SUPERCONDUCTING RESONATORS DEVELOPMENT FOR THE FRIB AND ReA LINACS AT MSU: RECENT ACHIEVEMENTS AND FUTURE GOALS


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Facility for Rare Ion Beams

- Large linear RIB facility
- In flight RIB production
  - Fast RIBs
  - Re-accelerated RIBs
- $600M total cost
- Conceptual Design in 2010
- Project completion in 2018

Driver

Reaccelerator
A front end, 3 straight linac sections, 2 folding sections (180°), a charge stripper, and a beam delivery system.

44 acceleration cryomodules, 5 matching cryomodules

- Output beam energy above 200 MeV/u
- Accelerate heavy ion beams up to uranium
- Beam power on target 400 kW, with 90% beams within 1 mm diameter
- It is necessary to accelerate 2 to 5 charge states simultaneously to reach the power goal
- In campus nuclear facility, sustain low beam loss and residual activation
The largest superconducting low-\(\beta\) linac worldwide

The first one working at 2 K

Heavy ion beams of different \(A/q\) and multi-charge beam transport capability

High beam current (0.66 mA)
  - beam loading in the kW range, large beam aperture, high reliability in operation
  - High performance to fulfill realistic specifications

>400 cavities to be built: low cost of resonators is mandatory
FRIB Driver Linac: 330 SRF Resonators

- 4 resonators types
  - 2 QWRs, 2 HWRs
- 2 frequencies:
  - 80.5 and 322 MHz
- Large aperture:
  - 34 mm, 40 mm

<table>
<thead>
<tr>
<th>type</th>
<th>$\beta_0$</th>
<th>$F$ (MHz)</th>
<th>$V_a$ (MV)</th>
<th>$a$ (mm)</th>
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<tbody>
<tr>
<td>$\lambda/4$</td>
<td>0.041</td>
<td>80.5</td>
<td>0.81</td>
<td>34</td>
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<tr>
<td>$\lambda/4$</td>
<td>0.085</td>
<td>80.5</td>
<td>1.78</td>
<td>34</td>
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<tr>
<td>$\lambda/2$</td>
<td>0.29</td>
<td>322</td>
<td>2.09</td>
<td>40</td>
</tr>
<tr>
<td>$\lambda/2$</td>
<td>0.53</td>
<td>322</td>
<td>3.7</td>
<td>40</td>
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</table>
FRIB resonators design guidelines

- high performance at low cost
  - Simplified geometries
  - Minimum number of ebw
  - No bellows
  - Thin Nb sheets
  - Ti He vessel, TIG welded
  - BCP surface treatment, no EP

- realistic design specifications
  - $R_{\text{res}} \leq 11 \ \text{n}\Omega$
  - $Df/dP \leq 4 \ \text{Hz/mbar}$
  - $LFD \leq 4 \ \text{Hz/(MV/m)}^2$

- reliable operating conditions
  - $E_p \leq 35 \ \text{MV/m}$, $B_p \leq 70 \ \text{mT}$
  - Operation at 2 (2.1) K
  - Large extra $E_a$ available

<table>
<thead>
<tr>
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<th>0.085</th>
<th>0.29</th>
<th>0.53</th>
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<tbody>
<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>0.81</td>
<td>1.8</td>
<td>2.1</td>
<td>3.7</td>
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<tr>
<td>$E_p$ (MV/m)</td>
<td>31</td>
<td>33</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>$B_p$ (mT)</td>
<td>55</td>
<td>70</td>
<td>60</td>
<td>63</td>
</tr>
<tr>
<td>$R/Q$ (Ω)</td>
<td>402</td>
<td>452</td>
<td>224</td>
<td>230</td>
</tr>
<tr>
<td>$G$ (Ω)</td>
<td>15</td>
<td>22</td>
<td>78</td>
<td>107</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>34</td>
<td>34</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>$L_{\text{eff}} = \beta\lambda$ (mm)</td>
<td>160</td>
<td>320</td>
<td>270</td>
<td>503</td>
</tr>
</tbody>
</table>

A. Facco, IPAC2012, New Orleans, Slide 6
ReA3 Re-accelerator Linac

- First SRF linac at MSU, in operation since 1 year
- Excellent test bench for FRIB QWRs
- Similar QWRs as in FRIB
- Operation $T=4.5K$

β₀ = 0.041  QWRs phase and voltage stability in operation

A. Facco, IPAC2012, New Orleans, Slide 7
$\beta_0 = 0.41$ QWR – 1 Year of Operation in ReA3

- **In FRIB**
  - Operation foreseen at 2 (2.1) K, with $E_p = 30$ MV/m, $B_p = 53$ mT

- **Naked test at 2 K**
  - $E_p = 80$ MV/m, $B_p = 140$ mT

- **In ReA3**
  - Operation at 4.5K, $E_p = 16$ MV/m, $B_p = 35$ mT successfully achieved
  - 7 cavities operating on line
  - Reliable and reproducible phase and amplitude lock
  - **FRIB fields reached**, but plate overheating

- **Bottom ring modified for improved plate cooling**
\( \beta_0 = 0.085 \) QWR – early problems, now solved

- ReA3, 1\(^{st}\) generation \( \beta_0 = 0.085 \) cavities:
  - Bad RF joint due to a subtle differential contraction problem
  - insufficiently cooled tuning plate due to NbTi bottom ring
  - Design successfully modified in several steps
    - Distance tuning plate-inner conductor increased
    - Rf and vacuum contacts unified
    - Rf coupler moved from the tuning plate to the side
    - New slotted tuning plate for increased range
The 2 prototypes of ReA3 cavity largely exceeded the FRIB goals both at 4.2K and 2K:

- Resonators exceeded $E_p=50$ MV/m and $B_p=120$ mT
- Q disease completely eliminated by 600° C baking
- Flat Q at 2K up to $E_p>40$ MV/m and $B_p>90$ mT

9 existing QWRs are being refurbished for ReA3.

J. Popielarski
WEPPC067

$\beta \lambda = 32$ cm

Leff $\equiv \beta \lambda = 32$ cm
Low temperature baking at 120° C under development at FRIB

Applied to a QWR cavity
- at 4.2 K significant improvement in Q
- At 2 K modest improvement

The treatment will be applied to ReA QWRs working at 4.5 K

Extension to all FRIB cavities is under evaluation but not in the baseline processing plan

Treatment of FRIB cavities showing Q slightly below specifications at vertical test is being considered fast procedure for cavity recovery
80.5 MHz, $\beta=0.085$ ReA3 Cryomodule

- Refurbishment of 10 existing ReA3 cavities
- ReA3 cryomodule under construction
  - In operation in 2012
- New cryomodule with upgraded QWRs in 2013
  - FRIB cryomodule prototype in ReA3
FRIB QWRs solutions

- **Mechanical damper**
  - damping of the inner conductor oscillations

- **High RRR Nb ring: low cost design**
  - New bottom ring made of Ti (or NbTi), with a small, high RRR Nb ring in contact with the tuning plate, directly cooled by liquid He

- **Final cavity tuning**
  - ±50 kHz spread in final f after construction
  - Differential etching if needed (±100 kHz)
  - Adjustable tuning puck welded after bulk etch and heat treatment (±30 kHz)
322 MHz HWRs Prototypes

- $\beta_0=0.53$ prototypes from 2 different vendors reached FRIB specifications
  - $V_{\text{acc}}=3.7$ MV, $E_p=31$ MV/m, $B_p=77$ mT
- Results confirmed at Jlab
- Possibility for improvements detected in 1st generation HWR prototypes:
  - $B_p/E_a$ reduction
  - Elimination of Ti bellows in He vessel
  - Simplification of cavity welding procedure

2° sound test: cavities limited by $B_p$
Prototype $\beta=0.53$ HWR Results Confirmed at JLab

- Test repeated at JLab
  - Verified calibration
  - Verified cavity performance
  - Verified cavity treatment

- FRIB specifications exceeded with a comfortable margin

- $R_{\text{res}}<5$ nohm up to 90 mT

- 120° C baking ineffective at 2K

- JLab is developing procedures for performing FRIB cavity treatment, assembly, and qualification

We have redesigned production cavities with lower $B_p/E_a$, shifting the $B_p$ from 77 mT to 63 mT and achieving larger technical margin.
Aim
- Develop HWR cryostat assembly procedures
- Test prototype $\beta=0.53$ cavities with final couplers and in the presence of a SC solenoid
- Cryogenic test of the module prototype

Components
- 2 $\beta=0.53$ HWRs already tested off line in VTA
- 1 superconducting solenoid

2K test ongoing

Phase and amplitude stability of HWR locked at low field at 2K
FRIB Couplers and Tuners

- $\beta=0.041$ QWR
  - Coupler: in operation; tested on line up to 1 kW, air cooling being implemented for 2 kW operation
  - Tuner: in operation

- $\beta=0.085$ QWR
  - Coupler: under development by ANL (new side coupler)
  - Tuner: in operation, same as for $\beta=0.041$ QWR

- $\beta=0.053$ and $\beta=0.029$ HWR
  - Coupler: 2 prototypes under testing at 2K, R&D ongoing
  - Tuner: prototypes under testing at 2K, R&D ongoing
Scope: operation with higher gradient and larger safety margin

Guidelines:
- New cavities **fitting the present cryostats** (flange to flange distance)
- Mechanical design resembling the previous ones, sharing the same tuners and couplers as much as possible
- Peak magnetic fields reduced to increase safety margin on gradient: \( B_p \leq 70 \text{ mT} \) and \( E_p \leq 35 \text{ MV/m} \) for all cavities (old \( B_p : 77 \text{ mT} \))
- Increased shunt impedance to allow operation at higher gradient without exceeding the specified cryogenic load

All these conditions could be fulfilled by increasing the cavities diameter and modifying the mechanical design, but keeping the original design concept.
Production Cavities: Increased Performance

- Increased performance: lower $E_p$ & $B_p$, higher $R_{sh}$
- Increased aperture of QWRs from 30 to 34 mm
- Increased operation $E_a$: the FRIB driver linac could be shortened by 2 cryomodules
- FRIB operation gradient now more conservative, with $B_p \leq 70$ mT, $E_p \leq 35$ MV/m

<table>
<thead>
<tr>
<th>cavity</th>
<th>$E_p/E_a$ %</th>
<th>$B_p/E_a$ %</th>
<th>$R_{sh}$ %</th>
<th>$E_a$ %</th>
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</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>

Production cavities increase in performance and baseline $E_a$
FRIB and ReA Cavity Surface Treatment

- Effective surface treatment developed

- Steps
  1. Degrease cavity: Ultra-sonic clean with agent (Micro 90), rinse with DI water
  2. Buffered chemical polish & rinse: 150 microns removal (bulk BCP), UPW rinse
  3. (if needed: differential etching in QWRs for frequency tuning)
  4. Hydrogen degas: 600° C for 10 hours vacuum furnace
  5. Degrease cavity & components: Ultra sonic clean Micro 90
  6. Light BCP & high pressure rinse (HPR): 30 micron removal, UPW rinse
  7. (If needed: 120° C baking for 48 hours)
  8. Assemble to test insert

- Special procedures
  1. Optimized acid circulation for homogeneous Nb removal
  2. Temperature stabilized BCP, cavity water cooled during processing
  3. Liquid particle count during HPR for cleanliness control
  4. Surface particle count after HPR and drying

- Cavities resulting nearly field emission free, high Q, high $E_p$ and $B_p$
Cavity Surface Treatment

BCP setup

Optimized BCP flow

HV furnace for 600° C baking

Liquid (left) and surface particle count for HPR water and resonator cleanliness monitoring

HWR 120° C bakeout setup
**Experimental $R_{\text{res}}$ in prototypes vertical test**

- $R_{\text{res}} < 5 \, \text{n} \Omega$ measured in prototypes for $B_p \leq 70 \, \text{mT}$
  - Cavity surface treatment now mature and mastered

- Specified residual resistance in operation at 2 K: $R_{\text{res}} \leq 11 \, \text{n} \Omega$
  - This value is consistent with our vertical test experimental data

<table>
<thead>
<tr>
<th>Cavity $\beta_0$</th>
<th>0.041</th>
<th>0.085</th>
<th>0.29</th>
<th>0.53</th>
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<tbody>
<tr>
<td>operation $B_p$ (mT)</td>
<td>55</td>
<td>70</td>
<td>60</td>
<td>63</td>
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Residual surface resistance $R_{\text{res}}$ vs. $B_p$ measured in the FRIB prototypes at 2K
Cold Mass Assembly Cycle

Window end assembly & vacuum components - vendors

Fundamental power Couplers – received ready to install

Solenoid (vendor) – cleaned at MSU

Cavity – Certified From vertical test

Ti rails & clean room cart - vendors

Window end assembly & vacuum components - vendors

A. Facco, IPAC2012, New Orleans, Slide 23
Total 49 plus 4 spares

\[ \beta = 0.041 \quad \text{QTY 3} \]

\[ \beta = 0.29 \quad \text{QTY 12 + 2 matching} \]

\[ \beta = 0.085 \quad \text{QTY 11 + 2 matching} \]

\[ \beta = 0.53 \quad \text{QTY 18 + 1 matching} \]

(under design optimization)
Cavity Processing and Testing Infrastructure

- Upgraded capability in the production phase from 2013
  - 5 cavities per week processed and tested
  - 2 cryomodule per month delivered and tested (1.5 average during production)
Cryomodule prototyping

FRIB Scope:

Name: TDCM
β = 0.53 cryomodule
Objective: 2 K operation
cavity/magnet interaction
cavity control

Engineering Prototype
1/3 of full-size cryomodule
structural and thermal behaviour
assembly fit and function

Pre-Production
β = 0.53 cryomodule
assembly line development
assembly fit and function
possibly used in FRIB linac

Pre-Production
β = 0.29 cryomodule
assembly line development
possibly used in FRIB linac

ReA Scope:

Name: ReA-3
β = 0.085 cryomodule
Objective: user operation

ReA-6 Prototype
ReA6 cryomodule parts, no cavities
assembly fit and function

ReA-6 Cryomodule
β = 0.085 cryomodule
user operation
also serves as
FRIB pre-production cryomodule

Demonstrate Cryomodule Performance

Develop Assembly Line
New, bottom-up design
- 2K for resonators, 4.2K for SC Solenoids
- Same design scheme for all resonators

322 MHz, $\beta = 0.53$ Cryomodule

FRIB Cryomodules
### Quarter Wave Resonators

<table>
<thead>
<tr>
<th>Type</th>
<th>Development Run (with helium vessel)</th>
<th>Pre-Production Run (with helium vessel)</th>
<th>FRIB LINAC</th>
<th>10% excess</th>
<th>spare</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta = 0.041$</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>1</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>$\beta = 0.085$</td>
<td>2</td>
<td>10</td>
<td>94</td>
<td>9</td>
<td>11</td>
<td>126</td>
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### Half Wave Resonators

<table>
<thead>
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<th>Type</th>
<th>Development Run (no helium vessel)</th>
<th>Pre-Production Run (with helium vessel)</th>
<th>FRIB LINAC</th>
<th>10% excess</th>
<th>spare</th>
<th>TOTAL</th>
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</thead>
<tbody>
<tr>
<td>$\beta = 0.29$</td>
<td>2</td>
<td>10</td>
<td>76</td>
<td>7</td>
<td>2</td>
<td>97</td>
</tr>
<tr>
<td>$\beta = 0.53$</td>
<td>2</td>
<td>10</td>
<td>148</td>
<td>14</td>
<td>0</td>
<td>174</td>
</tr>
</tbody>
</table>

**TOTAL**

|            | 330 |        | 414 |

A. Facco, IPAC2012, New Orleans, Slide 28
Conclusions

- More than 400 SRF resonators of 4 types will be fabricated for FRIB.
- Prototypes have been built and tested, reaching the required $E_a$ and $Q$.
- FRIB-type low-β QWRs are in operation in the ReA3 linac since 1 year.
- Construction techniques and surface treatment are now mature, leading to high $Q$, high $E_a$ resonators nearly field emission free in test cryostats.
- The cryomodule development is ongoing:
  - The Technology Demonstration Cryomodule (TDCM) is under testing at 2K.
  - The ReA 3 high-β QWR cryomodule is under assembly.
- The resonators design has been recently reviewed and assessed for the production cavities:
  - Performance increased with lower $E_p/E_a$, $B_p/E_a$ and higher $R_{sh}$ and $E_a$.
  - The total number of FRIB cryomodules has been reduced by two.
- The cavity production phase has started with the construction of 2 cavities per type (“development run”) by 2012.
We thank C. Crawford, M. Kelly, P. Kneisel, R. Laxdal and R. Webber for their precious advice