Options for ion irradiation tests of new collimator materials at GSI

M. Tomut

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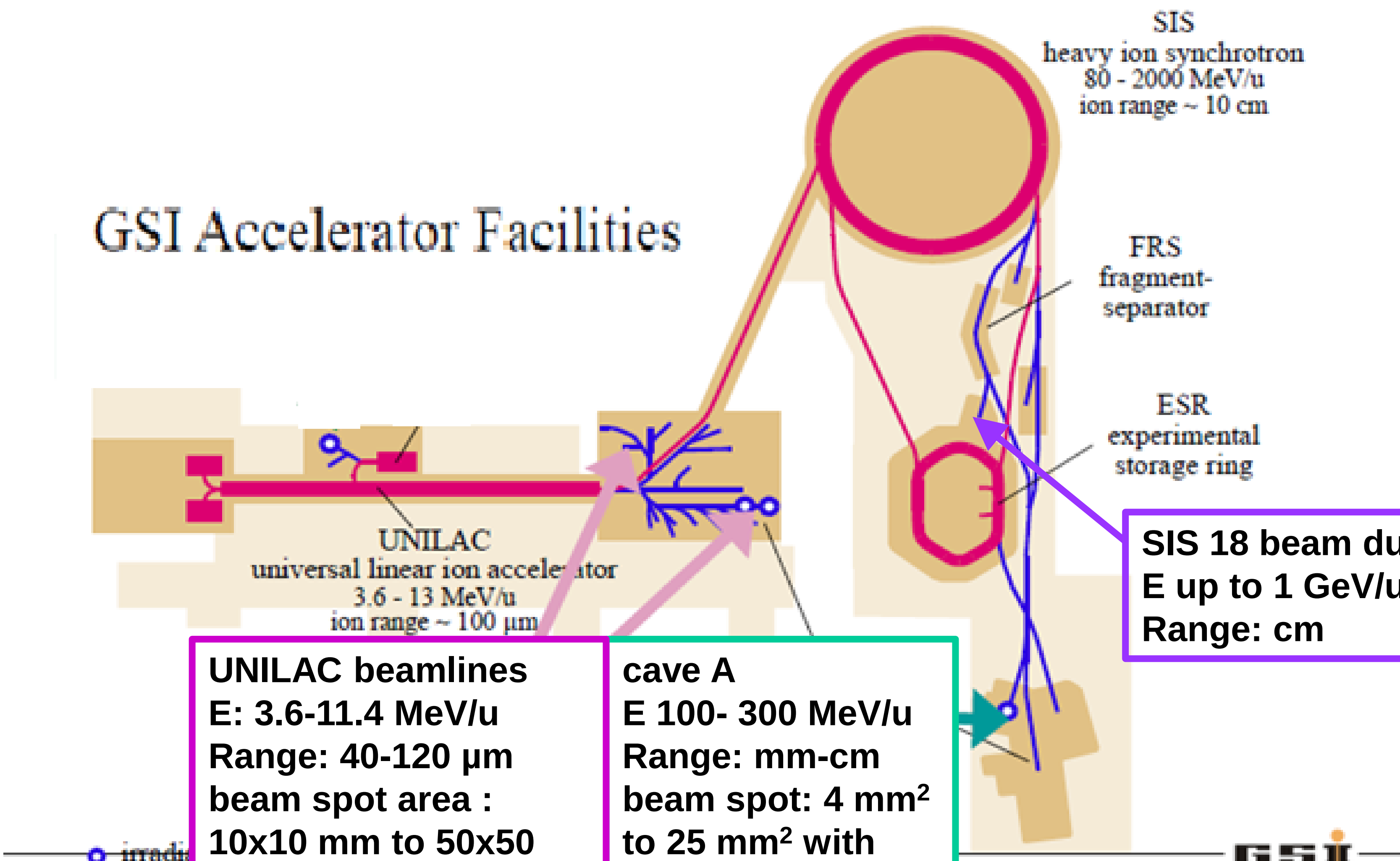
Ion irradiation facilities

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 mm^2 to 25 mm^2 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

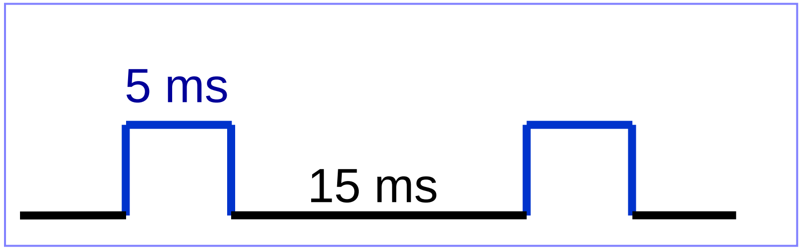
5 ms length of macropulse

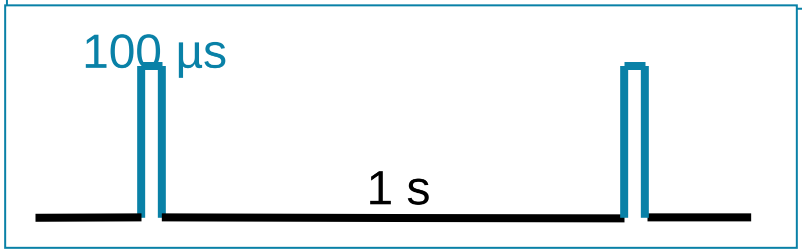
high-current mode (MEVVA source)

(for SIS experiments)

1-2 Hz

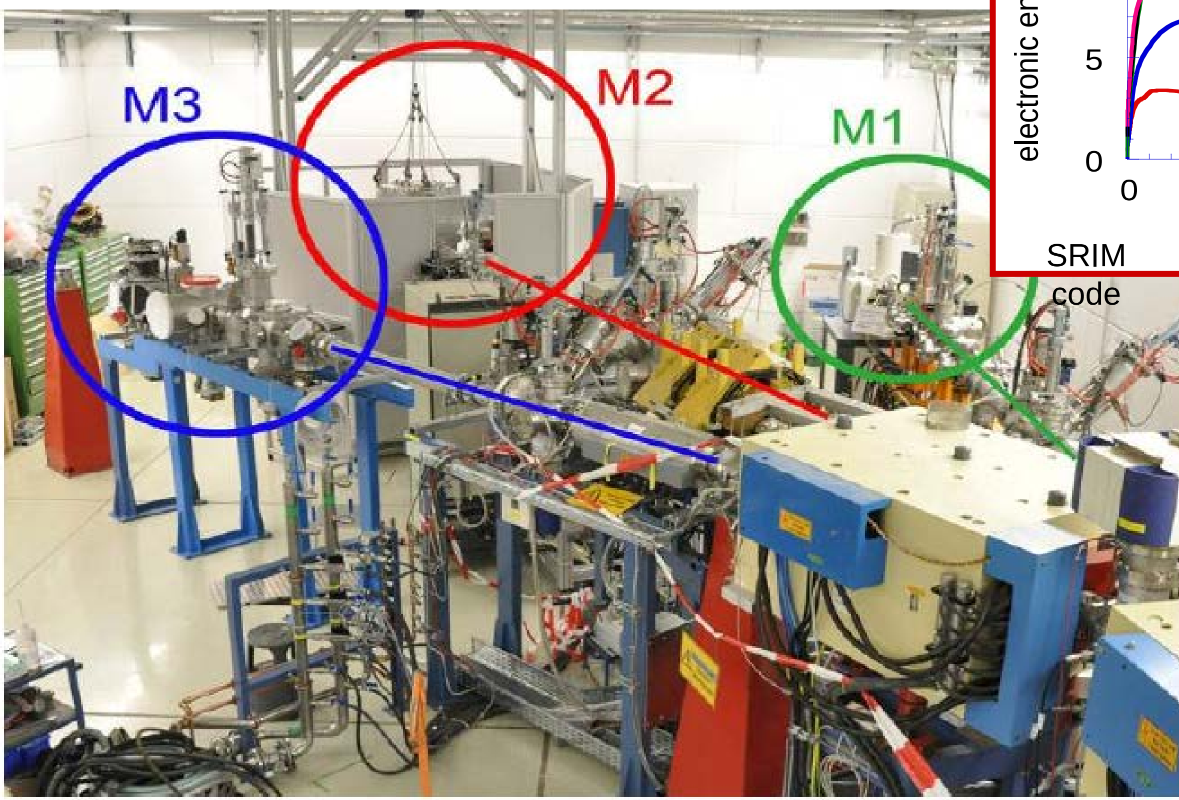
100-200 µs length of macropulse

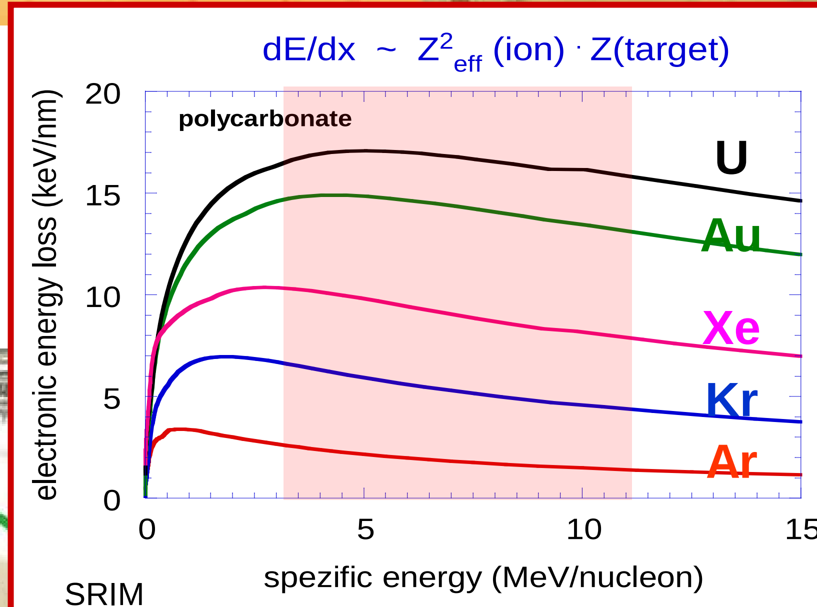




M-branch irradiation facility at GSI
In situ experiments

- energies close to Bragg peak:
  - to maximize energy deposition and damage
  - to avoid activation





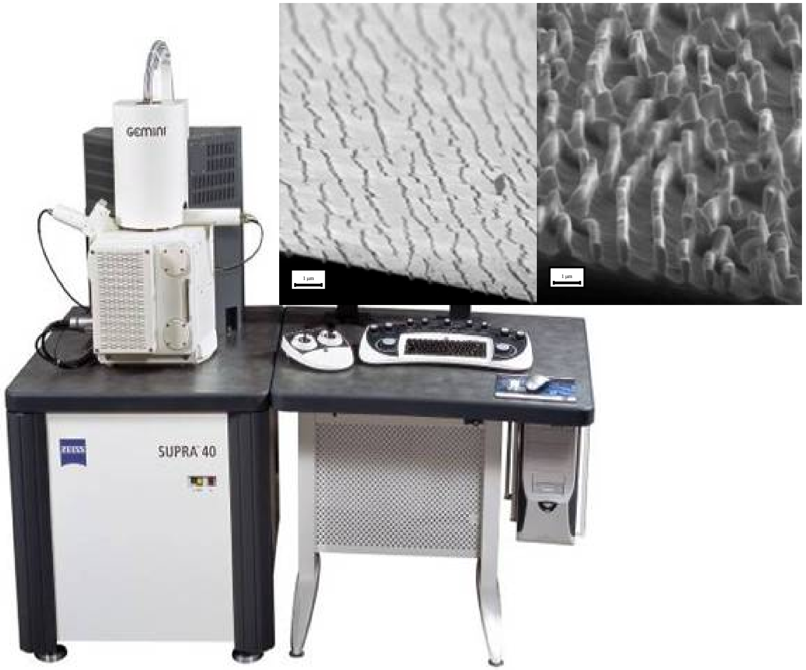
SRIM code

ion species ..C…Xe...U

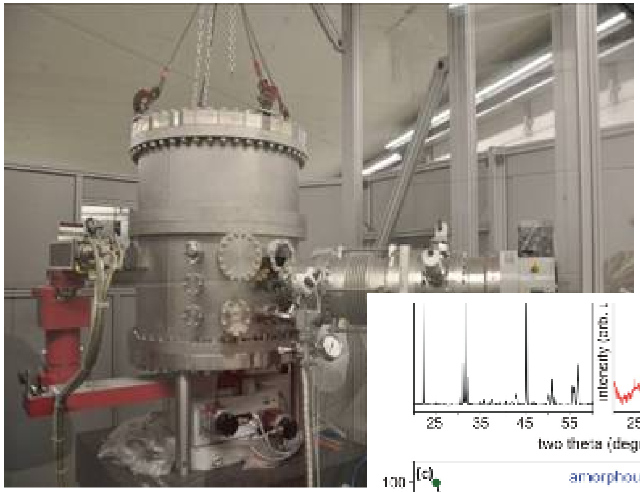
flux: up to10^{10} ions/cm^2 s

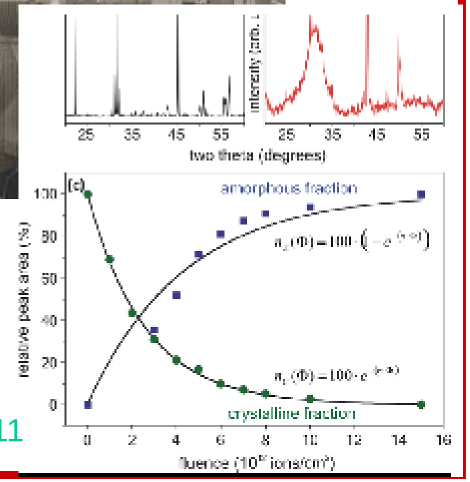
Online and in situ analysis facilities at GSI-UNILAC

M1
Electron Microscopy



M2
4-circle X-Ray Diffraction



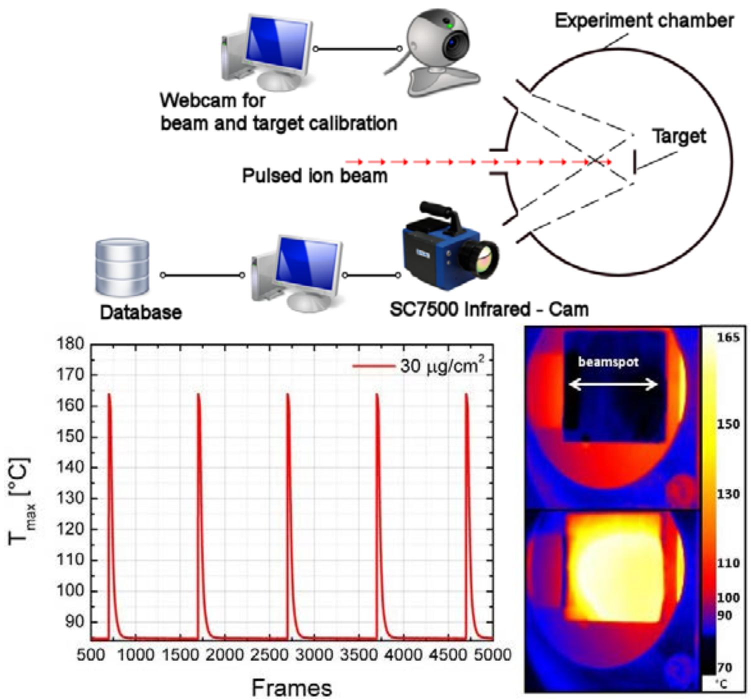


M. Lang GSI Sci Rep 2011

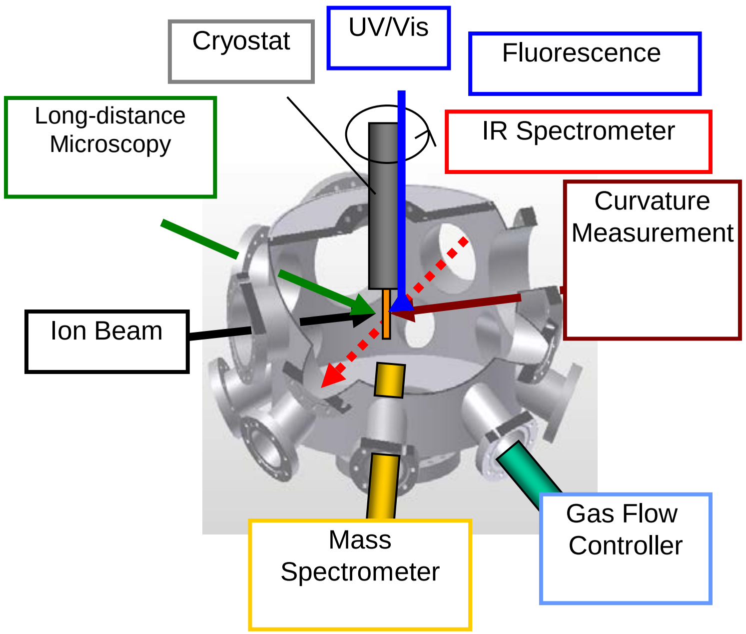
in collaboration with University of Stuttgart, and HZB

Online and in situ analysis facilities at GSI-UNILAC

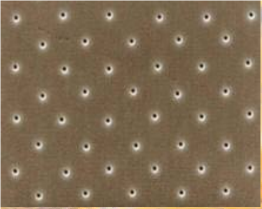
M3
High temperature irradiation
Online monitoring:normal and IR camera
Online resistivity measurements- in progress



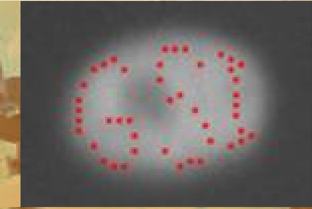
M3
Low temperature irradiation
On-line Spectroscopy
Ion beam-induced stress studies



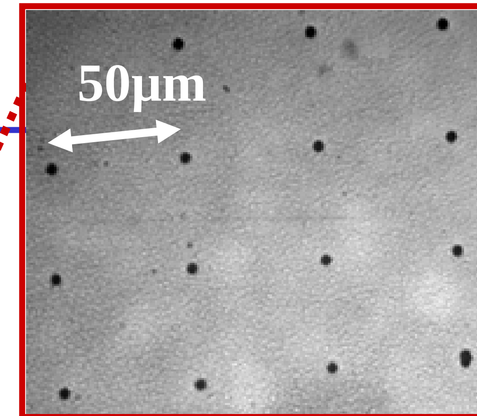
in collaboration with Univ. Darmstadt, Heidelberg, Jena

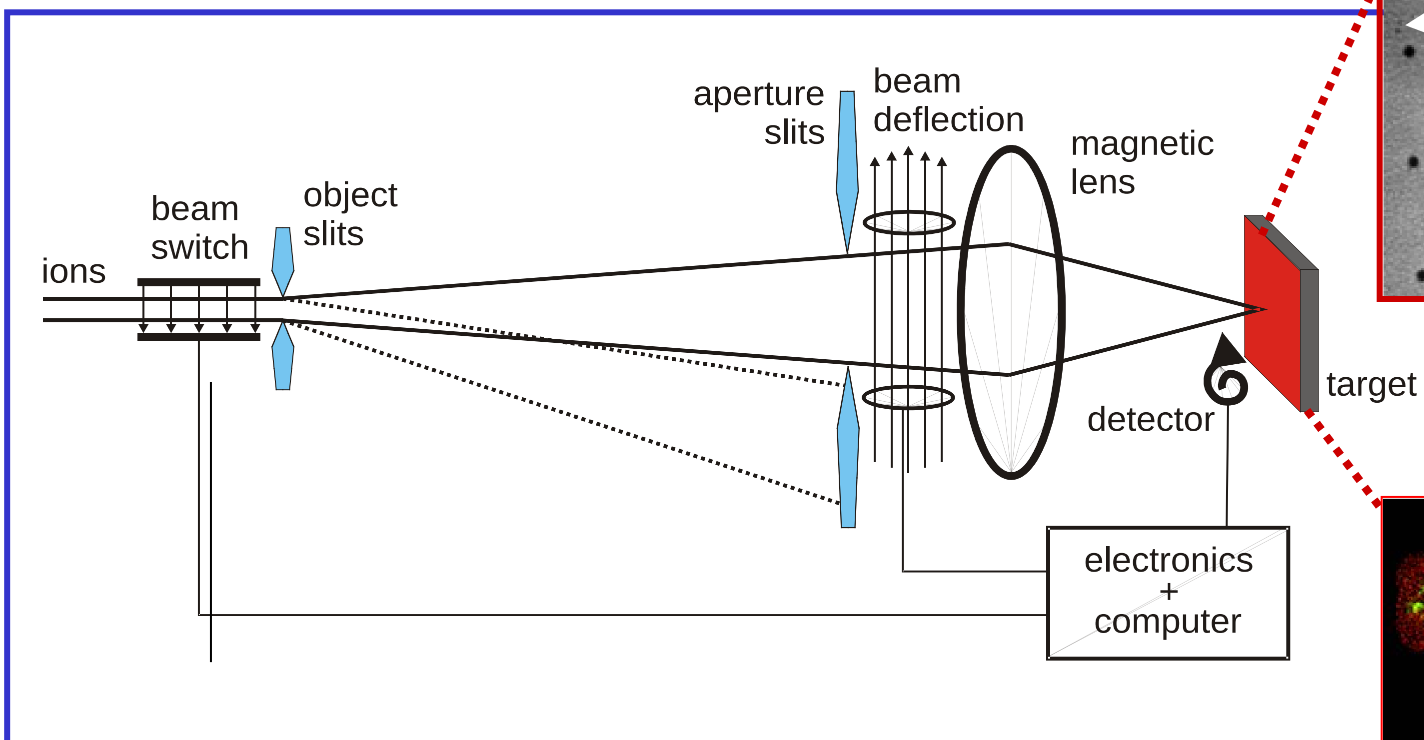


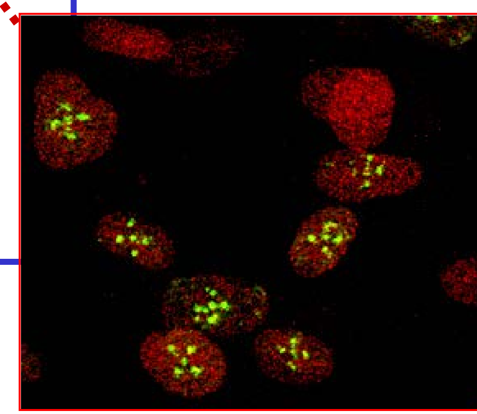
Heavy-ion microprobe X0



pore pattern in polymer film







Cave A @ Synchrotron SIS

ion beams: 100 – 300 MeV/u
range: mm – cm
scanning system
irradiation in air

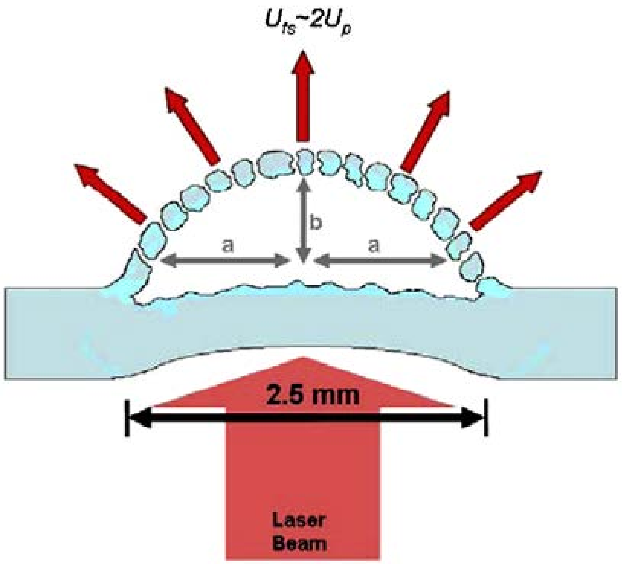
Spall strength studies using the PHELIX laser at GSI- experiment P089

Laser parameters:

	long pulse	short pulse
Pulse duration:	0.7-20 ns	0.5-20 ps
energy:	0.3-1 kJ	120 J
Max. Intensity:	10^{16} W/cm^2	10^{20} W/cm^2

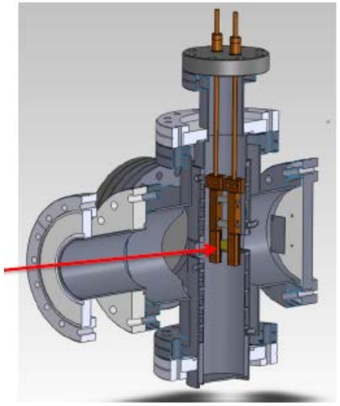
Expansion of the spalling surface in the laser shock experiments

Jarmakani H et al. , Acta Mater (2010)



In situ experiments on collimator related materials - results

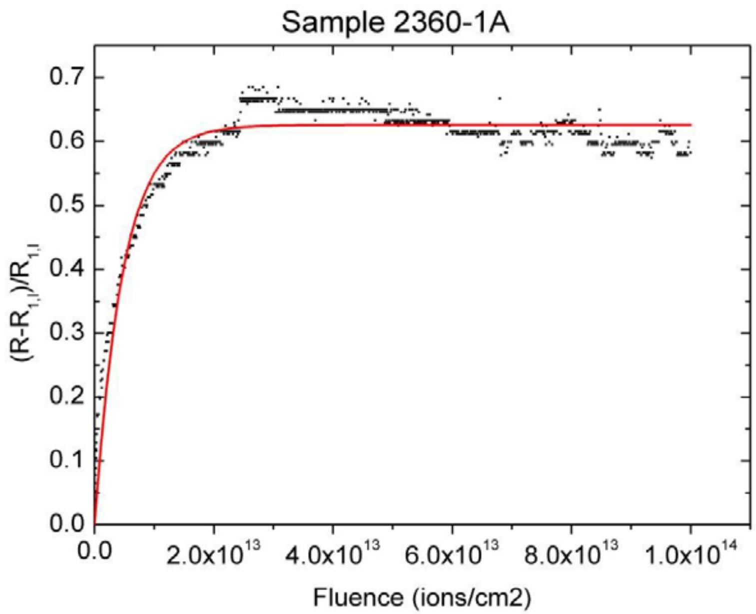
Online measurements of heavy ion-induced electrical resistivity increase of graphite



Collaboration with MSU

Experimental set-up M3 / UNILAC GSI

Irradiation conditions:
ions / energy: ^{197}Au, 8.6 MeV/u
beam intensity: up to 5×10^{10} i/cm^{2}s
dose: up to 10^{15} i/cm^2



Direct impact model fit:

- Poisson Law

$$\frac{\Delta R}{R} = \left(\frac{\Delta R}{R}\right)_{Sat} \left(1 - e^{-\sigma_a \Phi}\right)$$

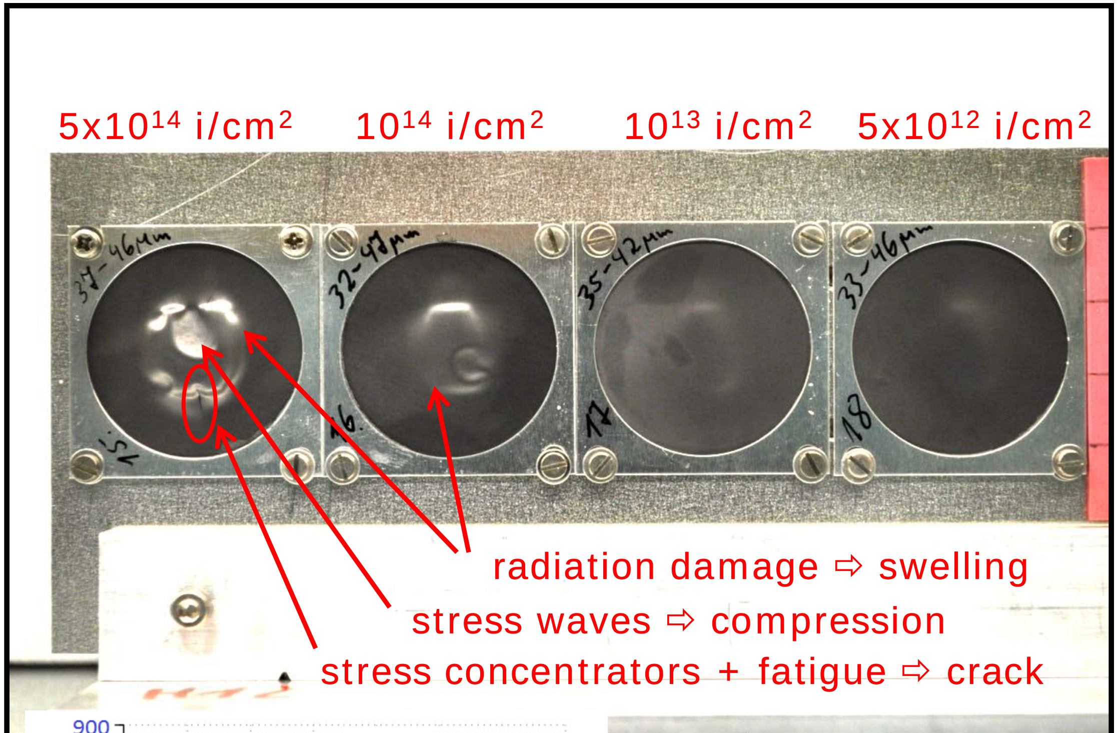
Damage cross section:

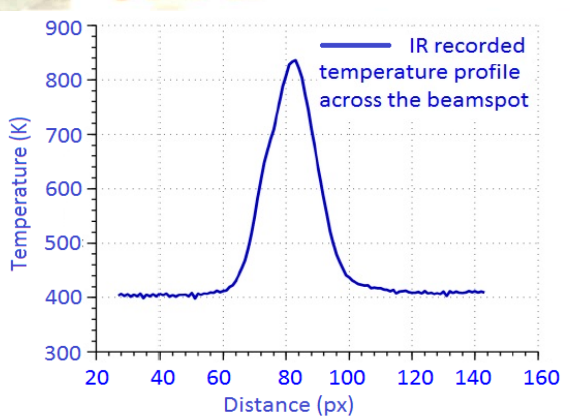
$\sigma_a = 6.0 \times 10^{-14}$ cm^{-2}

GSI FAIR

Failure of graphite exposed to pulsed U beam
Thermal camera monitoring

Experiment





RN

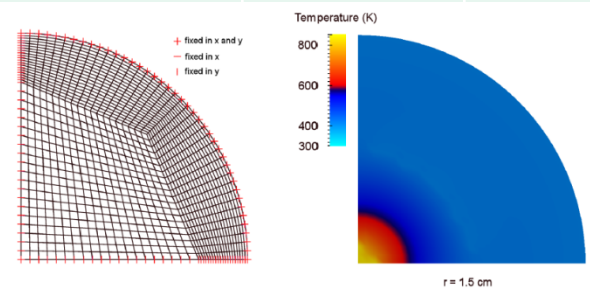
^{238}U, 4,8 MeV/u

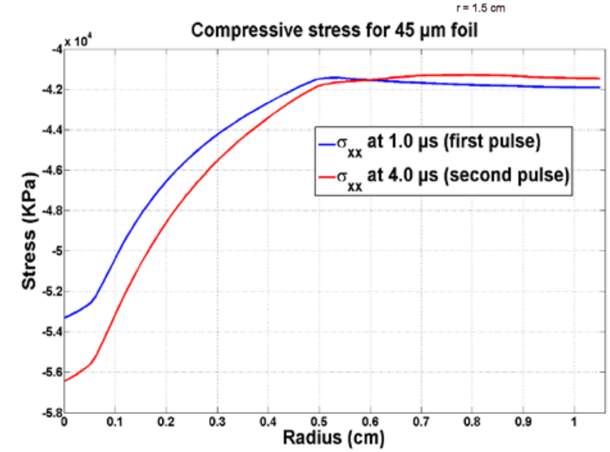
1.5 x10^{10} i/pulse

150 µs, 1 Hz

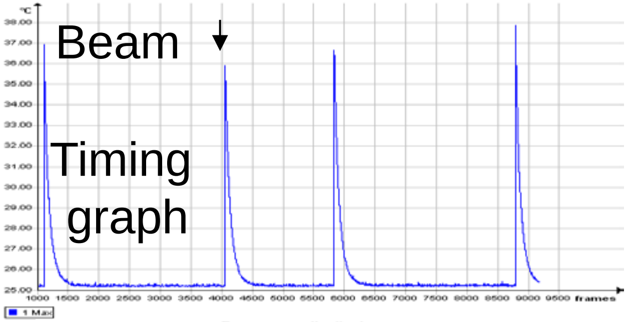
FEM simulations

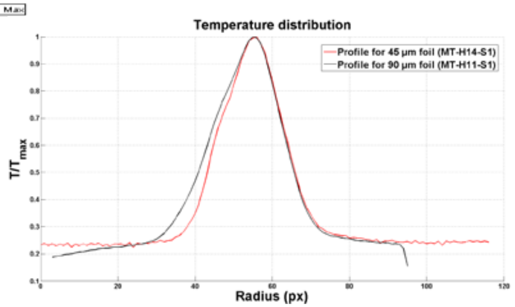
Graphite target / Pulse structure	Maximum compressive stress (MPa)	Maximum tensile stress (MPa)
45 µm (single pulse)	-53.3	0.5
45 µm (double pulse)	- 56.4	0.7



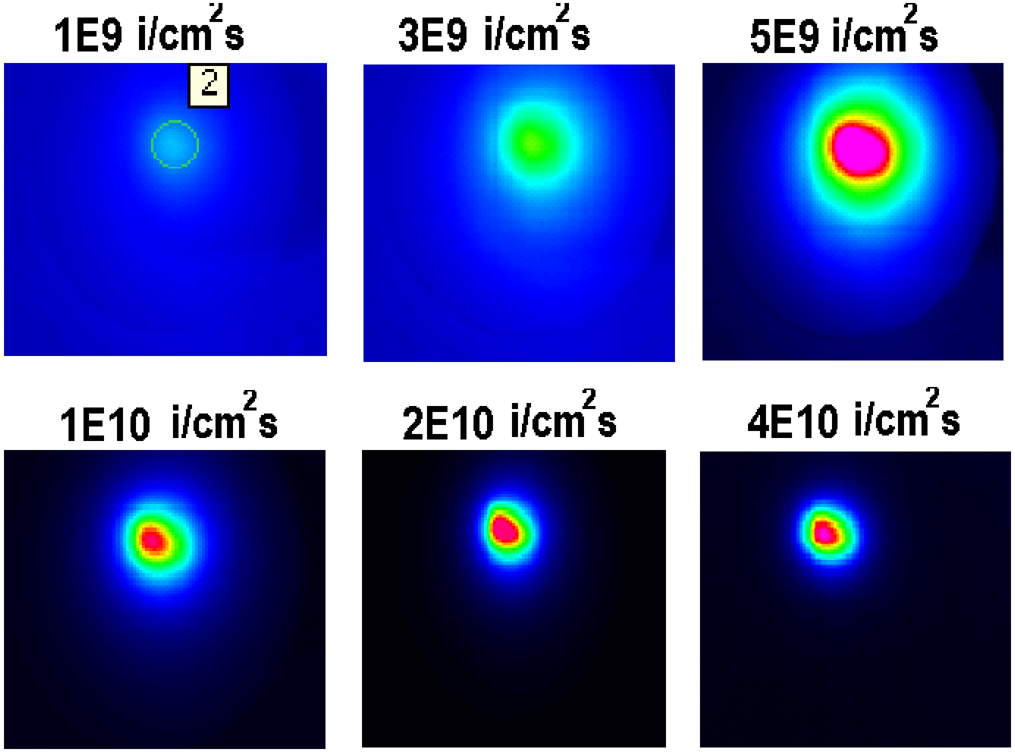


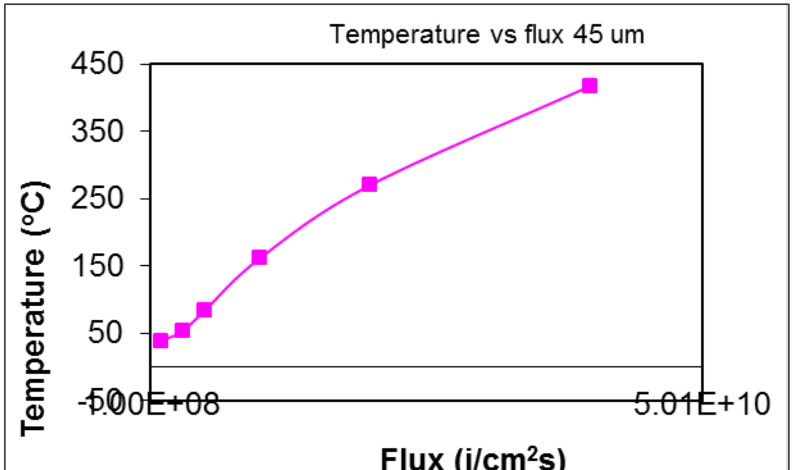
Beam monitoring on target by IR thermography





IR images of beam spot on thin graphite targets UNILAC experiments



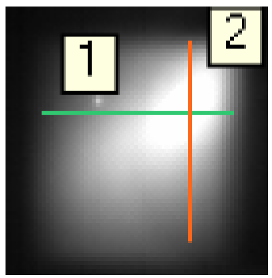


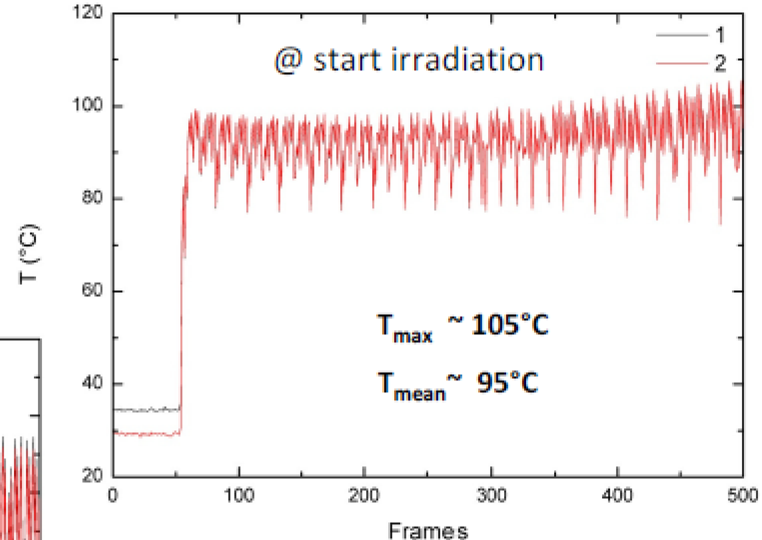
Temperature increase due to sample compaction in the beamspot

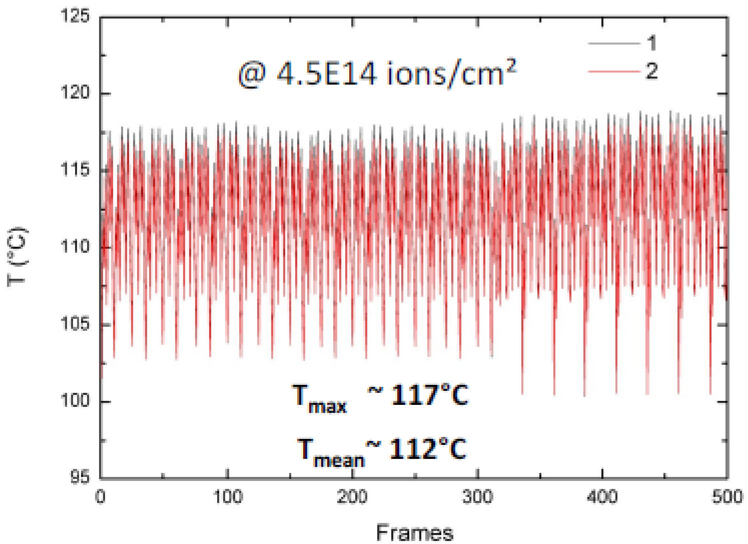
Amorphous Carbon, 21 µg/cm² (Targetlab)

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

flux: 1.0E10 ions/cm²s





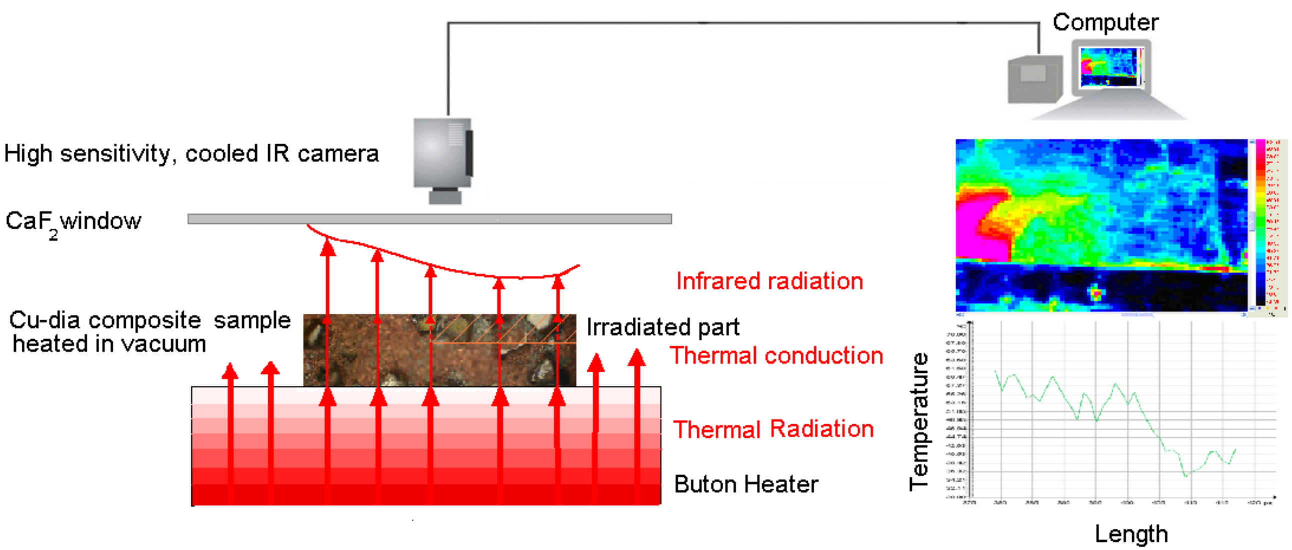


IR monitoring of thermal conductivity degradation of copper diamond composite

Proposed experiment:
thermal conductivity and thermal resistance degradation at interfaces during irradiation of new collimator materials

Preliminary offline test:

Post-irradiation IR imaging tests of thermal conductivity degradation in copper-diamond composites exposed to high doses of 4.8 MeV/u ^{197}Au ions at M-branch,

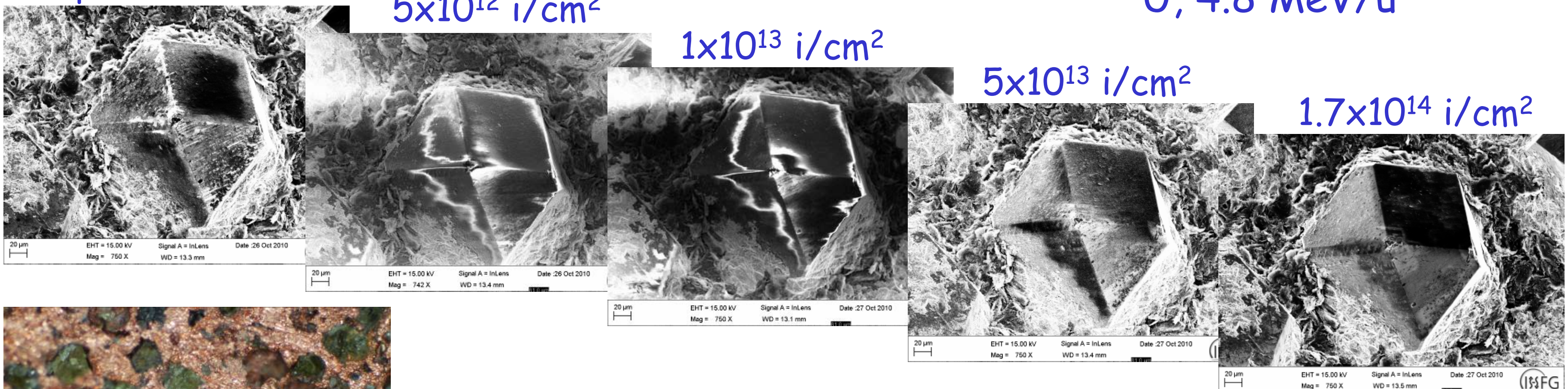


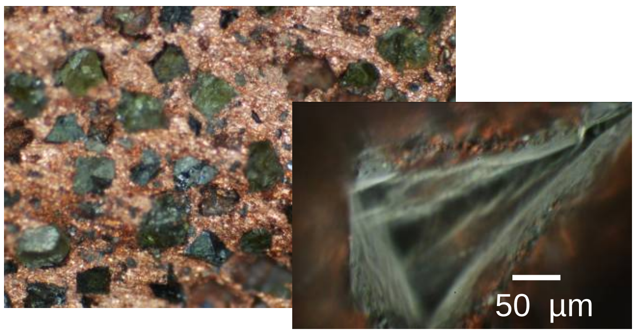
GSI FAIR

In situ SEM monitoring of heavy ion irradiation effects in novel copper-diamond composites

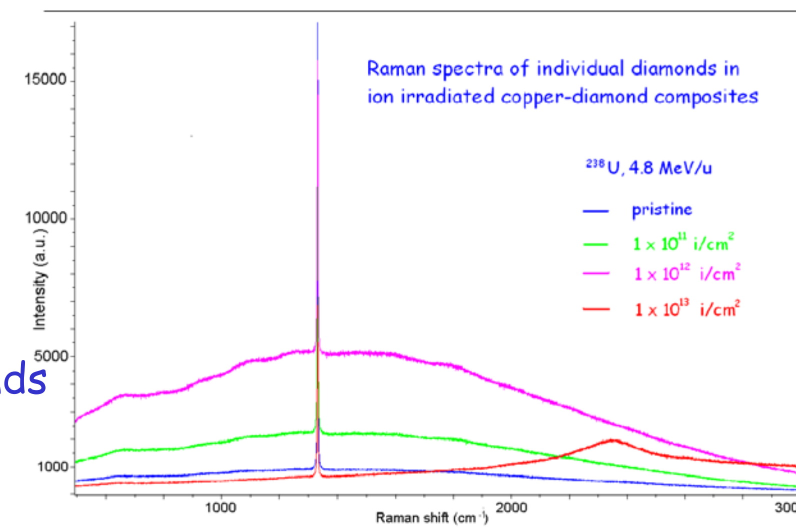
pristine $5x10^{12}$ i/cm² $1x10^{13}$ i/cm² $5x10^{13}$ i/cm² $1.7x10^{14}$ i/cm²

^{238}U, 4.8 MeV/u





Diamond



- In-situ- SEM during ion irradiation shows:
  - -no detachment or cracks at interfaces
  - -charge trapping at ion induced defects in diamonds
- Off-line Raman spectroscopy shows:
  - -increasing luminescence background due to ion-induced optical active defects

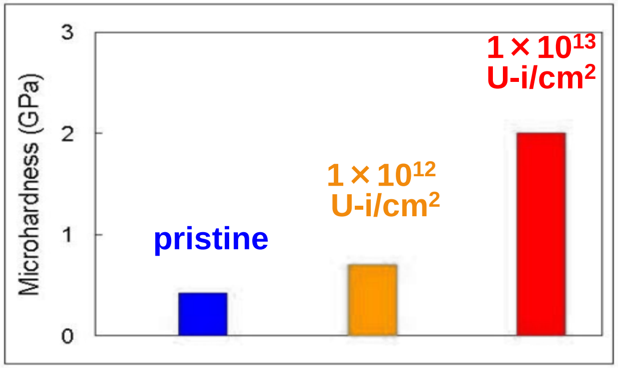
Post-irradiation analysis at GSI

- Mechanical properties
  - nano/microindentor up to 750 °C, with impact module
  - universal testing machine
- Thermo-mechanical
  - TMA up to 1650 °C
  - LFA up to 2000 °C
- High temperature microscopy stage with electrical contacts
- Large magnification objective for IR camera and software for stress distribution mapping

Ion- induced mechanical properties degradation

- nanoindentation investigation of:
  - radiation-induced hardening

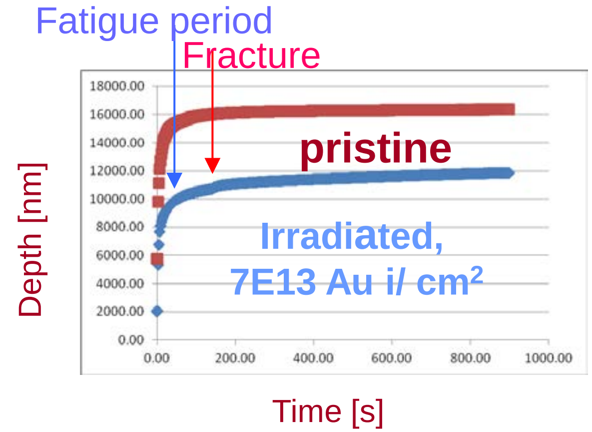
Ex: Hardening of U irradiated graphite



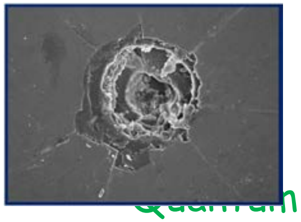
- Young modulus
- creep

- fatigue behaviour

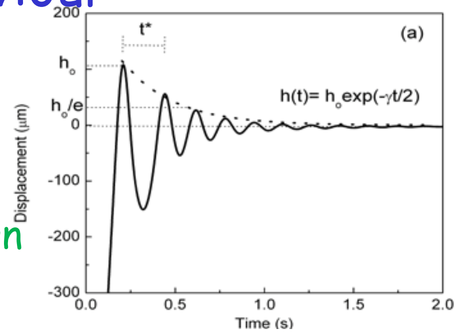
Ex: fatigue resistance degradation of ion irradiated graphite



- impact behaviour



LOT
Quantum Design



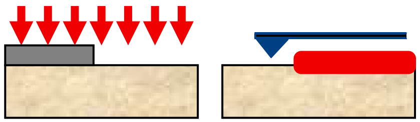
Dose dependence of thermal conductivity degradation of isotropic graphite

^{197}Au up to 1x10^{14} ions/cm^2, 5.6 MeV/u

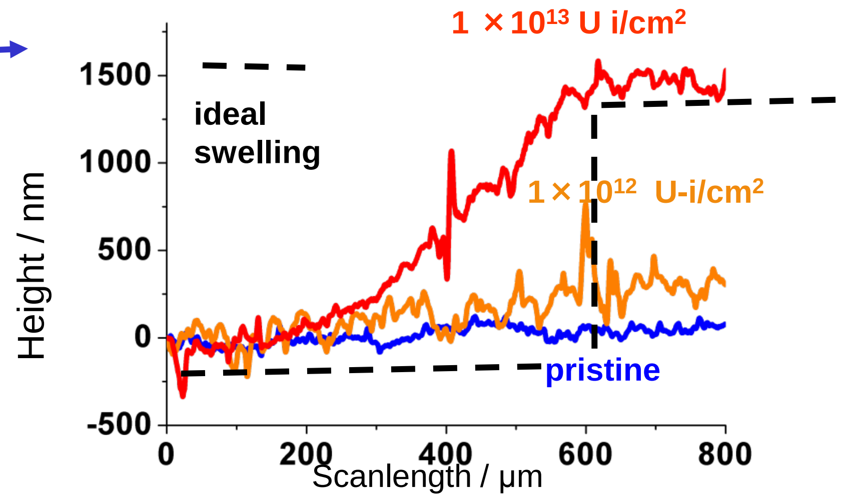
Fluence Au i/cm^2	pristine	1x10^{11}	1x10^{12}	5x10^{12}	5x10^{13}	1x10^{14}
Thermal conductivity W/K m	80	50.6	45.6	40.5	12	7

Ion- induced swelling and creep?

Profilometry



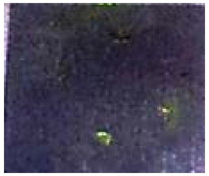
Low intensity U beams:
4.8 MeV/u,
flux 1x10^{8} i/cm^{2} s



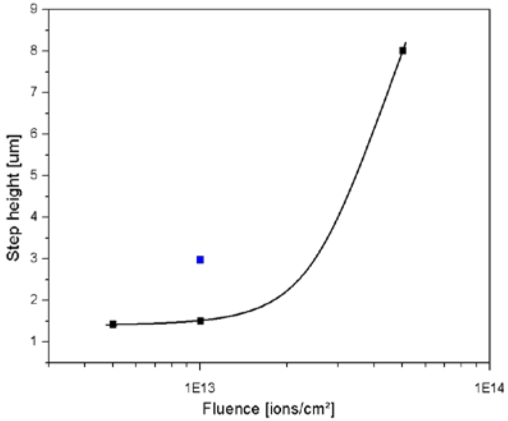
Out-of plane swelling - Profilometry

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

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

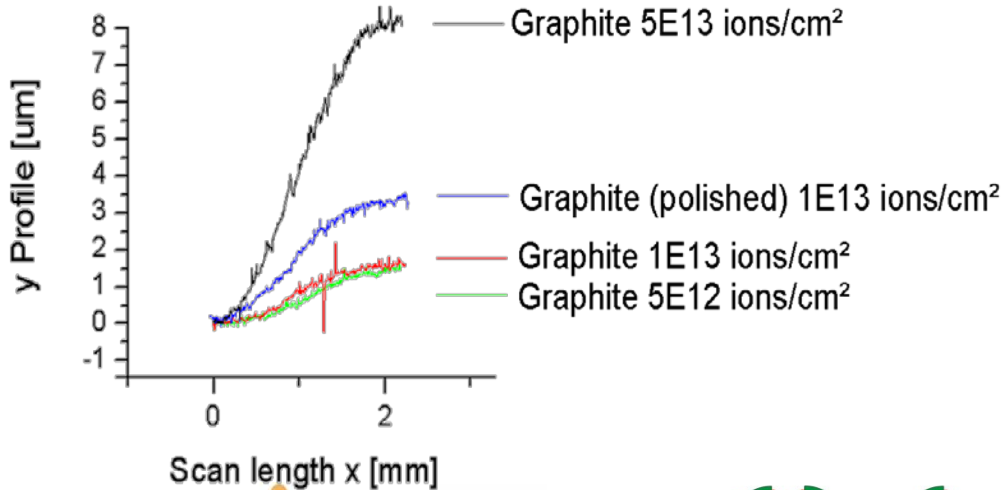


Step size dependence on fluence

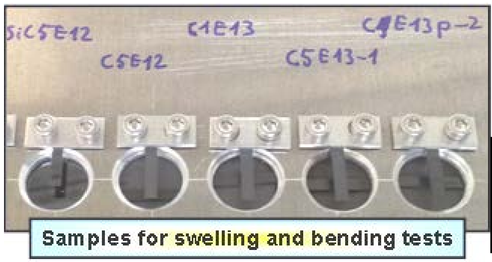


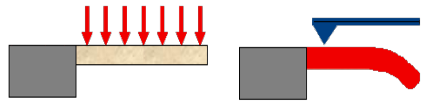
5x10^{13} i/cm^{2}

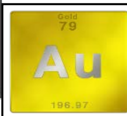
1x10^{14} i/cm^{2}



Irradiation- induced stress



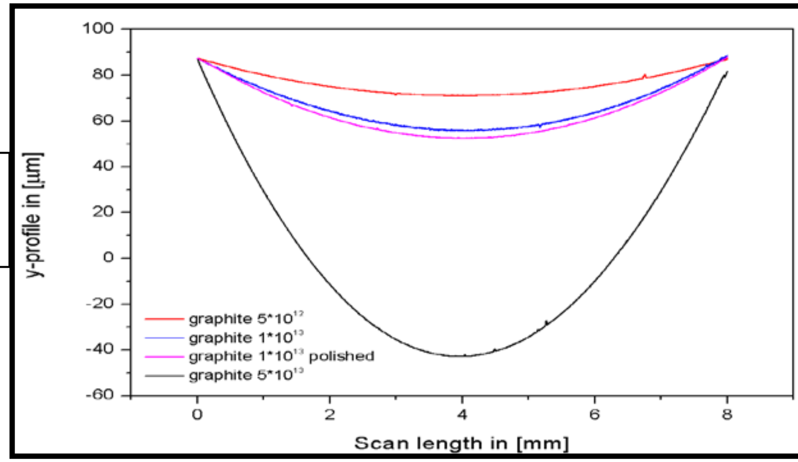




Charge state: + 25

Energies: 4.8 MeV/u

Fluences up to 5×10^{13} i/cm²



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

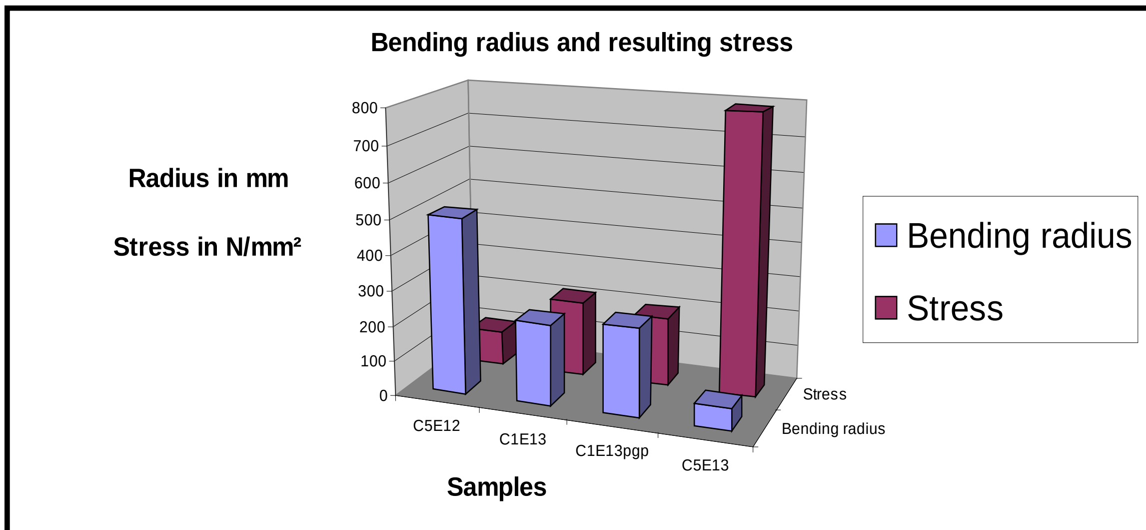
h_s = sample thickness

h_f = irradiated layer thickness

R_r = bending radius

ν_s = Poisson number

σ^f_{rr} = stress

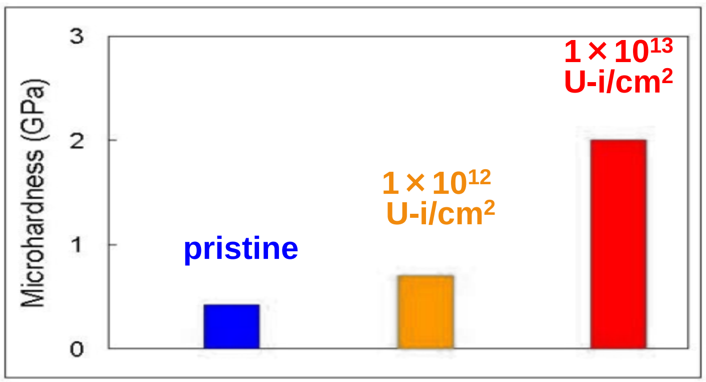


Hardening and embrittlement of ion- irradiated graphite

Nanoindentation testing of irradiated graphite

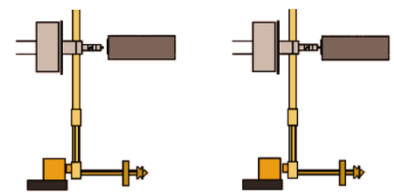
Cube Corner 20 mN max load; comparison pristine and irradiated samples

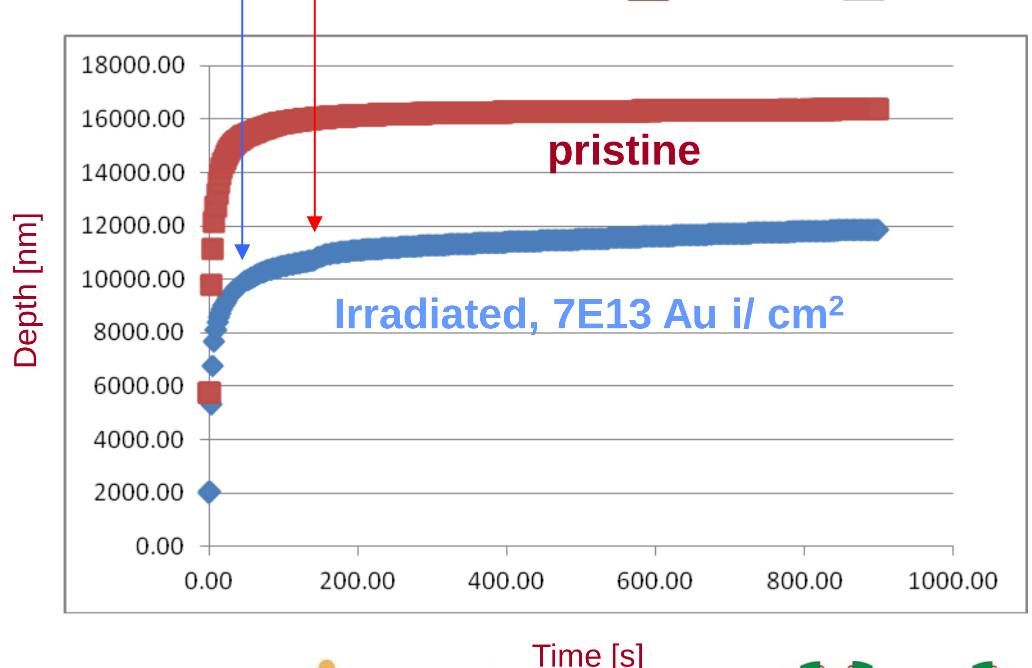
Hardening



Strong hardening
- Indentation -

Embrittlement





Outlook for EuCARD 2

Material irradiation and characterization of ion beam-induced radiation damage in situ and offline:

- online IR monitoring (bulk and interfaces)
- fatigue studies with pulsed beams
- characterization of mechanical properties degradation as a function of dose using micro- and nanoindentation: hardness, Young modulus, impact resistance, fatigue behaviour, creep
- other in situ possibilities still open

Spall strength studies of single component and model composite materials in ultrafast experiment, using the the Petawatt laser at GSI