Operational Experiences of FRIB Linac Beam-Intercepting Devices

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Outline

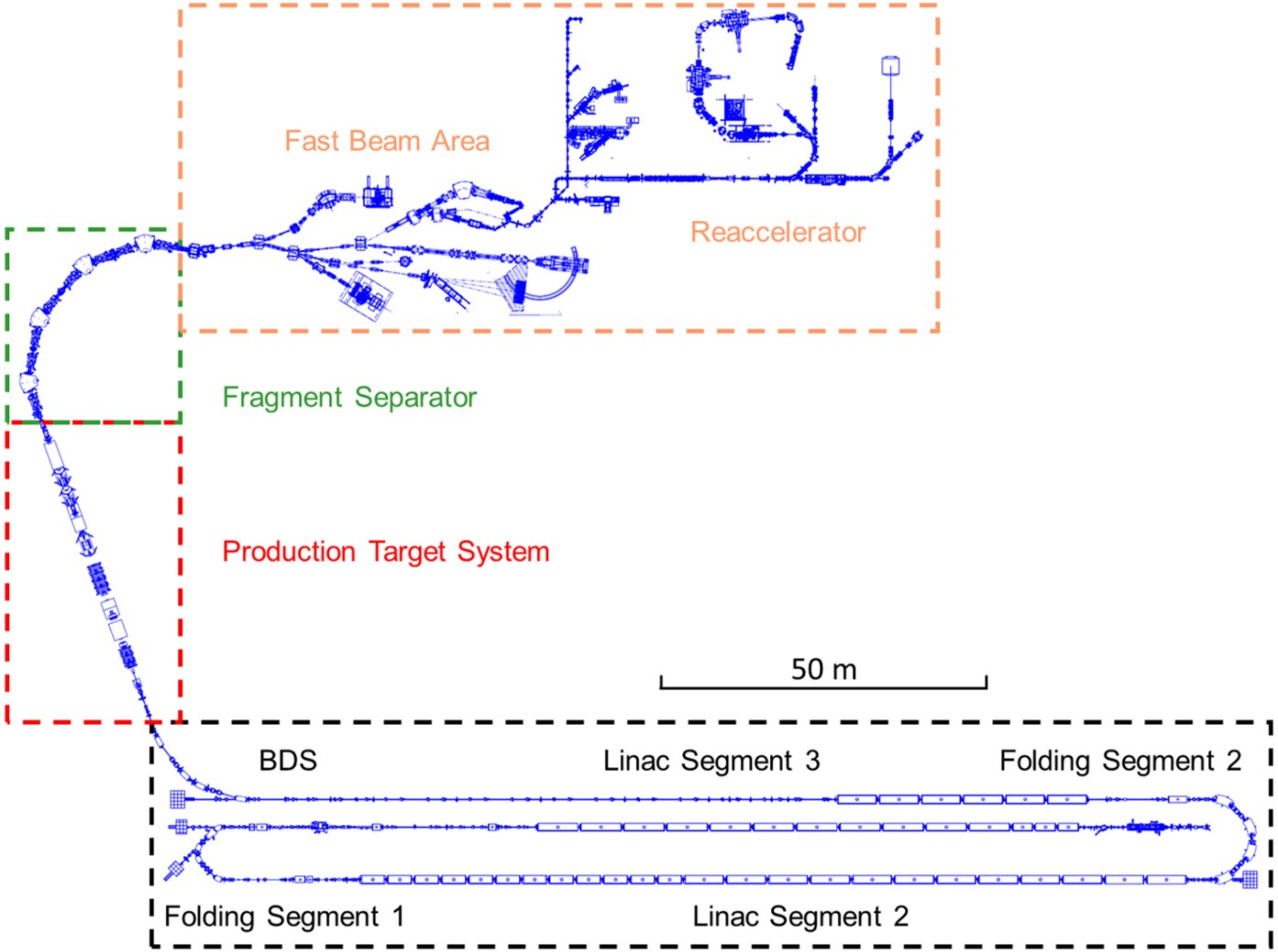
- FRIB overview
- Beam-intercepting devices (BID) in FRIB Linac
- Technical challenges in linac BIDs
- Operational performance of linac BIDs
  - Liquid lithium charge stripper
  - Rotating carbon charge stripper
  - Charge selector
- Summary

What is Facility for Rare Isotope Beams (FRIB) at Michigan State University?

- The FRIB is a scientific user facility of U.S. Department of Energy Office of Science (DOE-SC) for rare isotope research
- Linear accelerator
  - 200 / 320 MeV/u for Uranium / Oxygen beam
  - 324 SC cavities in 46 cryomodules
  - 400 kW, Continuous wave beam
    - » 10 kW operation started last week
- Fragmentation target system

Other FRIB talks:
- J. Song, 10:15-10:30am, Fri, Nov. 10
- M. Larmann, 10:45-11:15am, Fri, Nov. 10

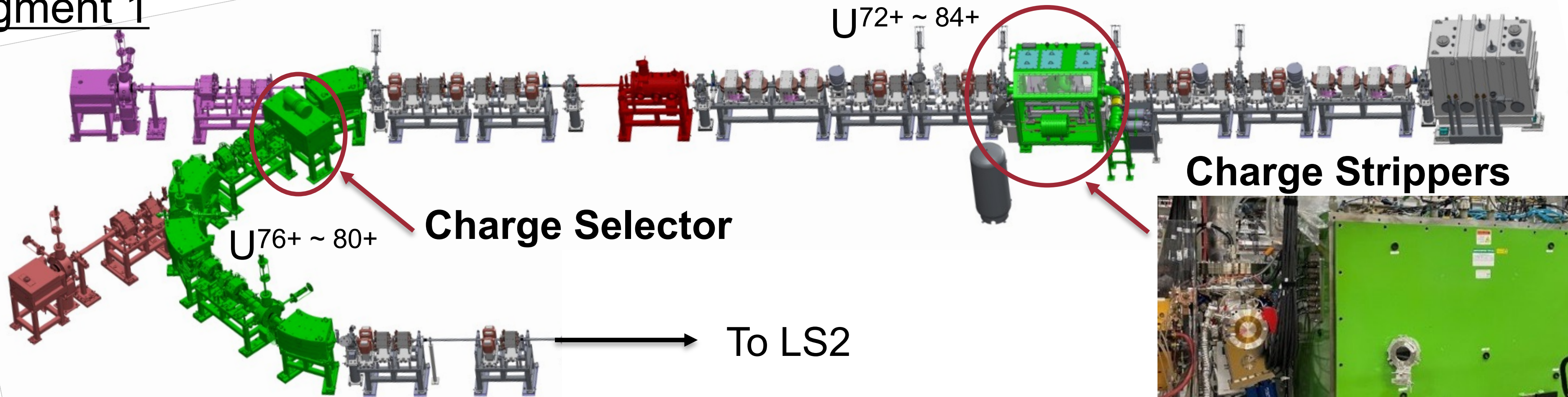
- 2-stage fragment separator
- Fast beamlines
- 12 nuclear science experiments completed in FY2023

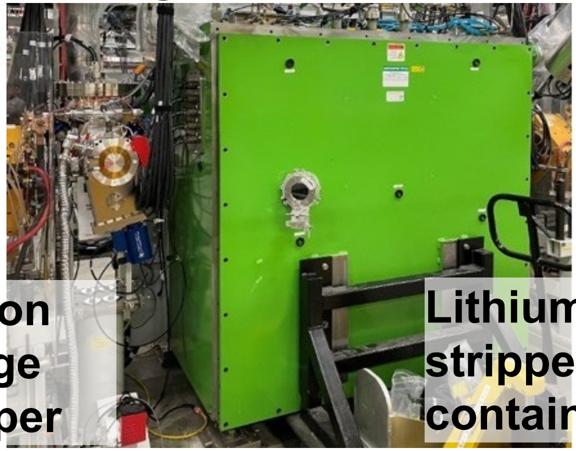


Major Beam-Intercepting Devices in FRIB Linac: Charge Stripper and Charge Selector

- Charge stripper removes electrons from the beam to increase energy gain. This process, however, produces multiple charge states after the stripper
- Charge selector intercepts unwanted charge states of the stripped beam. Charge selector is required to absorb up to 20 % of beam power (~10 kW)

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

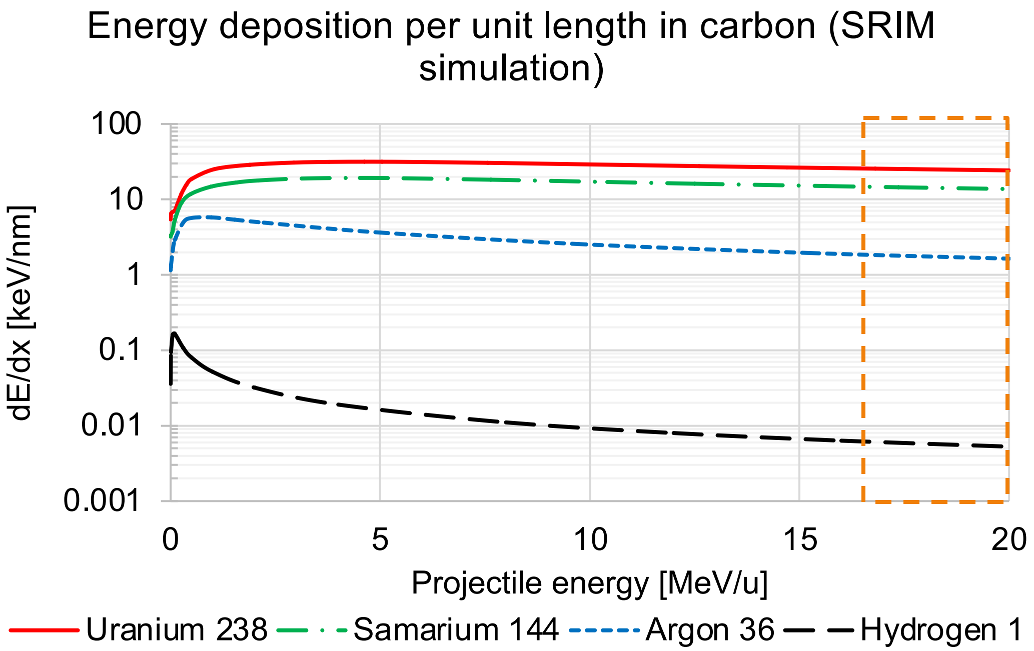




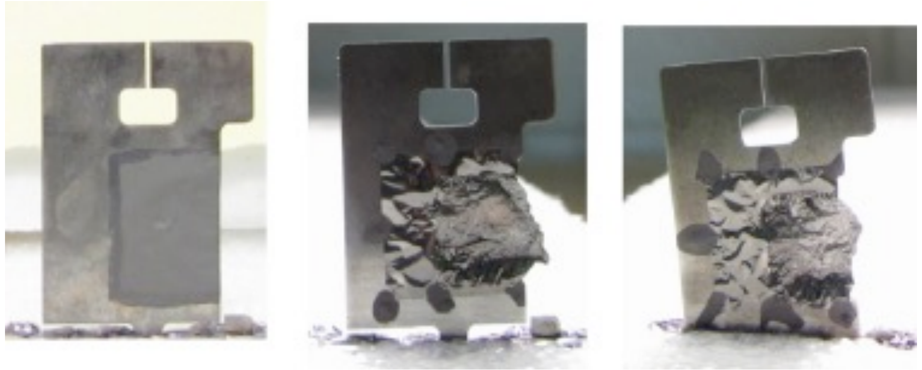
- Beam energy at FS1: 17-20 MeV/u
- Beam power at FS1: 40 kW (equivalent to 400 kW at target)

Technical Challenges in Charge Stripper and Charge Selector

- Extreme thermal load
- Radiation damage (when a solid material is used) by heavy ions



dE/dx of uranium is ***3 orders of magnitude*** higher than H !!!



Damage produced by 8.1MeV/u ^{208}Pb beam, 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

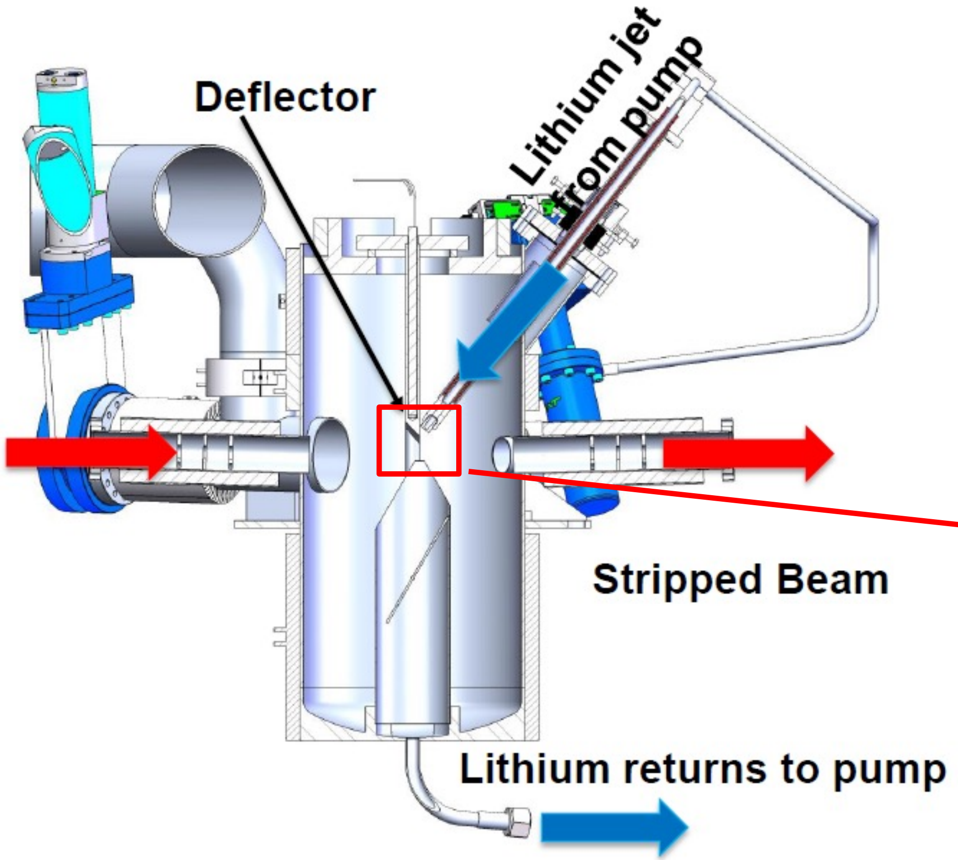
Technical Challenges in Charge Stripper and Charge Selector

- Charge stripper suffers the severest condition (beam focused and single footprint). Liquid lithium charge stripper is used for high power operations.
- Charge selector suffers milder condition (beam splits into multiple beamlets) but beams stop in jaws thus high DPA at Bragg peak. Glidcop is used now. Graphite is being considered as the next generation jaw material.

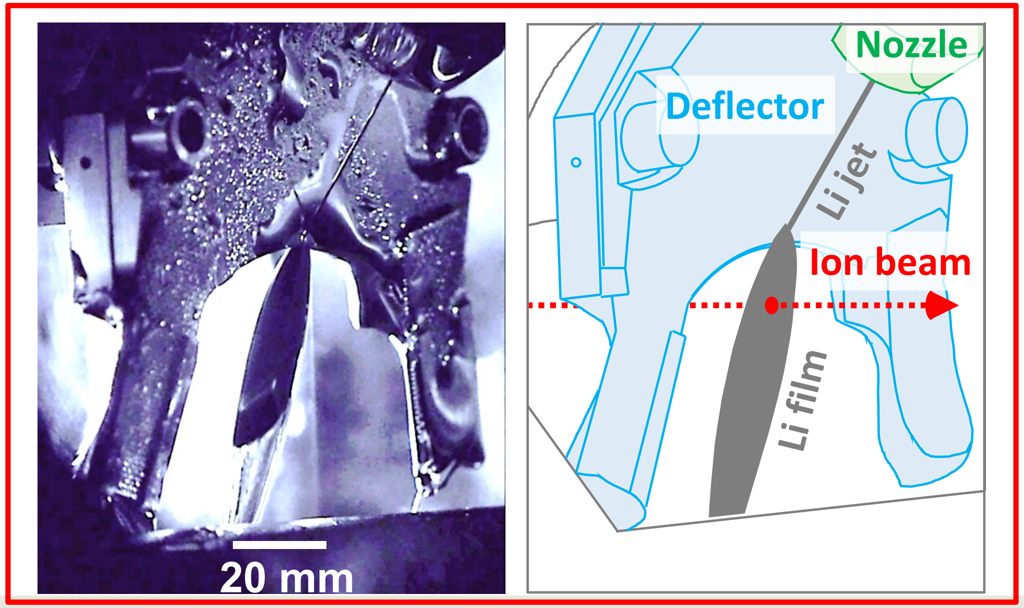
Parameters for Uranium beam

Beam power	Device	Material	Beam size	Thermal load (Uranium)		DPA rate (Uranium)	Status
1 kW (10 kW at target)	Charge stripper	1.5 mg/cm^2 Solid C	$\sigma_{x,y}$: 1.0 mm	47 W	2 MW/cm^3 (average)	~10^{-4} dpa/s assuming static foil	In operation
	Charge selector	Glidcop (Cu alloy)	σ_x: 0.7 mm σ_y: 1.3 mm	200 W (shared by 4 charge states)	0.3 MW/cm^3 (average)	~10^{-3} dpa/s at Bragg peak	In operation
40 kW (400 kW at target)	Charge stripper	1.5 mg/cm^2 Liquid Li	$\sigma_{x,y}$: 0.5 mm	1360 W	58 MW/cm^3 (average)	N/A	In operation
	Charge selector	Graphite	σ_x: 0.7 mm σ_y: 1.3 mm	10 kW (shared by 4 charge states)	6.5 MW/cm^3 (average)	~10^{-2} dpa/s at Bragg peak assuming static jaws	Planning

Liquid Lithium Charge Stripper: 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 beam spot.
- 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)

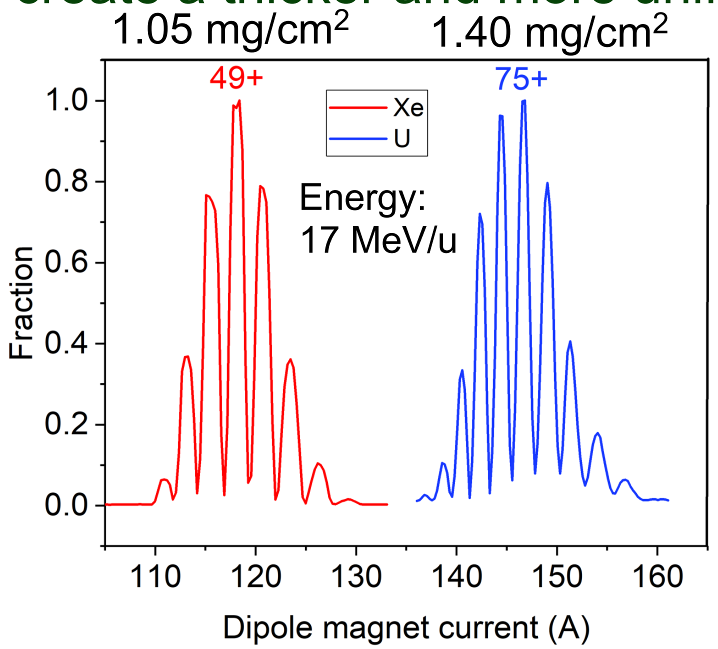


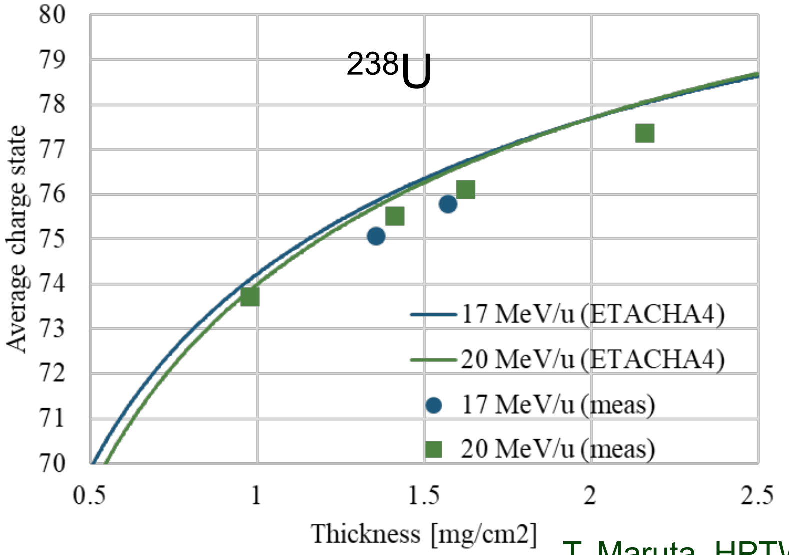
Characterization of Lithium Stripper by Beam: Thickness Distribution, Charge States of Stripped Beams

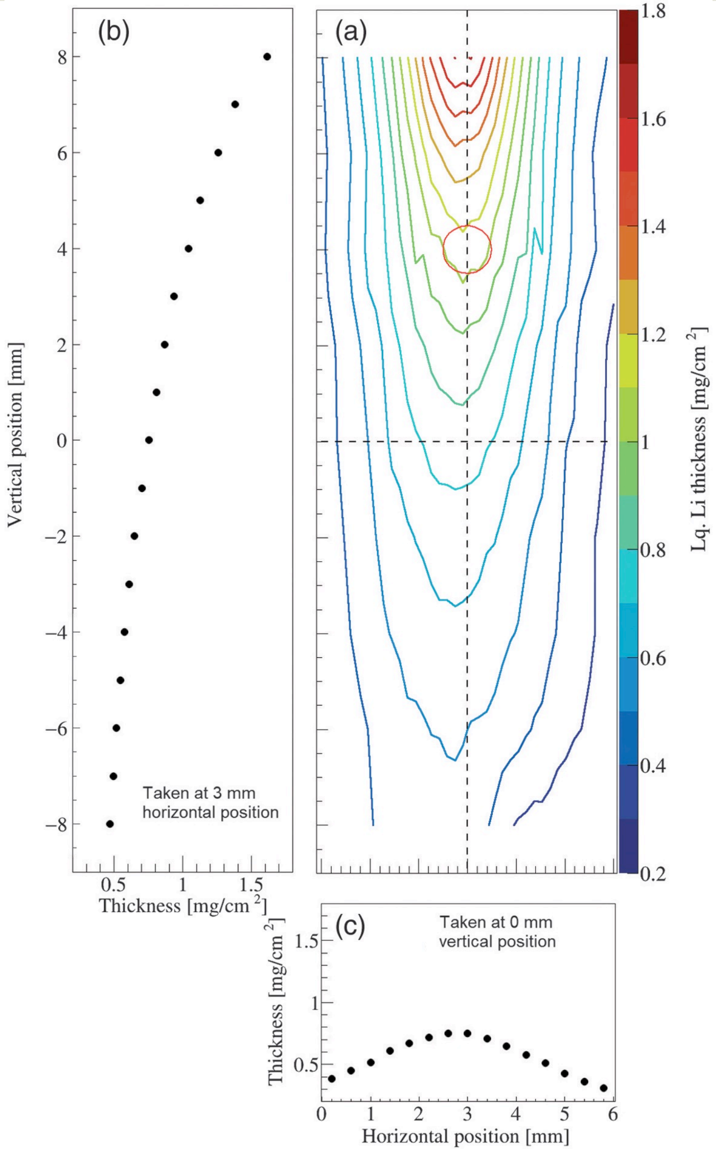
- Mass thickness: Measured energy loss + dE/dx obtained with SRIM
  - The closer to the impinging point, the thicker the film is, but the higher the thickness gradient becomes
  - At some distance away from the impinging point, the film is uniform enough for the 0.5-mm-radius beam
  - Because thickness gradient increases with thickness, currently 1 mg/cm^2 is the maximum thickness available for high power operation

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

- U beam design charge after stripper is 78+ to reach 200 MeV/u. R&D to create a thicker and more uniform film ongoing.





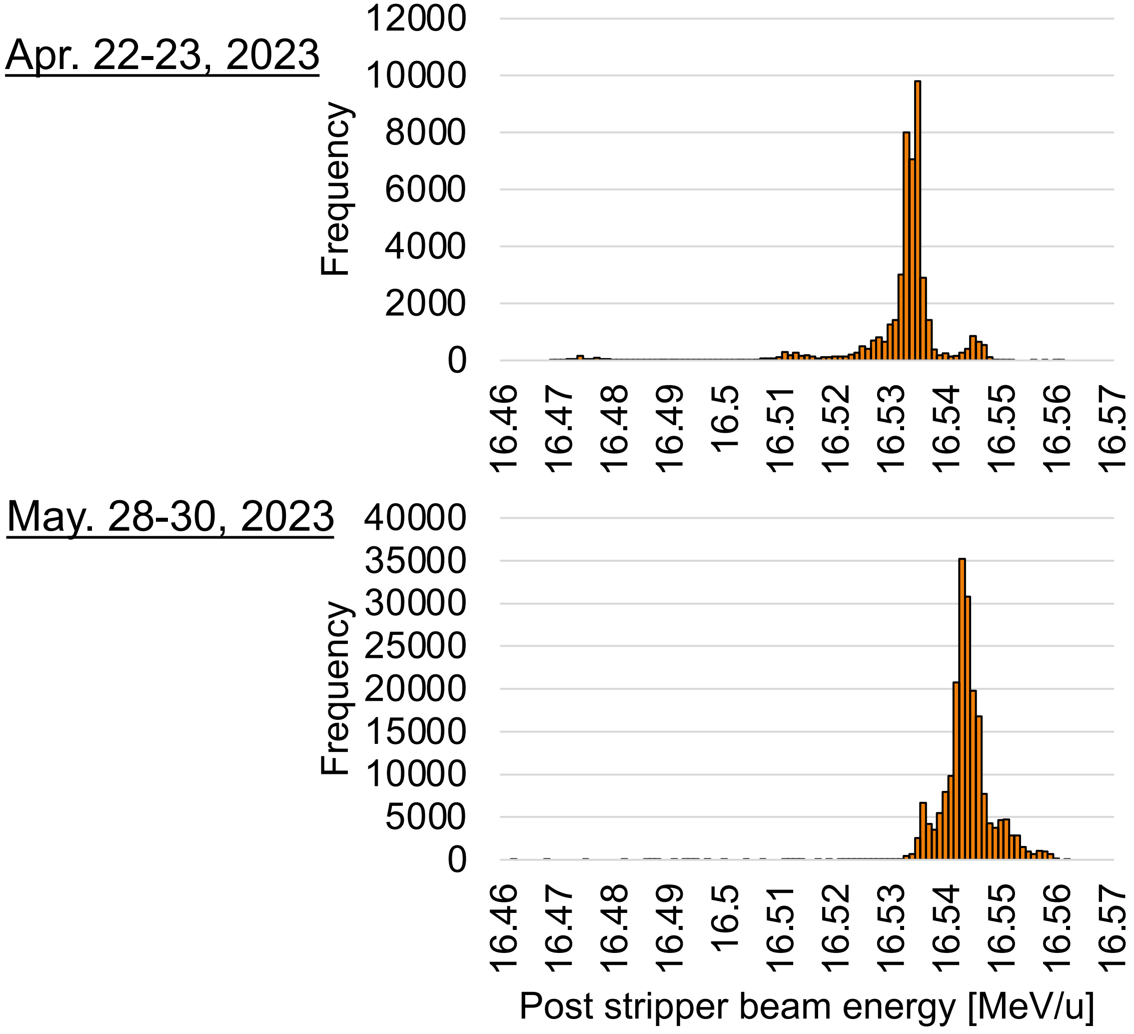


Recent Lithium Film Stability Issue

- Degradation of Lithium flow stability 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 leaked into the lithium loop a while ago, 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).
- Thickness stability tests with 17 MeV/u Xe beam carried out (next slide)

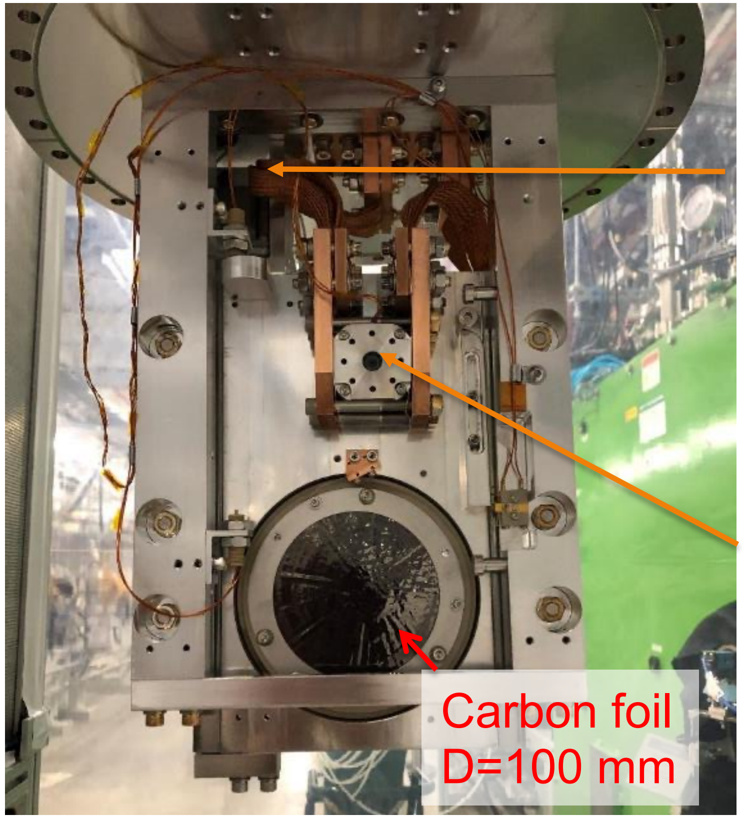
Lithium Film Thickness Stability Recovered

- 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. No significant beam loss. Ready for routine operation.



Rotating Carbon Charge Stripper

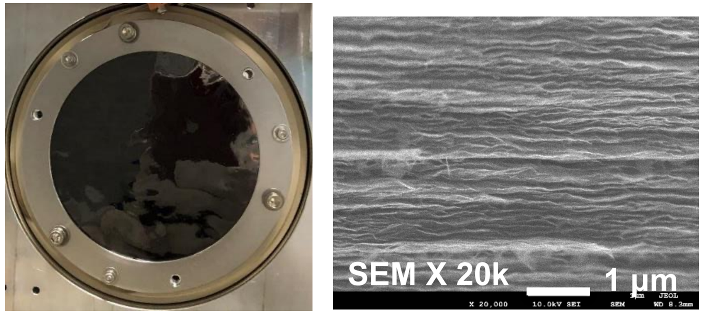
- Rotating carbon charge stripper next to LLCS, being used for user operations.
- Two movements used: rotation (100 rpm) and linear motion (slow up&down cyclic motion), which help distribute both thermal and radiation damage



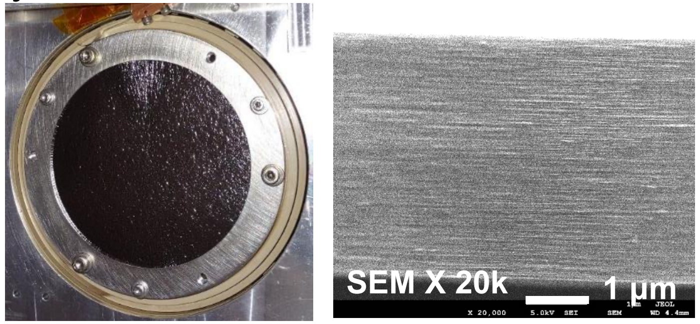
Motor for linear movement on back side (hidden in this photo)

Motor for rotation movement (gears on back side)

- Two types of graphene foil (Thickness: 1.0-1.5 mg/cm^2)
  - Type A: Made by a controlled reduction of graphene oxide by hydrazine with addition of ammonia in an aqueous dispersion (no heat treatment), having has a layered structure and seems to be made from graphene crystallites (See SEM image). Have been used in routine operations
  - Type B: Made from polyimide by carbonization (up to 1400 C) and then by graphitization (up to 3000 C), having a much higher degree of crystallinity and orientation of graphene layers (see SEM). Have not been used in routine operations yet.



Type A



Type B

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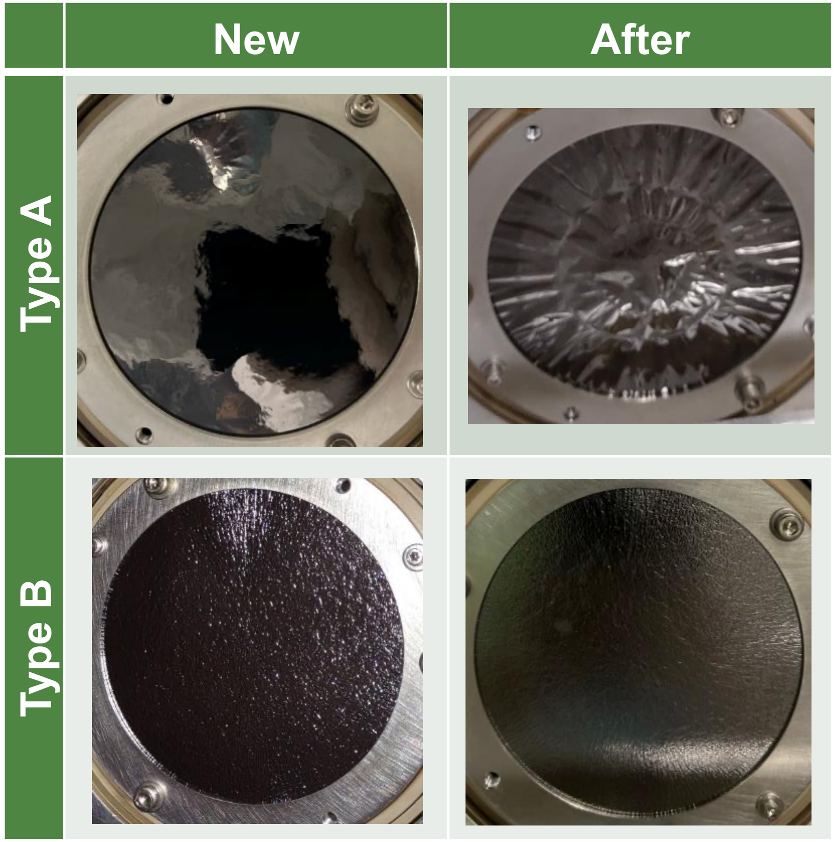
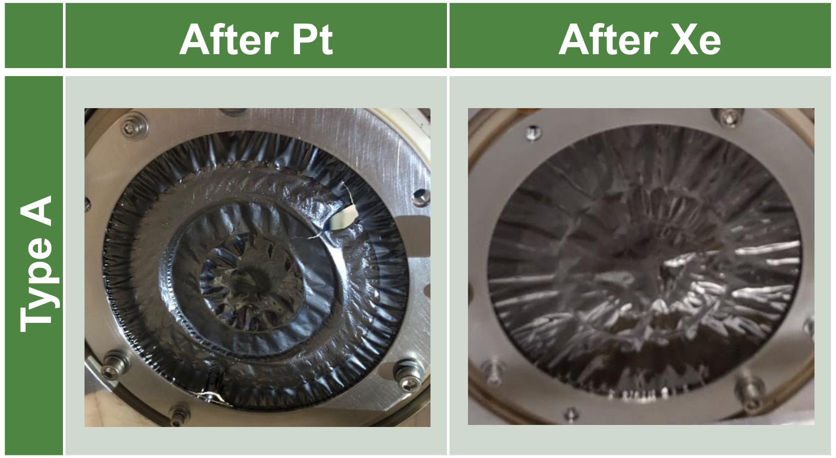
Foil Performance Comparison: After Beam Irradiation

- Xe beam irradiation
  - Type A: Buckled due to heat deposited from 5-kW-at-target Xe beam irradiation: 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
- Pt beam irradiation (only type A foil)
  - ^{198}Pt (Z=78) left severe damages in Type A carbon foil
    - » Power deposition to foil: 7 W (Intensity at foil: 90 pnA)
  - ^{124}Xe (Z=54) left only buckling
    - » Power deposition to foil: 16 W (Intensity at foil: 250 pnA)
  - Could be due to heavy ion induced rad. damage. E.g. ion hammering (ion-beam induced plastic deformation). No PIE tests yet.

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

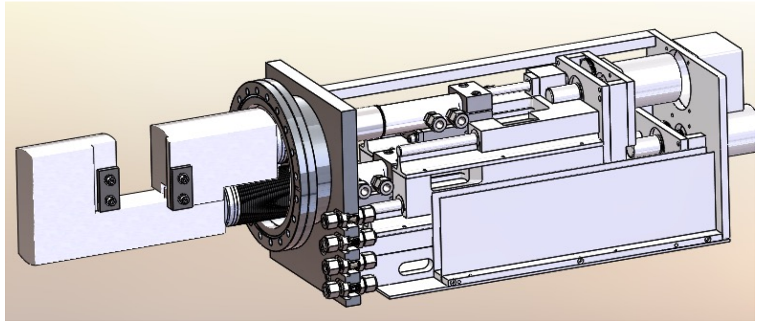


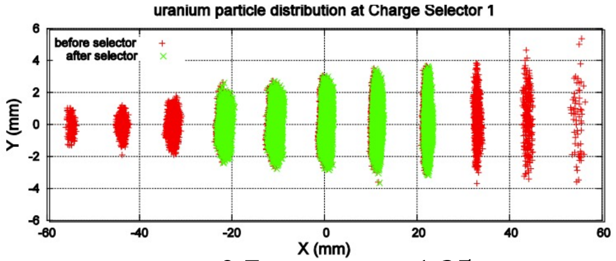
After Xe beam irradiation



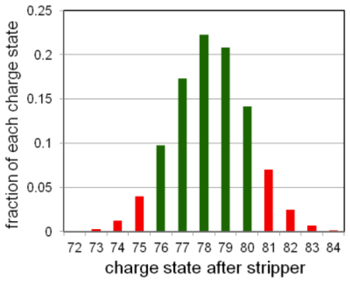
Low-Power Charge Selector in Operation: Glidcop Jaws Used to Intercept Beams

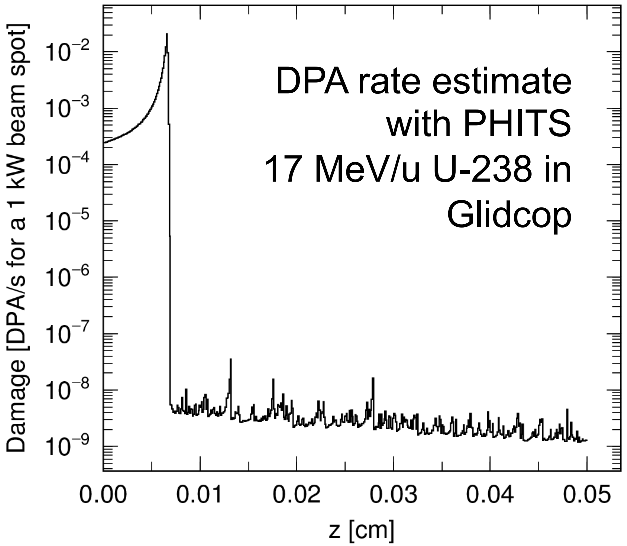
- Static jaws, cooled by water, made of Glidcop intercept unwanted charge states
- Limited to 500 W per beam spot of rms=(0.7x1.25) mm due to thermal stress in Glidcop (Peak temp estimate ~ 480 C). No radiation damage taken into account
- Small beam spot and very short range of heavy ions could create severe radiation damage
- 5-kW-on-target operations deposited < 80 W per beam spot
- Ion implantation rate: an order of 1 at.%/week/100 W beam spot
- Will be used up to 20-kW-on-target operations

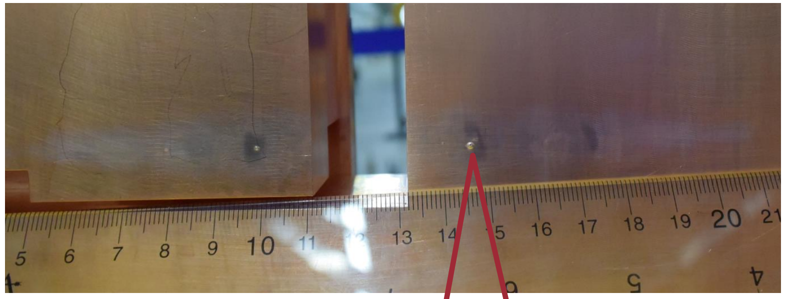




$\sigma_x = 0.7\ mm,\ \sigma_y = 1.25\ mm$







Discrete bumps and discoloration

Pinhole at center
Most likely caused by Xe beam

Summary

- Major beam-intercepting devices in FRIB linac, their technical challenges and recent operational performance were discussed.
- Charge strippers
  - Both lithium and carbon strippers in operation
  - Up to 5-kW-at-target Xe beams irradiated and no issue for beam operation
  - Routine 10 kW operations began November 2023
    - » Carbon stripper for ion species lighter than Xe
    - » Lithium stripper for ion species heavier than Xe
  - Radiation damage observed in Type A carbon foil by ^{198}Pt. Type B foil has never been irradiated by ions heavier than Xe at FRIB
- Charge selector
  - Low-power charge selector, jaws made of Glidcop, cooled by water, have been supporting user operations
  - Understanding of radiation damage by heavy ions is key for successful FRIB power ramp. Efforts have been initiated with help from experts

Acknowledgements

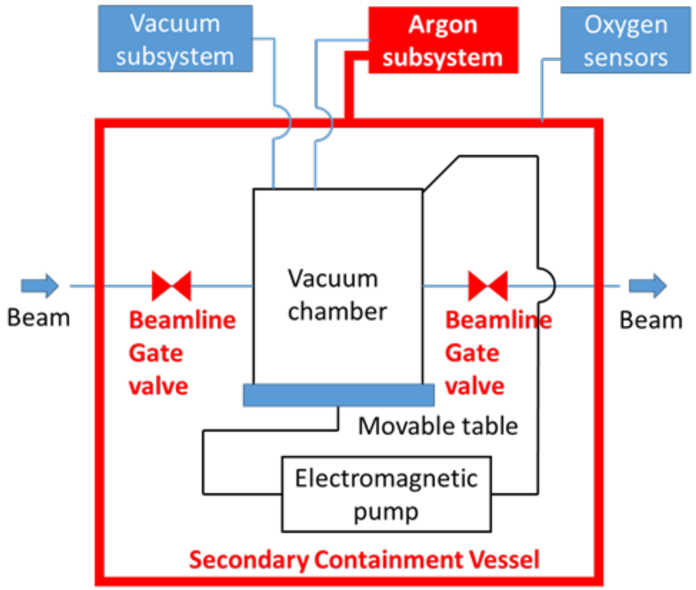
- The authors would like to express their gratitude to
  - All the FRIB staff members for their contributions to the work presented today
  - FRIB Targetry Advisory Committee (TAC) members, especially its chair, Dr. Patrick Hurh, FNAL, for their continued expert advice, guidance, supports, comments and encouragements on the high power targetry challenges that we are facing as we increase the beam power to the ultimate goal of 400 kW.
- This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

Thank you!

Backup Slides

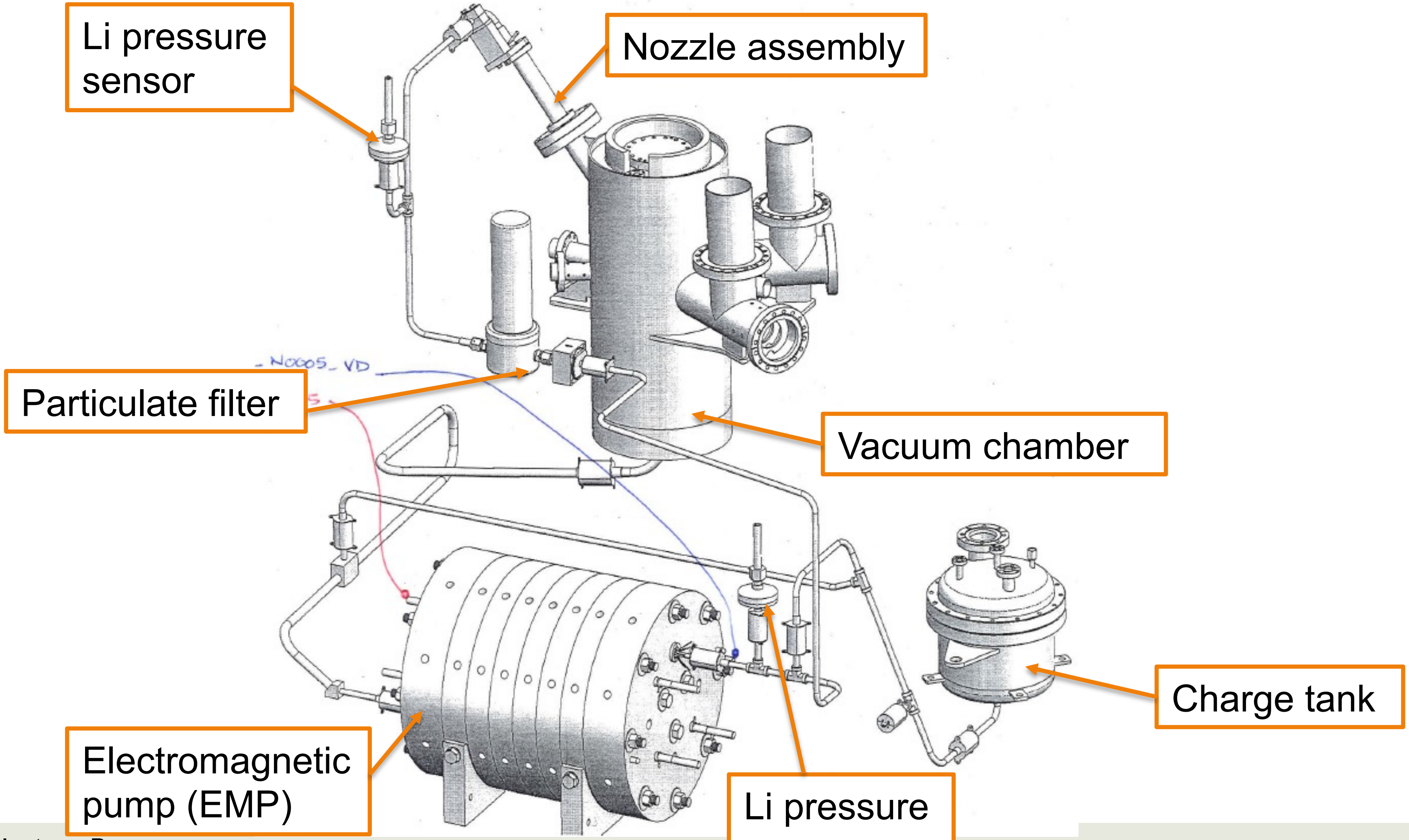
Liquid Lithium Charge Stripper (LLCS) System

- 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



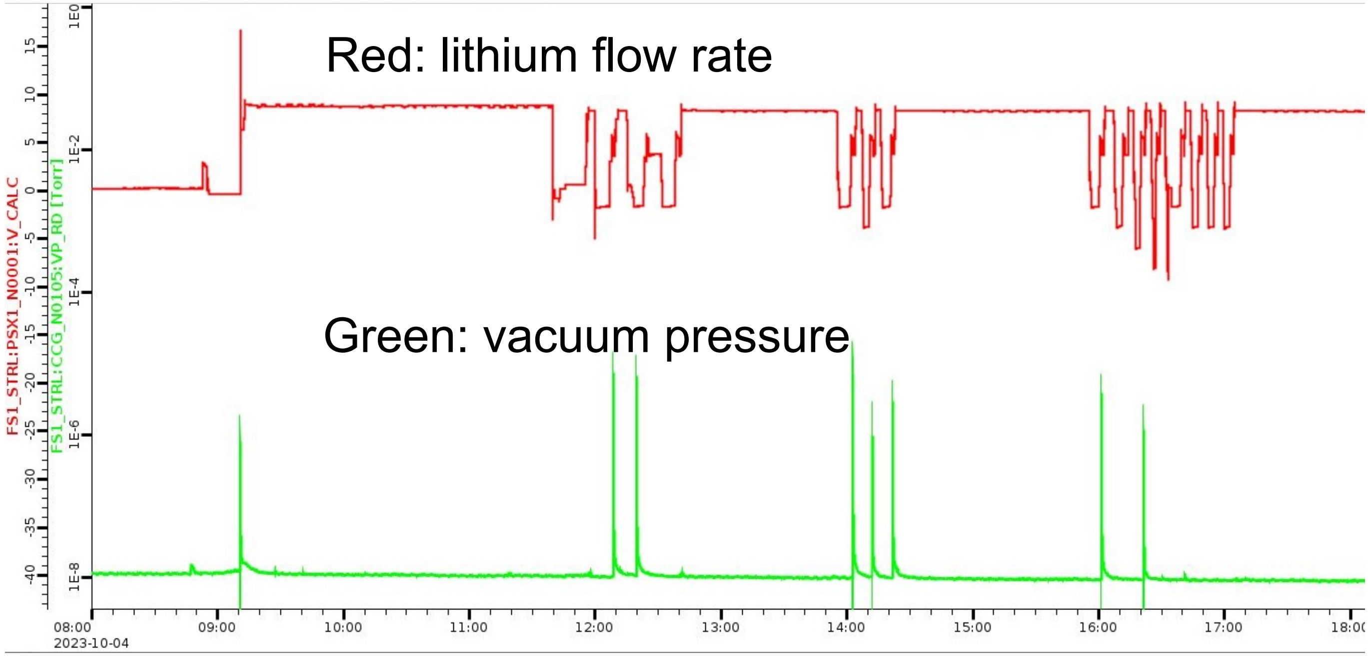
SCV in FRIB linac beamline

Lithium Loop Configuration



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.

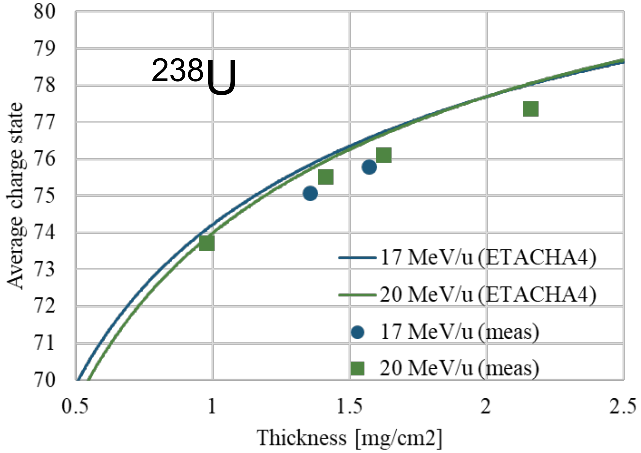


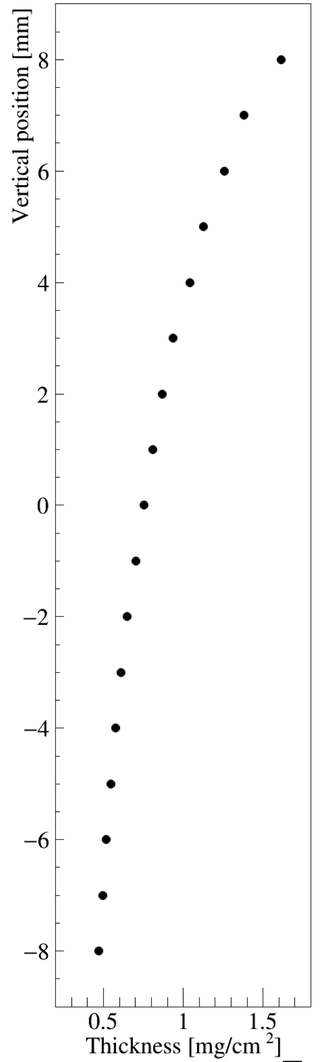
- Effectiveness of these gas releases on flow stability to be tested with a beam

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



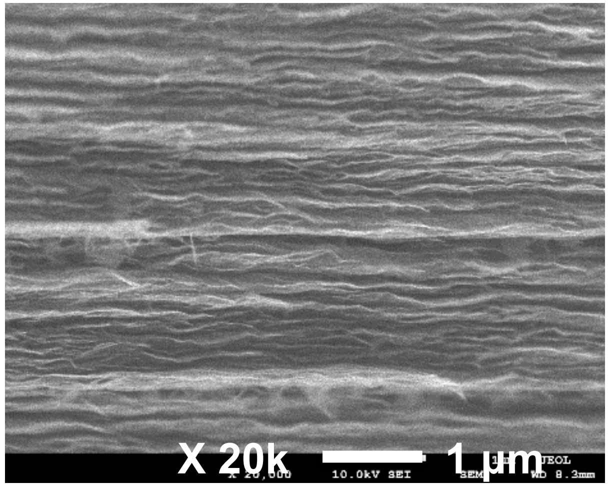


- Erosion and corrosion of nozzle and deflector
  - Accumulated lithium circulation hours has reached 1400 hours
  - Planning to replace them to do material analysis

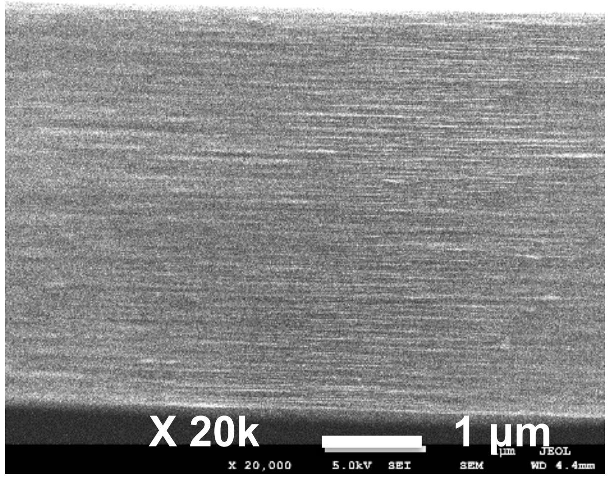
SEM / EDX of Foils

- 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



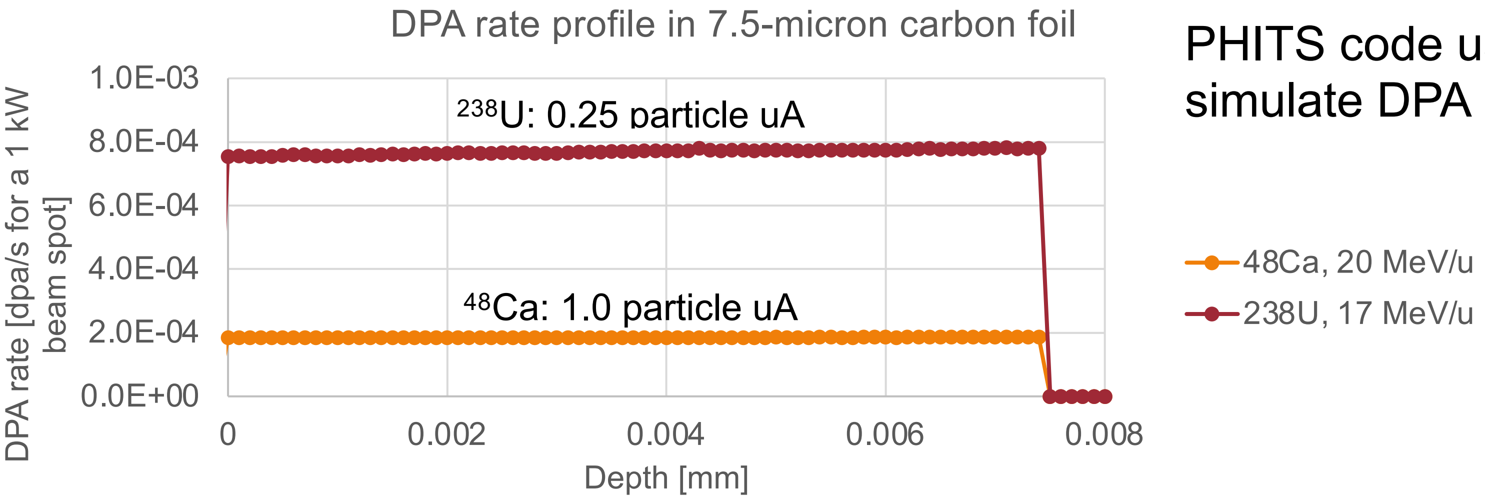
- Energy Dispersive X-ray spectroscopy (EDX) elemental analysis

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.

Toward Understanding of Radiation Damage

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

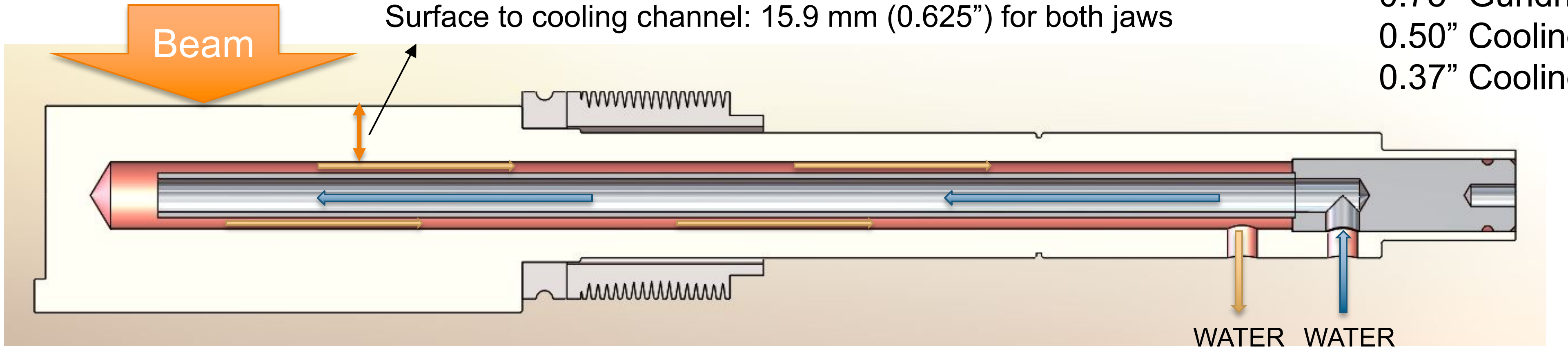


PHITS code used to simulate DPA rates

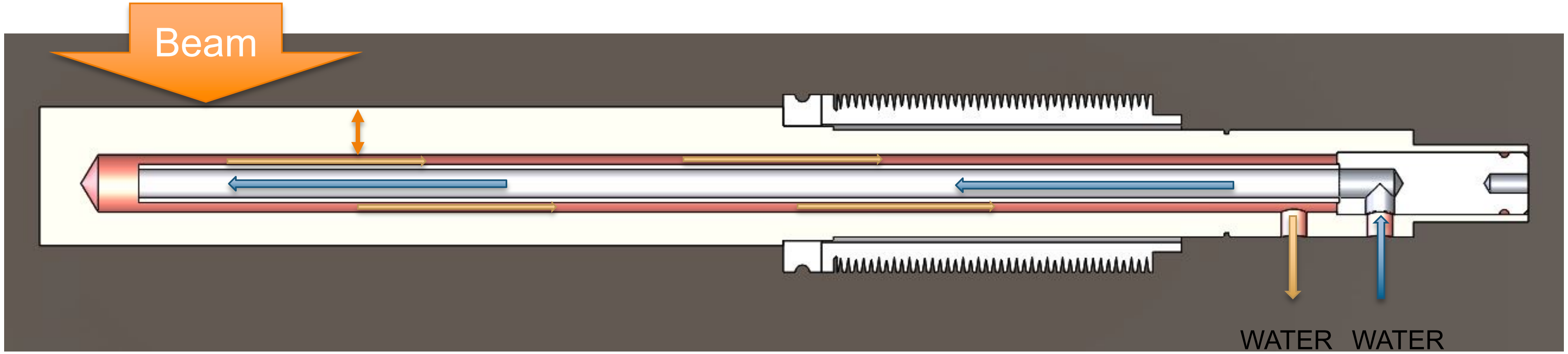
- DPA rates of Xe (Z=54) and Pt (Z=78) should be much closer (no calc for Xe nor Pt)
- Which doesn’t seem to be consistent with what we have observed
  - Pt damaged the foil after less than 1-day 2 kW irradiation
  - Xe didn’t leave severe damage after 1-week 5 kW irradiation
- Damage that is not characterized 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

Jaw Cooling

0.75” Gundrill Hole
0.50” Cooling Tube OD
0.37” Cooling Tube ID



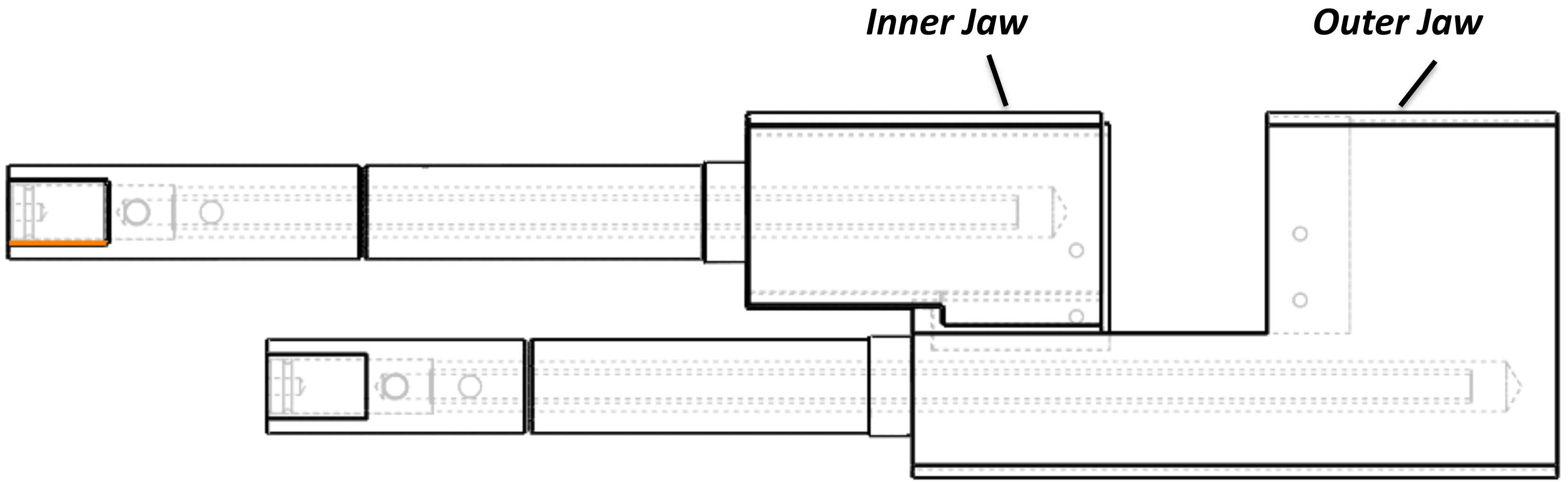
INNER JAW



OUTER JAW

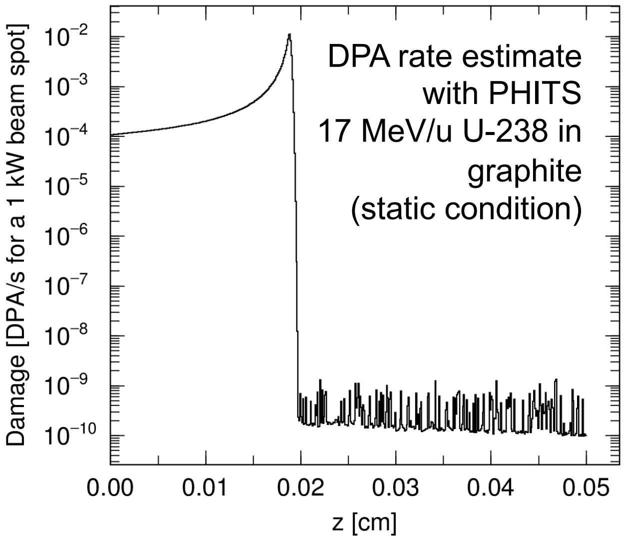
Low Power Charge Selector FEM Analysis Parameters

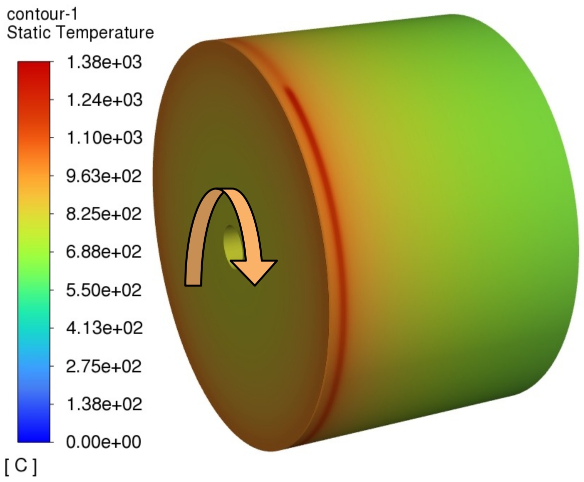
- Assumed five beamlets are intercepted by charge separation device
- Beamlets are separated by 10.3 mm gap and each beamlet of size (Gaussian with σ=0.7 mm and 1.25 mm (H and V), up to 4 σ in both H and V considered)
- Total power in each beamlet = 500 W
- Total beam power intercepted = 2.5 kW
- Assumed heat transfer coefficient of 0.5 W/cm^2/K for a flow rate of 1.9 LPM in Ø6.35 mm cooling channel



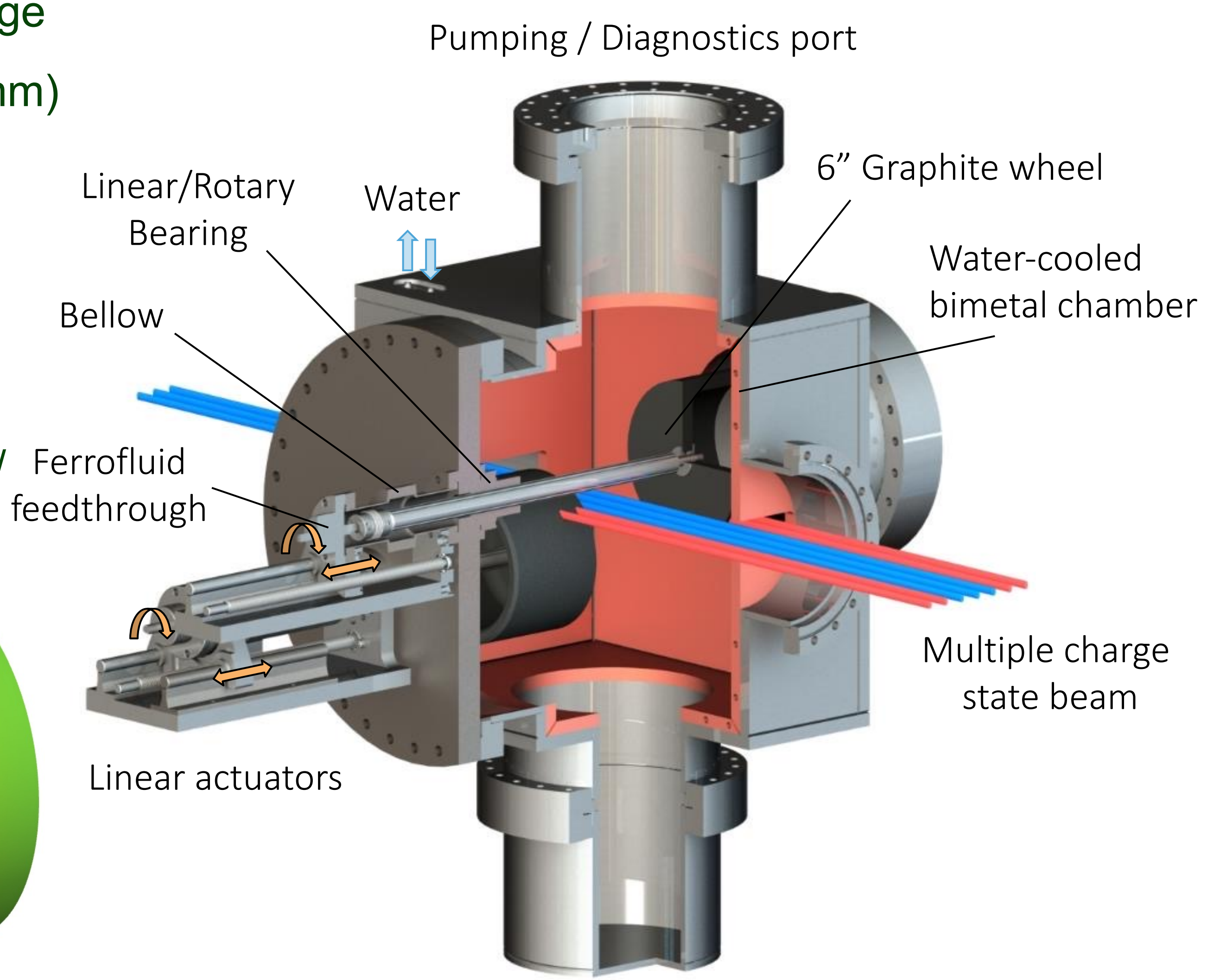
Intermediate-Power Charge Selector under Design: Graphite Wheel Jaws to be Used to Intercept Beams

- Rotating 6” wheel to spread thermal and radiation damage
- Thermo-mechanical limit: 5 kW / spot (rms=(0.7x1.25) mm)
- DPA rate (static condition case shown below)
  - Scaling with 6” wheel: factor of ~3e-3
  - Thus, 20 dpa / week for a 1 kW beam spot
- Ion implantation rate: an order of 1e-2 at.%/week/1 kW beam spot
- Goal is to support up to 100 kW operations (up to 2 kW / beam spot)



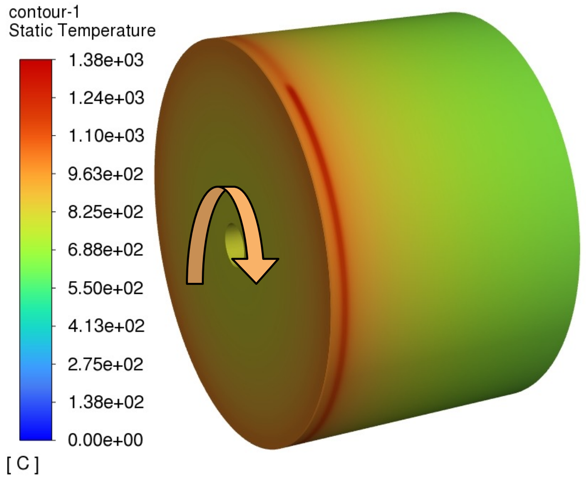


5000 W, 1200 rpm

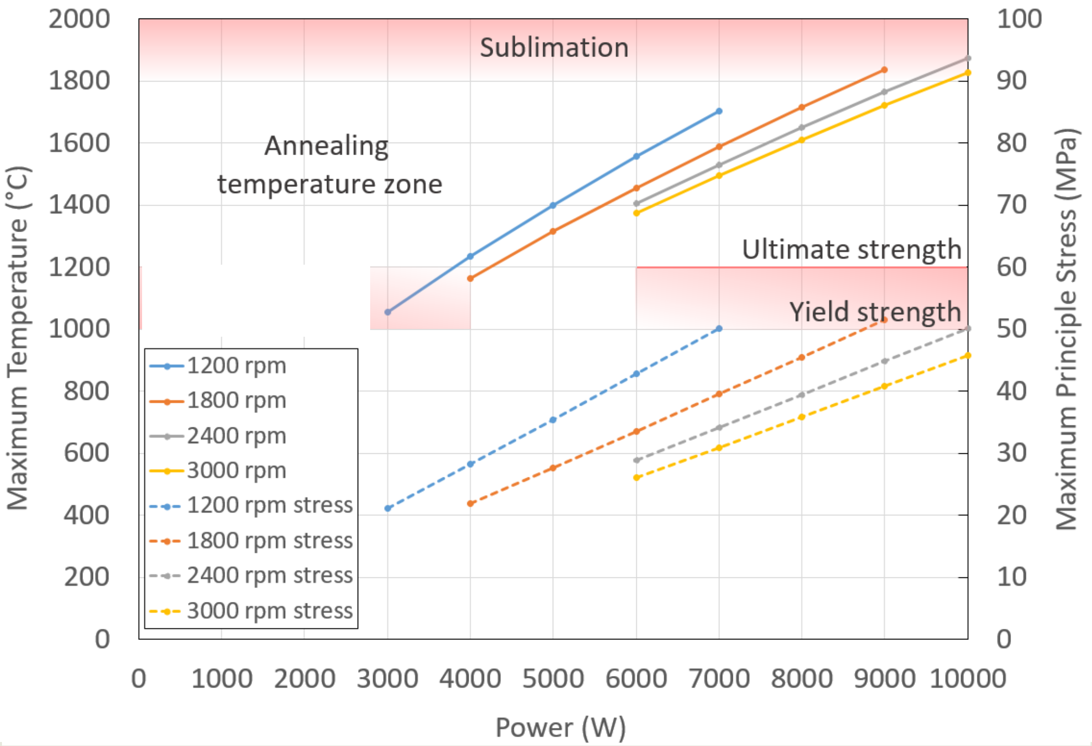


Thermal Analysis for Intermediate-Power Charge Selector

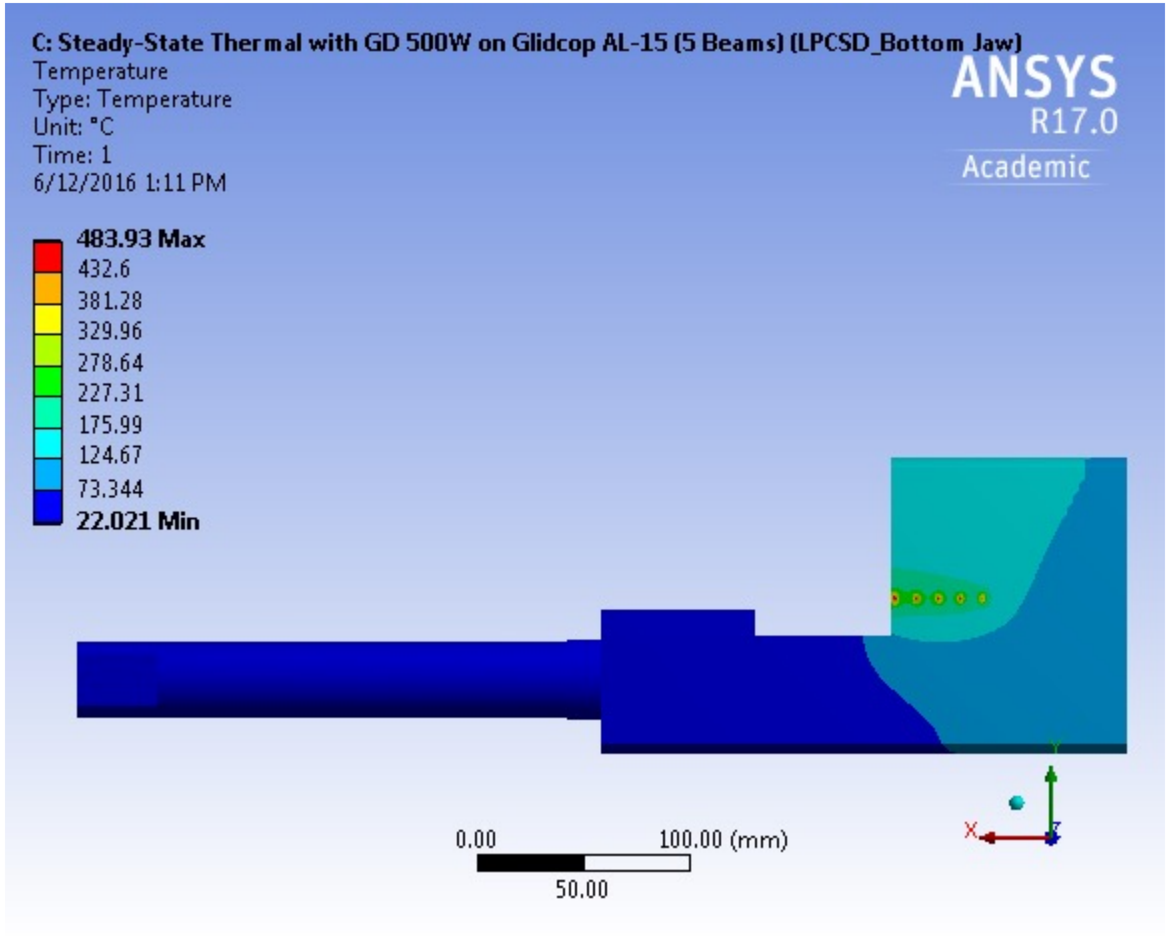
- Beam
  - ^{48}Ca on graphite
  - Beam size $\sigma_x = 0.7\,mm$, $\sigma_y = 1.25\,mm$, $depth = 0.372\,mm$
- Temperature and stress:



5000 W, 1200 rpm



Low Power Charge Selector FEM Analysis Result



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