FRIB ACCELERATOR IMPROVEMENT PROJECTS TO MITIGATE BEAM LOSSES IN POST-STRIPPER LINAC*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is planning four Accelerator Improvement Projects (AIPs) during a two-month summer shutdown to mitigate beam losses induced by the stripper. The motivation for this project has been described in previous publications. The implementation of these projects is required to accelerate multiple-charge-state heavy-ion beams simultaneously as beam power on target ramps up.

These projects require modification of approximately 30 meters of beamline within the FRIB tunnel and include installing larger-bore magnets and beamline components before and after the liquid lithium stripper, implementing new second-harmonic cavities, replacing the dipole chamber with a high-heat-load-rated version at Folding Segment 1, and installing new quadrupole magnets at Folding Segment 2. Effective integration of design, technical device fabrication, installation, and commissioning within a limited shutdown window requires close coordination among multiple engineering and physics teams. This paper presents the planning methodology, execution strategy, and planned performance outcomes of these upgrades to manage concurrent accelerator improvement projects within a constrained maintenance schedule.

INTRODUCTION

FRIB is currently in user operation, with primary beam power progressively increased from the kilowatt level to beyond 20 kW [1, 2, 3], and with an ultimate design goal of reaching 400 kW on target.

The FRIB accelerator is a state-of-the-art superconducting heavy-ion linear accelerator (linac). A key feature of the FRIB linac is the implementation of a liquid lithium stripper, which enables efficient acceleration at high beam power. In contrast to conventional carbon foil strippers—prone to rapid degradation under high power density—the liquid lithium stripper provides enhanced robustness and operational lifetime.

Despite transverse focusing of the beam onto the stripping medium, intrinsic thickness non-uniformity of the liquid lithium film across the beam spot introduces additional energy spread via spatially dependent energy loss, beyond the baseline contribution from energy straggling.

During routine operation, additional factors such as ion source instability and unintentional beam contamination can further induce beam losses. These losses may lead to vacuum degradation and increased risk of damage to downstream superconducting cavities. To mitigate these effects, four AIPs are being implemented; their design, integration, and impact are presented in this paper.

PROJECT SCOPE

2H Buncher Cavity

Multi-Gap buncher (MGB) cavities (operating at 161 MHz) are currently utilized at Folding Segment 1 (FS1) beamline for longitudinal matching between superconducting linac segments [4]. Beam after MGB1 shows non-linear "tails" in the longitudinal phase space distribution, which may cause beam loss at downstream Linac Segment 2 (LS2) cryomodule.

To mitigate this loss, 2H buncher cavity is designed [5] by linearizing the effective voltage of MGB. Beam dynamic analysis is performed to compare longitudinal acceptance with no 2H cavity, one 2H cavity, or two 2H cavities (one after each MGB cavity). Analysis results show that with two 2H cavities, all particles fit within the longitudinal acceptance of LS2. Figure 1 shows the MGB cavity upstream of the new 2H buncher cavity.

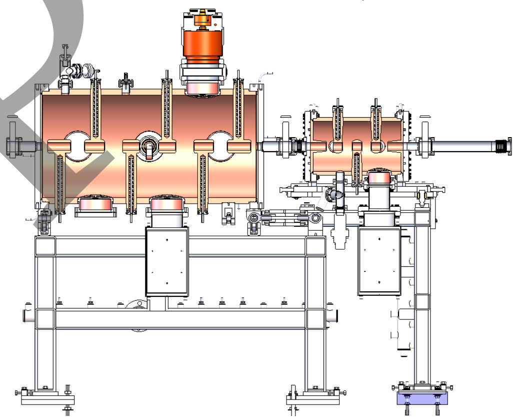

Figure 1: FRIB MGB upstream of 2H buncher cavity.

The 2H cavity operates at 322 MHz, and utilizes existing type of RF amplifier. β number is 0.186, calculated Q_0 value is 1.3×10^4, and the maximum RF power for Uranium beam is 4.6 kW. It has the same 36 mm aperture as MGB. Thanks to the successful fabrication and implementation of FRIB other room temperature cavities [6], the design use similar cavity and cooling design as FRIB MGB, and utilizes other existing systems (tuner, coupler, linear actuator, etc.) to streamline maintenance, repair and spare inventory management.

Larger Bore Beamline Near Stripper

Charge stripping is inherently accompanied by transverse and longitudinal emittance growth due to angular

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scattering and energy straggling of ions within the stripping material (liquid lithium film, in FRIB's case). In addition, spatial non-uniformity of thickness across the beam spot introduces a spread in energy loss, which is a dominant contribution to longitudinal emittance dilution. Minimizing these effects requires focusing the beam to a smaller spot size at the stripper location than in original beamline design.

In the FRIB stripper region, the achievable minimum spot size is largely constrained by the beam envelope upstream of the quadrupoles used to focus the beam onto the stripper. Achieving a smaller spot size therefore necessitates quadrupoles with larger apertures. A similar requirement applies to the downstream quadrupoles, which must accommodate the post-stripping beam while matching it into the FS1 bending section.

This modification (bore size changed from 50 mm to 72 mm) not only enables improved control of emittance growth through the liquid lithium stripper—whose region of thickness uniformity is limited for heavy-ion beams—but also increases the local transverse acceptance of the beamline. The latter is particularly important for operation with larger input emittance, such as beams extracted from an ECR ion source at high intensity or in dual charge-state mode as beam power is increased. Mitigation of the beam emittance growth by Larger Bore Beamline is important in the minimization of uncontrolled beam losses at higher energies downstream.

For this project, a total of 11 magnets are replaced by larger bore magnets (9 Quadrupole magnet and 2 corrector magnets), 2 more new beamline Quadrupole magnets, gate valve and beam pipe change, addition of water cooled collimator, diagnostics optimization (beam position/phase monitor BPM, beam current monitor, longitudinal profile monitor).

FS1 Dipole Next Version Chamber

The currently installed chamber in FS1 1st dipole magnet serves as a beam collimator (different from original expectation), has all stainless steel sub-components, and carries a beam load limit of 50 watts. A new intermediate power chamber shall be installed to support higher primary beam power, thus higher beam loss at this location. Two incidents of beam loss occurred during last year's operation right downstream of this chamber, and a new chamber with improved design would help mitigate this risk.

Figure 2 shows the layout of the chamber with different types of beams: the chamber intercepts not only unexpected contaminates from source, but also some of the charge state beams that can only be collimated here.

A distinctive feature of the intermediate chamber is the use of copper–stainless steel bimetallic plates for the sidewalls. The copper layer provides high thermal conductivity for efficient heat removal, while the stainless steel layer enables robust welding to the top and bottom plates, thereby defining and maintaining the vacuum boundary. Thermal analysis indicates that the new chamber can tolerate beam-induced heat loads at least eight times greater than those sustained by the existing chamber.

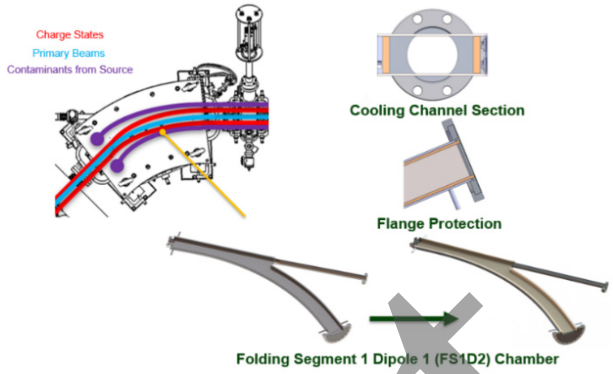

Figure 2: 1st FS1 dipole chamber and the features of intermediate chamber.

Four New Quadrupole Magnets at Folding Segment 2 (FS2)

In the existing beamline configuration, four quadrupoles are installed along the 12 m beamline between the charge-state (CG) buncher and the entrance of the LS3 cryomodule to match the transverse Courant–Snyder parameters of the beam. During multi-charge-state beam development, this configuration was found to be insufficient to simultaneously match all charge states within the transverse acceptance of LS3. The resulting mismatch leads to effective emittance growth and contributes to increased uncontrolled beam losses in the beam delivery system (BDS).

From a beam optics perspective, full matching of multiple charge states would ideally require twelve independently adjustable quadrupoles. However, beam dynamics simulations indicate that the installation of four additional quadrupoles provides a near-optimal solution, enabling substantially improved transverse matching into LS3 across the charge-state distribution. This improvement becomes increasingly critical for operation at beam powers exceeding 50 kW.

The proposed modification therefore enables more effective matching of multi-charge-state beams through LS3 and downstream into the Beam Delivery Segment (BDS), thereby reducing emittance growth for multi-q beams and minimizing uncontrolled beam loss.

PLANNING AND IMPLEMENTATION

During the design phase, strict spatial envelope and weight constraints were considered, particularly for components installed within the confined geometry of the FRIB tunnel. The design approach leveraged proven FRIB engineering concepts to maintain consistency with established standards in vacuum systems, alignment methodology, and mechanical interfaces, while incorporating targeted improvements derived from several years of operational experience and progressive beam power ramp-up. These enhancements include water system improvement based on operation experiences, improved thermal management, and more robust mechanical tolerances for cost effective fabrication.

Execution of the project requires coordinated involvement of multidisciplinary teams with prior FRIB project experience, including procurement, fabrication oversight, quality assurance, installation, alignment, RF, power supply, and commissioning. Vendor qualification, in-process inspection, and acceptance testing are critical elements to ensure that components meet stringent technical specifications and interface seamlessly with existing infrastructure.

Project planning must be initiated well in advance, with clearly defined scope, schedule, and risk mitigation strategies. It is essential that the technical benefits and performance gains of these upgrades—such as reduced beam loss, increased acceptance, and improved machine protection—are clearly communicated and understood across all stakeholder groups, including operations, engineering, and management. This alignment is necessary to ensure efficient execution and minimize disruptions during the shutdown period.

Waste management planning is also a nontrivial aspect of the project, given the significant volume of removed beamline components and associated materials. A well-defined waste handling and disposal strategy—including staging, re-use, and transport—can substantially improve workflow efficiency and reduce schedule pressure during demolition and installation activities.

A major constraint arises from the limited spatial clearance and restricted lifting capabilities within the tunnel environment. Available rigging equipment is constrained by both load capacity and vertical clearance, requiring careful planning of lifting paths, component segmentation, and installation sequencing. Three major upgrades in Folding Segment 1 (FS1) must be executed concurrently within the same maintenance window and in close physical proximity. This introduces additional complexity due to workspace congestion and potential interference between work crews. Furthermore, these activities must be coordinated with other maintenance tasks inside tunnel, requiring detailed scheduling, spatial conflict analysis, and strict work control procedures to ensure safe and efficient execution.

MANAGEMENT AND RISKS

Modification of approximately 30 meters of the existing beamline inside the FRIB tunnel requires a highly structured cross-team coordination involving accelerator physics, mechanical engineering, RF systems, magnet, power supply, controls, alignment, and operations. The scope includes removal of existing components, installation of upgraded hardware, and re-establishment of beamline alignment and vacuum integrity within a tightly constrained shutdown period, that can't be extended. This effort introduces multiple layers of technical risk, including fabrication delays, interface incompatibilities, and machining or assembly deviations that could impact fit-up, alignment tolerances, vacuum level or function performance. In parallel, schedule risk is dominated by critical path sensitivity, where delays in key components or installation steps can extend overall project completion.

To mitigate these risks, a rigorous quality assurance and quality control program has been implemented, including design reviews, fabrication inspections, fit checks, and pre-installation acceptance testing. Close collaboration with both external vendors and internal technical groups enables rapid identification and resolution of issues, minimizing impact on the project schedule. In addition, detailed installation sequencing, contingency planning, and resource allocation are used to maintain schedule integrity.

Despite these measures, residual operational risks remain, particularly during commissioning, where uncertainties in beam conditions and system integration may lead to unexpected behavior. To address this, schedule float is incorporated into the commissioning phase, and a comprehensive test plan is developed, including staged validation both with and without beam. This approach reduces commissioning risk, facilitates early detection of issues, and supports a controlled transition back to full operational capability to achieve the expected accelerator improvements.

EXPECTED PERFORMANCE & IMPACT

Following implementation of these upgrades, a substantial reduction in uncontrolled beam losses is expected, leading to a corresponding decrease in operational risk and improved machine reliability. The enhanced beamline acceptance, optimized optics for multi-charge-state transport, and upgraded high-heat-load components collectively enable stable operation at higher beam intensities, thereby supporting continued ramp-up of beam power.

In parallel, machine protection will be significantly strengthened through reduced loss-driven activation, lower thermal stress on critical components, and improved vacuum integrity in loss-sensitive regions. These improvements directly mitigate the risk of damage to downstream superconducting cavities and associated systems.

Beam dynamics studies and engineering assessments project a significant reduction in uncontrolled beam losses relative to current operating conditions. This reduction not only improves operational efficiency but also provides additional performance margin for high-power operation and future upgrades.

SUMMARY

FRIB is implementing four AIPs to support the ramp-up of high-power heavy-ion beam operation. These upgrades address beam loss mechanisms associated with liquid lithium stripping, including energy spread from film non-uniformity, emittance growth from scattering and straggling, and operational effects such as source instability and contamination. The scope includes installation of second-harmonic bunchers to improve longitudinal phase space control, replacement of beamline sections with larger-aperture quadrupoles to enhance transverse acceptance and multi-charge-state matching, deployment of a high-heat-load bimetallic intermediate chamber in FS1 to increase loss tolerance at its location, and addition of quadrupoles in FS2 to improve matching into downstream structures. These improvements are expected to maintain negligibly low beam losses at increased beam power, enhance machine protection, and improve operational availability for sustained high-power beam delivery.

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