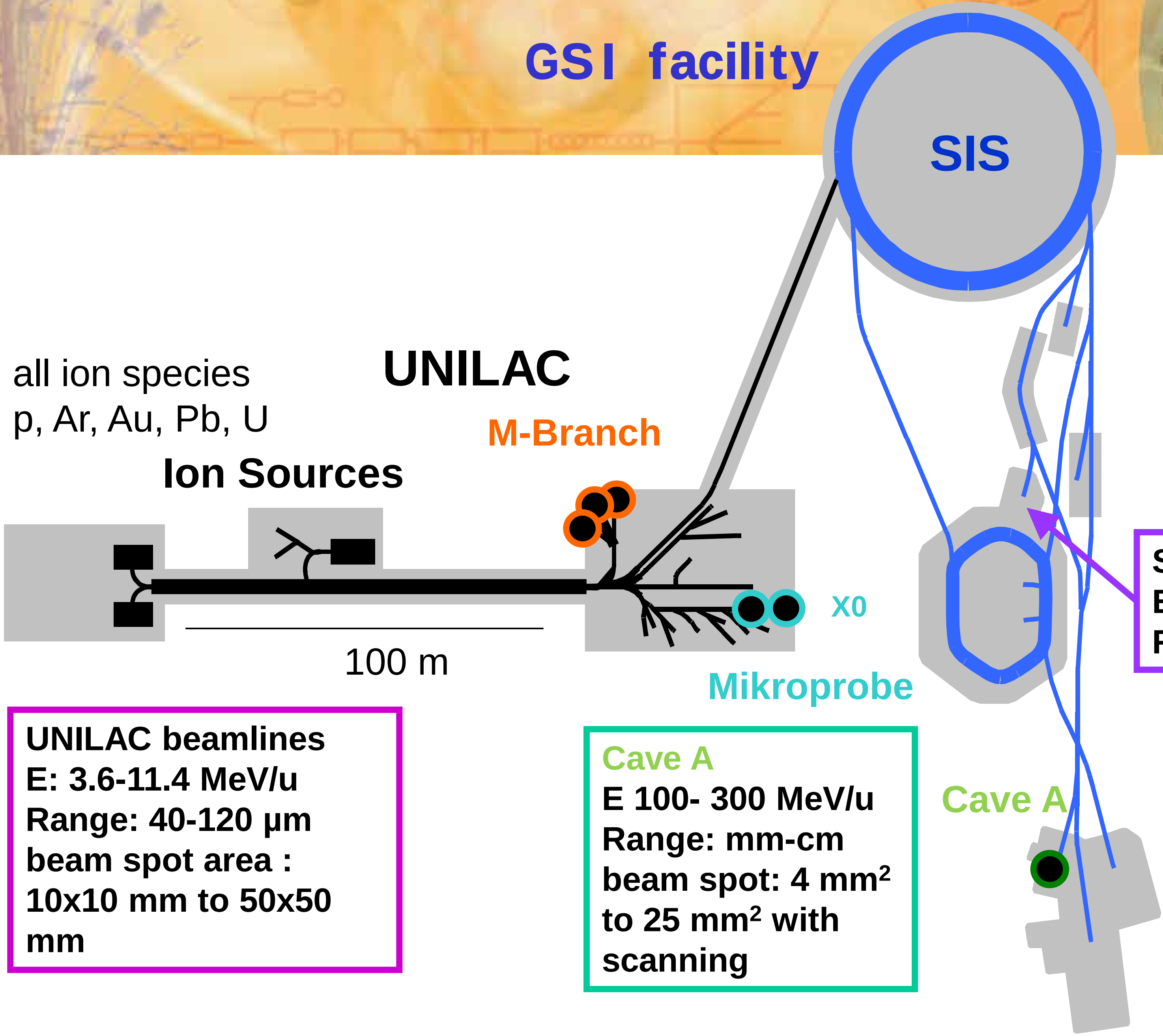
GSI tests status and preliminary results

M. Tomut
GSI

GSI facility



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

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

UNILAC: beam parameters

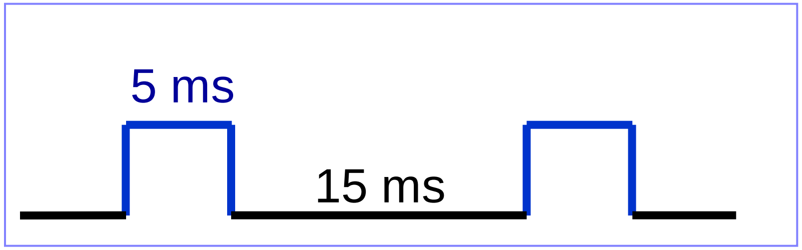
3.6 / 4.8 / 5.6 / 8.6 / 11.4 MeV/u typical energies

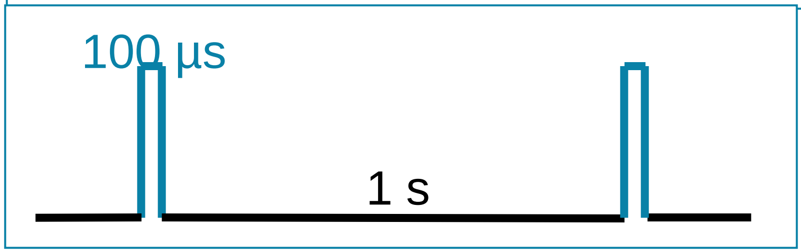
50 Hz Mode (Penning, ECR)

50 Hz
5 ms **length of macropulse**

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

1-2 Hz
100-200 µs **length of macropulse**





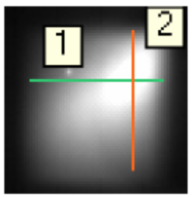
Thermal camera monitoring of sample temperature

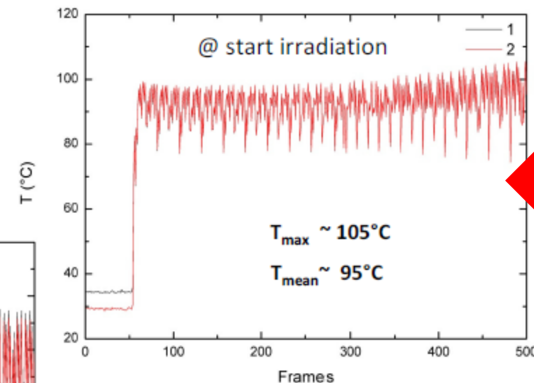
High duty cycle

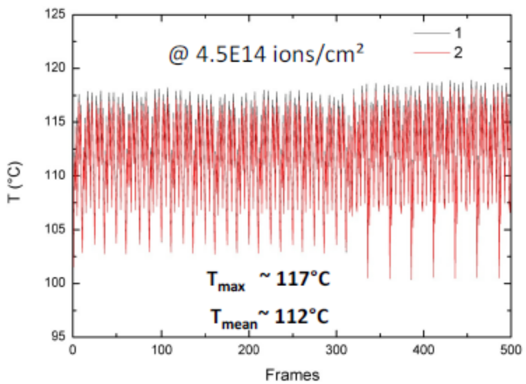
Amorphous Carbon, 21 µg/cm² (Targetlab)

Au^{25+} 3.6 MeV/u, 38 Hz, 4ms, defocused beam, beamspot 1.7x1.7cm (Ø sample 30mm)

flux: 1.0E10 ions/cm²s





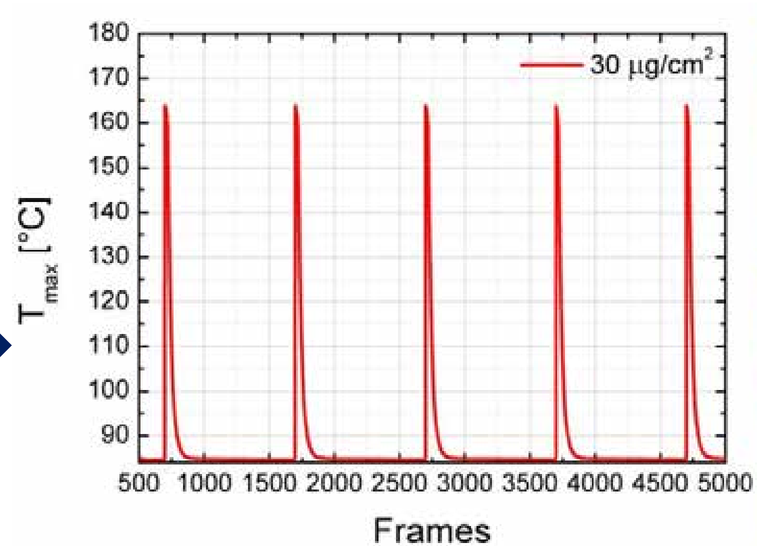


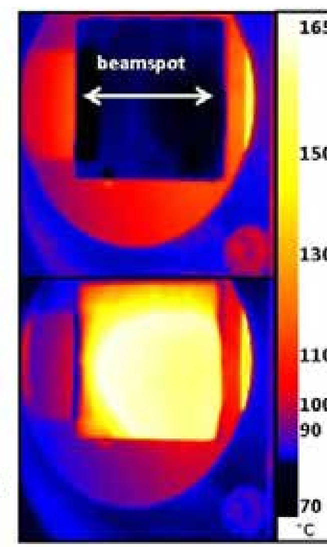
- **radiation damage**
- **thermal effects ð stress**

Low duty cycle

- **radiation damage**
- **short thermal spikes**

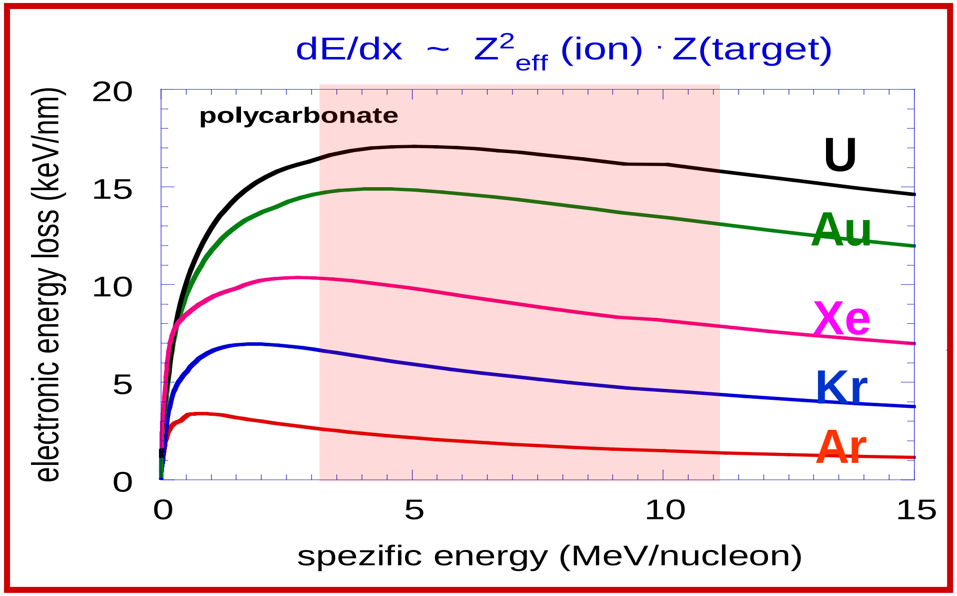
ð stress waves





Irradiation energy

- 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



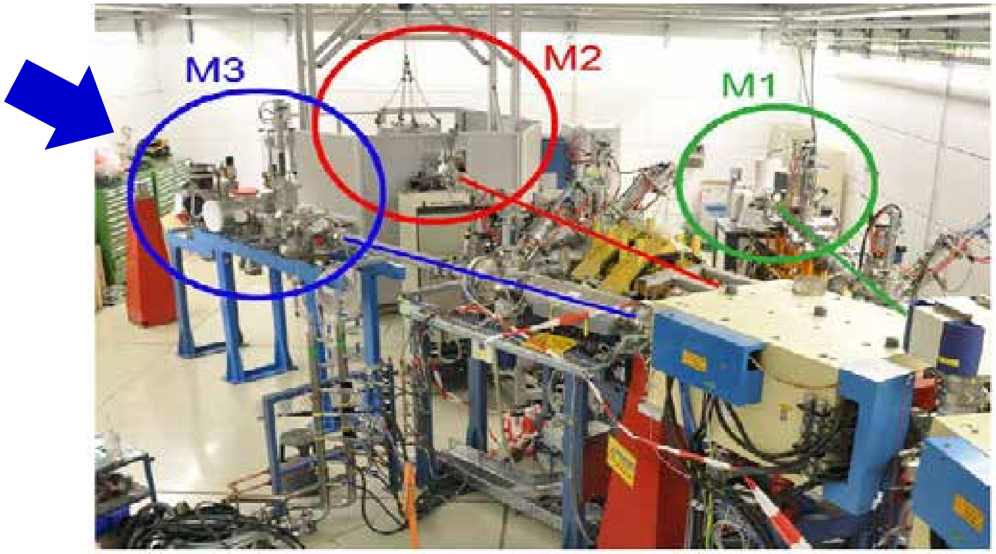
SRIM code

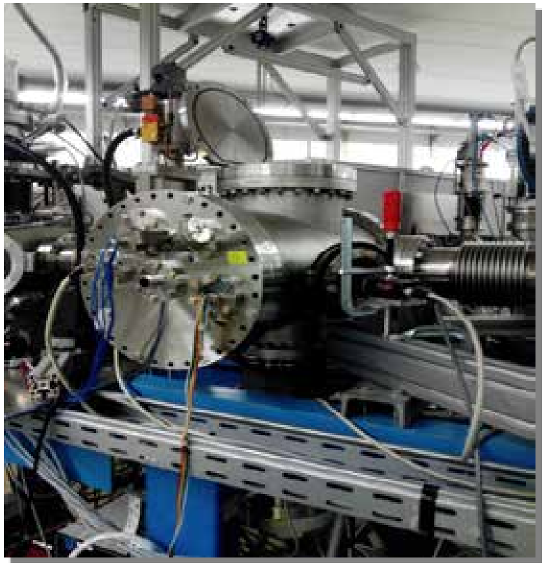
ion species ..C…Xe...U

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

Irradiation Tests at GSI

1) **Feb-Mar 2014:**
   - **^{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
   - **CuCD**, **CFC** (2 orientations), **MoGr** (MG 3110P, 2 orientations, samples not annealed) irradiated with fuences up to 1e14 ions/cm^2
2) **July 2014:**
   - **^{197}Au**: 945 MeV, 40 Hz, up to $2x10^9$ ions/cm^{2}s
   - **C**: 11.4MeV/u, $5x10^9$ ions/cm^{2}s





Thermal properties degradation

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

- Samples for LFA: in-plane thermal conductivity measurements
  - Mo-Gr discs in-plane and transversal; U irradiation
  - Cu-CD discs U and Bi irradiation, 4.8 MeV/u

Cu-CD

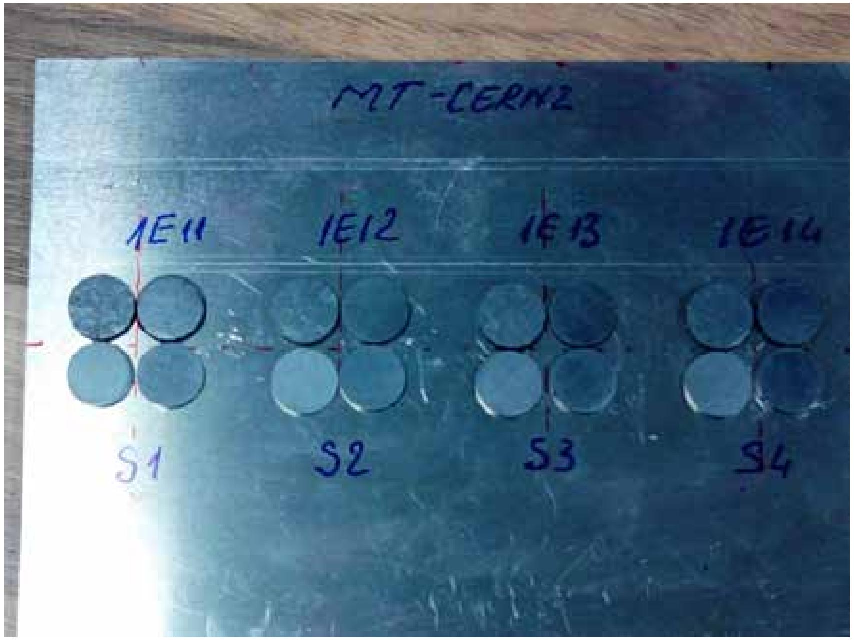
Mo-Gr I

- Irradiation holders for postirradiation thermal diffusivity tests

- Laser Flash analysis in-plane

Post-irradiation tests

- Samples for off-line tests:
- Cu-CD,
- Mo-Gr: 2orientations,CFC: 2 orientations (U, Au, Bi)



Microstructural characterization:

- Raman spectroscopy,
- SEM

Mechanical properties:

- Nanoindentation,

Electrical properties:

- 4.point probe resistivity measurements

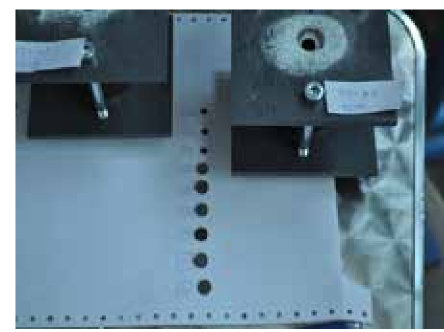
High energy deposition experiments using focused U beam

Irradiation of MoGr and Cu-Dia at high energy

- CuCD and MoGr samples treated @1800°C for 50 min prior irradiation!
- Planned for post-irradiation:
  - structural analysis
  - thermal conductivity measurements
  - mechanical test - nanoindentation

...some time after

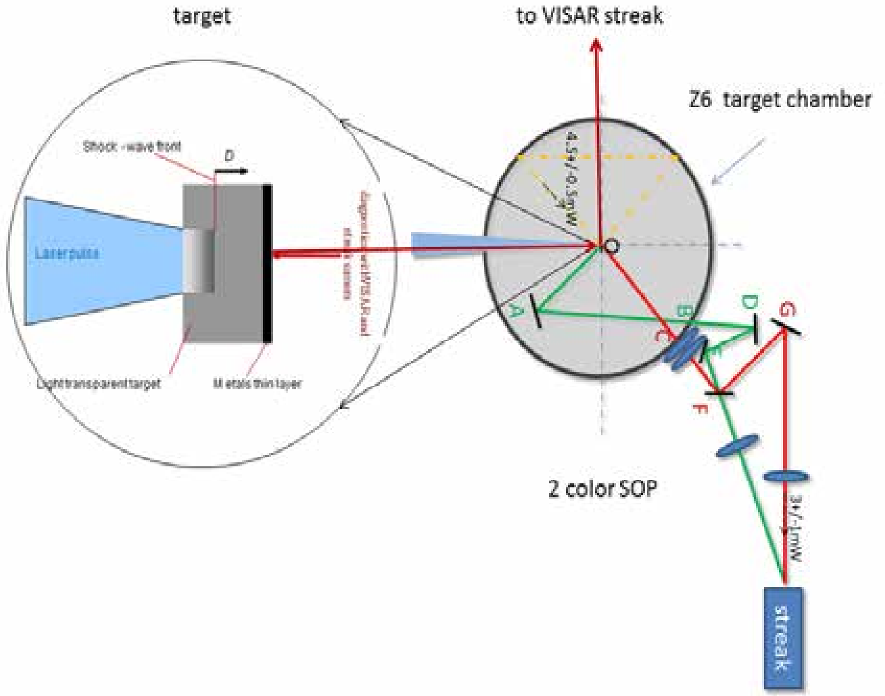
Sm^{152}
~ 300 MeV/u
range: mm
bulk samples



Shock tests of target and collimator materials using high power PHELIX laser at GSI:

Laser parameters:

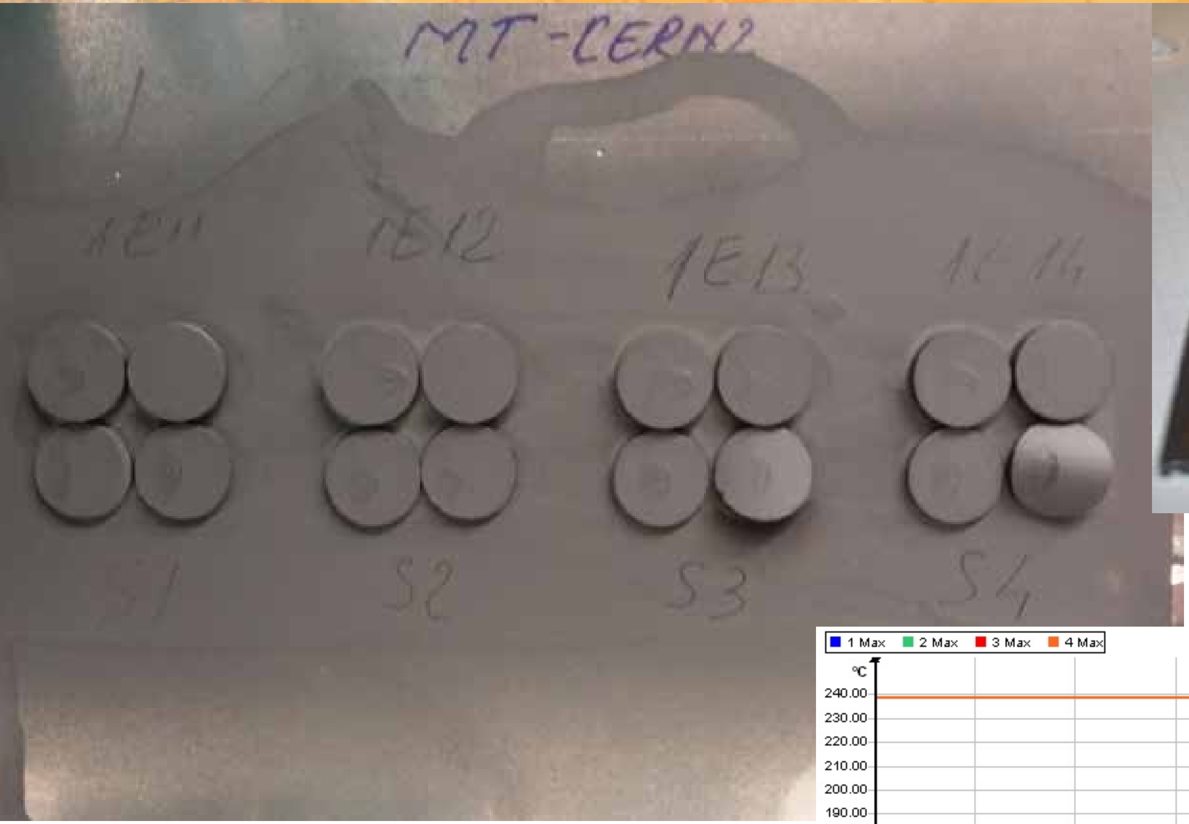
- Energy: 150 J (2ω)
- Focal spot at the target: 50
- Laser pulse duration: 7 ns
- Laser contrast ~10^{-5}–10^{-6}
- Intensity:10^{14} W/cm^2

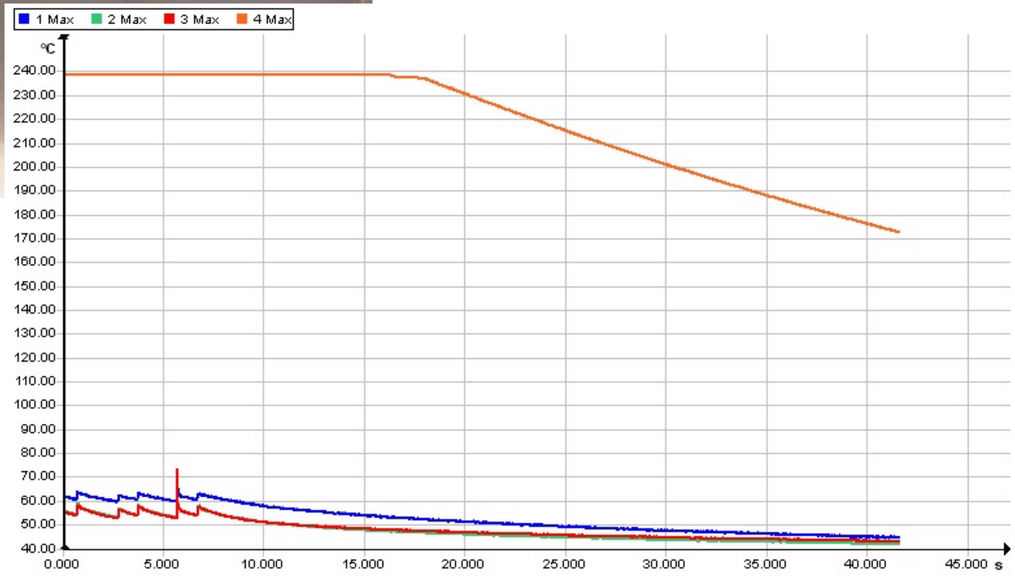


Diagnostics tested:

- VISAR-system available a
- Two color SOP (Streak op measurement

Deformation of Mo-GR samples transversal cut starting with 6E12 i/cm²





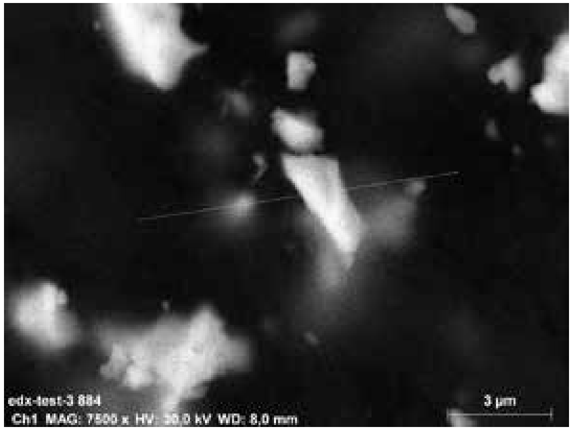
Thin Mo-Gr samples after irradiation

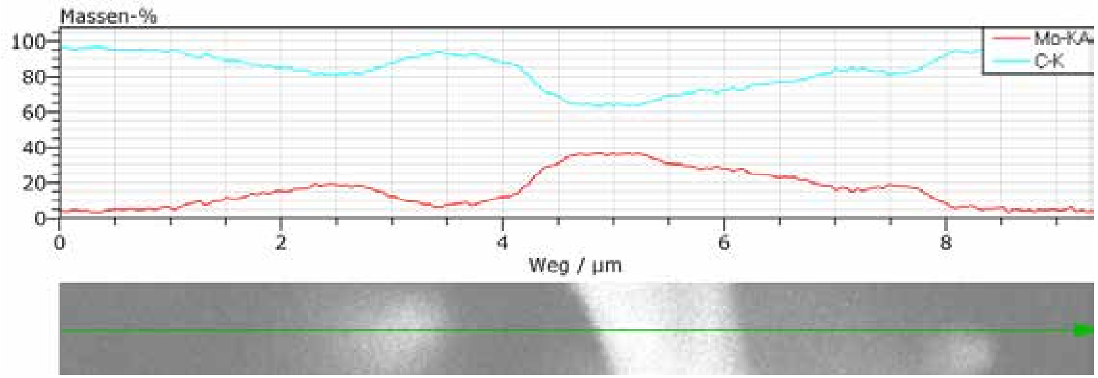
Mo_GR in-plane

Mo_GR transversal

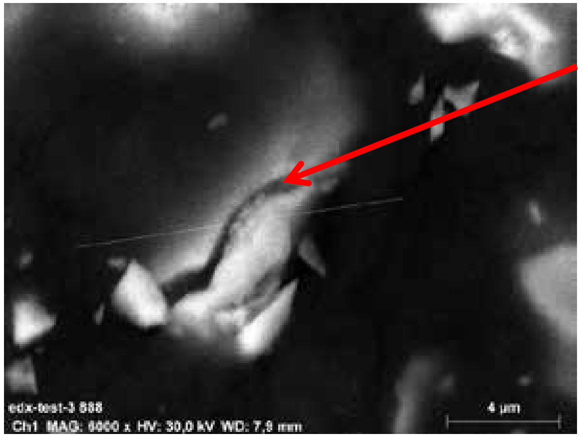
Microstructure and element distribution – SEM/EDX

Pristine Mo-Gr-transversal orientation

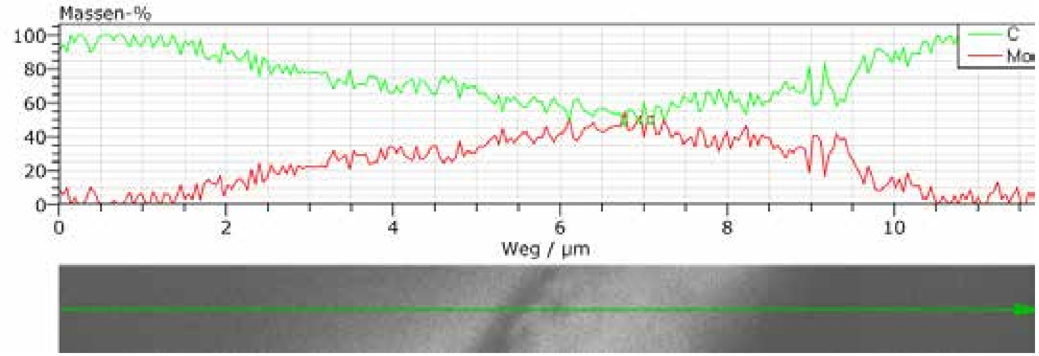




Mo-Gr-transversal orientation at 1E13 U ions/cm^2



Cracks In MoC particles – irradiation induced stress



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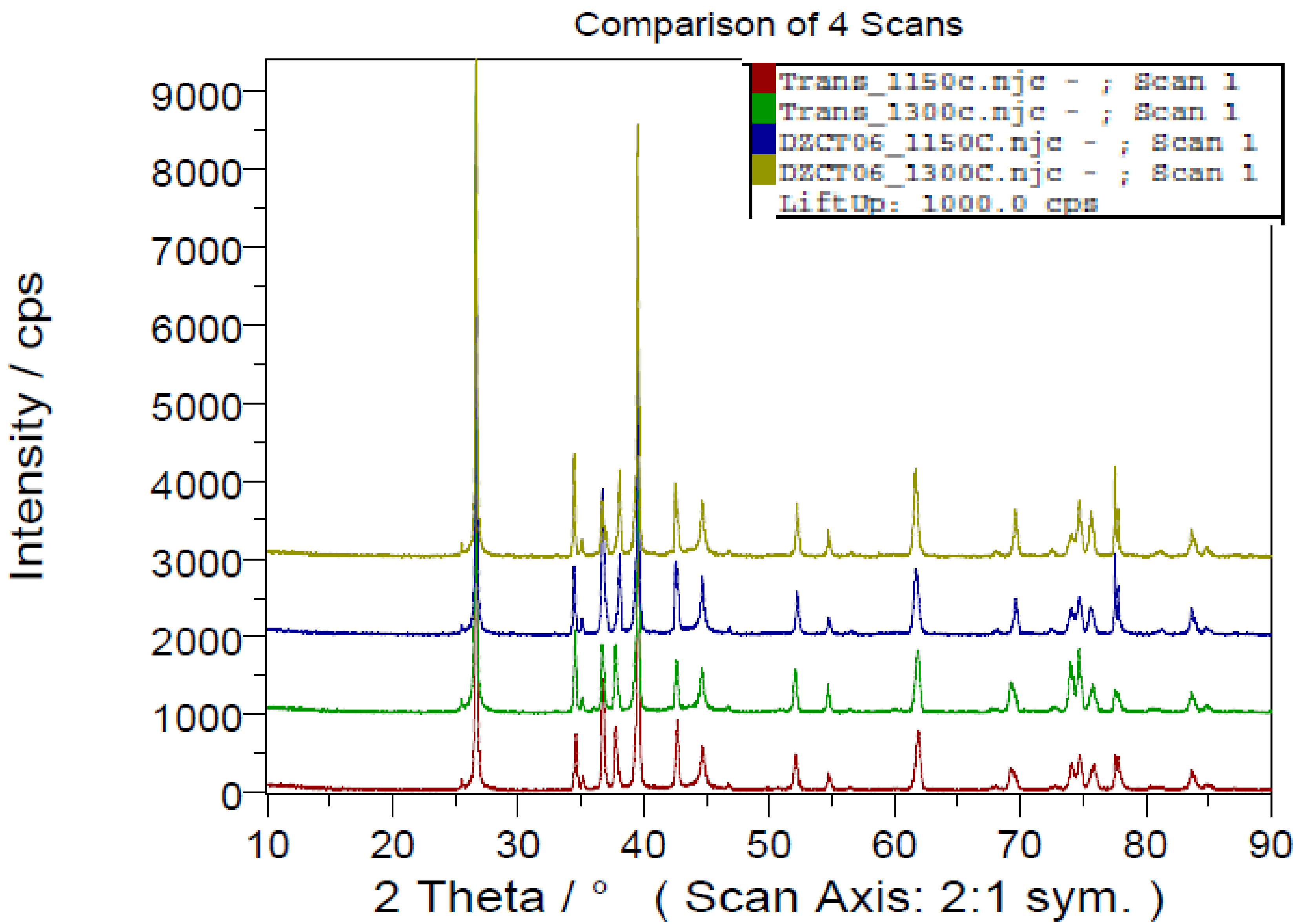
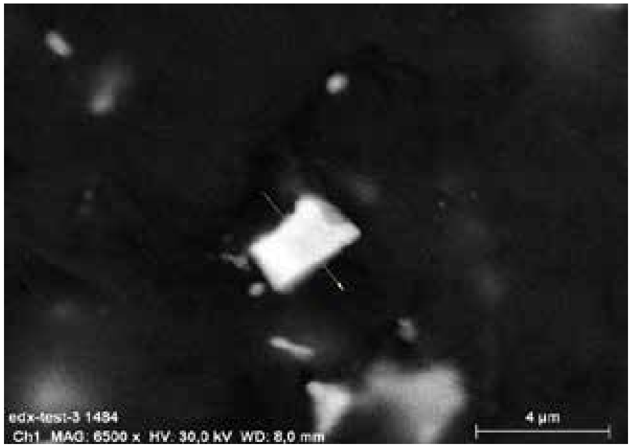
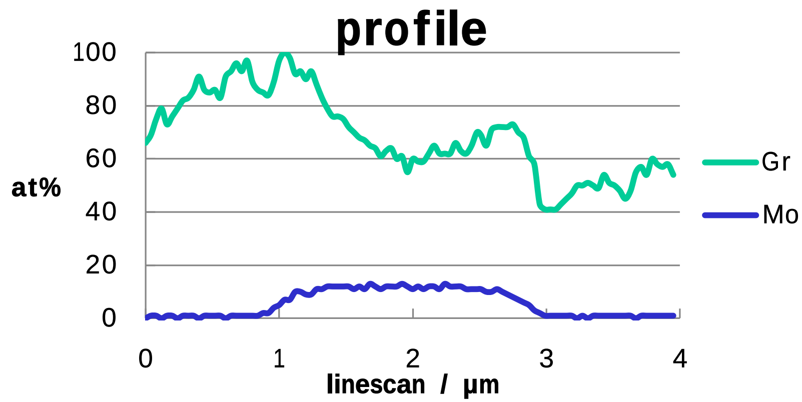
XRD analysis of optimized Mo-Gr samples: pristine and high fluence



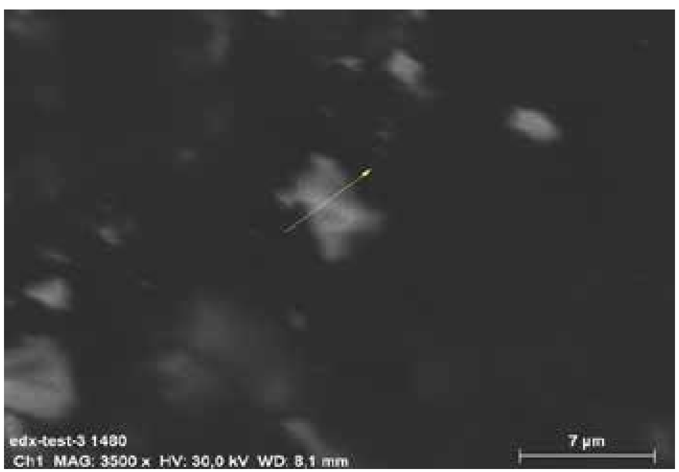
Microstructure and element distribution in optimized Mo-Gr– SEM/EDX

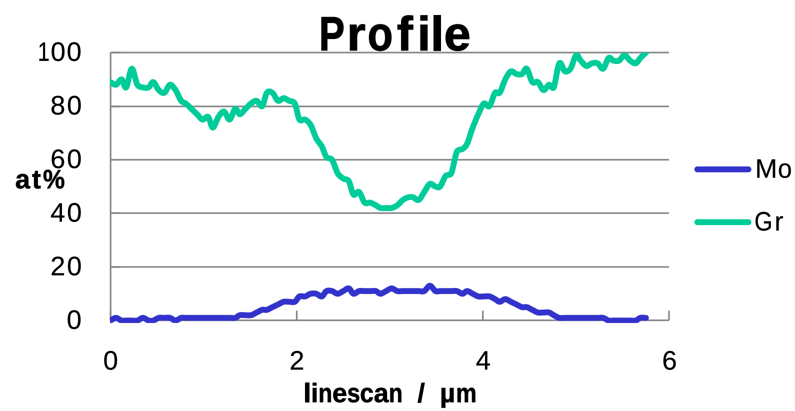
sample: MoGr-5220S-T-1150-1e11- Au





sample: MoGr-5220S-T-1150-1e12- Au





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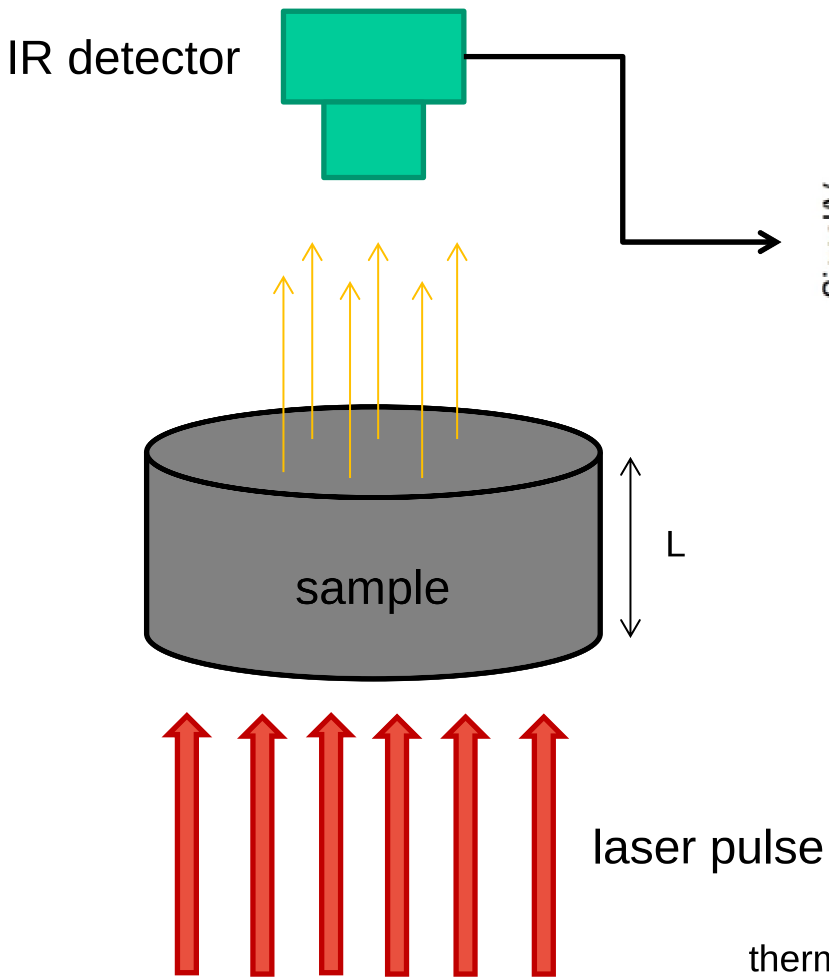
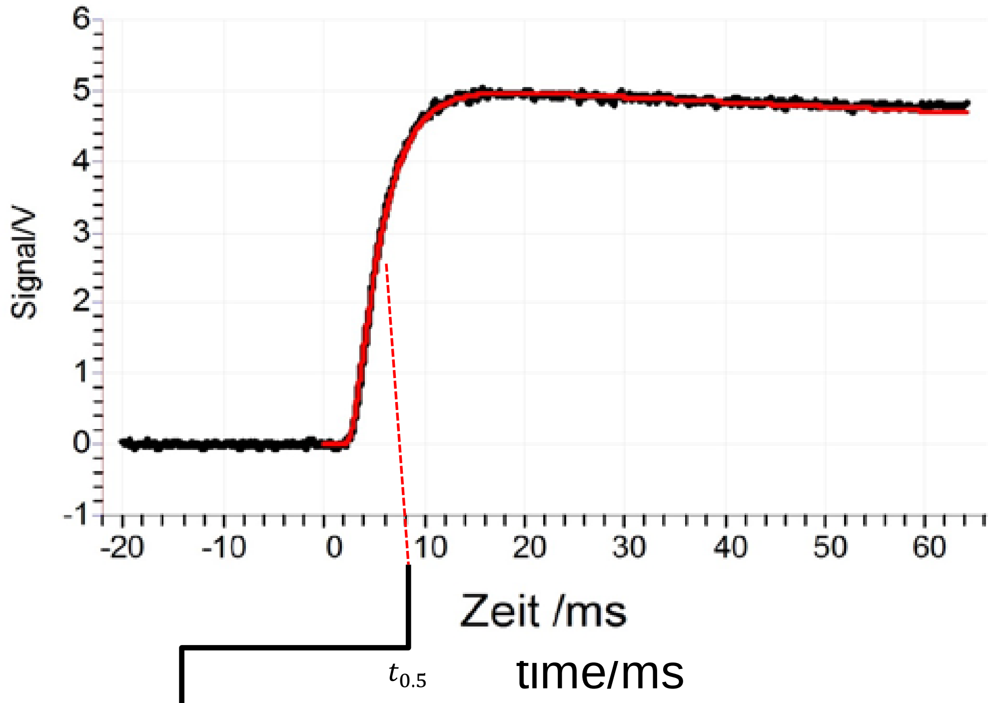
Thermal difussivity degradation - Laser flash analysis





thermal diffusivity

$$\alpha = \frac{0.1388 \cdot L^2}{t_{0.5}}$$

thermal conductivity

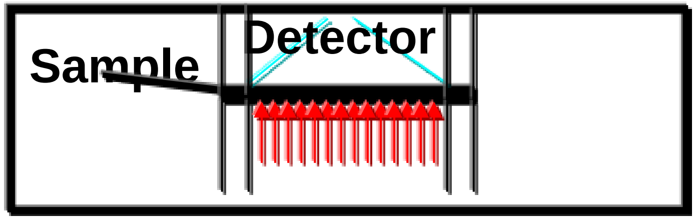
$$\lambda = \alpha \cdot \rho \cdot c_p$$

Thermal properties degradation -post-irradiation evaluation

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

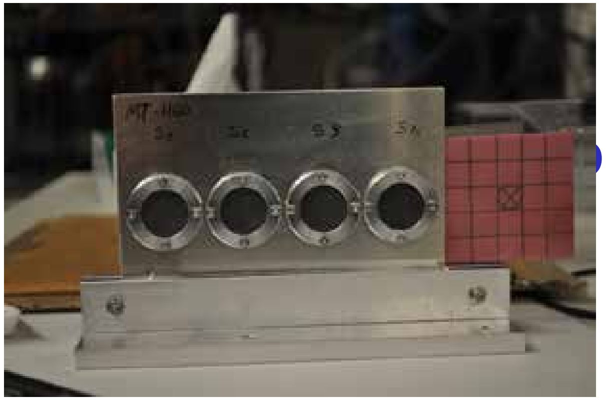
Samples for LFA: Isotropic graphite and flexible graphite

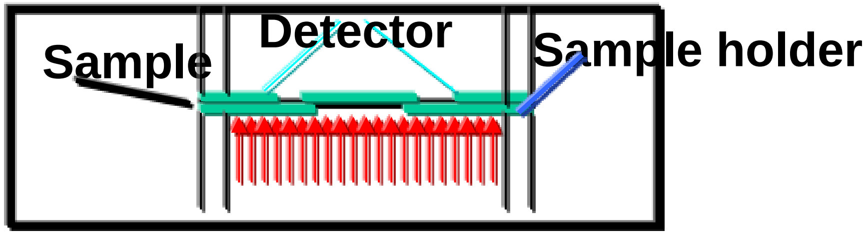
- classical transmission measuring geometry



Transmission

- in-plane measuring geometry

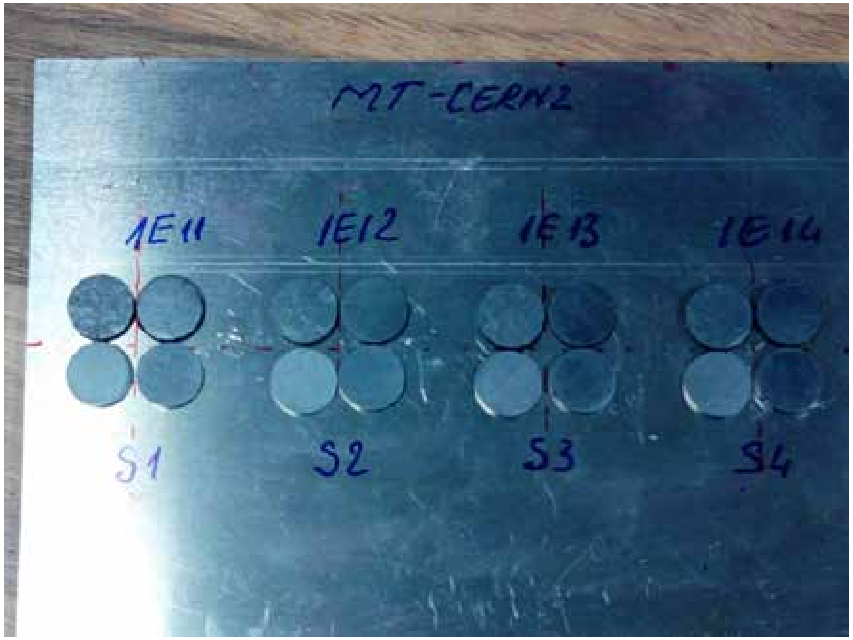




In-plane

Post-irradiation tests

- Samples for off-line tests:
- Cu-CD,
- Mo-Gr: 2orientations,CFC: 2 orientations (U, Au, Bi)



Microstructural characterization:

- Raman spectroscopy,
- SEM

Mechanical properties:

- Nanoindentation,

Electrical properties:

- 4.point probe resistivity measurements

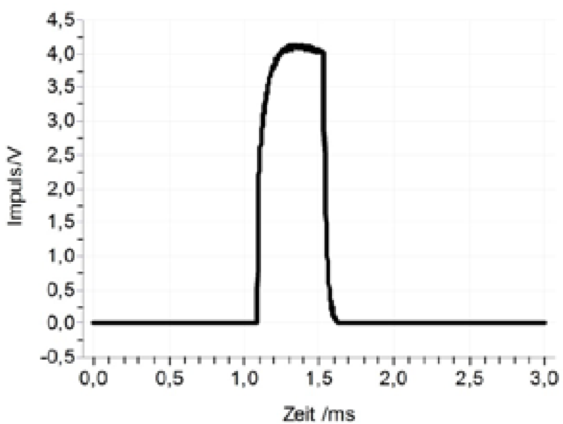
Mathematical models – heat loss

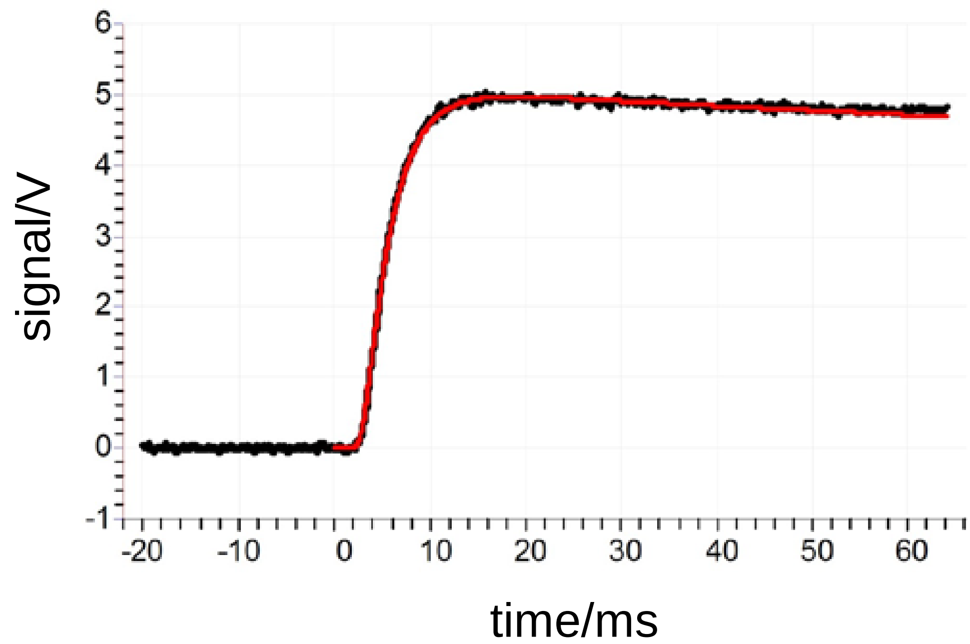
- Cape and Lehman (1963)

- included a heat loss term in the initial equation derived from Stefan-Boltzmann radiation law:

$$\nu = \frac{4\sigma\epsilon {T_0}^3}{\lambda}$$

-

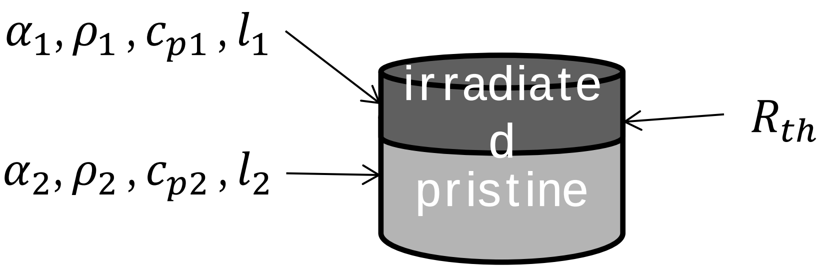




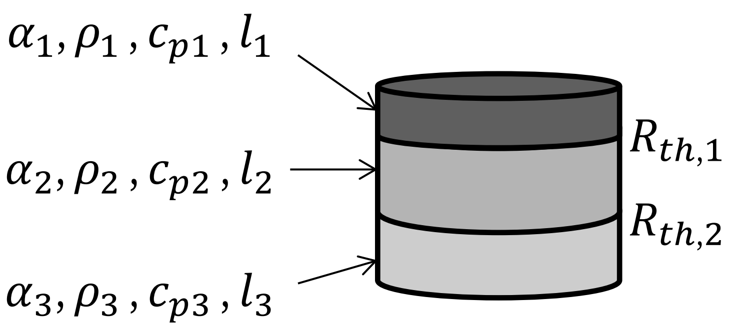
$$\alpha = 44.103\ mm^2/s$$

Layered composites

- contact resistance
  or
- diffusivity of the unknown layer
- values can be calculated from $t_{0.5}$

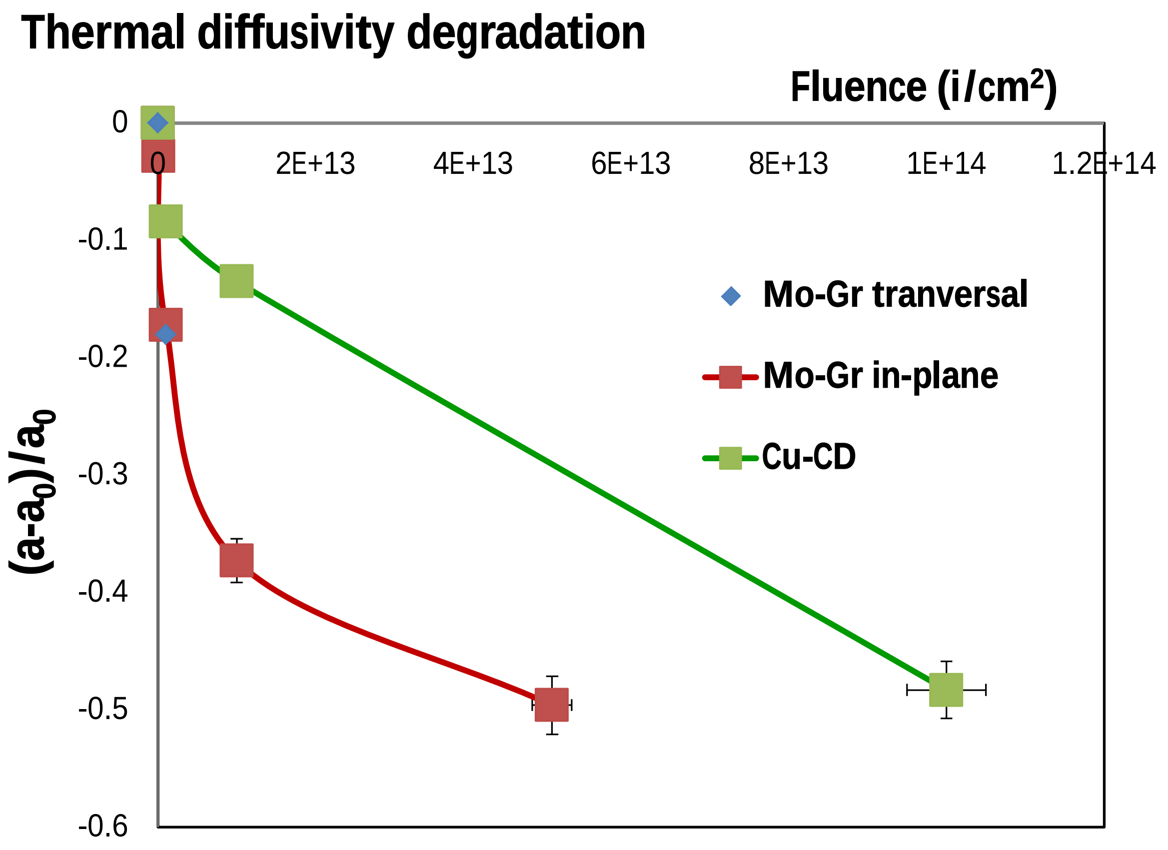


- more difficult for more layers:
- effective thermal conductivity is independent of the layer order
- but not the temperature history (boundary conditions)
- → $t_{0.5}$ depends on the order



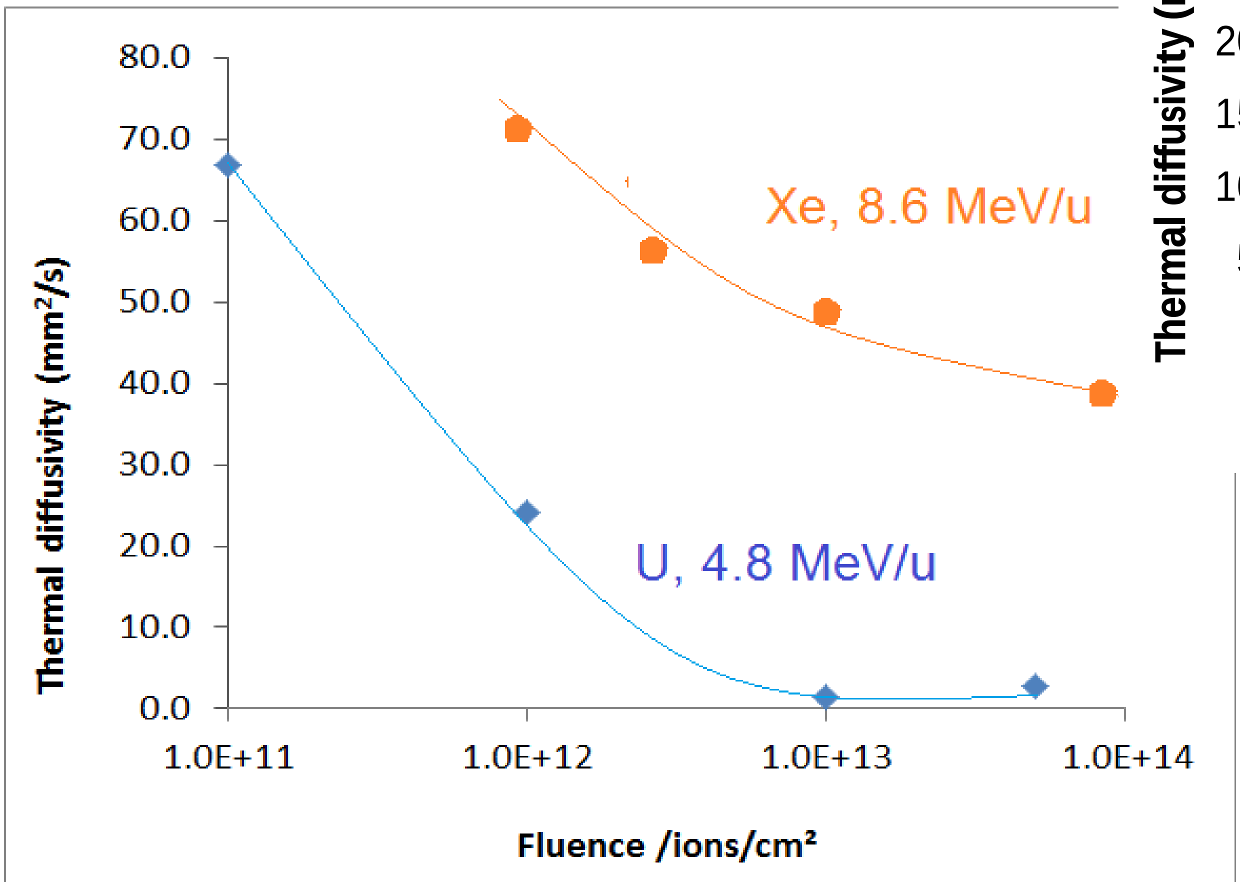
Thermal diffusivity degradation - composites

ion- irradiated Mo-Gr (non-optimized) and Cu-CD

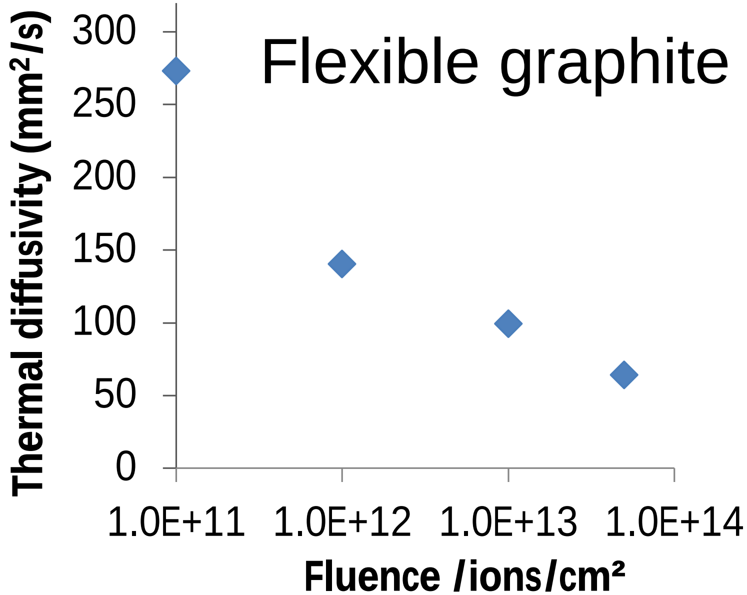


Ion-induced thermal diffusivity degradation of graphite

Comparison U vs Xe irradiation
graphite vs flexible graphite

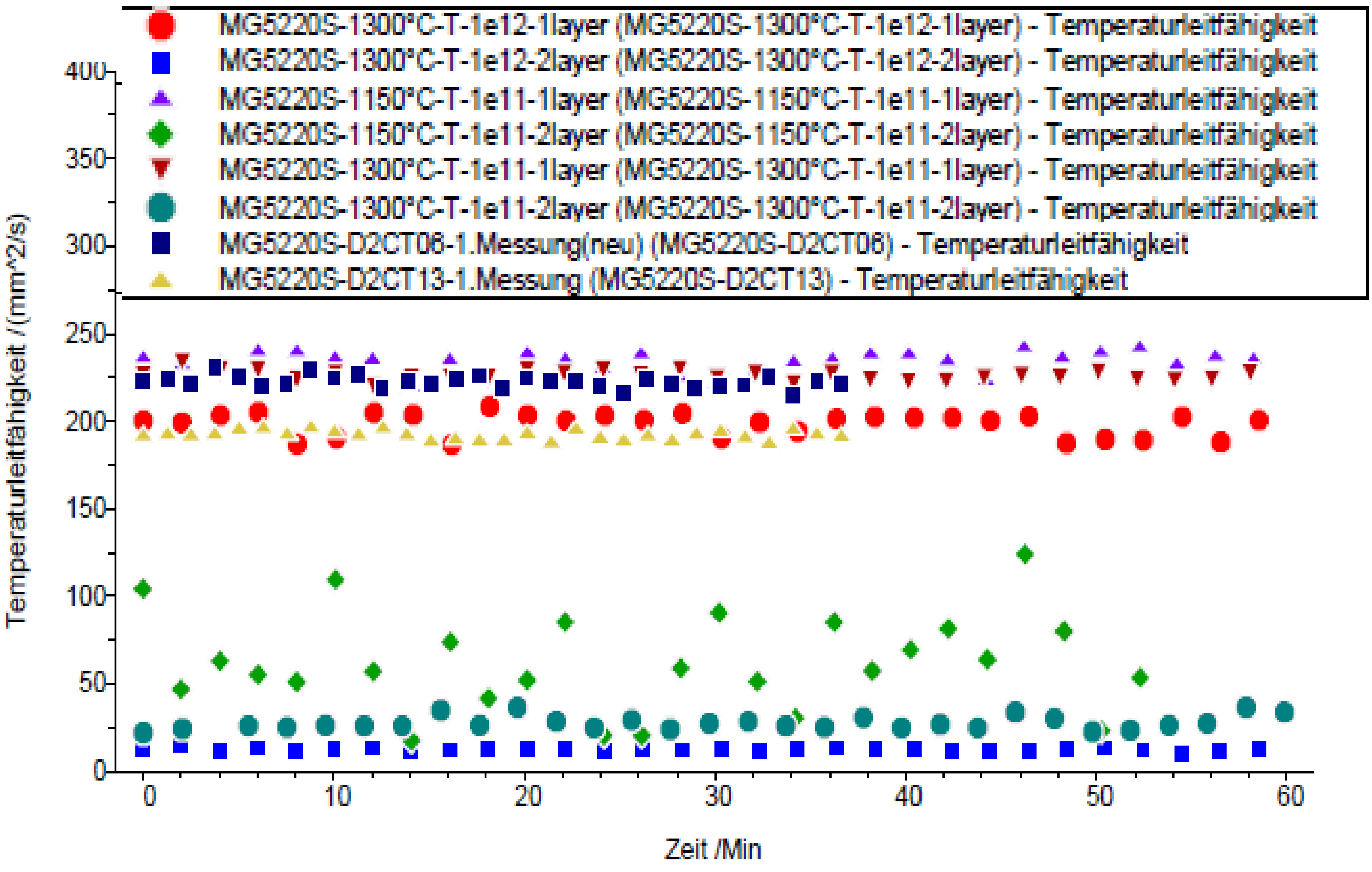


Isotropic graphite



Flexible graphite

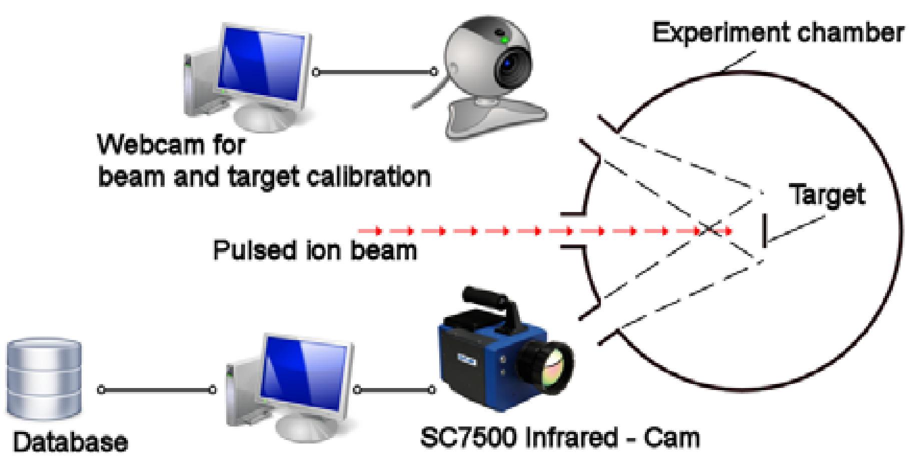
Thermal diffusivity degradation – optimized Mo-Gr

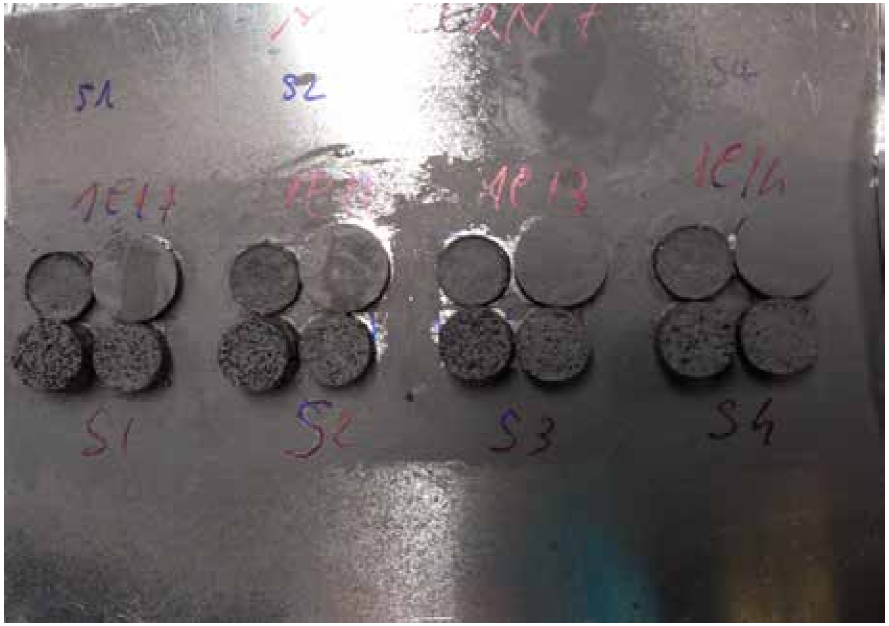


Thermal properties degradation - online

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

- 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)





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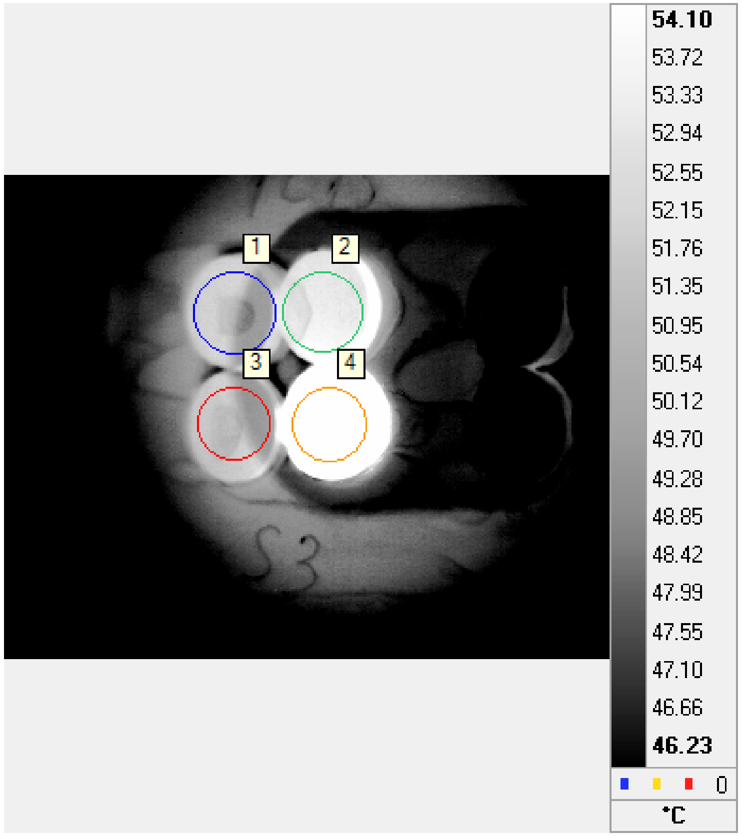
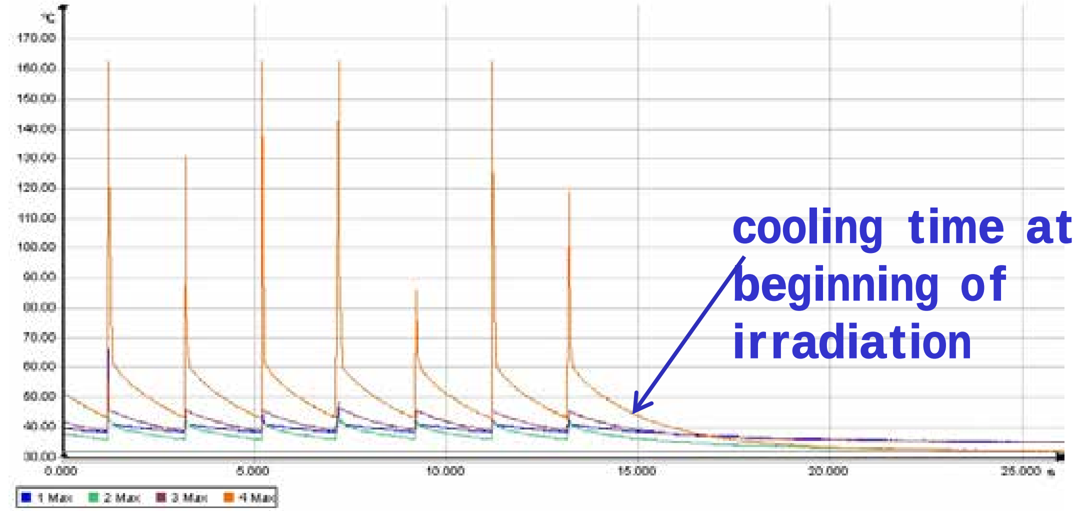
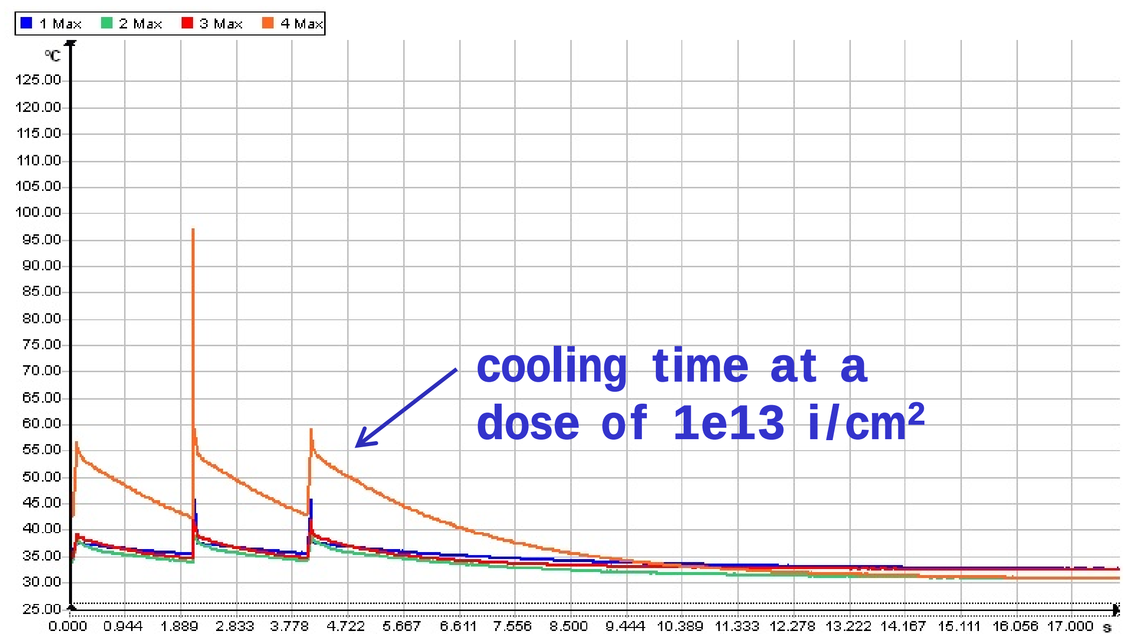
Thermal camera monitoring of sample temperature during cooling







Temporal evolution of maximum temperature in irradiated samples

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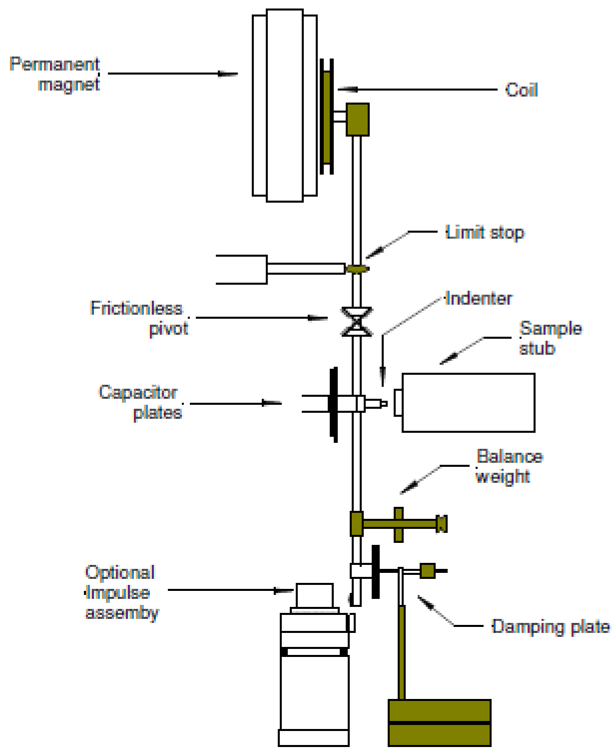
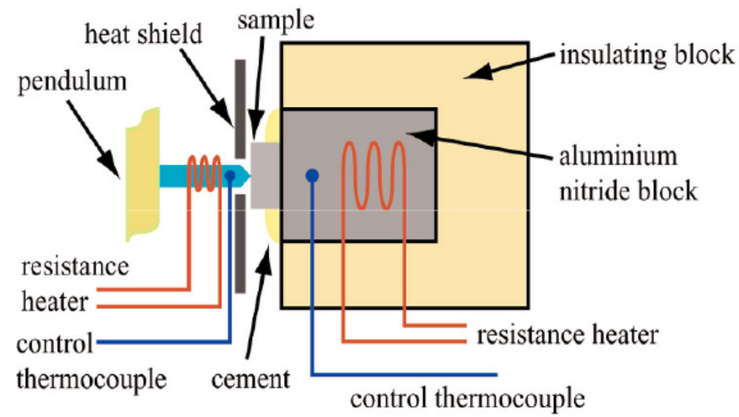
Mechanical properties degradation-nanoindentation

investigations of hardening and E modulus change of irradiated layers

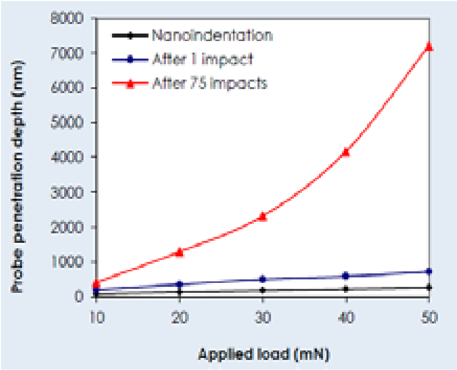
high temperature

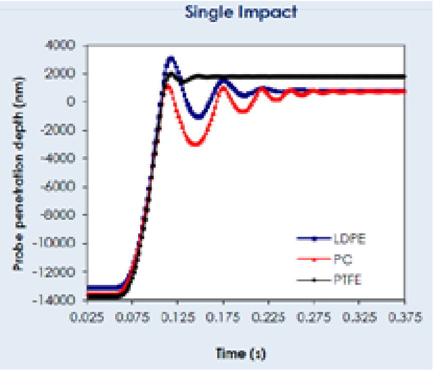


Courtesy LOT Quantum Design



Impact: fatigue damping





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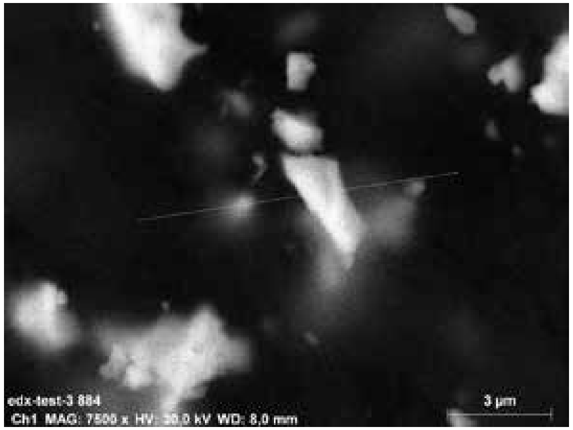
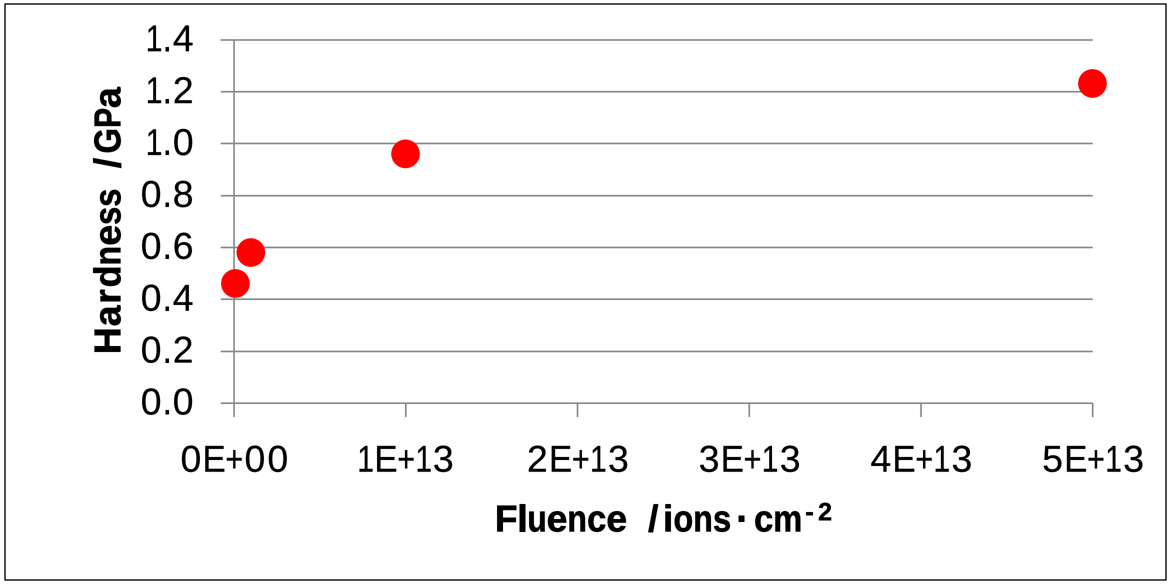
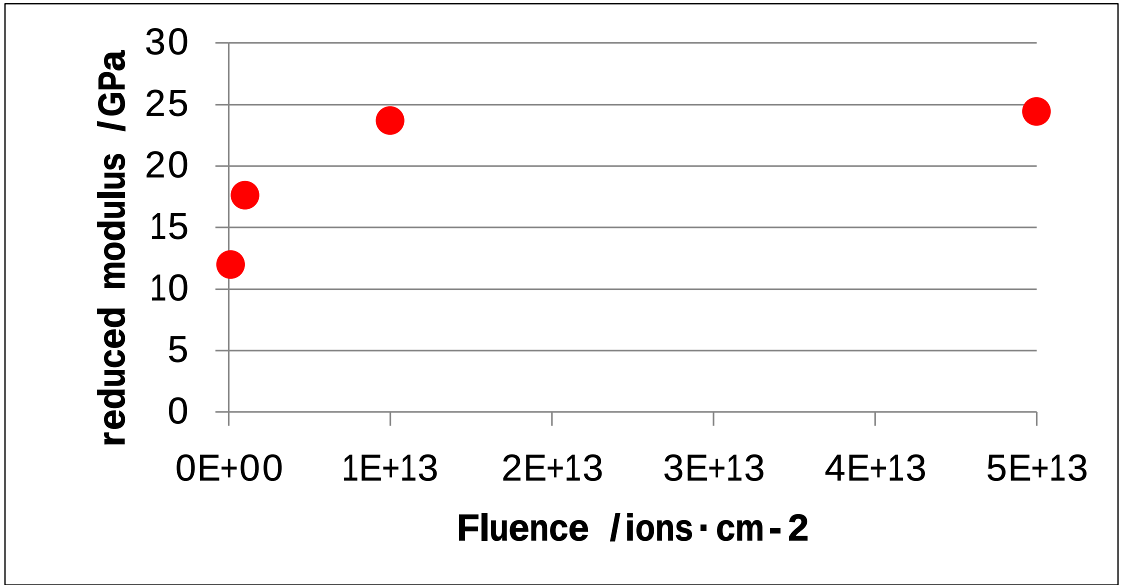
Molybdenum Graphite composite



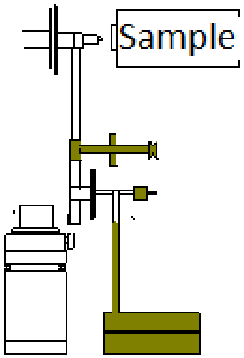
- **Bi,** 4.8 MeV/u
- Harder materials due to carbides
- Less radiation induced hardening than CFC

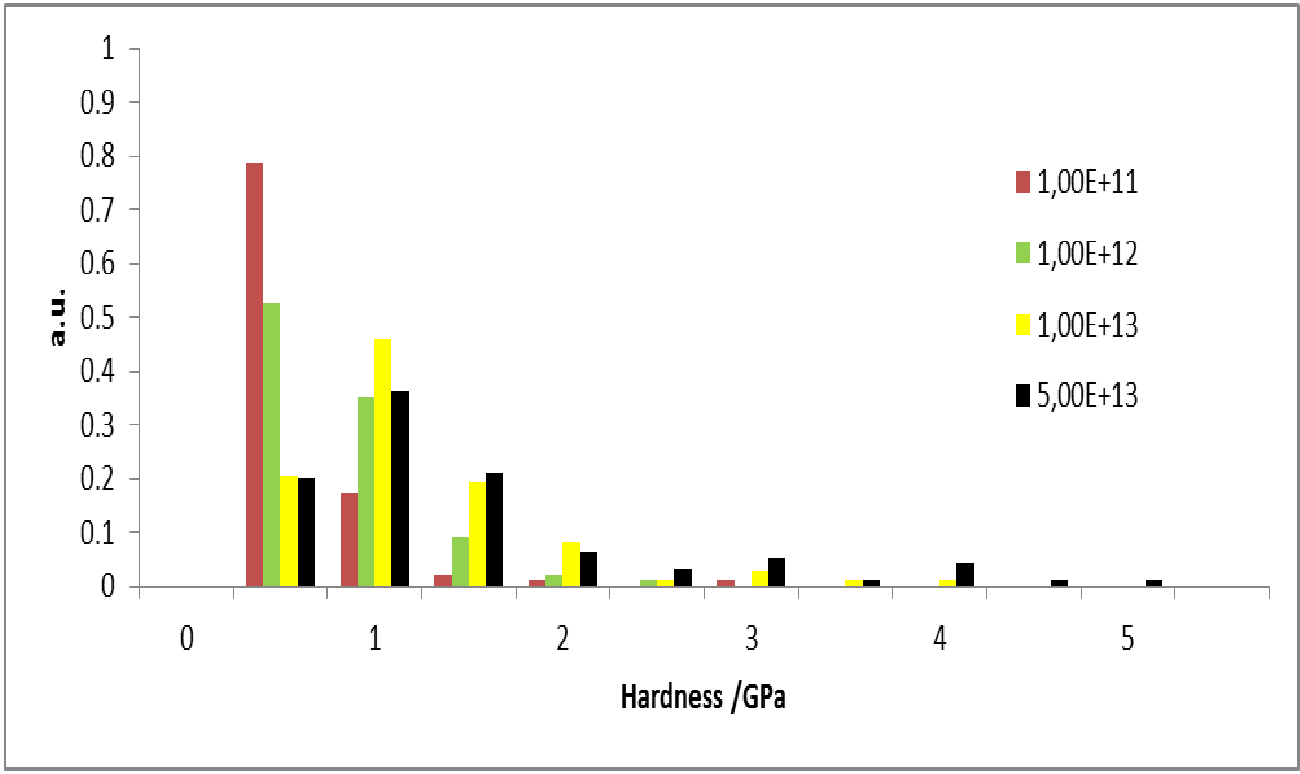




Mechanical behaviour of irradiated Mo-Gr

Nanoindentation





Histograms of

- **Hardness**
- **Young modulus**

•evolution with dose

•statistical approach for composites

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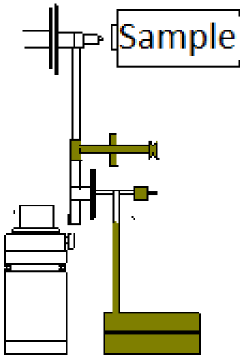
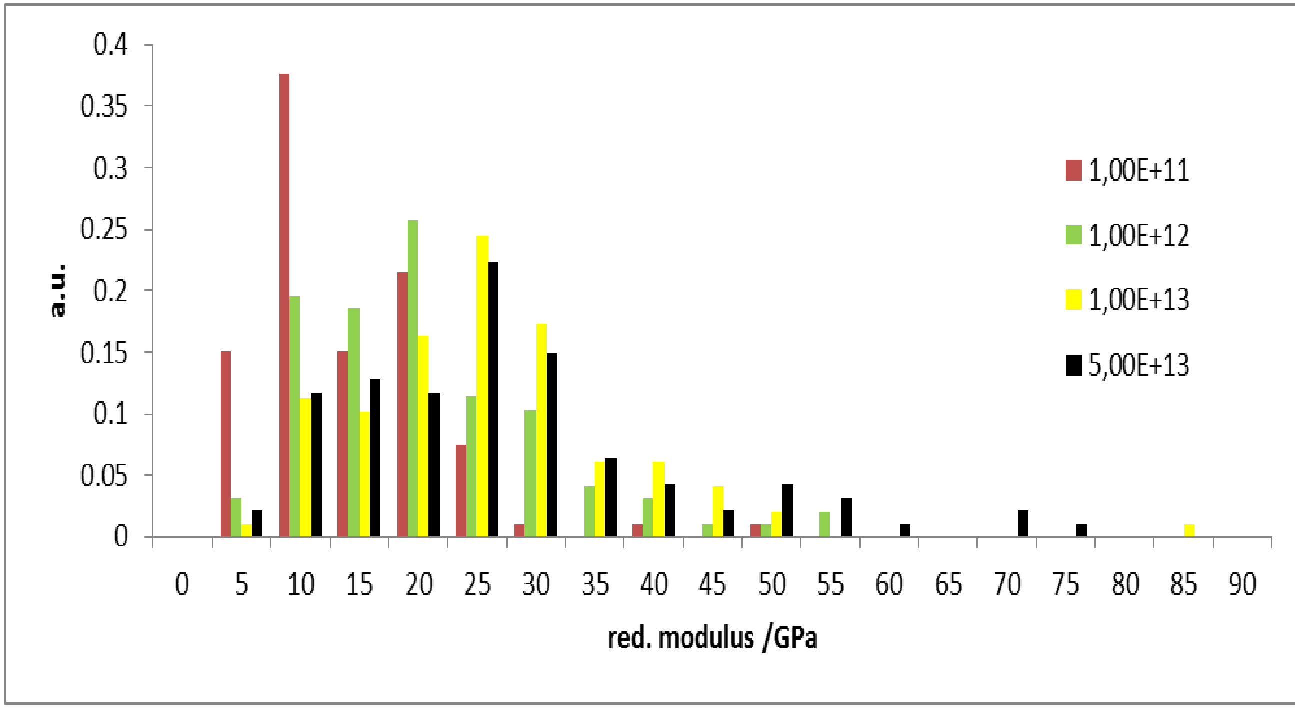
Mechanical behaviour of irradiated Mo-Gr

Nanoindentation





Histograms of

- **Hardness**
- **Young modulus**

•evolution with dose

•statistical approach for composites

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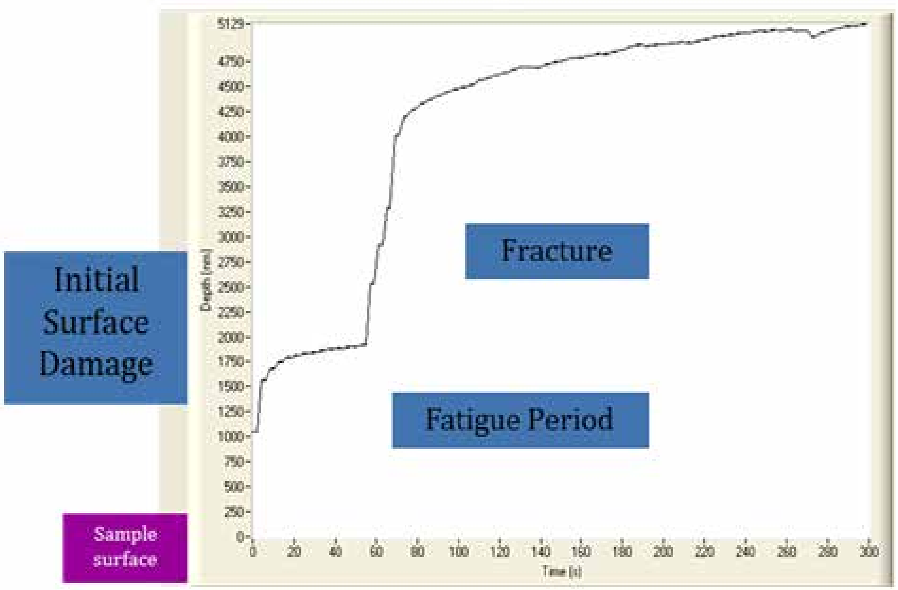
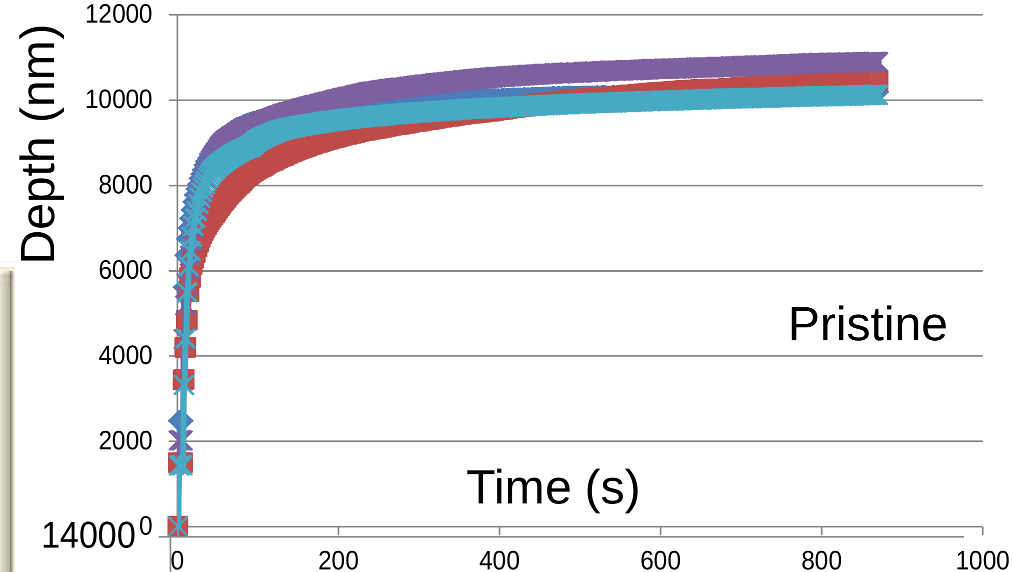
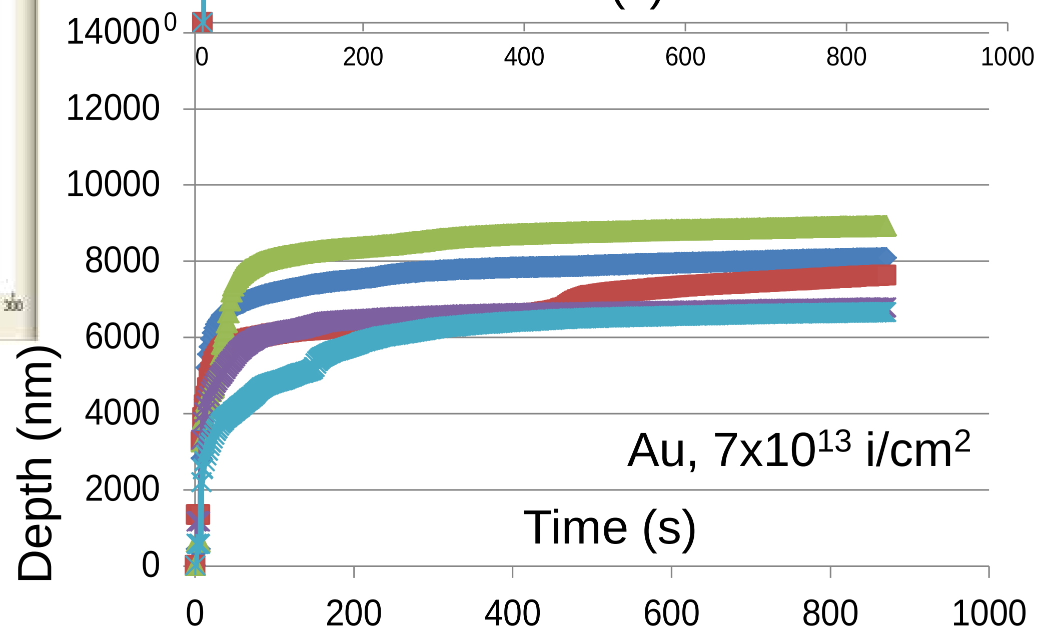
Impact nanoindentation study of fatigue behaviour of irradiated isotropic graphite

Cube Corner:

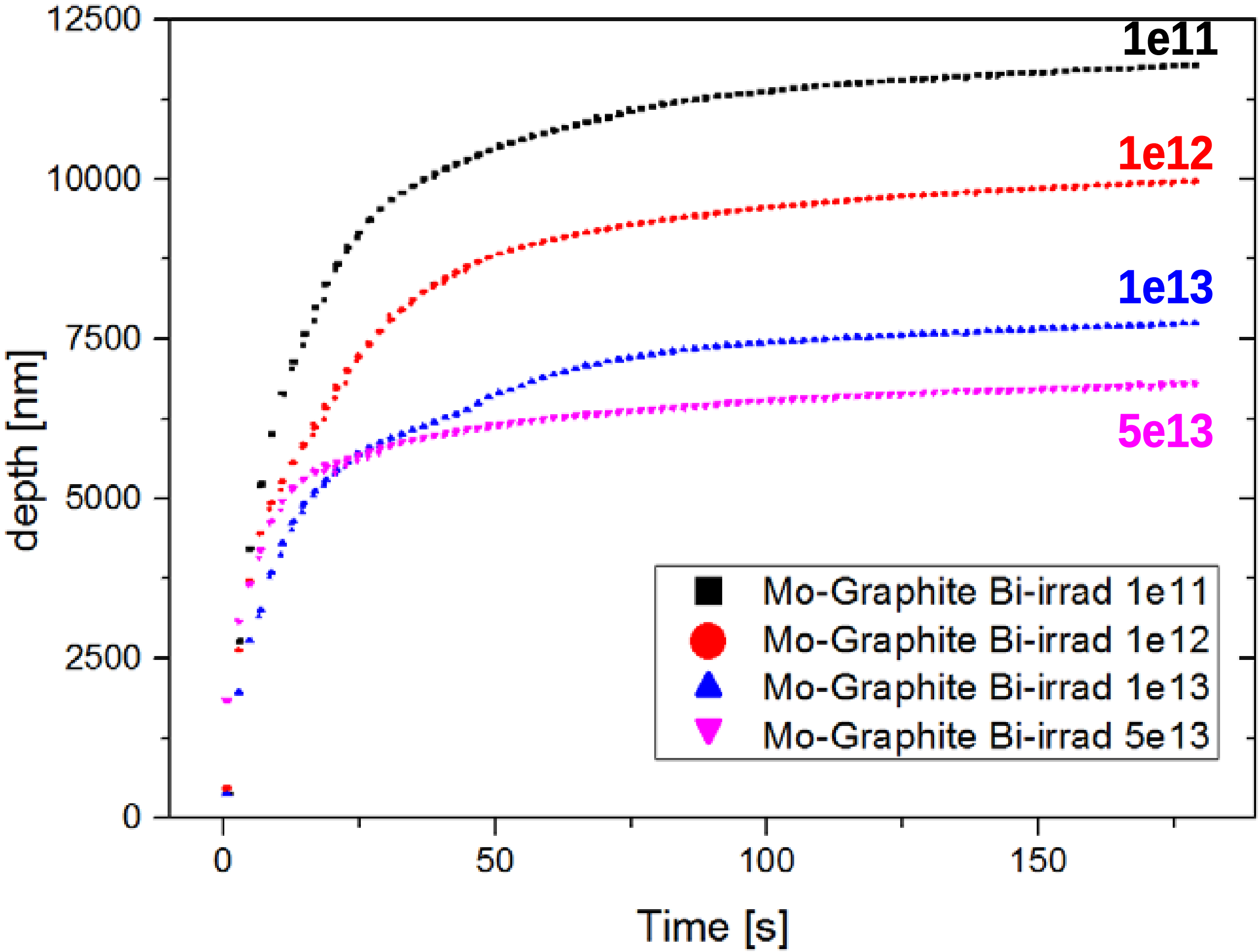
- **5 mN load,**
- **28 µm acceleration distance**







Impact/Woodpecker on Molybdenum Graphite

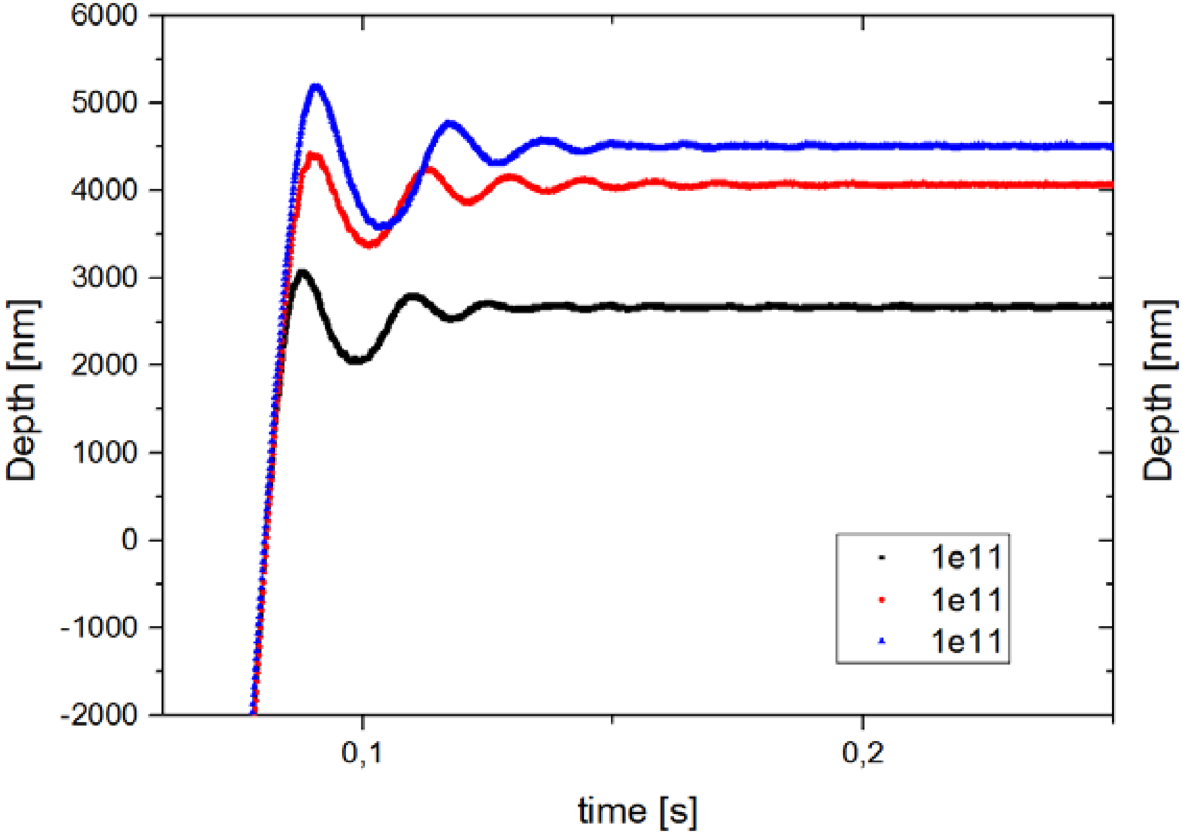


Irradiation:

Ion: Bi 27+
Energy: 4.8 MeV/u
Flux: 2e9 ions/cm²s
Frequency: 2 Hz
Pulse length: 0.3 ms

Impact frequency: 0.5 Hz
Impact load: 2mN
Impact distance: 15000 nm

Impact/dynamic hardness on Molybdenum Graphite



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Flux: 2e9 ions/cm²s
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Sampling time: 0.5 s
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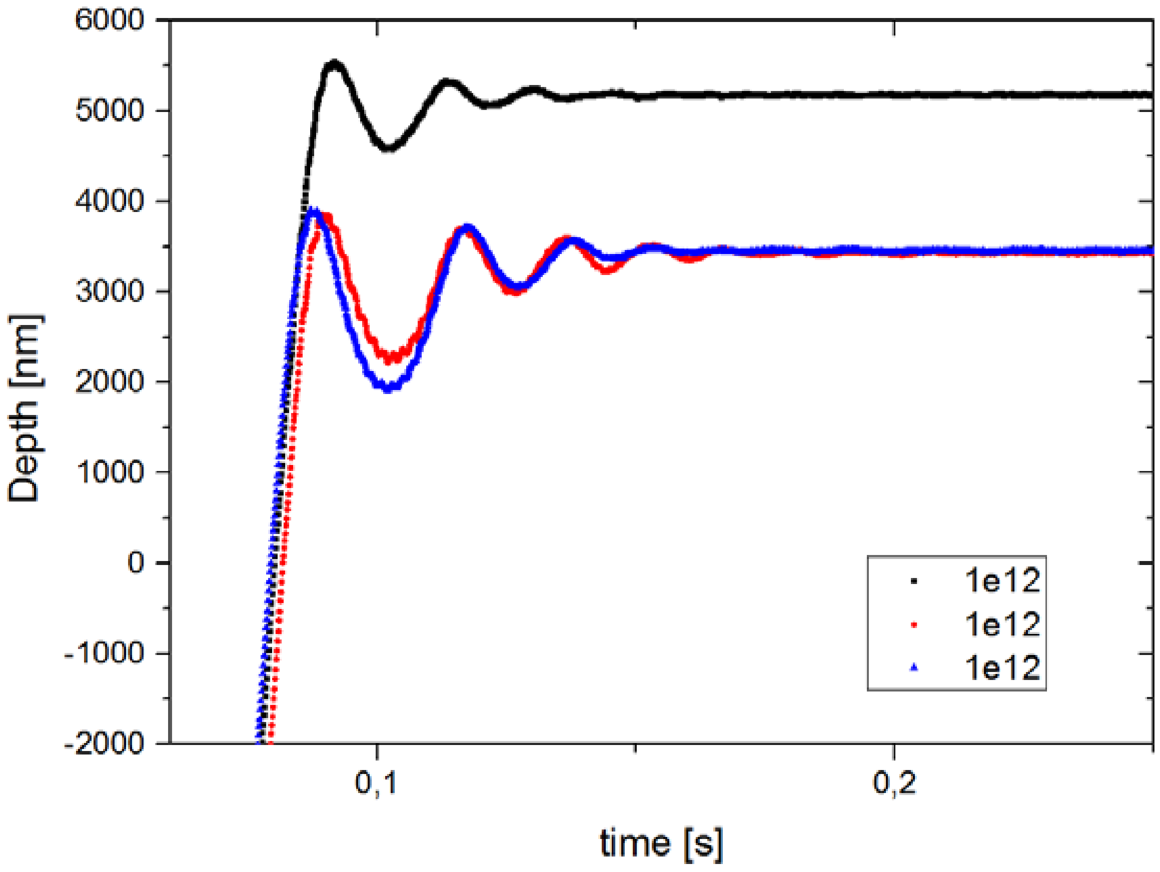
Impact/dynamic hardness on Molybdenum Graphite



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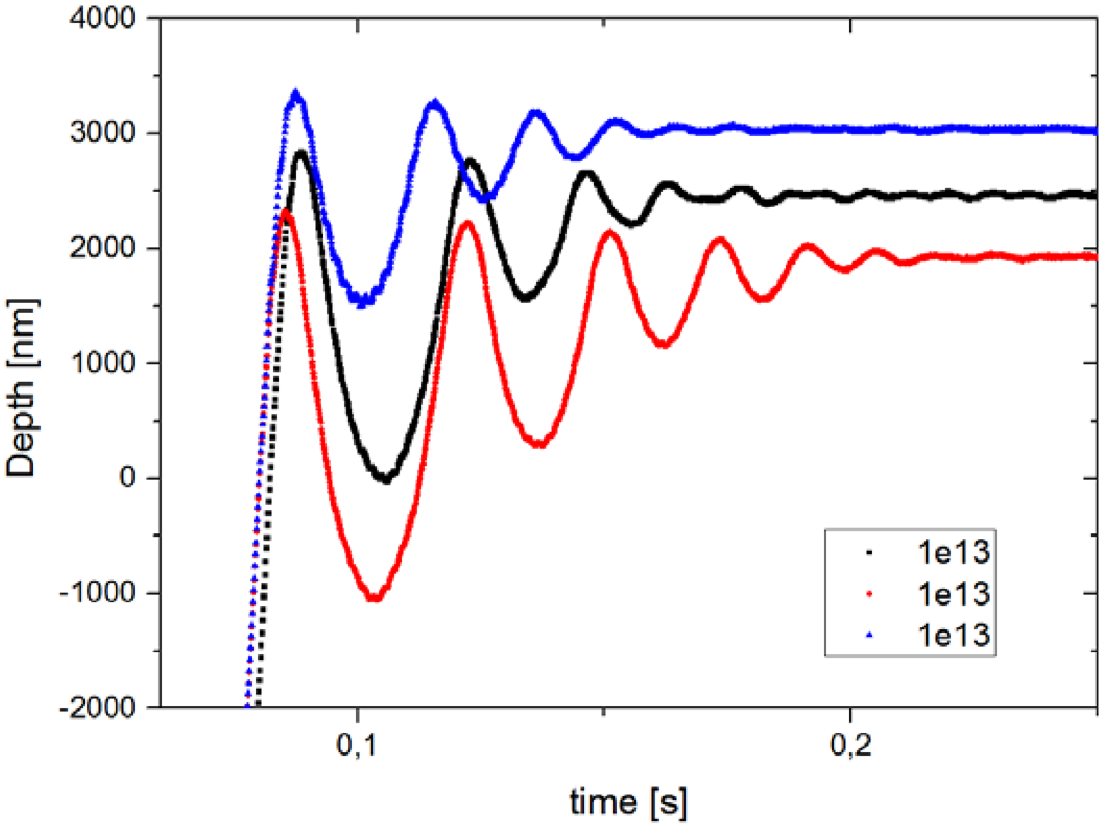

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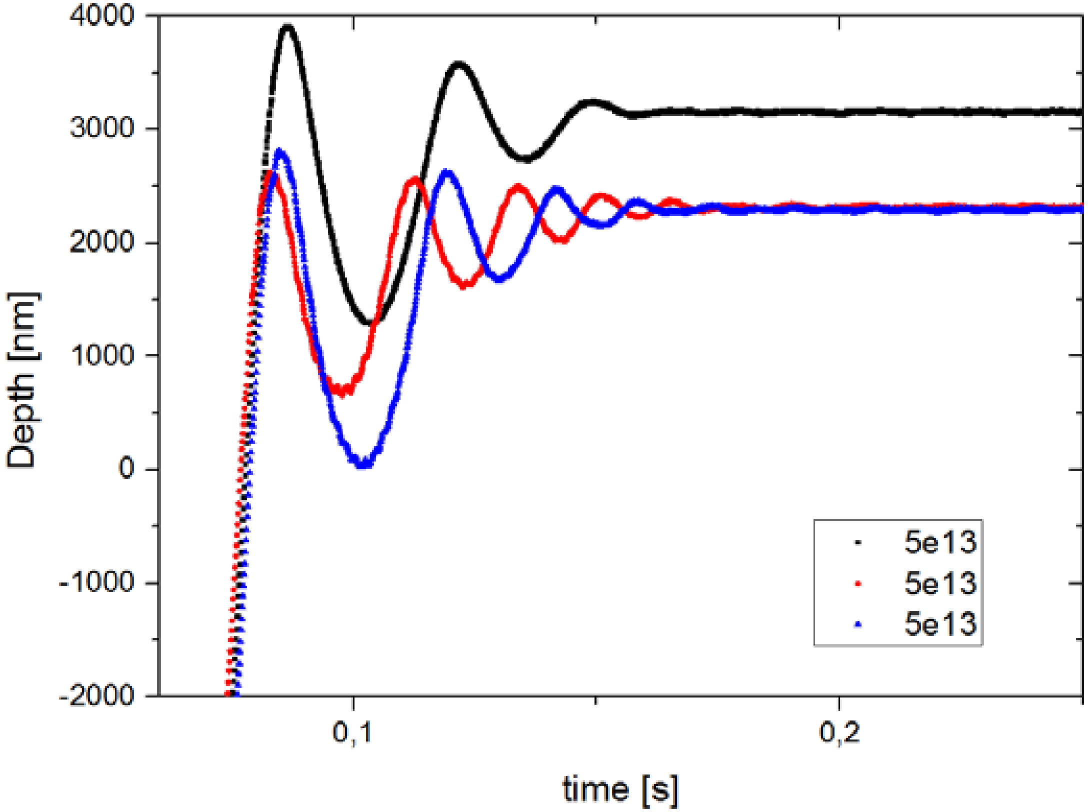

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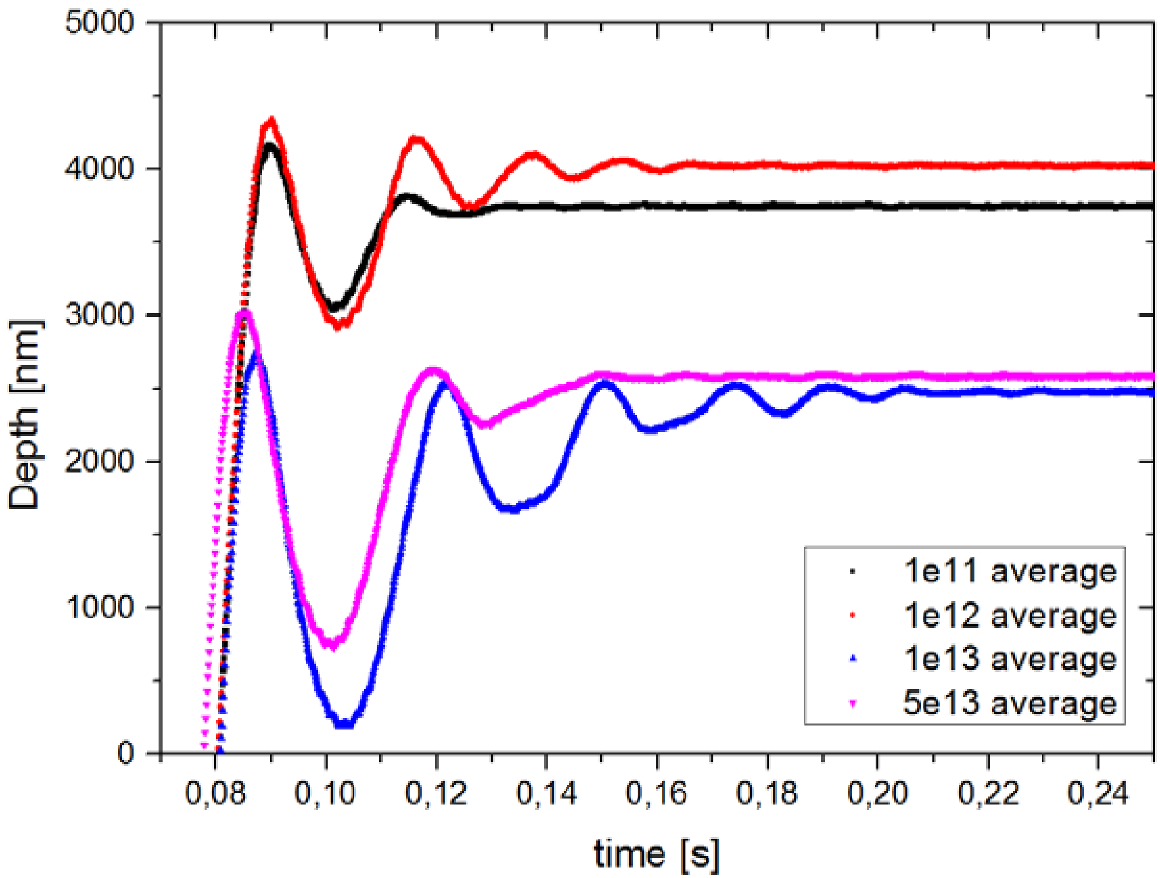
Impact/dynamic hardness on Molybdenum Graphite



1e12
1e11

5e13
1e13

Irradiation:

Ion: Bi 27+
Energy: 4.8 MeV/u
Flux: 2e9 ions/cm²s
Frequency: 2 Hz
Pulse length: 0.3 ms

Sampling time: 0.5 s
Impact load: 2mN
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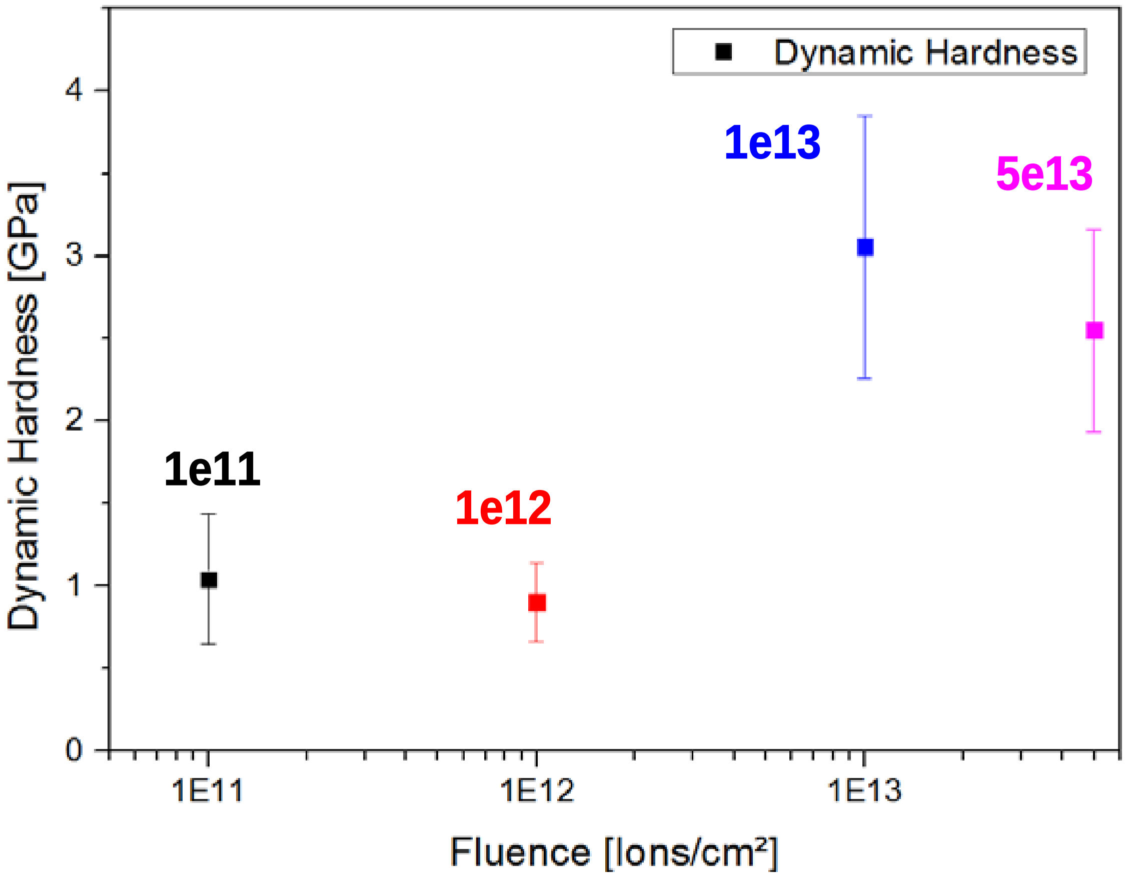
Impact/dynamic hardness on Molybdenum Graphite



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Conclusions and Outlook

- First irradiation tests of novel composite materials for LHC collimators at GSI

- For Mo-Gr the feed-back from irradiation results have been used to adjust the processing of the material to improve mechanical strength on transversal direction :
    - annealing at temperatures where vacancies are mobile in graphitic planes ans stress relaxation
    - test samples without long pitch carbon fibers
    - in-situ heat treatments

- Completion of thermo-mechanical and structural characterization of irradiated samples

- analysis of online thermal camera monitoring with increased frame rate

- Impact response of the novel material pristine and irradiated (fast extracted ion beam, laser beam, and nanoindenter)

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Brevetti Bizz

Stefano Bizzaro


Thank you for your attention!