Beam impact response of irradiated materials

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Outline

- Role of microstructure in materials response to beam impact
- Radiation- induced target material degradation:
  - *swelling*
  - *thermal diffusivity*
  - *hardening- new stress-concentrators*
  - *microimpact studies*
    - *- dynamic hardness, damping, fatigue*
  - *damage recovery at high temperature*
- Dynamic response in context of radiation damage
- Simulations of dynamic thermal fracture of targets in the context of radiation damage

Role of microstructure in materials response to beam impact

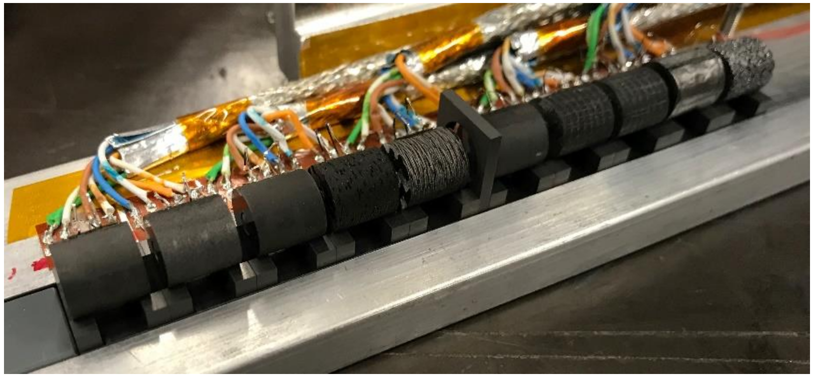
FlexMat experiment at HiRadMat-

- Graphitic materials response to beam impact
- applications for high power targets and beam dumps

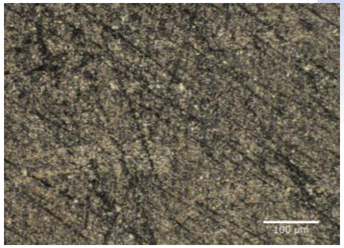
FlexMat - June 2018

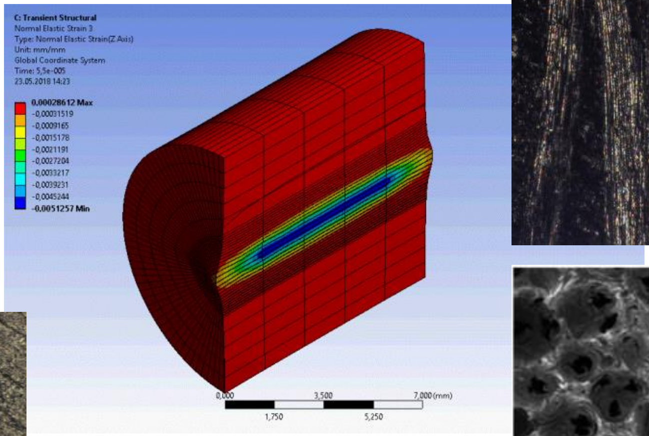
HiRadMat@SPS, CERN

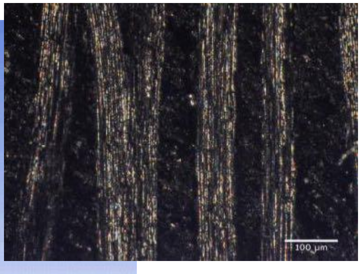
- 283 beam pulses
- total of 1.24E15 pot
- up to 1.3E11 ppb

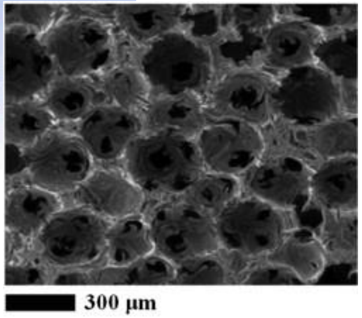


FlexMat mounting in SPS tunnel at CERN



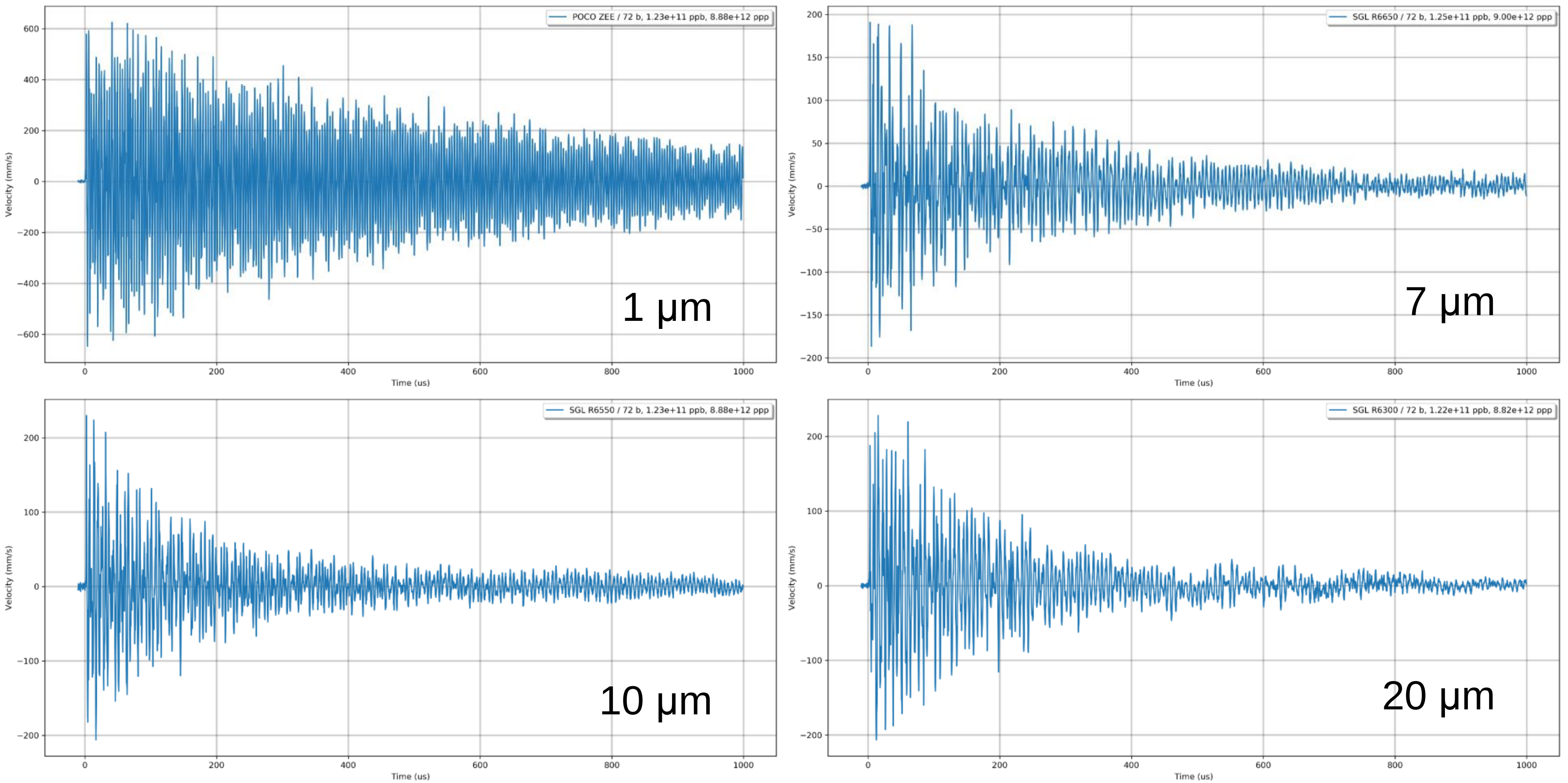






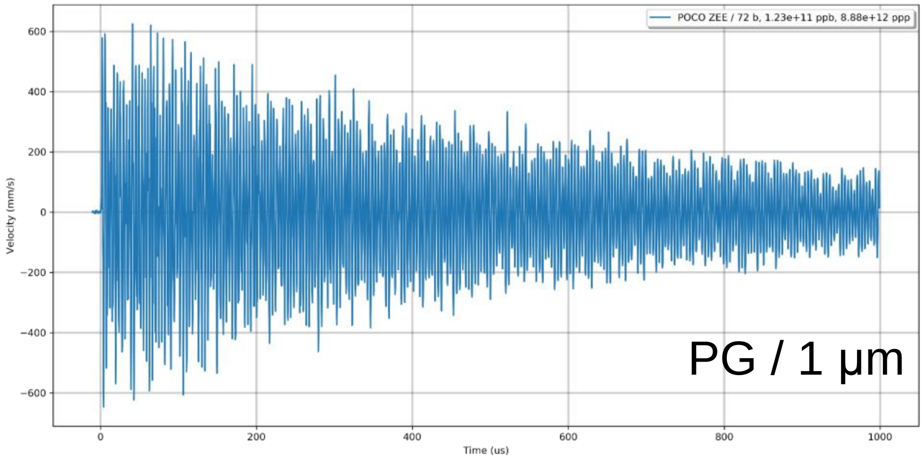
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

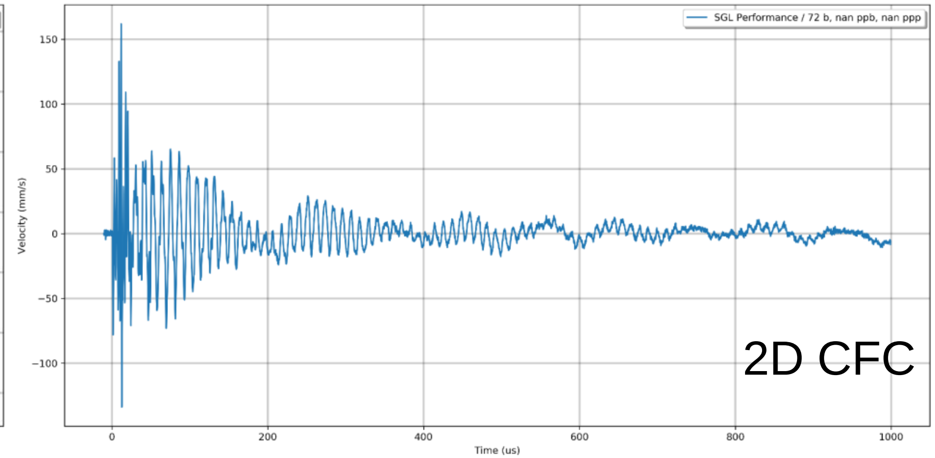
Beam impact response of graphite - microstructure influence

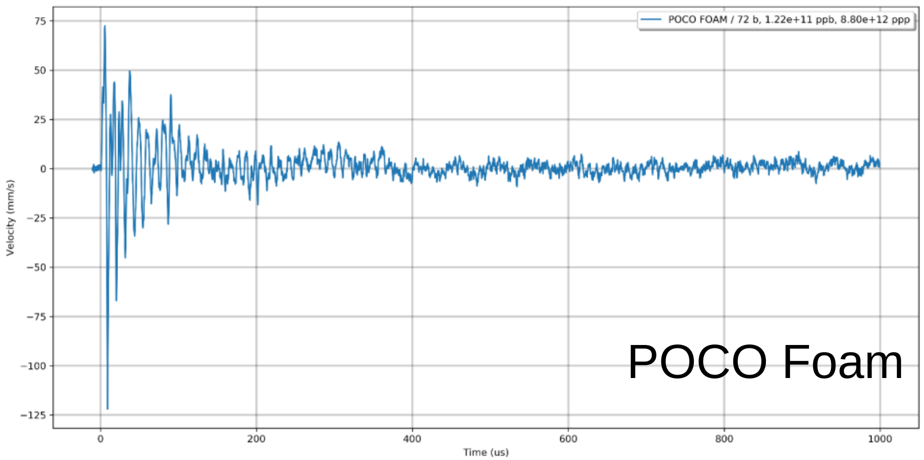


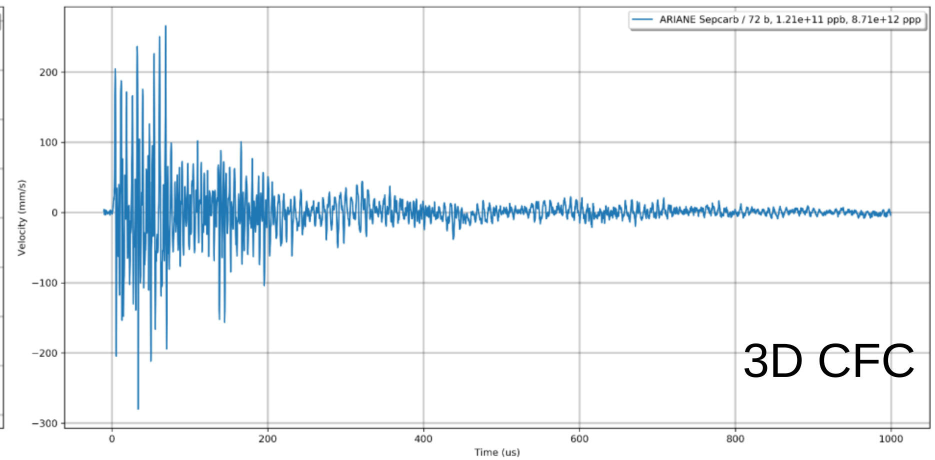
- Polycrystalline graphites with different grain sizes
- LDV signal- velocities

Beam impact response of other graphitic materials





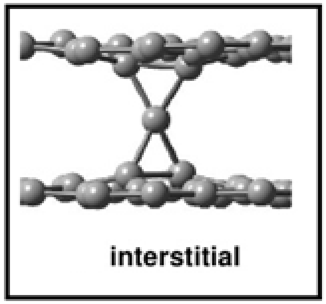


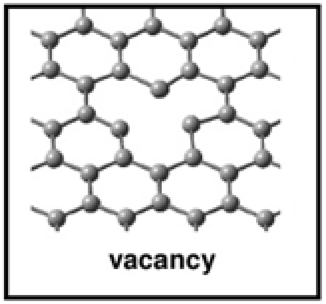


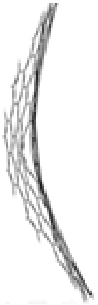
Radiation- induced thermo-mechanical properties degradation

Beam- induced swelling in graphite

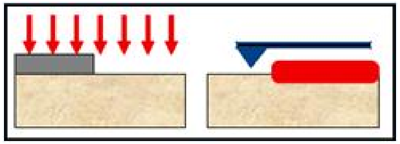
Swelling mechanism in irradiated graphite; defect creation

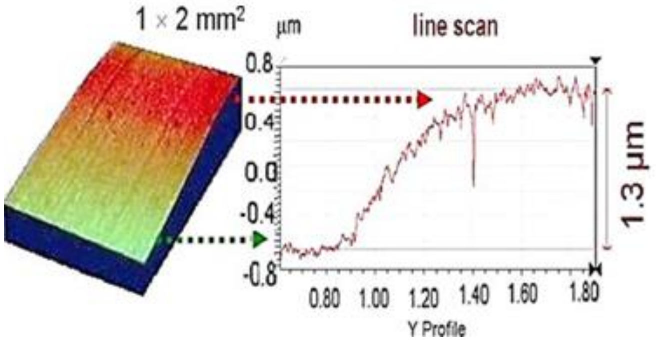


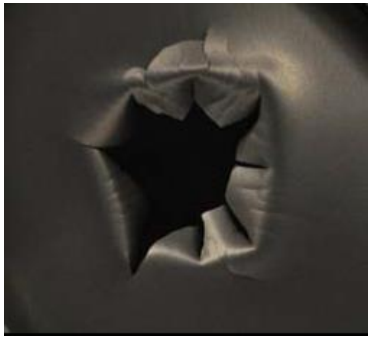




Swelling measurements- profilometry

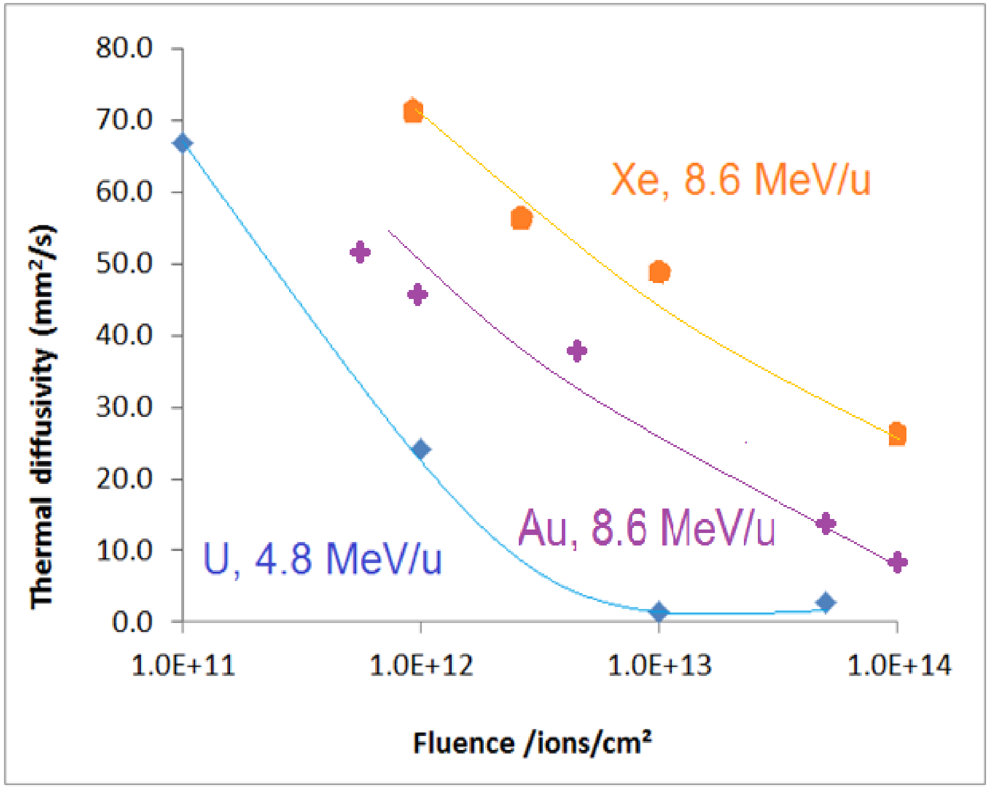




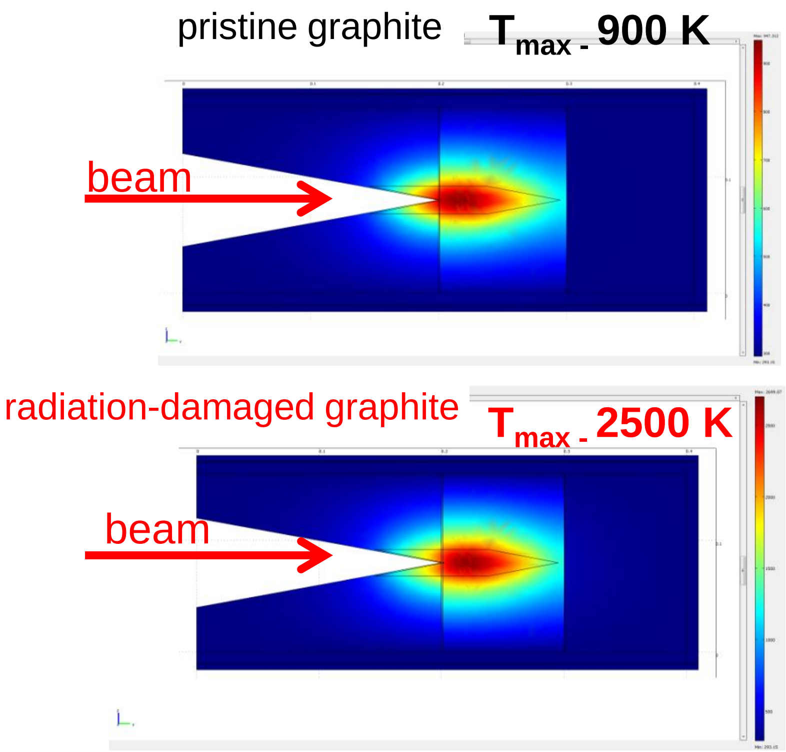


→ **Leads to additional stress at the edge of the beam spot on target**

Effects of beam- induced degradation of thermal diffusivity of graphite



Super-FRS Beam Catchers



(Ronja Knöbel, Helmut Weick, Super-FRS)

Thermal simulation shows cooling problem with radiation-damaged graphite:
- degradation of thermal diffusivity: 70-40 W/(m K) -> 15 W/(m K)

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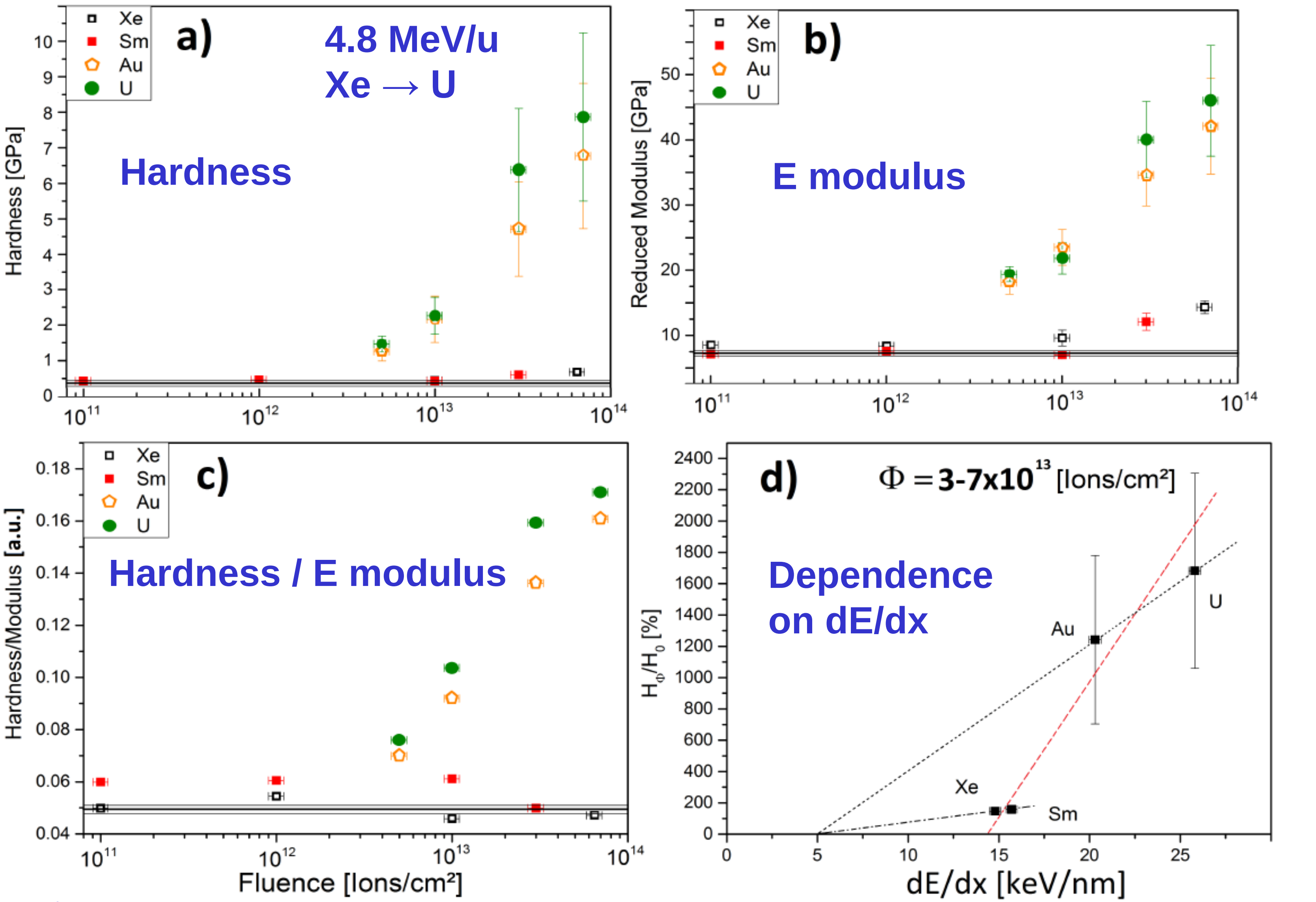
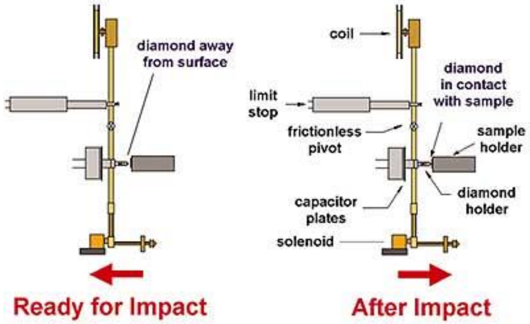
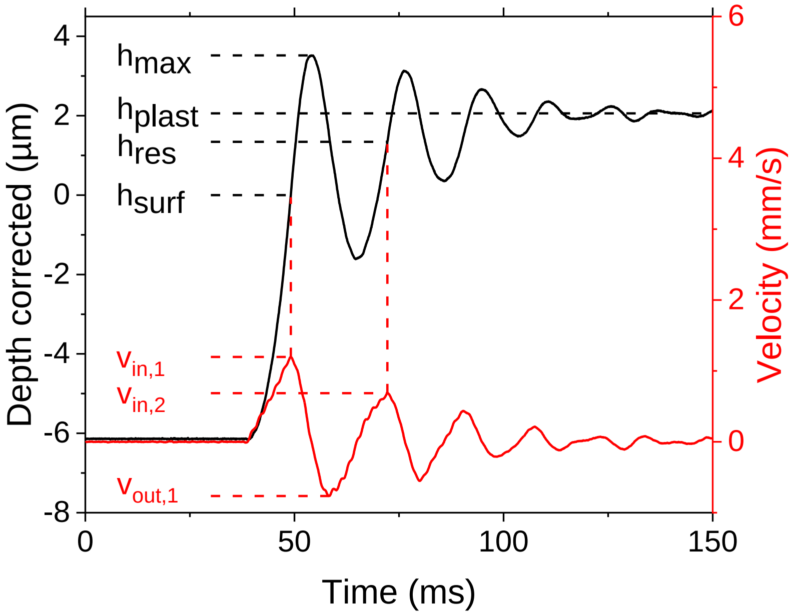
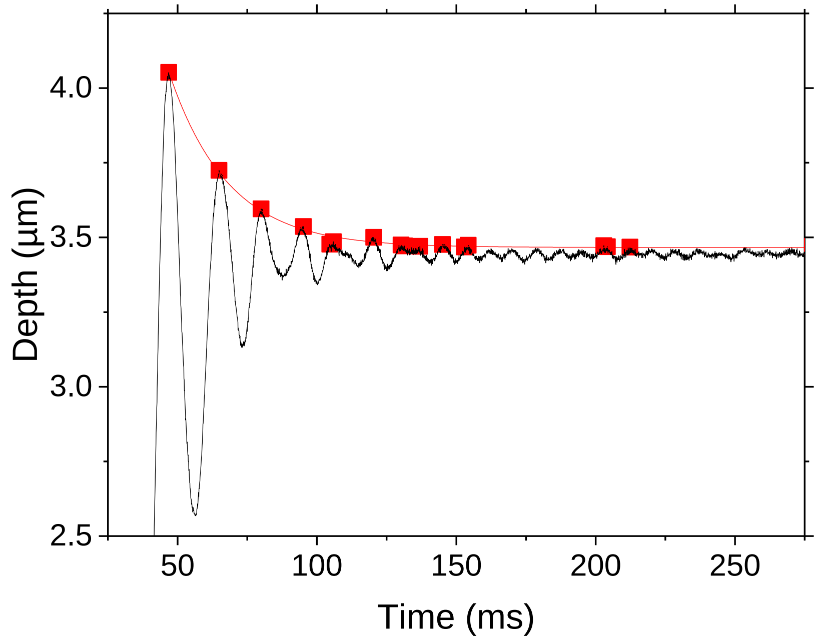
Ion beam induced hardening in graphite



Microimpact tests– derived parameters



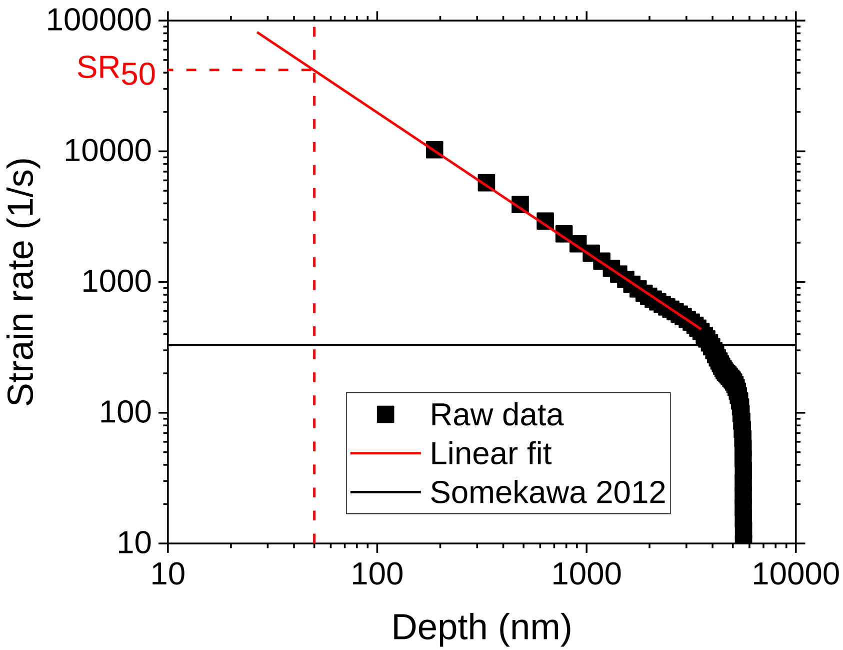


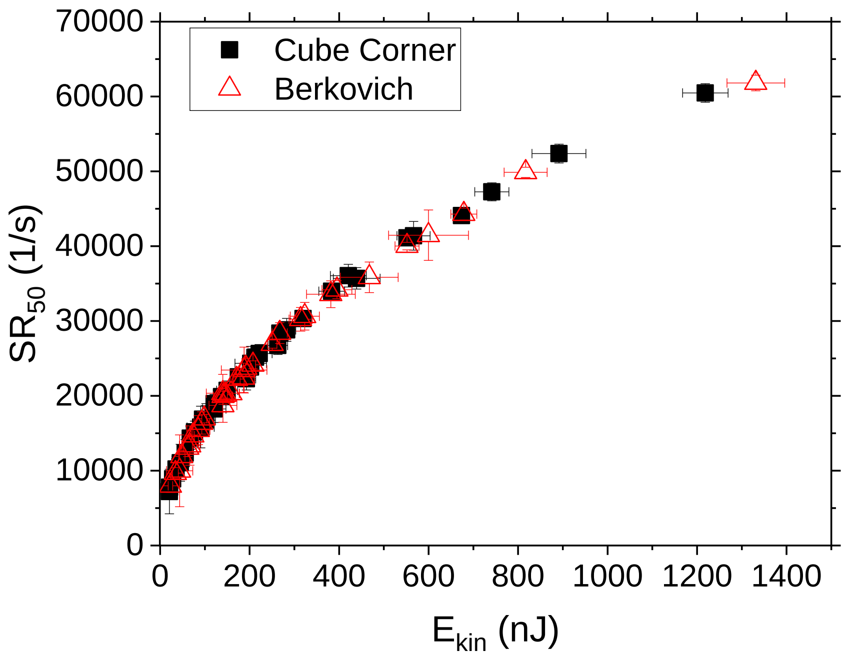


$$H_{dyn} = \frac{3 \cdot m \cdot (v_{in}^2 - v_{out}^2)}{2 \cdot c \cdot h_{res/plast}^3}$$

$$h = A \cdot e^{-DC \cdot t} + h_{plast}$$

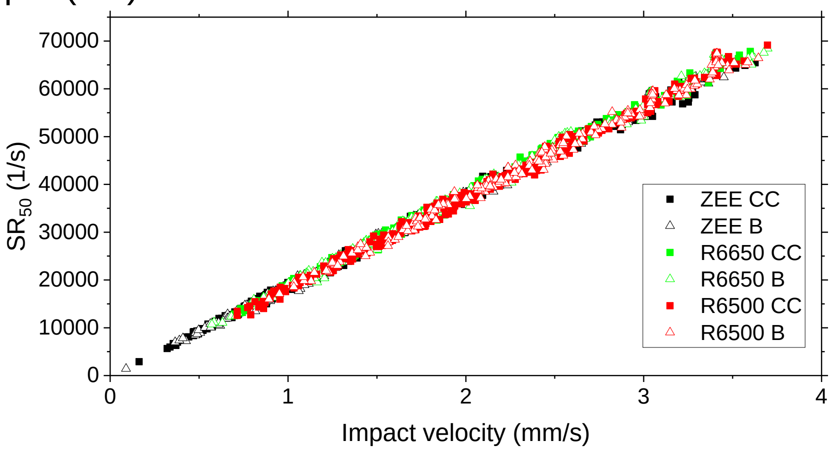
Microimpact tests- achieved strain rates





$$SR = \frac{\dot{h}}{h} = \frac{v(t)}{h(t)}$$

$$SR(Somekawa) = \frac{v_{in}}{h_{max}}$$

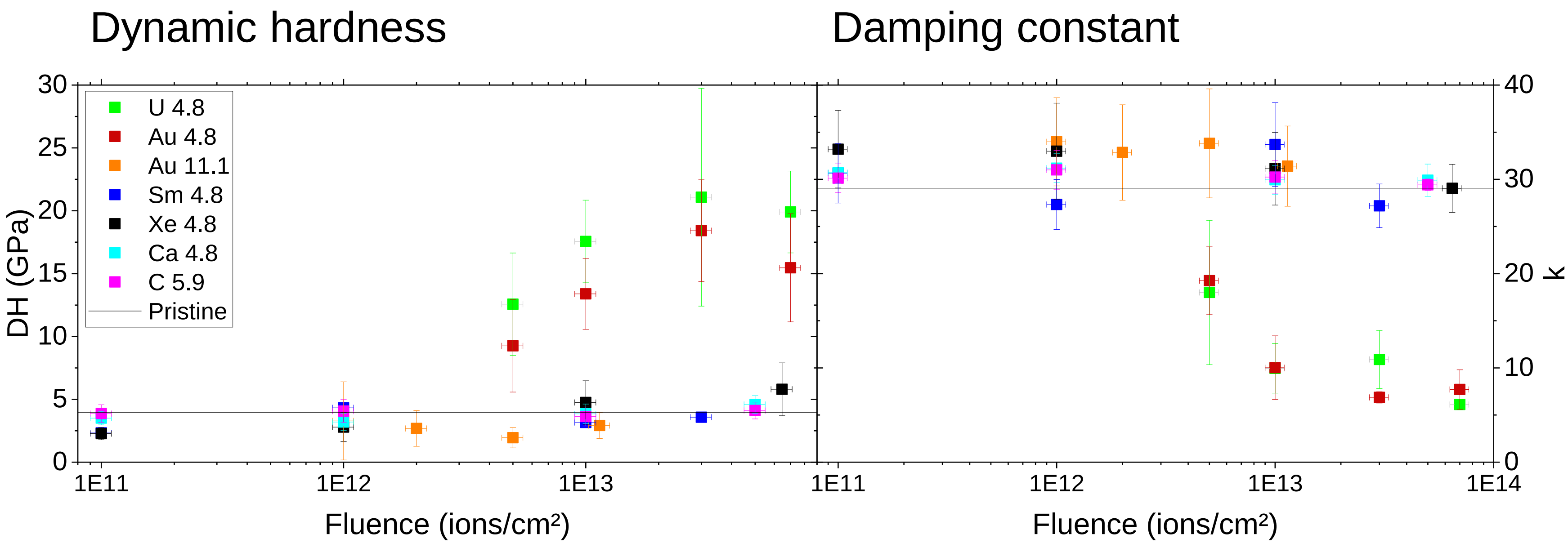


$$E_{kin} = \frac{m \cdot v_{in}^2}{2} \approx E_{pot} = d \cdot F$$

$$d = distance$$

$$F = acceleration\ force$$

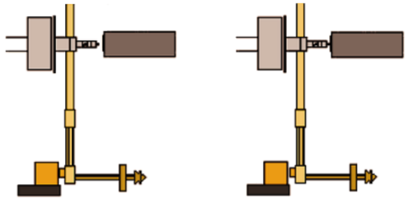
Microimpact – dynamic hardness and damping evolution with fluence

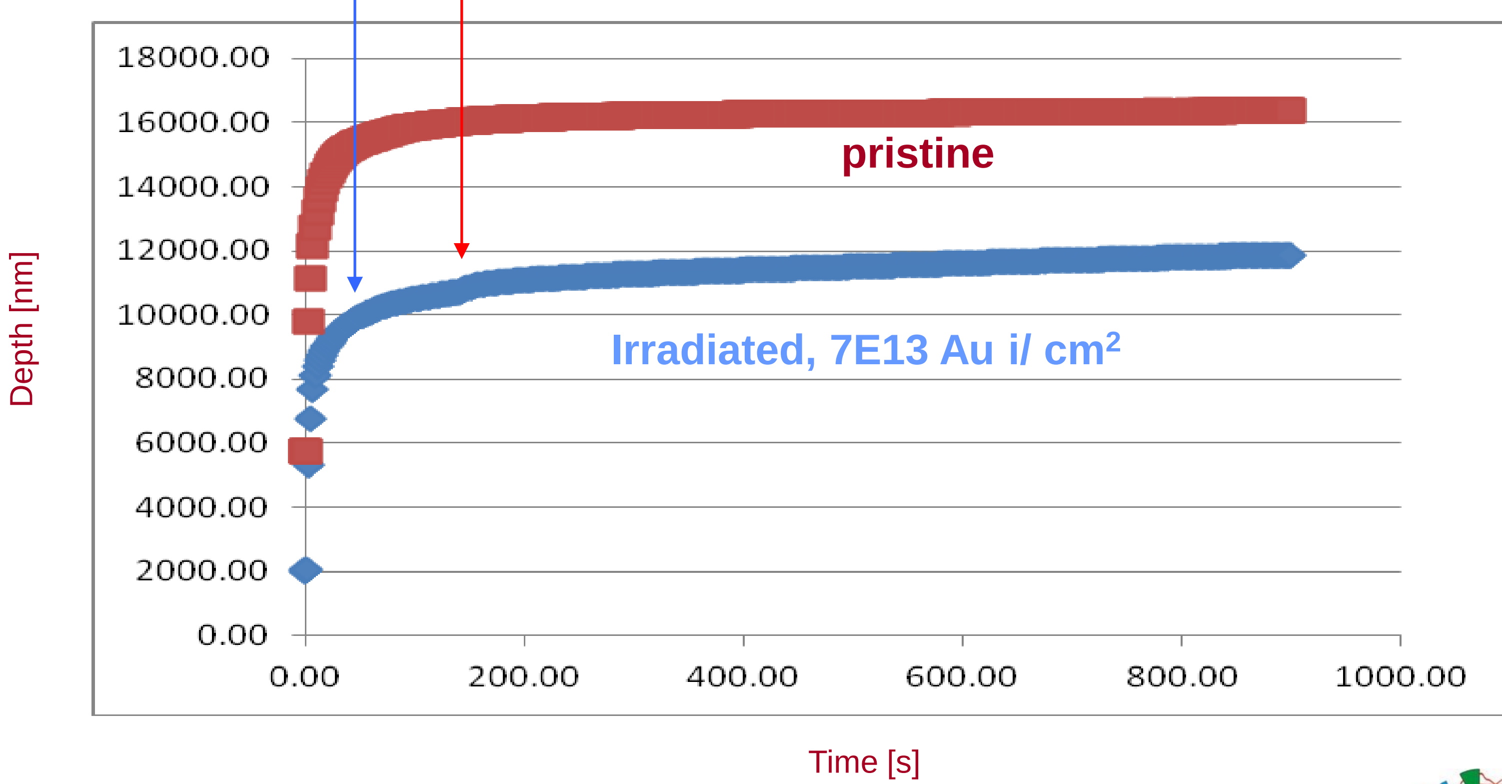


	Strain rate [s^{-1}]
Quasi static indentation	10^{-2} to 10^{-1}
Nanoimpact	10^{4}
Ion beam impact	10^{3} to 10^{5}

Multiple microimpact on irradiated graphite- fatigue

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

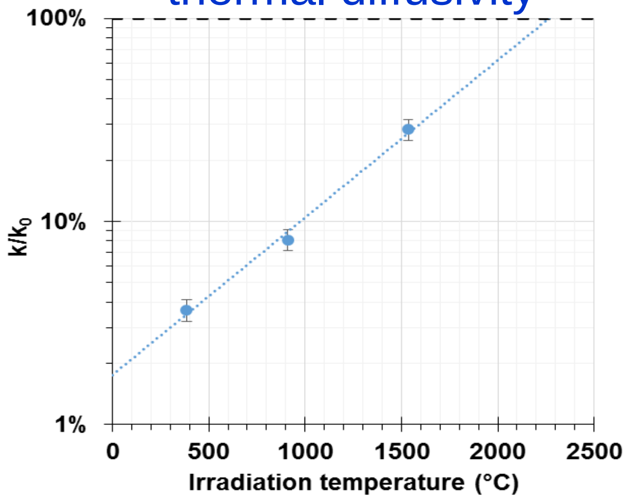




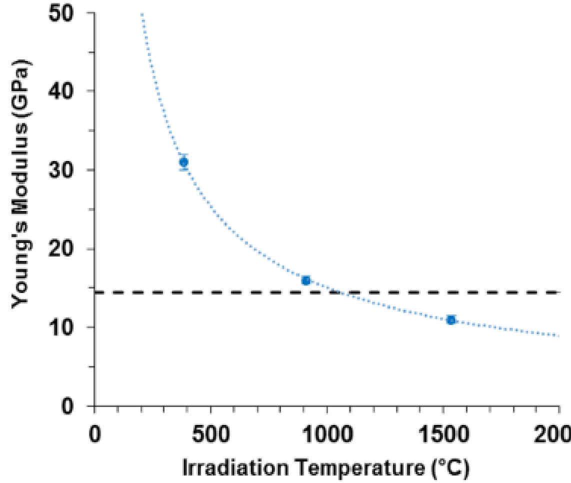
How to mitigate radiation damage effects in graphite (production targets and beam catchers materials)

Damage recovery by - operation at high temperatures (> 900 ºC)
- post-irradiation annealing

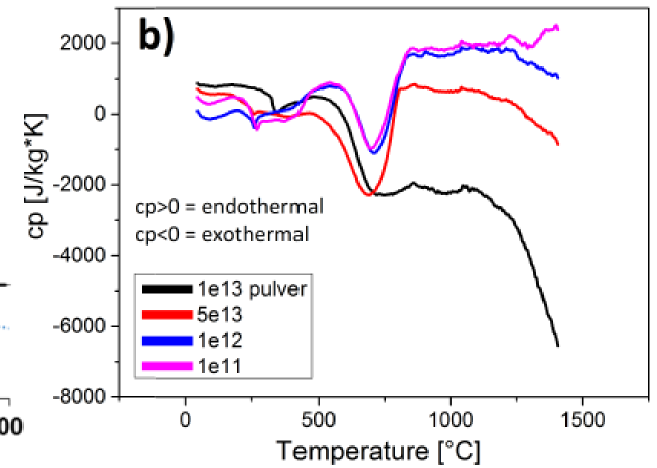
thermal diffusivity



Young modulus



DSC – defect annealing



F. Pellemoine et al., Nucl.Inst.Meth.B, (2015) DOI:10.1016/j.nimb.2015.09.007
C.Hubert et al., Nucl.Inst.Meth.B, (2015) DOI:10.1016/ j.nimb.2015.08.056

at T> 900 ºC → beneficial effect on recovery of thermo-mechanical properties

- thermal diffusivity reaches 30 % of the pristine value (1500 ºC)
- Young modulus reaches pristine value

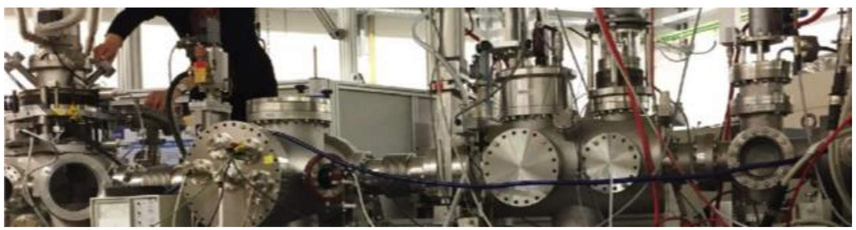
Dynamic response in context of radiation damage

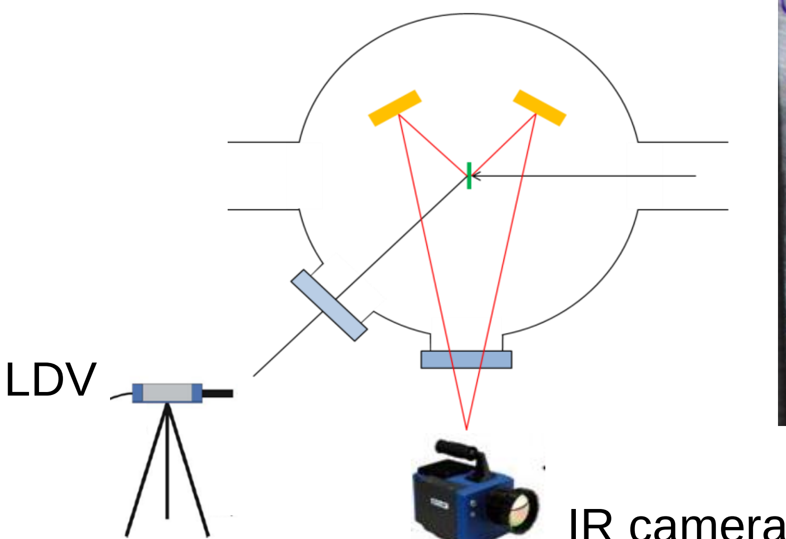
-experiments with 4.8 MeV/u U at UNILAC, GSI

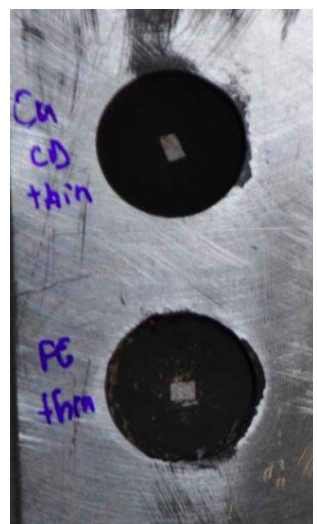
Experimental details
Irradiation parameters & set-up

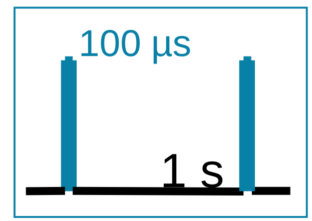
- Beam parameters
  - 4.8 MeV/u U^{28+}
  - Up to 1.5×10^{10} i/cm^2 per pulse
  - Up to fluences of 1×10^{14} i/cm^2

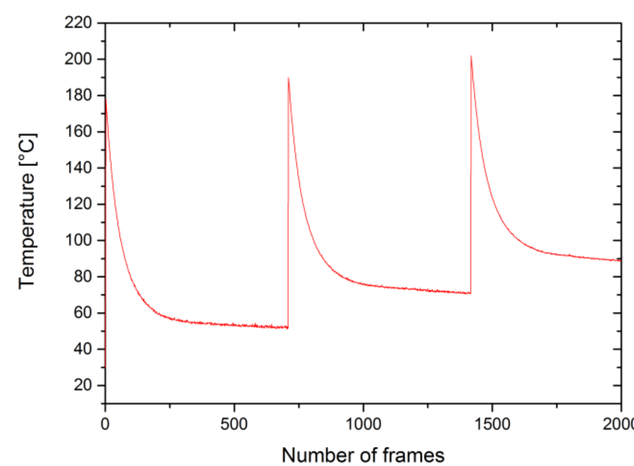
high-current mode (MEVVA source)
1-2 Hz
100-200 µm length of macropulse











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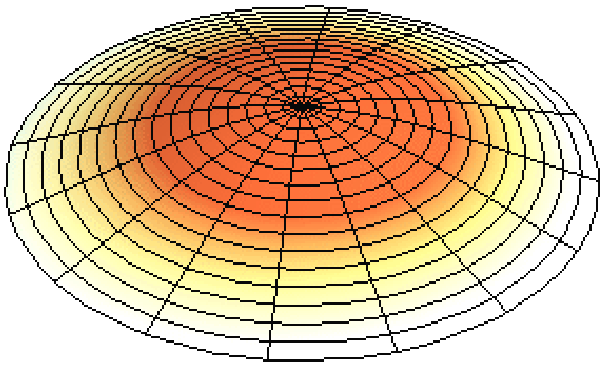
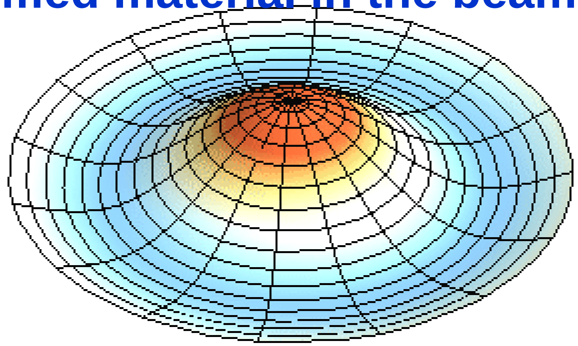
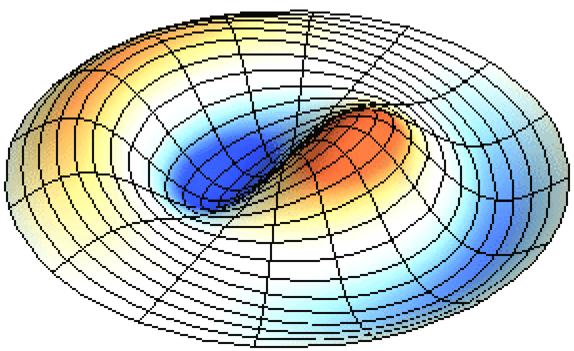
Vibration of a disc – beam modified material in the central beam spot

vibration with one circular node
pristine sample



vibration with two circular nodes
modified material in the beam spot





vibration with one circular node
and one diameter node – beam hits eccentric

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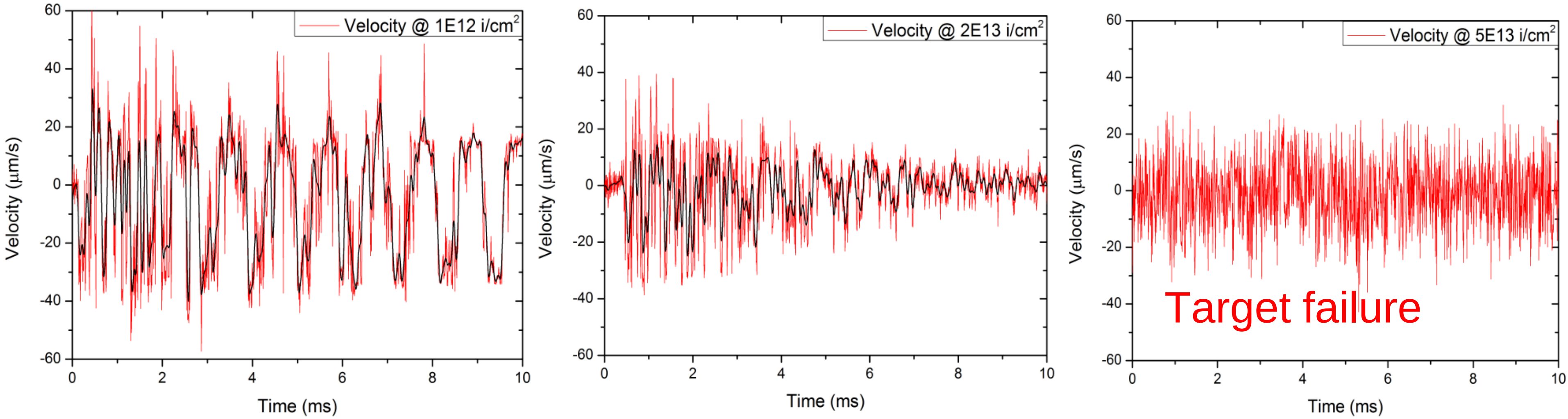
Animation - Dr. Dan Russell, Grad. Prog. Acoustics, Penn State

Oscillation monitoring as a function of fluence

Polycrystalline isotropic graphite 140 µm

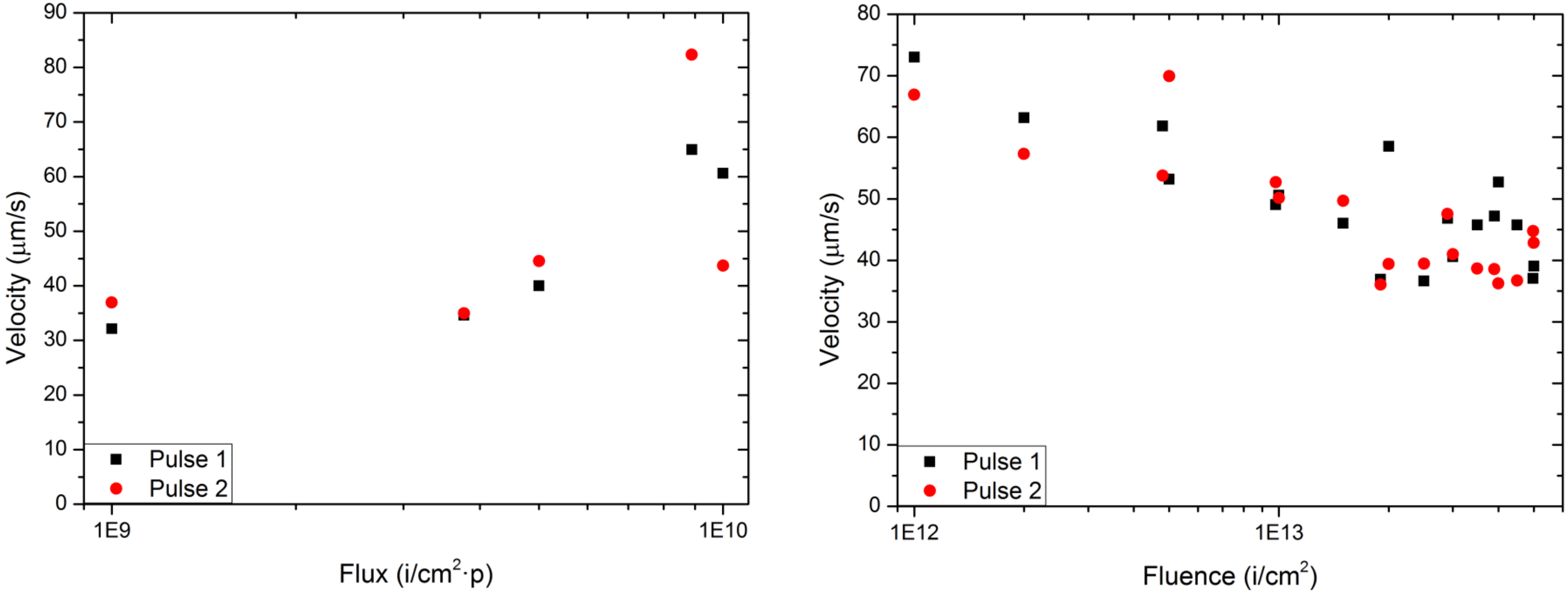


With radiation damage accumulation:

- Additional reflection at irradiated / non-irradiated interface

- increase of frecquency
- increase of damping
- decrease of velocity

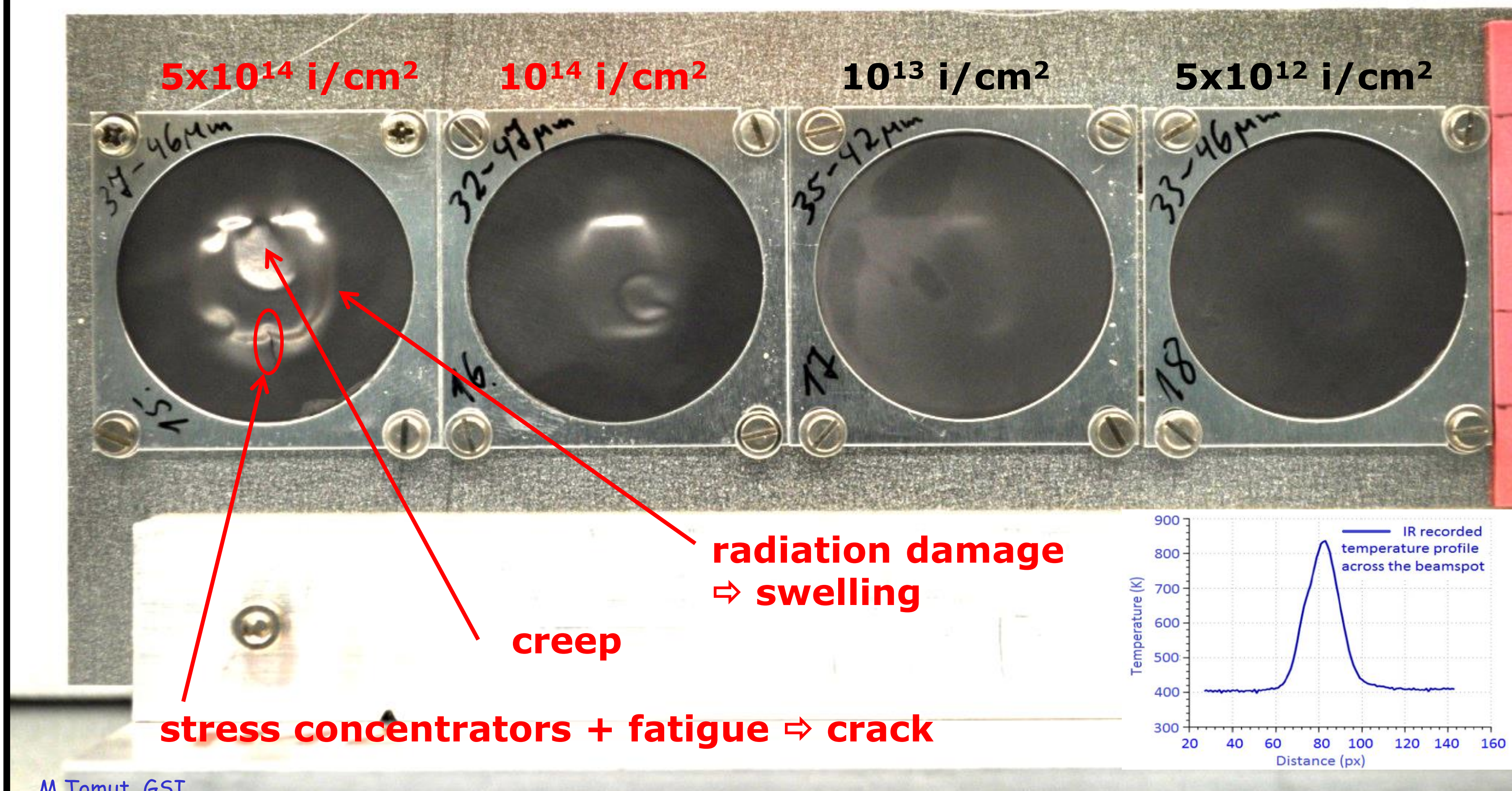
Measured maximum velocities - LDV



- Decrease of maximum velocity with accumulated dose:
  Radiation damage:
  - density reduction in beam spot
  - internal friction
  - plastic deformation processes

Failure of graphite exposed to pulsed GeV ^{238}U beam - accelerated radiation damage

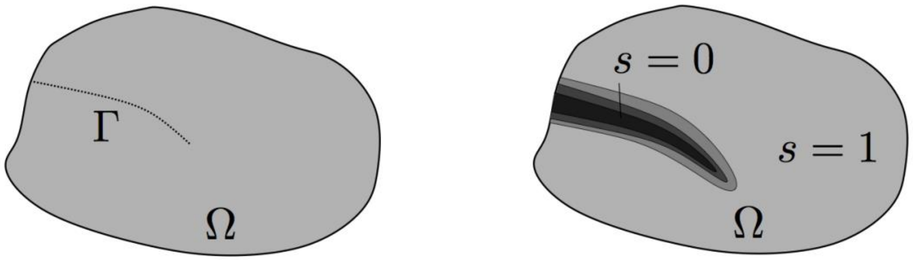
^{238}U, 1.14 GeV; 1.5 x10^{10} i/pulse ; 150 µs, 1 Hz



Simulations of dynamic thermal fracture of targets in the context of radiation damage

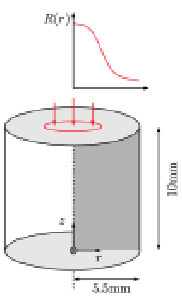
Phase field modelling of brittle fracture induced by pulsed beams

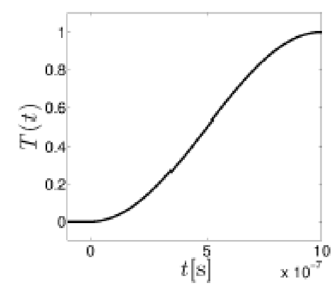
- Smooth field *s* approximates cracks
- Set of coupled PDEs determines deformation, heat transfer and fracturing

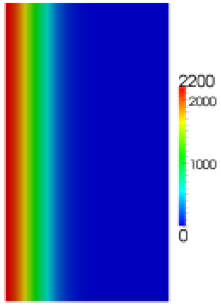


Beam deposits a large amount of energy in a short time interval

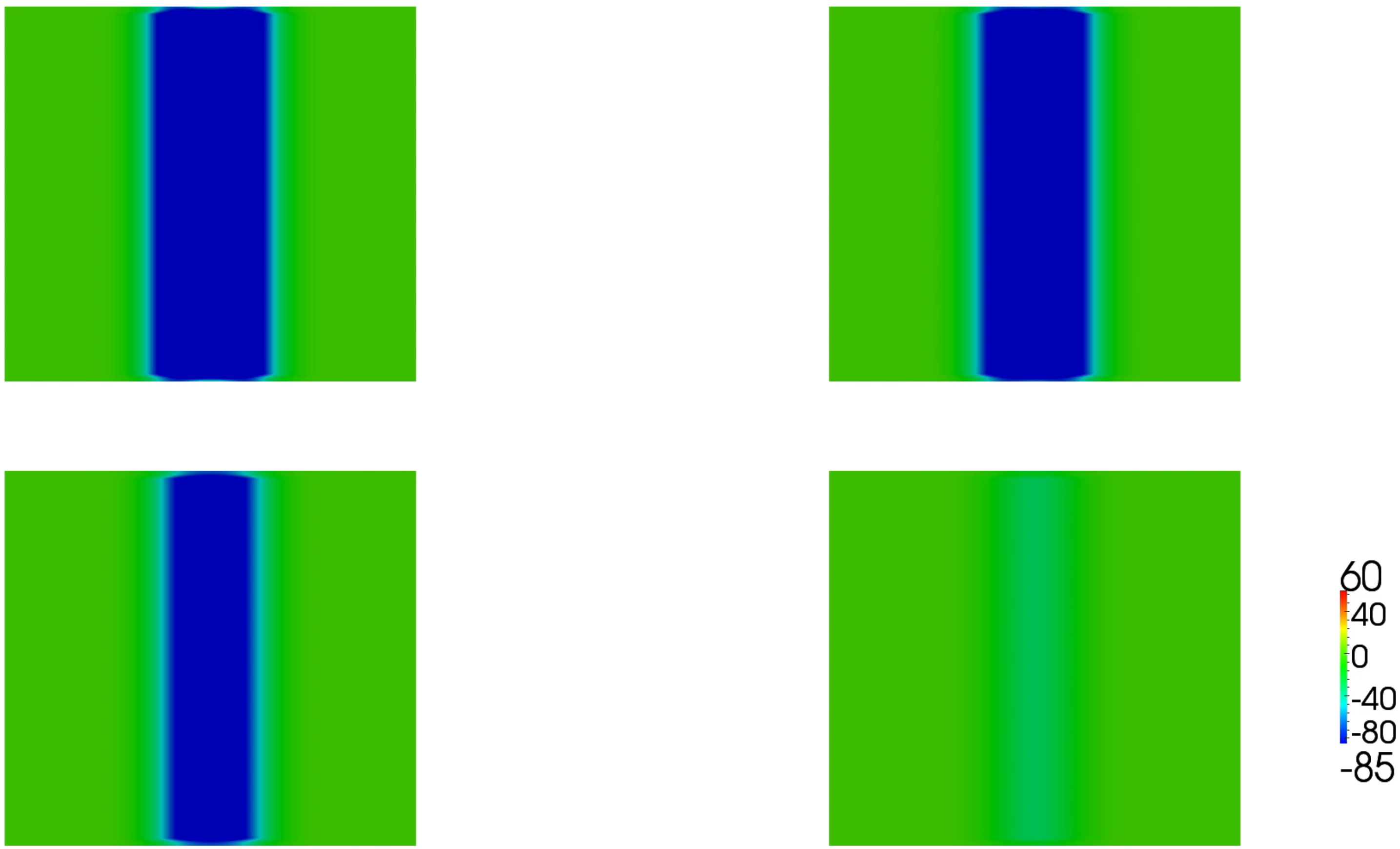
- Temperature rises
- Heat conduction is slow compared to elastic wave speed
- Model beam by defining a stationary temperature field: $\theta^* (r, t) = \theta_{\text{max}} R(r) T(t)$



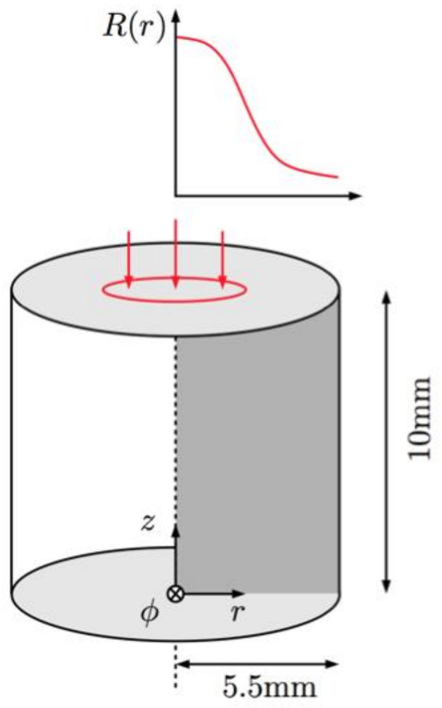


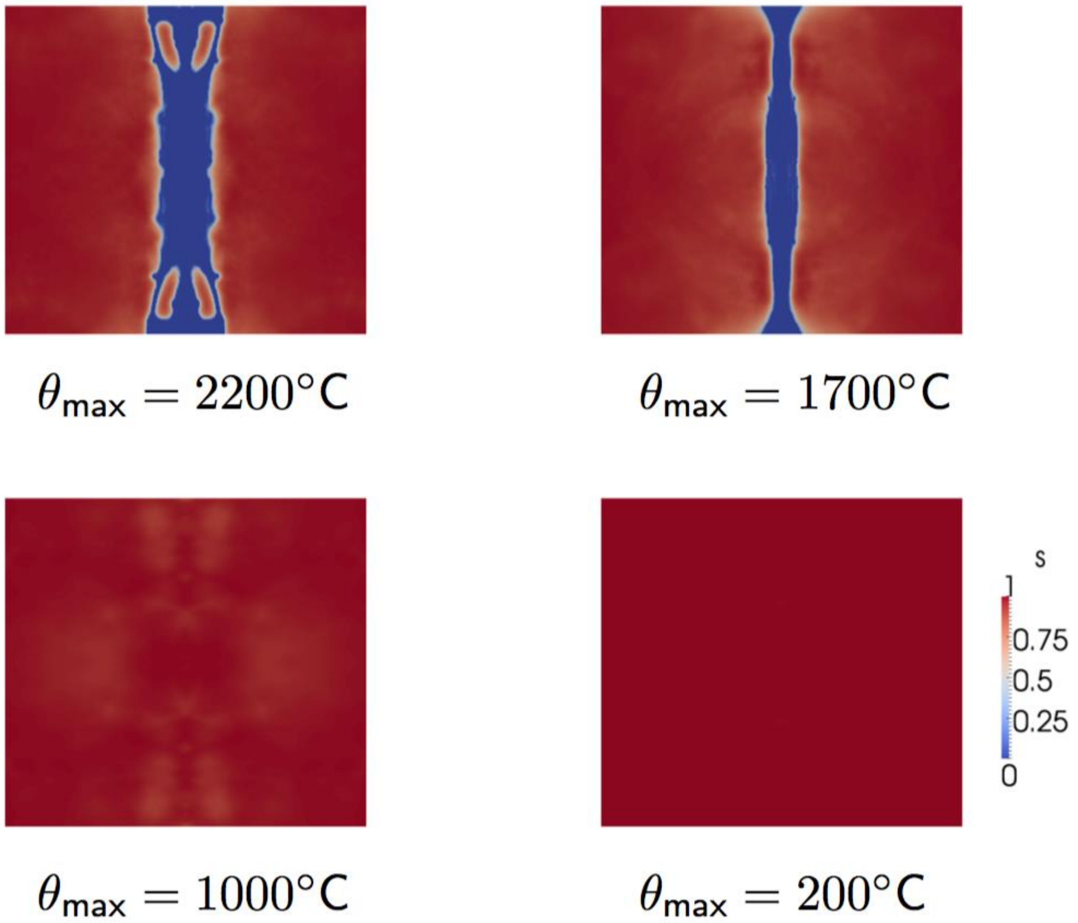


Fracturing of irradiated graphite cylinders at different beam-spot temperatures – Hoop stress



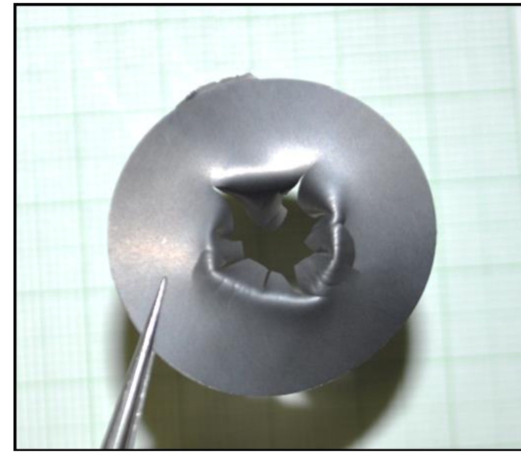
Fracturing of irradiated graphite cylinders at different beam-spot temperatures

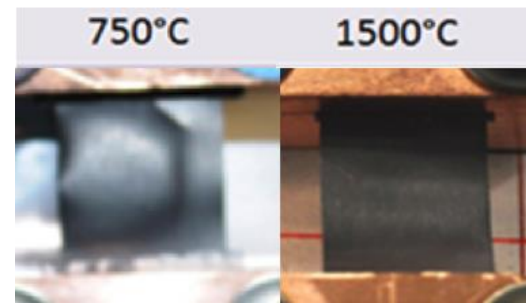




Conclusions and Outlook

- Dynamic response of irradiated materials to intense, short-pulse beam show in general earlier failure in the material that accumulated radiation damage
- A complex puzzle has to be assembled as not all effects of accumulated dose and high beam intensity have a detrimental effect on the target lifetime
- A concerted campaign, bringing together facilities for materials irradiation, materials characterization and those providing high-intensity pulsed beams, such as HiRadMat is needed
- Mitigation of earlier failure by using functionally graded materials and components





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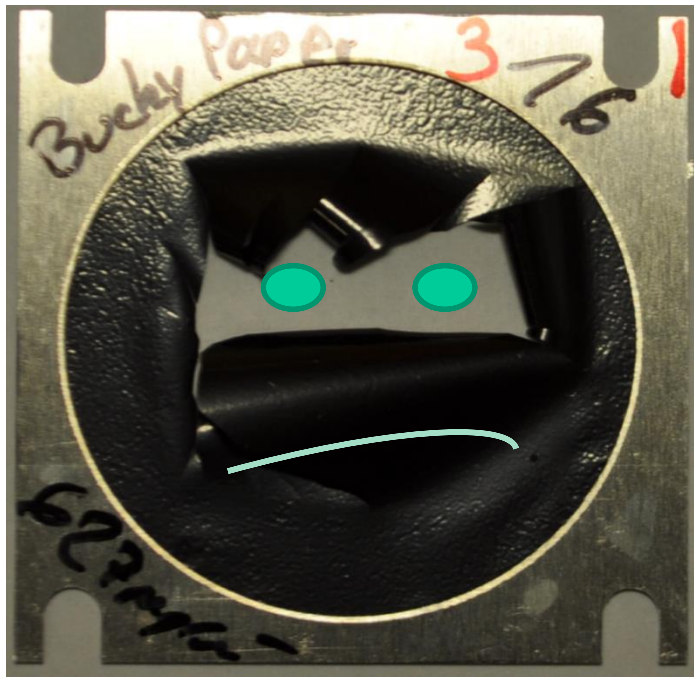

Too much stress ?