Materials under Irradiation by Heavy Ions and Perspectives for FRIB

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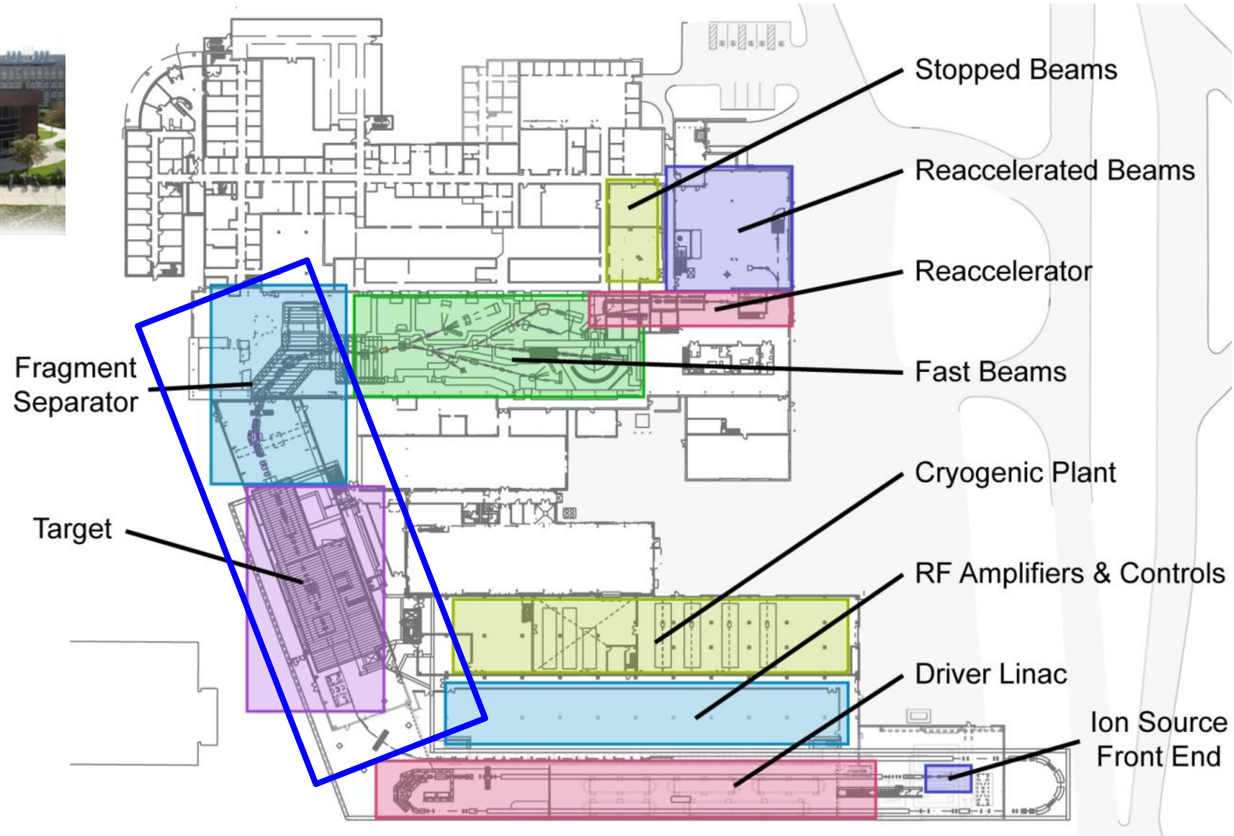
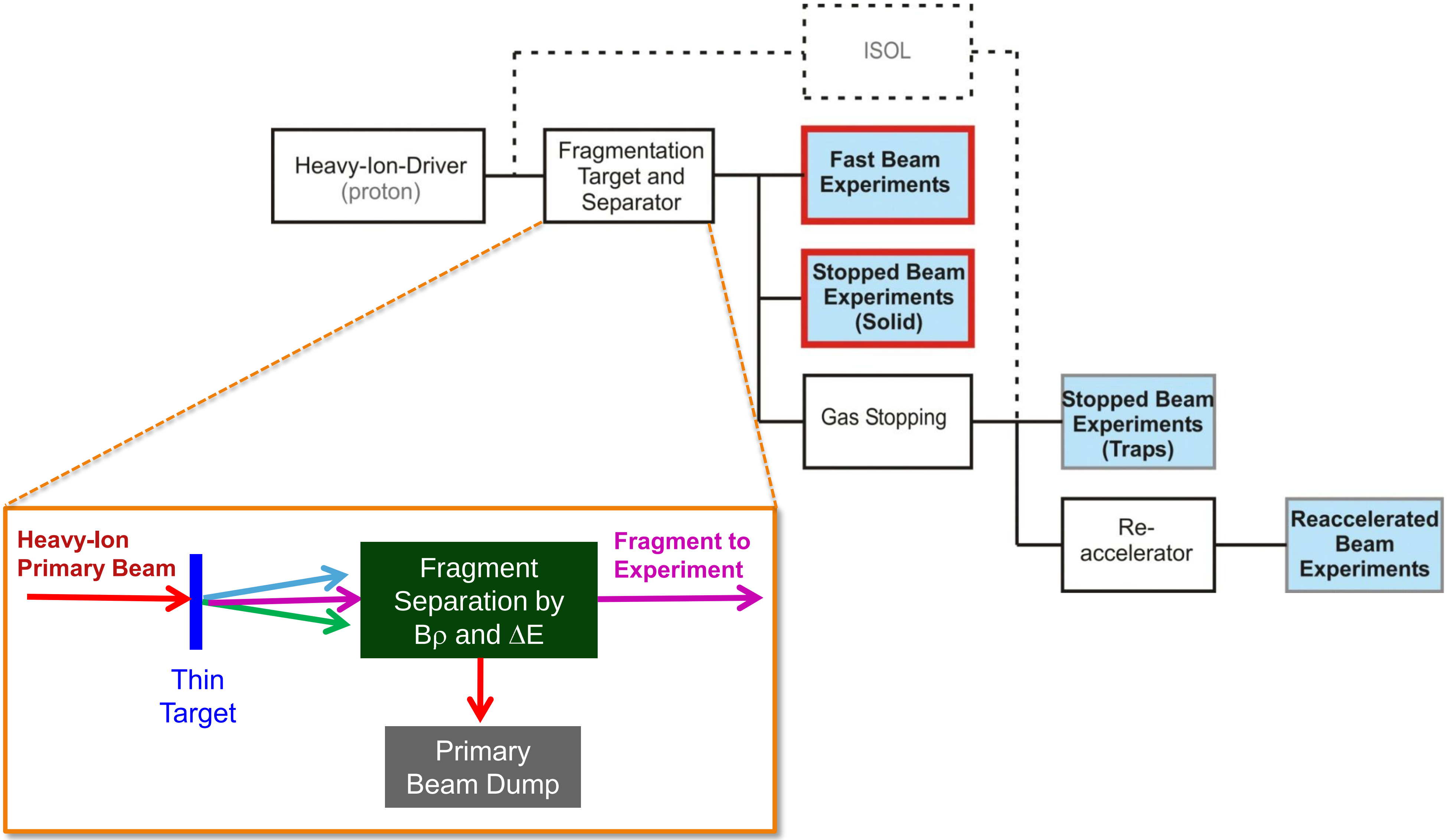
U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB at MSU Overview



- Rare isotope production with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and reaccelerated beam capability
- Experimental areas and scientific instrumentation for fast, stopped and reaccelerated beams

FRIB Rare Isotope Beams



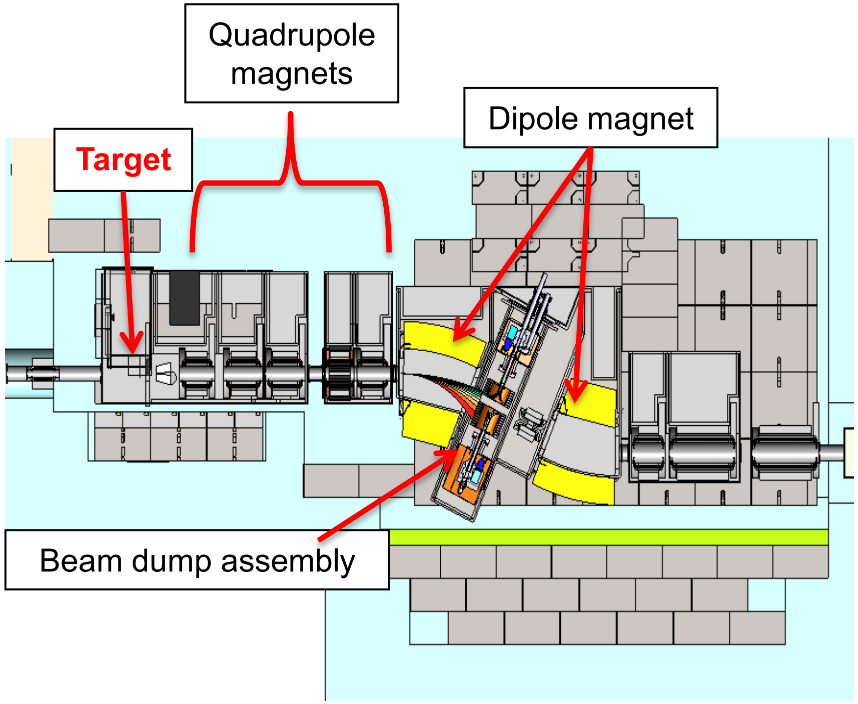
Challenges at FRIB for Intense Heavy Ion Beams Interacting with Materials

- Baseline power
  - 400 kW for 200 MeV/u ^{238}U beam
- Intense heavy ion beams that interact with materials at FRIB power present technical risks
  - Radiation damage
  - Power Density
    - » At Target (1mm diameter beam)
      - High power density: ~ 20 - 60 MW/cm^3
        - » c.f. SISSI at GANIL: 5 MW/cm^3, Spiral2 200 kW: ~1 MW/cm^3
    - » At Beam Dump
      - High power density: ~ 10 MW/cm^3
        - » c.f. 0.4 kW/cm^3 for 1 MW SNS target
- To help retire technical risks
  - Target and Beam Dump are R&D projects

FRIB Target

Rare isotope beam production with beam power of 400 kW at 200 MeV/u for uranium

- Up to 200 kW in a ~ 0.6 - 8 g/cm^2 target for projectile fragmentation
  - Optics requirements: 1 mm diameter beam spot
  - Max. extension in beam direction ~ 25 mm
- High reliability – lifetime: 2 weeks
- Ideally one target concept for all primary beams + fragmentation products



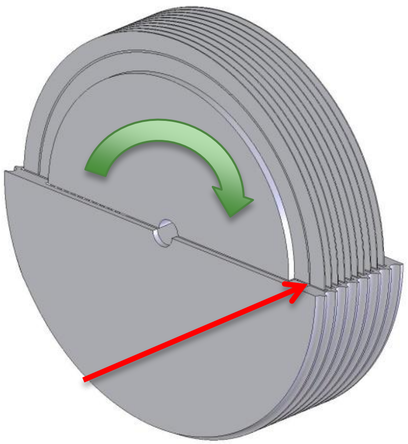
Technical Risk:

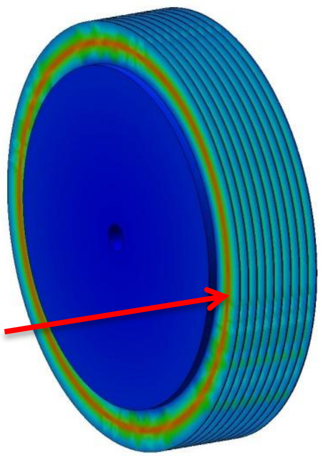
- High power density: ~ 20 - 60 MW/cm^3

SISSI at GANIL: 5 MW/cm^3
Spiral2 200 kW: ~1 MW/cm^3

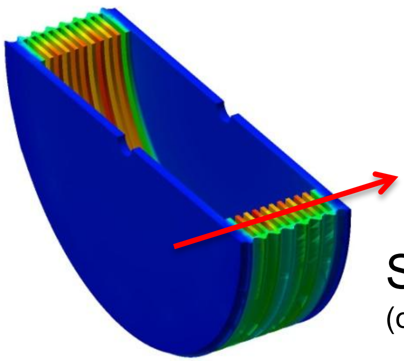
Chosen Concept: Multi-Slice Target

- Concept: radiation-cooled rotating solid-graphite target
- Increasing the radiating area by using multi-slice target

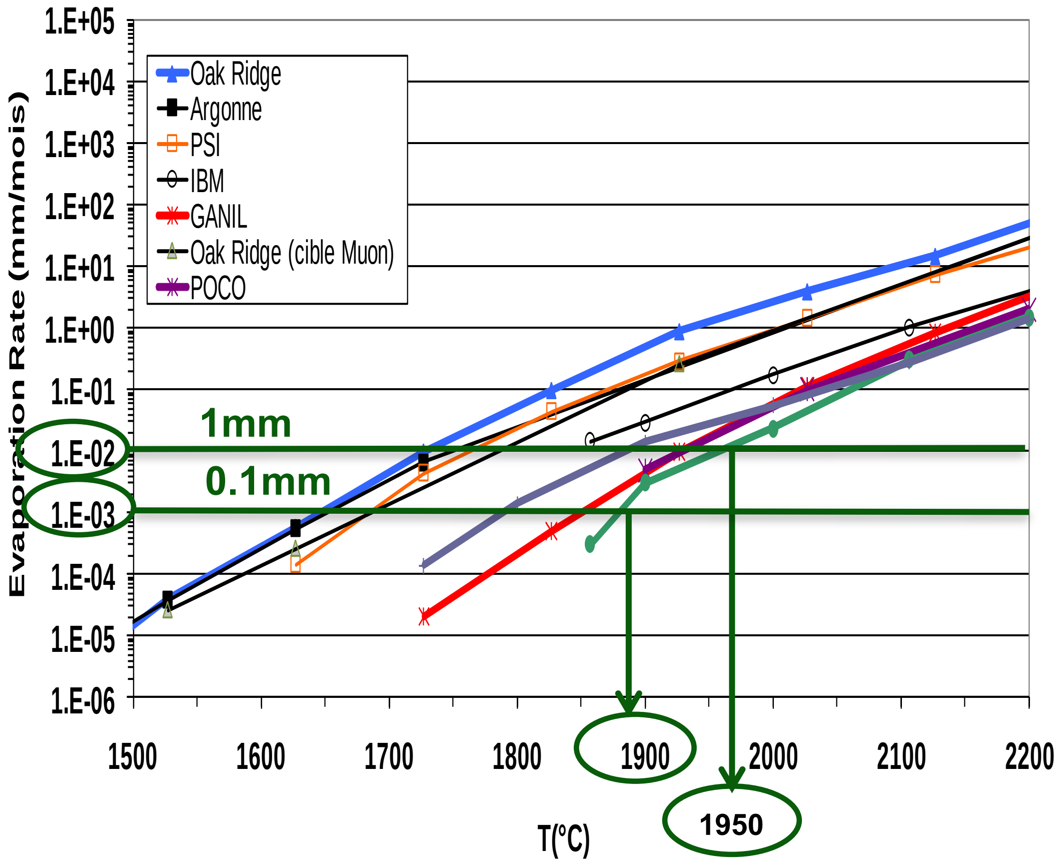




Rotating wheel



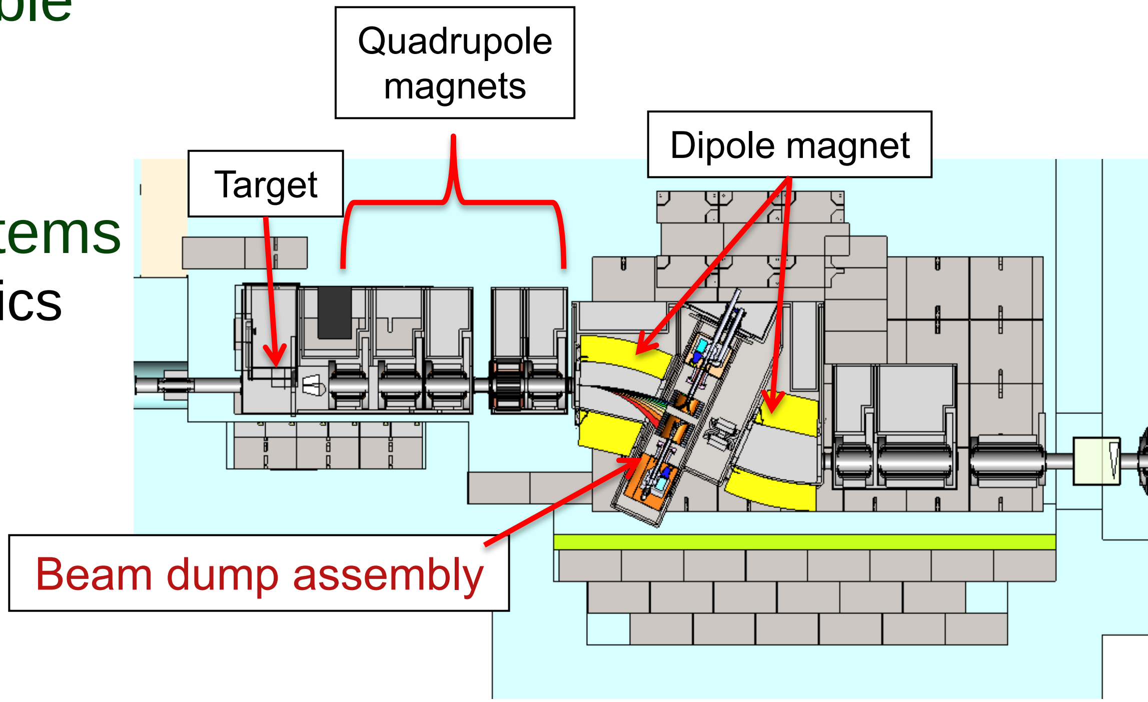
Static heat sink
(only lower half shown)



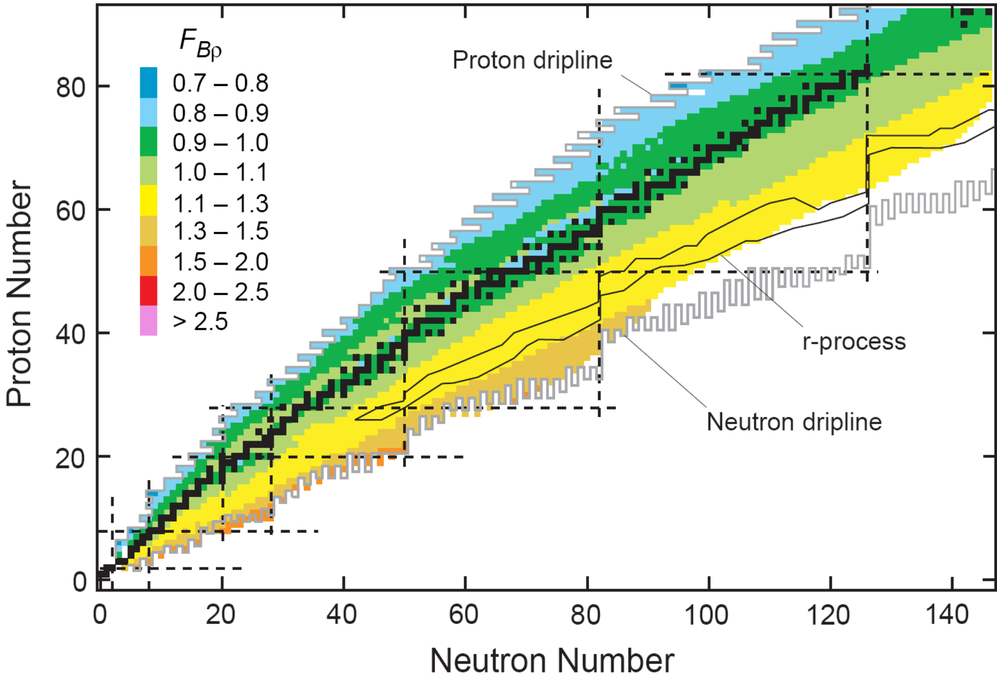
⇨ Maximum allowable temperature T_{max}≈ 1900 ˚C

Beam Dump

- Intercept primary beam at well-defined location
- High power capability up to 400 kW
  - High power density: ~ 10 MW/cm^3, c.f. 0.4 kW/cm^3 for 1 MW SNS target
- Long-lived or rapidly replaceable
  - 1 year desirable
  - Remote-handling capable
- Compatible with other subsystems
  - Fragment separator layout, optics
    - » Must meet Fit, Form, Function
- Safe to operate
- Technical risks
  - High power density
  - High radiation

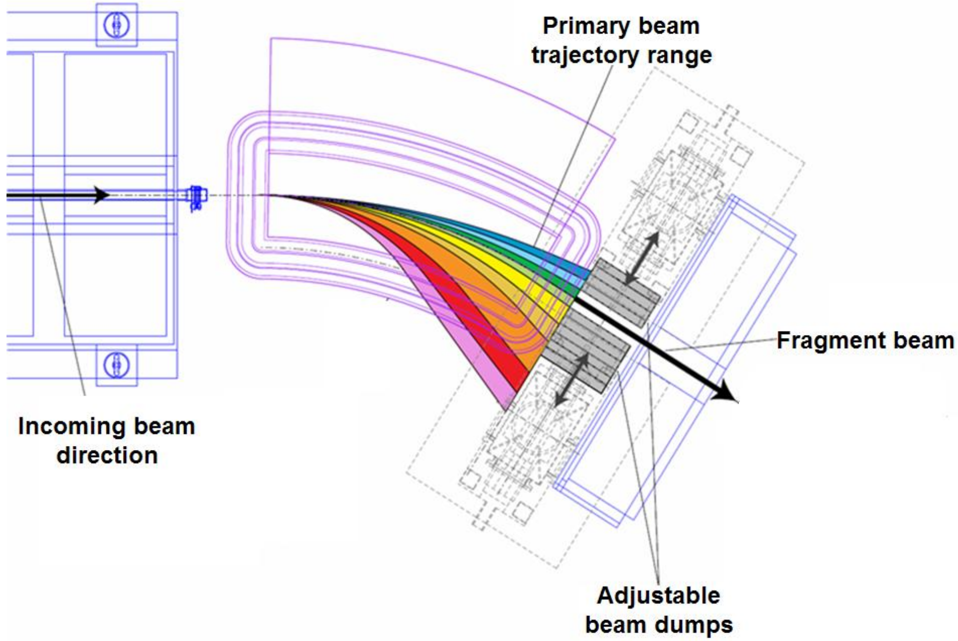


Primary Beam Position on Dump Changes with Fragment Selection



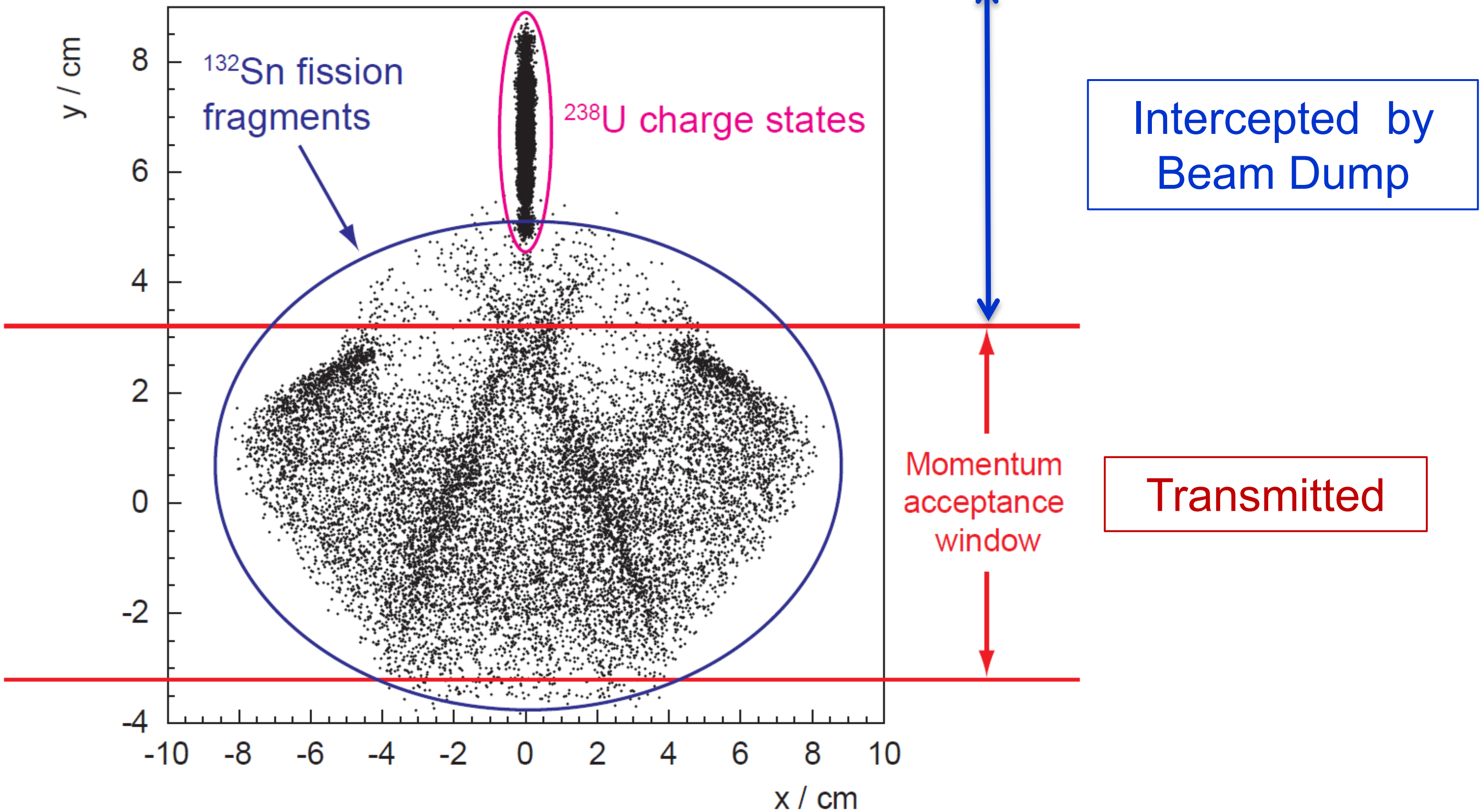
Color-code: $F_{B\rho}$ is the ratio of the magnetic rigidity of a given fragment to that of the primary beam.

The location of the primary beam at the beam dump is shown with the same color code.



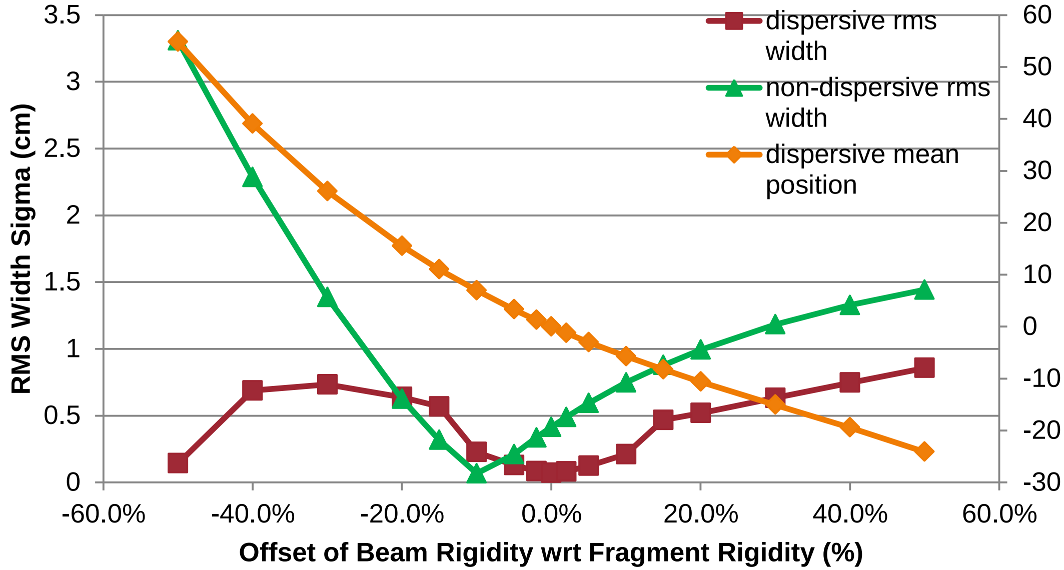
One Example of the Spatial Distribution of Beam and Fragments on Dump

- Primary Beam and ^{132}Sn Fragment Distributions for ^{238}U + C Fission Events
- Other beam/fragment combinations will be distributed differently
  - » In this example, beam and fragments are in close proximity
  - » 5 charge states, most restrictive "spot" sizes $\sigma_x \approx 2.3$ mm, $\sigma_y \approx 0.7$ mm



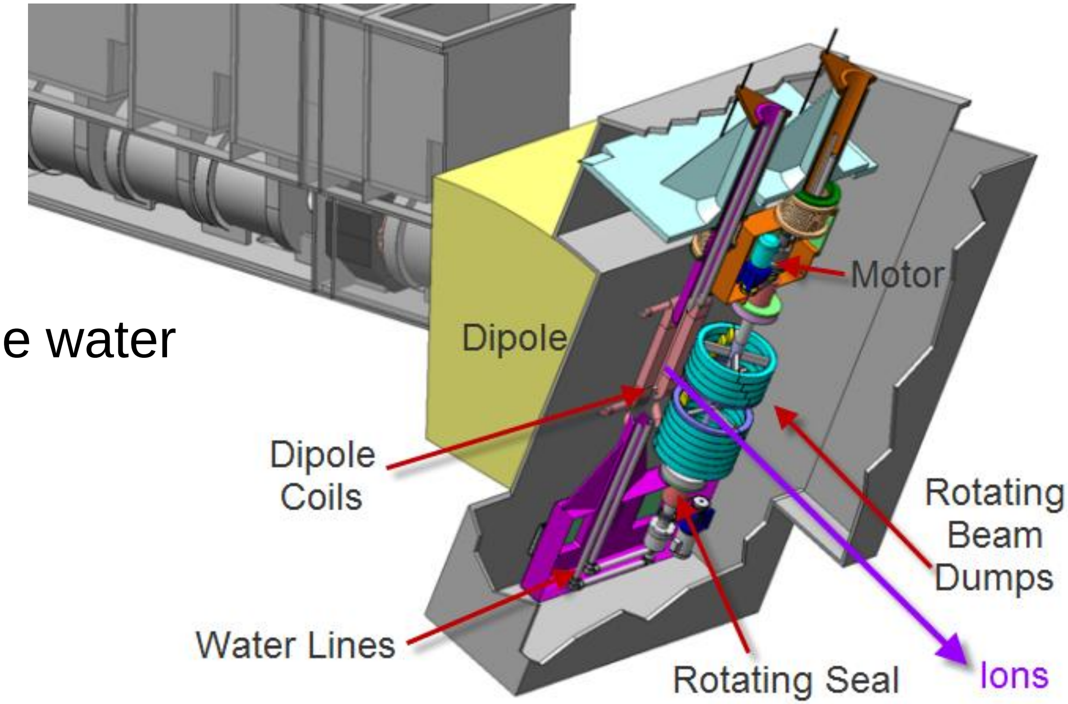
Beam Sizes and Power Density at Beam Dump

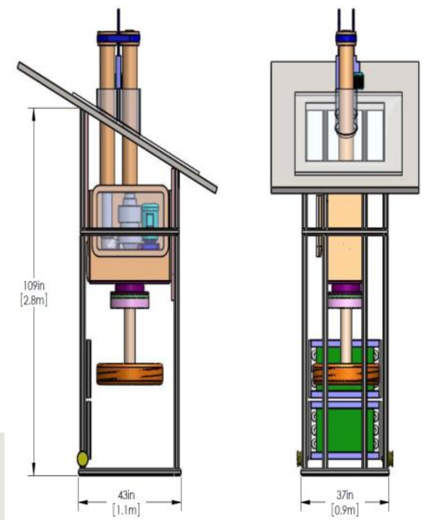
- Beam energy, size and material extent determine heat fluxes
  - Example shown is for 158 MeV/u ^{238}U
- Use results to parameterize distributions for thermal studies
- Power Densities
  - Range in Carbon (1.8 g/cm^2)
    - » 0.4 cm
  - Sigmas at -10% offset
    - » 0.7 mm, 2.3 mm
  - Power Density for 400 kW
    - » 10.5 MW/cm^3



Rotating Water-filled Aluminum-shell Dump
Preferred Concept

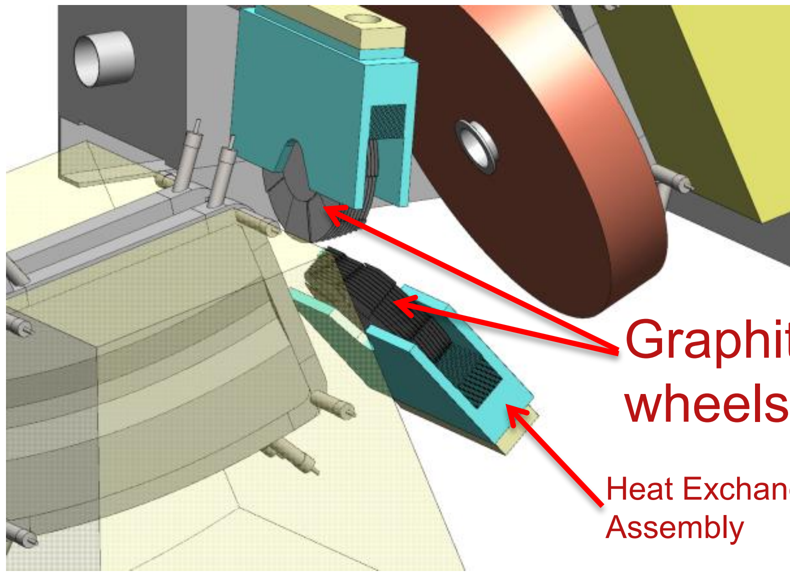
- Concept of rotating water-filled aluminum-shell dump
  - Heavy-ion beam penetrates rotating shell and stops in water
  - Water cools rotating shell
  - Produced activity is diluted by large water volume and water is filtered
    - » Activity is removed from loop
    - » Better radiological safety
    - » Potential for “isotope harvesting”
- Concept chosen because
  - Large-power-density risk retired
  - Life expectancy is sufficient
  - Supporting infrastructure is based on established concepts
    - » Water loop, filtration; HOG system
- Remaining risks
  - Radiation damage of aluminum shell not fully retired

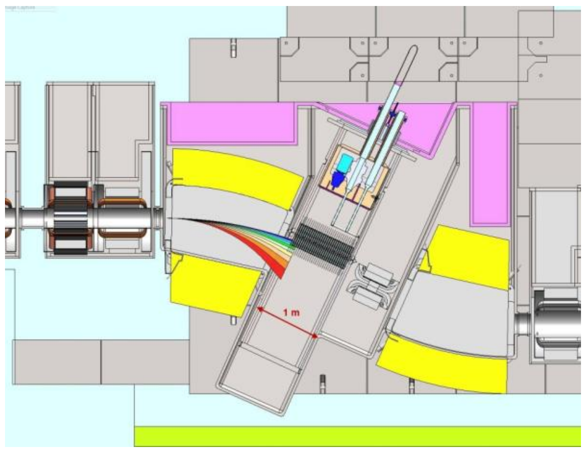


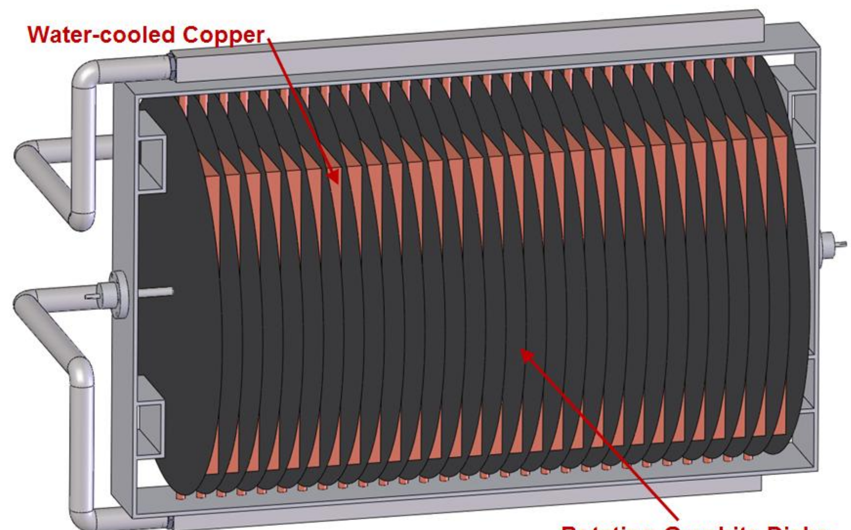


Radiation-Cooled Rotating Disk Graphite Dump
Backup Concept

- Concept chosen as backup because
  - Promising R&D on rotating multi-slice graphite target
  - Mechanical integrity less important - reduced radiation damage risk
- Issues
  - Power density at Bragg peak for heavy beams
  - Light ion stopping
  - Size limitations
  - Rotation speed







Sufficient Dump Lifetime

- Radiation damage is remaining issue for water-filled rotating beam dump
  - Radiation damage levels and mechanisms by fast heavy ion beams are largely unknown
    - » Transport codes (PHITS, MARS15, TRIM) predictions previously disagreed on levels of heavy-ion-induced damage
    - » Values from TRIM are largest
- TRIM damage predictions for 1.5 mm aluminum (assumed limit 10 dpa)

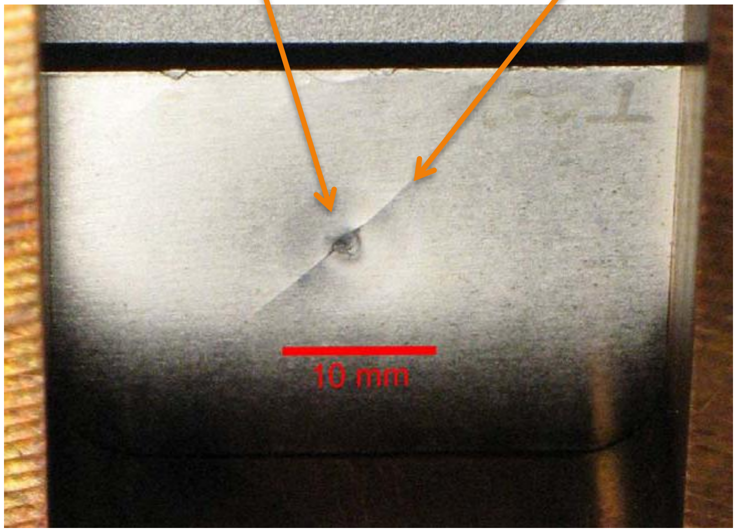
Beam	Effective Irradiation Area	dpa Rate	Lifetime
^{238}U, ~ 200 MeV/u	4 cm x 0.16 cm	4×10^{-4} s^{-1}	7 hours if beam is on the same spot
^{238}U, ~ 200 MeV/u	8 cm x 70 π cm Increased by rotation, variation of beam position	1.5×10^{-7} s^{-1}	~ 2 years
^{48}Ca, ~ 190 MeV/u	0.5 cm x 70 π cm Increased by rotation	4×10^{-10} s^{-1}	Life of facility

- Drum rotation and variation of beam position on dump increases lifetime
- A mix of light and heavy ion beams is expected to be required to satisfy the science needs
- What if radiation damage estimates factor 10 too low? Dump lifetimes of several months to several years expected depending on facility operation

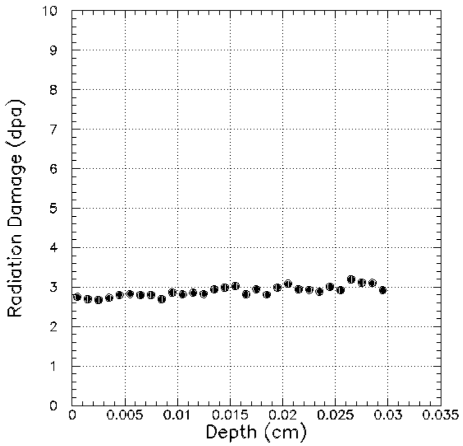
Observed Damage of Rare Isotope Production Targets at NSCL CCF

- Tungsten target 580 mg/cm^2 (0.03 cm)
  - $^{76}Ge^{30+}$ at 130 MeV/nucleon
  - Total fluence 5.77 x 10^{16} particles
  - Measured beam spot ranged from 0.3 mm^2 to 0.5 mm^2
  - 88W, 110 kW/cm^2 heat load

Radiation damage → swelling, embrittlement → crack
or
Radiation damage → melt layer erosion→ local melting → thermal tension → crater. crack



- In simulations
  - Round beam with area 0.3 mm^2 (r = 0.309 mm)
  - Radius of zones in which the damage was calculated 0.2 mm



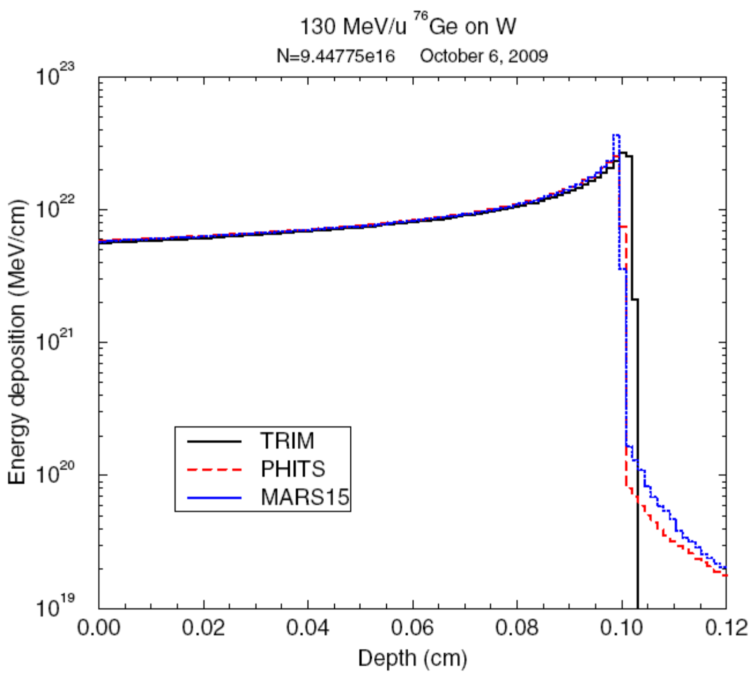
•Old analysis (~ 1 year ago):
- Averaged damage (MARS) = 2.83 dpa
- Damage calculated with TRIM = 73.60 dpa
- Damage calculated with PHITS = 0.92 dpa

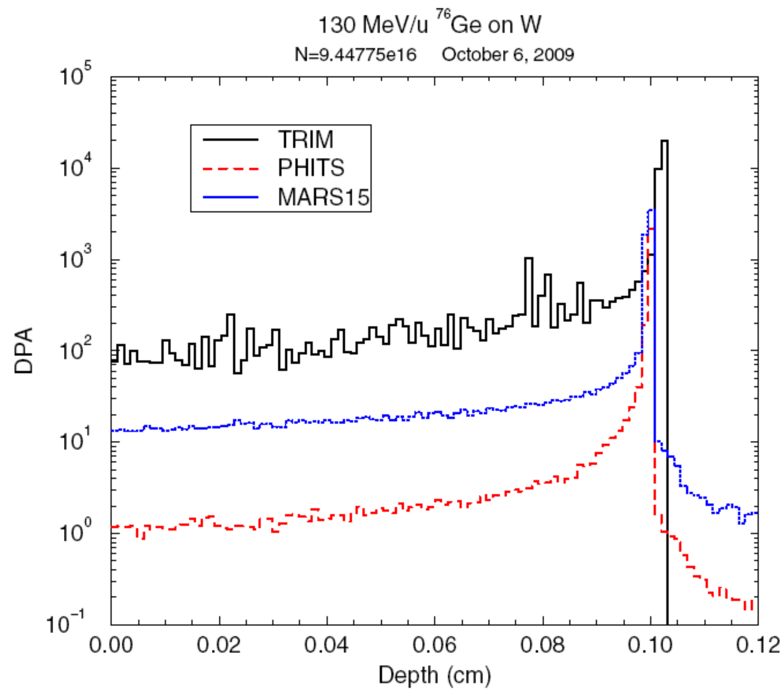
- Absorbed dose (MARS) = (9.733 ± 0.004) x 10^{12} Gy
- Absorbed dose (using experimental parameters) = 7.9 x 10^{12} Gy

Calculated by Mikhail Kostin (MSU)

Predicting Heavy-ion Induced Radiation Damage

- Calculation of radiation damage by energetic heavy ions is a challenge
  - State-of-art several years ago
    - Most of publicly available codes only took into account displacements induced by nuclear interactions
    - TRIM calculates damage induced by knocked-out electrons
    - Codes agree on energy deposition but disagree on DPA





Heavy-ion Induced Radiation Damage

- State-of-art 6 months ago
- MARS15 has been improved!

"SIMULATION AND VERIFICATION OF DPA IN MATERIALS"
N.V. Mokhov, I.L. Rakhno, S.I. Striganov
Presented at Workshop on Applications of High Intensity Proton Accelerators, October 19-21, 2009, Batavia, Illinois
Fermilab-Conf-09-645-APC (December 2009)

"RADIATION DAMAGE DUE TO ELECTROMAGNETIC SHOWERS"
Igor Rakhno, Nikolai Mokhov, Sergei Striganov
presented at the 9th Workshop on Shielding Aspects of Accelerators, Targets and Irradiation Facilities
(SATIF-9), April 21-23, 2008, Oak-Ridge, Tennessee, USA
Fermilab-FN-0817-APC (May 2008)

- New MARS15 results
  - Entrance DPA (values in the first hundred microns of the W target):

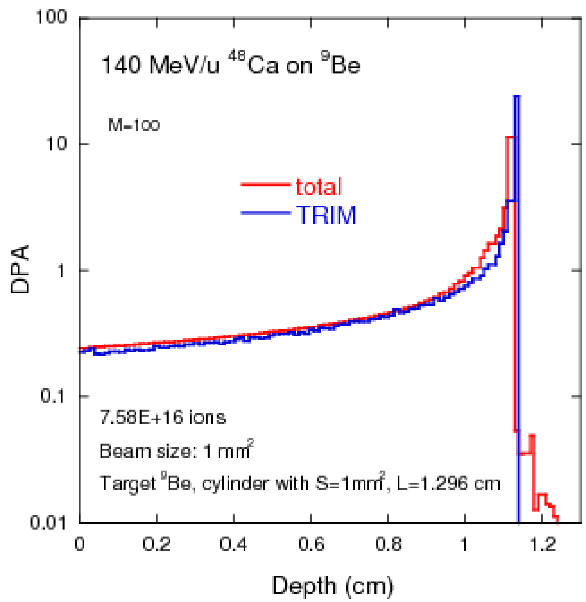
	TRIM	PHITS	MARS15
DPA/ion	8.04e-16	1.25e-17	1.43e-16

PHITS Recently Improved

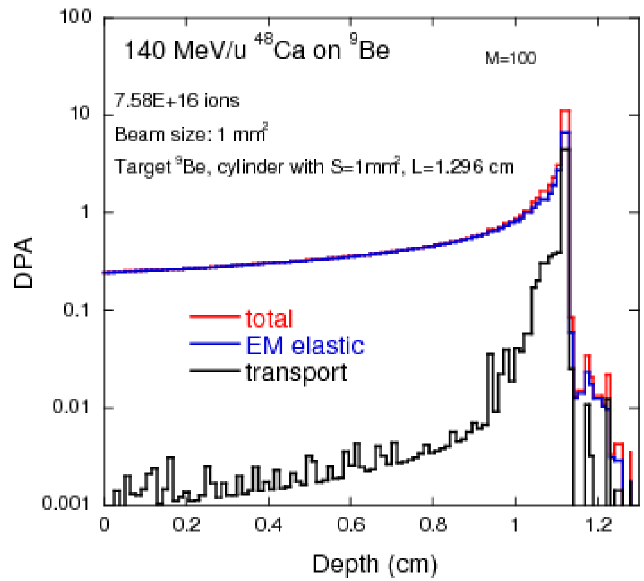
- PHITS improved by adding Rutherford scattering cross sections
  - Done using Lindhard, Nielsen, Scharff formalism
  - Damage cross sections calculated within Norgett, Robinson, Torrens formalism

DPA calculations using PHITS and TRIM - Courtesy of Yosuke Iwamoto (JAEA), 2010/9/13

Preliminary Result!



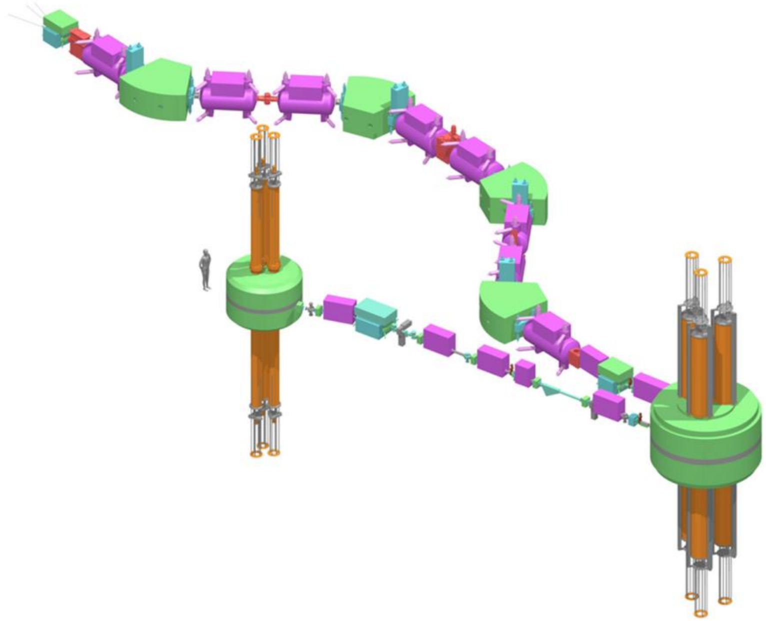
Preliminary Result!

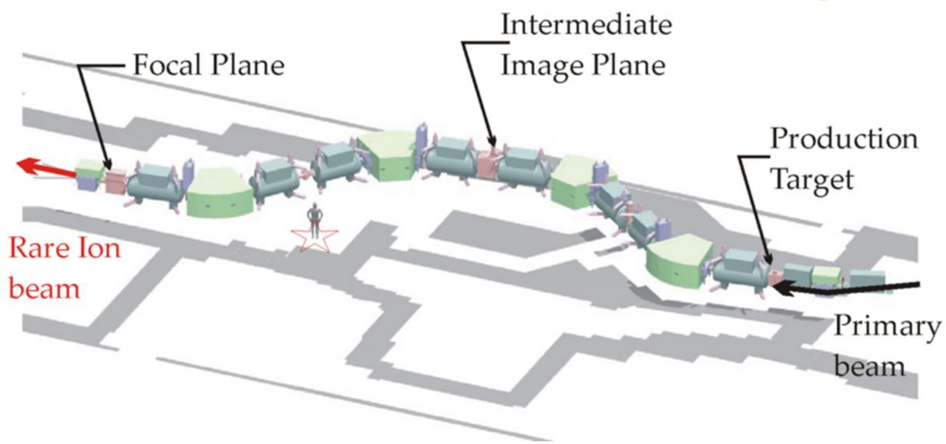


	Averaged region		DPA		
case	z minimum (cm)	z maximum (cm)	total	EM elastic	transport
09040 b)	0	0.7256	0.303	0.301	1.85E-03
beam range region	0	1.296	0.494	0.43	6.40E-02
peak region	1.11	1.13	11.56	7.06	4.5

Opportunity for NSCL CCF

- In light of suggestions by review committees:
  - Collect data of heavy-ion irradiation damaged rare isotope production targets from NSCL
    - » Detailed logging of the target history has been agreed on with NSCL operations





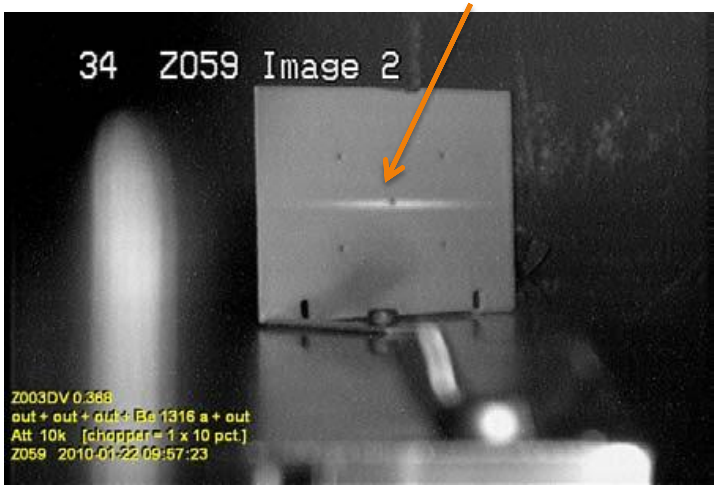
Heavy Ion Induced Radiation Damage Observed in Recent Experiments at NSCL CCF

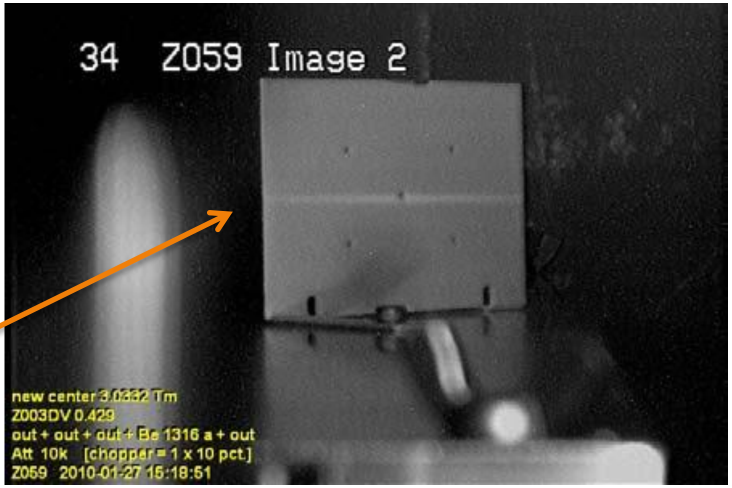
- 09030: Collectivity of Exotic Silicon Isotopes (A. Ratkiewicz, et al.)
- 09040: Study of Neutron Unbound States in ^{28}F (N. Frank, et al.)
- Primary beam: $^{48}Ca^{20+}$, 140 MeV/u
  - Beam intensity: 80 pnA (list), 120 pnA (maximum allowed)
  - Beam size: 1 mm^2
- Production targets:
  - 09030: Be 1269 mg/cm^2
  - 09040: Be 1316 mg/cm^2
    - » Targets used:
      - 1269a: 1274 mg/cm^2
      - 1269b: 1278 mg/cm^2
      - 1316a: 1341 mg/cm^2
      - 1316b: 1341 mg/cm^2
- Proposed beam-on-target time:
  - 09030: 129 h
  - 09040: 188 h

Evidence of Damage

- Evidence for radiation damage of targets
  - Increased energy loss in the target at the beam spot
    - » Surrounding areas are not affected
      - If beam is directed above or below original position, no effect
  - Increased energy straggling

At beginning of experiment, target thickness = 1340.587 mg/cm^2





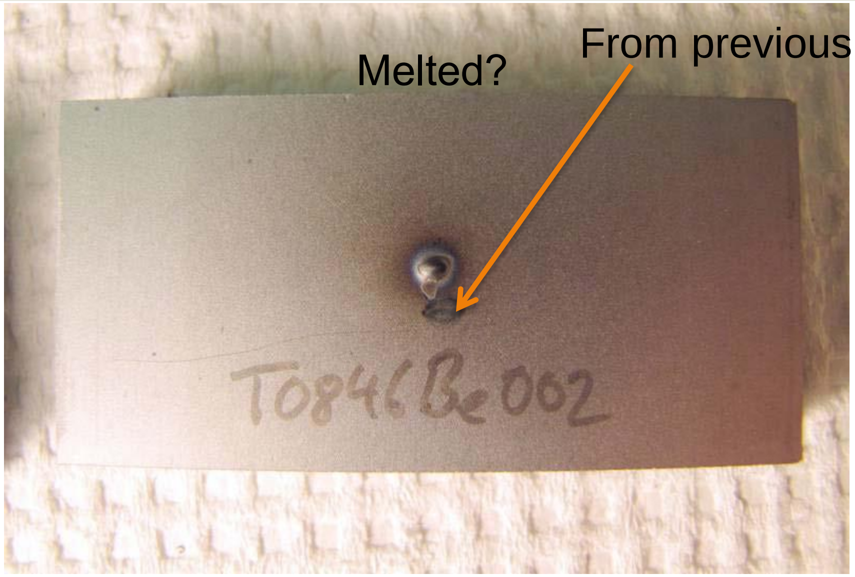
Separator Bρ adjusted to center beam

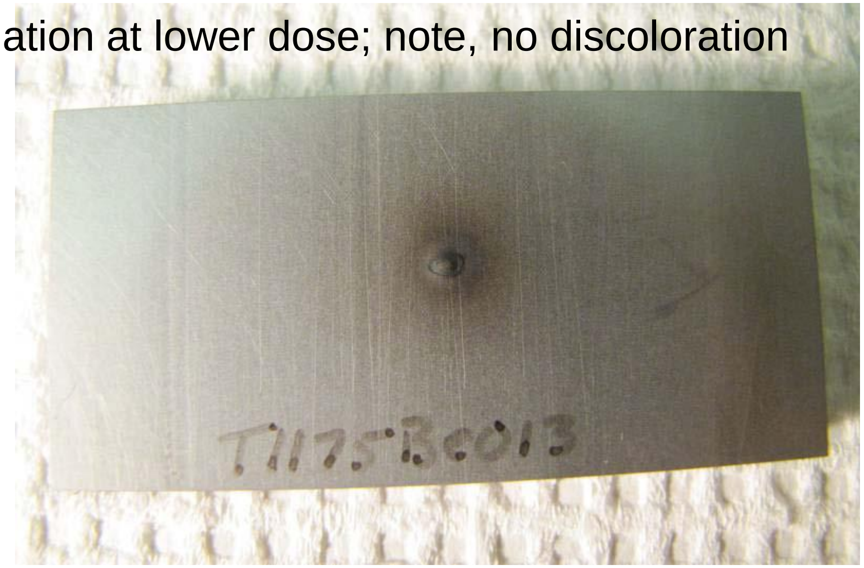
Measured thickness = 1393.355 mg/cm^2

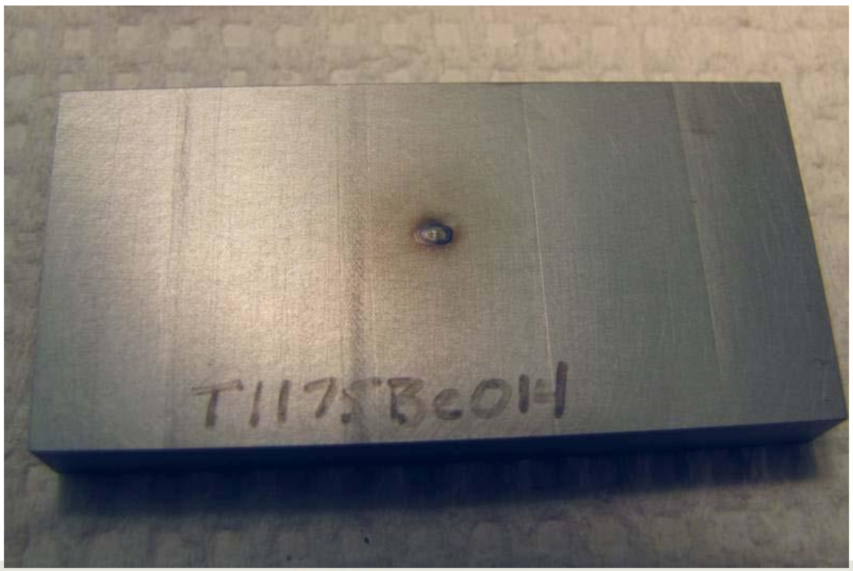
Visual Indications of Damage

Melted?

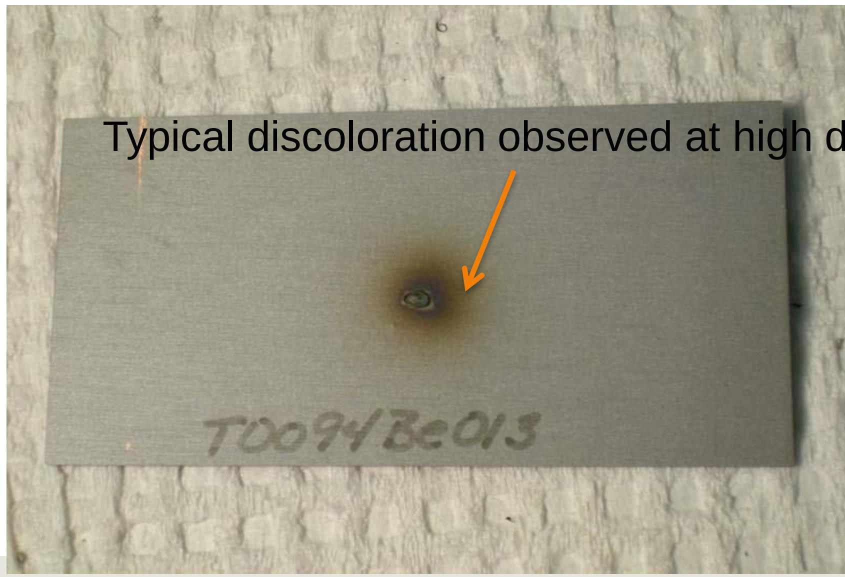
From previous irradiation at lower dose; note, no discoloration





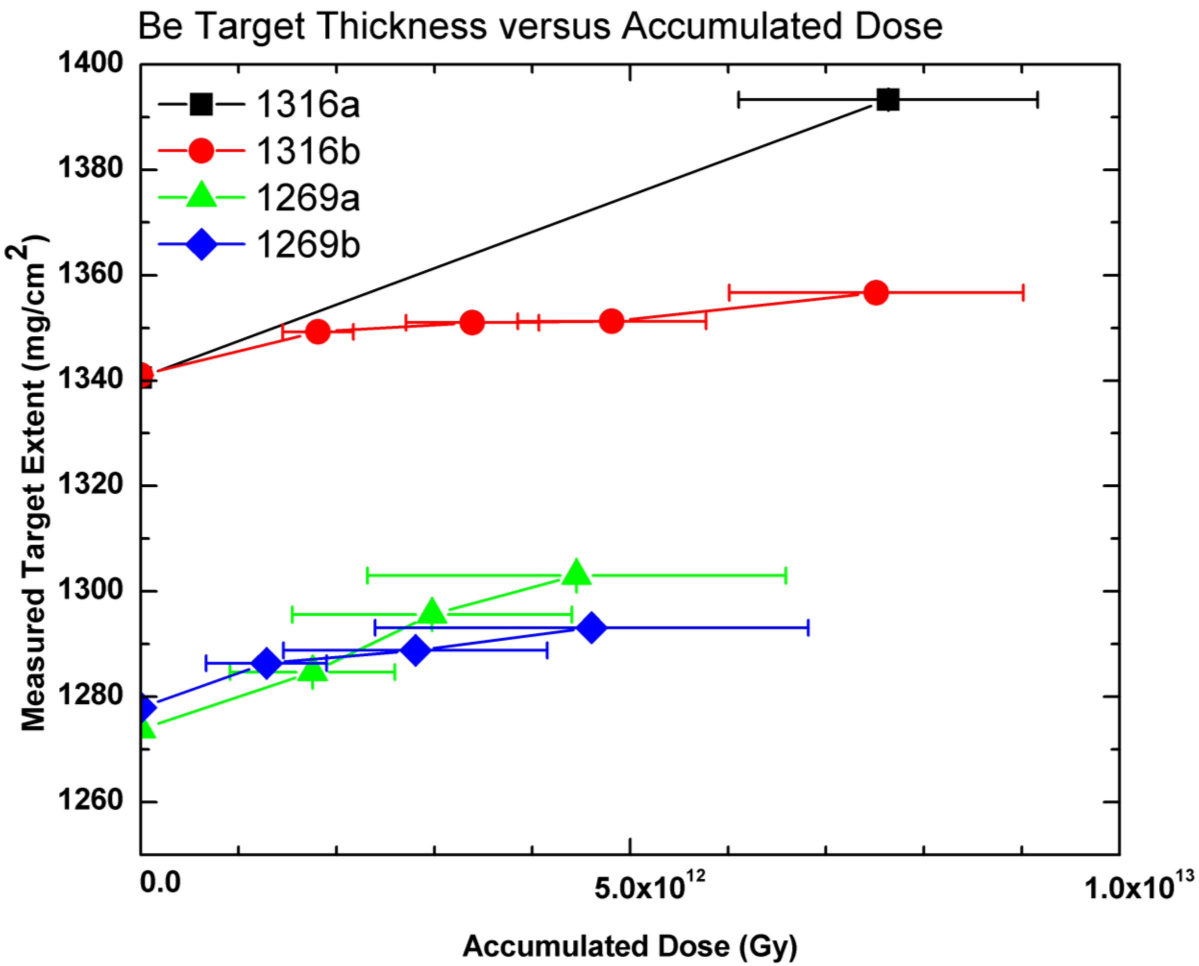


Typical discoloration observed at high dose



Heavy Ion Induced Radiation Damage Observed in Recent Experiments

- Damage anticipated
- Currently, target anticipated life is estimated by dose
- Two targets used in each experiment
- Thicknesses measured periodically during experiments
- Uncertainty in thickness measurement 0.02%
- Why do 1316 targets behave so different for the same dose?
  - Possible thermal damage, location in ladder

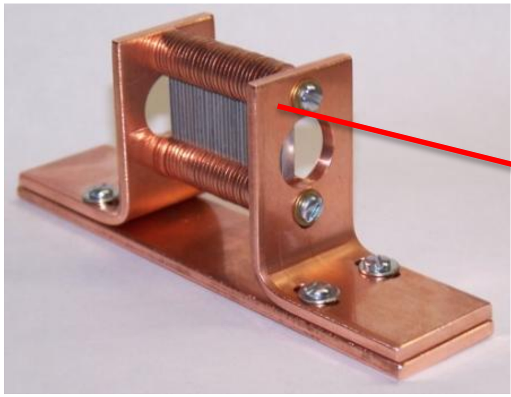


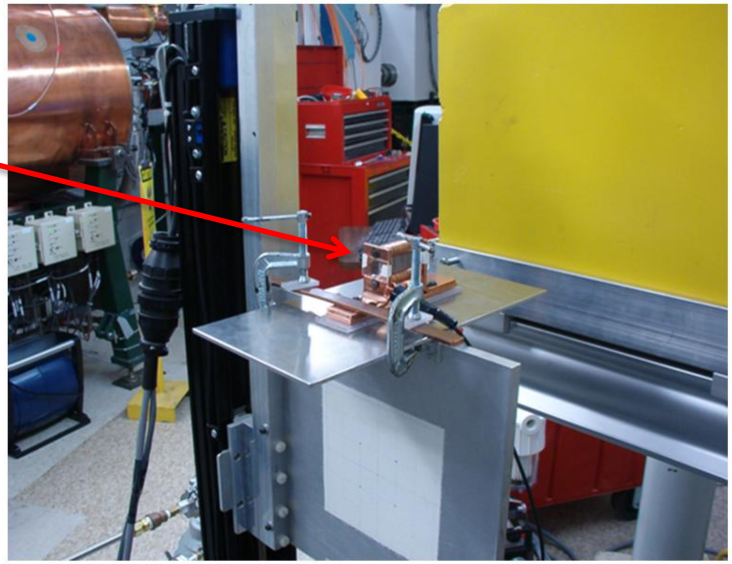
Heavy-ion Induced Radiation Damage – Past Effort

Funded by DOE under DE-FG02-07ER41472

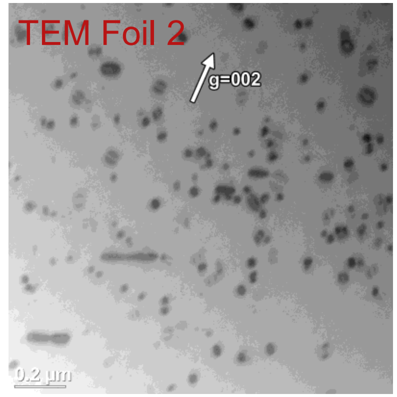
M. Kostin, R. Ronningen (MSU), L. Ahle (LLNL), T. Gabriel (SID),L. Mansur, K. Leonard (ORNL), N. Mokhov (FNAL), K. Niita (RIST, Japan)

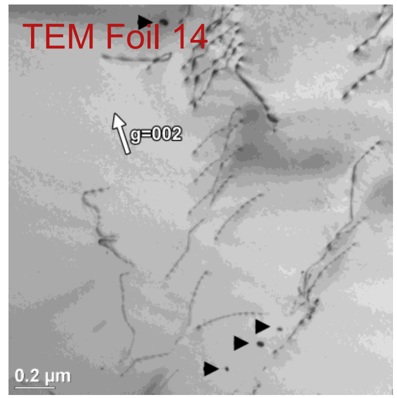
- Conducted radiation damage experiment with Aluminum at NSCL
  - ^{76}Ge beam at 130 MeV/u
  - Air-cooled stack of 30 Al foils, each 0.25 mm thick
  - Stopping range of beam 4.8 mm
  - Calculated with PHITS peak damage of 0.016 dpa at Bragg peak





TEM images





- Results
  - Electrical resistivity and micro-hardness measurements inconclusive (low dose, Al cold work)
  - TEM showed dislocation loop density falling sharply with depth – very different from *calculations*
    - » *Significant dislocation loop density at 0.5 mm (foil #2, most upstream foil analyzed)*
    - » Dislocations almost not visible in foil #4 (second most upstream foil analyzed)

Summary

- Energetic high intensity heavy ion beams interacting with materials can cause damage to materials
- Prediction of damage is necessary
  - As part of new facility design efforts, …
- Heavy ion transport codes recently have dramatically improved models that are used to calculate dpa
  - TRIM, MARS15, PHITS now agree well in general
- Guidance on relating predicted levels of dpa to material bulk property changes needed
- Experiments to measure heavy ion damage can be difficult
  - Temperature effects, gas production, material preparation etc. need careful attention
  - Nevertheless, these are sorely needed for benchmark, validation efforts
- Data on damage of materials, such as targets, at existing facilities could prove useful if irradiation parameters are documented