R&D of Liquid Lithium Stripper at FRIB

Takuji Kanemura, N. Bultman, M. LaVere, R. Madendorp, F. Marti, T. Maruta, Y. Momozaki[1], J.A. Nolen[1], P. Ostroumov, A. Plastun, J. Wei and Q. Zhao,

Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[1]Also at Argonne National Laboratory, Lemont, IL, USA

D. B. Chojnowski, C. B. Reed, J. R. Specht,

Argonne National Laboratory, Lemont, IL, USA

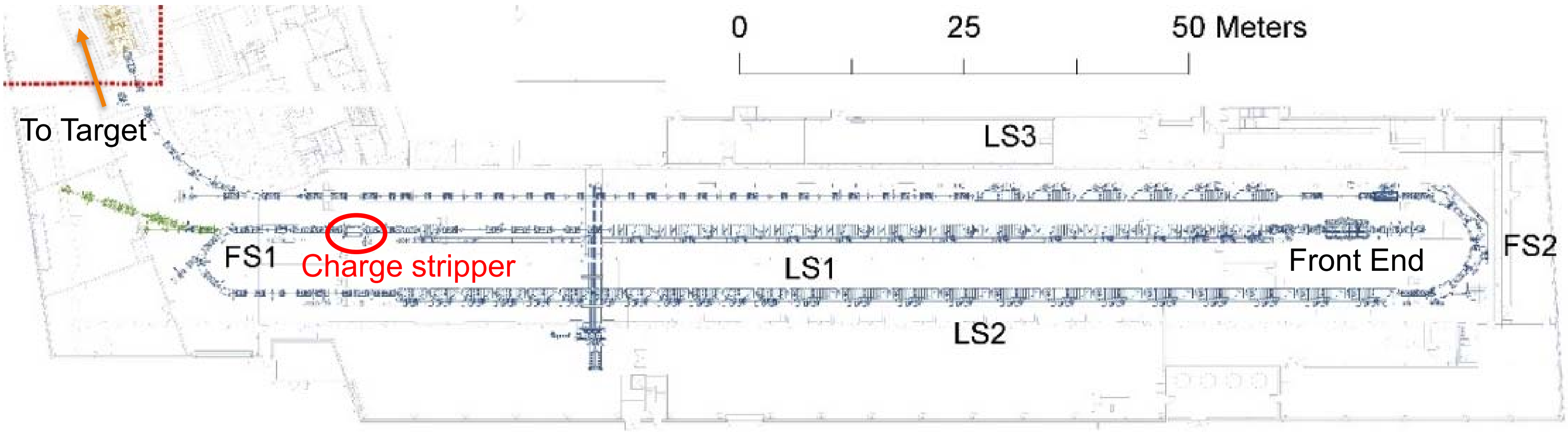
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University operates FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Introduction: FRIB liquid lithium charge stripper
- Design process of FRIB liquid lithium charge stripper system
  - Conceptual design
  - Proof of principle test
  - Detailed design and construction
  - Offline commissioning
  - Online commissioning
- Achieved performance
- Summary

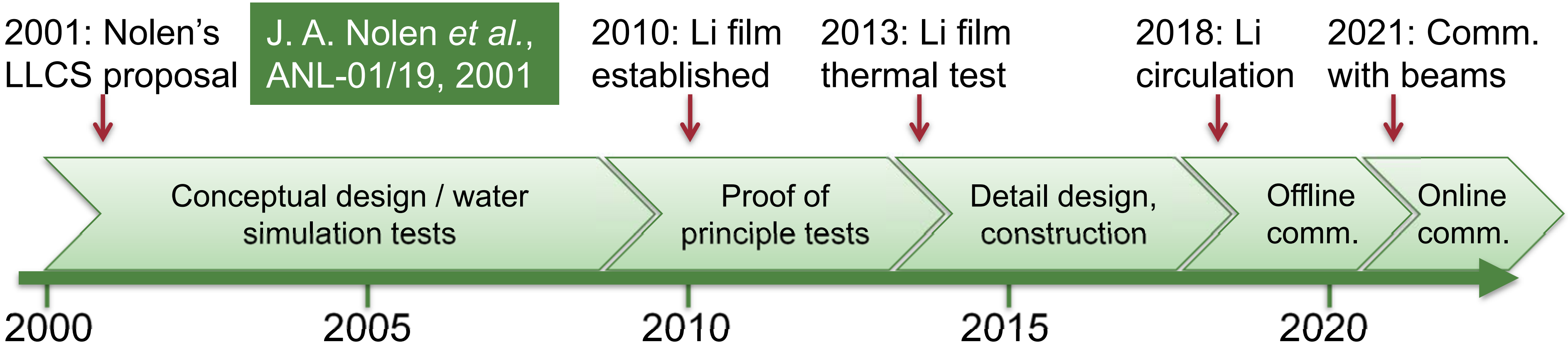
Introduction: FRIB Liquid Li Stripper

- The liquid lithium charge stripper (LLCS) strips ion beams to increase the charge state(s) of the beams by a factor of 2, thus increase the energy gain
- The LLCS is located at the end of Linac Segment 1 (LS1) at beam energies of 16-20 MeV/u and at a beam power of 40 kW
- Requirement specifications
  - Thermal: 450 W (56 MW/cm^3) heat deposition for full power U beam in lithium
  - Speed > 50 m/s
  - Dimensions: > 10 mm in width and height, 0.5-1 mg/cm^2 (10-20 μm) in thickness
- Question: How to design and validate such a system?



Design Process

- The following process was taken to develop FRIB LLCS
  - Conceptual design
    - » R&D tests for selected critical performance with water as a simulant of liquid lithium
  - Proof of principle (PoP) test (part of conceptual design stage)
    - » Small-scale liquid lithium system, or system with limited functions
  - Detail design and construction
    - » Liquid lithium system with full functions
  - Offline commissioning
    - » Stand-alone commissioning without ion beams
  - Online commissioning
    - » Commissioning with ion beams
- In general this approach can apply to other similar systems

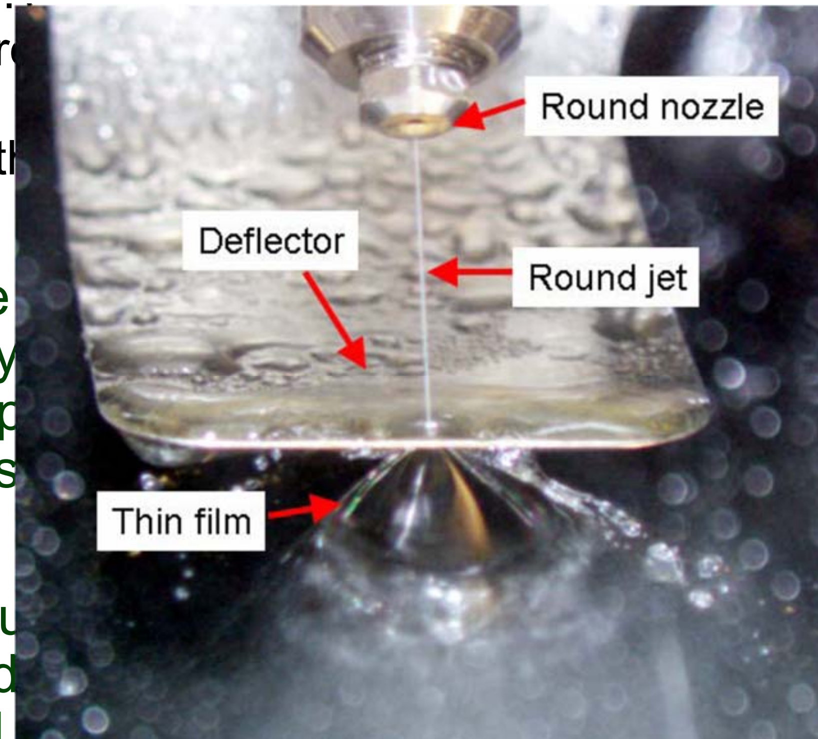


Conceptual Design Stage

- Critical performance;
  1. How could a stable and uniform thin (0.5-1 mg/cm^2 or 10-20 μm) liquid lithium film in a high vacuum environment be formed?;
  2. Could the film withstand the foreseen extreme thermal load (56 MW/cm^3) imposed by the full power uranium beam?;
  3. Could charge stripping characteristics of the lithium film be acceptable for further acceleration of stripped beams?
- Performance #1 was considered to be the most critical. It is not common to build a liquid lithium system until critical system performance is validated and there remain only validations that can be performed with liquid lithium (#2 and #3). This is because liquid lithium systems are normally complicated thus expensive.
- To efficiently test the concept, water was used as a simulant of liquid lithium. The law of similarity guarantees that two different types of flow become similar when these flows are properly scaled and relevant dimensionless numbers are the same.
- What was the concept to test?
- Nolen found an idea in his kitchen…

Conceptual Design Stage

- Critical performance;
  1. How could a stable and uniform thin (0.5-1 mg/cm^2 or 10-20 μm) liquid lithium film in a high vacuum environment be formed?;



J. Nolen *et al.*, ANL-06/11, 2006

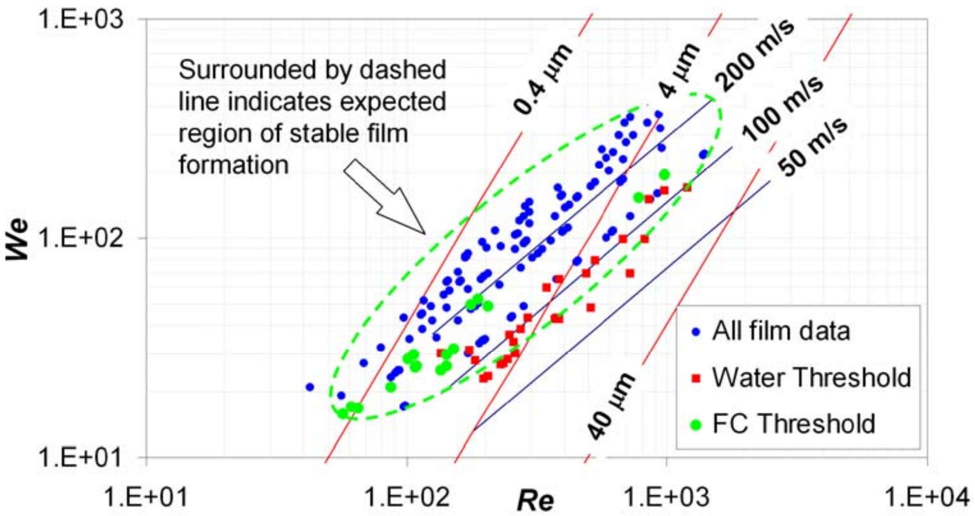
The law of similarity guarantees that two d ... ar when these flows are properly scaled and ... are the same.

- What was the concept to test?
- Nolen found an idea in his kitchen…

Conceptual Design Stage

- Relevant dimensionless numbers: Reynolds (Re) and Weber (We) numbers
- Stability diagram in Re-We regime

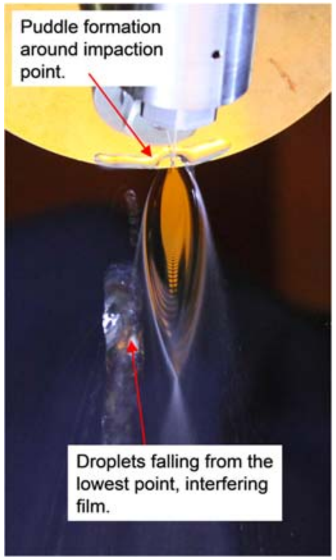
Y. Momozaki *et al.*, J. Inst., Vol.4, P04005, 2009

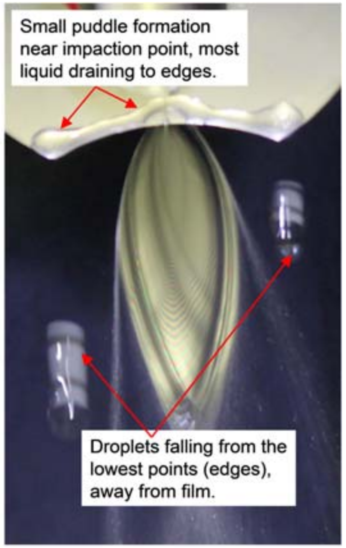


- Successful formation of stable water films
  - Lesson: the shape of the deflector edge was improved to avoid dripping water from disturbing the film
- Ready for PoP test with liquid lithium

Reynolds number $\mathrm{Re} = {UL}/{\nu}$
where L the characteristic length,
U the characteristic speed, and
ν the kinematic viscosity.

Weber number $\mathrm{We} = {\rho L U^2}/{\sigma}$
where ρ the density of the liquid,
σ the surface tension





C.B. Reed *et al.*, ANL/NE-11/01, 2011

Proof-of-Principle Test Stage

- Proof-of-principle test using liquid lithium

  C.B. Reed *et al.*, ANL/NE-11/01, 2011

  - A lithium system was built with limited functions (e.g. no circulation pump)
  - Successful formation of stable lithium film
  - The deflector was further refined by adding "wicks"

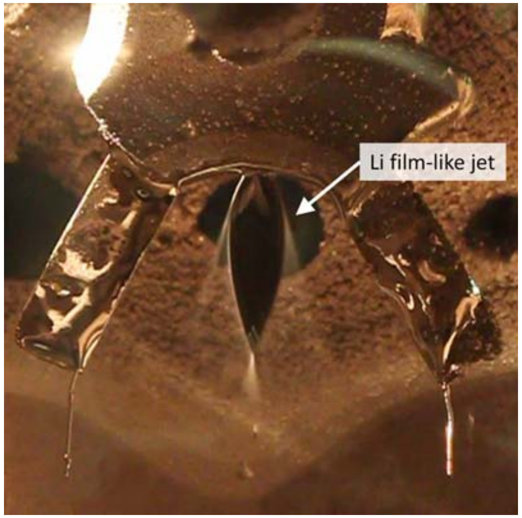
- Ultra-high power deposition test using the LEDA proton source (LANL)

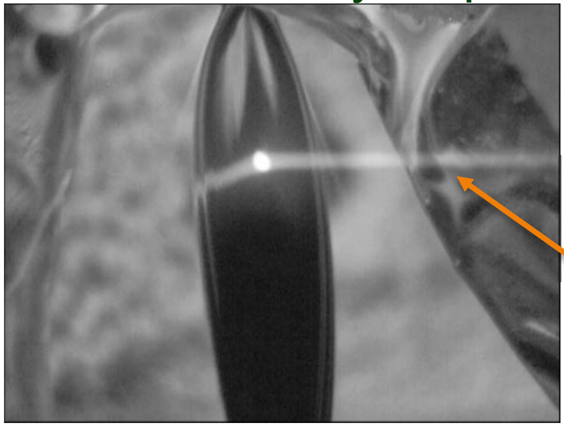
  Y. Momozaki *et al.*, *J. Radioanal. Nucl. Chem.*, vol. 305, pp. 843-849, 2015

  - The lithium film received 300-W 65-keV proton beam creating volumetric heat deposition of 65 MW/cm^3 > expected 56 MW/cm^3 for FRIB full power U beam
  - Lithium film survived

- Remaining question to answer: Can liquid lithium film really strip beams?

Li film formed with improved deflector





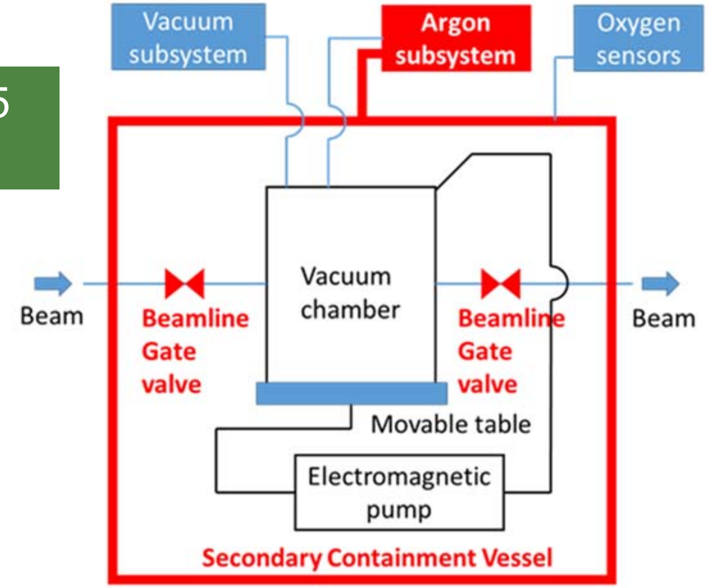
Film being irradiated by proton beam

Detail Design Stage

- Lithium circulation pump

R. Smither, AGP-III-M, ANL/APS Technical Memo, 1995
F. Marti et al., Proc. HIAT’15, 2015, pp. 134-138

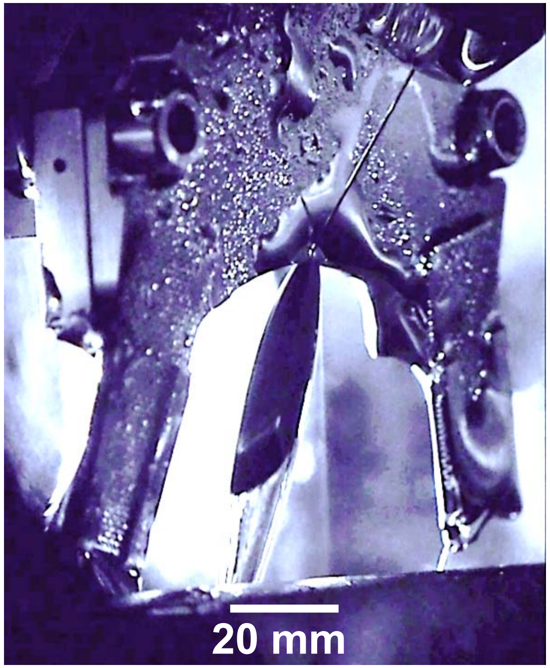
- Safety subsystem to prevent / mitigate lithium fire hazards
  - Secondary containment vessel (SCV) that completely encloses the lithium loop, and is always filled with argon during operations
  - Thus, even if a liquid lithium leak develops, it will not lead to fire and the system will be kept safe
- Lithium subsystem (lithium loop)
  - Only materials compatible with lithium
  - Operation at 220 °C (the melting point of lithium is 180.5 °C) with heaters
- Argon subsystem
- Vacuum subsystem

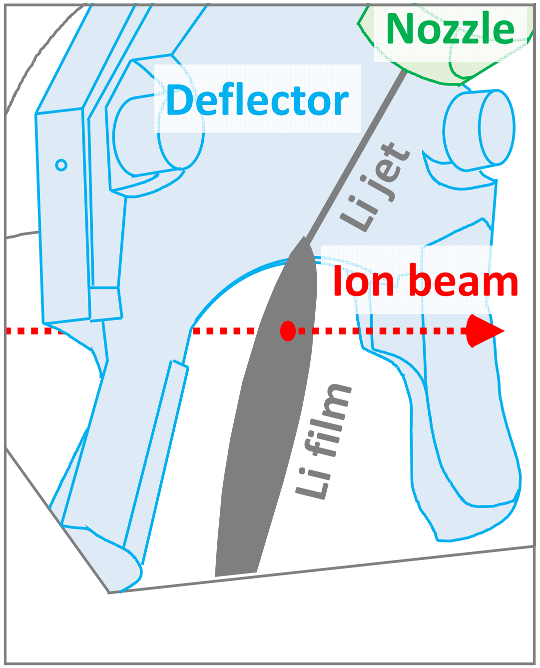


SCV in FRIB linac beamline

Offline Commissioning Stage

- Confirmed a lithium film that has equivalent quality of the film made at ANL 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 FRIB linac for commissioning with heavy ion beams

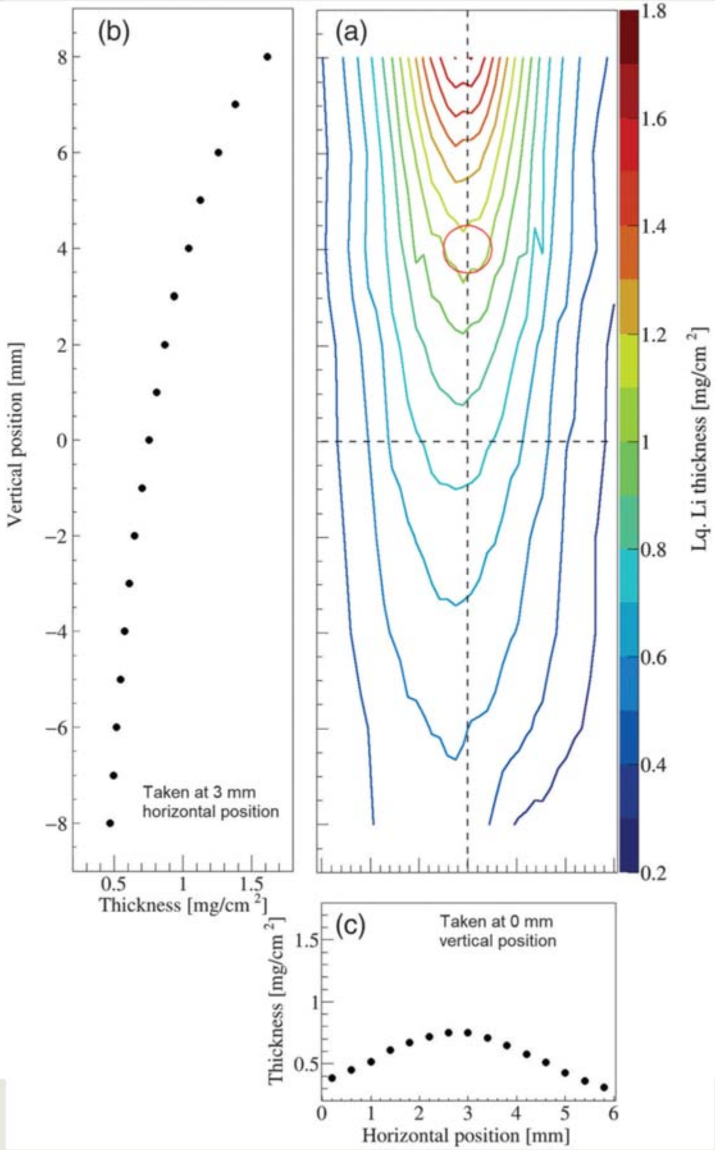




Online Commissioning and Achieved Performance: Lithium Thickness Measured by Beam

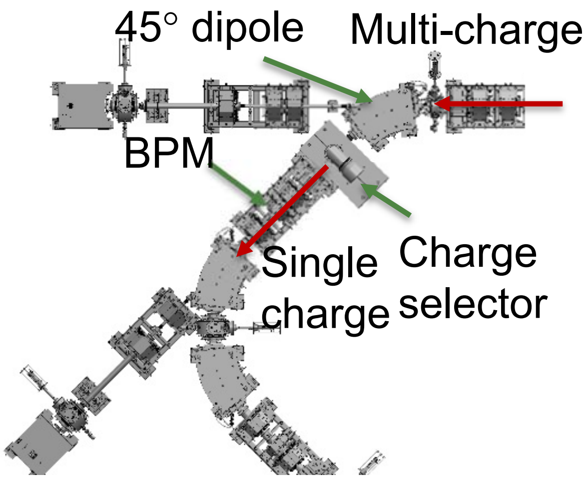
- Mass thickness measured
  - Exp: 20 MeV/u $^{36}Ar^{10+}$ beam energy loss measured over the film
  - Calc: Energy loss per unit length obtained from the SRIM code
- At some distance away from the impinging point, the film was uniform enough for the 0.5-mm-radius beam
- Consistent with past measurements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

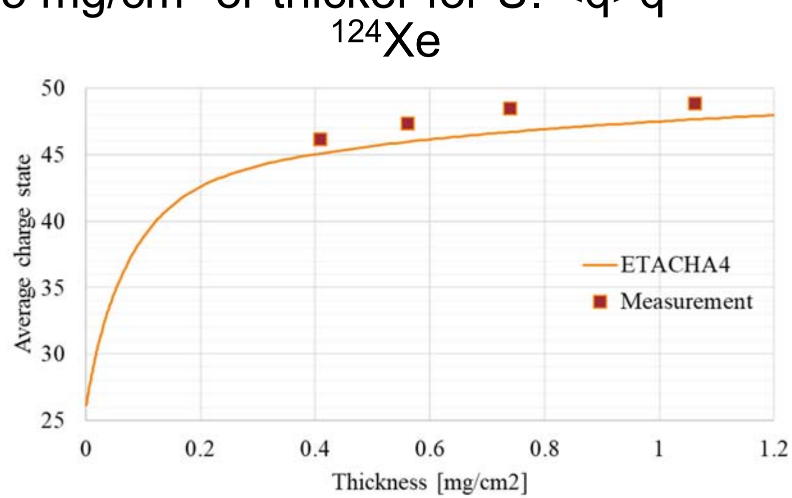
T. Kanemura, et al., Phys. Rev. Lett. **128**, 212301 (2022)

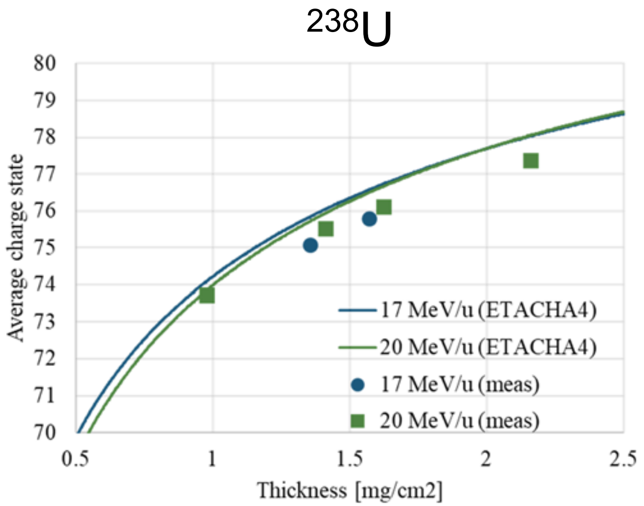


Online Commissioning and Achieved Performance: Charge States of Heavy Ion Beams [1/3]

- 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 is enough for Xe and Ar beams
- Uranium beam charge states are slightly lower than ETACHA4 prediction
  - 1.5 mg/cm^2 or thicker for U. <q>q



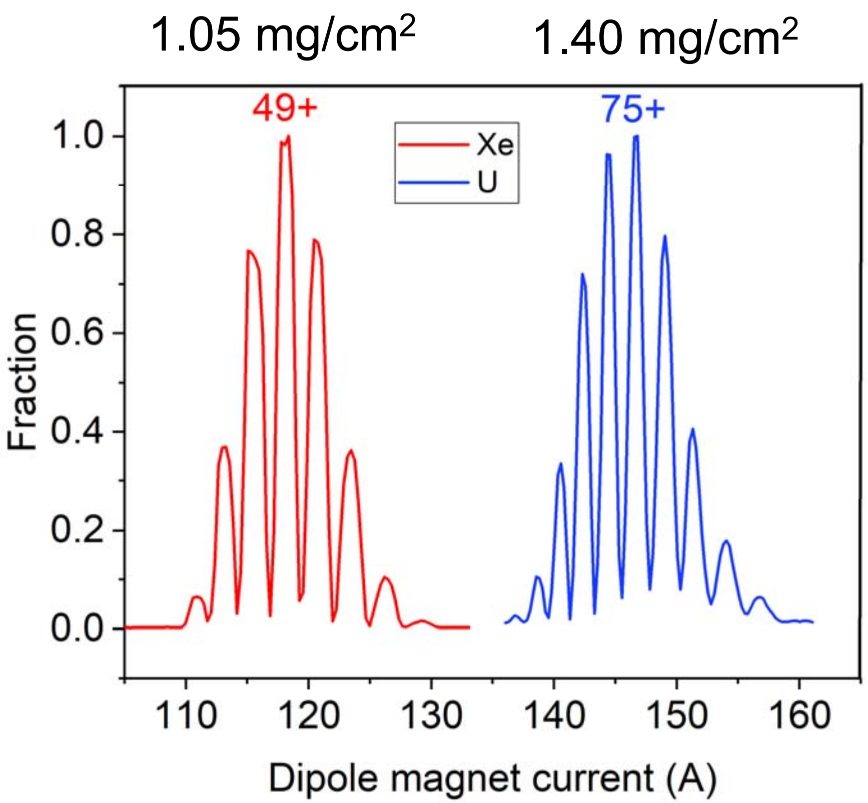




T. Kanemura *et al.*, *HIAT2022*, Darmstadt, Germany, June 2022, paper MO4I2

Online Commissioning and Achieved Performance: Charge States of Heavy Ion Beams [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.



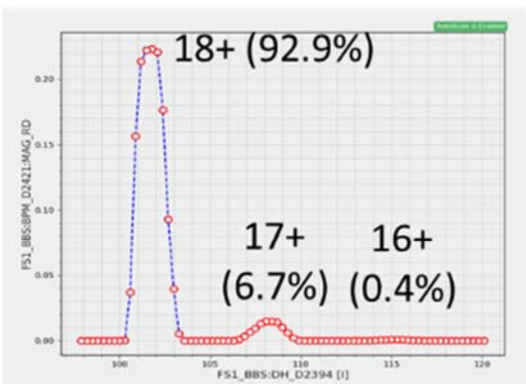
Charge State Distribution after LLCS

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

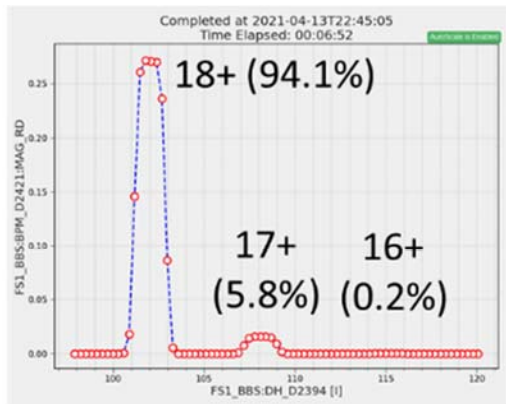
Online Commissioning and Achieved Performance: Charge States of Heavy Ion Beams [3/3]

- Charge state distributions after lithium and carbon strippers
  - 20 MeV/u ^{36}Ar beam
  - 20 MeV/u ^{48}Ca beam

^{36}Ar, 20 MeV/u

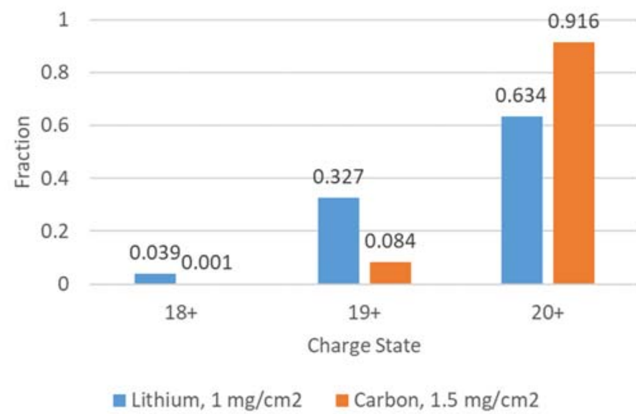


1.6 mg/cm² lithium



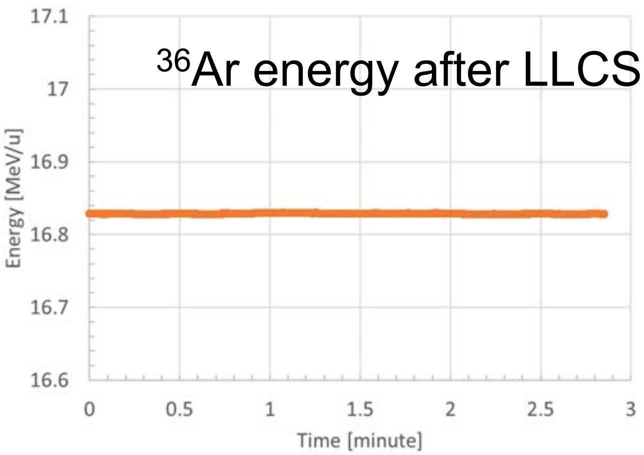
1.2 mg/cm² carbon

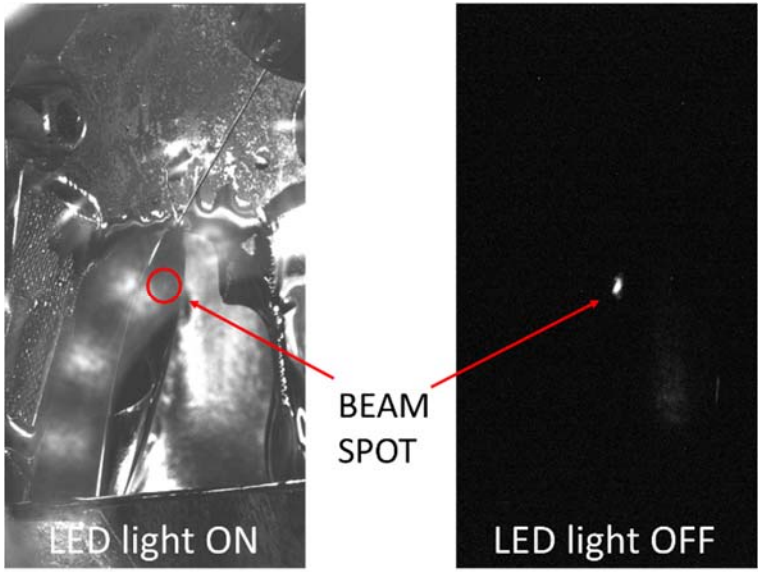
^{48}Ca, 20 MeV/u



Online Commissioning and Achieved Performance: 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

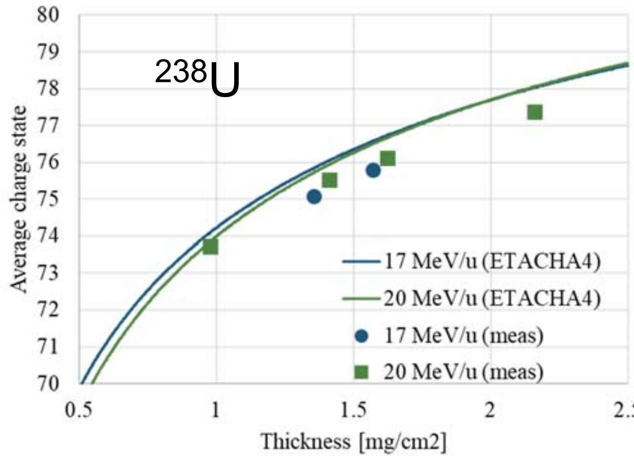


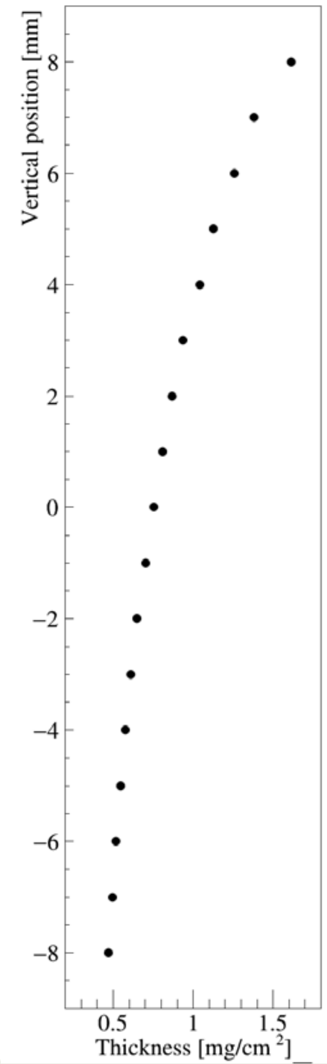


T. Kanemura *et al.*, *HIAT2022*, Darmstadt, Germany, June 2022, paper MO4I2

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)
- In this paper, design process and achieved performance of the FRIB LLCS system are presented
- Design process
  - Conceptual design and tests using simulant working fluids (water)
  - Proof of principle tests using liquid lithium
  - Detailed design and construction
  - Offline commissioning (standalone testing without beams)
  - Online commissioning with heavy ion beams
- Achieved performance of the LLCS system has been satisfactory. Ions used so far: ^{36}Ar, ^{48}Ca, ^{124}Xe, and ^{238}U.
- We will continue performance tests with heavy ion beams as FRIB ramps up the power. We will also seek a method to increase the film thickness and improve the film uniformity.

Acknowledgements

- The authors would like to thank all the FRIB staff members for their contributions to the successful commissioning of the liquid lithium charge stripper with heavy ion beams
- 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.

References

[1] J. Wei *et al.*, “Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams,” *Mod. Phys. Lett. A*, vol. 37, no. 9, p. 2230006, 2022. doi:10.1142/S0217732322300063

[2] T. Kanemura *et al.*, “Experimental Demonstration of the Thin-Film Liquid-Metal Jet as a Charge Stripper,” *Phy. Rev. Lett.*, vol. 128, no. 21, p. 212301, May. 2022. doi:10.1103/PhysRevLett.128.212301

[3] J. A. Nolen *et al.*, “Argonne Physics Division 2000 Annual Report,” Argonne National Laboratory, Lemont, USA, Rep. ANL-01/19, 2001.

[4] For example, K. Itoh, Y. Tsuji, H. Nakamura, and Y. Kukita, “Initial Free Surface Instabilities on a High-Speed Water Jet Simulating a Liquid-Metal Target,” Fusion Technol. Vol. 36, no. 1, pp.69-84, July 1999. doi:10.13182/FST99-A93

[5] Y. Momozaki *et al.*, “Development of a liquid lithium thin film for use as a heavy ion beam stripper,” *J. Inst.*, vol. 4, P04005, April. 2009. doi:10.1088/1748-0221/4/04/P04005

[6] C. B. Reed, J. Nolen, Y. Momozaki, J. Specht, D. Cho-jnowski, and R. Lanham, “FRIB lithium stripper thickness and stability measurements,” Argonne National Laboratory, Lemont, USA, Rep. ANL/NE-11/01, 2011.

[7] Y. Momozaki *et al.*, “Proton beam-on-liquid lithium stripper film experiment,” *J. Radioanal. Nucl. Chem.*, vol. 305, pp. 843-849, 2015. doi:10.1007/s10967-015-4074-9

[8] R. Smither, “Summary of the Operating Characteristics of the ANL Liquid Metal Pump After its Latest Modification (AGP-III-M), ANL/APS Technical Memo, September 20, 1995

[9] F. Marti, P. Guetschow, Y. Momozaki, J.A. Nolen, and C.B. Reed, “Development of a Liquid Lithium Charge Stripper for FRIB,” in *Proc. 13th International Conference on Heavy Ion Accelerator Technology (HIAT’15)*, Yokohama, Japan, Sep. 2015, pp. 134-138. doi:10.18429/JACoW-HIAT2015-PAPERID

[10] T. Kanemura, J. Gao, M. LaVere, R. Madendorp, F. Marti, and Y. Momozaki, “Progress of Liquid Lithium Stripper for FRIB,” in *Proc. 4th North American Particle Accelerator Conference (NAPAC2019)*, Lansing, USA, Sep. 2019, pp. 636-638. doi:10.18429/JACoW-NAPAC2019-WEYBB4

[11] T. Kanemura *et al.*, “Liquid Lithium Charge Stripper Commissioning with Heavy Ion Beams and Early Operations of FRIB Strippers,” presented at the 15th *International Conference on Heavy Ion Accelerator Technology (HIAT2022)*, Darmstadt, Germany, June 2022, paper MO4I2, submitted for publication

Thank You For Your Attention! Any Questions?