FRIB Project: Moving to Production Phase

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On behalf of FRIB, MSU
FRIB Project

Challenges in the FRIB SRF

Status of the SRF hardware production, not included cryomodule production

Plans for ramping to full production

For future large proton/ion SRF Linac projects

Summary

Acknowledgments

I would like to thank to many FRIB people and other collaborators for repairing this talk:


* FNAL, **INFN-LNL Italy, *** KEK Japan, ****TRIUMF Canada.
FRIB Project Overview

- Goal of the FRIB: Create cutting-edge nuclear physics by the various isotope produced by an 200 MeV/u ion driver linac.
- Build a 200 MeV/u@ 400 kW SRF high intensity heavy ion linac in MSU campus.
- DOE/MSU jointed project under Cooperative Agreement, project cost shared by both, total cost $730M.
- CF construction started in March 2014
- Accelerator system construction started October 2014
- Completion of Infrastructure in SRF highbay in November 2015
- Early beam commissioning to be 2017 – 2020 starting with the Front End
- Final completion in 2022
FRIB SRF Linac Goal and Features

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

- Features:
  - Heavy ion beam intensity frontier machine, e.g. $5 \times 10^{13}$ $^{238}$U/s, 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 Linac

All SRF cavities from beta 0.041 to 0.53, four type cryomodules, one cavity - one RF source (semiconductor amp.), high gradient CW operation at 2K

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

Quarter-Wave Resonators 80.5 MHz
N= 12
88
72
144

Half-Wave Resonators 322 MHz

K. Saito, September 14 SRF2015, Slide 5
FRIB Cryomodule Designs and Features

Example for 0.085QWR and 0.53HWR, 0.041/0.085 both QWRs and 0.29/0.53 both HWRs are similar

- **FRIB Cryomodule Features**
  - **Local magnetic shield**: cost reduction for magnetic shielding and reliable shielding
  - **Bottom-up supported design**: optimized for mass-production and efficient precision-assembly
  - **2K operation**: enhanced cavity performance and less micro-phonics by stable pressure control

Design of CM0.041 and CM0.29 are in WFO Jlab
### Main Hardware of FRIB SRF and Scope

<table>
<thead>
<tr>
<th>Cavity Type</th>
<th>Frequency &amp; Cavity type</th>
<th>Quantity of Cavities</th>
<th>Quantity of Modules</th>
<th>Quantity of Solenoids</th>
</tr>
</thead>
<tbody>
<tr>
<td>β=0.041</td>
<td>80.5 MHz, QWR</td>
<td>12 + 4 spare</td>
<td>3 + 1 spare</td>
<td>6 + 2 spare</td>
</tr>
<tr>
<td>β=0.085</td>
<td>80.5 MHz, QWR</td>
<td>88 + 8 spare</td>
<td>11 + 1 (Marching CM)</td>
<td>33 + 3 spare</td>
</tr>
<tr>
<td>β=0.29</td>
<td>322MHz, HWR</td>
<td>72</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>β=0.53</td>
<td>322MHz, HWR</td>
<td>144</td>
<td>18 +1 (Matching CM)</td>
<td>18</td>
</tr>
</tbody>
</table>

**Marching Cryomodules**
- 12 + 4 spare
- 3 + 1 spare

**Total**
- 332 + 16 spare
- 48 + 3 spare
- 69 + 5 spare

(1) Cavities
(2) QWR/HWR power couplers
(3) QWR/HWR Tuners
(4) QWR/HWR Magnetic shields
(5) SC 25/50cm solenoid packages
First Large Scale SRF LINAC $\beta = 0.041$ to $0.53$
- Four different types of cryomodule:
  - 0.041QWR, 0.085QWR, 0.29HWR, and 0.53HWR
- How to manage so many different components.
- Other labs help FRIB: Jlab for 0.041/0.29 MC design, ANL for coupler and tuner designs

Solenoid in the cryomodule
- FRIB is challenging to build compact SRF Linac with high beam quality
- Detail investigation cavity/solenoid fringe field interaction
- Designed solenoid package well optimized fringe field

Tighter Alignment Tolerance
- Smaller cavity bore diameter: 36 mm (0.041QWR), 40 mm (other type of cavity)
- Longitudinally tolerance 1 mm and transversely 0.5 mm
- Innovated bottom-up supported design cryomodule

Narrow Band width 30 – 40 Hz, Cavity Frequency Control in the Production
- Stack up tuning, innovated virtual EBW welding
- Developed deferential etching (QWR)
- Puck height control

High Gradient Cavity Operation at 2K
- $E_{acc} = 5 – 8$ MV/m, $E_p = 27$ - $34$ MV/m, $B_p = 55$ - 69 mT, Cavity design with lower $B_p/E_{acc}$ ratio
- Developed high QA control procedure
### FRIB Requirements for SRF Hardware and Validation Status

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Hardware Detail</th>
<th>Requirement</th>
<th>Validation</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity</td>
<td>0.041QWR (80.5MHz)</td>
<td>$E_{acc} = 5.29,\text{MV/m} @ Q_0 = 1.4 \times 10^9$</td>
<td>Done</td>
<td>2 K operation</td>
</tr>
<tr>
<td></td>
<td>0.085QWR (80.5 MHz)</td>
<td>$E_{acc} = 5.68,\text{MV/m} @ Q_0 = 2.0 \times 10^9$</td>
<td>Done</td>
<td>2 K operation</td>
</tr>
<tr>
<td></td>
<td>0.29HWR (322 MHz)</td>
<td>$E_{acc} = 7.89,\text{MV/m} @ Q_0 = 5.5 \times 10^9$</td>
<td>Done</td>
<td>2 K operation</td>
</tr>
<tr>
<td></td>
<td>0.53HWR (322 MHz)</td>
<td>$E_{acc} = 7.51,\text{MV/m} @ Q_0 = 9.2 \times 10^9$</td>
<td>Done</td>
<td>2 K operation</td>
</tr>
<tr>
<td>Coupler</td>
<td>QWR (80.5 MHz)</td>
<td>4 kW @CW</td>
<td>Done (Dewar integration test)</td>
<td>Working in ReA</td>
</tr>
<tr>
<td></td>
<td>HWR (322 MHz)</td>
<td>8 kW @CW</td>
<td>Done (Bench mark test)</td>
<td>KEK/SNS type</td>
</tr>
</tbody>
</table>
| Tuner    | QWR | Tuning range 30 kHz  
          |          | Tuning resolution 0.8 Hz | Done (ReA, ReA3 CM, ReA6-1) | Tuner plate + puck at bottom flange |
|          | HWR, ANL type Pneumatic tuner | Tuning range 120 kHz  
          |          | Tuning sensitivity 1.5 Hz | Done (Dewar integration test) | Continued design update |
|          |          |                                   | | ANL type pneumatic tuner |
| Magnetic Shield | Local shielding | $\mu > 10000 @ 25\,\text{K}$  
          |          | Remnant field at high $H_{RF}$ area of the cavity < 15 mG | Done (ReA, ReA3, ReA6-1) | Local magnetic shield at 25K |
| Solenoid Package | Main Solenoid (25cm/50cm) with bucking coil | 8 T (NbTi) | Done (ReA, ReA3, ReA6-1) | 4.5 K Operation |
|          | Steering dipole | 0.03 Tm (25 cm), 0.06 Tm (50cm) | Done (ReA, ReA3, ReA6-1) | 4.5 K Operation |

- Cavity preparation: BCP, Hydrogen degassed at 600 °C for 10 hr, and no 120 °C baking so far
- Solenoid: 8 T main solenoid with bucking coil to cancel the fringe field, X-Y beam steering dipoles
FRIB Cavity Design Validation
Processed by BCP, enough margin against FRIB requirements

- Pushed away high Q-slope by improved RF cavity design with lower Bp/Eacc.
- Less field emission by FRIB develop high pressing QA control
Validation Test of 90° Bend QWR FCP  
Confirmed stable operation for long run

**Validation**

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

RF ON  
24hr continuous long term operation

**Temperature monitoring around the coupler**

- In vertical test stand
- Warm window
- Cold Window
- 90° bend
- 300 K transition

- SC250 w/ANL style FPC - Heat Load
- Heat load measurement of FPC
ReA6-1 CM Integration Validation

- Validated the alinement tolerance by Bottom up supported design
  - Confirmed alignment within 0.5 mm in transverse
  - Twice cool down/warm up and confirmed reproducibility

- Validated stable operation of the integration system: Cavities/FPCs/Tuners/Solenoid package
  - Demonstrated stable operation 24 hr
  - Confidence for band width control

- Validated local magnetic shield benefits (A4K)
  - Meets FRIB remnant field < 15 mT
  - Needless of degaussing process
  - Very small field around cavity short area under 8T solenoid package operation, expected no Q-drop at cavity quench

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**Process** | **Fluxgates (mG)** | **Hall probes (mG) at beam port facing solenoid**
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| Top of cavity | Bottom of cavity | (low sensitivity at small fields)
| In | Out | In | Out | 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 | -5500±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 | 543±835 | 5400±2800 | -1967±1707 | 7733±1999 | 9006±9999 |
| 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±48 | -22061±90 | -1836±62 | -5217±74 | 22744

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S. Chandrasekaran et al. TUPB102

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S. Miller FRAA 06

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

K. Saito, September 14 2015 SRF2015, Slide 12
## Production Strategy, Validation, and Production Status

- **Development phase**: Produce 2 articles with MSU, Technology transfer to vendor for build to print, and vendor certification
- **Preproduction phase**: Produce 10 articles by the vendor own, judge the mass-production capability of the vendor, develop issues in mass production and resolve them.
- **Production phase**: Mass-production

<table>
<thead>
<tr>
<th>Component</th>
<th>Status, V(Validation), VC (Vendor Certification)</th>
<th>Delivery and Needed Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb materials</td>
<td>NbTi flange (done), Nb sheets (done), Seamless pipes (done)</td>
<td>FRIB production Nb material has been done</td>
</tr>
<tr>
<td>0.041QWR Vendor A</td>
<td>Development (2) Done V, VC</td>
<td>Production (19) done</td>
</tr>
<tr>
<td>0.085QWR Vendor B/C</td>
<td>Preproduction (10) Done V, VC, Delivered 10, done all</td>
<td>All 0.041QWRs has been delivered</td>
</tr>
<tr>
<td>0.285HWR Vendor D</td>
<td>Preproduction (10) Done V, VC, Delivered 3</td>
<td>Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)</td>
</tr>
<tr>
<td>0.53HWR Vendor D</td>
<td>Preproduction (10) Done V, VC, Delivered 10</td>
<td>Needs by Aug. 2017</td>
</tr>
<tr>
<td>Fundamental Power Coupler</td>
<td>QWR FPC (2)</td>
<td>QWR FPC(104) Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)</td>
</tr>
<tr>
<td>HWR Vendor E</td>
<td>HWR FPC (2) to be delivered Oct. 2015</td>
<td>HWR (217) Need by Apr. 2016 (FRIB 1st CM )</td>
</tr>
<tr>
<td>Tuner</td>
<td>Development (8) Done V, ReA3</td>
<td>Production(112) Delivered (8), tuning plates</td>
</tr>
<tr>
<td>HWR Tuner</td>
<td>Development (2) Done by integration test but still finalizing design</td>
<td>Needs by Sep. 2015</td>
</tr>
<tr>
<td>Solenoid</td>
<td>Development (1) Done V</td>
<td>Production (6)</td>
</tr>
<tr>
<td>25cm Vendor G</td>
<td>Preproduction (4) in MSU, completed for preproduction CM Other in vendor G</td>
<td>Need by March 2017</td>
</tr>
<tr>
<td>50cm Vendor G/MSU</td>
<td></td>
<td>Production (62)</td>
</tr>
</tbody>
</table>

- Needs 3 by Sep. 2015 for FRIB first 0.085 CM
Delivery Examples of SRF Components
So far, ~50 cavities delivered

Niobium material for FRIB production cavities

Microphonic dampers

Pneumatic tuner on 0.53 HWR

50 cm solenoid package ready for cold test

0.041 QWRs

Frequency Tuning plates for QWRs

0.085 QWR FPCs

0.085 QWRs and 0.53 HWRs

Magnetic shield and solenoid package on the rail of ReA6-1 CM
Infrastructure for FRIB Production
SRF Highbay, constructed by MSU fund, ready for cavity test in Sept. 2015

- FRIB is finalizing infrastructure for the production in SRF Highbay fund by MSU
- Functionalities of the SRF Highbay
  - Acceptance inspection, working already
    - Dimensional inspection by CAM
    - Cold shock test, Leak check
  - Cavity processing and assembly, working already
    - Large cleanroom
    - Cavity etching (BCP) system
    - High pressure rinsing system
    - Ultrapure water system
    - Hydrogen degassing furnace
  - Cavity vertical test system, Mid-November 2015
    - 2 Dewars and 4 cold inserts
  - Cold mass assembly, started Sep. 2015 (FRIB 0.085 first CM)
  - 900W liquid helium system, liquid helium in 3000L Dewar in Sep. 2015
  - Cryomodule two bunker test systems, under preparation
Ramping to Full Production

- So far ~ 50 cavities have been delivered. 7 cavities/month, now speeding up and complete cavity delivery by 1, 2017
- FRIB needs 8 -9 cavities/month in average
- SRF full production Mid- November 2015 expected 11 -12 cavities/month with 20% downtime and 20% rework Meets FRIB requirement!!

- From ReA3, ReA6-1 cryomodule assembly experiences, a 27 working days needs one bunker test.
- FRIB cryomodule production rate is 1.5 CMs per month, which can be met by two bunker systems
- Cryomodule installation to be started from 2/2018
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 confirmed this scheme is good choice for QWRs with local magnetic shield scheme
- The fringe field around cavity short area is small enough to not occur the Q-drop at cavity quench, for instance ReA6-1 result 162 mG at the full operation of 8 T solenoid and dipoles
- Local shield allows needless of degaussing procedure, which benefits on Operationability of cryomodule

Need careful solenoid package design
- The magnetic shield penetration field starts at ~ 250 G (defined as 1 G increased)
- Solenoid package has to be designed as fringe field strength is less than ~ 250 G on the magnetic shield, need well optimized bucking coil location.
Summary

- FRIB construction started on March 2014 and to be completed in 2022, early commissioning is scheduled in 2017 – 2020 starting from the Front End.
- FRIB is the first large scale SRF linac from very low beta to medium beta.
- FRIB SRF linac is the intensity frontier heavy ion machine.
- FRIB is challenging many innovative concepts to build a compact SRF linac with high quality beam: solenoid in the cryomodule, bottom up supported cryomodule assembly, and high gradient cavity. These concepts have been successfully validated.
- All hardware components have been successfully validated and has been ordered vendors. FRIB project is moving well into production phase.
- Infrastructures in SRF highbay is going into full operation since Mid-November 2015, enhances the production rate double, and ready for full production.
ReA Project in MSU
MSU own project, beam operation of SRF linac

- MSU has strong nuclear physics activities in the world (NSCL, ReA)
- ReA is the reaccelerate rare isotope system up to 3 MeV (upgrade 12 MeV future near future), and first SRF LINAC at MSU
- Excellent test bench for FRIB QWRs for beta: 0.041 QWRs and 0.085 QWR cryomodules
- ReA joins finally FRIB (Reaccelerates rare isotopes produced by FRIB)

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

In Operation since April 2012

0.041QWR Bunched SRF CM
0.041QWR SRF CM
0.085QWR ReA3 SRF CM,
accelerates up to 3MeV since 2014