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OPERATION AND R&D OF LIQUID LITHIUM CHARGE STRIPPER AT FRIB

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Abstract

Charge stripping is essential for the efficient acceleration of heavy-ions. The Facility for Rare Isotope Beams (FRIB) utilizes the Liquid Lithium Charge Stripper (LLCS) to produce the world's most powerful heavy-ion beams. This paper summarizes experiences of the LLCS after three years operation and ongoing R&D efforts including new method to form the liquid lithium film jet.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a scientific user facility operated by the U.S. Department of Energy Office of Science [1]. FRIB operates the world's most powerful heavy-ion accelerator for stable ions from ^{16}O to ^{238}U. So far, the beam power has been demonstrated up to 20 kW with 200 MeV/u energy including ^{238}U, and it will ultimately ramp-up to 400 kW in the future. In the high-power heavy-ion accelerators, charge stripping is a key technology used to strip electrons and produce highly charged ions for efficient acceleration.

LIQUID LITHIUM CHARGE STRIPPER

Conventionally, a thin carbon foil has been used for charge stripping. However, with high-power heavy-ion beams, the lifetime of the foil is limited due to significant energy deposition and radiation damage on the material. To overcome this technical issue, FRIB utilizes the Liquid Lithium Charge Stripper (LLCS) [2]. In this device, a free-surface liquid metal film jet is used to strip the electrons from the beams. Compared to solid-based methods, flowing a liquid metal is more compatible with harsh environments characterized by extreme thermal loads and radiation. Particularly, liquid lithium has a good thermal performance due to its relatively low melting point, high heat capacity and, low vapor pressure. The free-surface flow allows greater flexibility in dimensions with minimal mechanical support structures. In addition, low atomic number lithium offers physical advantages: the low electron capture cross-section of swift heavy-ions with respect to the lithium atom yields high charge stripping efficiency [3], while minimizing energy straggling and multiple scattering of the penetrating beam.

OPERATION EXPERIENCE

The LLCS is operated at the Folding Segment 1 (FS1), an early stage of the driver linac following the Linac Segment 1 (LS1), where the beam energy is 17-20 MeV/u (Fig. 1, top). For a case of the ^{238}U beam, the charge state of the beam is $Q = 35$ before stripping, and distributed around $Q = 75$ after stripping. Through subsequent acceleration in Linac Segments 2 and 3 (LS2 and LS3), up to five charge states ($Q = 73 - 77$) are accelerated and delivered to the rare isotope production target [4]. The other unused charge states ($Q < 73$ and $Q > 77$) are selected by a bending magnetic field and intercepted by a water cooled Glidcop jaws (charge selector).

A leaf-shaped liquid lithium film flowing at 50 m/s is produced by impinging a round jet (500 µm diameter) onto a deflector (Fig. 1, bottom left). The typical thickness of the film is 1.0 mg/cm^2 or approximately 20 µm corresponding to typical energy deposition of about 0.5 MeV/u. The bottom right panel of Fig. 1 shows an image of the lithium film during 20 kW beam power operation with a ^{238}U beam. The incident beam power is approximately 2 kW, corresponding

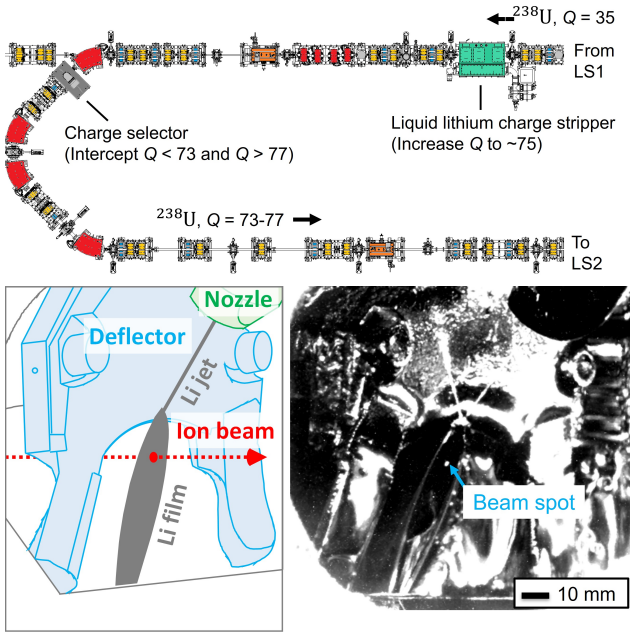

Figure 1: Top: Schematic view of the FS1. Charge states of the ^{238}U beam are indicated. Bottom left: Sketch of the film formation scheme reproduced from [2]. Bottom right: Picture of the liquid lithium filmed operated with the 20 kW ^{238}U beam. The beam spot on the film is indicated. Note that the poor quality of the image is due to radiation damages on the camera.

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to a power deposition of 50 W on the film. On the upper part of the film, a beam spot with a typical spot size of approximately 0.5 mm (RMS) is visible.

The LLCS has been supporting the beam power ramp-up since 2022. By the summer of 2025, the total operating hours of circulating liquid lithium in a high-temperature loop at temperatures above the melting point of 180.5 °C have exceeded 10,000 hours. The long operation hours have provided experience toward more reliable operation. For example, maintenance procedures for components degraded by lithium have been established, and R&D activities aimed at conceptual upgrades in the future have been identified.

During the operation, we observed two types of instabilities in the liquid lithium film. One type of instability involves a random transition in the film thickness, occurring at relatively long intervals (typically few hours). Figure 2 shows the distribution of the beam energy deposition on the film for ^{238}U and ^{124}Xe beams measured with phases of the beam bunch before and after the LLCS. We have observed a discrete peak structure for each beam species. The origin of such a peak structure is still unknown; it could be purely fluid dynamical (e.g., the free-surface flow exhibits multiple modes) or related to the system (e.g., flow rate instability caused by an electromagnetic pump).

Currently, we are investigating whether fluid dynamics inherently produce multiple modes in the film thickness using a water simulant and a film thickness gauge based on optical interferometry. In the operating device, sudden transitions in film thickness and beam energy result in beam loss at the LS2. To compensate for this beam loss, two types of feedback controls were implemented using two RF cavities: one is a fast (~0.1 s) feedback on the beam energy and the other one is a slow (~30 s) feedback on the film thickness via vertical mechanical movements of the film. The latter one works because the film has a vertical thickness gradient and the entire setup including the nozzle and deflector can be mechanically moved.

The other type of instability is an instantaneous (~100 µs) fluctuation of the film thickness, occurring at relatively short intervals (typically several minutes to hour). Figure 3 shows the measured beam currents at different locations when this instability was observed. At approximately 150 µs, the beam current after the LLCS starts dropping to the level measured before the LLCS. This indicates that the beam passes through an approximately several-mm region where the film is absent or extremely thin so that the charge state of the beam basically remains constant. With this condition, a majority of the beam is intercepted by collimators before the charge selector so that the beam current after the FS1 in Fig. 3 drops to nearly zero. It should be noted that the lost energy of 0.3 J does not cause any critical damage to the accelerator components.

Currently, we have been investigating possible causes that could produce voids or bubbles inside the lithium film jet. So far, we have excluded the possibility that these originate from interaction between the high-power beam and the lithium film based on a thermal test with high-power proton beam [5] and observed frequency of fluctuation that does not depend on the beam power.

R&D ACTIVITIES

Our major R&D effort is focused on developing a new scheme to form the liquid lithium film jet. The performance of the LLCS will be further improved by doubling the film thickness which improves the peak charge state of the ^{238}U beam from $Q = 75$ to $Q = 78$. In addition, improving the spatial uniformity and temporal stability of the film thickness can reduce beam loss and minimize emittance growth.

Due to difficulty with handling liquid lithium, fluid dynamical properties for new film formation schemes are studied using pure water. The stability of liquid lithium film can be indirectly investigated if Reynolds (Re) and Weber (We) numbers match with those of the water film. There were various theoretical and experimental studies on free-surface liquid film formation mostly oriented to high-power laser applications. In our case, however, one of the main challenges is forming a stable film with high flow speeds to reduce the thermal load, which requires relatively high Re and We

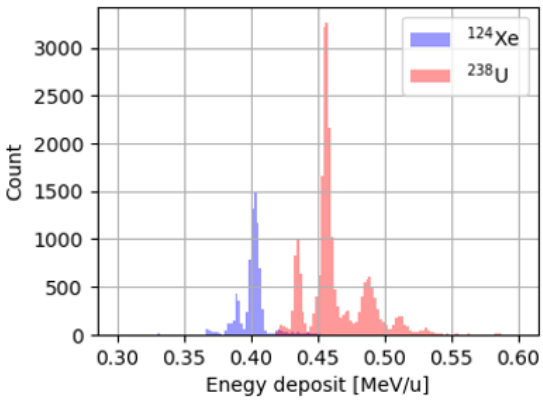

Figure 2: Distribution of the measured energy deposition on the film for 15 kW ^{238}U and 10 kW ^{124}Xe beams. The sampling period is 10 seconds. The approximate total sampled times for the ^{238}U and ^{124}Xe beams are 65 and 22 hours, respectively.

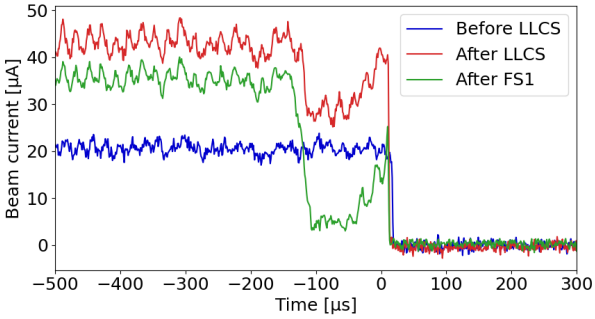

Figure 3: Measured beam currents at different locations with 20 kW ^{238}U beam. The beam was shut off at around 0 µs due to instability of the liquid lithium film.

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numbers. For example, Re = 900 and We = 66 are required for a 20 µm-thick film jet flowing at 50 m/s.

Figure 4 shows examples of different schemes that we studied for producing approximately 10 mm-wide water films. In scheme (a), the film is generated by colliding two round jets [6]. Based on the current LLCS setup, this is the most straightforward approach to double the film thickness by doubling the flow rate. Because of colliding free-surface flows, the round jets are smoothly transformed into a continuous film. For this reason, a good uniformity of the thickness was confirmed both by visually observing interference patterns with a sodium lamp and by measuring the thickness using an optical interferometry gauge. Nevertheless, drawbacks include the instability of the film at high Re and We numbers and requirement of precisely aligning two nozzles. Scheme (b) forms the film using a single-volume nozzle, where the flow is guided and collided inside a narrow internal channel [7]. Its significant advantage is in reduced mechanical complexity and good film stability even at high Re and We numbers. However compared to other methods, the produced film was less uniform as evidenced by a lack of interference pattern with the sodium lamp. This is presumably due to turbulent boundary layers developing inside the narrow channel (<1 mm) of the nozzle. Scheme (c), originally reported in [8], produces colliding flow components with flow contraction at exit of the single-volume nozzle. It is similar to the scheme (b) but offers greater flexibility in nozzle geometry so that it can have a larger volume of the fluid channel (>10 mm) suppressing development of the boundary layer. The produced water film exhibits both good stability at high Re and We numbers and uniformity as evidenced by the visible interference pattern in Fig. 4.

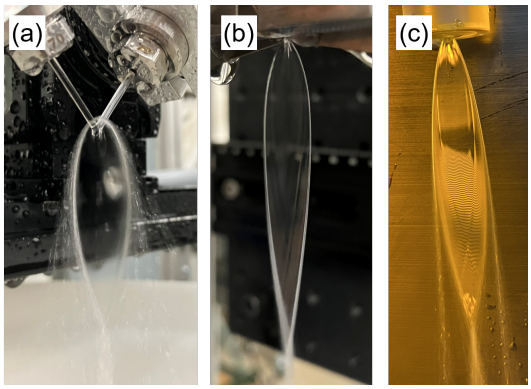

Figure 4: Water film jets produced with different schemes. (a): Colliding two round jets. (b): Internally colliding flows inside a single-volume nozzle. (c): Similar to (b) but colliding flow components are produced with contraction.

We are currently conducting extensive investigations with water into the scheme (c) aiming to use it with liquid lithium in the future. As the next step, we are refining the nozzle design to enable precise control over key film parameters, including thickness, width, and flow speed. In addition, the fabrication of the nozzle using materials compatible with liquid lithium (e.g., stainless steel) is being explored through precision machining techniques such as CNC milling and wire EDM. Once established, the new scheme will be tested with liquid lithium using the second LLCS module, which is currently under construction at FRIB.

The second R&D topic is to develop a new technique to measure the thickness of the liquid lithium film and diagnose its stability over both short and long time scales without using heavy ion beams. This is challenging because optical interference cannot be used for the opaque film and conventional radiation-based techniques such as electron diffraction and X-ray absorption spectroscopy are not applicable to this thickness range. We are currently studying a method to measure the thickness of a thin foil using multiple-scattering angle of 30 keV electron beam based on previous study [9].

In parallel, we have been working on several other topics. For example, we have developed a new gasket made from a material compatible with liquid lithium to replace conventional copper gaskets. Initially, we used steel gaskets. More recently, we developed a new annealed iron gasket that is softer than the steel gaskets. Moreover, we are studying the mechanism of light emission from the film at the beam spot (visible in Fig. 1, bottom right) using an optical CCD spectrometer. Finally, the accumulated impurities in lithium after extended operation as well as the migration of lithium atoms to other beamline components, is being investigated using inductively coupled plasma mass spectrometry (ICP-MS).

CONCLUSION

The established charge stripping technology using liquid lithium is now routinely used at FRIB, having supported high-power beam operations over the past three years and enabling future ramp-up to the ultimate goal of 400 kW. The extensive operational hours have yielded both new scientific insights and practical experience that contribute to increasing the reliability of the system. They also point toward directions for a conceptual upgrade, including the development of a new film formation scheme.

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