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# LINEAR ACCELERATOR FOR A NEXT GENERATION RARE ISOTOPE FACILITY*

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*Abstract*

We propose a linear accelerator concept for a Next Generation Rare Isotope Accelerator Facility - a versatile User Facility with high variety and availability of its instruments and beam time.

The concept is based on simultaneous acceleration of light and heavy ion primary beams. It improves the utilization of the superconducting driver-accelerator capabilities, and allows for the simultaneous and complementary rare isotope production in two different targets, namely a thin target for fragmentation of accelerated heavy ion beams, and a thick spallation target for an Isotope Separation On-Line (ISOL) system driven by light ion beams. This approach supports the multi-user operation of the facility, and enables other research driven by light ion beams.

The concept is presented as an upgrade of the Facility for Rare Isotope Beams (FRIB, MSU) with a 60-MV compact room-temperature continuous-wave light ion injector. Funneling of the light and heavy ion beams as well as their distribution to production targets is discussed.


## INTRODUCTION

The Facility for Rare Isotope Beams is a cutting-edge U.S. Department of Energy's Office of Science user facility. With its state-of-the-art superconducting RF (SRF) heavy ion accelerator [1], FRIB offers world-class research and educational programs in the fields of nuclear structure, nuclear astrophysics, fundamental symmetries, and application of isotopes for society. Since its user operations started in May 2022, the FRIB Users Organization [2] has already joined approximately 1,800 researchers eager to explore the facility's capabilities and conduct pioneering research.

The facility offers a unique range of experimental systems and capabilities with fast, stopped, trapped, and reaccelerated rare-isotope beams (RIBs) [3]. FRIB produces isotopes via the projectile fragmentation and fission of fast heavy-ion beams in thin targets [4]. A wide variety of isotopes with a large spread of charge states and masses, moving at nearly the projectile velocities, are purified in-flight by the brand-new Advanced Rare Isotope Separator (ARIS) and delivered to the experimental areas. The layout of FRIB and its currently available facilities are illustrated in Figure 1.

Purified RIBs are studied in the fast-beam area using existing instruments such as $\gamma$-ray and neutron detectors, as well as the high-resolution spectrograph S800 [3]. By 2028, the High Rigidity Spectrometer will also be available, increasing the luminosity for neutron-rich isotopes by 2–100 times compared to S800 [3, 5, 6]. Beams can be stopped using a solid or one of the gas stoppers, including a room-temperature linear gas cell, an advanced cryogenic gas stopper, or a gas-filled reverse-cyclotron stopper [7]. Stopped beams can be trapped for precision mass spectrometry and laser spectroscopy, or they can be reaccelerated [7].

In 2015, the experimental capabilities were greatly expanded with the commissioning of the ReA3 reaccelerator and start of its user operations. The reaccelerator consists of a room-temperature (RT) radio-frequency quadrupole (RFQ) and three SRF cryomodules providing the RIBs of 0.3 – 6 MeV/u to three target stations [8, 9]. In 2021, ReA3 was upgraded to ReA6 with the addition of one cryomodule and new experimental beamlines [10].

While the availability of fast, stopped, trapped and reaccelerated RIBs in a single facility is unique in the world, the current FRIB layout only allows one rare-isotope experiment to be conducted at a time, which can cause other instruments and users to wait for the beam time. The multi-user operation of FRIB is, therefore, highly demanded by users.

A Next Generation Rare Isotope Facility will be a versatile user facility with a high variety and availability of instruments and beam time. In this paper, we present a concept for a multi-user upgrade of FRIB that utilizes simultaneous acceleration of light and heavy ion beams. While the heavy ion beam is delivered to the fragmentation target to produce fast isotopes separated in-flight [4], the light ion beam will produce isotopes via spallation, fission and fragmentation of a thick heavy target. The isotopes (reaction debris) are diffused from the target, get ionized, and separated at energies of several tens of keV. This isotope production approach, known as Isotope Separation On-Line (ISOL), offers high rates of high-quality low-energy rare isotope beams [11, 12]. The radioactive beams produced by the fragmentation and ISOL methods have complementary characteristics and will serve to answer different scientific questions [12].

The proposed ISOL upgrade scheme is shown in red in Figure 1. It not only supports the multi-user operation but also enables a two-step scheme capable of producing very neutron-rich nuclei that currently cannot be reached using either of these methods [13, 14]. The two-step scheme offers up to 1,000 times higher yields of some very neutron-rich isotopes than in-flight fragmentation/fission.

## MULTI-USER OPERATION

Simultaneous acceleration of light and heavy ion species requires the proximity of their charge-to-mass ratios. The FRIB linac was designed to simultaneously accelerate multi-

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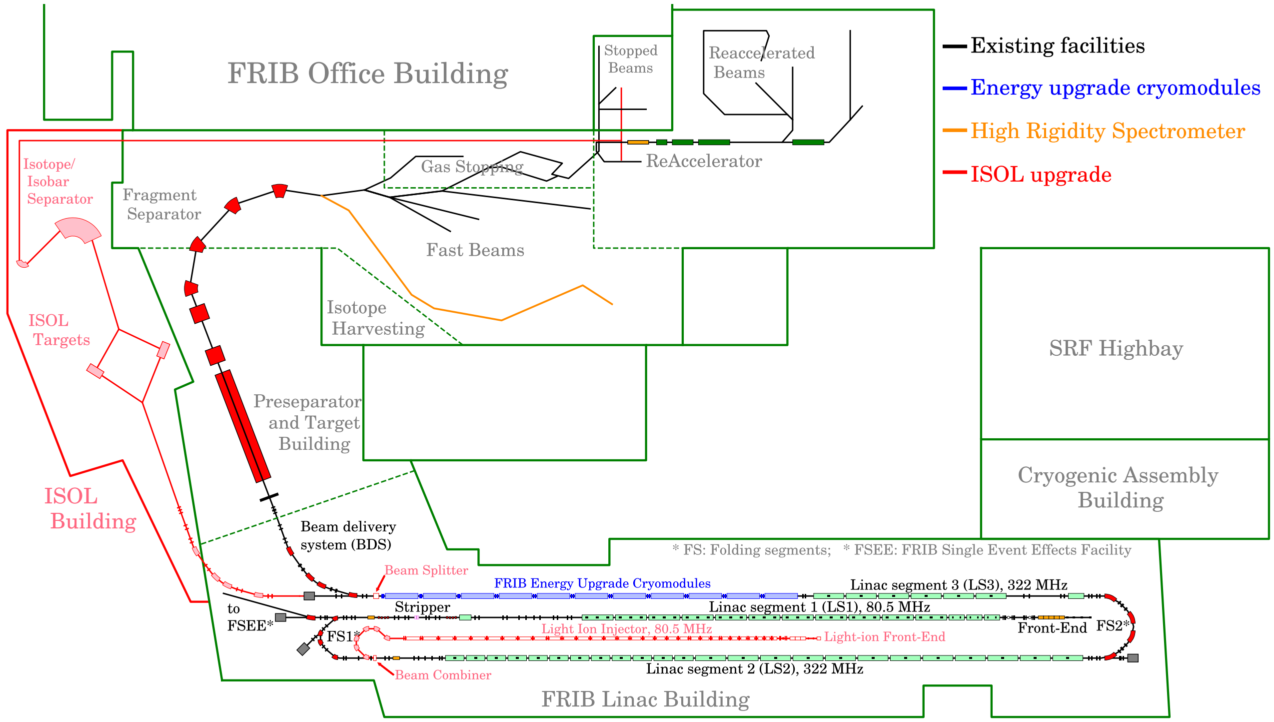


Figure 1: Simplified schematic FRIB layout. Existing and proposed facilities.

ple charge states of stripped heavy ion beams with a ±3.5% spread in charge-to-mass ratios [15]. The most demanded beam for the in-flight isotope production at FRIB is uranium. After stripping, the five-charge-state $^{238}U^{76+..80+}$ beam is accelerated up to 200 MeV/u. If properly combined, $^{3}He^{1+}$ ions suitable for ISOL production can also be simultaneously accelerated with the multiple-charge-state uranium beam. After implementing the FRIB400 upgrade project (blue contours in Figure 1), both beams can reach 400 MeV/u [16]. Light ions such as $^{2}H^{+}$ and $^{4}He^{2+}$ can be accelerated simultaneously with low-Z stripped heavy ions species, namely $^{16}O^{8+}$, $^{36}Ar^{18+}$, and $^{40}Ca^{20+}$.

In addition, the energies of the light and heavy ion beams must be matched precisely, meaning that the light ions must be pre-accelerated in a separate 60-MV injector.

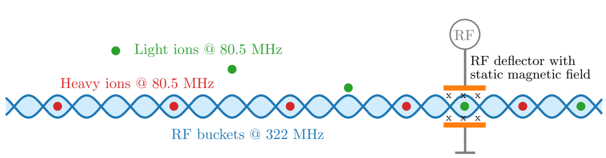


Figure 2: Schematic time structure of combination and simultaneous acceleration of two CW beams at FRIB. Vertical direction represents the beam offset from the linac axis.

In continuous (CW) beam facilities, users receive accelerated bunches from neighboring RF buckets. For example, in CEBAF, the RF deflectors share the CW electron beam between several target stations [17]. For FRIB, we propose alternation of light ion and heavy ion bunches, as presented in Figure 2. This approach requires the operating frequency of the RF linear accelerator to be a multiple of the beams' frequency. The FRIB case easily satisfies this requirement. Two different ion species can be combined by using an RFD operating at the beam frequency.

In the current state of FRIB, the light ion injector and ISOL operation are seen as a very promising upgrade option, "expanding science opportunities and enhancing (providing full) multi-user capability in the future" [3].

## LIGHT ION INJECTOR

We propose placing a compact RT light ion injector between the LS1 and LS2 segments of the FRIB linac as shown in Figure 1. This location does not interfere with any public areas and provides beams of 16.5 – 20 MeV/u, which are sufficient for injection in the post-stripper LS2 segment. The expected power consumption by the proposed RT linac is comparable to that of an SRF-based injector. The greatest advantage of the RT option is, therefore, its reduced construction and maintenance costs. To minimize these costs, we utilize H-type accelerating structures with a very robust and cost-efficient mechanical design, as shown in Figure 3).

H-type structures are highly efficient at low energies [18, 19]. They are widely used for light and heavy ion pulsed accelerators [20], as well as for CW heavy ion beams [21], but only at low ion velocities. At FRIB, we have developed, built, and successfully commissioned two 7-gap 161 MHz IH-buncher resonators designed for 16.5 MeV/u CW beams, as presented in Figure 3 [22]. The resonators demonstrated a 0.8-MV/m accelerating gradient and show potential for reliable operation at higher gradients.

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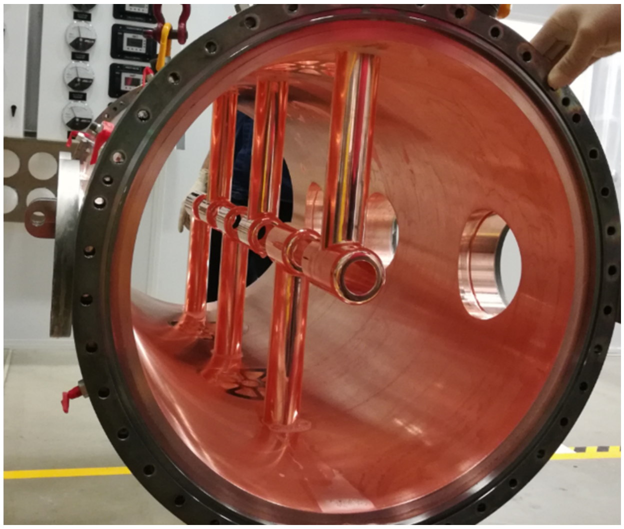

Figure 3: 7-gap resonator of the FRIB IH-buncher.

Since the required output energy range for light ion species is quite narrow, 16.5 – 20 MeV/u, the RT injector can be designed with a fixed velocity profile. The number of gaps per accelerating resonator, therefore, is not limited by transit-time and synchronism factors [23]. A few multigap resonators are more cost-effective than, for example, a set of three-gap cavities, because each cavity requires an RF coupler, a low-level RF controller, at least one movable tuner, and a vacuum pump, among other things. The lattice of the light ion injector may consist of multigap resonators and magnetic quadrupole doublets between them, making alignment and maintenance very easy. Although the frequency of the beam must remain at 80.5 MHz, the accelerating structures of the injector may operate at beam harmonics' frequencies, such as 161 MHz or 241.5 MHz, to maximize their cost efficiency through lower construction cost and higher shunt impedance. The front-end of the injector can also be placed in the FRIB linac tunnel. It would be based on a compact electron cyclotron resonance source of singly-charged ions [24] and a radio-frequency quadrupole (RFQ).

## BEAM COMBINER AND SPLITTER

After the 180° FS1 bend, the multiple charge-state heavy ion beam moves straight along the LS2 optical axis, while the light ion beam needs to converge to it at an angle of approximately 1° (20 mrad) by means of the beam combiner optics. To achieve that, we propose using an optical system that provides a 90° phase advance in horizontal plane, known as the parallel-to-point focusing system. The system transforms parallel and focused beams, moving 4.5 cm apart, into converging beams at the center of the RF deflector (RFD). Due to the proximity of the parallel trajectories, we propose using a Lambertson-type magnet for the last 45° bending magnet of the light ion injector. An RFD placed at the cross-point of converging light and heavy ion beams, produces the final kick that aligns the trajectories. To achieve this, we propose using a combination of the crossed electric RF field produced in a quarter-wave resonator and a superimposed static magnetic field, as shown in Figure 4. This compact option doubles the kick angle for light ions (electric and magnetic components of the Lorentz force are in the same direction) and cancels out the kick for heavy ions (electric and magnetic components of the Lorentz force are in the opposite directions) according to the scheme shown in Figure 2 [25, 26].

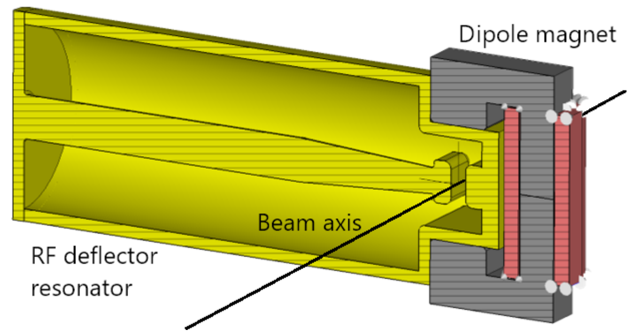


Figure 4: RF deflector (RFD) resonator and a dipole magnet for biasing the trajectories.

To mitigate the emittance growth caused by the transverse-to-longitudinal coupling in the RFD, we can create a flat-top waveform of the RF field by exciting the 241.5-MHz harmonic ($3\lambda/4$ RF mode) in the same cavity.

To separate the beams at 400 MeV/u by the same angle of about 20 mrad, the field strength in the RFD cavity and the magnets has to be a factor of six higher than that of the beam combiner RFD. A practical design for this would be a set of SRF deflecting cavities [27, 28] and two magnets upstream and downstream of them to bias the kick and direct heavy ions straight to the Beam Delivery System bend, see Figure 1.

## CONCLUSION

The presented concept is based on existing technologies and it opens new opportunities for FRIB to become a Next Generation Facility for rare isotope research. Its implementation would significantly increase the versatility and availability of the facility's instruments and beam time. This concept enables the ISOL production method at FRIB, allows for simultaneous multi-user operation and for the promising two-step production scheme.

Moreover, the light ion injector can serve as a driver for a multi-purpose neutron source. Simultaneous production of rare isotope and neutron beam creates a new tool for studying interactions between them [29]. In addition to advancing the nuclear physics research, the concept may also benefit other fields such as neutron physics, material science, medicine, and isotope production, where light-ion cyclotrons are commonly used [30].

Finally, the presented concept aligns with the "green accelerator" idea [31], as it realizes the full capabilities of the FRIB SRF linac.

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