Radiation Damage and Annealing in Graphite: Ways to Improve the Lifetime of Targets

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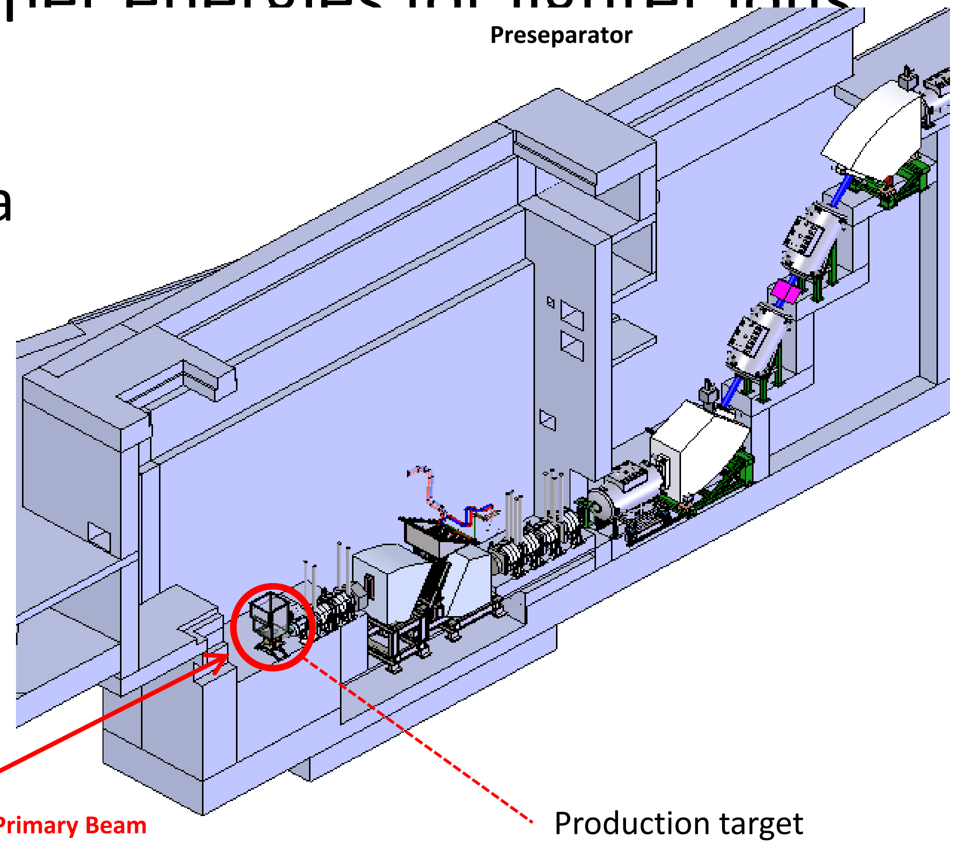
Outline

- FRIB High-power production targets
  - Design and challenges
  - Irradiation and annealing studies of graphite
    - Temperature effect
- NSCL-FRIB stripper
  - Challenges
  - Irradiation and annealing studies of graphite
    - Temperature effects
- Conclusions

High-Power Production Target

Scope and Technical Requirements

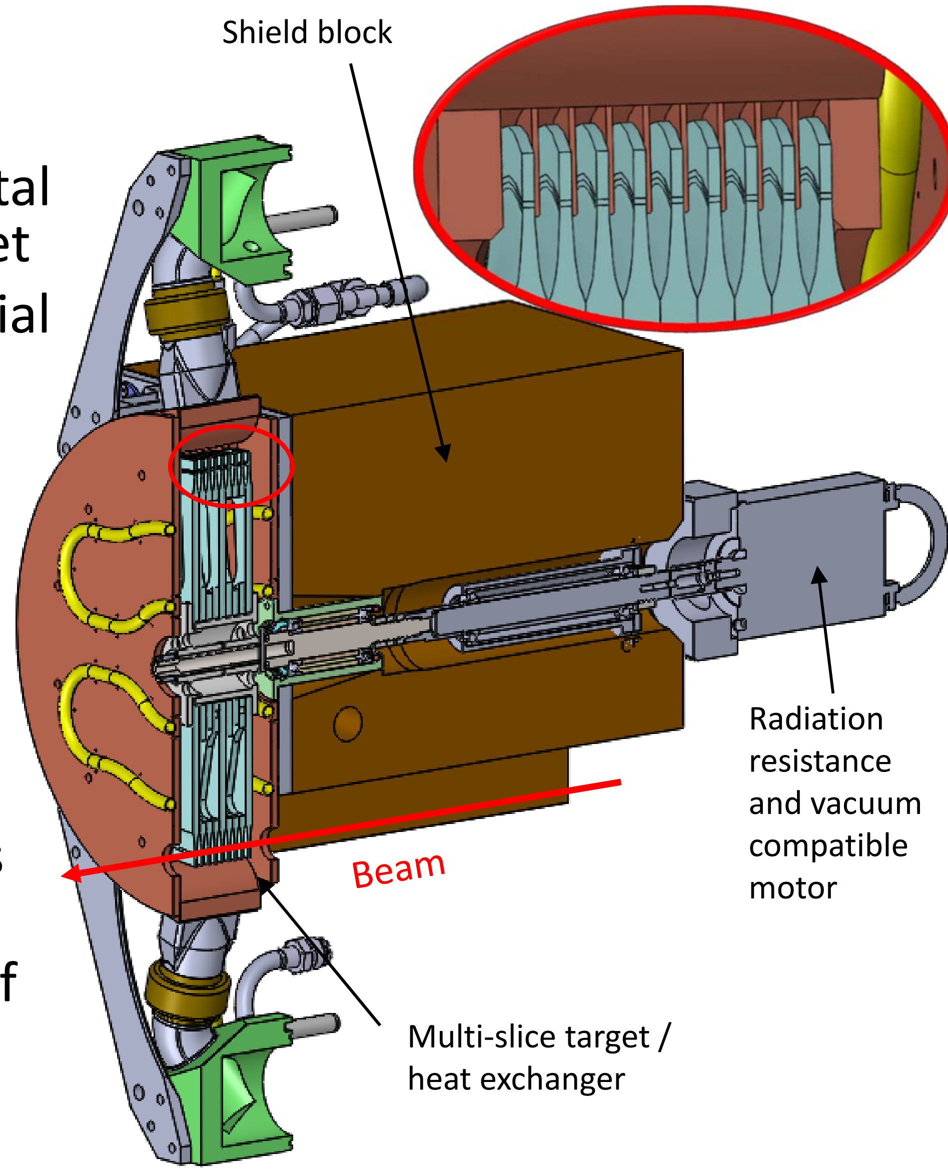
- In-flight rare isotope beam production with beam power of 400 kW at 200 MeV/u for ^{238}U and higher energies for lighter ions
- High power capability
  - Up to 100 kW in a ~0.3 - 8 g/cm² ta isotope production via projectile fragmentation and fission
- Required high resolving power of fragment separator
  - 1 mm diameter beam spot
  - Maximum extension of 50 mm in beam direction
- Target lifetime of 2 weeks to meet experimental program requirements



FRIB Production Target

Rotating Multi-slice Graphite Target Design

- Rotating multi-slice graphite target chosen for FRIB baseline
  - Increased radiating area and reduced total power per slice by using multi-slice target
  - Use graphite as high temperature material
  - Radiation cooling
- Design parameters
  - Optimum target thickness is ~ ⅓ of ion range
    - 0.15 mm to several mm
  - Maximum extension of 50 mm in beam direction including slice thickness and cooling fins to meet optics requirements
  - 5000 rpm and 30 cm diameter to limit maximum temperature and amplitude of temperature changes



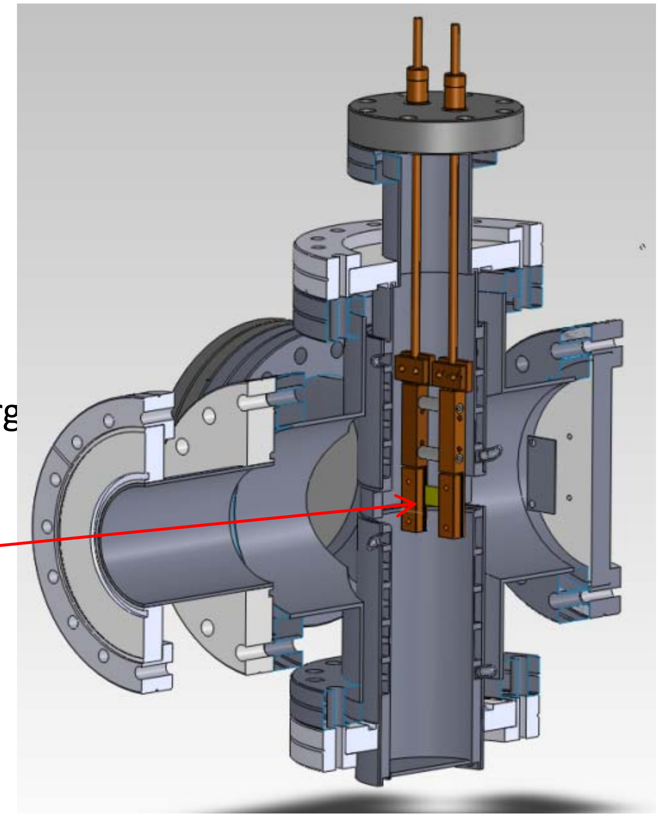
FRIB Production Target

Challenges

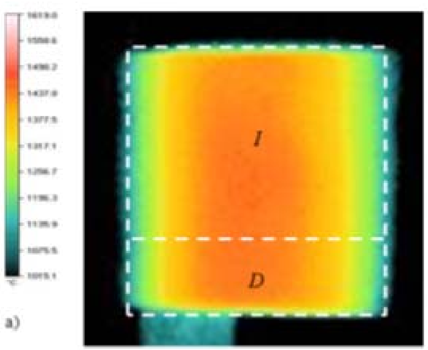
- Thermo-mechanical challenges
  - High power density: ~ 20 - 60 MW/cm^3
    - High temperature: ~ 1900 ºC: Evaporation of graphite, stress
  - Rotating target
    - Temperature variation: Fatigue, Stress waves through target
- Swift Heavy Ion (SHI) effects on graphite
  - Radiation damage induce material changes
    - Property changes: thermal conductivity, tensile and flexural strength, electrical resistivity, microstructure and dimensional changes, …
  - Swift heavy ions (SHI) damage not well-known
  - $5 \cdot 10^{13}$ U ions/s at 203 MeV/u may limit target lifetime
    - Fluence of ~$9.4 \cdot 10^{18}$ ions/cm^2 and 10 dpa estimated for 2 weeks of operation
- Similar challenges at
  - Facility for Antiproton and Ion Research (FAIR) at GSI
  - Radioactive Ion Beam Factory (RIBF) at RIKEN

Irradiation Test at UNILAC at GSI/Darmstadt

- Polycrystalline isotropic graphite
  - 2 Grades MERSEN 2360 (5 µm) / 2320 (13 µm)
- Irradiation test at UNILAC at GSI/Darmstadt
  - Au-beam 8.6 MeV/u
    - Up to $5.6 \cdot 10^{10}$ ions/cm²·s and fluence up to 10^{15} ions/cm²
      - Equivalent to a fluence of 10^{18} ions/cm² for FRIB beam energ or 2 days of operation
    - Electronic energy loss ≈ 20 keV/nm
  - Ohmic heating (up to 35 A, 250 W) of samples to different temperature during irradiation

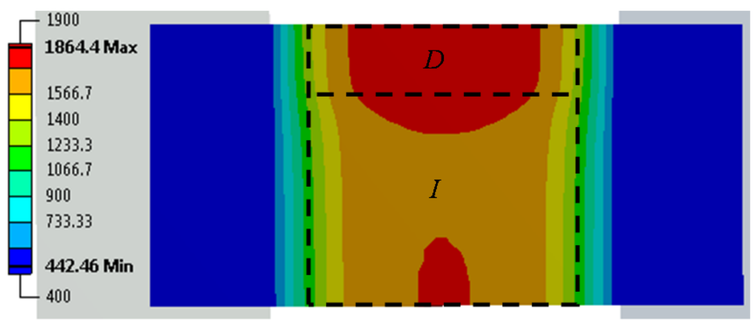


I = 35 A

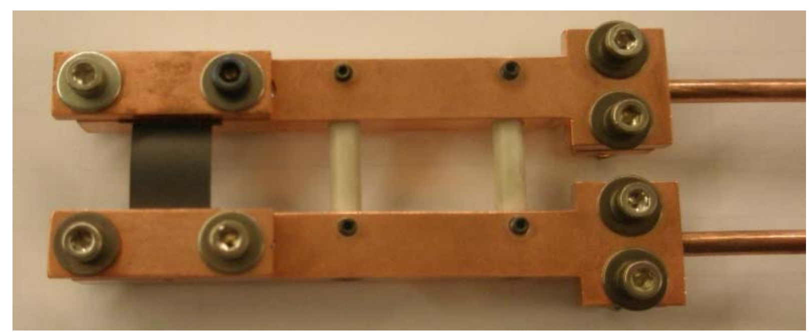


T_{max} = 1480 (± 30 ºC)

I = 35 A + beam



T_{max} = 1635ºC



Radiation Damage Studies in Graphite [1]

Annealing of Damage at High Temperature (> 1300ºC)

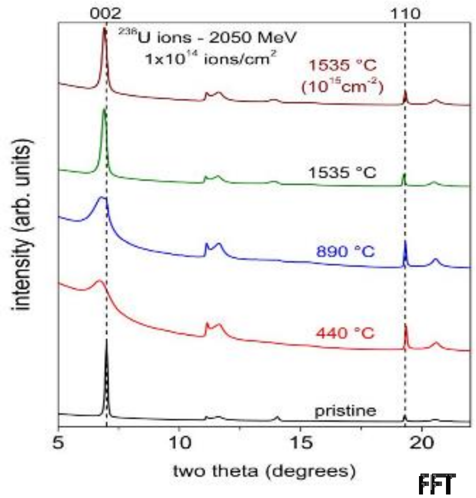
1 A - 350°C
10^{14} cm^{-2}

11 A - 750°C
10^{14} cm^{-2}

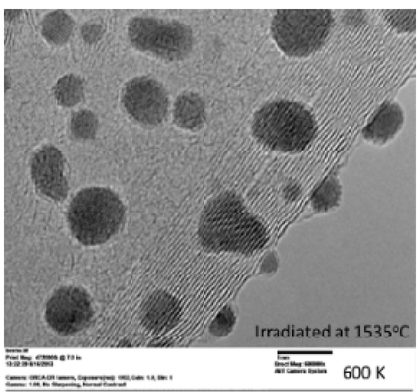
25 A - 1205°C
10^{14} cm^{-2}

35 A - 1635°C
10^{15} cm^{-2}

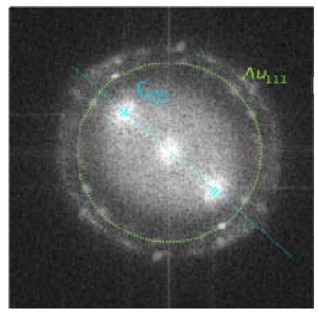
X-Ray Diffraction analyses

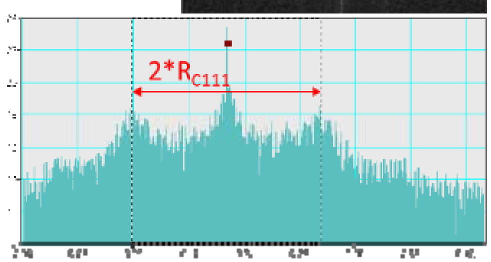


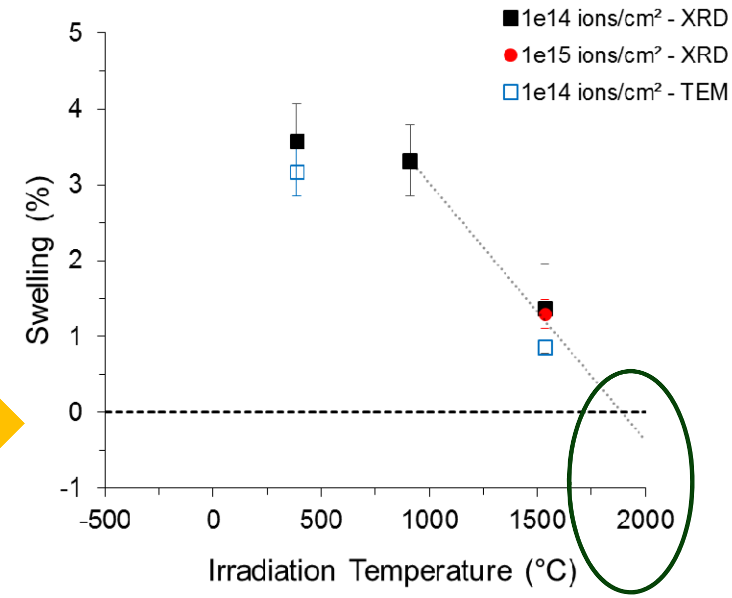
TEM analyses



FFT





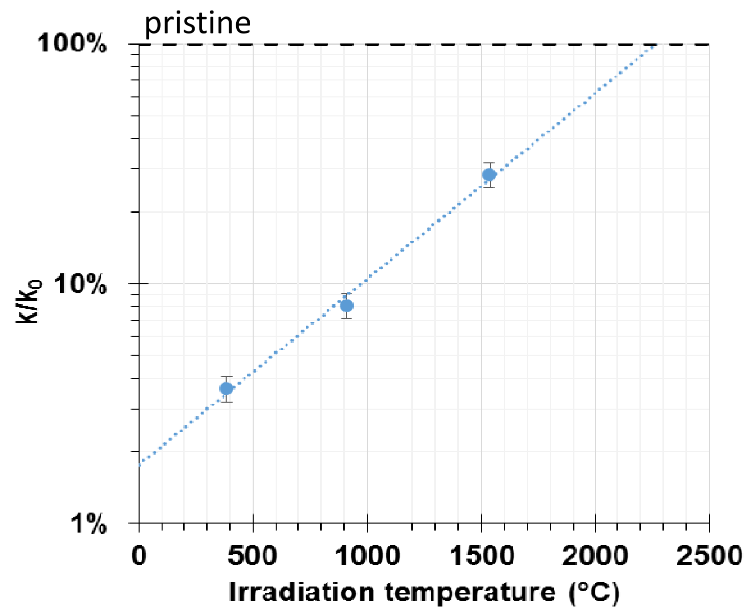


Swelling is completely recovered at 1900ºC

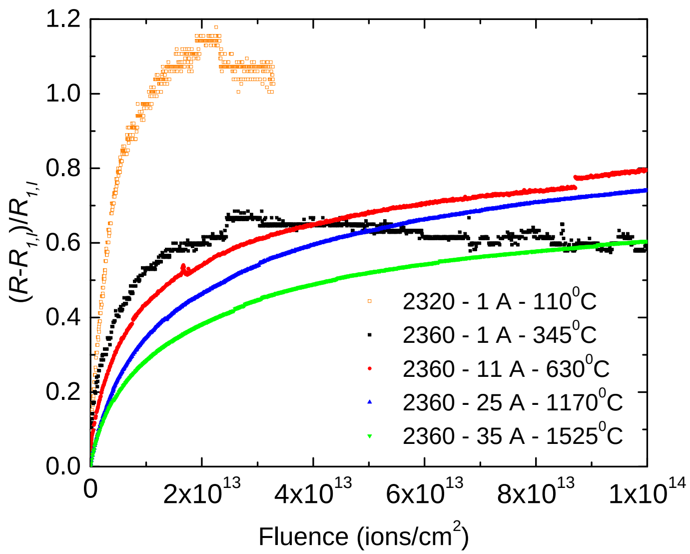
Radiation Damage Studies in Graphite [2]

Annealing of Damage at High Temperature (> 1300ºC)

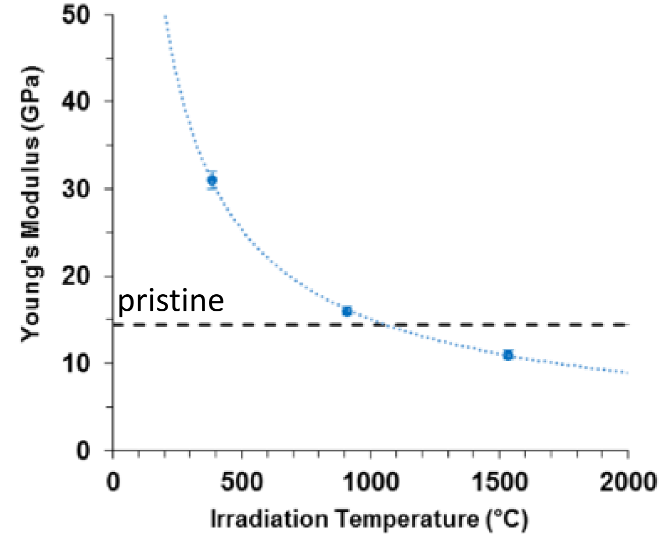
Thermal conductivity change of irradiated graphite samples - ^{197}Au fluence 10^{14} ions/cm²



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



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

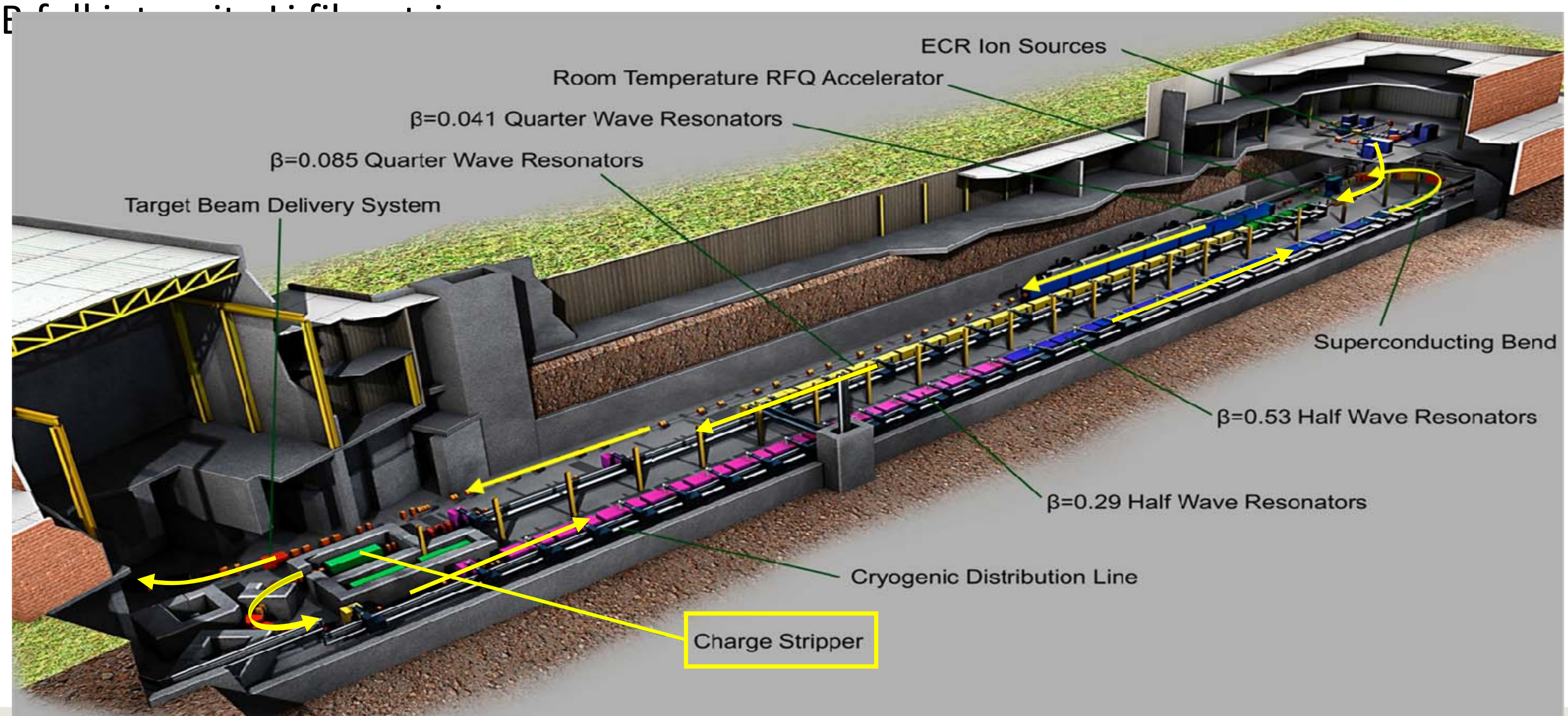


- Annealing at high temperature confirmed

NSCL-FRIB Strippers

Challenges

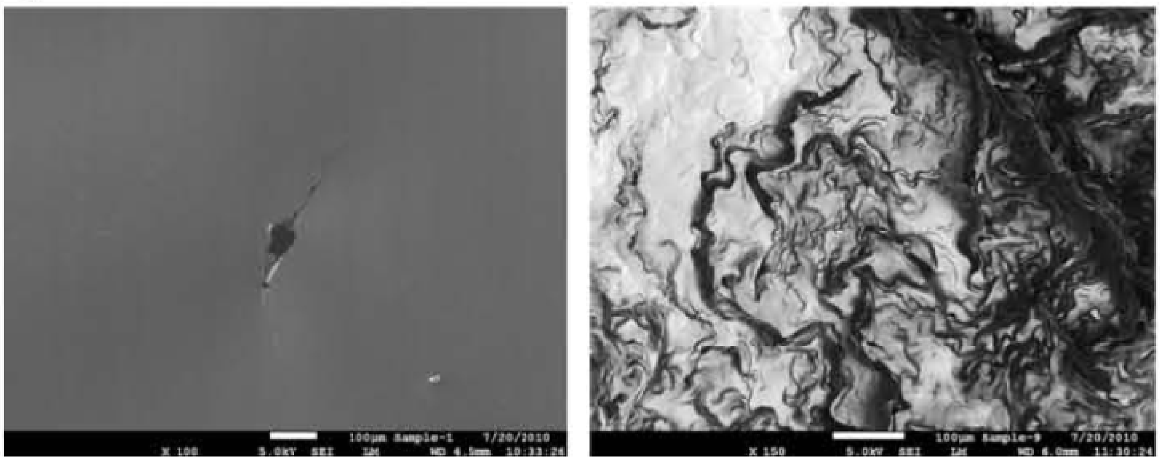
- It is known that thin foils (stripper) used in accelerator suffer a quick degradation due to radiation damage such as swelling and thermo-mechanical changes
  - Limits the lifetime of few hours
- How can we improve the lifetime?
  - Annealing at high temperature
  - Influence of nano-structure on annealing
  - FRIB
  - ….



NSCL-FRIB Strippers

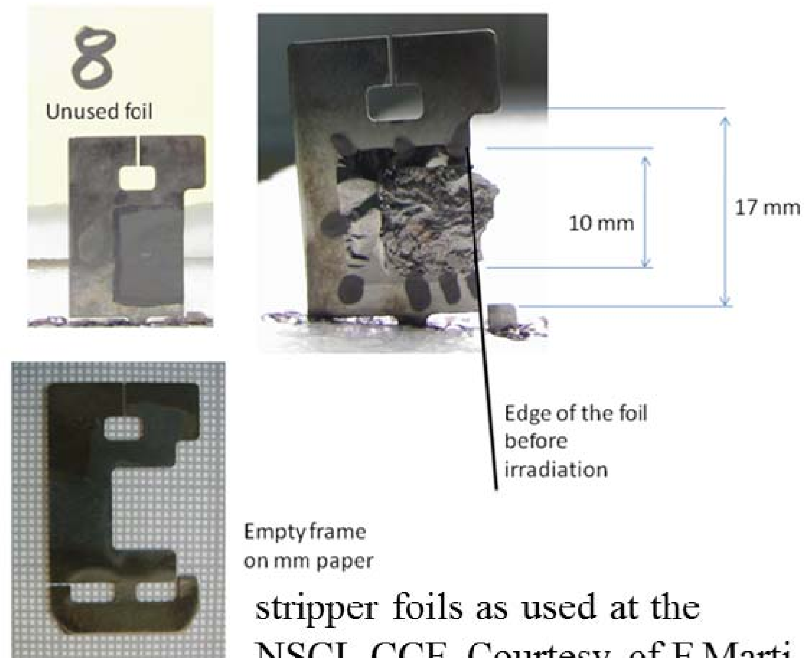
Radiation Damage

- Recent tests at NSCL have shown quick deterioration of graphite foils under heavy ion bombardment due to thermal and mechanical stresses and radiation damage
  - Carbon irradiated with Pb beam @ 8



SEM photographs of unused carbon foil (left) showing a small pinhole for illustration and a foil exposed to 8.1 MeV/u Pb beam

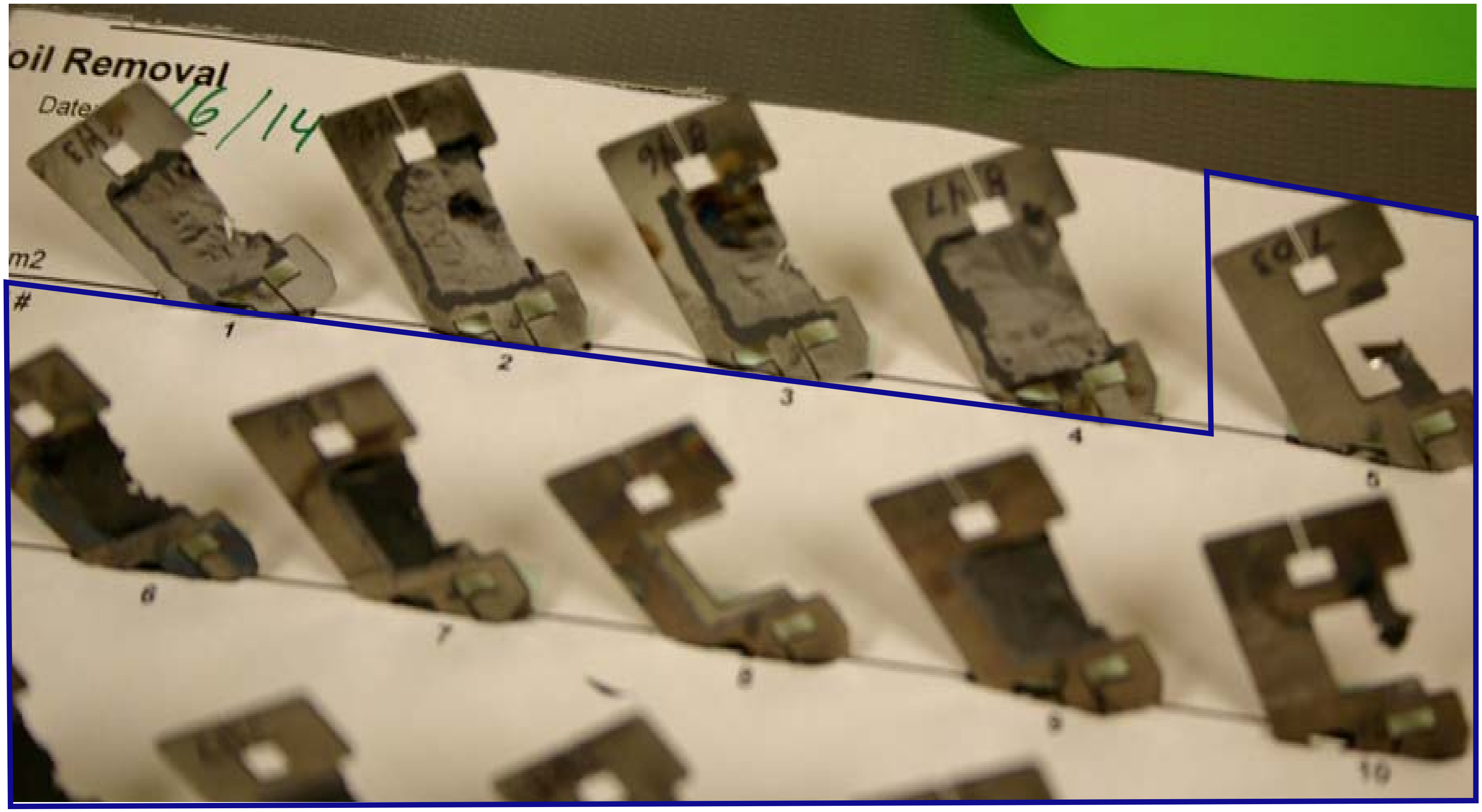
F. Marti et al., "A carbon foil stripper for FRIB", TUP 106, Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan, TUP105, 2010.



stripper foils as used at the NSCL CCF. Courtesy of F.Marti

NSCL-FRIB Strippers

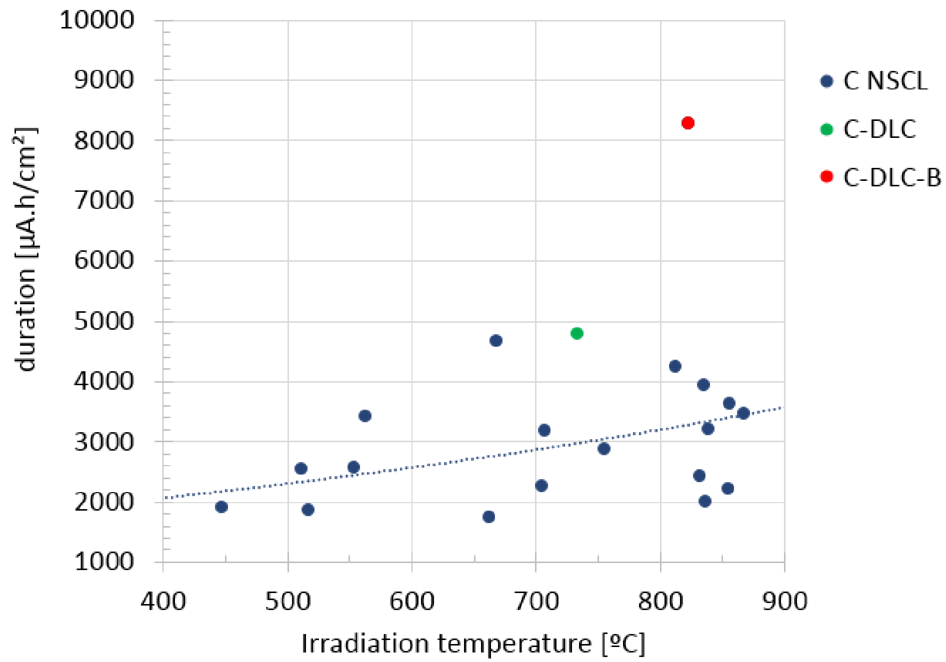
Irradiated Strippers at NSCL



Current carbon strippers used at NSCL

Improvement of the lifetime

- Previous studies [3] showed annealing effects of radiation damage at high temperature. The heating by the beam was evaluated to produce temperatures of up ~900 ºC. A clear tendency of increased lifetime with irradiation temperature was observed.
- The lifetime of the 10 multilayer foil C-DLC-B was significantly higher (factor 3) than the standard C-NSCL foils. The 10 multilayer foil C-DLC was somewhat superior (about a factor 2) as compared to the standard foils.



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

[3] S. Fernandes et al., "In-Situ Electric Resistance Measurements and Annealing Effects of Graphite Exposed to Swift Heavy Ions", Nucl. Instrum. Methods Phys. Res. B 314 (2013) 125-129.

Summary and Conclusions

- Heavy-ion irradiation tests and annealing studies performed in the context of high-power target and strippers for high intensity accelerator were performed
- High temperature annealing of heavy-ion induced radiation damage observed in production target
    - First experiment of this kind
    - Confirmed by several analysis
- Graphite as a material for FRIB beam production targets promises sufficient lifetime
- High temperature annealing of heavy-ion induced radiation damage observed in NSCL strippers

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Thank you for your attention

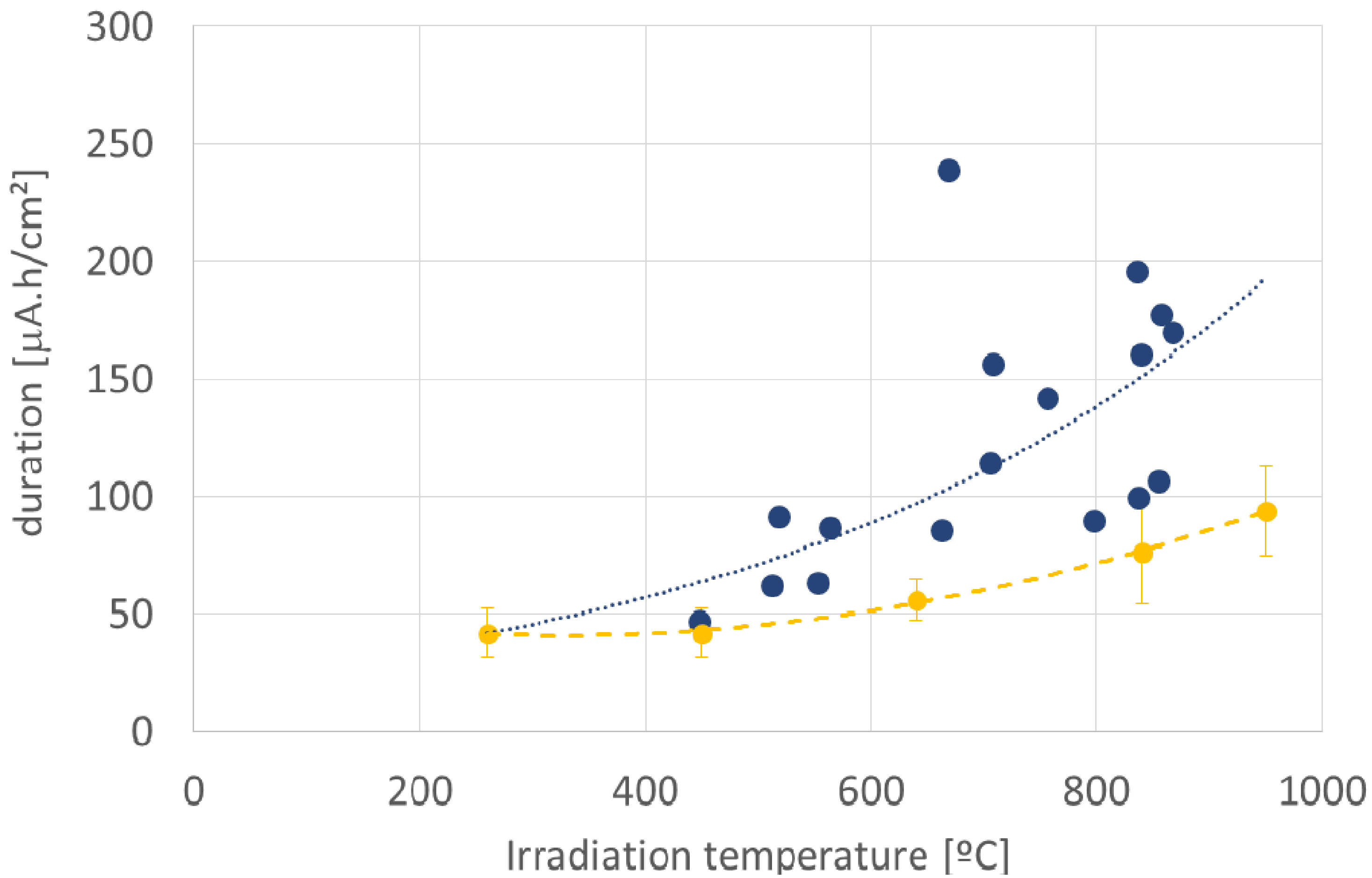
FRIB construction area – October 27 2014

NSCL-FRIB Strippers

Lifetime measurement at NSCL

- Effect of the temperature on lifetime improvement observed at NSCL

Preliminary results



$^{78}Kr^{14+}$ @ 13 MeV/u

^{20} Ne @ 3.2 MeV

Sugai et al., NIMB 269 (2011) 223-228