PHY905 Section 4
Ion Accelerator Technology
Lecture 20
- FRIB SRF -

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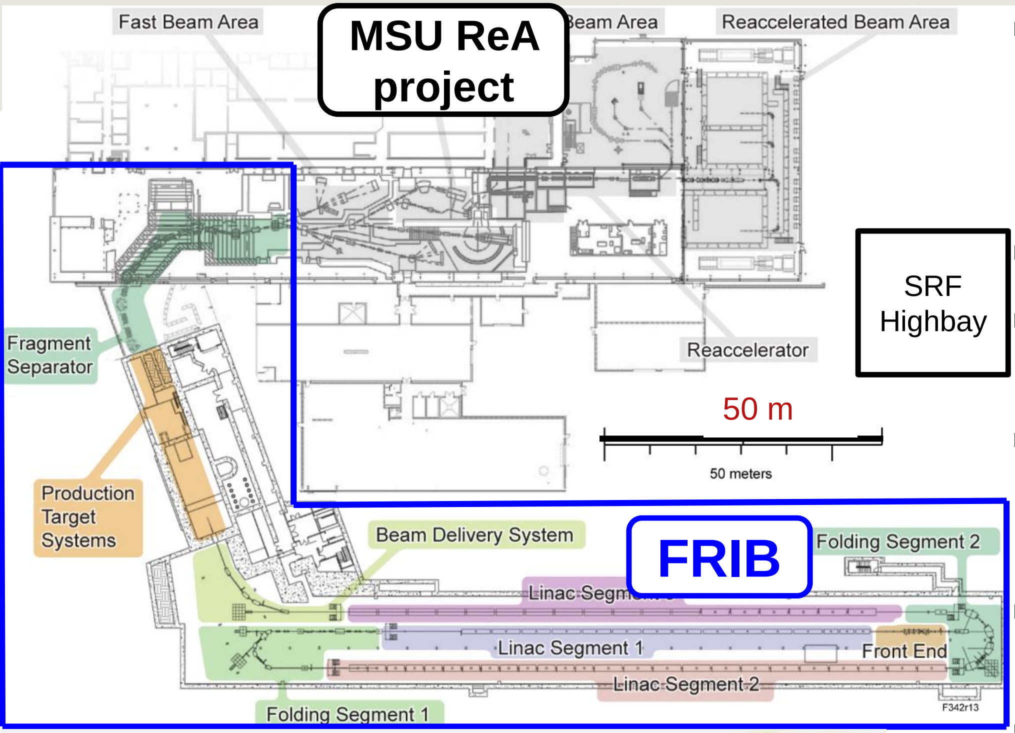
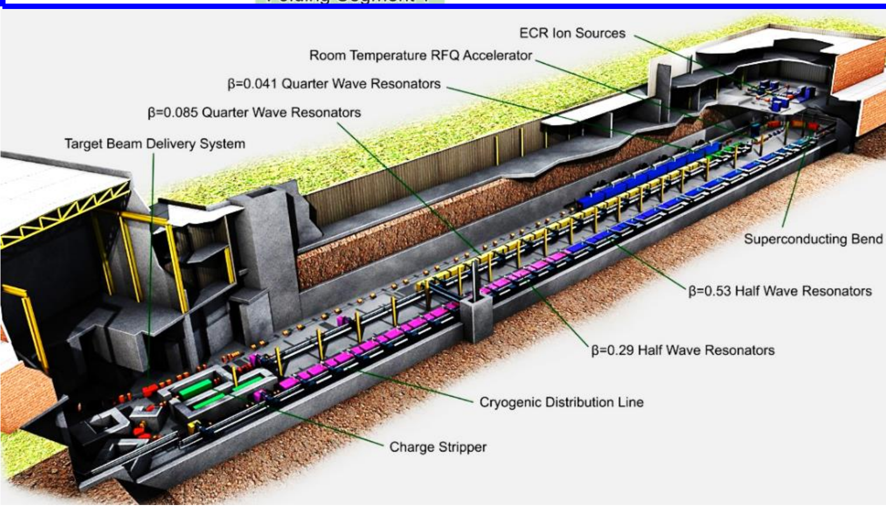
FRIB SRF Outline

FRIB SRF LINAC Overview





- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability, \$680M+\$300M MSU
- Three folded SRF linac (~500 m)
- Accelerate ion species up to ^{238}U with energies > 200 MeV/u
- Provide beam power up to 400 kW satisfy beam-on-target requirements
- Future energy upgradability > 400 MeV/u by filling vacant slots
- Early operation 2017(Front end) -2021
- CD4 in 2022

- **Features**:
  - Heavy ion beam intensity frontier machine, e.g. 5×10^{13} ^{238}U/s, 360μA, 250 times higher than ATLAS
  - All SRF from low beta to medium beta section and 2K operation
  - Large nuclear physics user (~1300 users) facility

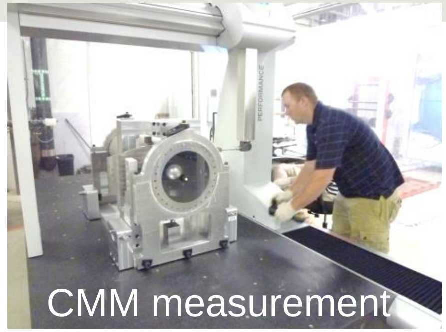
FRIB SRF Components

Cavities, FPCs, tuners, magnetic shields, and solenoid packages

Quarter Wave Cold Masses (Total scale of FRIB: 350 Cavities, 51 cryomodules)				
		Number of Cryomodules	Number of Cavities	Number of Solenoids
β = 0.041	Accelerating Cryomodules:	3 + 1 spare	12 + 4 spare	6 + 2 spare
β = 0.085	Accelerating Cryomodules:	11 + 1 spare	88 + 8 spare	33 + 3 spare
	Matching Cryomodules:	3 + 1 spare	12 + 4 spare	-
β = 0.29	Accelerating Cryomodules:	12	72	12
β = 0.53	Accelerating Cryomodules:	18	144	18
	Matching Cryomodules:	1	4	-
TOTAL		48 + 3 spare	332 + 16 spare	69 + 5 spare

SRF Infrastructure to Support FRIB Cryomodule Production by MSU Fund

- All critical SRF tasks are performed on-site
- Functionalities of the SRF Highbay
  - Acceptance inspection
    - Dimensional inspection by CMM
    - Cold shock test, Leak check, Demagnetization
  - Cavity processing and assembly
    - Large cleanroom
    - Degreasing system
    - Cavity etching (BCP) system
    - **Robotic high pressure rinsing system**
    - Ultrapure water system
    - Hydrogen degassing furnace
  - Cavity vertical test system
    - 3 Dewars and 4 cold inserts
  - Cold mass assembly
  - Bunker test system
  - Cryogenic system
    (Dedicated 900W helium refrigerator, helium purification and 2K system)


CMM measurement


Large cleanroom


BCP facility


Cavity assembly

Bunker test system


HPR system

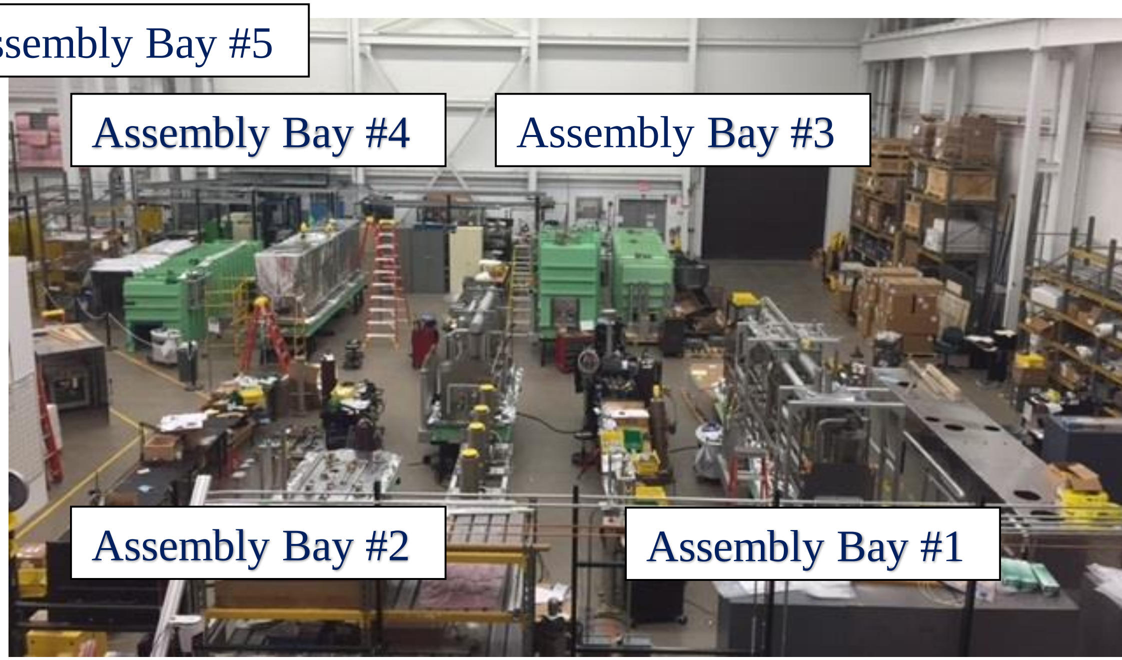

Vacuum furnace


Cold box and 5000L Dewar


Vertical test system

Cryomodule Assembly and Bunker Test

- Five Cryomodule Assembly bays setup
- Module is fixed on ground during the whole assembly process
- Cryomodule components are breakdown so that subsystem can be pre-fab and out-source
- Two bunker test areas (East HB and SRF HB)
- Six cryomodules bunker tested by early this month

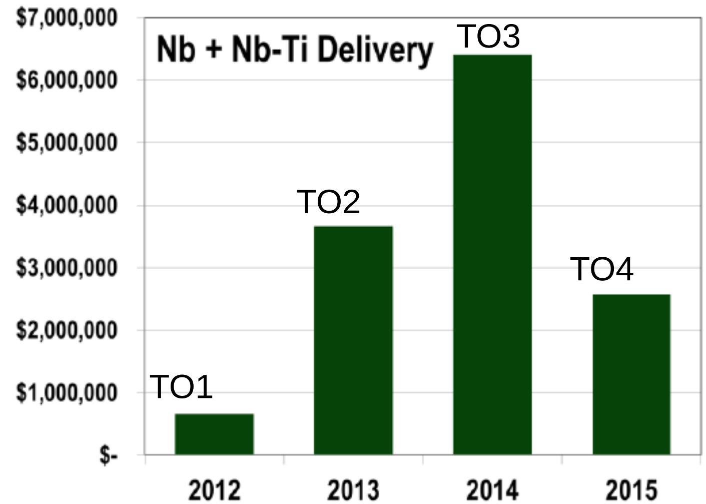


- Test bunker #1 at East Highbay
- Commissioned 2015
- 5 QWR cryomodule has been tested in this bunker

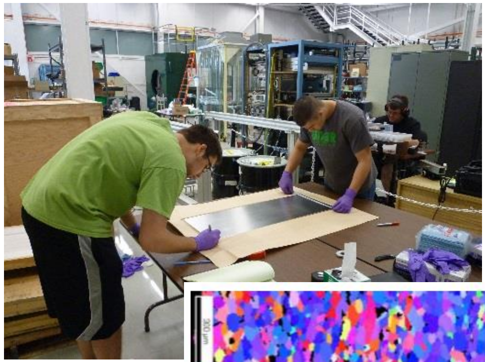
- Test bunker #2 at SRF Highbay
- Commissioned in 2016 fall
- First module (0.053CM) has completed test end of January 2017.

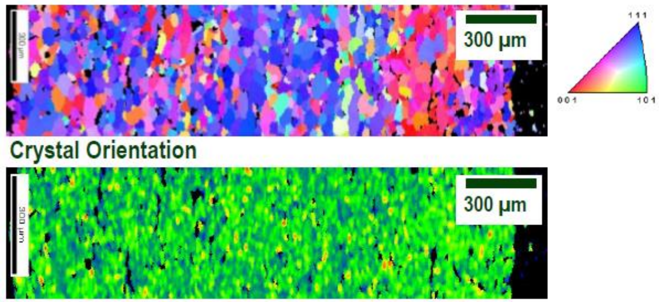
20.2 Niobium Materials for FRIB SRF

- **FRIB procures of niobium material from three vendors**
  - Wah Chang, US – NbTi flange material
  - Tokyo Denkai, Japan – RRR250 niobium sheets
  - Ningxia, China – RRR250 niobium sheets and tubes
- **Material specification**
  - Dimension check, surface inspection
  - RRR > 250 for niobium sheets
  - Grain size ASTM#5 (64μm)
  - 0.2% Yield strength > 48.3MPa
  - Tensile strength > 96.5MPa
  - Elongation > 40% (longitudinal), 35% (transverse)
  - Hardness < Hv = 60
  - Vender etching
- **FRIB acceptance tests**
  - Two samples per production lot are tested
  - Dimension and surface finish
  - Mechanical test (Ultimate, Yield, Elongation, Hardness)
  - Metallurgy properties measurement (Grain size, Crystal orientation, Recrystallization)
  - RRR/Thermal conductivity



Procurement schedule

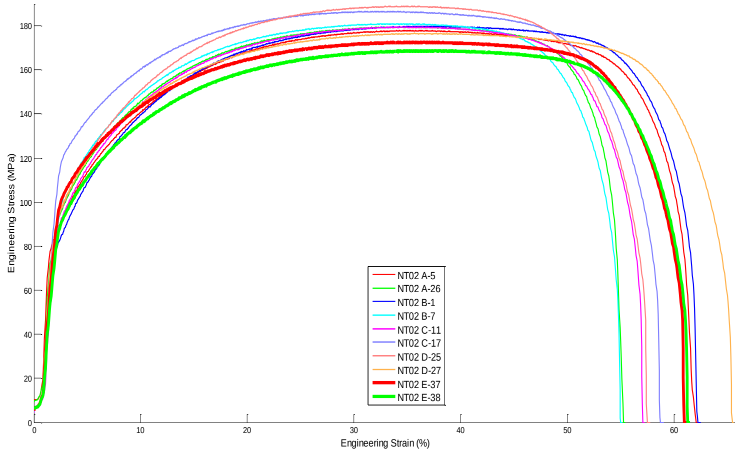


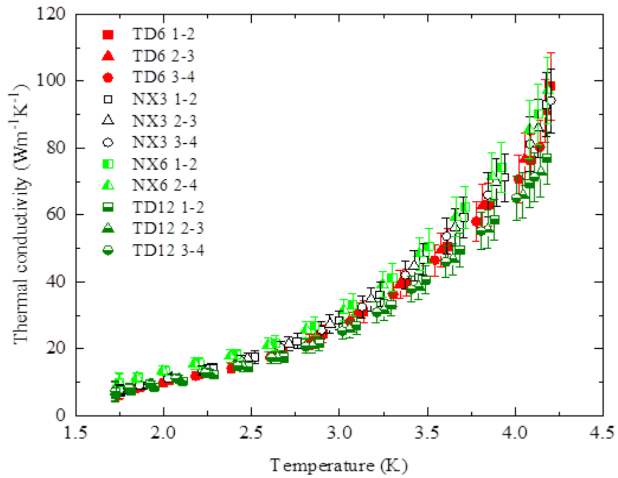


Crystal Orientation

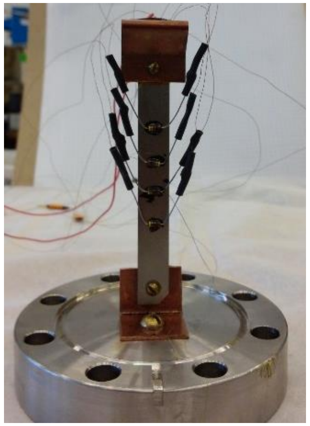
Misorientation Distribution

Material Acceptance Tests at MSU

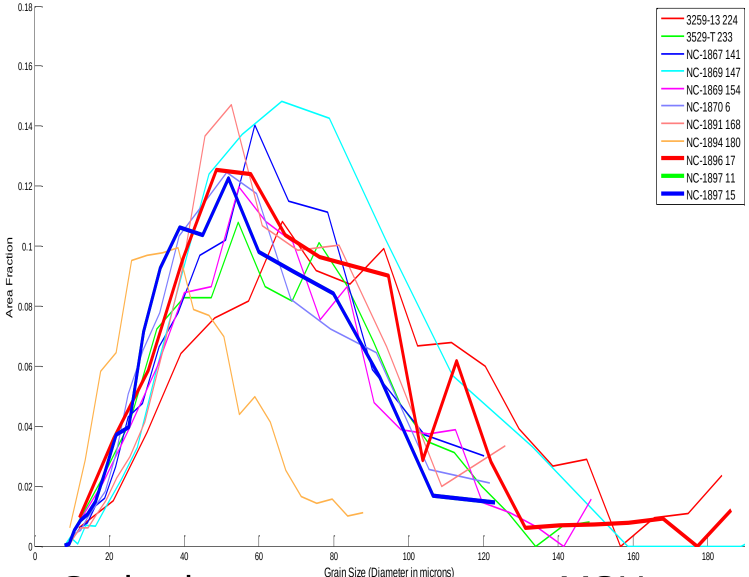




Thermal conductivity measurements at MSU



Thermal conductivity measurement



Grain size measurements at MSU

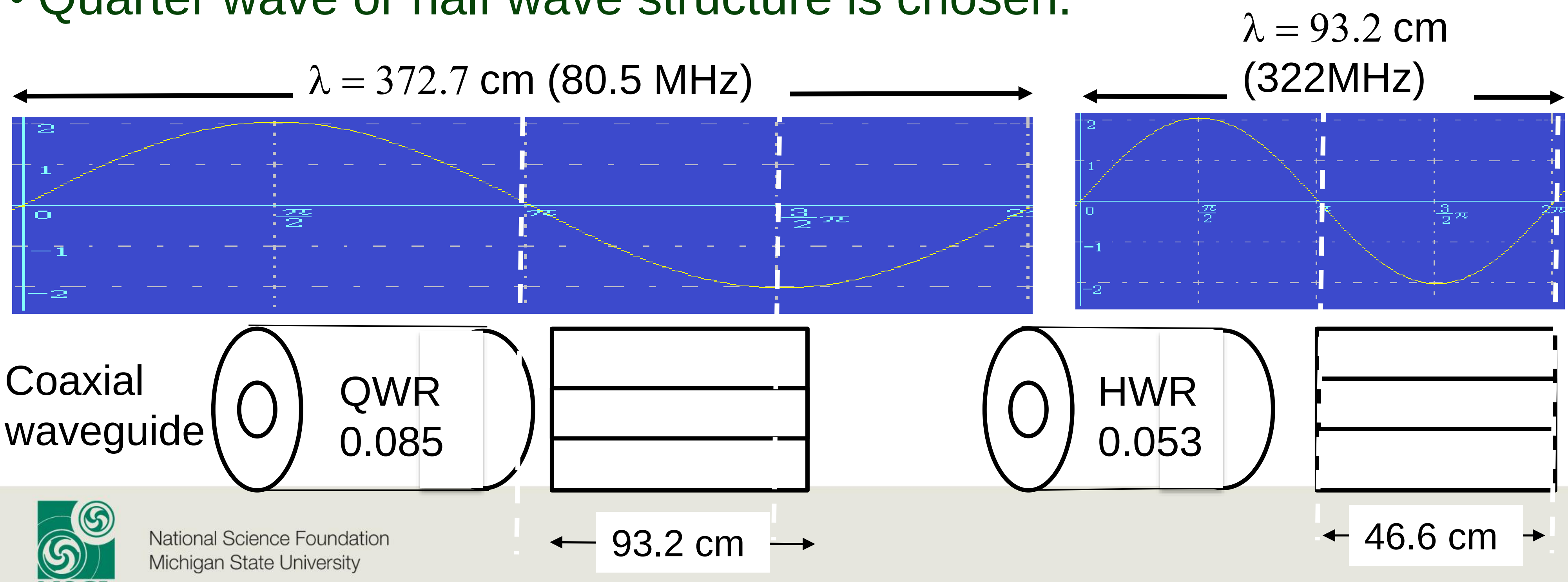
RRR measurement system at MSU

- **Enriched ACL tests**
  - Dimension check
  - Surface inspection
  - Mechanical tests
    - 0.2% Yield strength
    - Elongation
    - Tensile
  - Grain size
  - Crystal orientation
  - Thermal conductivity
  - RRR
- **Material quality is well controlled**

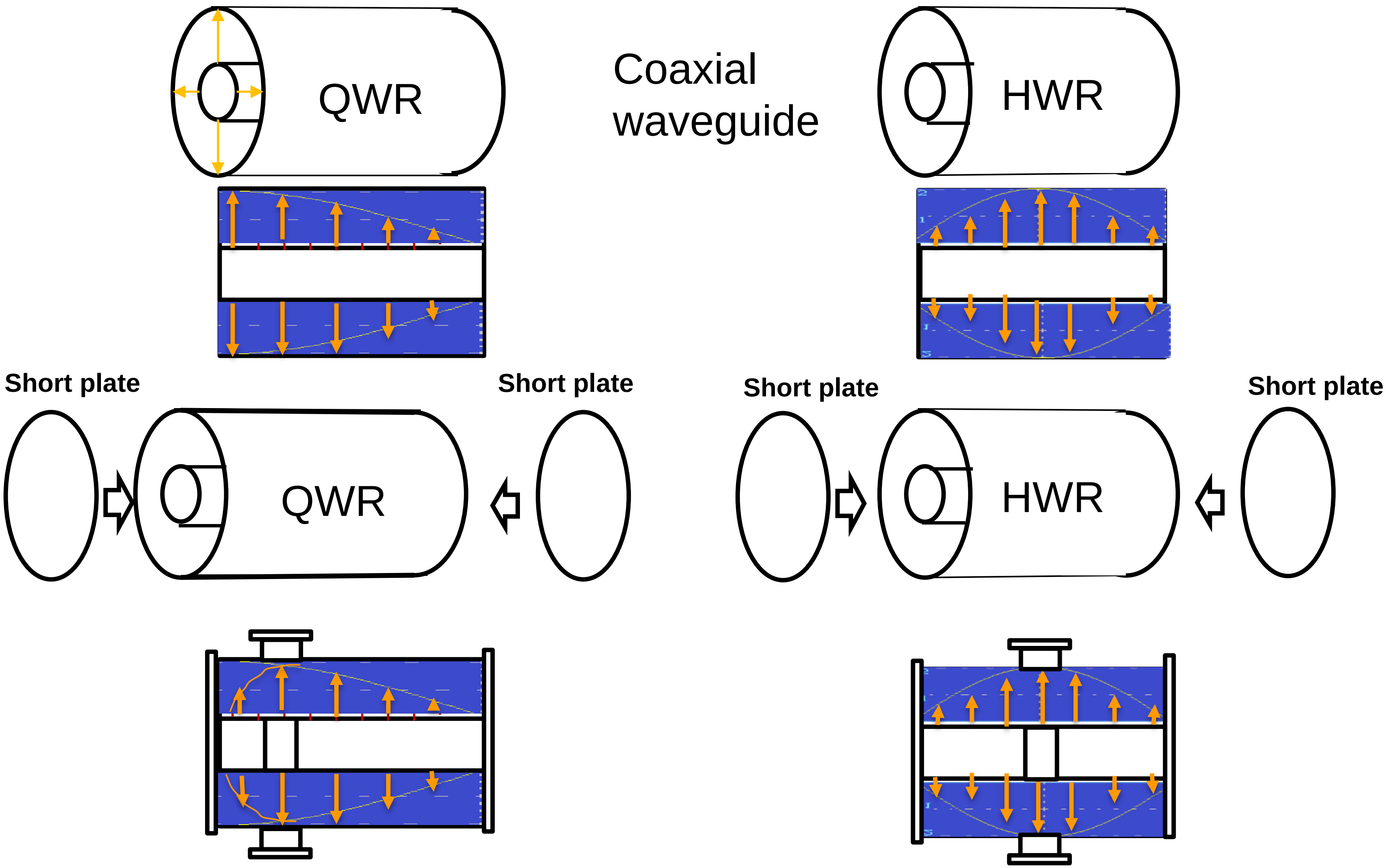
20.3 FRIB SRF Cavities

Low frequency preferred for low/medium beta cavities

- The cavity acceleration gap is $\frac{1}{2}\beta\lambda$, $\beta = \frac{v}{c}$, $\lambda = \frac{c}{f}$ for SRF cavities.
- β is very small in case of low/medium β, for instance β=0.041, 0.085, 0.29, and 0.53 with FRIB SRF cavities.
- Longer acceleration gap is needed for high acceleration efficiency, lower frequency is preferred for low/medium β cavities .
- However, the lower frequency makes cavity the larger.
- Quarter wave or half wave structure is chosen.

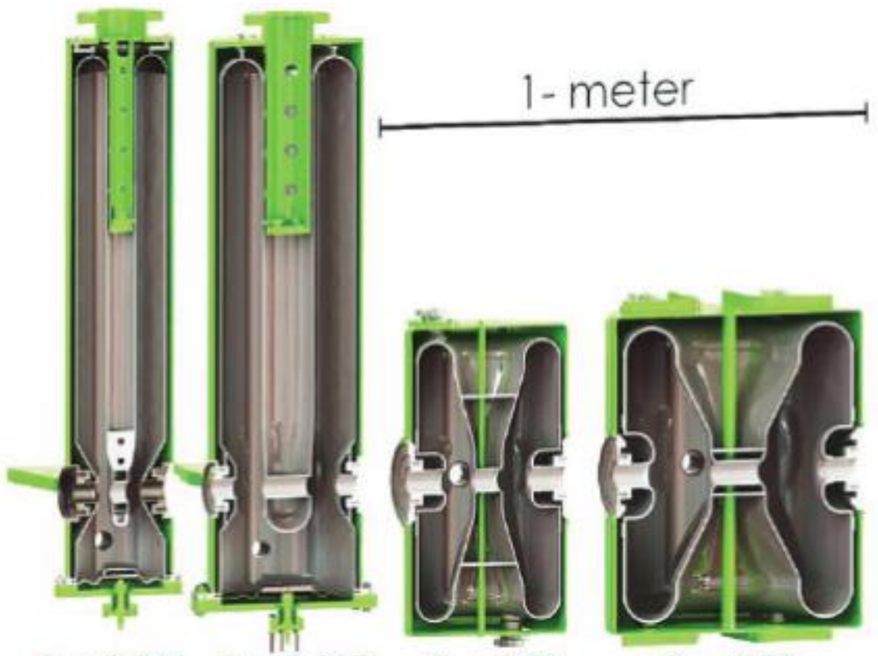


Principle of QWR and HWR Structures



FRIB Cavities

- Outer conductor is smashed at the beam port in the actual cavity design in order to enhance the field gradient at the beam port.
- Each cavity has two acceleration gaps, the acceleration gap length is a βλ per cavity.



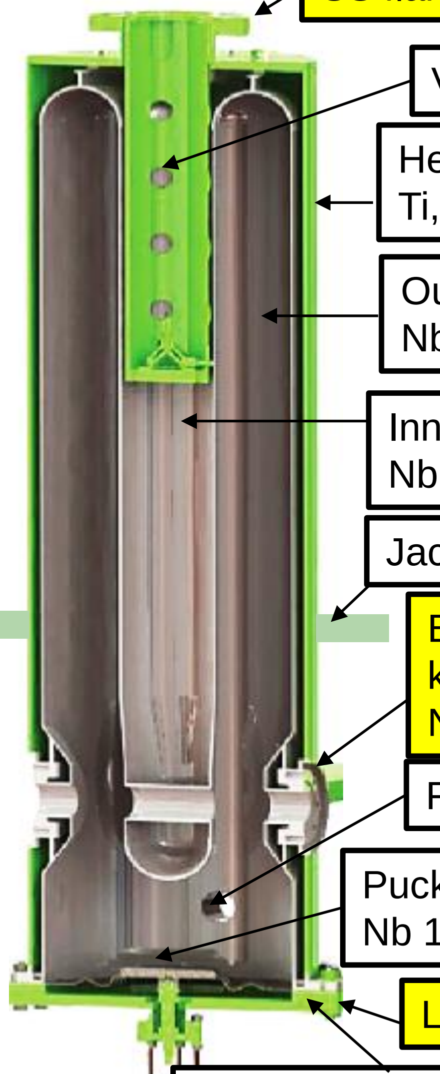
β_0 = 0.041 β_0 = 0.085 β_0 = 0.29 β_0 = 0.53
Quarter-Wave Resonators 80.5 MHz
Half-Wave Resonators 322 MHz

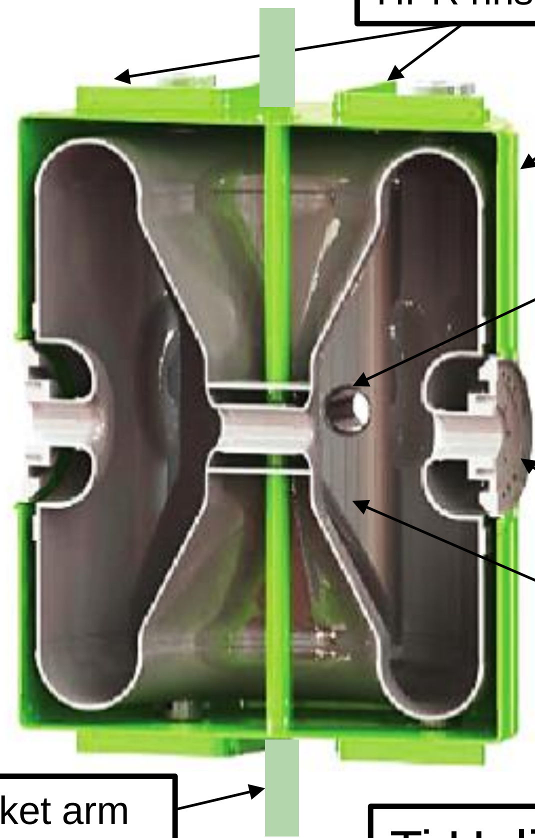
Table 1: RF Parameters for FRIB Cavities

Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
G [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m)^2]	< 4	< 4	< 4	< 4
Specific Q_0 @VT	1.4×10^9	2.0×10^9	5.5×10^9	9.2×10^9

Structure Details of FRIB SRF Cavities

Example: 0.085QWR and 0.53HWR



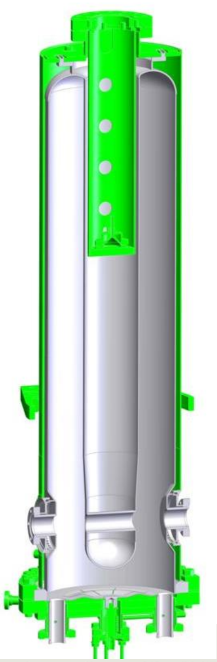


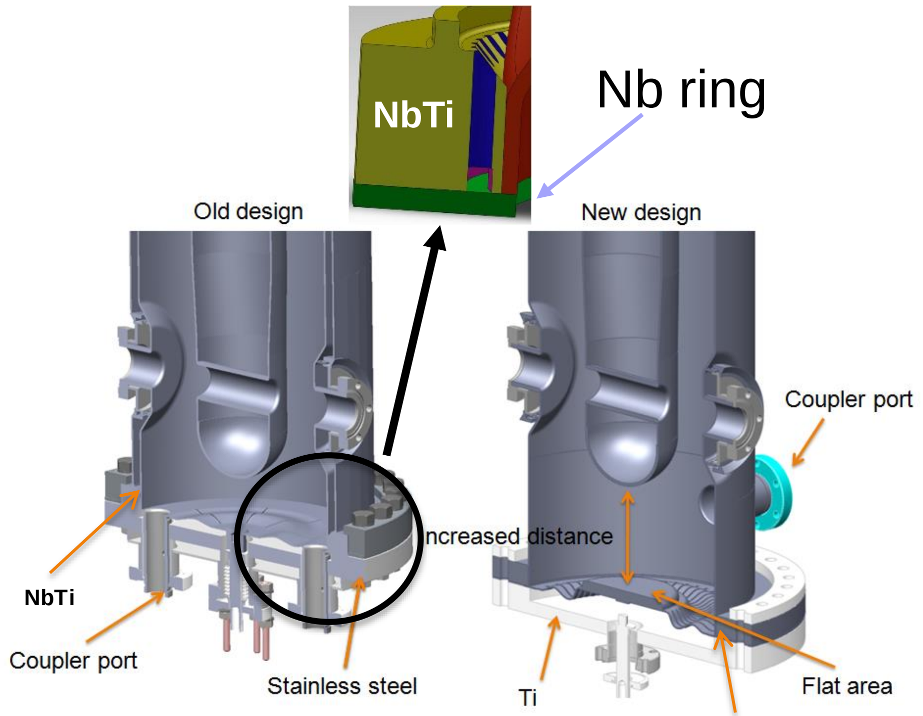
Naked cavity ⇨ Ti Helium jacketing, TIG weld ⇨ Machining of the jacket arm for alignment

Lessons Learned from ReA3 Construction

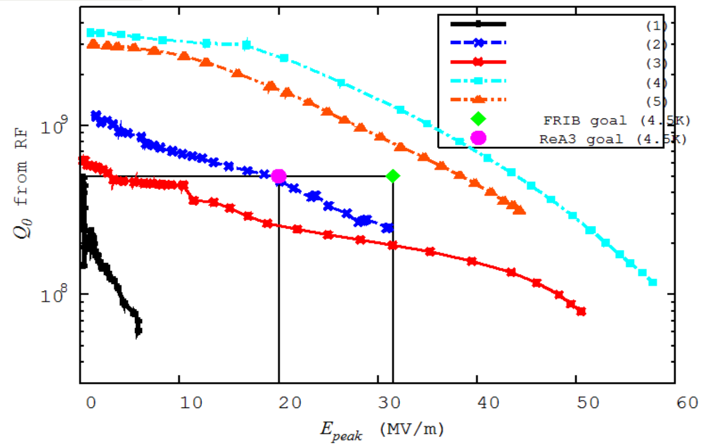
Bottom flange issue with 0.085QWRs

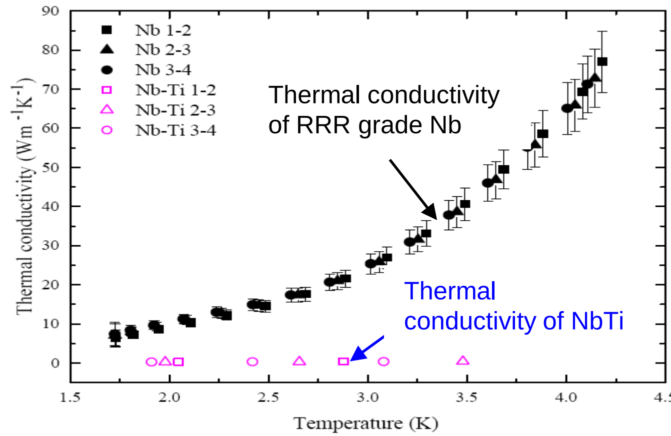
- **ReA3, 1st prototyped β=0.085 cavities**
  - The tuning plate insufficient cooling due to NbTi bottom flange has poor thermal conductivity
  - Modified design
  - ➢ Elongated the bottom outer tube to reduce magnetic field and made a distance tuning plate-inner conductor
  - ➢ RF coupler moved from the tuning plate to the side
- **Refurbished all 11 ReA3 QWRs Successfully validated the reliable performance with all refurbished cavities**

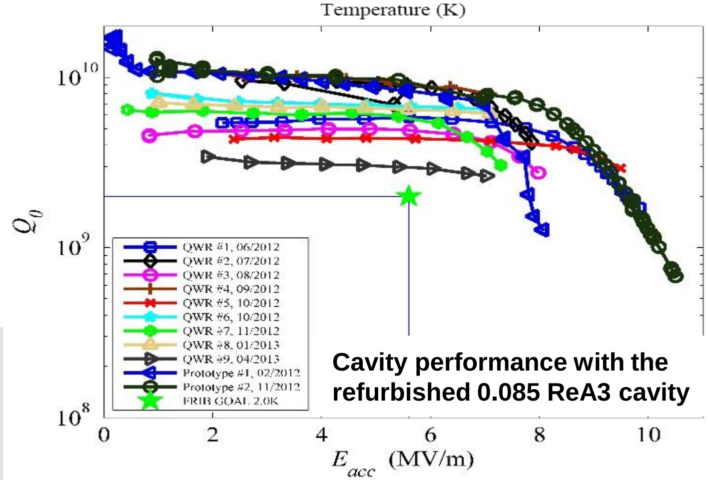




Cavity performance with the first prototyped 0.085 ReA3 QWR







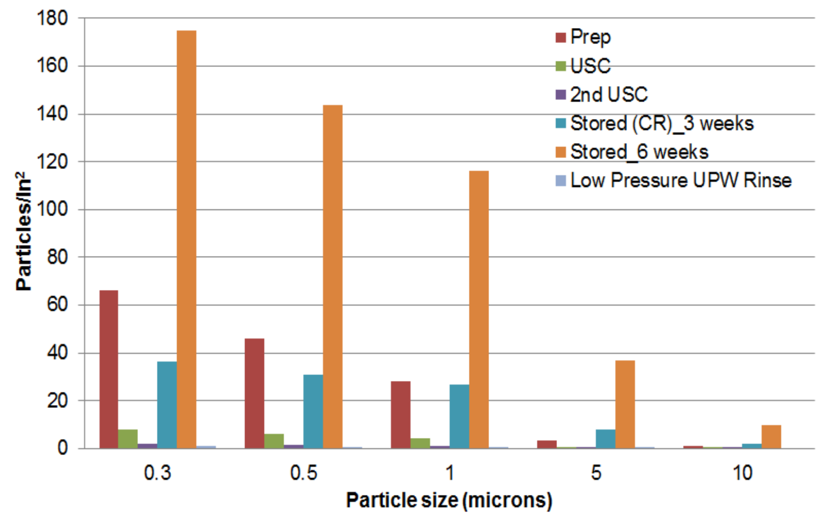
Cavity performance with the refurbished 0.085 ReA3 cavity

FRIB Unique QA Process Control

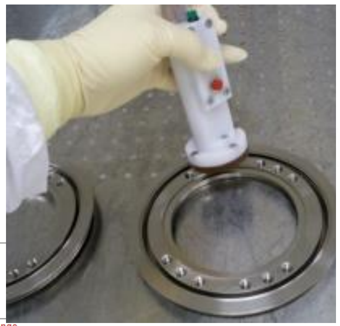
Particle contamination control based on particle counter

- **Established the QA procedure by diagnostic tools developed in the past R&D phase**
  - BCP, removed 150μm
  - HPR, 1hr
  - Monitoring particles in the HPR waste water
  - Monitoring particle contamination on flanges during cavity assembly
  - Baking 120^{O}C for 48hr
- **QA control by particle counter is very effective to reduce FE**

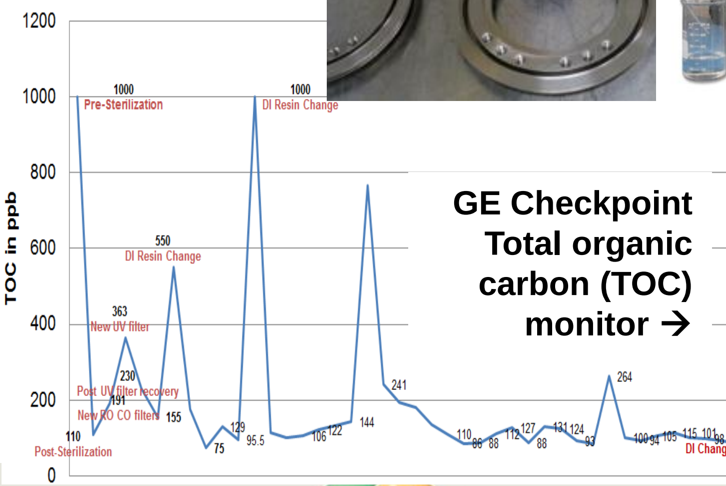
Average Surface Particle Counts on HWR Tapped Hole Flange for Various Procedures



QIII Surface Particle Counter →

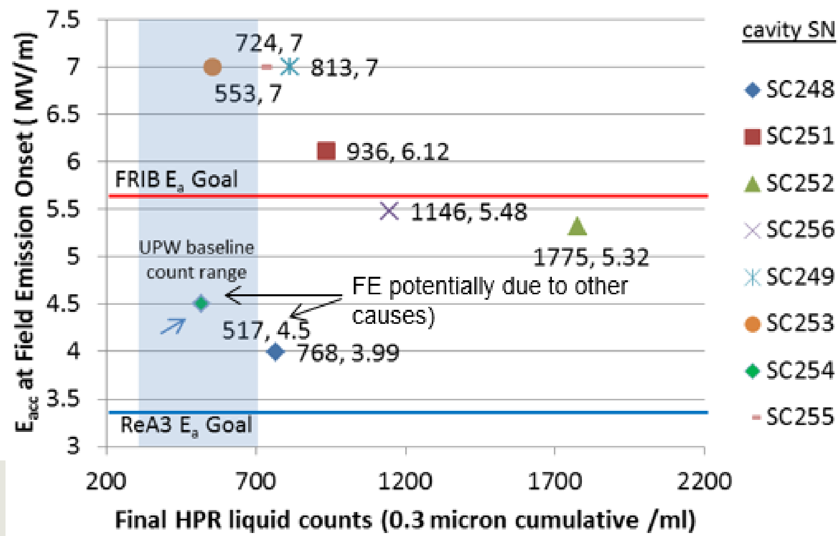


←SLS-1200 Liquid particle counter



GE Checkpoint Total organic carbon (TOC) monitor →

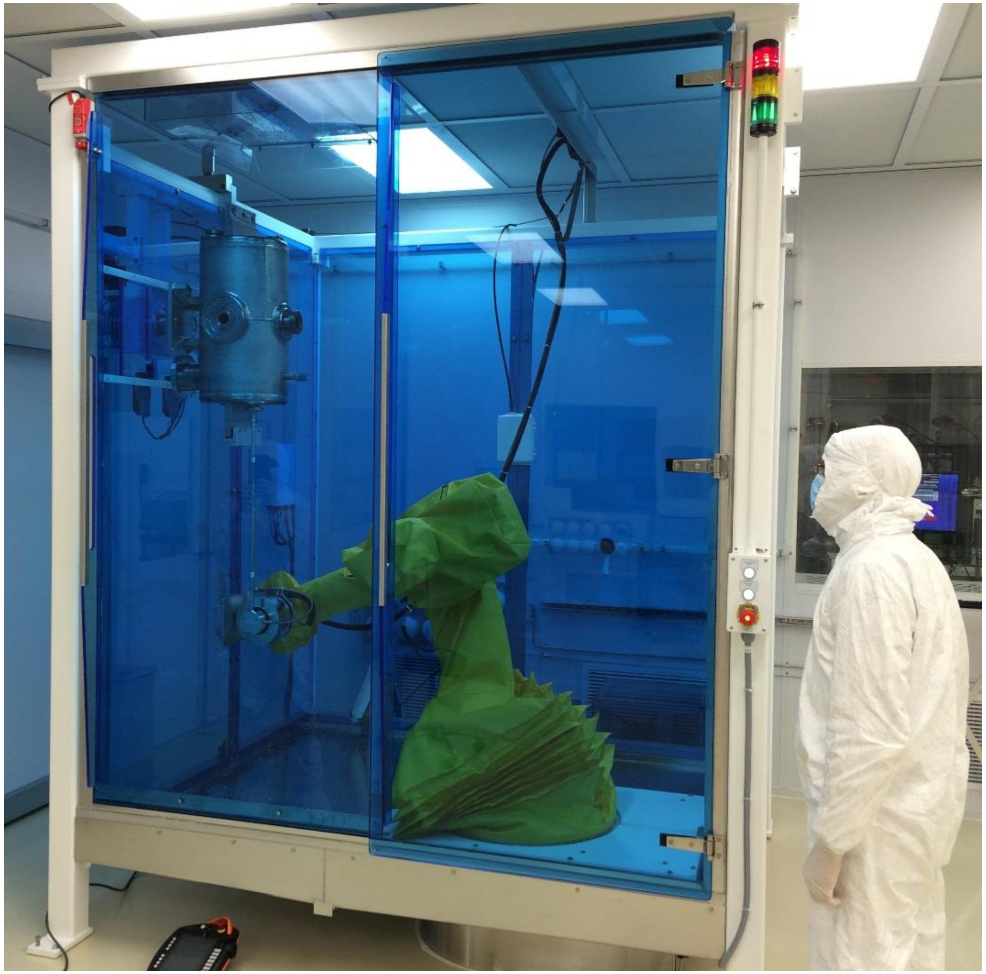
Good correlation between particle and FE onset



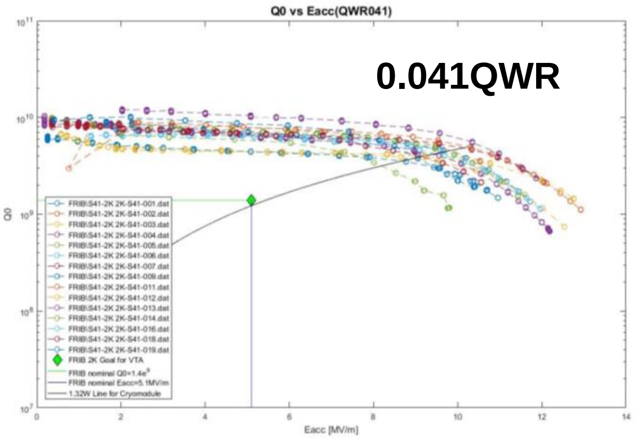
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

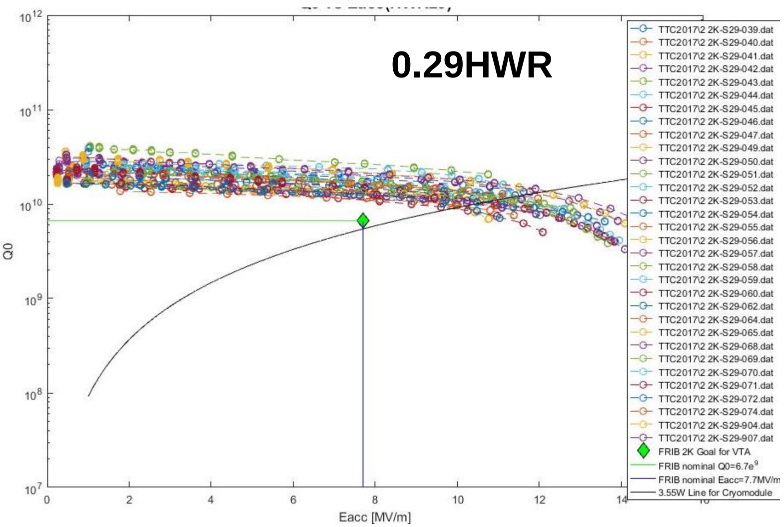
Robotic HPR Implemented to Enhance Production Capacity

- 92 rinse cycles have been completed since robot installation and commissioning in February 2016
- Cavities still meet performance requirements
- High Reliability → 96% System uptime since installation
  - Maintenance (oil, filter changes)
  - Repair (sensor repair and replacement)
- No cavity damage has occurred
  - Alignment concept and wand programming has been thoroughly validated
  - A redundant collision detection system planned for implementation this winter



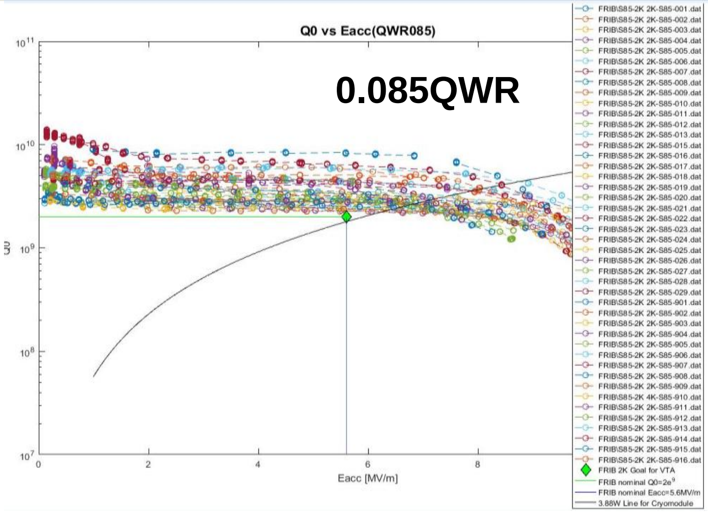
FRIB Production Cavity Performances
Exceed FRIB requirements

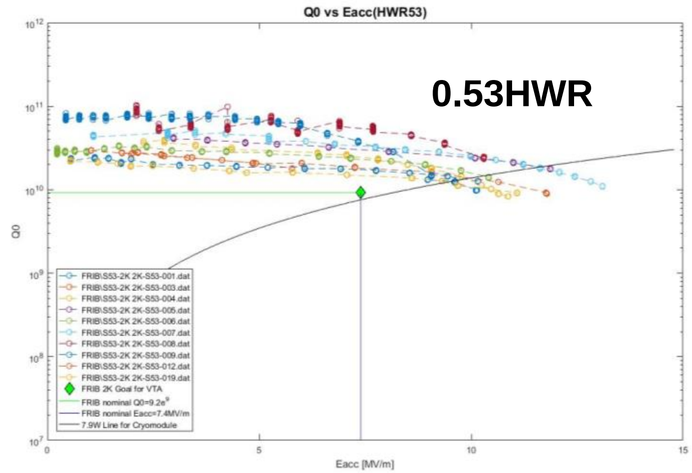




β₀ = 0.041 β₀ = 0.085
Quarter-Wave Resonators
80.5 MHz

β₀ = 0.29 β₀ = 0.53
Half-Wave Resonators
322 MHz





cavity	0.041 QWR	0.085 QWR	0.29 HWR	0. 53 HWR
E_a (MV/m)	☑ > 5.1	☑ > 5.6	☑ > 7.7	☑ > 7.4
Q_0	☑ > 1.4×10^9	☑ > 2×10^9	☑ > 6.7×10^9	☑ > 9.2×10^9
Df/dP (Hz/mBar)	☑ -2.7	☑ -1.85	☑ -2.2	☑ -6.7
LFD (Hz/(MV/m)^2)	☑ -3	☑ -2.9	☑ -5	☑ -4

Again Low Q Issue in Production 0.085QWRs
Not so serious, still continue effort to solve the issue

- In-house 0.085QWR (2) indicated high Q performance
- Production 0.085QWRs indicates low Q behavior in many cavities but still meet FRIB spec
- An additional heating of 2.5 W happens in this issue
- Not related to vendors
- Various potential cures are attempted but the root cause still not clear
- Ruled out;
  - ✓ Hydrogen Q-disease
  - ✓ Heating of tuning plate/puck
  - ✓ Titanium contamination during EBW between inner conductor and bottom flange
  - ✓ Magnetic field enhancement at the In seal gap

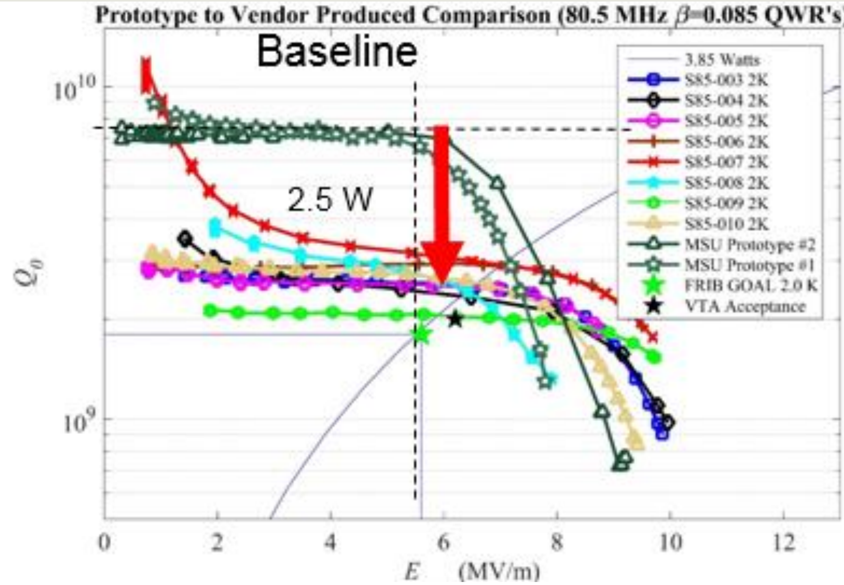
➢ Low temperature bake is helpful somehow but not decisive.

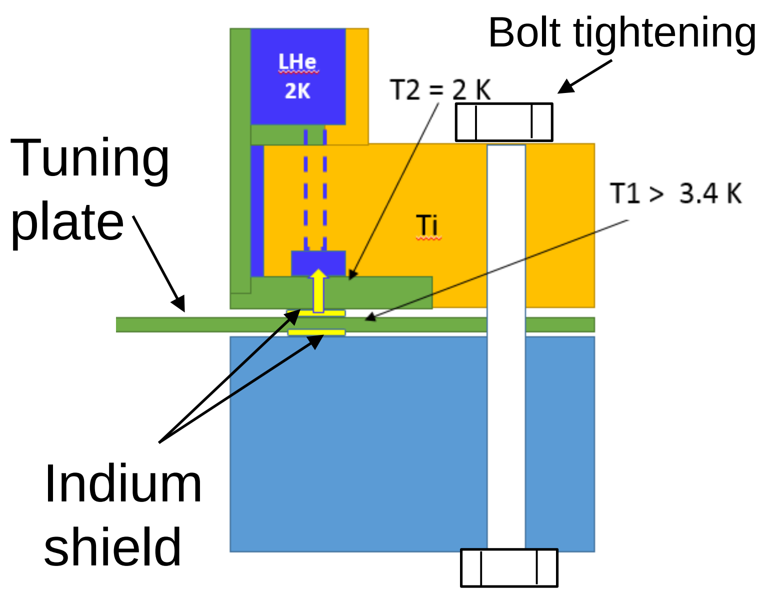
➢ Bottom flange etching seems to work but no reproducibility.

➢ Removing cavity defects like scratched seems to work but this issue happens in the cavities without defects

➢ RF contact at bottom flange, Indium seal ???

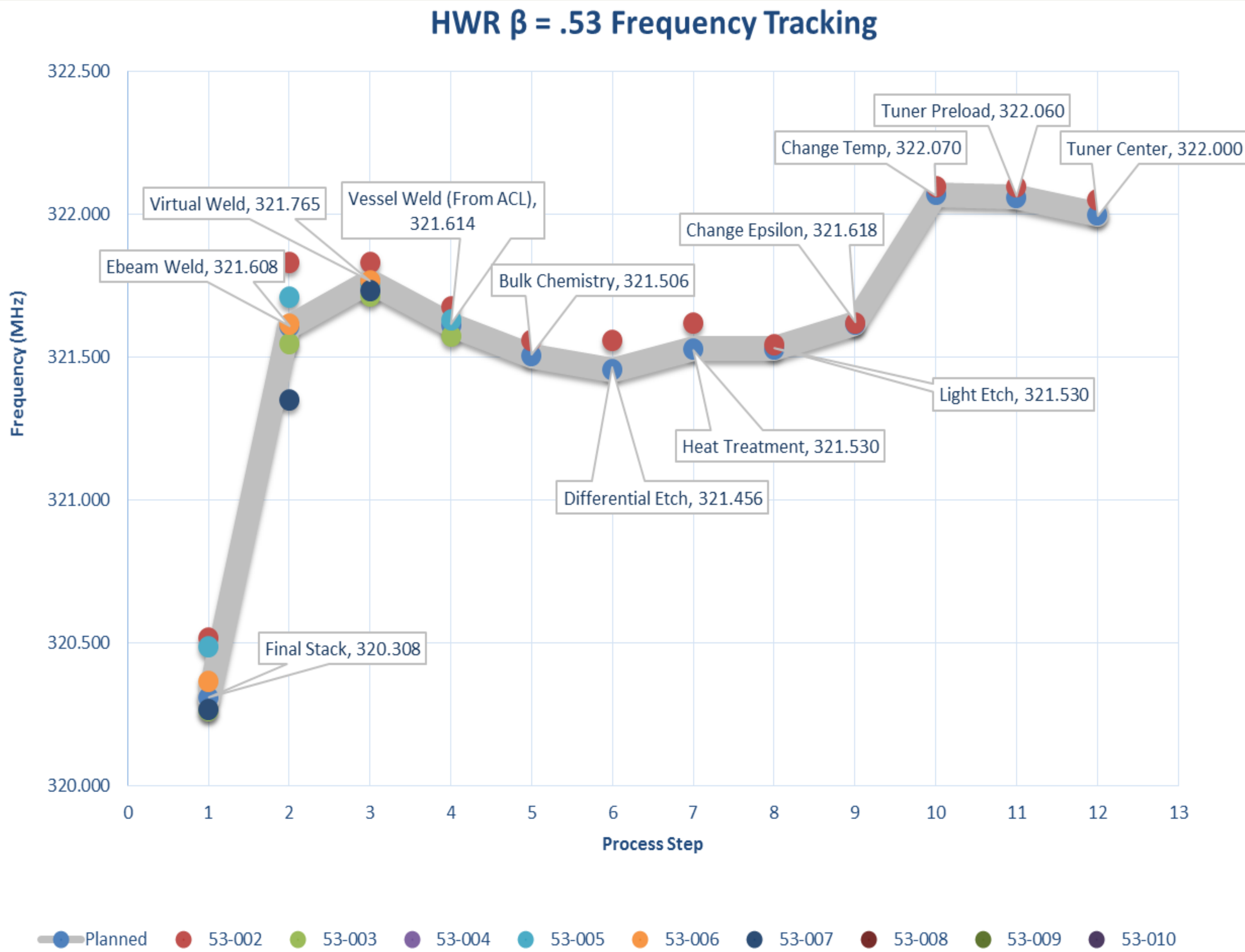
➢ Sensitive to clamping





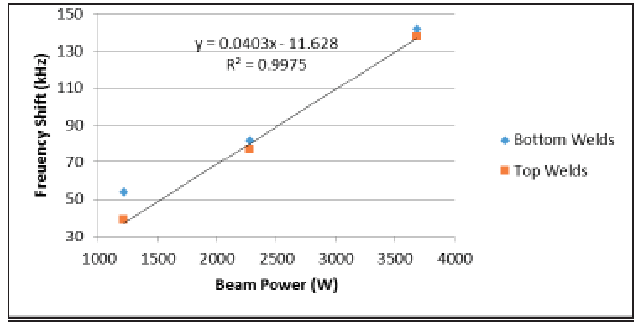
Cavity Frequency Control Example : FRIB 0.53HWR

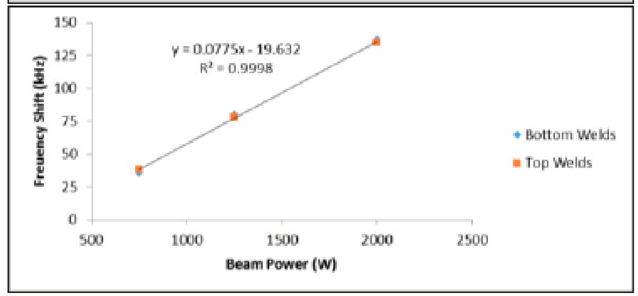
- Cavity frequency control during cavity fabrication
- Cavity frequency is control ~ ±30 KHz in the fabrication
- The deviated frequency was tuned by so called "virtual welding".
- Fine tuning also done by differential etching

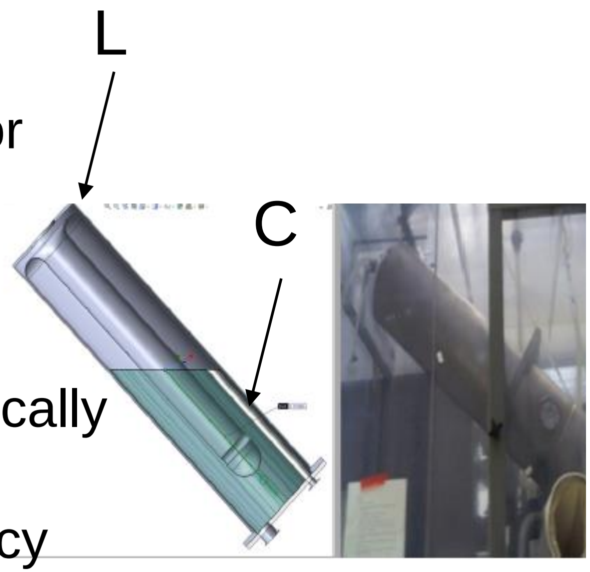


Cavity Tuning Methods FRIB Innovated
Virtual welding and differential tuning

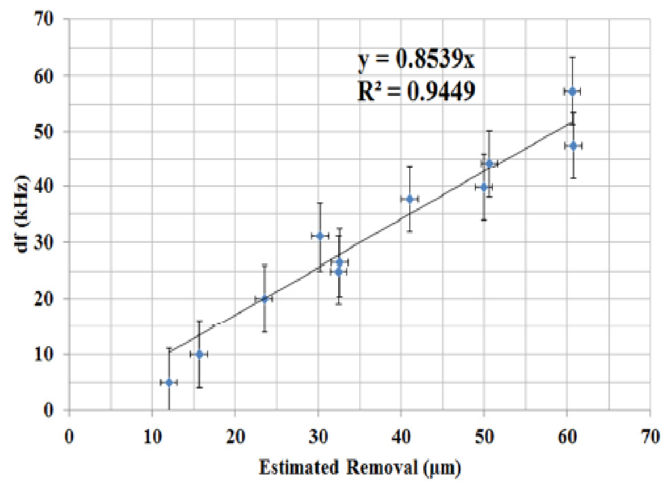
- **Virtual welding** for HWR cavity frequency control
  - Cavity shrinkage by EBW to increase cavity frequency
  - Possible to increase cavity frequency within a few % accuracy
- **Virtual TIG welding**
  - Increase cavity frequency for HWRs with helium vessel
- **Differential etching** for QWR frequency control
  - Remove high E-field area locally
  - Possible to increase cavity frequency within 5% accuracy



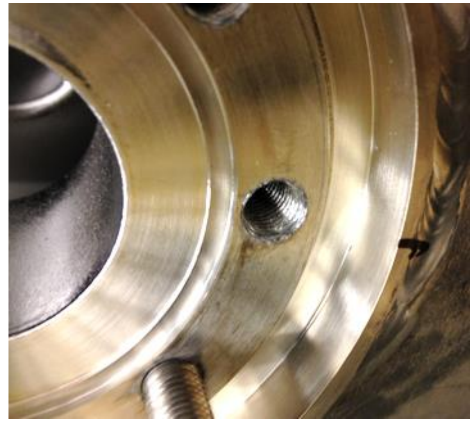




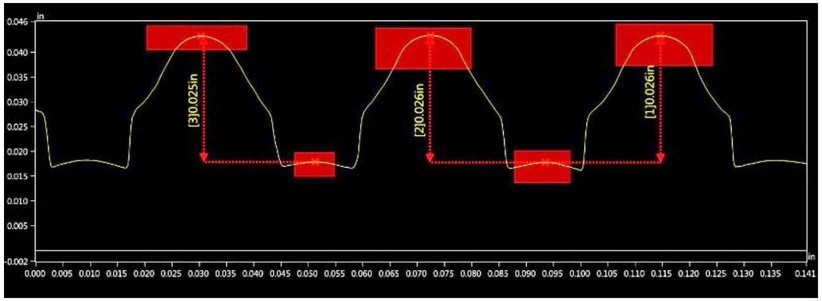
$$f = 1/[2\pi\sqrt{LC}]$$



Lessons Learned during FRIB Cavity Production (1)

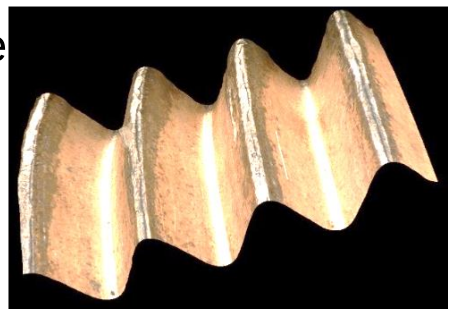


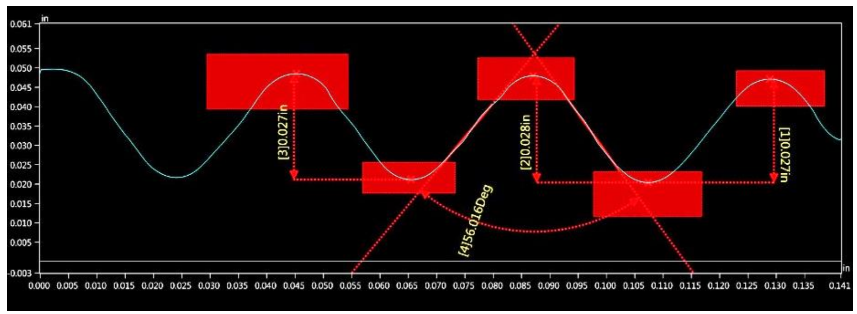
- **Gnawing of SS fasteners in the NbTi screws**
  - Make electropolishing on the SS fasteners
  - Careful inspection on Go/NoGo (2B) gauge
  - Concern about magnetization



- **Resolution: Take electropolishing fasteners**

- **Alternative material (NC25; hard copper)**
  - Proof of principle done,
    no gnawing and less particle
  - Perfect non magnetic

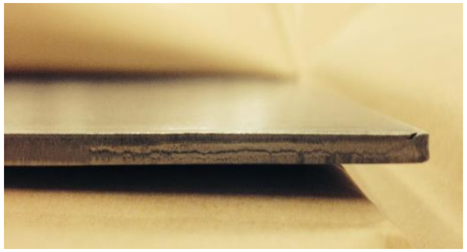


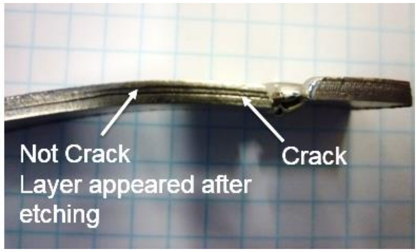


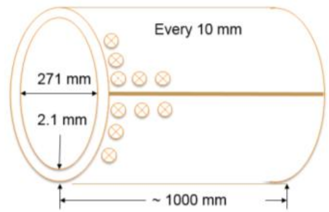
Lessons learned

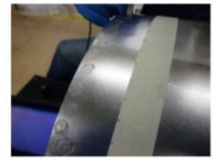
(2) Niobium materials issue and (3) ICF flange of NbTi issue

- **EBW problem on the QWR outer conductor due to niobium material defect (laminar structure)**
  - Vendor visit and instruction of inspection (ultrasonic check) by expert
  - Re-inspection of all stocked materials at FRIB

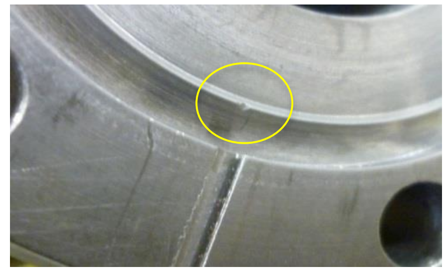


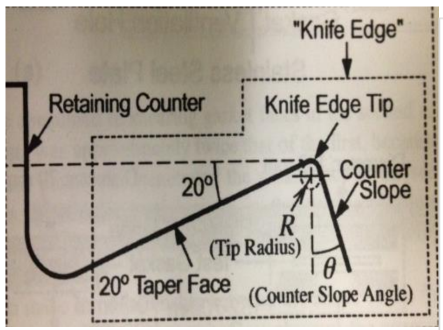




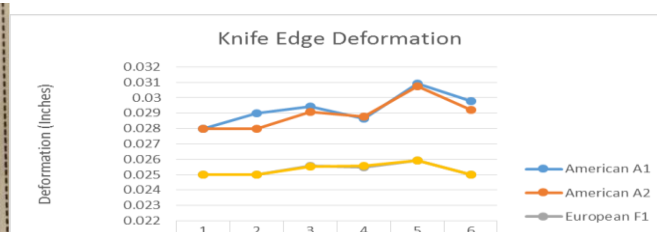


- **Leak at ICF seal on the NbTi flange**
  - Changed US ICF structure to EURO standard ICF
  - Careful gasket removing after leak check
  - Careful inspection





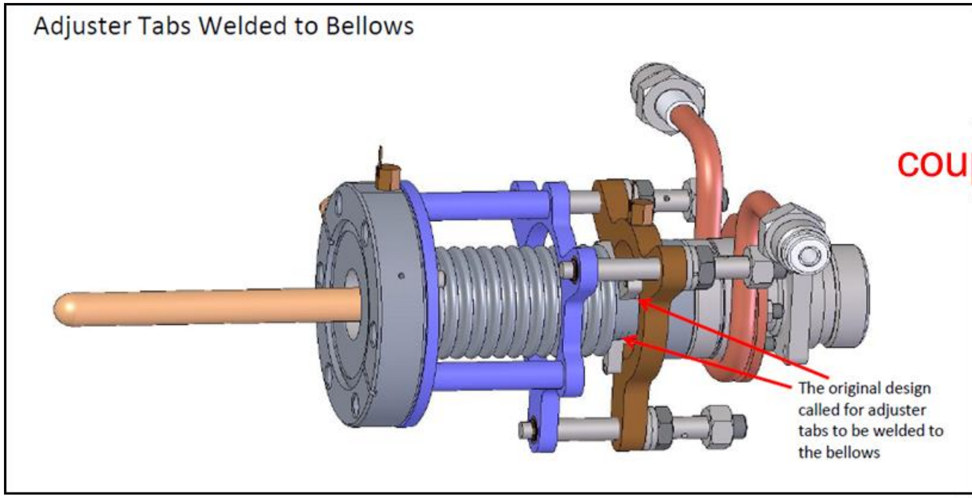
EURO ICF knife edge structure

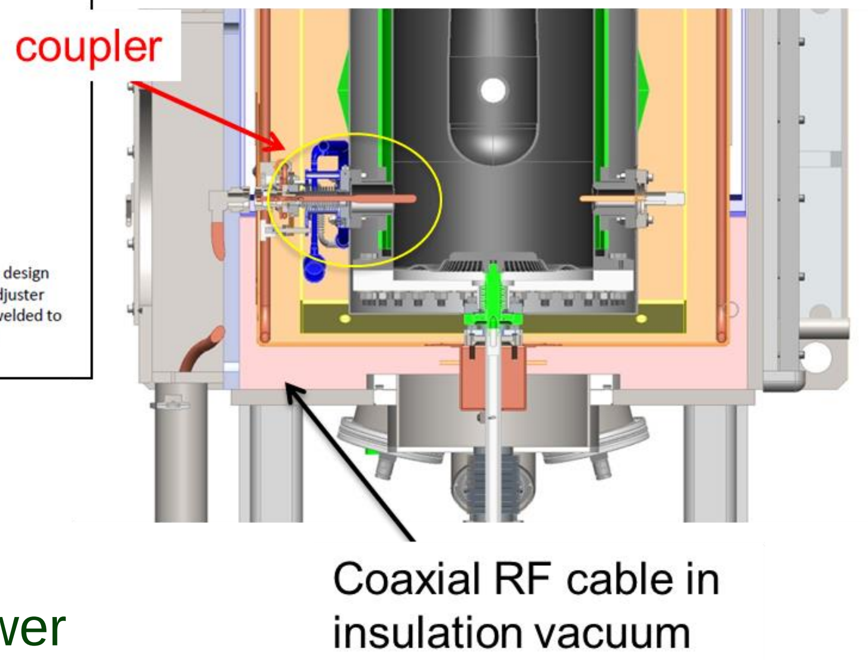


	1	2	3	4	5	6
American A1	0.028	0.029	0.02945	0.02866	0.0309	0.0298
American A2	0.028	0.028	0.02908	0.02878	0.03074	0.0292
European F1	0.025	0.025	0.02558	0.02547	0.02591	0.025
European F2	0.025	0.025	0.02551	0.02557	0.02593	0.025

20.4 FRIB Cavity Fundamental Coupler
0.085QWR FPC lessons learned from ReA3 coupler

- FRIB 0.085FPC was modified from ReA3 FPC
- ReA3 adjustable side coupler handling 2 kW (ReA3 800 W)
  – Development of a coaxial cable capable of transmitting 2 kW in insulation vacuum was challenging; original design experience was only for ~300 W (TRIUMF)

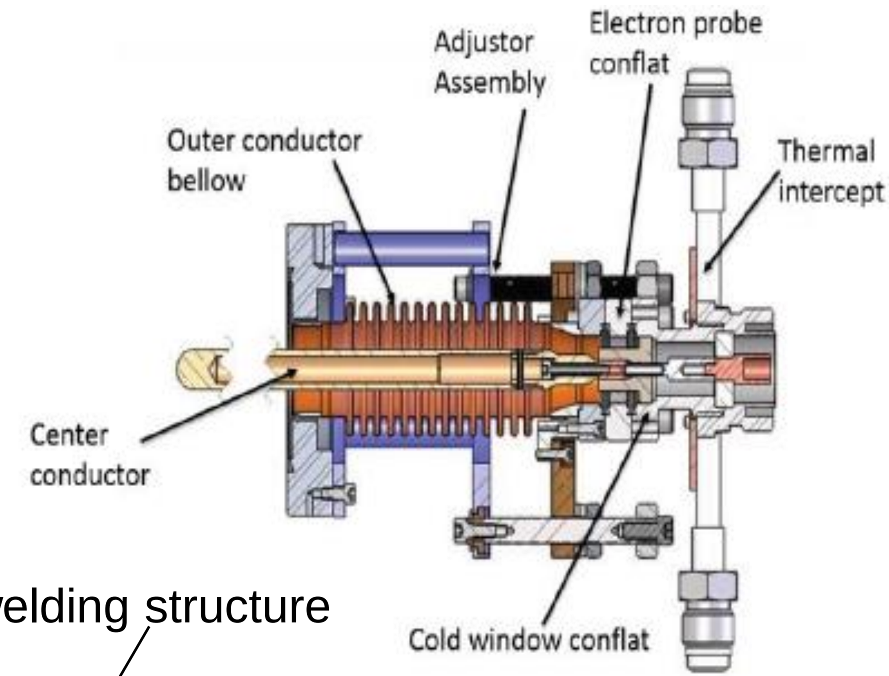




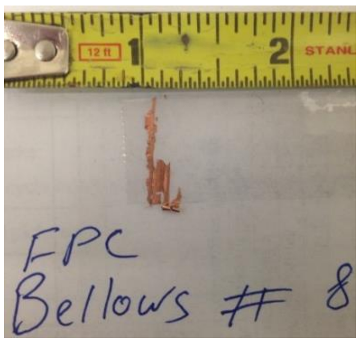
- ReA3 FPC specification
  f_o=80.500 MHz, bandwidth 90 Hz,
  Q_{in}=8.85E+5
  Average Power (CW) 800 W, Peak power 1.6 kW, designed 2 kW input(full)

Lessons Learned from ReA3 Coupler (1)
Poor copper plating of coupler bellows

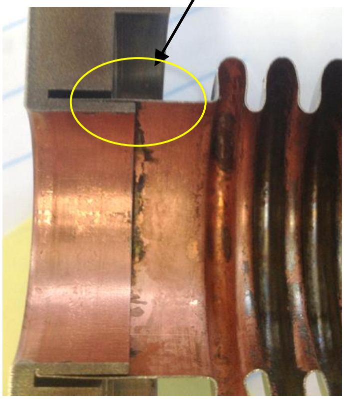
- Poor Copper Plating quality of coupler bellows
  - Peeling off copper flakes
  - Arcing at the wrong welding area
- Use qualified vendors
- Introduced strict QA process including tape peel off test

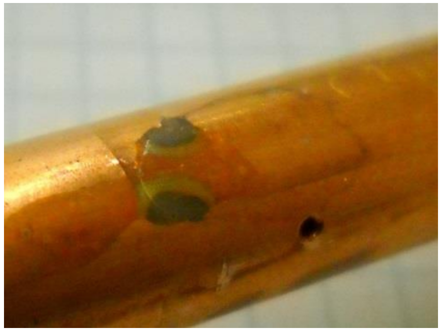


Very bad welding structure



Copper flakes

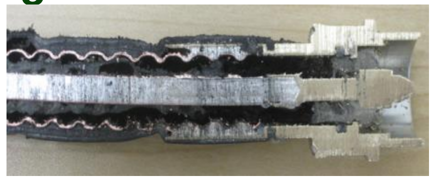


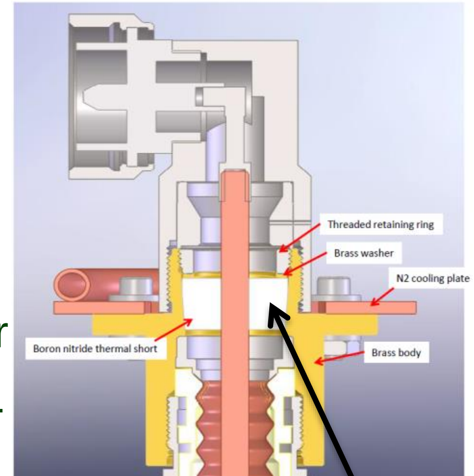


Wrong bellows brazing

Lessons Learned in ReA3 Coupler (2)
Inner conductor heating in the RF cable

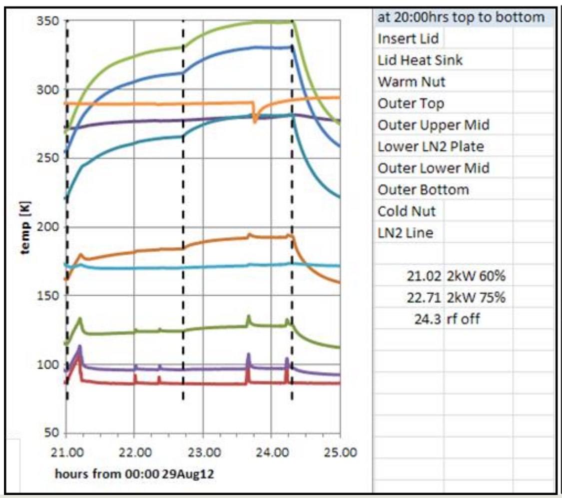
- **Inner conductor of cable overheating in insulating vacuum**
  - The heat transfer from inner conductor is too poor.
  - PE insulator easily melts due to inner conductor heating and burns up through vacuum discharge

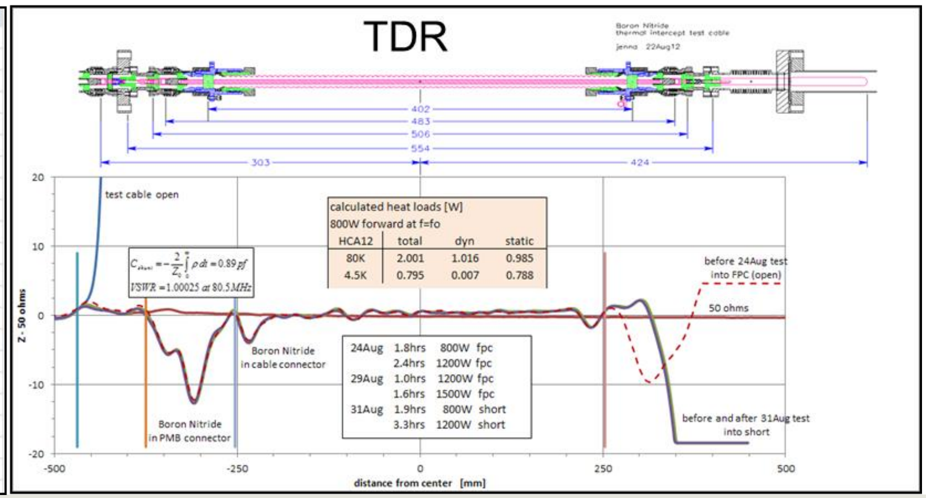




BN insert

- **Solution:** add a boron nitride insert (or sapphire) to the cable connector.
- Boron Nitride insert and LN_2 thermal intercept added to RF cable connector
- Confirmed stable operation:1.5 kW into FPC (at $f=f_o$) and 1.2 kW into short-circuit
  - ΔT 112 K warm window, 91 K cold window **without** Boron Nitride
  - ΔT 16 K warm window, 12 K cold window **with** Boron Nitride

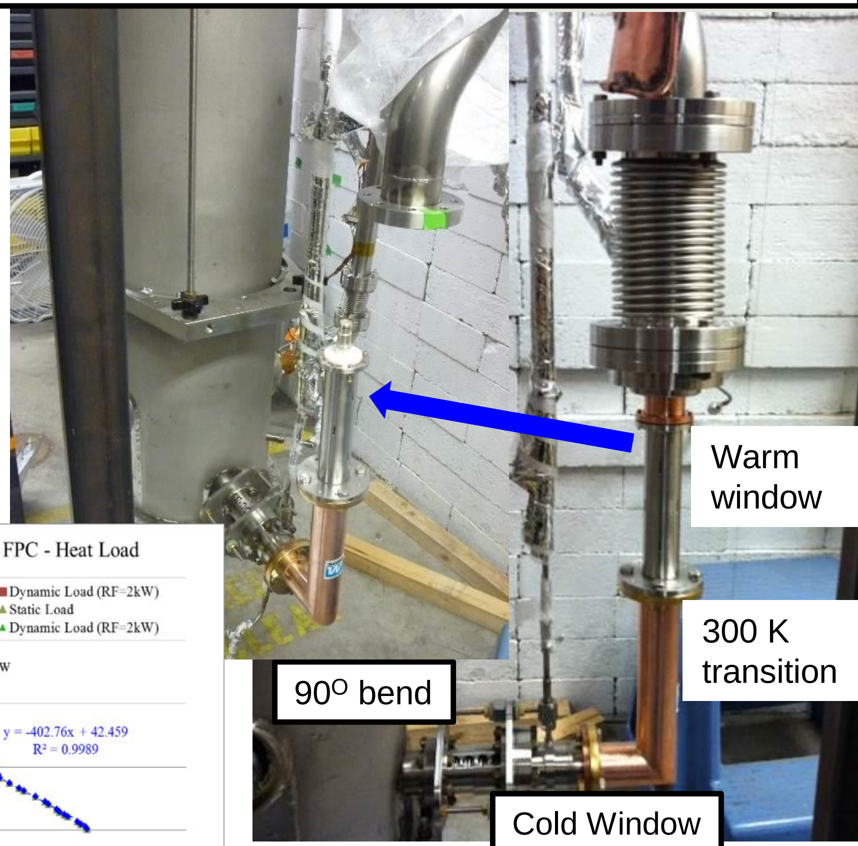




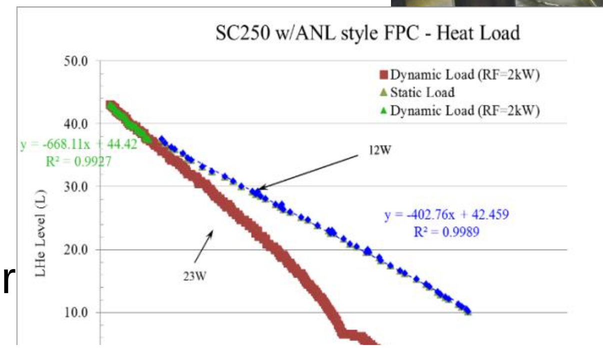
Successfully Validated 90° Bend FPC on ReA3 QWR

- 80.5 MHz QWR couplers are adjustable, not variable. Adjustment is a possibility only for a microphonics mitigation and is not easy to do.
- Pumping slots were added on the outer conductor to evacuate from insulation vacuum
- QWR coupler with 90° bend was successfully tested on a ReA3 QWR at MSU in February

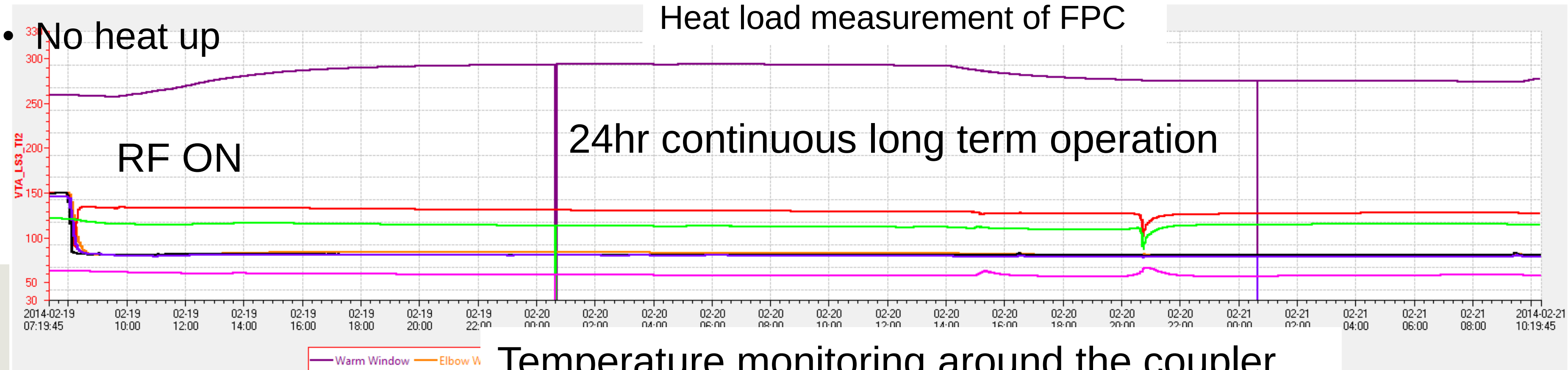
Integrated test in vertical test stand



- Succeeded in long run operation in VT
  - Total load: 23W
  - Static load 12W
  - Cavity dynamic load 12W
  - Heat load < 1W, Stable operation for 24hr continuous
  - No heat up



Heat load measurement of FPC



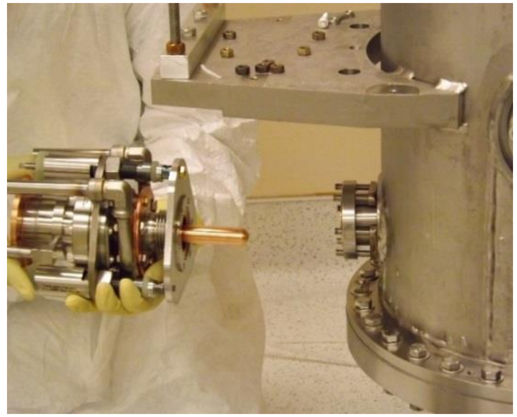
Temperature monitoring around the coupler

FRIB Couplers

ANL type for QWR and KEK/SNS type for HWRs

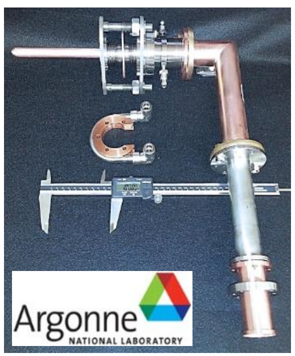
Coupler Type	QWR	HWR
Frequency [MHz]	80.5	322
Line Impedance [Ω] (*) will change to 75 Ω	50	50(*)
Cavity RF Bandwidth [Hz]	40	30
Installed RF Power [kW]	2.5	5
Max. Coupler Power Rating [kW]	4	10
Manual Coupling Adjustment	½ To 2 Times Bandwidth	
Coupler Interface	1-5/8" EIA	3-1/8" EIA
Total Heat Load To 2 K At Nominal RF Power [W]	0.13	0.6
Total Heat Load To 4.5 K At Nominal RF Power [W]	1.3	2.7
Total Heat Load To 55 K At Nominal RF Power [W]	7.1	6.2

QWR FPC ANL type

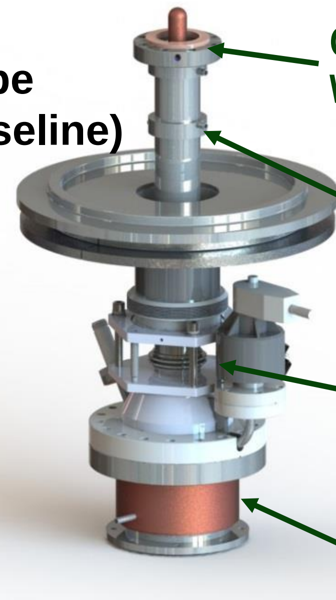


HWR FPC KEK type

QWR FPC ANL type

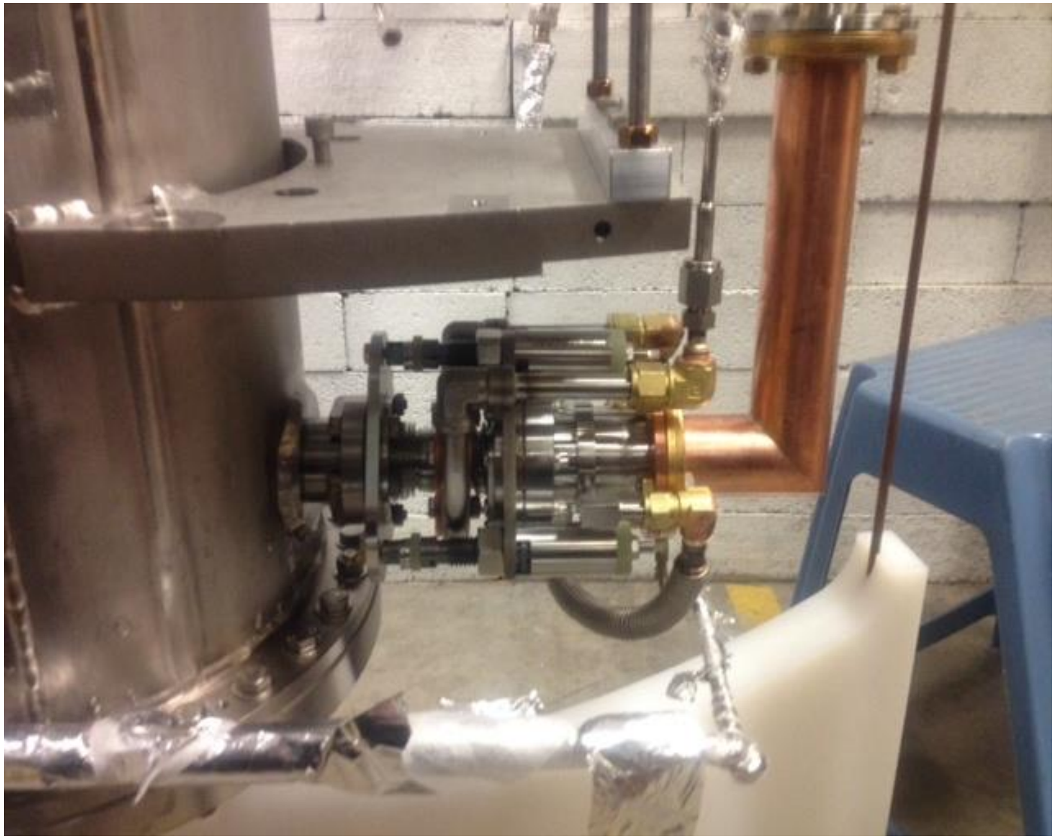


HWR FPC KEK/SNS type (Original Baseline)



Integrated Test: 0.085 QWR + Coupler
Operation validated in vertical Dewar

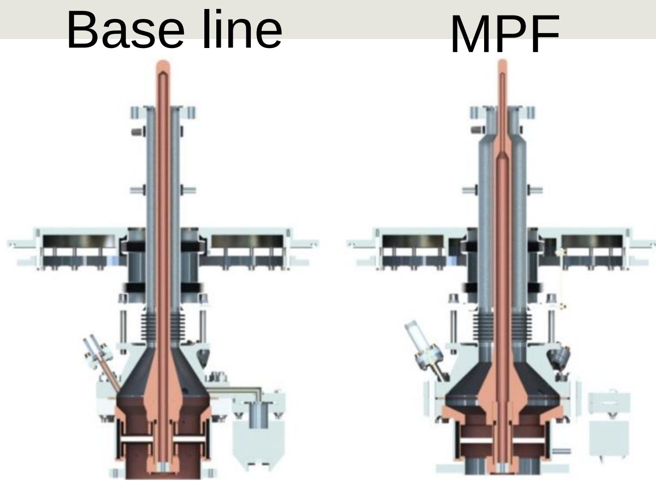
- First FRIB 0.085QWR FPC validation took place at ANL with ANL cavity
- Validation performed also at MSU with FRIB QWR and 90° RF line
- Cavity operated continuously for > 48 hr at 6.1 MV/m and 6h at 6.7 MV/m (10% and 20% above nominal FRIB gradient)
- Stable temperature with 1 kW cw rf power for several days
- No multipacting or field emission
- FRIB QWR + FPC system successfully validated



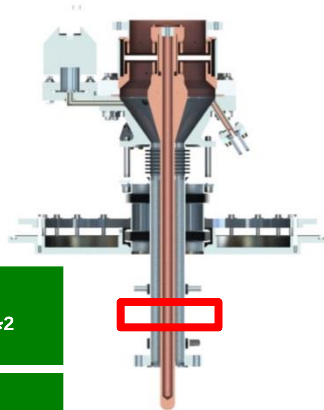
FRIB QWR coupler developed at ANL
Integrated test with FRIB QWR and 90^{O} RF line

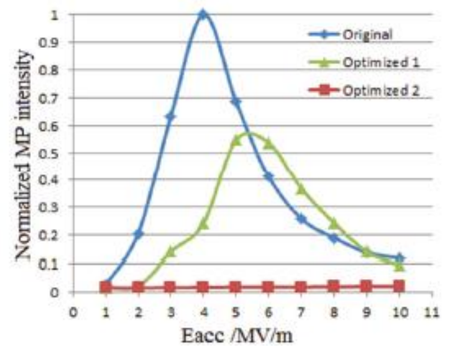
Multipacting Free HWR Power Coupler

MPF FPC demonstrated excellent performance by high power Conditioning



- Multipacting Free Fundamental Power Coupler
  - Increase impedance (65Ω) and push the MP level higher
  - No choke structure at RF window
  - Beam blinded RF window structure
- Baseline FPC conditioning
  - 9 out of 10 Baseline Model are conditioned but has heavy multipacting heating at 9 -10 kW (traveling wave model) and very long conditioning time.
  - #9 can not reach vacuum goal during after 140 hour conditioning
- MPF FPC conditioning
  - No multipacting heating observed
  - Quick conditioning time





Conditioning setup	Required time [h]*1	Heating	CW 5 kW*2
BL#3 + BL#4	40	#3 80°C, #4 80°C	
BL#5 + BL#6	51	#5 80°C, #6 80°C	✓
BL#7 + BL#8	63	None	✓
BL#9 + BL#10	140	#9 120°C, #10 40°C	✓
BL#2 + (Conditioned) MPF#1	6	None	✓

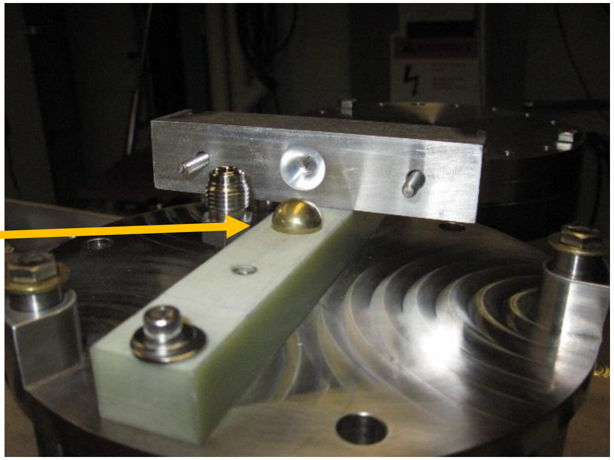
Conditioning setup	Required time [h]*1	Heating	CW 5 kW*2
MPF#1 + MPF#2	18	None	
MPF#1 + MPF#2	9	None	
MPF#1 + MPF#2	7	None	✓

Integration Test: HWR29 Coupler + Tuner

Successfully tested MPF FPC in the integration test

- Tuner parts mounted on the cavity with FPC and RF line
- VTA Test stand

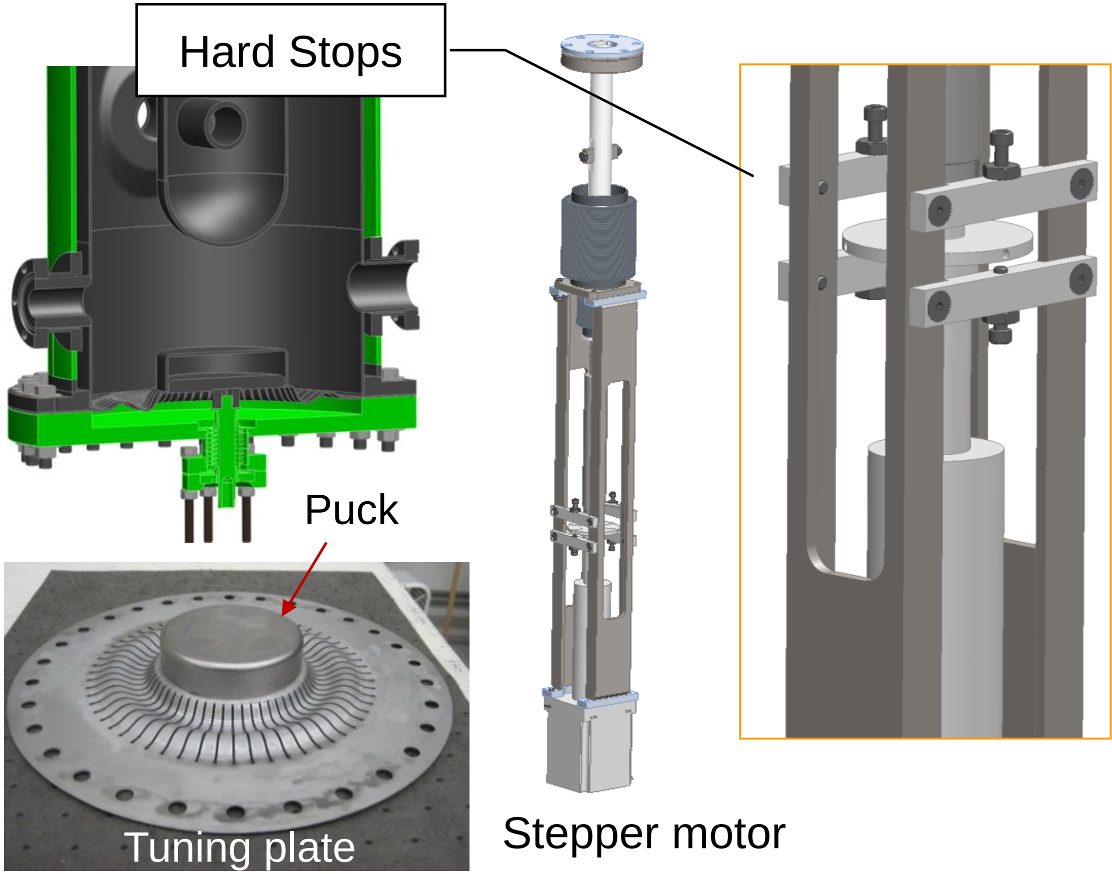
- Decoupling ball feature (FRIB) for better sliding and cables tension adjustment



20.5 Tuners for FRIB Cryomodules
FRIB baseline QWR(0.041/0.085) tuner

FRIB Tuner Specification

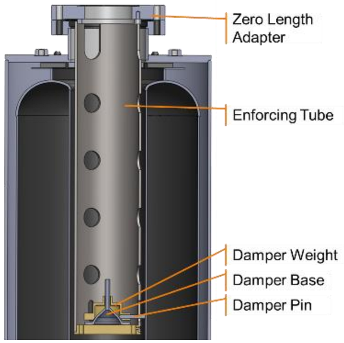
Tuner Type	QWR β=0.085
Minimum Tuning Range [kHz]	30
Tuning Resolution (2% of Bandwidth) [Hz]	0.8
Maximum Backlash (5% of Bandwidth) [Hz]	2
Cavity Tuning Sensitivity (calculated) [kHz/mm]	~ 3.2
Maximum Displacement [mm] (*) port-to-port	±7.5
Cavity df/dp (Free Tuner) (calculated) [Hz/torr]	~ -1.4
Cavity LFD (Free Tuner) (calculated) [Hz/(MV/m)^2]	~ -0.7

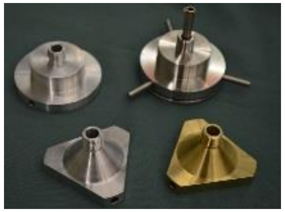


Final 0.085QWR w/vessel :
LDF = -1Hz/(MV/m)^2, well fits the simulation

- Increased tunability by welding "tuning puck" on tuning plate, yielding ± 30 kHz tuning range
- Similar tuners are working well in ReA3 for 3 years
- ReA3 operation in Summer 2014
- ReA6-I test in Winter 2014

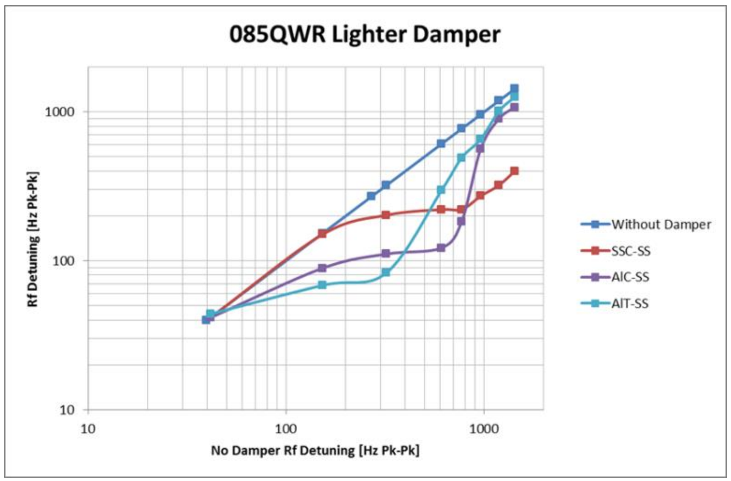
Damper for FRIB QWRs and Validation

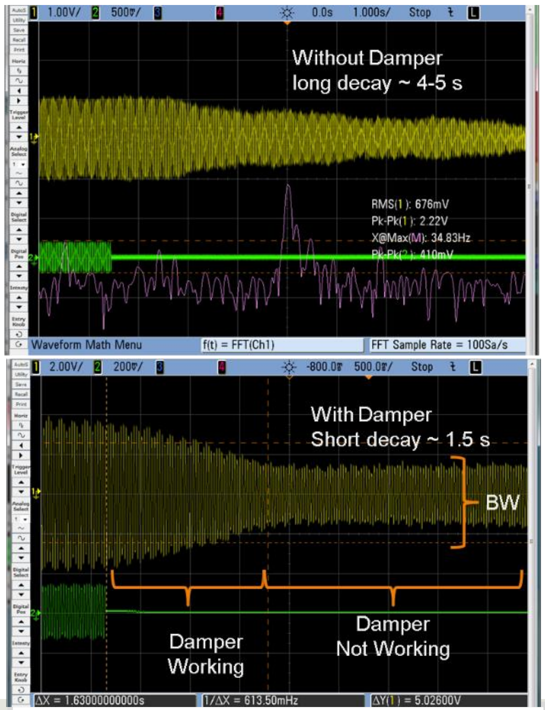




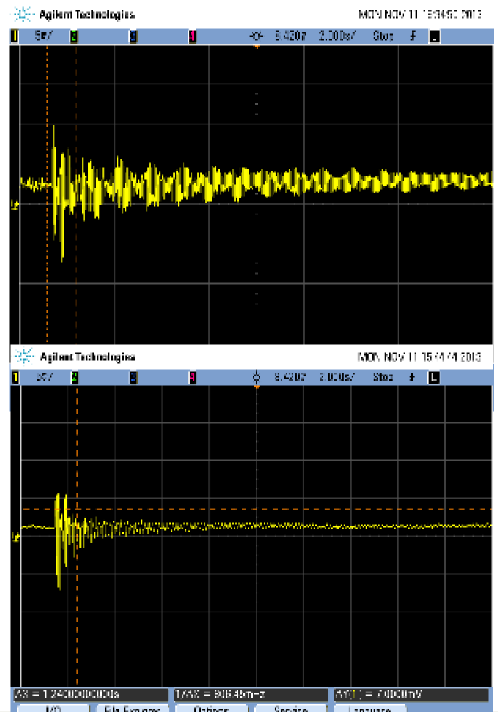
- Damper is well known as useful technology against microphonics
- INFN-LNL has used the damper for long time
- Validated damping effect in MSU at Dewar cavity test and on coldmass test.
- Installed on ReA3 QWRs
- Demonstration in ReA3 CM3 QWRs in Summer 2014

Design Optimization (Bench Measurements)





Validation (Dewar Test)



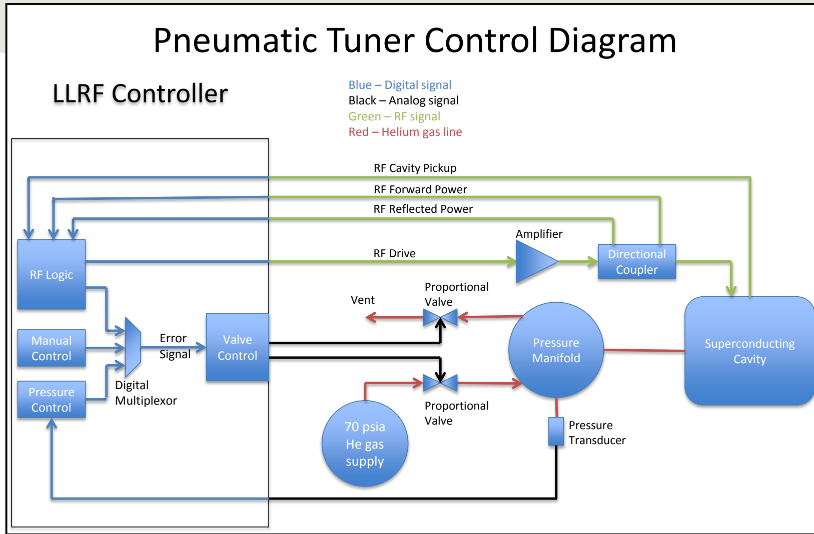
Verification (Test on Cold Mass)

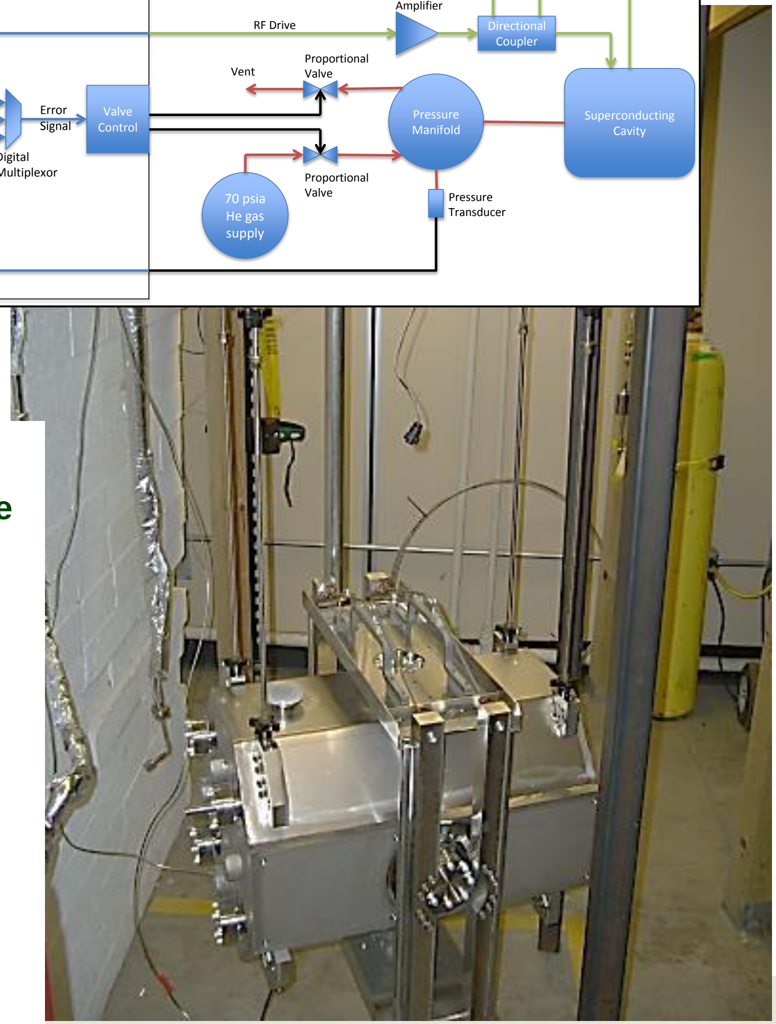
Pneumatic Tuners for FRIB HWRs (0.29, 0.53)

FRIB Tuner Specification

Tuner Type	HWR β=0.53
Minimum Tuning Range [kHz]	120
Tuning Resolution (2% of Bandwidth) [Hz]	0.6
Maximum Backlash (5% of Bandwidth) [Hz]	1.5
Cavity Tuning Sensitivity (calculated) [kHz/mm]	~ 236.2
Maximum Displacement [mm] (*) port-to-port	-0.5 (*)
Cavity df/dp (Free Tuner) (calculated) [Hz/torr]	~ -3.43
Cavity LFD (Free Tuner) (calculated) [Hz/(MV/m)^2]	~ -3

Final 0.53HWR w/vessel LFD = - 2.5Hz/(MV/m)^2, well fits the simulation





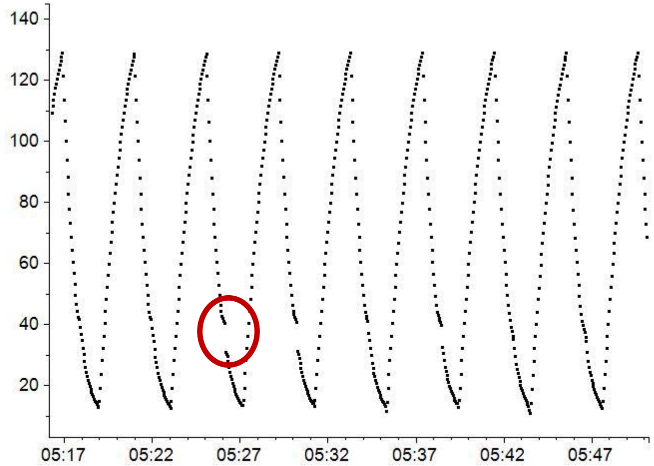
- **Demonstrated Performance in VT**
  - **Maximum tuning speed in regulation (phase < 2º peak to peak, amplitude < 2%)**
    - » +/- 0.35 Hz/sec
    - » Higher speeds (1 Hz/sec) were possible while detuning within the band width
    - » The background RF noise was higher than expected in this test (12 Hz peak to peak)
  - **Maximum tuning speed in self-excited loop (SEL) mode**
    - » - 400 Hz/sec (pressure increasing)
    - » + 363 Hz/sec (pressure decreasing)
    - » Δf/ΔP = 321 Hz/psi (4.566 kHz/kgcm^2 (frequency change from tuner pressure)
- **The final pneumatic tuner designs fits final HWR cavities (0.29/0.53) are ongoing, design complete data April 30, and fabrication completed date May 30**
- **More detailed test planned in integrated VT test system in Summer 2014**

HWR Pneumatic Tuner Development
Benchmark test and successful full integration test

- Testing of the bellows for long term operation at RT benchmark
  - Bellows break issue, TIG welding to EBW, so far 400 cycle leak tight
  - Stacking issue of bellows guide bushings, changed material to bronze
- ANL visited and closely information exchanged with ANL (M. Kelly)
  - Don't use stainless guide bushings and stainless guide rods, even with coatings
  - Bearing grade bronze rods and stainless bushing (both uncoated) seem to be an excellent choice in our recent experience
- Successful integration test; long run operation at VT
  - Locked for 24 hours at 7.7MV/m at 4.3 K with phase stability < 1° and amplitude stability < 0.5%, which satisfies FRIB goal

Full integration test at VT

Benchmark test at RT

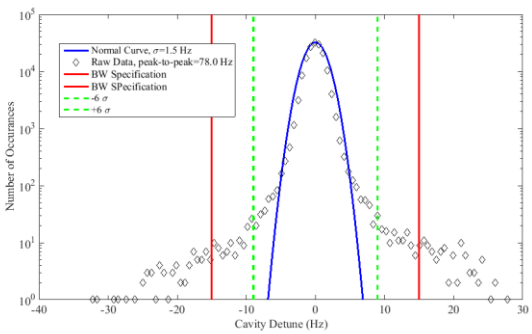


Investigating bellows guide bushing binding issue

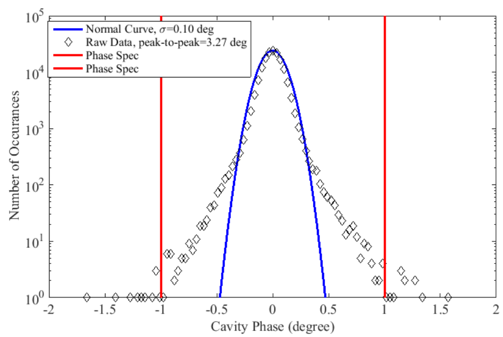
Integrated Test : β=0.53 HWR
Example 0.53HWR

- 24h run at 4.3 K and low field (2.7 MV/m) and 74 Hz BW with no unlocks
- Detuning from microphonics and phase/amplitude errors: σ fitting FRIB specifications, but long tails are still present
- Tuner control and LLRF parameters still to be optimized

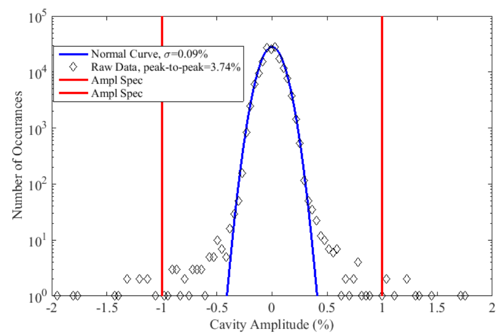
Detuning

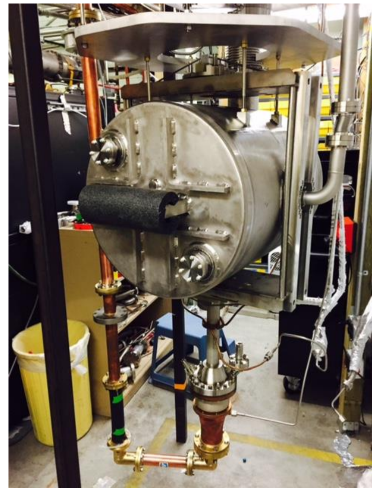


Phase error



Amplitude error

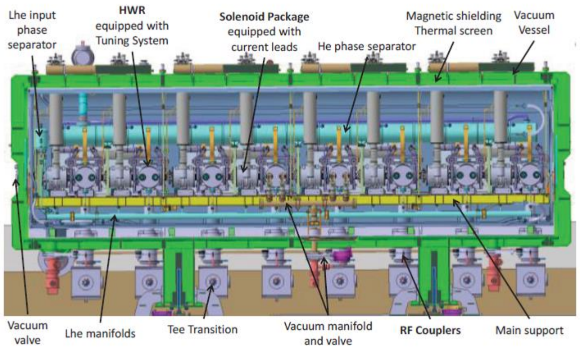




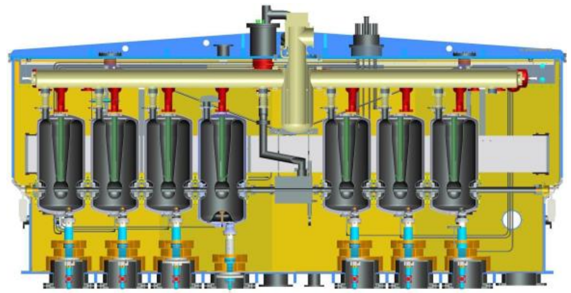
	Field	Detuning distr.		Phase err.		Ampl. Err.	
24h locked operation at 4.3K	E_a (MV/m)	σ (Hz)	p-p (Hz)	σ (deg)	pk-pk (deg)	σ (%)	p-p (%)
Measured up to now	2.7	1.5	78	0.1	3.3	0.1	3.7
FRIB goal 2 K	7.8	<1.25	<15	<0.25	<2	<0.25	<2

20.6 FRIB Cryomodule Design
Low-β cryomodules examples worldwide

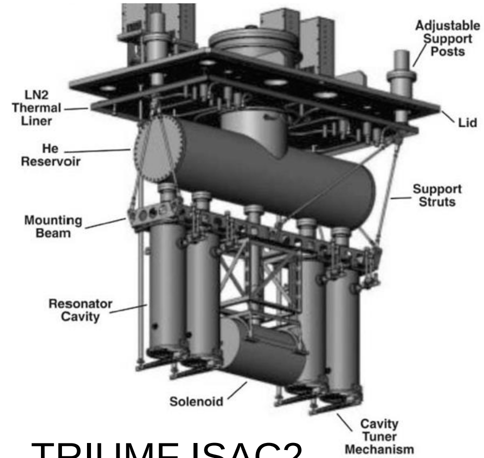
- Several working designs, useful examples for FRIB
- Other designs not immediately usable in FRIB without major adaptation work due to tight torelance



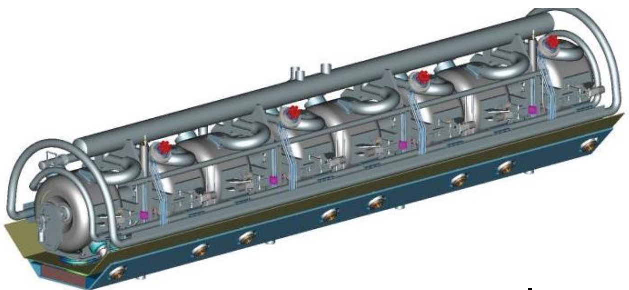
IFMIF EVEDA under prototyping (HWR, top down)



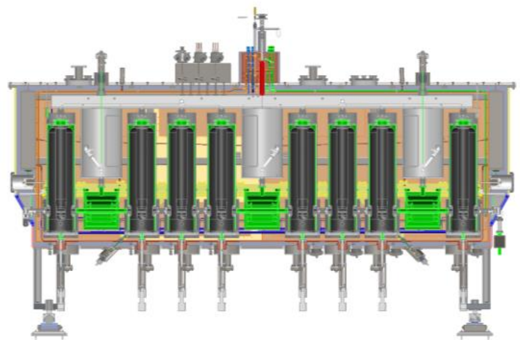
ANL ATLAS (QWR, top down) operating



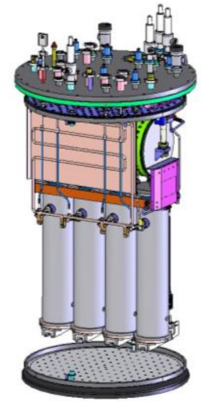
TRIUMF ISAC2 (QWR, top down) operating –common vacuum



FNL PXIE proposal (SPOKE, bottom up)



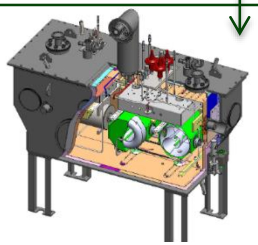
ReA MSU (QWR, top down) β=0.041 QWR CM operating



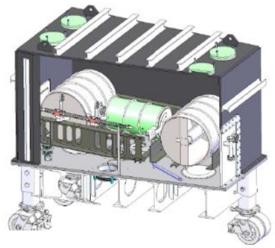
INFN Legnaro (QWR, top down) operating–common vacuum

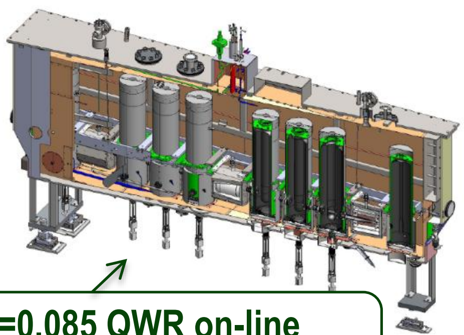
Cryomodule Prototyping Program Supports FRIB Construction

HWR TDCM, Decommissioned 2012



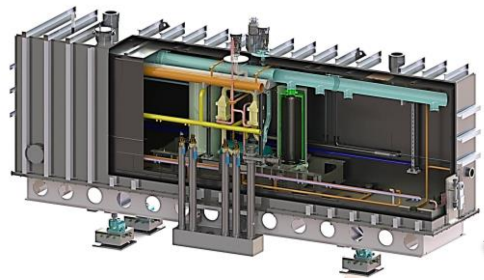
ETCM, Tests Completed in 2013



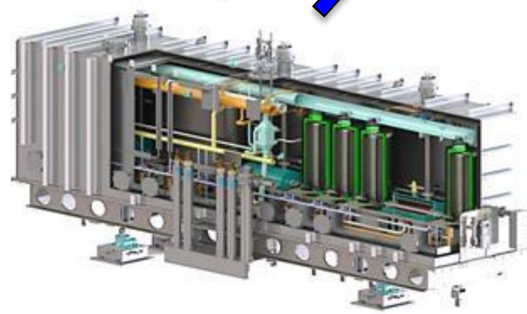


ReA3 β=0.085 QWR on-line
Successfully operating

ReA6/FRIB, CM with 2 QWRs
Successfully tested



FRIB 8 0.53HWRs CM
Construction planned in 2017

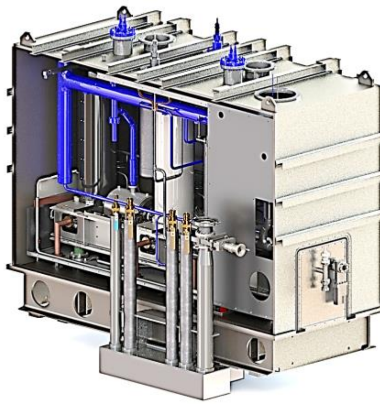


FRIB 8 0.085QWRs CM
Construction of components started in 2015

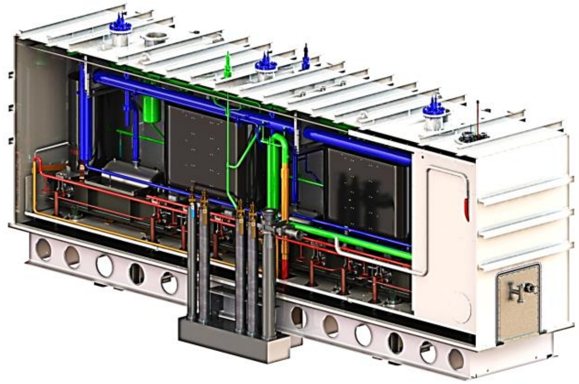
- Allowing to test
  - "Unestablished Design Assumptions"
    - » (RF BW, He pressure stability, mechanical stability)
  - Innovative CM design solutions
  - Integrated CM performance in operation conditions
- Scheduled to allow feedback to mass production

Six Cryomodule Designs Needed for FRIB Tunnel

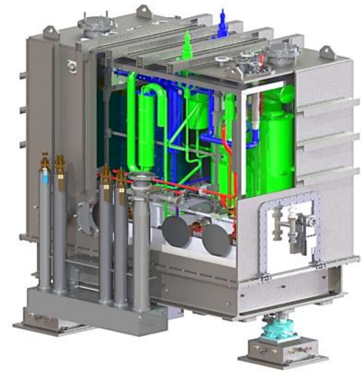
- All six modules using the same bottom-up design approach
- All cryomodules share large portion of common components to simplify design and facilitate fabrication.
- Collaborate with JLAB on cryomodule design (β=0.041 and β=0.29)
- Collaborate with ANL on coupler and tuner design



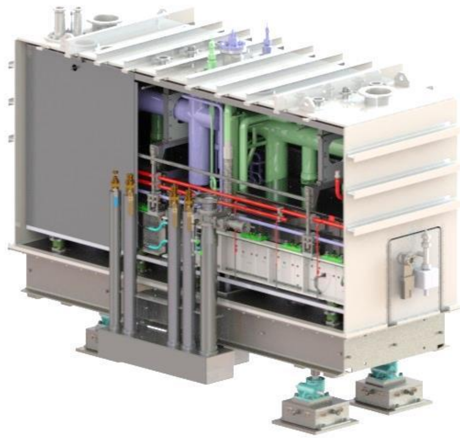
β=0.041



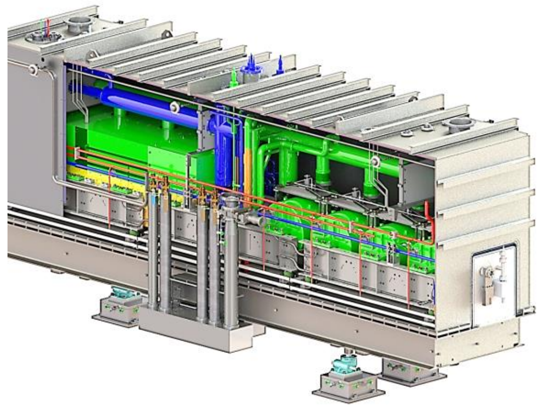
β=0.085



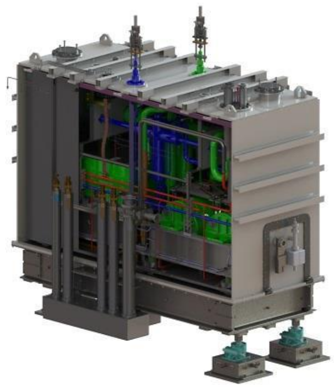
β=0.085 Matching



β=0.29



β=0.53



β=0.53 Matching

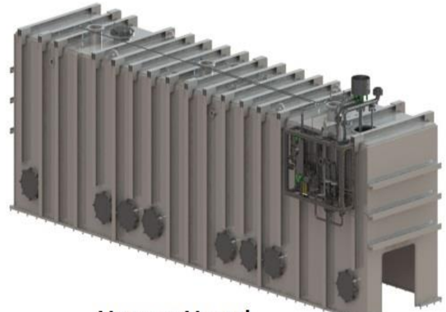
Jefferson Lab

Argonne NATIONAL LABORATORY

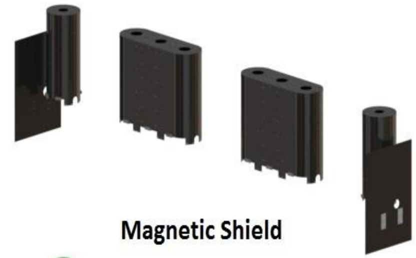
FRIB Unique Cryomodule Design
Bottom up assembly

The bore diameter of cavities is 40mm, which needs a tighter transvers tolerance ± 1mm. ⇨ Novel bottom-up assembly

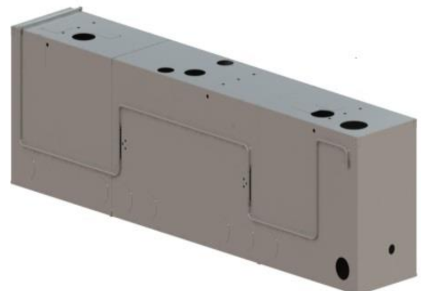
- Resonators operate at 2 K and magnets at 4.5 K and are both supported from the bottom to facilitate alignment
- Cryogenic system is decoupled from coldmass string to isolate vibration to minimize the microphonics
- Optimized and integrated with cryo-distribution
  - Bayonet interface to make easy cryomodule maintenance serviced independently
  - 2K-4K heat exchanger inside module to maximize 2K efficiency
- 8T superconducting solenoid package in the module
  - Enhance space efficiency
- Single layer “local” magnetic shield to be cost effective and less sensitive to magnet operation
- Use common cryomodule designs principles for all six cryomodule types
  - Support rails, cryogenic circuit, thermal shield, vacuum vessel



Vacuum Vessel

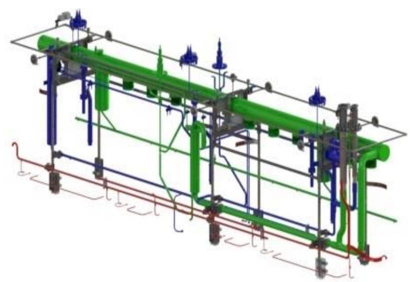


Magnetic Shield

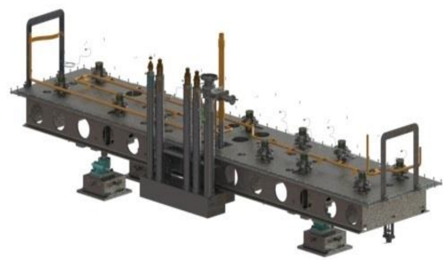


Thermal Shield

Cold Mass



Cryogenic System

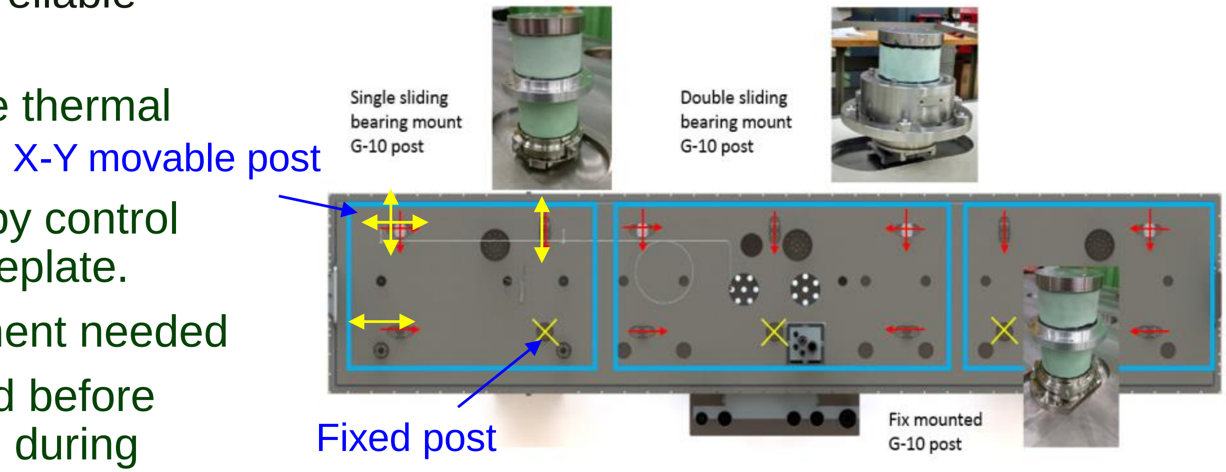


Baseplate

Bottom up Assembly

FRIB Cryomodule Alignment Approach

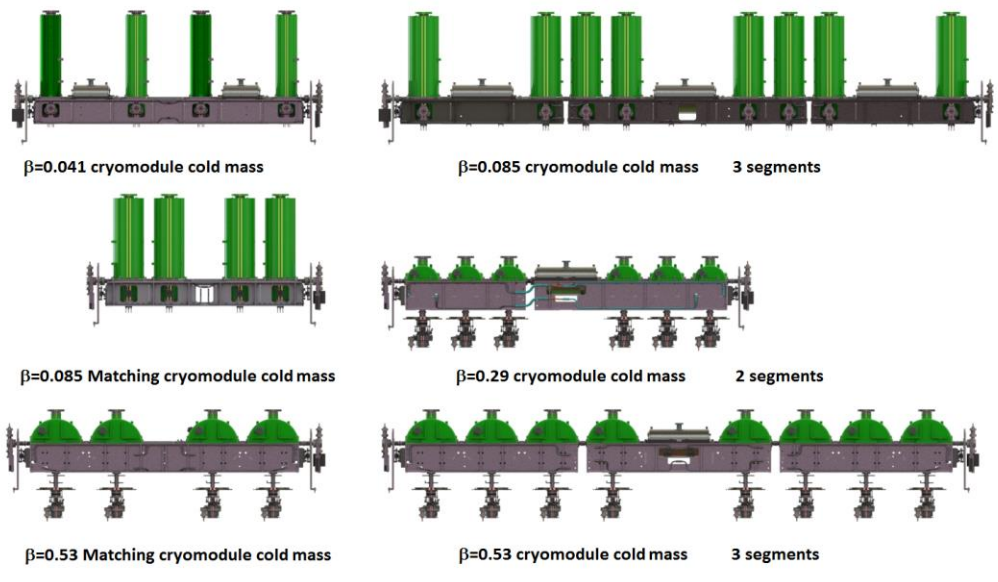
- Rigid baseplate provides stable and reliable platform for the cold mass
- Three divided baseplates to minimize thermal contraction (0.085 and 0.53 CMs)
- Alignment of cold string is achieved by control stack tolerance of coldmass and baseplate.
- No post assemble alignment adjustment needed
- Rails are made of 316L and annealed before final machining to minimize distortion during fabrication, cool down, and magnetization
- The alignment strategy has been certified by the six FRIB cryomodule.



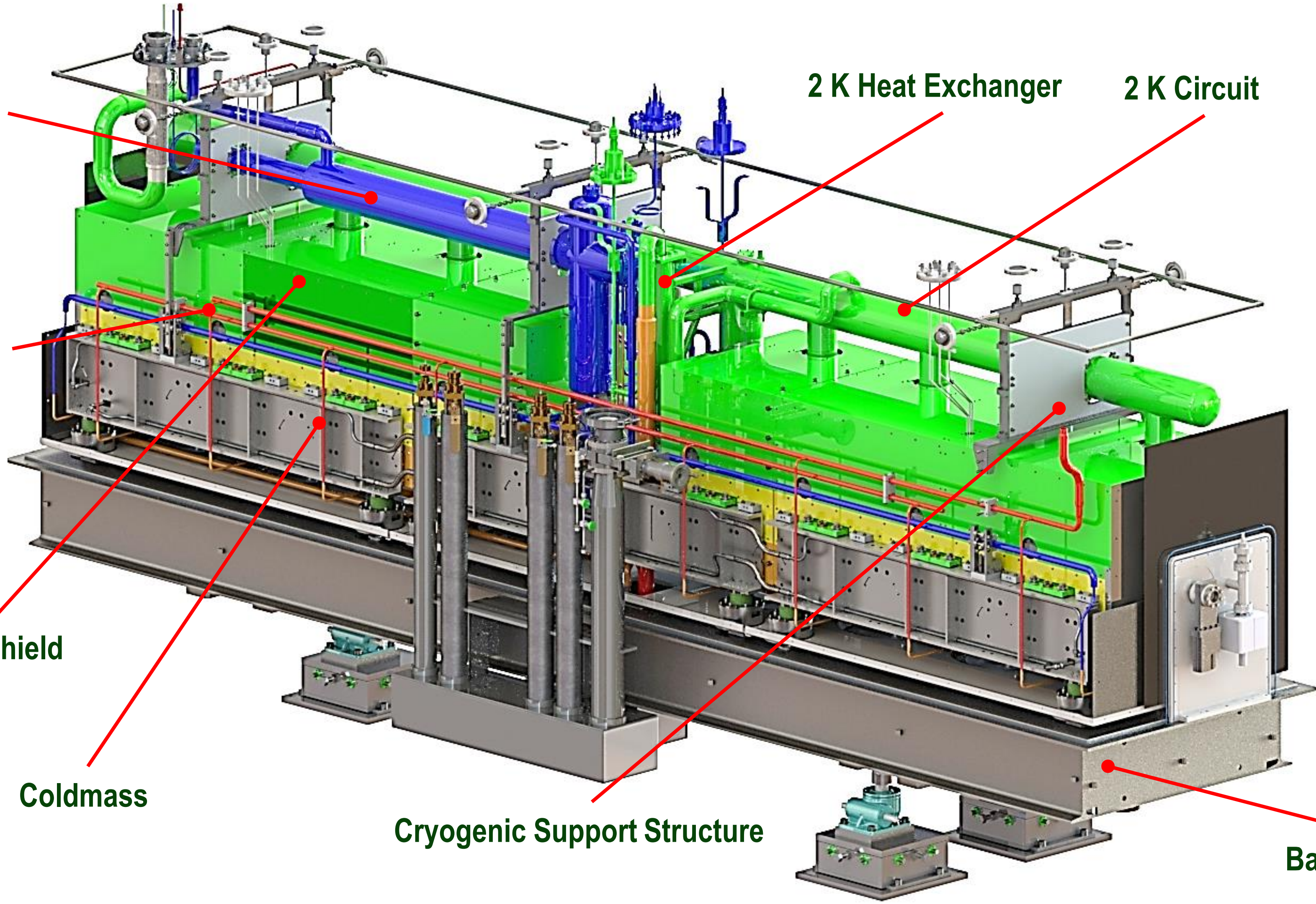
Cryomodule Alignment Survey Results.

Module	Resonator		Solenoid	
	Transverse (mm)	Vertical (mm)	Transverse (mm)	Vertical (mm)
SCM801	0.449	0.535	0.305	0.433
SCM802	0.37	0.31	0.20	0.26
SCM803	0.44	0.25	0.15	0.21
SCM401	0.25	0.52	0.26	0.07
SCM402	0.14	0.13	0.24	0.13
SCM501	0.807	0.71	0.106	0.096

* Cool down error is projected to be < 0.33 mm



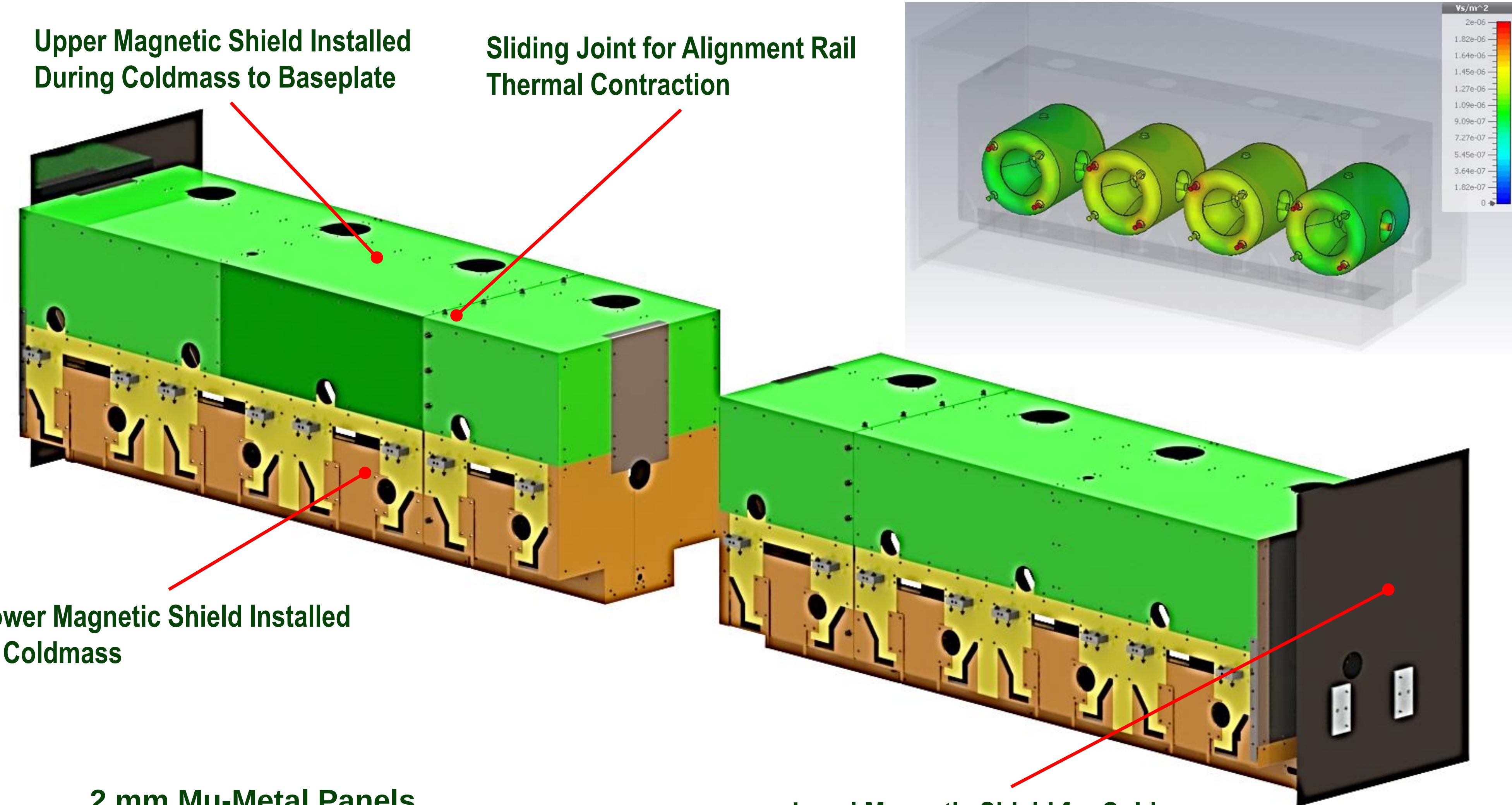
β = 0.53 Half Wave Cryomodule
Subassembly overview – coldmass to baseplate



β = 0.53 Half Wave Cryomodule
Subcomponent overview – magnetic shield

Upper Magnetic Shield Installed
During Coldmass to Baseplate

Sliding Joint for Alignment Rail
Thermal Contraction



Lower Magnetic Shield Installed
to Coldmass

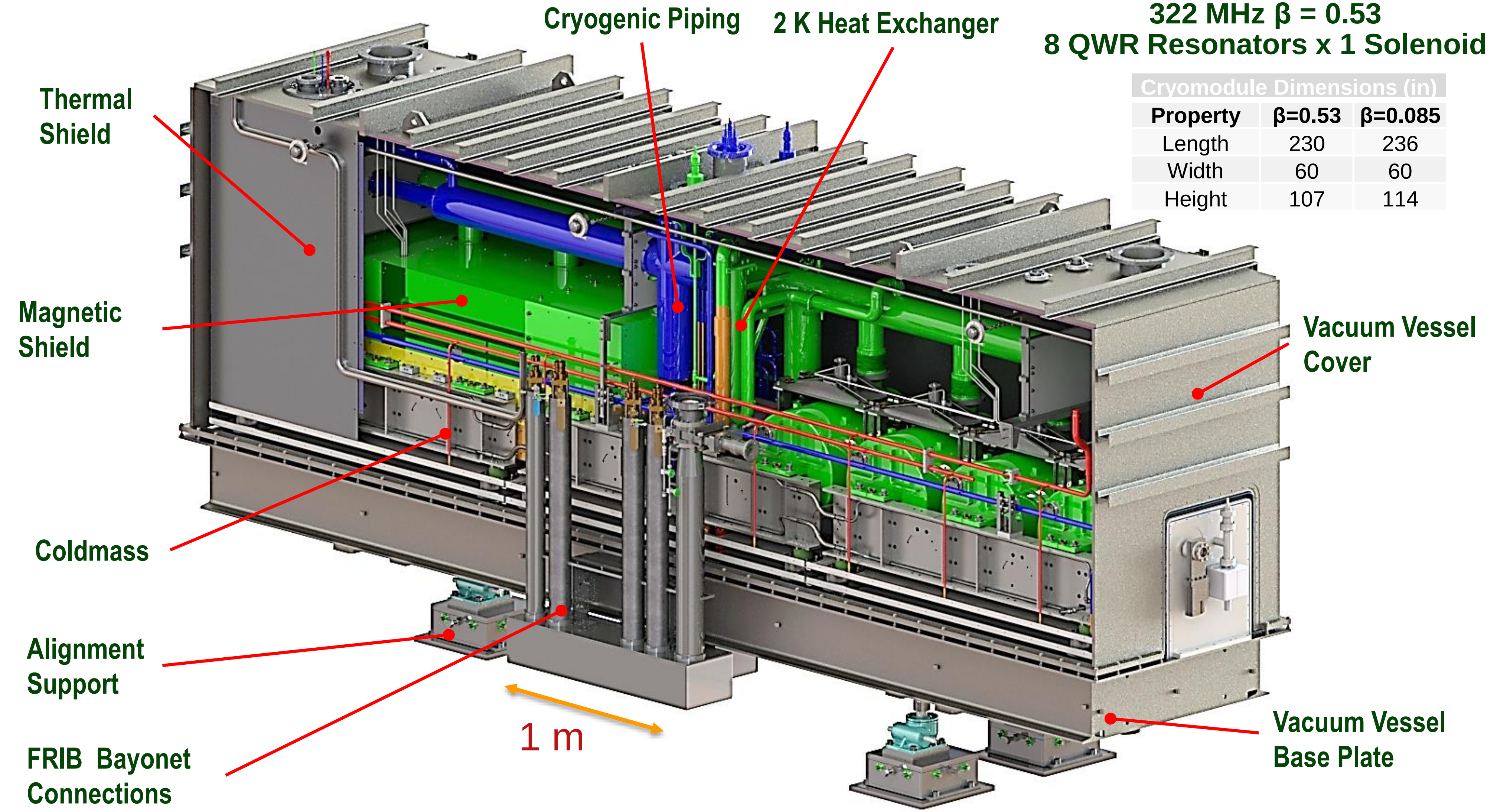
2 mm Mu-Metal Panels

Local Magnetic Shield for Cold
Cathode & Ion Pump

FRIB Half Wave Cryomodule
Modular design used on all FRIB cryomodule types

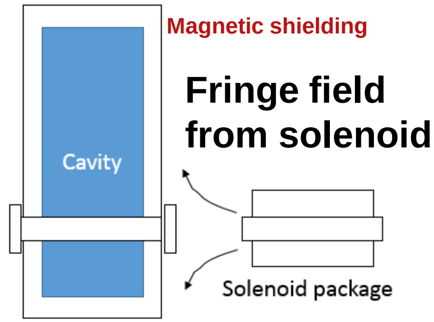
322 MHz β = 0.53
8 QWR Resonators x 1 Solenoid

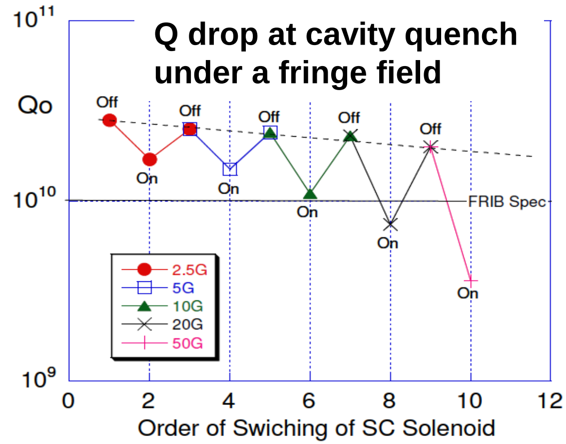
Cryomodule Dimensions (in)		
Property	**β=0.53**	**β=0.085**
Length	230	236
Width	60	60
Height	107	114

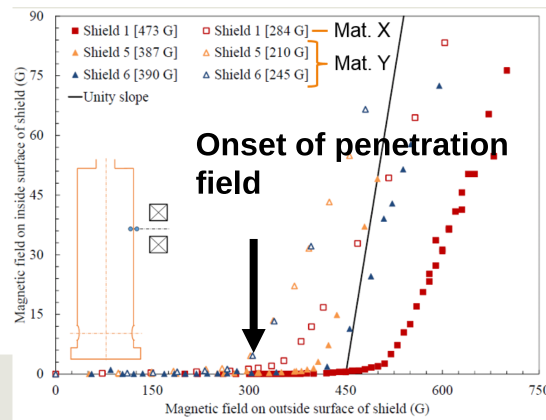


20.7 Magnetic Shielding for FRIB Cryomodules
Local magnetic shield and concerns

- **Solenoid Package in the Cryomodule**
  - FRIB is challenging to build the compact SRF linac with high beam quality
  - Need quick strong focusing heavy ion beam at low energy
  - Increase real state gradient to make short FRIB SRF linac
- **FRIB has to confirm the local magnetic shield scheme is good choice**
  - The fringe field around cavity short area should be small enough to avoid the Q-drop at cavity quench,
  - Local shield should be more reliable and meet the FRIB spec < 15mG inside magnetic shield
- **Need careful solenoid package design**
  - The magnetic shield penetration onset field (defined as 1 G increased inside magnetic shield)
  - Solenoid package has to be designed as fringe field strength is less than the onset field on the magnetic shield at the 8T full operation, need well optimized bucking coil location.
  - Investigate the possibility to use conventional Mu-metal instead of cryogenic shield material to reduce cost.

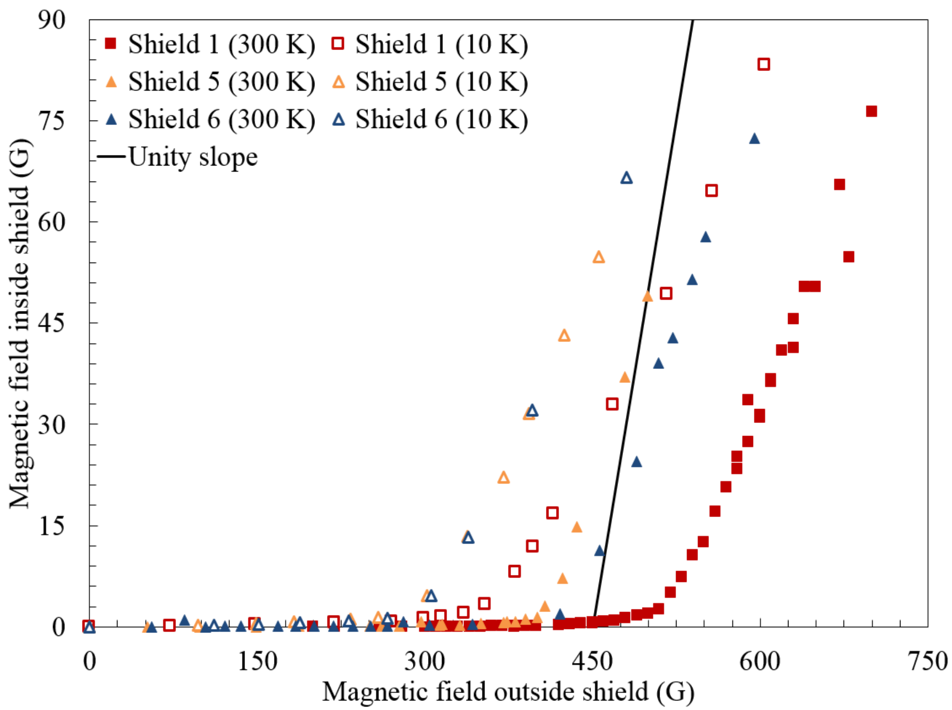






Magnetic Shield Performance of ReA6 Shield at Cryogenic Temperature

- **ReA6-1 Magnetic Shield (A4K)**
  - Magnetic field > 300 G start to penetrate the magnetic shield (1 mm thick) at cryogenic temperature (10 K)
  - Fringe field from the solenoid must be less than 300 G on the local magnetic shield outer surface



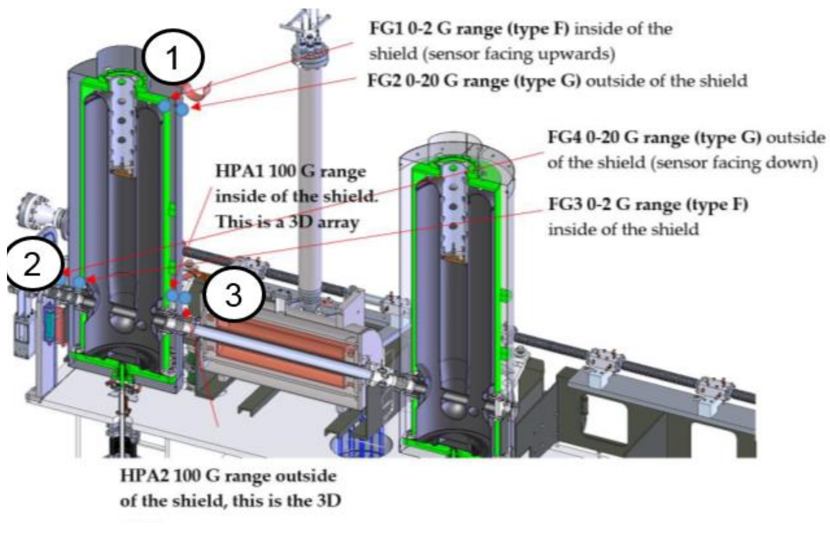
TALK by Saravan Chandrasekaran
Title: Magnetic Shield Material Characterization for the Facility for Rare Isotope Beams Cryomodules
Conference: Applied Superconductivity Conference, Charlotte, NC, USA 2014

Journal: IEEE Transactions on Applied Superconductivity
Vol., etc.: In press

Local Magnetic Validation by ReA6-1 CM Bunker Test

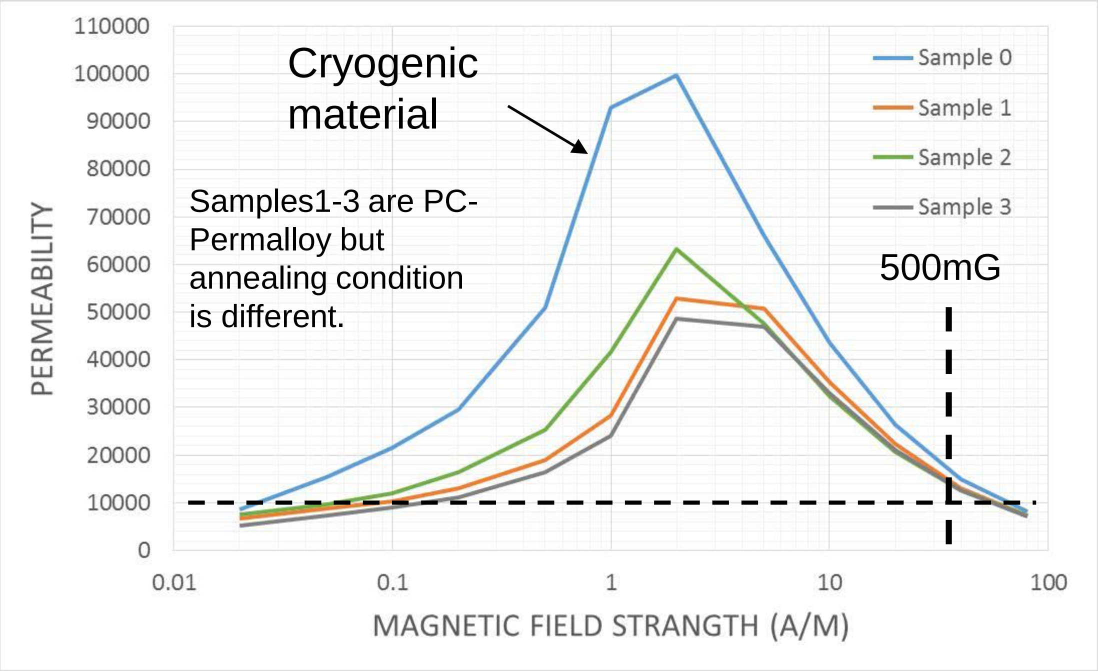
- **ReA6-CM includes two 0.85QWRs and one 50cm** solenoid package between the cavities
- **Local magnetic shield (A4K) validated by the ReA6-1**
  - Meets FRIB remnant field (2.5 mG) < 15 mG.
  - Very small field (162 mG) around cavity short area under 8T solenoid package operation, can expect no Q-drop at cavity quench.
  - Might not need degaussing process.
  - Confirmed local magnetic shield benefit.

Process	Fluxgates (mG)				Hall probes (mG) at beam port facing solenoid (low sensitivity at small fields)							
	Top of cavity		Bottom of cavity		In ③				Out			
	In ①	Out	In ②	Out	X	Y	Z	Mag.	X	Y	Z	Mag.
After cool down (shield T=24.5 K)	2.5	8.1	3.0	209.3	-850	-370	240	958	0	1000	1000	1414
During solenoid operation	-161.6 ±1.2	-361.2 ±2.1	1659.5 ±20.7	872.0 ±20.2	-6253 ±979	-3000 ±2438	-11350 ±1382	13596 ±2246	-55000 ±2800	-29900 ±2524	-91100 ±860	110849 ±1459
After solenoid operation	30.7 ±0.6	27.6 ±1.2	15.9 ±1.2	290.9 ±0.3	770 ±800	4317 ±833	3133 ±289	5434 ±835	5400 ±2800	-1967 ±1701	7733 ±1097	9906 ±1999
After full degauss	4.2 ±0.7	8.7 ±1.1	0.5 ±1.7	207.6 ±1.6	103 ±907	4133 ±1828	2667 ±2060	5058 ±2519	1933 ±2483	-4000 ±3378	-2767 ±3402	6719 ±1588
After CM warm-up	0 ±0.1	-5 ±0.1	0.6 ±0.1	205 ±0.1	16708 ±83	13845 ±67	7278 ±51	22887	-22061 ±90	-1836 ±62	-5217 ±74	22744



Conventional Mu-metal for FRIB Cryomodule

- **Cold performance measurement of Mu-metal**
  - PC-Permalloy (Mu-metal) has been measured at 4.2 K in KEK 2014 by M. Masuzawa and K. Tsuchiya, the results showed that the magnetic permeability > 9000 under 500mG (40Am).
  - Again PC-Permalloy has been measured at 20K in KEK 2015 by KEK/MSU collaboration, the results showed that the magnetic permeability > 10000 under 500mG (40Am).
  - Cryogenic material has little benefit (10-20%) under the these condition.
- **Mu-meal is acceptable for FRIB spec < 15mG in the shield, if magnetic shield is carefully designed**



FRIB Magnetic Shield Design, Example 0.085QWR

- **Full simulation for magnetic shield specification with FRIB QWR cryomodule**
  - MSU estimated the additional cavity power loss by the remnant field in the magnetic shield. This simulation includes the Earth magnetic field (500 mG), vacuum steel vessel, magnetic shield (1 mm thick), and cavity. The result shows that the magnetic permeability of 8000 meets the FRIB request (< 15 mG in side magnetic shield).
  - Above simulation does not included the triple shielding . The simulation was done for this magnetic shield scheme and found to need 16000 with 1 mm thick shield.
  - However, if additional shield is put between the cavity magnetic shield, magnetic permeability of 9000 will be Okay even for triple shield.

Different Permeability of QWR Magnetic Shielding

QWR085 Single cavity	Mue=2000	Mue=4000	Mue=8000	Mue=32500	FRIB requirement
R_{HEXT} [nΩ]	4.2	2.3	1.2	0.3	1.28
$P_{d\ HEXT}$ [W]	1.4	0.77	0.4	0.1	0.4
$H_{ext\ average}$ [mGs]	49	27	14	3.5	15

FRIB QWR085 design R_{HEXT}=1.28nΩ (corresponding equivalent average Hext=15mGs), $P_{d\ HEXT}$ is 0.4W, thus single shielding's critical mue=8000.

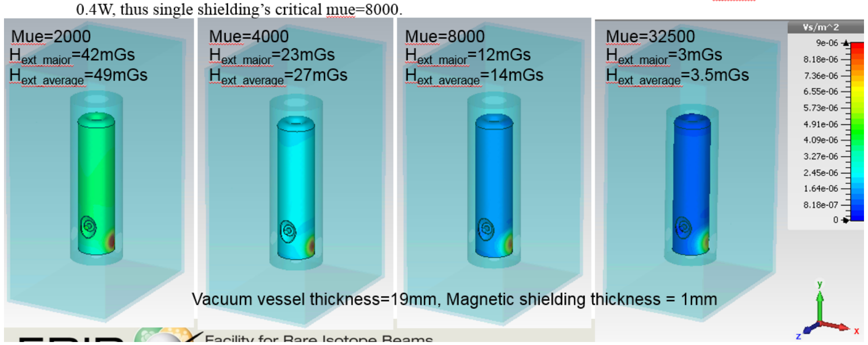


Figure 1: Simulation of magnetic shield for FRIB 0.085QWR magnetic shield, μ=8000 meets FRIB request.

QWR085 Triple Cavities Shielding

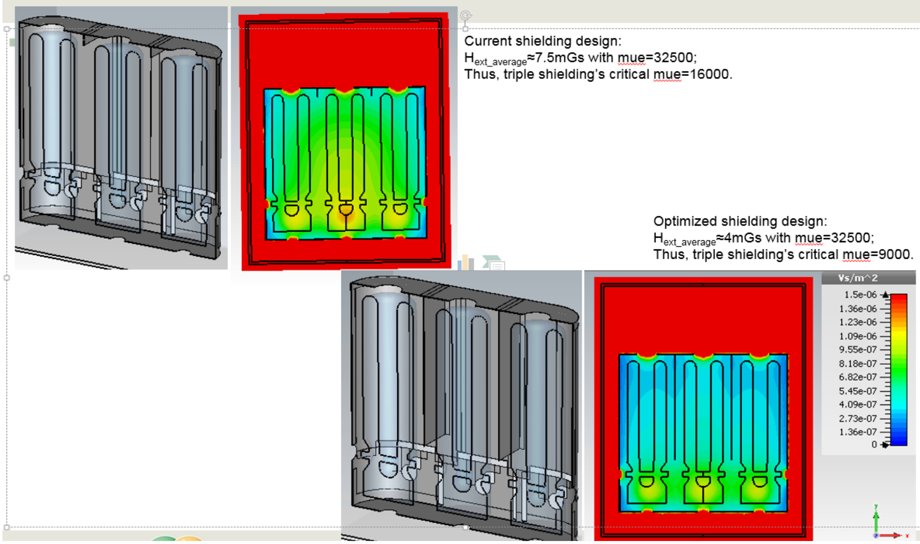
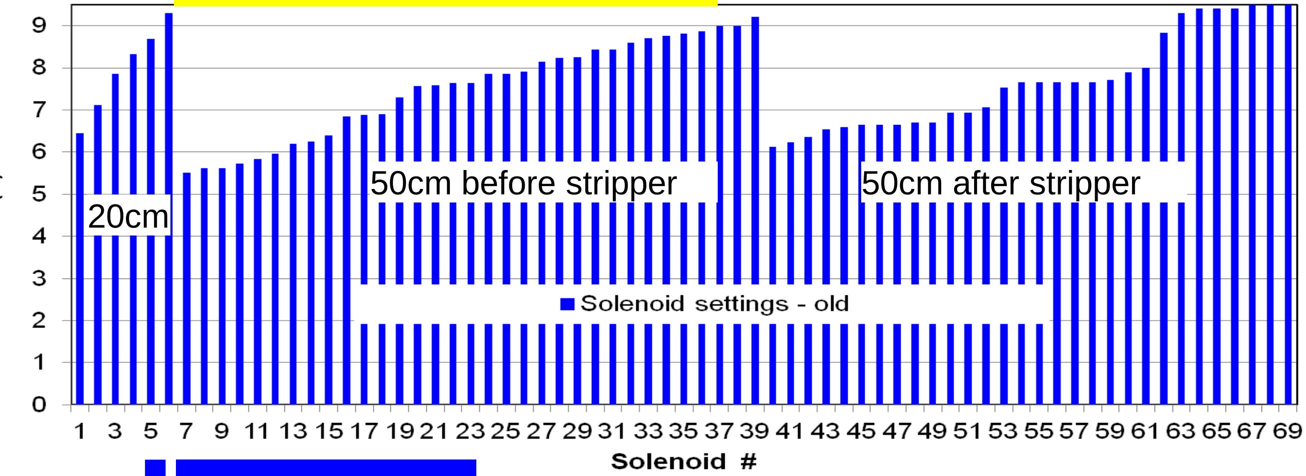


Figure 2: Additional shield between cavity magnet shield reduce the acceptable μ to 9000.

20.8 Superconducting Solenoid for FRIB CMs

New lattice in order to reduce the solenoid field

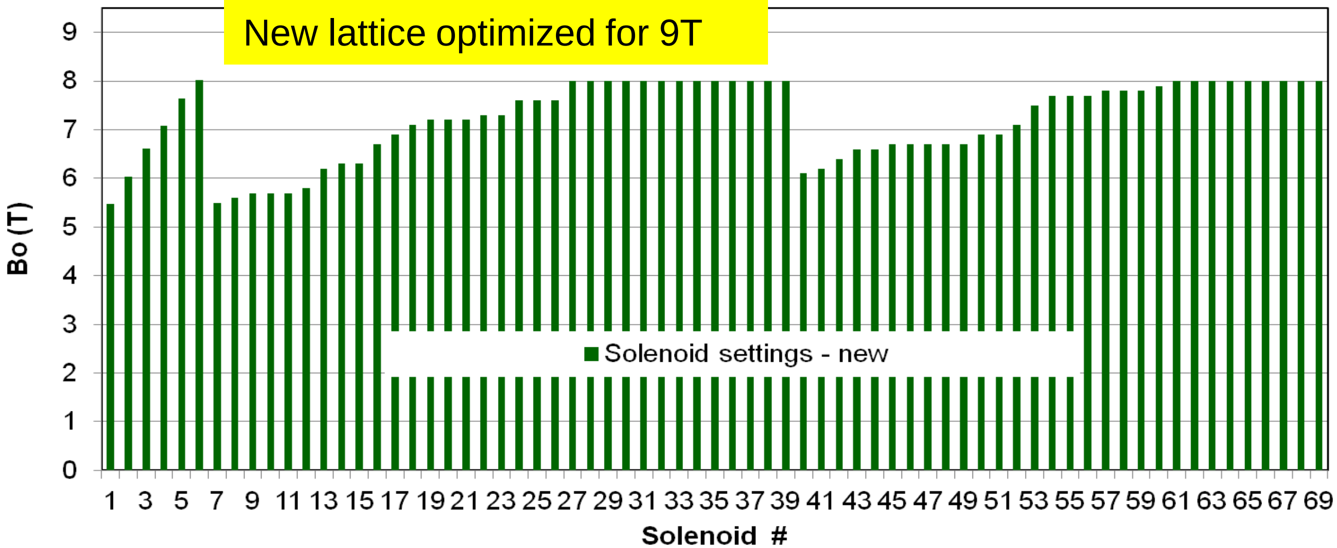
Original lattice designed for 9T



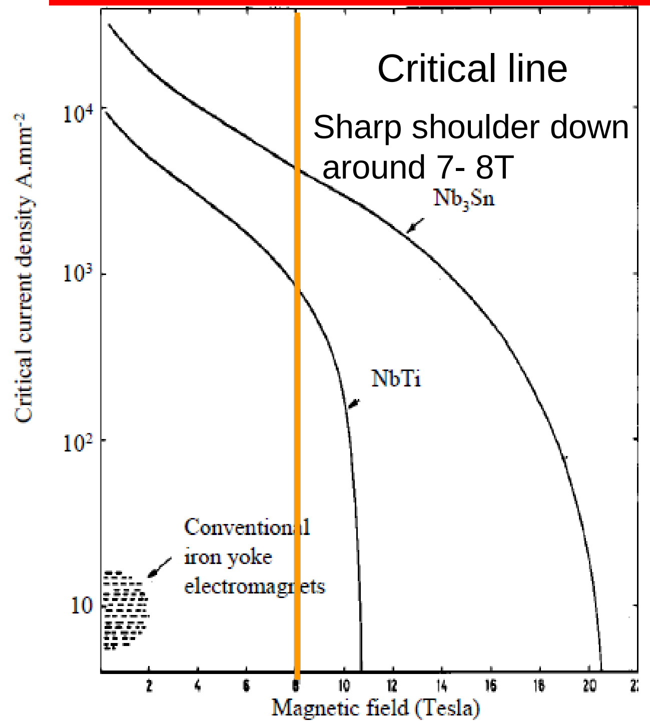
Changed length from 20cm to 25cm

New lattice for 50cm solenoids

New lattice optimized for 9T



9T is critical for TiNb SC wire



Original lattice : constant β(z)

Bo=9T, marginal !!

New lattice : constant beam size in high energy part

Bo= 8T

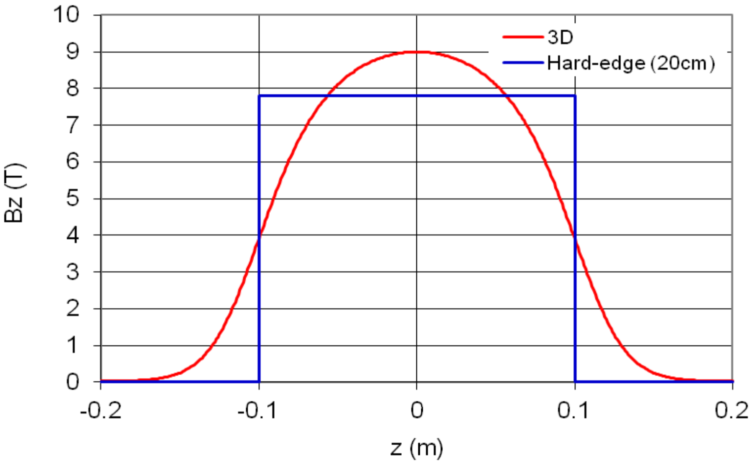
Solenoid Design Example
FRIB 25cm solenoid

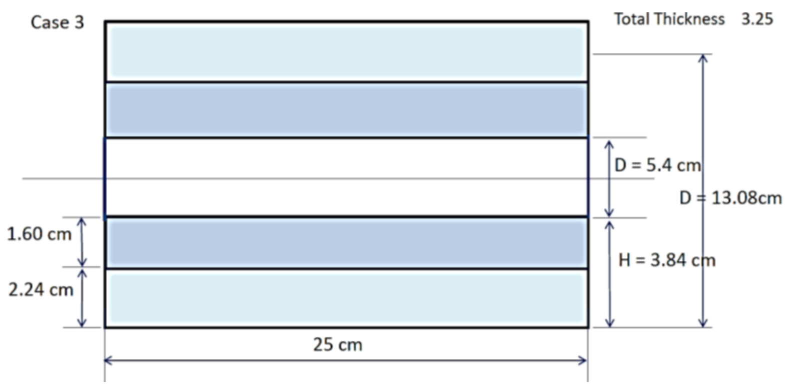
Specification of the 25cm solenoid package

FRIB 25 cm Solenoid Parameters		
Parameter	Units	Value
Operation temperature	K	4.5 +0.5/-0.0
Operation pressure	bar	1.3 +0.7/-0.0
I_{nom}, **solenoid nominal current**	A	≦ 100
$\int B_Z^2\, dz$ **at** I_{nom}	T^2m	≧ 13.6
Peak solenoid field on beam axis[2] **at** I_{nom} **(reference value)**	T	≧ 8.0
$\int B_Z^2\, dz$ **uniformity at < $2R_O$ = 0.8 × cold bore inner diameter (full width)**	%	≦ 2
Solenoid coil length (reference value)	cm	25
Cold bore inner diameter	cm	≧ 4.0
Minimum ramping rate using a 10 V power supply	A/s	≧ 0. 5% I_{nom}/s
Deviation of field center from mechanical center	mm	≦ 0.3
Steering Dipole Coil Parameters for 25 cm Solenoid Package		
$\int B_x$**dz ,** $\int B_y$**dz, integrated field strength**	Tm	≧ 0.03
$\int B_x$**dz ,** $\int B_y$**dz uniformity within 15mm from the beam axis**	%	≦ 5%
Mixing between $\int B_x$**dz and** $\int B_y$**dz (x, y field mixing or cross talk)**	%	≦ 2%
Perpendicularity tolerance between the X and Y dipoles	Degrees	≦ 1
Maximum current (see Section 1.5.9)	A	Option 1: ≦ 20 Option 2: ≦ 40
Only non-magnetic materials and components can be used in magnet construction		
Package total weight	kg	≦ 150

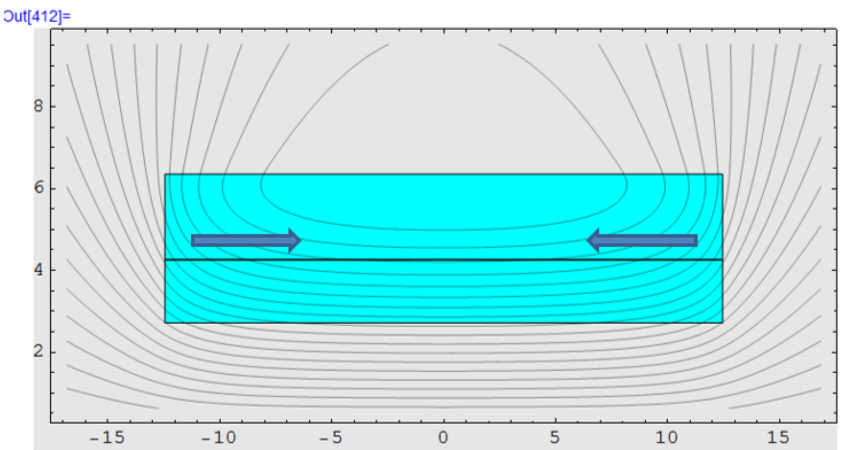
[2]The beam axis is as defined by the alignment fiducials (see Section 1.9).

Solenoid Coil Design
25cm solenoid, KEK





	Units	Inner Solenoid	Outer Solenoid
Solenoid length	cm	25	25
Inner Diameter	cm	5.4	8.6
Outer Diameter	cm	8.6	13.08
Layers		20	32
Turns per layer		312	357
Total turns		6240	11424
Total net length	m	1372	3888
Diameter of the bare SC wire	mm	0.75	0.65
Diameter of the wire with insulation	mm	0.80	0.70
Copper: SC		1.3	2.4
Filament diameter	µm	18	35
Critical current @ 4.2K	A	5 T: 600 6 T: 480 7 T: 370 8 T: 190 9 T: 100	4 T: 277 5 T: 234 6 T: 184 7 T: 142
Wire Vendor		Furukawa Denko	Hitachi Cable
Stored Energy at 100A	kJ	36.03	
Self-Inductance	H	7.2	
Field Enhancement Factor on the inner coil surface		1.0032	



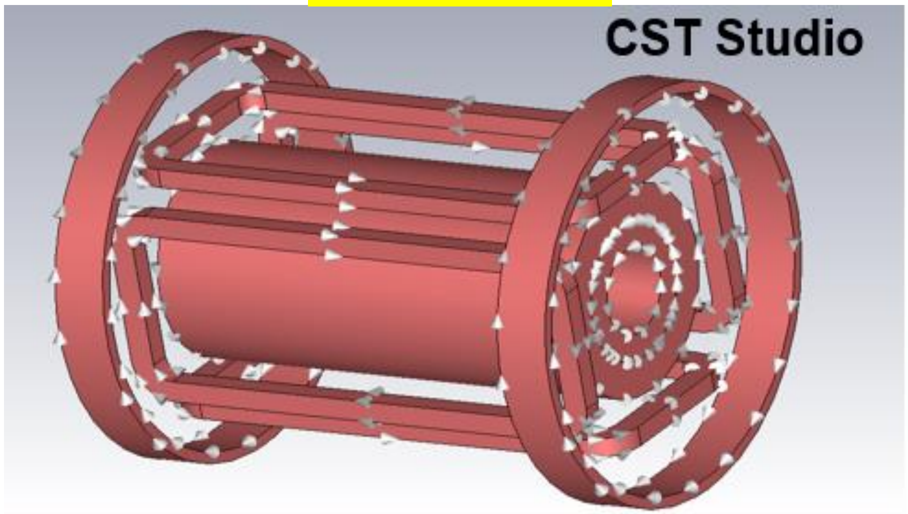
- Inner coil uses a bigger diameter wire due to higher field.
- A cure for magnet quench coil by movement of the frame due to Lorentz force is important
  - Epoxy impregnation
  - Dry winding

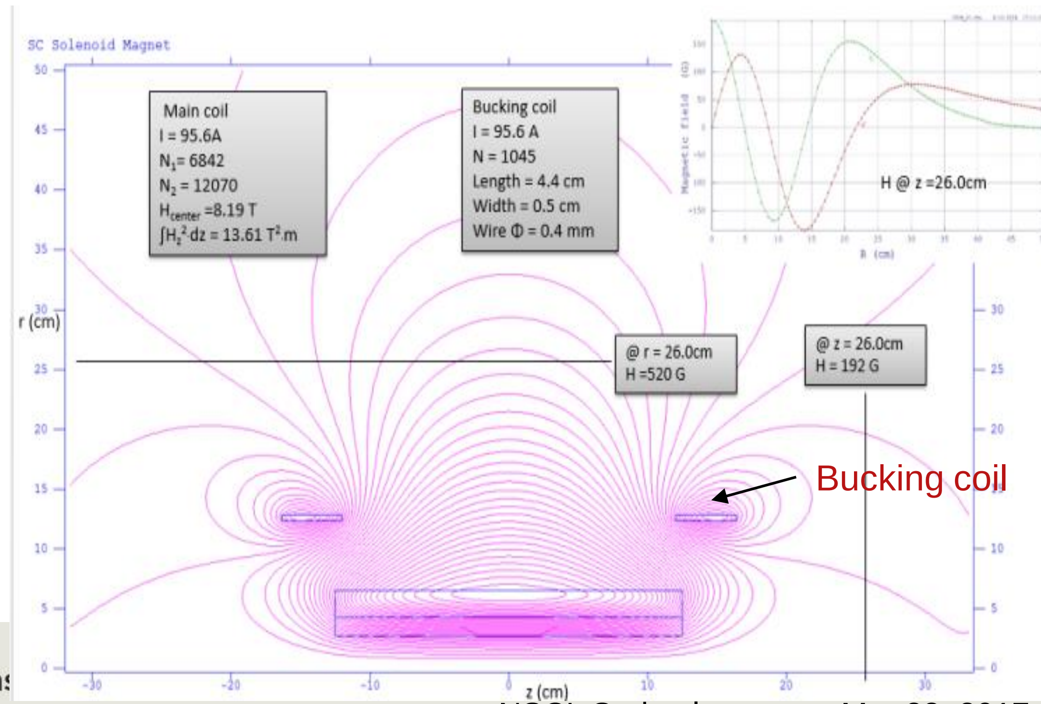
Optimization of Bucking Coil

Example FRIB 25cm solenoid

- Solenoid design based on KEK/MSU collaboration
- Cancel the strong fringe field from solenoid
- Fringe field on the local magnetic shield surface < 300 G
- Iron Yoke free design to avoid the hysteresis effect on the beam operation
- Solenoid package weight < 150 kg
  - Well optimized 25cm solenoid design with fringe field reduced to 300 G with a weight of 110 kg.

S. Shanab

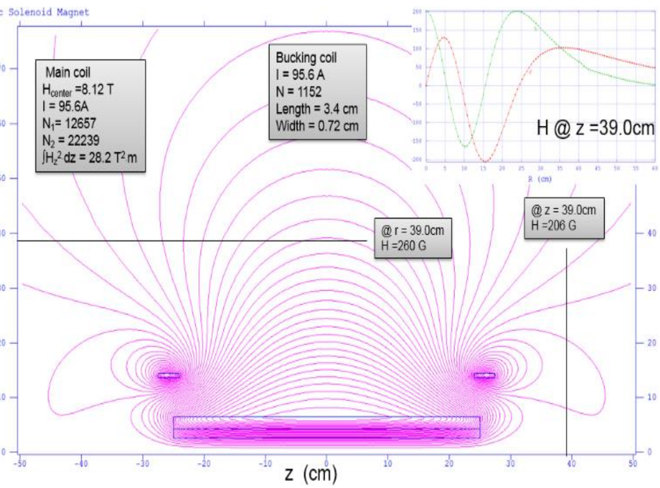




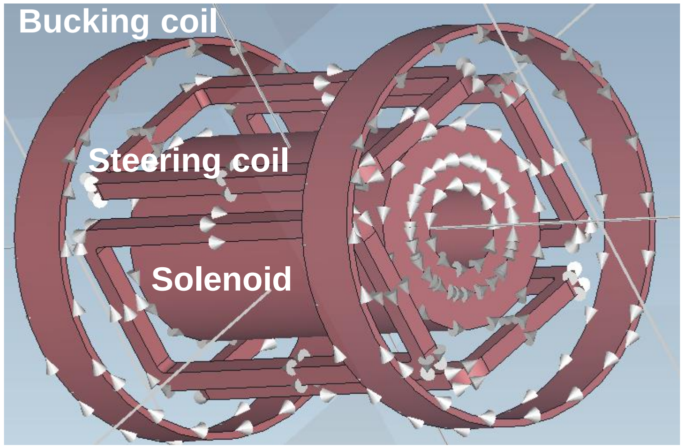
Simulation of Fringe Field Through the Shield

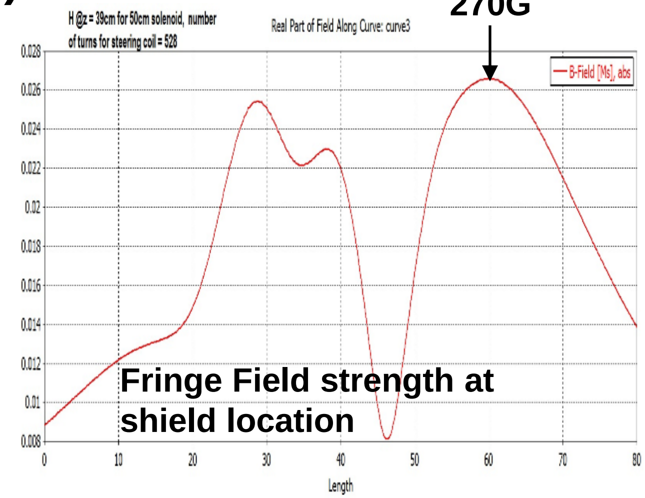
- Iron yoke free solenoid design has been completed with bucking coil
- 3D simulation by CST Studio shows the fringe field of 270G on the magnetic shield
- Fringe field of 100G exposes the high RF magnetic area
- Backup plan is being developing for Q-drop after quench, Meissner shield by niobium foil around the helium vessel might be a cure, which will be studied in the integration test

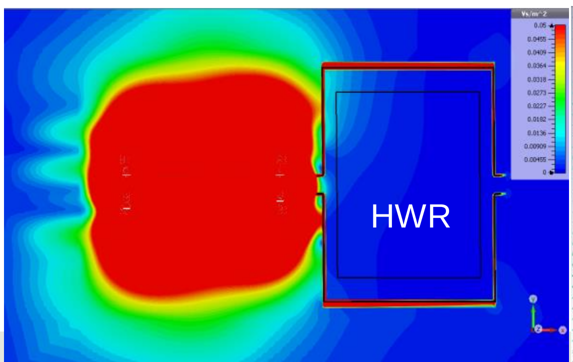
Poisson 2D

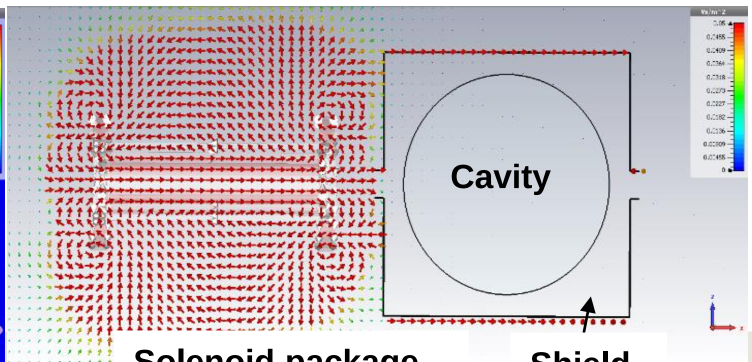


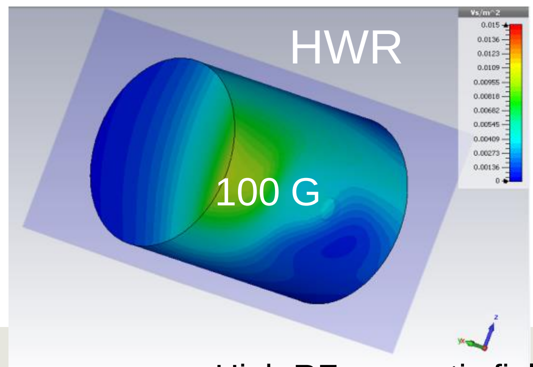
CST Studio 3D (solenoid package)









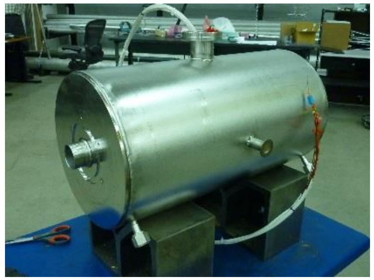


High RF magnetic field area

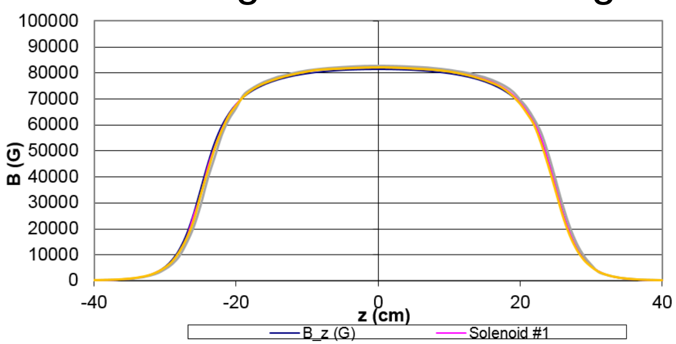
50cm Solenoid Package in House
Successfully completed in-house solenoid packages

- In-house solenoid package for the FRIB 0.085 first production CM
  - Wet winding with Epoxy, three solenoid package completed early September, Now on the FRIB 0.085 first production CM

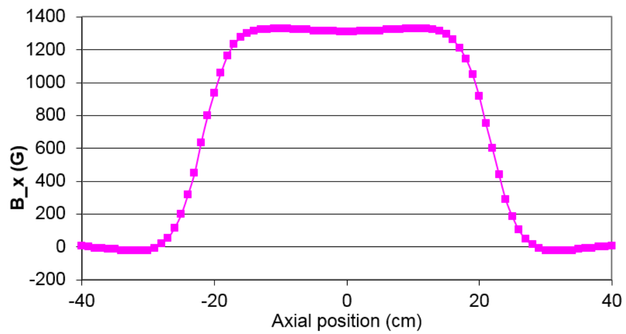




- Cold test results
  - Meets FRIB requirements
    - Solenoid, 86.8A, 8.26T (goal 8T), #1 and #2 no quench, #3 two quench training
    - Dipole, 0.054Tm @19A (goal 0.06Tm), 10% lower, solenoid design issue
    - Magnetic/mechanical center difference, 0.08 – 0.25 mm (goal < 0.3 mm).
    - Fringe field on the magnetic shield < 270 G (Goal 270G)



Solenoid field on axis



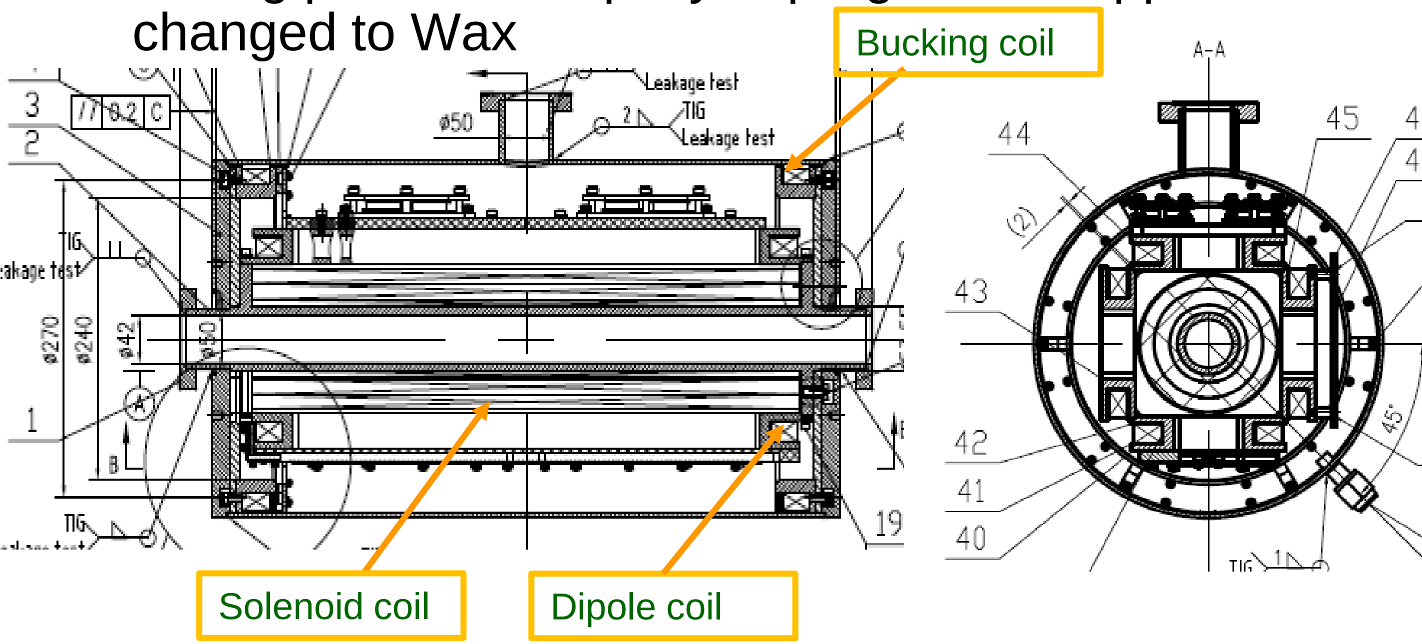
Dipole field Bx

	Z = -287 mm	Z = +287 mm
Solenoid #1	0.20	0.25
Solenoid #2	0.08	0.10
Solenoid #3	0.11	0.26

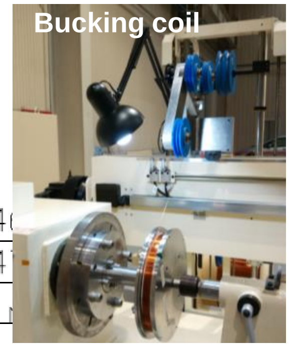
Magnetic/mechanical center difference

FRIB SC Solenoid Production in Vendor

- FRIB successfully contracted with a vender below BOE price
  - Design based on FRIB/KEK design
  - Vendor FRIB visit on April 29 -30, 2015
  - Vendor final mechanical drawing completed
  - Weekly meeting with the vendor on every Tuesday
  - Vendor completed test wiring for all magnets
  - During production Epoxy impregnation happened and changed to Wax



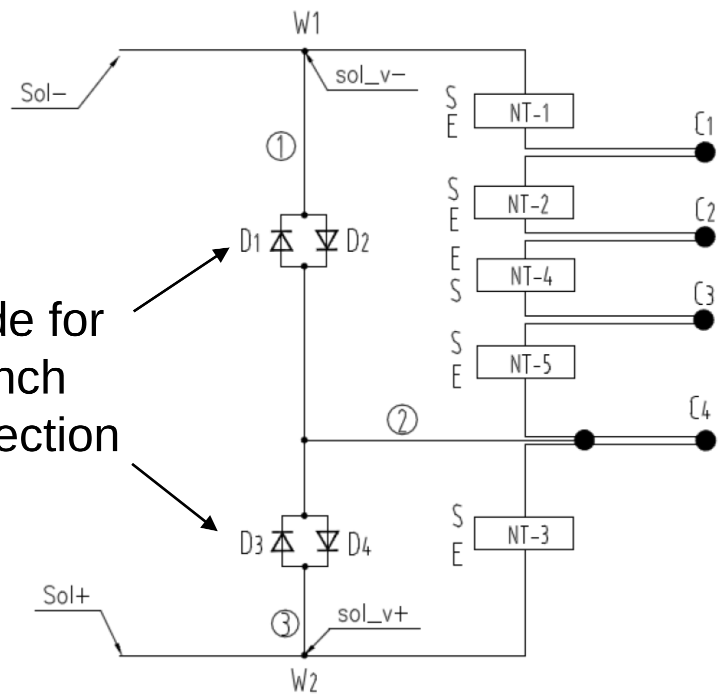
Main solenoid



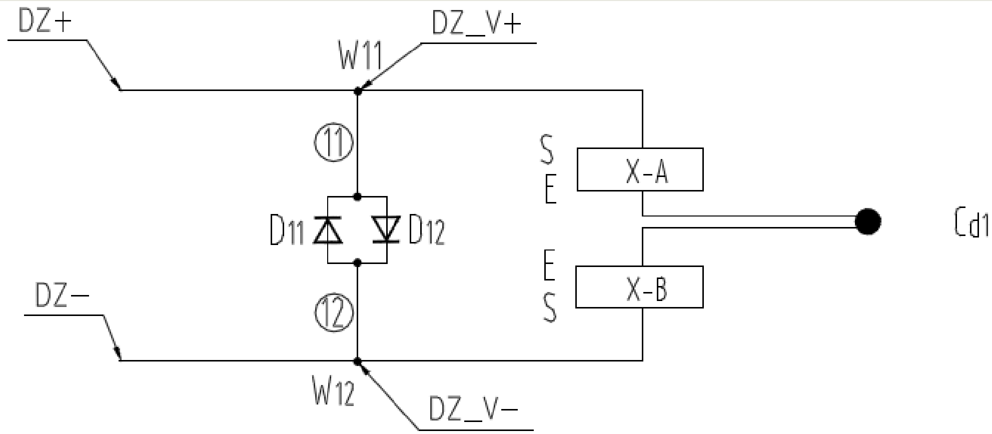
Winding of the solenoid at the vendor

Electric Circuit of Solenoid Package

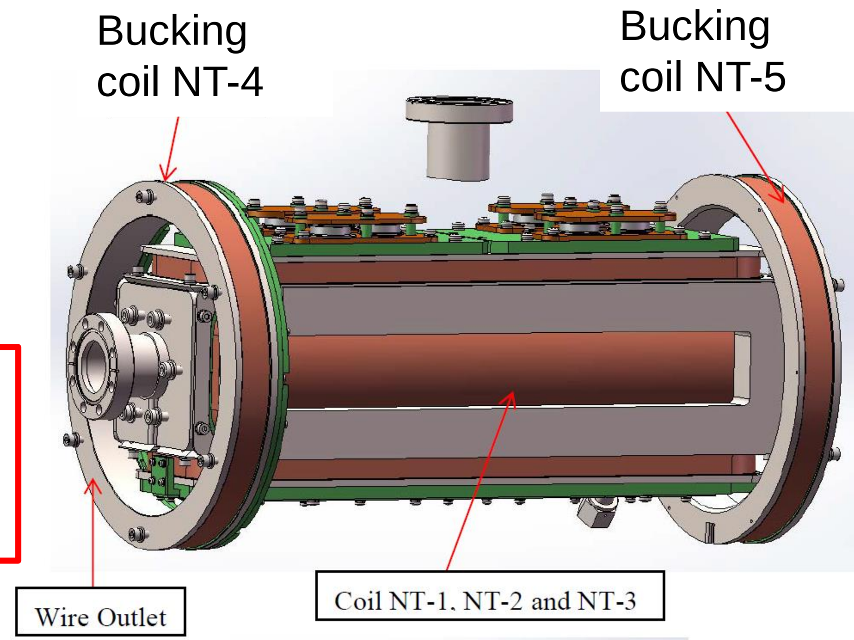
Diode for quench protection



Main solenoid



Dipole

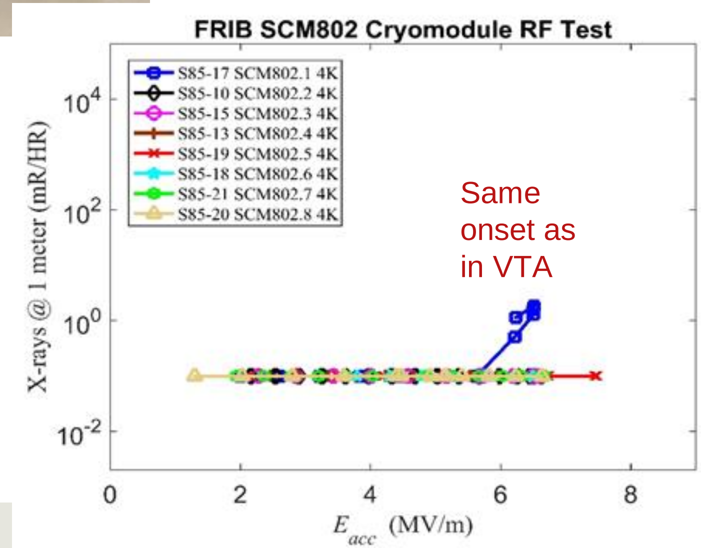


- 6 current leads/solenoid package
  - Current lead produces heat penetration
  - ~ 1W/ one lead

20.9 Coldmass Assemble, Example 0.085QWR production coldmass

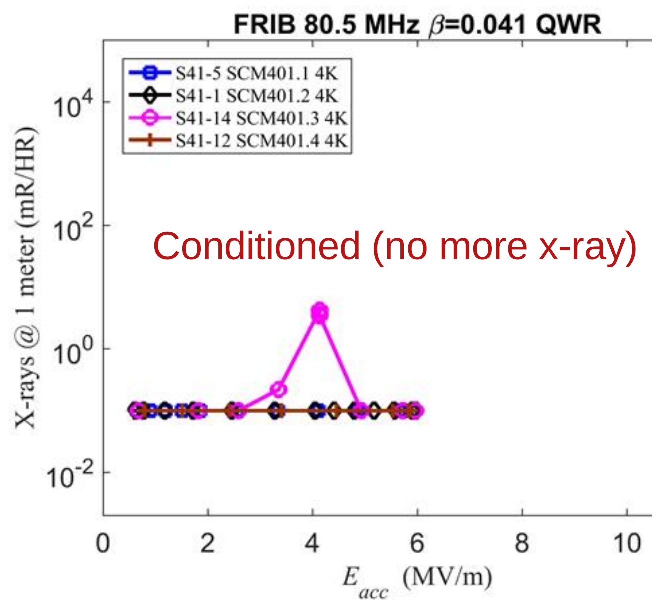
FPC installation tool

- FRIB 801and 802 cryomodule testing verified coldmass clean assembly procedures
- No degradation of cavity performance during cryomodule testing, same as vertical test
- No major issues reported during the coldmass assembly of 803 and 804



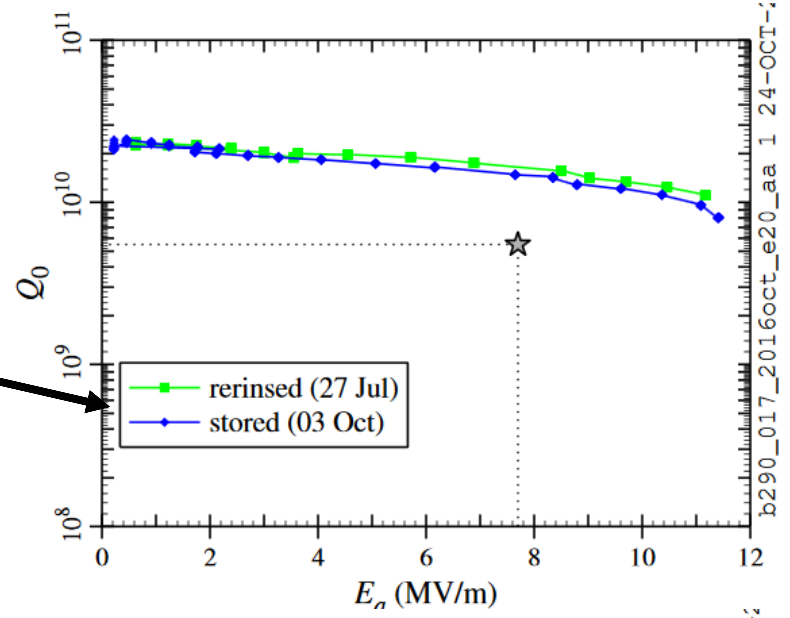
0.041QWR Coldmass Assembly
No cavity performance degradation validated in bunker tests

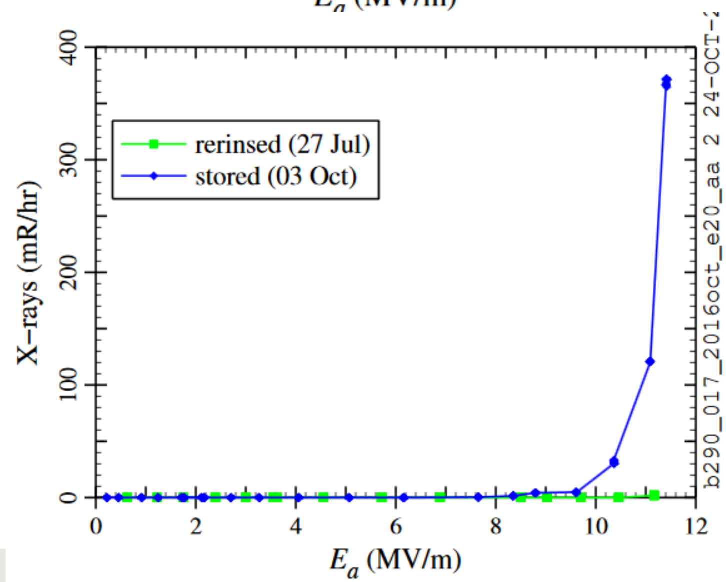
- Cold mass assembly issues
  - 401: Beamline center tube bellows leaked and had to be replaced
  - 402: Cavity helium vessel leak after coldmass removed from cleanroom. Coldmass returned to cleanroom and cavity swapped. All cavity helium vessels now leak checked after cold test and before string assembly
  - Spare 404: String assembly is ongoing
- No degradation of cavity performance during cryomodule testing



Certified Cavity Storage Procedure Verified

- Certified β=0.29 cavity bagged in cleanroom and placed in wood crate
- Stored in SRF Highbay rack for > 1 month and then retested
- 31 cavities in SRF rack storage
- Capability to store all certified β=0.29 cavities





20.10 FRIB Cryomodule Assembly
Cryomodule assembly bays in East highbay

- Four assembly bays ongoing, fifth assembly bay started in February 2017
- Two commissioned cryomodule test bunkers (East Highbay, SRF Highbay)
  - Additional assembly space for subcomponents (solenoid leads, O-rings, G-10 posts)
  - 2 overhead cranes
  - 2 loading bays for coldmass and completed cryomodule transport

0.53HWR CM Preproduction Assembly Sequence

Work Flow to be Verified to Launch Production

Completed cold mass assembly in clean room

Cold mass assembly transport to cryomodule assembly area

Cold mass ready for baseplate

Start baseplate assembly

Baseplate ready for cold mass

Cold mass on baseplate

Completed cryogenic circuit

Thermal shield installation

Vessel cover installation

Tuner valve manifold installation

Transport to SRF High Bay

Transport into bunker

Refine and Expand QA program as Production increases

- One β=0.041 cavity helium vessel on second cold mass: leak found at bimetal joint after cold mass transport to cryomodule assembly area
  - This cavity passed cold shock at ACL inspection and certification cold test without vacuum issue
  - Mitigation: additional leak check step added after cold test
- Preproduction β = 0.53 cryomodule vacuum vessel: found leak at final assembly step
  - Leak check performed at vendor
  - Leak check of large vessel is a technical challenge
  - Mitigation: educate vendor and send FRIB technical representative
- Instrumentation wiring broken after cool down
  - Instrumentation checked several times (warm) during assembly
  - Mitigation: Add cold shock step for soldered joints

β=0.041 cavity bimetal on helium vessel failure

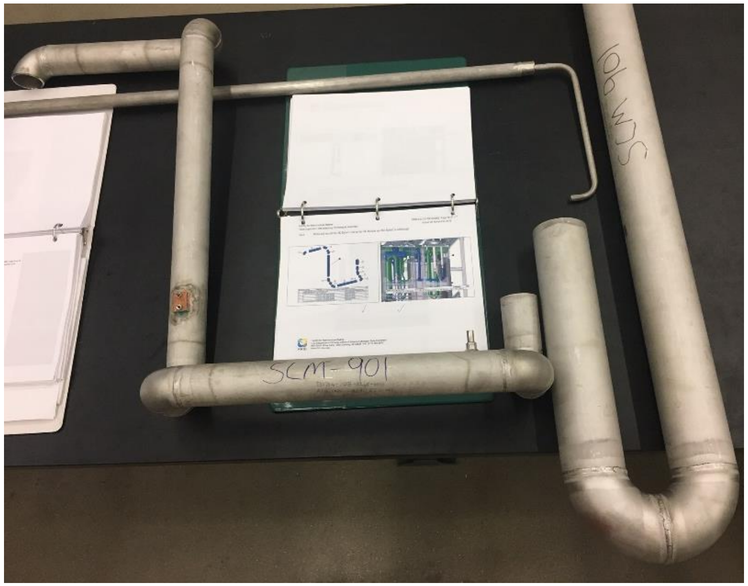
β=0.53 cryomodule vacuum vessel welding defect

Issues: Design Changes, Fabrication Changes, Human Error

- SC solenoid impregnation changed from Stycast 2850 to paraffin at preproduction stage
  - Overlooked impact on in-house processing: temperature during ultrasonic cleaning
  - Mitigation: changed ultrasound temperature setting; include stakeholders on ECO forms to communicate changes
- Human error
  - Damage to cold cathode vacuum gauge controller during welding
  - Damage to instrumentation wire due to welding
  - Mitigations: enhance training; educate on-floor workers on cryomodule basics; improve design to reduce risk of human error
- Rough handling at storage
  - Sealing surface of vacuum vessel damaged at storage facility after ACL. Storage facility staff transported the vessel improperly with folk lift.
  - Mitigation: FRIB Receiving Department developed documents to communicate special requirements for equipment handling

Lessons Learned – ease assembly/reduce risk

- Simplify piping – more subassemblies, less field welds, flexlines
- Magnetic shields – commercial sheet sizes, pop rivet construction, mostly bench assembled
- Solenoid lead protection – wiring centering harness
- Penetration covers - vacuum cover/thermal shield installation



Cryogenic piping subassemblies

Magnetic shields using rivet assembly

Protective covers for vacuum cover penetrations during installation

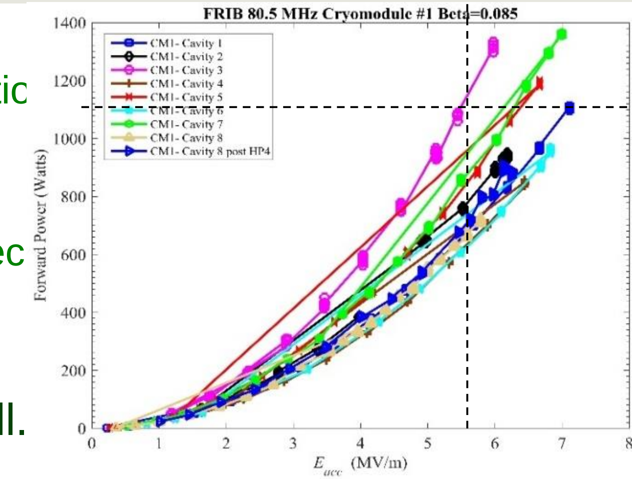
20. 11 Bunker Tests of FRIB Cryomodules

- Bunker tests are ongoing in two areas
  - EAST High Bay(QWRCMs)
  - SRF Highbay (HWR CMs)
  - 6 CMs have been done as of middle March 2017



Bunker Test Performance Example: SCM801 (FRIB First 0.085QWR Cryomodule)

P. Popielarski WG4



- Cavity gradient (Requirement 5.6 MV/m, P_f < 2.5 kW)
  - Result: Eacc ≧ 6 MV/m @ P_f max= 1.1 kW at 4 K , meets FRIB specificatic
  - Bandwidth 31 ± 9 Hz, meets Spec (40Hz)
- Dynamic Loss (spec 3.85 W, Q_0 =1.8 x 10^9 at 2 K)
  - Result: 2.8 W, Q_0=2.5 x10^9 in average at 2 K, ~ 40 % margin for FRIB Spec
  - No Q-degradation by cold mass assembly

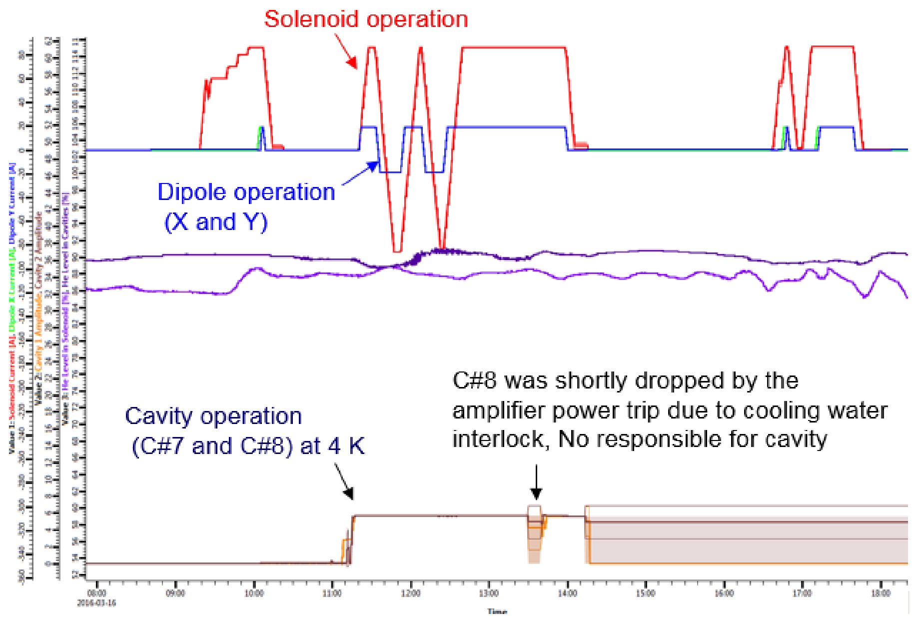
L. Popielarski WG4

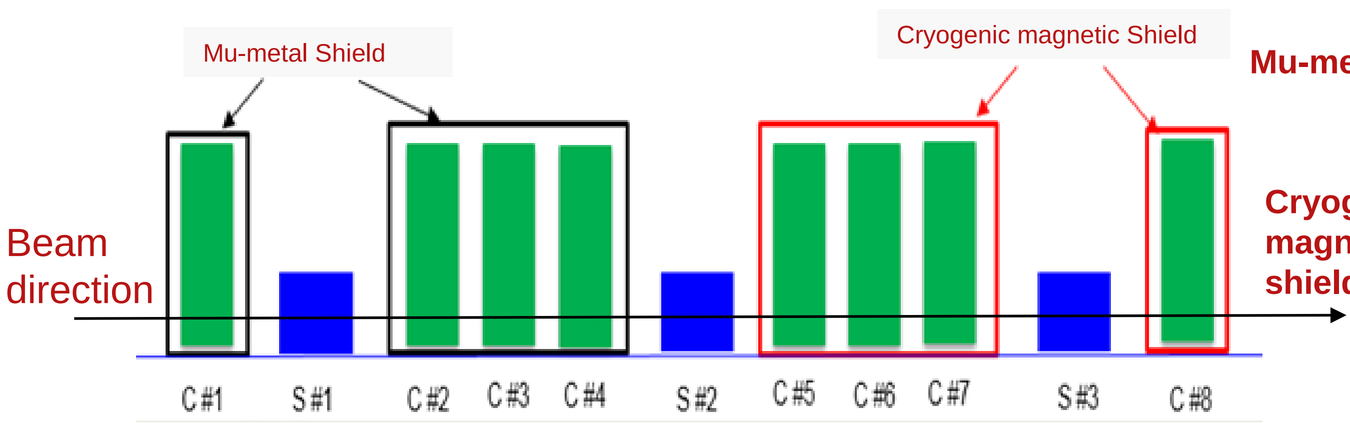
- Coupler and tuner work well
- All cavities are locked in spec at 4.5K for > 1hr, LL control works well.
- Cryogenics system is very stable throughout test period
- Heat loads (Static + dynamic heat loads)
  - Cavity header 28.8W (Spec 36W), meets spec.
  - Solenoid header 23.7W (Spec 22.6W), meets spec within measurement error (10%).

CAVITY	AMPLITUDE		PHASE		BW	FORWARD POWER			FORWARD PHASE		DETUNE	
#	Pk-Pk (%)	RMS (%)	Pk-Pk (deg)	RMS (deg)	BW (Hz)	Pnom (W)	Pave (W)	Pmax (W)	Pk-Pk (deg)	RMS (deg)	Pk-Pk (Hz)	rms
1					20.2	487						
2	0.64	0.05	0.58	0.07	38.6	931	1005	1552	68	7.7	29.2	3.3
3	0.08	0.01	0.09	0.01	43.6	1052	1163	1274	28	1.5	13.4	0.7
4	0.09	0.01	0.25	0.03	37	893	1076	1318	28	2.9	11.5	1.2
5	0.26	0.01	0.53	0.07	24.8	598	488	858	72	7.9	19.6	2.2
6	0.09	0.01	0.09	0.01	27.1	654	650	681	9	1.4	2.7	0.4
7	0.06	0.01	0.31	0.02	26.5	639	702	835	23	2.1	6.8	0.6
8	0.14	0.01	0.32	0.04	26.3	634	645	924	49	5.7	14.2	1.7
Average	0.19 ±0.21	0.02 ±0.02	0.31 ±0.19	0.04 ±0.03	30.5 ±8.1	736 ±196	818 ±259	1063 ±318	40 ±24	4.1 ±2.9	13.9 ±8.6	1.4 ±1.0
Spec	**2.00**	**0.25**	**2.00**	**0.25**	**40.0**				**90**		**< 20**	**< 2.25**

SCM801 Solenoid Operation and Magnetic Shield Validation

- Successful robust solenoid package operation with cavities
  - Solenoids ramped to full fields (8T) without any training quench. Same ting for Dipoles (19A).
  - Integrated test with cavity at 5.6 MV/m at 4.5 K for > 2 hr.
  - Vapor cooled current leads operate well, flow controller regulates the lead voltages stable.
- Magnetic shield material with μ > 9000 at cryogenic temperature meets FRIB requirement: Bin < 15 mG
- Validated: Mu-metal against remnant field for FRIB local magnetic shield design





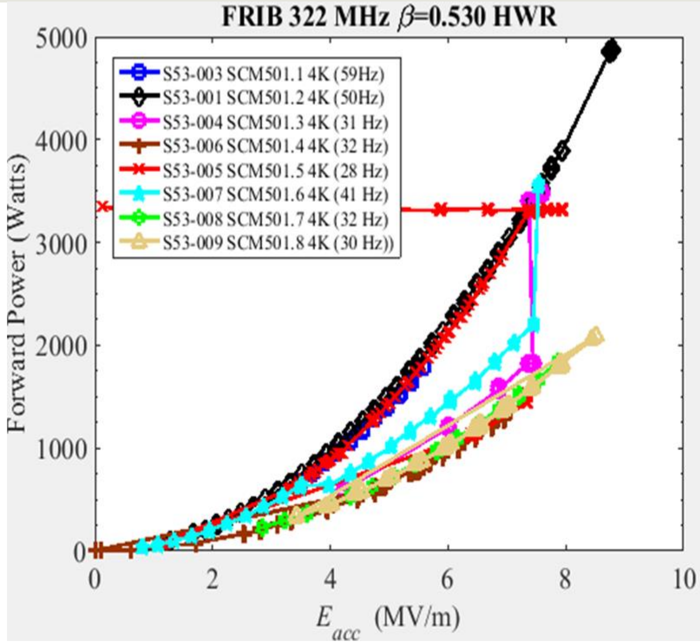
Mu-metal
- Cavity 1: 6.2W
- Cavity 2: 2.4W
- Cavity 3: 2.5W (split)
- Cavity 4: 1W (seems low)

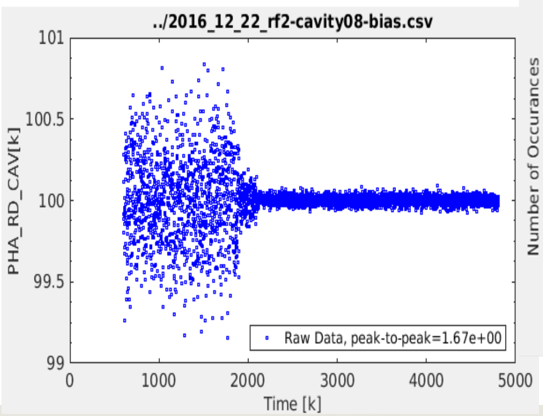
Cryogenic magnetic shield
- Cavity 5: 2.4W
- Cavity 6: 2.5W (split)
- Cavity 7: 2.4W
- Cavity 8: 2.6W

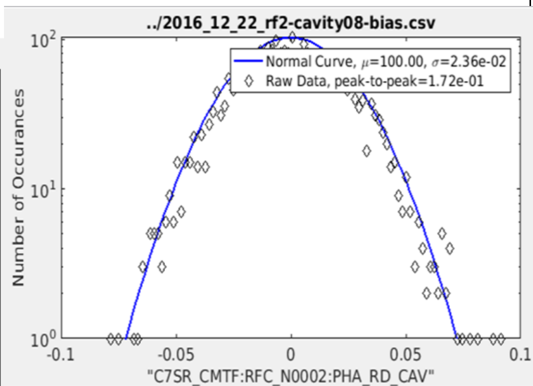
Dynamic heat load measurement at 2 K for each cavities

Bunker Test Result SCM501

- All cavities locked with 30 RF Hz BW, 4K within amplitude and phase specification: (<2 deg pk-pk phase stability, < 2% pk-pk amplitude stability)
- All cavities locked at greater voltage than the design value (5.6% higher overall for the cryomodule)
- Total dynamic load of all the cavities is 33 Watts, which has 30 Watt margin under our specification of 63W
- Magnet integration test successful
- Dynamic heat load had no change after degaussing and thermal cycle (Validates degaussing procedure!!)
- Cryomodule 4K measurements and conditioning can coexist with 2K VTA testing



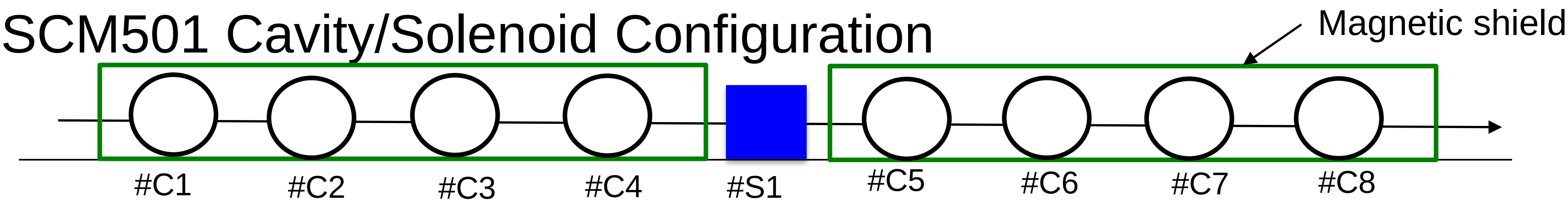




			pressure = gauge pressure					
			4K		2K		322 MHz Pressure	Measured
	2K VTA		pressure	freq	pressure	freq	predict	
S53-003	322.074	1	1.271	322.033	14.16	322.008	**20.83**	**20.93**
S53-001	322.075	2	0.793	322.041	13.89	322.015	**26.39**	**25.7**
S53-004	322.063	3	0.519	322.03	10.9	322.008	**17.57**	**17.77**
S53-006	322.071	4	0.882	322.034	11.9	322.016	**25.23**	**24.04**
S53-005	**322.086**	**5**	**0.996**	**322.053**	**12.1**	**322.034**	**40.43**	**39.83**
S53-007*	322.091	6	-0.218	322.039	19.5	322.009	**27.00**	**27.5**
S53-008	322.073	7	0.998	322.035	27.4	321.998	**25.73**	**27.75**
S53-009	322.082	8	1.162	322.046	23.9	322.012	**33.90**	**34.3**
							17.57	**17.77**
*S53-007 had frequency rework after VTA, (-20 kHz planned)							**40.43**	**39.83**
							22.87	22.06

SCM501 Solenoid Package Test

- SCM501 Cavity/Solenoid Configuration



  - Eight beta 0.53 HWRs
  - One in-house made 1st batch 50cm 8 T solenoid 0.06 Tm dipoles package
  - PC-Permalloy (Mu-metal) magnetic shield
  - First time solenoid test in SRF high bay

- Solenoid package test
  - Jan 19th package alone, solenoid up to 87A, dipoles up to 19.5A;
  - Jan 23th integral test with cavities (~7.5 MV/m). Cavities are stable.
- Thermal cycle test
  - After demagnetization, warmed up to 30K and re-cold tested at 2K
  - Cavity dynamic loss has no changed, no impact with solenoid operation (no flux trap)
  - Cryomodule was leak tight