Understanding Ion- Induced Radiation Damage in Target Materials

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Motivation

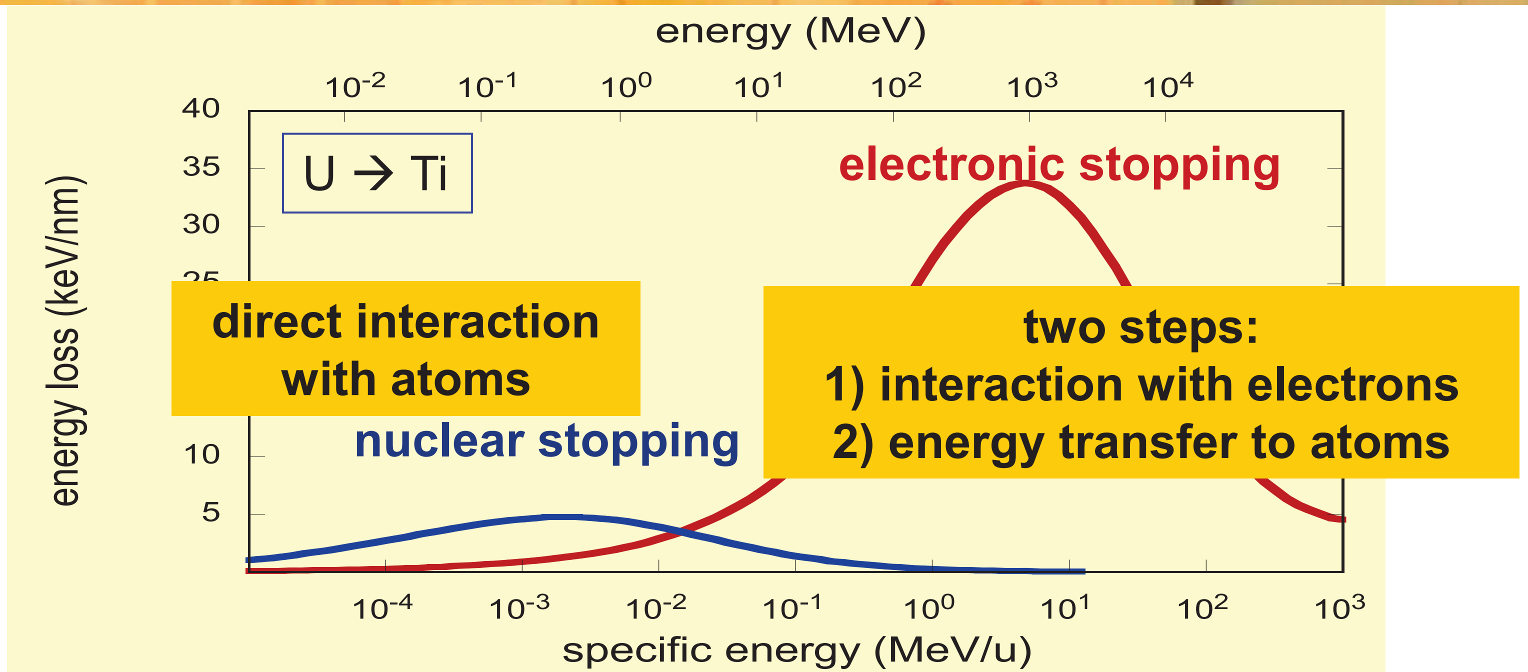
- high intensity heavy ions accelerator – extreme challenges to traditional materials for: targets, beam catchers, collimators..
- understand materials failure due to extreme radiation
- develop failure criteria
- provide reliable lifetime predictions
- develop monitor system
- new solution for extreme conditions

In collaboration and synergy with activities at LHC (CERN), FRIB (Michigan), RIBF (RIKEN)

Overview

- Mechanism of swift heavy ion induced damage – discussion of track formation with application to a common target material: graphite
- Heavy ion- induced structural and property changes in graphite
- High intensity operation conditions; high temperature recovery; pulsed beams
- Conclusions
- Outlook- monitoring and diagnostic of target and beam catcher material degradation

Swift heavy ions- energy deposition



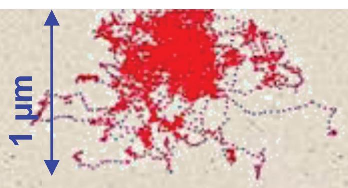
target atoms

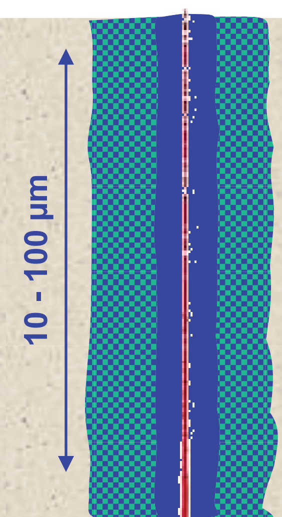
↓

atomic collision cascade

↓

defects





target electrons

↓

electron cascade

↓

coupling to lattice

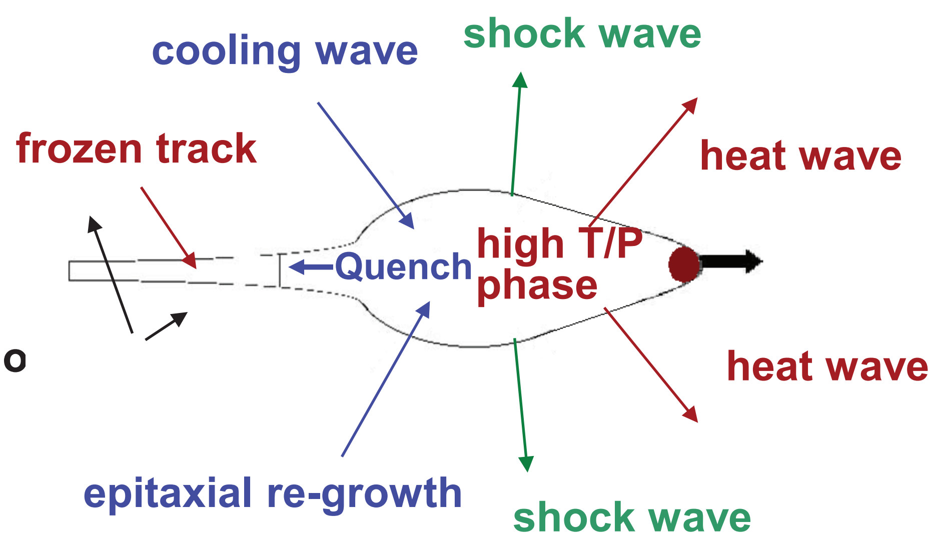
↓

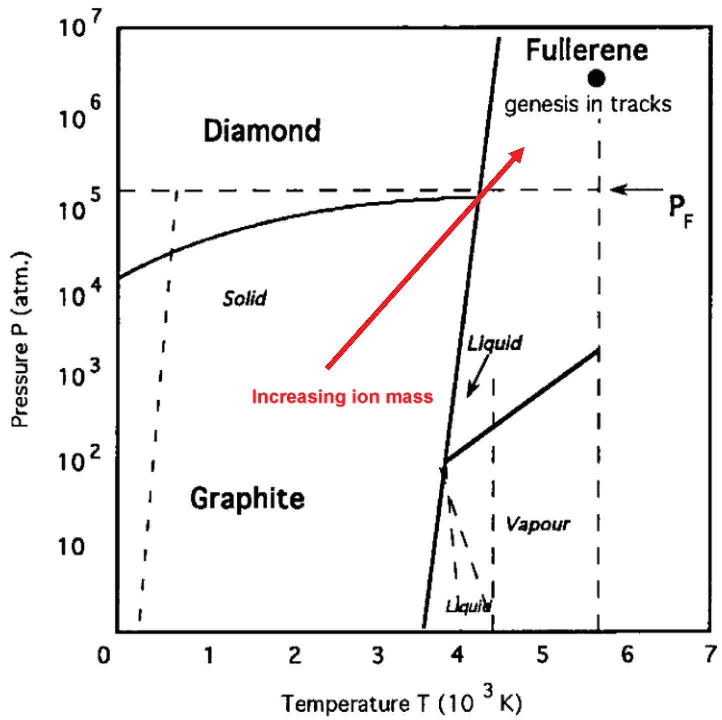
lattice disorder

↓

track

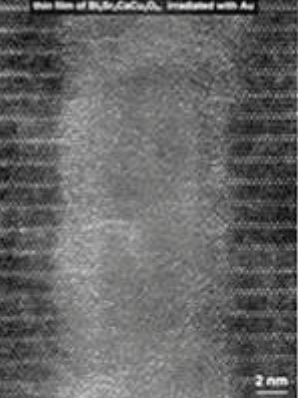
Ion track formation in graphite





(Gamaly and Chadderton, 1995)

- homo-epitaxial re-growth in the wake of the ion trails – high efficiency
- For heavy swift ions a fullerene transformation channel might be active in the track formation



Track formation depends on materials nature

high sensitivity		low sensitivity
dE/dx threshold ~1 keV/nm	~20 keV/nm	~50 keV/nm

insulators

- polymers
- oxides, spinels
- ionic crystals
- ~~diamond~~

semi-conductors

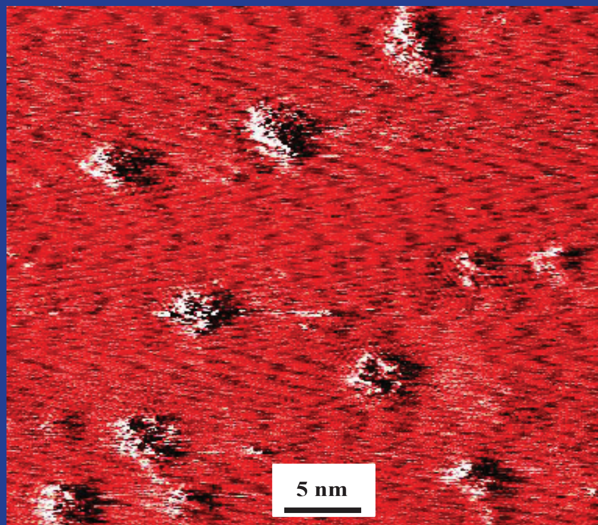
- amorphous Si
- GeS, InP, $Si_{1-x}Ge_x$
- ~~Si, Ge~~
- C??

metals

- amorphous alloys
- Fe, Bi, Ti, Co, Zr
- Au, ~~Cu~~, Ag,

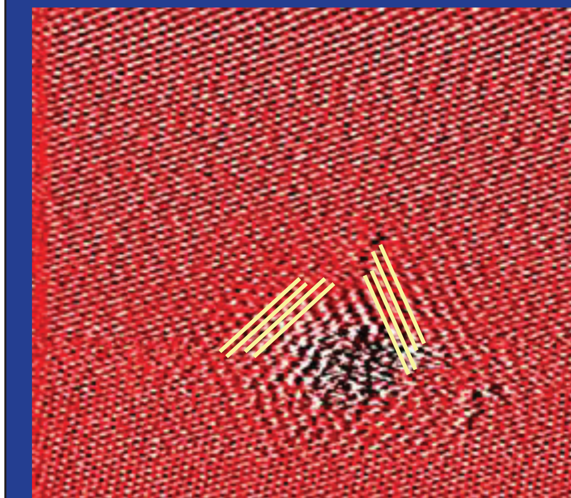
~~no tracks~~

Heavy ion induced tracks in graphite (HOPG)



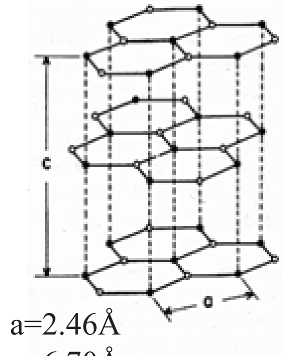
30 nm x 30 nm

U (2710 MeV)

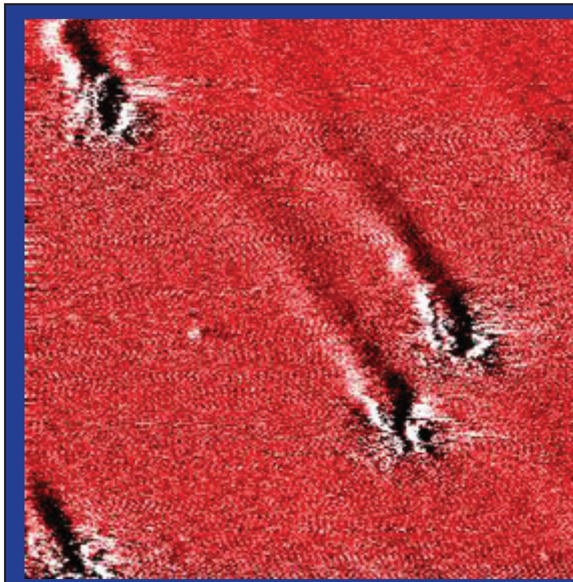


15 nm x 15 nm

Xe (475 MeV)



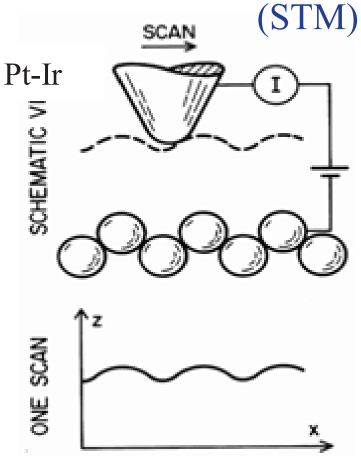
a=2.46Å
c=6.70Å



50 nm x 50 nm

U (2640 MeV)

Scanning tunneling microscopy (STM)



bias ~250 mV

const I~1 nA

Liu et al, PRB 64 (2001) 184115
NIMB 212 (2003) 303

How to test extreme radiation conditions at future facilities with existing accelerators?

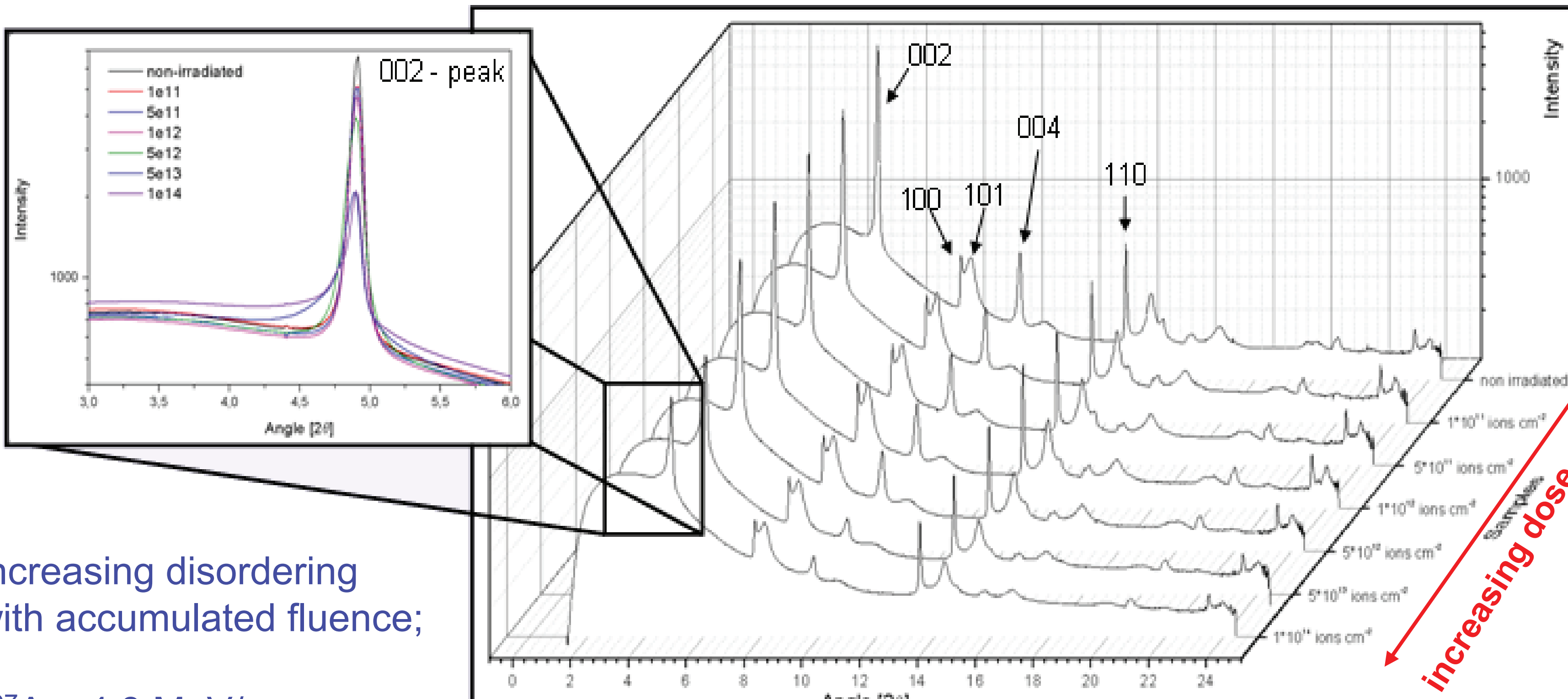
- limited beam time
- limited ion range at lower energy
- testing activated samples
- extrapolation to intensities not available yet
- which tests are suitable

?

- test 'worst case energy deposition scenario' → Bragg maximum
- 'easy' test to characterize the damage e.g. Raman spectroscopy
- study flux dependence- extrapolate
- study high temperature irradiation behaviour
- study damage evolution vs. accumulated dose / flux (extrapolation?)
- develop failure criteria from tests

Ion-induced structural transformation- XRD

Diffraction experiments at Petra 3 beamline at DESY



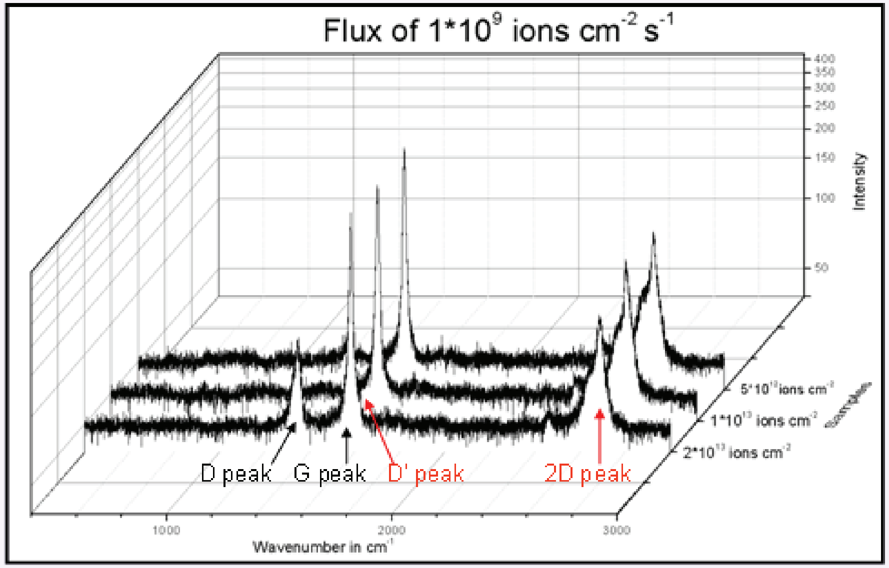
X-ray diffraction of a series of isotropic graphite irradiated up to a fluence of $1 \cdot 10^{14}$ ions cm^{-2}

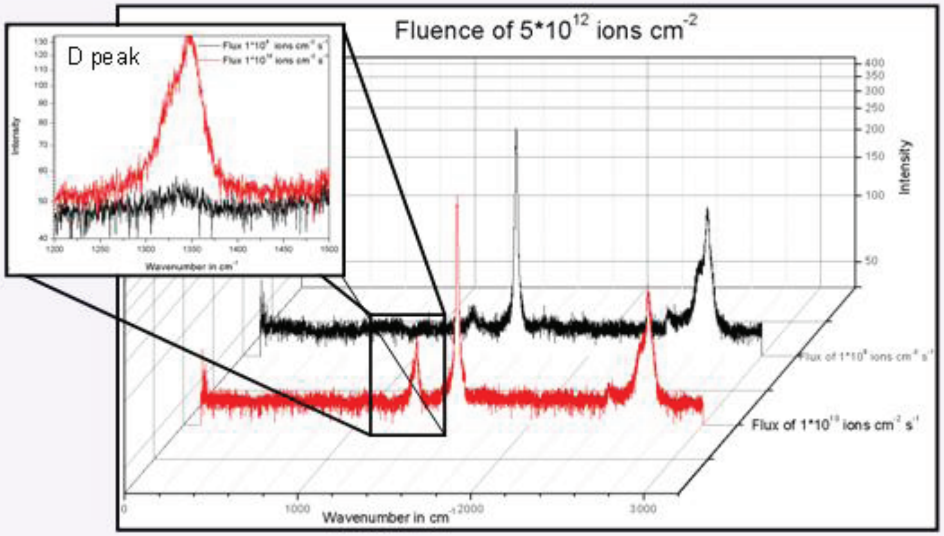
Increasing disordering with accumulated fluence;

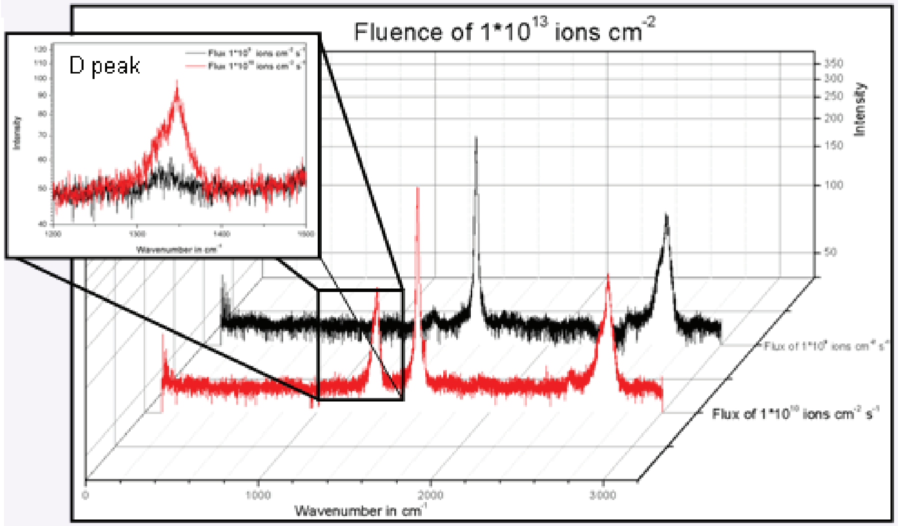
^{197}Au, 4.8 MeV/u,

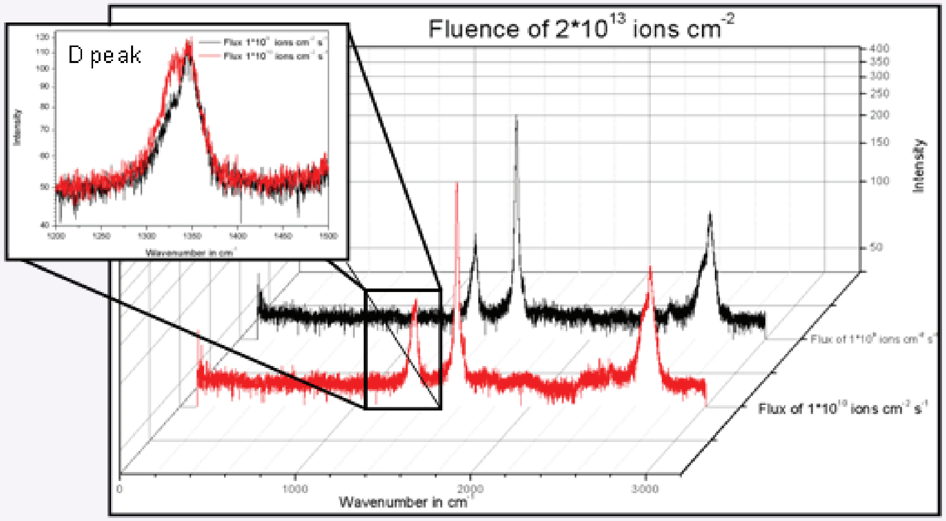
$1 \times 10^{12} - 1 \times 10^{14}$ i/cm^2

Defect formation as a function of dose and intensity - Raman spectroscopy on HOPG









Depth profiling of defects in along the ion track
defects in electronic stopping vs. nuclear stopping range

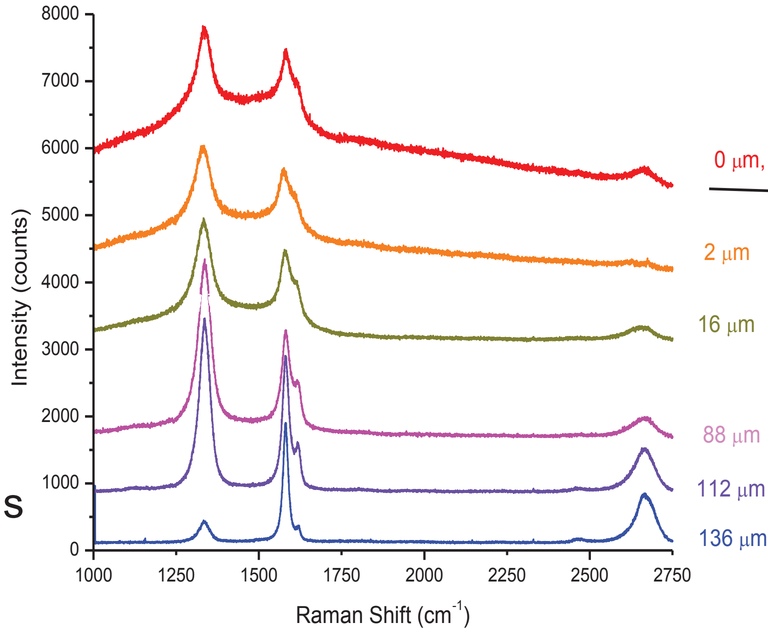
Fine-grained isotropic graphite exposed to $1x10^{13}$ ^{238}U ions/cm^2, 11.1 MeV/u

Raman spectra along the ion trajectory

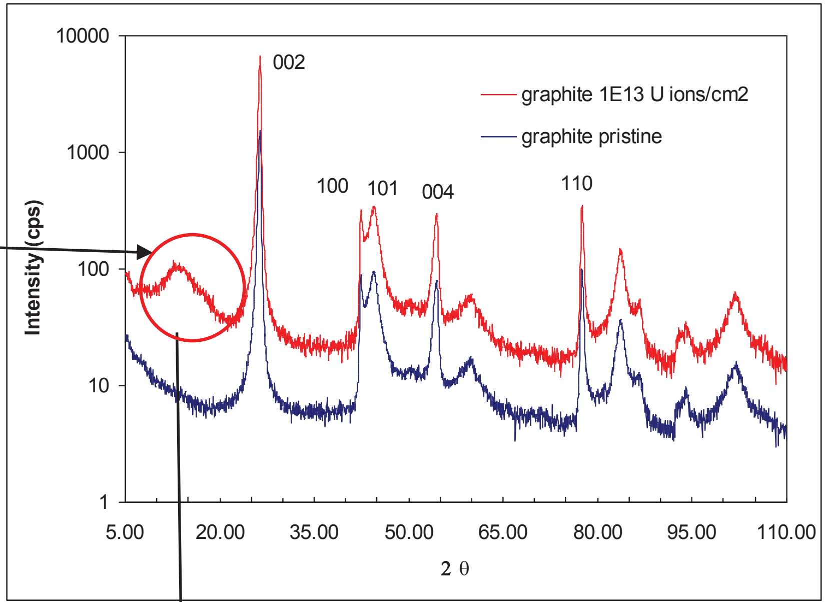
Sample surface

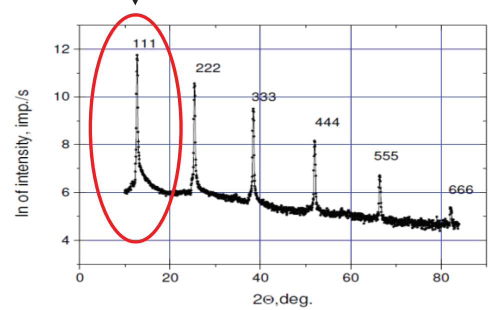
Elastic collisions

Bulk pristine



XRD

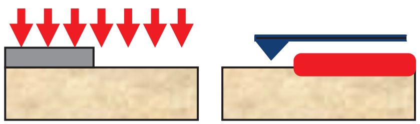




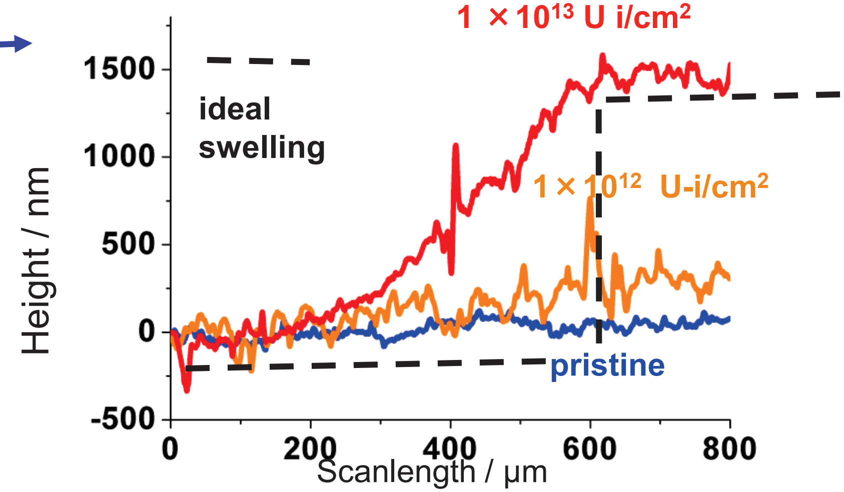
Fullerite

Ion- induced swelling and creep? Effects of high ion flux irradiation

Profilometry



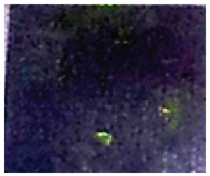
Low intensity U beams:
4.8 MeV/u,
flux $1x10^{8}$ i/cm^2 s



Out-of plane swelling - Profilometry

High intensity Au beams:
4.8 MeV/u,
flux $1x10^{10}$ i/cm^2 s

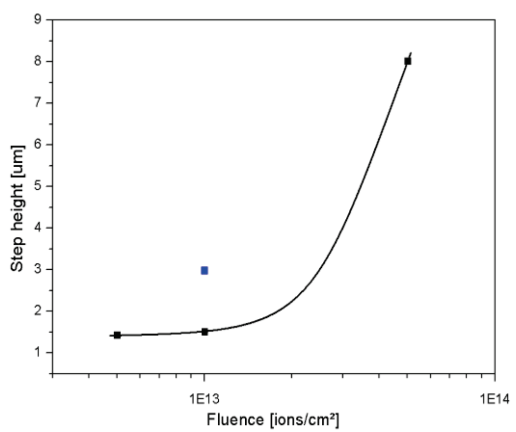
$5x10^{12}$ i/cm^2

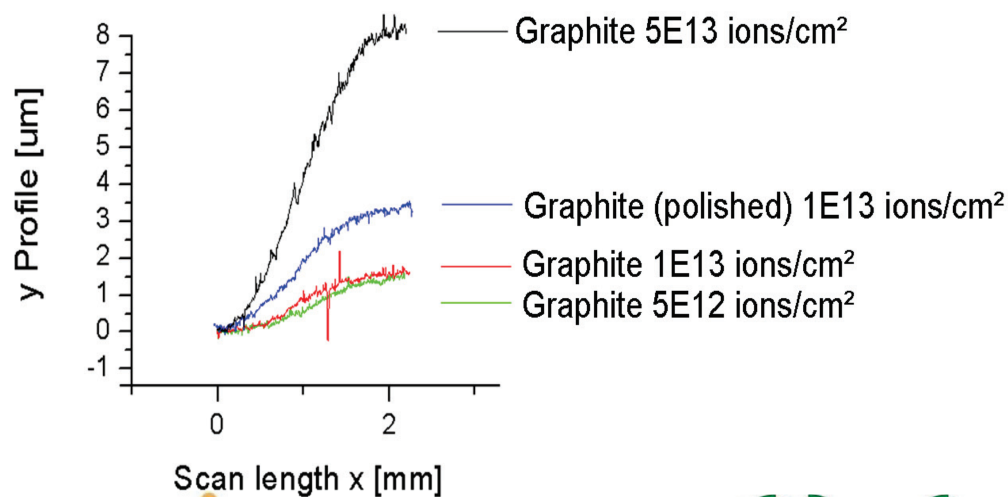


$5x10^{13}$ i/cm^2

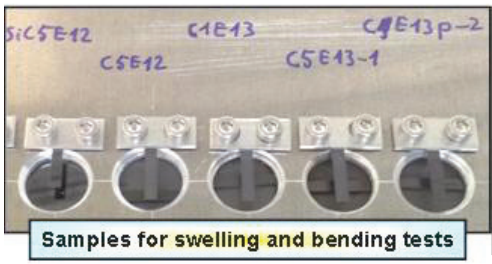
$1x10^{14}$ i/cm^2

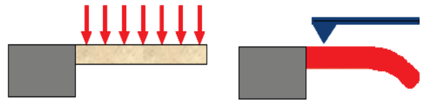
Step size dependence on fluence

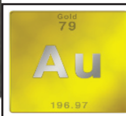




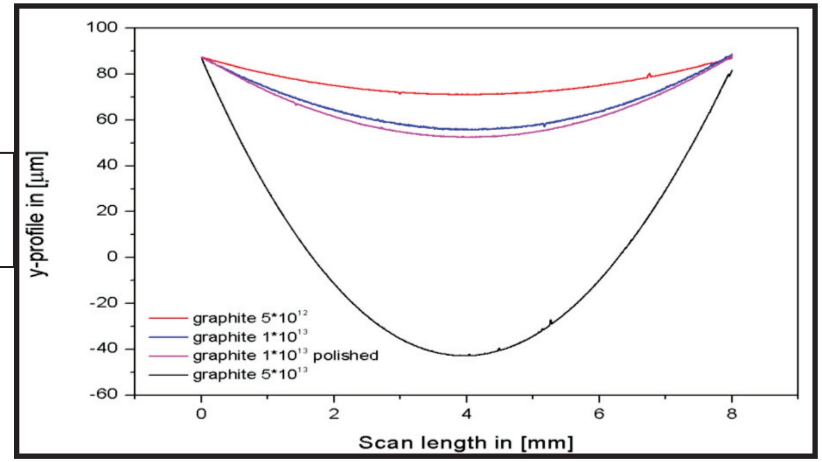
Irradiation- induced stress







Charge state: + 25
Energies: 4.8 MeV/u
Fluences up to $5x10^{13}$ i/cm^2



Swelling ⇨ Stress ⇨ Bending

$$\sigma_{rr}^{f} \simeq -\frac{E_s h_s^2}{6(1-\nu_s)h_f}\frac{1}{R_r}$$

E_s = elastic modulus

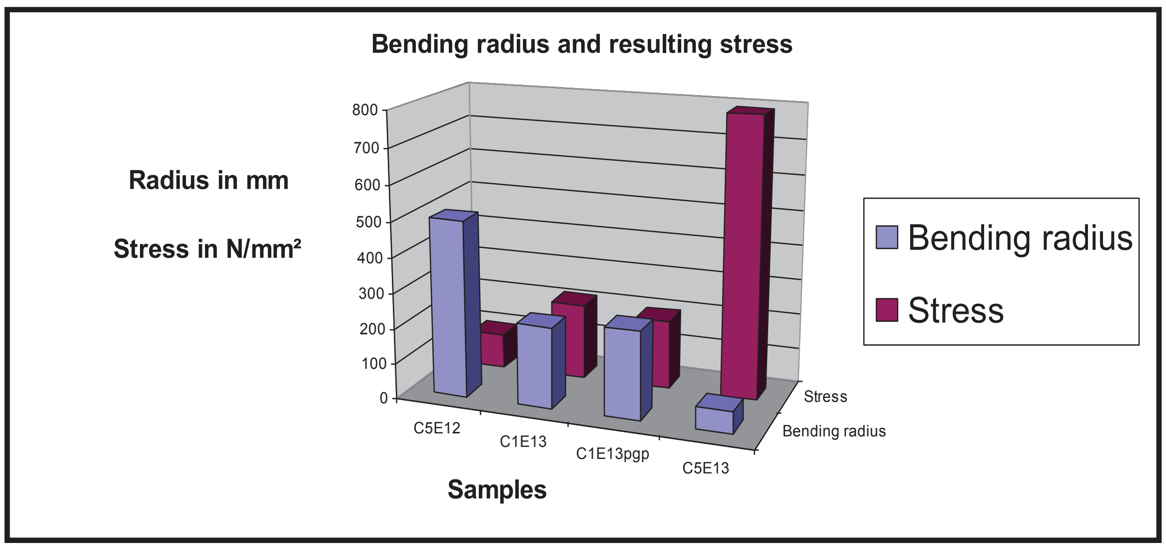
h_s = sample thickness

h_f = irradiated layer thickness

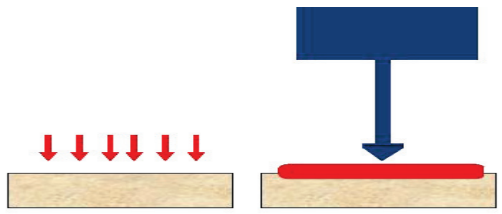
R_r = bending radius

ν_s = Poisson number

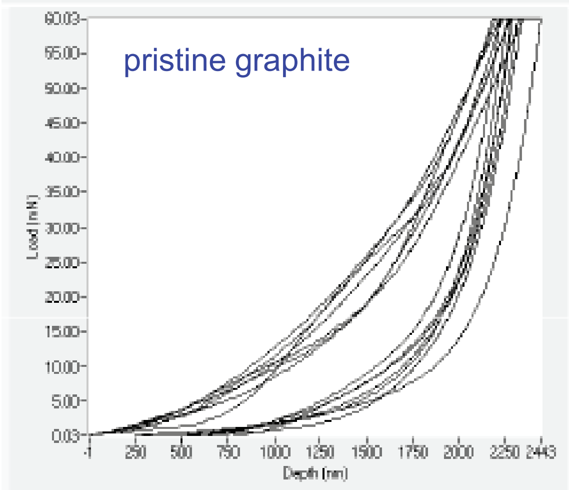
σ^f_{rr} = stress

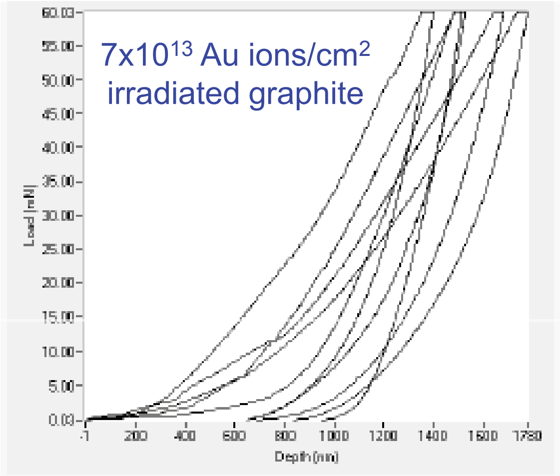


Ion- irradiation induced hardening

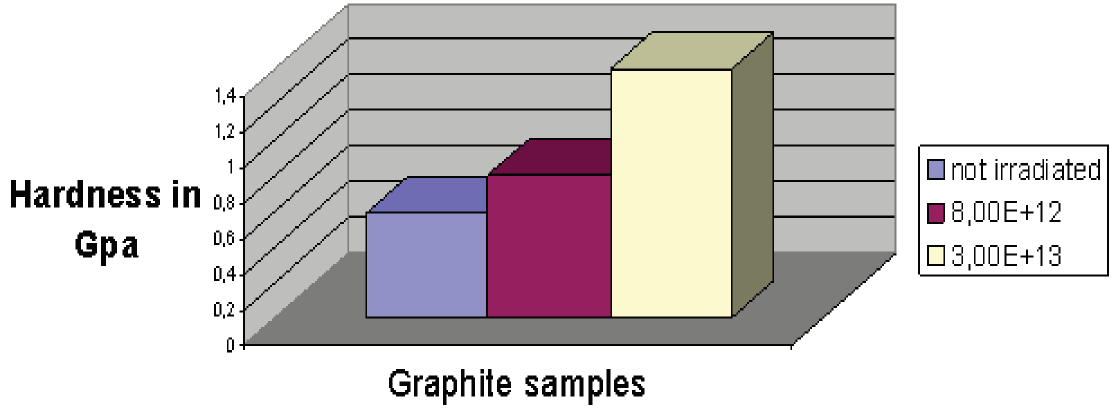


Charge state: + 25
Energies: 4.8 MeV/u
Fluences up to 7x10^{13} i/cm^2





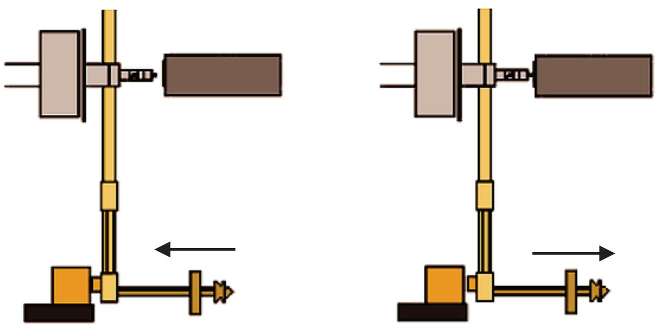
Hardening induced by irradiation of swift heavy Au ions (4,8 MeV/u)

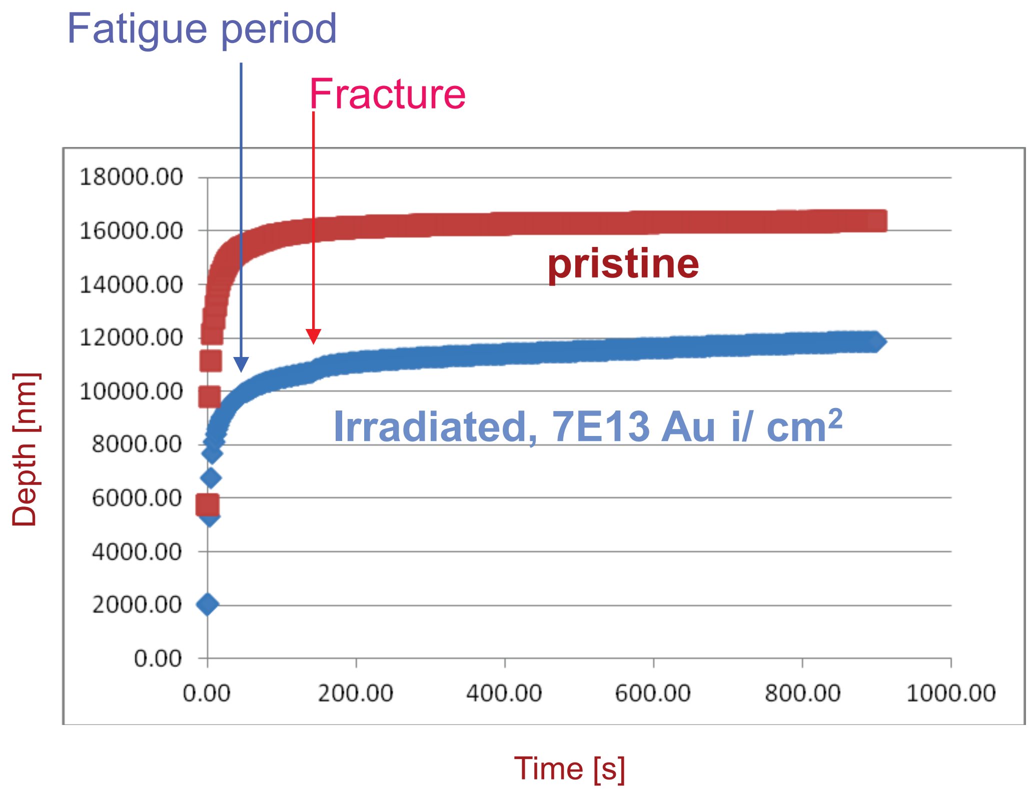


Fatigue resistance degradation of ion- irradiated graphite

Nanoindentation impact testing of Au irradiated graphite

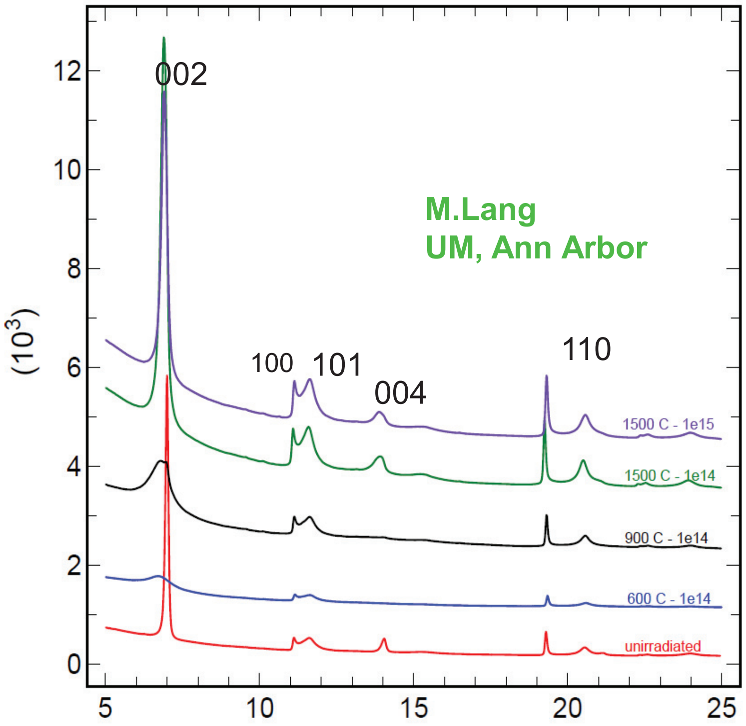
Cube Corner 20 mN max load; comparison pristine and irradiated samples



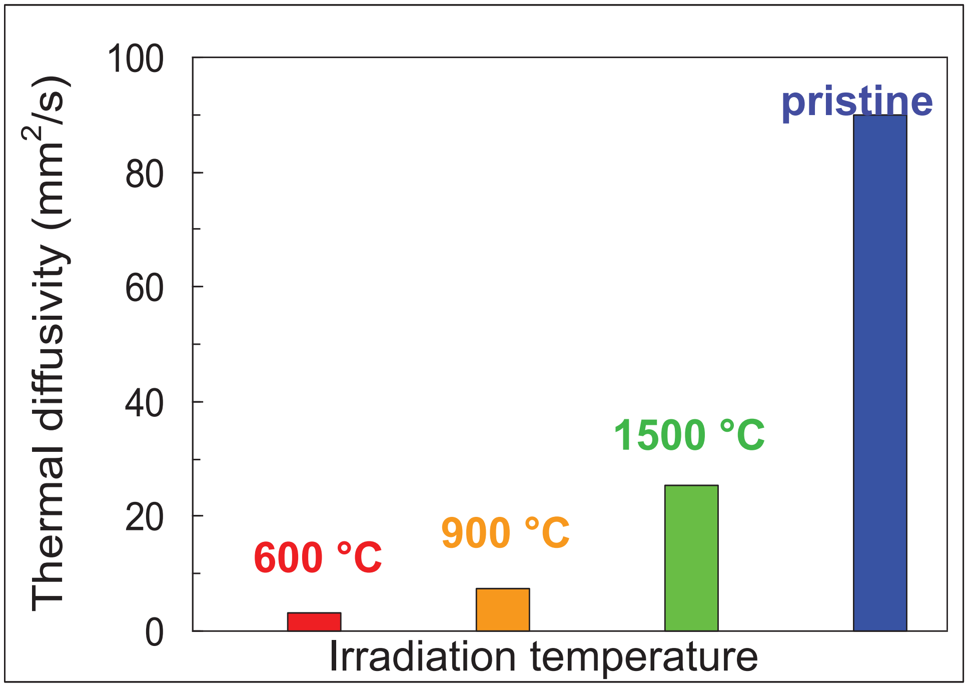


Structural defects recovery and effects on thermal conductivity for HT irradiation

XRD



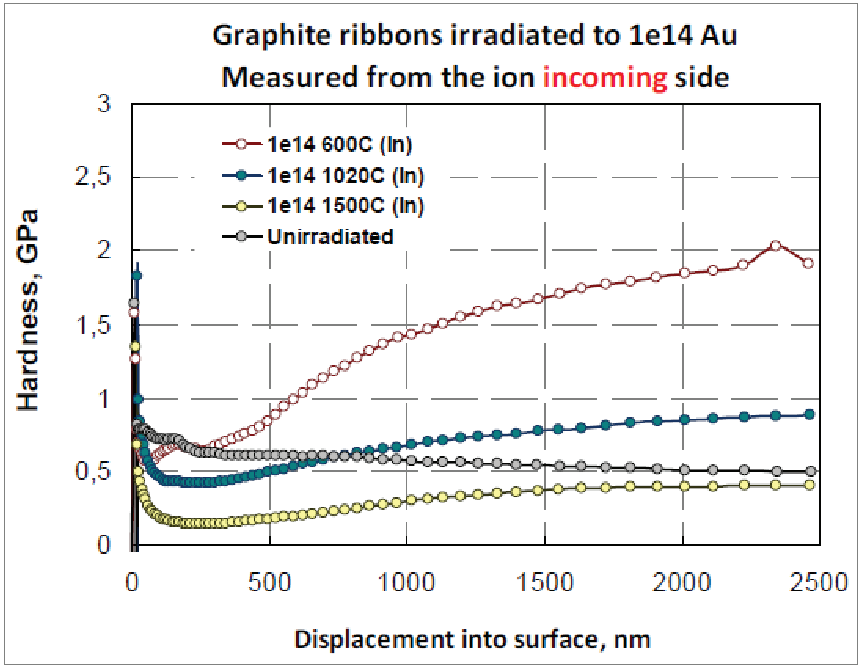
Thermal diffusivity



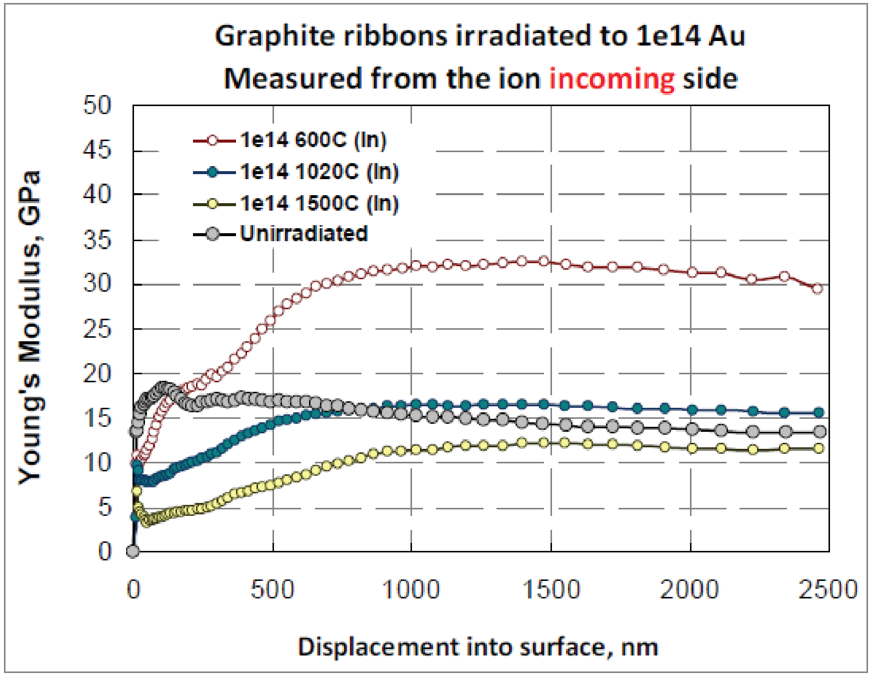
Fine-grained isotropic graphite irradiated to $1x10^{14}$ with ^{197}Au ions/cm^2, 8.6 MeV/u at increasing temperatures

Influence of high temperature irradiation on hardening and embrittlement

Hardness



Young modulus



Fine-grained isotropic graphite irradiated to $1x10^{14}$ with ^{197}Au ions/cm^2, 8.6 MeV/u at increasing temperatures

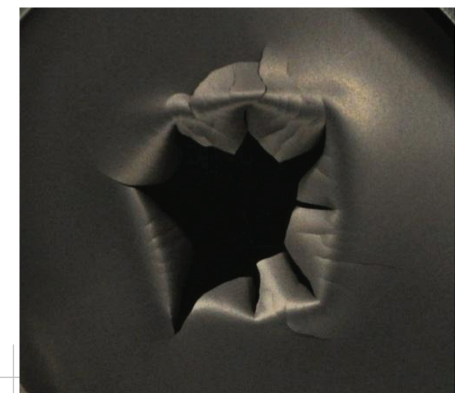
Effect of pulsed beams

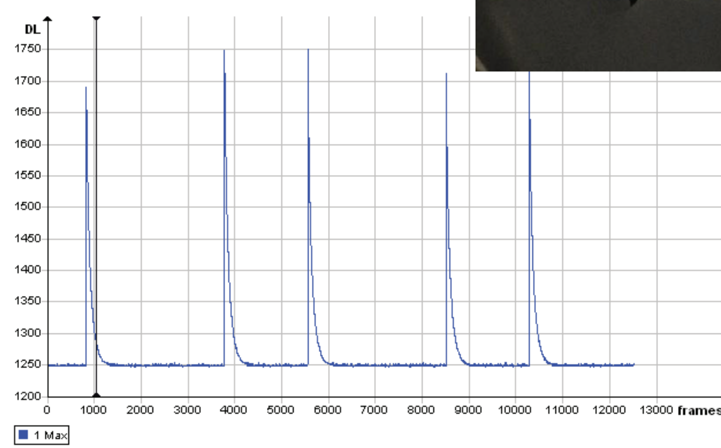
Quasi-continuous irradiation

^{197}Au: 5ms, 48 Hz, 4,8 MeV/u
accumulated fluence 1x10^{14} i/cm^2

Pulsed beams

^{197}Au: 150µs, 0.4 Hz, 4,8 MeV/u
accumulated fluence 1x10^{14} i/cm^2





Conclusions

General:

- Ion-induced disordering of graphite different form neutrons ⇨ swelling, stress concentrators, bending, hardening, degradation of thermal conductivity and fatigue resistance
- A steep degradation of properties takes place at doses corresponding to ion track overlapping (given by ion track size – depends on ion mass and energy)
- High temperature (above 1000 °C) operation of graphite extends lifetime due to defect recovery

Pulsed beams- FAIR & LHC:

- Fatigue induced by cyclic thermo-mechanical loading reduces lifetime
- Due to creep there is some stress accommodation, but lifetime depends on how much deformation one could tolerate

Monitoring systems for target materials

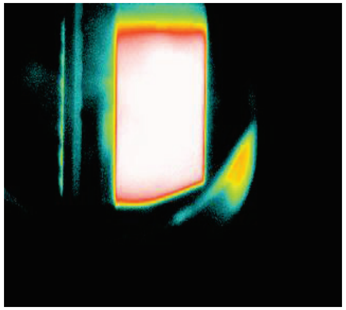
Problem: How to predict and localize failure

- in extreme operation conditions
- in high radiation fields
  - targets
  - protection elements
    (beam catchers, collimators)
  - rf cavities

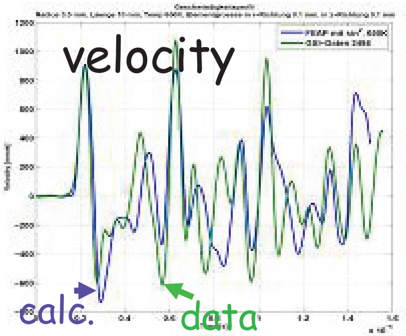
possible monitor systems to be tested

- Thermal imaging
- Acoustic emission
- Laser interferometry
- Resistivity monitoring - non-contact

Thermal imaging

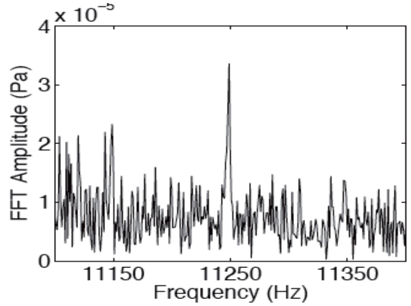


Laser vibrometer



Eddy current

Acoustic emission monitoring - LHC collimators



D. Deboy (CERN)

Collaborators

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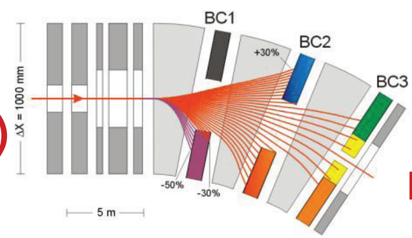
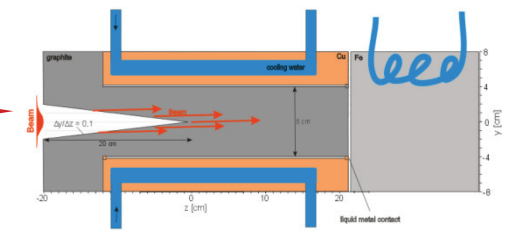
GRESPI-ECATHERM, Univ. Reims, France:
N. Horny, M. Chirtoc

Super-FRS production target: key parameters

Beam





1.5 A GeV ^{238}U
5×10^{11} ions/pulse
E ≈ 60 kJ

graphite (800 K)
small beam spot
E ≈ 10 kJ

graphite
large beam spot
E ≈ 40 kJ

medium Z
(neutrons)
E ≈ 10 kJ

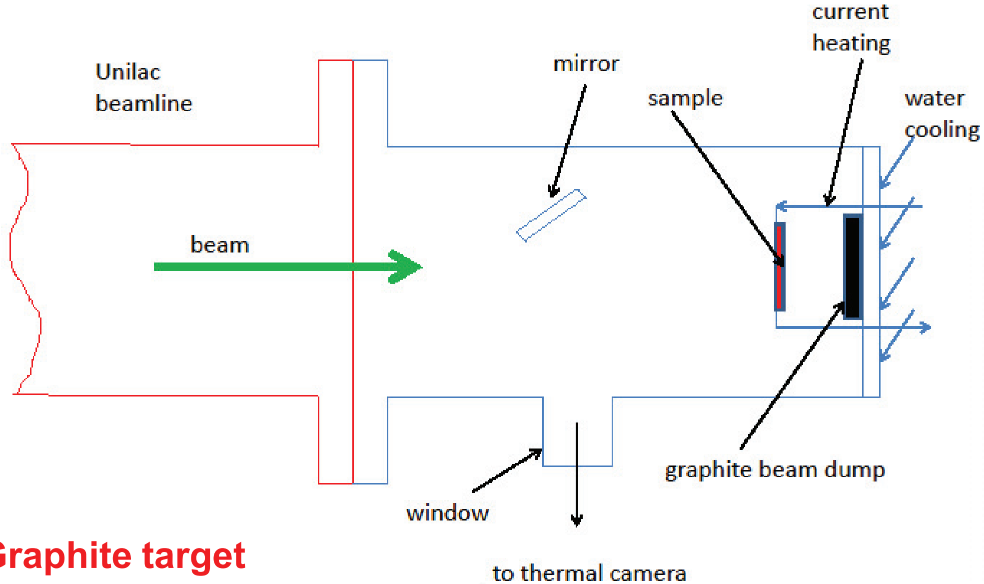
Case 1:
slow extraction (≈ 1 s); ~ 12 kW
→rotating wheel target
→**E/M ≈ 0.15 kJ/g**

Case 2:
fast extraction (≈ 60 ns); ~ 200GW
→rotating wheel target or liquid-metal target
→**fast: E/M ≈ 12 kJ/g!**

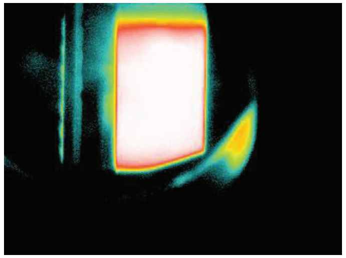
problems to face:
- radiation damage → material degradation
  thermal conductivity reduction, embrittlement, swelling
- intense transient loads → pressure waves
- cyclic thermal loads → thermal fatigue

High temperature irradiation of graphite targets

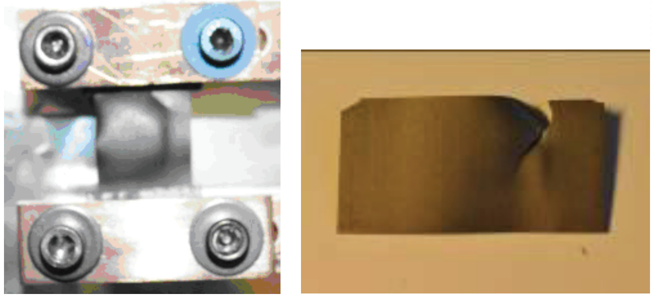
collaboration with W. Mittig et al. (MSU, FRIB)



Graphite target



In-beam thermal imaging



severe swelling and irradiation-induced stresses

M-branch UNILAC