Superconducting RF Development for FRIB at MSU

Kenji Saito on behalf MSU

MSU NSCL Professor
Superconducting RF Development Manager
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 $^{238}\text{U}$ with energies $>200\text{ MeV/u}$
- Provide beam power up to $400\text{ kW}$ Satisfy beam-on-target requirements
- Future energy upgradability $>400\text{ MeV/u}$ by filling vacant slots with 12 cryomodules

Features:

- Heavy iron beam intensity frontier machine, e.g. $5 \times 10^{13} \text{ } ^{238}\text{U}/s$, 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
Early completion 2020
CD4: Completion, to be 2022
Completed SRF Highbay, under installing infrastructure

Tunnel construction started in May 2014

Infrastructure installation in SRF highbay

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**FRIB SRF Scope**

**Challenge:** All SRF from low $\beta(0.041)$ to middle $\beta(0.53)$

<table>
<thead>
<tr>
<th>Cavity Type</th>
<th>QWR</th>
<th>QWR</th>
<th>HWR</th>
<th>HWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_0$</td>
<td>0.041</td>
<td>0.085</td>
<td>0.285</td>
<td>0.53</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td>80.5</td>
<td>80.5</td>
<td>322</td>
<td>322</td>
</tr>
<tr>
<td>$V_a$ [MV]</td>
<td>0.810</td>
<td>1.80</td>
<td>2.09</td>
<td>3.70</td>
</tr>
<tr>
<td>$E_{acc}$ [MV/m]</td>
<td>5.29</td>
<td>5.68</td>
<td>7.89</td>
<td>7.51</td>
</tr>
<tr>
<td>$E_p/E_{acc}$</td>
<td>5.82</td>
<td>5.89</td>
<td>4.22</td>
<td>3.53</td>
</tr>
<tr>
<td>$B_p/E_{acc}$ [mT/(MV/m)]</td>
<td>10.3</td>
<td>12.1</td>
<td>7.55</td>
<td>8.41</td>
</tr>
<tr>
<td>R/Q [Ω]</td>
<td>402</td>
<td>455</td>
<td>224</td>
<td>230</td>
</tr>
<tr>
<td>G [Ω]</td>
<td>15.3</td>
<td>22.3</td>
<td>77.9</td>
<td>107</td>
</tr>
<tr>
<td>Aperture [m]</td>
<td>0.036</td>
<td>0.036</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>$L_{eff} \equiv \beta \lambda$ [m]</td>
<td>0.153</td>
<td>0.317</td>
<td>0.265</td>
<td>0.493</td>
</tr>
<tr>
<td>Lorenz detuning [Hz/(MV/m)$^2$]</td>
<td>$&lt; 4$</td>
<td>$&lt; 4$</td>
<td>$&lt; 4$</td>
<td>$&lt; 4$</td>
</tr>
<tr>
<td>Specific $Q_0@VT$</td>
<td>$1.4E+9$</td>
<td>$2.0E+9$</td>
<td>$5.5e+9$</td>
<td>$9.2E+9$</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>$6.3E+6$</td>
<td>$1.9E+6$</td>
<td>$5.6E+6$</td>
<td>$9.7E+6$</td>
</tr>
</tbody>
</table>

$b_0 = 0.041$  $b_0 = 0.085$  $b_0 = 0.29$  $b_0 = 0.53$

$N = 12$  88  72  144

316 cavities need, total 347 including matching module, spares

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FRIB Cryomodules, Examples

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

- **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
- Additional FRIB type CM (ReA6, 0.085) will be installed and tested by December 2014

Existing
4.5K operation

Under construction

Under commissioning

Existing

4.5K operation

Under construction

FRIB
Lessons Learned from ReA3 Construction
Bottom flange issue

- **ReA3, 1st prototyped $\beta=0.085$ 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
Redesigned QWR Flange as FRIB Baseline (Indium seal): Validated already, used refurbished ReA3 QWRs

- Vacumm leak tight confirmed
- Good RF contact confirmed by paper pressure test

Alternative (metal gasket seal): Under developing
• TDCM: confirm FRIB 2K operation
  - CM construction leak tight at 2K
  - Demonstrate cavity, FPC and microphonics

• ETCM: validate bottom-up assembly
  - Validation of alignment tolerance in the bottom-up assembly

• Feedback to future FRIB mass production
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, $\Delta f_{pp}\leq0.5$ BW)
- Fast detuning distribution: Gaussian, $\sigma \sim 0.5$ Hz, $\Delta f_{pp} < 6$ Hz $\equiv \pm 6\sigma < 0.5BW$, 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

Cavity performance limited by FE
- Dewar test at 2K (baseline)
- TDCM 2K FE limited the performance
- TDCM 4K FE on set

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

FRIB specifications fulfilled in TDCM

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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
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
• Vendor 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
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 150\(\mu\)m
  - HPR, 1hr
  - Monitoring particles in the HPR waste water
  - Monitoring particle contamination on flanges during cavity assembly
  - Baking 120\(^\circ\)C for 48hr

- QA control by particle counter is very effective to reduce FE

![QIII Surface Particle Counter](image1)

![SLS-1200 Liquid particle counter](image2)

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

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Particle Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prep</td>
<td>180</td>
</tr>
<tr>
<td>USC</td>
<td>160</td>
</tr>
<tr>
<td>2nd USC</td>
<td>140</td>
</tr>
<tr>
<td>Stored (CR) 3 weeks</td>
<td>120</td>
</tr>
<tr>
<td>Stored 6 weeks</td>
<td>100</td>
</tr>
<tr>
<td>Low Pressure UPW Rinse</td>
<td>80</td>
</tr>
</tbody>
</table>

Good correlation between particle and FE onset

![Graph showing correlation](image3)

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FRIB Final Cavity Design
Improved cavity design with lower $E_p/E_{acc}$ and $E_p/E_{acc}$

- 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 $B_p \leq 70$ mT,

<table>
<thead>
<tr>
<th>cavity</th>
<th>$E_p/E_{acc}$</th>
<th>$B_p/E_{acc}$</th>
<th>$R_{sh}$</th>
<th>$E_{acc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QWR085</td>
<td>-9%</td>
<td>-11%</td>
<td>+38%</td>
<td>+10%</td>
</tr>
<tr>
<td>HWR29</td>
<td>-3%</td>
<td>-28%</td>
<td>+47%</td>
<td>+10%</td>
</tr>
<tr>
<td>HWR53</td>
<td>-17%</td>
<td>-19%</td>
<td>+13%</td>
<td>(+6)%</td>
</tr>
</tbody>
</table>

$\beta = 0.29$  \hspace{1cm} $\beta = 0.53$  \hspace{1cm} $\beta = 0.085$

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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

- 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

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

**QWR FPC ANL type**
- Adjustable Bellows With 4.5 K Thermal Intercept
- 55 K Cold Window
- 90 Degree Bend
- Warm Transition
- Warm Window At Cryomodule Feedthrough

**HWR FPC KEK/SNS type**
- Cavity Flange With 4.5 K Thermal Intercept
- Coaxial Line With 55 K Intercept
- Adjustable Bellows For Coupling Adjustment
- Single Warm Window

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MOPP042, TUPP044
J. Popielarski

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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

- **Electron emission images at 4 kW**

- **The particle sources density kept similar for three geometries**

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

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

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K. Saito, September 2014 LINAC14 THIOA02, Slide 19
FRIB Tuner Specification

<table>
<thead>
<tr>
<th>Tuner Type</th>
<th>HWR $\beta=0.53$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Tuning Range [kHz]</td>
<td>120</td>
</tr>
<tr>
<td>Tuning Resolution (2% of Bandwidth) [Hz]</td>
<td>0.6</td>
</tr>
<tr>
<td>Maximum Backlash (5% of Bandwidth) [Hz]</td>
<td>1.5</td>
</tr>
<tr>
<td>Cavity Tuning Sensitivity (calculated) [kHz/mm]</td>
<td>$\sim 236.2$</td>
</tr>
<tr>
<td>Maximum Displacement [mm]</td>
<td></td>
</tr>
<tr>
<td>Cavity $df/dp$ (Free Tuner) (calculated) [Hz/torr]</td>
<td>$\sim -3.43$</td>
</tr>
<tr>
<td>Cavity LFD (Free Tuner) (calculated) [Hz/(MV/m)$^2$]</td>
<td>$\sim -3$</td>
</tr>
</tbody>
</table>

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 $< 2^\circ$ peak to peak, amplitude $< 2\%$)
    - $+/− 0.35$ Hz/sec
    - Higher speeds (1 Hz/sec) were possible while detuning within the bandwidth
    - 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/kgcms$^2$ (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
- All components are ready for FRIB production, full integration test (cavity, FPC, tuner) is planned in VT for component long term operation.

- 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.
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 $\beta(z)$-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
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

- **Q₀-drop by the Quench**
  - Q₀ 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 Q₀-drop by a quench under
  - “Annealing effect” can be use the Q₀ recovery

- **“Annealing effect”**: when a Q₀-drop happened by cavity quench, switch off the solenoid and repeat RF processing, then Q₀ recovers (FNAL).
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

Field enhancement near the shield surface

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

* Saturation field is defined at 1G increase
Cold Measurement of Magnetic Shield Property

Saturation Field Measurement at 10K

Field Strength Inside Shield

Atten_{cryo} \approx 0.68 \cdot \text{Atten}_{RT}

- 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
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)**

![Diagram showing the solenoid package, steering coil, and bucking coil](image)

- Fringe Field strength at shield location: 270G
- High RF magnetic field area: 100 G
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