Liquid Lithium Charge Stripper Commissioning with Heavy Ion Beams and Early Operations of FRIB Strippers

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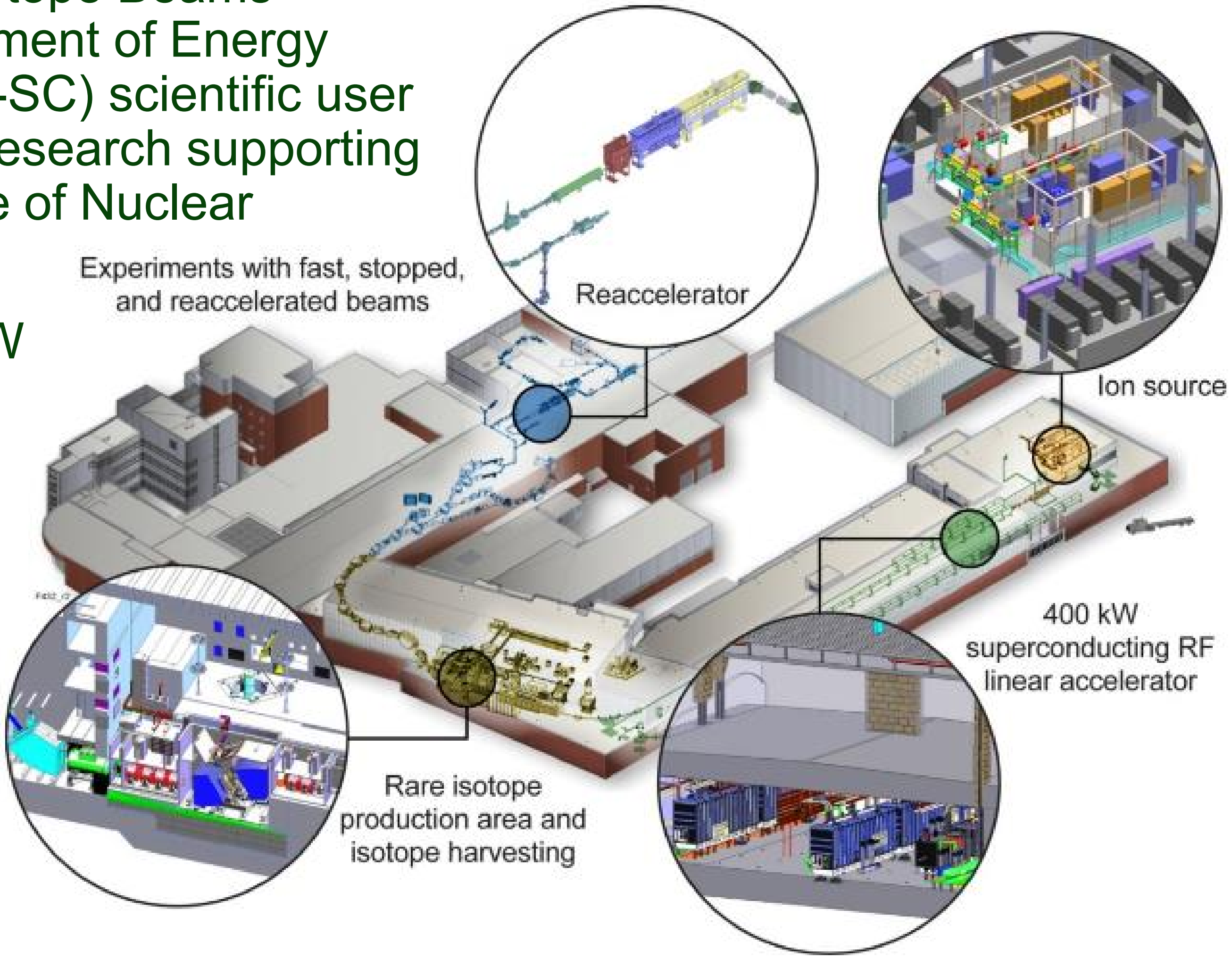
Outline

- What is FRIB?
- Charge stripper options: why liquid lithium?
- FRIB liquid lithium charge stripper system
- Commissioning with heavy ion beams
- Early operation experiences
- Future perspective
- Summary

What is FRIB?

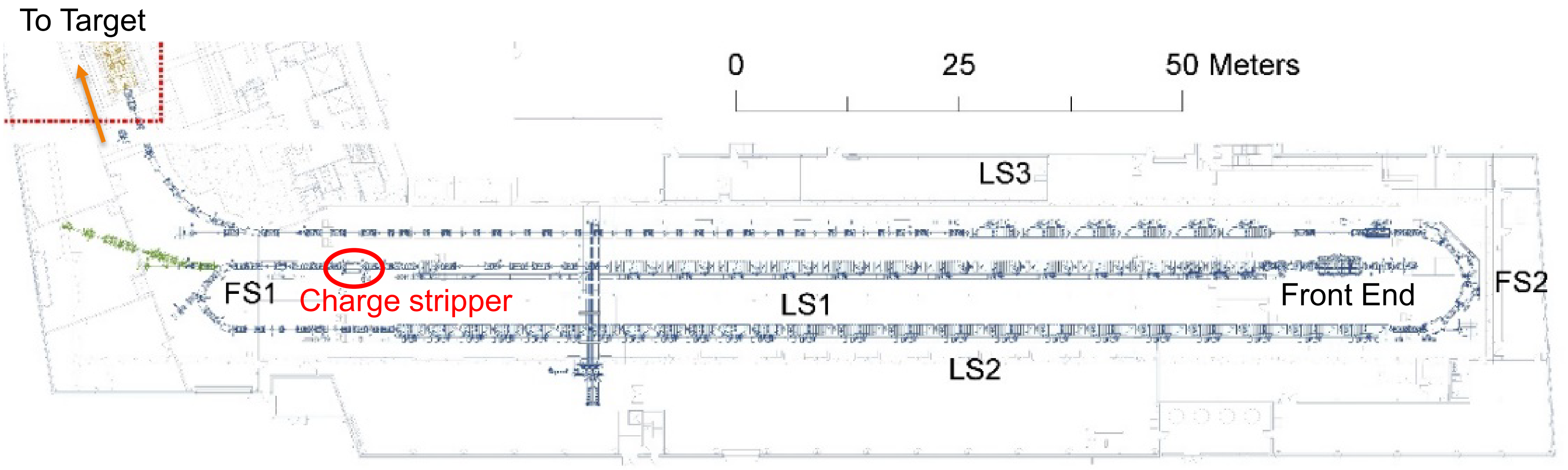
- The Facility for Rare Isotope Beams (FRIB) is a U.S. Department of Energy Office of Science (DOE-SC) scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC
- Key features are 400 kW beam power for all ions (8pμA or 5x10^{13} ^{238}U/s) and E/A>200 MeV/u
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



FRIB Driver Linac

- Three linac segments with two folding segments for a compact design (ion sources located above the linac tunnel)
- The charge stripper is located at the end of Linac Segment 1 (LS1), where ions have energies between 16 and 20 MeV/u. The bend (FS1) will select multiple charge states of the stripped beam (up to five charge states for uranium ions) for simultaneous acceleration in the rest of the linac

P. N. Ostroumov, *et al.*, *Phys. Rev. Lett.* **126**, 114801 (2021)



Why Liquid Lithium?

- Unprecedentedly high intensity (8 pμA or 5x10^{13} ^{238}U/s)
  - Requires a self-replenishing stripping medium, instead of the traditional carbon foil, to avoid radiation and thermal damages
- Two options are available: liquids and gases.
  - Solid carbon foils can be still used with lower intensity beams
- Liquids are preferred because they can give higher charge states than gases
- For liquids, liquid lithium is the best option
  - It has a relatively low melting point (181 C), low vapor pressure at that temperature (10^{-7} Pa), high heat capacity as well as high latent heat
  - There had been already significant R&D efforts done by Dr. Nolen and colleagues of ANL under the RIA project
  - The negative aspect is its reactivity with air, water and many other materials

Liquid Lithium Becoming Popular in Accelerator Community

- SARAF
  - Neutron production target
  - Demonstrated with proton beam
- IFMIF (or the most recent IFMIF-DONES, ANS)
  - Neutron production target
  - Standalone validation completed
- FRIB
  - Charge stripper
  - Demonstrated with heavy ion beams

I. Silverman et al., AIP Conference Proceedings **1962**, 020002 (2018)

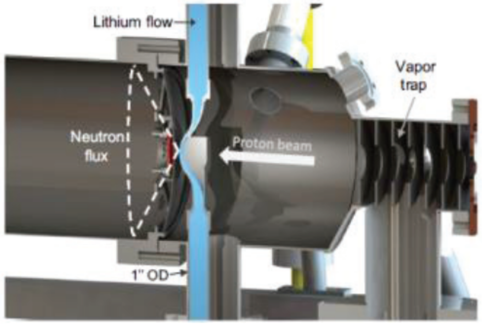


FIGURE 3. LiLiT target, for details see [5]. The sample to be irradiated by the neutrons can be placed at about 1 cm from the target (the red line) and is exposed there to neutron flux of about 2×10^{10} n/s/cm²/mA

H. Kondo et al., Nucl. Fusion **57** (2017) 066008 (10pp)

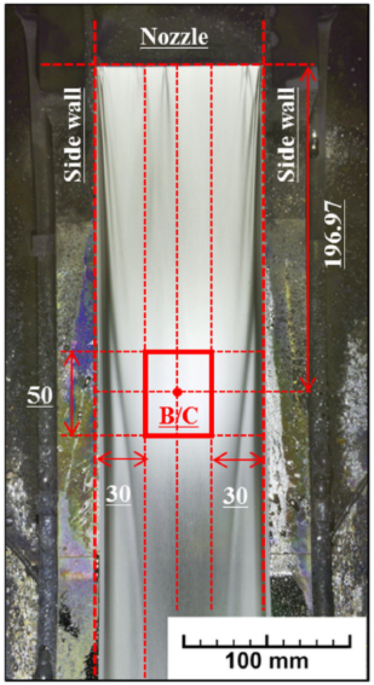
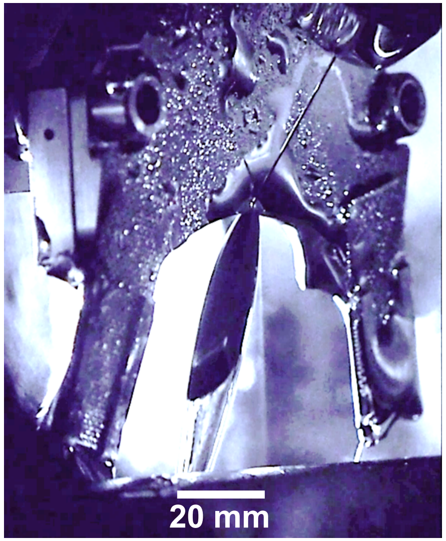


Figure 8. Appearance of the Li target under the IFMIF conditions (250 °C, 15 m s^{-1}, 10^{-3} Pa).



T. Kanemura et al., Phys. Rev. Lett. 128, 212301 (2022)

R&Ds to Test the Lithium Stripper Concept:
Originated by ANL. Later under collaboration between ANL and FRIB

- Original proposal by Nolen
  - J. A. Nolen *et al.*, ANL-01/19, 2001
- Proof-of-principle test using water, and then film making test using liquid lithium
  - C.B. Reed et al., ANL/NE-11/01
- Ultra-high power deposition test using the LEDA proton source (LANL)
  - Y. Momozaki et al., J. Radioanal. Nucl. Chem. DOI 10.1007/s10967-015-4074-9
  - Achieved 200% of volumetric power deposition expected at FRIB
  - Lithium film survived
- Remaining question to answer: Can liquid lithium film really strip beams? Stripping performance?

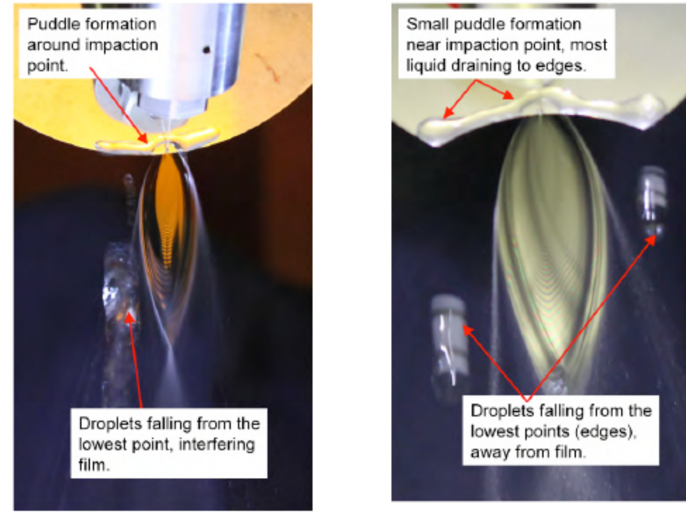
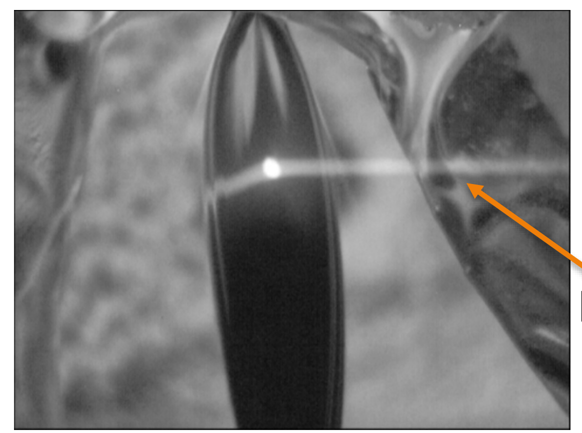


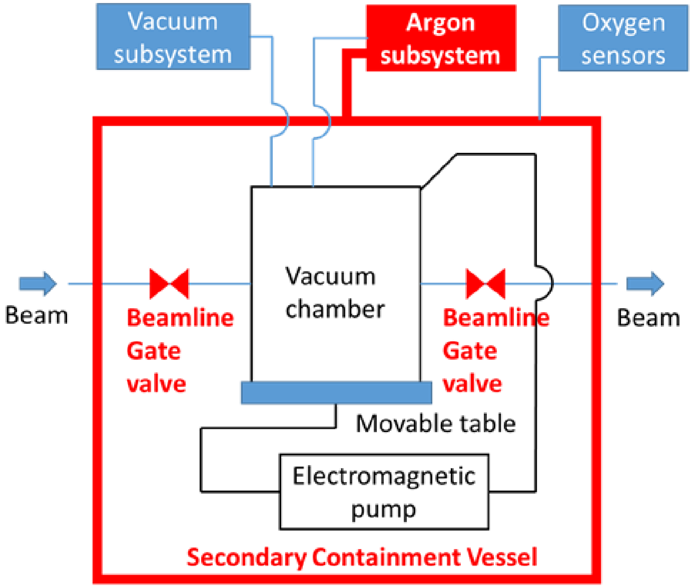
Figure 43 – Pictures of old and new deflectors in operation.



Film being irradiated by proton beam

FRIB Liquid Lithium Charge Stripper (LLCS) System Constructed

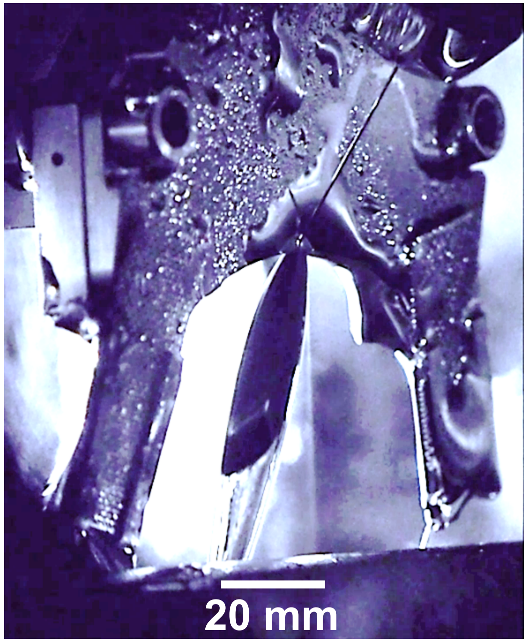
- Safety subsystem to prevent / mitigate lithium fire hazards
  - Secondary containment vessel (SCV) that completely encloses the lithium loop, and is always filled with argon during operations
  - Thus, even if a liquid lithium leak develops, it will not lead to fire and the system will be kept safe
- Argon subsystem
- Vacuum subsystem
- Lithium subsystem (lithium loop)
  - Operation at 220 degree C (the melting point of lithium is 181 degree C)

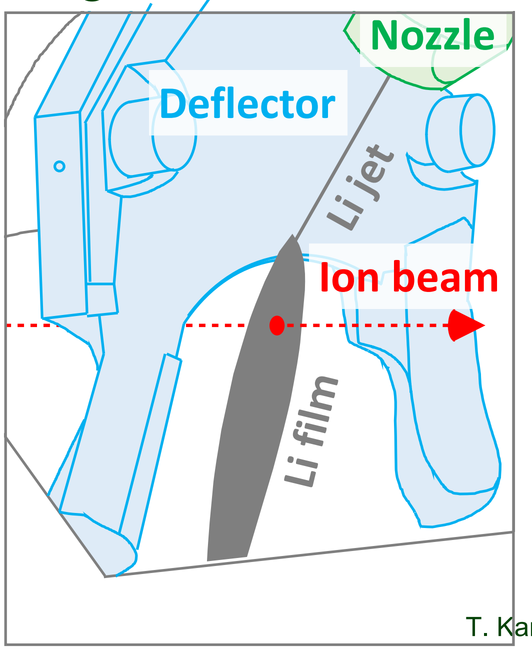


SCV in FRIB linac beamline

Liquid Lithium Film Formed at FRIB and Ready for Commissioning with Beams

- Confirmed a lithium film that has equivalent quality of the ANL film can be formed
  - Lithium speed: > 50 m/s
  - Vacuum pressure: ~ 1e-6 Pa
- Confirmed LLCS system was ready to be transported and mated to the linac for beam commissioning

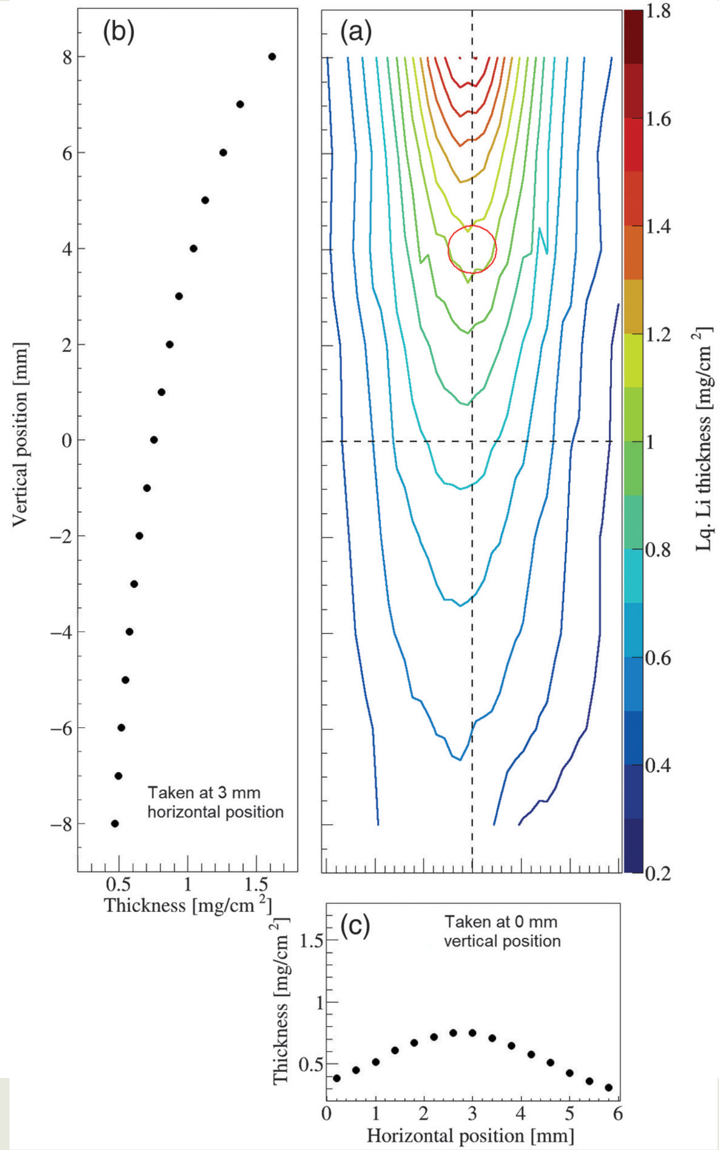




Milestones	Year
Establishment of lithium film and thickness measurement at ANL	2010
Full (2X) power density test of lithium with Low Energy Demonstration Accelerator (LEDA) proton source at ANL	04/2013
Liquid lithium electromagnetic pump test	04/2017
First liquid lithium circulation	08/2018
Measurement of lithium film thickness with electron gun system	09/2019
Commissioning with heavy ion beams	04/2021

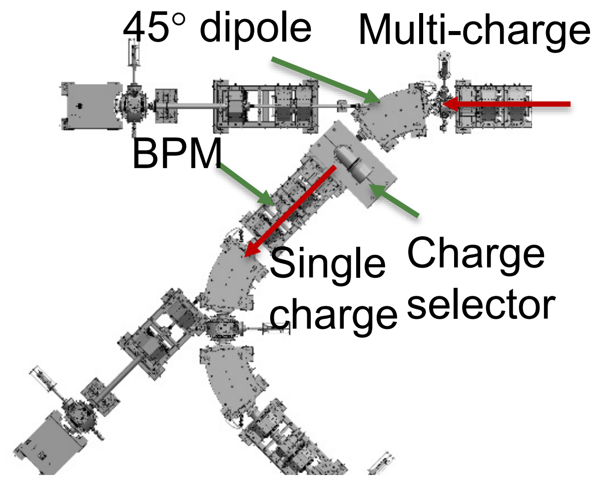
Lithium Thickness Measured by Beam

- Mass thickness measured
  - Exp: 20 MeV/u $^{36}Ar^{10+}$ beam energy loss measured over the film
  - Calc: Energy loss per unit length obtained from the SRIM code
- At some distance away from the impinging point, the film was uniform enough for the 0.5-mm-radius beam
- Consistent with past measurements using low energy electron beams
- Energy fluctuations after the stripper was less than 0.1% of the incoming beam energy, acceptable for further acceleration

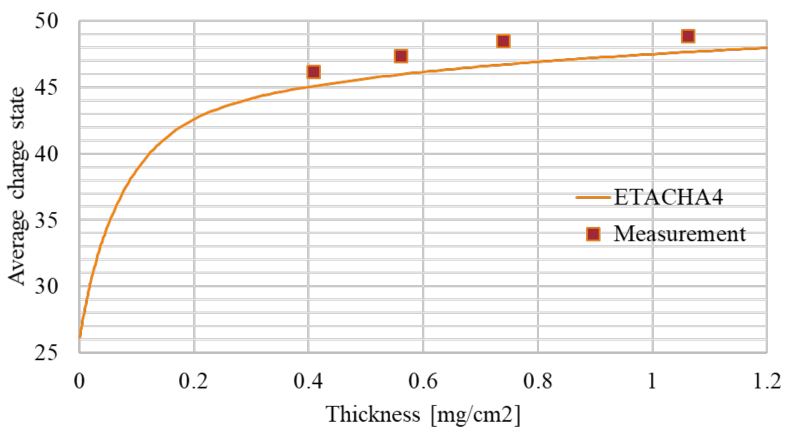


Charge States of Heavy Ion Beams after the LLCS Measured [1/3]

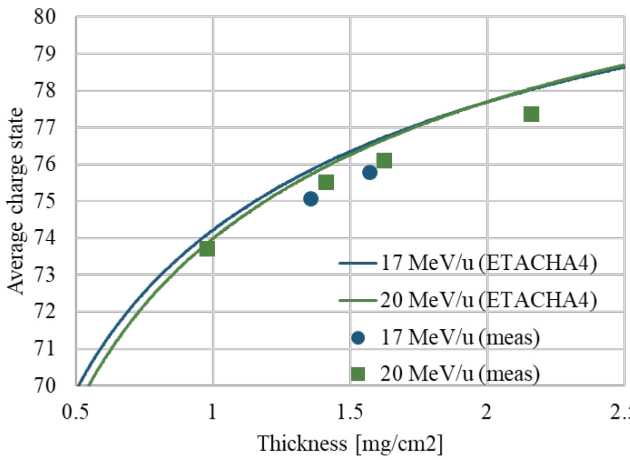
- Charge states measured by scanning the 1st dipole magnet in FS1
  - 17 and 20 MeV/u Ar, Xe and U beams
- For Xe, Ar, the average charge states are slightly higher than ETACHA4 prediction
  - 1 mg/cm^2 for Xe and Ar beams
- Uranium beam charge states are slightly lower than ETACHA4 prediction
  - 1.5 mg/cm^2 for U



^{124}Xe

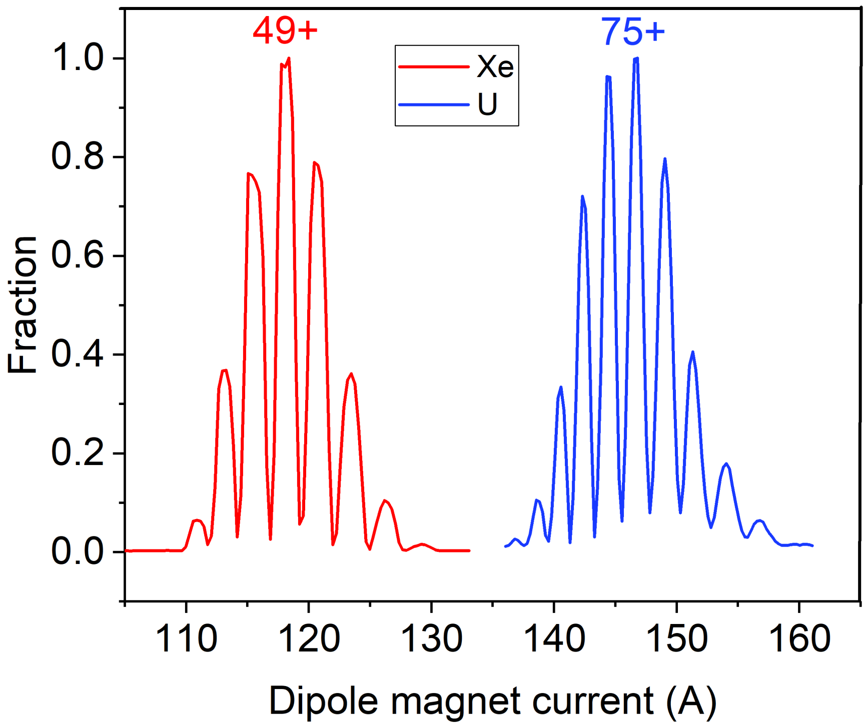


^{238}U



Charge States of Heavy Ion Beams after the LLCS Measured [2/3]

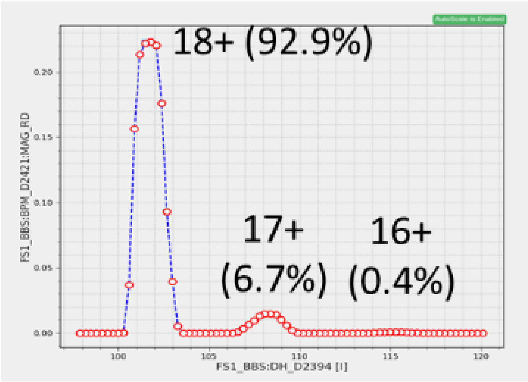
- Charge state distributions of the xenon (red) and uranium (blue) beams after the LLCS.
- Beam energy was 17 MeV/u for both beams.
- The film thickness was 1.05 and 1.40 mg/cm^2 for the xenon and uranium beams, respectively.



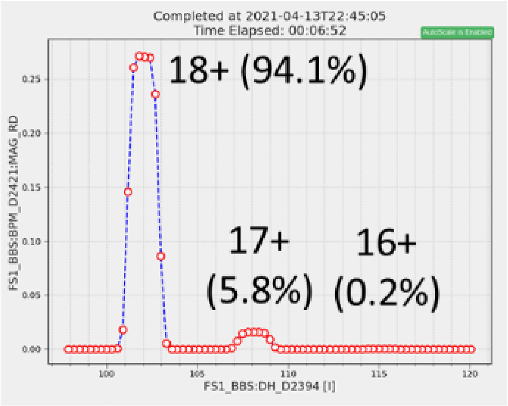
Charge States of Heavy Ion Beams after the LLCS Measured [3/3]

- Charge state distribution comparison between lithium and carbon.
- 20 MeV/u argon beam: Even though the lithium film was thicker than the carbon foil, the lithium film produced a lower fraction of the fully stripped $^{36}Ar^{18+}$.

^{36}Ar
20 MeV/u



1.6 mg/cm^2 lithium

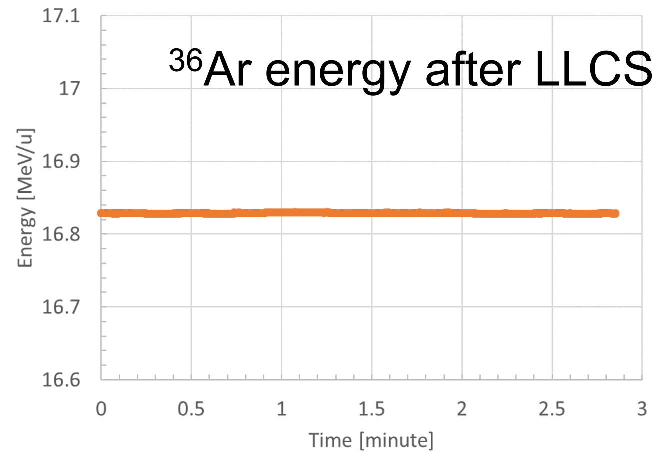


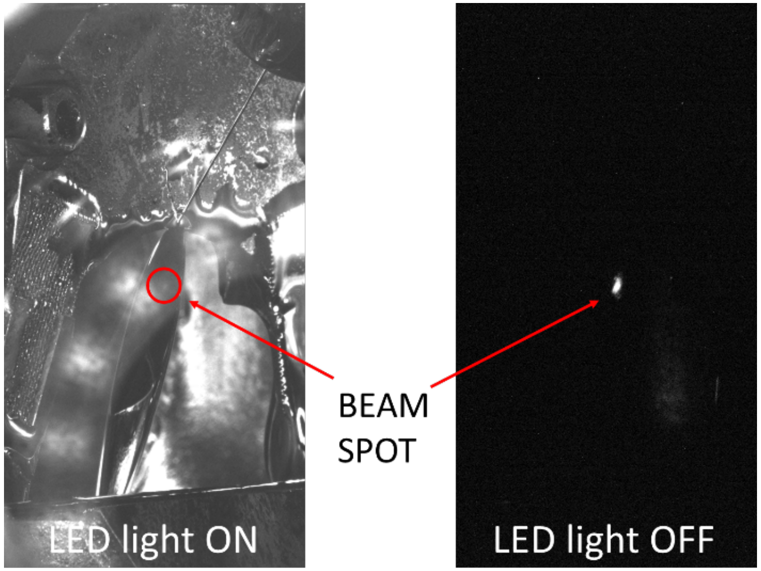
1.2 mg/cm^2 carbon

- 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

High-Intensity Beam Test

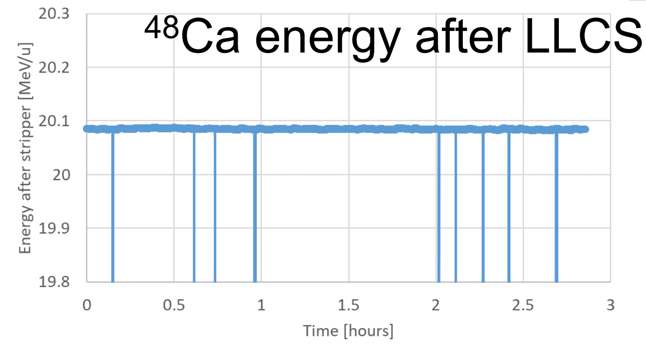
- High-intensity pulsed ^{36}Ar beam, 17 MeV/u
  - 12 particle μA
  - 5.4% duty cycle (10 Hz, 5.4 ms pulse width)
  - Peak power 7400 W
    - » Average 400 W (limitation of average beam power into beam dump in FS1 < 500 W)
    - » Equivalent power at the production target in CW mode: >74 kW.
  - Peak volumetric power deposition: 6 MW/cm^3 (peak power loss 50 W), 10% of the FRIB full power uranium beam operation value.
- Beam parameters and LLCS system operating parameters were stable

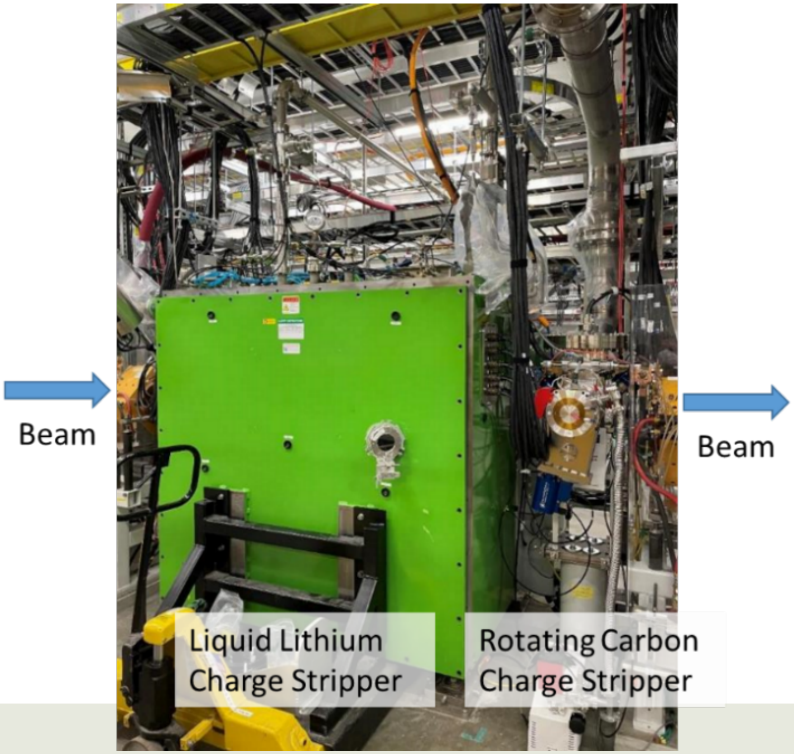




Early Operation Experiences

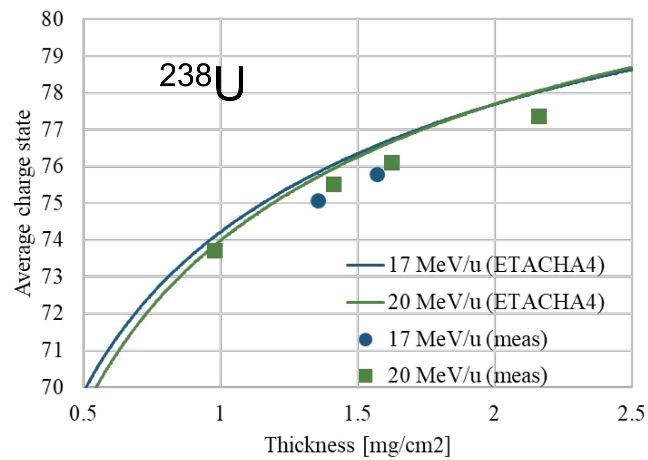
- FRIB officially started the user program in May 2022
- The LLCS was used during the first user operation, primary ^{48}Ca beam up to 1 kW at the production target (about 100 W at the stripper)
- The long-term operation with the primary ^{48}Ca beam was validated
- A carbon foil stripper as a backup stripper exists adjacent to the LLCS
- A carbon foil (purchased from Applied Nanotech, Inc) was also used with 1 kW ^{82}Se beam in a user operation, and worked well

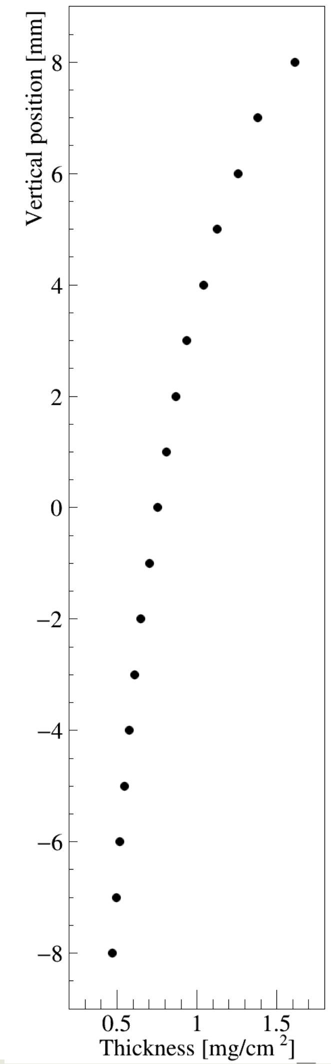




Future Perspective

- Measurement data of U beam charge stripping with lithium showed that a 1 mg/cm^2 thick film gives an average charge state of 74+
  - Accelerator designed with 78+
  - Thicker part of film is too steep to use (beam RMS radius 0.5 mm)
- R&Ds to improve film uniformity and to make a thicker film for U beam stripping
  - Starting with water test
  - Our goal: 1.5 mg/cm^2





Summary

- FRIB at Michigan State University has become the world's first accelerator which utilizes a liquid lithium charge stripper (LLCS)
- The LLCS was successfully commissioned with heavy ion beams: ^{36}Ar, ^{48}Ca, ^{124}Xe, and ^{238}U.

  T. Kanemura, et al., Phys. Rev. Lett. **128**, 212301 (2022)

  - For the first time, the charge stripping performance of liquid lithium was measured.
  - Average charge states were lower for U but higher for Ar, Xe than ETACHA prediction.
  - 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 operation. And a rotating carbon stripper is also available as a backup

Acknowledgements

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- This work is supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan, and Michigan State University.

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May 27, 2022: *Phys. Rev. Lett.* cover article
“Experimental demonstration of the thin-film liquid-metal jet as a charge stripper”, T. Kanemura *et al.*

NEWSPAPER

Photograph of the liquid lithium film charge stripper in the Facility for Rare Isotope Beams. Selected for a Synopsis in *Physics* [Kanemura *et al.* Phys. Rev. Lett. **128**, 212301 (2022)]

PHYSICAL REVIEW LETTERS

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Any Questions?