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

- ECR Ion Sources
- Room Temperature RFQ Accelerator
- $\beta=0.041$ Quarter Wave Resonators
- $\beta=0.085$ Quarter Wave Resonators
- Target Beam Delivery System
- Energy Upgrade
- Superconducting Bend
- $\beta=0.53$ Half Wave Resonators
- $\beta=0.29$ Half Wave Resonators
- Cryogenic Distribution Line
- Charge Stripper

National Science Foundation
Michigan State University

J. P. Holzbauer
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

\[ \lambda \beta_{opt} = A + B \]
\[ \vec{E}(\rho, \phi, z) = E_0 A \cos \left( \frac{\pi z}{2L} \right) e^{i \omega t} \hat{\rho} \]
\[ \vec{B}(\rho, \phi, z) = \frac{E_0 A}{cp} \sin \left( \frac{\pi z}{2L} \right) e^{i \omega t + \frac{i \pi}{2}} \hat{\phi} \]
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
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

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

\[ TTF = \frac{V_{acc}}{V_0} = \frac{\int_{-\infty}^{+\infty} E_{acc} \sin \left( \frac{\omega z}{\beta c} + \phi \right) dz}{\int_{-\infty}^{+\infty} |E_{acc}| dz} \]
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 $|df/dP| < 2 \text{ Hz/torr}$

- 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.

  \[
  \frac{\Delta f}{f_0} = \frac{1}{4U} \int_{\Delta V} (\varepsilon_0 E^2 - \mu_0 H^2) dV = \frac{1}{U} \int_{\Delta V} (P) dV
  \]

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

  - Note: PdV is always positive, meaning \( \Delta f \) 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.
  - \( K_L > -3 \text{ [Hz/(MV/m)^2]} \) 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 \text{ [MHz]}, \beta = 0.29 \text{ HWR for RIA}

- Prototyped and Tested in Cryomodule
  - Extremely simple construction
  - Little electromagnetic optimization
  - Achieved electromagnetic goals at 2K
  - Poor mechanical performance
322 [MHz], $\beta = 0.53$ 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 $\sim$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 ~600°C 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
  - \(~93 \text{ [mT]}\)
Advanced Manufacturing Design

- **Design Modifications**
  - Several modifications based on cavity testing and vendor 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
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

\[ \nabla^2 + k^2 \mathbf{E} = 0 \]
**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 $\beta_{\text{opt}}$

<table>
<thead>
<tr>
<th>Figure of Merit</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
<td>322.5 [MHz]</td>
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<tr>
<td>$G$</td>
<td>66.5 [Ω]</td>
</tr>
<tr>
<td>$R/Q$</td>
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</tr>
<tr>
<td>$V_{\text{acc}}$</td>
<td>1.90 [MV]</td>
</tr>
<tr>
<td>$E_{pk}$</td>
<td>34.7 [MV/m]</td>
</tr>
<tr>
<td>$B_{pk}$</td>
<td>69.7 [mT]</td>
</tr>
<tr>
<td>$U$</td>
<td>8.15 [J]</td>
</tr>
</tbody>
</table>
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 $\beta_{\text{opt}}$ 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], $\beta = 0.29$
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

<table>
<thead>
<tr>
<th>CavLength [mm]</th>
<th>R_OC [mm]</th>
<th>L_cup,2 [mm]</th>
<th>G [Ω]</th>
<th>R/Q [Ω]</th>
<th>$E_{pk}$ [MV/m]</th>
<th>$B_{pk}$ [mT]</th>
<th>U [J]</th>
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<td>239</td>
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<td>145.0</td>
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<td>78.4</td>
<td>264</td>
<td>39.7</td>
<td>57.9</td>
<td>6.75</td>
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</table>
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 $B_{pk}/\sqrt{U}$
  - 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

<table>
<thead>
<tr>
<th>CavLength [mm]</th>
<th>R_top [mm]</th>
<th>R_cup,2 [mm]</th>
<th>G [Ω]</th>
<th>R/Q [Ω]</th>
<th>$E_{pk}$ [MV/m]</th>
<th>$B_{pk}$ [mT]</th>
<th>U [J]</th>
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<td>65</td>
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<td>77.4</td>
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<td>41.1</td>
<td>54.2</td>
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<tr>
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<td>73.1</td>
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<td>8.00</td>
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<td>69.1</td>
<td>205</td>
<td>41.6</td>
<td>54.6</td>
<td>8.71</td>
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</table>
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 straightforward 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]

<table>
<thead>
<tr>
<th>CavLength [mm]</th>
<th>R_bottom [mm]</th>
<th>R_cup,2 [mm]</th>
<th>G [Ω]</th>
<th>R/Q [Ω]</th>
<th>$E_{pk}$ [MV/m]</th>
<th>$B_{pk}$ [mT]</th>
<th>U [J]</th>
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<td>260</td>
<td>26</td>
<td>59</td>
<td>78.8</td>
<td>231</td>
<td>36.9</td>
<td>55.1</td>
<td>7.75</td>
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<tr>
<td>255</td>
<td>30</td>
<td>60</td>
<td>78.2</td>
<td>238</td>
<td>38.5</td>
<td>54.6</td>
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<td>32</td>
<td>62</td>
<td>77.4</td>
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<td>41.1</td>
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<tr>
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<td>64</td>
<td>77.8</td>
<td>242</td>
<td>42.3</td>
<td>54.3</td>
<td>7.38</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Figure of Merit</th>
<th>Initial Value</th>
<th>Final Value</th>
<th>Units</th>
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<td>321.8</td>
<td>[MHz]</td>
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<td>$\beta_{opt}$</td>
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<td>0.287</td>
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<tr>
<td>$G$</td>
<td>66.5</td>
<td>77.7</td>
<td>[\Omega]</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>219</td>
<td>231</td>
<td>[\Omega]</td>
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<td>69.7</td>
<td>55.8</td>
<td>[mT]</td>
</tr>
<tr>
<td>$U$</td>
<td>8.15</td>
<td>7.71</td>
<td>[J]</td>
</tr>
</tbody>
</table>
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
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

<table>
<thead>
<tr>
<th></th>
<th>0.29 for RIA</th>
<th>New 0.29 Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{opt}}$</td>
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<td>0.290</td>
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<tr>
<td>$f$ (MHz)</td>
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<td>322.0</td>
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<tr>
<td>$V_a$ (MV)</td>
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<td>1.9</td>
</tr>
<tr>
<td>$E_p$ (MV/m)</td>
<td>30.0</td>
<td>30.5</td>
</tr>
<tr>
<td>$B_p$ (mT)</td>
<td>83</td>
<td>56</td>
</tr>
<tr>
<td>$R/Q$ (Ω)</td>
<td>199</td>
<td>231</td>
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<tr>
<td>$G$ (Ω)</td>
<td>61</td>
<td>78</td>
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<tr>
<td>Design $Q_0$</td>
<td>$6.1 \times 10^9$</td>
<td>$7.8 \times 10^9$</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>$U$ (joules)</td>
<td>8.9</td>
<td>7.7</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Thickness [mm]</th>
<th>$df/dF$ [kHz/kN]</th>
<th>$df/dx$ [kHz/mm]</th>
<th>$K_L$ [Hz/(MV/m)$^2$]</th>
<th>$df/dP$ [Hz/torr]</th>
</tr>
</thead>
<tbody>
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<td>2</td>
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<td>-599</td>
<td>-3.1</td>
<td>-4.1</td>
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<tr>
<td>3</td>
<td>-96.2</td>
<td>-637</td>
<td>-2.2</td>
<td>-3.1</td>
</tr>
<tr>
<td>4</td>
<td>-83.6</td>
<td>-656</td>
<td>-1.9</td>
<td>-3.8</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>$df/dF$ [kHz/kN]</th>
<th>$df/dx$ [kHz/mm]</th>
<th>$K_L$ [Hz/(MV/m)$^2$]</th>
<th>$df/dP$ [Hz/torr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-96.6</td>
<td>-637</td>
<td>-1.73</td>
<td>-0.98</td>
</tr>
</tbody>
</table>
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)
- $-1383 \ [\text{Hz/µm}]$ is the etch rate for an ideal HWR at 322 MHz
- $0 \ [\text{Hz/µm}]$ 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)