Heavy ion induced degradation of carbon materials

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Materials Research within Target Area at Super-FRS

- understand materials failure due to extreme radiation
- develop failure criteria
- provide reliable lifetime predictions
- develop monitor system
- new solution for extreme conditions

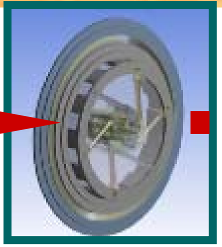
In collaboration and synergy with activities
at LHC (CERN), FRIB (Michigan), RIBF (RIKEN)

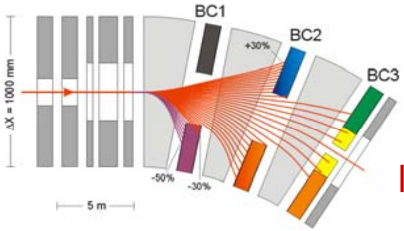
Overview

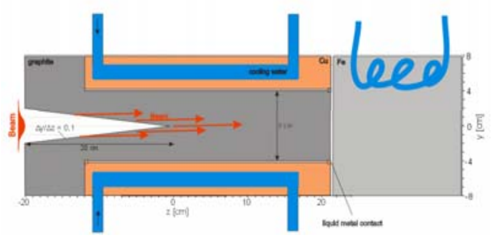
- Radiation hardness of heavy ion exposed target and beam catcher materials- common to next generation heavy ion -driven fragment separators
- High temperature operation
- Pulsed primary beams case- pressure waves, failure criteria
- New target solutions for fast extraction
- Monitoring and diagnostic of target and beam catcher material degradation

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!**

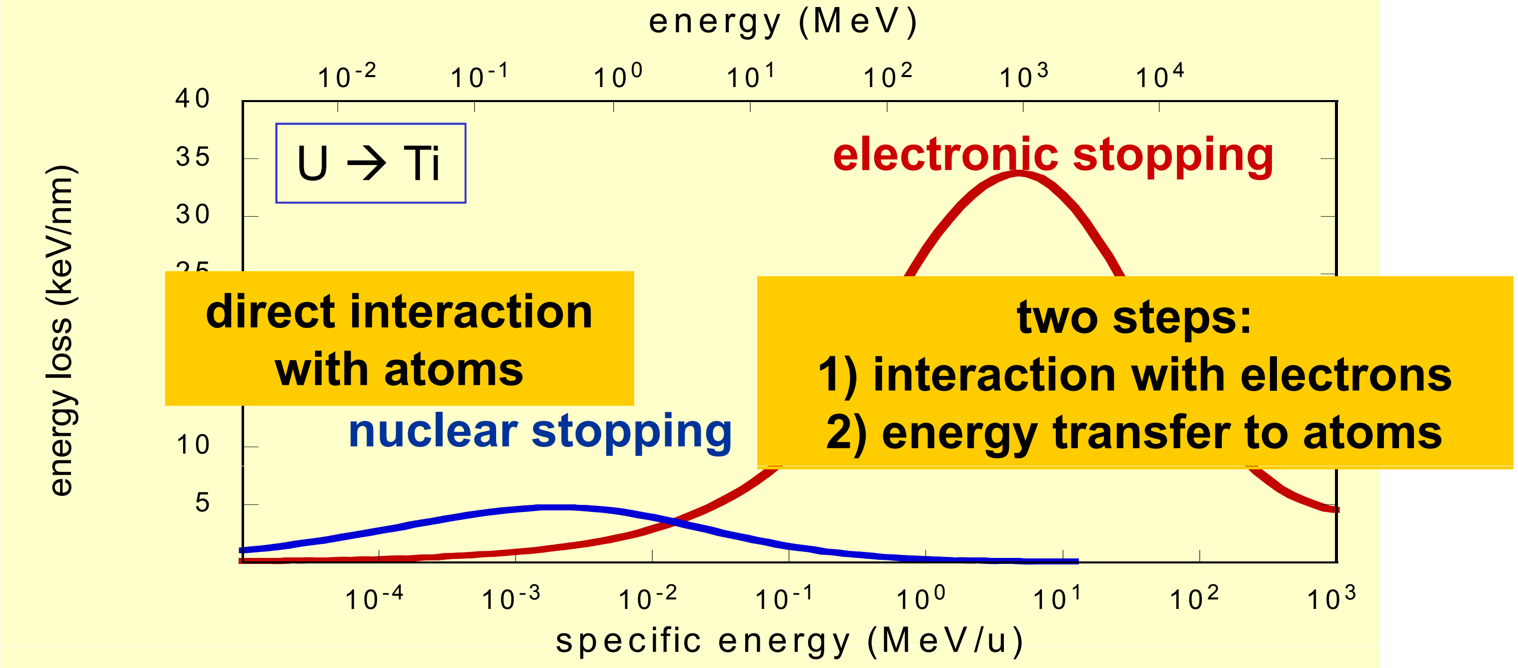
problems to face:

- radiation damage → material degradation

  thermal conductivity reduction, embrittlement, swelling

- intense transient loads → pressure waves
- cyclic thermal loads → thermal fatigue

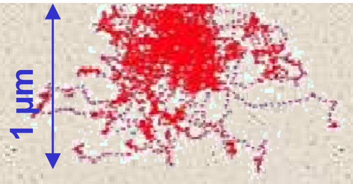
Swift heavy ions- energy deposition

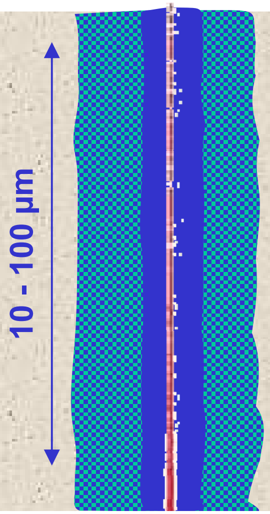


direct interaction with atoms

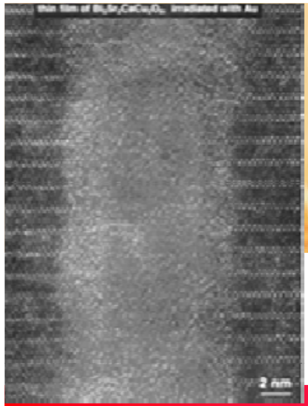
two steps:
1) interaction with electrons
2) energy transfer to atoms

target atoms
↓
atomic collision cascade
↓
defects





target electrons
↓
electron cascade
↓
coupling to lattice
↓
lattice disorder
↓
track



Track formation depends on materials nature

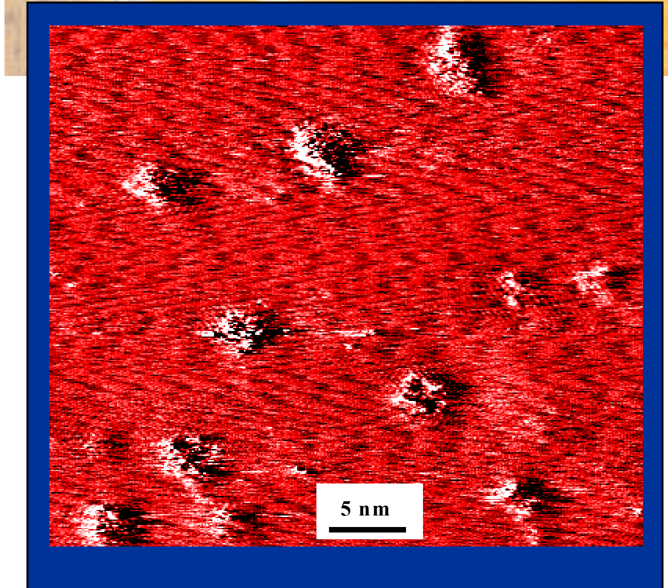
high sensitivity → low sensitivity

dE/dx threshold	~1 keV/nm	~20 keV/nm	~50 keV/nm

insulators	semi-conductors	metals
- polymers	- amorphous Si	- amorphous alloys
- oxides, spinels	- GeS, InP, $Si_{1-x}Ge_x$	- Fe, Bi, Ti, Co, Zr
- ionic crystals	- ~~Si, Ge~~	- Au, ~~Cu~~, Ag,
- ~~diamond~~		

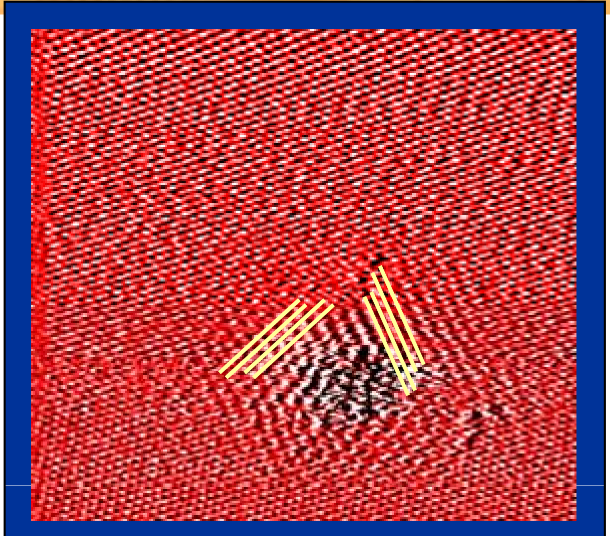
~~no tracks~~

Heavy ion induced tracks in graphite (HOPG)



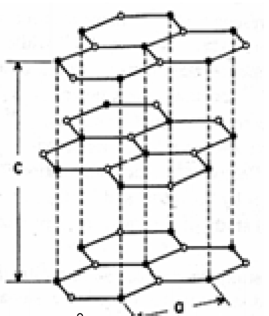
30 nm x 30 nm

U (2710 MeV)



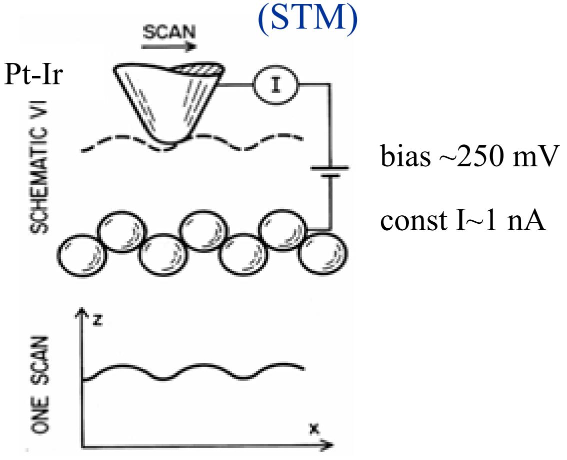
15 nm x 15 nm

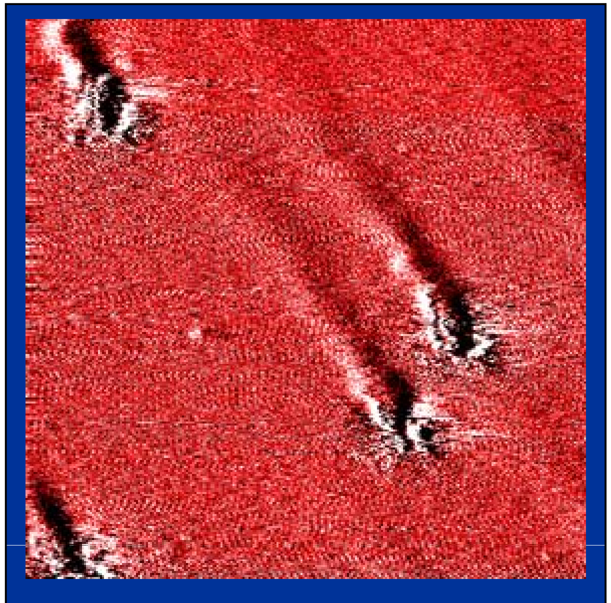
Xe (475 MeV)



a=2.46Å
c=6.70Å

Scanning tunneling microscopy (STM)





50 nm x 50 nm

U (2640 MeV)

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

How to test extreme radiation conditions at FAIR with existing UNILAC or SIS beams?

- limited beam time
- limited ion range at UNILAC
- testing activated samples
- which tests are suitable
- etc.

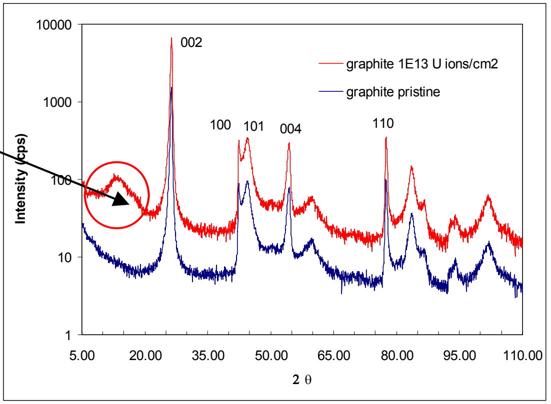
- ➢ test 'worst case scenario' → UNILAC, Bragg maximum
- ➢ compare effect of light versus heavy ions (dE/dx dependence, threshold,..)
- ➢ perform 'easy' test to characterize the damage e.g. Raman spectroscopy
- ➢ study evolution of damage versus accumulated dose (extrapolation?)
- ➢ develop failure criteria from tests

Heavy ion- induced radiation damage in graphite

Irradiation at UNILAC, energies close to Bragg peak

Structural changes: formation of glassy carbon phase

XRD

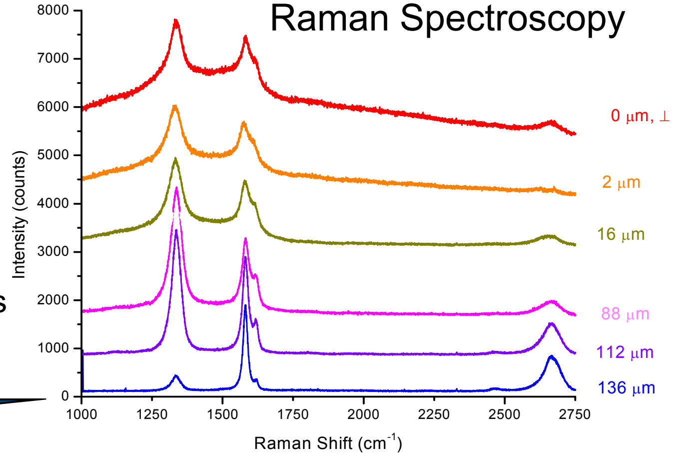


Sample surface

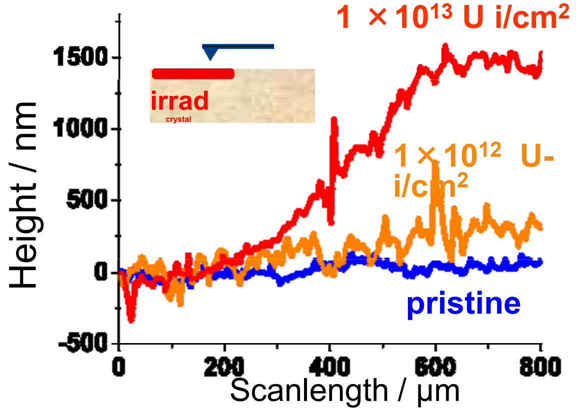
Elastic collisions

Bulk pristine

Raman Spectroscopy

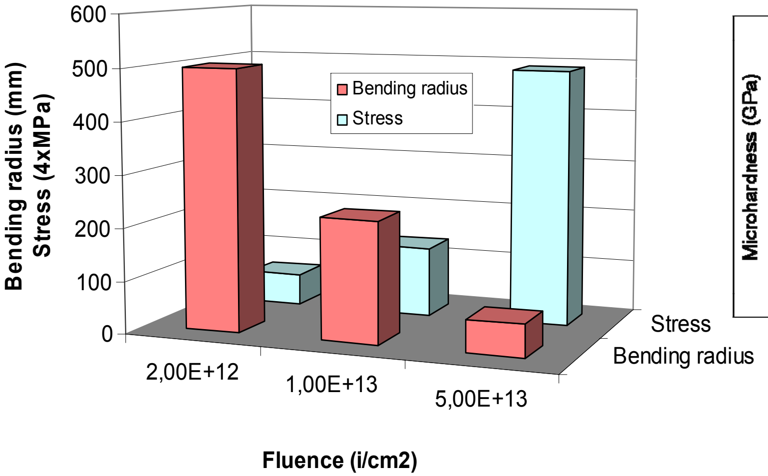


Swelling

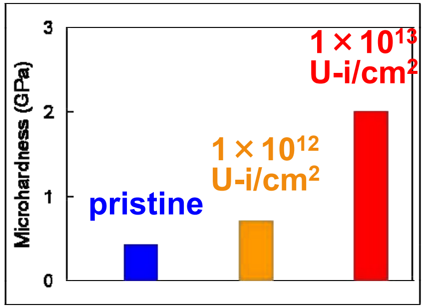


Out-of plane swelling - Profilometry

Stress



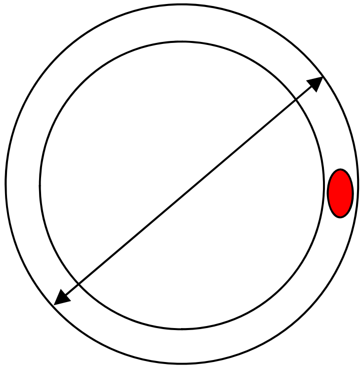
Hardening



Strong hardening - Indentation -

How long will the Super-FRS graphite target last: slow extraction

- 10^{13} tracks/cm^2 is a critical density of ion tracks for ^{238}U, worst case:
  - » high values of swelling and induced stresses which are relaxed through crack formation



Fluence/puls = 10^{12} / A ring =$1.11*10^{10}$ i/ cm^2

Fluence /year = 10^7pulses/year x fluence/puls ~ 10^{17} i/cm^2

Heavy ion track yield at Super-FRS energies of primary beam and target temperatures

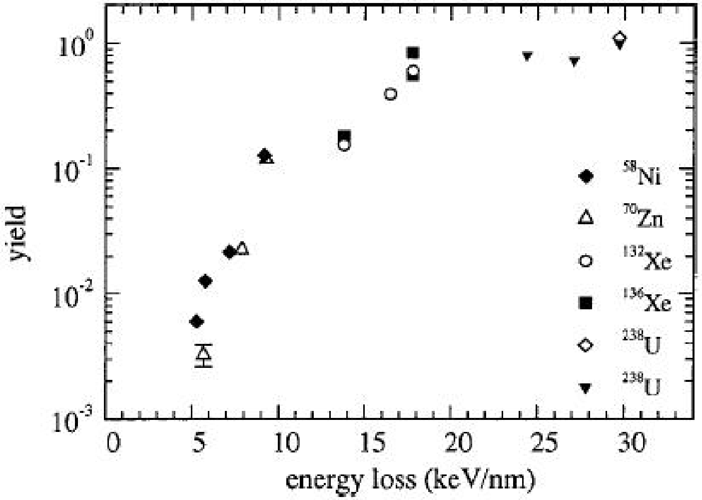
- **Track yield is highly reduced at high ion energy and target temperature (*Liu et al, PRB 64 (2001) 184115)***

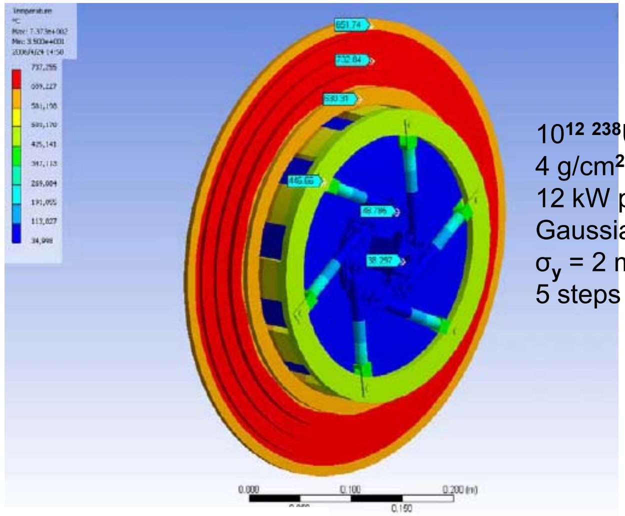
- **10^{-3} efficiency of track formation at Super-FRS energies**

- **10^{-3} efficiency of track formation at temperatures above 800 K *(J.Liu et al./ NIM B 245 (2006) 126-129)***

- **estimation of the track density/ year in the Super-FRS target:**

☞ 10^{11} tracks/cm^2



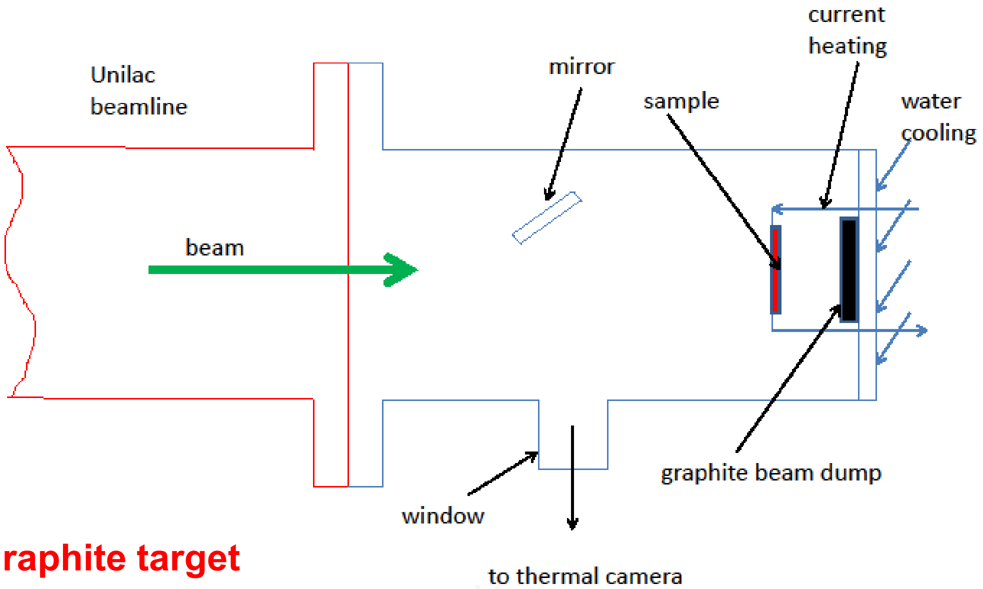


10^{12} ^{238}U/s
4 g/cm^2 C target
12 kW power
Gaussian vertical profile,
σ_y = 2 mm
5 steps (1 – 8 g/cm^2)

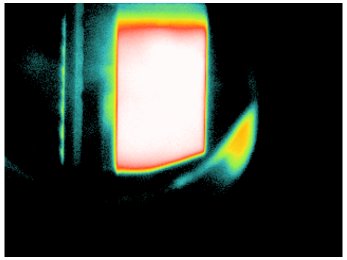
**B. Achenbach,
ANSYS workbench**

High temperature irradiation of graphite targets

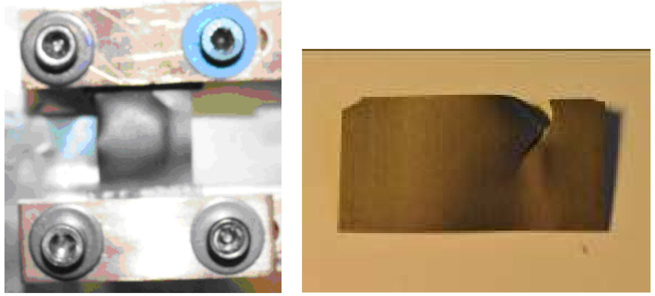
collaboration with W. Mittig et al. (MSU, FRIB)



Graphite target

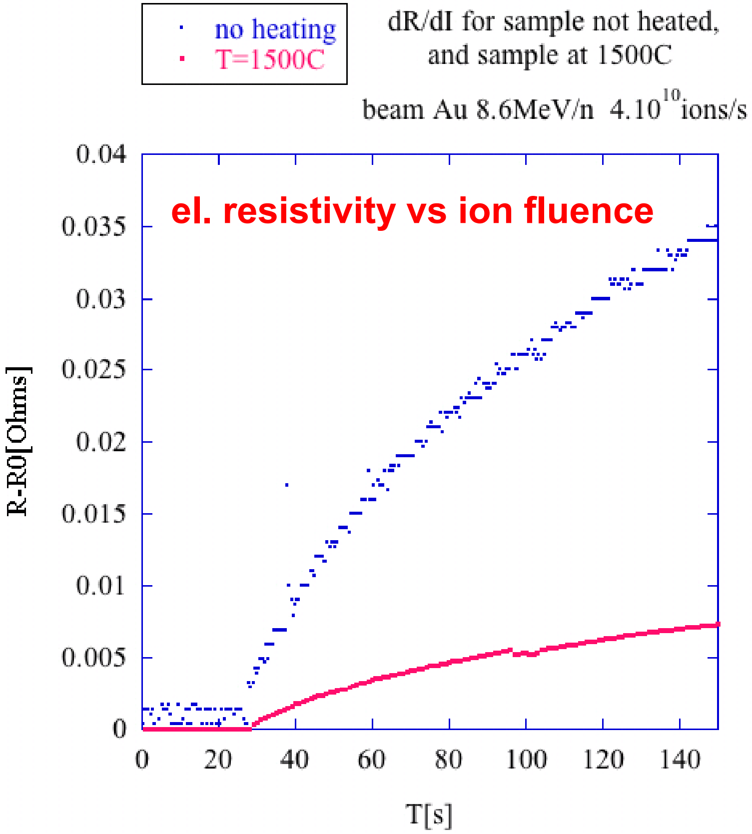


In-beam thermal imaging



severe swelling and irradiation-induced stresses

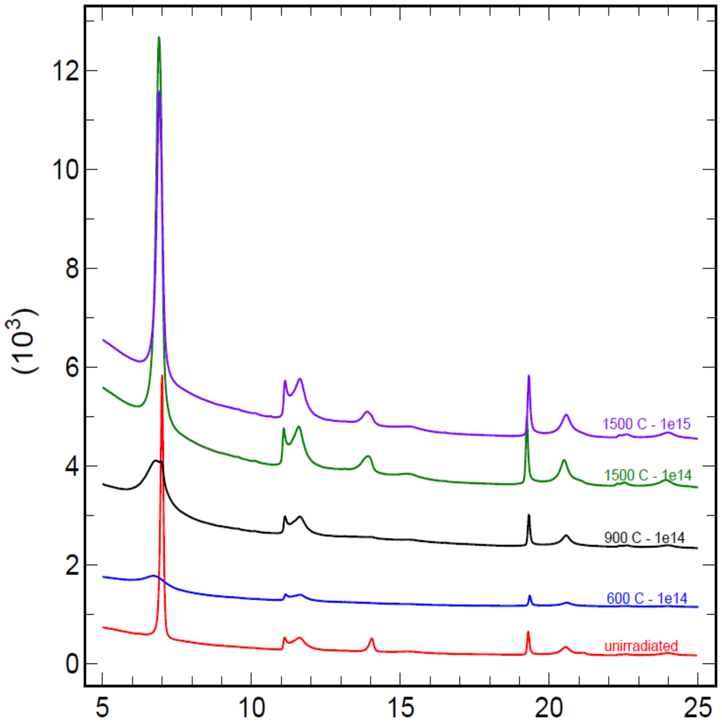
M-branch UNILAC



dR/dI for sample not heated, and sample at 1500C

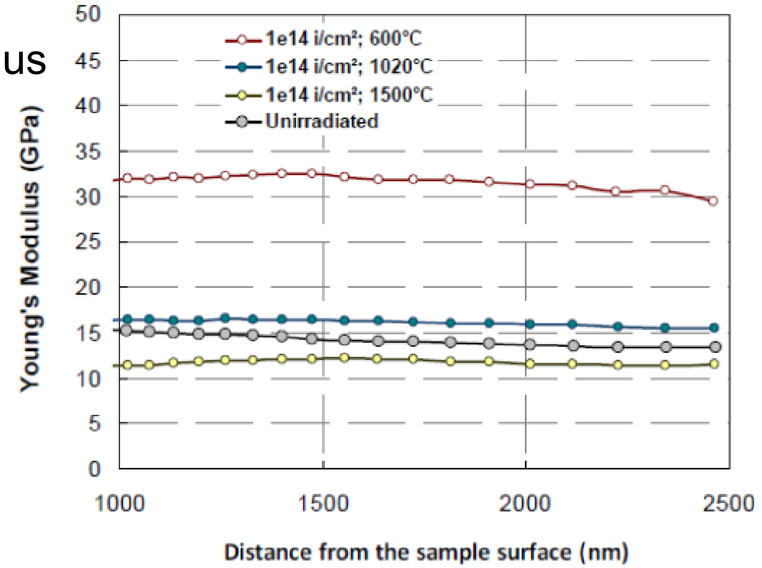
beam Au 8.6MeV/n 4.10^{10}ions/s

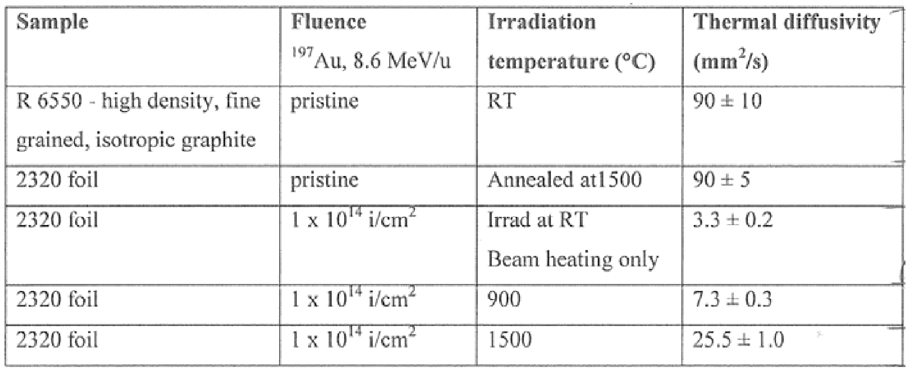
Structural defects recovery and effects on macroproperties for HT irradiation



XRD

Young modulus



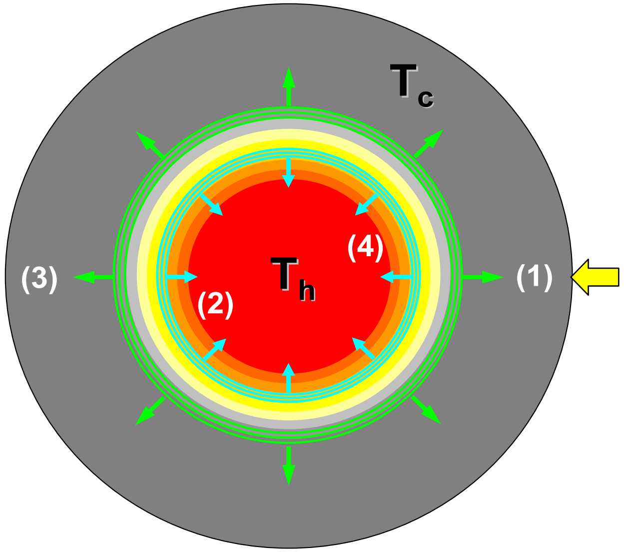


Sample	Fluence ^{197}Au, 8.6 MeV/u	Irradiation temperature (°C)	Thermal diffusivity (mm^2/s)
R 6550 - high density, fine grained, isotropic graphite	pristine	RT	90 ± 10
2320 foil	pristine	Annealed at1500	90 ± 5
2320 foil	1 x 10^{14} i/cm^2	Irrad at RT Beam heating only	3.3 ± 0.2
2320 foil	1 x 10^{14} i/cm^2	900	7.3 ± 0.3
2320 foil	1 x 10^{14} i/cm^2	1500	25.5 ± 1.0

Thermal diffusivity

Fast extraction operation of Super-FRS target: earthquake and aftershocks

Elastic Radial Stress-Wave



(1) . . . Compression wave,
(2) . . . Tension wave,
(3) . . . Compression → reflection → tension front,
(4) . . . Tension → reflection → compression front.

- Preliminary calculations: limiting values for temperature and pressure:

T = 3000K

P = 150MPa

  - 65 MPa (tensile failure)> σ > -150 MPa (compressive failure)

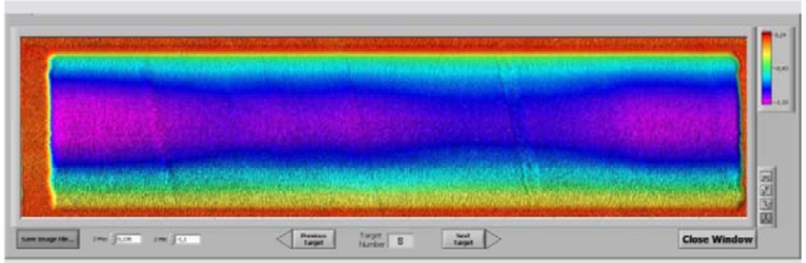
- Mechanical failure of graphite described by models applying to brittle ceramics
  - statistical concepts (failure probability)
  - defects- internal surface, number, distribution
  - loading mode
  - amount and topology of stressed volume

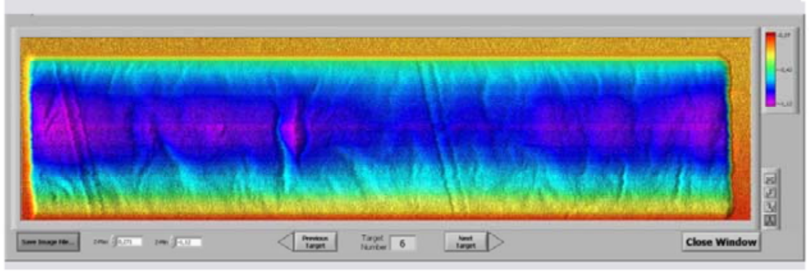
Different failure modes for fast and slow extraction

- Experiment with thin a-carbon targets at UNILAC

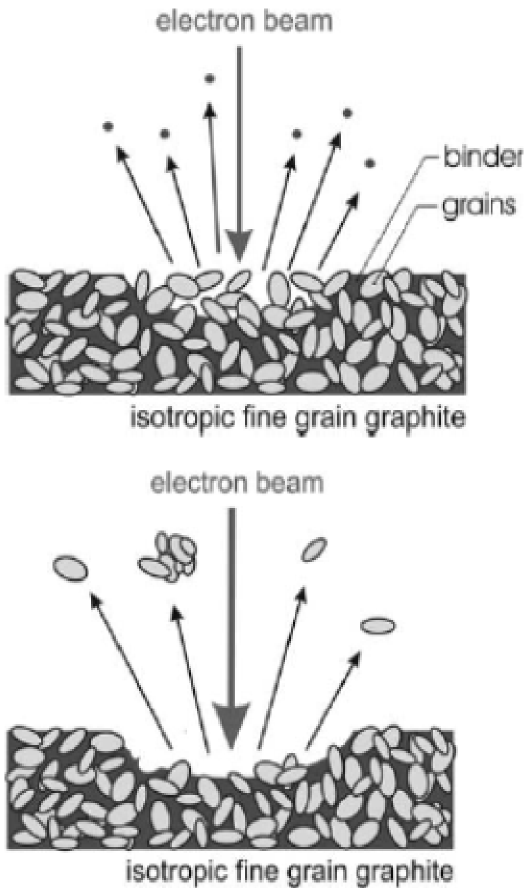
^{238}U, 3.6 *A* MeV, ~1E11 i/s, 100 µs

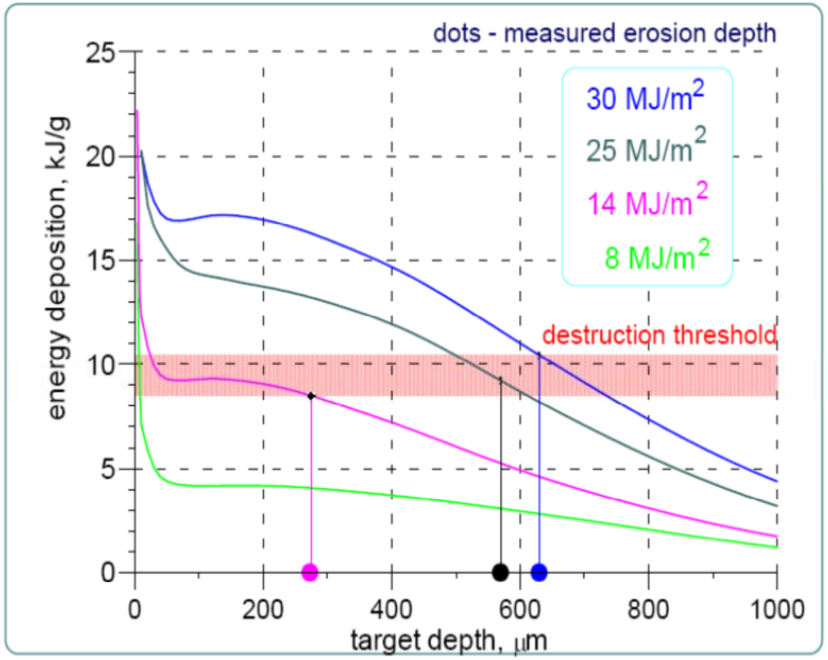
^{197}Au, 3.6 *A* MeV, ~1E11 i/s, 3 ms





Energy density criteria for the destruction threshold in electron beam tests





Energy density destruction threshold for fine grained isotropic graphite:

8-10 kJ/g

(A.V. Burdakov EUROMAT2005)

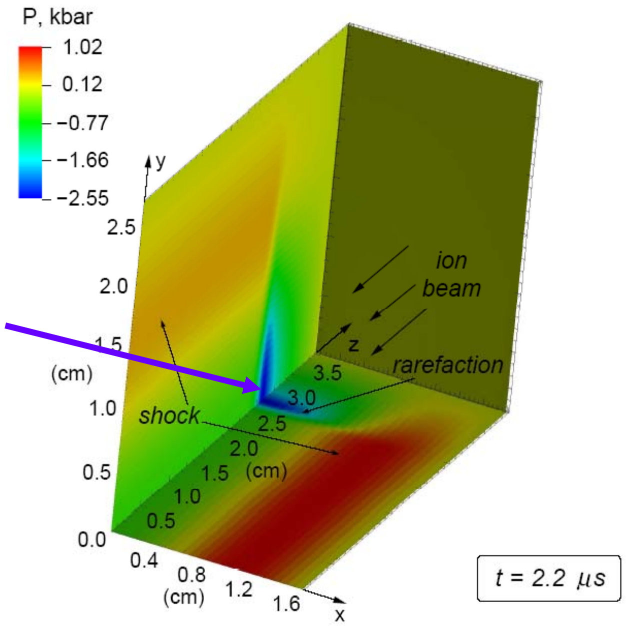
Feasibility study of a liquid-metal (Li) jet

Dynamical calculation of pressure inside liquid lithium

An.Tauschwitz et al., NIM A (2008)

Anna Tauschwitz *et al.*

250 MPa!



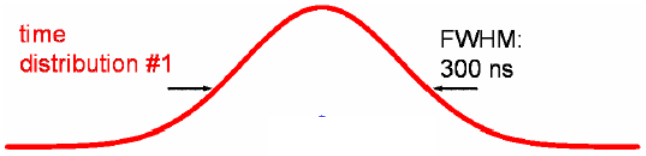
Theoretical spall (tensile) strength of liquid lithium:

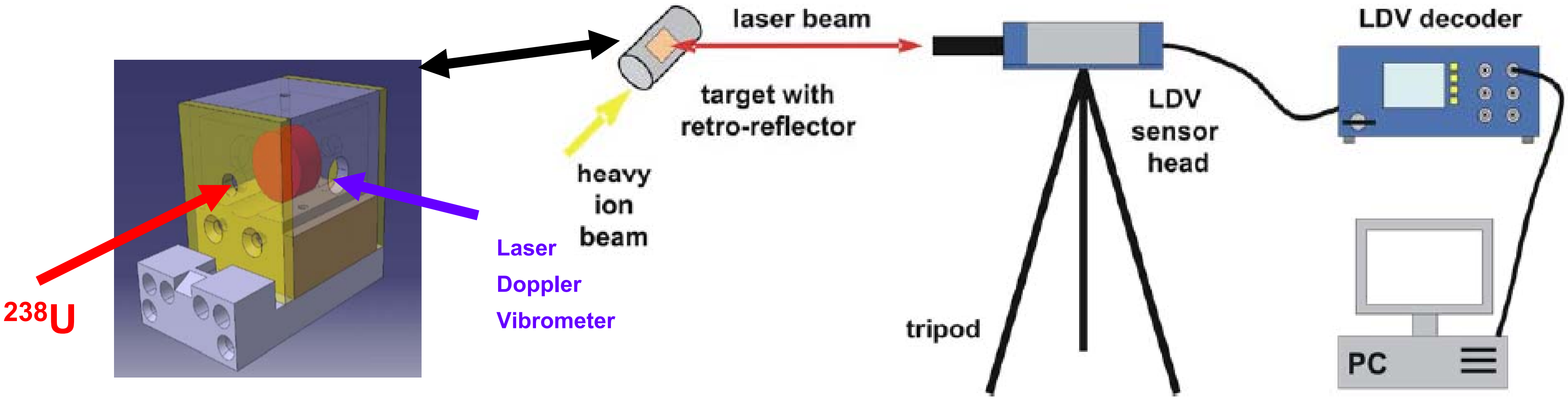
calculated to be only 9 MPa!

- **experimental verification in collaboration with V.Efremov *et al.***

Experimental investigations of pressure waves in graphite

Measure surface vibrations of graphite target with laser Doppler vibrometer (LDV)



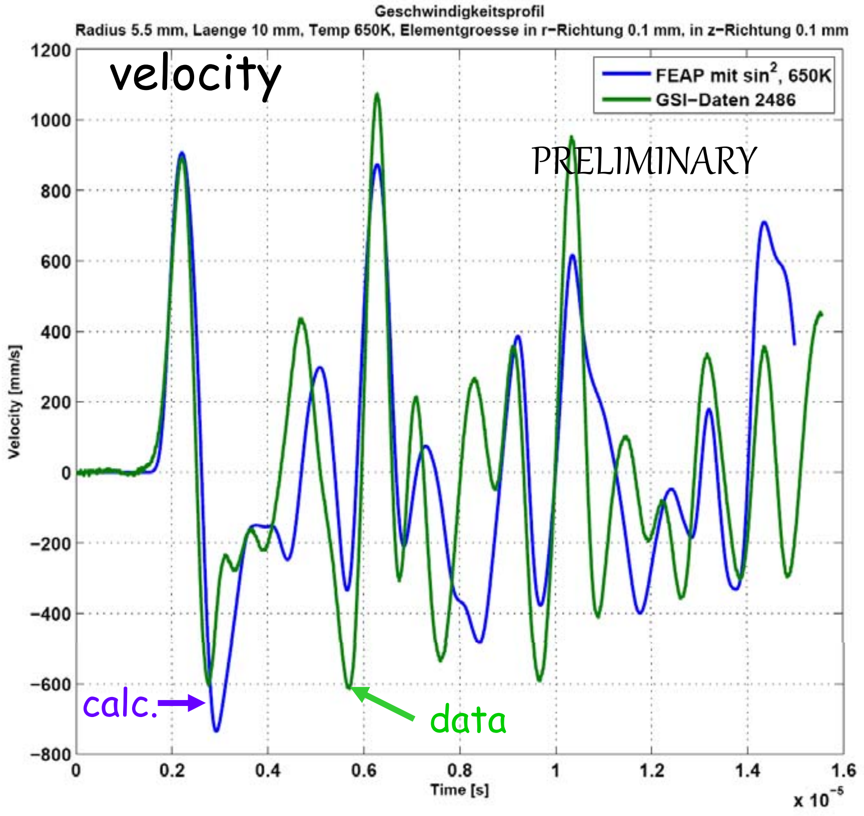


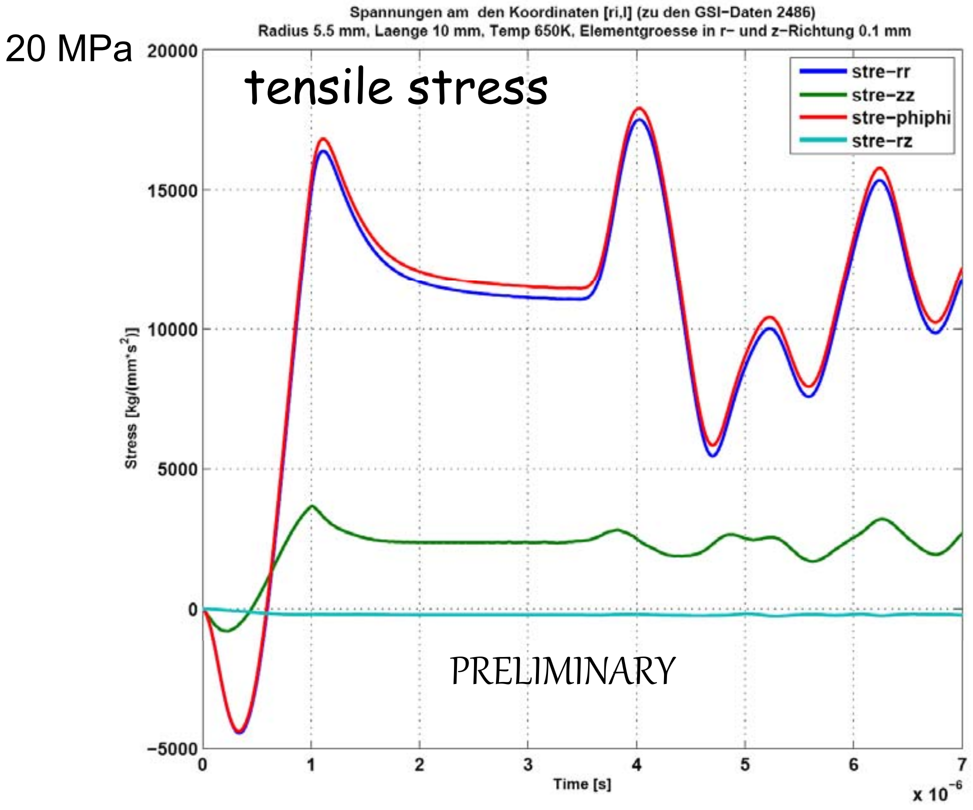
Exp. S334 at SIS18
A.Kelic, R.Wilfinger, D.Varentsov *et al.*

Fast-extracted SIS 18 beam pulses:

$N \leq 4 \cdot 10^9$ ^{238}U/pulse
Gaussian time distribution: FWHM ≈ 300 ns
Beam spot size: $\sigma_x = \sigma_y \approx 0.38$ mm

Comparison with FEAP calculations





S334 - 2.5·10^9 part/pulse

Velocity amplitudes are reasonably well reproduced → derive stress amplitudes

C. Plate, R. Mueller *et al.* (TU Darmstadt)

Estimated tensile stress values for graphite targets

Extrapolation from **S334 measured data** to **Super-FRS operation**:

case	Beam intens. (1/pulse)	Beam energy (MeV/u)	time width FWHM [ns]	Sigma width $\sigma_x \cdot \sigma_y$ [mm^2]	Specific energy $\Delta E/M$ [kJ/g]	Temp. rise ΔT [K]	Static pressure p [MPa]	Dynamic pressure LS-DYNA [MPa]	Dynamic pressure FEAP [MPa]
1	**5.48×10^8**	**350**	**300**	**$0.38 \cdot 0.38$**	**0.25**	**170**	**9**	**4**	
2	**2.40×10^9**	**350**	**300**	**$0.38 \cdot 0.38$**	**1.0**	**650**	**31**	**25**	**≈20**
3	5.0×10^{10}	1000	50	$1 \cdot 2$	0.11	110	5.5		
4	5.0×10^{11}	1000	50	$4 \cdot 6$	0.96	580	30		≈37

limit: ≈ 65 MPa

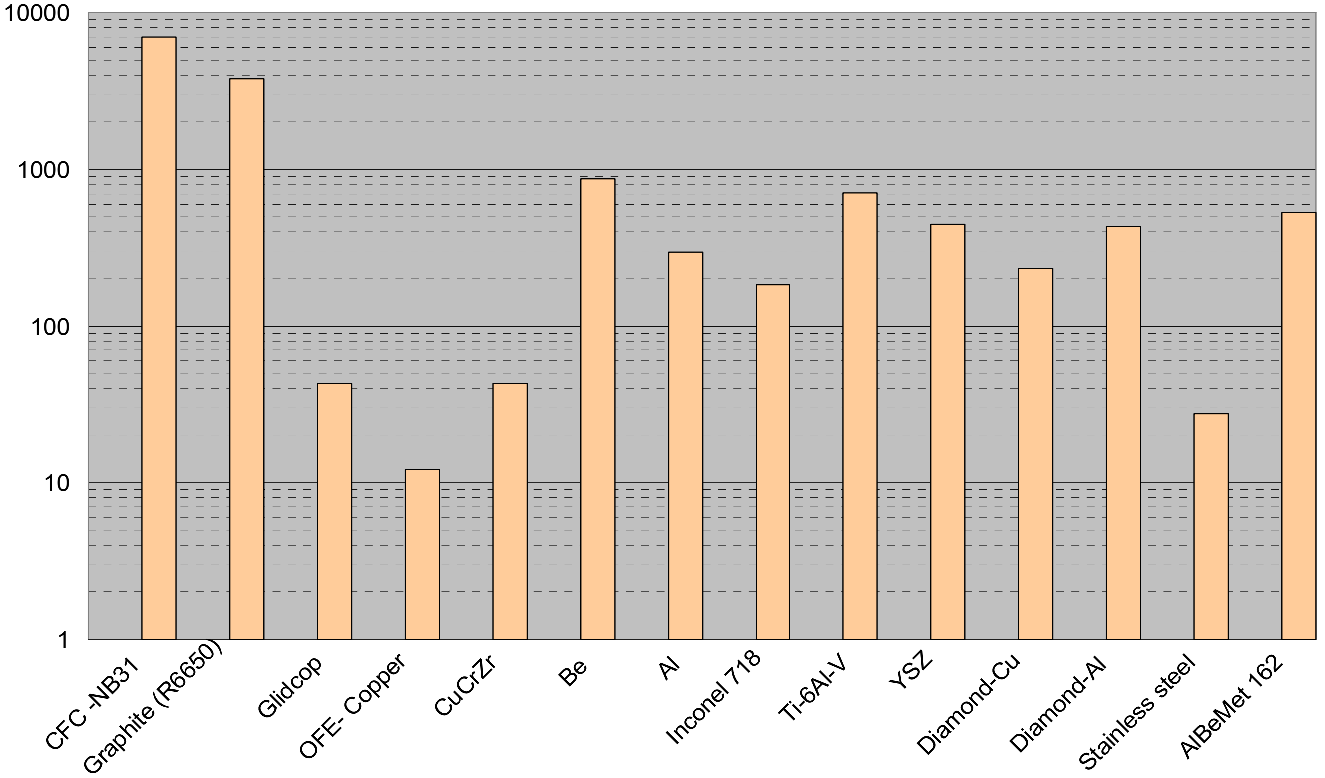
Conclusions:

- **Super-FRS graphite target can be operated with SIS100 design intensity even with fast extraction**
- **Moderate beam spot size: $\sigma_x \approx 4$ mm, $\sigma_y \approx 6$ mm provides large safety margin**

Figure of Merit

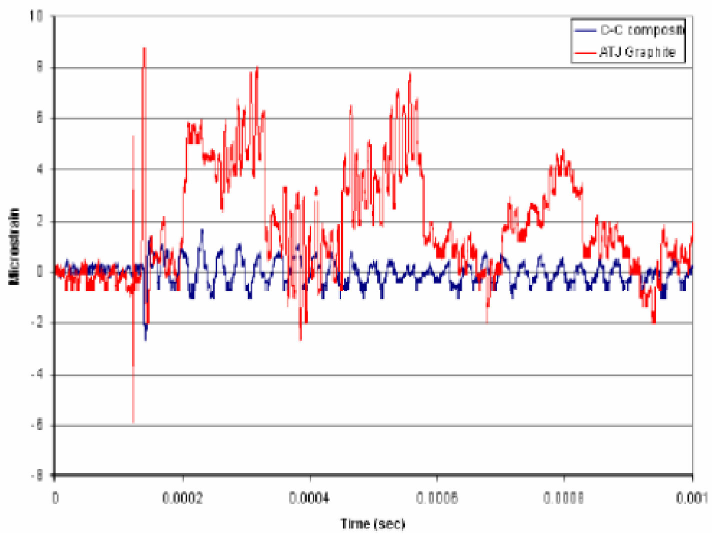
Materials resistance to ion beam-induced thermal stress waves

Ion beam-induced shock parameter- $[\sigma_y(1-\nu)c_p] / [E\alpha \ dE/d(\rho x) \ A]$



Carbon- based composite solutions for fast extraction

Minimizing amplitude of pressure waves induced by an energetic proton bunch using a 3D CFC target



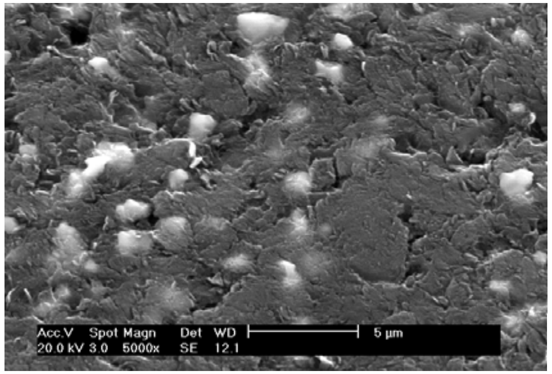
Response to stress waves induced by energetic proton bunches (24 GeV, intensity 4x10^{12}) of ATJ graphite and a 3D C-C composite (N Simos et. al)

But:

- 3 D CFC have increased inhomogeneity and porosity

Known to be more sensitive to radiation damage

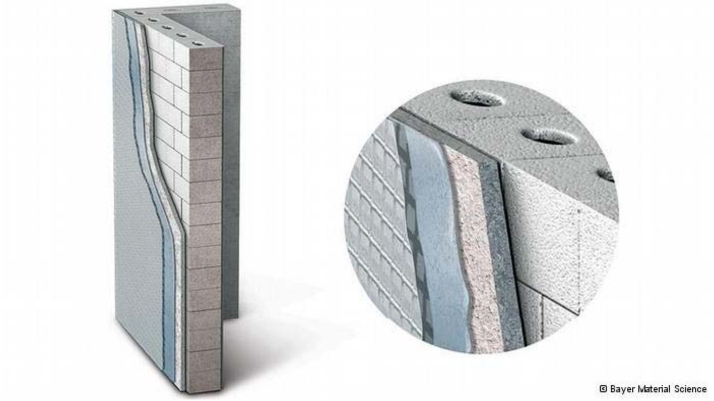
Reduced brittle destruction in Ti- doped graphite under electron beam thermal shock loading

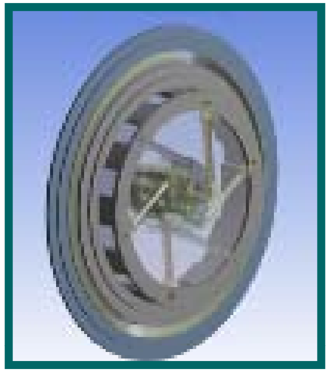


(C. Garcia- Rosales)

Making the target earthquake proof

“Seismic wallpaper” solution





+ carbon nanotubes fabric

Conclusions

Slow extraction:

1. One year operation of target feasible
2. High temperature operation of target and beam catchers extends lifetime due to defect recovery
3. Target annealing campaigns between experiments at sub-critical doses can helps in extending lifetime- induction heating system

Fast extraction:

1. A graphite solid target will work for lower Z, smaller intensities in the starting FAIR version.

1. Highest U intensities: graphite, but larger beam spot?

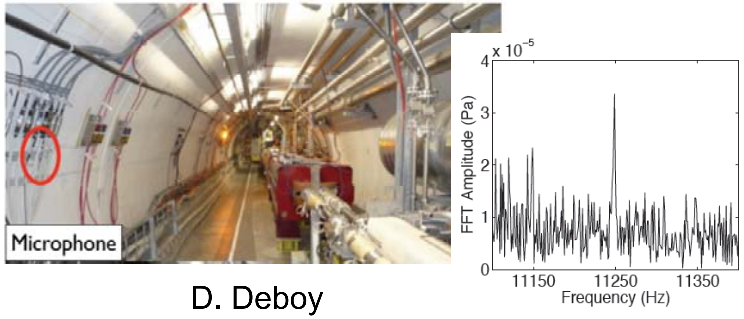
2. Experimental tests on promising carbon-based composite materials and “sandwich” design are needed.

Monitoring systems for target materials

Problem: How to predict and localize failure

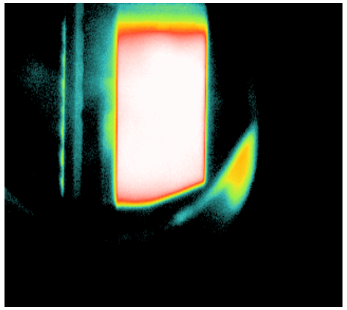
- in extreme operation conditions
- in high radiation fields
  - targets
  - protection elements (beam catchers, collimators)
  - rf cavities

Acoustic emission monitoring of LHC collimators

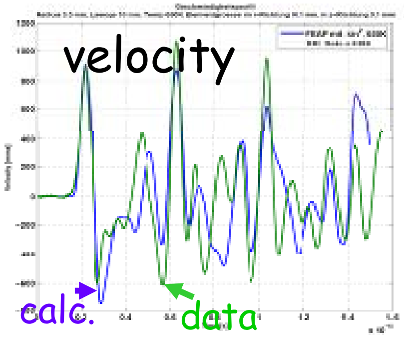


D. Deboy

Thermal imaging



Laser vibrometer



Eddy current

possible monitor systems to be tested

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

Co-workers

GSI Darmstadt:

B. Achenbach, K.-H. Behr, H. Geissel, M. Gleim , A. Hug, H. Iwase, C. Karagiannis,
A. Kelić, B. Kindler, B. Lommel, C. Scheidenberger, K. Schwartz, K. Sümmerer, N.
A. Tahir, C. Trautmann, D. Varentsov, H. Weick, M. Winkler

TU Darmstadt:

M. Krause, J. Menzel, N. Mueller, S. Udrea, C. Plate, R. Müller

CERN Geneva:

J. Lettry, H. Richter, R. Wilfinger

University of Latvia, Institute of Solid State Physics, Riga :

I. Manika, J. Maniks, R. Zabels

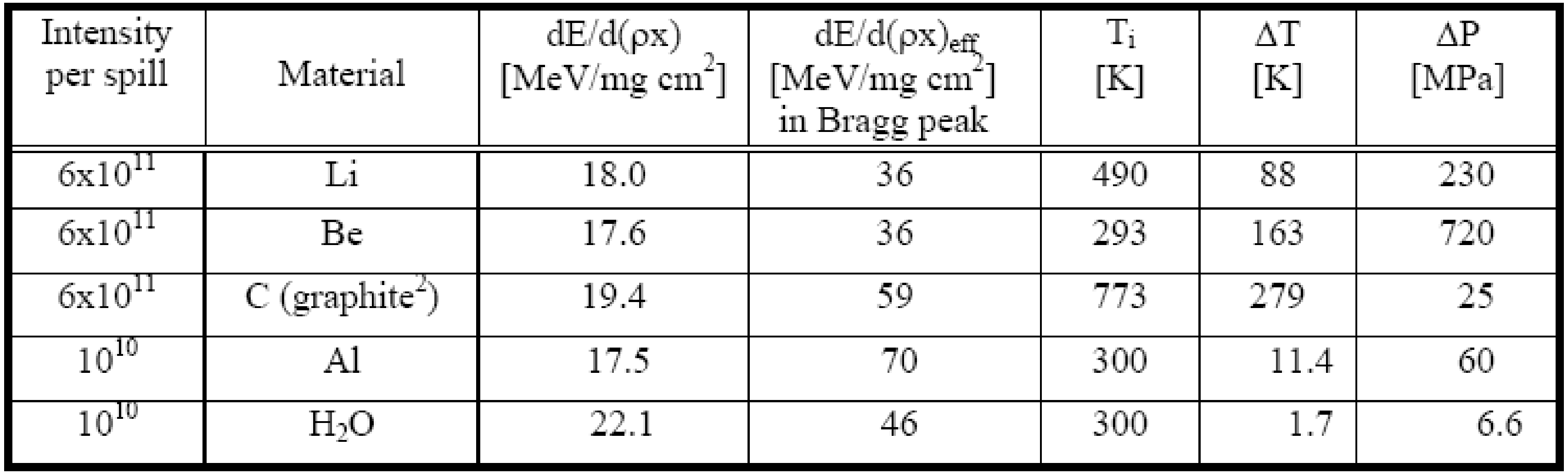
MSU/ FRIB, East Lansing, USA:

W. Mittig, M. Avilov, S. Fernandes, F. Pellemoine

Materials for Beam Catcher

Values for fast extraction

Primary beam 6×10^{11} ^{238}U starting at 740 MeV/u after target.
Minimal spot size from previous plots ($\sigma_x \times \sigma_y$ = 1.7x1.7 cm^2) and
maximal energy deposition in Bragg peak (540 J/g in graphite).



Intensity per spill	Material	dE/d(ρx) [MeV/mg cm^2]	dE/d(ρx)$_{eff}$ [MeV/mg cm^2] in Bragg peak	T_i [K]	ΔT [K]	ΔP [MPa]
6×10^{11}	Li	18.0	36	490	88	230
6×10^{11}	Be	17.6	36	293	163	720
6×10^{11}	C (graphite^2)	19.4	59	773	279	25
10^{10}	Al	17.5	70	300	11.4	60
10^{10}	H_2O	22.1	46	300	1.7	6.6

[2] Values based on SGL carbon group grade R 6650.

Graphite seems the best choice (limit ~ 65 MPa for fast pulse),
also carbon-carbon composites, maybe Beryllium at some positions
because of fast strain rate (use many thin layers for damping).