Low-Beta Cryomodule Design Optimized for Large-Scale Linac Installations

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Outline

- Quarter Wave Cryomodule Modular Design
- Quarter Wave Cold Mass
  - Alignment Rail System
  - Fundamental Power Coupler
  - Tuner
  - Wire Position Monitor
- Magnetic Shields
- Cryogenics
- Thermal Shields
- Vacuum Vessel
- Assembly
- Summary
FRIB Quarter Wave Cryomodule
Modular Design to be Used on All FRIB Resonator Types

Magnetic Shield
Thermal Shield
Alignment Support
FRIB Bayonet Connections

2K Heat Exchanger
Cryogenic Piping
Vacuum Vessel Base Plate

80.5 MHz $\beta = 0.085$
8 QWR Resonators x 3 Solenoids

1 m
Cryomodule Main Components Allow Modular Procurement

- Simplify where possible and look toward production and design improvements
- Optimized for mass production with interchangeable parts and machined fits
- 3 piece strong back supports tighter alignment requirements to remove or reduce ‘cross-talk’ between resonator position during assembly
- Assembly is in front at waist level with nothing overhead improving visibility

- Fewer assembly fixtures – no upper assembly stand needed for building therefore multiple modules can be assembled at the same time
- Attachment of slot covers to thermal shield, nothing to restrict access and fewer slots
- Minimize the hanging of critical components during assembly
- MLI easier to manage and not hanging in the way
- Improved alignment and mass-production, better serviceability
FRIB Quarter Wave Cold Mass
Modular Design to be Used on All FRIB Resonator Types

- Solenoid Leads
- Solenoid
- \( \beta = 0.085 \) Cavity
- Alignment Support Post
- Cold Mass Support Rails
- WPM
- ANL RF Coupler
- BPM
## Cold String Configurations

<table>
<thead>
<tr>
<th>Cryomodule Configuration (qty/FRIB)</th>
<th>Resonator Type (qty/FRIB)</th>
<th>Solenoid $L_{\text{eff}}$ [m]</th>
<th>BPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3)</td>
<td>QWR $\beta = 0.041 (4)$</td>
<td>0.2 (2)</td>
<td>(2)</td>
</tr>
<tr>
<td>(11)</td>
<td>QWR $\beta = 0.085 (8)$</td>
<td>0.5 (3)</td>
<td>(3)</td>
</tr>
<tr>
<td>(12)</td>
<td>HWR $\beta = 0.29 (6)$</td>
<td>0.5 (1)</td>
<td>n/a</td>
</tr>
<tr>
<td>(18)</td>
<td>HWR $\beta = 0.53 (8)$</td>
<td>0.5 (1)</td>
<td>n/a</td>
</tr>
<tr>
<td>(2)</td>
<td>HWR $\beta = 0.29 (2)$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>(2)</td>
<td>QWR $\beta = 0.085 (3)$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>(1)</td>
<td>QWR $\beta = 0.53 (4)$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

$L_{\text{eff}} = 0.2$ m & 0.5 m 8T Solenoids with integrated X-Y dipole magnets

Commercial solenoid leads interface directly with solenoid

2 QWRs at 80.5 MHz: $\beta = 0.041$ & 0.085
2 HWRs at 322 MHz: $\beta = 0.29$ & 0.53
Alignment Post
Fabricated out of G-10 Supports Rails System

Heat Treatment Data from Vendor
14 hours
- 1,100 °C max temp
- Cool down in inert atmosphere

Cavity mount provides stress-free thermal contraction with significant anti-rocking stiffness – essential for quarter wave resonators
FRIB Kinematic Support System Has Been Tested During Several Cool-Downs And Functions Consistently At High Repeatability and Accuracy (1)

**Bottom-up cryomodule design validated**

- Ease of assembly significantly optimized for mass-production
- Excellent alignment repeatability
- Alignment verified through optical targets and wire position monitor
- Cryomodule supports have been optimized based on vibration response spectrum analysis
FRIB Kinematic Support System Has Been Tested During Several Cool-Downs And Functions Consistently At High Repeatability and Accuracy (2)

- Alignment of cavities and solenoid stay well within alignment specifications

- First optical target measurement results
  - Cavity alignment
    » within +/- 0.003” (0.076 mm) horizontally
    » within +/- 0.002” (0.05 mm) vertically

- First WPM measurements
  - Cavity alignment
    » within +/- 0.003” (0.076 mm) horizontally
    » within +/- 0.001” (0.03 mm) vertically
QWR will utilize ANL coupler with cold window and 90 degree bend, HWR will utilize SNS-style coupler with single warm window.

Adjustable Bellows With 4.5 K Thermal Intercept
55 K Cold Window
90 Degree Bend
Warm Transition
Warm Window At Cryomodule Feedthrough

Cavity Flange With 4.5 K Thermal Intercept
Coaxial Line With 55 K Intercept
Adjustable Bellows For Coupling Adjustment
Single Warm Window

M. Leitner: MOIOA01
M. P. Kelly, et al, Compact 4 kW Variable RF Power Coupler For FRIB Quarter-Wave Cavities, LINAC 2012, Tel-Aviv

L. Popielarski: THP067, R. Oweiss: THP053
FRIB Quarter-wave Resonators Will Utilize the Same Tuning Mechanism as ReA3, Half-wave Resonators Will Utilize ANL Concept

Increased cavity frequency tunability by welding “tuning puck” to tuning plate providing ±30 kHz final tuning range.

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<th>Tuner Properties</th>
<th>$\beta = 0.085$</th>
<th>$\beta = 0.53$</th>
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</thead>
<tbody>
<tr>
<td>Pressure Sensitivity (Hz/torr)</td>
<td>-1.4</td>
<td>-3.4</td>
</tr>
<tr>
<td>Lorentz Force Detuning (Hz/(MV/m)$^2$)</td>
<td>-0.7</td>
<td>-3.0</td>
</tr>
<tr>
<td>Tuning Sensitivity (kHz/mm)</td>
<td>3.2</td>
<td>100</td>
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</table>
Wire Position Monitor (WPM) System To Actively Monitor Cavity and Solenoid Position

WPM System Bench Test

WPM Sensor

Sensor Resolution: ± 0.05mm

1 Sensor Per Cavity
2 Sensor Per Solenoid

WPM System Tracking for ETCM

WPM System Bench Test
Local Magnetic Shielding is Designed to Keep Resonator Surfaces Below 15 mG When Transitioning to Superconducting

4 individual shields that encompasses helium vessels
Assembled with, closed-end pop rivets & screws

Penetration holes for FPC
Penetration holes for beam port
Penetration holes for header bellow

Local Shielding Detail Design Is Based On ReA3 Experiences
Better shielding choice for large cryomodules, lower cost
Cryogenic System Independently Cool Solenoids to 4.5K and Cavities to 2K

- Independent 4.5 K and 2 K Helium circuits to allow warm (~10-20 K) resonators and degaussing cycle of SC solenoid magnets

- Minimize total heat load to the cryoplant to the cryomodule system

- Optimize P&ID for 2 K process improvements

- Provide for dp >2.5 psi for gas vapor cooled magnet leads

- Able to withstand installation and transport loads

- Designed in consistence with ASME 31.1 piping code

- Cryogenics system was developed with collaboration with FRIB cryogenics group and

### Projected Heat Load

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Static (W)</th>
<th>Dynamic (W)</th>
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</thead>
<tbody>
<tr>
<td>2 K</td>
<td>5.8</td>
<td>32.0</td>
</tr>
<tr>
<td>4.5 K</td>
<td>30.4</td>
<td>2.1</td>
</tr>
<tr>
<td>38/55 K</td>
<td>168.1</td>
<td>33.4</td>
</tr>
</tbody>
</table>

Bayonet Box:
- Efficient & repeatable cryomodule installation
- Fabricated separate from the vacuum vessel
Thermal Shield is Designed to Minimize/Regulate Thermal Radiation Hitting the Cold mass

- Overlapping sections allow the shield to contract and expand thermally
- Covers to provide access to welding locations during installation
- Cooling channels supplied by the module’s cryogenics
- Design is broken up into 3-sections corresponding to the cold mass rail sections
- Sliding panels provide post-assembly access to FPC

Thermal shield will be received as unit and assembled around the cold mass
- 3 bottom plates will be assembled before cold mass is mounted
- 6 panels construct the sides and top of shield after cold mass and cryogenics are installed

Cost analysis appraising material and assembly showed a benefit using aluminum vs. OFE copper for production quantities
Vacuum Vessel Bottom Assembly Provides Stable Platform for Kinematic Alignment Supports & Vacuum Vessel Top Assembly Provides Platform To Maintain Insulating Vacuum with FRIB Three Dimensional O-ring Concept

Maximum Sidewall Deflection = 3.3 mm

Maximum Vertical Deflection = .07mm Under Cold mass Load
Three Way Seal O-ring Has Been Demonstrated. Increases Space for Diagnostics Between Cryomodules.

Beam line Hoods are Attached to Cold mass

Vacuum Vessel Is Lowered on Baseplate

O-ring Inserted into Hood and Vacuum Vessel

Seal Plate Presses O-ring to Vessel Assembly and Hood
Cryomodule Assembly Sequence Developed And Linked To SRF High Bay Workflow
SRF Department continues to prepare for mass-production

Procurement oversight is intense but results in first successes
  • Quality assurance techniques scale to mass production

Cryomodule design choices are finalized
  • Next focus will be on building FRIB cryomodule prototypes (QWR + HWR) to verify performance