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LIQUID LITHIUM CHARGE STRIPPER COMMISSIONING WITH HEAVY ION BEAMS AND EARLY OPERATIONS OF FRIB STRIPPERS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a 400 kW heavy ion linear accelerator. Heavy ion accelerators normally include a charge stripper to remove electrons from the beams to increase the charge state of the beams thus to increase the energy gain. Thin carbon foils have been the traditional charge stripper but are limited in power density by the damage they suffer (sublimation and radiation damage) and consequently short lifetimes. Because of the high beam power, FRIB had decided to use a liquid lithium charge stripper (LLCS), a self-replenishing medium that is free from radiation damage. FRIB recently commissioned a LLCS with heavy ion beams (^{36}Ar, ^{48}Ca, ^{124}Xe and ^{238}U beams at energies of 17-20 MeV/u). Since there had been no experimental data available of charge stripping characteristics of liquid lithium, this was the first demonstration of charge stripping by a LLCS. The beams were successfully stripped by the LLCS with slightly lower charge states than the carbon foils of the same mass thickness. The LLCS started serving the charge stripper for FRIB user operations with a backup rotating carbon foil charge stripper. FRIB has become the world's first accelerator that utilizes a LLCS.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University produces rare isotopes through nuclear reactions between a production target and heavy ions that are accelerated to energies above 200 MeV/u by a driver linac [1]. Figure 1 shows the configuration of the FRIB driver linac, which consists of three linac segments and two folding segments. At FRIB, the charge stripping occurs in the 1st folding segment (FS1), where beams are accelerated to 17-20 MeV/u after the 1st linac segment (LS1). When the facility is operated at the full power, the beam power at the stripper would reach 40 kW.

It is known that heavier ion beams deposit higher energy in matters as the beams traverse them [2]. Full power uranium beams at FRIB would deposit a thermal power of 1600 W within a 1.5 mg/cm^2 thick carbon foil, or a thermal density of about 70 MW/cm^3 assuming the beam diameter is 2 mm. This ultra-high thermal load would cause serious damages to the carbon foil. The solid carbon foil would also suffer radiation damages. Even the best performance carbon foil that has been successfully used in RIKEN's Radioactive Isotope Beam Factory (RIBF) [3] would not allow continuous full power operations at FRIB.

To overcome this, a self-replenishing medium was sought because it is free from radiation damage and could be a good heat remover. A helium gas stripper has been successfully operated at RIKEN's RIBF [4], and a new charge stripping device based on the helium gas stripper (charge stripper ring, CSR) has been proposed [5]. A drawback of using a gas as the stripping medium is that the equilibrium charge state is significantly lower than solids or liquids. Therefore FRIB has decided to use liquid lithium as the stripper medium as proposed by Nolen [6]. FRIB also considered the helium gas stripper as a backup option of the liquid lithium charge stripper. The key technology to develop was an efficient isolation between the high-pressure helium cell and the ultra-high-vacuum beamline. Because of the limited space available in the driver linac, FRIB cannot use a differential pumping system like the one used in RIKEN, thus sought to develop a "plasma window" [7]. The recent results are published elsewhere [8].

Recently FRIB commissioned a liquid lithium charge stripper (LLCS) with heavy ion beams [9], which was the world's first demonstration of a LLCS. FRIB has also started user operations after the successful completion of its construction. The LLCS as well as a rotating carbon foil charge stripper were used in user operations. This paper describes the results obtained in those tests and operations.

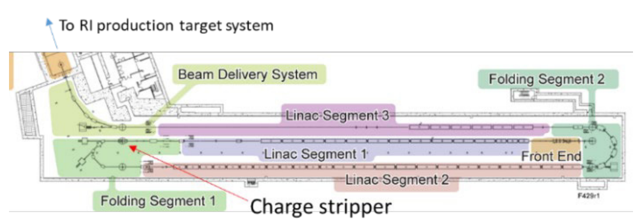

Figure 1: FRIB driver linac configuration. There are three linac segments (LS1, LS2 and LS3) and two folding segments (FS1 and FS2). The charge stripper is located at FS1 before the beam makes a 180 degree turn where the desired charge state(s) is selected for the acceleration at LS2 and LS3.

LIQUID LITHIUM CHARGE STRIPPER SYSTEM AT FRIB

Figure 2 shows a sketch of the FRIB LLCS system. Since liquid lithium is reactive with air, water, and many other materials, safety in use of liquid lithium is the key to

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successful operations. The system has several safety controls to prevent / mitigate lithium-related hazards. The most notable is the secondary containment vessel that completely encloses the lithium loop and is always filled with argon during operations. Thus, even if a liquid lithium leak develops, it will not lead to fire and the system will be kept safe.

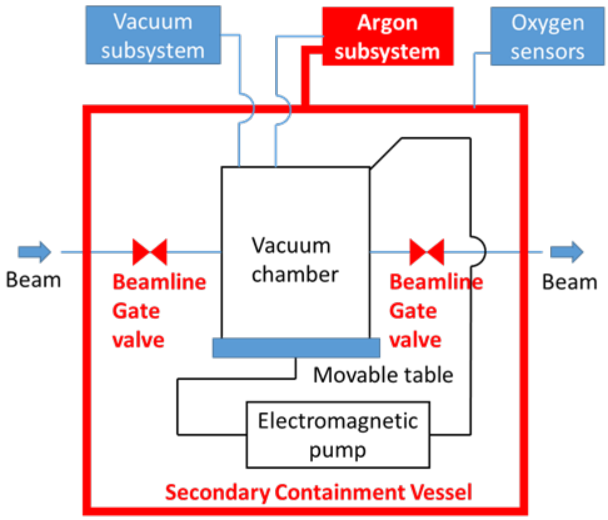

Figure 2: FRIB liquid lithium charge stripper system. The liquid lithium loop is completely enclosed by a secondary containment vessel as a safety control. Noted by red are safety controls.

The LLCS system consists mainly of an argon subsystem, a vacuum subsystem, and a lithium subsystem. The vacuum subsystem is connected to the vacuum chamber, which is part of the lithium loop, where a lithium stripper film is formed. The vacuum chamber is placed on a table that can be moved with stepper motors. This enables scanning of the film while the beam stays in its beam axis.

Figure 3 shows a photograph of the LLCS film formed in the FRIB linac, and a sketch for what is seen in the photograph. The lithium film is made by a round jet issuing from a 0.5 mm orifice impinging on a flat surface with a sharp edge, so-called deflector.

The flow speed was >50 m/s, which is required to not only produce a stable film but also to remove a heat deposited from high power beams. Under a collaboration with Argonne National Laboratory (ANL), the superior heat removal performance of a liquid lithium film flowing at >50 m/s was demonstrated with a proton beam [10]. The volumetric power deposition during this demonstration was higher than the one foreseen during full power uranium beam operations.

To generate a high-speed jet, a custom made direct current (DC) electromagnetic pump was fabricated [11], which can pump liquid lithium at pressures of higher than 1 MPa. The liquid lithium loop is operated at 220°C with electrical heaters to keep lithium melted (the melting point of lithium is 181°C). The vacuum pressure in the vacuum chamber is typically around 1e-8 Torr. As a main vacuum pump, a cryopump was selected. Among advantages of using cryopumps in a liquid lithium system, most notable is that they can operate in a closed environment unlike turbo molecular pumps, which always need an auxiliary backing pump, and cannot create a physical boundary between atmosphere and the lithium environment. Use of a turbo pump in a liquid lithium system would require a reliable gate valve that isolate the lithium environment from atmosphere in case of pump failures.

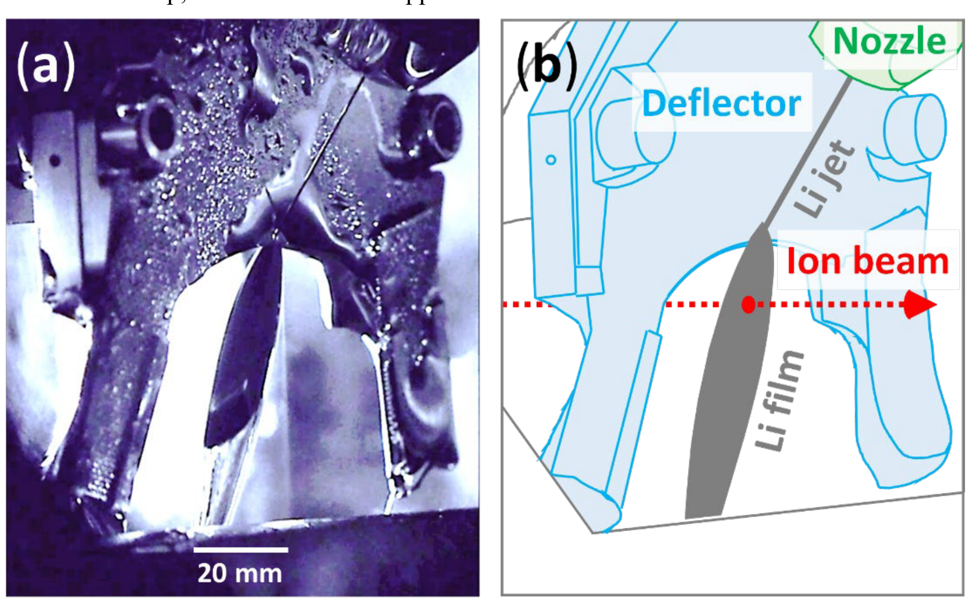

Figure 3: Liquid lithium charge stripper formed in a vacuum chamber which is part of the FRIB linac beamline. (a) Photograph of the lithium film and (b) sketch of what's seen in the photograph. A round jet of liquid lithium being issued from a nozzle impinges on a flat surface ("deflector"). The jet is then deflected forming a stable film that intercepts beams. The film is stable enough to have a mirror surface that reflects the surrounding components in the vacuum chamber or its inner wall.

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COMMISSIONING WITH HEAVY ION BEAMS

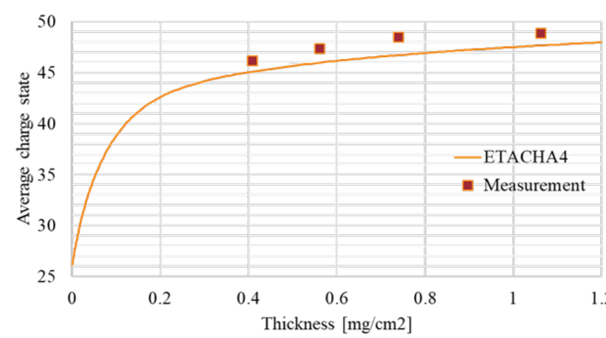
After a series of offline commissioning tests without beams was completed, the LLCS system was transported to the linac tunnel, mated to the linac beamline, and commissioned with heavy ion beams. Three heavy ions ($^{36}Ar^{10+}$, $^{124}Xe^{26+}$, $^{238}U^{36+}$) were used for the commissioning. Table 1 summarizes the beam conditions. The commissioning tests included measurement of LLCS film thickness, measurement of charge states after the LLCS, and high power beam test. The root-mean-square (rms) beam radius was estimated to be 0.5 mm at the stripper.

Table 1: Heavy Ions Used During LLCS Commissioning With Heavy Ion Beams

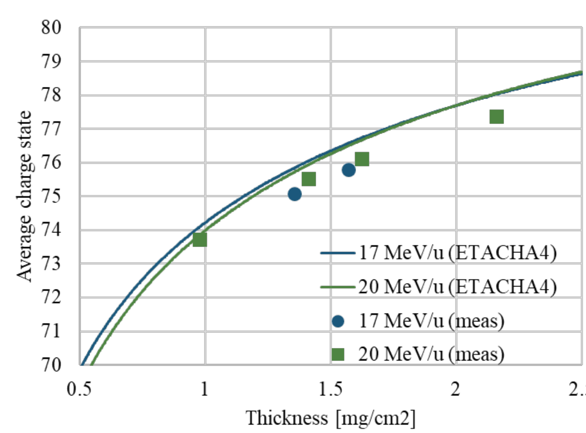
Ions	Energy
$^{36}Ar^{10+}$	17 MeV/u & 20 MeV/u
$^{124}Xe^{26+}$	17 MeV/u
$^{238}U^{36+}$	17 & 20 MeV/u

Measurement of the film thickness was conducted with combination of experiment and calculation. A 20 MeV/u $^{36}Ar^{10+}$ beam was used for the experiment. In the experiment, the beam energy loss at the stripper was measured, and then using the energy loss per unit length obtained from the SRIM code [12], the thickness was estimated. The energy loss was measured over the entire film by moving the table where the vacuum chamber is placed. The measured film was thicker, and its gradient was steeper at locations closer to the impinging point [9]. In other words, at some distance away from the impinging point, the film was uniform enough for the 0.5-mm-radius beam. The measured mass thickness ranged from 0.5 to 1.5 mg/cm^2, which corresponds to physical thickness of approximately 10 to 30 μm. This result was consistent with past measurements using low energy electron beams [13]. The fluctuations of the beam energy after the stripper was less than 0.1% of the incoming beam energy over a period of 2.5 hours, which is acceptable in the further acceleration in the linac. These energy fluctuations were found to be correlated with the temperature fluctuations of the vacuum chamber. By improving the temperature control scheme, this energy fluctuations could be eliminated. Those observations indicated that the film was stable and spatially stationary.

Measurement of charge states was conducted by scanning the current of the first dipole magnet after the stripper and analysing the intensity of beams that pass through a slit after the dipole magnet. The measured charge states were compared with simulation results obtained with the ETACHA code [14,15]. Results showed that the average charge states obtained with the Ar and Xe beams were higher than the calculated values. On the other hand, the average charge states obtained with the U beams were lower than the calculated values, as shown in Figure 4. Figure 5 shows charge state distributions of the xenon (red) and uranium (blue) beams after the LLCS. The beam energy was 17 MeV/u for both beams. The film thickness was 1.05 and 1.40 mg/cm^2 for the xenon and uranium beams, respectively. Figure 6 shows charge state distributions of the 20 MeV/u argon beam after the LLCS and a carbon foil stripper. Thickness was 1.6 mg/cm^2 and 1.2 mg/cm^2 for the lithium and the carbon, respectively. Even though the lithium film was thicker than the carbon foil, the lithium film produced a lower fraction of the fully stripped $^{36}Ar^{18+}$. The charge state distributions of the 20 MeV/u uranium beam were also measured in the liquid lithium and a carbon foil at 1 mg/cm^2 thickness. It was found that the average charge states are 73.7 and 76.9 for the liquid lithium and carbon, respectively.



(a) Average charge states of xenon beam stripped by lithium.



(b) Average charge states of uranium beam stripped by lithium

Figure 4: Average charge states of heavy ion beams stripped by lithium as a function of lithium thickness. The lines show the simulation results with ETACHA4, and symbols show the measured values.

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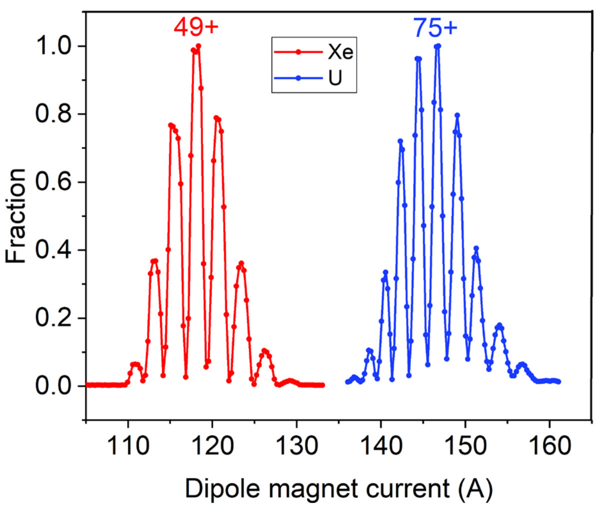

Figure 5: Xenon (red) and uranium (blue) charge state distributions after the liquid lithium stripper. The thickness is 1.05 mg/cm^2 for the xenon beam and 1.40 mg/cm^2 for the uranium beam.

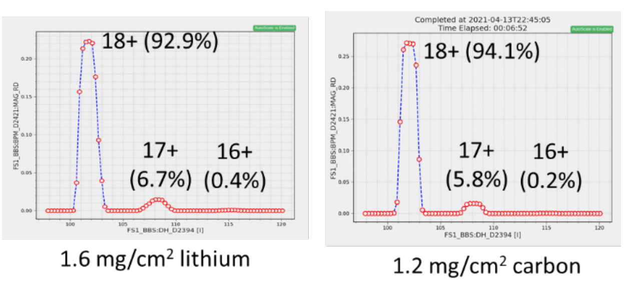

Figure 6: Charge state distributions of 20 MeV/u argon beam after the LLCS and carbon foil stripper. Thickness was 1.6 mg/cm^2 and 1.2 mg/cm^2 for the lithium and the carbon, respectively.

To test thermal responses of the LLCS to a high power heavy ion beam, the LLCS was irradiated by a high-intensity 17 MeV/u $^{36}Ar^{10+}$ beam. The beam power that can be transported to a beam dump in FS1 is limited to 500 W. Therefore, to conform to this limitation but utilize the maximum peak power available, the beam intensity was kept to the maximum value of 12 particle µA that the ion source was able to produce while the beam duty cycle was limited to 5.4% with the repetition rate of 10 Hz. With these parameters, the average beam power was 400 W while the peak power was 7400 W at the stripper during each 5.4 ms period. Since it took approximately 20 µs for the flowing lithium at 50 m/s to completely cross the beam spot of 1 mm, it was considered that the longest time constant of any thermal and fluid dynamic responses of the lithium flow was 20 µs. Thus the 5.4 ms long beam, which was 270 times longer than the longest time constant, may be considered well representing a continuous beam. If this beam had been transported to the production target in the CW mode, the final power at the target would have been more than 74 kW. The peak volumetric power deposition into the lithium was estimated to be 6 MW/cm^3 (peak power loss 50 W) during the test, which is about 10% of the FRIB full power uranium beam operation value. As expected from the past thermal performance test at a higher volumetric power deposition [10], the beam parameters and LLCS system operating parameters were stable during the test without an issue. Figure 7 shows the beam energy after the LLCS during the test. Figure 8 shows a photo of beam spot on the film during the test.

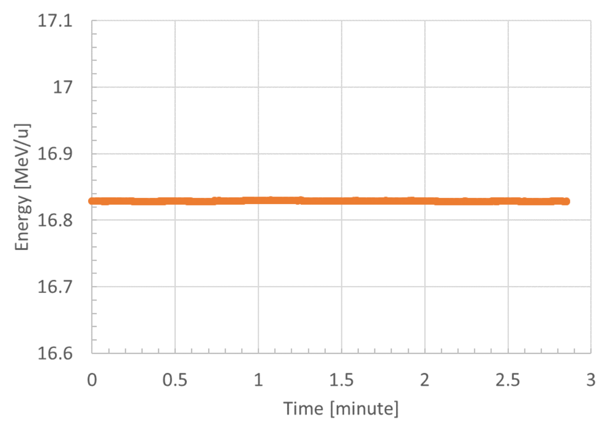

Figure 7: ^{36}Ar beam energy after the lithium stripper during the high-intensity irradiation test (peak intensity 12 particle µA, peak beam power 7400 W (average 400 W, duty cycle 5.4%), peak power loss 50 W (volumetric power deposition 6 MW/cm^3).

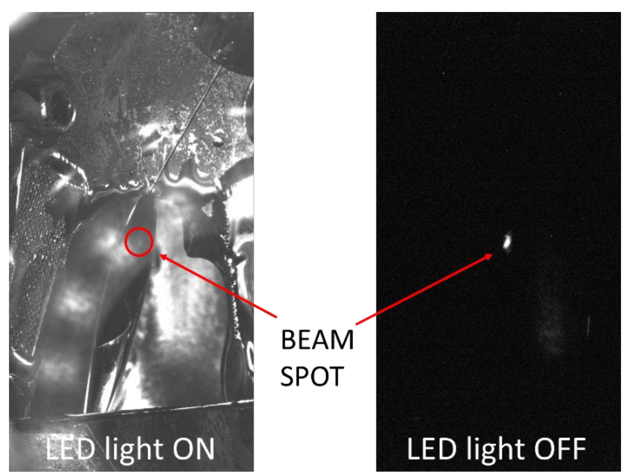

Figure 8: Beam spot on the LLCS during the high-intensity irradiation test. The LED light was turned off on the right photo to take a clear beam spot.

EARLY OPERATION EXPERIENCES

FRIB officially started the user program in May 2022 [16,17]. The LLCS was used during the first user operation conducted in May 2022. The primary beam was ^{48}Ca and beam power was up to 1 kW at the production target (about 100 W at the stripper). Rare isotopes were successfully delivered to the user station. The long-term operation with the

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primary ^{48}Ca beam was validated. Figure 9 shows an example of the beam energy after the LLCS during the operation.

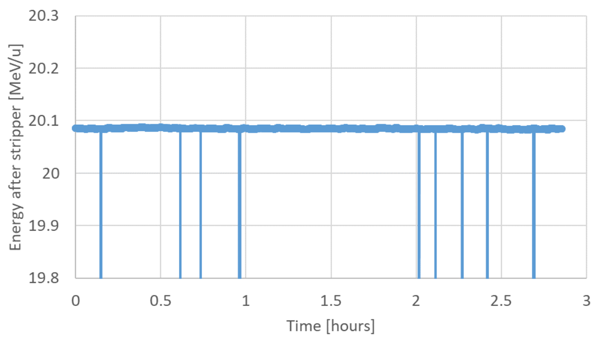

Figure 9: ^{48}Ca beam energy after the lithium stripper. At downward spikes the beam was tripped.

A rotating carbon foil charge stripper was also used for user operations. The carbon stripper is located in FS1, adjacent to the LLCS, as shown in Figure 10. These strippers are lined up tandemly in the beamline. This configuration was adopted to use the carbon stripper as a backup stripper. The carbon stripper cannot be used for high power heavy ion beams, but this flexibility gives an option of switching one stripper to another. When the facility operates at a high power (>10 kW), we use the LLCS. But in case it fails, our plan is to switch to the carbon stripper with a reduced beam power to continue delivering beams to users.

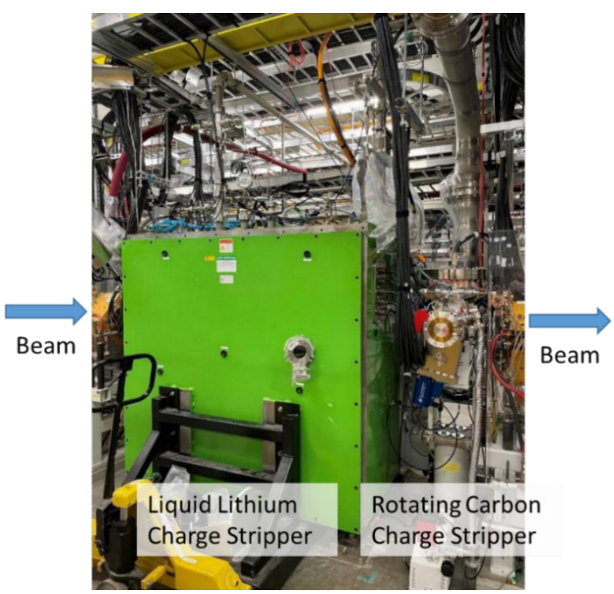

Figure 10: Photograph showing the LLCS and the carbon charge stripper connected in series in FS1 of the FRIB linac. The LLCS is located upstream of the carbon stripper.

The carbon stripper system is equipped with two independent motors that can rotate and move vertically a 100-mm-radius carbon foil. This mechanism increases the available area of the foil for irradiation, and thus reduces the local fluence of ions passing through the foil, which can longer the foil lifetime. The rotational motion is intended to reduce the maximum temperature of the foil. Thus the combination of both motions reduces thermal and radiation damages to the foil, prolonging its lifetime.

During the second user operation in June 2022, a 1.5 mg/cm^2 graphene foil purchased from Applied Nanotech Inc served as the stripper for this operation. The primary beam was ^{82}Se. The beam energy and power at the stripper were 20.3 MeV/u and 270 W, respectively. Among 270 W, about 5 W was estimated to be deposited to the carbon foil (about 50 kW/cm^3 volumetric heat deposition). Except for the initial thickness reduction (about 3%) during the conditioning, the foil didn't show a significant thickness reduction over a week. It contributed to the successful user operation.

SUMMARY

The Facility for Rare Isotope Beams (FRIB) at Michigan State University has become the world's first accelerator in which a liquid lithium charge stripper (LLCS) is used [9]. The LLCS was successfully commissioned with heavy ion beams: $^{36}Ar^{10+}$, $^{48}Ca^{10+}$, $^{124}Xe^{26+}$, and $^{238}U^{36+}$. For the first time, the charge stripping efficiency of a lithium film was measured and compared with simulation results. Charge state evolutions tend to agree with simulations, but the average charge states didn't show a good agreement with simulations. The beam energy loss measurement showed that the lithium film was stable enough for the beam to be accelerated in the subsequent stages of the linac. Measured charge states after the lithium stripper were lower than those after the carbon stripper of the same thickness. The peak heat deposition of 6 MW/cm^3 from ^{36}Ar beam, which is equivalent to a condition of >74 kW beam at the target, didn't cause any issue in the lithium stripper. After the successful commissioning, the LLCS started serving as a charge stripper for FRIB user operations with a backup rotating carbon foil charge stripper.

ACKNOWLEDGEMENTS

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