FRIB

Beam Intercepting Devices in FRIB: Status and Challenges

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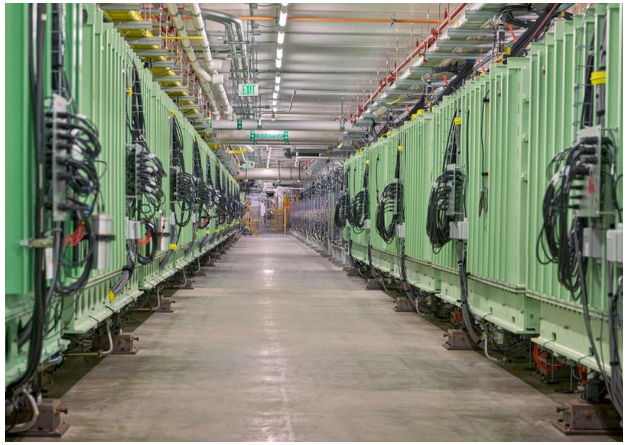
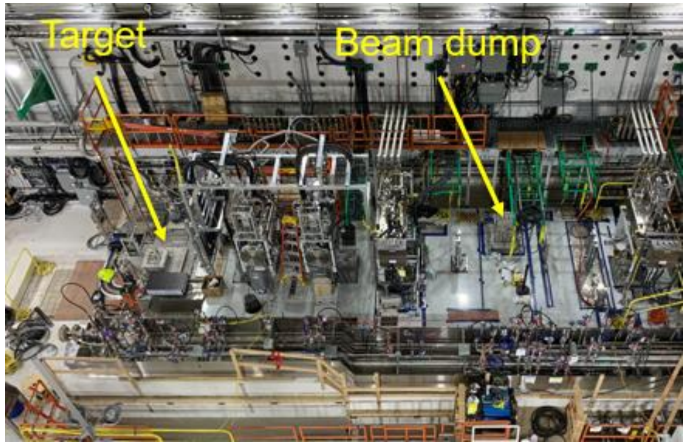
Outline

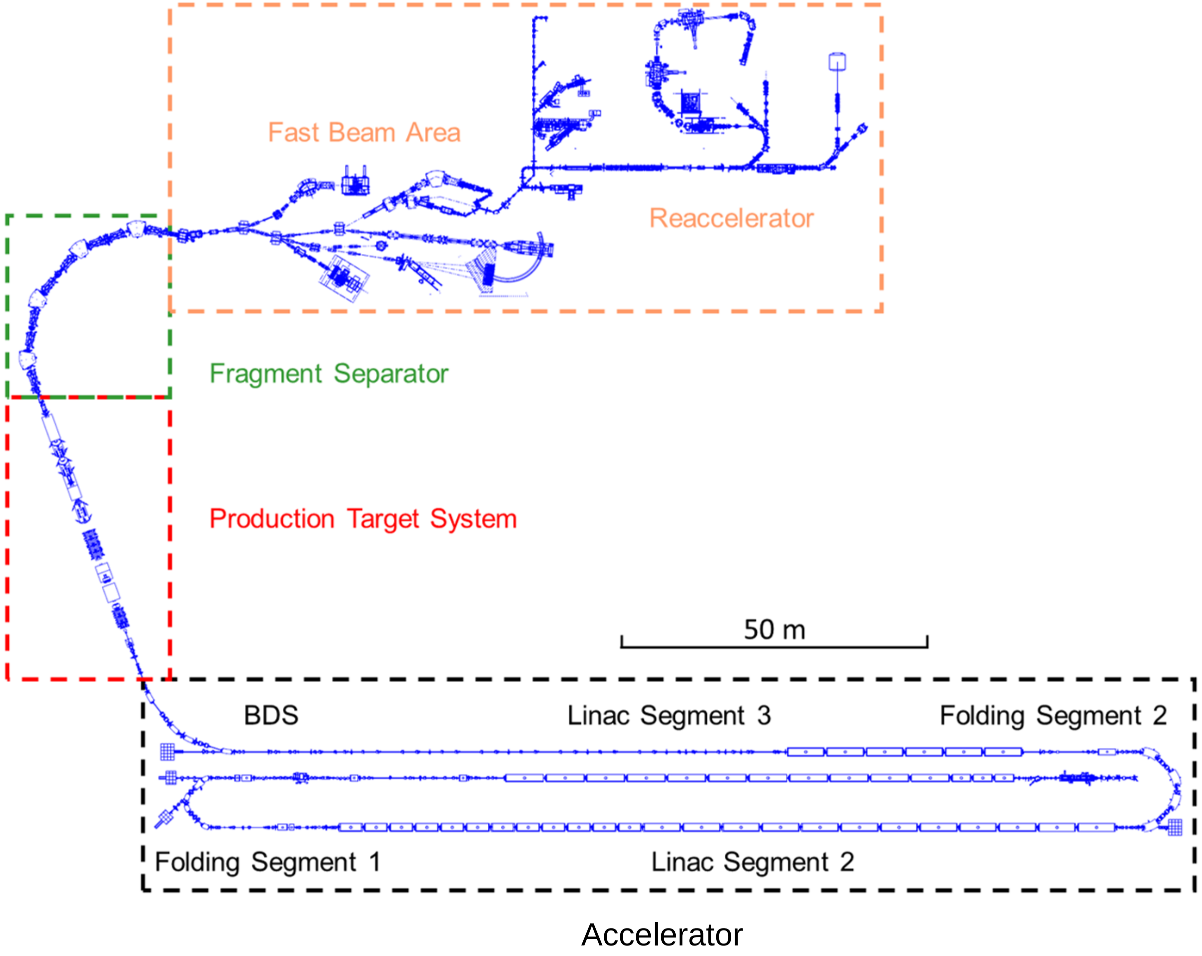
- Facility for Rare Isotope Beams (FRIB) Overview
- Beam intercepting devices (BIDs) used in FRIB
- BID challenges
- Approach, status and path forward
- Radiation damage study and importance of PIE facility
- Summary

Facility for Rare Isotope Beams (FRIB) Overview

- The FRIB accelerator consists of a 400 kW superconducting RF linac accelerating stable ions up to uranium to energies of at least 200 MeV/u
- Rare isotope beams are produced in a rotating graphite target and magnetically separated in the fragment separator
- The facility is commissioned to 10 kW primary beam power. A power increase to 20 kW is planned this month. Test run at 22 kW was successful this July.



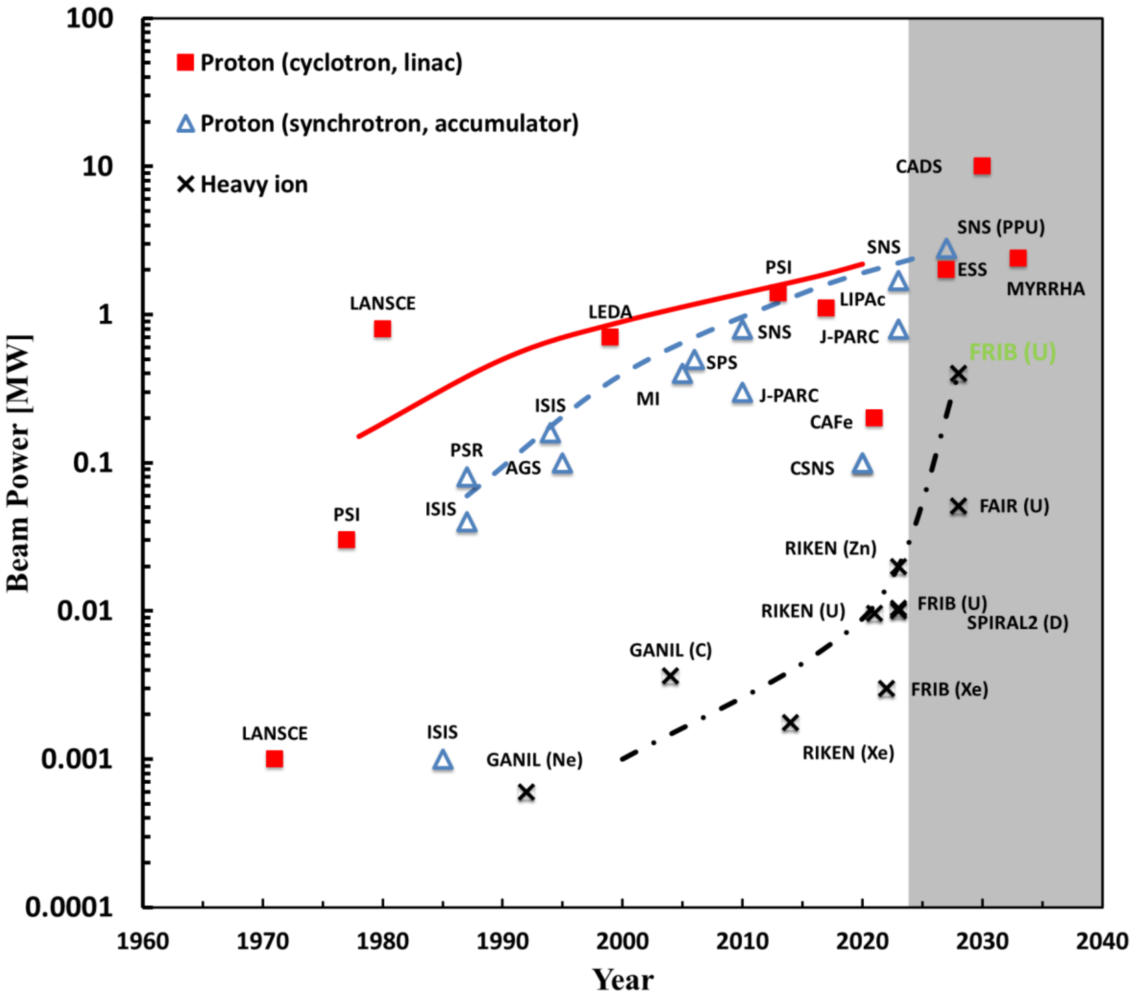




Addressing Challenges in Beam Power Ramp Up

Safe Ramp Up of Beam Power with Investments

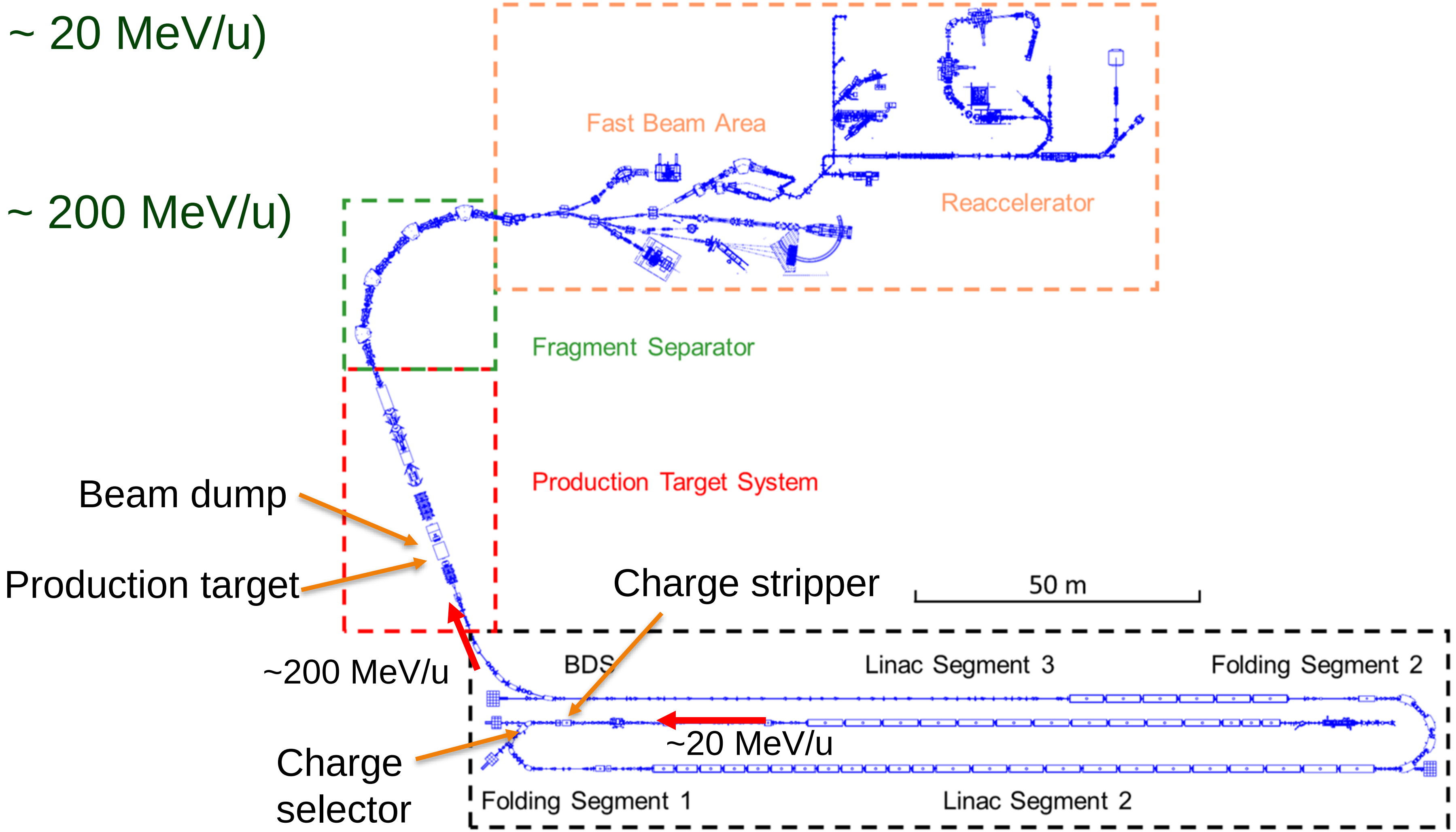
Heavy ion accelerator power ramp up is much more difficult than for proton facilities due to short stopping range and high-power density



- FRIB will raise heavy-ion power frontier by almost two order of magnitudes
- Targetry systems are the key to support beam power ramp up
- FRIB strategically phased deployment of targetry systems to safely ramp up without incidents
  - Deploying "mini-channel" beam dump during 2024 summer maintenance
  - Preparing next phase thin-shell water beam dump
- SNS took 8 years for the accelerator to reach the design proton beam power of 1.4 MW and 13 years to steadily operate addressing targetry issues
  - J.D. Galambos: Proc. NAPAC'13, pp. 1443 (2013)
  - S. Cousineau, IPAC'24, (2024)

High Power Targetry Devices in FRIB

- Linac (FS1, beam energy ~ 20 MeV/u)
  - Charge stripper
  - Charge selector
- Target hall (beam energy ~ 200 MeV/u)
  - Production target
  - Beam dump

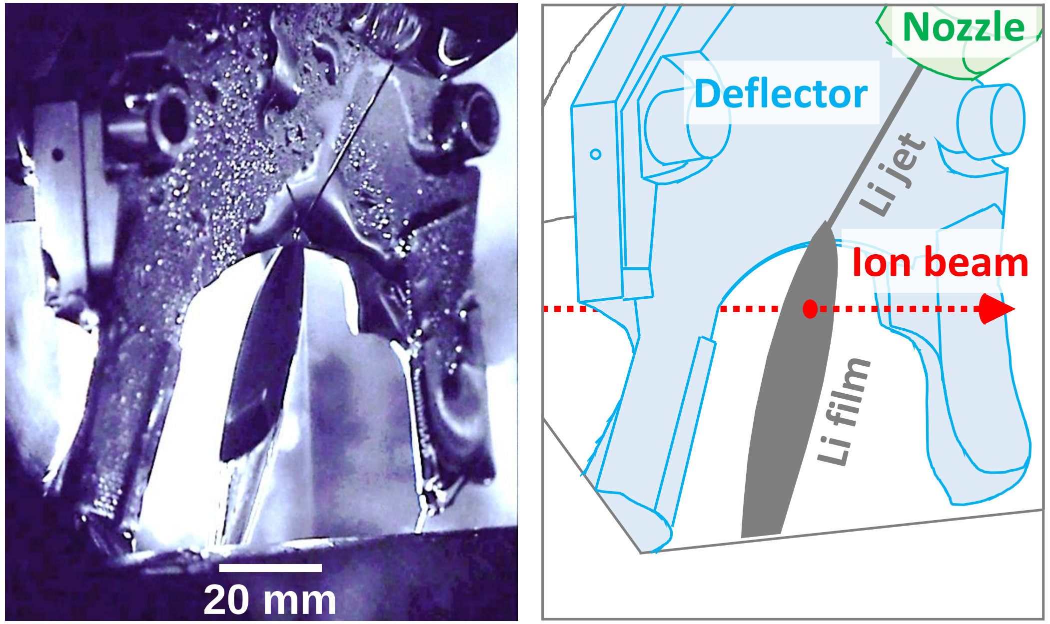


High Power Targetry Devices in FRIB: Charge Stripper

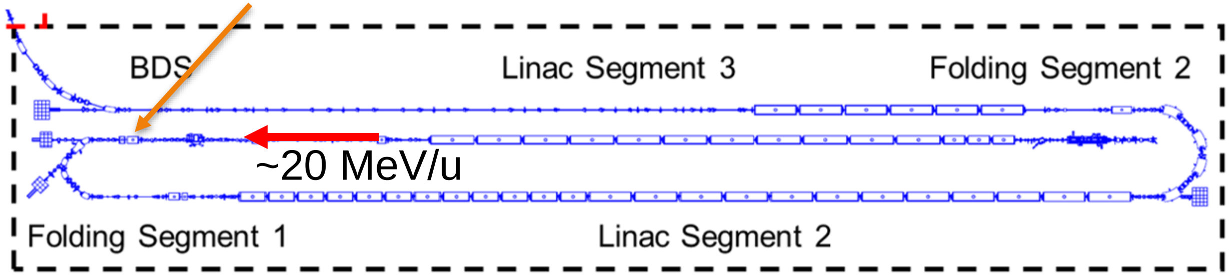
- Charge stripper removes electrons from the beam being accelerated to increase energy gain by a factor of 2 (e.g., $^{238}U^{35+}$ >> $^{238}U^{75+}$).
- This process, however, produces multiple charge states after the stripper, and not all charge states can be accepted in post-stripper linac
- Required thickness: 1.0-1.5 mg/cm^2
- Liquid lithium charge stripper is used for user operations

T. Kanemura, Phys. Rev. Lett. **128**, 212301, 2022

- A carbon stripper is available for low power and light ion beams

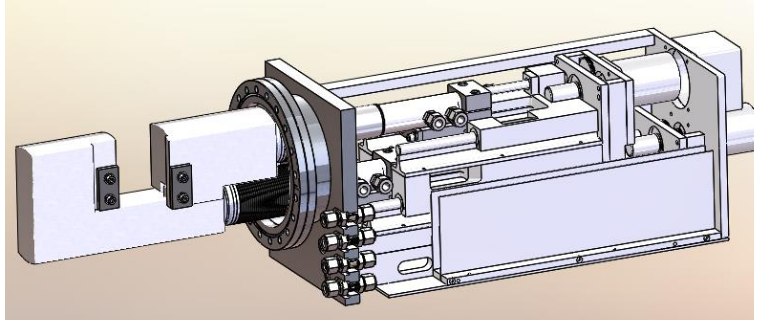


20-μm thick liquid lithium film in vacuum

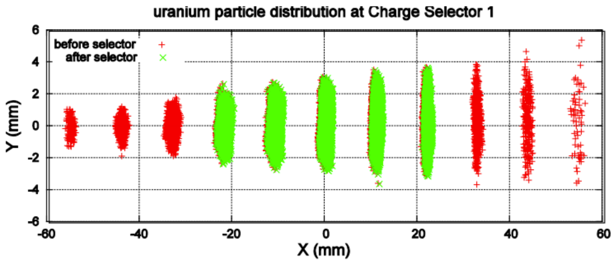


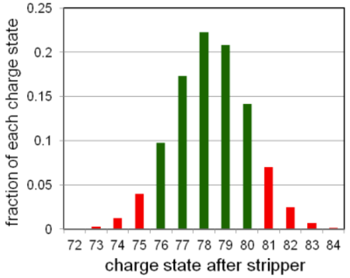
High Power Targetry Devices in FRIB: Charge Selector

- Charge selector stops unwanted charge states of the stripped beam, while transporting wanted charge states to the post-stripper linac.
- FRIB linac is capable of multi-charge simultaneous acceleration



Static jaws made of Glidcop AL-15 are used in Low Power Charge Selector

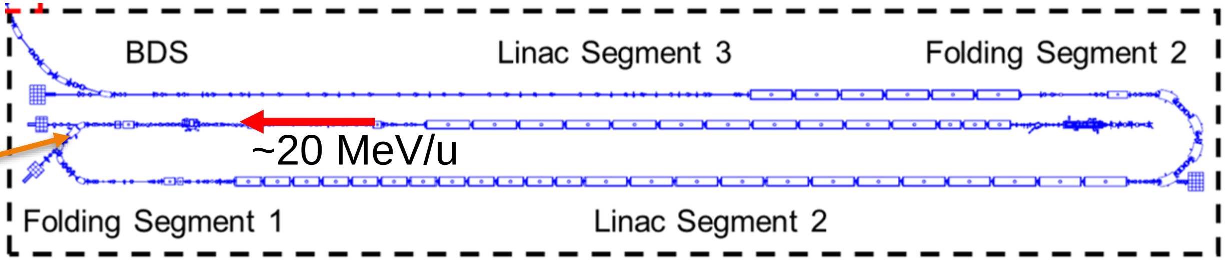




$\sigma_x = 0.7\ mm,\ \sigma_y = 1.25\ mm$

Example: ^{238}U particle distribution (left) and charge state distribution (right)

Charge selector

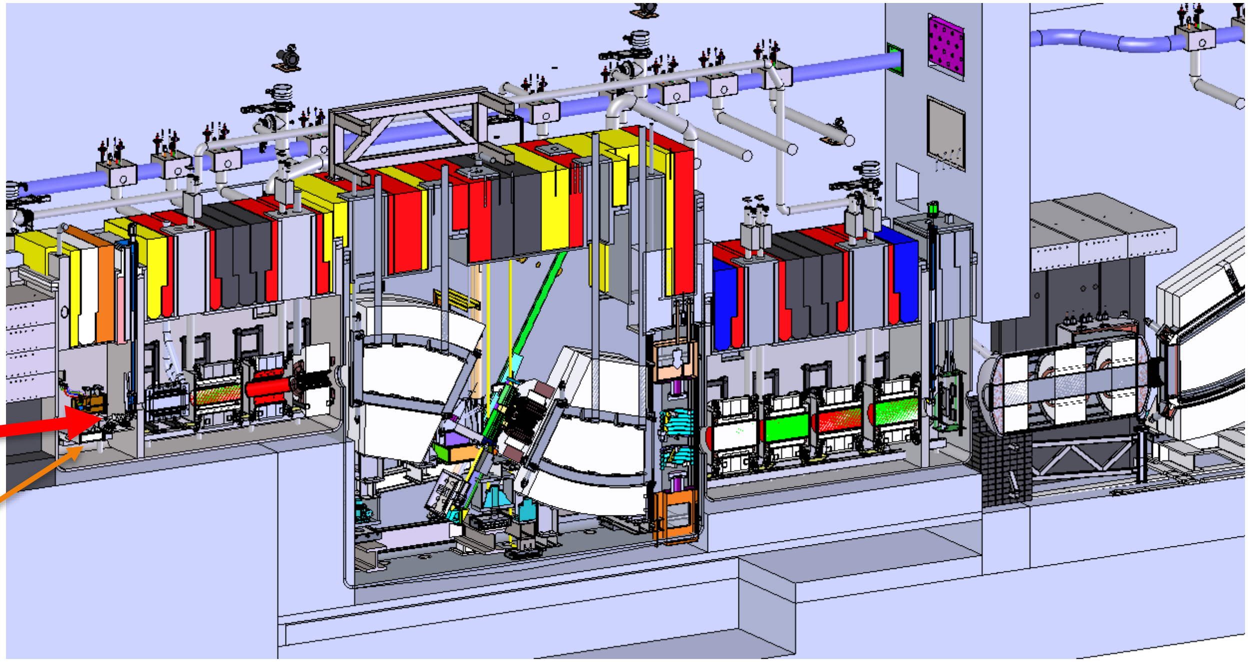


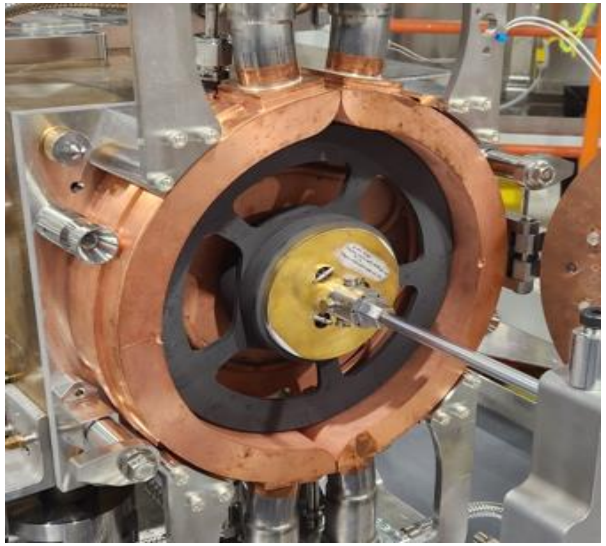
High Power Targetry Devices in FRIB: Production Target

- ~25% of primary beam power deposited in target (~100 kW for full power operations)
- Single-slice graphite target in use
- Multi-slice target and 5000 rpm rotation for full power beam

Beam from linac (~200 MeV/u)

Production target



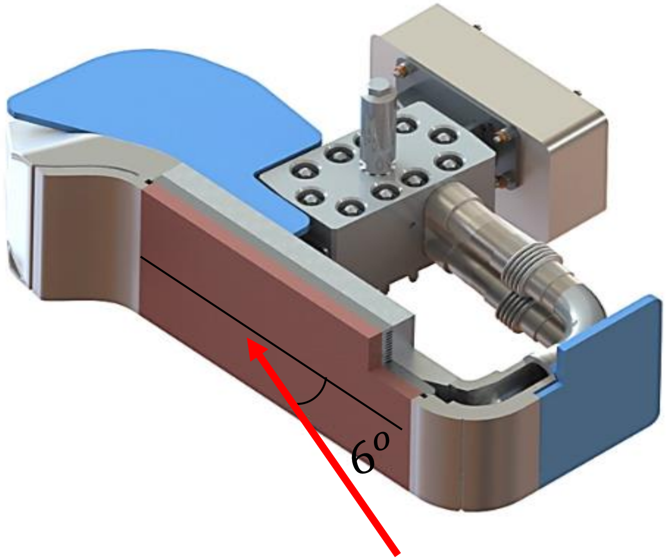


Single-slice target in service

Multi-slice disc module (prototype)

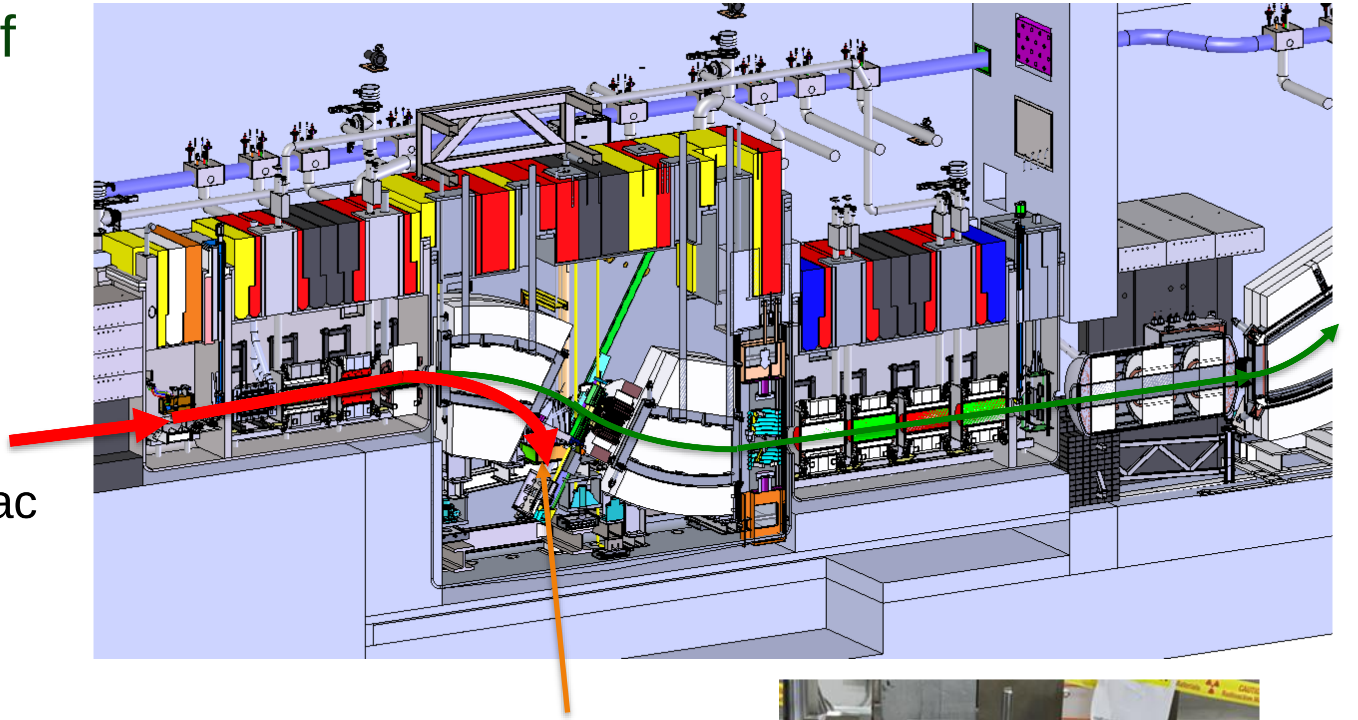
High Power Targetry Devices in FRIB: Beam Dump

- Unreacted primary beam absorbed, ~75% of primary beam power dumped (~300 kW for full power operations)
- Water cooled static beam dump in use
- Rotating water beam dump for high power beam



6º static mini-channel beam dump

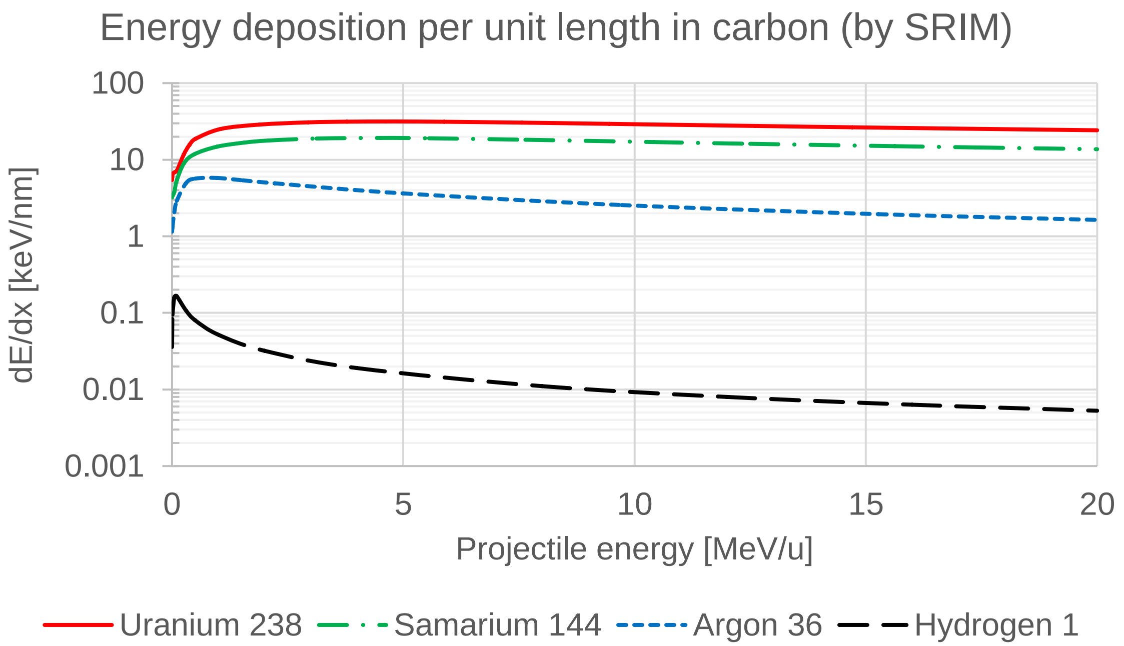
Beam from linac (~200 MeV/u)



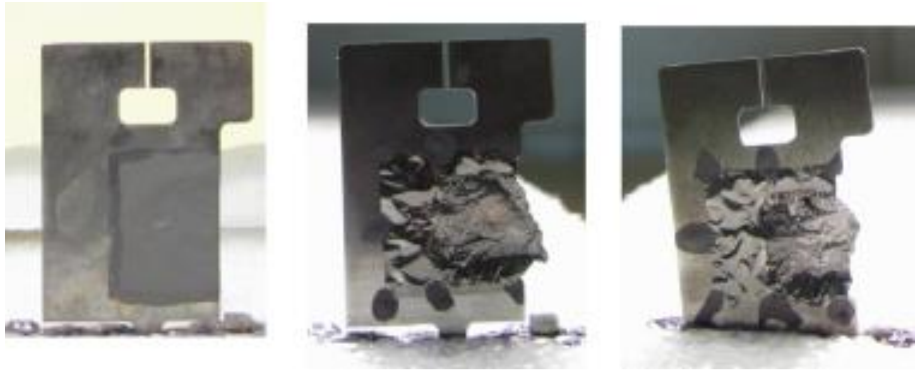
Beam dump

Technical Challenges in FRIB Beam-Intercepting Devices

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



- dE/dx of uranium is ***3 orders of magnitude*** higher than hydrogen (> ~2 MeV/u)!!!
- dE/dx decreases as beam energy increases

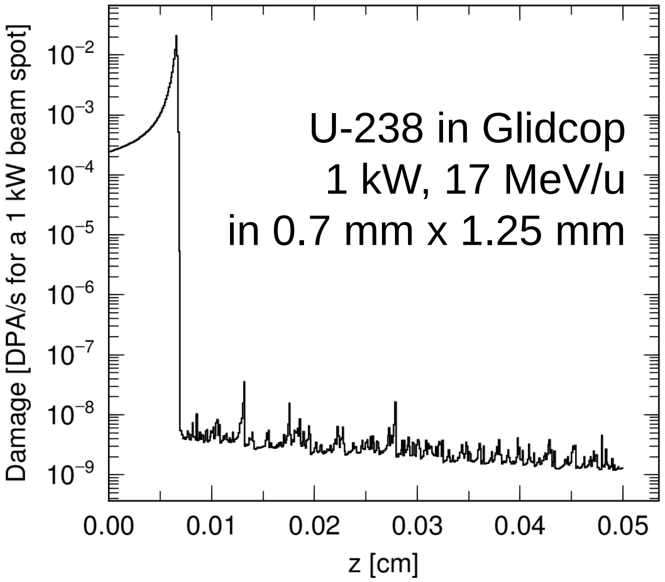


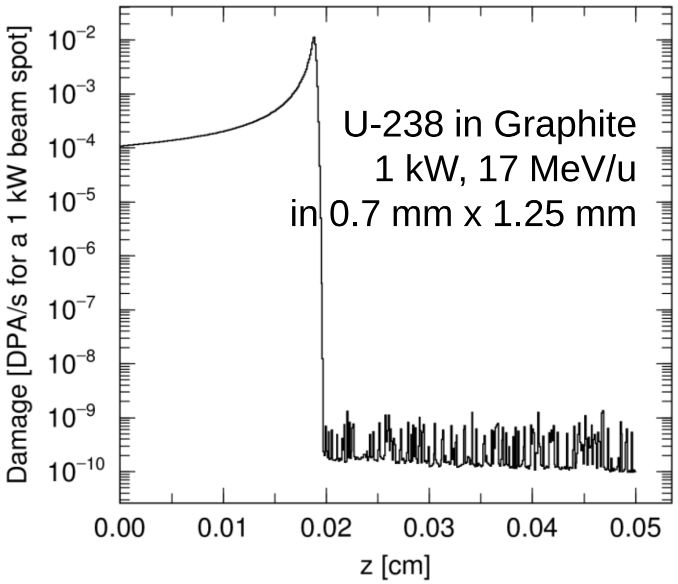
Damage produced by a $^{208}Pb^{27+}$ beam, 8.1MeV/u, on DLC foils in the NSCL K1200 Cyclotron. The leftmost photo shows an unused foil, and the middle and rightmost photos show two different foils exposed to the beam.

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

Example of DPA Estimate: Charge Selector Case

- DPA rate estimated assuming static condition with PHITS
- Beam: ^{238}U, 17 MeV/u, 1 kW, spot size 0.7 mm (hor. rms) x 1.25 mm (ver. rms): typical size of one U-238 charge state





- Very short stopping range
- Very high dpa rate especially at the Bragg peak (~1 dpa/min at 1 kW in beam spot)

Summary of Irradiation Condition: Uranium Beam

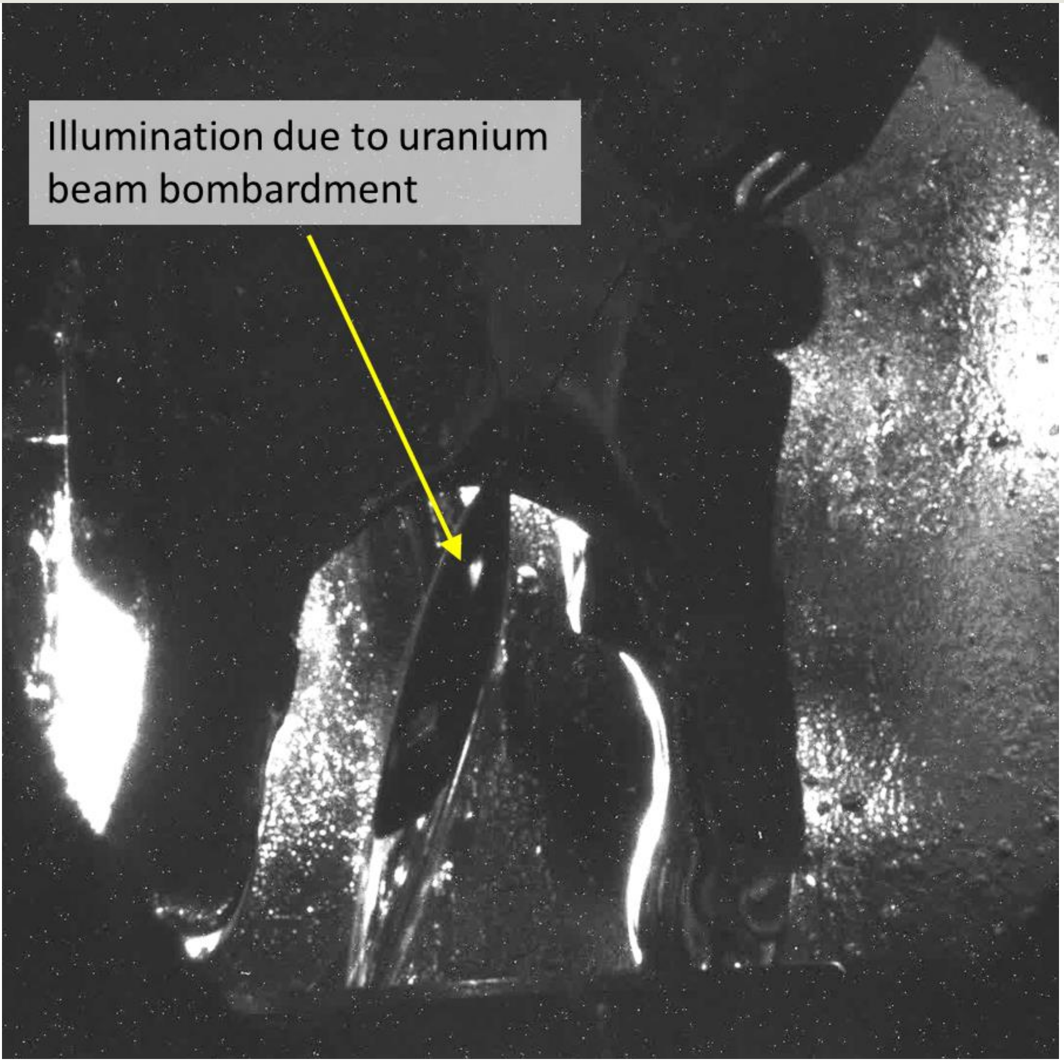
	Device	Material	Beam power at device (power at target)	Thermal load (Uranium) Deposited Power and Density		Type	Max. temperature	DPA (irrad. period)	Implanted ion concentration
Linac (FS1) ~ 20 MeV/u	Charge stripper	Graphene sheet	2 kW (20 kW)	94 W	4 MW/cm³	Rotating solid	> 1000 °C	9 dpa (1 week)	N/A
		Liquid lithium	50 kW (400 kW)	1360 W	60 MW/cm³	Liquid film w/o window	800 °C	N/A	N/A
	Charge selector	Glidcop AL-15 (Cu alloy)	2.5 kW (20 kW)	500 W (shared by 4 charge states)	0.6 MW/cm³	Static solid, water cooled	500 °C	3000 dpa (1 week, at peak)	10 at% (1 week)
		Graphite (planned)	13 kW (100 kW)	3 kW (shared by 4 charge states)	4 MW/cm³	Rotating solid	> 1000 °C	80 dpa (1 week at peak)	0.07 at% (1 week)
		TBD (liquid metal)	50 kW (400 kW)	10 kW (shared by 4 charge states)	~10 MW/cm³	Liquid film w/o window	TBD	N/A	N/A
Target Hall ~ 200 MeV/u	Target	Graphite	400 kW (400 kW)	100 kW	60 MW/cm³	Rotating solid	> 1000 °C	8 dpa (2 weeks)	N/A
	Beam dump	CuCrZr	15 kW (20 kW)	15 kW	0.6 MW/cm³	Static solid, water cooled	250 °C	12 dpa (1 week)	0.02 at% (1 week)
		Water in thin-wall Ti shell	300 kW (400 kW)	300 kW	30 MW/cm³	Rotating liquid w/ window	150 °C	7 dpa in shell (1 year)	N/A

Roadmap: Phased Approach Supports Power Ramp Up
Green Indicates "Functional"

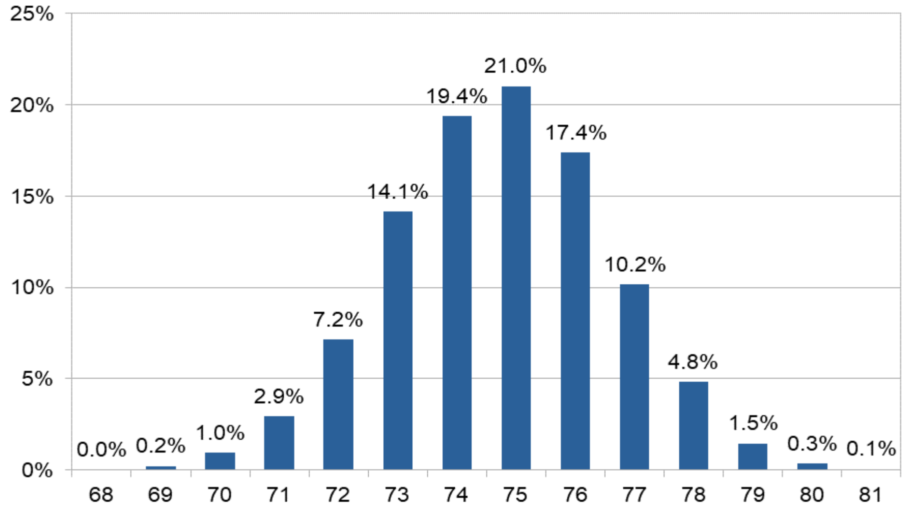
EPOCH	1	2	3	4	5	6
Beam power	10 kW	20 kW	50 kW	100 kW	200 kW	400 kW
Charge stripper						
- Carbon						
- Lithium						
Charge selector						
- Low power: static jaws made of Glidcop						
- Intermediate power: rotating graphite						
- High power: liquid metal option						
Target						
- Single slice						
- Multi slice						
Beam dump						
- 6° static Al						
- 6° static bi-metal mini-channel beam dump						
- Rotating water beam dump (1 mm Ti shell)						
- Rotating water beam dump (0.5 mm Ti shell)						

Current

Liquid-Lithium Charge Stripper Works: 10.4 kW Uranium Beam Delivery to Target Achieved with High Stripping Efficiency



- Successful uranium beam stripping
- Multi-charge-state acceleration is key to efficient beam acceleration
  - ^{238}U stripping efficiency ~ 57% with three charge states was achieved in this test



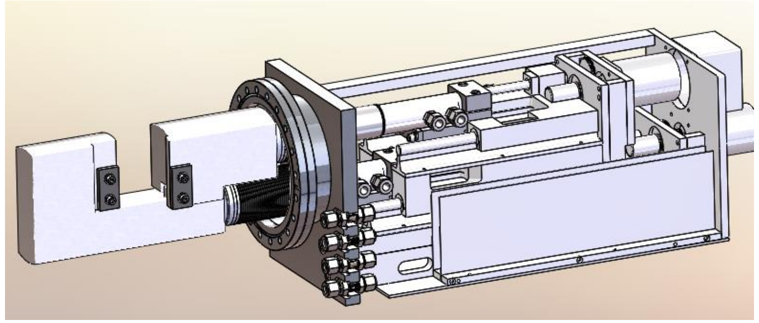
P.N. Ostroumov, et al., Phys. Rev. Accel. Beams 27, 060101, 2024

- Five-charge-state acceleration, 80% stripping efficiency, was demonstrated afterwards

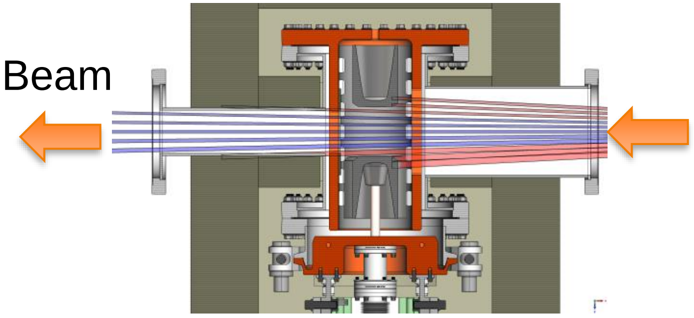
Charge Selector Roadmap: Implementing Phased Deployment with Increasing Power

- Present charge selector: Low Power Charge Selector (LPCS), static Glidcop jaws
- Next phase: Intermediate power charge selector (IPCS), rotating Graphite wheel jaws

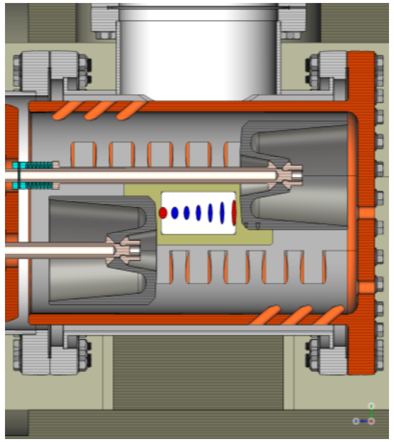
EPOCH	1	2	3	4	5	6
Beam power	10 kW	20 kW	50 kW	100 kW	200 kW	400 kW



Low Power Charge Selector (LPCS): Static Glidcop jaws



Top view



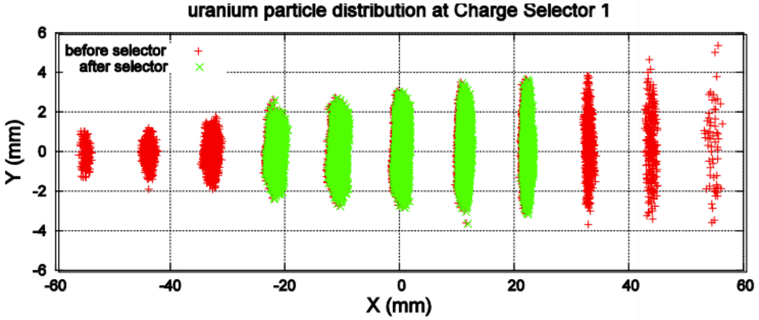
Front view

Intermediate Power Charge Selector (IPCS): Rotating graphite wheel jaws

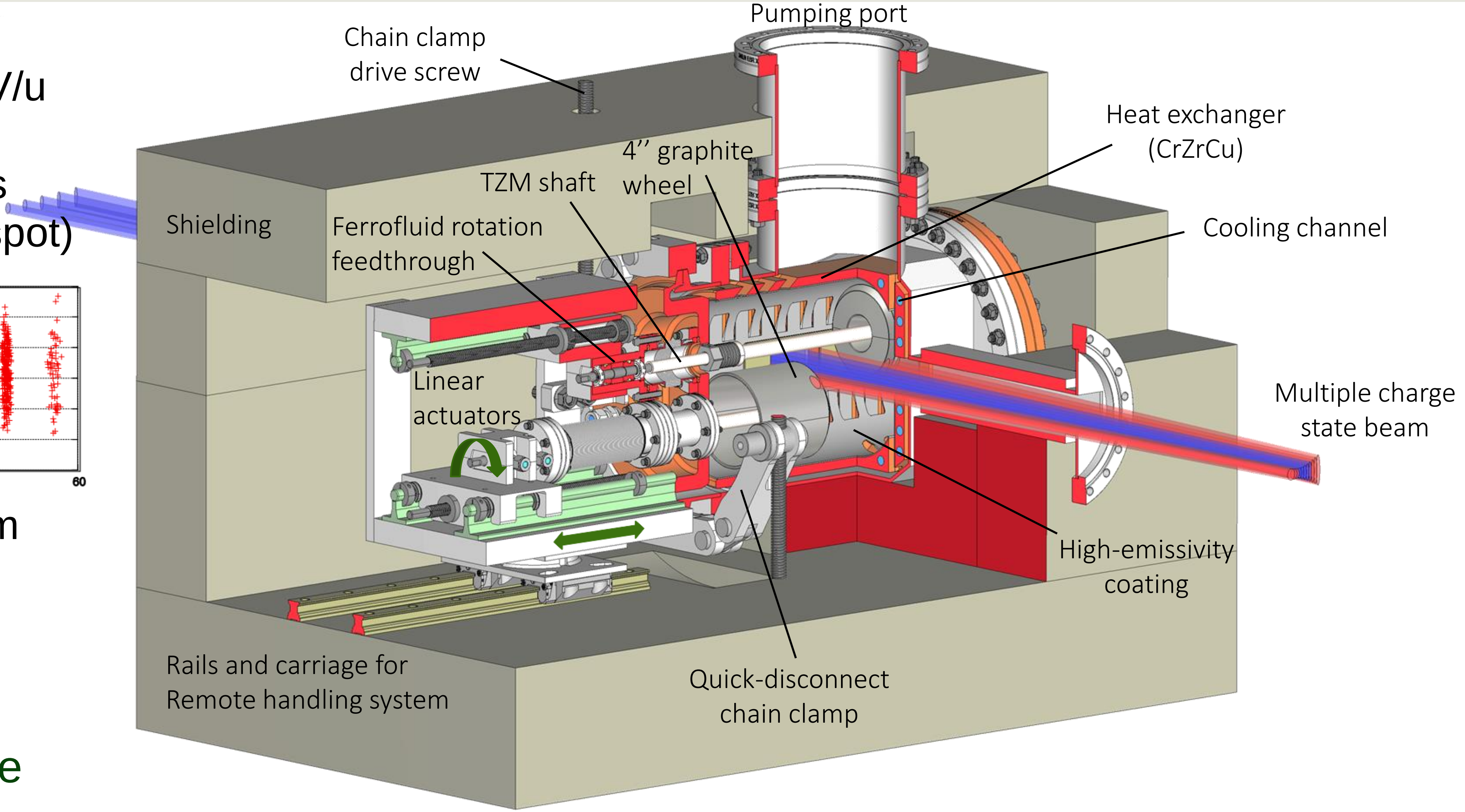
High Power Charge Selector (HPCS): Liquid metal films (TBD)

Intermediate Power Charge Selector (IPCS)
Unique Facility Requires Unique Solutions

- Requirements:
  - ^{16}O – ^{238}U, 16 – 20 MeV/u
  - 450 W/mm^2
  - Spot 0.7 × 1.25 mm rms
  - (2.5 kW of ^{238}U in one spot)



  - Min. jaw range ±30 mm
  - Ready by EPOCH 3
- Modular design
- Design for Maintenance



Expected Performance

- Expected performance is highly dependent of the stripping efficiency
- Estimate based on ETACHA4 simulations of stripping in Lq.Li film, and multi-Q acceleration
- No radiation damage and ion implantation is considered
- Minimum requirement of 450 W/mm^2 covers all green and yellow

Ion	Z	A	Number of accelerated charge states	Power on Target (kW) 10	20	50	100	200	400	Note
O	8	16	1							Assumed 100% stripping efficiency
O	8	18	1							
Ne	10	20	1							
Ne	10	22	1							
Ar	18	36	1							Improves by using the carbon stripper
Ar	18	40	1							
Ca	20	40	2							
Ca	20	48	2							
Ni	28	58	2							
Ni	28	64	2							
Se	34	82	2							
Kr	36	78	2							
Kr	36	86	2							
Zr	40	96	2							
Mo	42	92	3							
Cd	48	106	3							
Sn	50	112	3							
Sn	50	124	3							
Xe	54	124	3							
Xe	54	136	3							
Sm	62	144	3							
Dy	66	156	4							
Er	68	162	4							
Yb	70	168	4							
Yb	70	176	4							
Os	76	184	4							
Pt	78	190	4							
Pt	78	198	4							
Hg	80	196	4							
Hg	80	204	4							
Pb	82	204	4							
Pb	82	208	4							
Bi	83	209	4							
U	92	238	5							

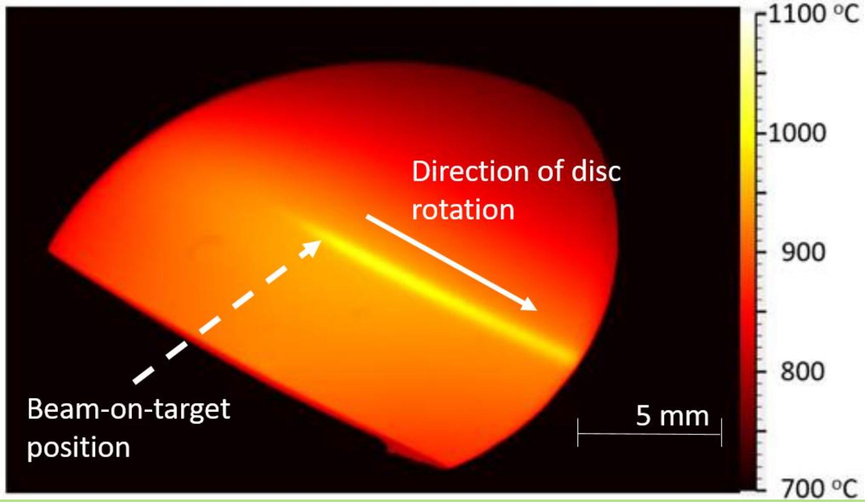
- LPCS
- IPCS (Min requirement)
- IPCS (Goal)
- HPCS

Target System Accomplished Reliable Single-Slice Target Supporting Stable 10-kW Operations and Ready for 20 kW

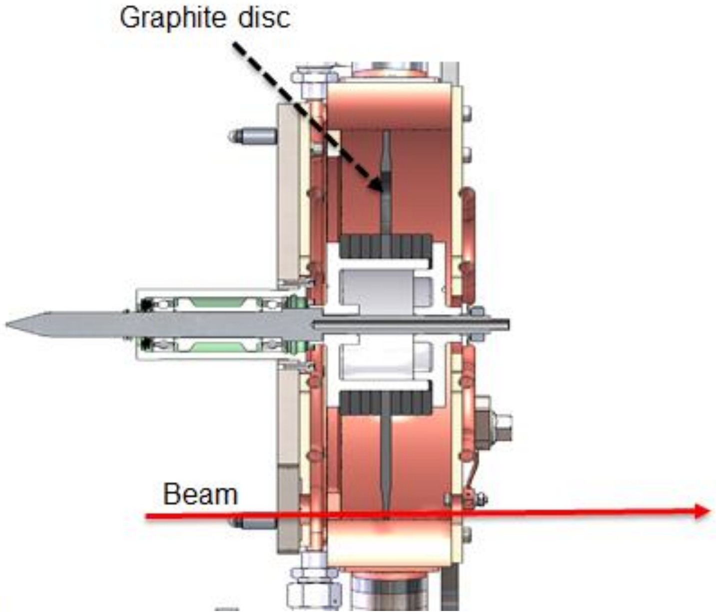
- Single-slice target is in operation supporting 10 kW and ready for 20 kW
- Supported the world record 10.4 kW uranium beam demonstration without an issue
- Supported the 22 kW test run with 228 MeV/u Se-82 beam this July

<u>Radiation Damage</u>

- DPA < 0.05 after one week operation at 10 kW
- Max temp ~ 800-1000 C
- Disc can be re-used multiple times
- No degradation observed



10.4 kW ^{238}U beam on target rotating at 500 RPM reaching 1004ºC peak temperature

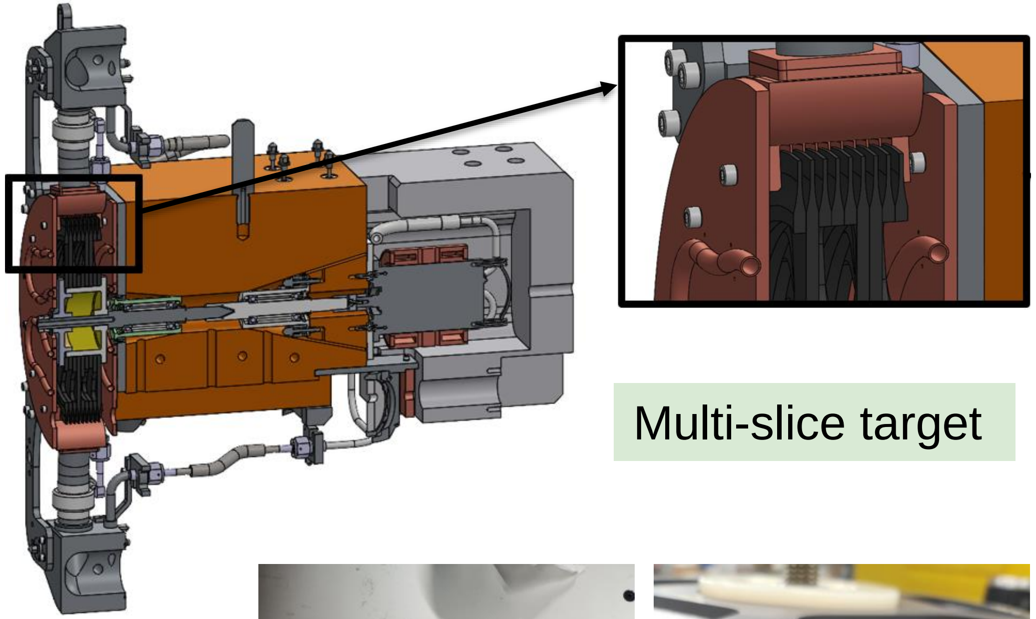


Requirements / specifications

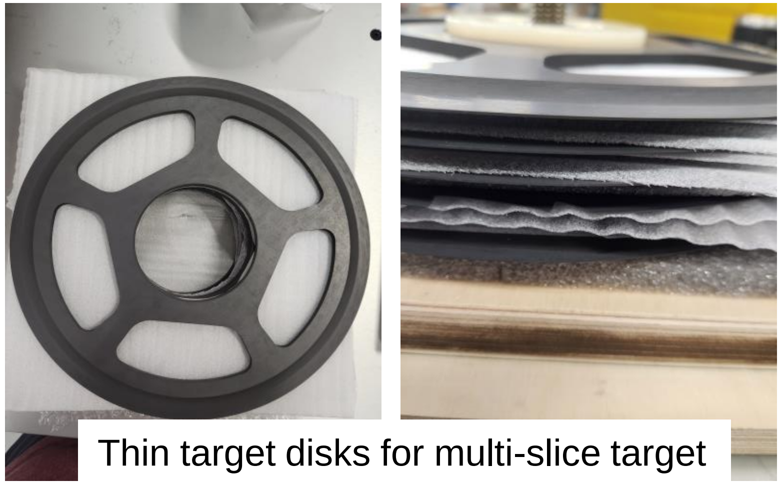
- Mersen Graphite, Grade 2160
- grain size: 5 μm, density: 1.86 – 1.93 g/cm^3
- >2 weeks lifetime (typical experiment duration 1 week)
- Remote replacement and maintenance
- 30 cm graphite disc, 1–20 mm total thickness
- Target disc temperature <1900 ºC

Target Roadmap: Implementing Phased Deployment with Increasing Power

- Single slice target: Up to 50 kW
  - Improvements made this summer as prep for 20 kW
    - » Shaft replacement: Invar to Inconel to withstand higher thermal stress
    - » Bearing replacement: increase temperature limit from 150 ºC to 230 ºC
  - Single-slide target will be able to support up to 50 kW
    - » Power limitation will be the thermal load in the disk
- Multi-slice target: from 50 kW
  - Multi-slice target to reduce thermal load per disk
  - Multi-slice disc fabrication
  - In-house thickness measurement device being assembled as quality assurance process
  - Heat exchanger design improvements for disk replacement
  - High temperature bearing development



Multi-slice target

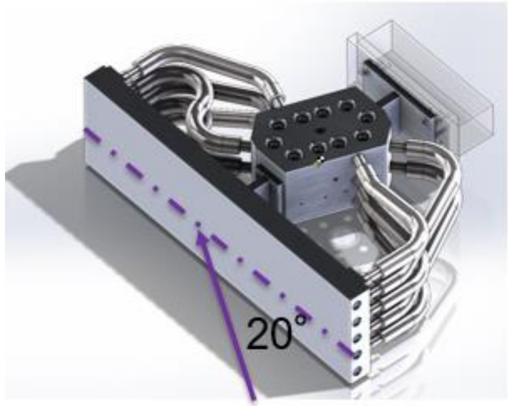


Thin target disks for multi-slice target

Beam Dump Roadmap: Implementing Phased Deployment with Increasing Power

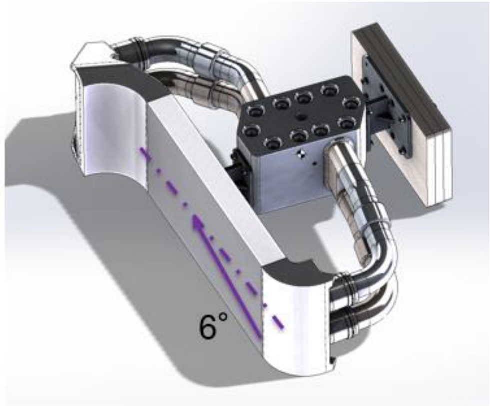
- Present beam dump: 6º static aluminum beam dump
- Next phase: 6º static mini-channel beam dump (MCBD)

EPOCH	1	2	3	4	5	6
Beam power	10 kW	20 kW	50 kW	100 kW	200 kW	400 kW

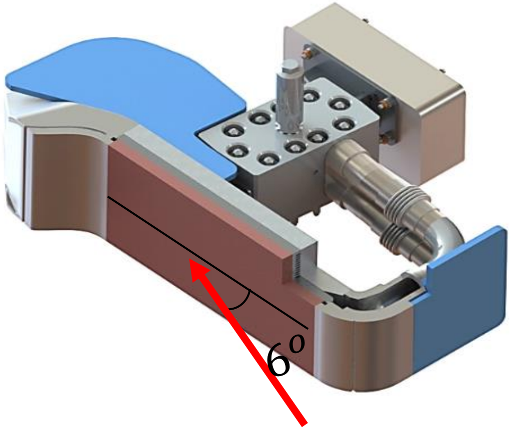


Primary beam

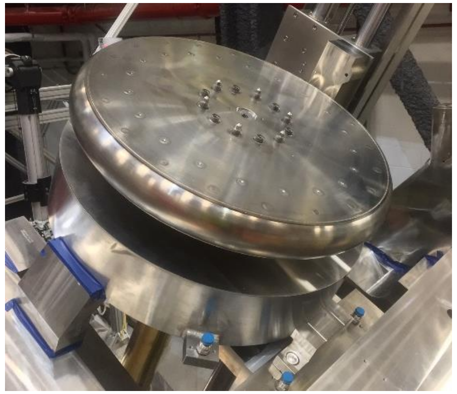
20º static Al beam dump
< 1 kW



6º static Al beam dump
<= 10 kW



6º static mini-channel beam dump > 10 kW

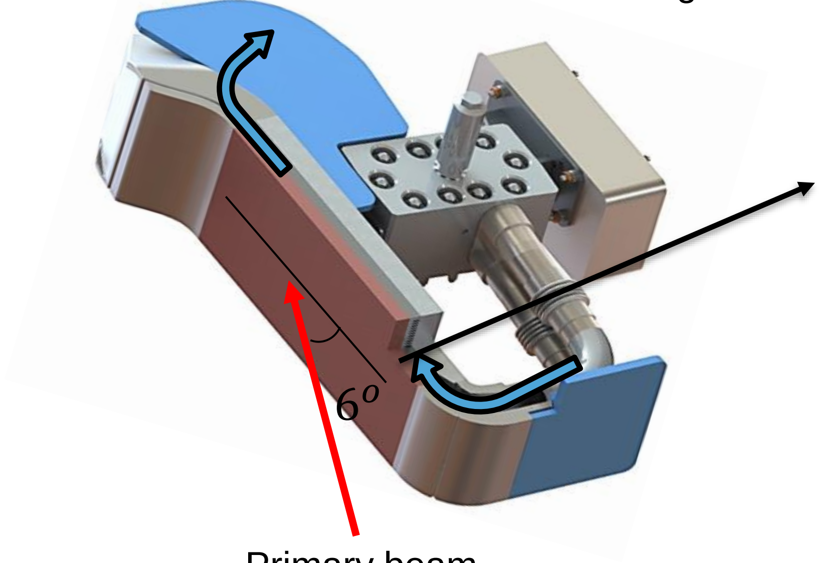


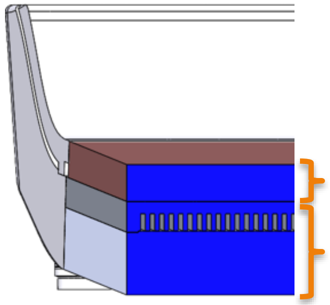
Rotating water beam dump
(1 mm shell)

Rotating water beam dump
(0.5 mm shell)

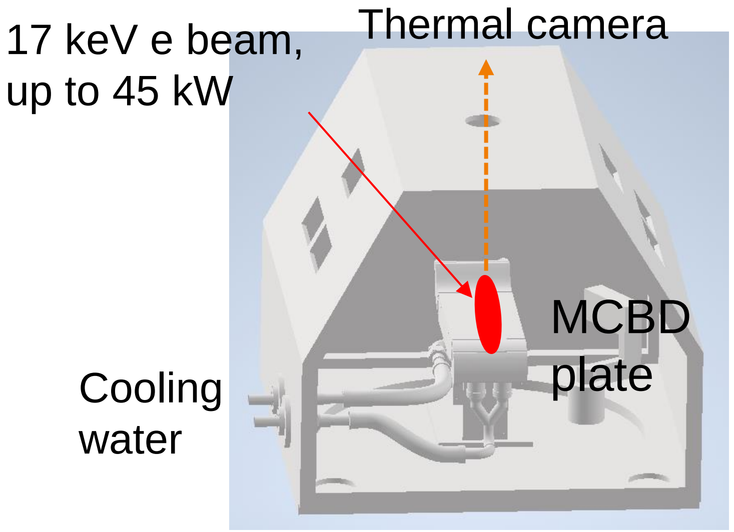
Next Beam Dump Is Ready for 20 kW Operations

- New beam intercepting plate being fabricated (mini-channel beam dump (MCBD))
  - CuCrZr/Al2219 (bimetal) with mini-channel water cooling
  - The primary beam stops within CuCrZr (penetration < 1mm)
- MCBD can accept 20 kW beam power
- Thermal performance of the new dump has been demonstrated up to 20 kW with an E-beam. Higher power test is planned.

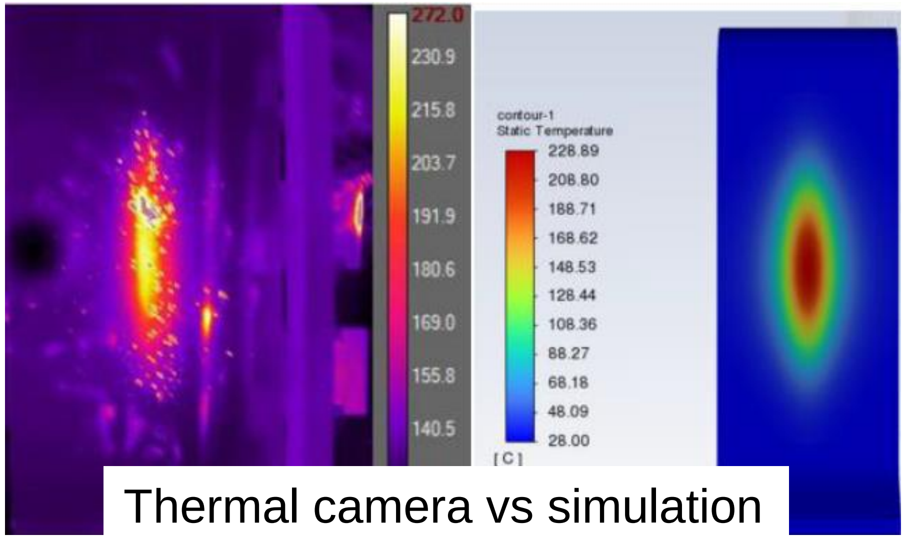




2 mm width mini-channel



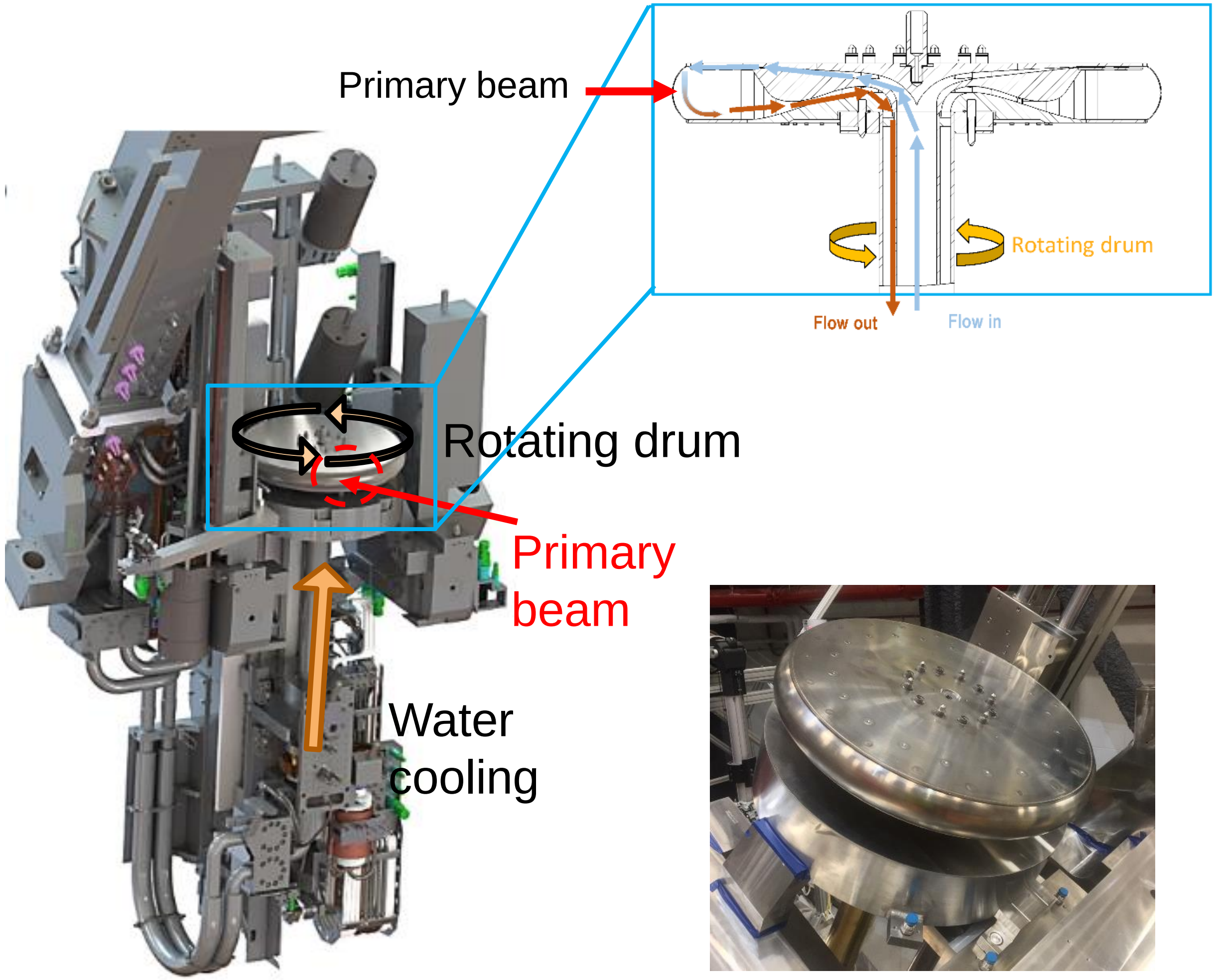
E-beam test setup



Thermal camera vs simulation

Toward Rotating Beam Dump for > 50 kW Operation

- FRIB baseline: Rotating water beam dump concept chosen for high power operations
- Ti-6Al-4V alloy selected for the beam dump shell material
- Primary beam stops in water
- Design parameters
  - Thin Ti-alloy shell to minimize heat deposition in the shell
  - 1 mm shell has been manufactured
  - 600 rpm and 70 cm diameter to limit maximum temperature and amplitude of temperature changes
  - 60 gpm water flow
- Design improvements: rotating water seal
  - Seeking a rotating water seal based on proven and available commercial products
  - Multiple (double or even triple) seal configuration to prevent water from migrating into the beamline vacuum
- Integrity of the shell is critical as pressure boundary



Approach to Radiation Damage in Materials

- FRIB Targetry Advisory Committee (TAC) recommended including PIEs of used BIDs in the lifecycle management of BIDs, fully utilizing the RaDIATE collaboration
- The biggest unknown about FRIB's BIDs as we ramp up beam power is radiation damage in materials.
  - High thermal load applications are much more common than radiation damage by energetic heavy ions
- Understanding of radiation damage in material is critical for safe operation of high-power accelerators. Beam power is often limited by BIDs performance.
- Nowhere other than FRIB will be able to provide irradiation conditions scalable to full power FRIB conditions.
- Therefore, PIE'ing our own materials would be the most efficient way to understand material behaviors
  - This includes the materials that are used in production and ones that are irradiated for a test purpose
- However, FRIB has no capability of PIE. We need to work with outside PIE facilities.
- We have been working with PNNL to develop a Statement of Work to do PIE of replaced Glidcop jaws. We don't know other PIE facilities where we could have our materials PIE'ed.
  - We also have two beam dump heads in storage. We will have more.

Importance of PIE Facility

- If there would be more PIE facilities with capabilities of handling highly activated materials, that is absolutely welcome.
  - We are even thinking we might need to have our own PIE facility.
- Therefore, a proposal of building multi-purpose proton beam irradiation facility with PIE capability by J-PARC team is very encouraging.

Summary

- FRIB has been operating for ~ 2 year, delivering annually > 5000 hours of beam time for both scientific and industrial experiments with > 92% availability
- The primary beam power is being steadily raised from 1 to 10 kW; 22 kW test run was a success; preparing for 20 kW user operation
- Thermal management and careful choice of BID materials, understanding of the materials' behaviors under irradiation conditions, and monitoring of the material integrity during operations, are becoming more and more important as FRIB ramps up its power.
- To ramp up to the ultimate design beam power of 400 kW, we are taking a phased targetry system deployments approach.
- Understanding of radiation damage in beam-intercepting materials needs PIE facility. A new PIE facility that can handle highly activated material is absolutely welcome. The proposal of multi-purpose proton beam irradiation facility by J-PARC team is very encouraging.

Acknowledgements

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- We thank FRIB's Targetry Advisory Committee (TAC) members for their invaluable advice and guidance and willingness to support our endeavor toward the unprecedented 400 kW heavy ion beam power. We especially thank the TAC Chair, Patrick Hurh, for his dedication.
- We also thank the MCBD Design Review Committee members, Patrick Hurh (FNAL), Antonio Perillo-Marcone (CERN), Drew Winder (SNS-ORNL), Mike Fitton (RAL), who also serve as members of the TAC.

Thank You

Backup Slides

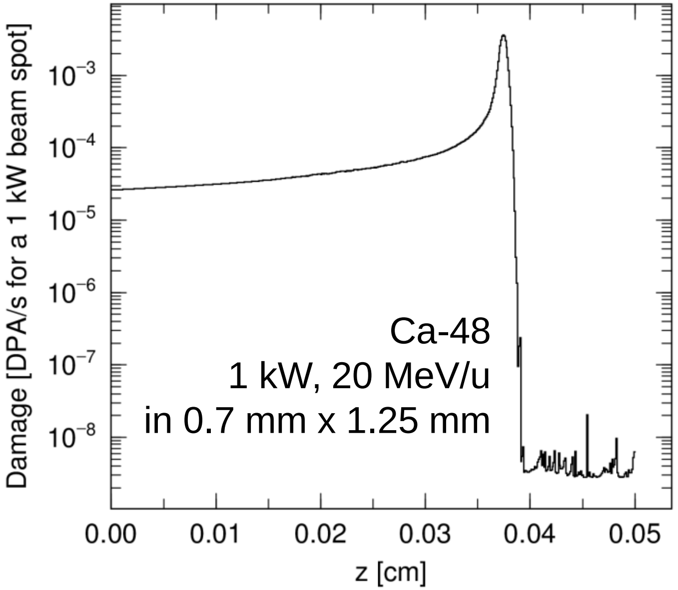
Thermal Conditions: Uranium Beam

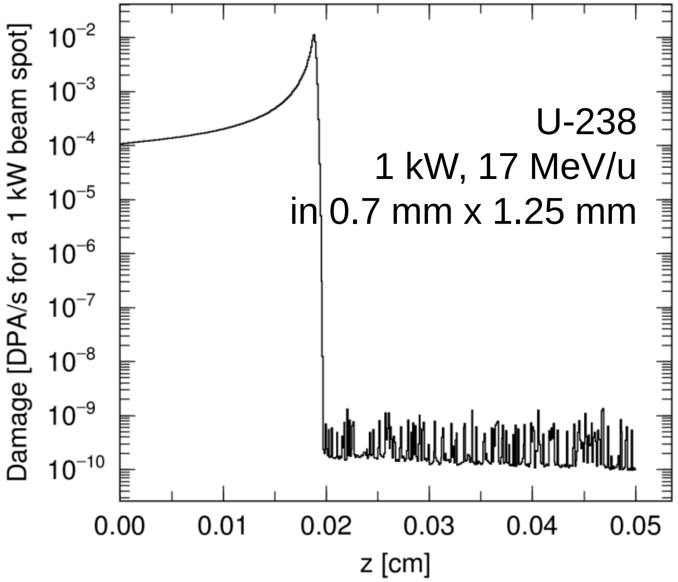
- Charge stripper suffers the severest condition (beam focused on thin film, high dE/dx due to low energy).
- Target will have a similar thermal load but have advantage of thickness (rigid). Graphite is ok.
- Beam dump and charge selector for high power operations will be liquid due to Bragg peak.

	Device	Material	Power at device (power at target)	Beam size	Thermal load (Uranium) Deposited Power and Density		Type	Max. temperature
Linac (FS1) ~ 20 MeV/u	Charge stripper	Graphene sheet	2 kW (20 kW)	σ 1 mm	94 W	4 MW/cm^3	Rotating solid	> 1000 °C
		Liquid lithium	50 kW (400 kW)	σ 0.5 mm	1360 W	60 MW/cm^3	Liquid film w/o window	800 °C
	Charge selector	Glidcop AL-15 (Cu alloy)	2.5 kW (20 kW)	σ_x 0.7 mm σ_y 1.25 mm	500 W (shared by 4 charge states)	0.6 MW/cm^3	Static solid, water cooled	500 °C
		Graphite (planned)	13 kW (100 kW)		3 kW (shared by 4 charge states)	4 MW/cm^3	Rotating solid	> 1000 °C
		TBD (liquid metal)	50 kW (400 kW)		10 kW (shared by 4 charge states)	~ 10 MW/cm^3	Liquid film w/o window	TBD
Target Hall ~ 200 MeV/u	Target	Graphite	400 kW (400 kW)	σ_x 0.25 mm σ_y 0.25 mm	100 kW	60 MW/cm^3	Rotating solid	> 1000 °C
	Beam dump	CuCrZr	15 kW (20 kW)	σ_x 1-10 mm σ_y 2-50 mm	15 kW	0.6 MW/cm^3	Static solid, water cooled	250 °C
		Water with Ti shell	300 kW (400 kW)		300 kW	30 MW/cm^3	Rotating liquid w/ window	150 °C

Example of DPA Estimate: Intermediate Power Charge Selector Graphite Wheel Jaws

- DPA rate estimated assuming static condition with PHITS
- Beam spot size used is typical of one U-238 charge state:
  - 0.7 mm (horizontal rms) x 1.25 mm (vertical rms)





- DPA rate shall be scaled by expected beam power and graphite wheel size
- 5 kW irradiation in 6” wheel for 1 week would cause 80 dpa at the Bragg peak in the beam spot

Ion Implantation Estimate for Intermediate Power Charge Selector Graphite Wheel Jaws

- Material: Graphite, 6” (152.4 mm) diameter
- Beam parameters:

Parameters	Values	Units	Note
Beam power at spot	5000	W	
RMS beam size (H x V)	0.7 x 1.25	mm	
Range	~ 0.3	mm	Dependent on ion species
Beam energy	17	MeV/u	Ion Z >= 54 (Xe)
	20	MeV/u	Ion Z < 54 (Xe)

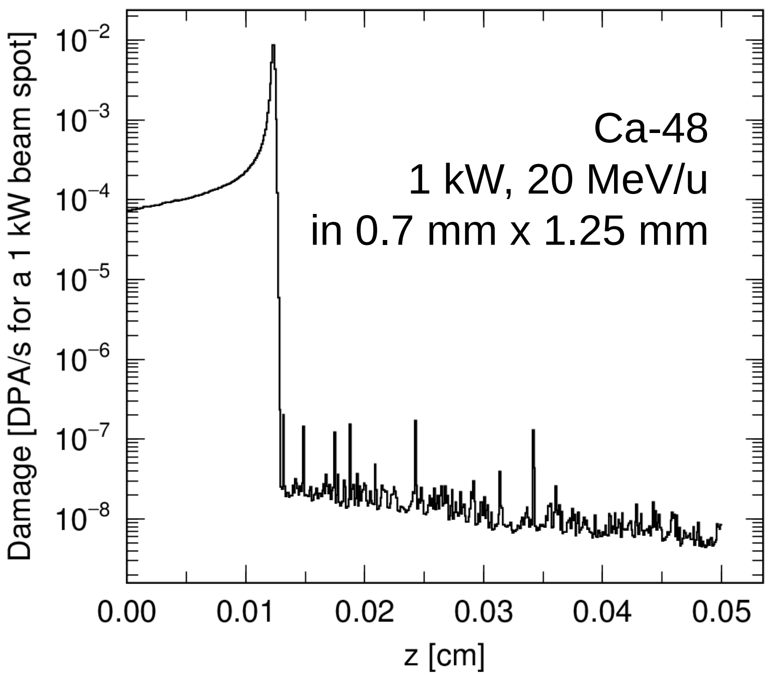
- Ion concentration after 1-week continuous irradiation (spread over 6” wheel surface)

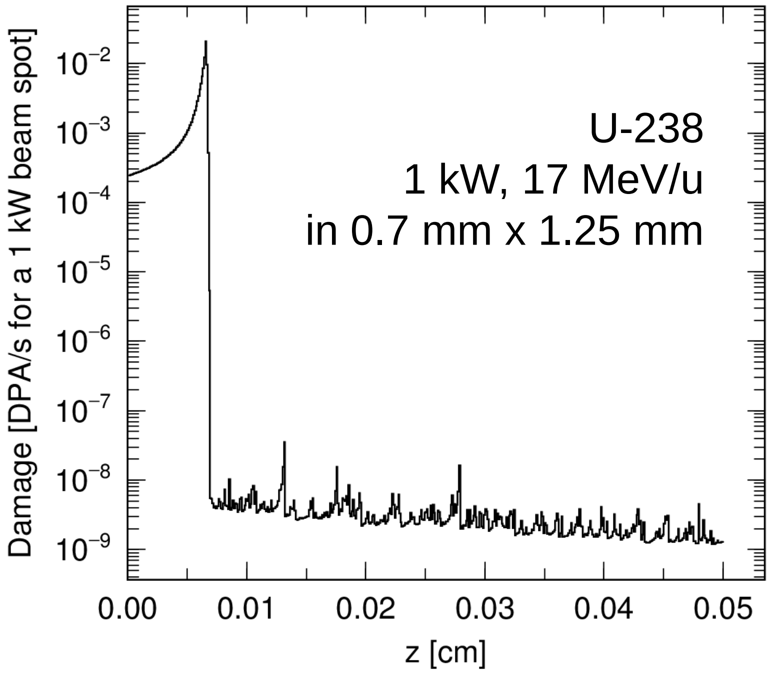
	Ar-36	Ca-48	Xe-124	U-238
Implanted primary ion concentration	0.16 at%	0.15 at%	0.09 at%	0.07 at%

- No consideration of diffusion nor nuclear reactions; H and He production to be estimated

DPA Estimate for Glidcop Jaws, Ca-48 and U-238 Beams

- Beam spot size used is typical of one U-238 charge state
  - 0.7 mm (horizontal rms) x 1.25 mm (vertical rms)
- DPA rate shall be scaled by expected beam power (e.g. 1 kW to 500 W)
- 500 W irradiation for 1 week would cause 3000 dpa at the Bragg peak in the beam spot





Ion Implantation

- Material: Pure copper (representing Glidcop AL-15)
- Beam parameters:

Parameters	Values	Units	Note
Beam power at spot	500	W	
RMS beam size (H x V)	0.7 x 1.25	mm	
Range	~ 0.1	mm	Dependent on ion species
Beam energy	17	MeV/u	Ion Z >= 54 (Xe)
	20	MeV/u	Ion Z < 54 (Xe)

- Ion concentration after 1 week continuous irradiation

	Ar-36	Ca-48	Xe-124	U-238
Implanted primary ion concentration	23 at%	20 at%	12 at%	9 at%

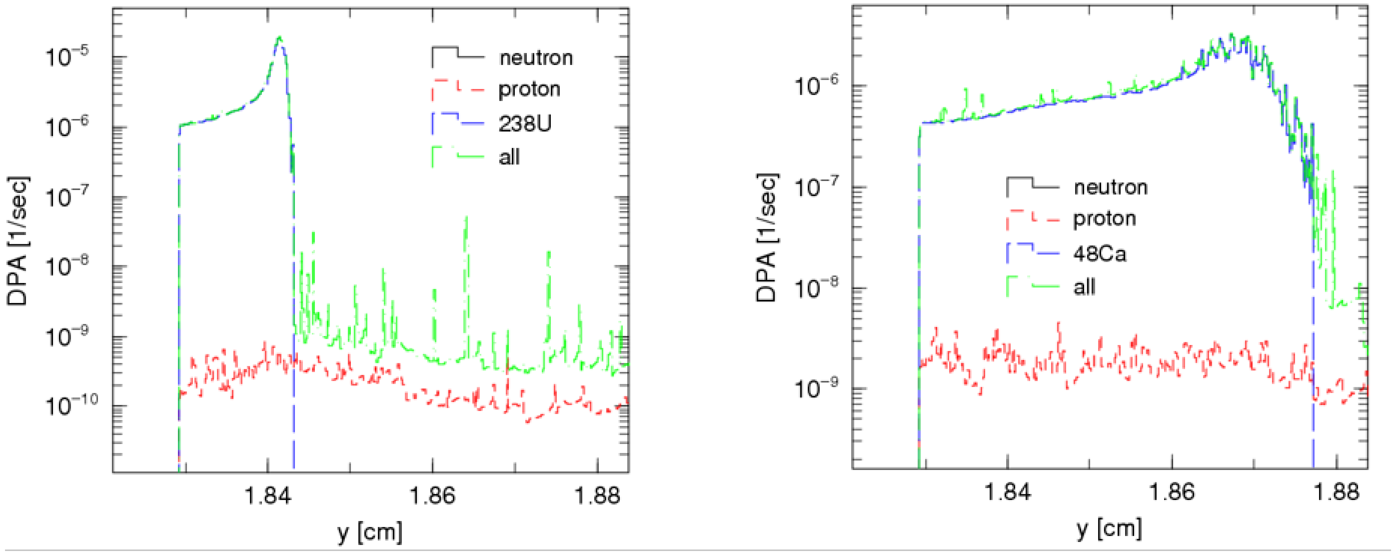
- No consideration of diffusion nor nuclear reactions; H and He production to be estimated

Radiation Damage to Beam Dump

- DPA calculation performed for ^{238}U and ^{48}Ca beam
  - Beam size: 5 mm x 10 mm (worst case scenario for the ^{238}U beam with 2.1 mm thick graphite target disc
  - Beam power: 20 kW beam power
  - DPA Result: ^{238}U: 12.1 dpa/week; ^{48}Ca: 2.2 dpa/week
- RIKEN experiment results:
  - No void formation in the CuCrZr alloy at 20 dpa
    - Reference:
      K. Yoshida et al., *High-power beam dump system for the BigRIPS fragment separator at RIKEN RI Beam Factory* NIMB 317 (2013)
- Primary beam position will vary with each experiment setting
  - Radiation dose distributed over larger surface

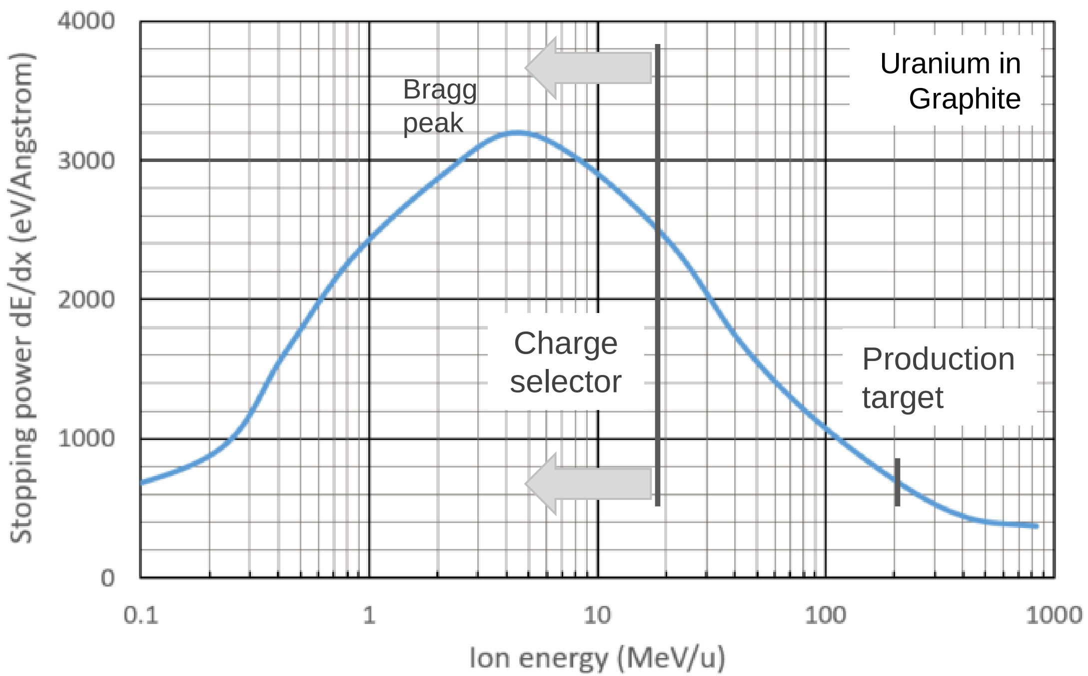
DPA: ARC model

- 238U: 10 kW primary beam power
  - peak dpa per second =2e-5
  - Peak dpa per week = 12.1
- 48Ca: 10 kW primary beam power
  - peak dpa per second =3.6e-6
  - Peak dpa per week = 2.18



Extreme Stopping Power

- Power density on the charge selector (5 kW per ^{238}U spot) is **comparable** with that on the target during the **10-kW test** for 177 MeV/u ^{238}U beam



	Target	Charge Selector	
Beam energy	177	16.5	MeV/u
Deposited power	3.7	5.0	kW
Stopping power	7.4 MeV/um	26	MeV/um
Stopping range	(disk thickness) 2.1	0.15	mm
Spot size	0.25 x 0.25	0.70 x 1.25	mm
Peak density	**4.5**	**6.0**	kW/mm^3
Power on Target	10	200	kW