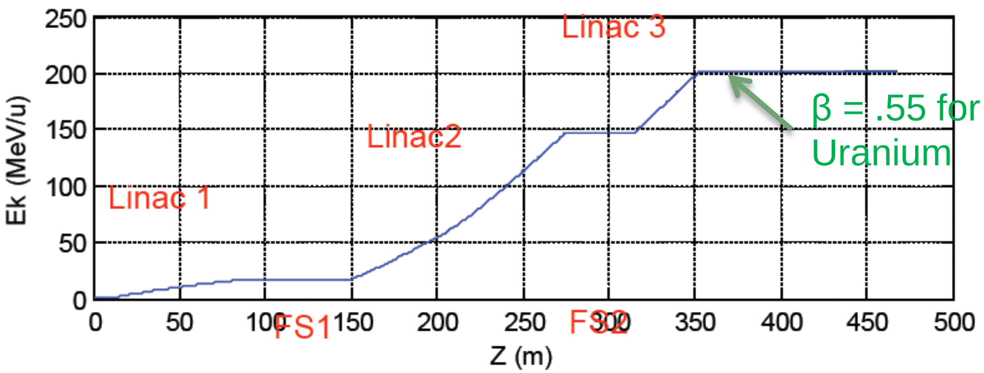


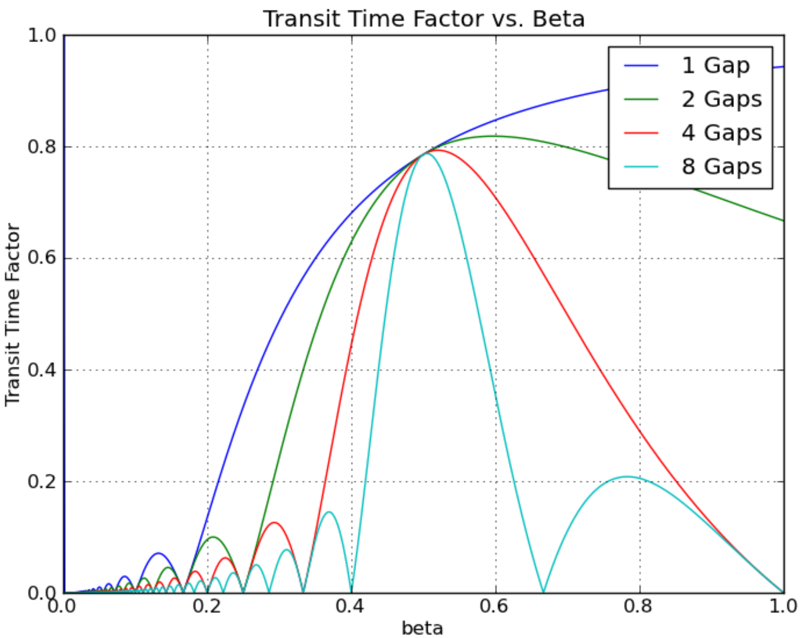
QWR and HWR usage for FRIB

- Transit Time Factor is a measure of the loss of acceleration from the fields varying with time
  - More synchronized gaps reduces the velocity range of particles you can efficiently accelerate

$$TTF = \frac{Vacc}{V_0} = \frac{\int_{-\infty}^{+\infty} E_{acc} \sin\left(\frac{\omega z}{\beta c} + \phi\right) dz}{\int_{-\infty}^{+\infty} |Eacc| dz}$$

- Flexible Primary Beam
  - FRIB is designed to accelerate anything from Oxygen to Uranium
  - 2-gap structures offer this flexibility





How are cavity designs judged?

- Efficiency Figures of Merit
  - R/Q (Effective Shunt Impedance)
    - » Measure of how effectively the cavity can transfer its stored energy to the beam

$$\frac{R}{Q} = \frac{V_{acc,\beta_{opt}}^2}{\omega U}$$

  - Geometry Factor (Quality Factor)
    - » Measure of how efficiently the cavity stores energy

$$G = r_s Q = \frac{\omega U r_s}{P_d}$$

  - Transit Time Factor
    - » Measure of possible acceleration lost by time-varying fields (not as critical for SRF cavities)

- Electromagnetic Figures of Merit

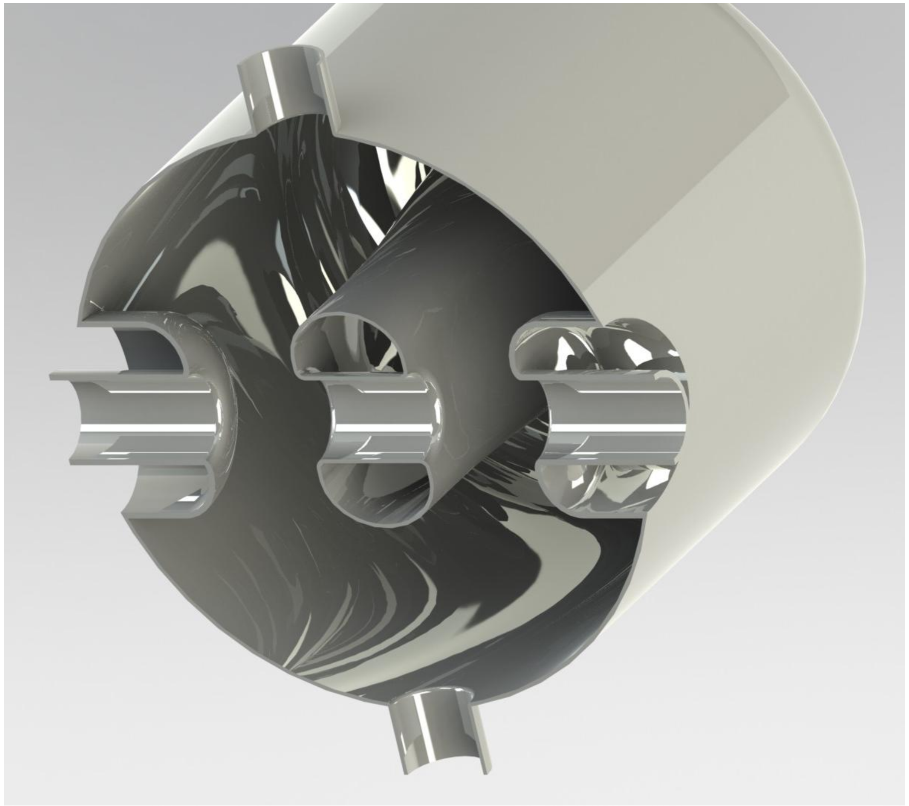
$$\frac{V_{acc}}{\sqrt{U}} \quad \frac{E_{pk}}{\sqrt{U}} \quad \frac{B_{pk}}{\sqrt{U}}$$

  - These simulated quantities are required to interpret cavity test data
  - These values may not accurately represent the reality of a cavity

- Performance Limits
  - High surface electric fields give more risk of field emission, tighter processing tolerances (~30 [MV/m])
  - High surface magnetic fields limit ultimate cavity performance at quench field (~120 [mT] for low beta)

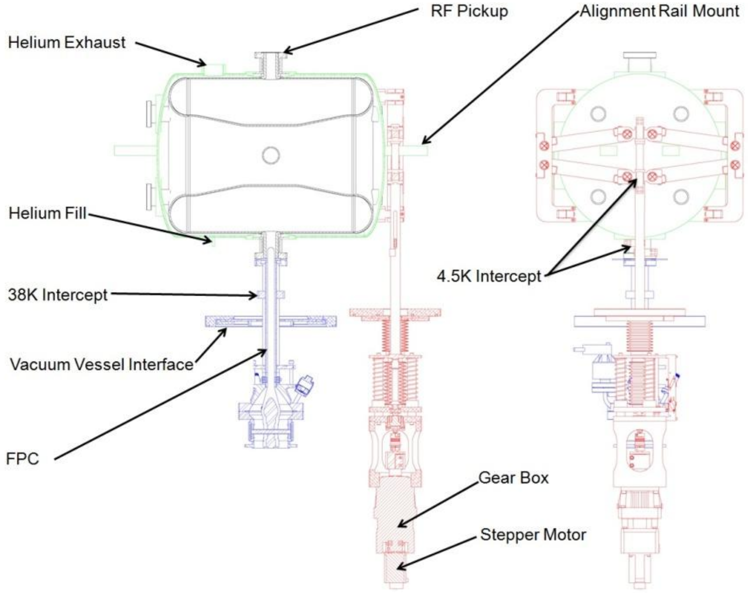
Judging Mechanical Behavior

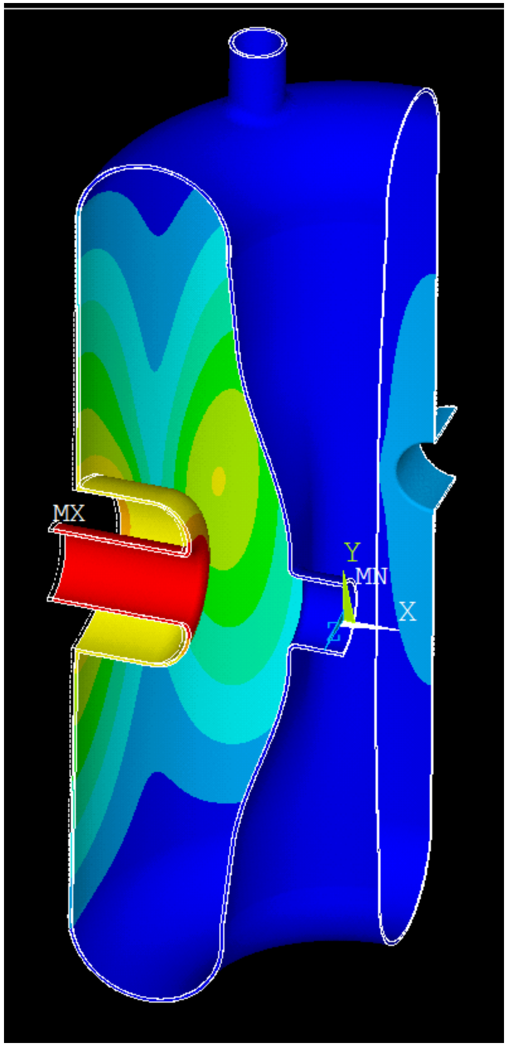
- The cavity is not static and unchanging in operation
  - The cavity will have a variety of pressures exerted on it, and the resulting deformation may shift the cavity frequency
  - These shifts in cavity frequency must be understood and optimized to give the best performance in operation
- Relationship between applied pressures and deformation depends strongly on mechanical design and fabrication



Cavity Tuning

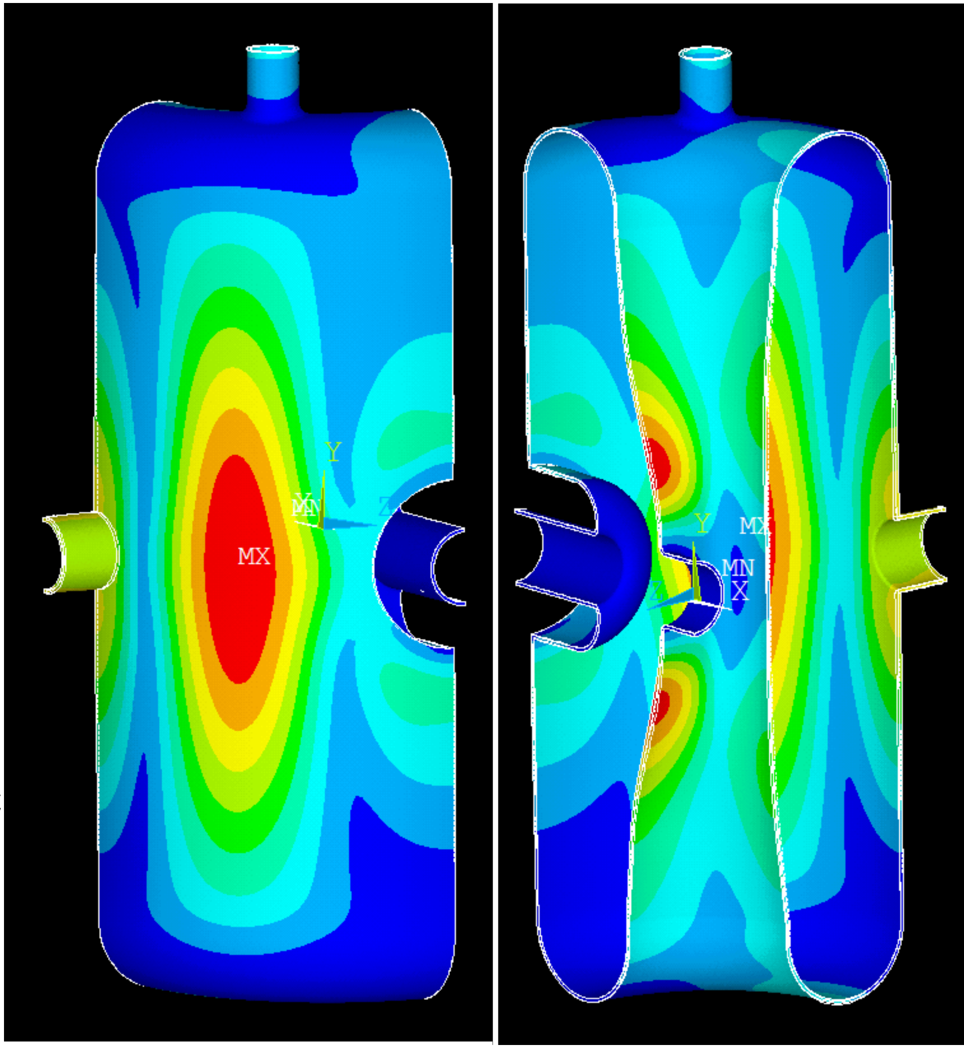
- Tuning Parameters
  - Our HWR designs are tuned through beam port deformation
  - Force is applied symmetrically on the beam ports
  - Force required, resulting deformation, and frequency shift are simulated
  - These numbers are used to drive tuner design





Pressure Sensitivity

- Helium bath pressure sensitivity
  - Cavity will be cooled by liquid helium at ~28 torr, but this will vary
  - Varying pressure will deform the cavity
  - This deformation cannot affect the cavity frequency more than the LLRF can control it
  - Desired shift is |df/dP| < 2 Hz/torr
- Mitigation Techniques
  - Overall stiffening can be used to improve performance (expensive)
  - Deformation in magnetic and electric regions contribute opposite shifts
  - Careful choice of stiffening can be used to tune these shifts, giving very small |df/dP|



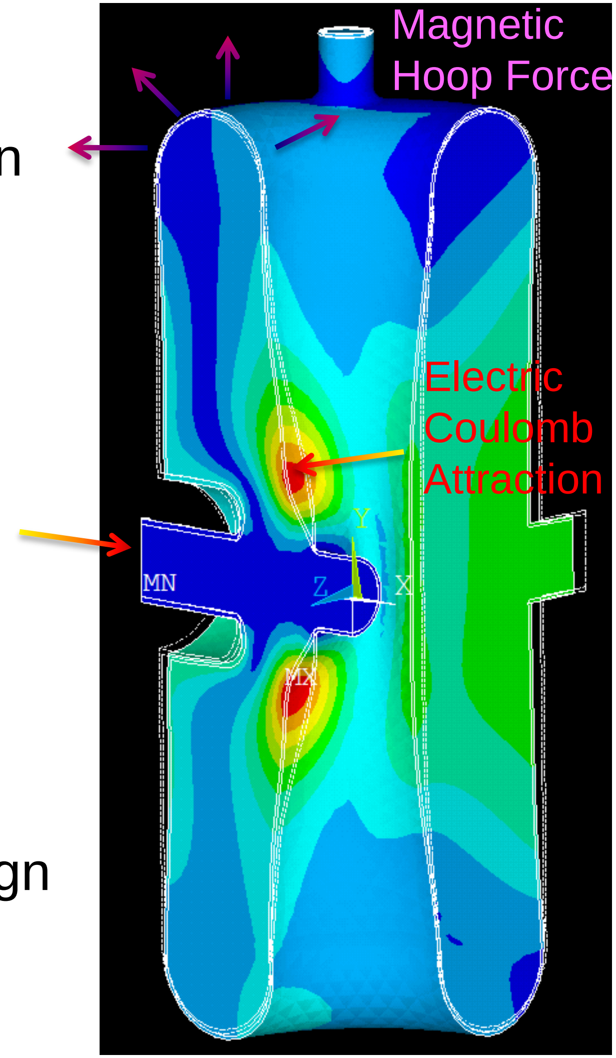
Lorentz Force Detuning

- Cavity/Field Interaction
  - The fields in the cavity interact with the surface currents and charges they induce, inducing force on the cavity

$$\frac{\Delta f}{f_0} = \frac{1}{4U}\int_{\Delta V}(\epsilon_0 E^2 - \mu_0 H^2)dV = -\frac{1}{U}\int_{\Delta V}(P)dV$$

$$K_L = \frac{\Delta f}{(\Delta E_{acc})^2}; E_{acc} = \frac{V_{acc,\beta_{opt}}}{\beta_{opt}\lambda}$$

  - Note: PdV is always positive, meaning Δf is always negative
- Mitigation Techniques
  - Compensation cannot be used, as with df/dP
  - Overall design philosophy of a very stiff cavity design
  - CW operation allows larger tolerance
  - K_L > -3 [Hz/(MV/m)^2] is desired



Historical Use of Low Beta SRF Resonators

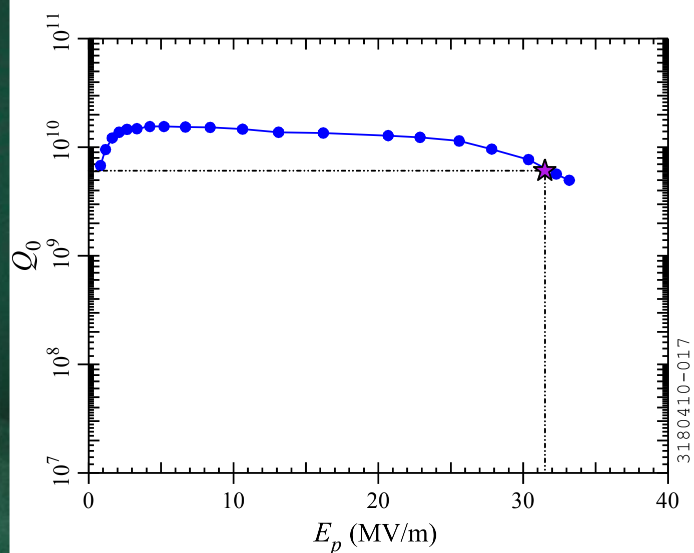
- QWR Operational Experience:
- PIAVE-ALPI at INFN-Legnaro
  - ~80 SRF cavities booster for a tandem
- ATLAS @ Argonne National Lab
  - Countless contributions to the technology
- ISAC – II @ TRIUMF
  - RIB Post Accelerator
- SPIRAL2 – Light Ions for RIB Production
- RεA3(6) – Under construction @ MSU
- *Very Little for HWRs*
- SARAF – Progress accelerating light beams

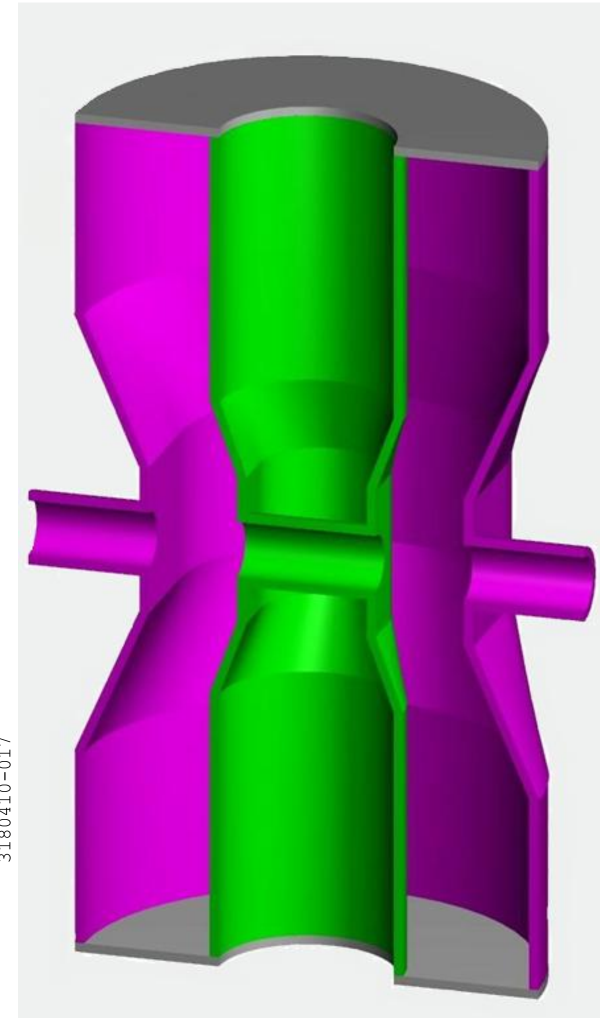
Experience with HWRs at Michigan State University

Prototyping and Testing

322 [MHz], β = 0.29 HWR for RIA

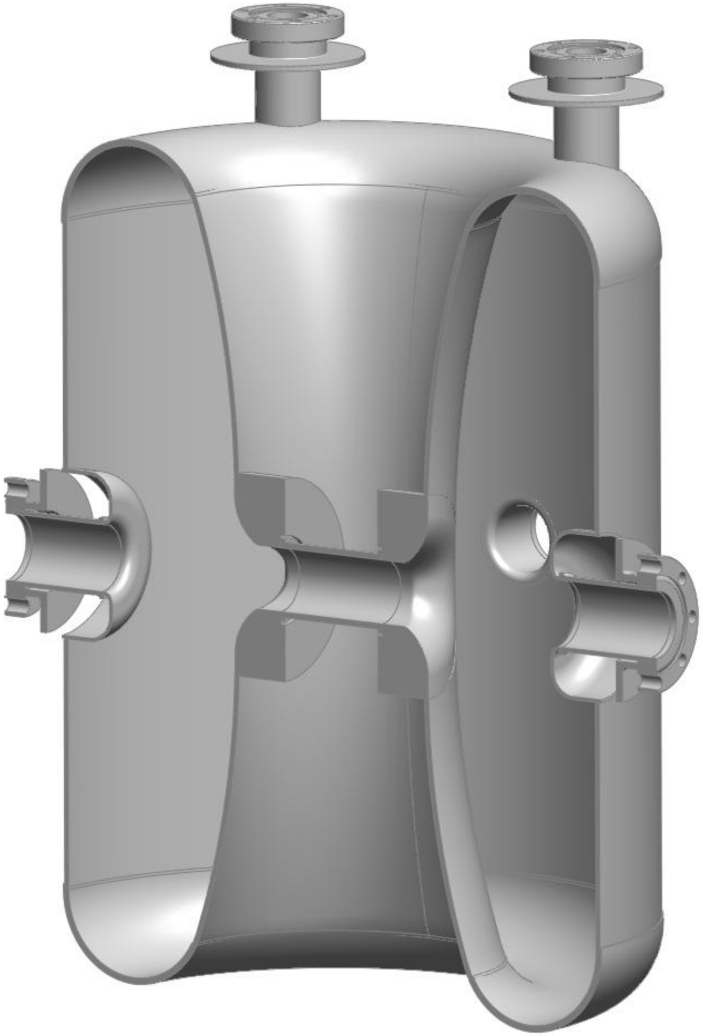
- Prototyped and Tested in Cryomodule
  - Extremely simple construction
  - Little electromagnetic optimization
  - Achieved electromagnetic goals at 2K
  - Poor mechanical performance





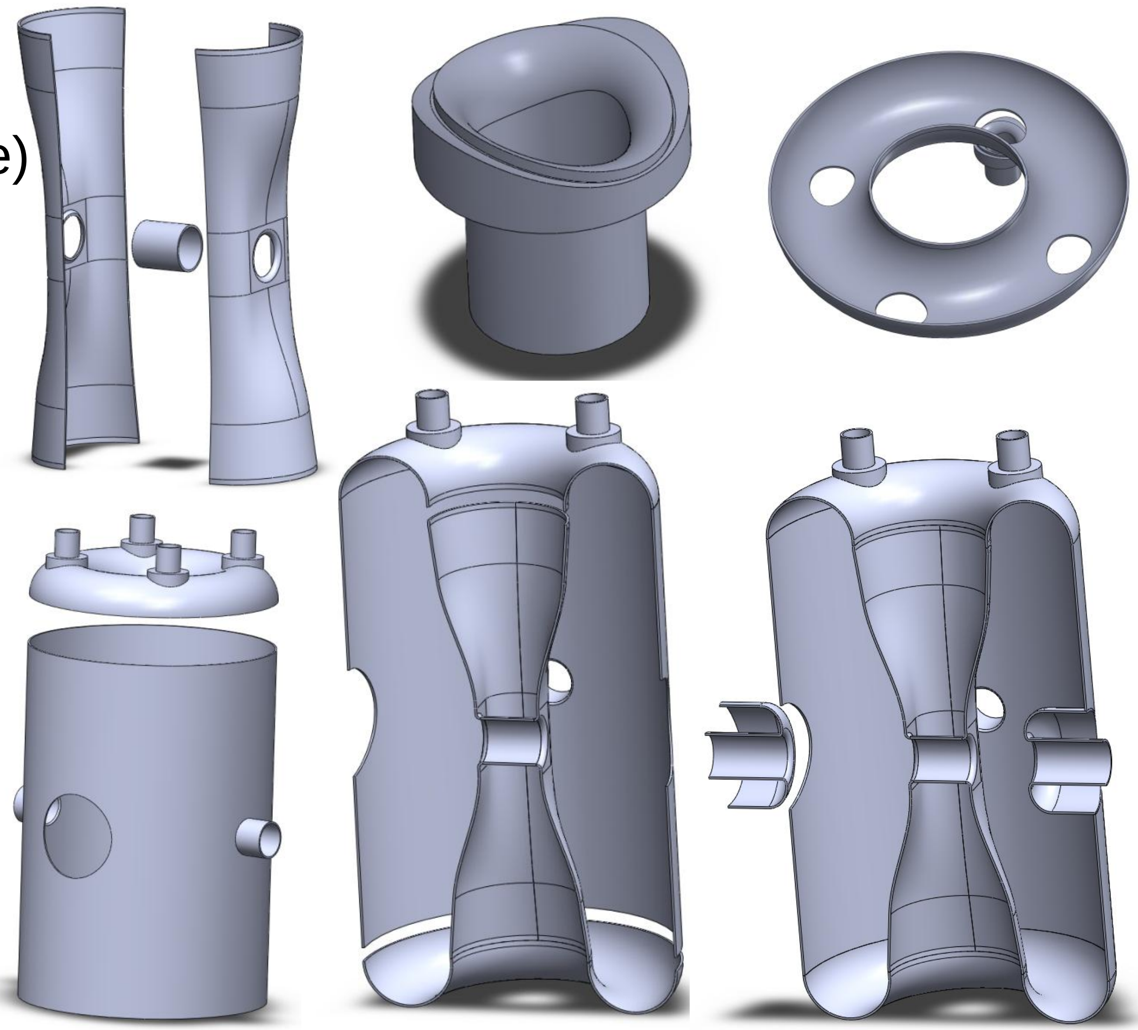
322 [MHz], β = 0.53 HWR for FRIB

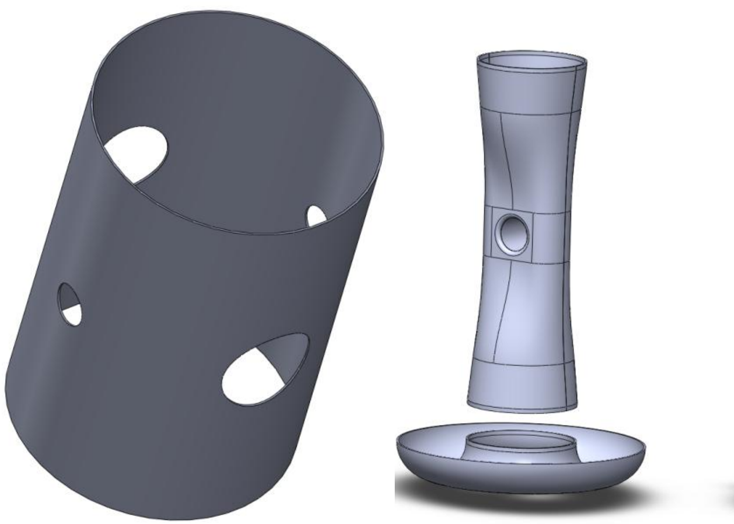
- Five HWR53s have been fabricated
  - 1 was made in-house at NSCL
  - 4 were ordered as subassemblies from industry (Roark & AES) and finished in-house
- Four cavities have been tested
  - Three have achieved FRIB field and quality factor
  - Quench limit is between 90 mT and 110 mT (design Bpk ~75 mT)
- Testing has successfully demonstrated cleaning and processing equipment



Fabrication

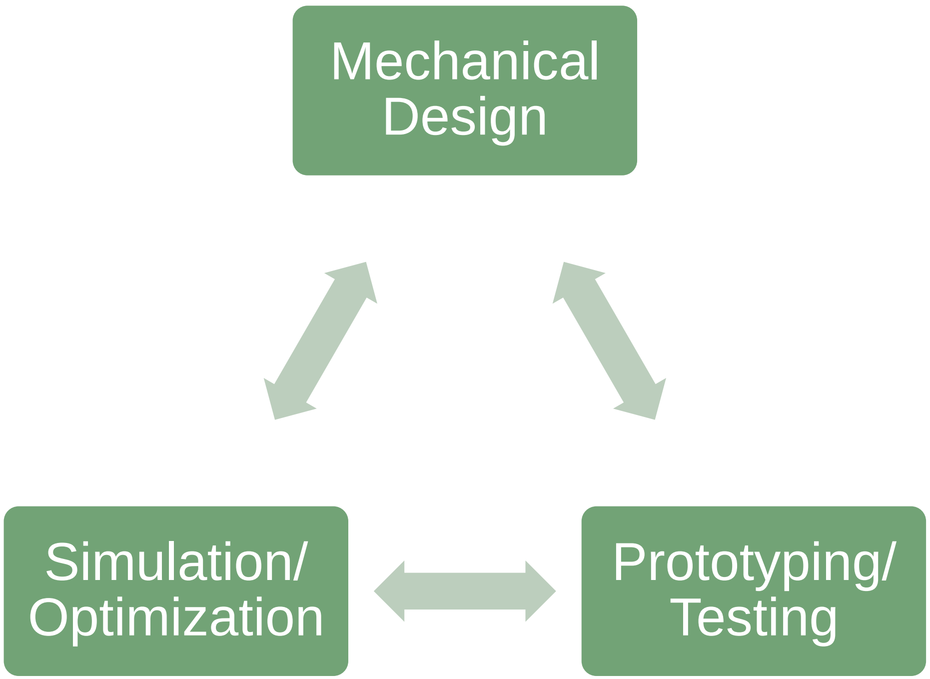
- Subassemblies
  - Outer Conductor
  - Inner Conductor (w/drift tube)
  - Beam Port Cups
  - Short Plates
  - Rinse Ports
  - Coupler Ports





Cavity Design Cycle

- Cavity design is very complex
  - Electromagnetic performance
  - Electromechanical performance
  - Mechanical performance
  - Complexity/Repeatability of fabrication
    - » Forming/Trimming
    - » Welding
    - » Processing/Handling
  - COST
- Simulated cavity is the *GOAL*
  - Simulations have no imperfections
  - Simulated results are used to interpret cavity test data
  - The goal of cavity design is to have fabricated cavities converge toward simulated performance

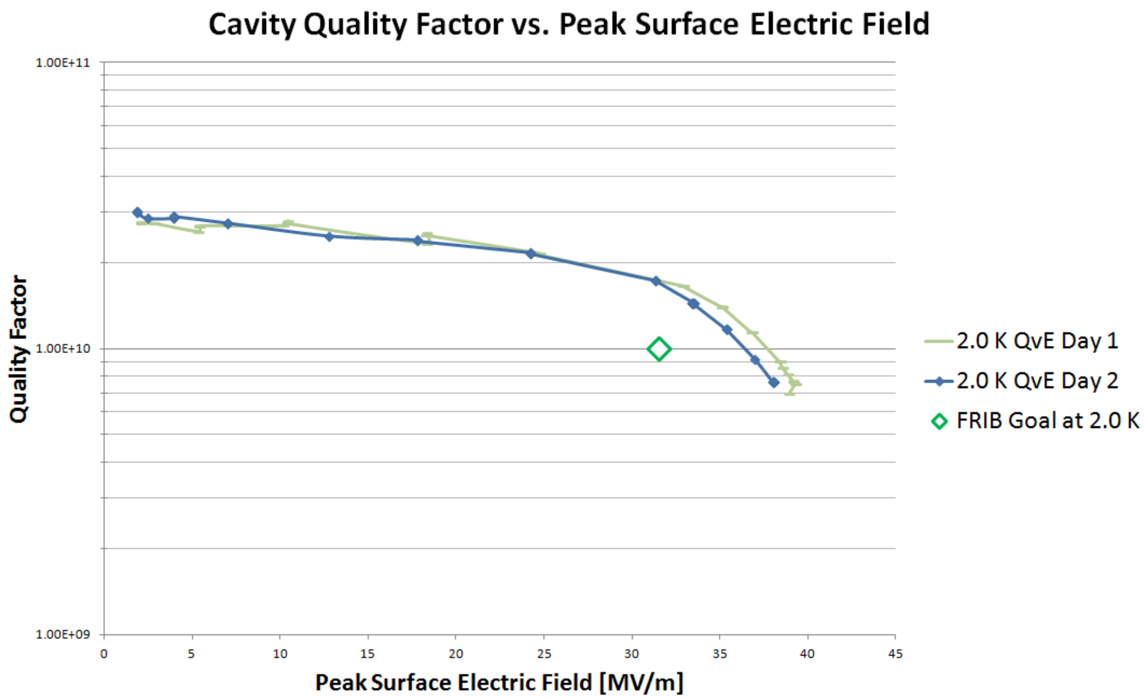


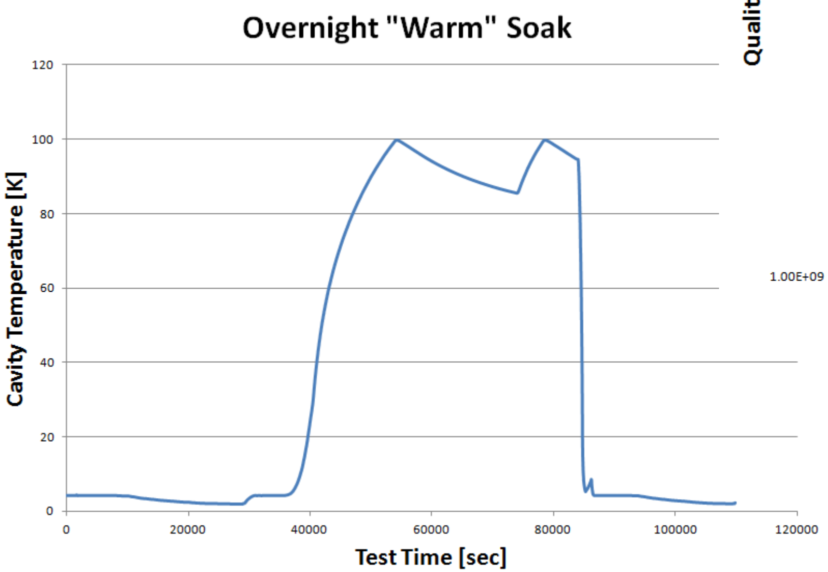
Cavity Test Setup and Goals

- Verify Cavity Performance
- Verify Effectiveness of Cavity Baking
  - The cavity was baked for 10 hours at ~600ºC in vacuum to drive off hydrogen in the bulk material
  - This hydrogen, introduced mostly during etching, forms lossy Niobium-hydrides if the cavity is cooled too slowly
  - After first day of testing, cavity was warmed to ~100K and “soaked” at that temperature overnight
  - The cavity was cooled and retested the second day of testing

Cavity Testing Results

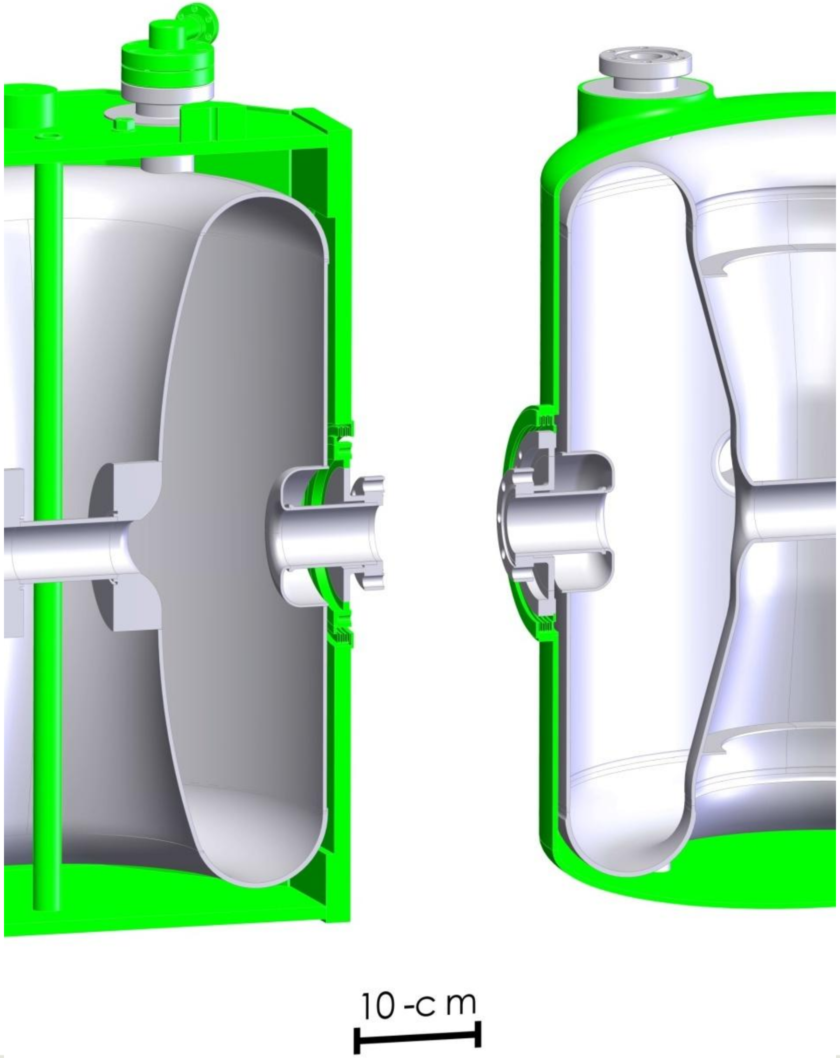
- Good electromagnetic performance
- Strong high field Q-slope
  - Weld Quality?
- Repeatable quench limit
  - ~93 [mT]





Advanced Manufacturing Design

- Design Modifications
  - Several modifications based on cavity testing and vender experience
- Subassembly Tolerances
  - Welding presented a significant challenge depending on subassemblies tolerances
  - Instead of tightening tolerances ($$$), a short straight section was added on the inner conductor
  - This allowed a stacking/trimming step before welding for increased repeatability and quality of the weld
- Other changes
  - Plungers removed, Drift tube simplified

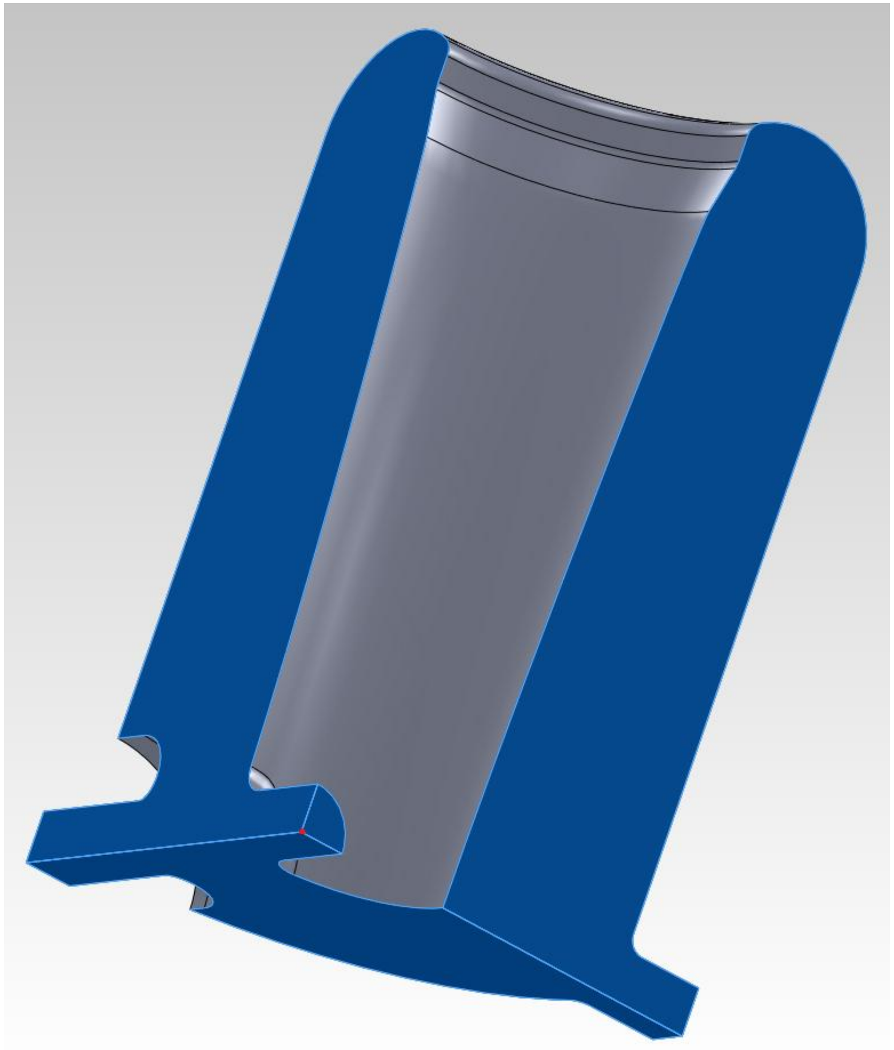


Half Wave Resonator Design: Simulation and Optimization

A Worked Half Wave Resonator Design

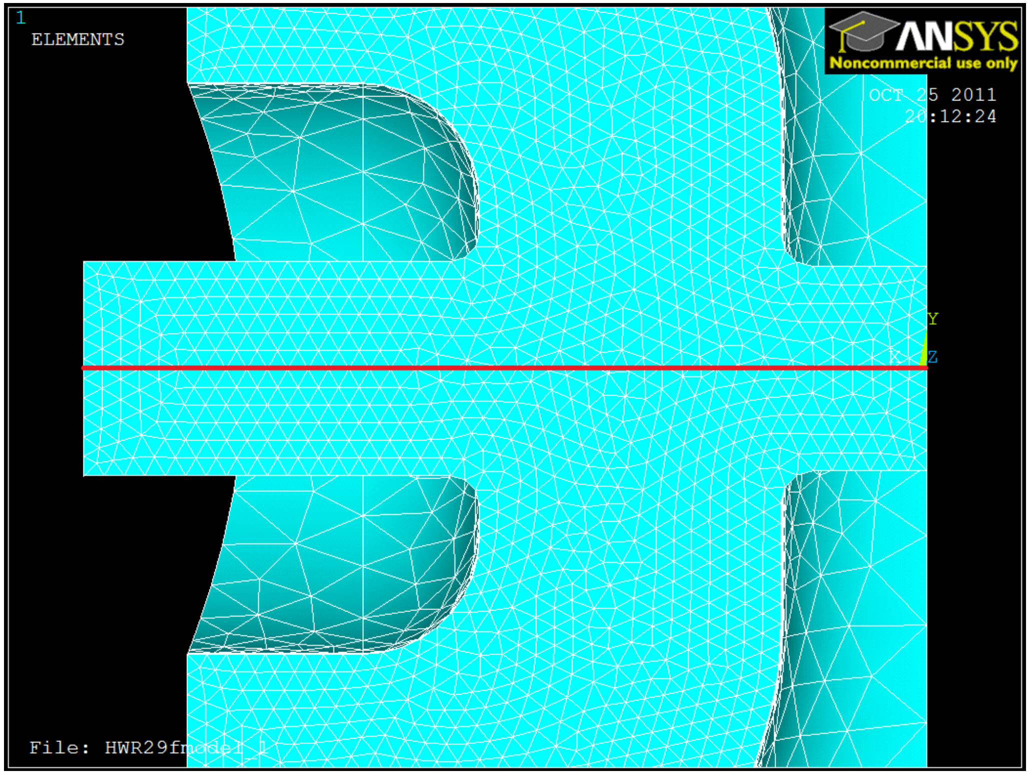
Electromagnetic Simulation

- Geometry Creation
  - SolidWorks CAD software
  - Appropriate choice of parameters for optimization
  - Take advantage of symmetry
- Boundary Conditions
  - Perfect Electric Conductor
    - » Normal electric fields, tangential magnetic fields
    - » RF surfaces
  - Perfect Magnetic Conductors
    - » Normal magnetic fields, tangential electric fields
    - » Generally symmetry planes (with exceptions, depending on the mode)
  - RF losses
    - » Surface resistivity for dissipated power

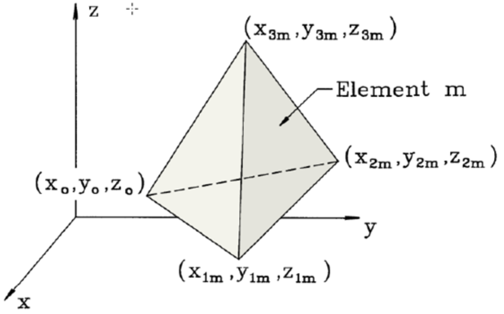


Computational Methods

- Finite Element Solvers
  - Cavity volume is broken into interlocking tetrahedral “elements”
  - Fields inside of an element are assumed to have a simple form
  - Matrix describing mesh is inverted to get eigenvalues/eigenvectors



Representation of field with linear elements in 3d



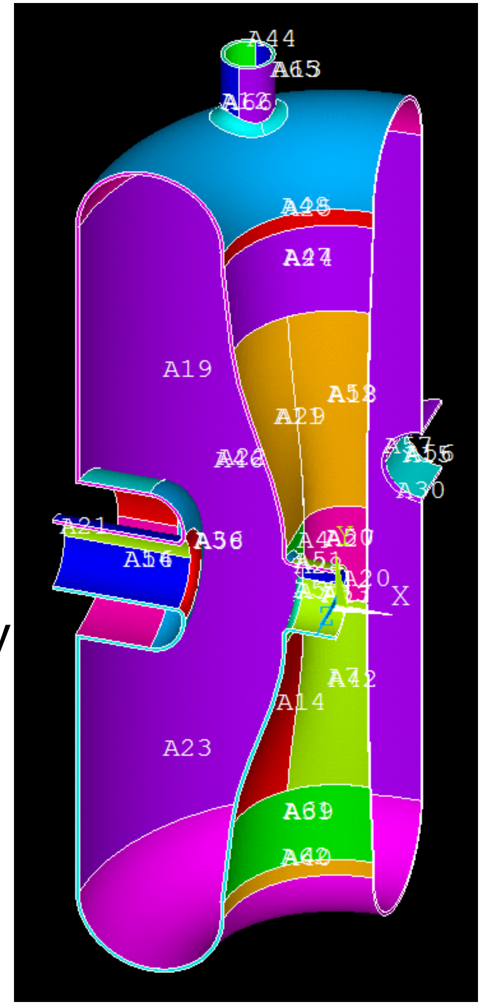
$$\mathrm{E}_m = \alpha_{1m}\mathrm{x} + \alpha_{2m}\mathrm{y} + \alpha_{3m}\mathrm{z}.$$

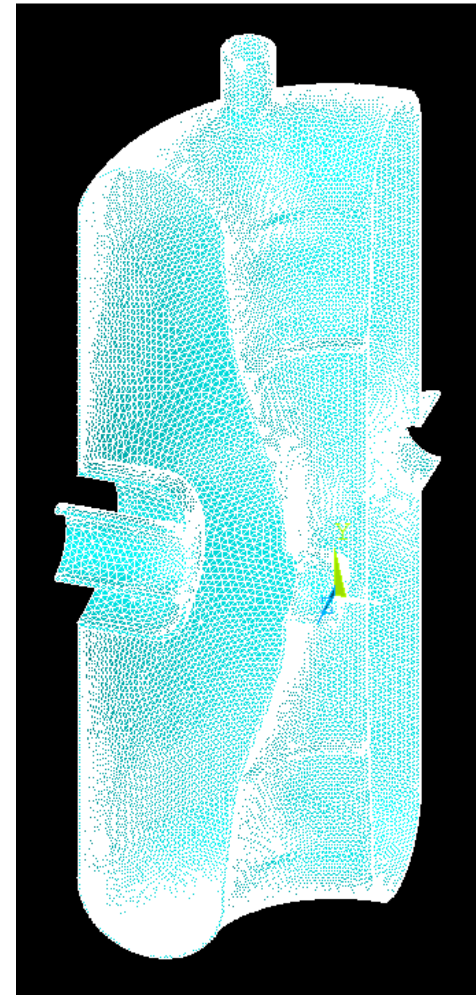
Helmholtz Equation

$$(\nabla^2 + k^2)\vec{E} = 0$$

Coupled EM & Mechanical Simulations

- Accurate frequency shifts can be achieved from small mechanical deformations
  - Mesh and solve eigenmode
  - Mesh material space
  - KEEP vacuum space mesh as extremely weak material
  - Apply desired pressure and solve for deformation
  - Change back to vacuum and resolve eigenmode to get frequency shift
- *By perturbing the existing mesh, extremely high accuracy can be achieved, down to the Hz level*

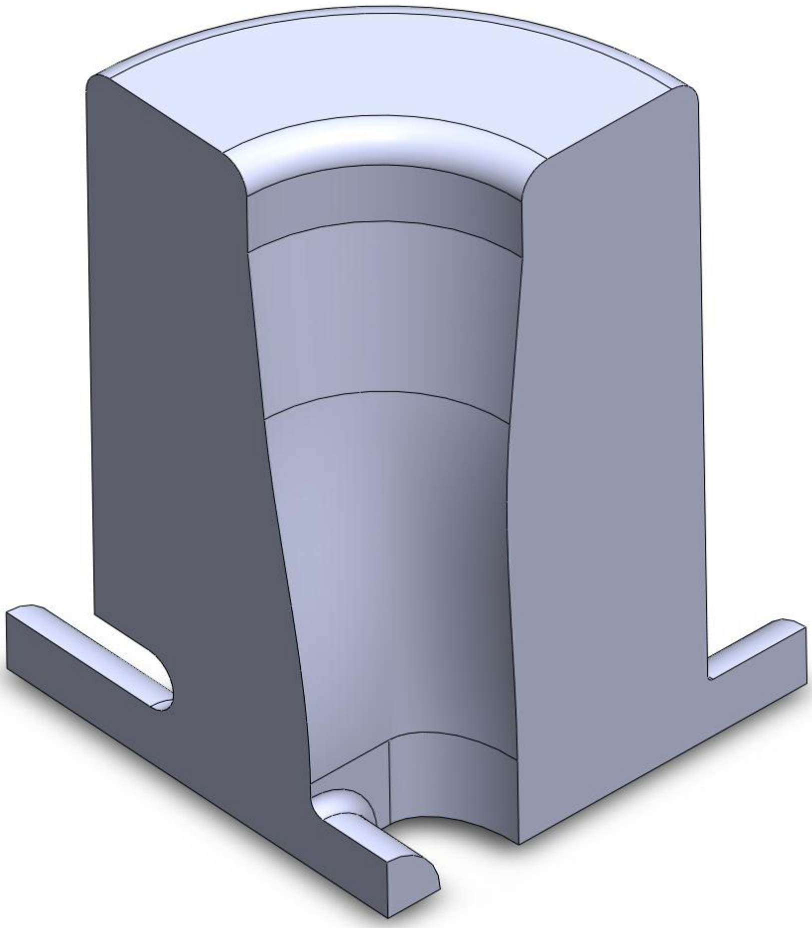




Starting Geometry

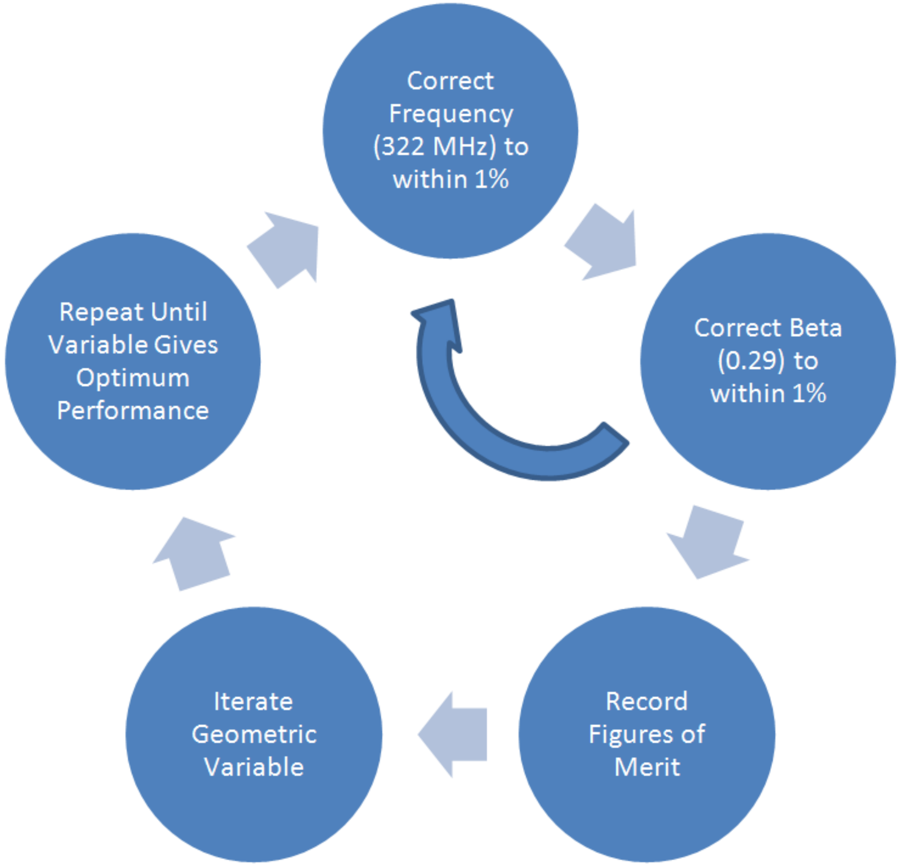
- This geometry has the appropriate features for optimization
  - Cylindrical magnetic field region (with straight section!)
  - Shaped electric field region
  - Cylindrical outer conductor (stiff!)
  - Beam port cup to give proper β_{opt}

Figure of Merit	Value
Frequency	322.5 [MHz]
β_{opt}	0.293
G	66.5 [Ω]
R/Q	219 [Ω]
V_{acc}	1.90 [MV]
E_{pk}	34.7 [MV/m]
B_{pk}	69.7 [mT]
U	8.15 [J]



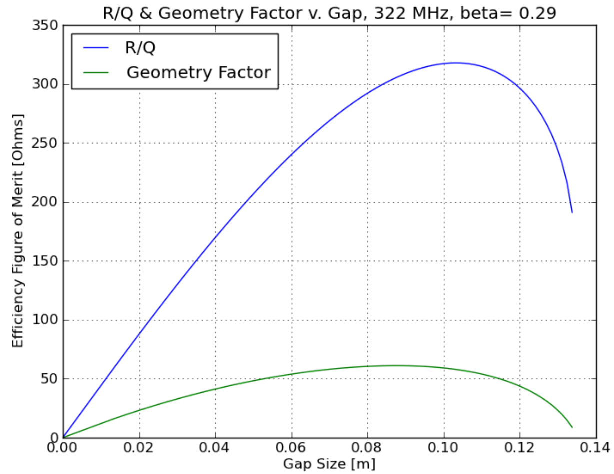
Geometrical Optimization

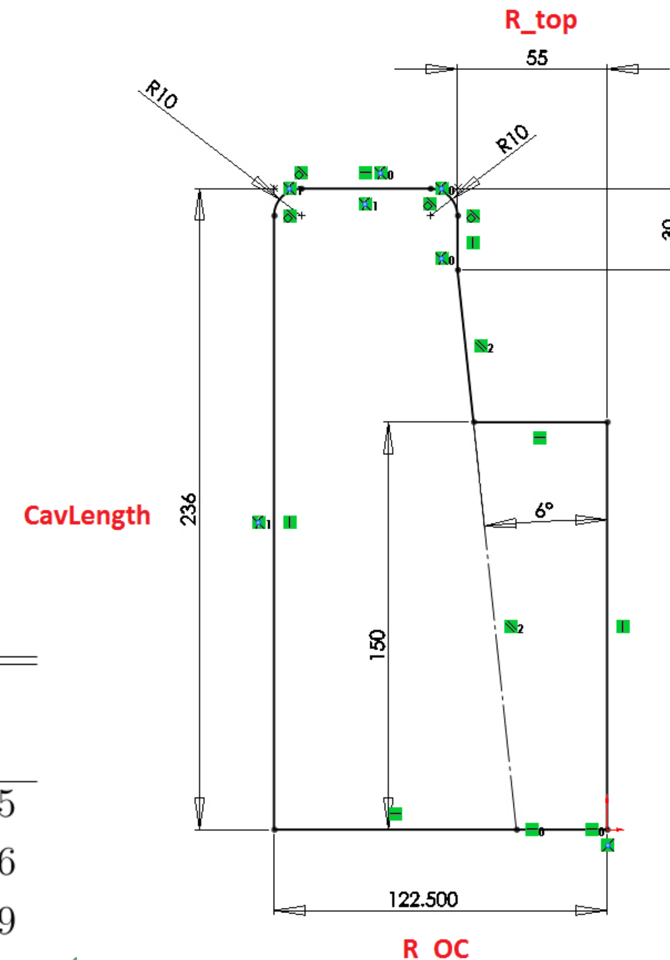
- Two Stages of Variable Optimization:
  - "Large" Variables (e.g. IC/OC Radius)
  - "Local" Variables (e.g. Drift tube fillet)
- *All Design Is Compromise*
- Frequency and β_{opt} must be consistent to compare different designs
  - Cavity length will be used to correct frequency
  - Beam port cup will be used to correct beta
- 322 [MHz], 1.9 [MV], β = 0.29



Variable 1: Outer Conductor Radius

- Larger Outer Conductor Improves Efficiency
  - Voltage for given stored energy driven by this distance
  - 145 [mm] maximum set by FRIB lattice

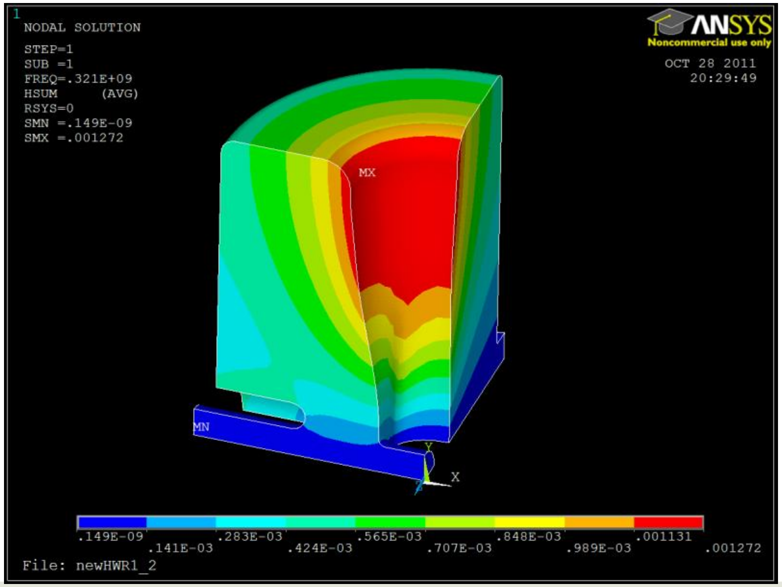


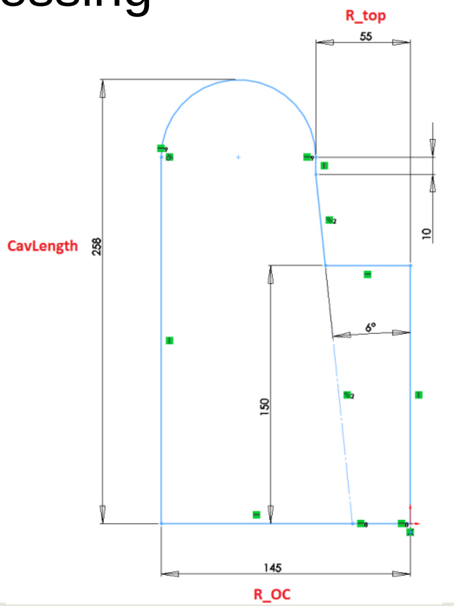


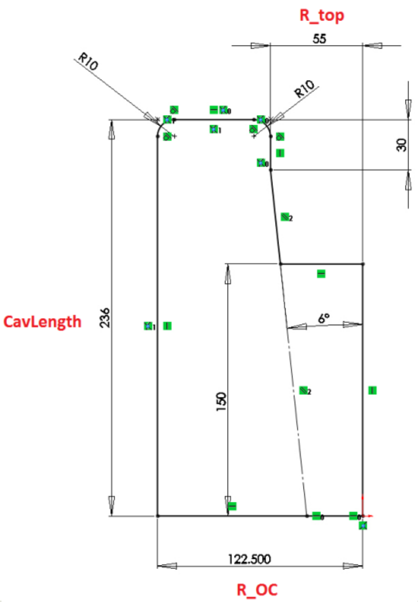
CavLength [mm]	R_OC [mm]	L_cup,2 [mm]	G [Ω]	R/Q [Ω]	E_{pk} [MV/m]	B_{pk} [mT]	U [J]
241	122.5	37	66.5	219	34.7	69.7	8.15
239	131.0	48	71.7	236	38.2	64.4	7.56
236	138.0	55	75.2	247	39.7	61.2	7.19
233	145.0	62	78.4	264	39.7	57.9	6.75

Short Plate Geometry

- Flat Short Plate Implications
  - Increased rounding improves peak magnetic field and Geometry Factor
- Fully Rounded Short Plate
  - Improved magnetic field distribution
  - Easier to manufacture
  - Most robust geometry that can be made with formed sheet Niobium
  - Improved draining during cavity processing

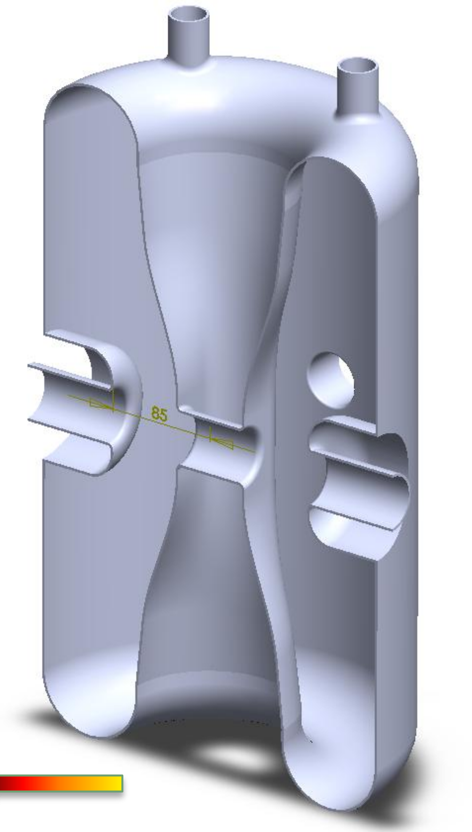






Variable 2: Magnetic Field Region IC Radius

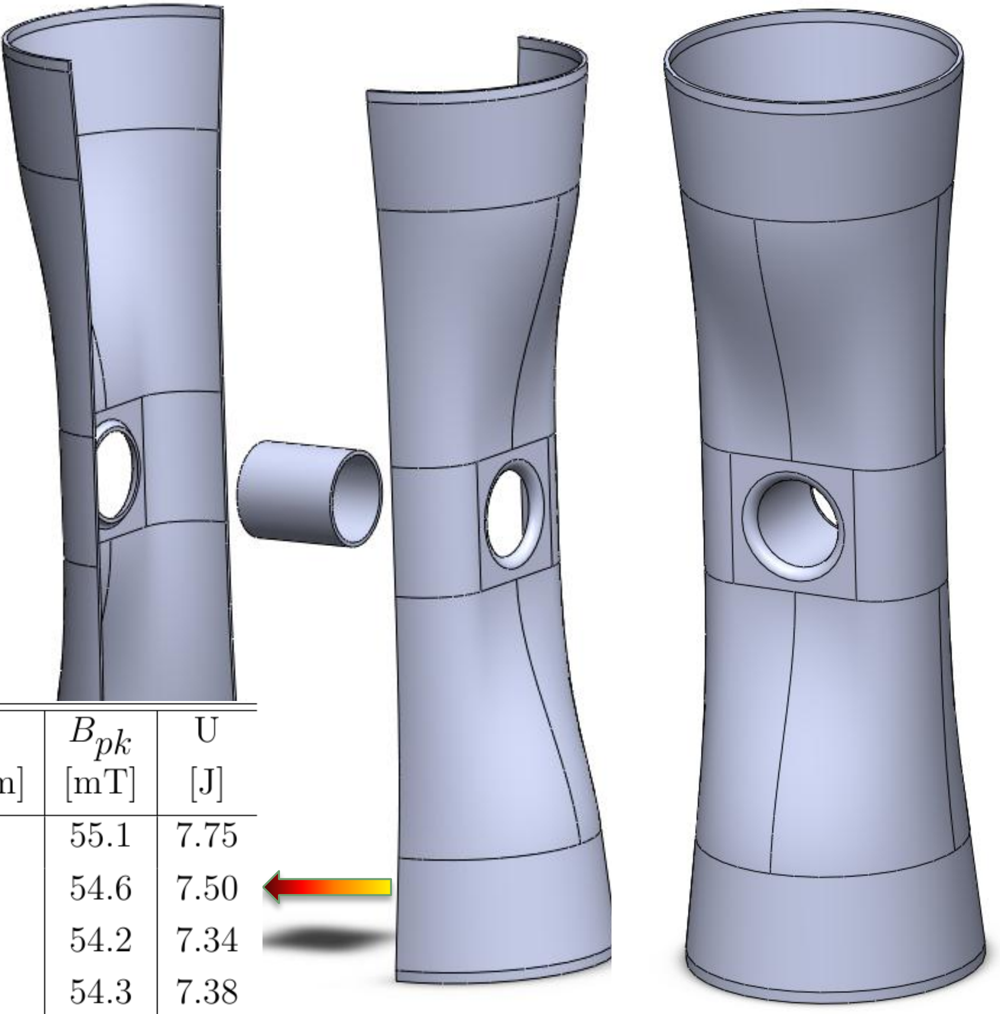
- Reducing the Peak Surface Magnetic Field
  - Increasing the inner conductor radius decreases Bpk/√U
  - Almost no change in electric field region
- Significant Decrease in Efficiency
  - Both Geometry Factor and R/Q drop dramatically with increased inner conductor radius
  - Radius of 65 [mm] was chosen as a compromise between these two effects



CavLength [mm]	R_top [mm]	R_cup,2 [mm]	G [Ω]	R/Q [Ω]	E_{pk} [MV/m]	B_{pk} [mT]	U [J]
240	55	62	80.1	263	40.2	56.9	6.78
250	65	62	77.4	243	41.1	54.2	7.34
260	75	62	73.1	223	41.3	53.7	8.00
270	85	62	69.1	205	41.6	54.6	8.71

Variable 3: Electric Field Region IC Width

- IC Width is Relatively Insensitive
  - Choice of large, flat region on IC makes cavity figure of merit relatively insensitive to its width
  - This design is also quite straight-forward to manufacture (easy coining for drift tube)
  - This also means Epk should be insensitive to fabrication errors
  - Compromise of R/Q and Epk at a half-width of 30 [mm]



CavLength [mm]	R_bottom [mm]	R_cup,2 [mm]	G [Ω]	R/Q [Ω]	E_{pk} [MV/m]	B_{pk} [mT]	U [J]
260	26	59	78.8	231	36.9	55.1	7.75
255	30	60	78.2	238	38.5	54.6	7.50
250	32	62	77.4	243	41.1	54.2	7.34
250	34	64	77.8	242	42.3	54.3	7.38

Final Optimization – Beam Port Cup

- Beam Port Cup Shape Dominates Peak Surface Electric Field
  - The cup was optimized to give fields that are as uniform as possible, minimizing peak surface electric fields
  - Also helps shape accelerating electric field, improving R/Q

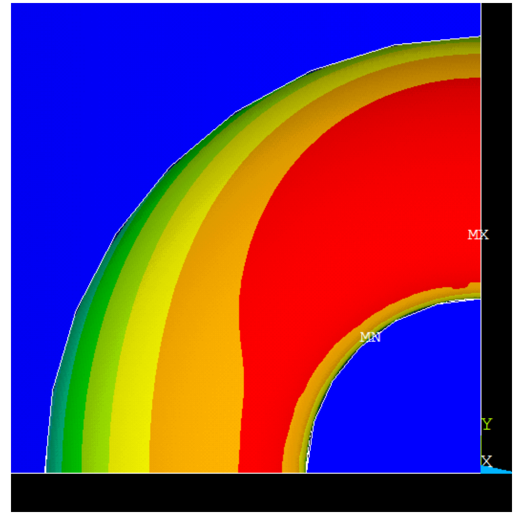
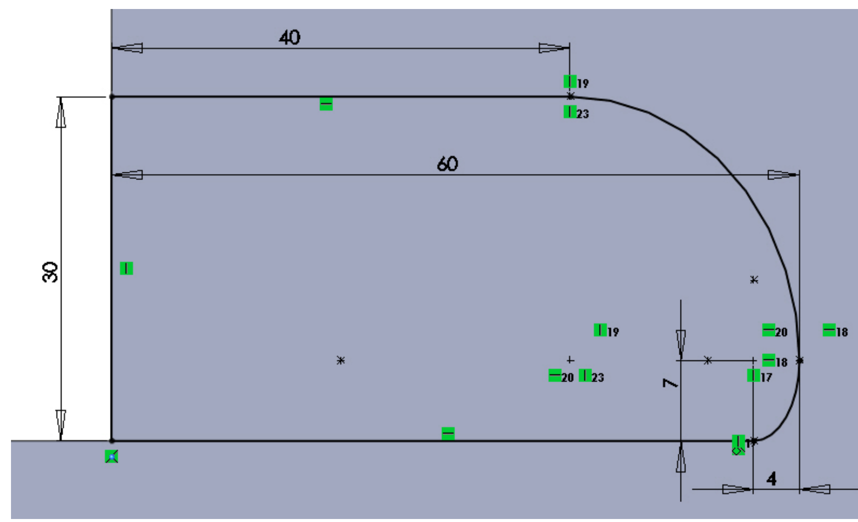
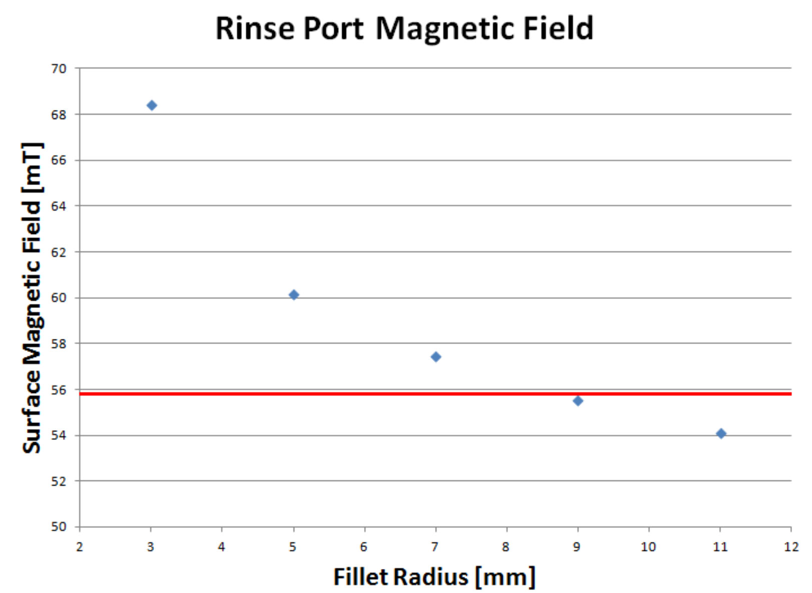


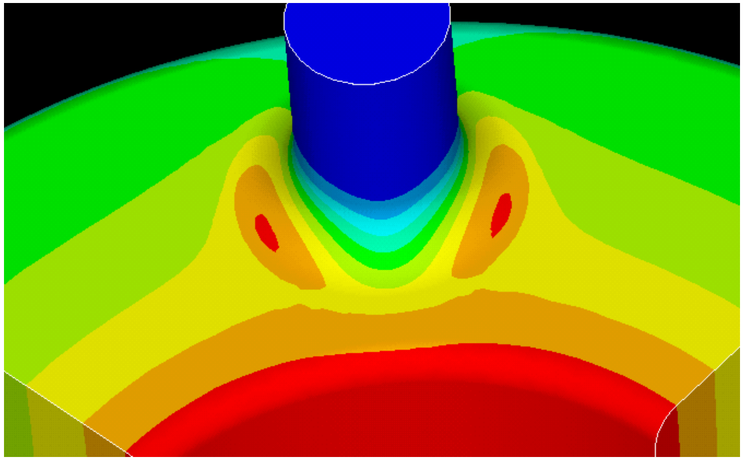
Figure of Merit	Initial Value	Final Value	Units
Frequency	322.5	321.8	[MHz]
β_{opt}	0.293	0.287	
G	66.5	77.7	[Ω]
R/Q	219	231	[Ω]
V_{acc}	1.90	1.90	[MV]
E_{pk}	34.7	30.4	[MV/m]
B_{pk}	69.7	55.8	[mT]
U	8.15	7.71	[J]



Cavity Processing

- Cavity Etching and High Pressure Rinsing
  - While the beam ports and RF ports are available, the access they provide is unsatisfying for providing reliable cavity surfaces
- Minimizing Perturbation
  - These ports perturb the magnetic field of the cavity





Design Comparison

- Comparing the design presented, the improvement is obvious
  - Peak surface magnetic field is significantly decreased by more sophisticated construction methods
  - Efficiency improved with increased outer conductor diameter and beam port cups
  - Aperture increased by 1/3 because of evolving beam dynamics requirements
  - Designed specifically to be mechanically robust

	0.29 for RIA	New 0.29 Design
β_{opt}	0.285	0.290
f (MHz)	322.0	322.0
V_a (MV)	1.9	1.9
E_p (MV/m)	30.0	30.5
B_p (mT)	83	56
R/Q (Ω)	199	231
G (Ω)	61	78
Design Q_0	6.1×10^9	7.8×10^9
Aperture (mm)	30	40
U (joules)	8.9	7.7

Achieving 322.000000 [MHz] ± 30[Hz]

- 322 MHz = In Operation
  - 300K -> 2K (df/dT)
  - 1 atm -> 28 torr (df/dP)
  - Air -> Vacuum (df/dε)
  - Installation of FPC/Tuner (Assembly & Preloading)
  - Etching
  - Welding of Helium Vessel
- Positioning the Beam Port Cups
  - This welding step allows adjustment of the cavity frequency and field flatness (~100s [kHz])
  - Plastic deformation of beam ports for final tuning (~100 [kHz])
  - Tuner range = ± 75 [kHz]
  - Tuner resolution ~1 [Hz]
  - *Mostly based on experience (prototyping!)*
  - *Process must be repeatable*

Cavity Stiffening

- It is desirable to make the cavity entirely from 2 [mm] sheet Niobium
  - However, electromechanical performance isn't satisfactory
  - The most obvious first stiffening is to use thicker material for the beam port cup

	df/dF [kHz/kN]	df/dx [kHz/mm]	K_L [Hz/(MV/m)^2]	df/dP [Hz/torr]
2 [mm]	-126	-599	-3.1	-4.1
3 [mm]	-96.2	-637	-2.2	-3.1
4 [mm]	-83.6	-656	-1.9	-3.8

- With 3 [mm] beam port cups, additional stiffening was required
  - A simple stiffening ring (2 [mm] thick) was added to the inner conductor, and its position was optimized

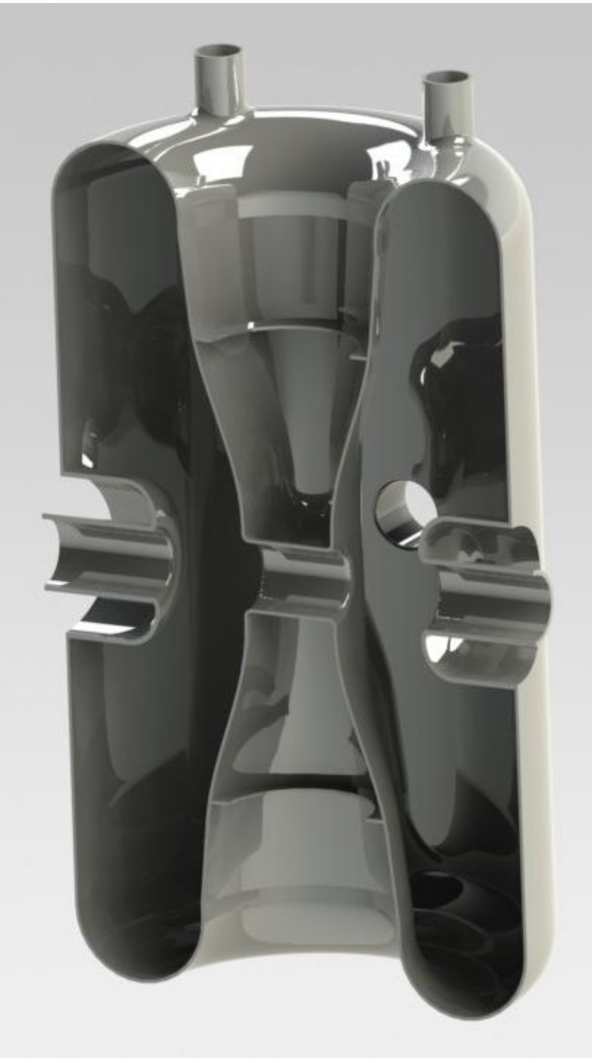
df/dF [kHz/kN]	df/dx [kHz/mm]	K_L [Hz/(MV/m)^2]	df/dP [Hz/torr]
-96.6	-637	-1.73	-0.98

Further Design Considerations

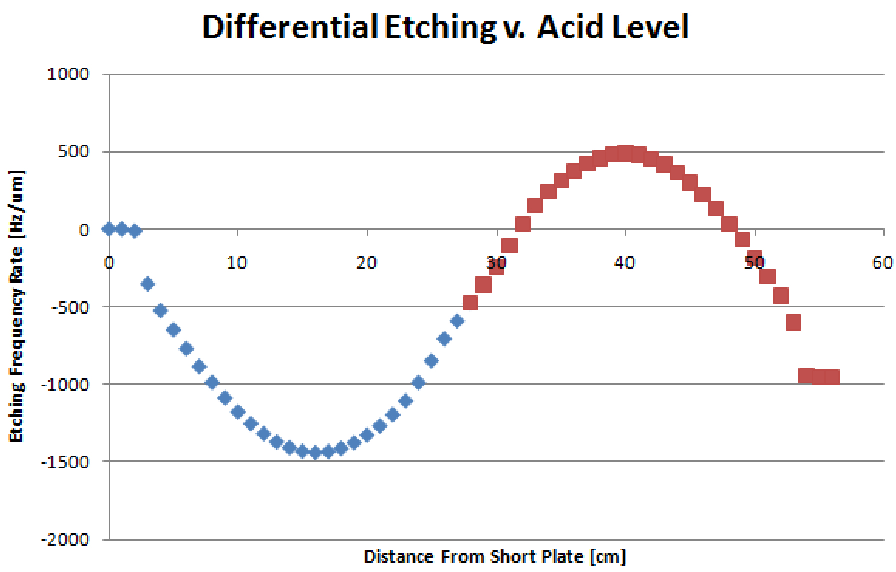
- Electromagnetic performance is close to optimal
  - The peak surface magnetic field was intentionally raised slightly to improve efficiency (could be reversed)
  - With demonstrated repeatability and quality of cavity processing, a more ambitious accelerating voltage may be possible
- Electromechanical performance is acceptable
  - Beam port tuning sensitivity is very high
  - If tuners can be designed such that minimum step size is in applied force, the beam port cups can be stiffened to achieve the required coefficient
  - Alternative tuning methods should be investigated
- Mechanical design is quite robust
  - Both high magnetic and high electric field regions have been designed to be insensitive to most manufacturing errors
  - Overall cavity is quite stiff, requiring little additional stiffening
  - Stiffening suggested should be straight-forward to include in cavity fabrications
  - Changes to cavity design and addition of helium vessel should not required drastic changes in stiffening

Conclusions

- Resonator design is a coupled process
  - Simulation, mechanical design, and prototyping are essential components for a successful final design
- Half Wave Resonators are a very new technology
  - Much has been learned at MSU about HWR design
  - A mature beta = 0.29 HWR design has been presented, but some questions need to be answered during mechanical design and prototyping
    - » Tuning
    - » Helium Vessel design
    - » Goal Bench Frequency
  - The same procedure presented here can be repeated as the design changes



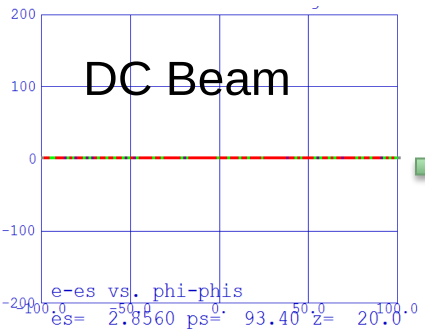
Differential Etching

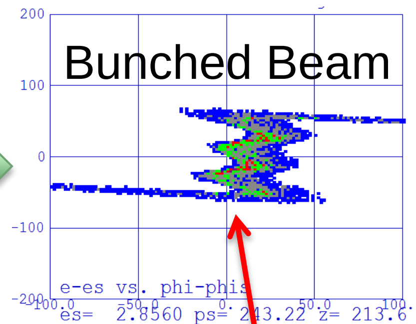


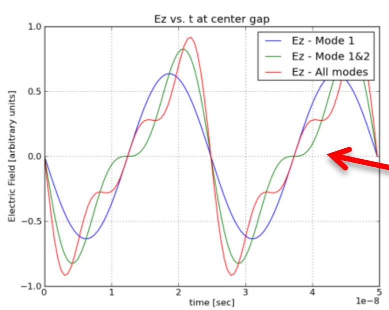
- If desired, differential etching can be used to increase HWR frequency
  - HWR frequency shift from etching is more dominantly negative than QWRs
  - With careful choice of acid fill level, a positive frequency shift can be achieved
  - While this study was done on an older geometry, it is likely similar to current designs
  - This shift has yet to be demonstrated experimentally (at MSU)
  - -1383 [Hz/µm] is the etch rate for an ideal HWR at 322 MHz
  - 0 [Hz/µm] is the rate for the ideal QWR

Multi-Harmonic Buncher

- Three Harmonics in Two Resonators
  - First three harmonics of a sawtooth wave
  - Efficient bunching of a DC beam from ion source







Transferred wave structure of three harmonics is evident (4th Harmonic only +2-3% capture)