Radiation damage of materials relevant for FRIB production target and beam dump

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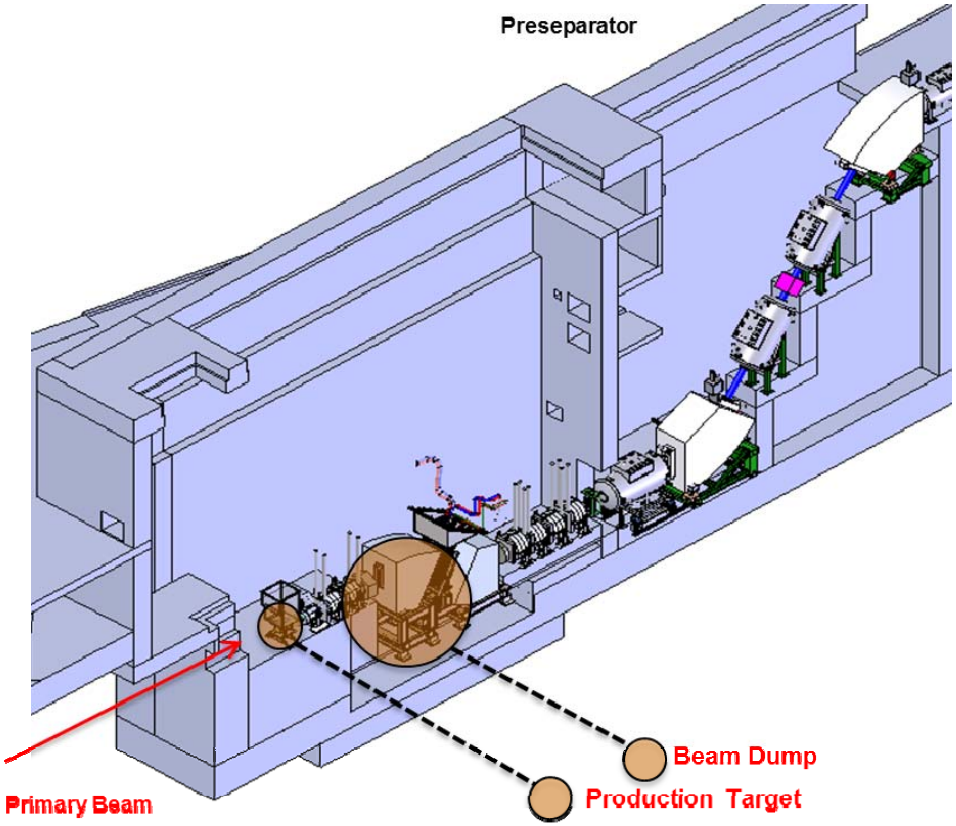
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- FRIB context
- FRIB production target
  - Radiation damage studies in graphite
  - Annealing of radiation damage at high temperature
- FRIB beam dump
  - Radiation damage studies in Titanium alloys
  - Low energy swift heavy ion irradiation
- FRIB production target and beam dump
  - Irradiation studies of ferrofluidic feedthrough
- Summary

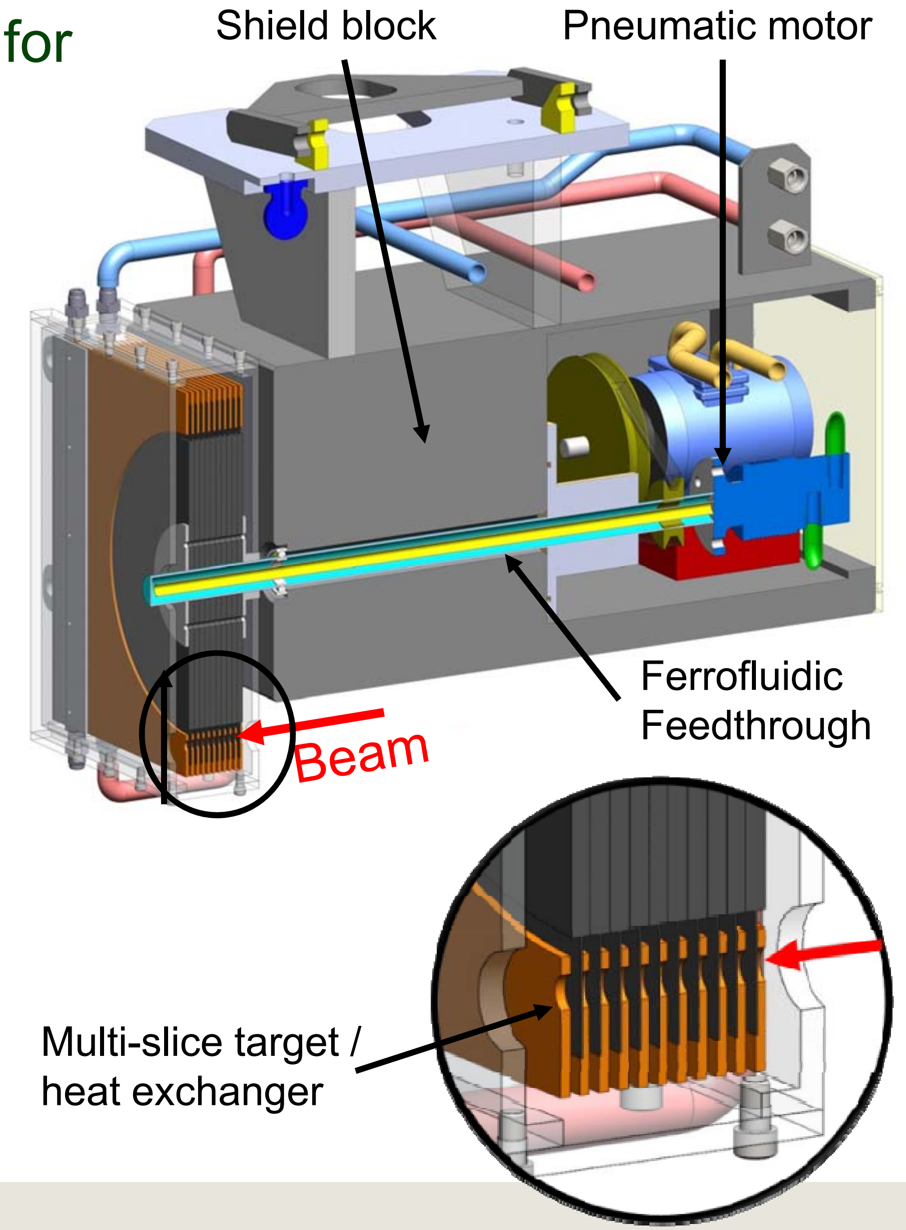
In-flight Rare Isotope Beam Production Facility



- Swift Heavy-ion induced radiation damage
  - $5 \cdot 10^{13}$ U ions/s
  - Understanding Swift Heavy Ion (SHI) effects on material that can limit target and beam dump lifetime
  - Different than neutron or proton irradiation
    - » Low gas production
    - » High dpa rate
    - » Electronic excitation ⇨ track formation along the ion path in material
      - Electronic stopping power ~ 1-20 keV/nm for heavy ion beam
        - » Only 10^{-6} keV/nm for proton @ 120 GeV in graphite

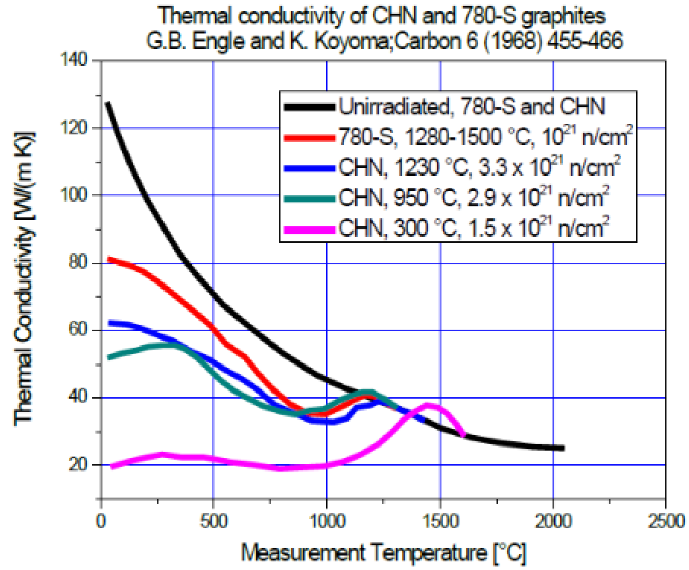
FRIB Production Target Design

- Rotating multi-slice graphite target chosen for FRIB baseline cooled by thermal radiation
- Target parameters defined by thermo-mechanical simulations
  - 5000 RPM and 30 cm diameter to limit maximum temperature and amplitude of temperature changes
  - High temperature: ~ 1900ºC
    - » Evaporation of graphite mitigated
- Target requirements
  - Up to 100 kW power deposition in 1 mm diameter beam spot
  - Target lifetime of 2 weeks desired to meet experimental program requirements
    - » fluence ~$7 \cdot 10^{18}$ ion/cm²
    - » dpa (U beam) ~ 7 (dpa/rate ~ $6 \cdot 10^{-6}$ dpa/s)

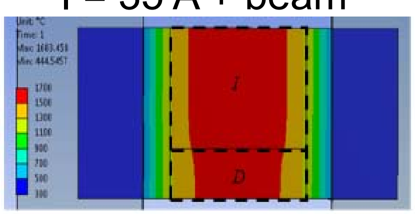


Radiation Damage Studies in Graphite
For Better Lifetime Predictions

- Irradiations by charged heavy ion induce changes of physical properties ⇨ decrease target performance
  - Thermo-mechanical properties (thermal conductivity, tensile and flexural strength), Electronic properties (Resistivity), Structural properties (microstructure and dimensional changes, Swelling)
- Most of the studies were done with neutron and proton irradiation but not a lot of data for heavy ion beams
- How much will annealing help?
- Two types of polycrystalline graphite (5 and 13 µm grain size) irradiated with Au-beam 8.6 MeV/u
  - Up to $5.6 \cdot 10^{10}$ cm^{-2}.s^{-1}, Fluence up to 10^{15} cm^{-2}
  - Samples heated to different temperature

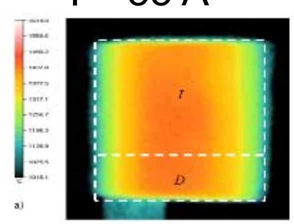


I = 35 A + beam

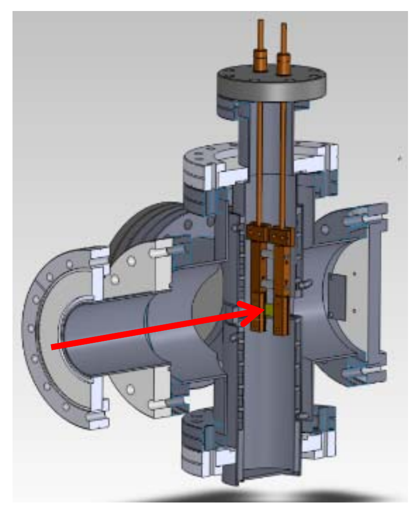


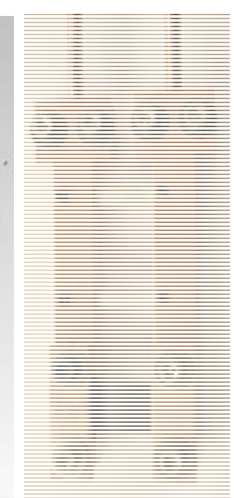
T_{max} = 1600 ºC

I = 35 A



T_{max} = 1480 (± 30 ºC)





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Radiation Damage Studies in Graphite
Annealing of Damage at High Temperature (> 1300ºC)

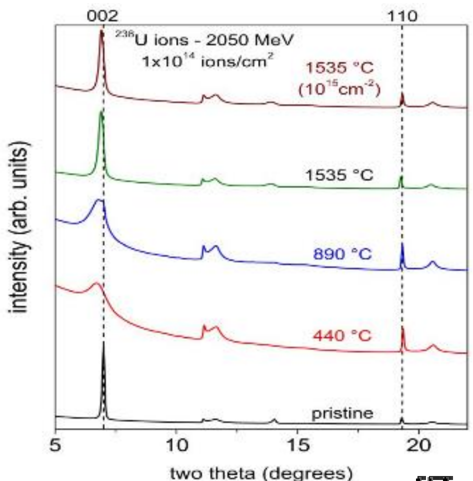
1 A - 350°C
10^{14} cm^{-2}

11 A - 750°C
10^{14} cm^{-2}

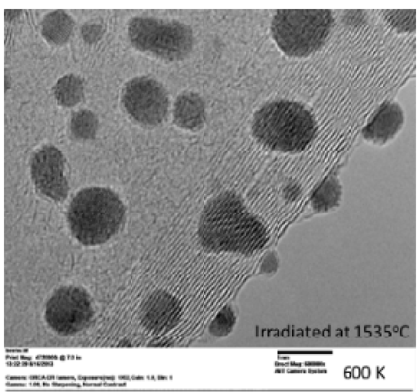
25 A - 1205°C
10^{14} cm^{-2}

35 A - 1635°C
10^{15} cm^{-2}

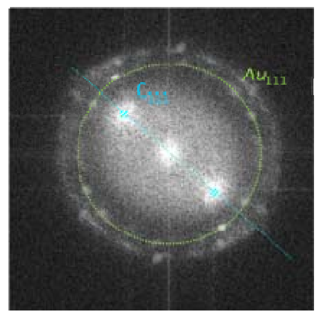
X-Ray Diffraction analyses

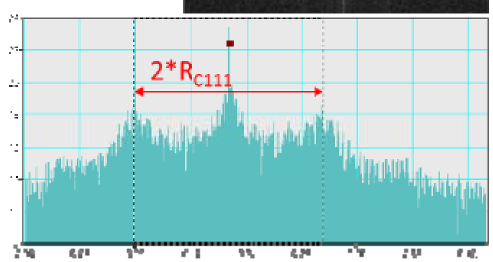


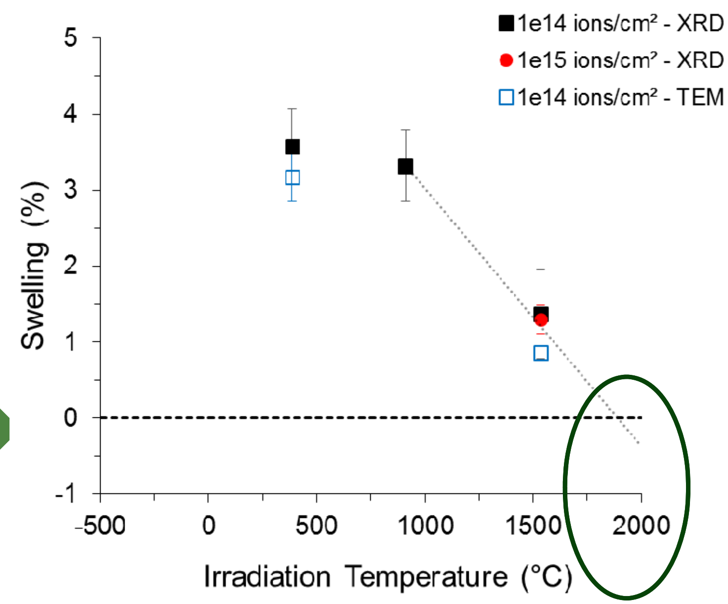
TEM analyses



FFT





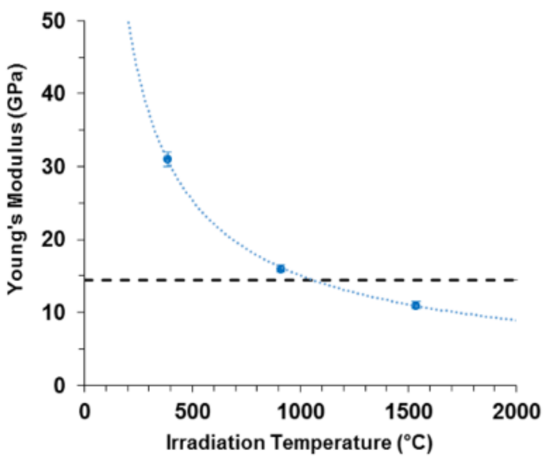


Swelling is completely recovered at 1900ºC

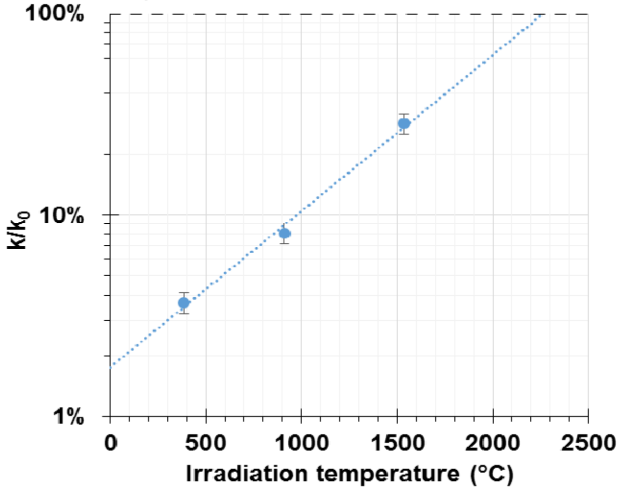
Radiation Damage Studies in Graphite
Annealing of Damage at High Temperature (> 1300ºC)

- Additional analyses (Young's modulus, thermal diffusivity, electrical resistance) of irradiated samples all confirm annealing at high temperature
- Results of material property changes were used as input in thermo-mechanical studies
  - Swelling is completely recovered at 1900ºC
  - 30% of thermal conductivity value will be recovered but lead to insignificant change in average temperature of the production target. Main heat transfer in target is thermal radiation at high temperature
  - Electrical resistivity change has no impact on thermo-mechanical behavior
- Annealing promises sufficient lifetime for FRIB beam production targets

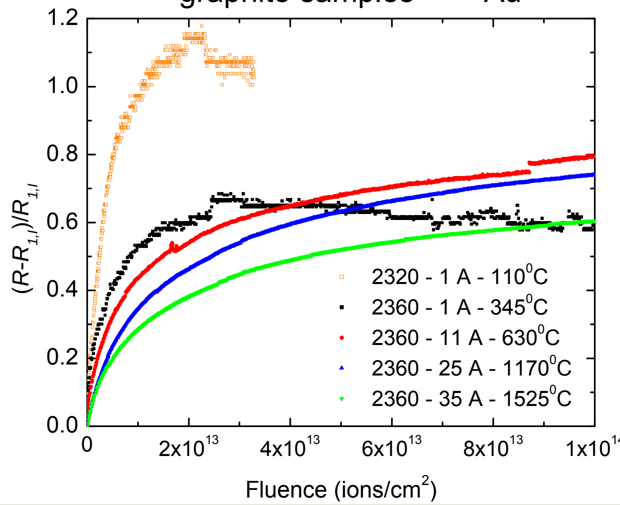
Young's Modulus of irradiated graphite samples - ^{197}Au – fluence 10^{14} ions/cm²



Thermal conductivity change of irradiated graphite samples - ^{197}Au – fluence 10^{14} ions/cm²

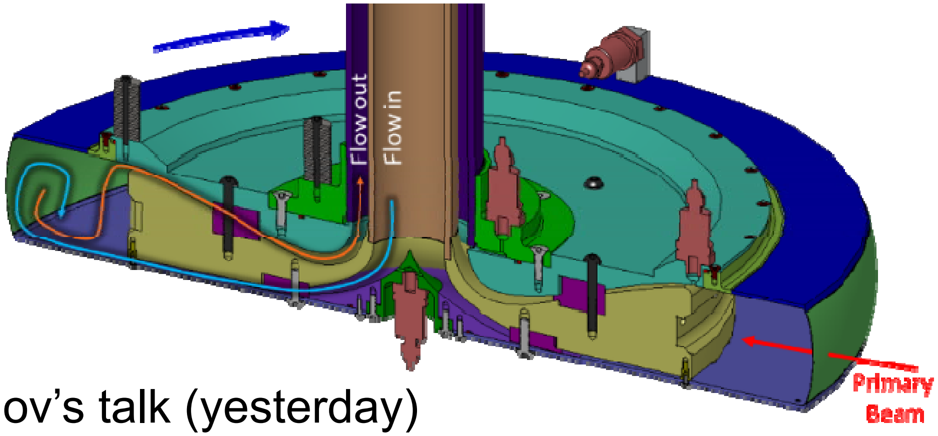


Electrical resistivity change of irradiated graphite samples - ^{197}Au



FRIB Beam Dump Design

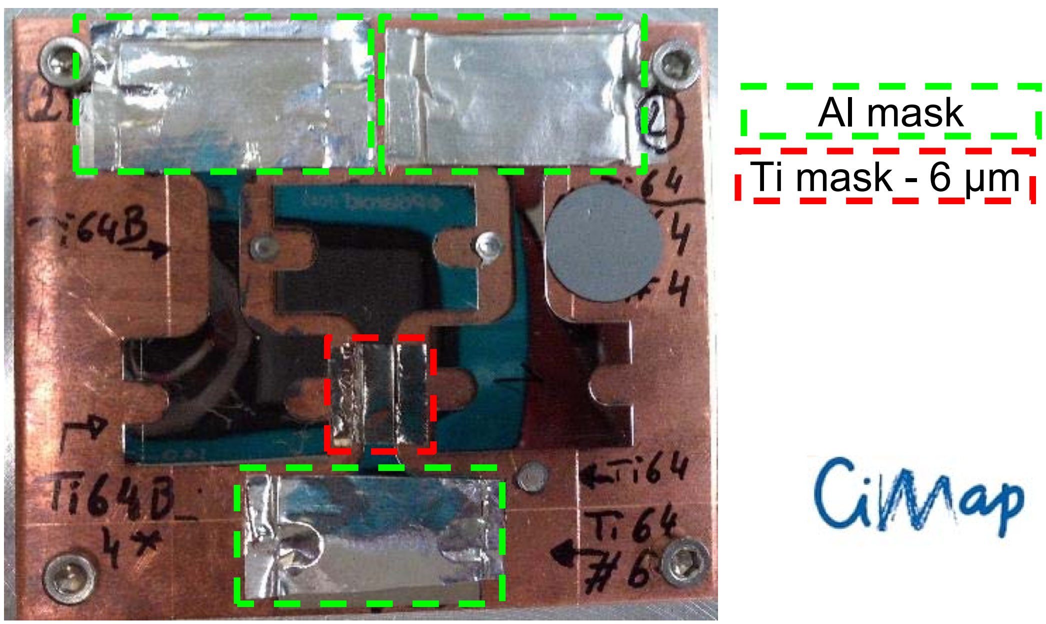
- Water-filled rotating drum beam dump chosen for FRIB baseline
- Parameters defined by thermo-mechanical simulations
  - 400 RPM rotational speed and 70 cm diameter to limit maximum temperature and amplitude of temperature changes
- Beam Dump lifetime of 1 year (5500 h) desired
  - fluence ~10^{18} ion/cm²
  - dpa (U beam) ~ 8.5 (dpa/rate ~ $4 \cdot 10^{-7}$ dpa/s)
- No heavy ion beam facility exists that allows us to test all challenges combined together
  - Perform studies that combine some material challenges using existing facilities
    - » Electron beams, neutron beams, SHI beams
    - » Radiation damage, corrosion, creep

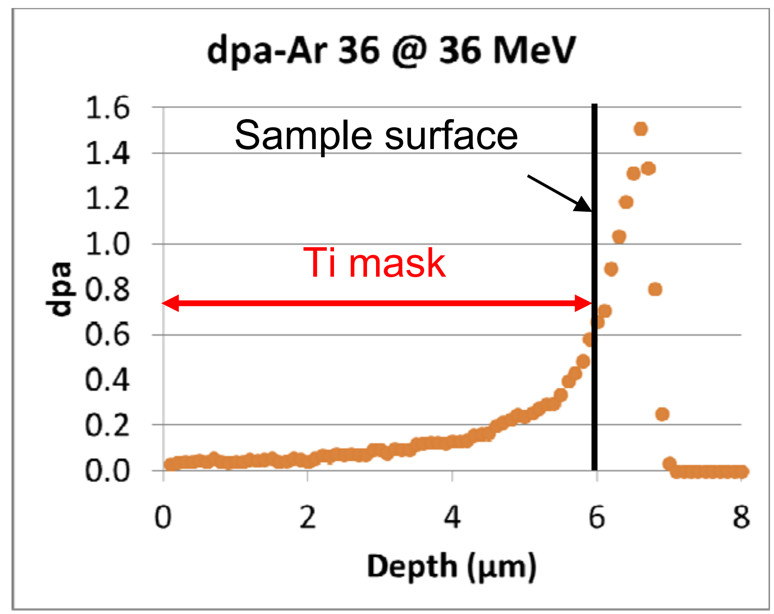


M. Avilov's talk (yesterday)

Radiation Damage Studies
For Better Lifetime Predictions

- Systematic comparative radiation damage studies between both Ti-alloys
  - Use of Ti-6Al-4V-1B is preferred for shell material compare to Ti-6Al-4V (M. Avilov's Talk)
- Study influence of different parameters on radiation damage
  - Ion species, beam energy, electronic energy loss Se, fluence
    - » IRRSUD - CIMAP – France: low energy ion beams on Ti-6Al-4V and Ti-6Al-4V-1B
      - 4 beams (^{36}Ar to ^{131}Xe), 4 energies (25 to 92 MeV), fluence from $2 \cdot 10^{11}$ to $2.5 \cdot 10^{15}$ ions/cm²
      - 41 samples irradiated: foils, dog-bone and TEM

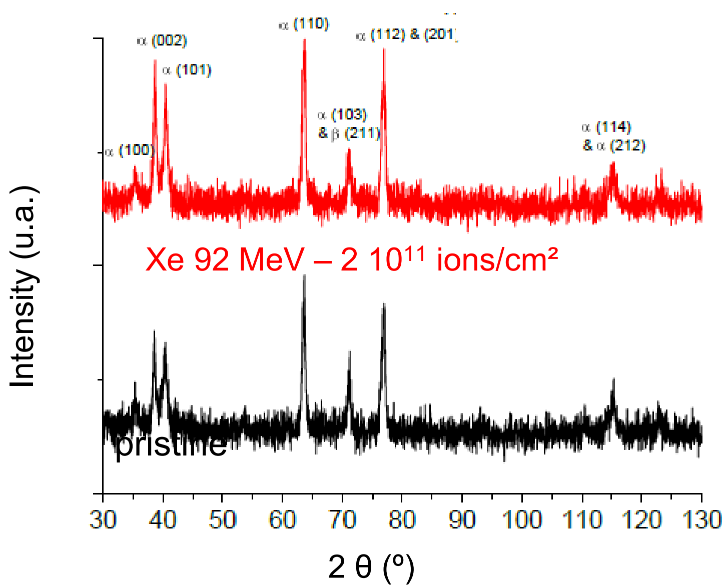


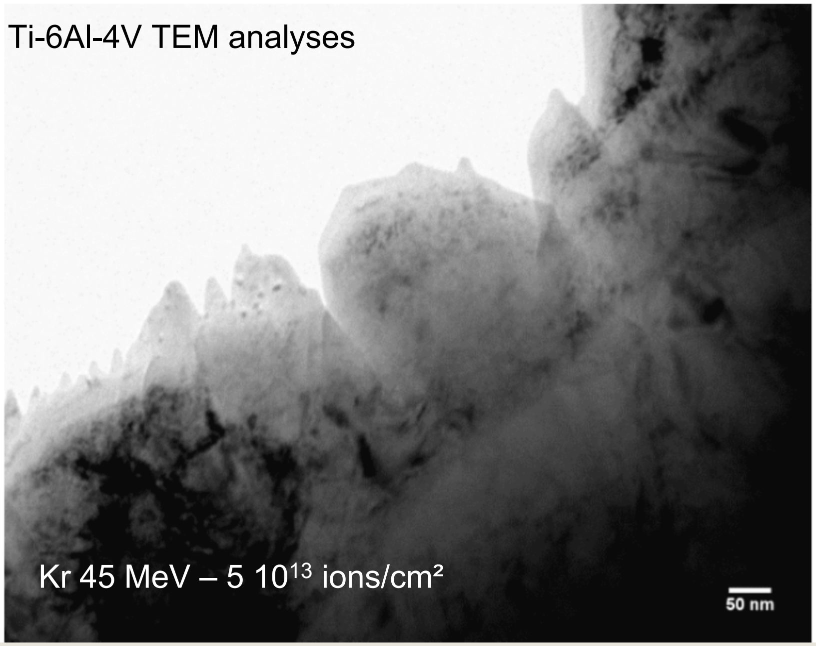


Radiation Damage Studies in Ti-alloys
Electronic Excitation Influence

- Are Ti-alloys sensitive to electronic excitation?
- No evidence of phase transformation and ion track in Ti-6Al-4V that promises good radiation resistance of this alloy
  - Ti-alloys not sensitive to electronic excitation by swift heavy ions (Se~ 13 keV/nm – Kr @ 45 MeV; 20 keV/nm – Xe @ 92 MeV)
    - FRIB: Se from 0.08 keV/nm (with O beam) and 12.6 keV/nm (with U beam)

Preliminary XRD results with Ti-6Al-4V

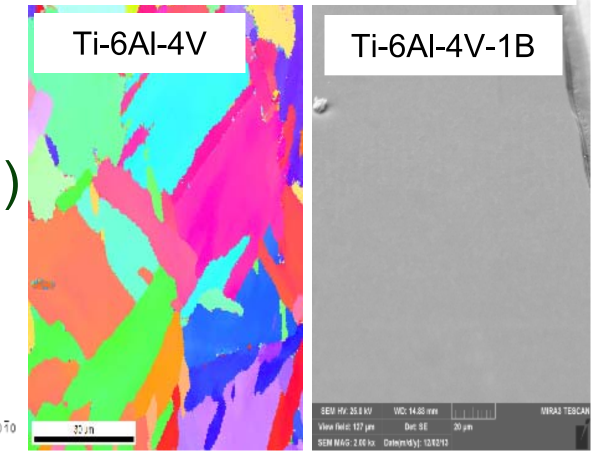


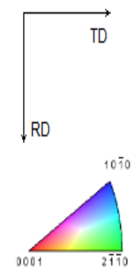


Low Energy SHI Beam Irradiations
No Significant Change Observed

- Collaboration with C. Boehlert and A. Amroussia (CHEMS)
  - Michigan State University Strategic Partnership Materials under Extreme Conditions (MaTX)
- Preliminary results from SEM (Scanning Electron Microscope) / EBSD (Electron Backscatter Diffraction) analyses show no significant change in the microstructure or in orientation of the grain at the surface of the samples
  - Degradation of the quality of the EBSD scan after irradiation
- Vickers Hardness tests show no significant change but damage on the surface is very low (~ 0.038 dpa, $2 \cdot 10^{-6}$ dpa/s)

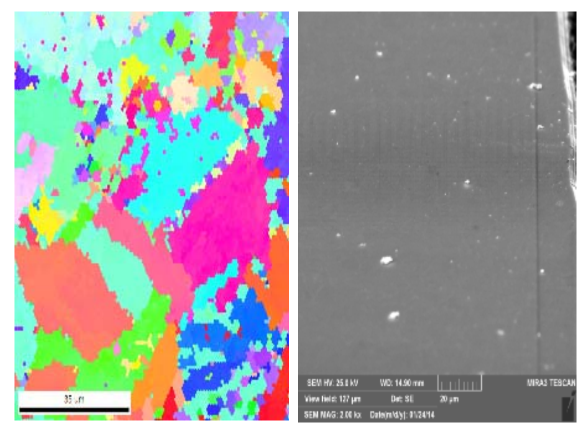
Before irradiation

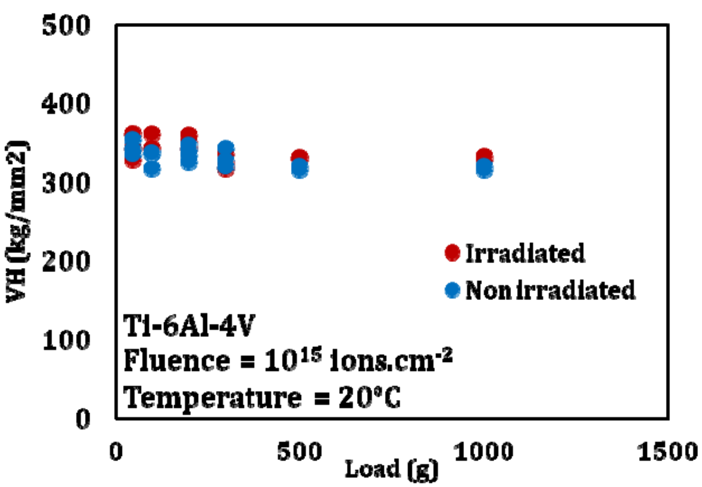


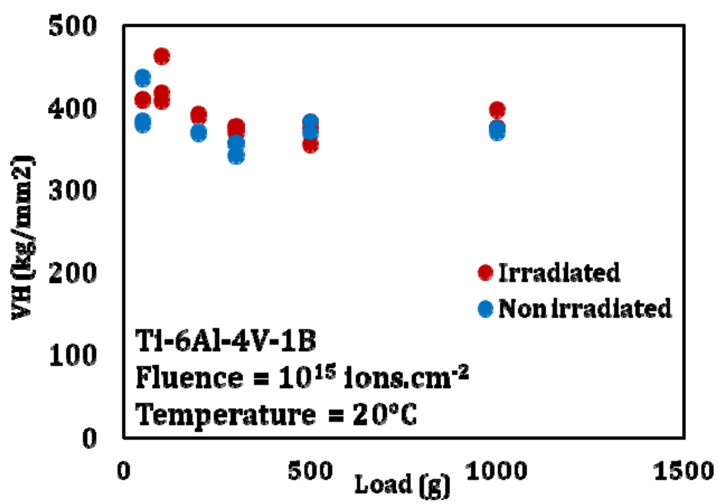


Ti-alloys at 350 ºC irradiated with ^{36}Ar at 36 MeV
10^{15} ions/cm² - 0.038 dpa on surface

After irradiation

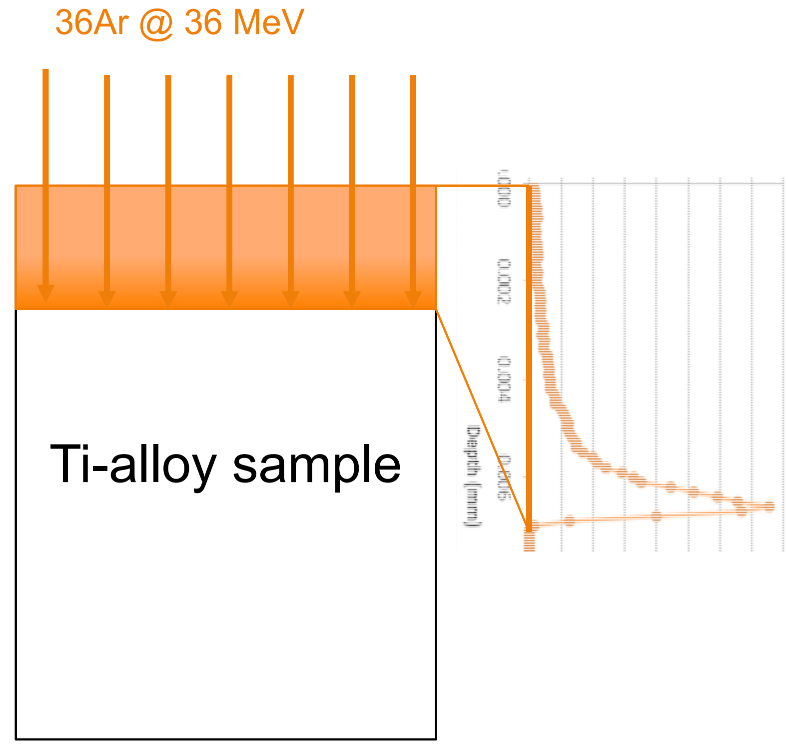






SHI Irradiation Study of Ti-alloys

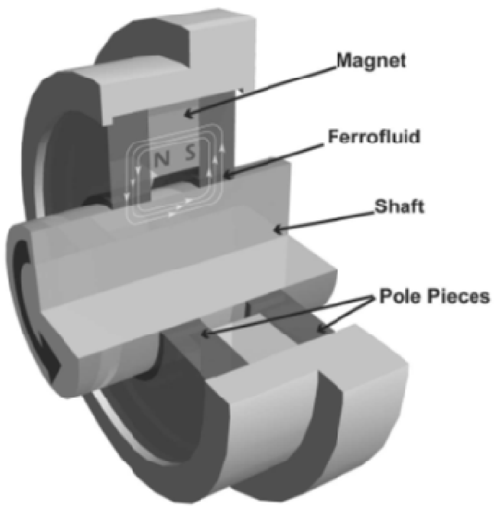
- Analyses ongoing
  - Nano-indentation study will allow extraction of hardness and Young modulus in the cross section of the sample in order to reach higher dpa
  - In-situ SEM during tensile tests (MSU – C. Boehlert)
    - » Study doesn't give bulk properties of Ti-alloys but allows us to observe if the deformation mechanisms on irradiated Ti-alloys are different from un-irradiated samples

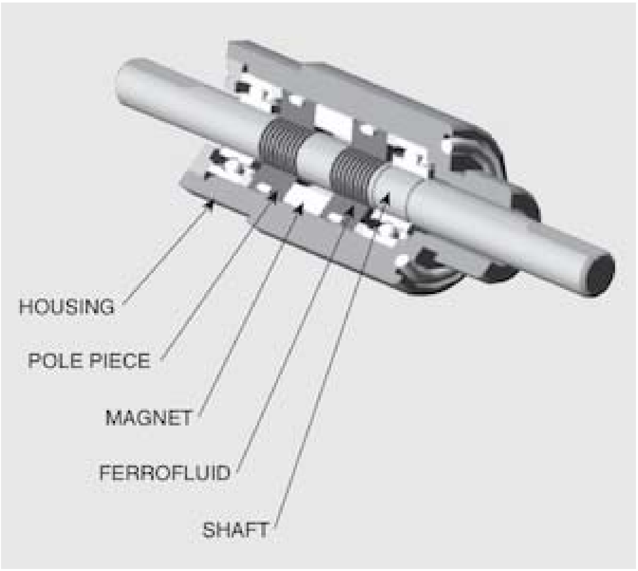


- Future analyses
  - New EBSD analyses planned after polishing samples
  - Swelling study for each samples
  - Possibility to use FIB (Focused Ion Beams) to study damage in the depth of the sample for TEM, SEM/EBSD analyses

Design Support for Target and Beam Dump
Radiation Effects in Ferrofluidic Feedthroughs

- Ferrofluidic Feedthrough will be used in both units (target and beam dump)

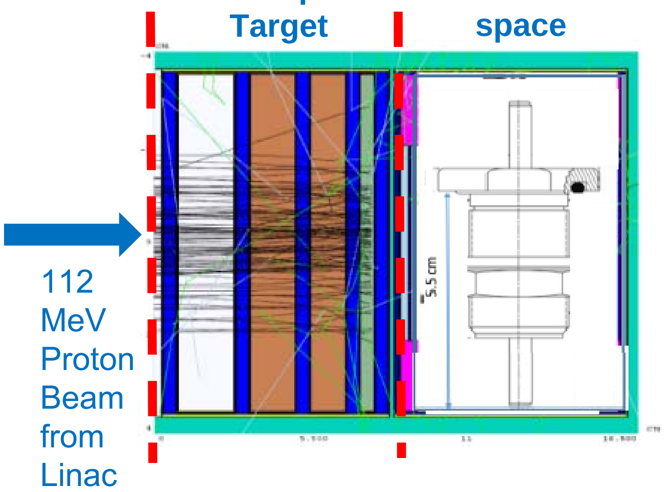


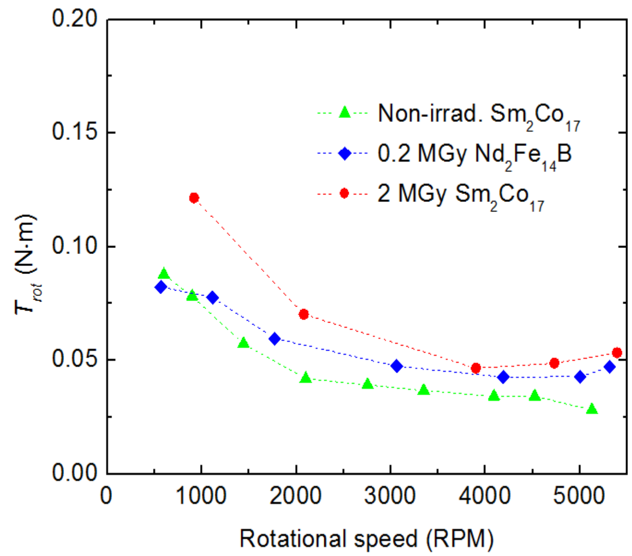


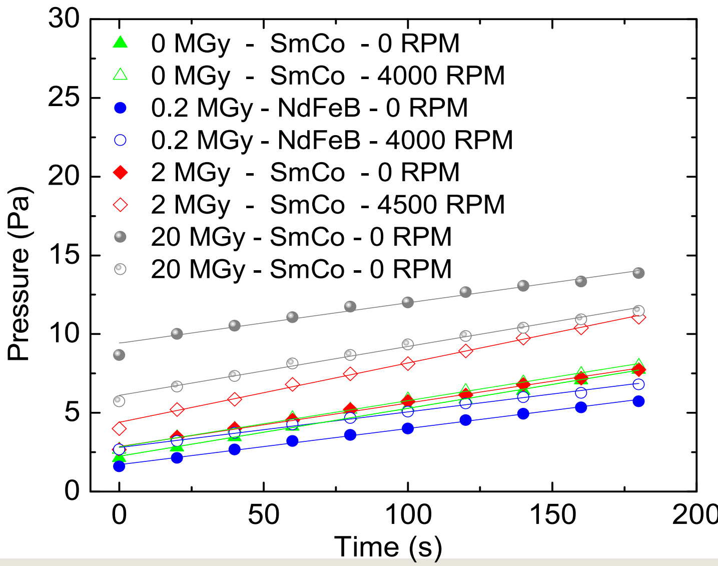
- Maximum dose to Ferrofluidic Feedthroughs
  - Target (2 weeks of operation)
    - » 1 MGy (^{18}O beam at 266 MeV/u with 15” cast iron shielding)
    - » Estimate 7.5 MGy without shielding
  - Beam dump (1 year of operation)
    - » 3.5 MGy (^{18}O beam, 637 MeV/u (conservative upgrade-energy assumption) with 5” of steel shielding)

Design Support for Target and Beam Dump
Radiation Effects in Ferrofluidic Feedthroughs

- FFFT irradiation tests at BNL in June 2011
  - 0.2, 2, 20 MGy mixed proton, neutron and gamma irradiation from stopped proton beam
- Torque and vacuum tests performed in Nov 2011 and Feb 2012
  - No significant change in FFFT performance observed up to a total dose of 2 MGy
    - » Feedthrough blocked for a total dose of 20 MGy
    - » No significant leaks found
- FFFT is a valid technical choice







Summary

- Radiation damage on material for FRIB project are performed
  - with heavy ion beams
    - » Polycrystalline graphite (E = 8.6 MeV/A at GSI)
    - » Titanium alloy : Ti-6Al-4V and Ti-6Al-4V-1B (E = 1 MeV/A at CIMAP)
  - with secondary beams at BNL
    - » Ferrofluidic feedthrough
- Graphite and FFFT studies promise a sufficient lifetime for FRIB production target
- No show-stoppers in Beam dump material studies foreseen but need more investigation with higher dpa and higher energy beam to be closer to FRIB conditions

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Thanks for your attention

Back up slides

- Ti-alloys irradiations at CIMAP and NSCL

Facilities	Beam	Energy [MeV]	Range [µm]	S_e [keV/nm]	Fluence [ions/cm^2]	Max dpa in sample	Date	Number of samples	Type
IRRSUD	^{82}Kr	25	4.73	9.9	5.10^{11}- 5.10^{12}-2.10^{14}	0.6	Jul-2013	6	Foils
	^{131}Xe	92	8.5	19.7	2.10^{11}	0.001	Jul-2013	2	Foils
	^{82}Kr	45	6.43	13.1	5.10^{11}-5.10^{13}	0.16	Jul-2013	4	Foils
	^{82}Kr	45	6.43	13.1	2.10^{14} $2.5.10^{15}$	8	Oct-2013	6	Foils
	^{36}Ar	36	6.8	7.5	10^{15}	1.5	Dec-2013	23	TEM and dogbone
	^{129}Xe	92	8.5	19.7	3 10^{14} estimated	1.7 (Estimated)	June-2014 scheduled		Dogbone
NSCL	^{40}Ca	2000	800	1.5	6 10^{12}	10^{-5}	Aug-2013	1 x Ti64	Dogbone