FRIB

Irradiated Material studies for NSCL and FRIB

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U.S. DEPARTMENT OF ENERGY | Office of Science

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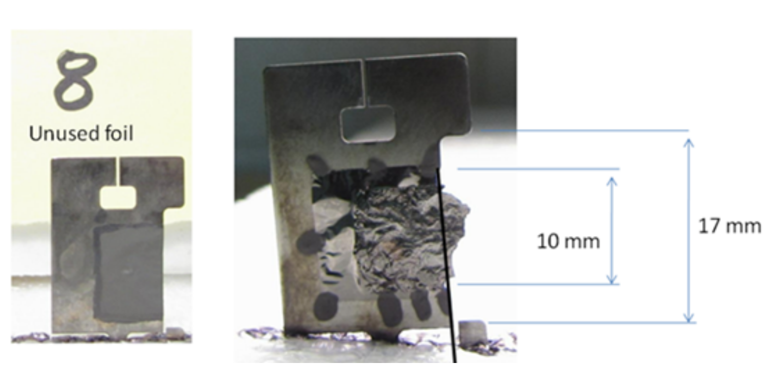
Outline

- Material study for NSCL charge stripper foil
  - Context
  - Radiation damage studies
- Material study for FRIB beam dump and wedge
  - context and challenges
  - Radiation damage studies
- Future material studies for beam dump and wedge
- Summary

Charge Stripper Studies Context at NSCL

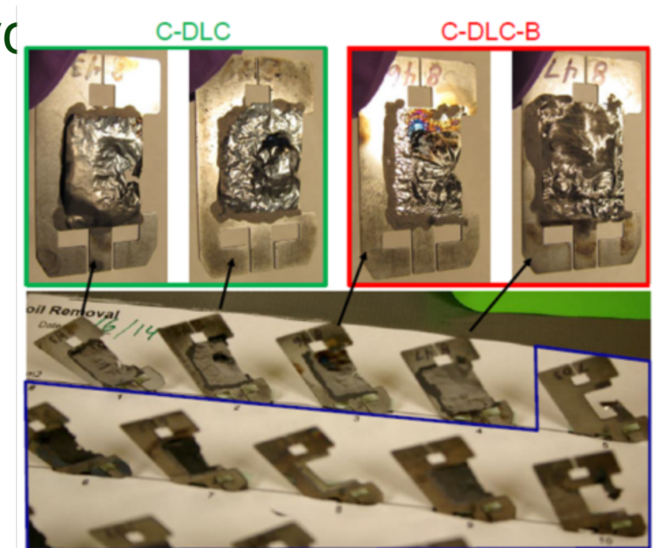
- Charge strippers play an important role in heavy ion beam production facilities
  - Need high charge state to accelerate heavy-ion beam at high energy using small accelerator
  - Carbon stripper foils are one of the dominant types of stripper foils and have been studied for decades
- It is known that thin foils (stripper) used in accelerator suffer a quick degradation due to radiation damage such as swelling and thermo-mechanical changes
  - Limits the lifetime of few hours
- How can we improve the lifetime?
  - Annealing at high temperature
  - Influence of nano-structure on annealing by using multi-layer foil



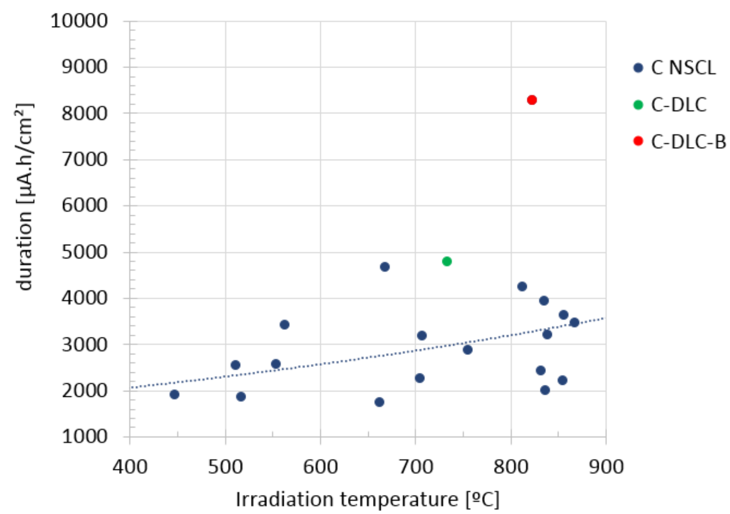
- SBIR (Small Business Innovation Research) project with NSCL- UHV Technologies, Inc. ,Fort Worth, TX, who developed multi-layers thin foils
  - Award Number: DE-SC0011287, "*Low Z Thin Films for Stripper Foils, Targets and X-Ray Windows*"

SBIR NSCL/UHV – Phase I
Temperature and nanostructure effect

- 10-multi-layer foils (C-DLC-B and C-DLC) irradiated at NSCL at MSU with $^{78}Kr^{14+}$ at 13 MeV/u at the stripping injection of the K1200 cyc



Current carbon strippers used at NSCL



Lifetime time (µA·h/cm²) as a function of the irradiation temperature and the microstructure of graphite stripper foils.

- Increased lifetime with irradiation temperature was observed.

- Increased lifetime of the 10 multilayer foils C-DLC-B and C-DLC compare to the standard C-NSCL foils.

SBIR NSCL/UHV – Phase II
Nano-structure effect [1]

- Ar^{4+} beam at 12MeV using 5U facility at Notre Dame University
- 8 foil types – thickness between 1.7 to 2.5 µm
  - DLC (Diamond Like Carbon): monolayer foil (type 1 and 3)
  - HBC (Hybrid Boron Carbon) : 7, 9, 17, 48, 100 layers
  - BC Monolayer: 10% B + 90% C

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HBC 9 layers

DLC Type 1

HBC 7 layers

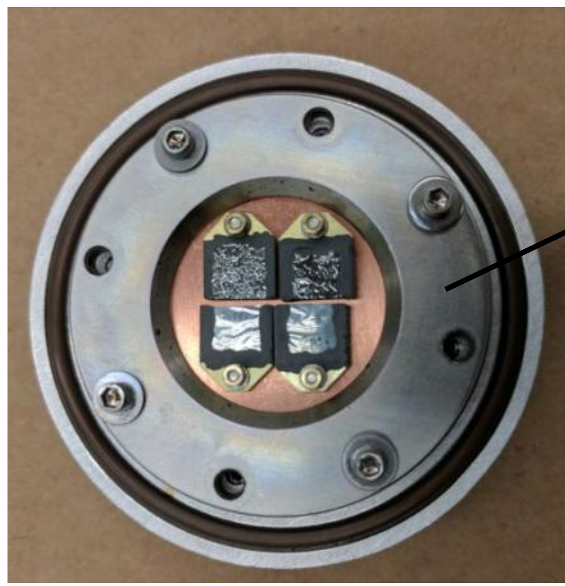
DLC Type 3

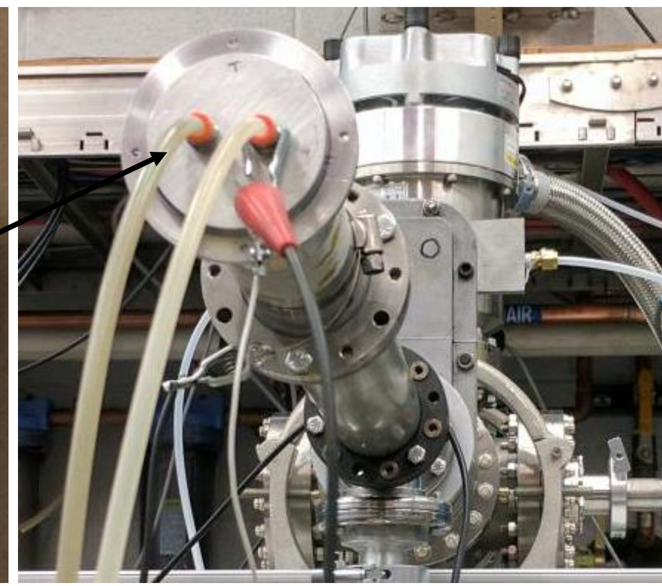
HBC 17 layers

HBC 100 layers

HBC 48 layers

BC mono





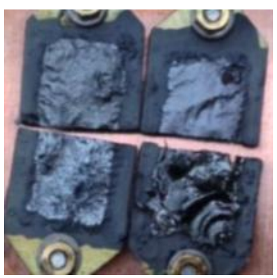
SBIR NSCL/UHV – Phase II
Nano-structure effect [2]

- Increased lifetime of the HBC multilayer foils compared to DLC or BC monolayer

1.4 µAe

HBC 9 layers	HBC 7 layers
DLC Type 1	DLC Type 3

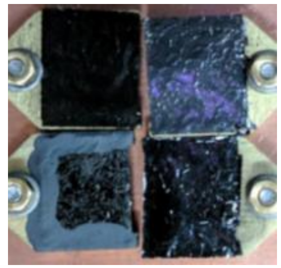
HBC 17 layers	HBC 48 layers
HBC 100 layers	BC mono

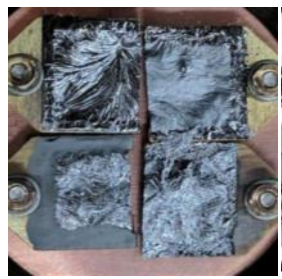


1.37E+15 ion/cm²

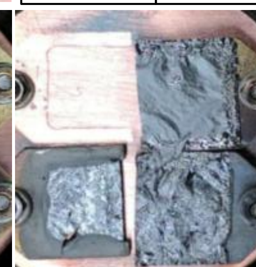
1.4µAe

DLC Type 1	HBC 17 layers
HBC 48 layers	HBC 100 layers



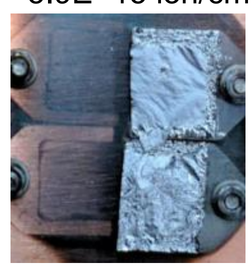


2.92E+15 ion/cm²



5.9E+15 ion/cm²

8.91E+15 ion/cm²



1.4E+16 ion/cm²

1.4µAe

HBC 9 layers	HBC 7 layers
DLC Type 1	DLC Type 3

5.02E+15 ion/cm²

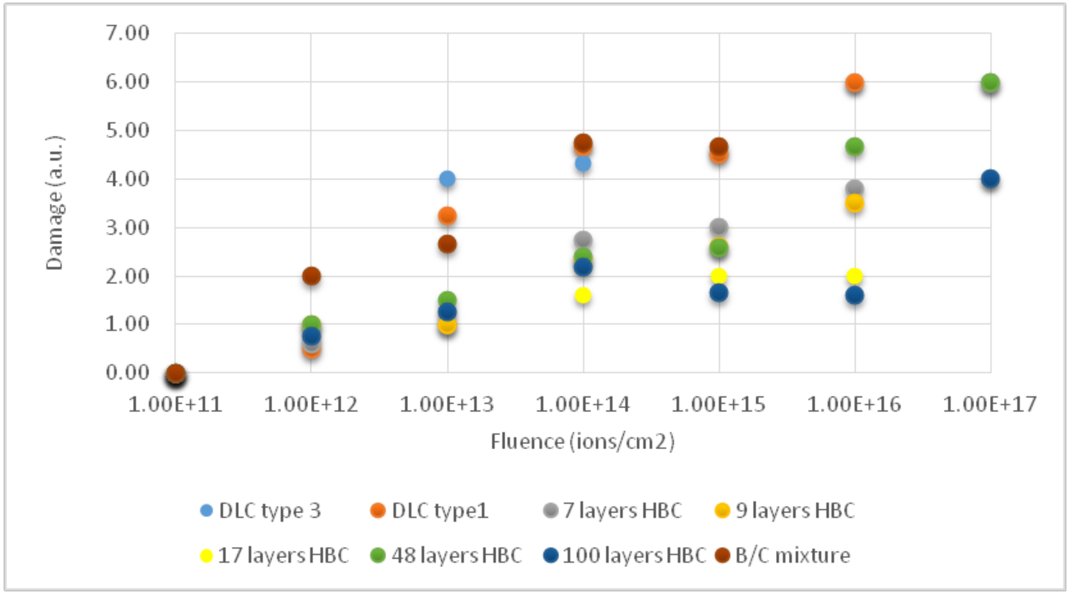
7.50E+15 ion/cm²

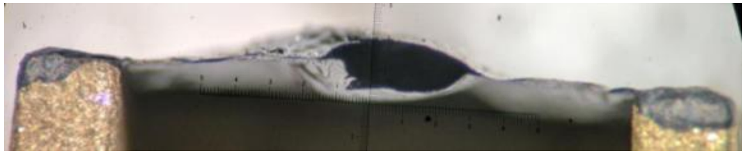
1.01E+16 ion/cm²

1.4E+16 ion/cm²

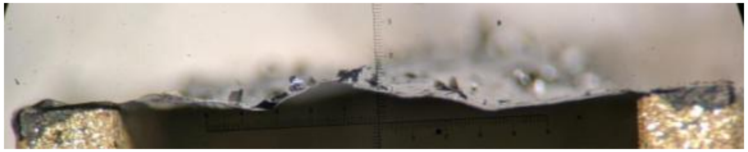
SBIR NSCL/UHV – Phase II
Analyses ongoing

- Better structural stability of 100 layers-HBC foils
  - Nanostructure effect

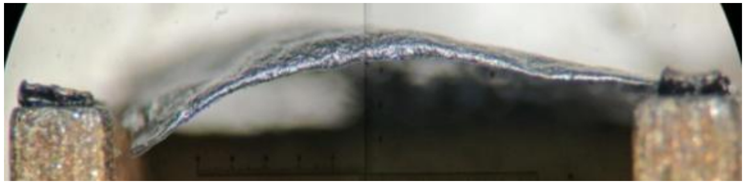




HBC – 7 layers – 1.4 μAe – 7e14 ions/cm²



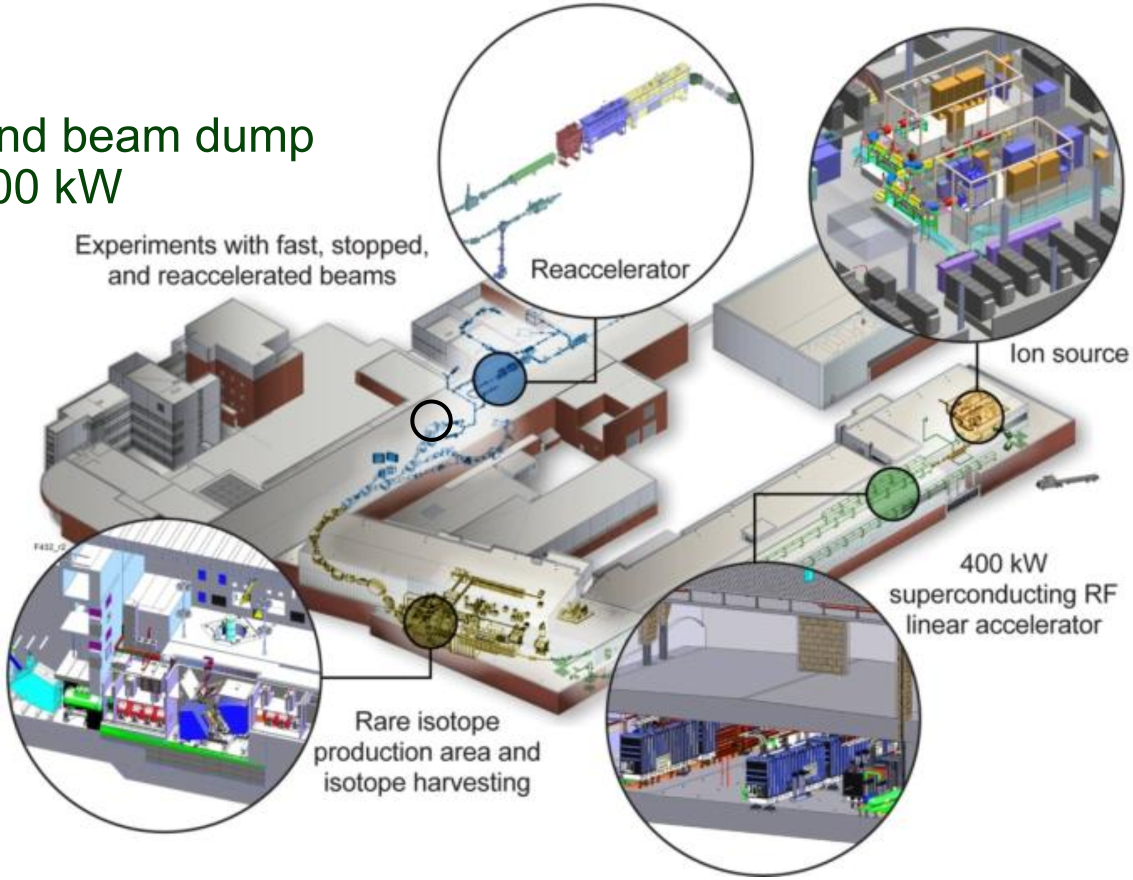
HBC – 100 layers – 1.4 μAe – 7e14 ions/cm²



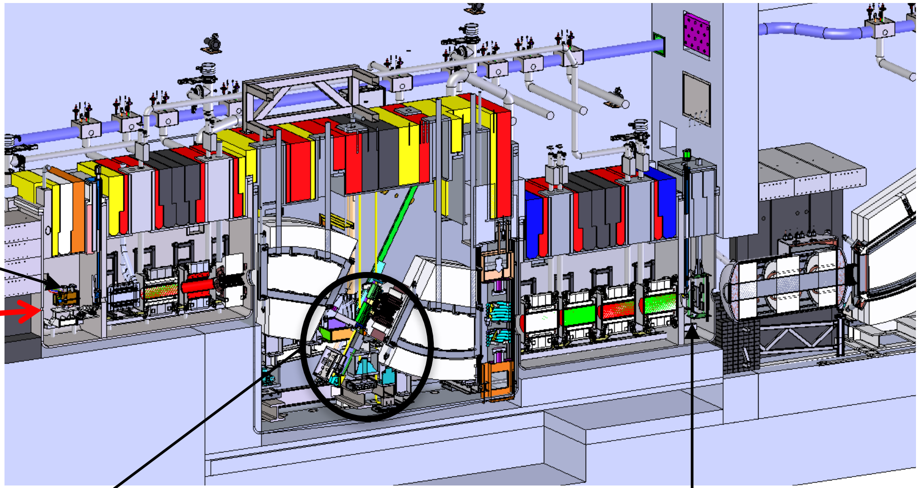
HBC – 100 layers – 4 μAe – 5e16 ions/cm²

Facility for Rare Isotope Beams

- World-leading heavy ion accelerator facility for rare isotope science
  - Nuclear Structure
  - Nuclear Astrophysics
  - Fundamental Interactions
  - Isotopes for Societal Needs
- Rare isotope production targets and beam dump compatible with beam power of 400 kW at 200 MeV/u for ^{238}U (>200 MeV/u for lighter ions)



Materiel Challenge in Experimental System Area



Production target (graphite)

$E = 202 – 260$ MeV/u

$P_{beam} = 400$ kW

$P_{deposited} \sim 100$ kW

$\sigma_{x\,beam} = 0.24$ mm

$\sigma_{y\,beam} = 0.29$ mm

$P = 60$ MW/cm³

Dose ~ 8 dpa

Beam dump drum (Ti-alloy)

$E = 156 – 260$ MeV/u

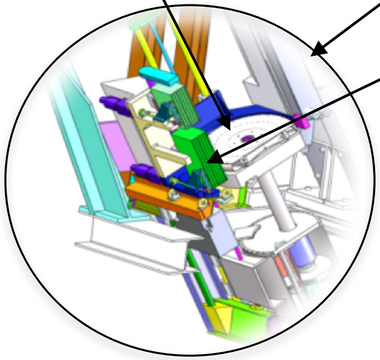
$P_{deposited} \sim 325$ kW

$\sigma_{x\,beam} = 1$-10 mm

$\sigma_{y\,beam} = 2$-50 mm

$P = 30$ MW/cm³

Dose ~ 7 dpa



Wedge (Al-alloy)

$E = 156 – 260$ MeV/u

$P_{deposited} < 2$ kW

σ_{beam} = mm-cm

$P = 13$ kW/cm³

Dose ~ 1 dpa

Fragment catcher (Al-alloy)

$E = 156 – 260$ MeV/u

$P_{deposited} < 10$ kW

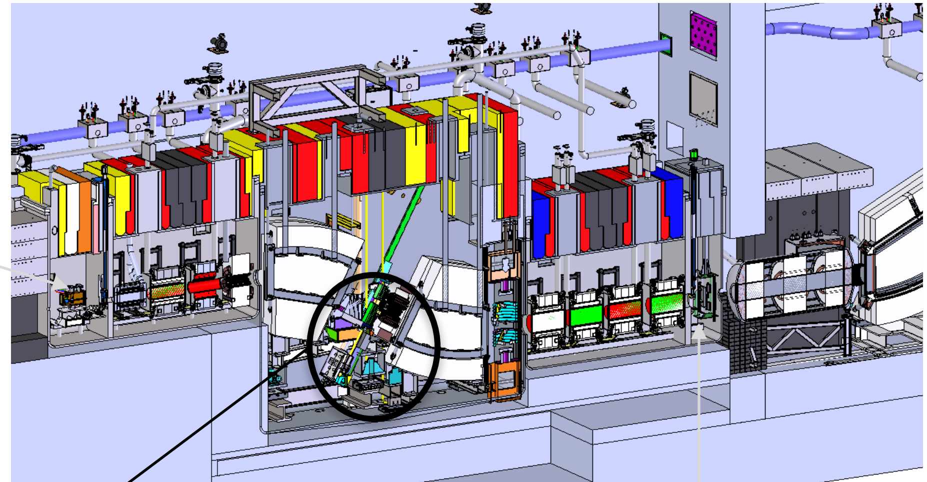
$\sigma_{x\,beam}$ = up to 15 cm

$\sigma_{y\,beam}$ = up to 5 cm

$P = 1.2$ kW/cm³

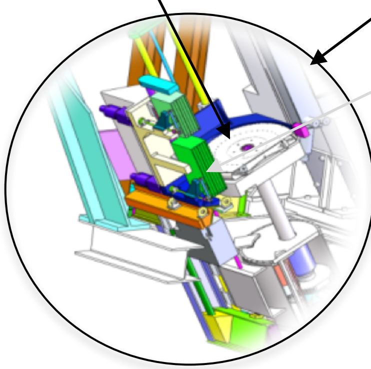
Dose ~ 2.5 dpa

Materiel Challenge in Experimental System Area



Production target (graphite)
- E = 202 – 260 MeV/u
- P_{beam} = 400 kW
- $P_{deposited}$ ~ 100 kW
- $\sigma_{x\ beam}$ = 0.24 mm
- $\sigma_{y\ beam}$ = 0.29 mm
- P = 60 MW/cm³
- Dose ~ 8 dpa

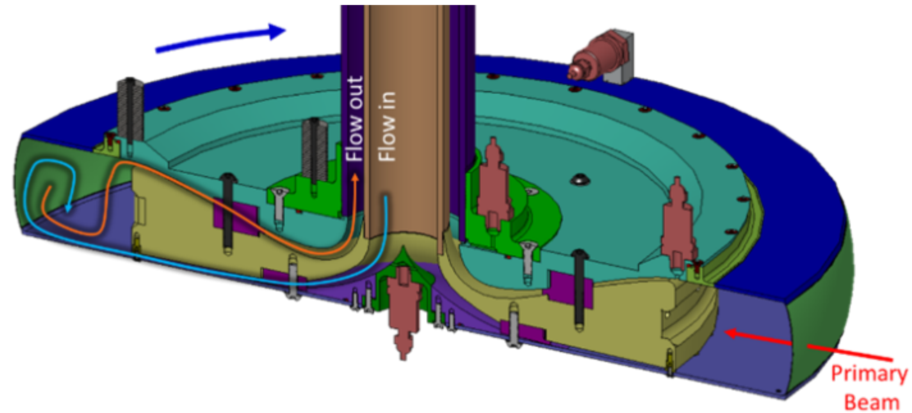
Beam dump drum (Ti-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ ~ 300 kW
- $\sigma_{x\ beam}$ = 1-10 mm
- $\sigma_{y\ beam}$ = 2-50 mm
- P = 30 MW/cm³
- Dose ~ 7 dpa



Wedge (Al-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ < 2 kW
- σ_{beam} = mm-cm
- P = 13 kW/cm³
- Dose ~ 1 dpa

Fragment catcher (Al-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ < 10 kW
- $\sigma_{x\ beam}$ = up to 15 cm
- $\sigma_{y\ beam}$ = up to 5 cm
- P = W/cm³
- Dose ~ 2.5 dpa

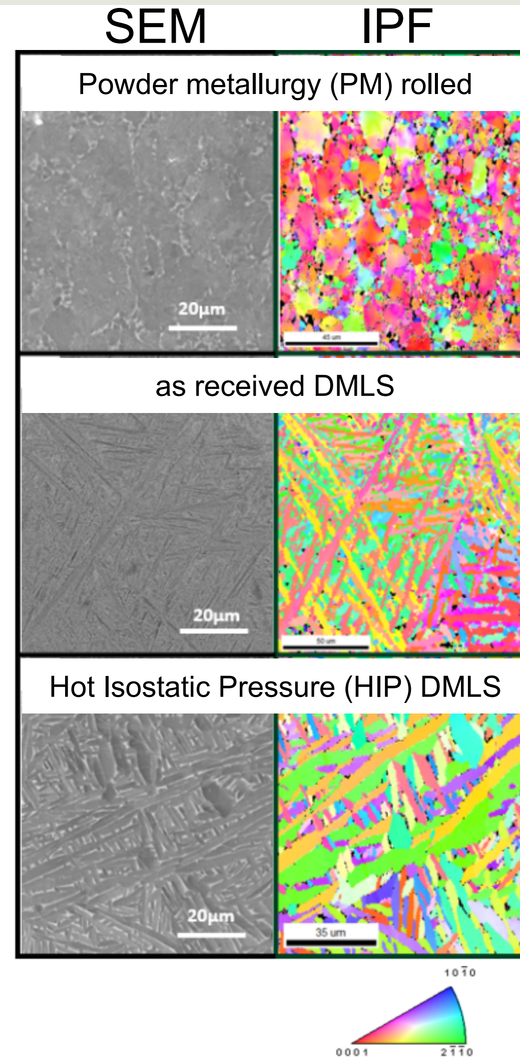
Primary Beam Dump
Water-filled Rotating Drum Concept



- Beam Dump requirements
  - High power capability up to 325 kW
  - 1 year (5500 h) lifetime desirable
    - » dpa (U beam) ~ 7 (~ $4 \cdot 10^{-7}$ dpa/s)
  - Remote replacement and maintenance
- Water-filled rotating drum concept chosen for FRIB baseline
  - Using water to stop the primary beam and absorb beam power
  - Shell temperature limited to 150ºC to avoid nucleate boiling of cooling water
- Design parameters
  - Ti-alloy shell thickness 0.5 mm to minimize power deposition in shell
  - 600 rpm and 70 cm diameter to limit maximum temperature and amplitude of temperature changes
  - 60 gpm water flow to provide cooling and gas bubble removal
  - 8 bar pressure inside the drum increases water boiling point to 150ºC
- Ti-6Al-4V was chosen as candidate material for the beam dump shell

3D Printed Material for Beam Dump Drum
Which impact on material properties/behavior?

- 3D printing (with Direct Metal Laser Sintered DMLS process) likely fabrication process for FRIB beam dump shell
  - Microstructure of Ti-6Al-4V alloys may change due to fabrication process
    - » Characterization of different microstructures (Powder Metallurgy (PM) rolled, 3D printed (As received DMLS), 3D printed Hot Isostatic Pressure (HIP) (HIP-ed DMLS) ongoing
    - » 3D printed sample analysis shows lamellar microstructure
- The HIP (Hot Isostatic Pressure) was performed at a temperature of 900ºC at 102 MPa for 2 hours
- The powder used for DMLS samples is Grade 23 Ti-6Al-4V

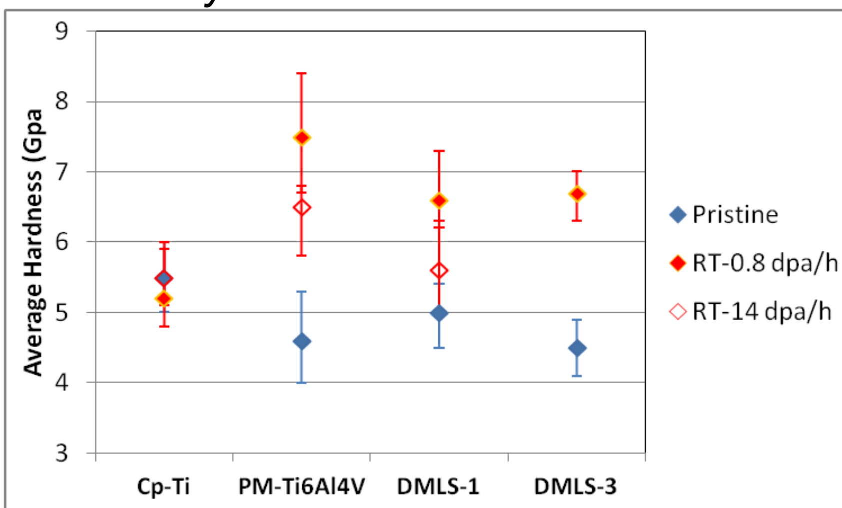


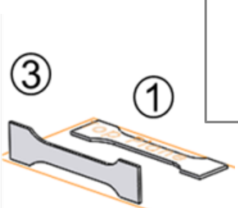
3D Printed Material for Beam Dump Drum

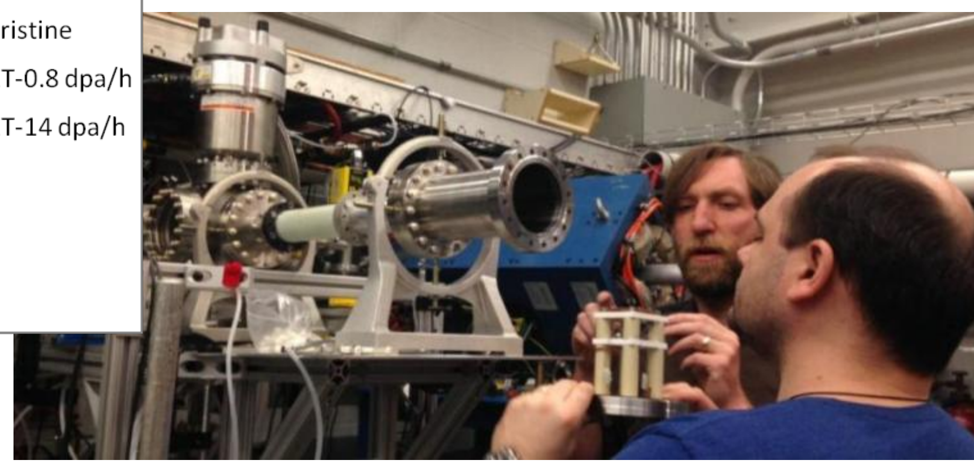
Build Orientation and Radiation Damage Effect [1]

- Irradiation at University Notre Dame with $^{40}Ar^{2+}$ at 4 MeV up to a fluence of $5 \cdot 10^{16}$ ions/cm² (14 dpa)
  - 4 different microstructures of Ti-alloy: Cp-Ti, PM-Ti6Al4V, DMLS-1, DMLS-3
  - at room temperature and at 350ºC
  - Two different dose rates (~14 dpa/h and 0.8 dpa/h)

Preliminary results





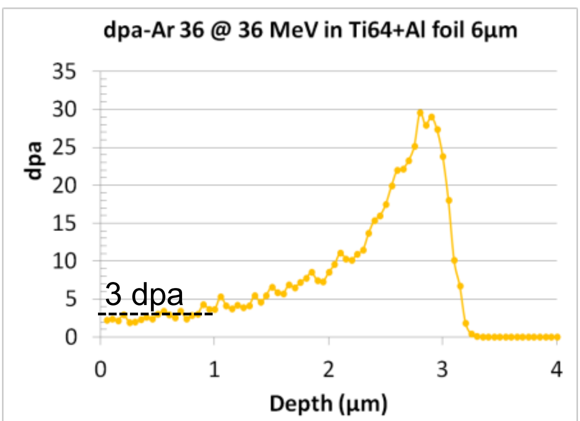


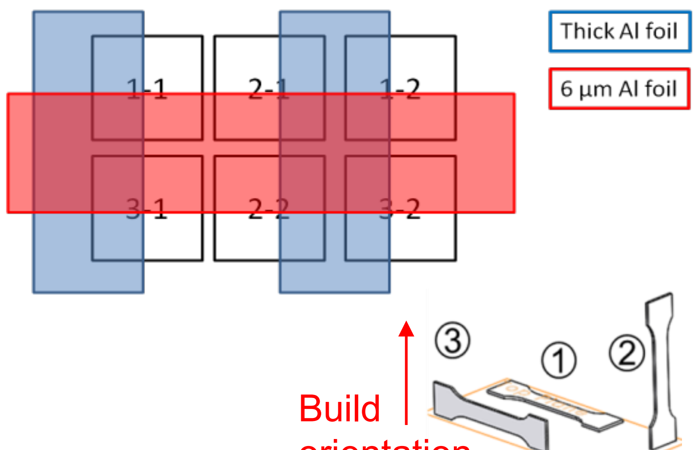
3D Printed Material for Beam Dump Drum

Build Orientation and Radiation Damage Effect [2]

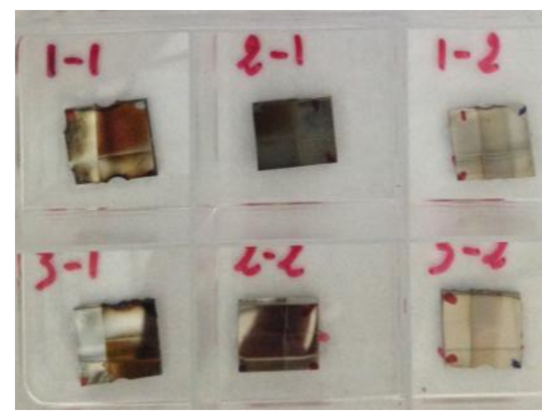
- Low energy $^{36}Ar^{10+}$ beam irradiation performed in July (18-24)
  - 3 different doses / sample by using a 6 µm and thick Al foil

Ref	Temp	Surface [cm2]	Fluence [ions/cm2]	time	dpa average in 1 microns	dpa average in 2 microns	dpa average in 1 microns after Al foil	dpa average in 2 microns after Al foil	dpa Bragg Peak
Ti64-1-1	150	7.5	2.38E+16	16h+26h	0.644	0.773	2.818	4.392	29
Ti64-1-2	150	12	6.00E+15	16h	0.163	0.195	0.712	1.11	7.1
Ti64-2-1	150	7.5	2.38E+16	16h+26h	0.644	0.773	2.818	4.392	29
Ti64-2-2	150	12	6.00E+15	16h	0.163	0.195	0.712	1.11	7.1
Ti64-2-3	RT	9	3.74E+15	21h	0.101	0.122	0.443	0.691	4.5
Ti64-3-1	150	7.5	2.38E+16	16h+26h	0.644	0.773	2.818	4.392	29
Ti64-3-2	150	12	6.00E+15	16h	0.163	0.195	0.712	1.11	7.1



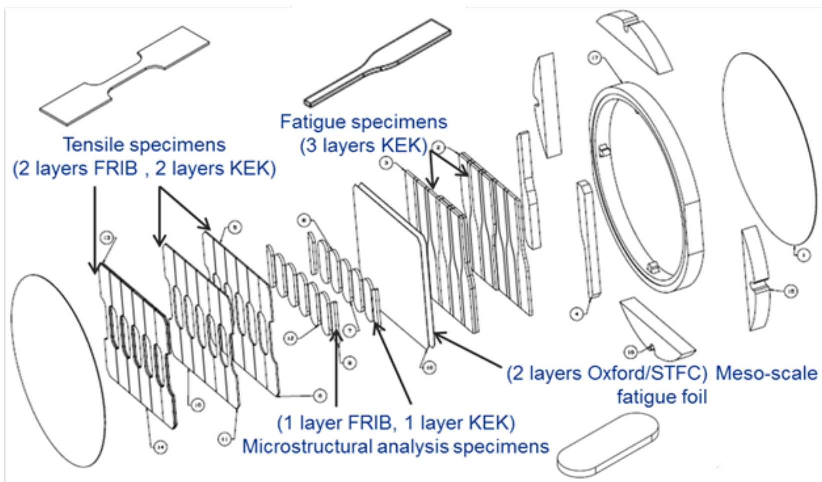


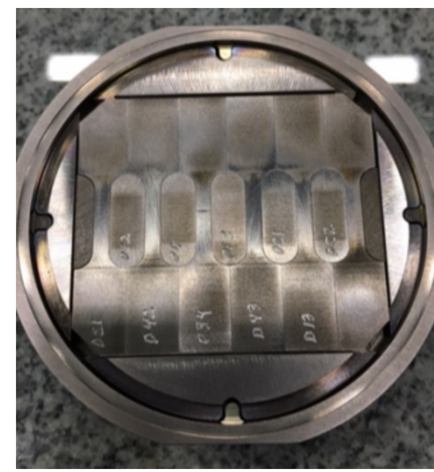
T_{irr} = 150˚C



3D Printed Material for Beam Dump Drum
Build Orientation and Radiation Damage Effect [3]

- Test at BNL-BLIP facility started in April 2017 with RaDIATE collaborators
  - Irradiate several Ti-alloys with high energy protons for an extended period of time (8 weeks, up to 1 dpa in Ti samples) and characterize property changes due to proton induced damage
  - FRIB and KEK will irradiate DMLS and conventional Ti-alloy (Grade 5 and 23), compare and share results



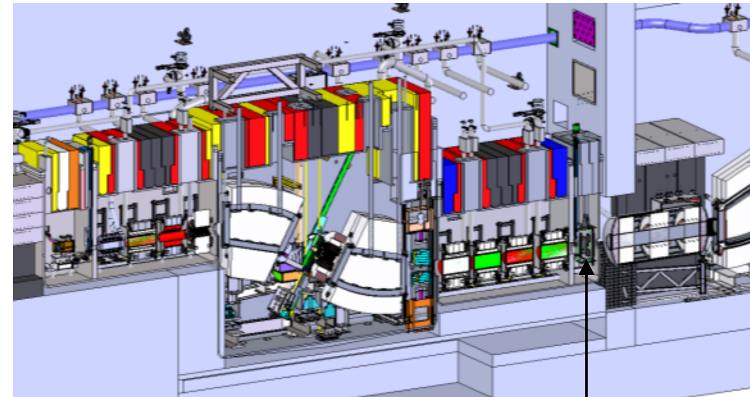


RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

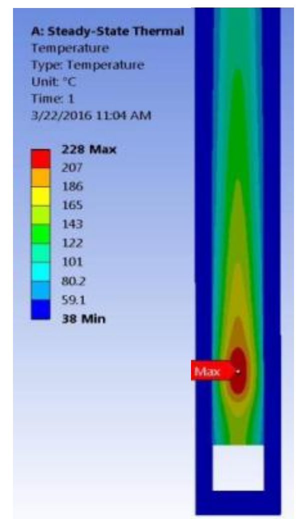
BROOKHAVEN NATIONAL LABORATORY · Fermilab · FRIB · CERN · Pacific Northwest NATIONAL LABORATORY · UNIVERSITY OF OXFORD · ess EUROPEAN SPALLATION SOURCE · Science & Technology Facilities Council

Wedge context [1]

- Wedge needed to compress momentum spread of isotope beams in high resolution Fragment Separator
  - Each fragment beam likely requires a unique wedge (slope, thickness)
  - High power density needs to be dissipated
- Material studies to assess lifetimes
  - High temperature Aluminum alloy is necessary to support high temperature and high stress due to thermo-mechanical constraint



Wedge (Al-alloy)
E = 156 – 260 MeV/u
$P_{deposited}$ < 2 kW
σ_{beam} = mm-cm
P = 13 kW/cm³
Dose ~ 1 dpa

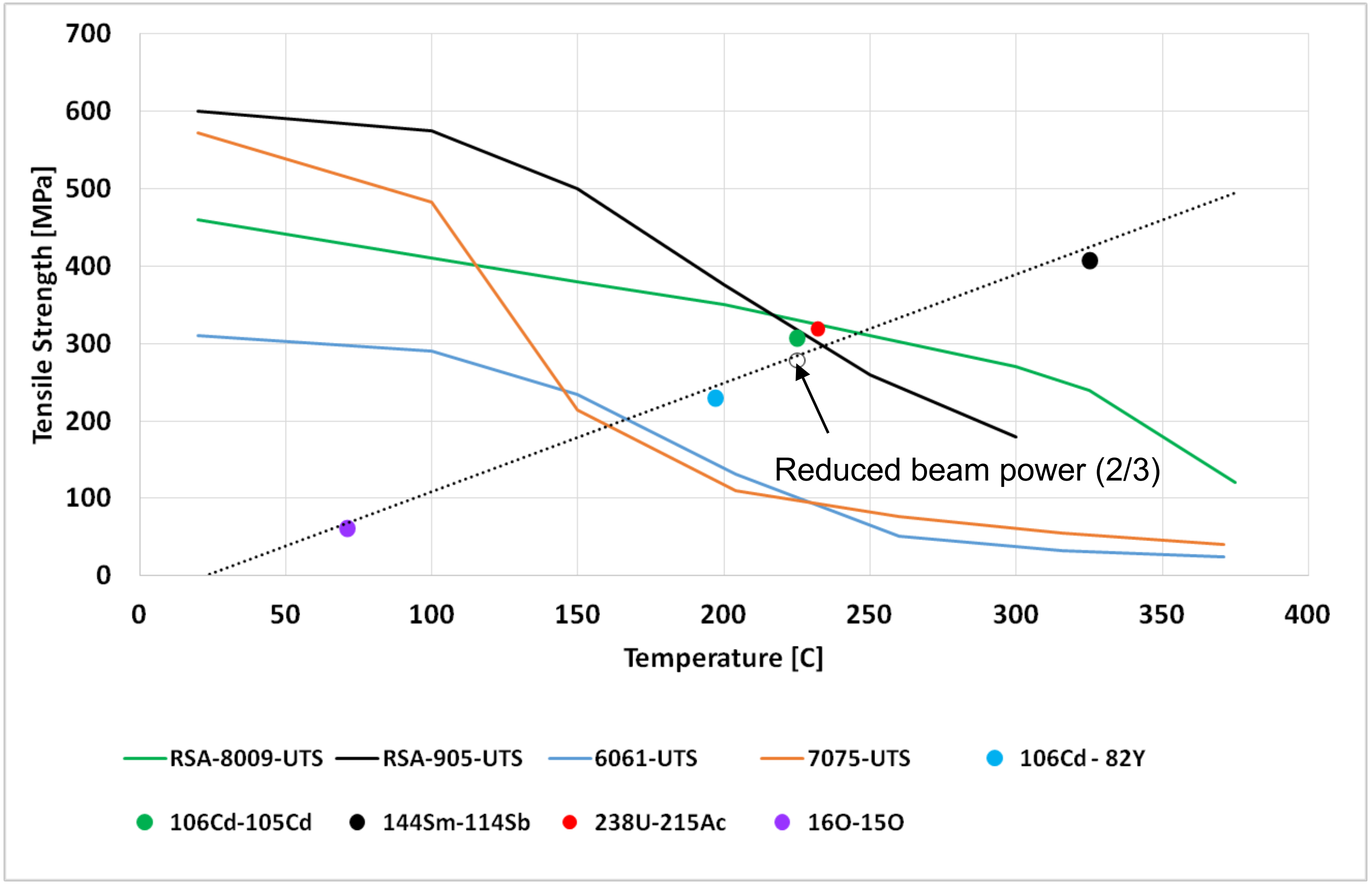


Wedge width = 10mm
L = 25 cm
t = 0.9 – 1.9 mm

Wedge ^{144}Sm – ^{114}Sb settings 10 mm

Wedge context [2]

- 3 alloys are under consideration
  - 6061, 7075 and RSA 905

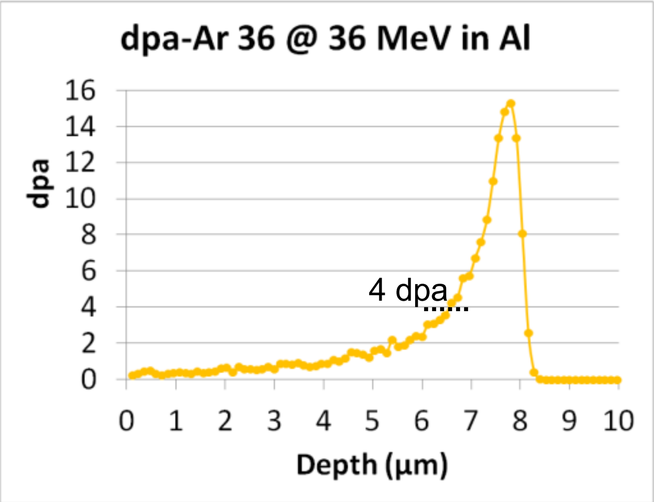


Al-alloy study for Wedge
Radiation Damage Effect

- Low energy $^{36}Ar^{10+}$ beam irradiation performed in July (18-24)
  - 3 different doses / sample by using a 6 µm and thick Al foil

CiMap

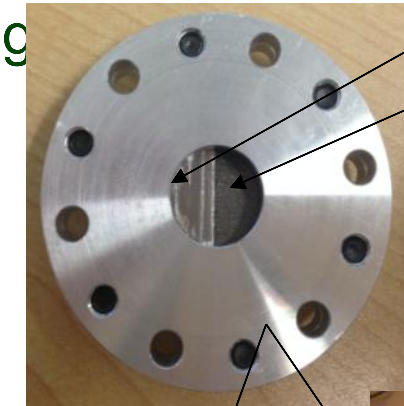
Ref	Temp	Surface [cm2]	Fluence [ions/cm2]	time	dpa average in 1 microns	dpa average in 2 microns	dpa average in 1 microns after Al foil	dpa average in 2 microns after Al foil	dpa Bragg Peak
Al-6061-1	RT	9	3.74E+15	21h	0.083	0.095	1.007	1.784	3.6
Al-6061-2	180-200	6.6	1.56E+16	18h	0.347	0.397	4.216	7.471	15
Al-6061-3	180-200	6.6	1.56E+16	18h	0.347	0.397	4.216	7.471	15
Al-7075-1	RT	9	3.74E+15	21h	0.083	0.095	1.007	1.784	3.6
Al-7075-2	180-200	6.6	1.56E+16	18h	0.347	0.397	4.216	7.471	15
RSA905-1	RT	9	3.74E+15	21h	0.083	0.095	1.007	1.784	3.6
RSA905-2	180-200	6.6	1.56E+16	18h	0.347	0.397	4.216	7.471	15

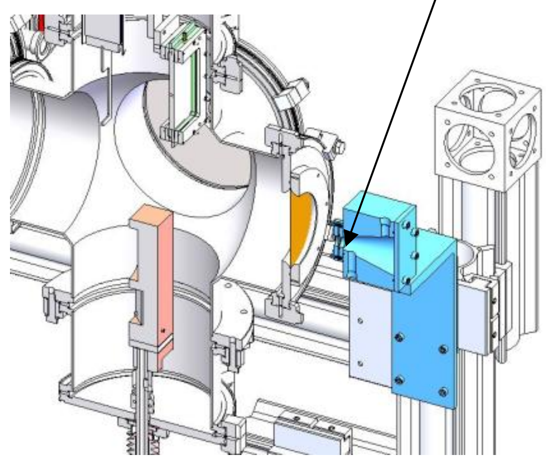


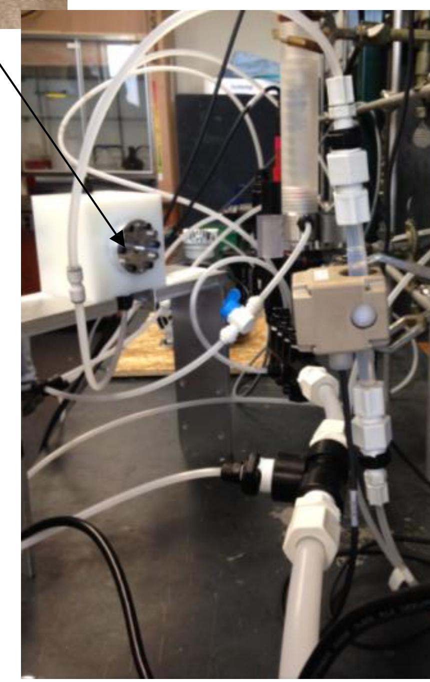
T_{irr} = 180-200˚C

Material studies Path Forward

- Corrosion Test for a Better Understanding of Lifetime of Beam dump shell
  - Short irradiation at NSCL with high energy heavy ion beam
    - » Windows made of 3D printed Ti-6Al-4V
    - » Water cell fabricated
    - » Benchmark gas production in water
    - » Study first stage of corrosion on Ti-6Al-4V
- Analyses of low energy irradiation samples to investigate mechanical property changes







Conclusion

- Graphite stripper gain in lifetime when using nanostructure with multi-layer foils
- Beam Dump and wedge face various thermo-mechanical and chemical challenges
  - Some effects may be enhanced by the presence of the other
    - corrosion in presence of radiation, stress limit change in the presence of radiation
- Up to now no facility exists to study the impact from all effects combined together
  - The changes of materiel have to be studied case-by-case experimentally
- 3D printed Ti-6Al-4V seems to be better radiation resistance than standard Ti-6Al-4V
  - Less mechanical property change observed from several studies promises good radiation resistance of this alloy and gives confidence in lifetime
- Investigation on Al-alloys started to support FRIB wedge design

Acknowledgements

- GANIL-CIMAP
  - F. Durantel, C. Grygiel, I. Monnet, M. Toulemonde
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- RaDIATE Collaboration
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  - N. Kumar
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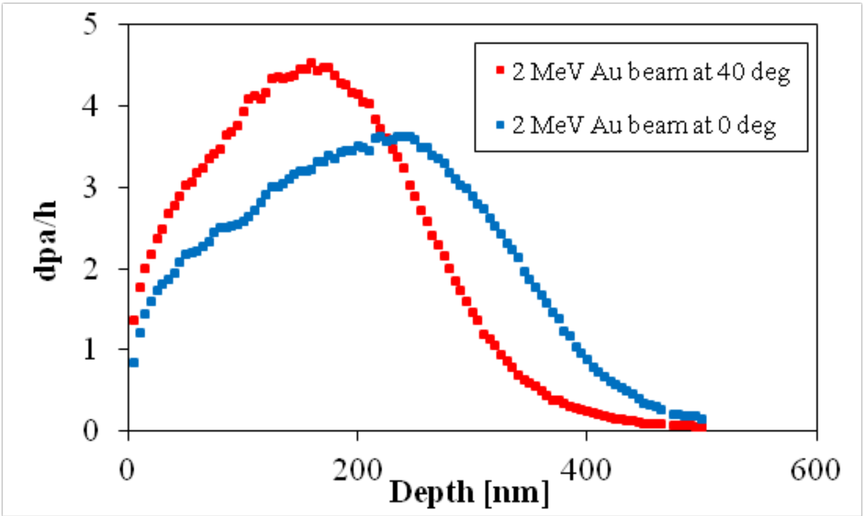
Need expert on TEM for Ti-6Al-4V

- In-situ TEM on Ti-alloy at JaNNUS-Orsay (France) accepted next year between February and Spring 2018 (to be defined)
- Our TEM expert left
- Instead of canceling the experiment we would like to share it if somebody is interested in TEM study focussed on Ti-alloy
  - Possibility to add one or 2 samples of other material
- JaNNUS : ARAMIS + TEM
  - 5 days
  - Au beam at 2 MeV
  - Minimum flux = 1e11 ions/cm².s

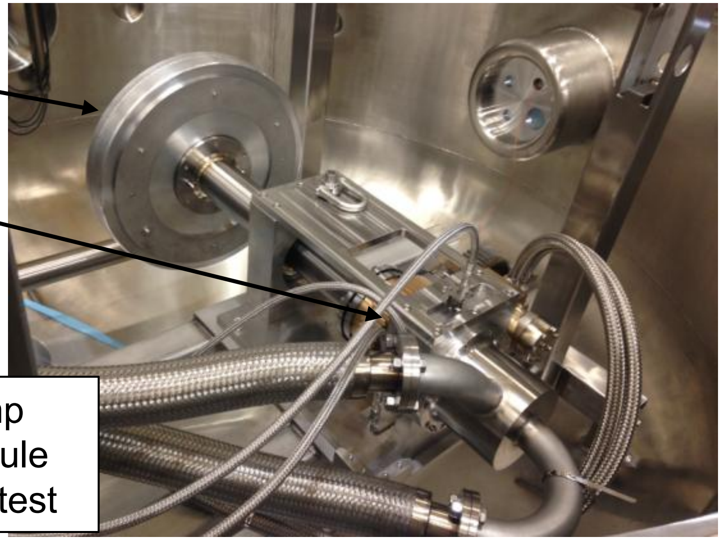


Flux = 10^{11} ions.cm^{-2}.s^{-1}

Thank you for your attention

Rotating Drum

Rotating water seal

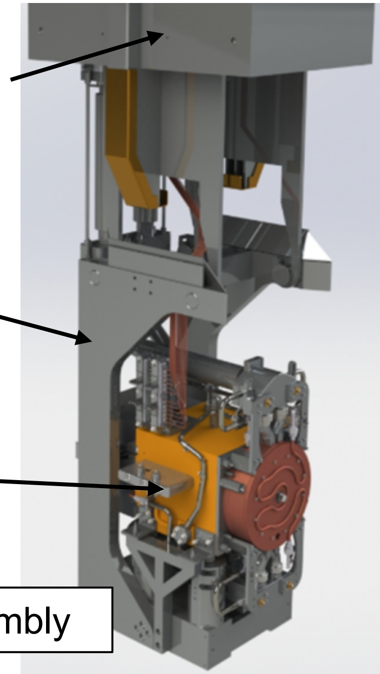


Beam Dump rotation module with Al drum test

In-vacuum shielding

Target Cradle

Target module



Target Assembly