FRIB Cavity Production Status

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Outline

- Overview
  - FRIB SRF Linac
  - FRIB SRF cavity evolution

- Cavity production status and performance

- Cavity inspection and acceptance

- Cavity production oversight
  - Frequency control
    » Virtual welding development
  - Aperture alignment control
  - Low-cost flange optimization
  - Cavity vacuum reliability
    » European knife-edge design
  - Thread fabrication

- Summary
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
- $\beta=0.53$ Half Wave Resonators
- $\beta=0.29$ Half Wave Resonators
- Superconducting Bend
- Cryogenic Distribution Line
- Charge Stripper
- 200 MeV beam energy, 400 kW beam power
- 332 cavities housed in 48 cryomodules
- Four cavity designs – two cavity classes, two frequencies, and four betas ($\beta_0$)
- Started technical construction (CD-3) Aug. 2014
- Managing to early completion in FY2021

80.5 MHz
$\beta_0 = 0.041$

80.5 MHz
$\beta_0 = 0.085$

322 MHz
$\beta_0 = 0.29$

322 MHz
$\beta_0 = 0.53$
FRIB SRF Cavity Evolution

- FRIB production cavity designs evolved from internal prototype efforts at MSU
  - ReA3 project successfully in operation
  - 3 cryomodules – 16 quarter-wave cavities

- Implemented design changes to improve performance and reduce costs
  - Quarter-wave – outer conductor extension, relocate coupling ports, bottom flange redesign
  - Half-wave – rinse port balancing, straight section, removed RF pick-up port (use rinse port)
- Worked with industrial vendors to optimize workflow for FRIB production
- Multiple vendors with large scale production experience

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>Development</th>
<th>Preproduction</th>
<th>Production</th>
<th>TOTAL</th>
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</thead>
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<tr>
<td>0.041</td>
<td>2 (2)</td>
<td></td>
<td>17 (17)</td>
<td>19 (19)</td>
</tr>
<tr>
<td>0.085</td>
<td>2 (2)</td>
<td>10 (10)</td>
<td>103</td>
<td>115 (12)</td>
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<tr>
<td>0.29</td>
<td>2 (2)</td>
<td>10 (3)</td>
<td>68</td>
<td>80 (5)</td>
</tr>
<tr>
<td>0.53</td>
<td>2 (2)</td>
<td>10 (8)</td>
<td>150</td>
<td>162 (10)</td>
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</tbody>
</table>

* Numbers in red indicate cavities received to date

Production $\beta_0 = 0.041$ cavities being sequenced for cavity processing
FRIB SRF Cavities Exceeding Performance Specification

- FRIB cavity certification goals indicated by ★

\[ \beta_0 = 0.041 \]

\[ \beta_0 = 0.085 \]

\[ \beta_0 = 0.29 \]

\[ \beta_0 = 0.53 \]
All received cavities are inspected in reference to the Acceptance Criteria List (ACL)

ACL inspection points defined
• Vendor report review
• Dimensional inspection
• Visual inspection – RF surfaces, sealing interfaces, and weld beads
• Frequency measurement
• Leak check

All nonconformances are reported and documented in FRIB tracking system

FRIB works directly with vendor to identify root cause and implement corrective actions
Quarter-wave cavities (80.5 MHz +/- 20 kHz)
- Traditional stack and trim procedure
- Experience through ReA3 and ReA6 projects
- Developments from other projects
  » Differential etching – TRIUMF
  » Tuning plate puck adjustment – TRIUMF

Half-wave cavities (322 MHz +/- 50 kHz)
- Initial design – using beam-cup adjustment for frequency tuning
- Improved design – stack-up and trimming of outer and inner conductors
- Now implementing reference fixtures for stack-up
- Frequency tuning developments
  » Mechanical deformation – unjacketed cavity
  » Virtual welding – with and without helium vessel
  » Differential etching – with helium vessel
FRIB developed calibrated reference fixtures to increase reproducibility in the stack-up and trim steps of half-wave cavity fabrication.

- **Niobium short plate measurement**
  - Niobium short plates are machined to print
  - Frequency of short plates measured against a calibrated reference copper cavity.

- **Niobium outer and inner conductor measurement**
  - Niobium outer and inner conductors left long
  - Frequency is determined by stacked-up measurement using calibrated reference copper short plates
  - The outer and inner conductors are trimmed and re-stacked until goal frequency is met.
- FRIB developed frequency adjustment for half-wave cavities using virtual welding

- Virtual welding is non-structural welds strategically placed to cause material shrinkage resulting in a controlled frequency shift

- Virtual welding used for frequency adjustment in cavities with and without helium vessel

Virtual electron-beam welding

Virtual TIG welding

Electron-beam power calibrations for virtual welding of half-wave cavities ($\beta_0 = 0.29$ and 0.53) prior to helium vessel integration
Cavity Frequency Control

QWR $\beta_0 = 0.085$ Frequency Tracking

1. Initial Stack, GBF #1, 80.366
2. Weld cavity, 80.437
3. Weld vessel, 80.398
4. Bulk etch #1, 80.423
5. Bulk etch #2, 80.423
6. Differential etch, GBF #2, 80.41
7. Heat treatment, 80.355
8. Fine tune with puck, GBF #3, 80.357
9. Weld puck, final etch, 80.365
10. Cold test (2K), 80.505

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University
Work with vendors to optimize aperture alignment
- Design tolerance +/- 0.381mm (+/- 0.015 inch)

Work with FRIB Physics Department to set aperture tolerances

Several processes developed to improve alignment
- Improved tooling during electron-beam welding
- Post fabrication mechanical deformation – quarter-wave cavities
- Post fabrication machining – half-wave cavities

Corrective actions and oversight have improved alignment
Vacuum Sealing Reliability Addressed [1]

- All incoming cavities are cold shocked and vacuum leak checked; both cavity and helium vacuum spaces
  - Leak check pass = be free of leaks as measured by a calibrated helium mass-spectrometer leak detector having a sensitivity of <1x10^{-10} STD cc He/sec

- Several warm and cold leaks reported on early prototype and development cavities
  - Worked with vendors to improve fabrication tolerance, fabrication methods, surface quality control, and post fabrication repairs

Developed method of repairing Conflat flanges on completed cavities

Electrical Discharge Machining (EDM) Conflat flange fabrication

Damage to knife-edge profile

Damage repaired
■ Knife-edge degrading observed after multiple assemblies
  • Knife-edge appears to be degrading/rolling over

■ Implemented European knife-edge design to reduce point loading
  • Knife-edge profile integrity maintained after design change

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**Vacuum Sealing Reliability Addressed [2]**

knife-edge breakdown

knife-edge profile designs

knife-edge deformation tracking

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Conflat Standard | Tip radius (mm) | Counterslope angle (degrees)
--- | --- | ---
American | A | 0.050 | 5
European | E | 0.105 | 40

Knife Edge Deformation

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C. Compton, September 16, 2015 – SRF Conference, Slide 15
Low-cost Flange Optimization

- Low-cost flanged designed to maintain high thermal conductivity properties and reduce costs
- Original design fabricated from niobium-titanium material
  - Poor thermal conductivity
- Redesigned cavity flange fabricated using high RRR niobium material
  - Improved thermal conductivity
  - Large cost increase – required thick niobium plate
- Developed low-cost flange option
  - Thin disk of niobium welded into a titanium flange to reduce material cost
  - Addition of cooling channels allows direct cryogenic cooling to niobium disk
To optimize cavity spacing in the cryomodule, blind tapped holes implemented into cavity design
 • Tapped holes fabricated into niobium-titanium flanges

Formed vs machined threads
 • Formed tapped holes not passing go/no-go gauge
   » Titanium materials have a lot of spring back
 • Machined threads vary in surface roughness
   » High fiction when engaging fasteners

Weld distortion from helium vessel fabrication
 • Require post weld clean-up of tapped holes

Implemented use of electro-polished fasteners to reduce friction
 • Fasteners prepared to Cleanroom standards – clean with no lubricants

Thread mill insert
Summary

- SRF cavity prototyping successful in establishing path to FRIB production designs
- SRF cavity production is quickly ramping up with awarded contacts and development of multiple cavity vendors
- A project focus on vendor management is required to ensure high quality product and maintain schedule
- FRIB has implemented a thorough acceptance inspection philosophy
- Early nonconformances mitigated by strong working relationships with vendors to identify root causes and implement corrective actions
- Cavity production on track to meet FRIB project goals