FRIB

Overview and Status of FRIB Charge Stripper and Charge Selector

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

(Facility of Rare Isotope Beams, Michigan State University, East Lansing, MI, USA)

([1]also at Argonne National Laboratory, Lemont, IL, USA)

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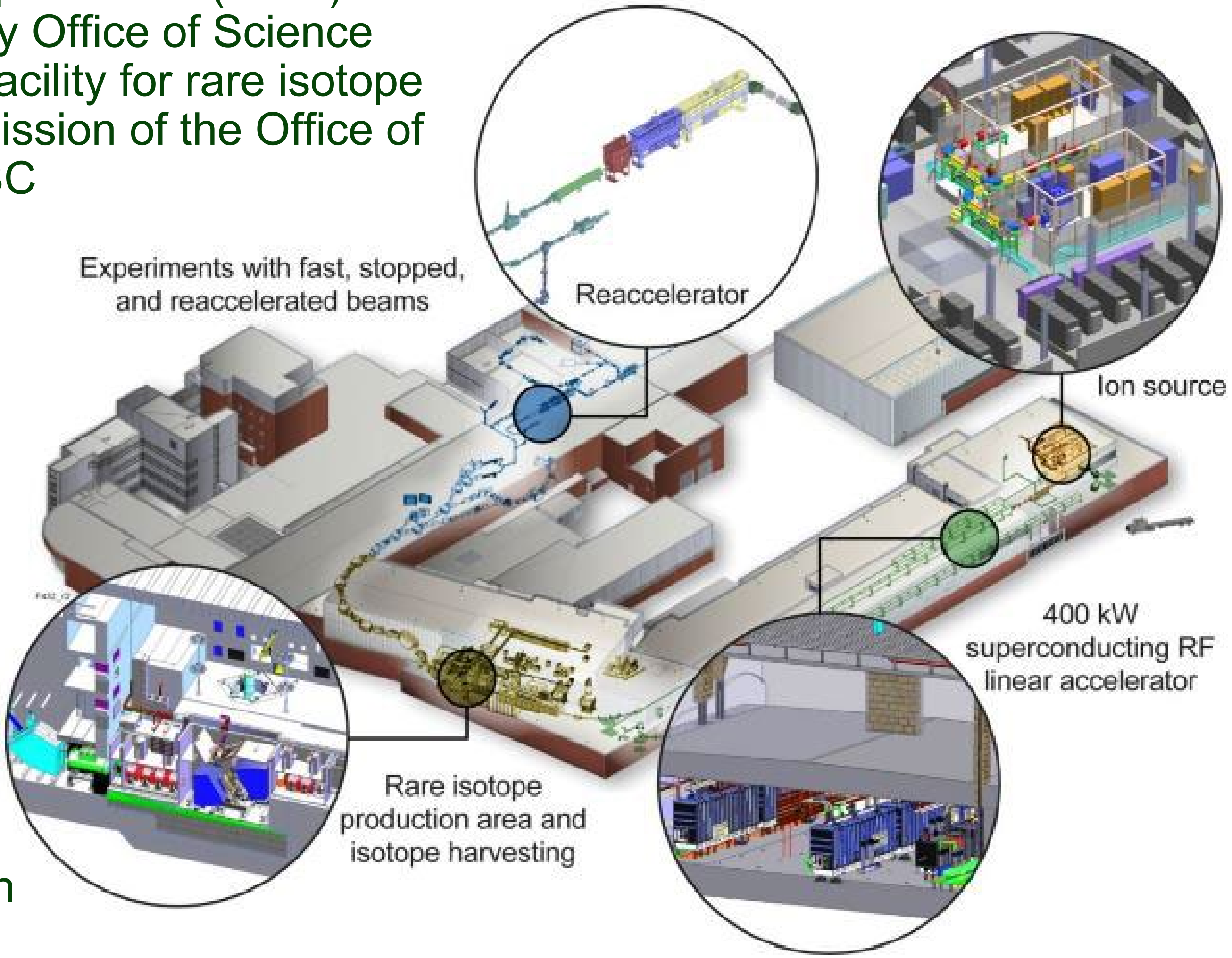
Outline

- What is FRIB?
- What are charge stripper and charge selector?
- Technical challenges of charge stripper and charge selector
- Charge stripper at FRIB; overview, status and future perspective
- Charge selector at FRIB; overview, status and future perspective
- Summary

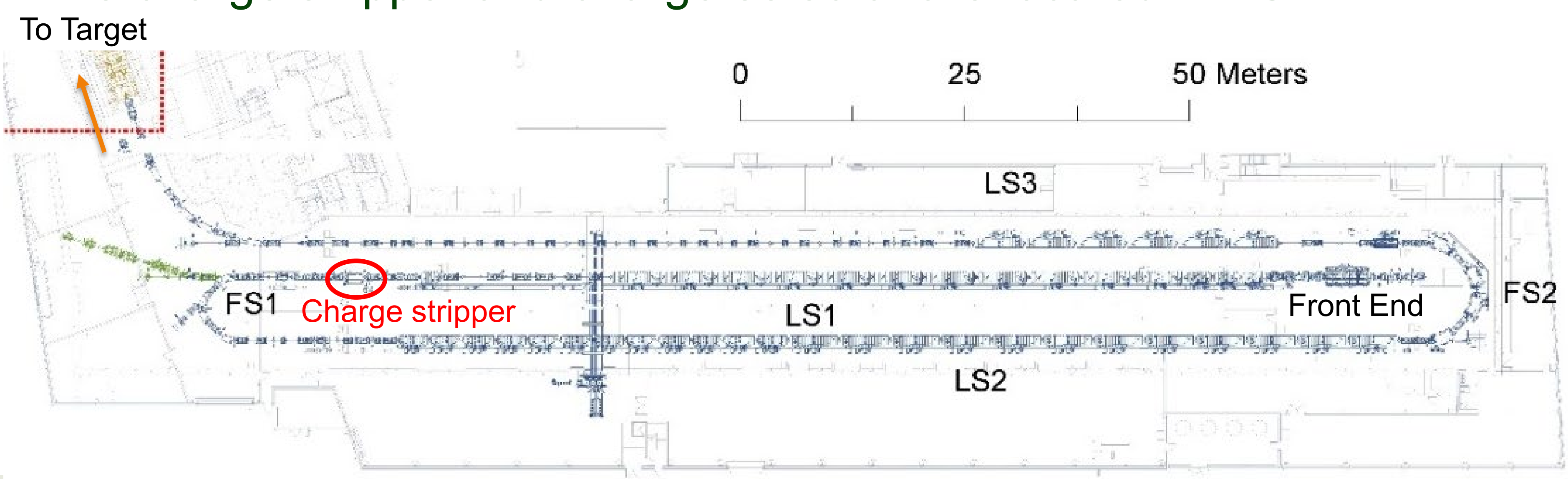
What is FRIB?

- 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 (8 pμA or 5×10^{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
- User operation started with 1 kW in 5/2022
- 400 kW full power operation in six years



FRIB Driver Linac: 400 kW CW SRF Linac

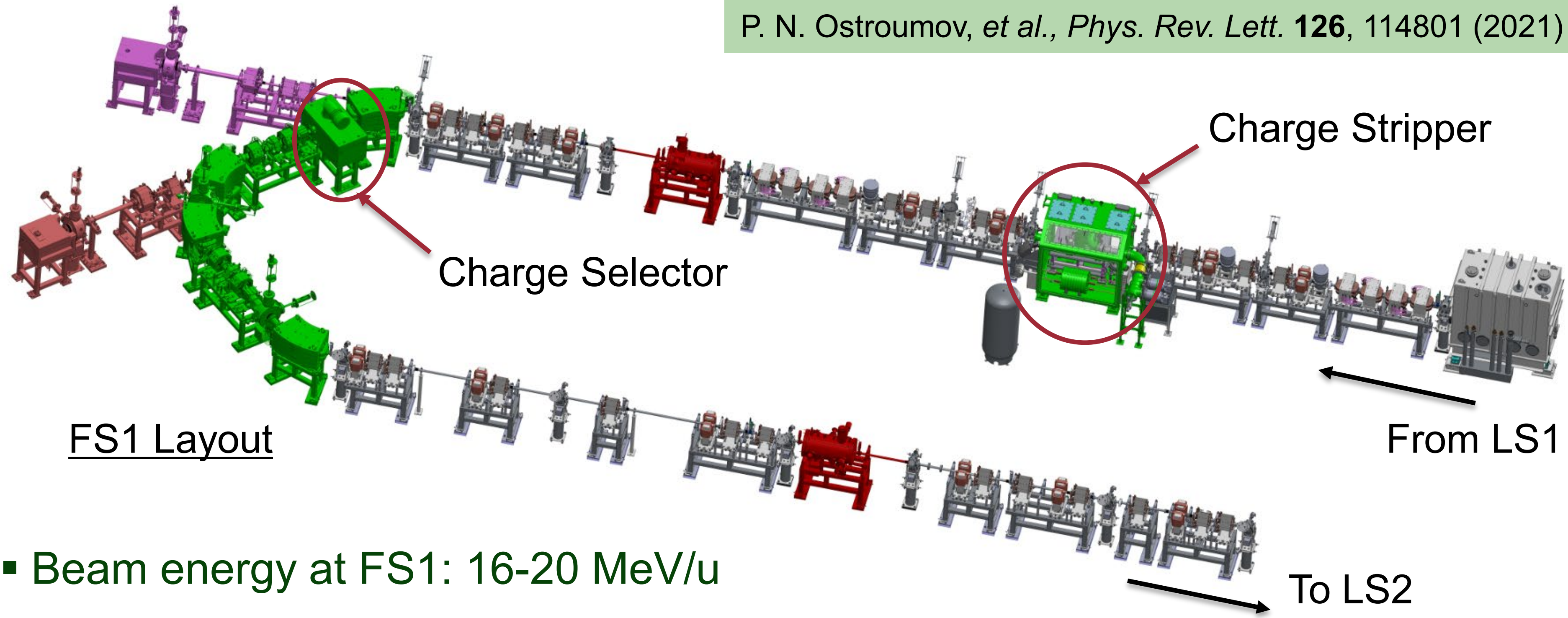
- FRIB linac includes the front end and 46 superconducting RF cryomodules
  - ECR ion sources, RFQ
  - 324 SRF cavities in 46 cryomodules with velocity β from 0.041 to 0.53
- Three linac segments (LS1, LS2 and LS3) with two folding segments (FS1 and FS2) for a compact design
- The charge stripper and charge selector are located in FS1



What are Charge Stripper and Charge Selector?

- Charge stripper removes electrons from the beam being accelerated to increase energy gain by a factor of 2 (e.g. $^{238}U^{36+}$ >> $^{238}U^{78+}$). This process, however, produces multiple charge states after the stripper
- Charge selector selects wanted charge state(s) of the stripped beam. FRIB linac is capable of multi-charge simultaneous acceleration (up to 5 for U beam). Charge selector receives 20 % of beam power (~10 kW)

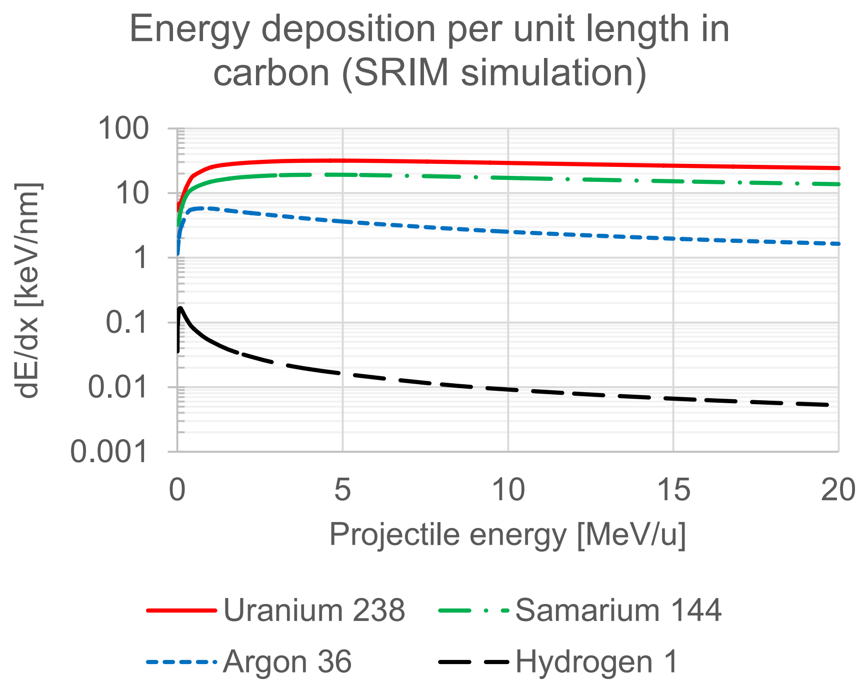
P. N. Ostroumov, *et al., Phys. Rev. Lett.* **126**, 114801 (2021)

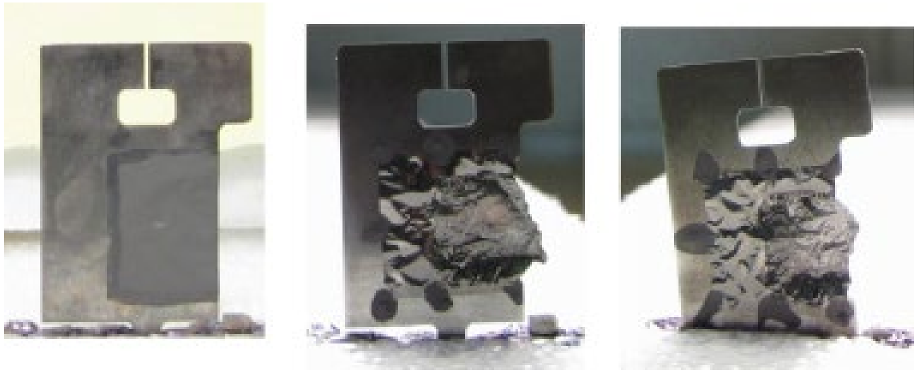


- Beam energy at FS1: 16-20 MeV/u
- Beam power at FS1: 40 kW (full power)

Technical Challenges in Charge Stripper and Charge Selector

- Technical challenges (common in both charge stripper and selector)
  - Extreme thermal load, and
  - Radiation damage (when a solid material is used) by heavy ions (^{238}U)





Damage produced by a $^{208}Pb^{27+}$ beam, 8.1MeV/u, on DLC foils in the NSCL K1200 Cyclotron. The leftmost photo shows an unused foil, and the middle and rightmost photos show two different foils exposed to the beam.

dE/dx of uranium is ***3 orders of magnitude*** higher than H (> ~2 MeV/u)!!!

J. A. Nolen and F. Marti, *Reviews of Accelerator Science and Technology*, Vol. 6 (2013) 221–236

Technical Challenges in Charge Stripper and Charge Selector

- Technical challenges (common in both charge stripper and selector)
  - Extreme thermal load, and
  - Radiation damage (when a solid material is used) by heavy ions (^{238}U)
- Charge stripper suffers the severest condition (beam focused and single footprint). Our solution is liquid lithium charge stripper.
- Charge selector suffers milder condition (beam not focused and multiple footprints thanks to different rigidities of charge states). We think graphite disk can still be used for charge selector.

Device	Medium	Beam power	Beam size	Thermal load (uranium)		DPA rate
Charge stripper	1.5 mg/cm^2 Solid C	1 kW (10 kW at target)	σ 1 mm	47 W	2 MW/cm^3 (average)	Not yet calculated
	1.5 mg/cm^2 Liquid Li	40 kW (400 kW at target)	σ 0.5 mm	1360 W	58 MW/cm^3 (average)	N/A
Charge selector	Glidcop (Cu alloy)	1 kW (10 kW at target)	σ_x 0.7 mm σ_y 1.25 mm	200 W (shared by 4 charge states)	0.3 MW/cm^3 (average)	Being calculated
	Graphite (planned)	40 kW (400 kW at target)	σ_x 0.7 mm σ_y 1.25 mm	10 kW (shared by 4 charge states)	6.5 MW/cm^3 (average)	To be calculated

Charge Stripper
Overview, Status and Future Perspective

FRIB Charge Stripper:
Liquid Lithium Film for Full Power Operation with Back up Carbon Foil

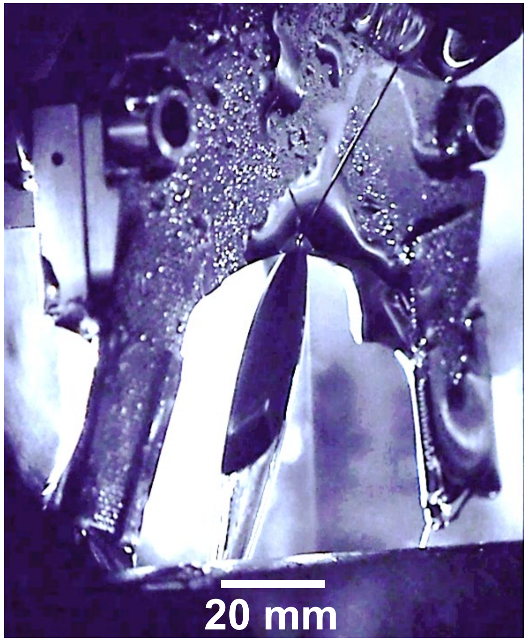
- FRIB has established a liquid lithium charge stripper (LLCS) for full power U beam operations.
- Commissioning with heavy ion beams was successful. LLCS has served a user operation.

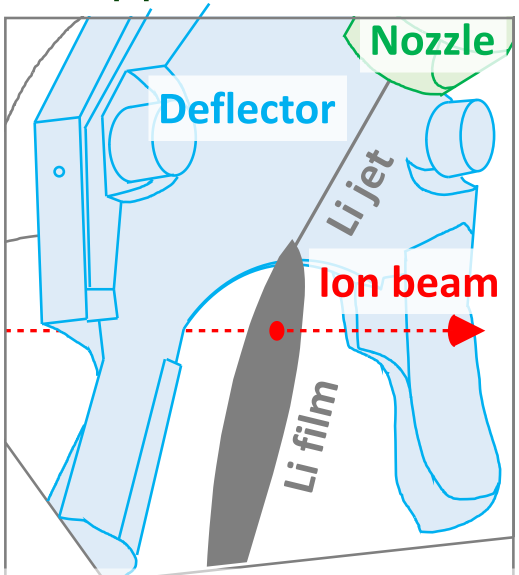
T. Kanemura, et al., *Phys. Rev. Lett.* **128**, 212301 (2022)

T. Kanemura, et al., MO4I2, HIAT 2022, Darmstadt, Germany

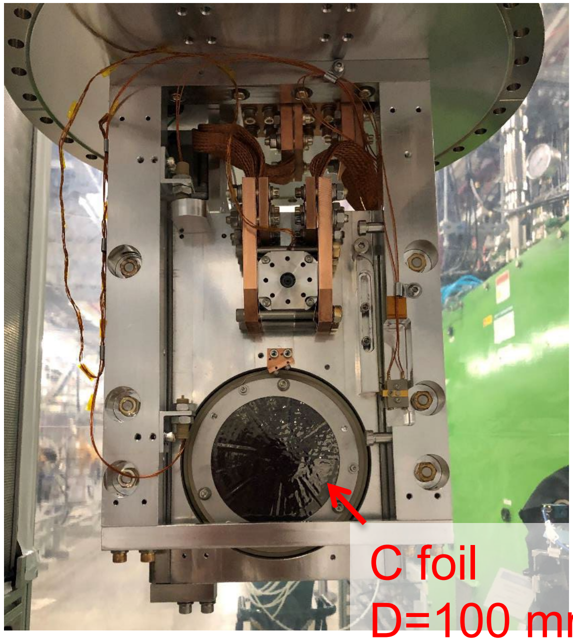
T. Kanemura, et al., TH1AA05, LINAC 2022, Liverpool, UK

- Rotating carbon charge stripper next to LLCS as a back up stripper



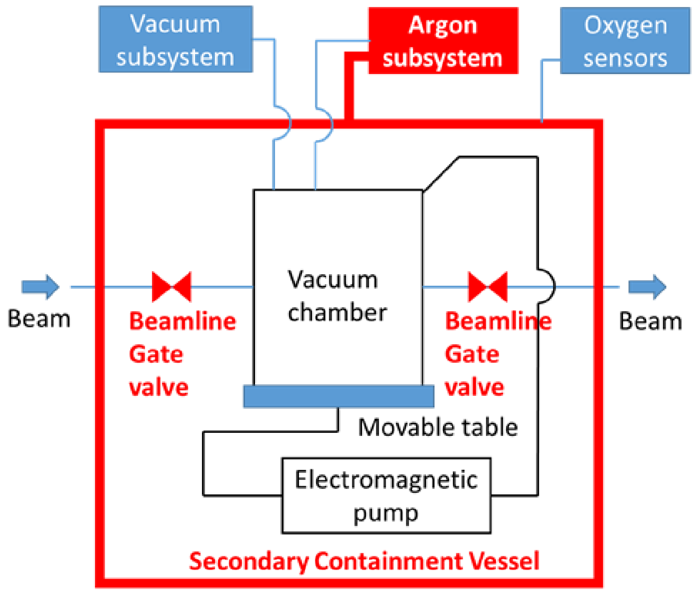


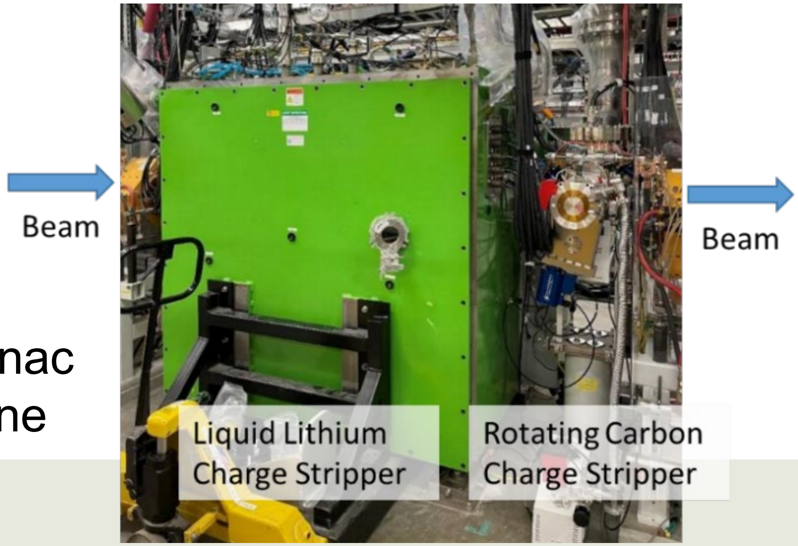
Lithium speed: 60 m/s
Vacuum pressure: 1e-6 Pa



FRIB LLCS System

- 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)

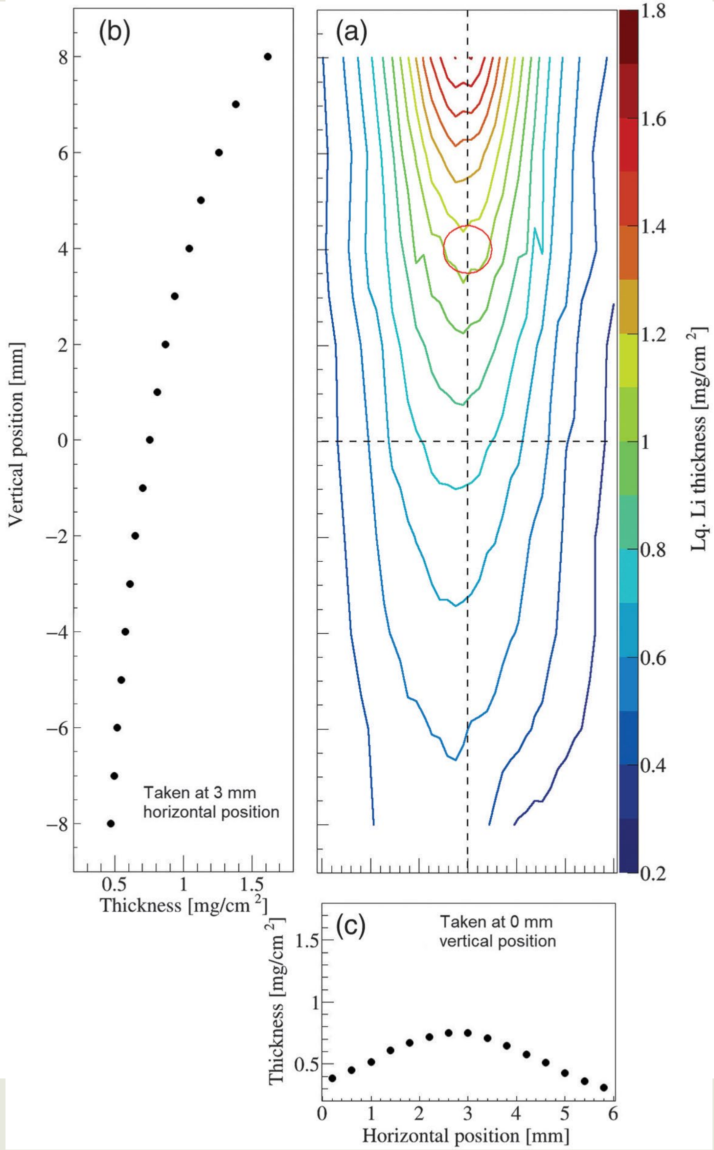




SCV in FRIB linac beamline

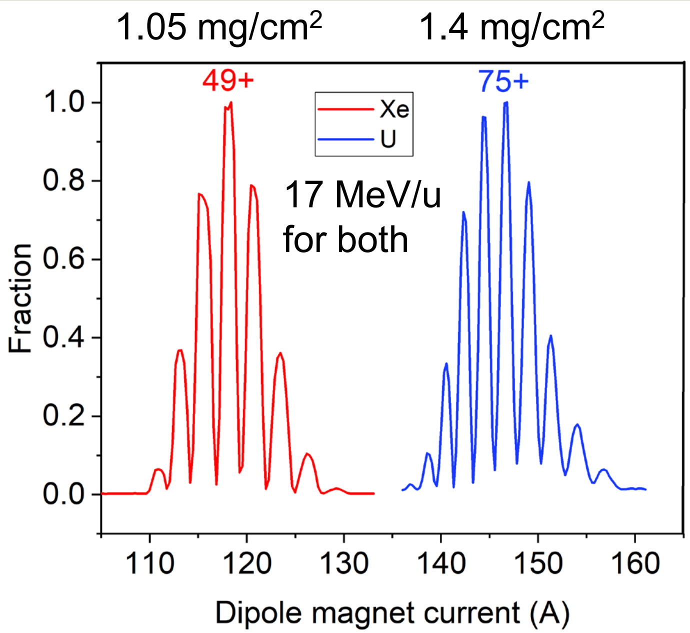
Lithium Thickness Measured by Beam: Uniformity and Stability Confirmed

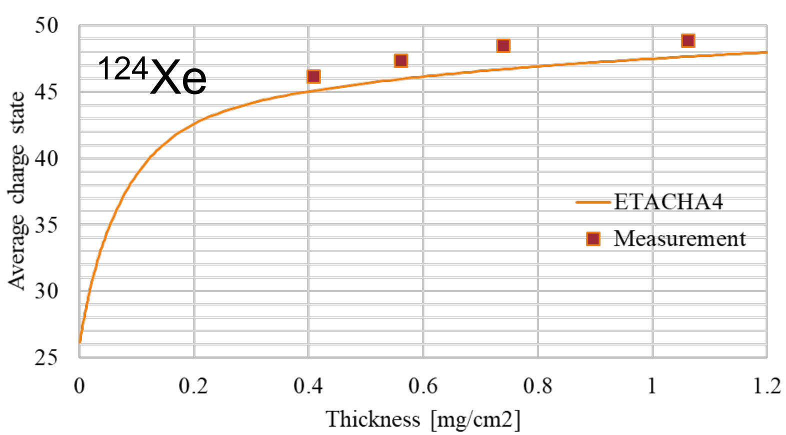
- Mass thickness measured
  - Exp: 20 MeV/u $^{36}Ar^{10+}$ beam energy loss measured over the film
  - Calc: Energy loss per unit length obtained from the SRIM code
- At some distance away from the impinging point, the film was uniform enough for the 0.5-mm-radius beam
- Consistent with past measurements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

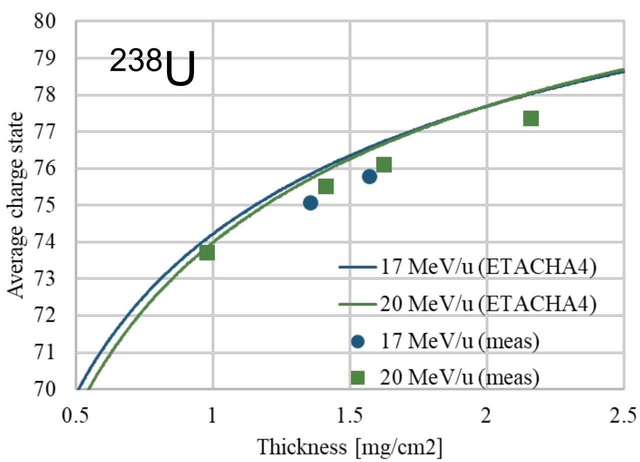


Charge States of Heavy Ion Beams after LLCS

- 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



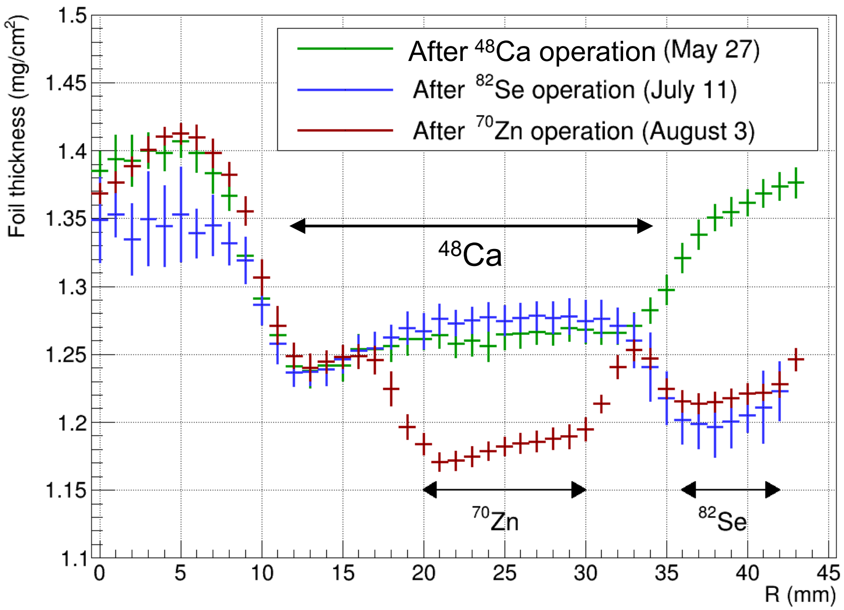




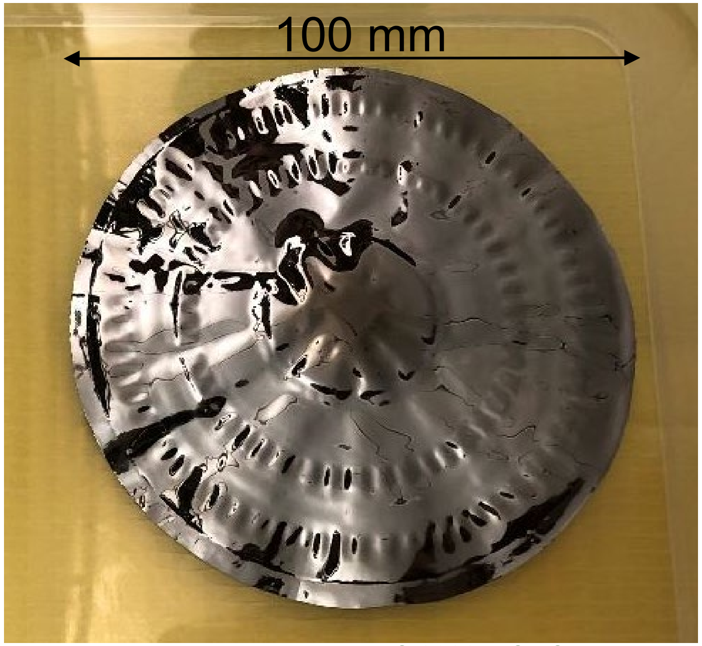
Rotating Carbon Charge Stripper: Operational Experiences

- Foil: 1.5 mg/cm^2 Graphene sheets from Applied Nanotech, Inc. (API)
- Foil movement: rotational (100 rpm) and vertical (3 mm/s)
- Irradiation history

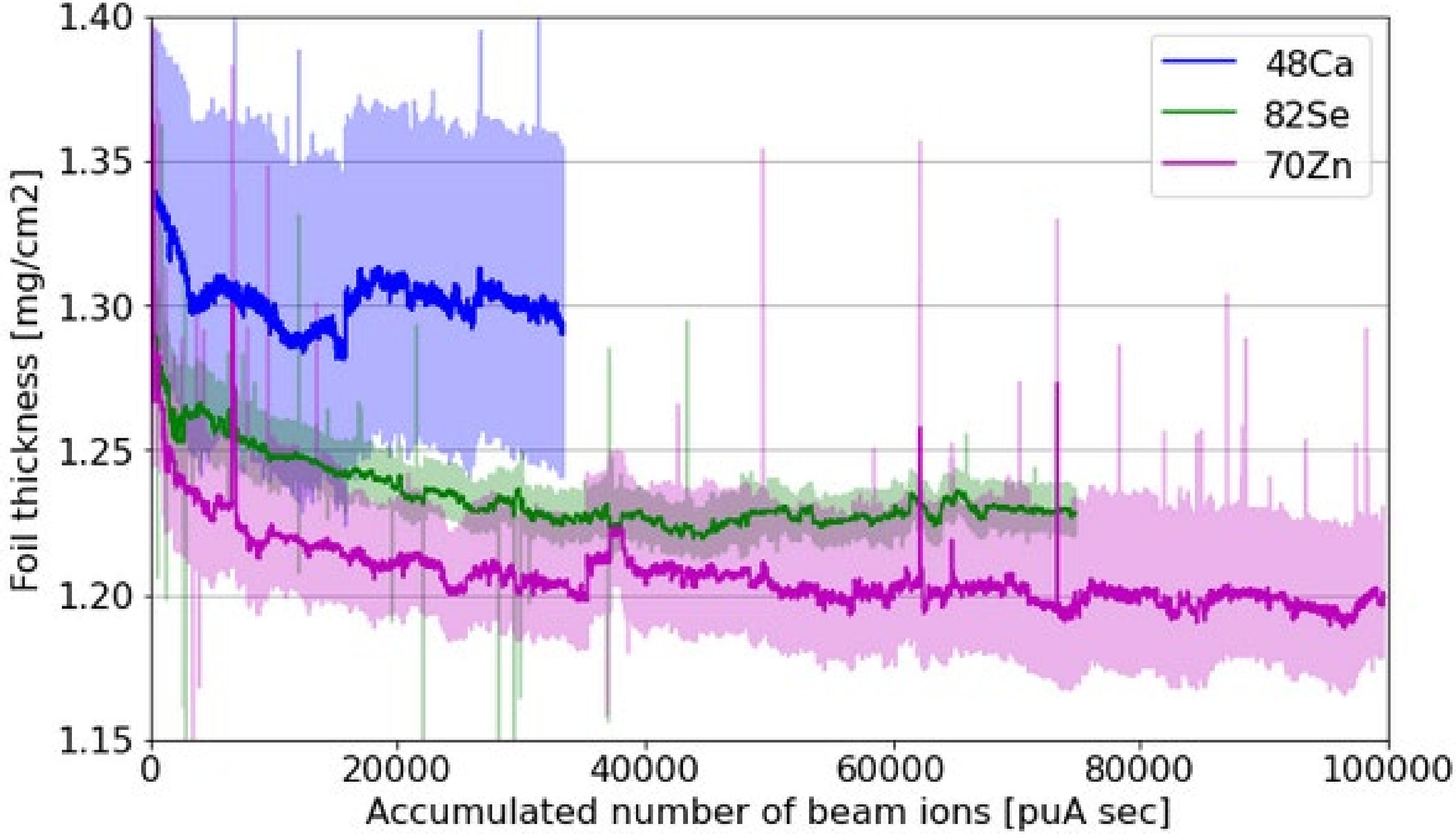
Beams	Energy [MeV/u]	Intensity [puA]	Total ions irradiated
^{48}Ca	20	0.13	2E17
^{82}Se	20	0.18	5E17
^{70}Zn	20	0.17	6E17



Original thickness was not measured…



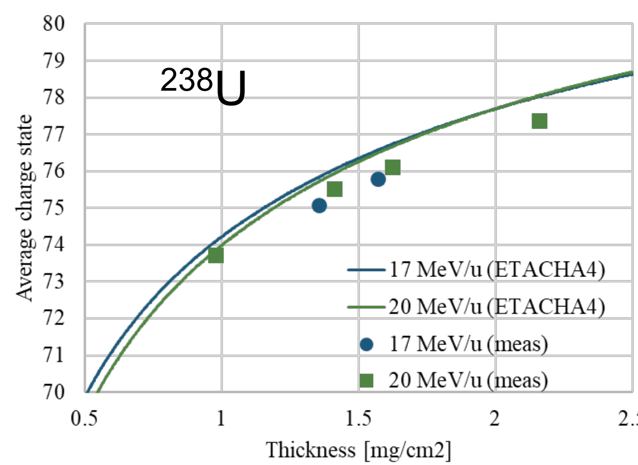
Rotating Carbon Charge Stripper: Operational Experiences

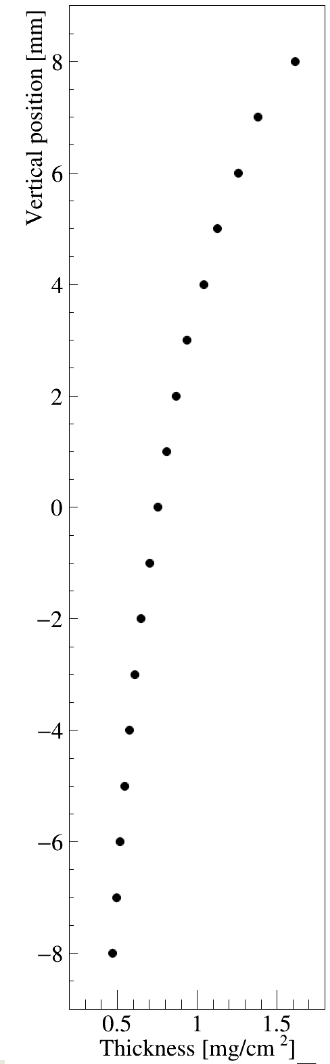


Number of ions: 1.3E17 2.5E17 3.8E17 5E17 6.3E17

Future Perspective: Charge Stripper

- Lithium stripper
  - Improvement of film uniformity and thickness
    - » Current film can provide uniform thickness up to 1 mg/cm2, which turned out to be not thick enough for U beams (Accelerator designed with 78+)
    - » Goal: 1.5 mg/cm^2
    - » R&D efforts, starting with water simulation tests
  - Lithium technology R&Ds
    - » Leak detection
    - » Online Li purification/monitoring
    - » Lithium pressure sensors
- Carbon stripper
  - Understanding of irradiation effects on API foil
  - R&Ds and design improvement to accommodate Kaneka foils



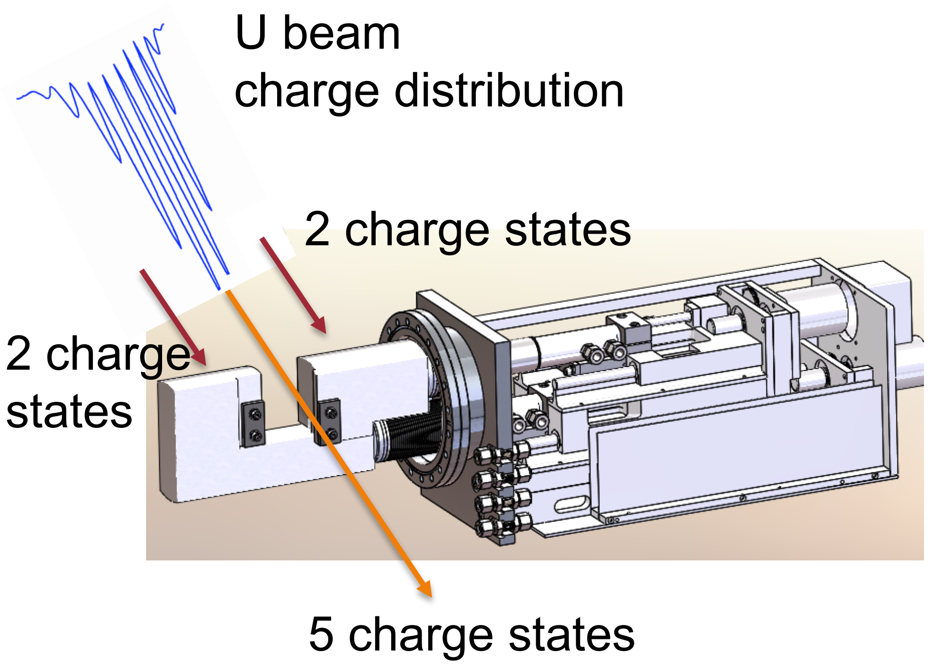


Charge Selector

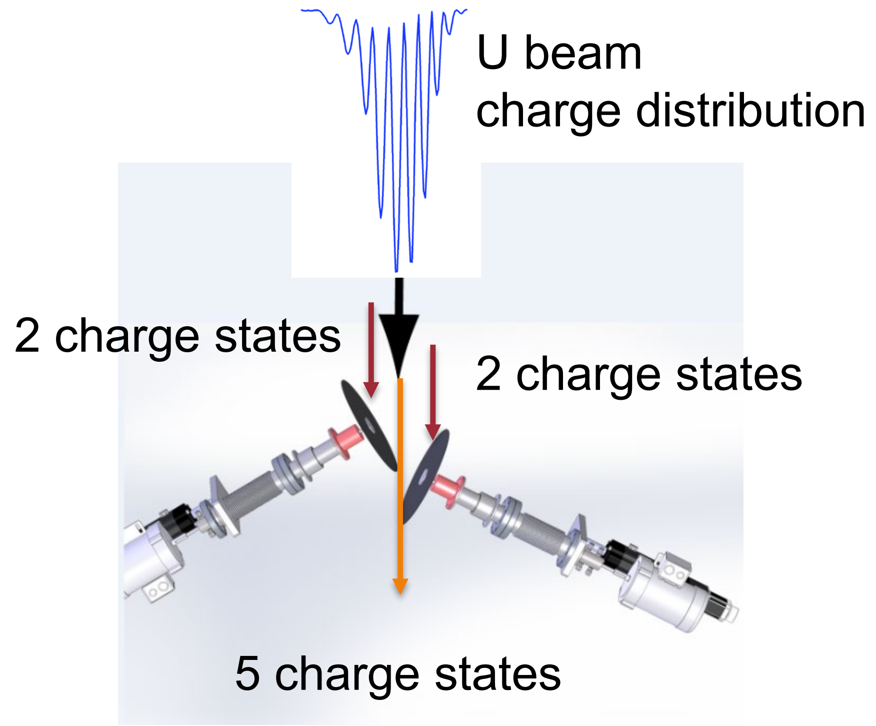
Overview, Status and Future Perspective

FRIB Charge Selector:
Low-Power CS Installed, High-Power CS Being Designed

- Low-power charge selector: water cooled slits made of Glidcop (Cu alloy with small amounts of aluminum oxide ceramic particles)
- High-power charge selector: rotating carbon disks with water cooled shaft (conceptual design stage), similar to carbon stripper / production target



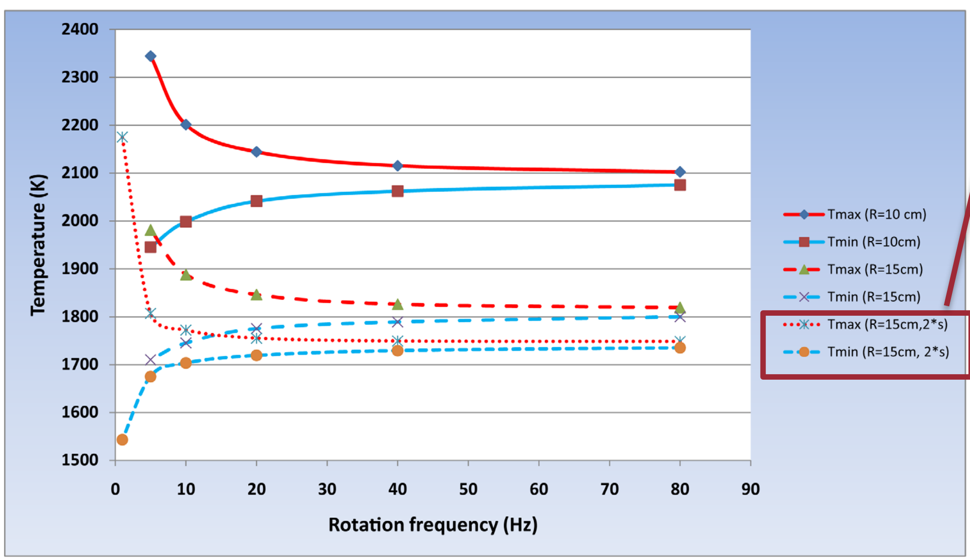
Low-power CS (operational)



High-power CS (conceptual design)

Rotating Carbon Disk Charge Selector Feasibility Study

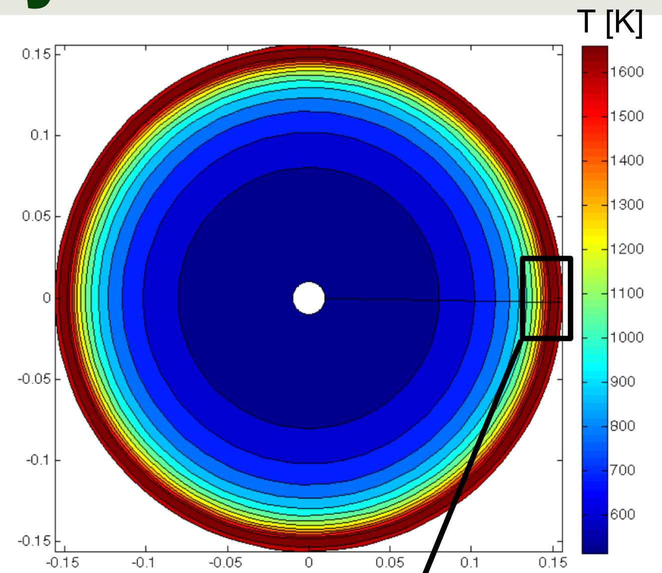
- Thermal analysis
  - U case, Different foil radius, Different incident angle
  - 10 kW in each beamlet
- 40 Hz seems sufficient to minimize a T difference in one cycle (thermal stress)
- < 1900 K to minimize sublimation
- Results look promising. Three beamlets would increase T by 100 K. Design being refined
- Radiation damage will be the key

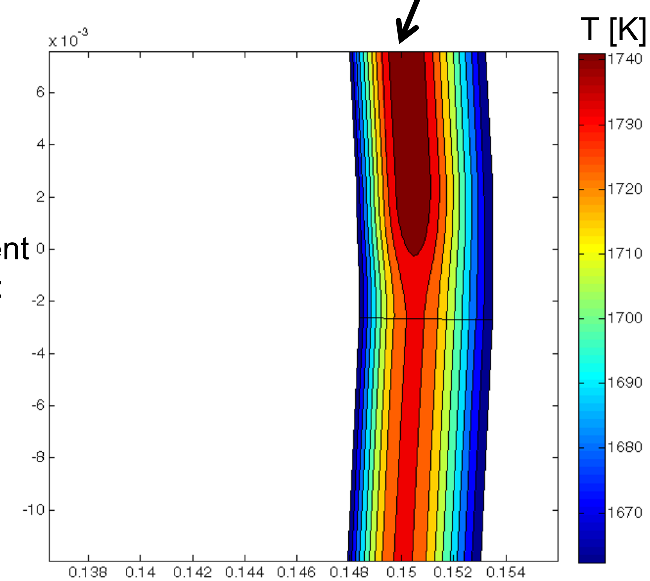


Incident angle: 90°

30°

Results for single beamlet

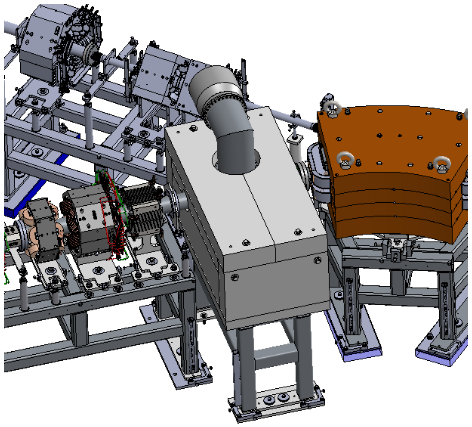




R=15cm, θ=30°

Future Perspective: Charge Selector

- Conceptual design of high-power charge selector: thermal load plus the following challenges need to be resolved
- Irradiation effects (lifetime estimate)
  - Minimum: 2 weeks (typical duration of experiment)
  - Radiation damage will most likely determine lifetime. However, we are not aware of studies of radiation damages caused by heavy ions that stop in graphite at FRIB intensity. Please advise us!
- Diagnostics
  - Beam footprint monitoring (temperature sensors, such as thermal imaging)
  - Fast Machine Protection System in case beams get lost / graphite disk fails
- Limited space issue
  - Enough radiation shielding necessary to allow workers to be around. However the available space is limited.
- Maintenance issue
  - Single-point failure; needs maintenance
  - Very high residual dose rate
  - Little provision for remote handling capability
  - Will need to replace the device as a whole with shielding



You Wanted!

- Physicists / engineers (any rank including postdoc / PhD student)
  - Liquid lithium charge stripper
    - » No need to have lithium handling experiences. Training will be provided
  - Carbon charge stripper
  - Charge selector
  - Production target and beam dump
- Material scientists (any rank including postdoc)
  - Characterization and understanding of interactions between intense high energy heavy ions (up to uranium) and materials
  - This is universal among all beam-intercepting devices in FRIB
    - » Intensity: 5 x 10^{13} ^{238}U/s (CW)
    - » Energy: 20 MeV/u at charge stripper and selector, 200 MeV/u at production target and beam dump
- High-power beam-intercepting devices are full of new interesting opportunities which require innovations
- Contact: Takuji Kanemura, kanemura@frib.msu.edu

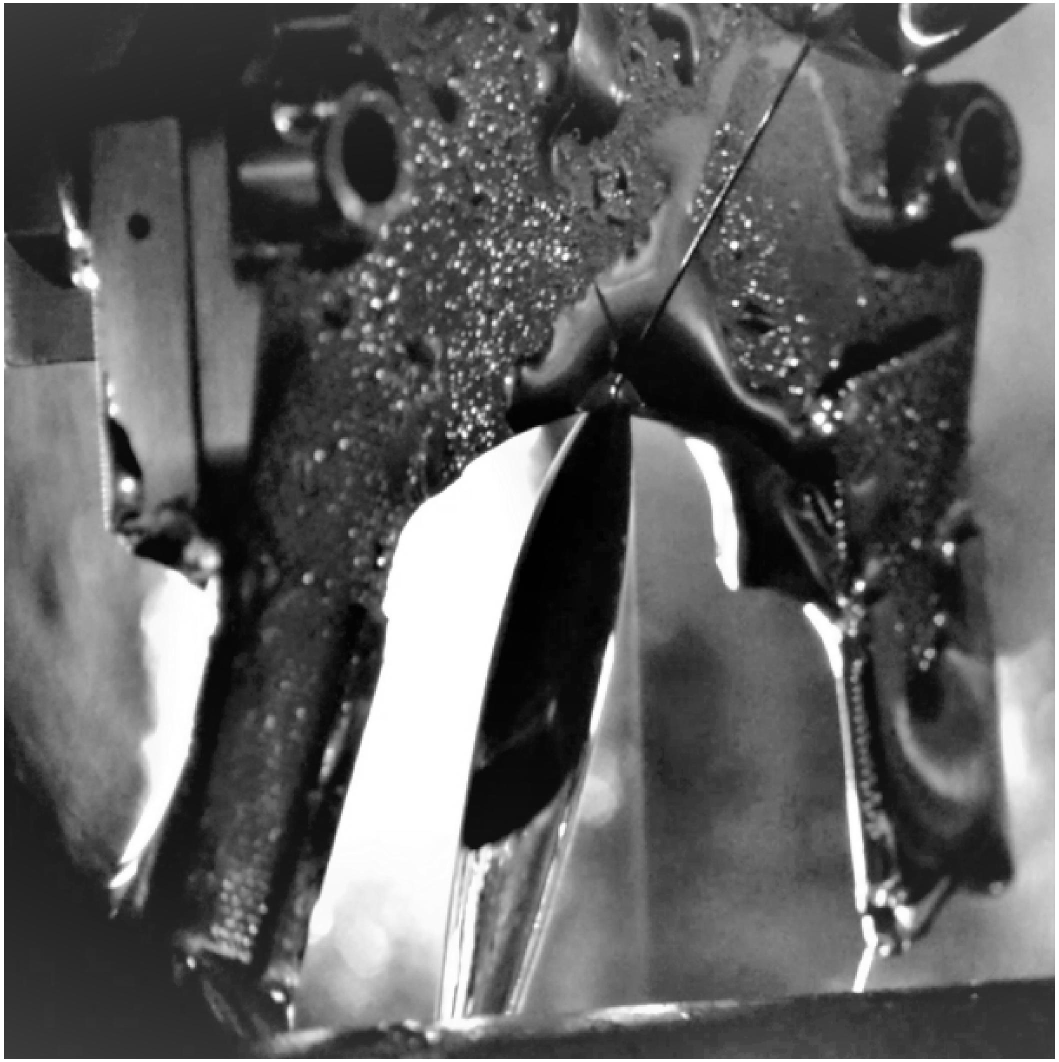
Summary

- FRIB has established two types of charge stripper
  - Liquid lithium charge stripper for high power operation (world's 1st)
  - Rotating carbon charge stripper for low power operation
- FRIB has established a charge selector for low power operations (up to 10 kW at target), which needs to be improved to receive high power beams and to meet our power ramp up plan.
- Charge stripper and selector have common technical challenges
  - Extreme thermal load, and
  - Radiation damage, caused by heavy ions especially uranium beams
- Among many challenges in high power targetry, the above two are unique because these stem from interactions with intense heavy ions, which are interesting have still lack knowledge worldwide.
- Please feel free to contact me if you are interested in our challenges
- Community's advice to our endeavor will be appreciated very much

Acknowledgements

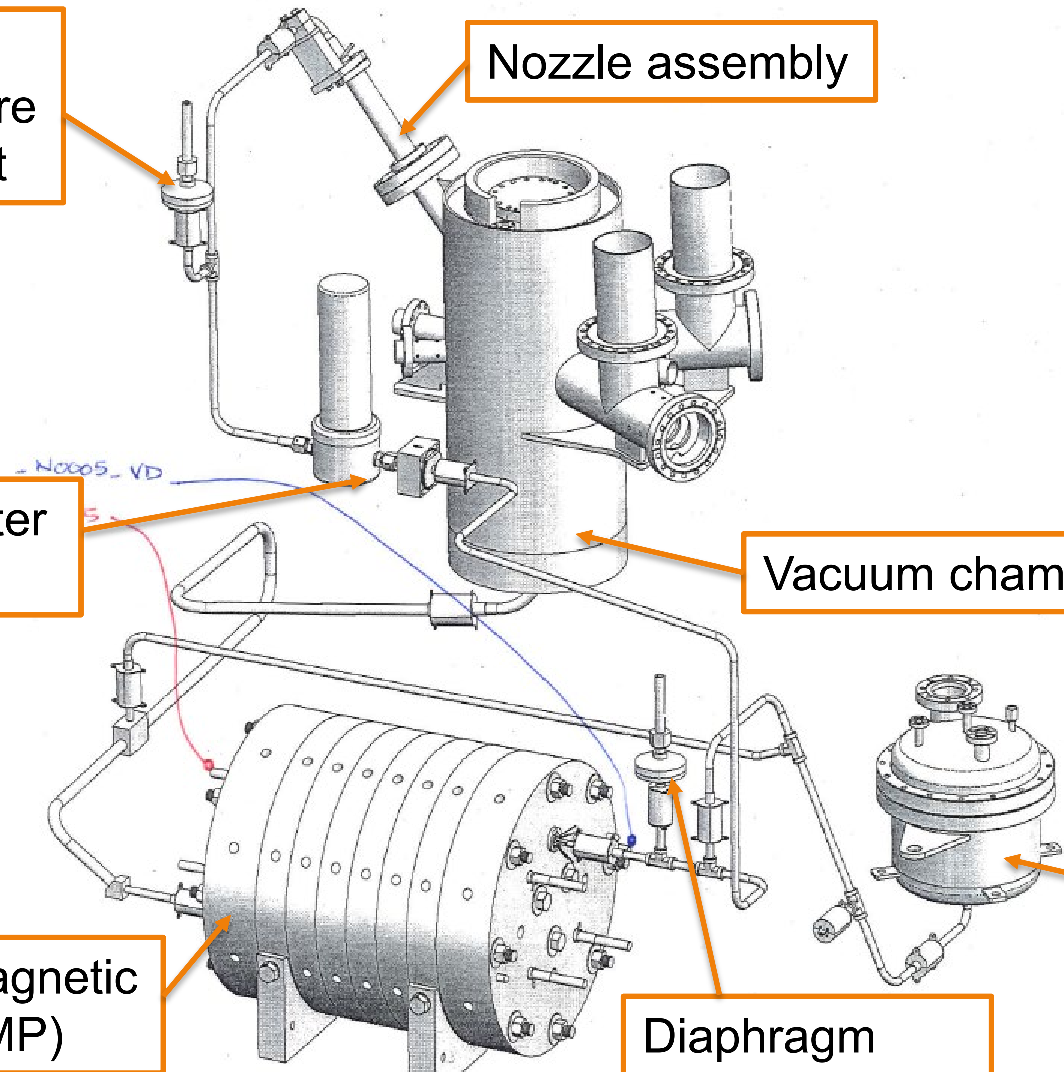
- The authors would like to thank all the FRIB staff members for their contributions to the successful commissioning of the liquid lithium charge stripper with heavy ion beams
- This work is supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan, and Michigan State University.

Thank You!
Any Questions?

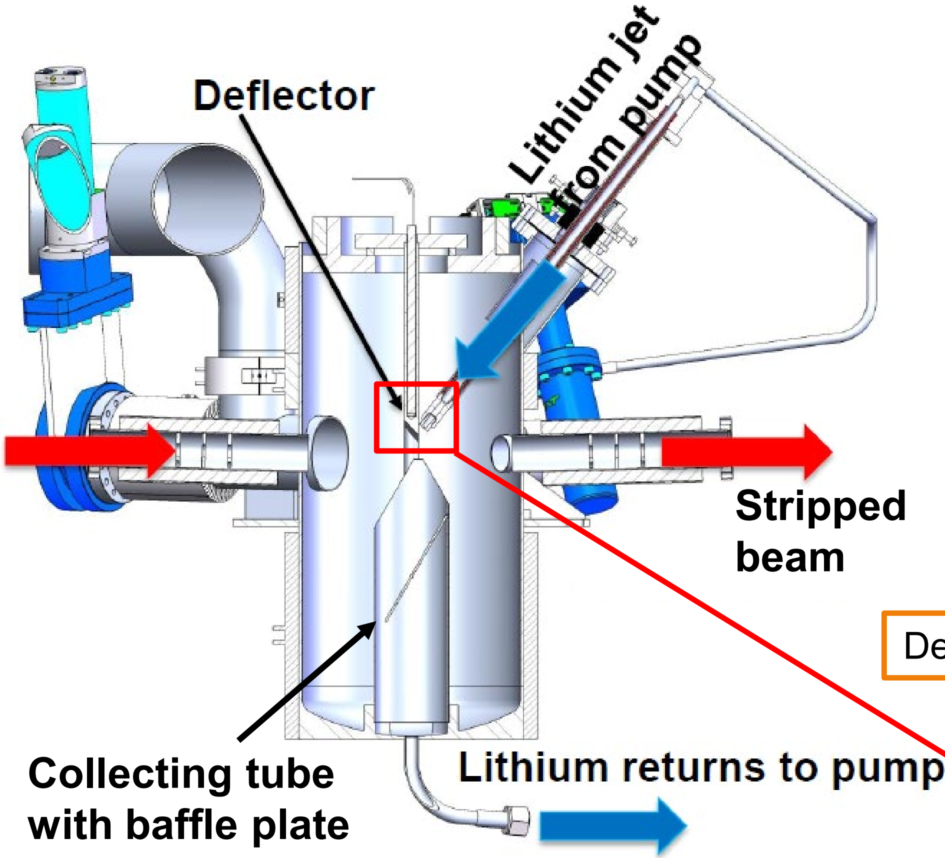


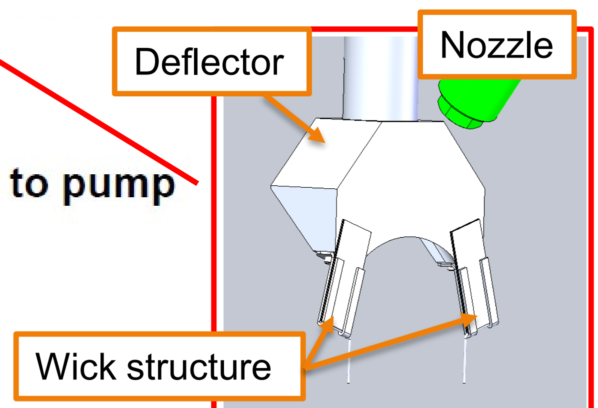
Appendices

Lithium Loop Configuration

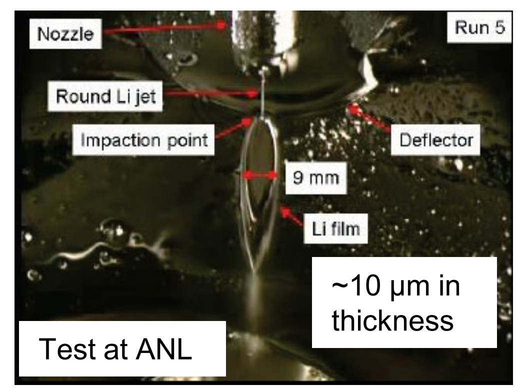


Stripper Film Produced by High Velocity Jet





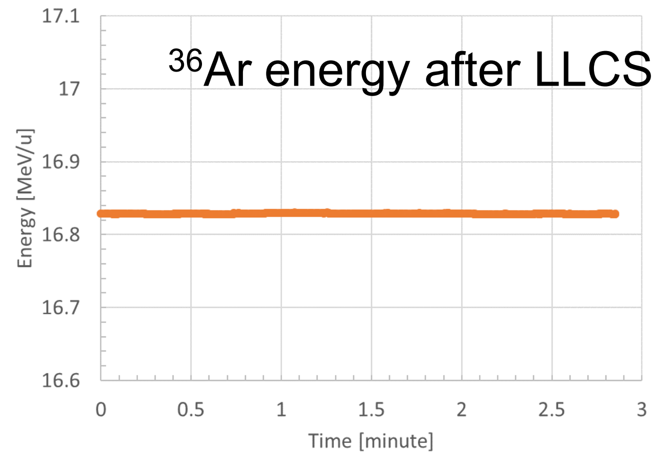
- The thin lithium film needs to move very fast (~ 50 m/s) to remove the heat away from the impact point.
- This is achieved by producing a high pressure (~1.4 MPa) lithium flow in a 0.5 mm diameter nozzle.
- The jet impinges on a flat deflector and produces the thin film.

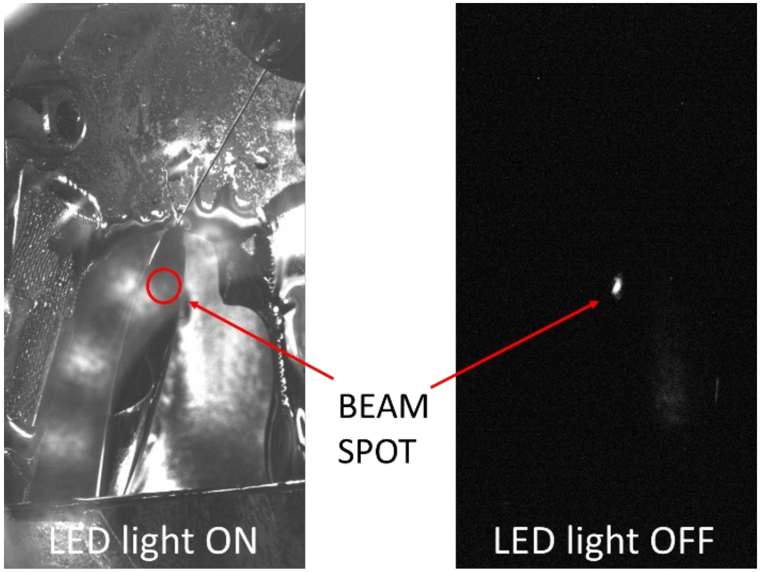


Y. Momozaki et al., 2009 JINST 4 P04005

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

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"

Los Alamos NATIONAL LABORATORY EST.1943

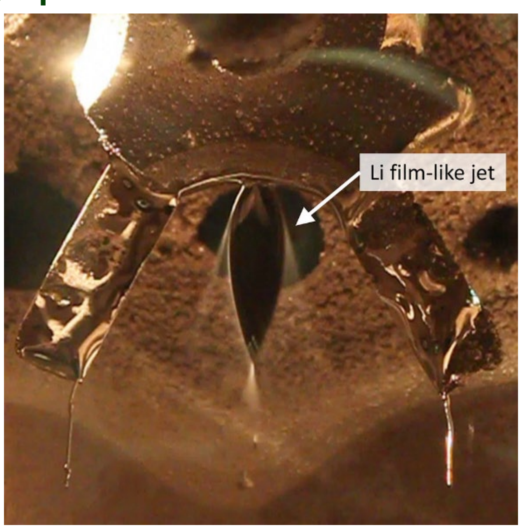
- Ultra-high power deposition test using the LEDA proton source (LANL)

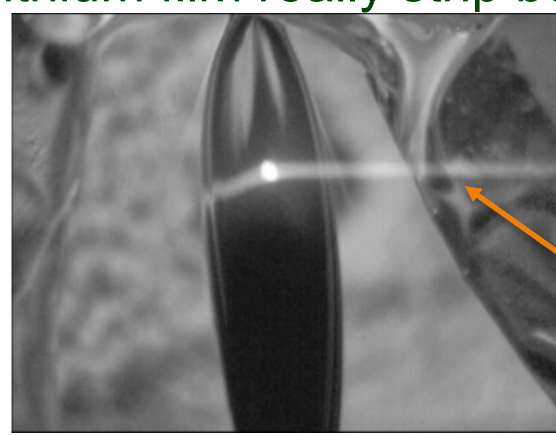
Y. Momozaki *et al.*, *J. Radioanal. Nucl. Chem.*, vol. 305, pp. 843-849, 2015

  - 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

Analysis Parameters

- Beam Profile (Horizontal Projection)

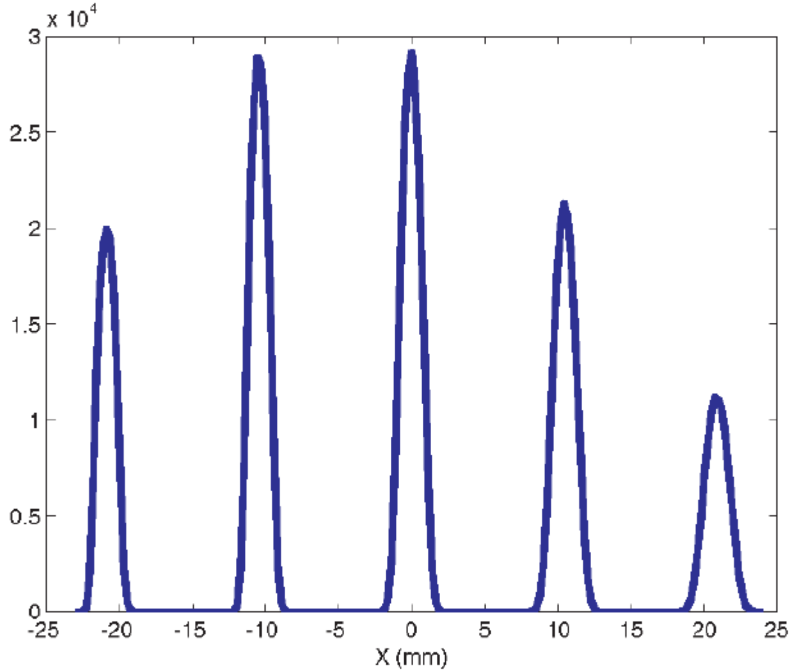
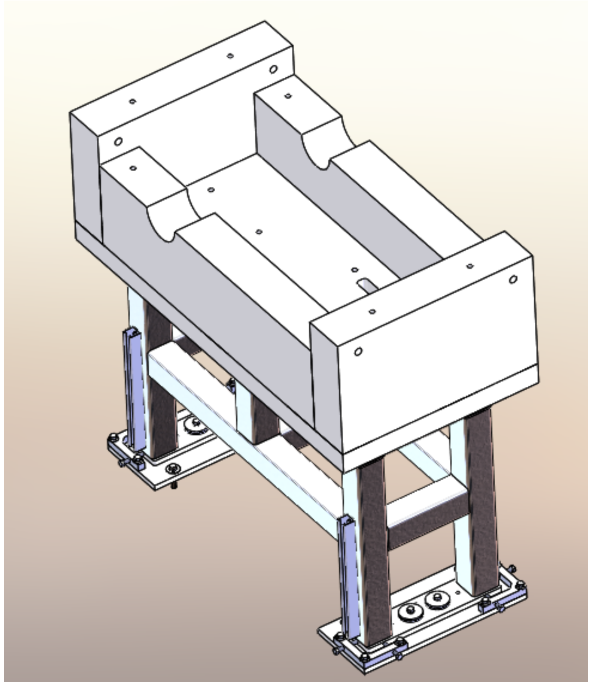


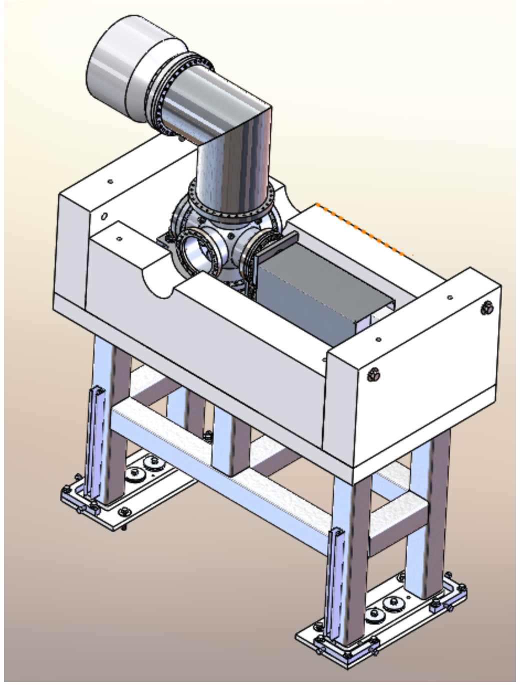
Figure 1: Beam profile at the charge selector location for an U beam after stripping at 16.5 MeV/u. Horizontal projection, arbitrary units. (Data provided by Q. Zhao)

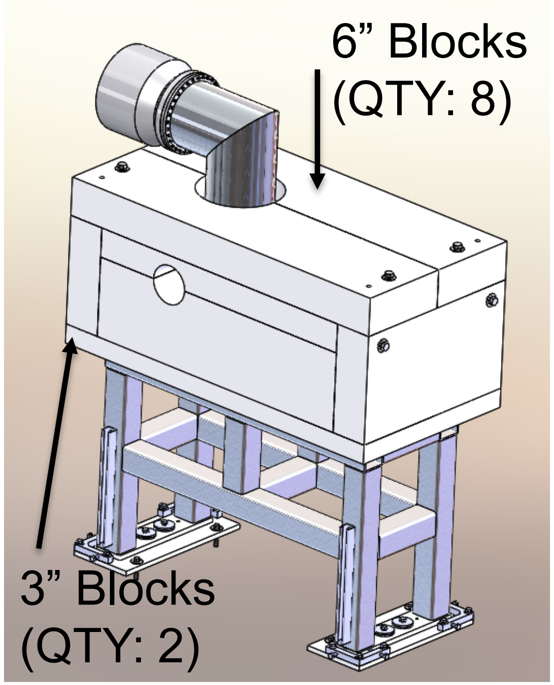
Reference: *Preliminary Thermal Design of Folding Segment 1 Charge Selector (FRIB-T30706-TD-000610-R001)*

Radiation Shielding

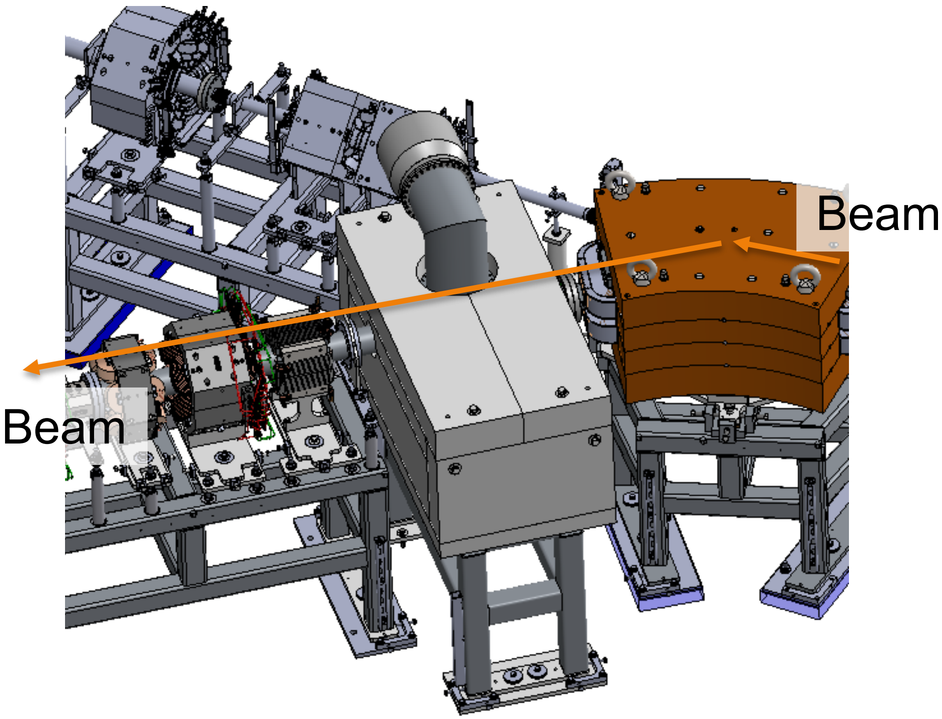
- A36 steel shielding blocks of 6” thickness required
- 3/4”-10 bolts used for the assembly of the shielding
- Threaded holes in each piece for hoist rings to be attached
- Designed to disconnect flanges and pull entire assembly if necessary

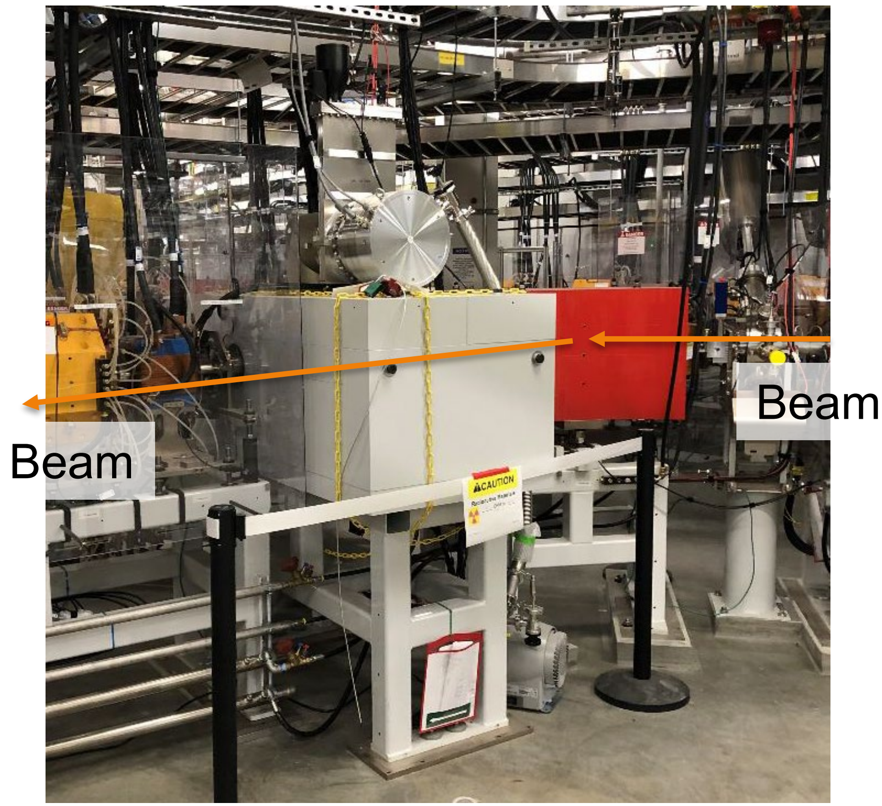






Low Power Charge Selector Operational, Serving User Operations





Thermo-mechanical Analysis for Low-Power Charge Selector

- Five beamlets intercepted on one slit, each has 500 W, total 2.5 kW
  - 5 kW in total received on both sides, corresponding to ~ 200 kW at target
  - Expected power deposition at charge selector is 200 W, corresponding to 10 kW at target
- Beamlets separated by 10.3mm and each size is 4.2 mm (horizontal) x 7.5 mm (vertical) considering U beam case (Gaussian with σ_H=0.7 mm, σ_V=1.25 mm and range of 0.14 mm)
- Cooling water flow rate 2 liter/min in 6 mm channel, 22 °C at inlet
- Effects of heavy ion irradiation need to be taken into account