# ACCELERATOR CHALLENGES OF HIGH INTENSITY LINACS AND THE FACILITY FOR RARE ISOTOPE BEAMS*

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*Abstract*

This paper surveys the key technologies and design challenges that form a basis for the next generation of high intensity hadron accelerators, including projects operating, under construction, and under design for science and applications at MW beam power level. Emphasis is made on high intensity linacs like the Facility for Rare Isotope Beams (FRIB).

## INTRODUCTION

During the past decades, accelerator-based neutron-generating facilities like SNS [1], J-PARC [2], PSI [3] and LANSCE [4] advanced the frontier of proton beam power to 1 MW level, as shown in Fig. 1 with the beam-on-target power as the product of the average beam current and the beam kinetic energy [5]. For heavy ion, the power frontier will be advanced by more than two-order-of-magnitudes to 400 kW with the construction of the Facility for Rare Isotope Beams currently underway at Michigan State University [6].

Cutting edge technologies continuously developed for accelerator systems have sustained continuous growth in beam intensity and power. High-power operations have been made possible by various types of accelerators: linac, cyclotron, synchrotron and accumulator. During the past decade, superconducting RF related technology has becoming indispensable for next generation machines.

High power hadron accelerators [5] can be categorized by their goals for high-energy physics (AGS [7], SPS [8], MI [9], J-PARC/MR [2], PIP-II [10] for neutrino, Kaon and Muon physics), nuclear physics (RIKEN [11], SPIRAL2 [12], FAIR [13], FRIB for rare isotope physics; FAIR for antiproton physics; LANSCE), basic energy science and applications (LANSCE, PSI, SNS, J-PARC/RCS [2], ISIS [14], SARAF [15], SPIRAL2, CSNS [16], ESS [17] for neutron sources; KOMAC [18] for proton applications), radioisotope production (SARAF), material neutron irradiation (IFMIF and its validation prototype LIPAc [19]), and accelerator driven subcritical systems (CADS [20] and MYRRHA [21] for nuclear waste transmutation and power generation). Other operating or proposed projects include LEDA [22], PSR [23], HIAF [24], RAON [25], CPHS [26] and those proposed at CERN (SPL, LAGUNA-LBNO, SHIP) [27] and RAL [28].

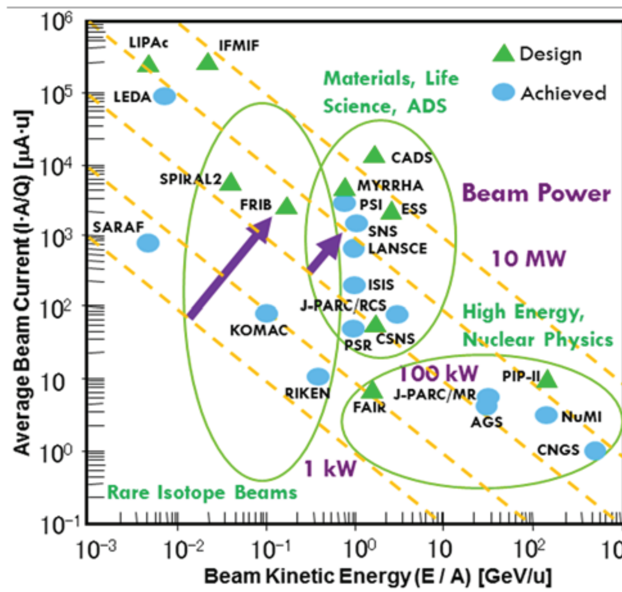


Figure 1: Hadron accelerator power frontier at design, construction, and operation stages.

The figure of merit of these accelerator facilities is the amount of useful secondary beams produced from the target. It is proportional to the target yield and the primary beam intensity. As the optimum energy range is often determined by the target yield, high beam intensity corresponds to a high beam-on-target power.

The beam structure on target largely determines the accelerator type. Synchrotrons (AGS, SPS, MI, J-PARC, ISIS, FAIR, CSNS, PIP-II) and accumulators (PSR, SNS) are used downstream of the injector accelerators to

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produce pulsed beams on target. When pulsed operation is not required, cyclotrons (RIKEN and PSI) and linacs (LANSCE, KOMAC, SARAF, FRIB, SPIRAL2, IFMIF, ESS, CADS, and MYRRHA) are used to reach high beam power at high beam duty factors.

The type of primary beams is largely determined by the facility purpose. Rare isotope production using the projectile fragmentation method requires heavy ion beams (RIKEN, FRIB, SPIRAL2). Neutron production at high energy using the spallation process prefers high intensity proton beams (SNS, J-PARC, LANSCE, PSI, ISIS, CSNS, ESS, CADS, MYRRHA). Neutron production at lower energy favours deuteron beams (SARAF, IFMIF, and SPIRAL2). In synchrotron and accumulators for proton beams (ISIS, PSR, SNS, J-PARC, CSNS), the injector linac often accelerates $H^-$ beams for multi-turn injection to reach high peak intensity on target.

This paper focuses on the physical and technological challenges pertaining to high intensity hadron linacs including the Facility for Rare Isotope Beams.

## KEY TECHNOLOGIES

### *Superconducting RF (SRF)*

For hadrons, SRF technology is first extensively used in the SNS linacs for the high energy-efficiency, high accelerating gradient, and operational robustness (Fig. 2) [29]. For pulsed operations, resonance control by means of fast tuners and feedforward techniques is often required to counteract Lorentz force detuning [30], and the need of higher order mode damping is to be expected [31]. FRIB as a heavy ion continuous-wave (CW) linac extends SRF to low energy of 500 keV/u. 330 low-β (from 0.041 to 0.53) cavities are housed in 49 cryomodules. The resonators (at 2 K temperature) and magnets (at 4.5 K) supported from the bottom to facilitate alignment and the cryogenic headers suspended from the top for vibration isolation. High performance subsystems including resonator, coupler, tuner, mechanical damper, solenoid and magnetic shielding are necessary [32].

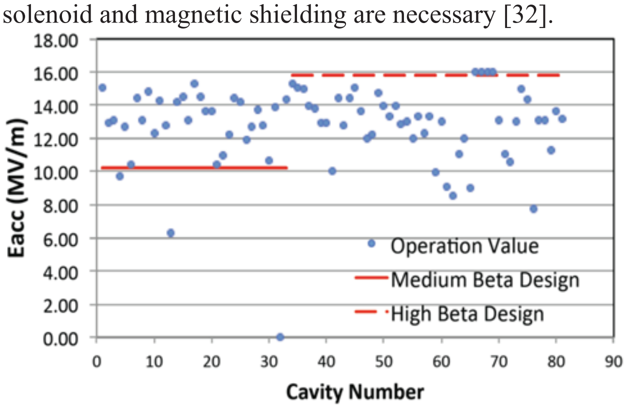


Figure 2: Accelerating gradients of the 81 SNS β=0.61 (medium) and β=0.81 (high) cavities in 23 cryomodules.

### *Large-scale Cryogenics*

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations. The FRIB refrigeration system adopts the floating pressure process – Ganni Cycle [33] for efficient adaptation to the actual loads. Distribution lines are segmented and cryomodules are connected with the U-tubes to facilitate stage-wise commissioning and maintenance (Fig. 3). The 4-2 K heat exchangers are housed inside the cryomodules for enhanced efficiency.

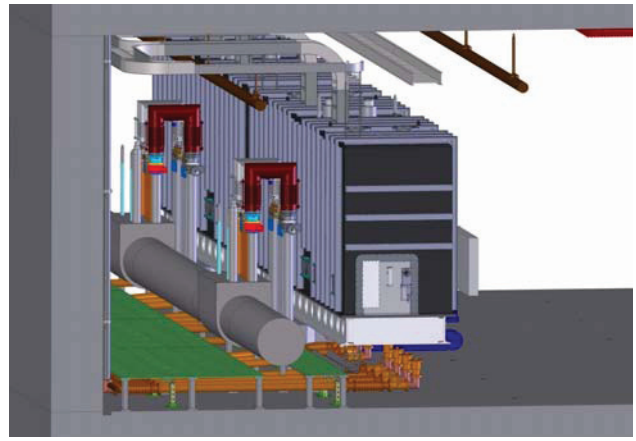

Figure 3: FRIB cryomodule with U-tube connections.

### *Loss Detection and Machine Protection*

Machine protection is crucial to the availability of the high power accelerators. FRIB adopts multi-time scale, multi-layer approaches: the fast protection system (FPS) is designed to prevent damage from acute beam loss by quickly activating the beam inhibit device; the run permit system (RPS) continuously queries the machine state and provides permission to operate with beam; the even slower but highly sensitive RPS prevent slow degradation of SRF system under small beam loss (Table 1).

Table 1: Machine Protection for the FRIB Driver Linac

| Mode | Time | Detection | Mitigation |
|---|---|---|---|
| FPS | ~ 35 μs | LLRF controller;<br>Dipole current monitor;<br>Differential BCM;<br>Ion chamber monitor;<br>Halo monitor ring;<br>Fast neutron detector;<br>Differential BPM | LEBT bend electro-static deflector |
| RPS (1) | ~ 100 ms | Vacuum status;<br>Cryomodule status;<br>Non-dipole PS;<br>Quench signal | As above;<br>ECR source HV |
| RPS (2) | > 1 s | Thermo-sensor;<br>Cryo. heater power | As above |

Challenges remain for intense low-energy heavy ion beams due to the low detection sensitivity and high power concentration/short range. Innovative techniques include the halo monitor ring [34] for high-sensitivity loss detection and current monitoring modules for critical magnet power supply inhibition. ADS machines like MYRRHA demand mean-time-between-failure of trips exceeding 3 s to be longer than 250 h [19].

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### *Front End (Ion Source, RFQ, LEBT Transport)*

Among a wide range of ion sources meeting different primary-beam requirements, Electron Cyclotron Resonance (ECR) ion sources are essentially the only choice for high intensity (CW), high charge state beams. To reach higher plasma densities, ECRs continue to be developed for higher resonance frequency and magnetic field. High power ECR sources operate at frequencies up to 28 GHz and RF power of ~10 kW [35]. The required superconducting (SC) sextupole and solenoids push the state-of-the-art in SC clamping technology. Cesium-seeded, volume production sources are most promising for the demand on high current, long pulse, low emittance $H^-$ beams [36].

Four-vane, room temperature RFQs are commonly used for high intensity operations. LEDA RFQ with a variable voltage profile accelerated 100 mA CW proton beam to 6.7 MeV [37]. Alternatively, RFQ with trapezoidal vane modulation is tested for shunt impedance and acceleration efficiency enhancement (Fig. 4) [38]. The LEBT transport between the source and RFQ is often used for chopping, collimation, beam inhibition, and prebunching.

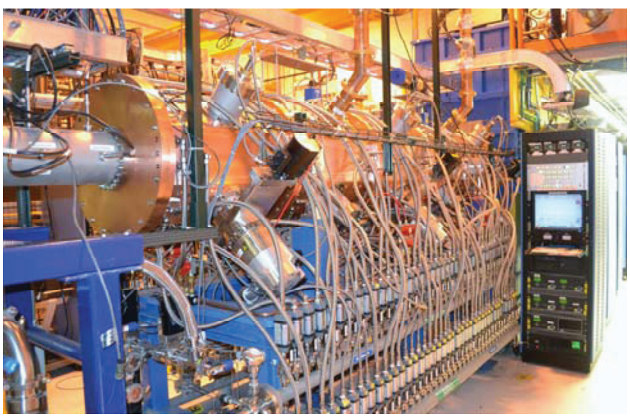

Figure 4: ATLAS heavy-ion CW RFQ in operation since December 2012 [38].

### *High-power Charge Stripping*

Intense heavy ions at low energies may cause severe damage on stripping material. Innovative stripping mechanisms are under development worldwide. RIKEN uses helium gas with differential pumping (Fig. 5) [39]. Plasma windows are being tested to establish a high gas density [40]. FRIB uses a liquid lithium film moving at ~50 m/s speed. Tests with a proton beam produced by the LEDA source demonstrated that power depositions similar to the FRIB uranium beams could be achieved without destroying the film (Fig. 6) [41].

Injection of intense $H^-$ beams into rings require sophisticated charge stripping designs [5]. Innovative schemes like laser stripping are tested [42]. Stripping can also be used to split $H^-$ beam to multiple beam lines [43].

### *Collimator*

Collimators are indispensable to reduce uncontrolled beam loss for hands-on maintainability [5]. Collimation can be performed in both the transverse and longitudinal phase space (momentum cleaning and beam gap cleaning). Charge stripping is often used for $H^-$ and partially stripped heavy ions for efficient collimation. Multi-stage collimations are used on fully stripped beams like protons [44] (Fig. 7).

For heavy ions, beams of unwanted charge states need to be removed downstream of the stripper. Such "charge selector" must sustain high power, low energy beams of short range. The FRIB charge selector, designed to absorb ~42 kW of heavy ions at 12 – 20 MeV/u, consists of two rotating graphite discs similar to the FRIB target [45].

Figure 5: Test of He gas charge stripper using Uranium beams at RIKEN [39].

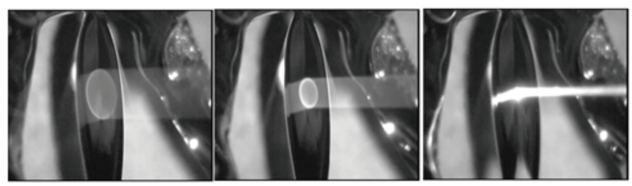

Figure 6: Liquid lithium film intercepting a proton beam of ~ 60 kV for beam power survival test [41].

Figure 7: SNS multi-layered collimators, each designed to withstand 10 kW protons at 1 GeV.

### *Target, Radiation-resistant Magnets, Handling*

Target scenario is chosen based on secondary-beam requirements [46]. High-power primary beams often demand non-stationary targets like circulating liquid or rotating solid targets. For pulsed neutron production at MW level, both SNS and J-PARC/RCS use liquid mercury. Target pitting issues are largely mitigated by vessel surface treatment, mercury flow and bubble controls [47]. For lower-energy neutron production both SARAF [48] and IFMIF use liquid lithium (Fig. 8) while SPIRAL2 prefers a rotating carbon wheel. MYRRHA's



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ADS target uses liquid Pb-Bi eutectic [49]. For in-flight RIB production FRIB needs to focus 400 kW of heavy ion beam onto an area of 1 mm diameter (~60 MW/cm$^3$). A radiation-cooled multi-slice graphite target of 30 cm diameter rotates at 5000 rpm [45]. While neutron targets are designed to absorb most beam power, FRIB's RIB target is designed to absorb ~25% power; targets for high-energy physics (ν, μ, K) typically absorb <5% power.

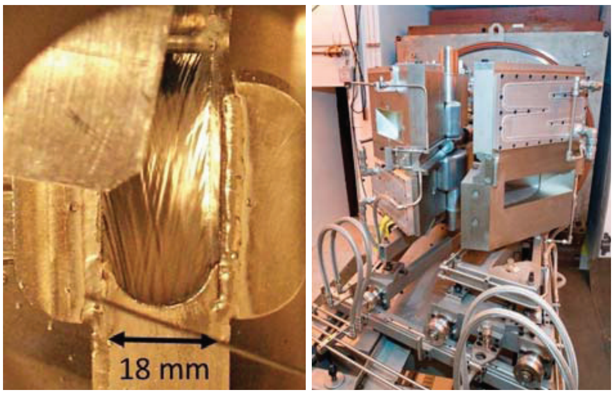


Figure 8: (left) SARAF's liquid lithium target under test [48] and ISIS spallation target station 2 [46].

Radiation resistance is important for magnets in the target region. Quadrupoles wound with mineral-insulated cables are built as an integral part of the shielding in front of the SNS target [50]. Quick-disconnect vacuum flanges and remote water fittings allow easy access. FRIB uses high-temperature SC magnets (YBCO) in the high radiation area of the target and primary beam dump [51].

## ACCELERATOR PHYSICS CHALLENGES

### *Beam Loss Control*

Key to the design and operations of a high-power accelerator is to control the beam loss. Measures of loss control include beam collimation, beam dump and shielding for charge stripping and charge selection (Table 2). Uncontrolled losses must be kept below a level (about 1 W/m for protons around 1 GeV and less stringent for heavy ions [52]) to facilitate hands-on maintenance. Personnel protection system is designed against radiation exposure under both normal and fault machine conditions.

Table 2: Estimated FRIB Beam Losses

| Type and location | Energy [MeV/u] | Peak power | Duty factor |
|---|---|---|---|
| Uncontrolled loss | 0 – 200 | ~1 W/m | 100% |
| Controlled loss: | | | |
| Charge selector | 12 – 20 | 42 kW | 100% |
| Charge stripper | 12 – 20 | ~1 kW | 100% |
| Collimators | 0 – 200 | ~1 kW | 100% |
| Dump FS1-a | 12 – 20 | 42 kW | 0.03% |
| Dump FS1-b | 12 – 20 | 12 kW | 5% |
| Dump FS2 | 15 – 160 | 300 kW | 0.03% |
| Dump BDS | 150 – 300 | 400 kW | 0.03% |

### *Space Charge, Coupling Impedance, Instability*

Space charge and other coupling impedances can have performance-limiting effects for machines of low energy, high peak intensity beams. In linacs beam halo can be generated through core-halo parametric resonances and resonances between the transverse and longitudinal motion [53 – 56] (Fig. 9).

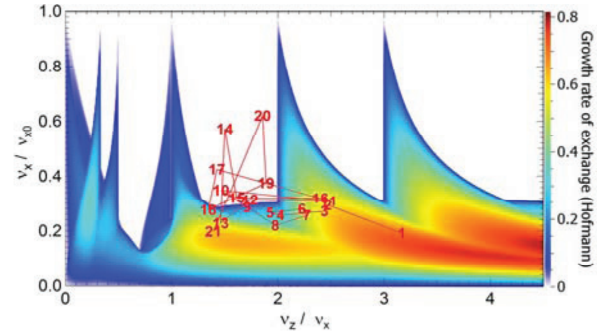


Figure 9: Tune footprint along the four IFMIF cryomodules superimposed to the Hofmann chart [60].

### *Multiple Charge State Acceleration*

To reach high design beam intensity, simultaneous acceleration of heavy ion beams of multiple charge state is often needed due to the broad charge spectrum upon stripping. The FRIB driver linac accelerates up to five charge states simultaneously, transversely overlapping at charge stripper location and at the target (Fig. 10). Machine optics, diagnostics, and fault mitigation are designed in detail to meet the performance goals.

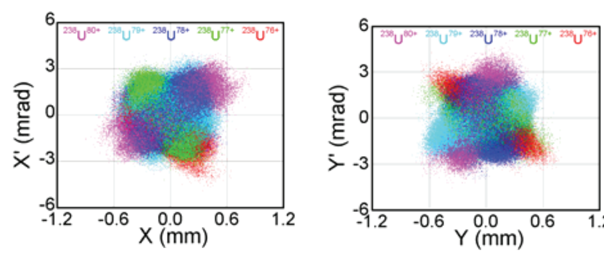


Figure 10: Five charge states of the uranium beam designed to overlap at the FRIB target.

Other topics include magnet interference [57] and fringe field [58] pertaining to large aperture and tight spacing, and H$^-$ stripping issues [59 - 61].

## FRIB PROJECT STATUS

In August 2013, the Department of Energy's Office of Science approved Critical Decision-2, Approve Performance Baseline, and Critical Decision-3a, Approve Start of Civil Construction and Long Lead Procurements, for the FRIB Project. The ground was broken in March 2014. In October 2014, the Critical Decision-3b was approved allowing the start of technical construction. The Total Project Cost for FRIB is $730M, of which $635.5M will be provided by DOE and $94.5M will be provided by Michigan State University. The project will be completed by June 2022 [62]. "When completed, FRIB will provide access to completely uncharted territory at the limits of

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nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes."

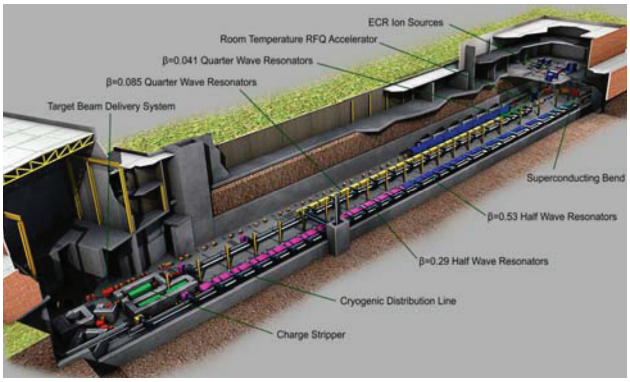


Figure 11: Layout of the FRIB driver accelerator.

### *Specific Challenges and Design Philosophy*

FRIB shares the physical and technological challenges described in the previous Sections. In addition, FRIB is sited in the middle of university campus with tight real estate constraints. The driver linac is "folded" twice demanding special design considerations (Fig. 11). The folding segments must be designed as 2$^{nd}$ order achromats allowing a wide momentum acceptance. Beam loss at high energy interferes with loss detection of low-energy beams. Hazard analysis upon beam faults is complicated, and installation and commissioning are interlaced. Finally, as the linac service/utility area and cryogenics area are near the accelerator tunnel housing cryomodules, the vibration issue must be carefully addressed.

Full-energy linac technology is chosen to deliver primary beam that can meet the FRIB requirements of rare-isotope productivity and separation accuracy. Up to 400 kW of beams are focused to a diameter of 1 mm (90%), energy spread of 1% (95% peak-to-peak), and bunch length of < 3 ns (95%) on the target.

Superconducting (SC) technology is the energy-efficient choice for the CW linac. SC acceleration of heavy-ion beams is feasible from low energy (500 keV/u) with practically sized cavity bores by housing both the cavities and solenoids in a cryomodule. A two-gap scheme is chosen throughout the entire linac providing both efficient acceleration and focusing. Developments of digital low-level RF control and solid-state RF amplifier technologies have made individual cavity powering and control reliable and cost efficient.

High availability, maintainability, reliability, tunability, and upgradability are especially required for FRIIB to operate as a national scientific user facility [62].

### *Collaboration and Partnership*

FRIB accelerator systems design has been assisted under work-for-others agreements by many national laboratories including ANL, BNL, FNAL, JLab, LANL, LBNL, ORNL, and SLAC, and in collaboration with many institutes including BINP, KEK, IMP, INFN, INR, RIKEN, TRIUMF, and Tsinghua University.

The cryogenics system is designed in collaboration with the JLab cryogenics team. The refrigeration process incorporates the cumulative experience from both JLab and SNS cryogenic systems. The recent experience gained from the JLab 12 GeV cryogenic system design is utilized for both the refrigerator cold box and the compression system designs. The cryogenic distribution adopting a modular design is prototyped at JLab and tested at MSU along with the cryomodule prototype.

The charge stripping system is under development in collaboration with ANL. Upon successful prototyping and integrated test (Fig. 5), the present focus is on the development of the electromagnetic pump for lithium circulation and on the production design including safety considerations. BNL collaborated on the development of the alternative helium gas stripper.

The SRF development benefited greatly from the expertise of the low-β SRF community. FRIB adopted the ANL design of the QWR coupler and HWR tuner and is further assisted in the design and validation of critical SRF subsystems. We are assisted by JLAB on cavity processing and cryomodule developments, and by FNAL on cavity heat treatment and material analysis.

The high-power ECR ion source coldmass and magnets are under development in collaboration with LBNL.

## PERSPECTIVES

At a time when accelerator projects at the high-energy frontier are experiencing difficulties in gaining financial support, projects at the high-intensity frontier are flourishing worldwide. Demands for such accelerators extend from science to applications, and for primary beams from proton to heavy ions. Efforts worldwide are readying the technologies and designs meeting the requirements of user facilities with high reliability, availability, maintainability, tunability, and upgradability. With the present technology, we speculate to reach multi MW beam power using cyclotrons, synchrotrons or accumulators, and up to 100 MW with SRF linacs [5].

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