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

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May 19, 2015
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 \(\sim 0.3 - 8 \text{ g/cm}^2\) target for 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/cm³
    • High temperature: ~ 1900 °C: 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 $\sim 9.4 \cdot 10^{18}$ ions/cm² 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
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 $5.6 \times 10^{10}$ ions/cm²·s and fluence up to $10^{15}$ ions/cm²
  - Equivalent to a fluence of $10^{18}$ ions/cm² for FRIB beam energy or 2 days of operation
- Electronic energy loss $\approx 20$ keV/nm
- Ohmic heating (up to 35 A, 250 W) of samples to different temperature during irradiation

$T_{\text{max}} = 1480 (\pm 30 \, ^{\circ}\text{C})$

$T_{\text{max}} = 1635 \, ^{\circ}\text{C}$
Radiation Damage Studies in Graphite [1]

Annealing of Damage at High Temperature (> 1300°C)

1 A - 350°C
10^{14} cm^{-2}

11 A - 750°C
10^{14} cm^{-2}

25 A - 1205°C
10^{15} cm^{-2}

35 A - 1635°C
10^{15} cm^{-2}

X-Ray Diffraction analyses

TEM analyses

Swelling is completely recovered at 1900°C

F. Pellemeoine, Nov. 2014 MaTX-2, GSI
Radiation Damage Studies in Graphite [2]
Annealing of Damage at High Temperature (> 1300°C)

- 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 full intensity Li film stripper
  • ….
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 @ 8.1 MeV/u.

Fig. 3A: Y’-y’ profile and 4.5 \times 10^{16} ions.

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


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 °C. 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.

![Graph showing lifetime (μA·h/cm²) as a function of the irradiation temperature and the microstructure of graphite stripper foils.]

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
Acknowledgements

- FRIB/NSCL Michigan State University
  - Mikhail Avilov, Saul Beceiro Novo, Sandrina Fernandes, Felix Marti, Mike Schein, Andreas Stolz, Genevieve West

- GSI Helmholtzzentrum für Schwerionenforschung GmbH
  - Markus Bender, Markus Krause, Daniel Severin, Marilena Tomut, Christina Trautmann

- University of Michigan
  - Rodney Ewing, Maik Lang, Weixing Li
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

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C NSCL
78 Kr14+ @ 13 MeV/u

C-Sugai
20 Ne @ 3.2 MeV

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