Operational Performance with FRIB Liquid Lithium and Carbon Charge Strippers

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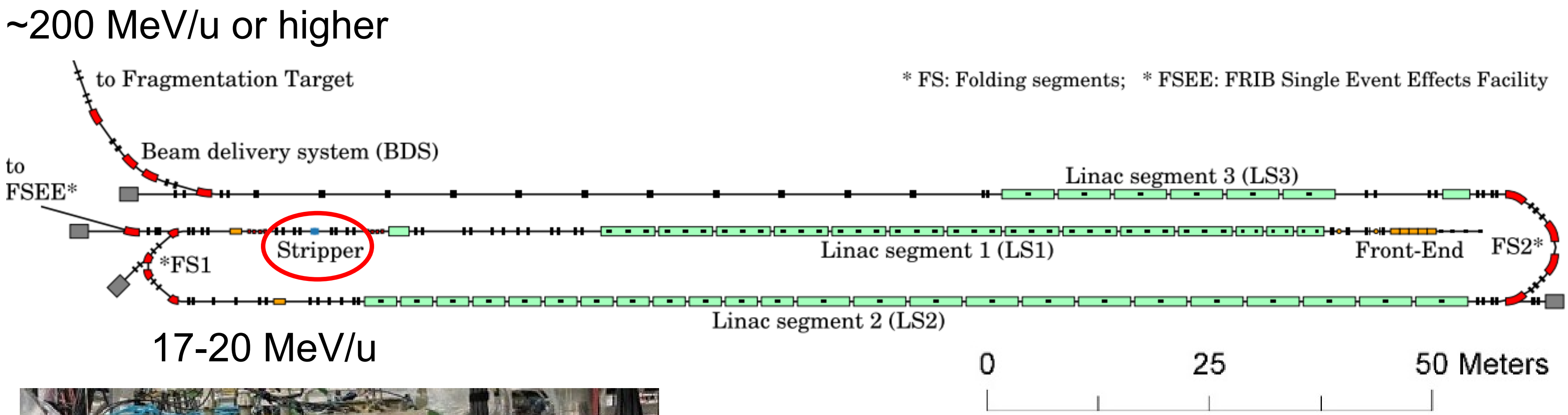
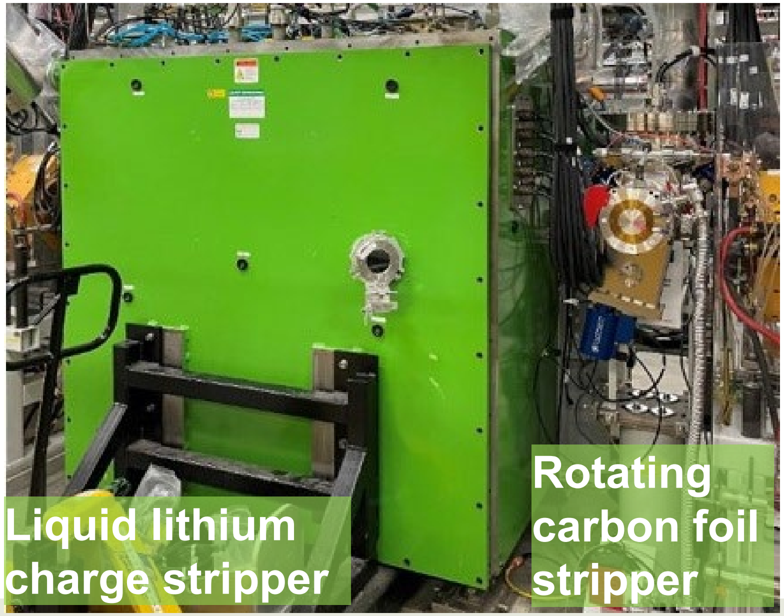
Outline

- Charge strippers in FRIB Linac
- Technical challenges in charge strippers
- Operational performance
  - Liquid lithium charge stripper
  - Rotating carbon charge stripper
- Summary

Charge Strippers in FRIB Driver Linac

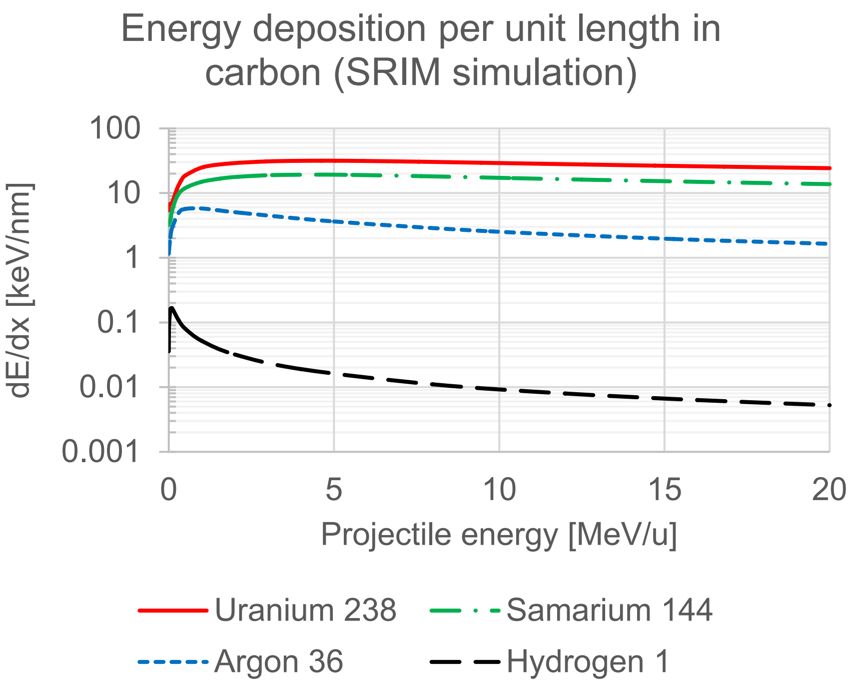




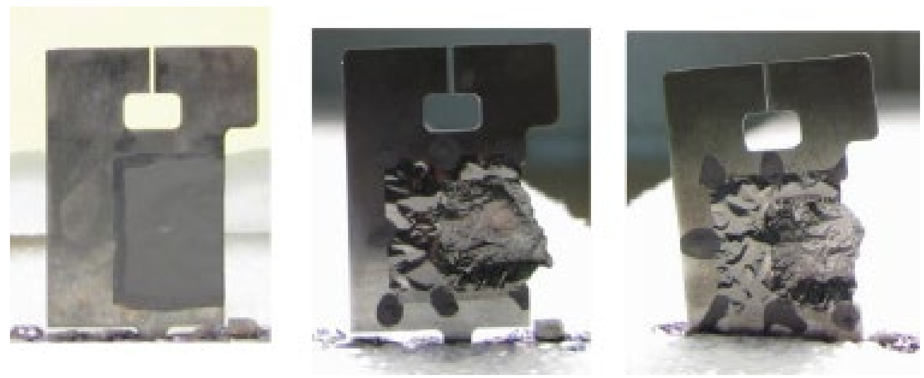
- Charge strippers are located in Folding Segment 1 (FS1)
- Charge strippers remove electrons from ions being accelerated to increase their charge state(s) by a factor of approx. 2, thus increase the energy gain in Linac Segment 2 (LS2) and Linac Segment 3 (LS3)

Technical Challenges in Charge Strippers [1/2]

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



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

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

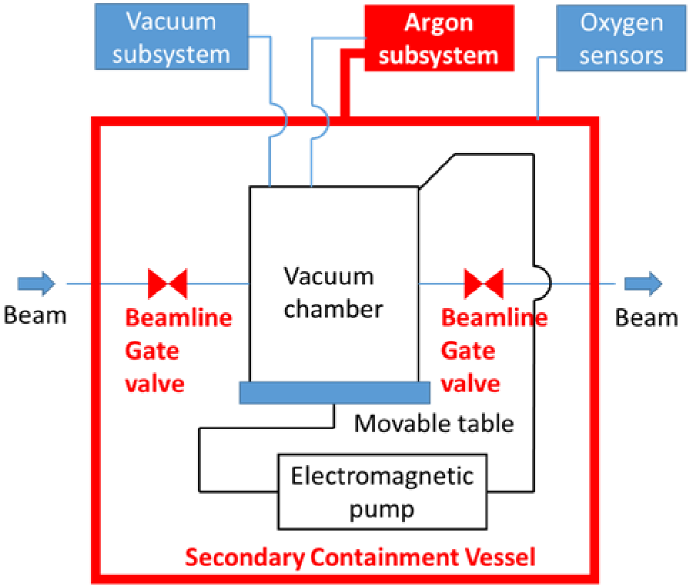
Technical Challenges in Charge Strippers [2/2]

- Deposited power density and DPA rates for uranium beam shown below
- Liquid lithium charge stripper for heavy ion and high power operations

Medium	Beam power	Beam size	Thermal load (uranium)		DPA rate
1.5 mg/cm^2 Solid C	1 kW (10 kW at target)	σ 1 mm	47 W	2 MW/cm^3 (average)	~10^{-4} dpa/s assuming static foil
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

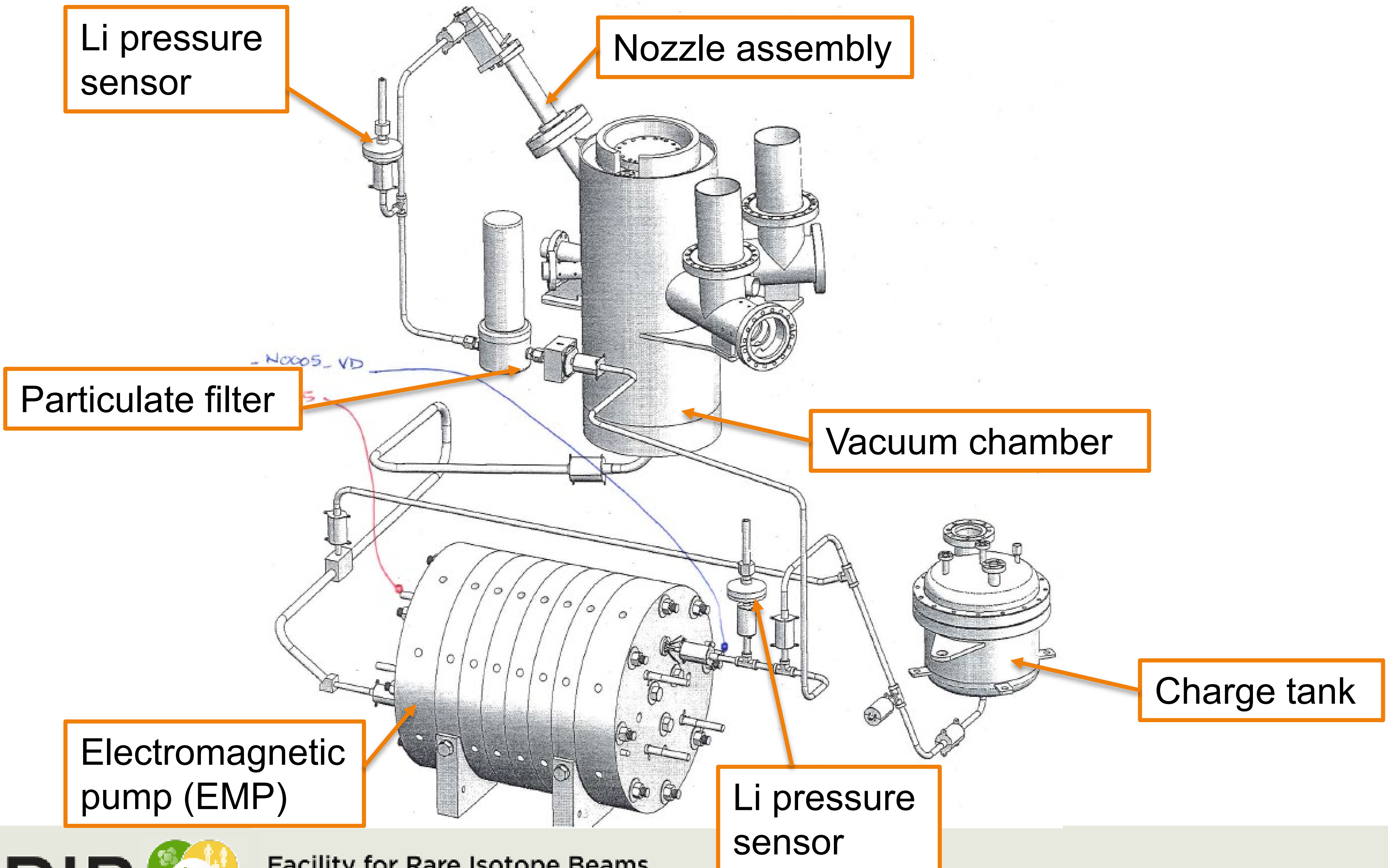
Liquid Lithium Charge Stripper (LLCS) System

- 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
- 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

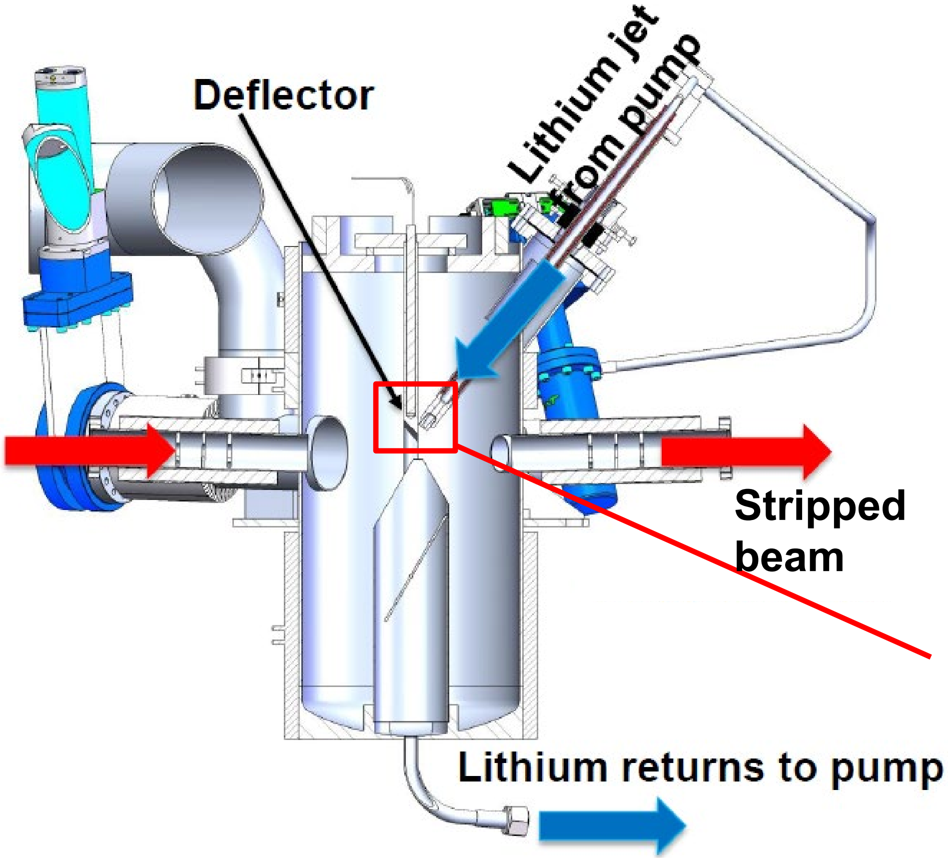


SCV in FRIB linac beamline

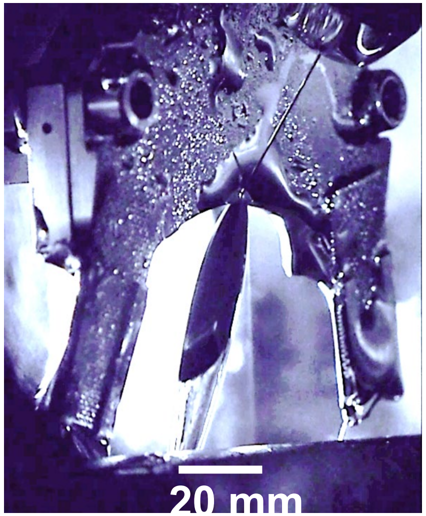
Lithium Loop Configuration

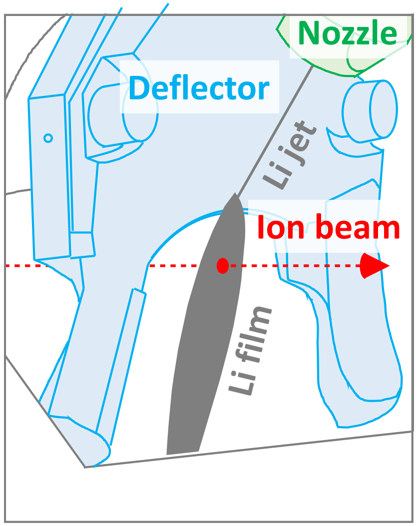


Stripper Film Produced by High Velocity Jet



- The thin lithium film needs to move very fast (~ 60 m/s) to remove the heat away from the impact point.
- A 0.5-mm round jet impinges on a flat deflector and produces the thin film.
- No vacuum windows. The film is in accelerator vacuum environment (chamber vacuum ~10^{-6} Pa)



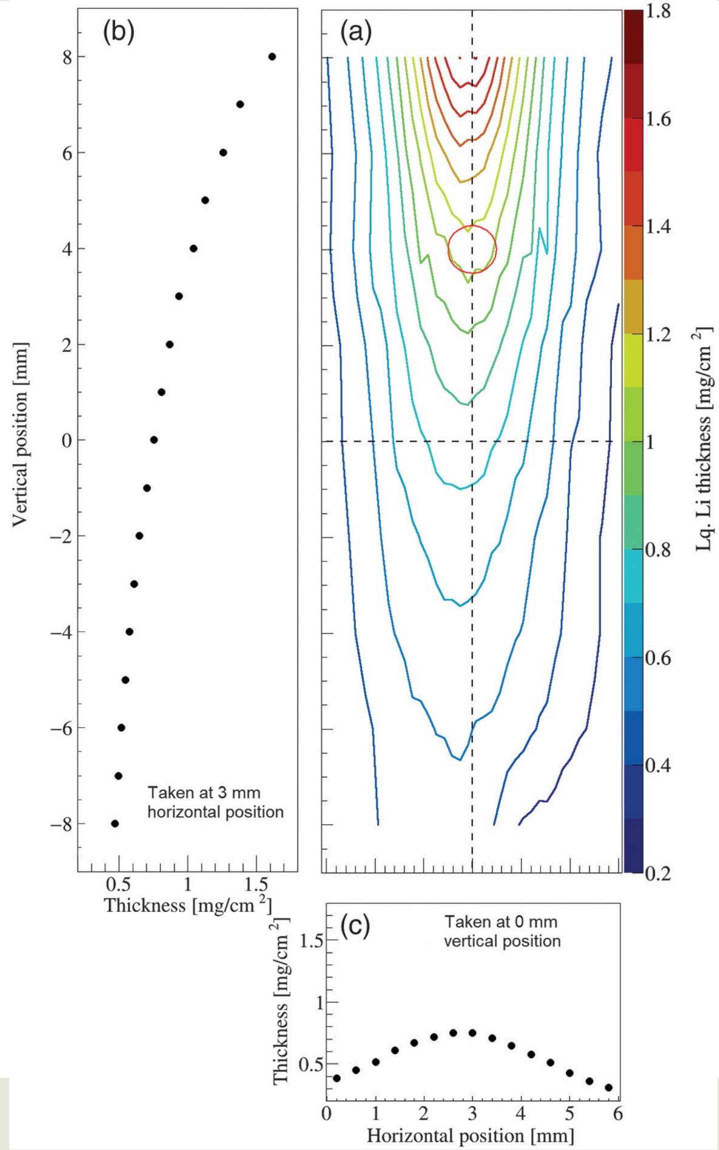


Operational Performance

- Ions that have been stripped by LLCS: ^{36}Ar, ^{48}Ca, ^{124}Xe, ^{198}Pt and ^{238}U.
- Film thickness measured by beams
- Charge states measured
- Stability of lithium film

Operational Performance: Lithium Film Thickness

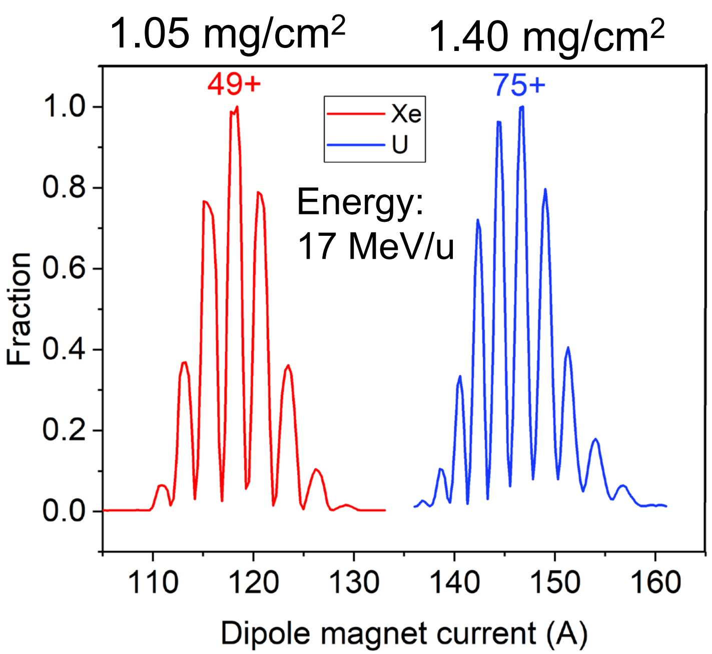
- Mass thickness measured
  - Exp: 20 MeV/u $^{36}Ar^{10+}$ beam energy loss measured over the film
  - Calc: Energy loss per unit length obtained from the SRIM code
- The closer to the impinging point, the thicker the film is, but the higher the thickness gradient becomes
- At some distance away from the impinging point, the film is uniform enough for the 0.5-mm-radius beam

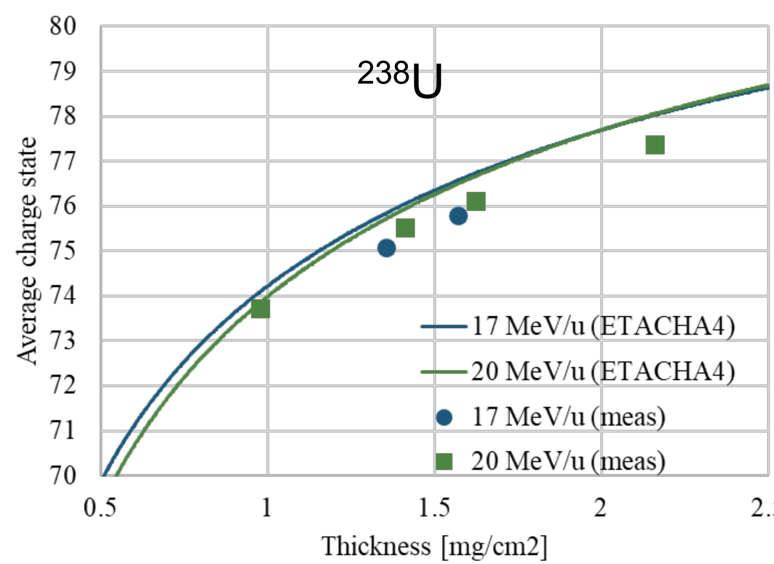


T. Kanemura, et al., Phys. Rev. Lett. **128**, 212301 (2022)

Operational Performance: Charge States of Stripped Beams

- Charge state distributions of the xenon (red) and uranium (blue) beams after the LLCS (bottom left).
- Average charge state of ^{238}U after LLCS as a function of thickness (bottom right)
- Because thickness gradient increases with thickness (previous slide), currently 1 mg/cm^2 is the maximum thickness available for high power operation



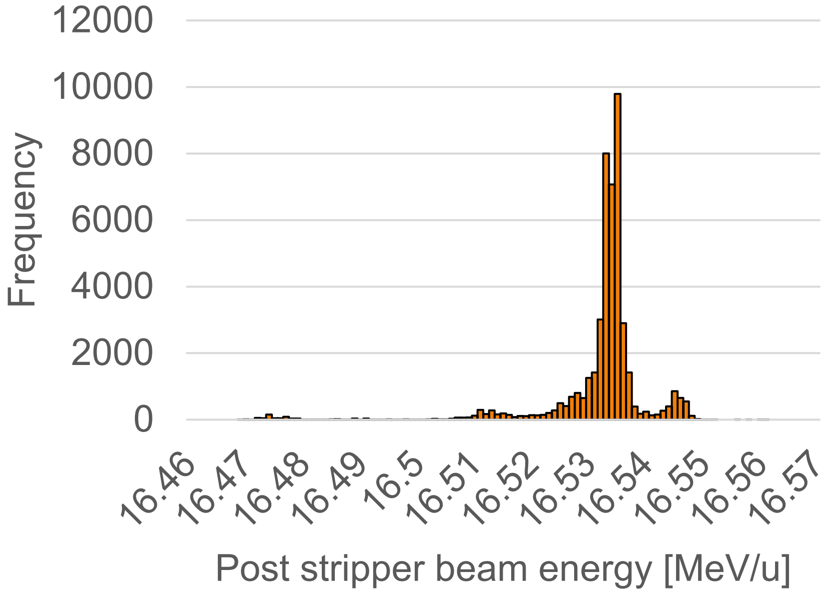


Lithium Film Stability Issue

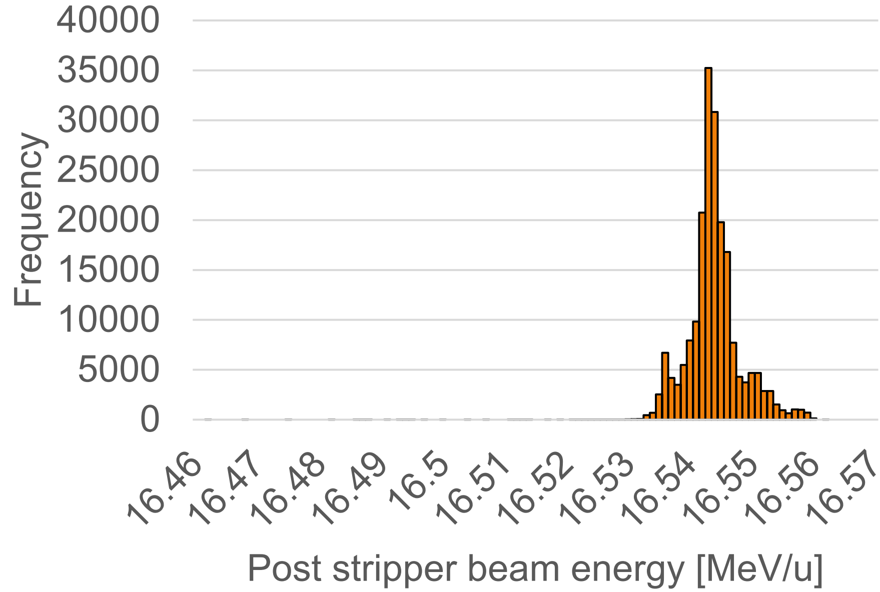
- Lithium flow stability degradation was observed
  - Suddenly the pressure drop at the particulate filter increased, which decreased the flow rate and increased its fluctuations
  - The most probable scenario would be as follows:
    - This is probably because the oil that was leaked into the lithium loop when the old diaphragm used to transfer lithium pressure to the pressure transducers failed, started reacting with lithium although we thought it had been removed.
    - The reaction products started to be trapped in the particulate filter
- The particulate filter was replaced in March 2023, and flow rate and pressure drop has been recovered
- However, the replacement work introduced argon in the loop (all Li maintenance work is done under argon environment). Even micro bubbles could affect flow stability because the film is very thin (20 μm).
- Stability tests with 17 MeV/u Xe beam carried out (next slide)

Lithium Film Stability Recovered

- Two film stability tests after the filter replaced with 17 MeV/u Xe beam
- Test #1 Apr. 22-23, 2023
  - Post stripper beam energy, average: 16.532 MeV/u, standard deviation: 0.009 MeV/u
- Test #2 May 28-30, 2023
  - Post stripper beam energy, average: 16.544 MeV/u, standard deviation: 0.004 MeV/u
- Stability improved at Test #2. Circulation helped release trapped argon.



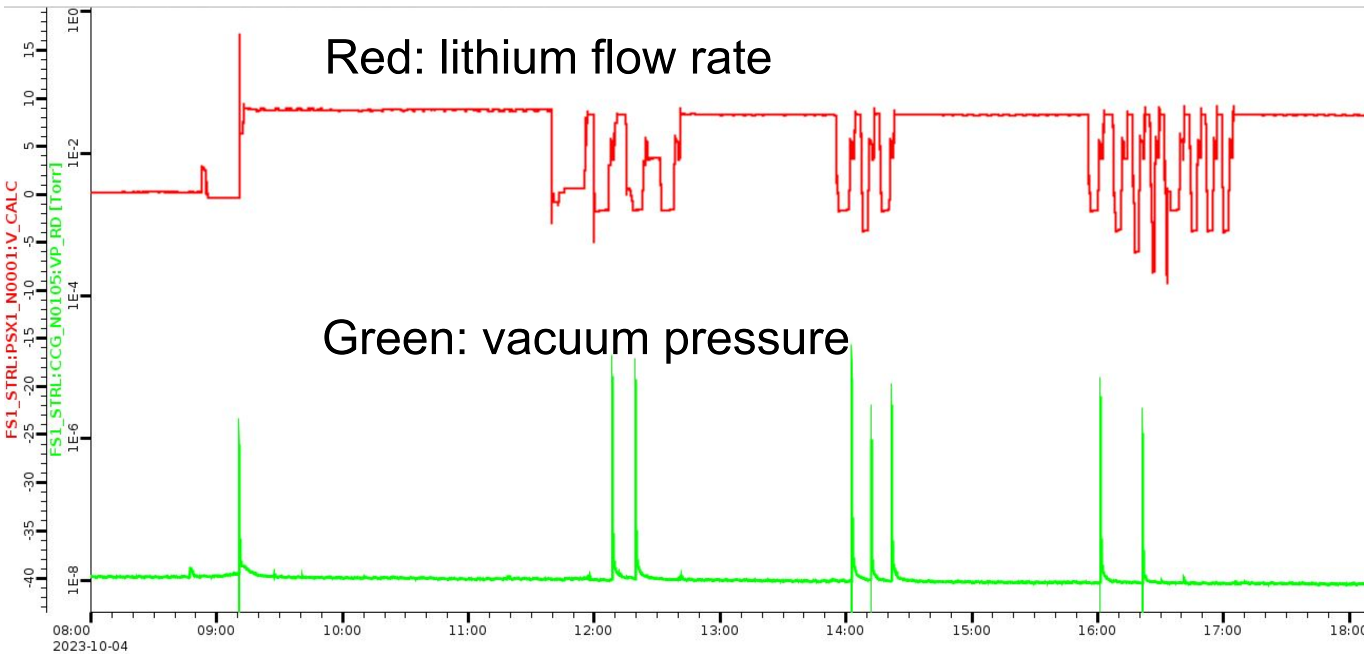
Apr. 22-23, 2023



May. 28-30, 2023

Further Attempts to Improve Lithium Film Stability

- Last month, a polarity switch of the lithium pump power supply has been installed to allow a reverse flow to expose pipe elements that could trap argon to vacuum.
- During the subsequent reverse flow test conducted last week, reverse-normal flow cycles induced big vacuum spikes (from base pressure 1e-8 Torr to 1e-5 Torr) 7 times.

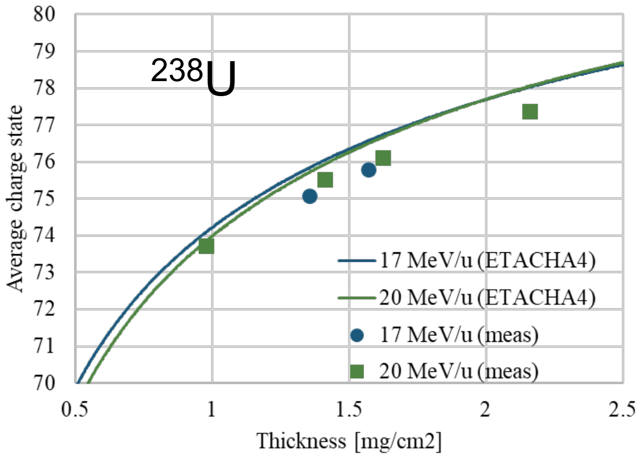


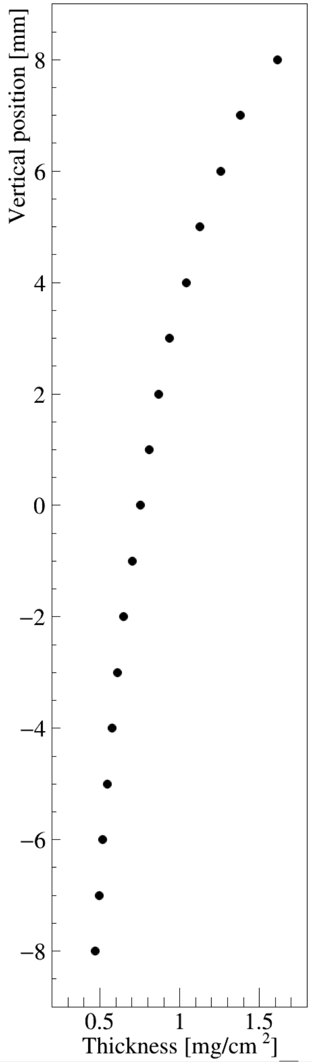
- Effectiveness of these gas releases on flow stability to be tested with a beam

Future Works

- Film thickness improvement
  - Average charge states of U beam was 74+ at 1 mg/cm^2 thickness
    - » Accelerator designed with 78+
  - R&Ds to improve film uniformity and to make a thicker film for U beam stripping
    - » Started water tests (two-jet method)
  - Our goal: 1.5 mg/cm^2

Two-jet film formation test

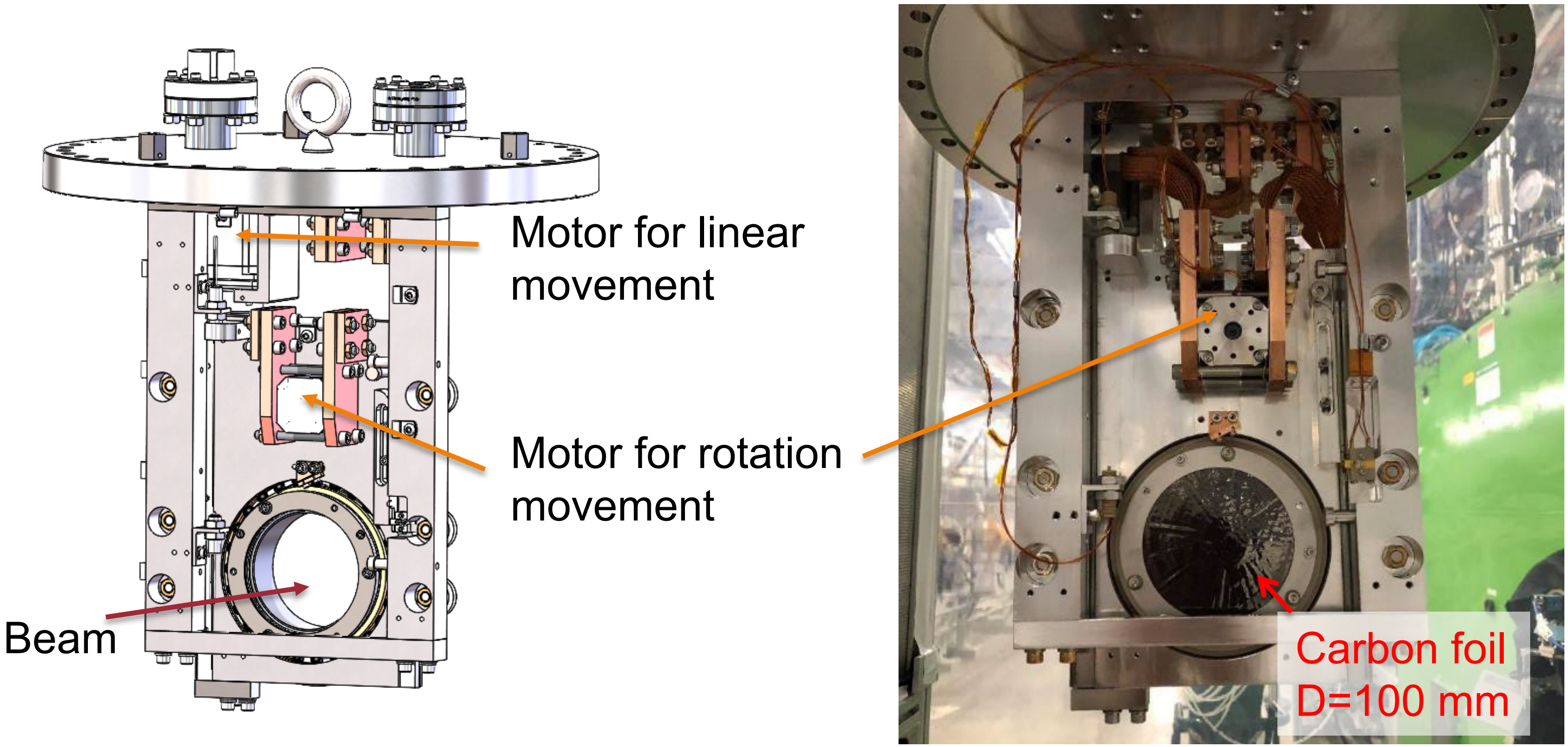




- Erosion and corrosion of nozzle and deflector
  - Accumulated lithium circulation hours has reached 1400 hours
  - Planning to replace them to do material analysis

Rotating Carbon Charge Stripper

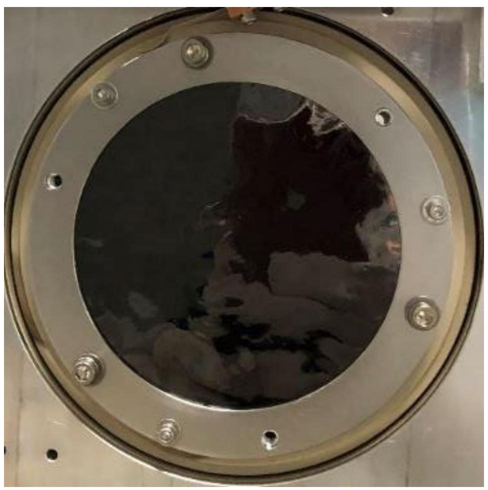
- Rotating carbon charge stripper next to LLCS, being used for user operations.
- Two movements used: rotation (100 rpm) and linear motion (slow up&down cyclic motion), which help distribute both thermal and radiation damage



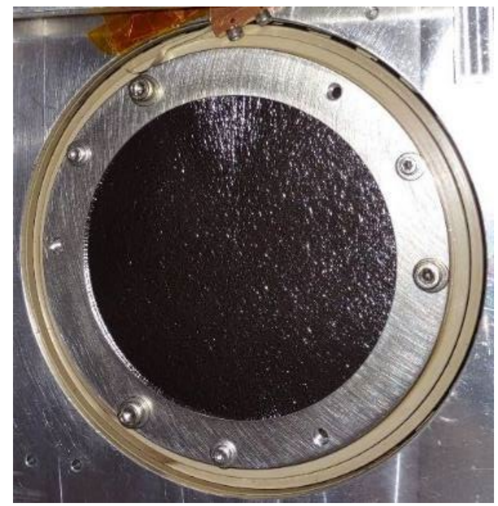
Carbon Foils Used in FRIB

- We have used two types of graphene foil (reported high thermal conductivity of 1500 W/m/K)
  - Type A. Foils made by a controlled reduction of graphene oxide by hydrazine with addition of ammonia in an aqueous dispersion (no heat treatment).
  - Type B. Foils made from polyimide by carbonization (up to 1400 C) and then by graphitization (up to 3000 C).

Type A



Type B

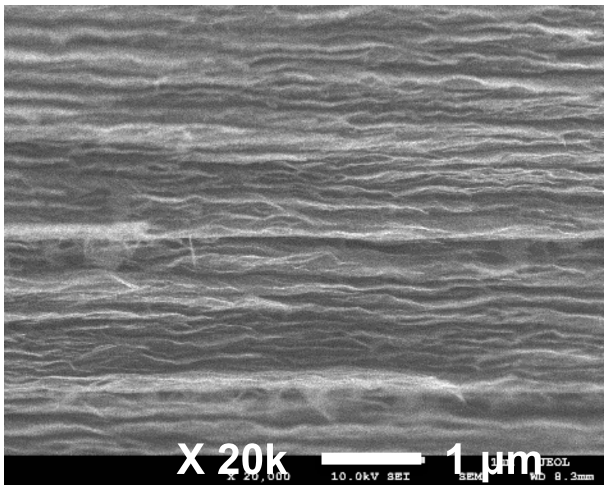


- Thickness: 1.0-1.5 mg/cm^2 (approx. 5-7.5 um)
- Type B foils have been used at RIKEN RIBF to strip high-power U beams

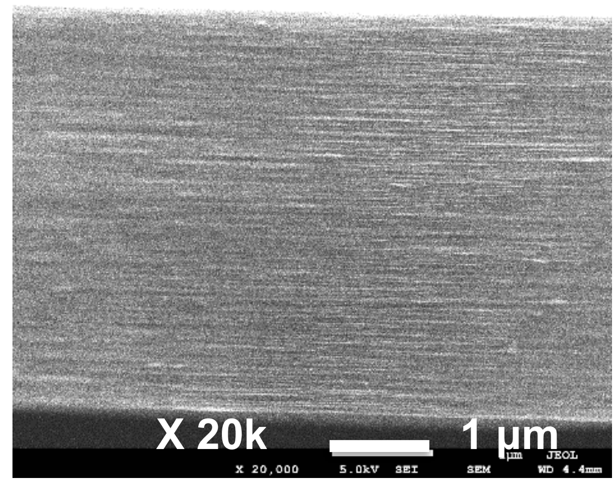
SEM / EDX of Foils

- Scanning Electron Microscopy (SEM) observation
  - Type A has a layered structure and seems to be made from graphene crystallites
  - Type B has a much higher degree of crystallinity and orientation of graphene layers

Type A



Type B



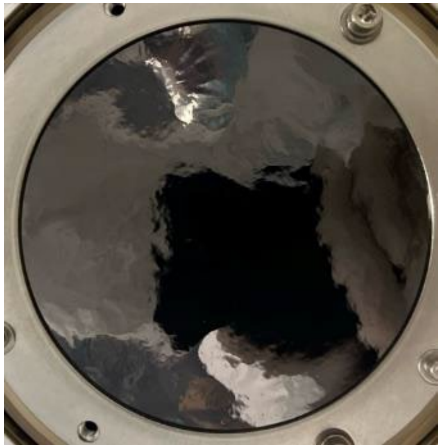
- Energy Dispersive X-ray spectroscopy (EDX) elemental analysis

Type	Carbon purity	Main impurity
A	> 90 At%	Oxygen
B	> 99 At%	Oxygen

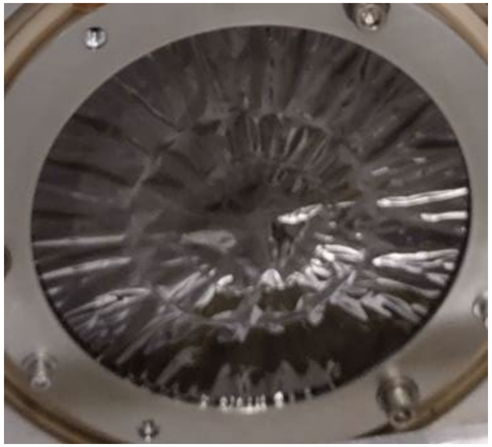
- Note: EDX cannot detect H.
- O might exist as H_2O in Type A, which explains why foil conditioning (outgassing) takes a few hours
- Type B foil doesn't outgas.

Foil Performance Comparison: after 5-kW-at-target Xe beam irradiation

- Type A: Buckled due to heat deposited from 5-kW-at-target Xe beam irradiation, which suggests it is susceptible to heat (plastic deformation due to heating). Could support continuous 5 kW Xe beam operations
- Type B: even after 5-kW-at-target Xe beam irradiation, still looks new, consistent with Riken's experiences



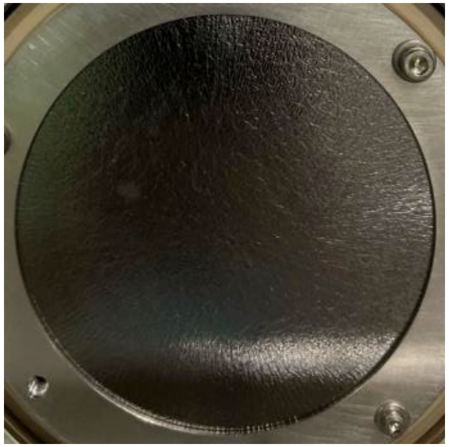
New



After

Type A

New

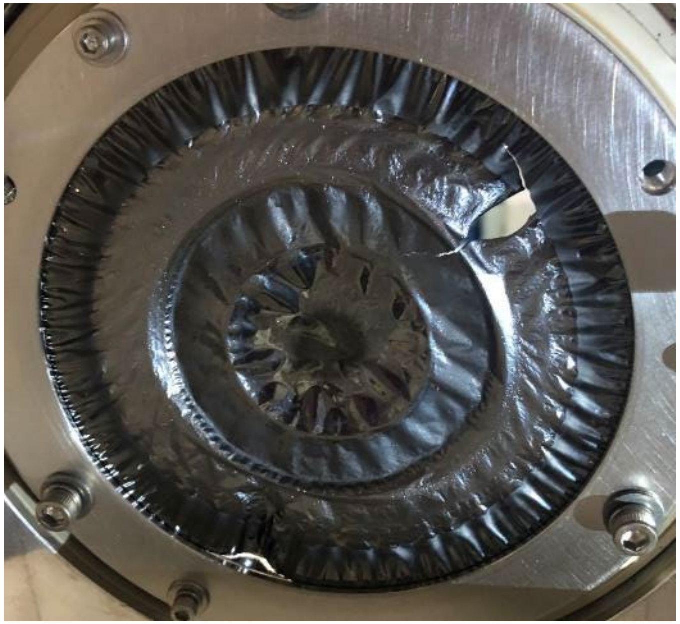


After

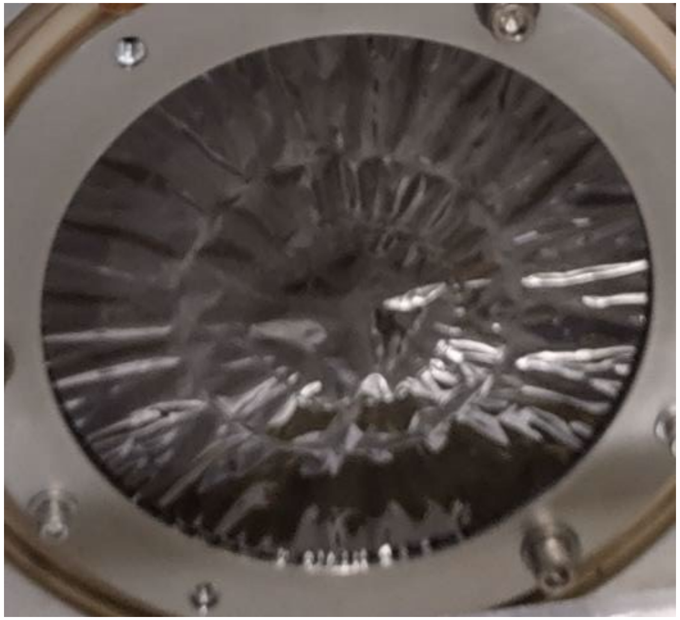
Type B

Radiation Damage to Type A Foil with Pt beam

- ^{198}Pt (Z=78) left severe damages in Type A carbon foil
  - Beam power at stripper: 200 W (2 kW at target), 90 pnA
  - Power deposition to foil: 7 W (estimate)
- ^{124}Xe (Z=54) left only buckling
  - Beam power at stripper 500 W (5 kW at target), 250 pnA
  - Power deposition to foil: 16 W (estimate)



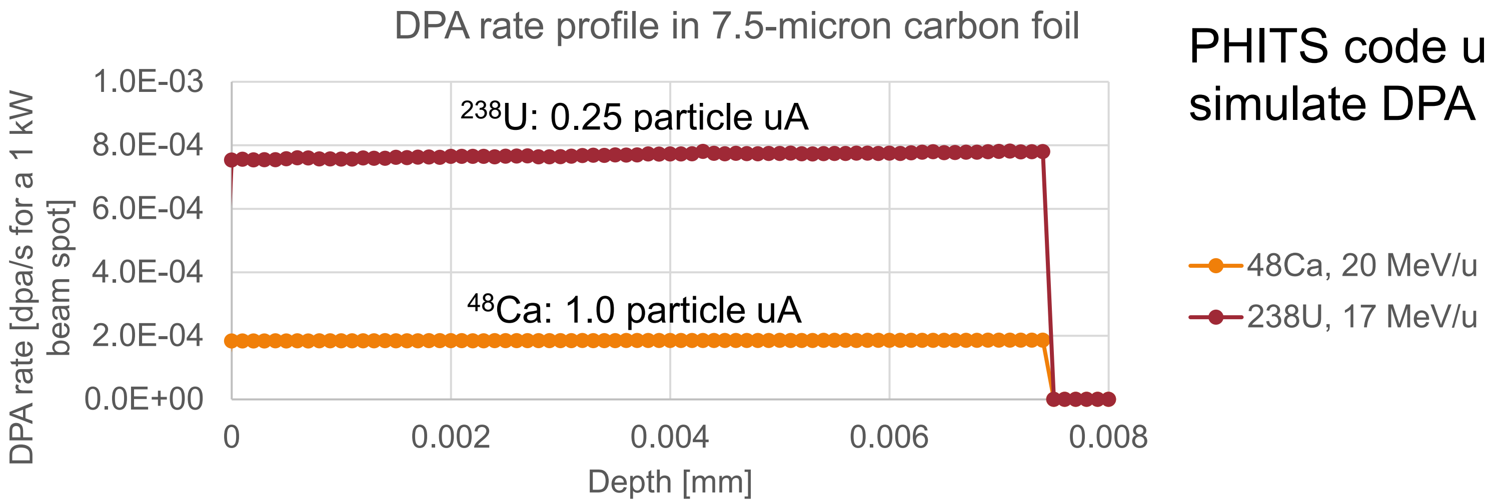
After ^{198}Pt irradiation



After ^{124}Xe irradiation

Toward Understanding of Radiation Damage

- Difference in displacement-per-atom (DPA) rates between Ca (Z=20) and U (Z=92): Only factor of 4



PHITS code used to simulate DPA rates

- DPA rates of Xe (Z=54) and Pt (Z=78) should be much closer (no calc for Xe nor Pt)
- Which doesn't seem to be consistent with what we have observed
  - Pt damaged the foil after less than 1-day 2 kW irradiation
  - Xe didn't leave severe damage after 1-week 5 kW irradiation
- Damage that is not characterized by dpa should have happened with heavy ions. E.g. ion hammering (ion-beam induced plastic deformation)

A. BENYAGOUB and S. KLAUMONZER, Radiation Effects and Defects in Solids, 1993, vol. 126, pp. 105-110

- No post-irradiation examination (PIE) tests yet. Looking for opportunities

Summary

- FRIB has used two types of charge stripper
  - Liquid lithium charge stripper
  - Rotating carbon charge stripper
- Operational performance of liquid lithium charge stripper
  - Tested up to 5-kW-at-target Xe beams
  - Ready for higher power beams including uranium
- Operational performance of rotating carbon charge stripper
  - Two brands of graphene foils
  - Tested up to 5-kW-at-target Xe beams
  - Type A foil was damaged by ^{198}Pt most likely due to radiation damage
  - Type B foil has never been irradiated by ions heavier than Xe at FRIB
- Routine 10 kW operations will begin October 2023
  - Carbon stripper for ion species lighter than Xe
  - Lithium stripper for ion species heavier than Xe