Ion-irradiation induced degradation of thermo-mechanical properties of carbon-based materials

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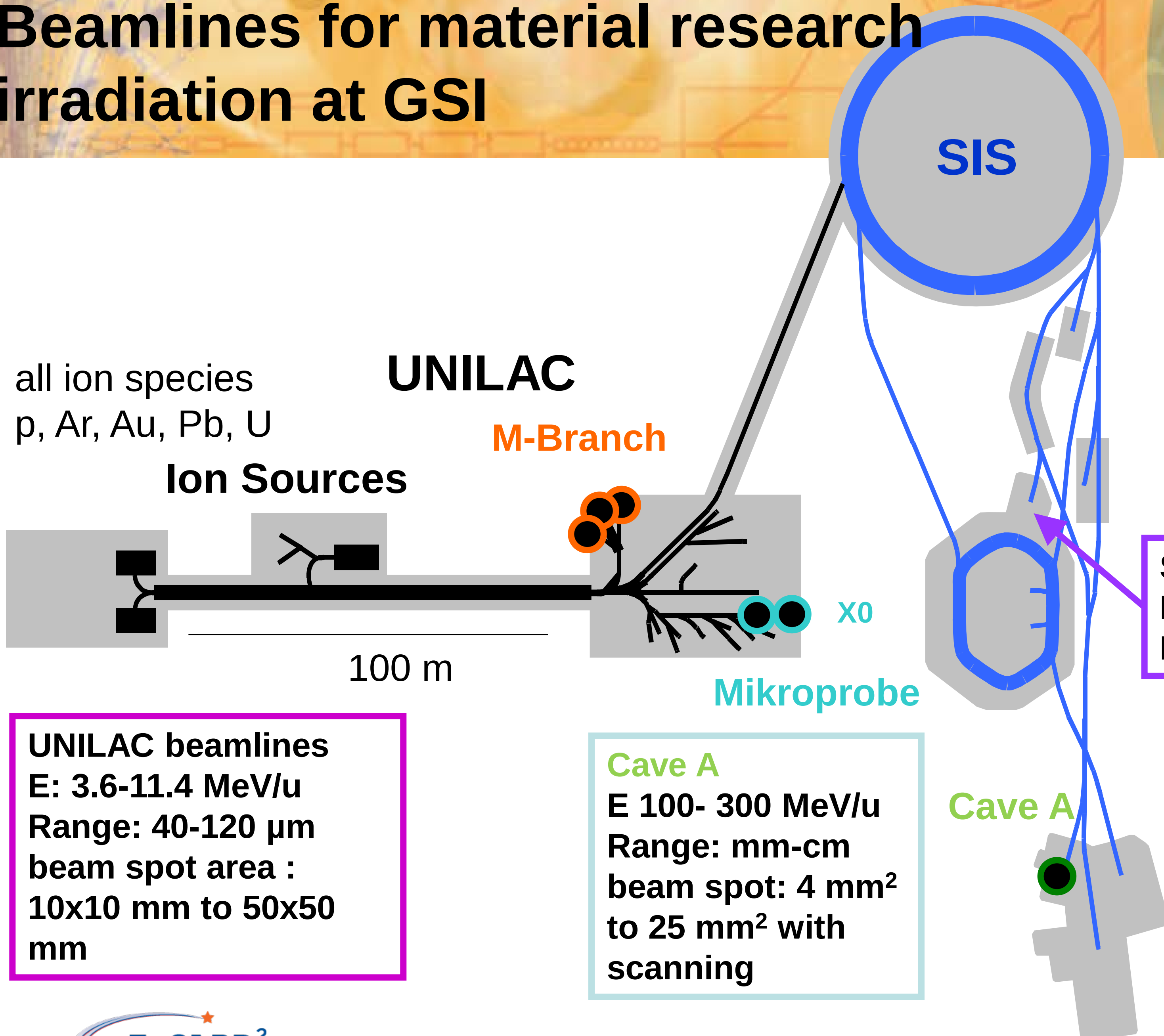
Summary

- Materials irradiation facility at GSI
- Irradiation experiments: online and post-irradiation evaluation
- Radiation -induced thermal diffusivity degradation in graphite
- Nanoindentation investigation of mechanical properties of irradiate carbon materials
- Fatigue tests using nanoindentation
- First online creep tests on ion -irradiated carbon materials

Materials irradiation facilities at GSI

Beamlines for material research irradiation at GSI



SIS 18 beam dump
E up to 1 GeV/u
Range: cm

UNILAC beamlines
E: 3.6-11.4 MeV/u
Range: 40-120 µm
beam spot area :
10x10 mm to 50x50 mm

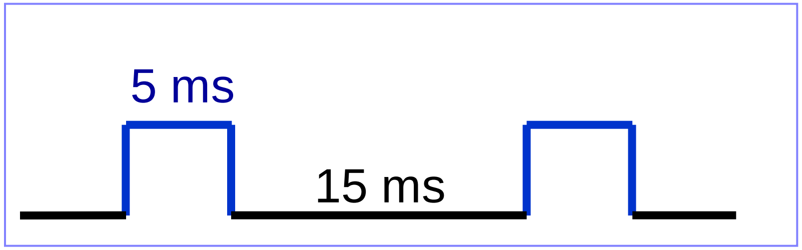
Cave A
E 100- 300 MeV/u
Range: mm-cm
beam spot: 4 mm² to 25 mm² with scanning

UNILAC: beam parameters

3.6 / 4.8 / 5.6 / 8.6 / 11.4 MeV/u typical energies

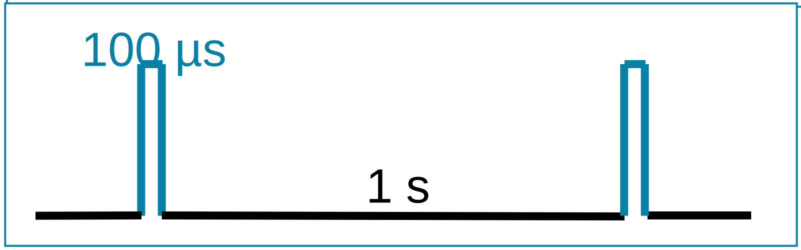
50 Hz Mode (Penning, ECR)

50 Hz
5 ms length of macropulse

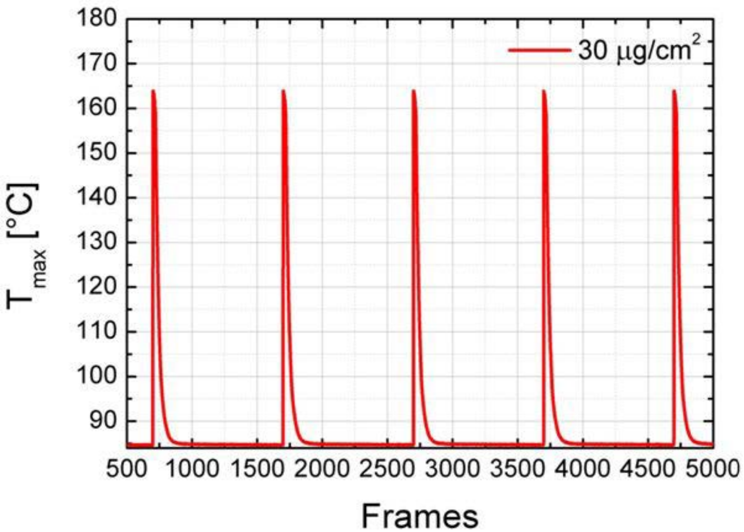


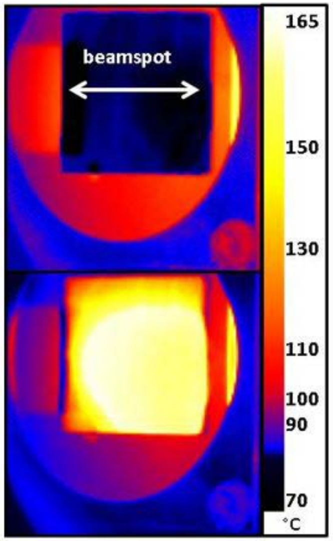
high-current mode (MEVVA source)
(for SIS experiments)

1-2 Hz
100-200 µs length of macropulse



Thermal camera monitoring of sample temperature





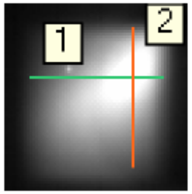
Low duty cycle

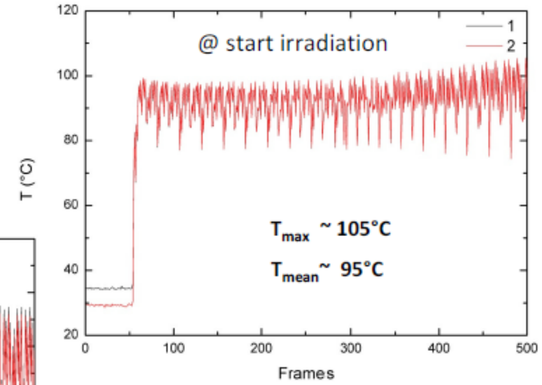
High duty cycle

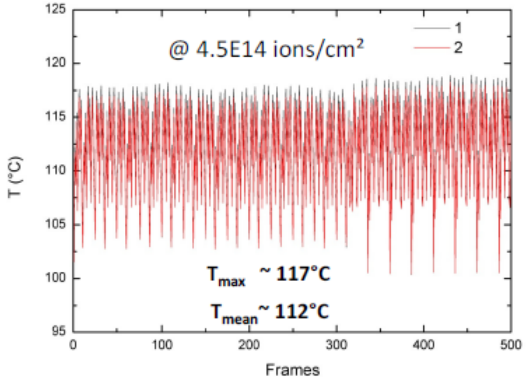
norphous Carbon, 21 µg/cm² (Targetlab)

/u, 38 Hz, 4ms, defocused beam, beamspot 1.7x1.7cm (Ø sample 30mm)

flux: 1.0E10 ions/cm²s

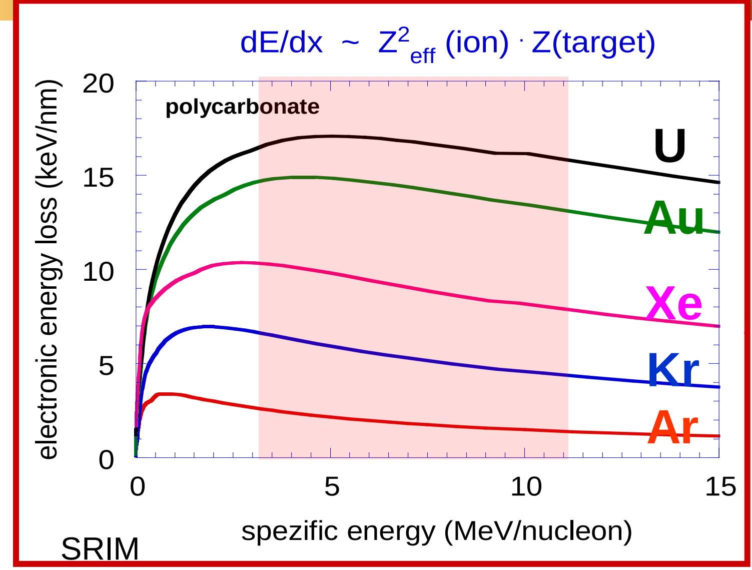




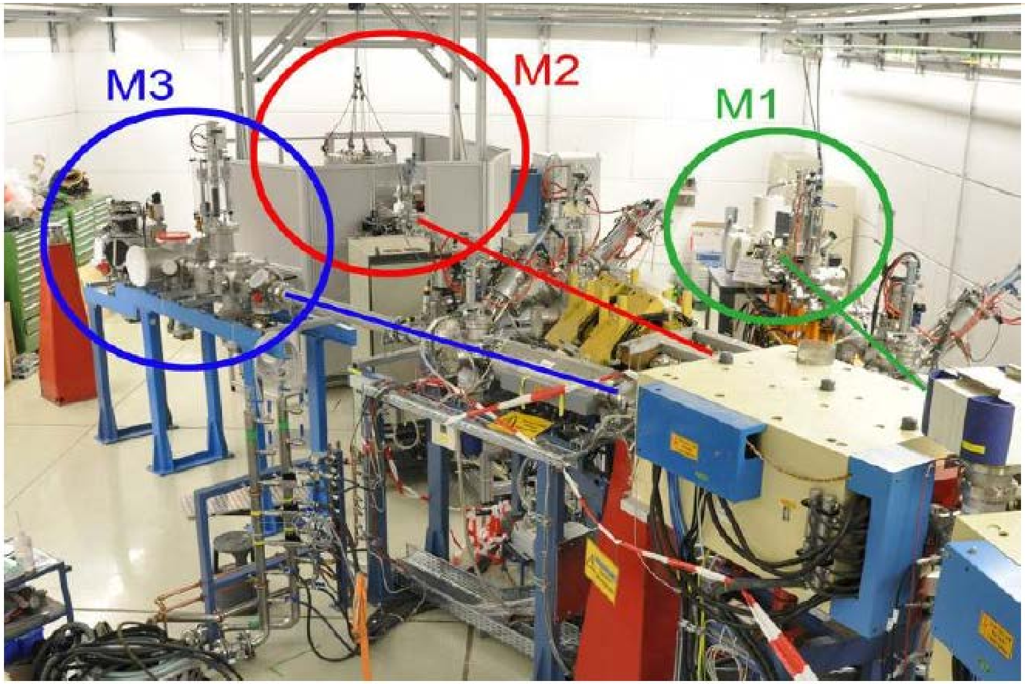


M-branch irradiation facility at GSI
In situ experiments

- energies close to Bragg peak:
  - to maximize energy deposition and damage
  - to avoid activation
- online and in situ monitoring: video camera, fast IR camera, SEM, XRD, IR spectroscopy



SRIM code

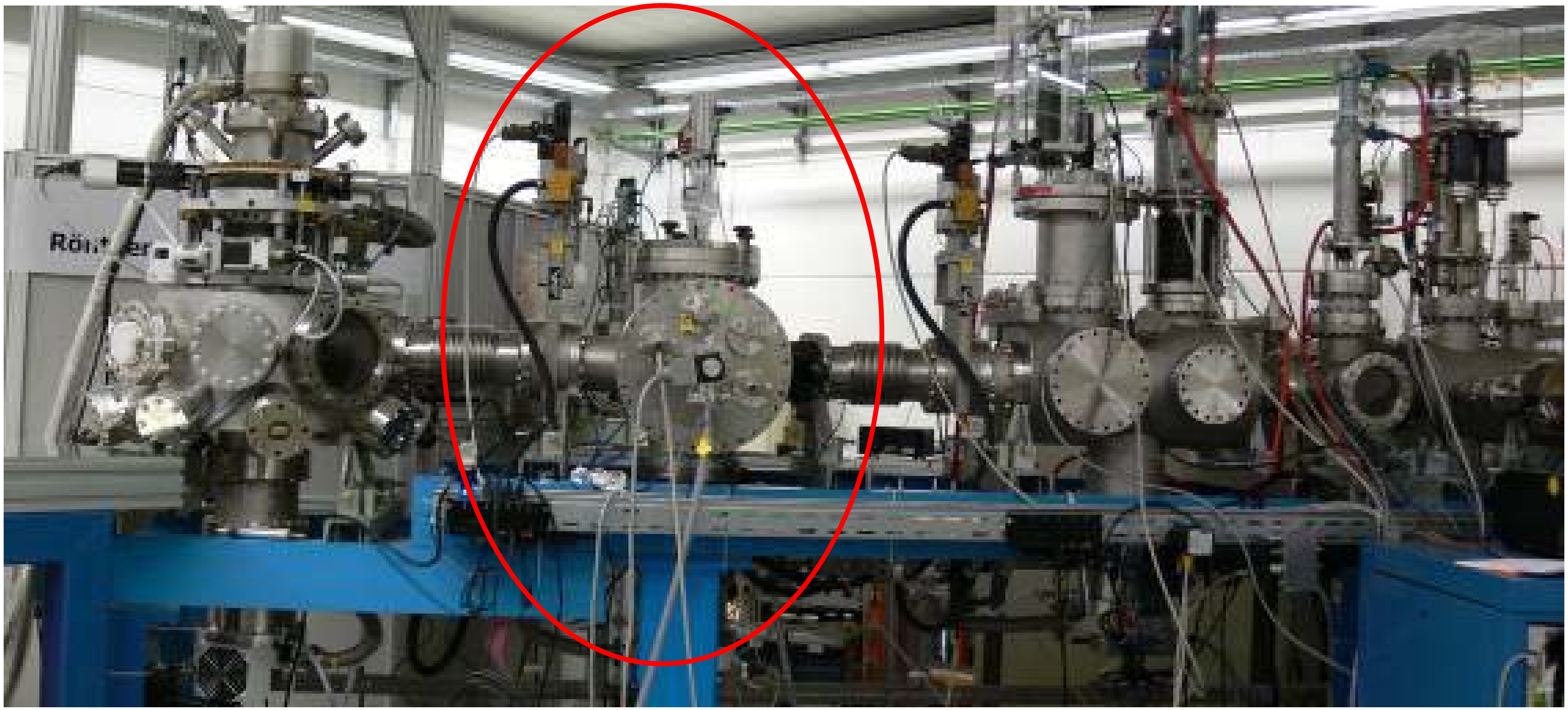


ion species ..C…Xe...U

flux:
up to10^{10} ions/cm^2 s

Irradiation experiments at M3-branch, UNILAC, GSI

- ^{238}U, 1.14 GeV, 0.5 ms, 0.6 Hz, 4x10^{9} ions/cm^{2} s
- ^{208}Bi, 1 GeV, 0.5 ms, 3.4 Hz, 1.2x10^{9} ions/cm^{2} s
- ^{197}Au, 945 MeV, 2ms, 40 Hz, 4x10^{9} ions/cm^{2} s



Irradiation experiments

- online

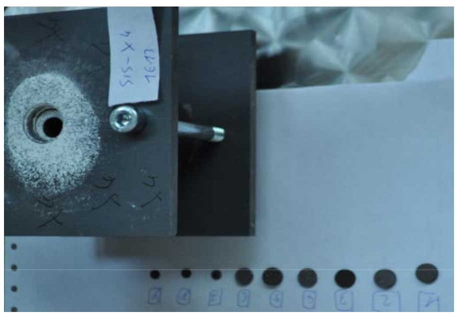
- post-irradiation evaluation

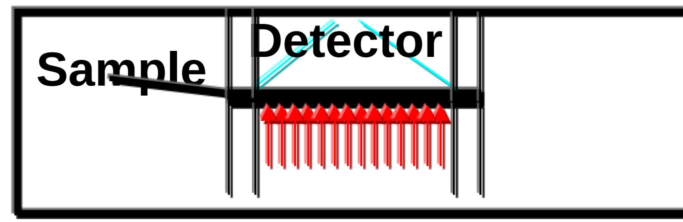
Thermal properties degradation -poistirradiation evaluation

fluences: 1e11, 1e12, 1e13, 5e13/1e14 i/cm^2 at fluxes ~5e9 i/cm^{2}s

Samples for LFA: Isotropic graphite and flexible graphite

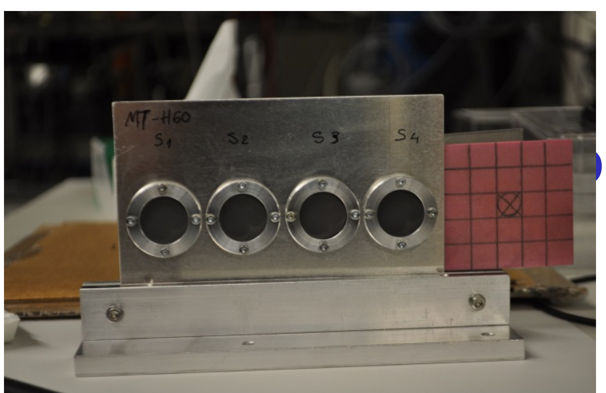
– classical transmission measuring geometry

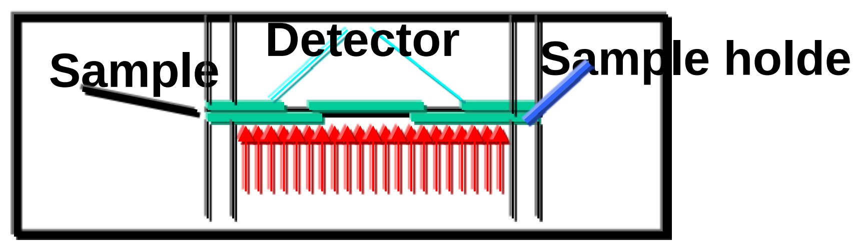




Transmission

– in-plane measuring geometry





In-plane

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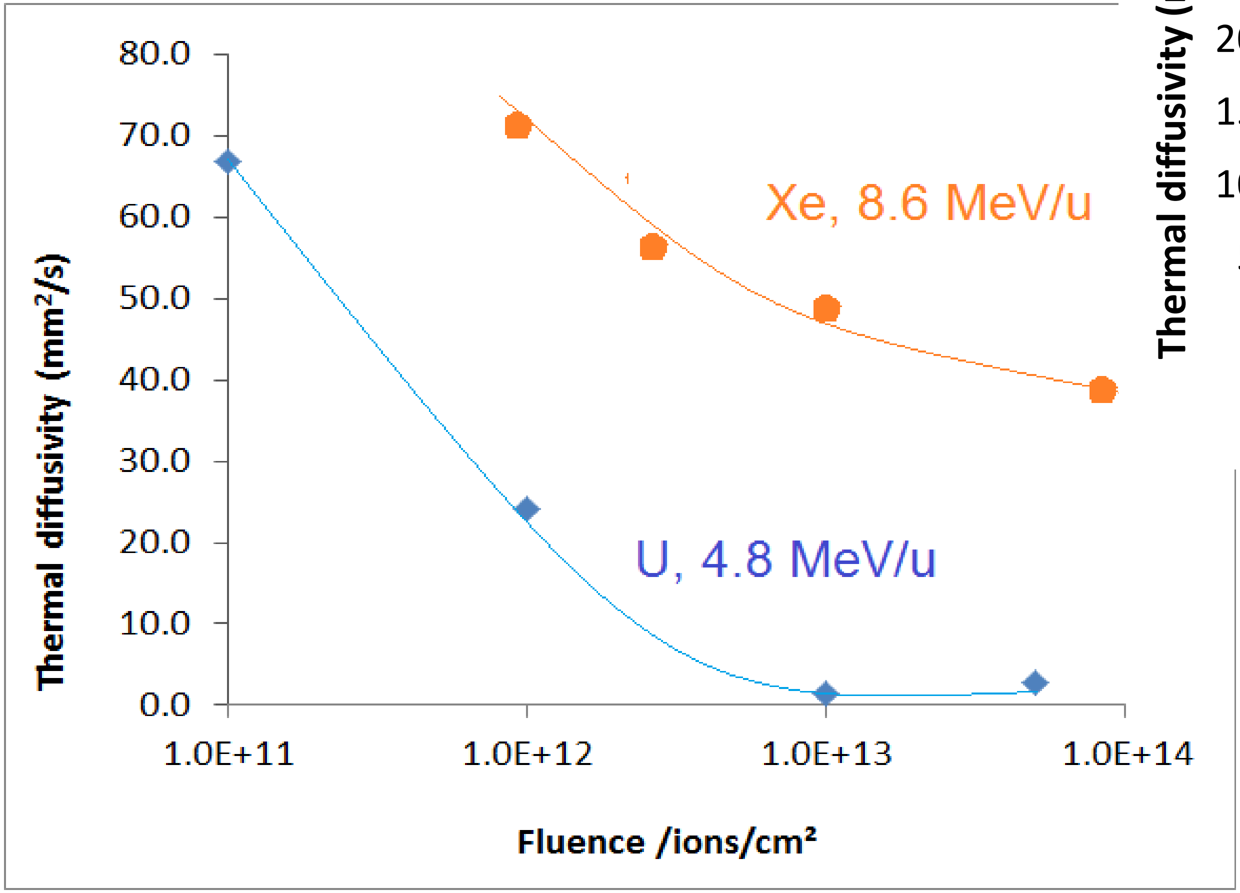
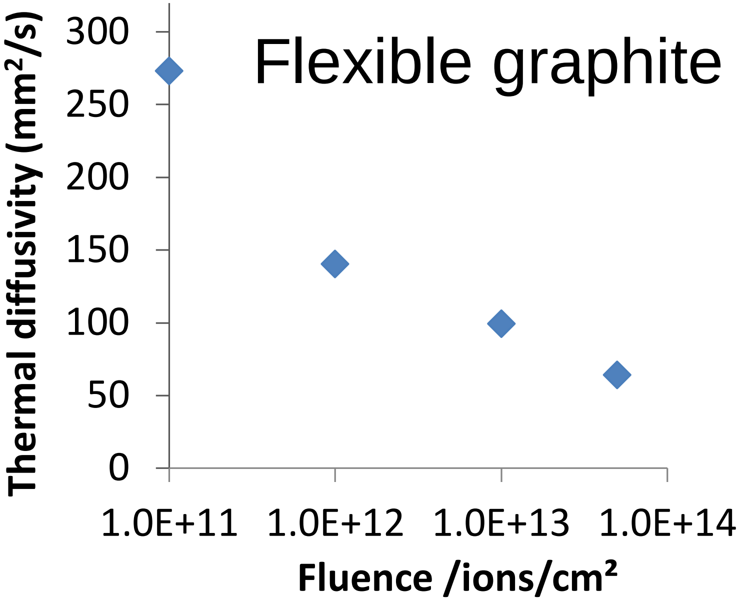
Ion-induced thermal diffusivity degradation of graphite

Comparison U vs Xe irradiation
graphite vs flexible graphite



Isotropic graphite



Flexible graphite

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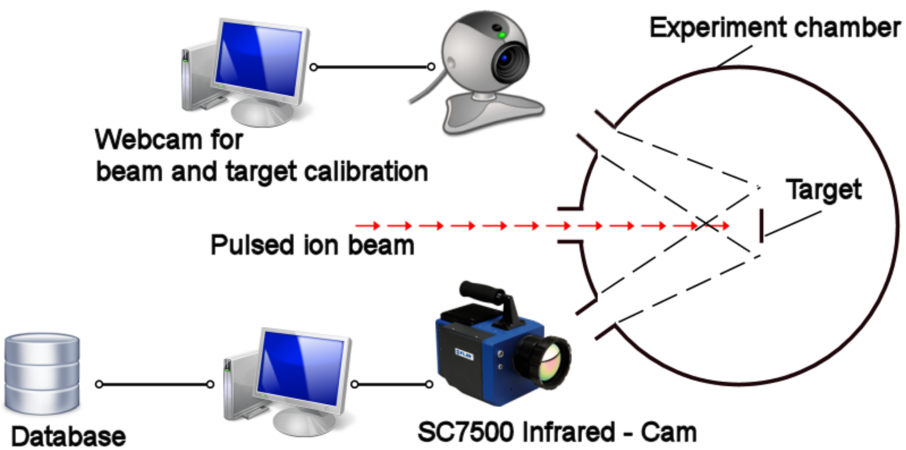
Online monitoring of thermal properties degradation

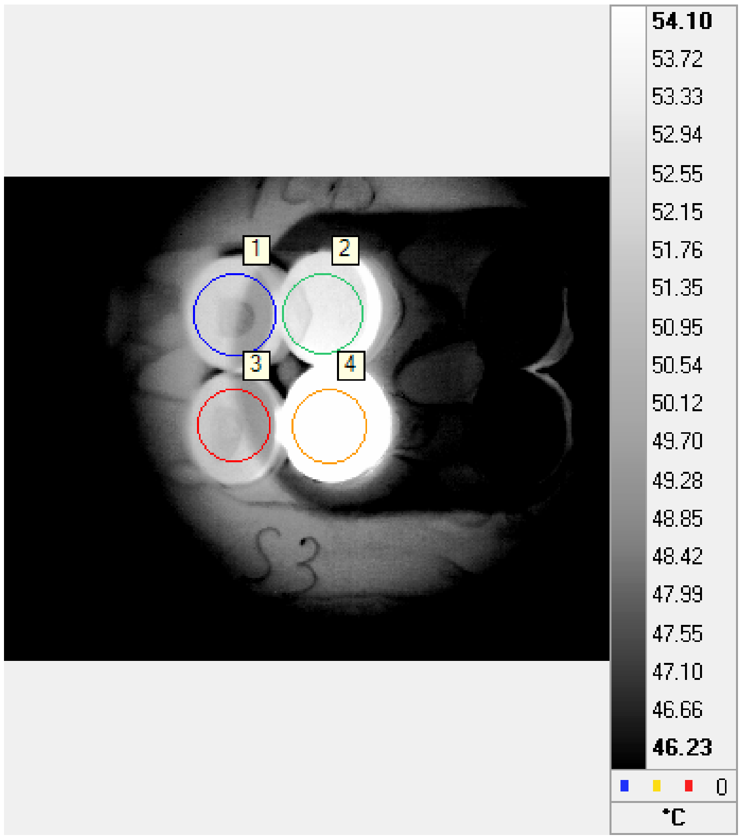
fluences: significant increase of experimental points number due to online capabilities i/cm^2

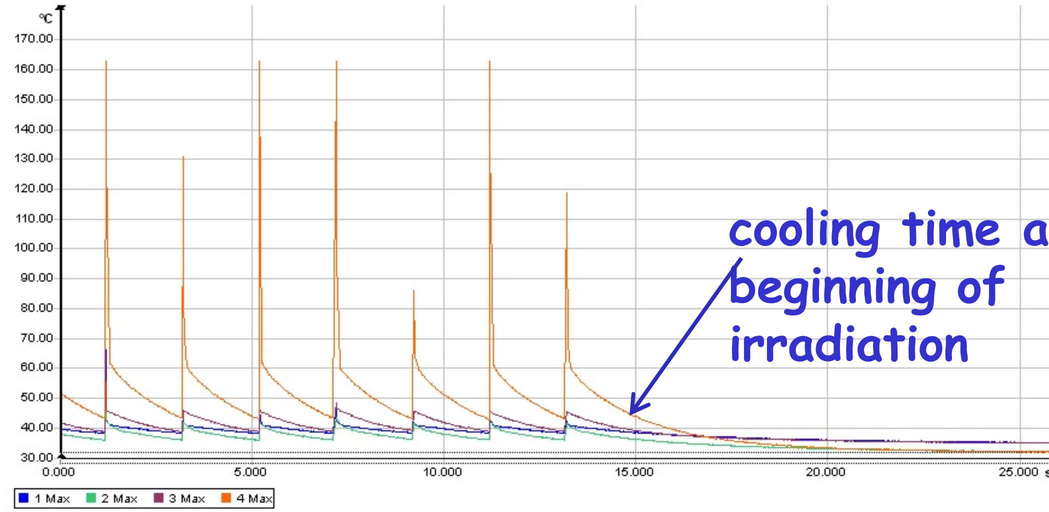
at fluxes ~5e9 i/cm^{2}s

- Thermal conductivity degradation monitoring (on-line using thermal camera: estimation of time constant at cooling)
  - Cu-CD, Mo-Gr: 2orientations,CFC: 2 orientations (U, Bi)

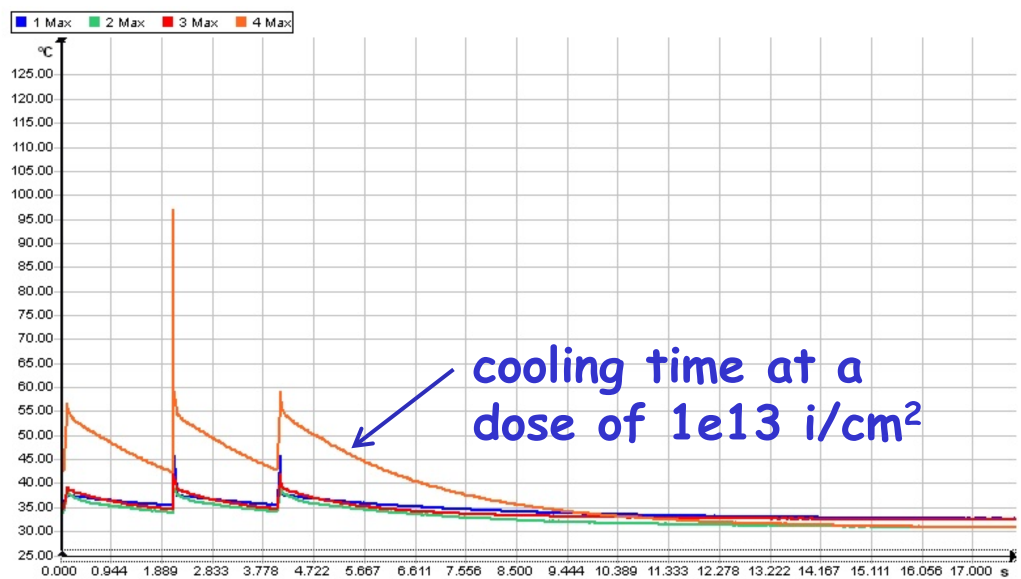


Thermal camera monitoring of sample temperature during cooling





cooling time at beginning of irradiation



cooling time at a dose of 1e13 i/cm^2

Temporal evolution of maximum temperature in irradiated samples

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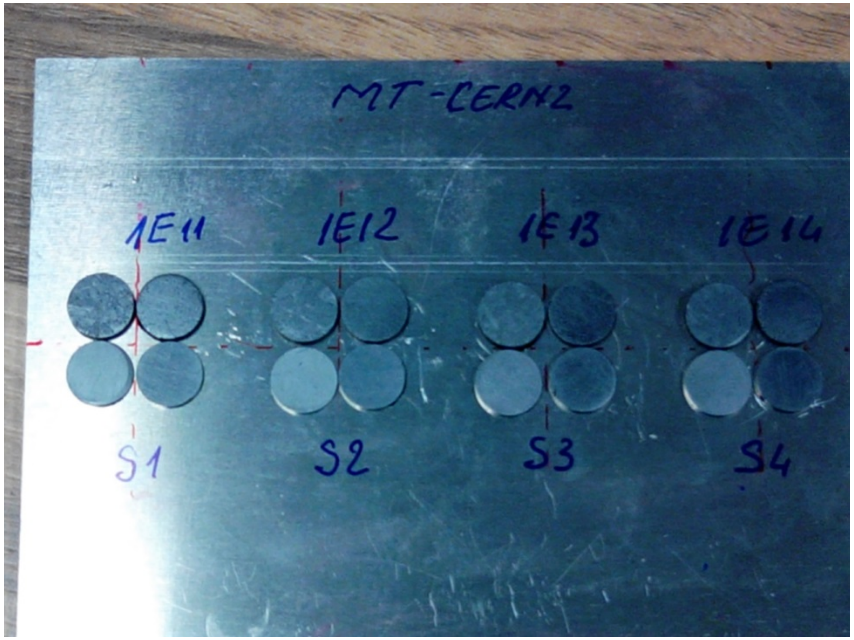
Post-irradiation tests

- Samples for off-line tests: U, Bi, Au, Xe
- Isotropic graphite, low density graphites: foams and flexible graphite grades,CFC: 2 orientations



Microstructural characterization:

- Raman spectroscopy,
- SEM

Mechanical properties:

- Nanoindentation,

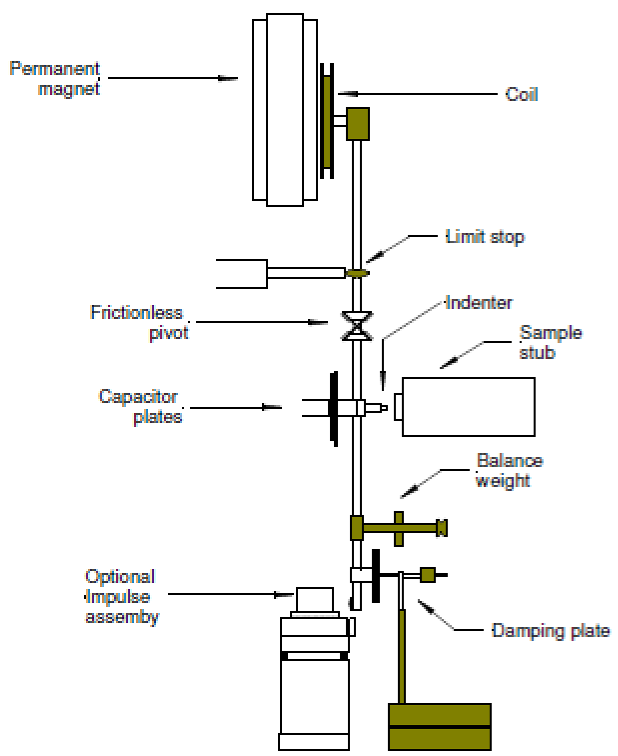
Electrical properties:

- 4.point probe resistivity measurements

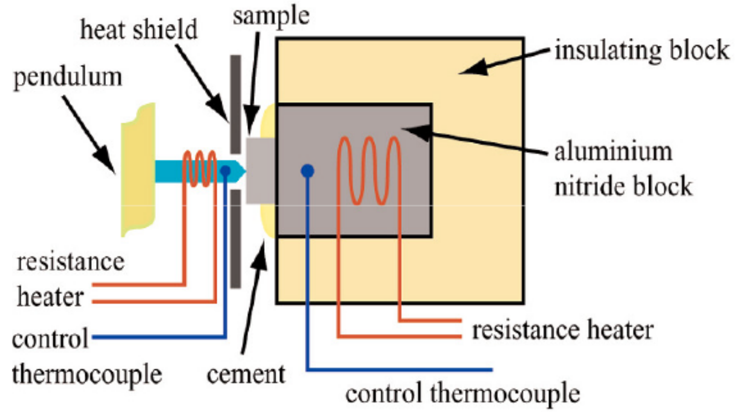
Mechanical properties degradation-nanoindentation

investigations of hardening and E modulus change of irradiated layers

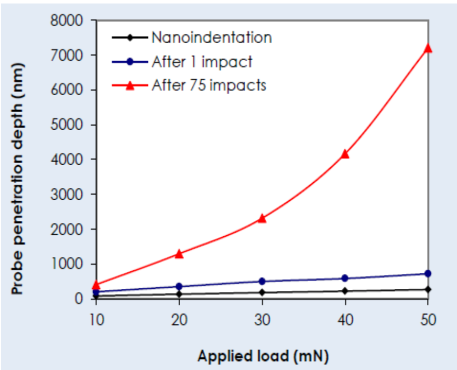
high temperature

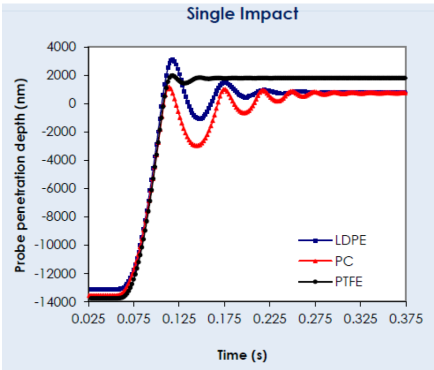


Courtesy LOT Quantum Design



Impact: fatigue damping





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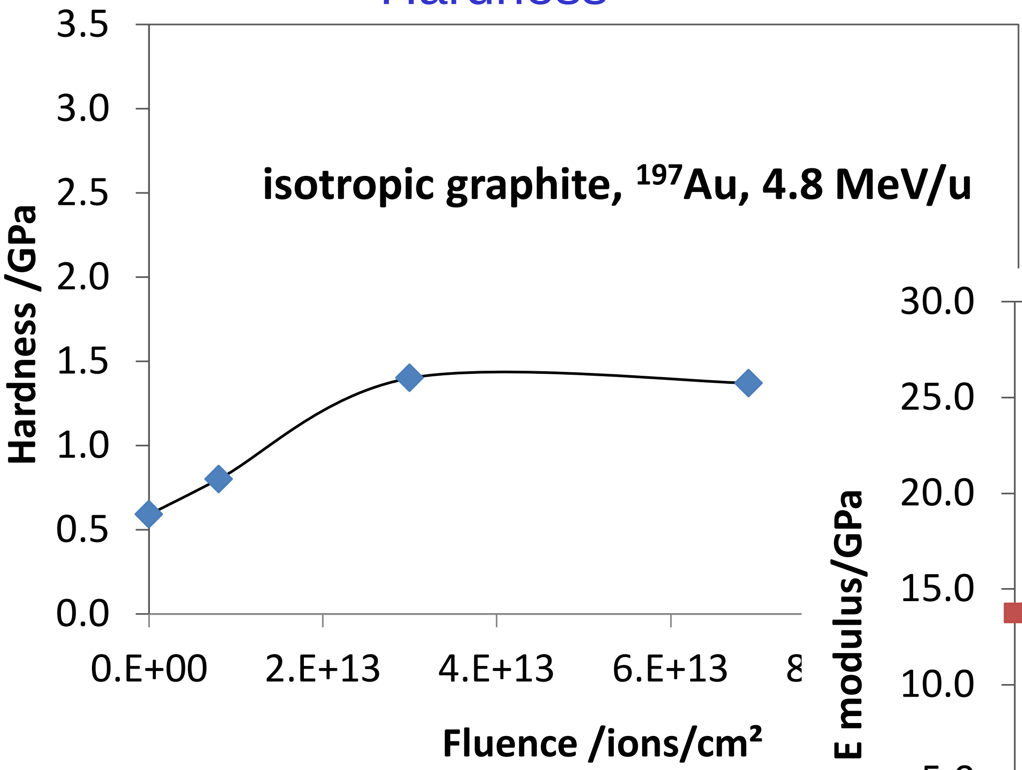
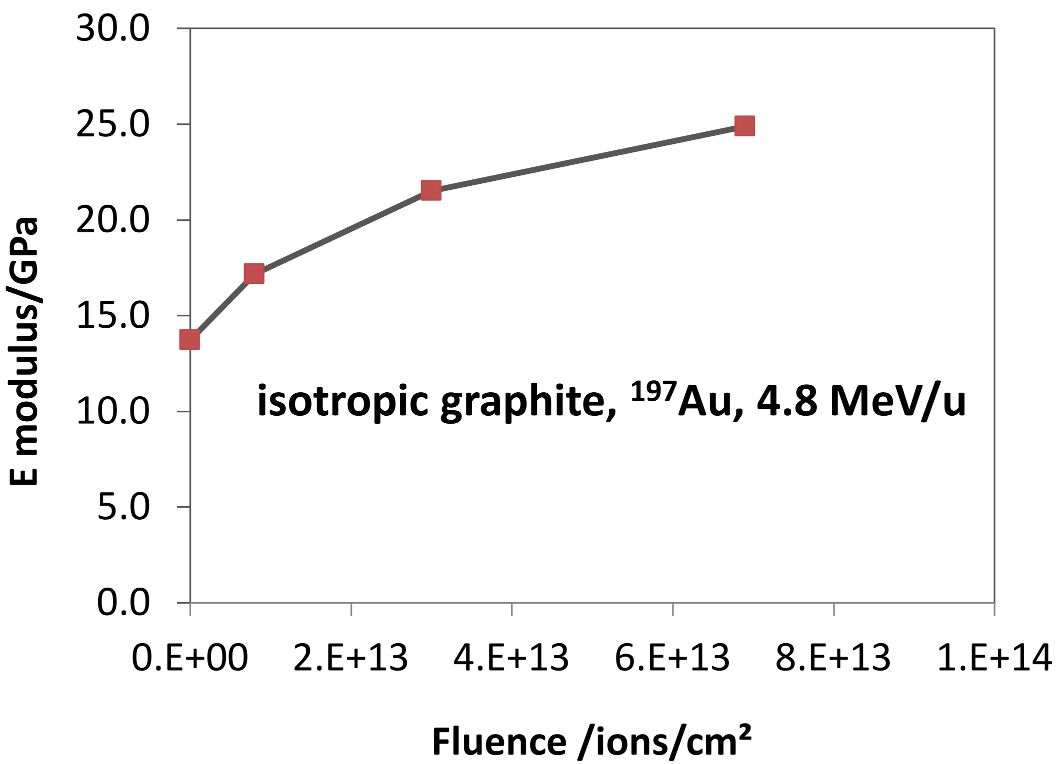
Mechanical behaviour of irradiated isotropic graphite

Evolution with accumulated dose:

Hardness



Young modulus



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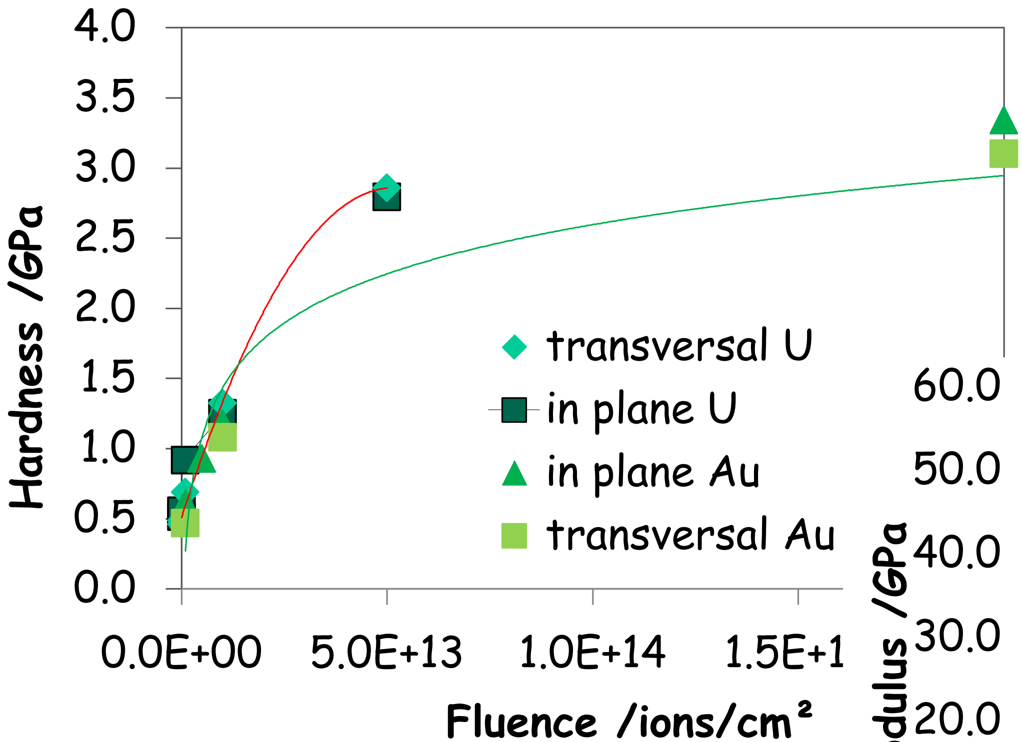
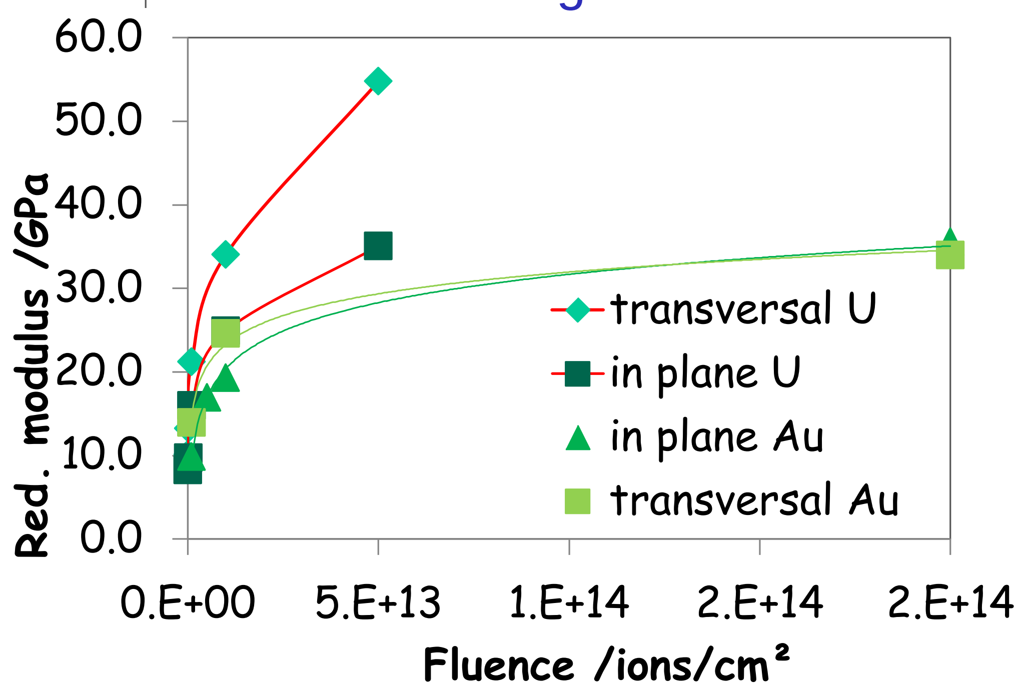
Mechanical behaviour of irradiated CFC

Evolution with accumulated dose:
Hardness



Young modulus



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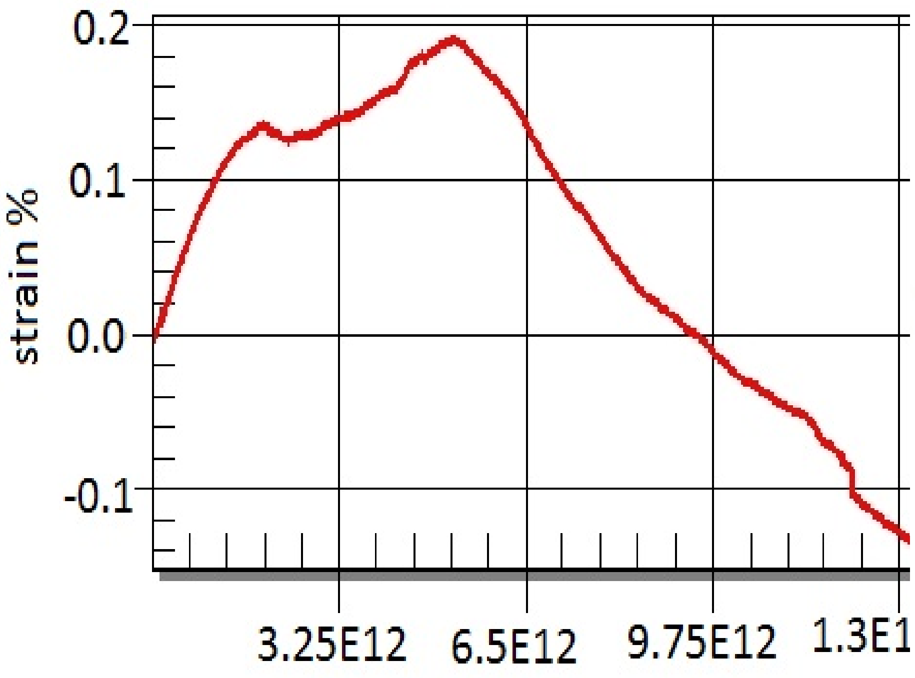
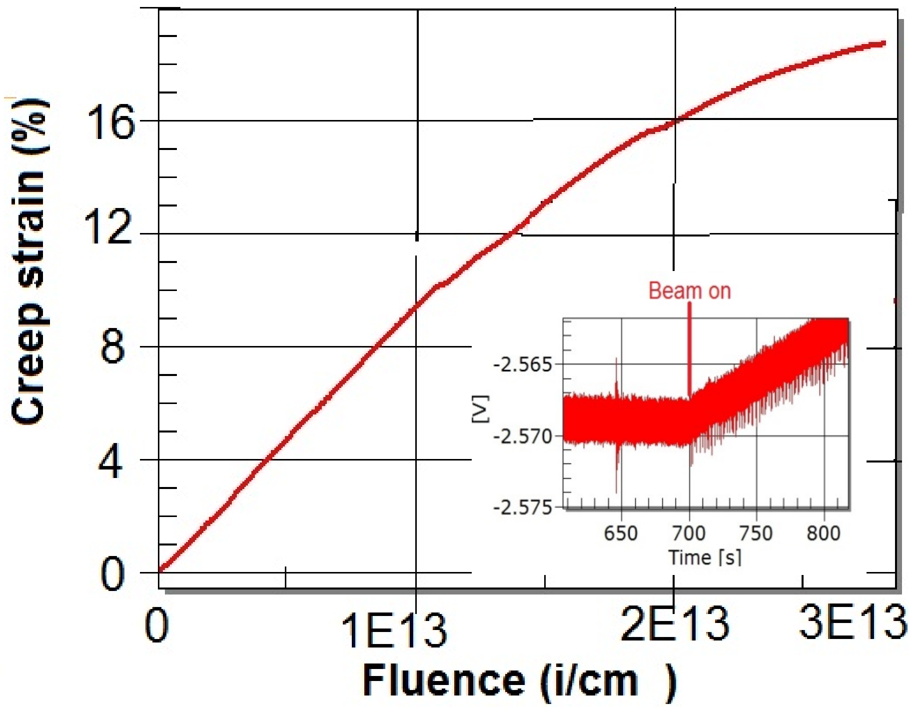
Radiation induced creep measurements on flexible graphite

Au, 4.8 MeV/u

no weight



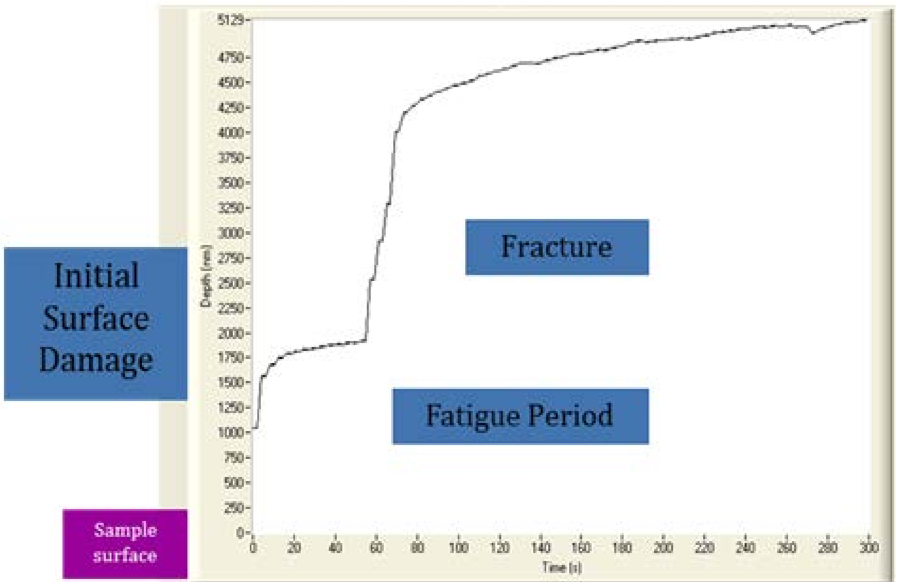
weight on

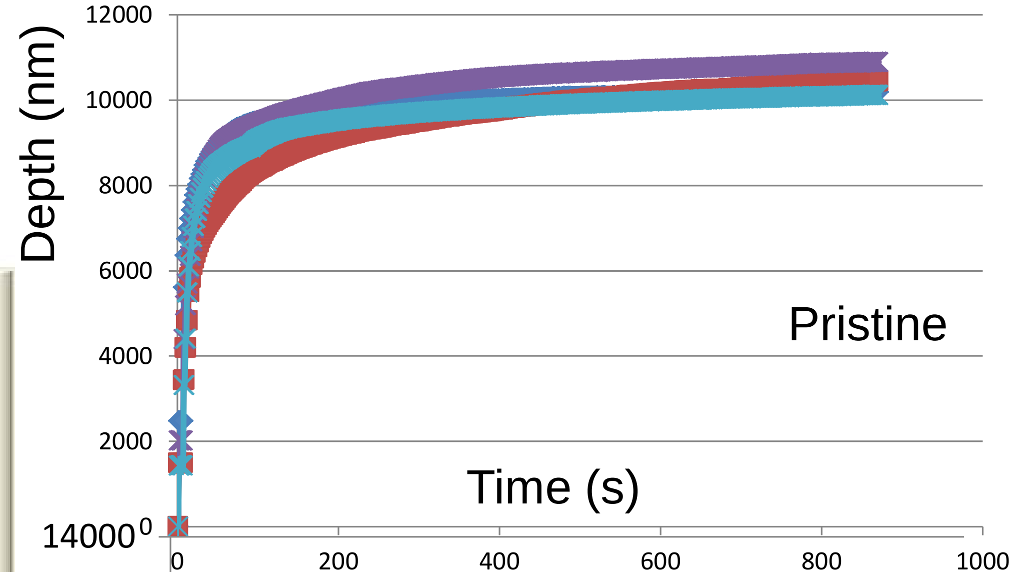


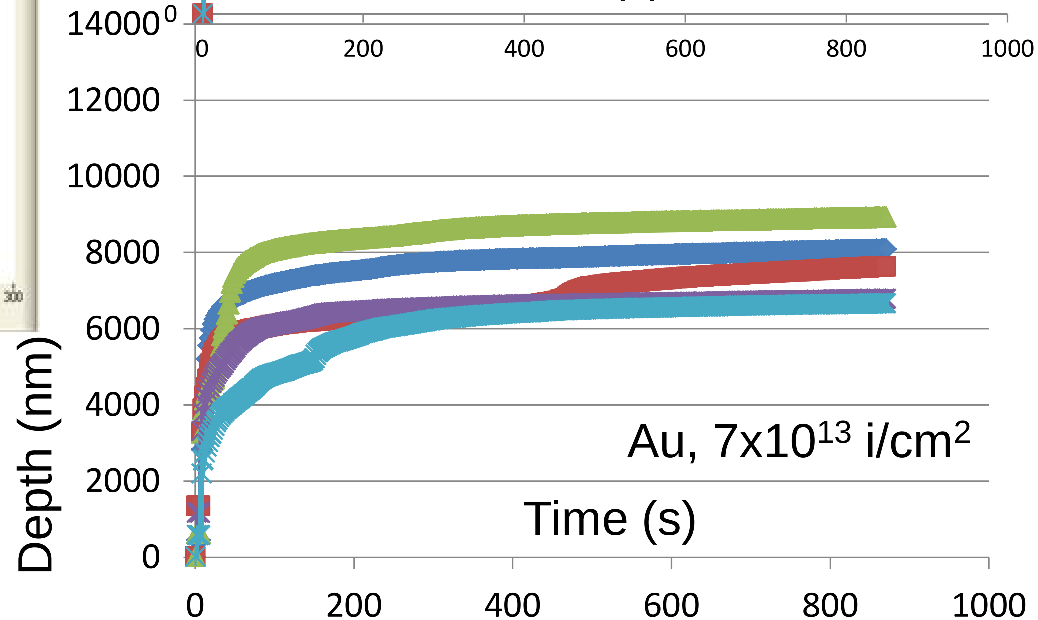
Impact nanoindentation study of fatigue behaviour of irradiated isotropic graphite

Cube Corner:

- 5 mN load,
- 28 µm acceleration distance







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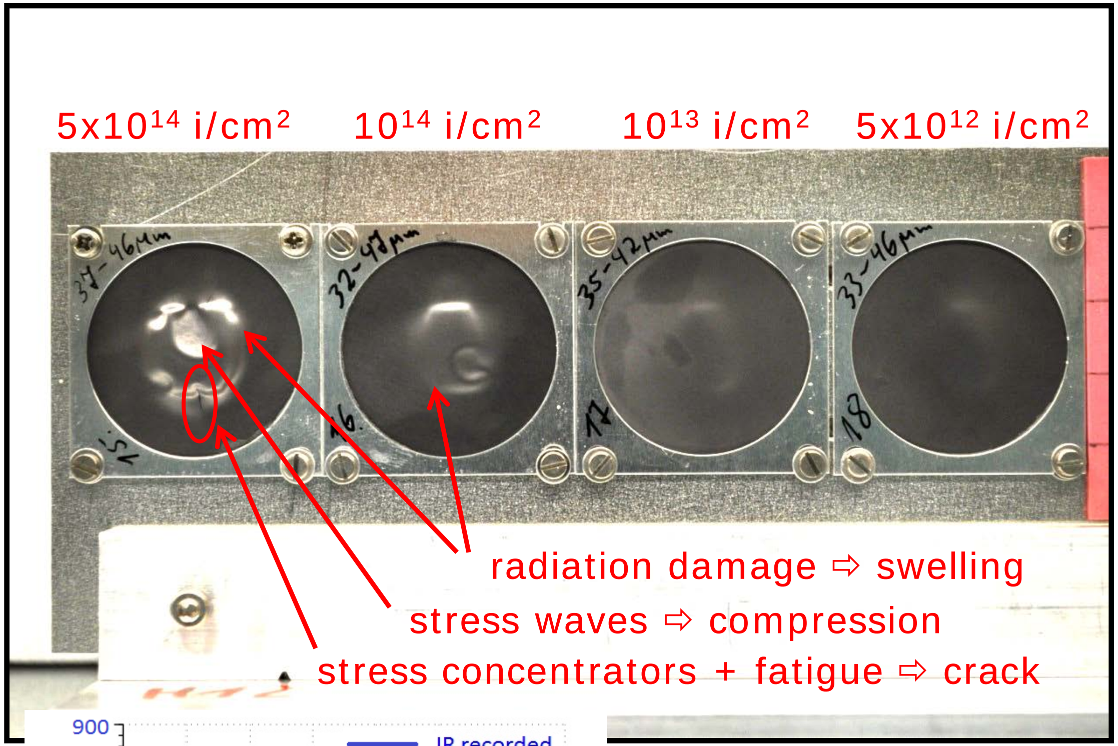
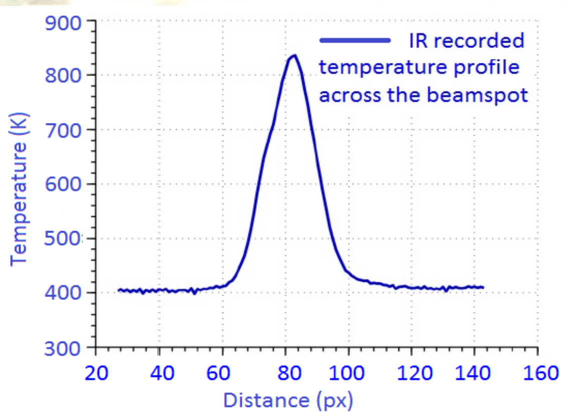
Failure of graphite exposed to pulsed ^{238}U beam

Experiment





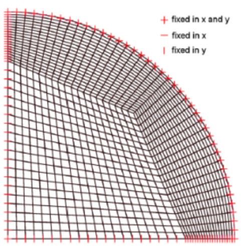
^{238}U, 1.14 GeV

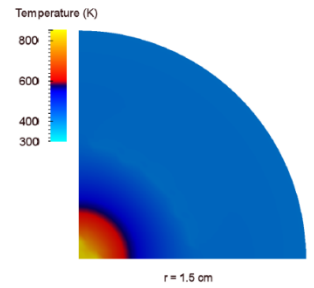
1.5 x10^{10} i/pulse

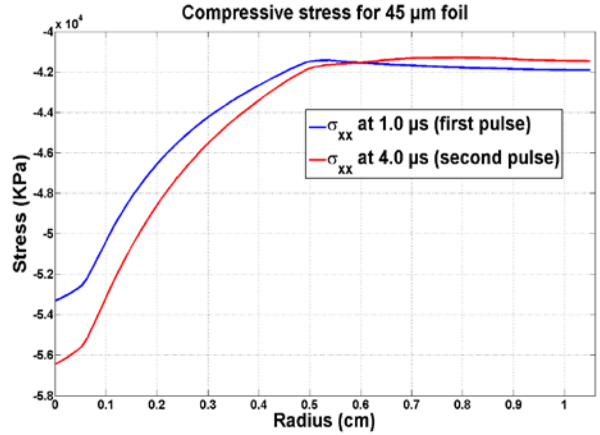
150 μs, 1 Hz

FEM simulations

Graphite target / Pulse structure	Maximum compressive stress (MPa)	Maximum tensile stress (MPa)
45 μm (single pulse)	-53.3	0.5
45 μm (double pulse)	- 56.4	0.7







Conclusions and Outlook

- Ion irradiation induces:
    - early degradation of thermal diffusivity
    - hardening and increase in E modulus
    - fatigue resistance decrease
    - Creep!

dependent on dE/dX

⇒ **Failure**


Thank you for your attention!