Superconducting RF Development for FRIB at MSU

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Acknowledgment

First, we would like to thank to FRIB ASAC (Accelerator System Advisory Committee) members for their encouragements and valuable recommendations :

Bisognano Jeseph(University of Wisconsin),

Ozaki Satoshi (BNL),

Laxdal Robert (TRIUMF),

Knobloch Jens (Helmholtz Zentrum Berlin, HZB, Institute of SRF Science and Technology),

Roser Thomas (BNL),

Dalesio Bob (BNL),

Than, Yatming Robert (BNL),

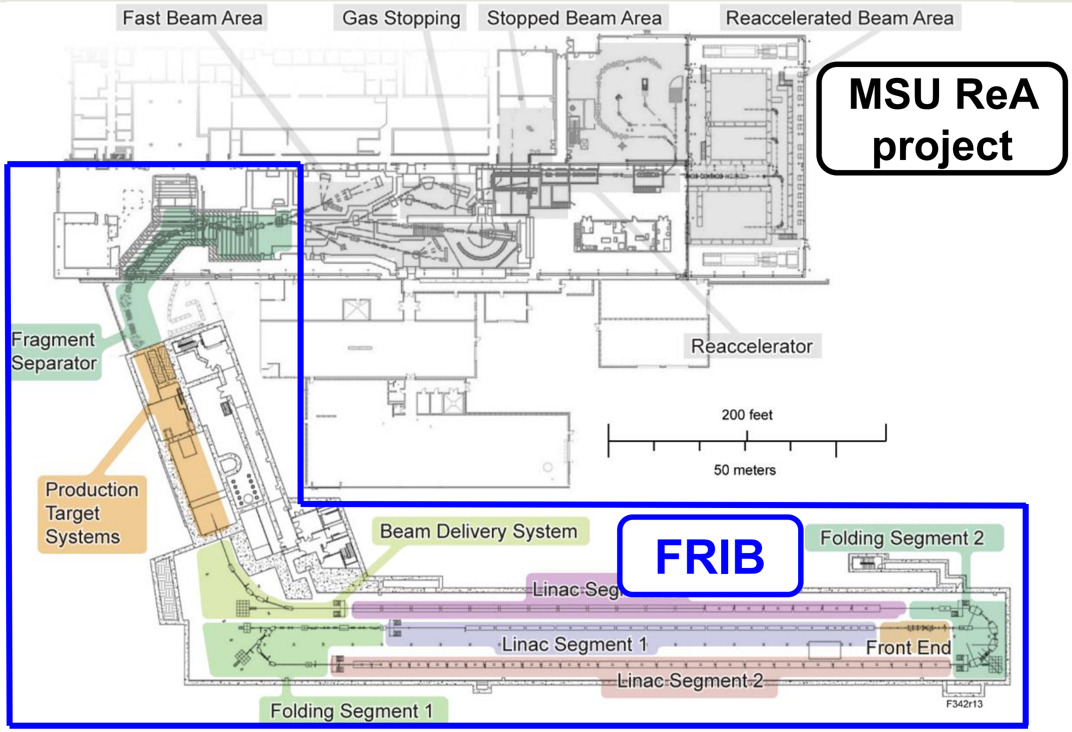
Helen Edward(FNAL)

Outline

- **FRIB Project**
- **FRIB Cryomodule Prototyping**
- **FRIB SRF Development around Cavity**
  - Niobium materials
  - Processing
  - Cavities
  - Coupler and Tuner
- **Cavity/Fringe Field Interaction**
  - 8T solenoid prototyping
  - Magnetic shield behavior exposed high magnetic field
  - Cavity/fringe field interaction
  - 3D full modeling
- **Summary**

FRIB Scope & Machine Requirements

FRIB is a DOE project for nuclear science, total fund $730M



- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- 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 with 12 cryomodules

- Features:

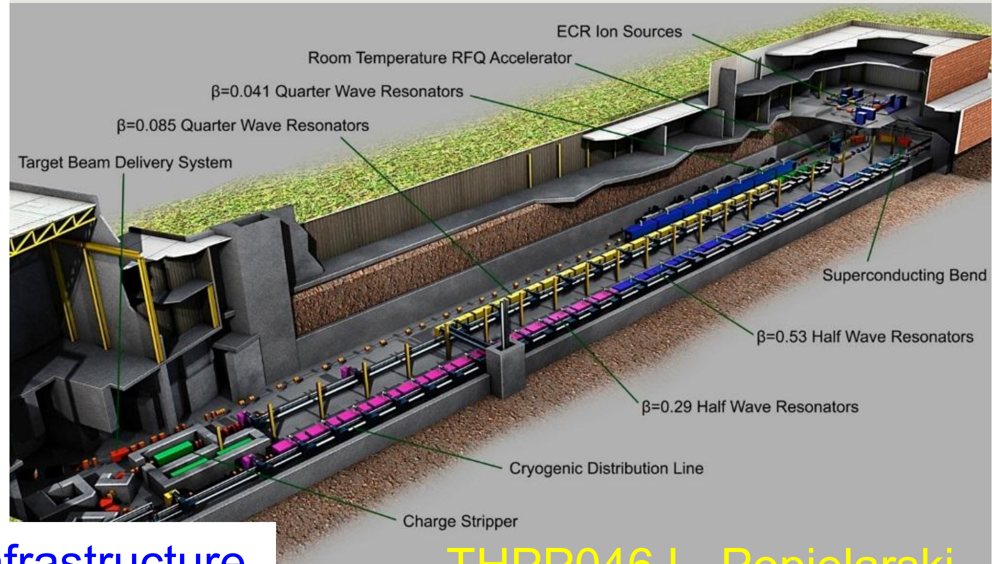
• Heavy iron beam intensity frontier machine, e.g. $5\text{x}10^{13}$ ^{238}U/s, 250 times higher than ATLAS

• All SRF from low beta to middle beta section and 2K operation

• Large nuclear physics user (~1300 users) facility

FRIB CF Constriction and SRF Highbay

Project Stage
CD0: Planning
CD1: Proposal, Sept. 2010
CD2: Baseline design, Aug. 2012
CD3-a: Conventional facility, June 2013
CD3-b: Accelerator system, August 2014
Acc. System construction starts Oct. 2014
Early completion 2020
CD4: Completion, to be 2022



THPP046 L. Popielarski

Completed SRF Highbay, under installing infrastructure

Tunnel construction started in May 2014

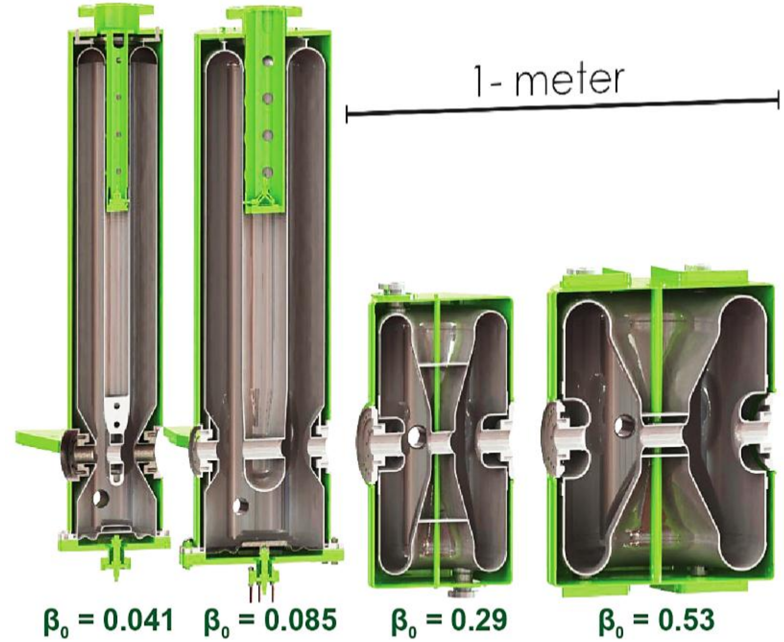
SRF highbay

Infrastructure installation in SRF highbay

FRIB SRF Scope

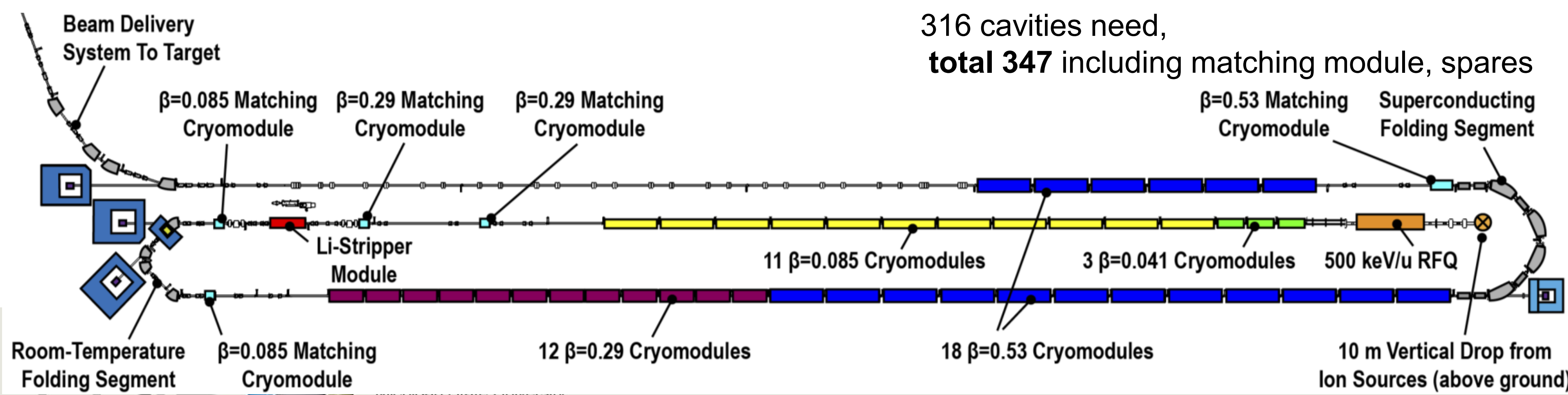
Challenge: All SRF from low β(0.041) to middle β(0.53)

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_O@VT	1.4E+9	2.0E+9	5.5e+9	9.2E+9
Q_L	6.3E+6	1.9E+6	5.6E+6	9.7E+6



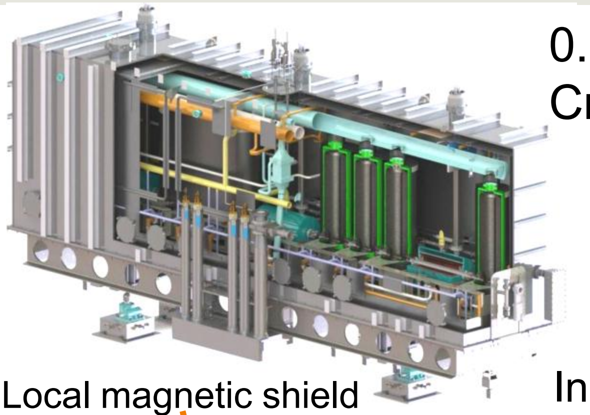
N = 12 88 72 144

316 cavities need,
total 347 including matching module, spares



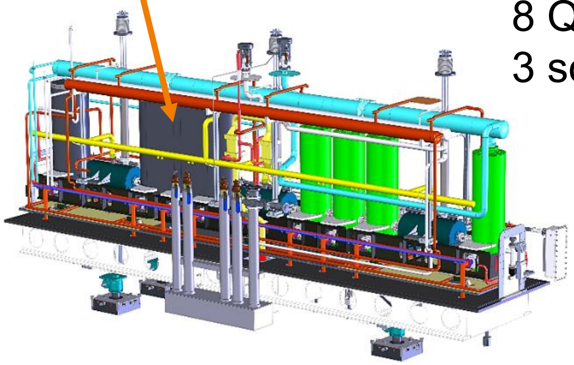
FRIB Cryomodules, Exsamples

Need totally 49 CMs: 3(0.041), 11(0.085),12(0.29), 18(0.53), and 5 matching CMs

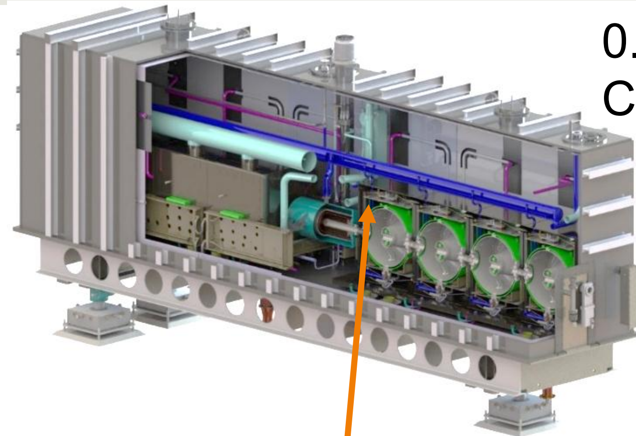


0.085QWR Cryomodule

Local magnetic shield



Includes 8 QWRs and 3 solenoids



0.53HWR Cryomodule

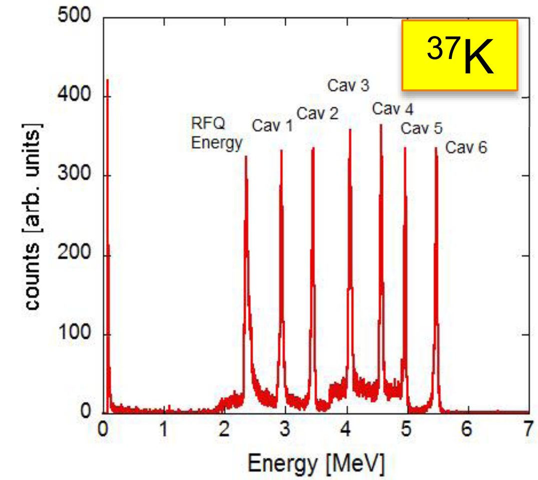
Local magnetic shield

Includes 8 QWRs and 1 solenoids

- **FRIB Cryomodule Features**
  - **Local shield**: cost reduction for magnetic shielding and reliable shielding
  - **Bottom-up assembly**: easy assembly and better alignment
  - **2K operation**: better cavity performance and less micro-phonics by stable pressure control

Cryomodule Developments at MSU
ReA is a benchmark for FRIB

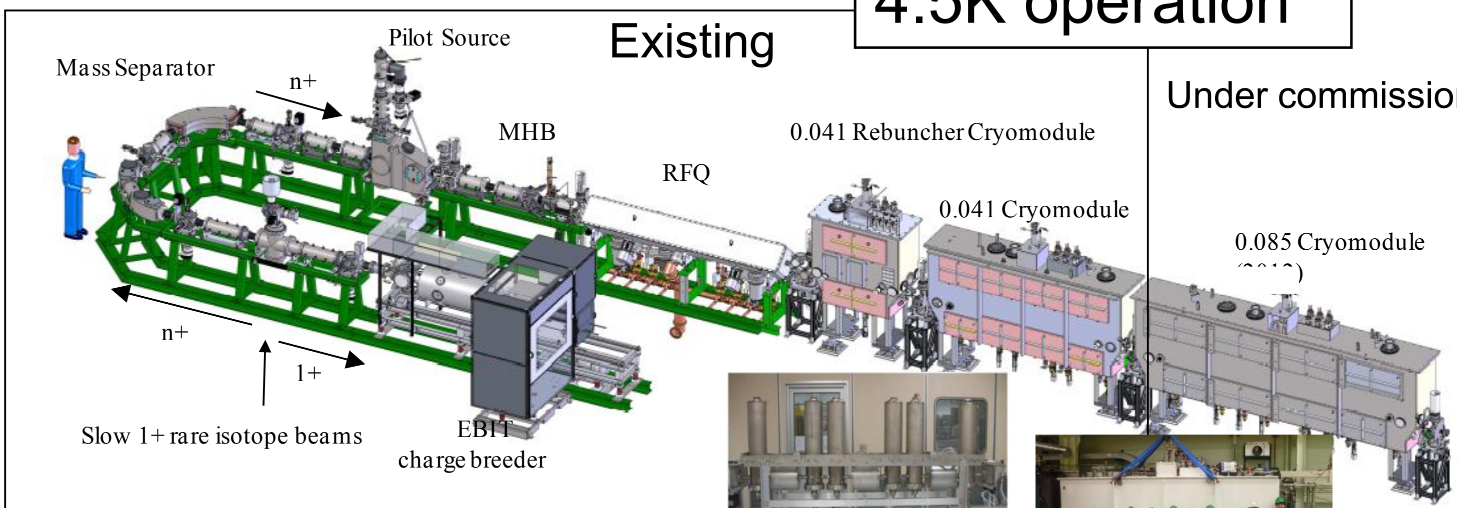
- MSU is constructing ReA project by own fund
- ReA SRF system as a benchmark for FRIB CM system
- A buncher (CM#1, 0.041) and an accelerator module (CM#2, 0.041) are successfully operated with beam since 2012
- Additional 0.085 CM (CM#3) has been installed and is under commissioning August-September 2014 **MOPP044, T. Xu**
- Additional FRIB type CM (ReA6, 0.085) will be installed and tested by December 2014



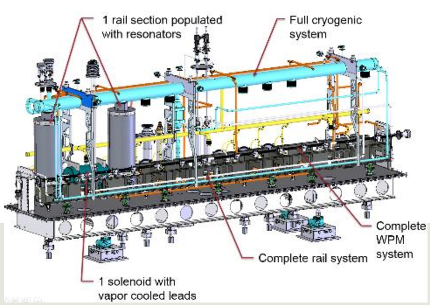
4.5K operation

Existing

Under commissioning



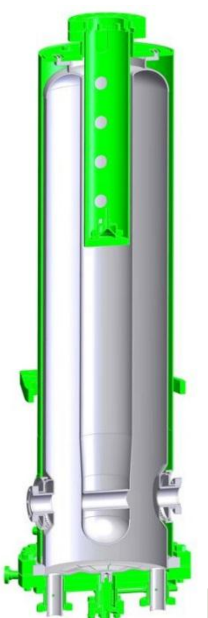
Under construction

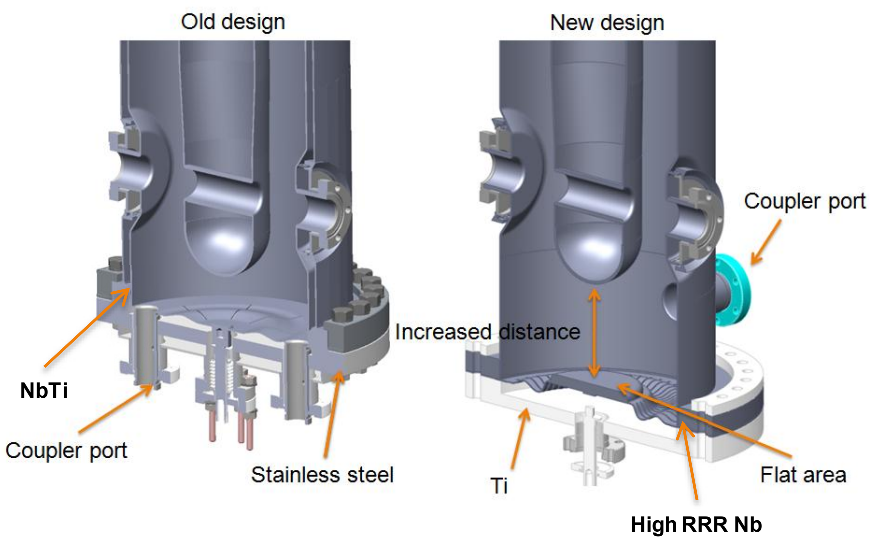


Lessons Learned from ReA3 Construction

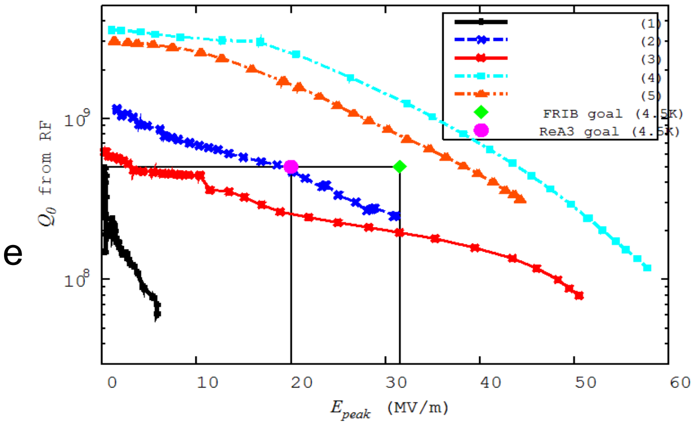
Bottom flange issue

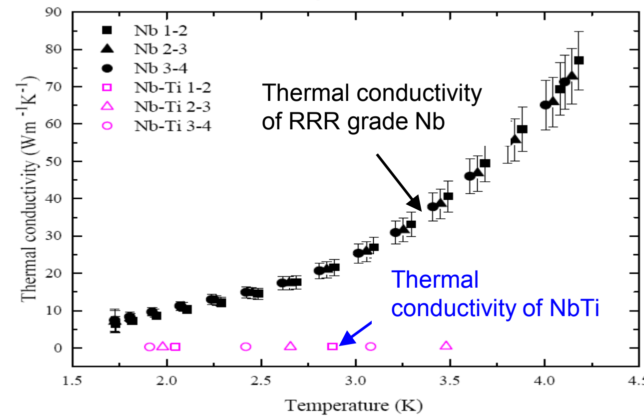
- **ReA3, 1st prototyped β=0.085 cavities**
  - Insufficient cooling the tuning plate due to NbTi bottom flange with poor thermal conductivity
  - Modified design
    - ➢ Elongated the bottom outer tube to reduce magnetic field and made a distance tuning plate-inner conductor
    - ➢ RF coupler moved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

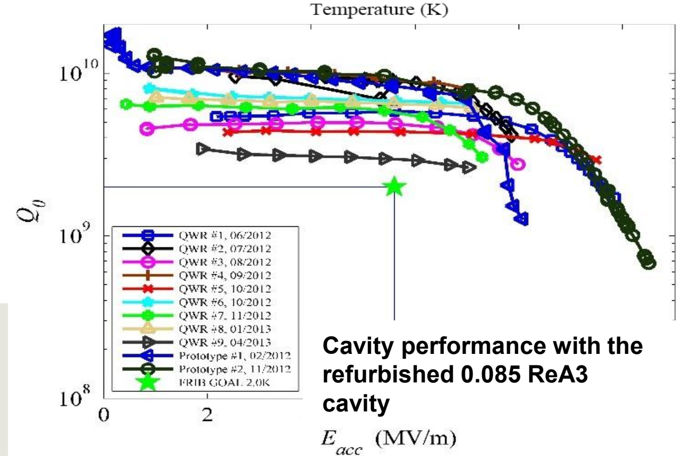




Cavity performance with the first prototyped 0.085 ReA3 QWR





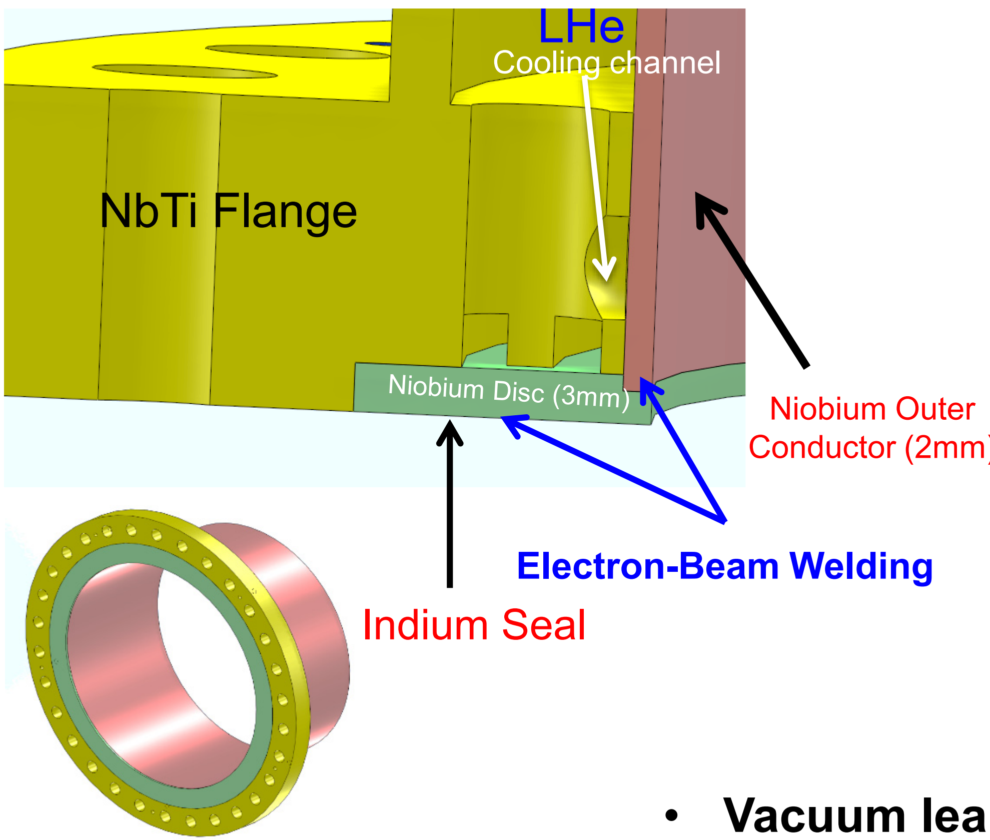


Cavity performance with the refurbished 0.085 ReA3 cavity

Redesigned QWR Bottom Flange and Alternative

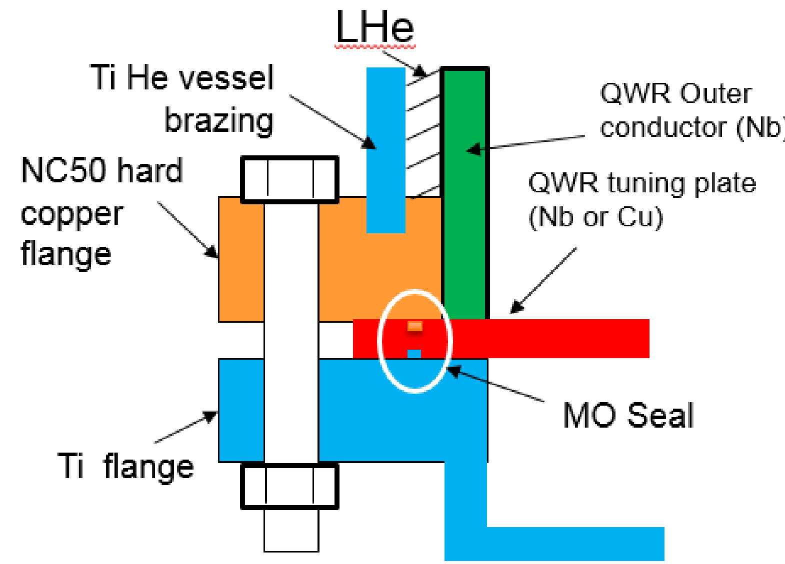
Improved cooling, Metal gasket seal flange is also under developing

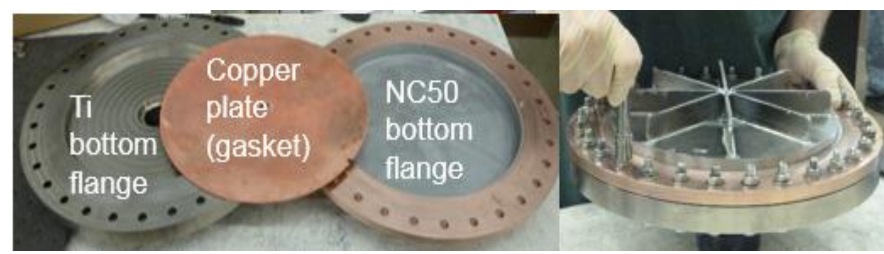
Redesigned QWR Flange as FRIB Baseline (Indium seal): Validated already, used refurbished ReA3 QWRs



Bottom View

Alternative (metal gasket seal): Under developing

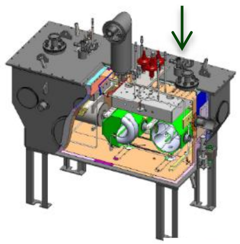




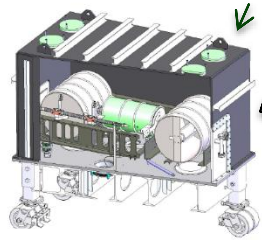
- **Vacuum leak tight confirmed**
- **Good RF contact confirmed by paper pressure test**

Cryomodule Prototyping Aproch for FRIB

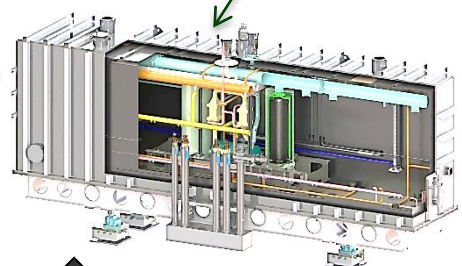
TDCM
(Technical Demonstration of CryoModule at 2K) 2012- 2013

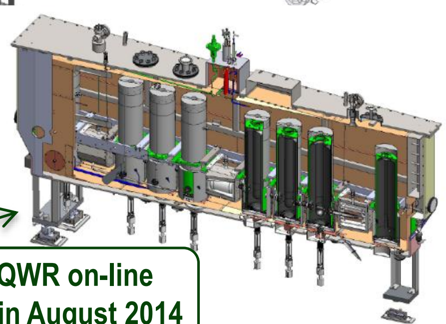


ETCM, Engineering Test CryoModule 2013



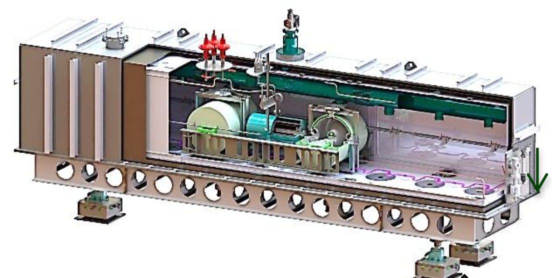
ReA6/FRIB QWR-Under Construction, 2 cavities and one solenoid on-line testing Dec 2014





ReA3 β=0.085 QWR on-line Commissioning in August 2014

HWR, 2 cavities and one solenoid, Design in advanced stage
Construction planned in 2015
Testing in new SRF bay in 2016

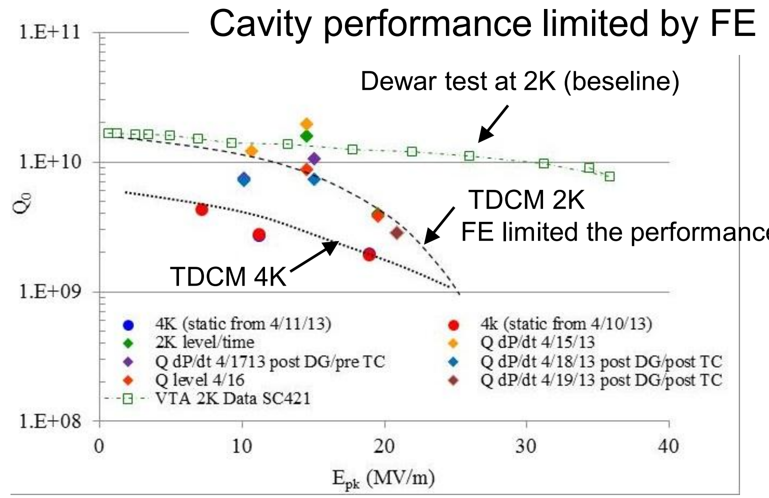


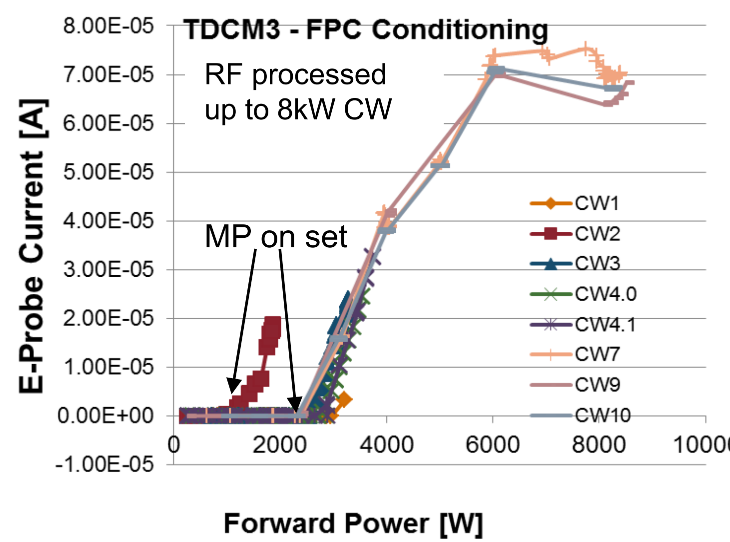
FRIB first 0.041 CM early 2016

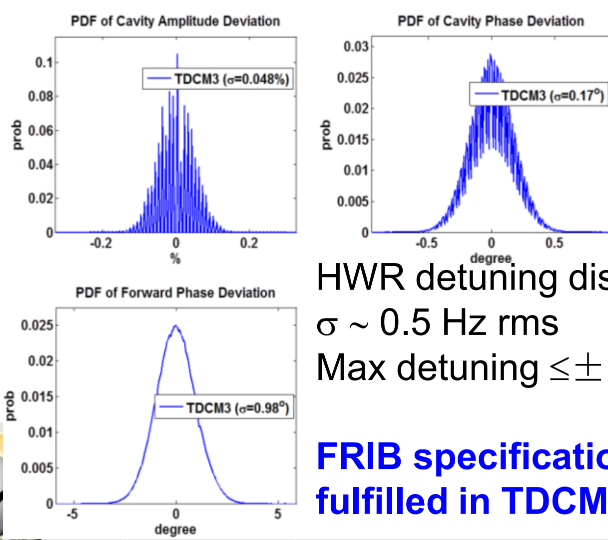
- TDCM: confirm FRIB 2K opertaion
  - CM construction leak tight at 2K
  - Demonstrate cavity, FPC and microphonics
- ETCM: valudate bottom-up sassembly
  - Validation of alighment tolerance in the bottom-up assembly
- Feedback to future FRIB mass production

TDCM (Technology Demonstrate Cryomodule)
Demonstrated 2K operation and verified FRIB design concept

- **Cavity and FPC**
  - Cavity performance limited by FE, need improve assembly procedure
  - Degaussing
  - FPC demonstrated 8kW feed and stable operation at 6 - 7kW CW, MP is an issue
- **HWR RF bandwidth (Specified: BW=30 Hz, $\Delta f_{pp} \leq 0.5$ BW)**
  - Fast detuning distribution: Gaussian, $\sigma \sim 0.5$ Hz, $\Delta f_{pp} < 6$ Hz $\equiv \pm 6\sigma < 0.5$BW, satisfied FRIB specification
  - Slow detuning following He pressure
- **2 K He bath pressure stability**
  - $\Delta P \leq \pm 0.1$ mbar peak, as in SNS





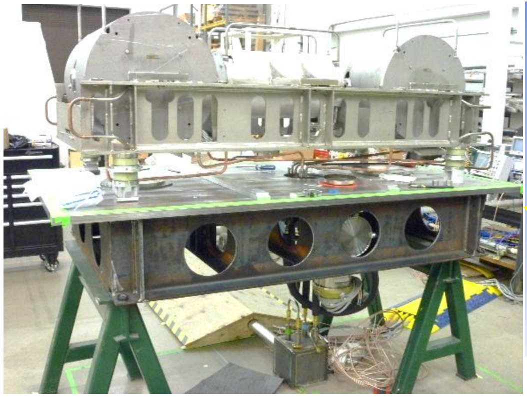


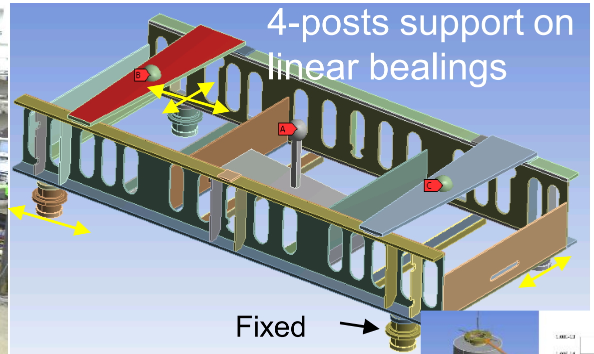
HWR detuning distribution:
$\sigma \sim 0.5$ Hz rms
Max detuning $\leq \pm$ 6 Hz p-p

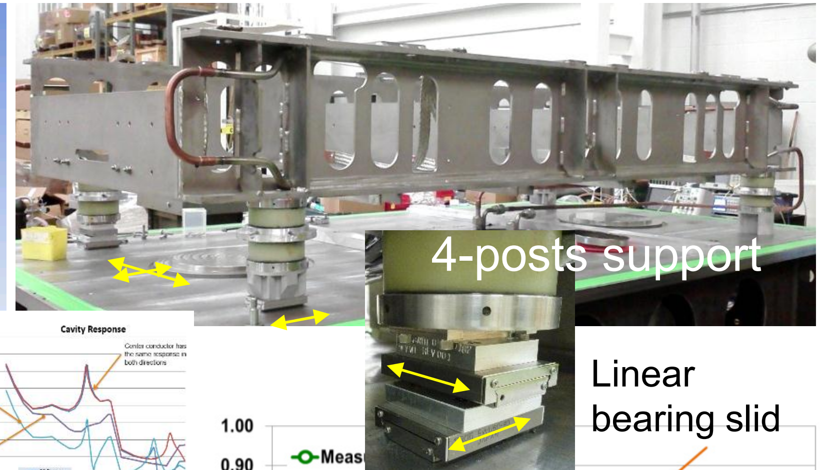
FRIB specifications fulfilled in TDCM

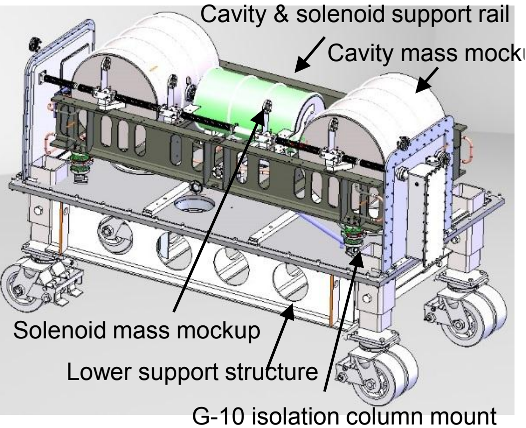
ETCM (Engineering Test Cryomodule)

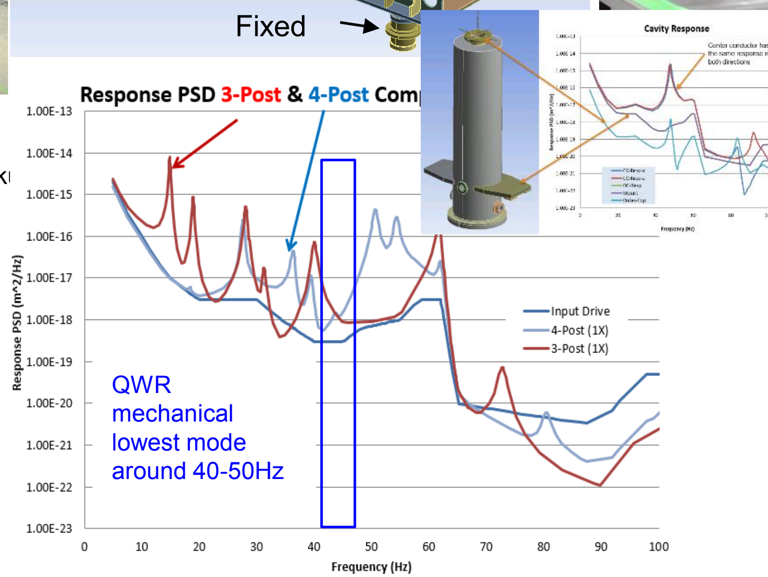
Validated bottom-up cryomodule assembly concept with high alignment accuracy (~ 0.1 mm)

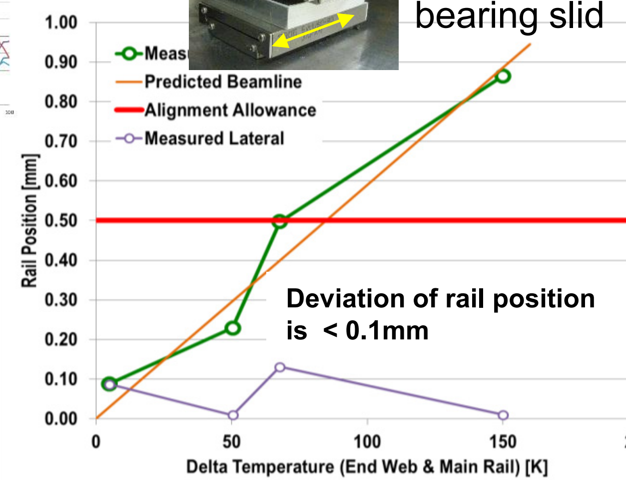












- Successfully verified cavity self-aligning by linear bearings during liquid nitrogen cool-down & vacuum vessel enclosure
- 4-post support established as design choice based on vibrational response analysis
- Successfully evaluated vibration, test with actual load and realistic configuration
- Divided into three sections for the FRIB QWR support rail to eliminate lower mechanical modes

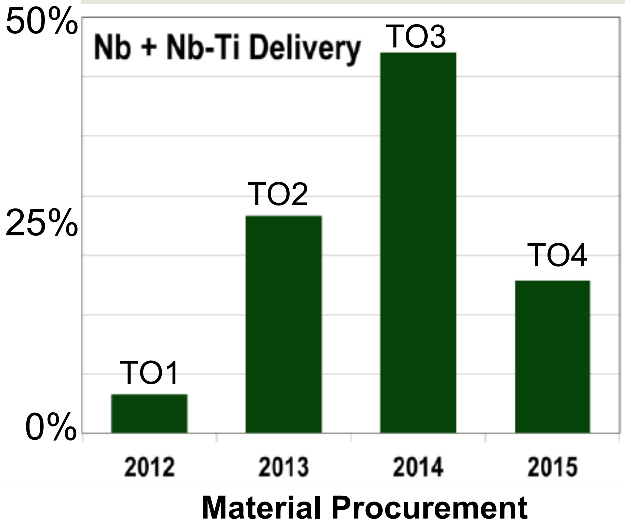
Niobium Materials for FRIB

Early procurement, all materials will be delivered by end of 2014

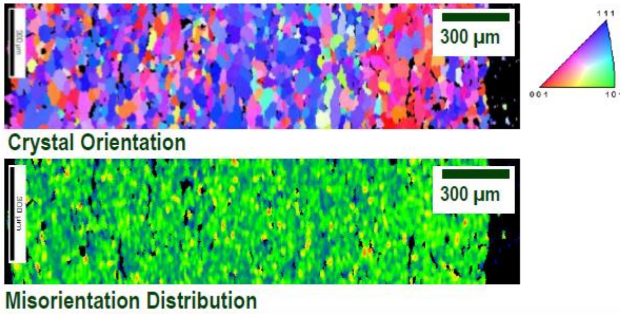
- **FRIB procures of niobium material from three vendors**
  - Wah Chang – NbTi flange material
  - Tokyo Denkai – RRR250 niobium sheets
  - Ningxia – RRR250 niobium sheets and tubes
- **Material specification**
  - Dimension check, surface inspection
  - RRR > 250 for niobium sheets
  - Grain size ASTM#5 (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 from per production lot are tested
  - Dimensional and surface finish
  - Mechanical test (Ultimate, Yield, Elongation, Hardness)
  - Metallurgy properties measurement (Grain size, Crystal orientation, Recrystallization)
  - RRR/Thermal conductivity
- **Materials are well controlled at FRIB**

NbTi flange material

Seamless Nb tubes



Nb sheet material



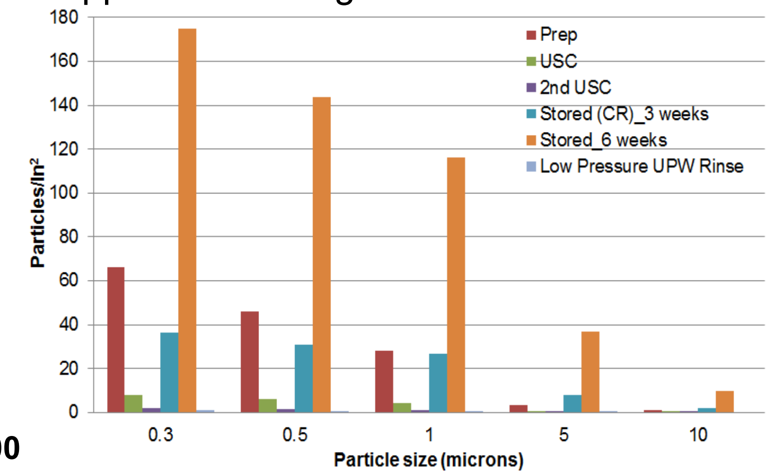
FRIB Unique QA Process Control

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**

LINAC2012, L. Popielarski and R.Oweiss et al.

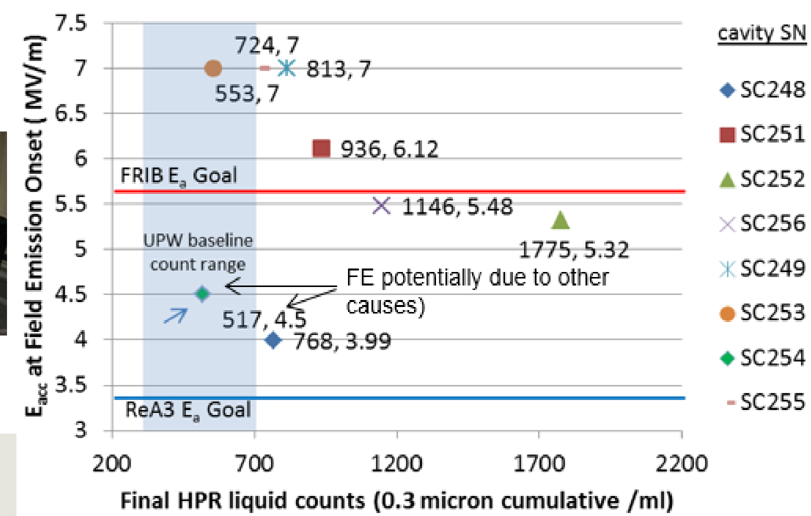
Average Surface Particle Counts on HWR Tapped Hole Flange for Various Procedures

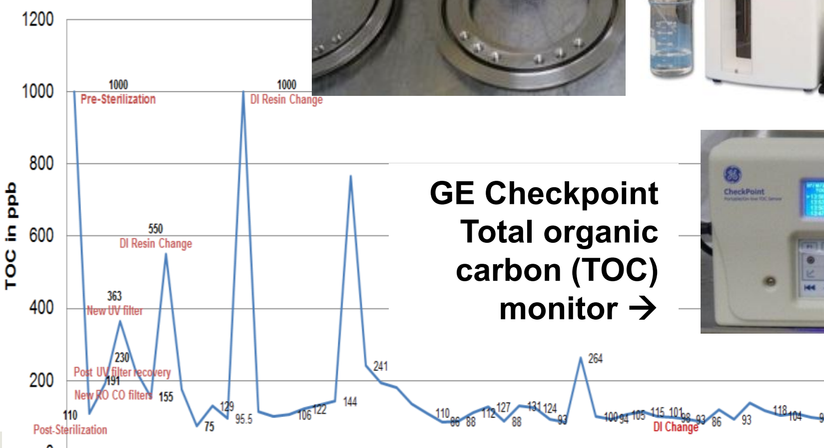


QIII Surface Particle Counter →

←SLS-1200 Liquid particle counter

Good correlation between particle and FE onset





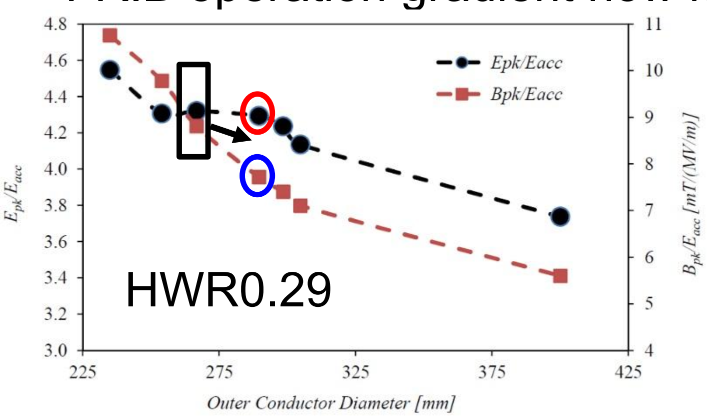
GE Checkpoint Total organic carbon (TOC) monitor →

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

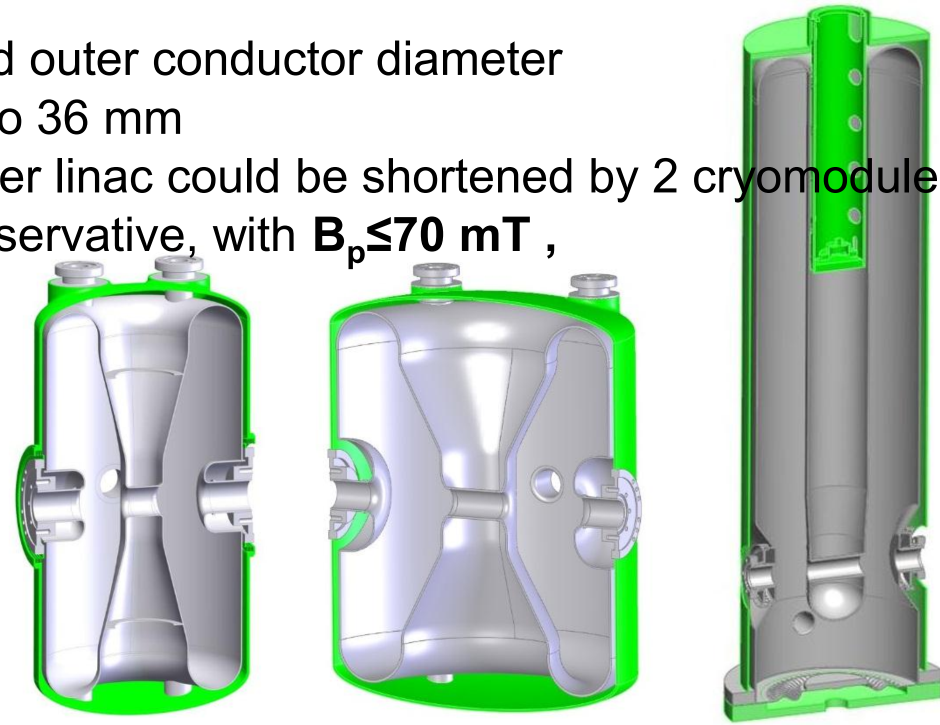
FRIB Final Cavity Design

Improved cavity design with lower Hp/Eacc and Ep/Eacc

- The SRF Review Committee in 2011 recommended not to exceed **E_p=35 MV/m** and **B_p=70 mT** in operation based on experimental data of 40 QWRs in operation at TRIUMF
- FRIB has adopted this specification to guarantee reliable operation of its linac with a good safety margin
  - **lower E_p & B_p, higher R_{sh}** by increased outer conductor diameter
  - Increased aperture of QWRs from 30 to 36 mm
  - Increased operation **E_{acc}**: the FRIB driver linac could be shortened by 2 cryomodules
  - FRIB operation gradient now more conservative, with **B_p≤70 mT ,**



cavity	E_p/E_{acc}	B_p/E_{acc}	R_{sh}	E_{acc}
QWR085	-9%	-11%	+38%	+10%
HWR29	-3%	-28%	+47%	+10%
HWR53	-17%	-19%	+13%	(+6)%



β=0.29 β=0.53 β=0.085

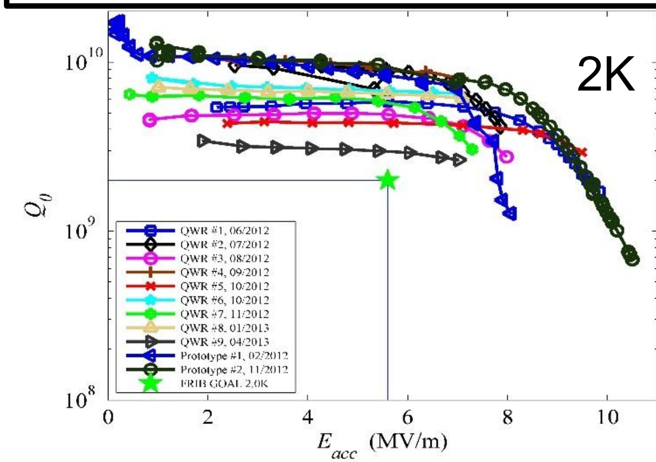
Validation of the FRIB Final Cavity Design

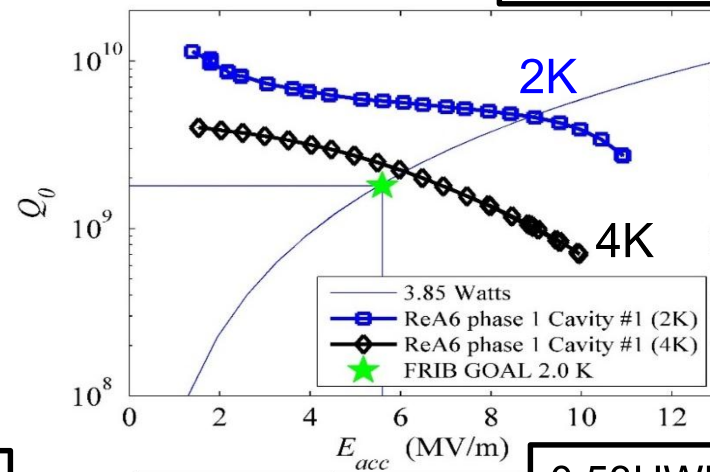
Comparison with first prototyped cavity and final design cavity

ReA3 refurbished 0.085QWR@2K

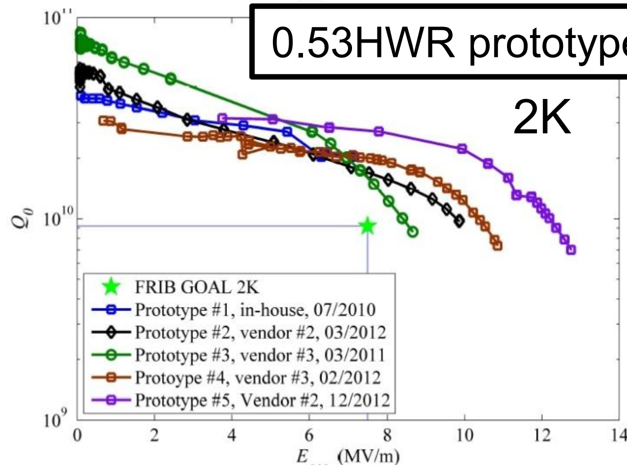
MOPP044, J. Popielarski

FRIB 0.085QWR@2K

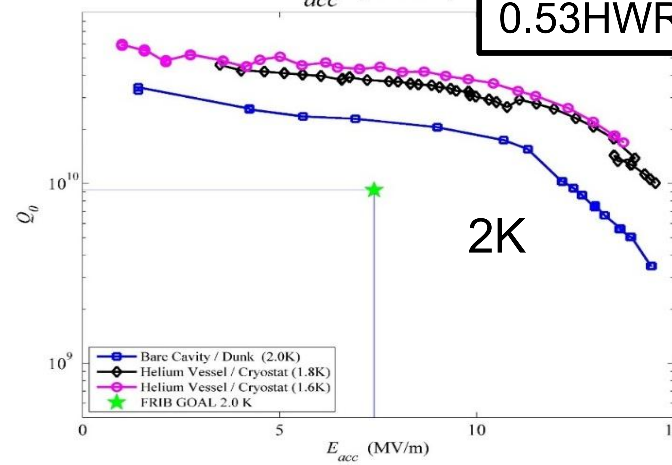




0.53HWR prototype@2K



0.53HWR FRIB@2K



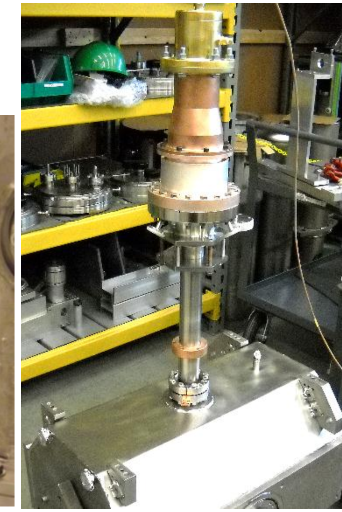
- Mitigated high Q-slope by improved design with lower Bp/Eacc
- Improved enhanced performance margin as expected
- All four cavity types have been successfully validated with helium vessel

FPCs for FRIB Cryomodule
ANL type for QWR and KEK/SNS type for HWR

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

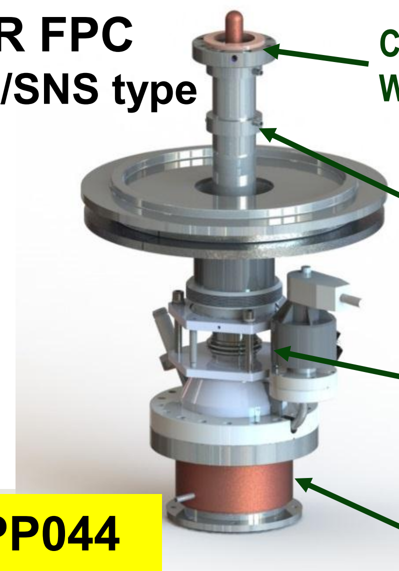
QWR FPC ANL type

HWR FPC KEK type



QWR FPC ANL type

HWR FPC KEK/SNS type

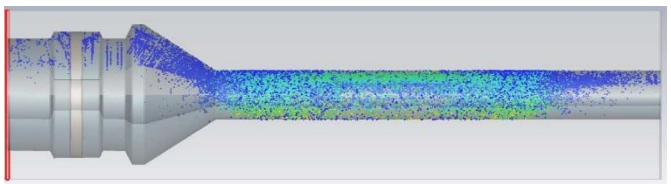


MOPP042, TUPP044
J. Popielarski

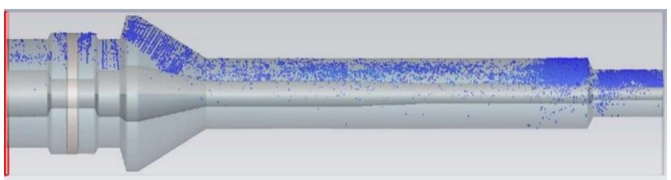
Alternative FPC: MP Free Coupler

- **The principle of the FPC design**
  - Simple structure: choke free at window
  - Multipacting free: increase impedance, pushed up the MP over the usable range
  - Electron screening for ceramic surface

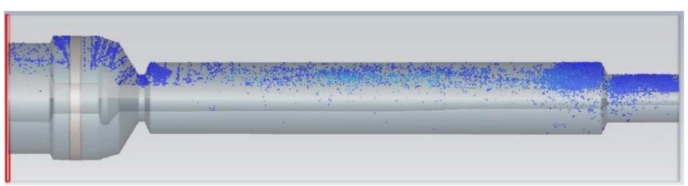
6.75” Baseline (50-84-50-50 Ohm)

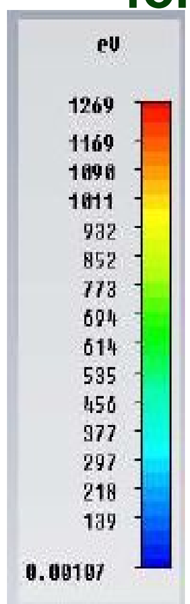


8” MP Free (50-84-50-61-75 Ohm)

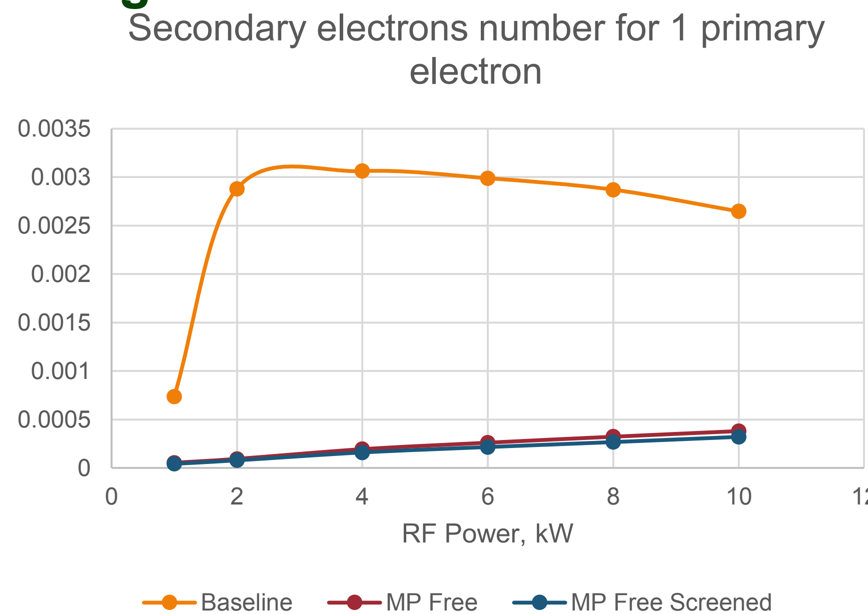


6.75” MP Free (50-84-61-75 Ohm).
Complete screening





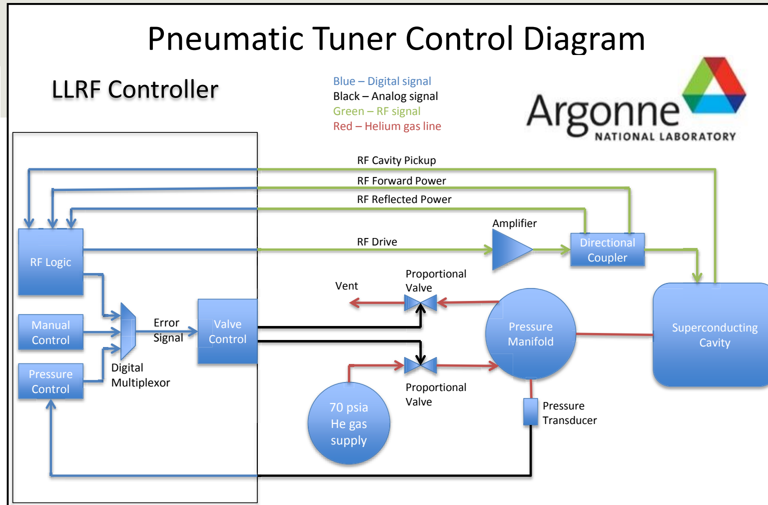
- **Electron emission images at 4 kW**
- **The particle sources density kept similar for three geometries**



Pneumatic Tuner for HWRs(0.29, 0.53)

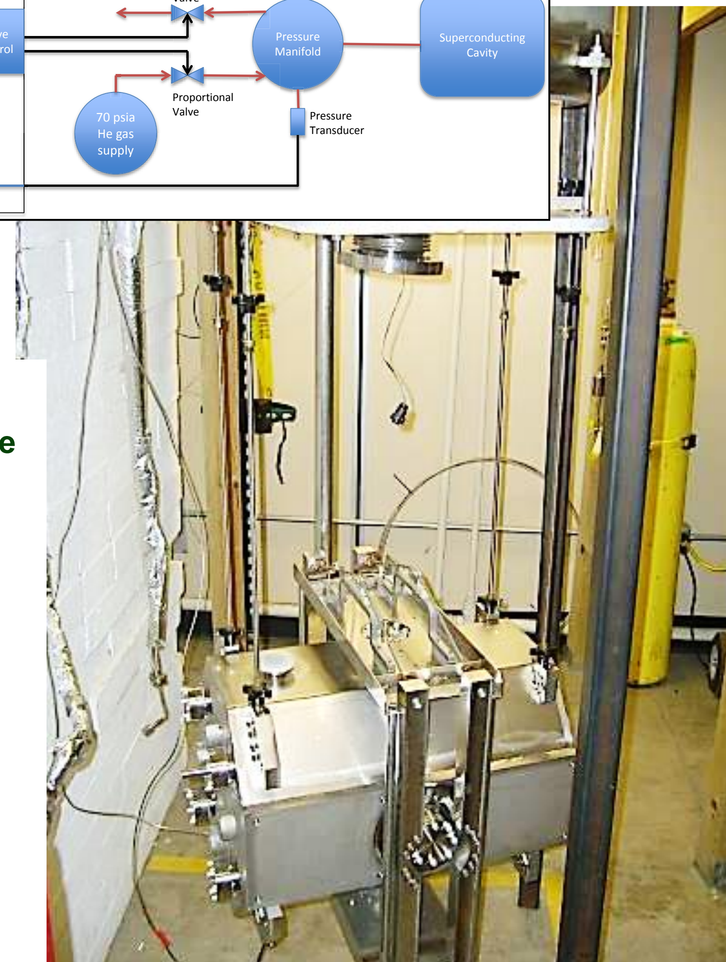
FRIB Tuner Specification

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)
    - » $\Delta f/\Delta P$ = 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).**
- **Final integrated validation test in vertical Dewar is under preparation**

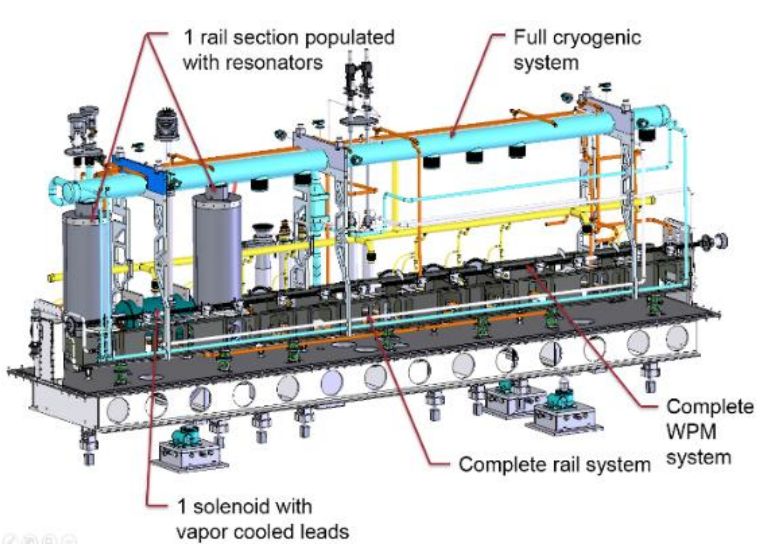


J. Popielarski, MOPP042

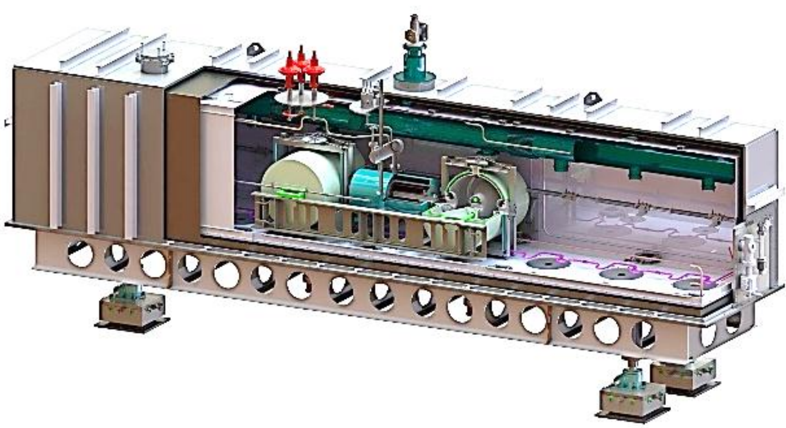
Integrated Certification Test Plan

- All components are ready for FRIB production, full integration test (cavity, FPC, tuner) is planned in VT for component long term operation. **THPP047, J. Popielarski**
- ReA6 CM is the first FRIB CM for QWR, of which phase-1 test is to be completed in mid-December 2014.
- The cavity-solenoid interaction will be confirmed in ReA6-1.
- ReA6/FRIB CM full Integrated test is to be done in December 2014.
- 0.53 HWR CM-1 (two cavity and one solenoid) will be tested 2016

VT integrated Test



ReA6-1

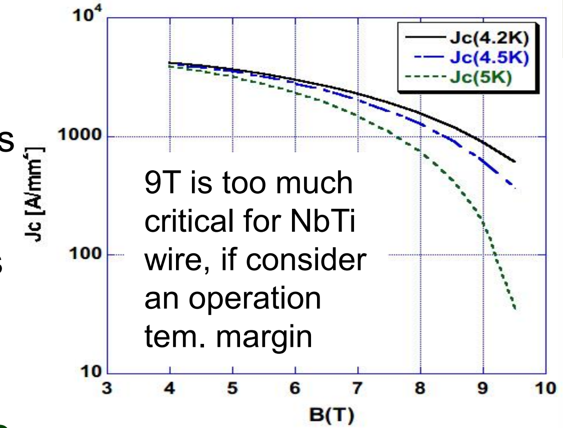


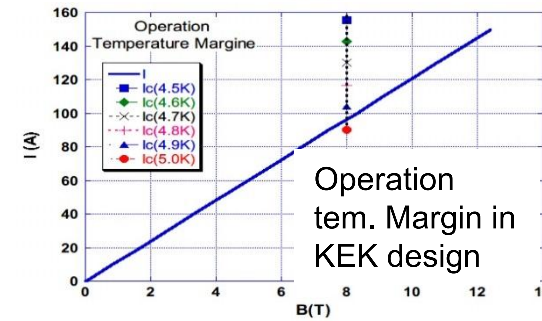
0.53HWR CM-1

8T SC Solenoid Prototyping by MSU/KEK Collaboration

Dry winding technique has been confirmed high performance and no training

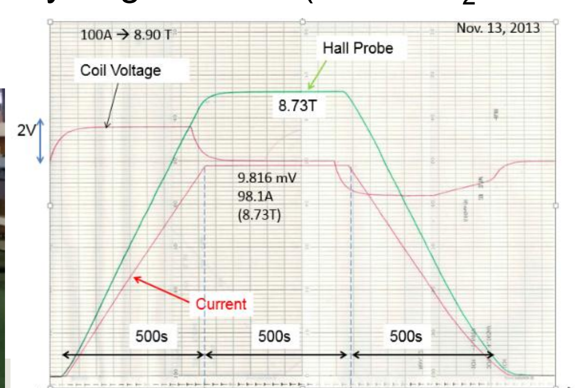
- **Changed FRIB solenoid specification from 9T to 8T**
  - Solenoid is not allowed to quench during machine operation from cavity protection point of view, solenoid has to be in stable operation
  - Reduced solenoid field from 9T to 8T by changing constant β(z)-function optics to constant beam sized one
  - Original FRIB commercial solenoid design has only 0.1K operation margin
  - ASAC 2014-12 recommended for the solenoid to have an operation margin as much as 0.5K
- **Designed 8T solenoid package with 0.5K operation temperature margin under KEK/MSU collaboration**
- **Prototyped 25cm 8T solenoid package: solenoid + steering dipole coils at KEK**
  - Pursued cost-effective fabrication method: dry winding technique
- **Demonstrated the reliable performance for both main solenoid and steering dipole coils**
  - Solenoid has no quench up to 8.9T and no tanning
  - Steering coils have no quench up to 100A(nominal 50A), no training
  - No performance change post thermal cycling 12 times (RT to LN_2 temperature)
  - Established dry winding technique





Dry winding, no use epoxy

Completed solenoid



First excitation test

Completed steering coils

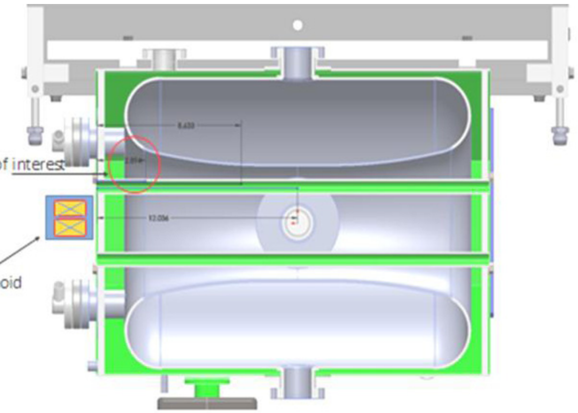
Solenoid package

Cavity/Fringe Field Interaction

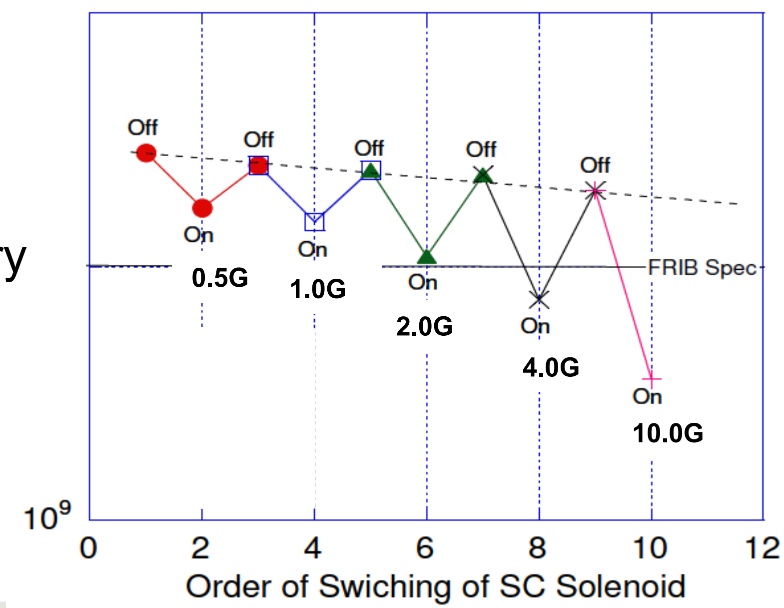
A fringe field of 4G causes a Q-drop under FRIB spec. with 0.53HWR when cavity happened quench

- **Meissner Shield**
  - Cavity performance no change up to 2500G fringe field, if no quench happens
- **Q_O- drop by the Quench**
  - Q_O drops under the FRIB specification (HWR) at > ~ 4G of fringe field
  - Flux trapping by quench is proportional to the increased fringe field strength
- **"Annealing effect" (discovered at FNAL, by T. Khabiboulline, et al.)**
  - Confirmed "annealing effect" against the Q_O-drop by a quench under
  - "Annealing effect" can be use the Q_O recovery

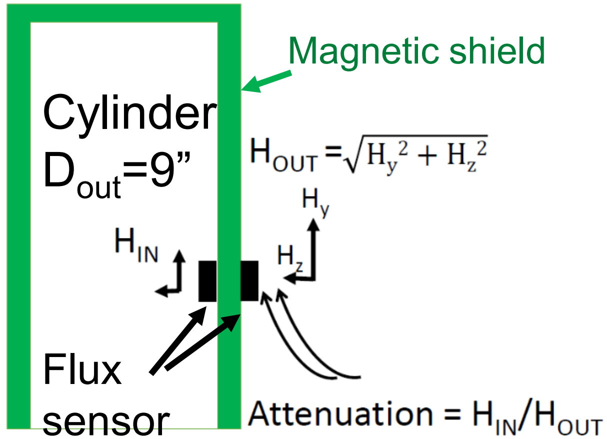
"**Annealing effect**": when a Q_O-drop happened by cavity quench, switch off the solenoid and repeat RF processing, then Q_O recovers (FNAL).

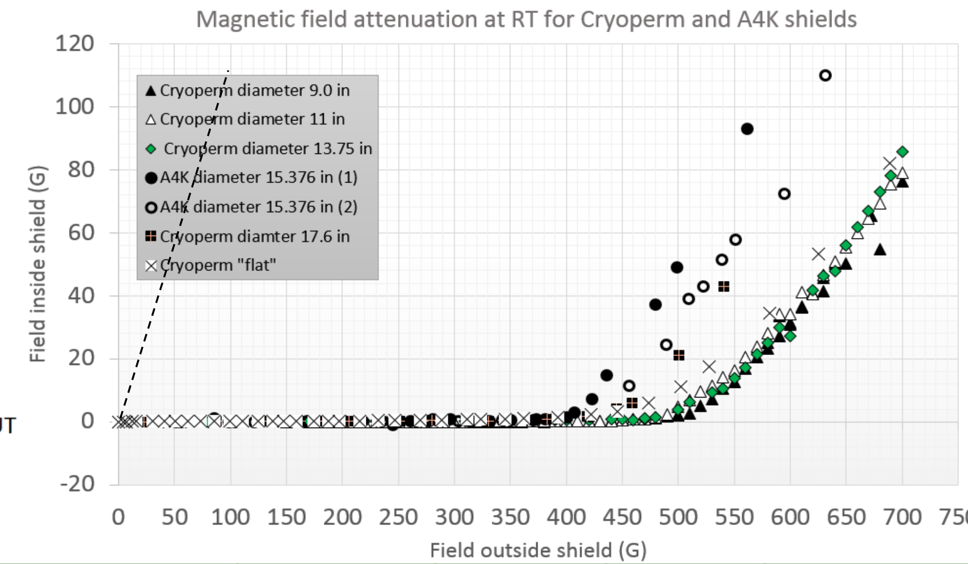


Q_O-drop and Annealing effect @ Eacc=7.5MV/m

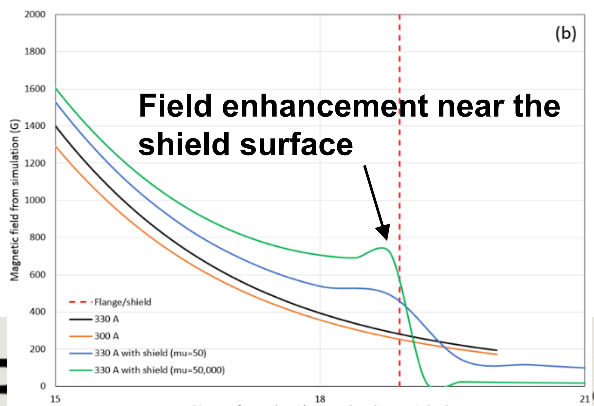


Saturation Field Measurement at FRIB





- The saturation field, which is defined at the external field produced 1G inside shield was measured.
- Saturation field is 365 at R.T. for A4K for instance
- Field enhancement on the shield surface by a factor 2

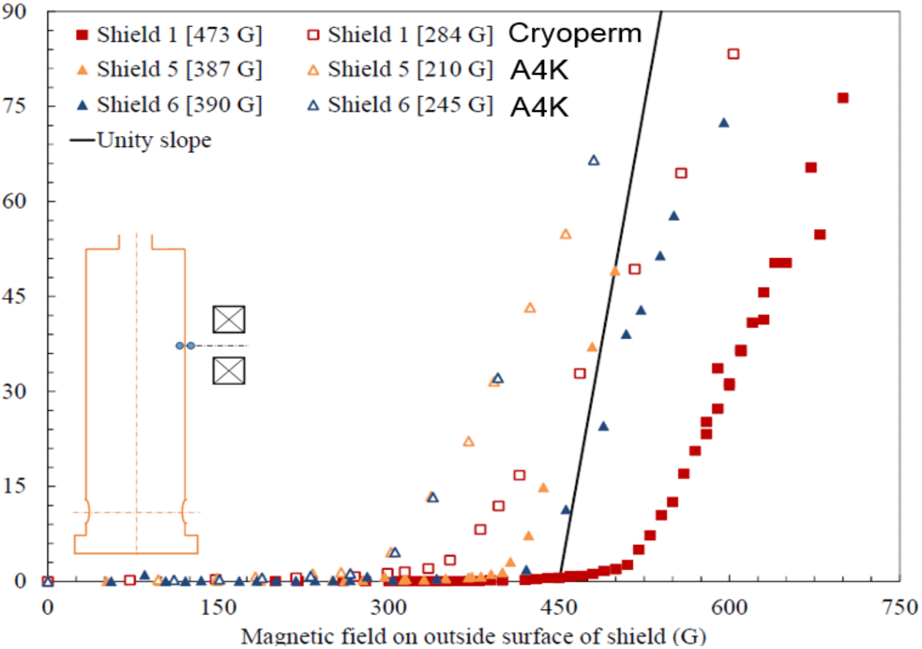


Material	Thickness (mm)	Diameter (cm)	Height (cm)	Saturation* (G)
Cryoperm	1.0	34.9	30.5	472
Cryoperm	1.0	21.6	99.1	470
Cryoperm	1.0	27.9	70.6	475
Cryoperm	1.0	44.7	38.9	450
Cryoperm	1.0	Flat		390
A4K (ReA6#1)	1.0	39.0	86.4	368
A4K (ReA6#2)	1.0	39.0	86.4	365

* Saturation field is defined at 1G increase

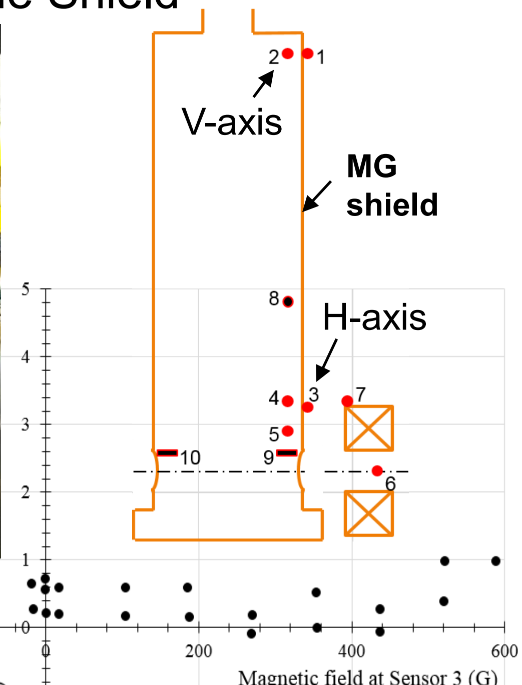
Cold Measurement of Magnetic Shield Property

Saturation Field Measurement at 10K



$Atten_{cryo} \approx 0.68 \cdot Atten_{RT}$

Field Strength Inside Shield

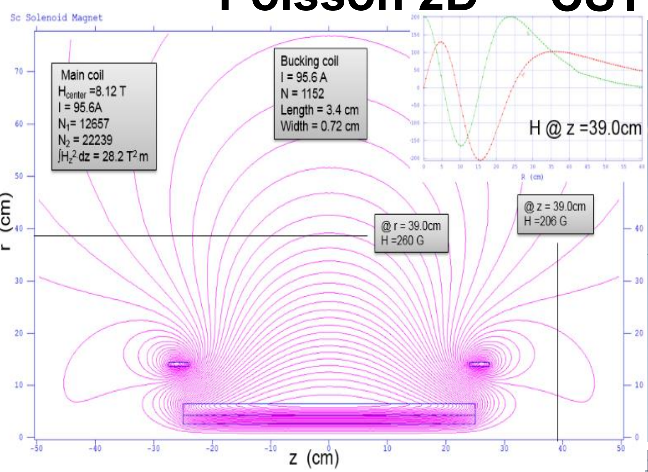


- Fringe field of 600G produces a remanent field of < 1G at high RF magnetic field area of QWR
- QWR will be no problem even for the Q-drop after cavity quench

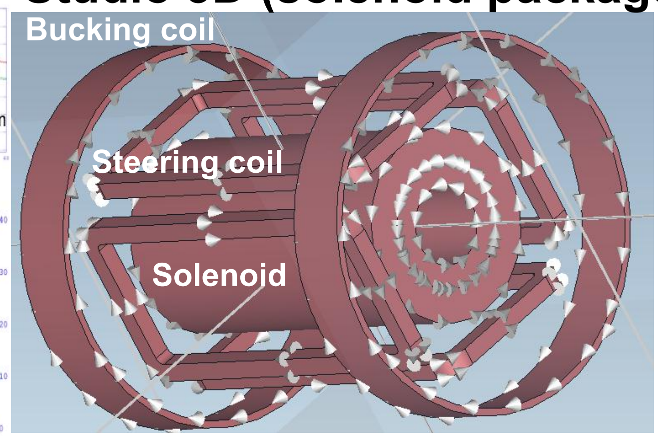
Fringe Field Simulation on the Cavity Wall

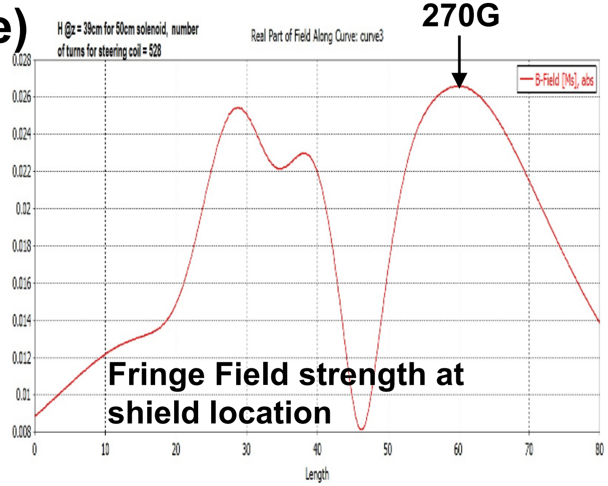
- Iron yoke free solenoid design has been completed with bucking coil
- 3D simulation by CST Studio shows the fringe field of 270G on the magnetic shield
- Fringe field of 100G exposes the high RF magnetic area
- Backup plan is being developing for Q-drop after quench, Meissner shield by niobium foil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

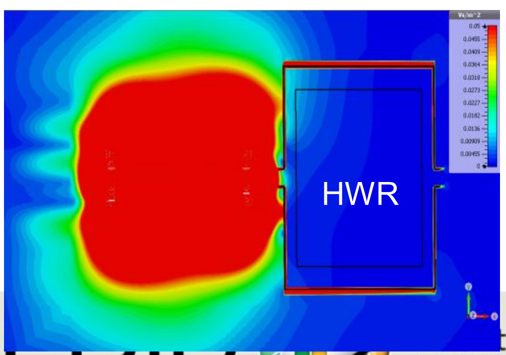
Poisson 2D

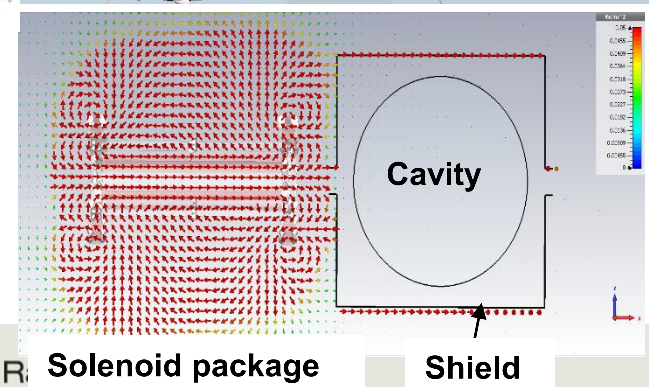


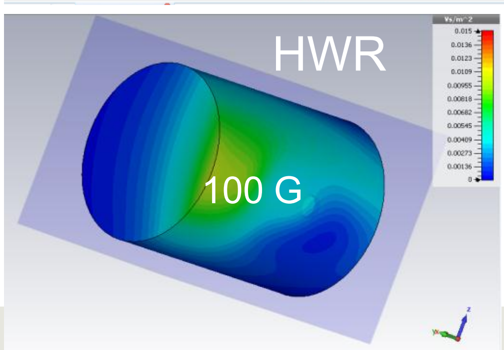
CST Studio 3D (solenoid package)











High RF magnetic field area

Summary

- FRIB SRF components have been all designed and prototyped and successfully validated.
- Integration test at vertical Dewar is under preparation for final validation
- Cavity/fringe field interaction is well understood and a backup plan is under developing against the Q-drop at quench for reliable FRIB operation
- Cryomodule prototyping is going very steadily
- SRF highbay has been constructed and the infrastructure are being installed. Accelerator system construction will start October 2014