Superconducting Magnets for the FRIB Fragment Separator

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Outline

- History of rare isotope science at Michigan State University leads to FRIB
- Unique FRIB framework: Cooperative Agreement for financial assistance
- Fragment separator
- Magnets

- Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661
Michigan State University
57,000 people; 36 sq mi; $1.8B annual revenue; 552 buildings
Experimental Nuclear Physics at MSU

1958: MSU hires first accelerator expert
1961: NSF approves sector focused K50 cyclotron
1965: Research with K50; single turn extraction
1975: NSF approves superconducting cyclotron magnet prototype
1977: NSF approves K500 cyclotron
1978: NSAC recommends national user facility at MSU
1982: Research with stable beams from K500
1989: Research with stable beams from K1200
1990: Research with fast rare isotope beams from A1200
1996: NSF approves coupled cyclotron facility (CCF)
2001: Research with fast rare isotope beams from CCF
2002: Infrastructure for SRF linac R&D
2005: Research with trapped rare isotope beams
2006: MSU funds ReA3 reaccelerator project
2008: DOE selects MSU to establish FRIB
2010: Research with reaccelerated rare isotope beams from ReA3
2018: FRIB operations

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

Zeller, RESMM12, Slide 4
“The committee concludes that the science addressed by a rare-isotope facility, most likely based on a heavy ion linac driver, should be a high priority for the United States.” - NRC

The committee concludes that nuclear structure and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Moreover, nuclear structure-related research provides the scientific basis for important advances in medical research, national security, energy production, and industrial processing.

The Gathering Storm report argued that strong public support of basic research can help fuel the national economic engine... While it is nearly impossible to argue that any one specific investment is critically necessary to maintain the future health of the enterprise, the committee does recognize the value of a U.S. FRIB as one element of a much broader portfolio in the physical sciences.”

—Scientific Opportunities with a Rare Isotope Facility, December 2006
FRIB – a DOE-SC National User Facility
Enabling Scientists to Make Discoveries

Properties of nucleonic matter
- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks

Nuclear processes in the universe
- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter

Tests of fundamental symmetries
- Effects of symmetry violations are amplified in certain nuclei

Societal applications and benefits
- Bio-medicine, energy, material sciences, national security
Major Configuration Alternatives Considered


All configurations meet requirements: \( \geq 200 \text{ MeV/u} \), 400 kW for all ions; fast, stopped, reaccelerated beams; support infrastructure; space for 100 users at a time; world-class science program at start of operations

Future upgrade options for all configurations: Space to double experimental area; ISOL addition; Light-ion injector addition; multi-user option addition

Future energy upgrade options

\( \geq 400 \text{ MeV/u} \) for all ions with baseline \( \lambda/2 \) cryomodules

\( \geq 400 \text{ MeV/u} \) for all ions with baseline \( \lambda/2 \) cryomodules

\( \geq 400 \text{ MeV/u} \) for all ions with high-performance cryomodules (35% gradient increase over baseline cryomodules)
Civil Design Complete & Integrated with Technical Systems
Early Science Opportunities with Fast, Stopped, and Reaccelerated Beams

- Collaborations form early while FRIB is being constructed
- Post-production elements commissioned before FRIB driver linac complete
- Ensures world-class scientific research program at start of FRIB operation
<table>
<thead>
<tr>
<th>System</th>
<th>Parameter</th>
<th>Performance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator System</td>
<td>Accelerate multiple charge states of a heavy ion beam of $^{86}$Kr</td>
<td>Measure FRIB driver linac beam w/ energy &gt; 200 MeV/nucleon &amp; beam current &gt;20 pnA</td>
</tr>
<tr>
<td>Experimental System</td>
<td>Produce a fast rare isotope beam of $^{84}$Se</td>
<td>Detect &amp; identify $^{84}$Se isotopes in FRIB fragment separator focal plane</td>
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<td></td>
<td>Stop a fast rare isotope beam in gas and reaccelerate a rare isotope beam</td>
<td>Measure reaccelerated rare isotope beam energy &gt; 3 MeV/nucleon</td>
</tr>
<tr>
<td>Conventional Facilities</td>
<td>Linac tunnel</td>
<td>Beneficial occupancy of subterranean tunnel of ~ 500 feet path length (minimum) to house FRIB driver linear accelerator</td>
</tr>
<tr>
<td></td>
<td>Cryogenic helium liquifier plant—bldg &amp; eqmt</td>
<td>Beneficial occupancy of the CHL plant bldg and installation of CHL plant complete</td>
</tr>
<tr>
<td></td>
<td>Target area</td>
<td>Beneficial occupancy of target area and once beam line installed and ready for commissioning</td>
</tr>
</tbody>
</table>
Upgrade Options for Preferred Alternative

- Energy upgrade: \( \geq 400 \text{ MeV/u} \) for all ions (high performance \( \lambda/2 \) cryomodules)

- Light ion injector upgrade: \(^3\text{He}^+, 195 \text{ MeV/u}\)

- ISOL targets: \(^3\text{He}, 400 \text{ MeV/u}\)

- Multiuser capability with light ion injector

- Experimental Area: double space if science needs it
Common target building for in-flight and ISOL beam production. Compatible with V1 separator.

Common target building for in-flight and ISOL beam production. Compatible with V2 separator.

Common target building for in-flight and ISOL beam production. Compatible with H1 separator.

Single target building for in-flight production only. Compatible with V2b separator. Provides ISOL upgrade path.

A-V1 ✗
A-V2 ✗
A-H1 ✗
B-V2 ✓

B-V2 is chosen alternative: lowest-cost option with best performance for baseline requirements.

= chosen  ✗ = not chosen

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Space for 2\textsuperscript{nd} beam dump included in design

- Increased dispersion and resolving power enable selection of rare isotope between charge states of primary beam
- Large gain factors where alternative is to use weak rare isotope charge state
- Most applicable for heavy primary beams, namely for uranium
- Second beam dump option fully integrated in the ion-optical design, main driver to increase dipole bend angles to 30 degrees
Preseparator Beam Optics
Versatile Design Supports Multiple Operational Modes

- Combination of multiple modes maximizes covered science range

- Image at beam dump 1
  - Optimized for rare isotopes far from stability
  - Maximum momentum acceptance
    - Compressed by factor of 3
  - Maximum magnetic rigidity of 8 Tm
  - Trajectories shown in 5th order with aberration correction

- Image at beam dump 2 (upgrade option)
  - Optimized for heavy rare isotopes near stability
  - Selection of rare isotope beam between primary beam charge states
  - Enhanced dispersion/resolving power at beam dump
  - Trajectories shown in 5th order
Overview Experimental Systems
Fragment Separator

- **Scope**
  - In-flight separation of rare isotopes with high acceptance and high resolution
    » Leverage rare isotope production at 400 kW beam power
    » Provide purest-possible rare isotopes beam to maximize science reach

- **Technical specifications**
  - High-acceptance preseparator provides first beam purification step, provides defined location(s) for primary beam dump
  - 2 additional separation stages to guarantee high beam purity
  - Provide future upgrade opportunities for isotope harvesting
Carbon Disk / Heat Exchanger Approach

- Multi-slice target test assembly (5 slices shown)
- Sized for 50 to 70 kW dissipated power
- Dimensionally, functionally, and mechanically very similar to operational assembly
Target speed requirement
• 5,000 rpm disk rotation – needed to prevent overheating of carbon disks

Water cooled HX, subject of ongoing design validation efforts
• Allows rapid extraction of heat from beam interaction with target disks

1 mm positioning tolerance

Remotely serviceable/replaceable from lid

Sufficient space available to accommodate future target designs (incl. liquid metal)
• 1.5 m cube available
• Standard types of utilities provided (power, signal, water, air)
Target Assembly

- Compact fully integrated target design approach adopted
- Shielded motor in one atm pressurized enclosure
- Shaft powers target wheel through ferrofluid vacuum feedthru
- Target rests on kinematic mounts that provide automatic positioning after target module changes
Overview Experimental Systems [1]
Target Facility T.4.02/T.4.04

- **Scope**
  - High-yield production of rare isotopes via in-flight production with light and heavy primary beams (400 kW, >200 MeV/u)

- **Technical specifications**
  - Self-contained target building
    - Keep most-activated and contaminated components in one spot
  - State-of-the-art remote handling
    - Fast and safe target changes
  - Target applicable to light and heavy beams
    - Minimize number of target technologies needed
  - Flexible upgrades, fast implementation
    - Design for 400 kW 400 MeV/u uranium energy upgrade
    - Facility design compatible with future upgrades by implementing ISOL and multi-user capability
- Water-filled rotating drum selected for FRIB baseline

- Risks: high power density, radiation damage
  - Several alternatives studied
    » Rotating water-filled dump
    » Rotating graphite dump
    » Windowless liquid metal dump
  - Rotating water-filled dump selected for FRIB baseline

- Technical risks largely retired, residual risks acceptable and mitigation in place
  - Thermal and hydrodynamic studies, materials evaluation, radiation damage assessment

- Mechanical mockup for rotating drum for design validation designed and under construction
Beam dump assembly is composed of a structural frame, beam dump module with rotating water cooled drum, and fragment dump module.

- One of the largest and more complex components remotely handled.
- Modularized.
- Total weight: 23,000 lbs.
Remote Handling Concept Defined

Example: Beam Dump

- **Remote beam dump removal**
  - Shielding is remotely removed and stored using in-cell crane
  - Beam dump assembly removed using in-cell crane with multi-axis coordinated motion
  - Removal of beam dump with a vertical trajectory was evaluated and determined to be not feasible
- MSU has many years experience in designing superconducting and resistive magnets
- Magnet mechanical design concepts are well established

High Temperature Superconductor Quadrupole
Warm Iron SC Quadrupoles
30 Degree SC Dipoles
RT Octopole
Warm Iron SC Quadrupoles
RT Multipole
50 Degree SC Dipoles
Hot Cell
Cold Iron SC Quad Triplets

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Assumptions

- Five year ramp to full 400 kW
  - Use radiation tolerant coils (cyanate ester)
  - Use HTS for first quad after target (BNL – see talk by Ramesh Gupta)
  - Use HTS for two dipoles in hot cell

- All magnets have to be replaceable using remote handling
Fragment Separator Magnet Design Process

Beam Physics Requirements

Magnetostatic Requirements

Remote Handling Requirements in Hot Cell

Mechanical Design
Warm iron quad (half)

- Connection box
- Link
- Yoke key
- Quad Coil
- Support
- Multipole coils
Warm iron quad(2)
30 degree dipole
30 degree dipole

Conventional coil

HTS Coil (from Ramesh Gupta)
Radiation resistant hex-oct

Uses 19 mm metal-oxide insulated hollow copper
- Structural analysis performed
  - Realistic design for vacuum vessel and local shielding – basis for credible cost estimates

- Vacuum vessel design optimized
  - Improved pumping performance supports fast target and wedge changes

- Component alignment and mounting
  - Mount and alignment system design in hot-cell refined
  - Solutions for downstream fragment separator components developed

- Component design progressing
  - Details being developed
  - Remote-handling included
SC Magnet Remote Handling – Two Concepts Under Evaluation

Remove upper yoke and coil package as a unit, leave lower yoke in vacuum vessel, close tolerance assembly process done with limited visibility, but kinematic mount is protected from damage.

Remove complete magnet as a unit, all high precision assemblies completed at the window workstation but kinematic mounts are exposed to damage.
Magnets and beam line components require long term mount stability

High precision adjustment is provided at initial installation

Remotely serviceable shim system used to maintain magnet alignment after beam activation

Individual tri-leg kinematic mounts are used by each beam line component to provide permanent automatic alignment during reinstallation after removal

All kinematic mounts will have capability of adjustment after beam line activation through use of a reconfigured shim system

- Realignment measurements are used to machine new shims with adjusted thicknesses and center positions
- Magnet or other component to be realigned is removed from vacuum vessel with crane and placed at manipulator window workstation
- Old shims are removed and new shims installed, then component is reinstalled onto alignment/support rails
Yoke design will be compatible with different coil technologies, HTS or LTS.

In the process of evaluating BNL HTS coil design for baseline.

Detailed coil design is pending coil type decision, with no expected impact on availability of design at CD-2:
- SC coil design very similar to 50 degree dipoles
- HTS coil design is less complex, i.e. no helium Dewar

Yoke iron configuration provides some challenges to assembly process with the limited crane capacity and restricted access inside vacuum vessel.

Mounting scheme defined; independent of magnet type decision.
Dipole Remote Handling - Two Concepts Under Evaluation

CONCEPT 1
Consider mechanism to allow yoke halves to translate apart.

CONCEPT 2
Consider tapered yoke hardware to insure intimate contact between parts to react magnetic loads.

Estimated yoke mass about 75 tons, estimated coil package life is 3-5 years

Both yokes likely requires active cooling estimated heat load 5 kW for dipole 1, 10 kW for dipole 2

Assembled

Approaches to Disassemble
Design References for Fragment Separator
Dipole Magnets

75 tons per dipole is similar in size to the FRIB 30 degree dipoles

NSCL – S800 Spectrograph
Outside of hot cell, radiation decreases, so we can use more conventional magnet construction techniques.
Horizontal cold iron triplet
Cold iron triplet on 50° line
A1900 triplet cold assembly

Inserting the cold assembly into the helium vessel
50 degree dipoles
NSCL A1900 Type Magnets
Fabrication Technique Established

Complete coil

Coils free standing – not wound on bobbin

Coil in bobbin

Stainless steel tubes are used to provide pre-load

Zeller, RESMM12, Slide 42
Major radiation analyses are complete and support CD-2/3A
- Radiation effects drive target facility design directly or indirectly (Ronningen)

Bulk shielding determined and sufficient
- Ground water and soil activation, air activation
- Prompt radiation from beam interaction and from non-conventional utilities

Inventory and activation analyses support system designs and hazards analysis
- Inventory in cooling loops – potential releases
- Activation of components

Radiation heating and damage analyses to support equipment and utility design
- Magnet heating, lifetime of critical components
Target Facility Engineering/Design
On Track for CD-2/3A in Spring 2012

- Interfaces and boundaries defined
  - FRIB accelerator tunnel
  - Existing NSCL and MSU buildings and infrastructure
  - NSCL beam distribution system
  - Interruption of NSCL/CCF operation during civil construction

- Engineering/Design
  - Incorporates target/fragment separator system
  - Accommodates support systems (non-conventional utilities and remote handling equipment)
  - Fulfills maintenance and remote-handling requirements
  - Provides adequate shielding
  - Optimized room utilization, verified installation path
Target Facility Engineering/Design [2]
Supports CD-2/3A in Spring 2012

- Target hot cell, subterranean
  - Production target
  - Fragment preseparator
  - Primary beam dump(s)
  - Remote handling (RH) equipment

- Target facility building high bay
  - 50 ton bridge crane
  - Second and third stage of fragment separator
  - Fragment separator power supplies

- Support areas, 3 subterranean levels
  - Cascade ventilation
  - Non-conventional utilities
  - RH control room
  - RH gallery
  - Waste handling

- Optimized and engineering advanced
  - Layout of subterranean support areas to provide space for supporting equipment
  - Equipment location and ergonomics
  - Path for equipment installation
Conclusions

- Preliminary design that supports initial operations
- Integrated into complete target facility
- Transition to HTS coils in future upgrades