Cryogenics and Cryomodule for Large Scale Accelerators

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Cryogenic Systems Requirements
• SRF technology based accelerators require “2 K” Cryo System (sub atmospheric)
  Apply Lessons learned from operating machines
• Prototype and validate new technologies

Integrated Cryogenic system design to support the Functional Requirements and Operational Parameters

Successful examples of Large SRF Cryogenic systems in operation
• JLab
  » Cryogenics Commissioning “challenges” and new technologies developments
• SNS
  » Application of the lessons learned
  » The beauty of the flexibility of the superconducting LINAC
  » One unexpected result that testifies for the design

FRIB
• Accelerator scope and requirements
• Cryogenic Distribution system and cryomodule validation tests

Dedicated to JLab’s technical leadership in cryogenics, cryomodule engineering and systems integration
Temperature levels and stability requirements
• Bottom up requirements
• Devices
• Efficiencies at different levels

Heat Loads definition
• Bottoms up system requirements analysis with integrated load characteristics cryogenic plant and utility design

Operating Parameters
• CW, Pulsed
• Heat Loads Implications, design consequences

Operating modes Requirements
• Impact on capacity margin
• Impact on component matching

Iterations and optimization processes
Integrated Cryogenic System Design to Support the Functional Requirements and Operational Parameters

- Availability, Reliability, Maintainability and Upgradability considerations
  - Repair strategy

- Cryogenic Distribution and Loads Segmentation
  - Warm up and cool down requirements
  - Safety Implications

- Vacuum Spaces Segmentation
  - Leak Checking
  - Vent lines location
  - Safety Implications

- Installation and Commissioning Strategy considerations

- Safety integrated with design
- Prototyping and design validation tests to minimize risks
- Iterations and optimization processes
  - Real estate and facility requirements
JLab Cryogenic Distribution Planning (1980s)

NEW FOR
12 GeV

NEW
12 GeV
JLab Cryogenic System

- **Helium Refrigerator System**
  - 4.6 kW @ 2.1 K
  - 12kW @ 38/50 K
  - 10g/s Liquefaction @ 4.5 K

- **Cryogenic Transfer Line System**
  - 4.5 K & 38 K Helium Supply and 2.2 K & 50 K Helium Return
After three years of unsuccessful attempts by the equipment suppliers, JLab took over and developed the pump down path to achieve the 2 K operating temperature.

- Added new components (HXs, Cold Compressor, etc)
- Modified Design
- Improved thermal isolation and LN2 cooling
- Lessons Learned applied to new JLab 2 K Cold Boxes and SNS system
Process Block Diagram of the SNS Refrigerator System (~1/2 JLab’s size). (2000’s)

- Helium Refrigerator System
  - 2400 W Capacity @ 2.1 K
  - 8300 W Shield Load @ 38/50 K
  - 15g/s Liquefaction at 4.5 K
  - 80g/s Liquefaction Mode

- Cryogenic Transfer Line System
  - 4.5 K & 38 K Helium Supply and 4.0 K & 50 K Helium Return

The first high-energy SC linac for protons, and the first pulsed operational machine at a relatively high duty. High reliability and availability, stable and flexible operations. Multiple components warm up and repair.
Unexpected Result: 1GeV@4.47 K
A tribute to the Design
CM Cryogenic Design Considerations [1]

- JLab helium distribution system
  - CEBAF distribution system heat in leak of $\sim 12\text{W}$ per CM + CM Static heat in leak of $\sim 18\text{W}$ per CM is adsorbed at $2\text{K}$

![Diagram of helium distribution system with heat exchange and heat leak indications.](image)

Large 4.5-2 K HX located in 2 K CBX

$\Delta h_{in} \approx 18.5 \text{ J/g}$

CM Cryogenic Design Considerations [2]

- SNS helium distribution system
  - SNS distribution system heat in leak ~10W per CM is adsorbed at ~4 K (which is equivalent to ~3W at 2 K)

4.5-2 K HX located in each CM

$\Delta h_{lh} \approx 19.5 \text{ J/g}$

CM Cryogenic Design Considerations [3]

- Generalized distribution system
  - Enthalpy flux can improve ~9.3% for the same mass flow rate as compared to SNS


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\[ \Delta h_{th} = 21.85 \text{ J/g} \]
2 K Heat Exchanger Design Benefit from JLab and SNS Successful Experiences

- **JLab design (1980s)**
  - Centralized heat exchanger in the cold box
    - Transfer Line loads are at 2 K

- **SNS design (2000s)**
  - Distributed heat exchangers at the loads
    - Transfer line loads are not at 2 K anymore

- **JLab designed a 4 K/2 K Heat Exchanger to improve 2 K process**
  - A prototype HX of ~5 g/s constructed at JLab

- **Test cryostat with 4 K/2 K Heat exchanger designed by JLab and built by FRIB/MSU**
  - Tested at JLab

- **FRIB baseline incorporates SNS design but continues to support work on the Joule Thomson (JT) Valve in between two sections of the HX to Improve capacity for the same mass flow rate**


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Cycle Improvements: The Ganni Cycle (Patent)

- System operates closed to optimum conditions for majority of operating modes by implementing the Ganni cycle: floating pressure, constant pressure ratio
- Minimum operating costs
- Minimum capital costs
- Minimum maintenance costs
- Maximum system capacity
- Maximum availability of the system
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 of no less than 200 MeV/u

Provide beam power up to 400 kW

Satisfy beam-on-target requirements

- Option for energy upgrade to >400 MeV/u by filling vacant slots with ~ 12 cryomodules
- Maintain Isotope Separation On-Line (ISOL) option
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector
FRIB Cryogenic Systems and Cryomodules Layout

<table>
<thead>
<tr>
<th>Cavity Type</th>
<th>Quantity of Cavities</th>
<th>Quantity of Modules</th>
<th>Quantity of Solenoids</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta=0.041 )</td>
<td>12+4</td>
<td>3+1</td>
<td>6+2</td>
</tr>
<tr>
<td>( \beta=0.085 )</td>
<td>88+8</td>
<td>11+1</td>
<td>33+3</td>
</tr>
<tr>
<td>( \beta=0.29 )</td>
<td>72</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>( \beta=0.53 )</td>
<td>144</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Additional Matching Modules</td>
<td>12+4</td>
<td>3+1 (( \beta=0.085 ))</td>
<td>n/a</td>
</tr>
<tr>
<td>Total</td>
<td>332+16</td>
<td>48+3</td>
<td>69+5</td>
</tr>
</tbody>
</table>

Linac Distribution Segment 1,3

Linac Distribution Segment 2

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## FRIB Cryogenic Heat Loads & Capacity

### Cryogenic heat loads T30200-TD-000244

<table>
<thead>
<tr>
<th>Load (W)</th>
<th>2 K</th>
<th>4.5 K</th>
<th>38/55 K</th>
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<tbody>
<tr>
<td>Cryomodules</td>
<td>2349</td>
<td>1195</td>
<td>7331</td>
</tr>
<tr>
<td>Magnets</td>
<td>0</td>
<td>573 + 4 g/s</td>
<td>1640</td>
</tr>
<tr>
<td>Beam Loss</td>
<td>0</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Distribution</td>
<td>514 @ 4.5 K</td>
<td>492</td>
<td>4787</td>
</tr>
<tr>
<td>Total</td>
<td>2349 + 514 @ 4 K</td>
<td>2285 + 4 g/s</td>
<td>13758</td>
</tr>
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</table>

### Refrigeration System Design Capacity T30201-SP-000160

<table>
<thead>
<tr>
<th>Mode</th>
<th>2 K</th>
<th>4.5 K</th>
<th>38/55 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Capacity (W)</td>
<td>3600 (180 g/s) + &gt; 514 @ 4 K</td>
<td>4200 + 14 g/s</td>
<td>20000</td>
</tr>
</tbody>
</table>
Process Block Diagram of the FRIB Refrigerator
Integrated design of the cryogenic refrigeration, distribution and cryomodule systems is key to efficient SRF operation

- Ganni Cycle: floating pressure process that adapts efficiently to changing loads
- Cryogenic Distribution systems are segmented to facilitate commissioning, operation and maintenance
- Cryomodules connected with U-tubes for maintenance, availability and safety
- 4 K-2 K Heat Exchangers housed inside the cryomodules to optimize efficiency

Fundamental Design principles support user facility mission for:
- Availability, Reliability, Maintainability and Upgradability
Single refrigerator system with the capabilities needed to support the operations of superconducting cavities at sub atmospheric pressure and superconducting magnets

The distribution system consists of three separate linac segment lines and one separator distribution line

Each segment may be cooled down and warmed up independently

U-tubes are utilized to optimize availability, operability and maintainability

Supercritical helium supply (3 atm-4.5 K) to the cryomodules and magnets in parallel

4 K / 2 K heat exchanger and JT Valves in the cryomodule

Sub-atmospheric system using cold compressors

The system shall also provide refrigeration loads at 4.5 K, liquefaction loads at 4.5 K for the magnet power leads, and shield loads between 38 K and 55 K

A safety factor of 30-50% based on component knowledge and optimization

Cryomodules and magnets will be allowed to be warmed up and/or cooled down independently
FRIB Cryogenic Plant
Cold Box Room Isometric View
Compressor Room Isometric
Warm Compressor Status

HP skid layout
HP Skid Layout—Cooler Side
Linac Distribution Breakdown

- Independent transfer lines to each of the three linac segments to support
  - Staged commissioning
  - Maintenance

Linac transfer line contains
  - 2 K return
  - 4 K supply and return
  - Shield supply and return
Cryogenic Distribution Designed to Optimize Installation, Commissioning and Operation

- Design of the distribution allows us to install and commission in parallel for different segments
- Commission without 2 K cold box which is an improvement from SNS
- Each segment can run at 2 K or 4 K independently
Cryomodules and Cryogenic Systems Design is Integrated and Optimized to Provide Availability and Maintainability. Safety is Integrated with Design.

- Cryogenic Safety and Oxygen Deficiency Program T10401-AD-000168
- FRIB Cryoplant Oxygen Deficiency Hazard Analysis T30200-CA-000056
- FRIB Linac Tunnel Oxygen Deficiency Hazard Analysis T30200-CA-000041
- FRIB Policy on Pressure Design T10500-PO-000009
FRIB Cryomodules Design Approach

- Resonators operate at 2 K and magnets at 4.5 K and are both supported from the bottom to facilitate alignment
- Cryogenic headers are suspended from the top for vibration isolation
- Use common cryomodule designs principles for all seven cryomodule types
  - Support rails, cryogenic circuit, thermal shield, vacuum vessel
- Build and test 0.085 prototype cryomodule (ReA6) to validate fundamental FRIB cryomodules design
- Build and test a full preproduction 0.085 cryomodule to launch 0.85 production
- Build and test a preproduction 0.53 cryomodule
- In parallel to completing the design and test of 0.085 preproduction cryomodule start and complete design at JLab of 0.041 cryomodule
- While completing the design and test of 0.53 preproduction cryomodule complete the design at JLab of 0.29 cryomodule
- Downsize the full size cryomodule designs to two types of matching cryomodules
β=0.085 prototype cryomodule (ReA6) allows testing and design validation of FRIB cryomodule fundamental design and its subsystems

- CM with 1 complete rail (2 QWRs and 1 solenoid) installed in ReA linac for full testing

Scheduled to complete in March 2015

Design, Assemble and Test FRIB CM0.085 preproduction in 2015
FRIB Cryogenic Distribution Prototype Installed for $\beta=0.085$ Prototype Cryomodule Validation Project

- FRIB Transfer Line Test Assembly
  1. 1\textsuperscript{st} TL section
  2. 2\textsuperscript{nd} TL section
  3. Loop End Assembly
  4. Relief End Cap & Parallel Plate Relief Assembly

- Modular design
- Bayonet connections
- Expansion joints
- Flow isolation valves
- Thermal shield

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TL Prototypes: Modular design, bayonet connections, expansion joints, flow isolation valves, thermal shield
- 1st unit shipped – June 2014
- 2nd unit delivery – August 2014
- Testing – March 2015
Alignment survey demonstrated the alignment tolerance can be met by 6 point supports during assembly.

Major aspects to be confirmed:
- Alignment upon cool down to confirm previous Engineering Test Cryomodule results
- Frequency locking in vibrational environment

Lessons learned:
- Delays due to vendor and fabrication error, sophisticated cryogenic piping and supports, staff inexperience and resource inefficiency
- Knowledge will lead to a better design for FRIB production cryomodule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
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<tr>
<td>QWR certified</td>
<td>Done, 6/2014</td>
</tr>
<tr>
<td>Integrated QWR test with ANL coupler</td>
<td>Done, 6/2014</td>
</tr>
<tr>
<td>Coldmass assembled on baseplate</td>
<td>Done, 10/2014</td>
</tr>
<tr>
<td>Alignment survey complete</td>
<td>Done, 11/2014</td>
</tr>
<tr>
<td>Cryomodule assembly complete</td>
<td>2/2015</td>
</tr>
<tr>
<td>Cryomodule cool down and test</td>
<td>3/2015</td>
</tr>
</tbody>
</table>
Major results
- Welding construction conforms to ASME B31.3 piping codes and pressure vessel codes
- Design debugged; work flow, work instructions, tooling and fixture needs developed

Major aspects to be confirmed
- Alignment upon cool down to confirm previous Engineering Test Cryomodule results
- Frequency locking in vibrational environment

Lessons learned and improvements
- Process and piping design simplification
- Value engineering for major components

<table>
<thead>
<tr>
<th>Objective Measures</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>Quarter Wave Resonator (QWR) certified</td>
<td>Done, 06/2014</td>
</tr>
<tr>
<td>Integrated QWR test with ANL coupler</td>
<td>Done, 06/2014</td>
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<tr>
<td>Coldmass assembled on baseplate</td>
<td>Done, 10/2014</td>
</tr>
<tr>
<td>Alignment survey complete</td>
<td>Done, 11/2014</td>
</tr>
<tr>
<td>Cryomodule assembly complete</td>
<td>Done, 03/2015</td>
</tr>
</tbody>
</table>

**β=0.085 FRIB prototype cryomodule upon assembly completion**

- Yaw error: 0.5 mm
- Pitch error: 0.2 mm

FRIB β=0.085 Prototype Cryomodule @4 K, RF locked at FRIB specs. Alignment verified after multiple cool downs. Thermal loads verified. Very stable conditions. Test program ongoing
ReA6 Cryomodule Alignment Factors & Results

- Alignment control broken into three main areas
  1. Manufacturing and assembly steps to produce an accurate cold mass assembly with meaningful and reliable external fiducials for installation
  2. Control and verification of the warm-to-cold offset movements during cool-down
  3. Installation and placement accuracy of the cryomodule assembly in the tunnel

Alignment Results through ReA6 testing
- Alignment of coldmass components on baseplate during assembly within ± 0.4mm
  - Laser Tracking during Assembly
- Alignment of coldmass components during cooldown within ± 0.25 mm of predicted
  - Indicated by WPM and direct measurement on cavity tuners
- Alignment within ± 0.65mm
- Specification: ± 1mm

| Best-Fit Line Frame (Through US & DS Component Centers) No Cover, 6pt Support (meters) |
|-----------------------------------------------|---|---|---|
| Long | Transverse | Vertical |
| Cavity1 US | - | -0.000050 | 0.000505 |
| Cavity1 Center | - | -0.000143 | 0.000192 |
| Cavity1 DS | - | -0.000327 | -0.000122 |
| Solenoid US | - | 0.000362 | -0.000349 |
| Solenoid Center | - | 0.000113 | -0.000464 |
| Solenoid DS | - | -0.000135 | -0.000580 |
| Cavity2 US | - | 0.000128 | 0.000141 |
| Cavity2 Center | - | 0.000030 | 0.000273 |
| Cavity2 DS | - | -0.000068 | 0.000404 |

Coldmass Alignment on Baseplate
Prototype Cryomodule @4.3 K. Phase and Amplitude Processed RF Data Supports FRIB Specs and RF bandwidth, earthquake certified (Sat May 2nd, 12:30pm magnitude 4.2 earthquake, 2nd largest ever in West MI, the state’s strongest recorded event was in August 1947, a 4.6 magnitude in almost the exact same location). Both cavities are locked to 80.4905 MHz, $E_a=5.7$ MV/m (two hours data)

<table>
<thead>
<tr>
<th>Gradient</th>
<th>Detuning</th>
<th>Phase</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3K test</td>
<td>$E_a$ (MV/m)</td>
<td>$\sigma$ (Hz)</td>
<td>pk-pk (Hz)</td>
</tr>
<tr>
<td>Measured QWR 1</td>
<td>5.7</td>
<td>0.5</td>
<td>9.7</td>
</tr>
<tr>
<td>Measured QWR 2</td>
<td>5.7</td>
<td>0.6</td>
<td>16.7</td>
</tr>
<tr>
<td>FRIB goal 2 K</td>
<td>5.7</td>
<td>&lt;2.25</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

\[ \beta = 0.085 \]
FRIB $\beta=0.085$ Prototype Cryomodule Outside the Experimental Vault
FRIB $\beta=0.085$ Prototype Cryomodule
View of the Gate to the Experimental Vault
FRIB $\beta=0.085$ Prototype Cryomodule Inside the Experimental Vault
FRIB $\beta=0.085$ Prototype Cryomodule
FRIB Transfer Line and Cryomodule View
FRIB $\beta=0.085$ Prototype Cryomodule
U-tubes Connections to the Cryomodule, Electrical Valve Actuators. 2 K Return
FRIB $\beta=0.085$ Prototype Cryomodule
FRIB $\beta=0.085$ Prototype Cryomodule
Cool Down Return and Lead Flow Return
FRIB $\beta=0.085$ Prototype Cryomodule U-tubes Connections
FRIB $\beta=0.085$ Prototype Cryomodule
RF Lines, Controls and Instrumentation
Continue to Leverage Collaborations
New WFO Contracts Signed with JLab and ANL

- **ANL**
  - Liquid lithium stripper
  - Beam dynamics verification; $\beta=0.29$ HWR design; SRF tuner validation
- **BNL**
  - Plasma window & charge stripper, physics modeling, database
- **FNAL**
  - Diagnostics, SRF processing
- **JLab**
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler **
  - HWR processing & certification*
  - QWR and HWR cryomodule design
- **LANL**
  - Proton ion source
- **LBNL**
  - ECR coldmass design; beam dynamics**
- **ORNL**
  - Diagnostics, controls
- **SLAC***
  - Cryogenics**, SRF multipacting**, physics modeling
- **RIKEN**
  - Helium gas charge stripper
- **TRIUMF**
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching*
- **INFN**
  - SRF technology
- **KEK**
  - SRF technology, SC solenoid prototyping
- **IMP**
  - Magnets*
- **Budker Institute, INR Institute**
  - Diagnostics
- **Tsinghua Univ. & CAS**
  - RFQ
- **ESS**
  - AP*
- **DTRA**
  - RFQ power supply**

* Under discussion or in preparation
** Completed

Red: Active/actively planned WFO contract
Summary

- FRIB Cryomodule and Cryogenic System design are integrated and optimized to assure safety, maximum efficiency, availability, installation and commissioning optimization and enhanced maintenance capabilities.

- $\beta=0.085$ prototype (ReA6) cryomodule is a very important milestone to validate FRIB cryomodule design. Tests are ongoing.

- The fabrication, installation and testing of the FRIB prototype cryogenic transfer line in the framework of the $\beta=0.085$ prototype cryomodule validation project is an important FRIB technical milestone.

- JLab’s collaboration and leadership in cryogenics and cryomodule engineering is a fundamental technical partnership toward FRIB completion and success.
FRIB cryoplant building meets system requirements

- Cold box room: 4484 sq. ft.; compressor room: 7828 sq. ft. (~twice JLab CHL#2 building size)

Ventilation

- Cold Box Room: 18,300 cfm design
  - Supplied high at north wall and low at south wall
  - Returned high at east wall
  - Min Required Flows
    - 18,300 cfm for Oxygen Deficiency Hazard (ODH)
    - 16,000 cfm for equipment cooling

- Compressor Room: 120,000 cfm design
  - Supplied near ceiling at west wall
  - Returned at lower level at east end
  - Min Required Flows
    - 27,500 cfm for ODH
    - 120,000 cfm for equipment cooling (5.25 MW @ 15)

Adequate reserve in water, compressed air, and power

- Uninterrupted power supply (UPS) backup for controls (lasts about 20 seconds)
- ~10 seconds after outage: two 750 kW diesel generators turn on
- Within 30 minutes of the outage: gas turbine generator at MSU power station provides 4 MW to FRIB/NSCL
The FRIB cryomodules have some unique characteristics and mechanical solutions which have never been used before in this category of devices, namely:

- Bottom up construction
- Cavity alignment system with sliding supports
- Operation at 2 K with low-β resonators
\[ \beta = 0.085 \] Prototype Cryomodule @4.3 K. Phase and Amplitude Processed RF Data Supports FRIB Specs and RF bandwidth, earthquake certified (Sat May 2\textsuperscript{nd}, 12:30pm magnitude 4.2 earthquake, 2\textsuperscript{nd} largest ever in West MI, the state's strongest recorded event was in August 1947, a 4.6 magnitude in almost the exact same location). Both cavities are locked to 80.4905 MHz, \( E_a = 5.65 \text{ MV/m} \)