FRIB Cavity Production Status

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Outline

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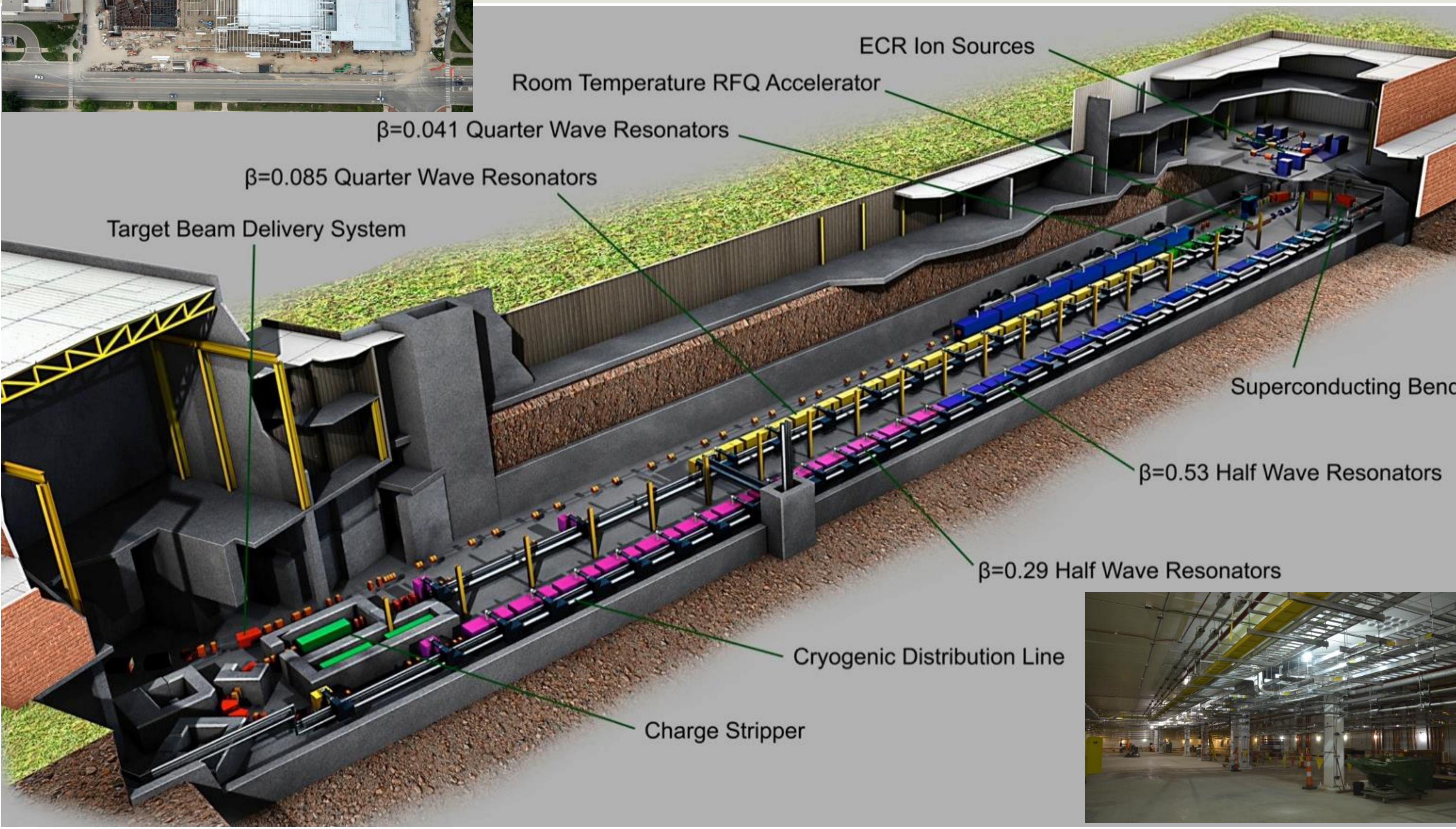
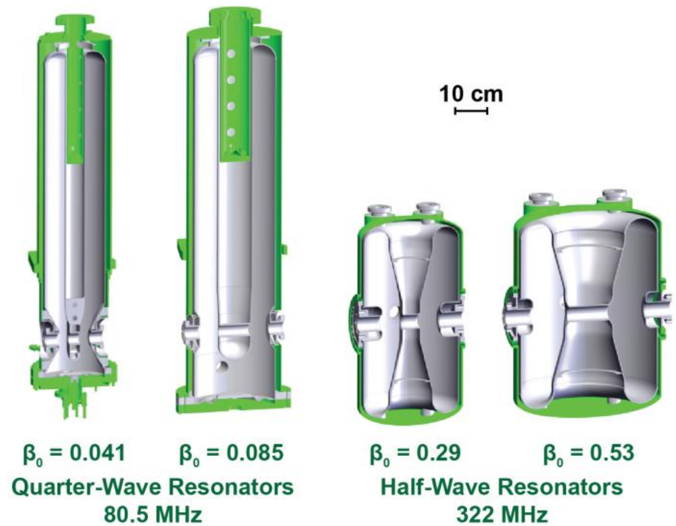
  - FRIB SRF cavity evolution
- Cavity production status and performance
- Cavity inspection and acceptance
- Cavity production oversight
  - Frequency control
    - » Virtual welding development
  - Aperture alignment control
  - Low-cost flange optimization
  - Cavity vacuum reliability
    - » European knife-edge design
  - Thread fabrication
- Summary

FRIB Driver Linac



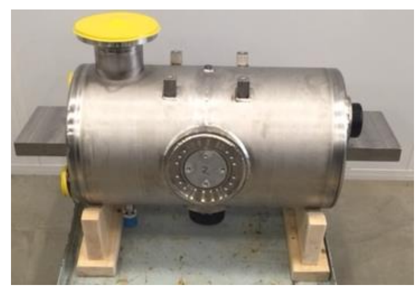
FRIB Project – SRF Acceleration

- 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 (β_0)
- Started technical construction (CD-3) Aug. 2014
- Managing to early completion in FY2021



80.5 MHz
β_0 = 0.041

80.5 MHz
β_0 = 0.085



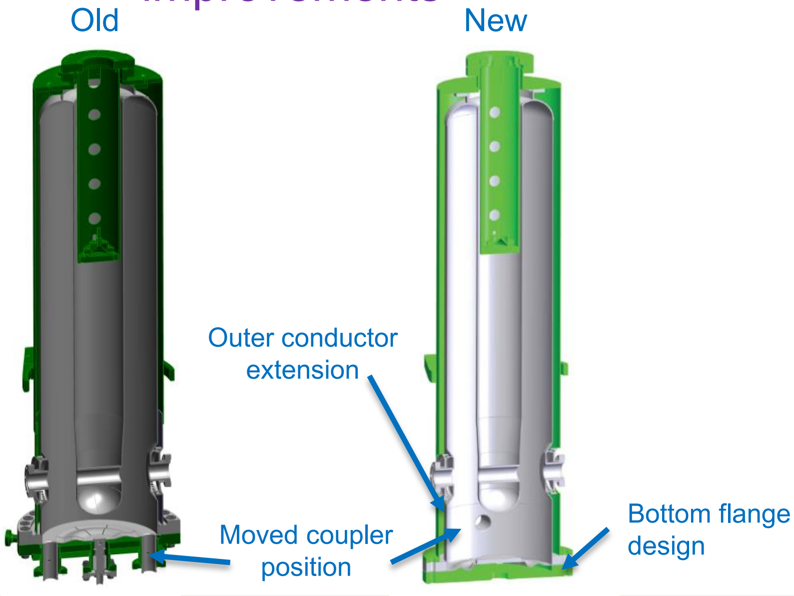
322 MHz
β_0 = 0.29

322 MHz
β_0 = 0.53

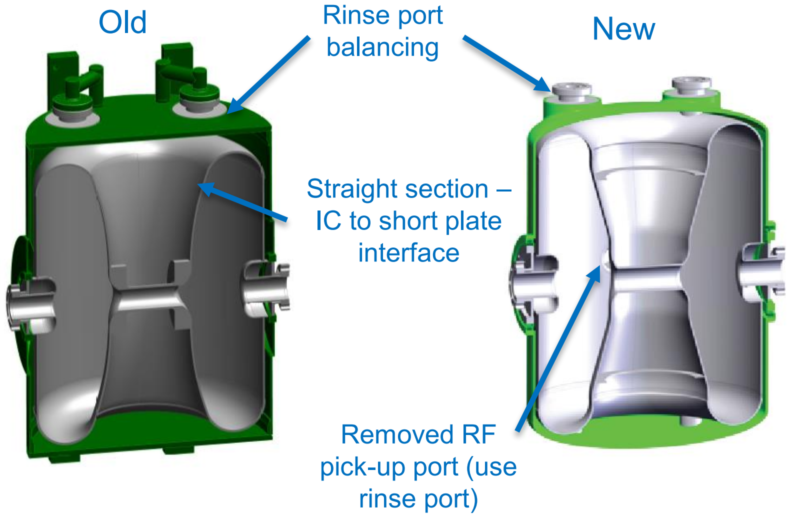
FRIB SRF Cavity Evolution

- 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)

Quarter-wave cavity design improvements



Half-wave cavity design improvements



Cavity Production Status for FRIB Driver Linac

- Worked with industrial vendors to optimize workflow for FRIB production
- Multiple vendors with large scale production experience

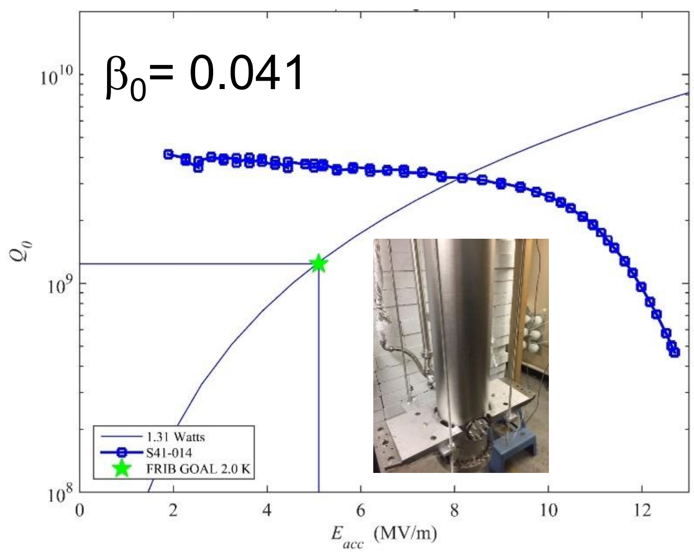
β_0	Development	Preproduction	Production	TOTAL
0.041	2 (2)		17 (17)	19 (19)
0.085	2 (2)	10 (10)	103	115 (12)
0.29	2 (2)	10 (3)	68	80 (5)
0.53	2 (2)	10 (8)	150	162 (10)

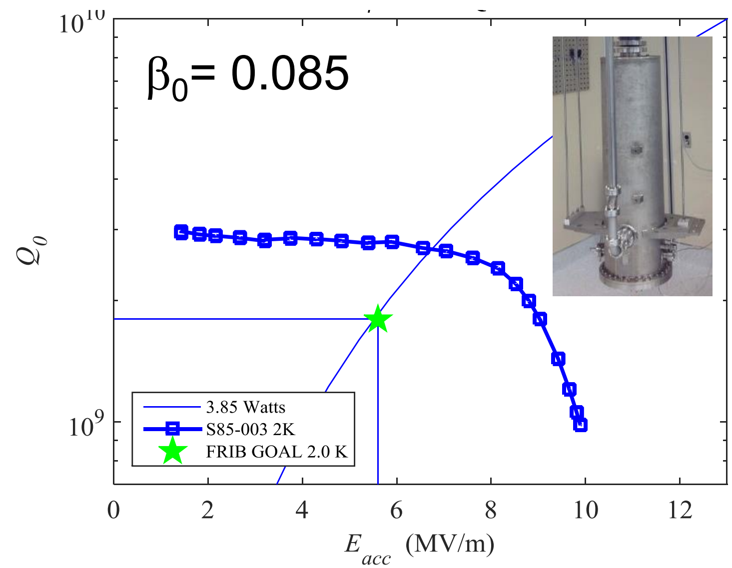
* Numbers in red indicate cavities received to date

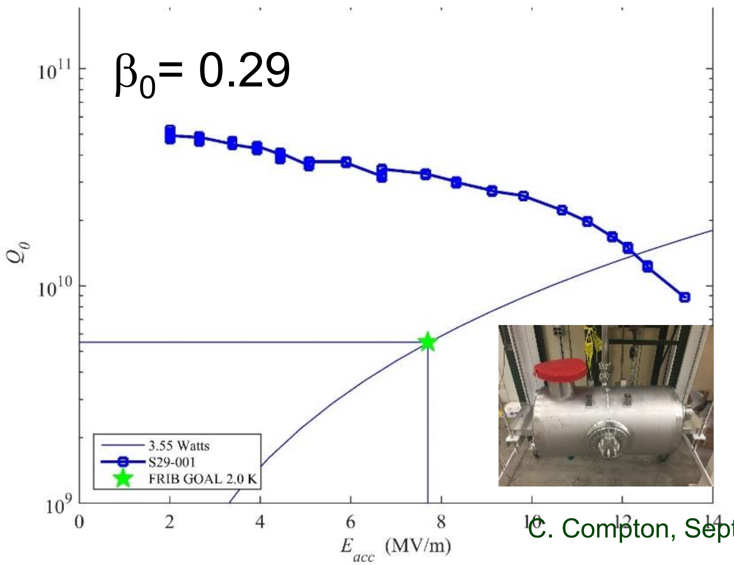
Production β_0 = 0.041 cavities being sequenced for cavity processing

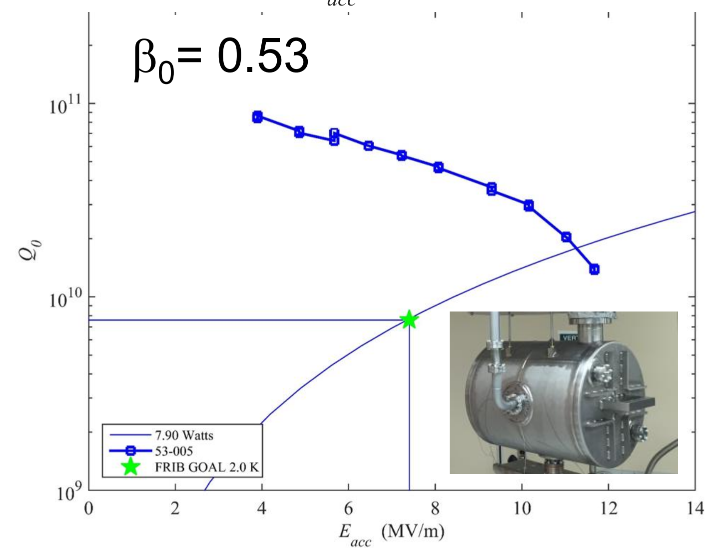
FRIB SRF Cavities Exceeding Performance Specification

- FRIB cavity certification goals indicated by ★









SRF Cavity Acceptance

- 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

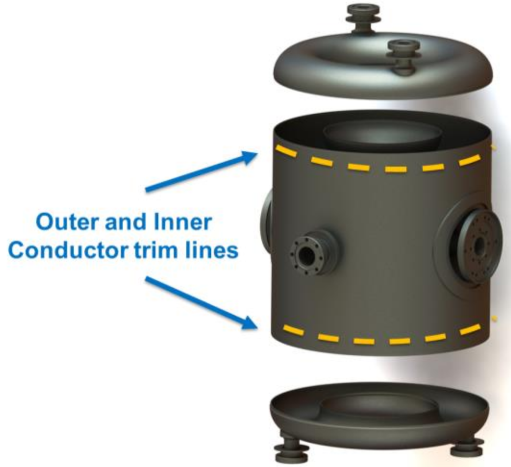
Dimensional inspection using Coordinate Measuring Machine (CMM)

Internal boroscope inspection

FRIB Cavity Frequency Control

- 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

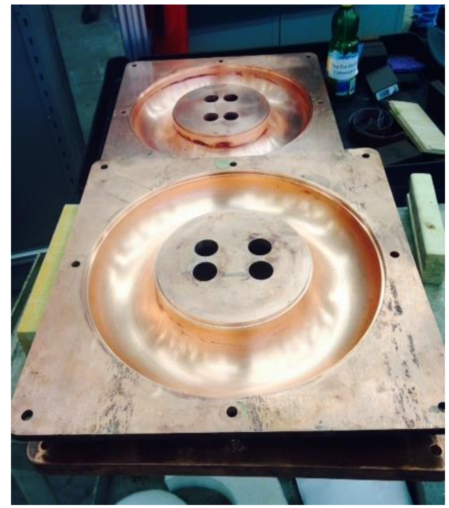
HWR frequency tuning using beam cup positioning

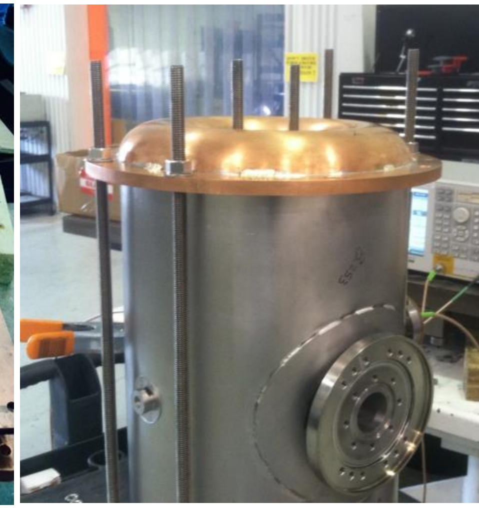


HWR frequency tuning using OC and IC stack and trimming

Half-wave Cavity Reference Stack-up Fixtures

- 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

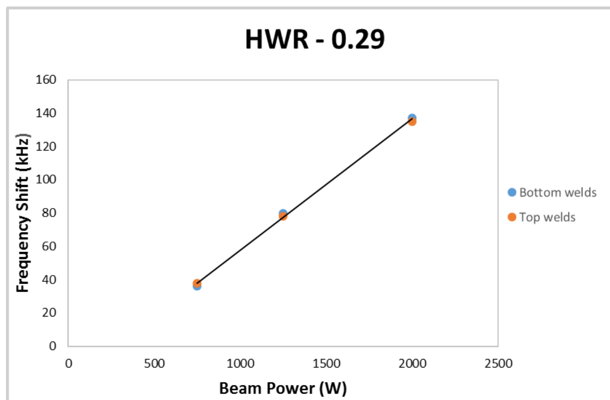
- **Niobium outer and inner conductors left long**
- **Frequency is determined by stacked-up measurement using calibrated reference copper short plates**
- **The outer and inner conductors are trimmed and re-stacked until goal frequency is met.**

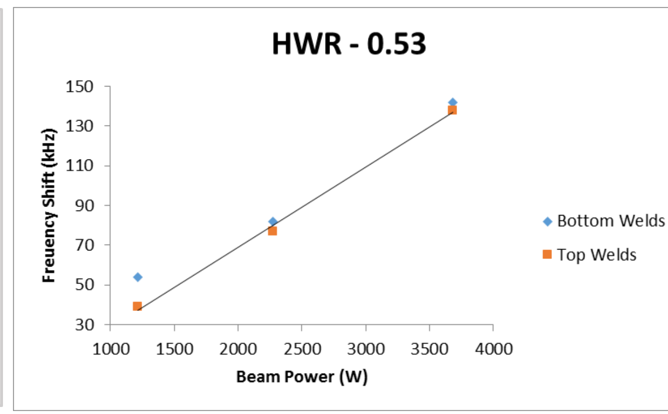
Virtual Weld Frequency Adjustment in Half-wave Cavities

- 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

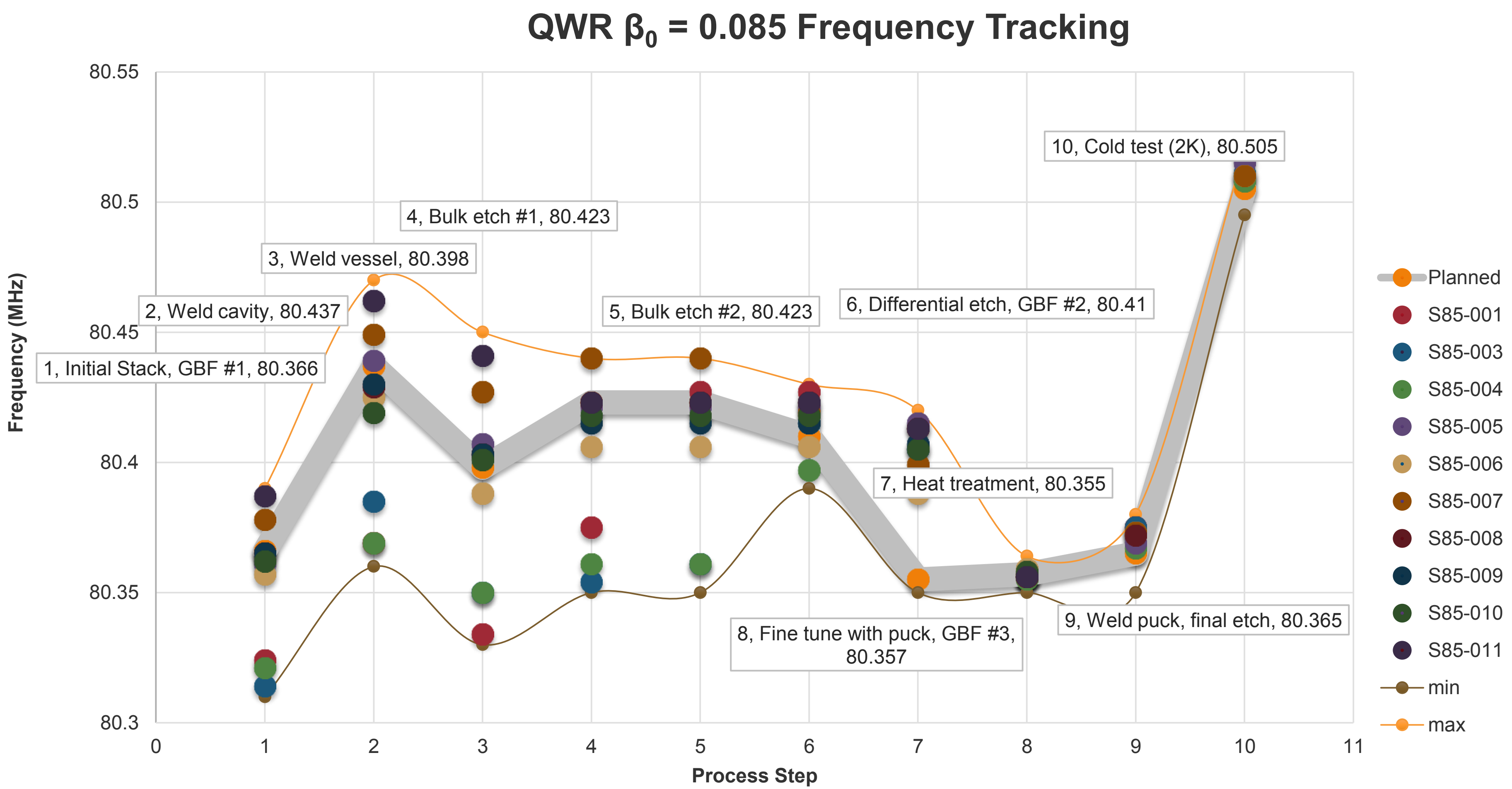
Virtual TIG welding





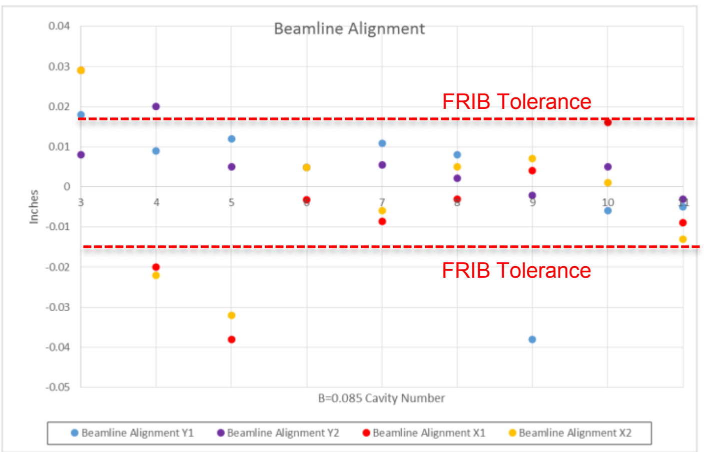
Electron-beam power calibrations for virtual welding of half-wave cavities (β_0 = 0.29 and 0.53) prior to helium vessel integration

Cavity Frequency Control

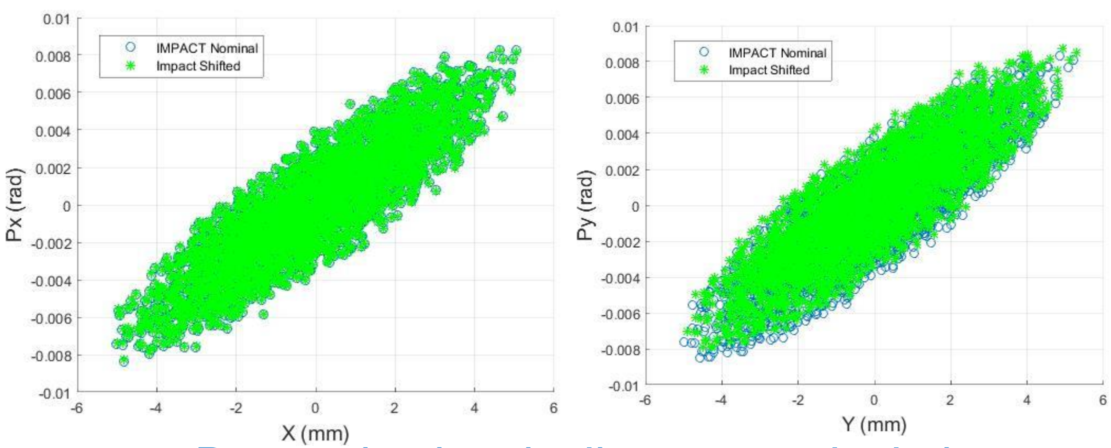


Aperture Alignment Issues Mitigated

- 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



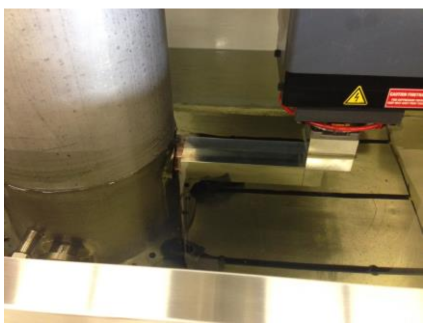
Aperture alignment tracking

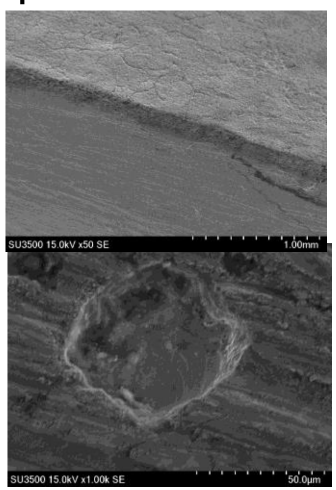


Beam physic misalignment calculations

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 $<1\text{x}10^{-10}$ 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



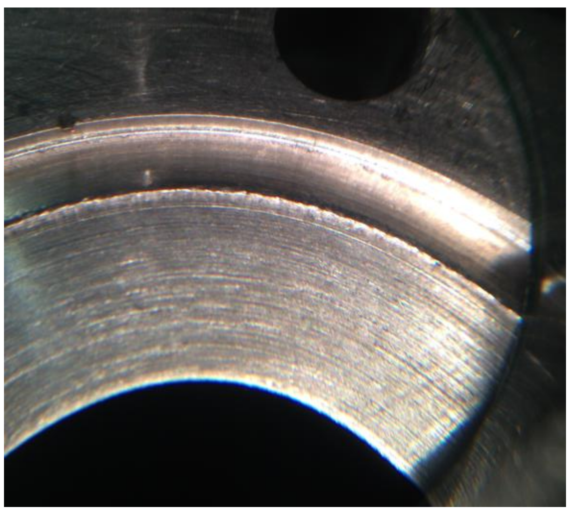


Electrical Discharge Machining (EDM) Conflat flange fabrication

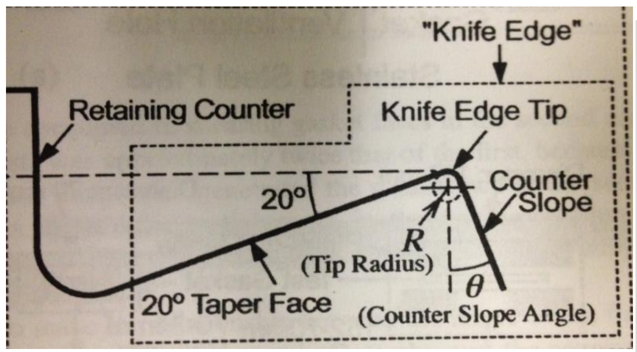
Developed method of repairing Conflat flanges on completed cavities

Vacuum Sealing Reliability Addressed [2]

- 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

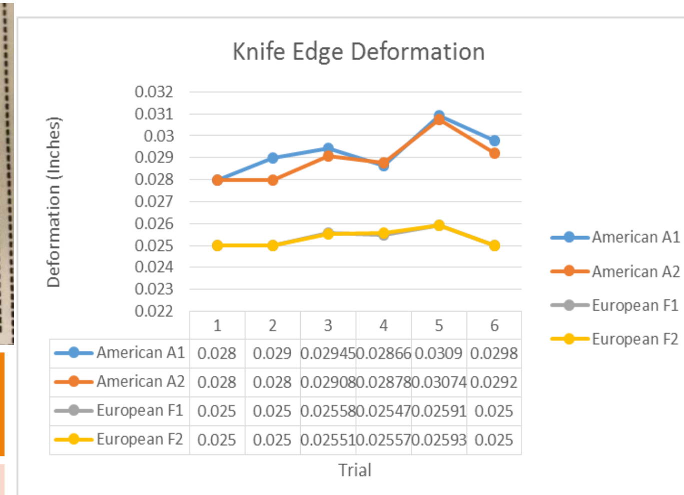


Knife-edge breakdown



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

Knife-edge profile designs

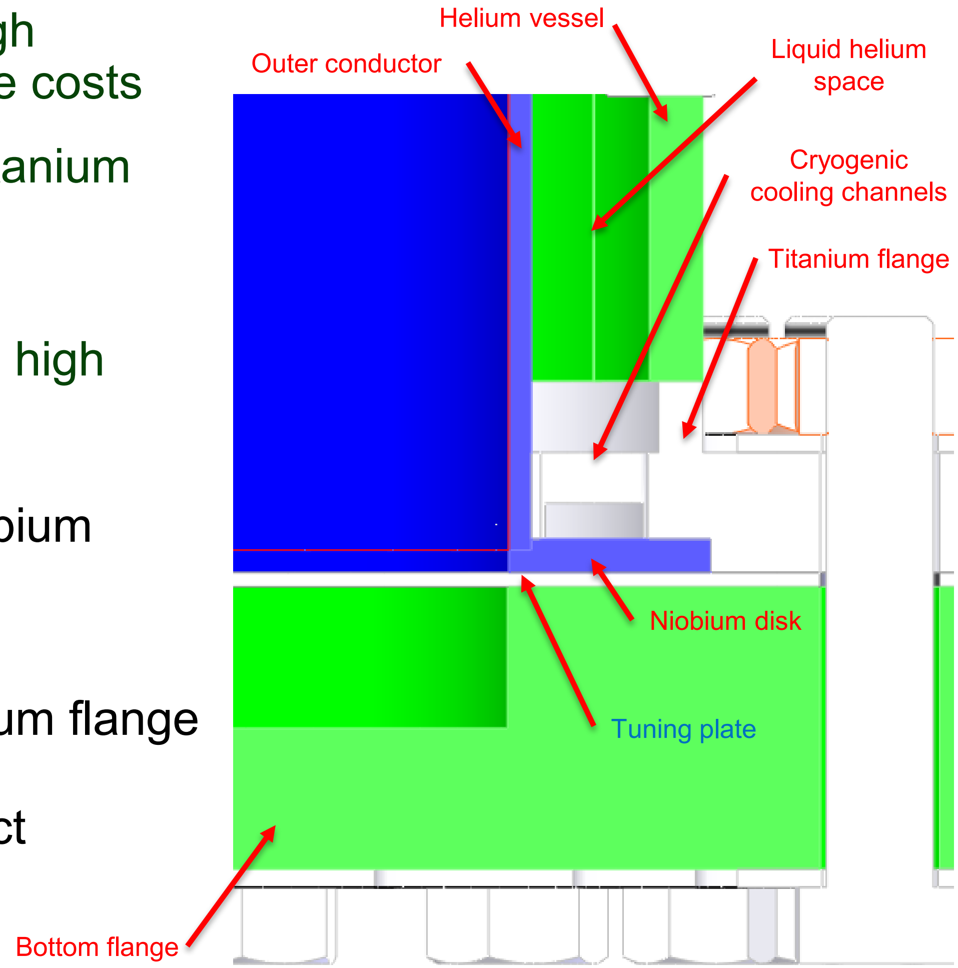


	1	2	3	4	5	6
American A1	0.028	0.029	0.02945	0.02866	0.0309	0.0298
American A2	0.028	0.028	0.02908	0.02878	0.03074	0.0292
European F1	0.025	0.025	0.02558	0.02547	0.02591	0.025
European F2	0.025	0.025	0.02551	0.02557	0.02593	0.025

Knife-edge deformation tracking

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



Thread Fabrication Lessons Learned

- 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