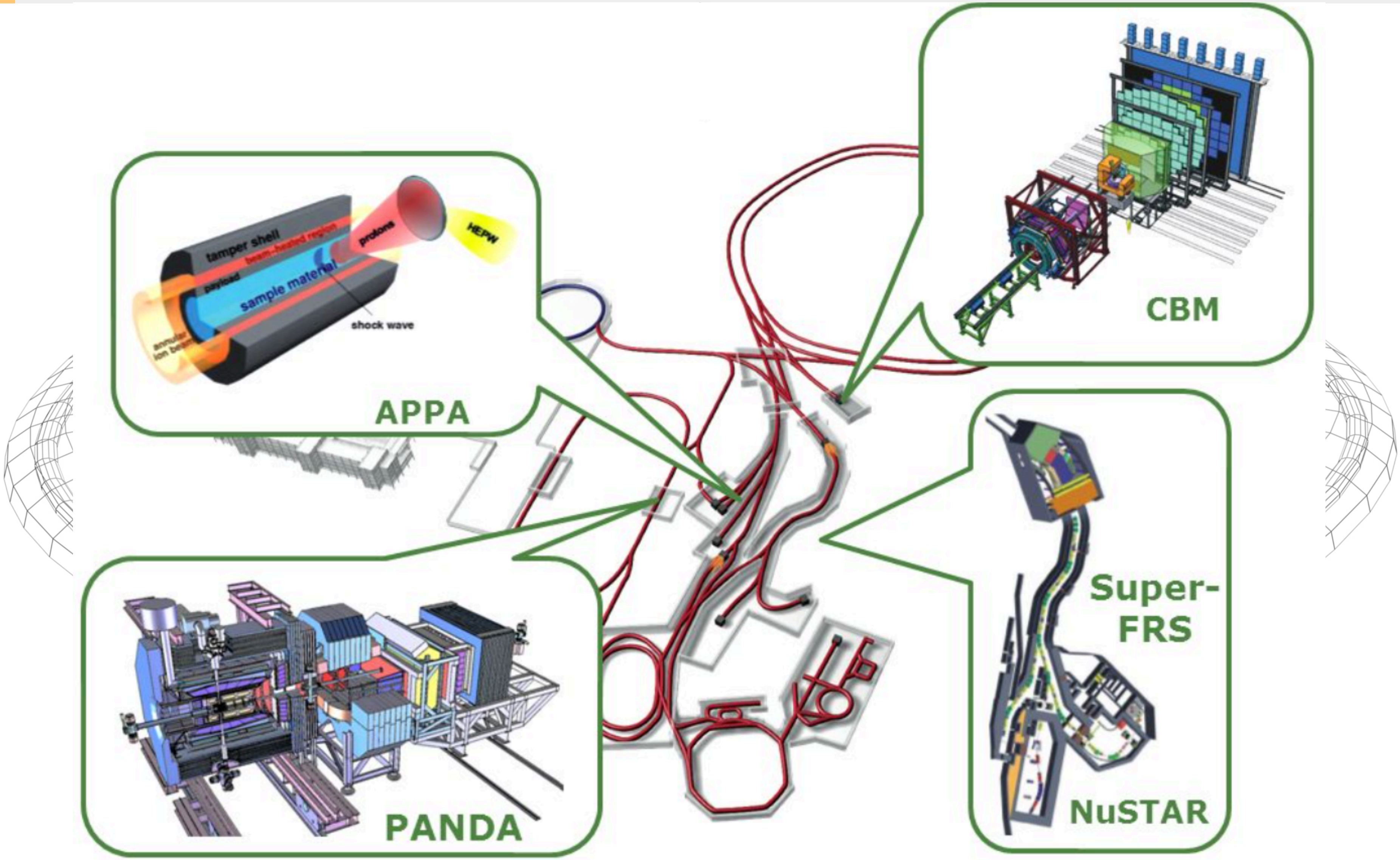
Materials Research at FAIR

M. Bender, GSI Materials Research


tamper shell
protons
HEPW
sample material
shock wave
APPA
CBM
PANDA
Super-
FRS
NuSTAR

GSI Helmholtzzentrum für Schwerionenforschung GmbH

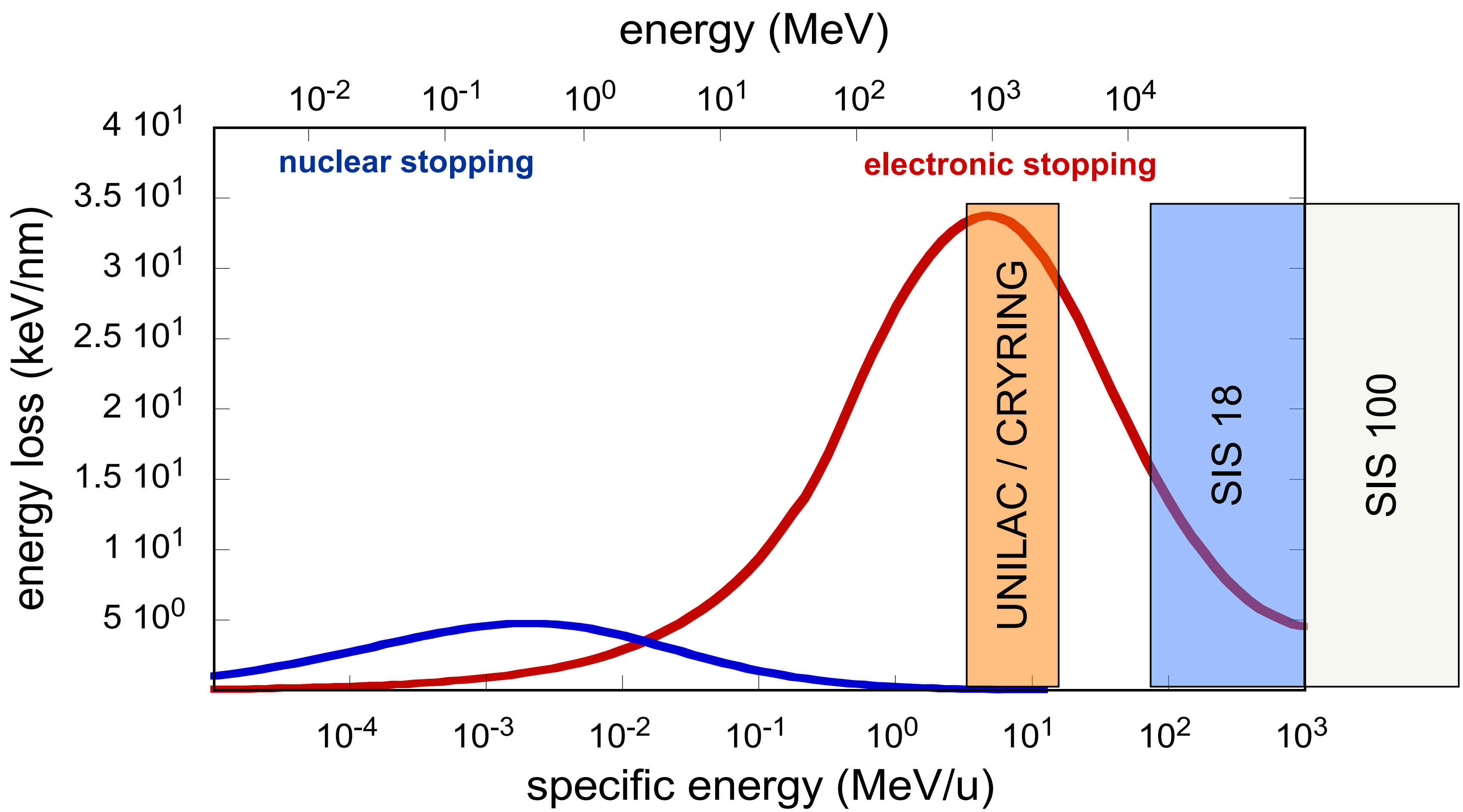
Materials Research ~~at~~ for FAIR

M. Bender, GSI Materials Research

Outline

- Interaction of ions with matter
  - Motivation ☺
  - Motivation ☹
- Experimental sites
  - M-Branch
  - CRYRING
  - BioMAT @ APPA
- Planned experiments and hitherto results
  - Surface phenomena
  - Materials under extreme conditions

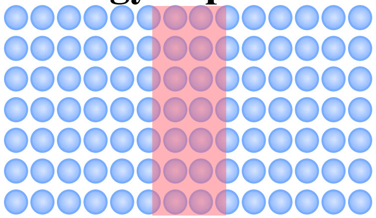
Interaction of ions with matter



Interaction of ions with matter

10^{-17} - 10^{-16} s

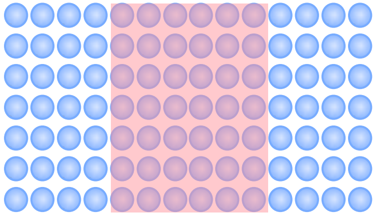
energy deposition



electronic excitation & ionization
'hot' electrons

10^{-15} - 10^{-14} s

electron cascade

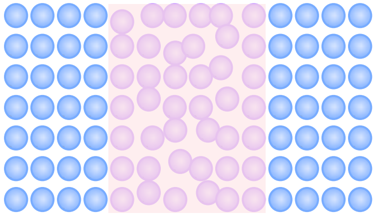


energy diffusion in electronic subsystem
cooling of hot electrons
'cold' lattice

Coulomb explosion

10^{-13} - 10^{-12} s

electron-phonon interaction



energy diffusion to atoms
lattice heating
melting

thermal spike

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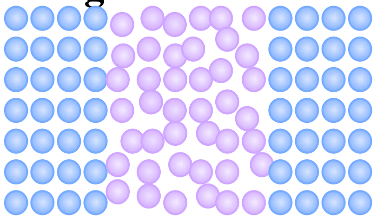
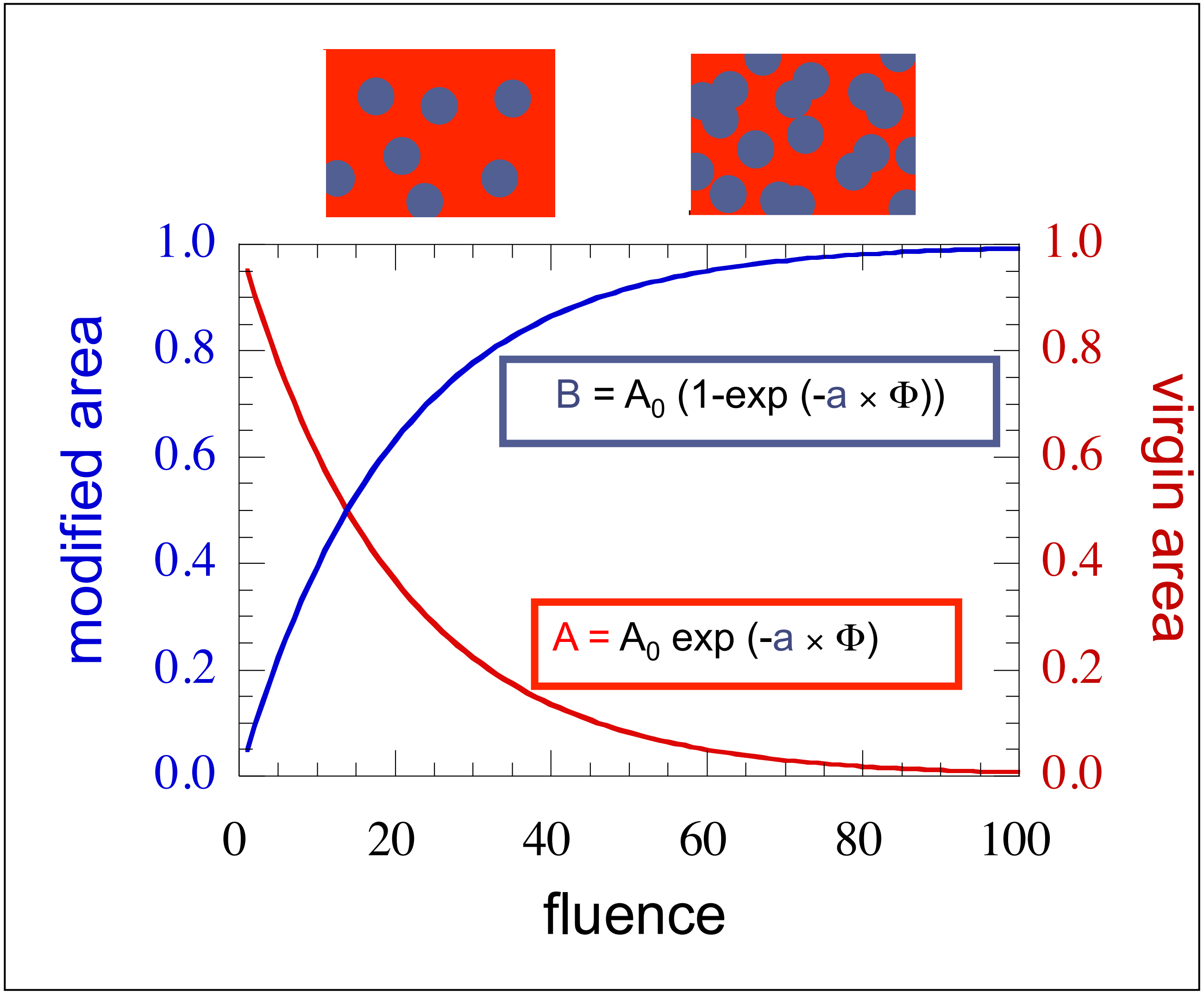
metals ~ 10^{-12} s
insulators ~ 10^{-10} s

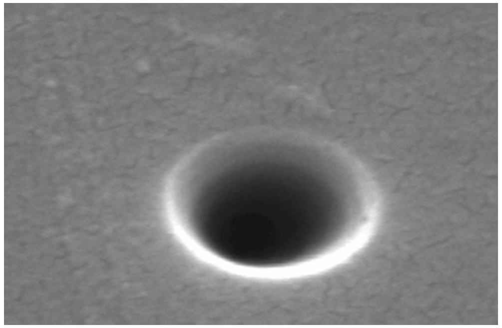
quenching of atomic disorder

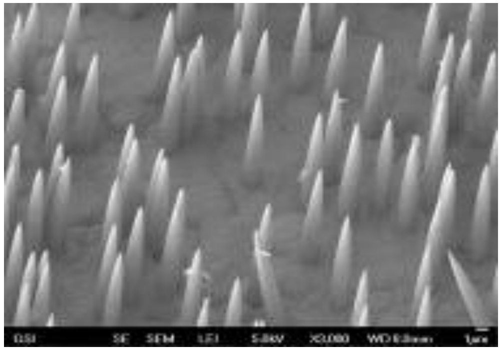


fast cooling of atoms
defect formation

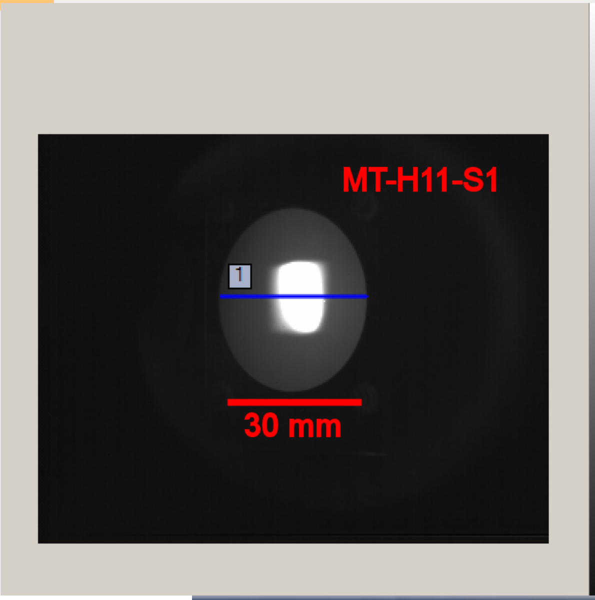
Interaction of ions with matter

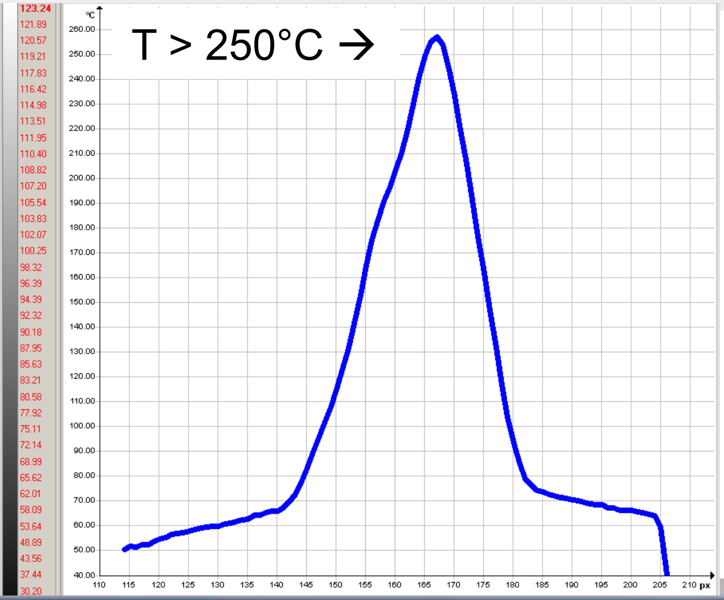


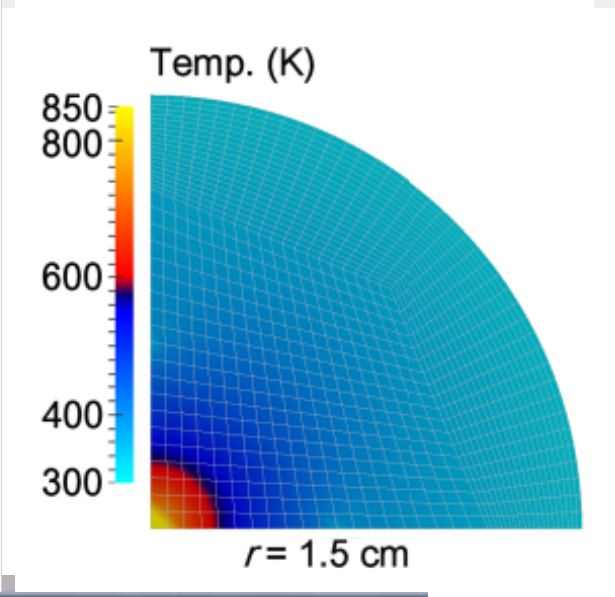




Interaction of ions with matter





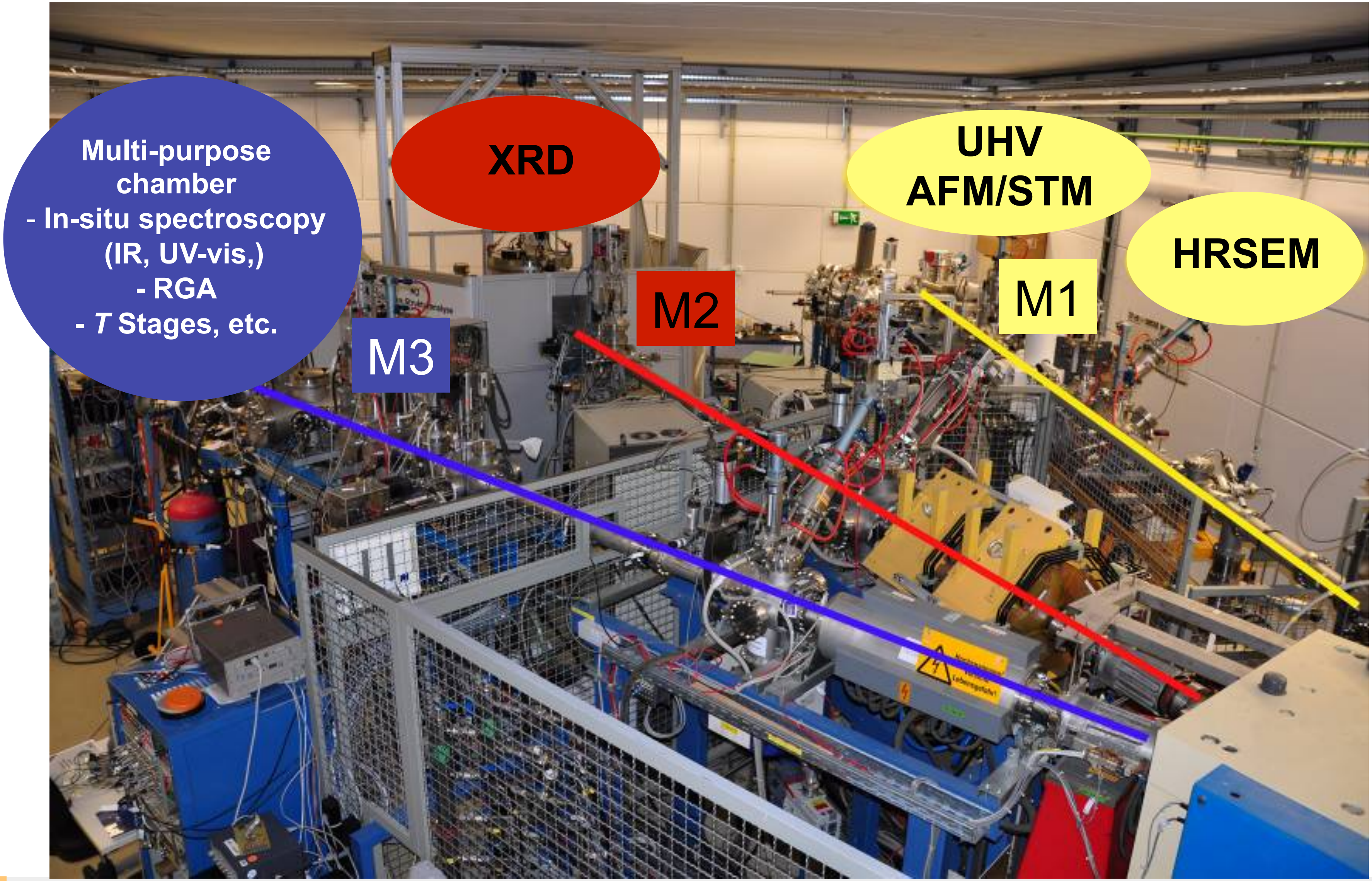


Interaction of ions with matter: conclusion

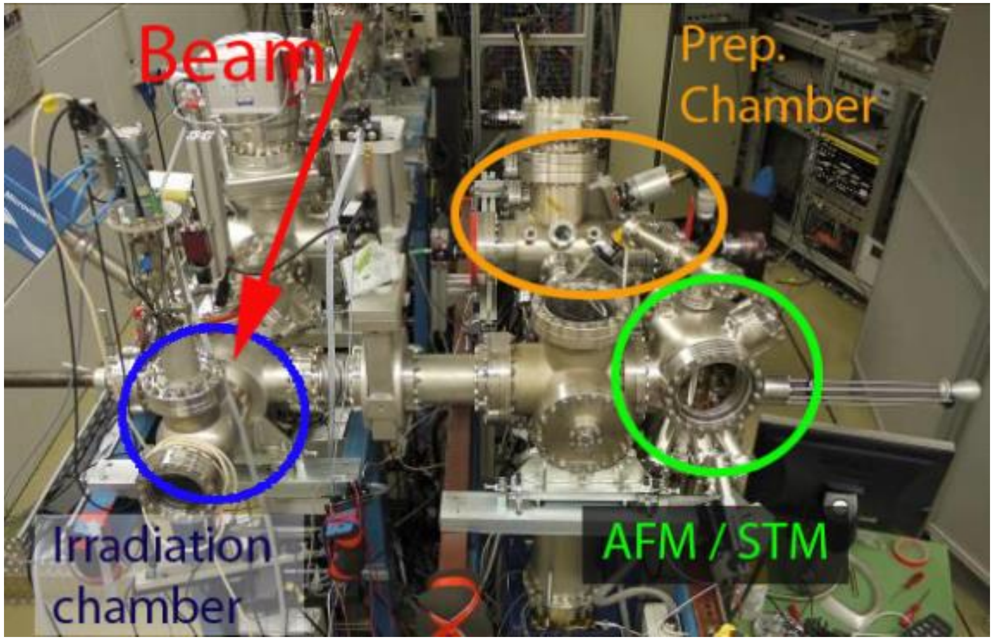
- Transient thermal process for each single ion
  - Depending on material: track formation / sputtering
  - ☺ Nano structures like pores, needles, networks, ...
  - ☹ Radiation defects with higher fluences

- For ion pulses (e.g., 10^{11} ions in ≤ 1 ms)
  - Short heat pulse of some 100°C
  - → Pressure pulse: mechanical damage of functional materials
  - ☺ Matter under extreme conditions
  - ☹ Life time limitation of facilities like FAIR!
  - → develope new materials
  - → develope online techniques for damage control
    - → predict life time

Experimental sites: M-Branch



Experimental sites: M-Branch

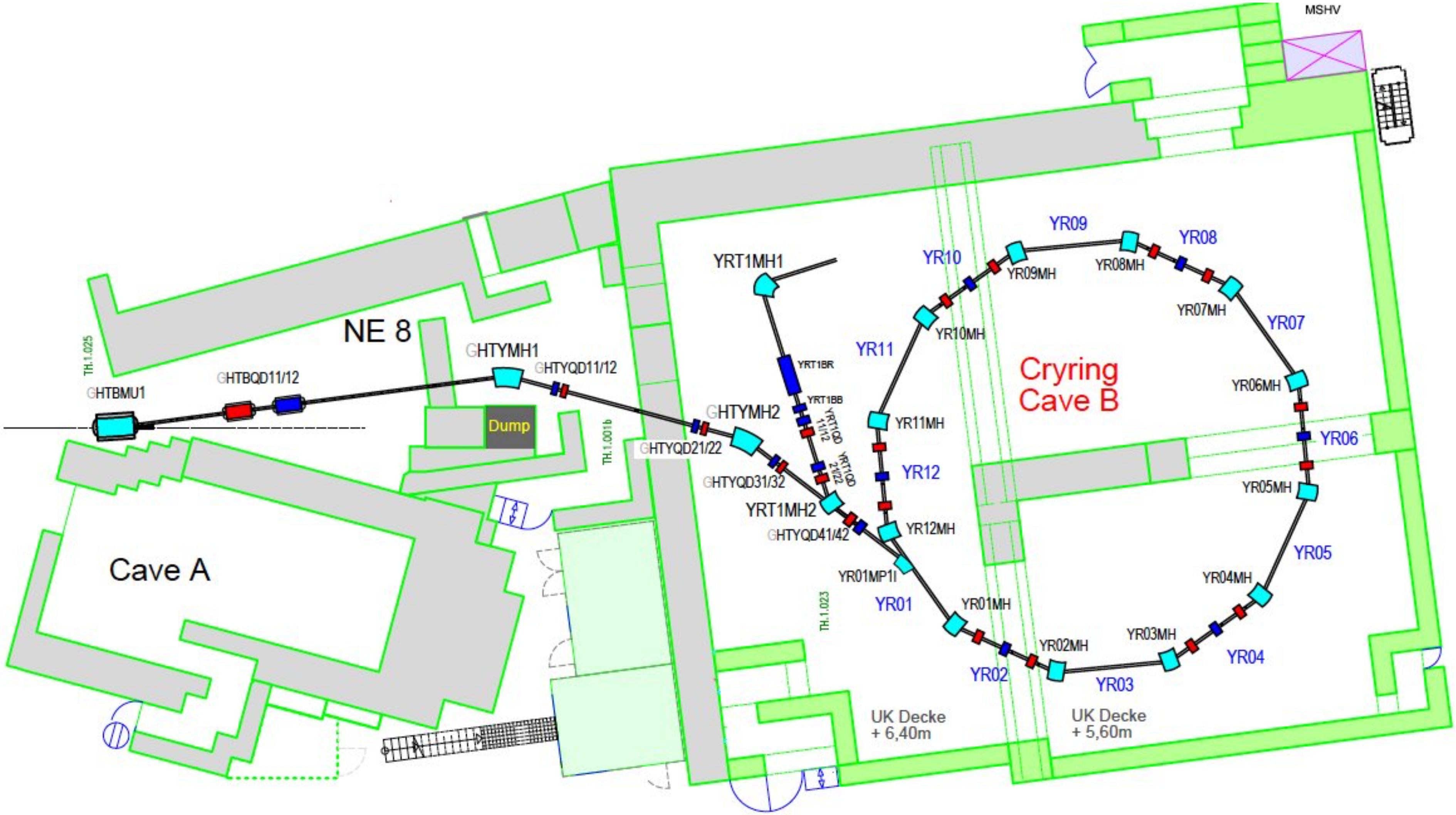


M1:
- Best vacuum for investigation of surface phenomena
- Precise stage for irradiation under defined (gracing) angles
- Load lock system for quick sample exchange
- Preparation chamber with heater
- AFM / STM, ToF-SIMS, RGA

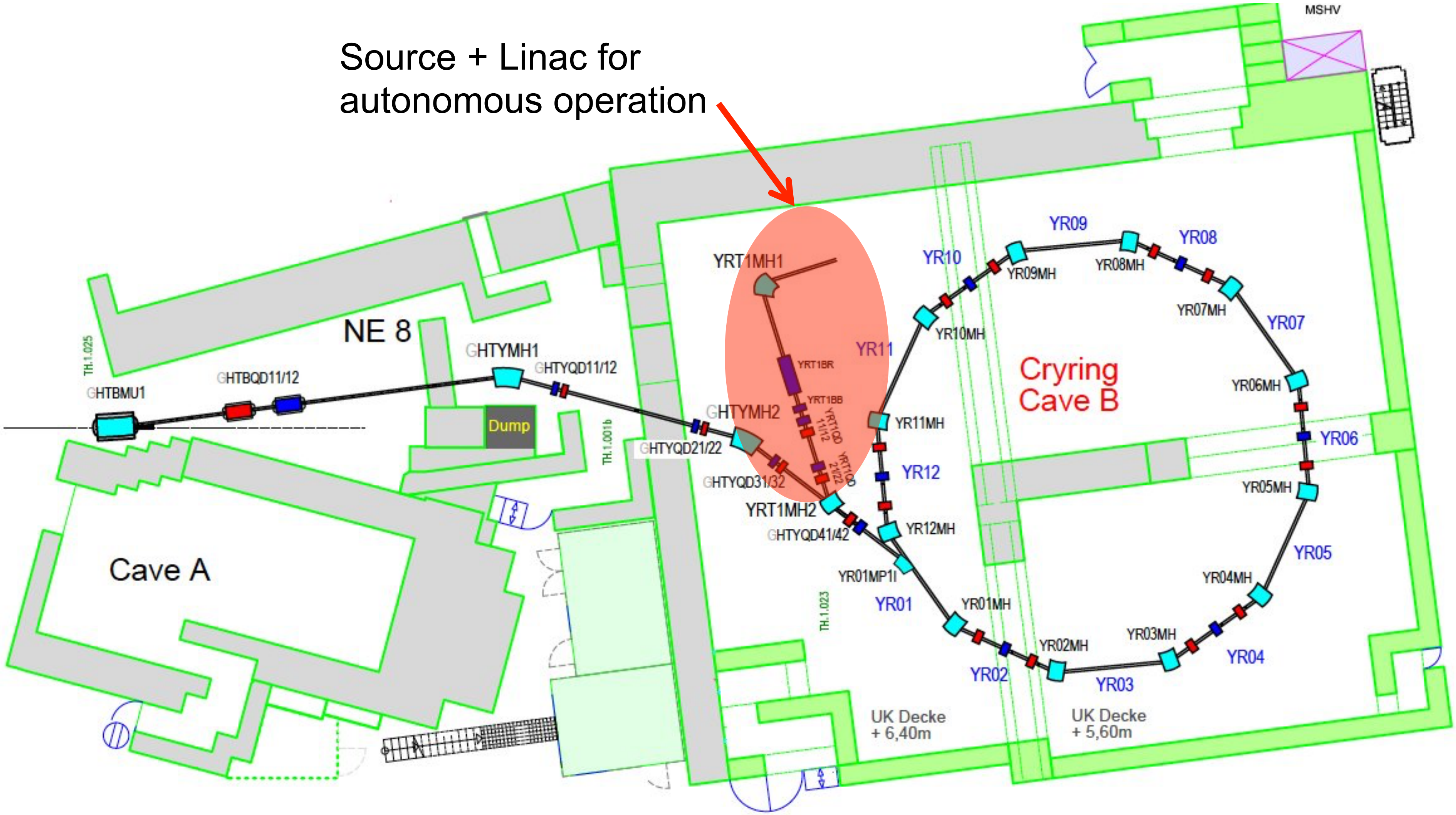
(M2: XRD for bulk phenomena)

M1:
- Multi-purpose spectroscopy for in-situ and online investigations
- Irradiation of samples from 10 K to 1000 K
- FTIR, Raman, RGA, stress, creep, thermo camera, resistivity, …

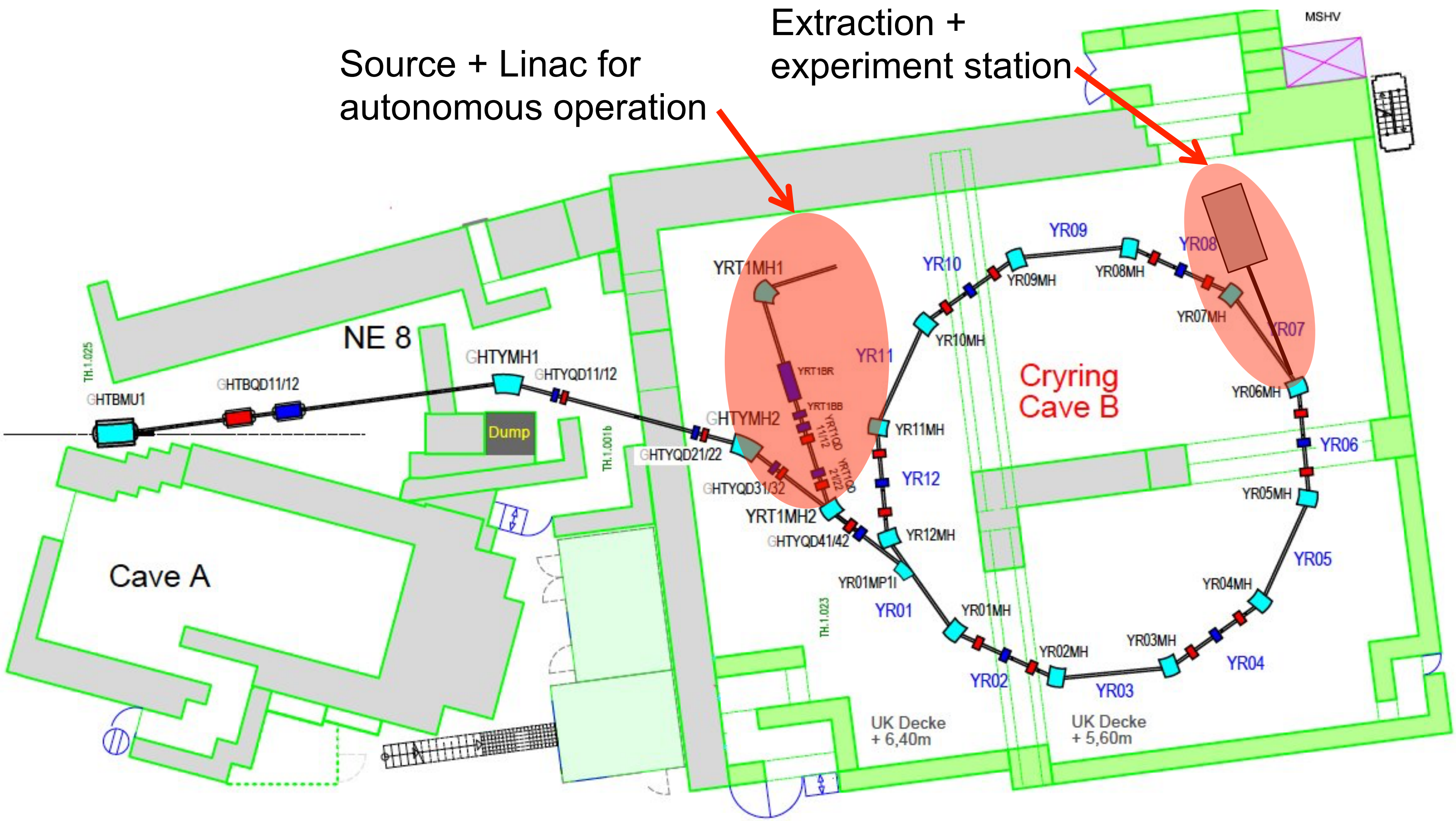
Experimental sites: CRYRING



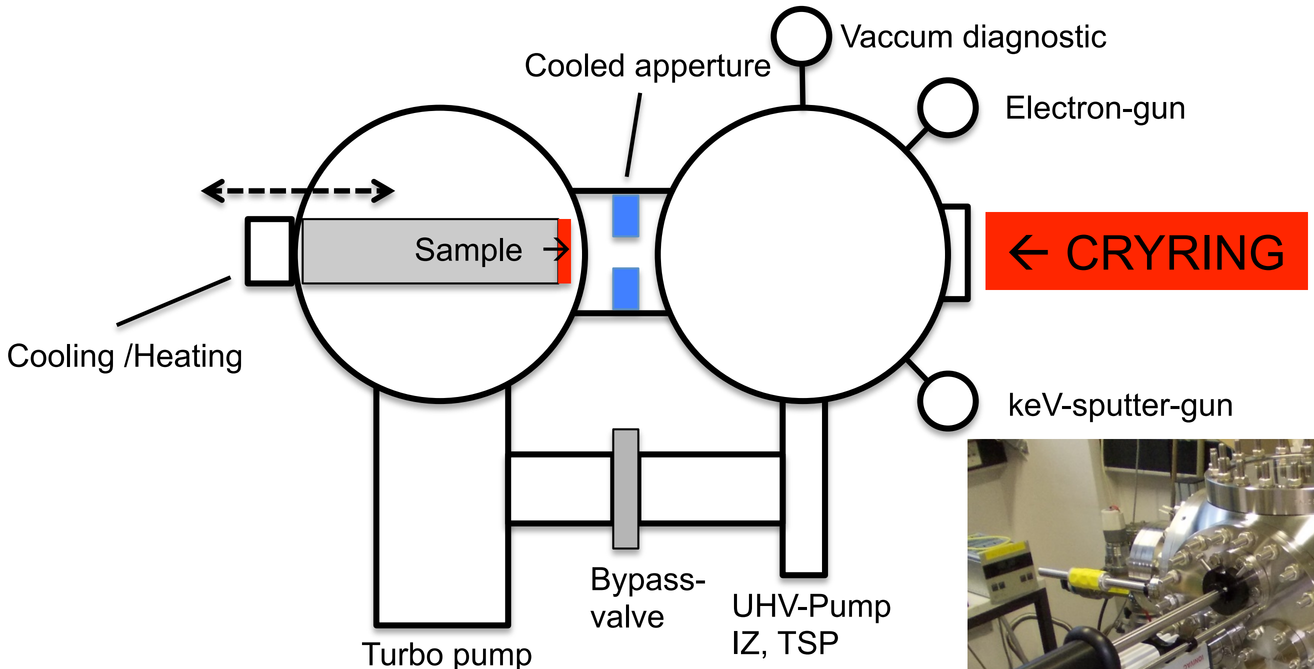
Experimental sites: CRYRING

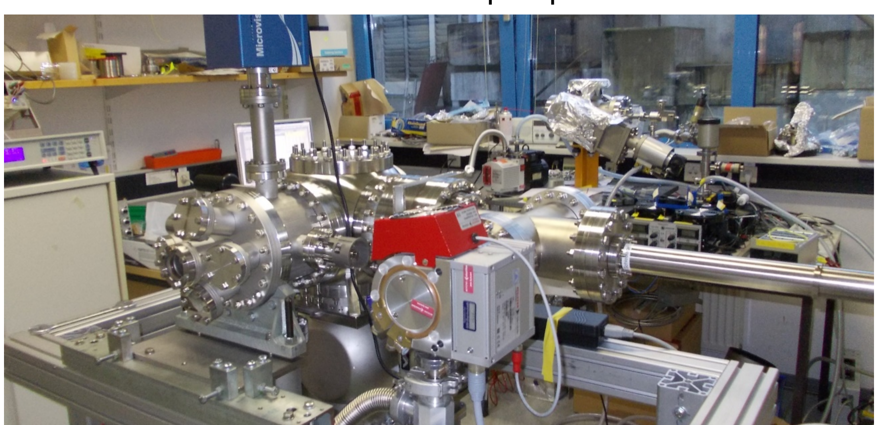


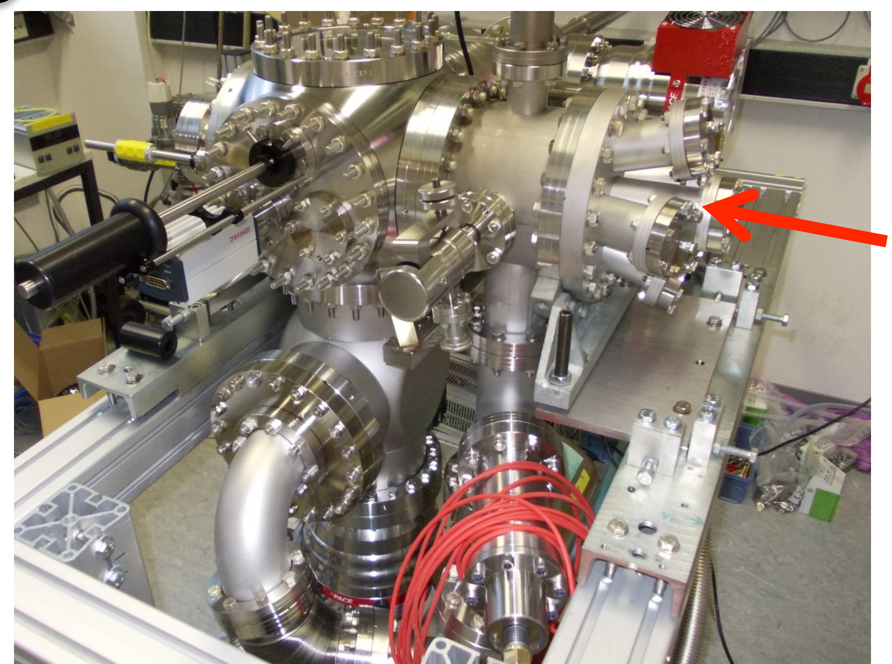
Experimental sites: CRYRING



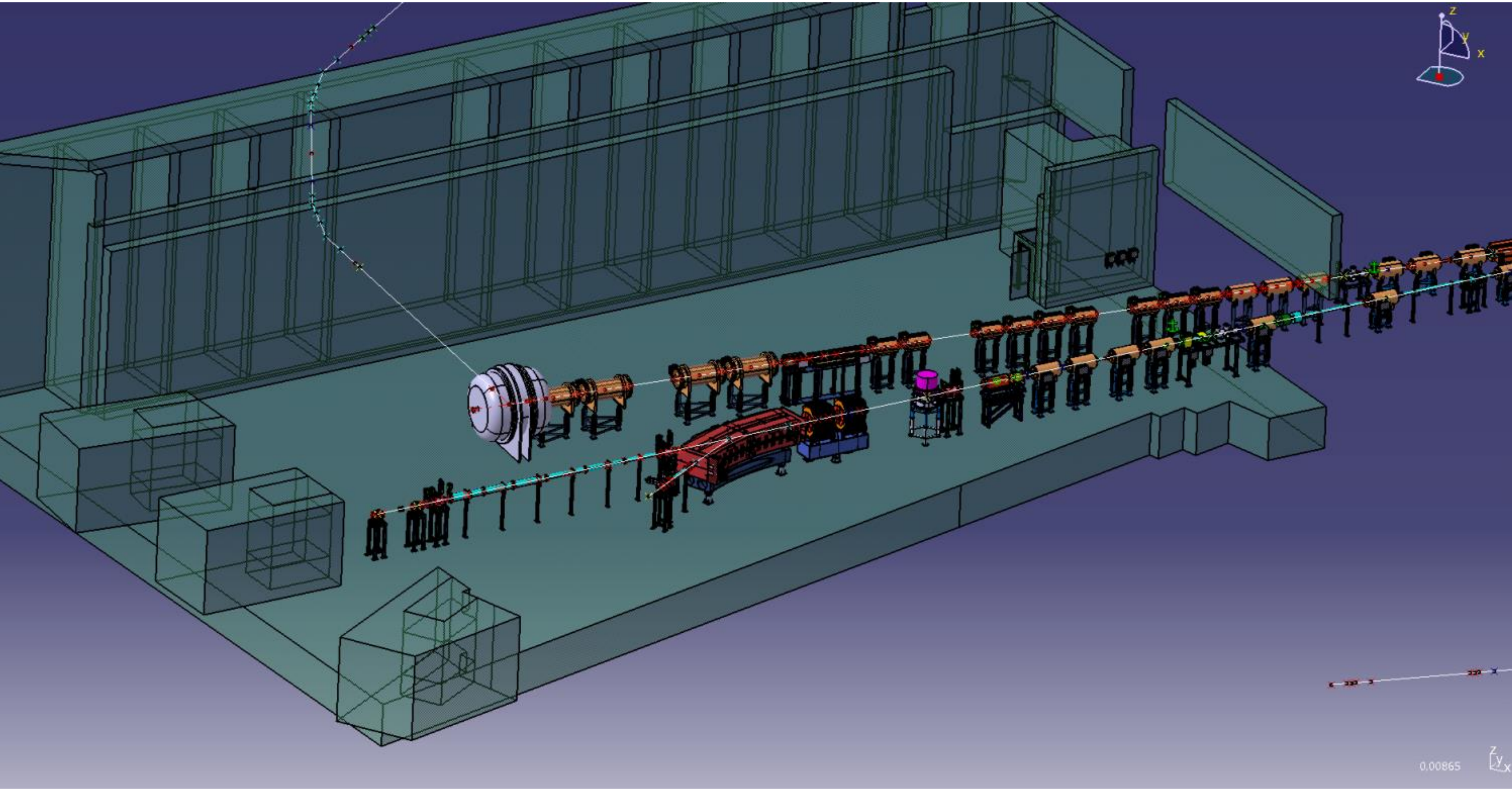
Experimental sites: CRYRING







Experimental sites: BioMAT@APPA



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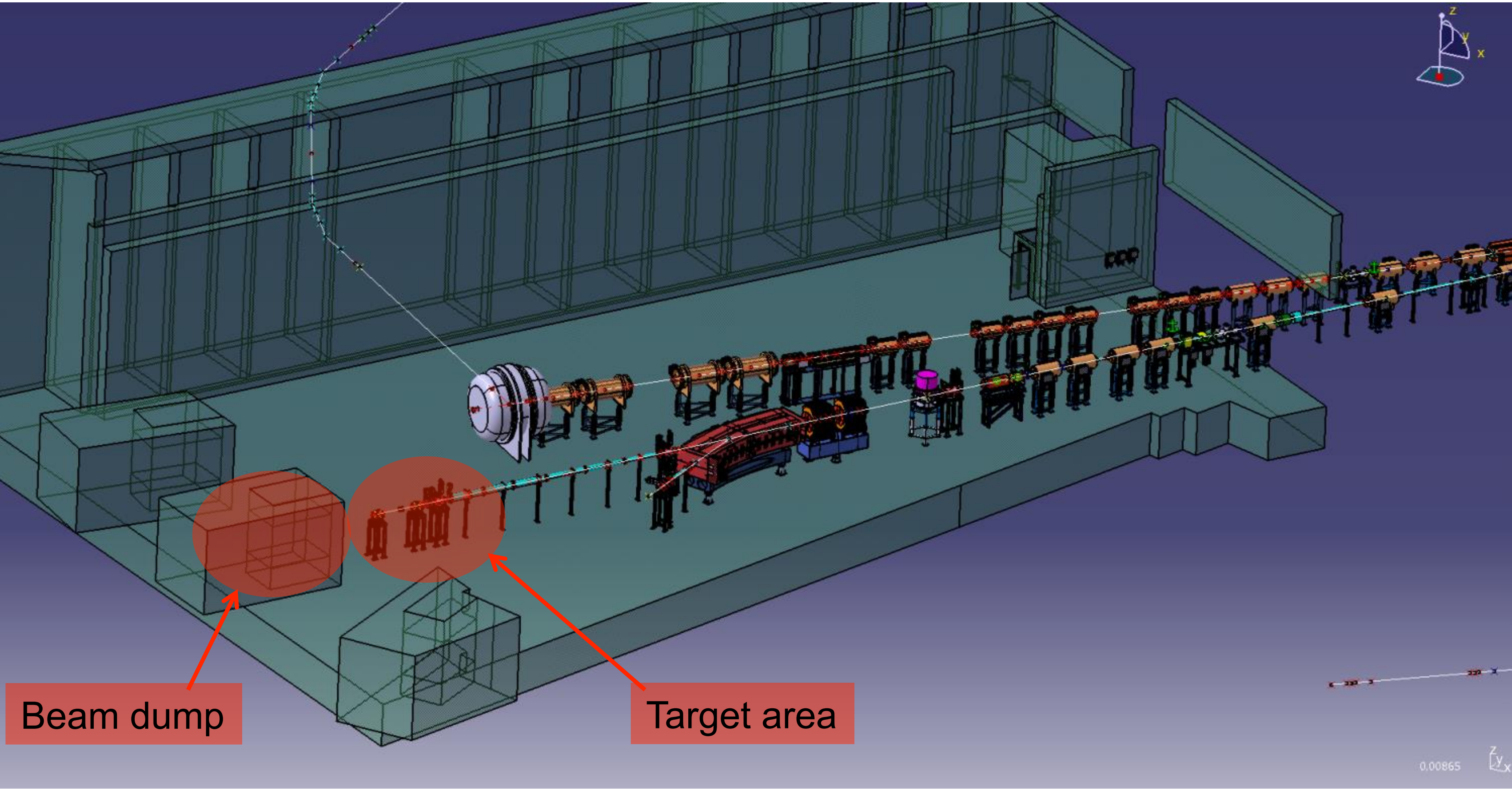
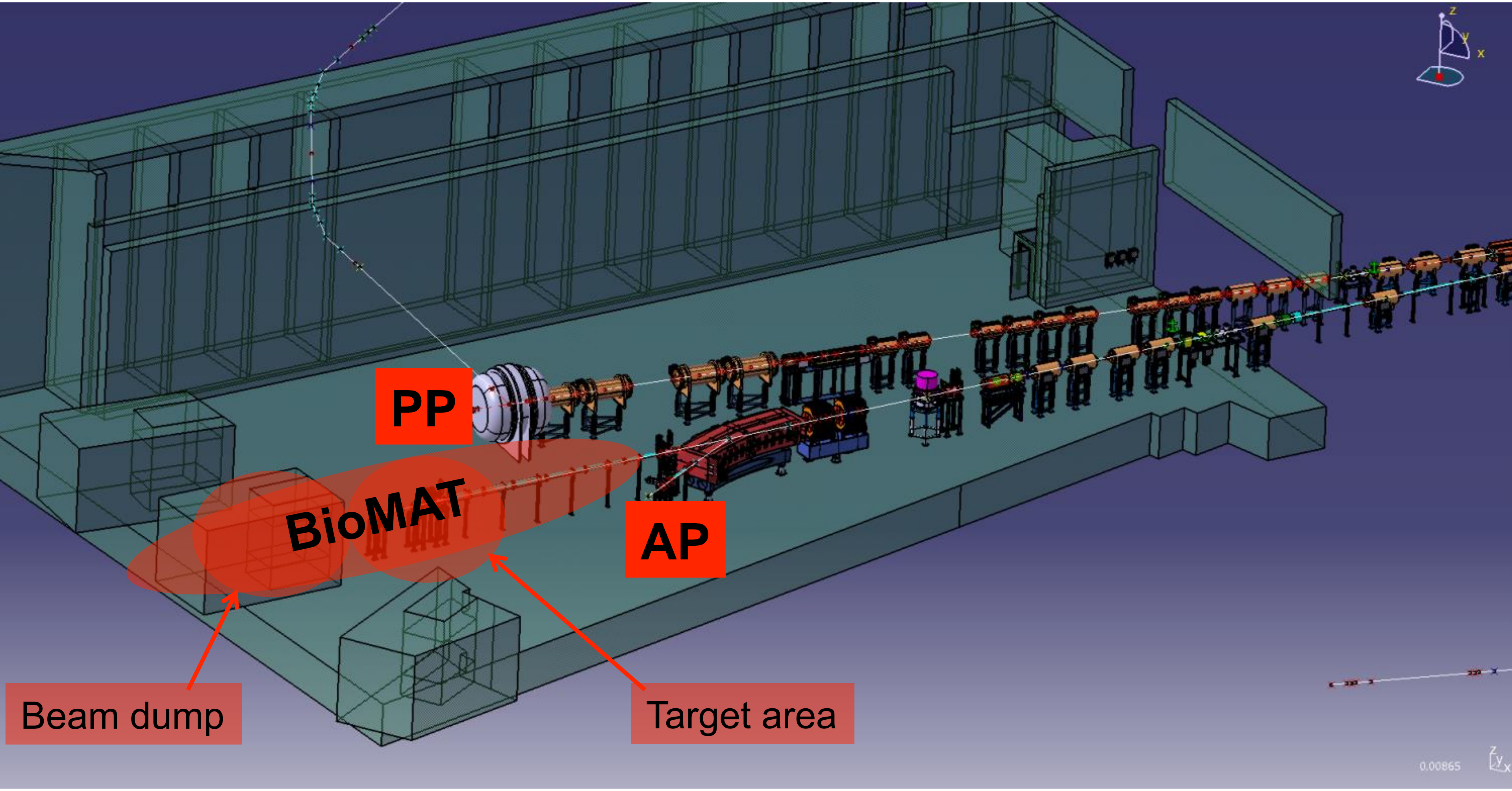
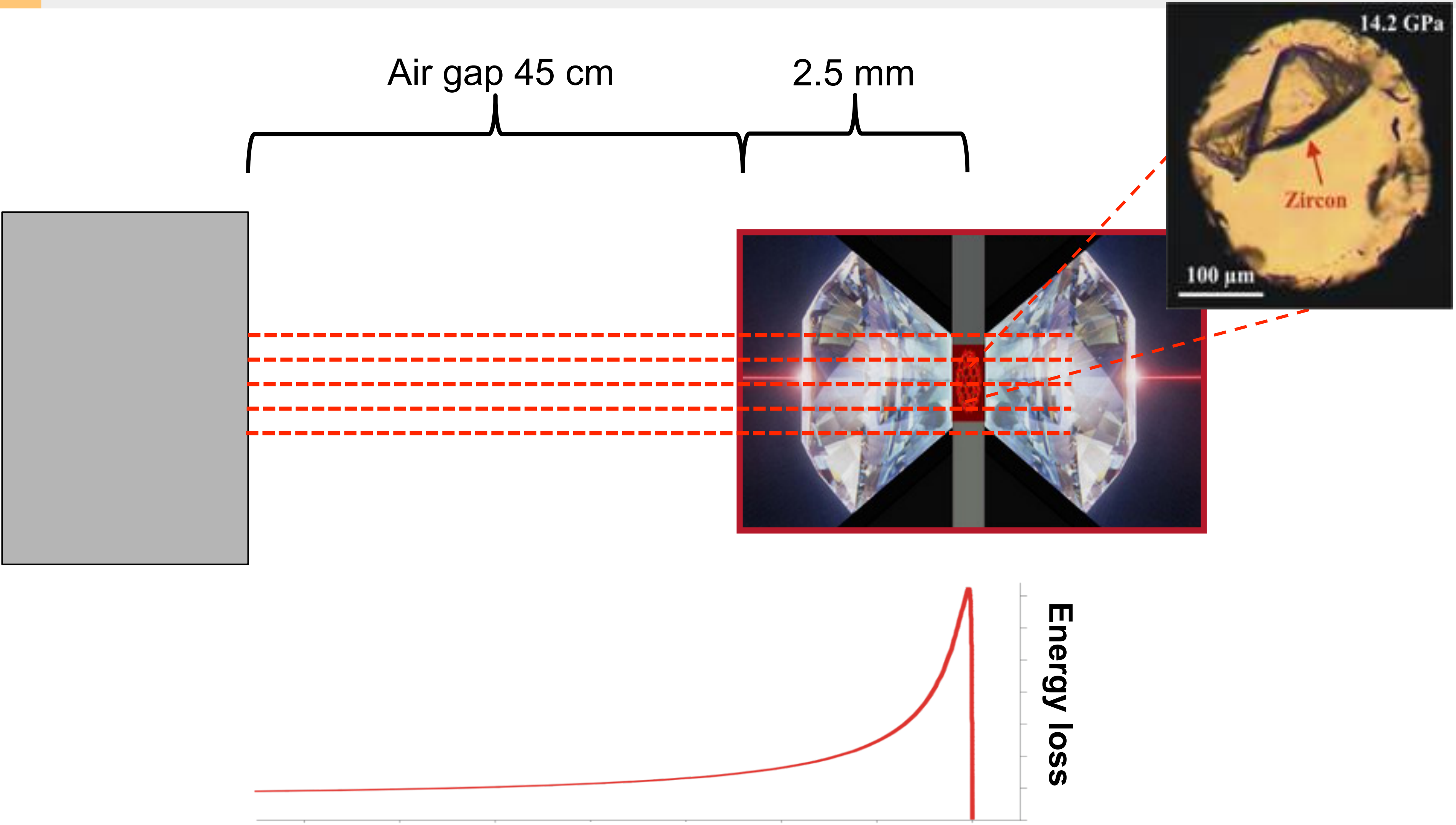


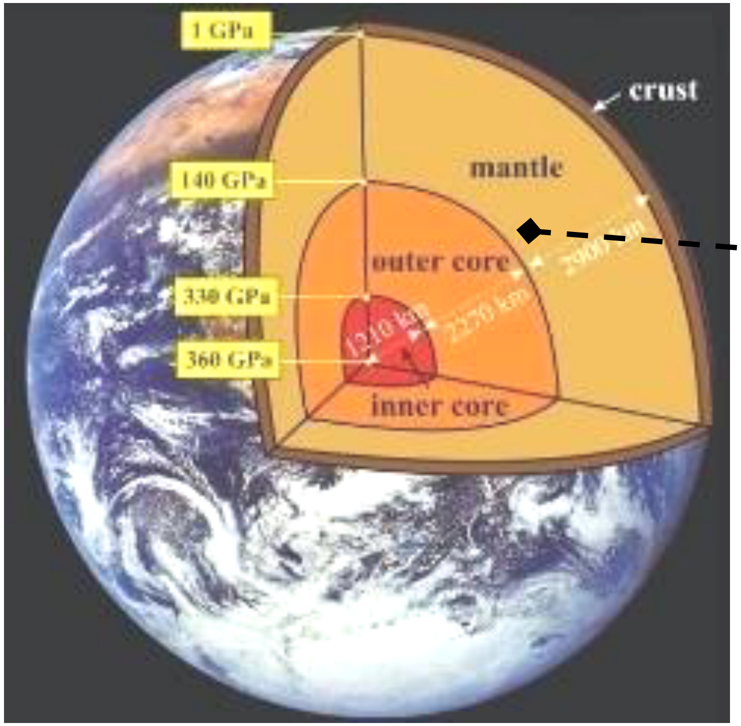
Experimental sites: BioMAT@APPA

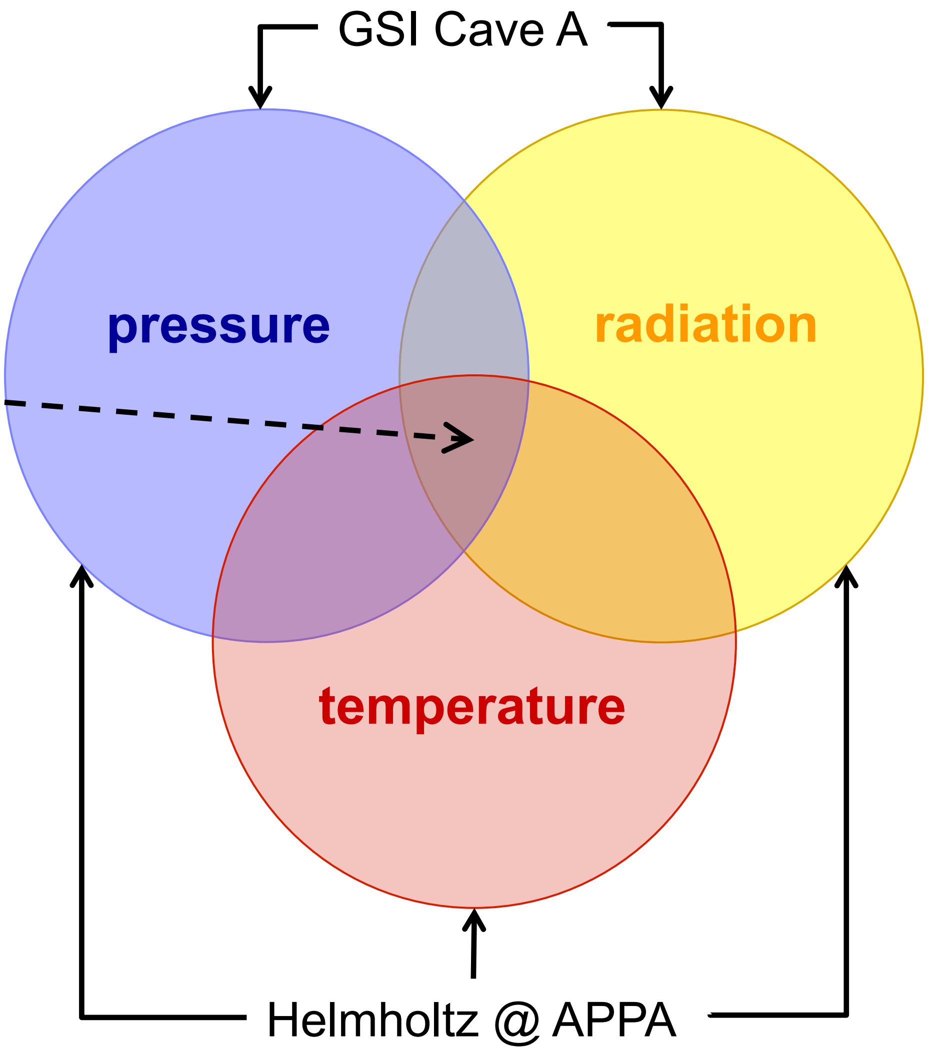


Experimental sites: BioMAT@APPA



Experimental sites: BioMAT@APPA





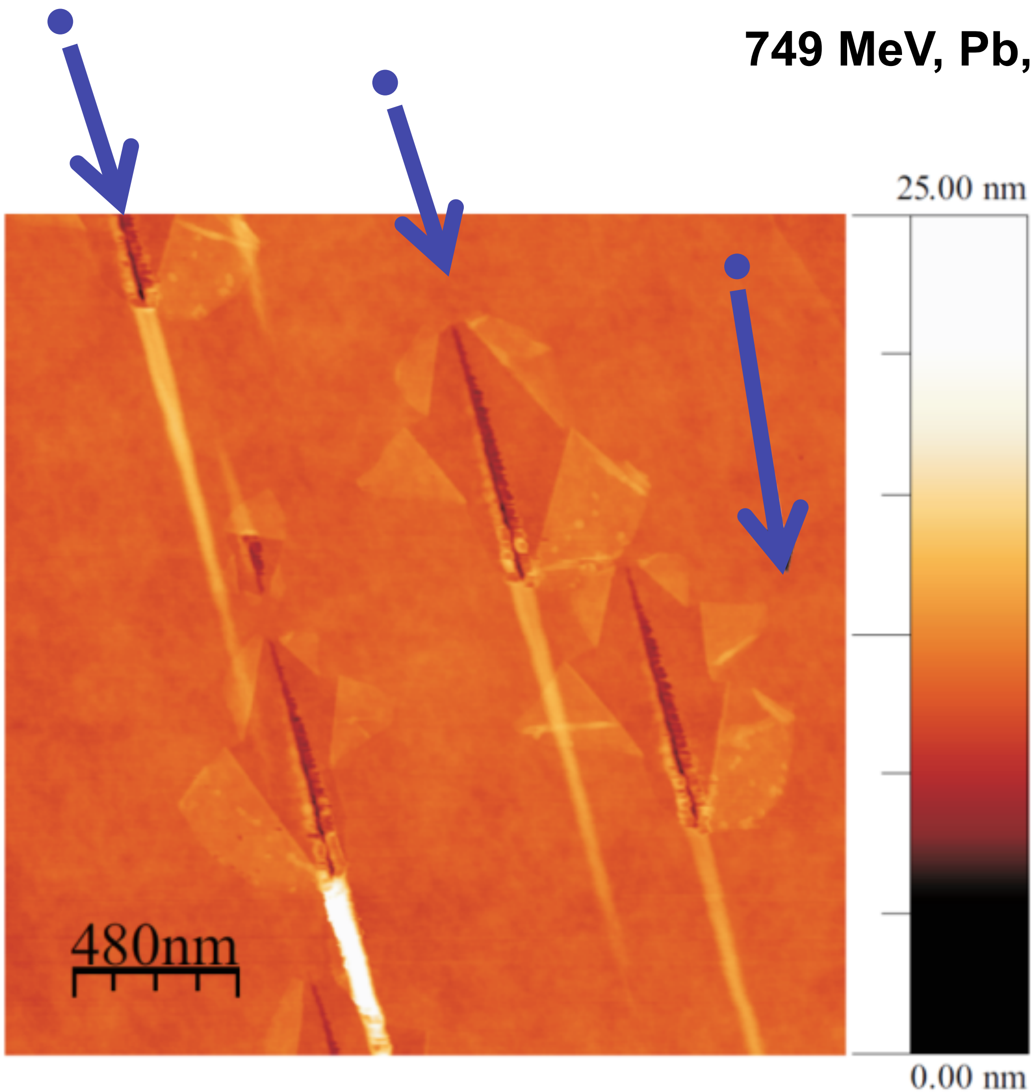
Experimental sites: conclusion

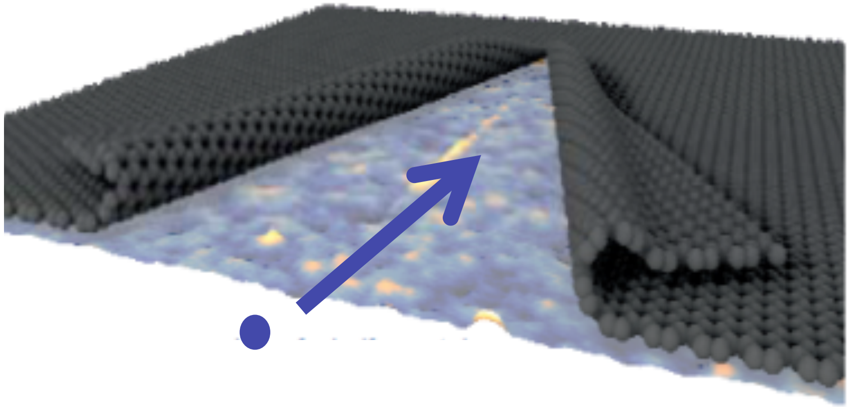
- Materials research operates many experimental sites
  - (not shown: X0, cave A)
  - All ions possible (though highest dE/dx at heaviest ions)
  - Fluxes up to 1e11 ions per second
  - Fluences up to 1e15 / cm^2 or more
  - Energies from 1.4 MeV / u to 1 GeV / u
  - Short pulses, e.g. 1e11 ions in 1 ms (→ pulse load > 10 kW)

- FAIR beams:
  - Energy up to 10 x
  - Pulse Intensity up to 1000 x
  - Additional laser beam

Surface phenomena: Graphene

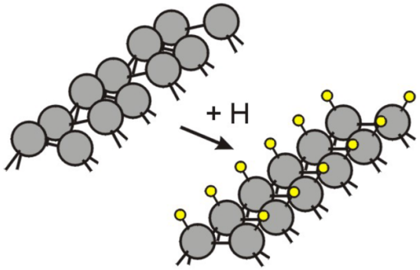
749 MeV, Pb, θ = 2°



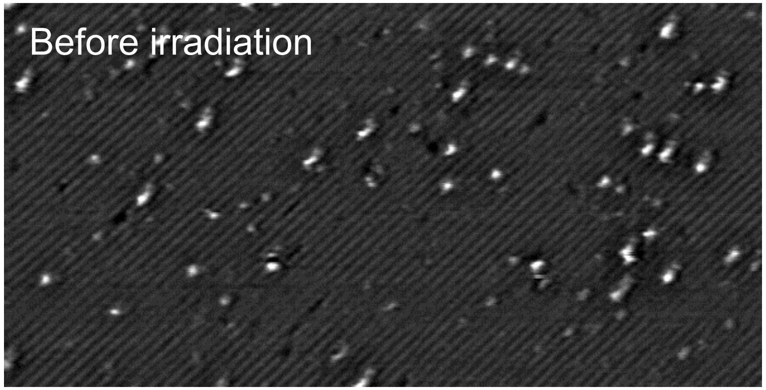


Single graphene layer on PMMA or SiO_2

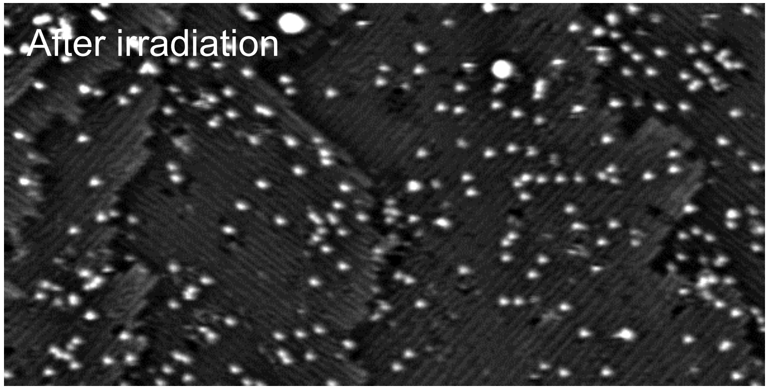
Surface phenomena: Si



Hydrogen terminated surface:
- H termination prevents from oxidation
- Preparation in M1 preparation chamber or ex-situ and transport with UHV container



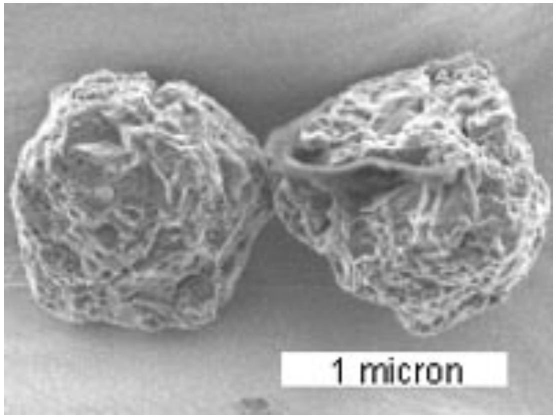
Before irradiation:
- H-terminated surface
- Some defects



After irradiation with 5e11 cm^{-2} U ions (4.8 MeV/u) under 45°:
- Additional bright features
- No change on reference sample, even though, reference sample was also in irradiation chamber
- Size of features in the order of one dimer row

Surface phenomena: sputtering and radiolysis of astrophysical ice

- Radiation affects interstellar and solar system ice mantles
- Amorhization & compaction (H_2O)
- Radiolysis (CO, CO_2)
- Complex organic chemistry



Simple model: CO_2 ice

Surface phenomena: sputtering and radiolysis of astrophysical ice

- Radiation affects interstellar and solar system ice mantles
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- Radiolysis (CO, CO_2)
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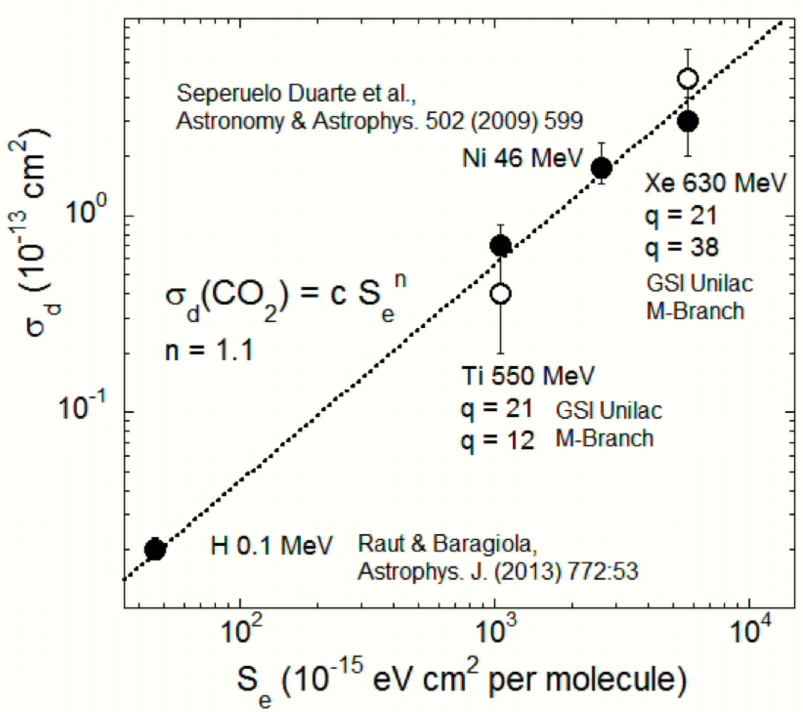
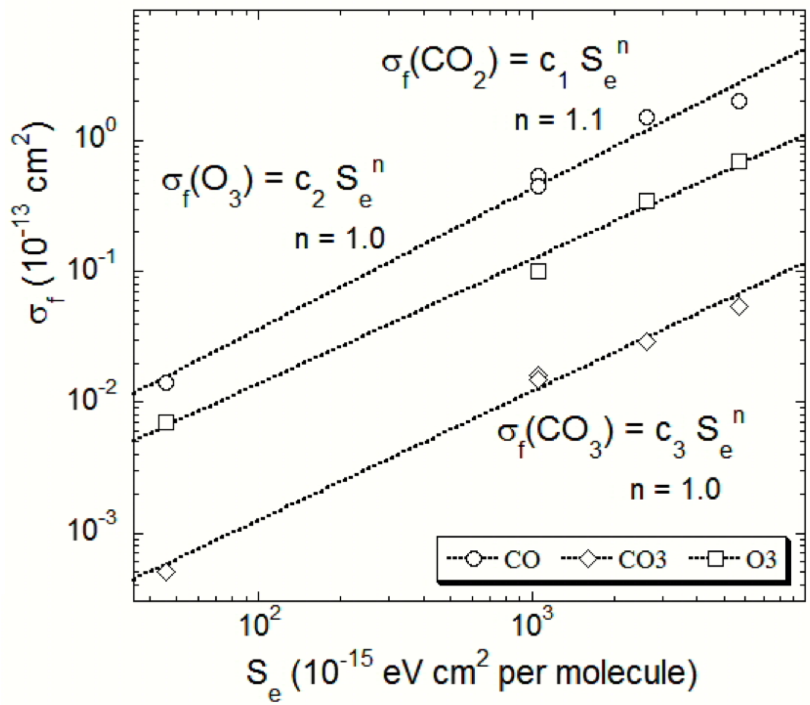
destruction cross section →



energy loss →

formation cross section →



CO

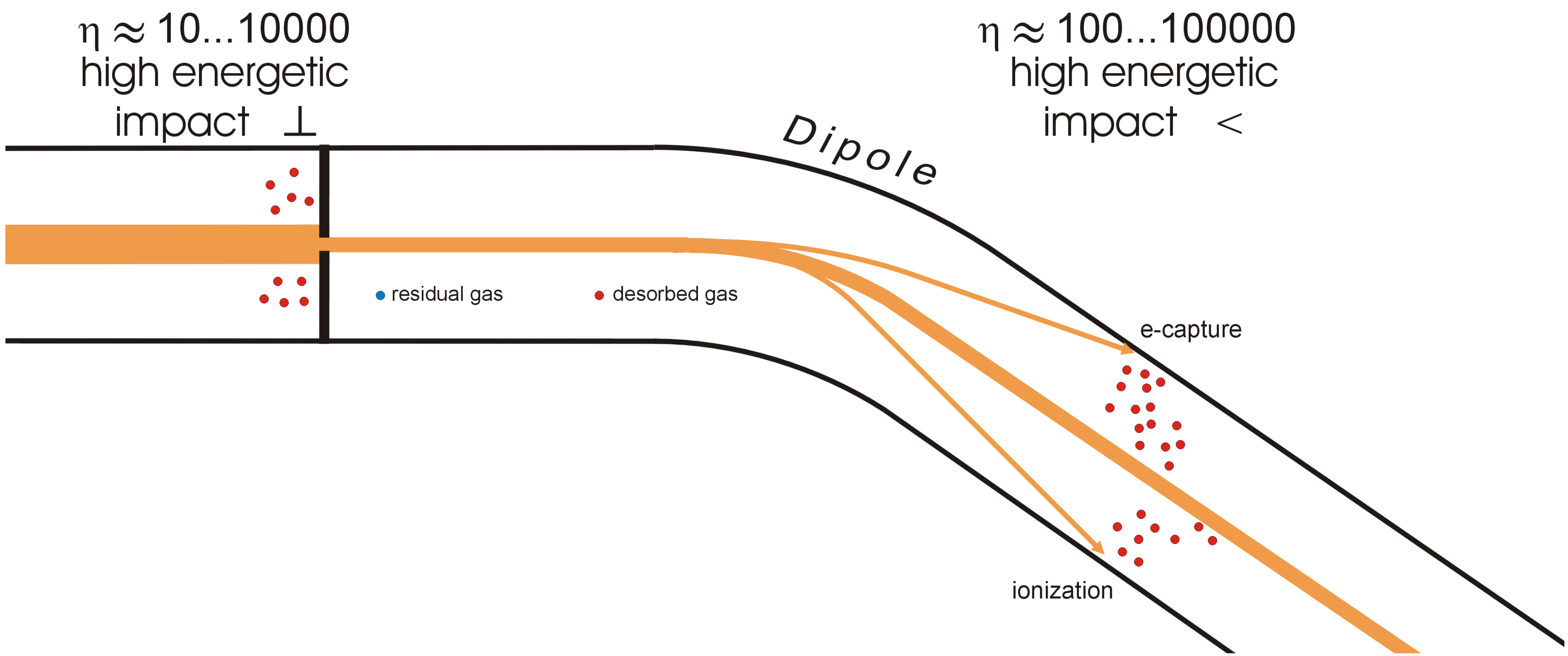
O_3

CO_3

energy loss →

Surface phenomena: gas desorption

Dynamic vacuum limits beam intensity / lifetime

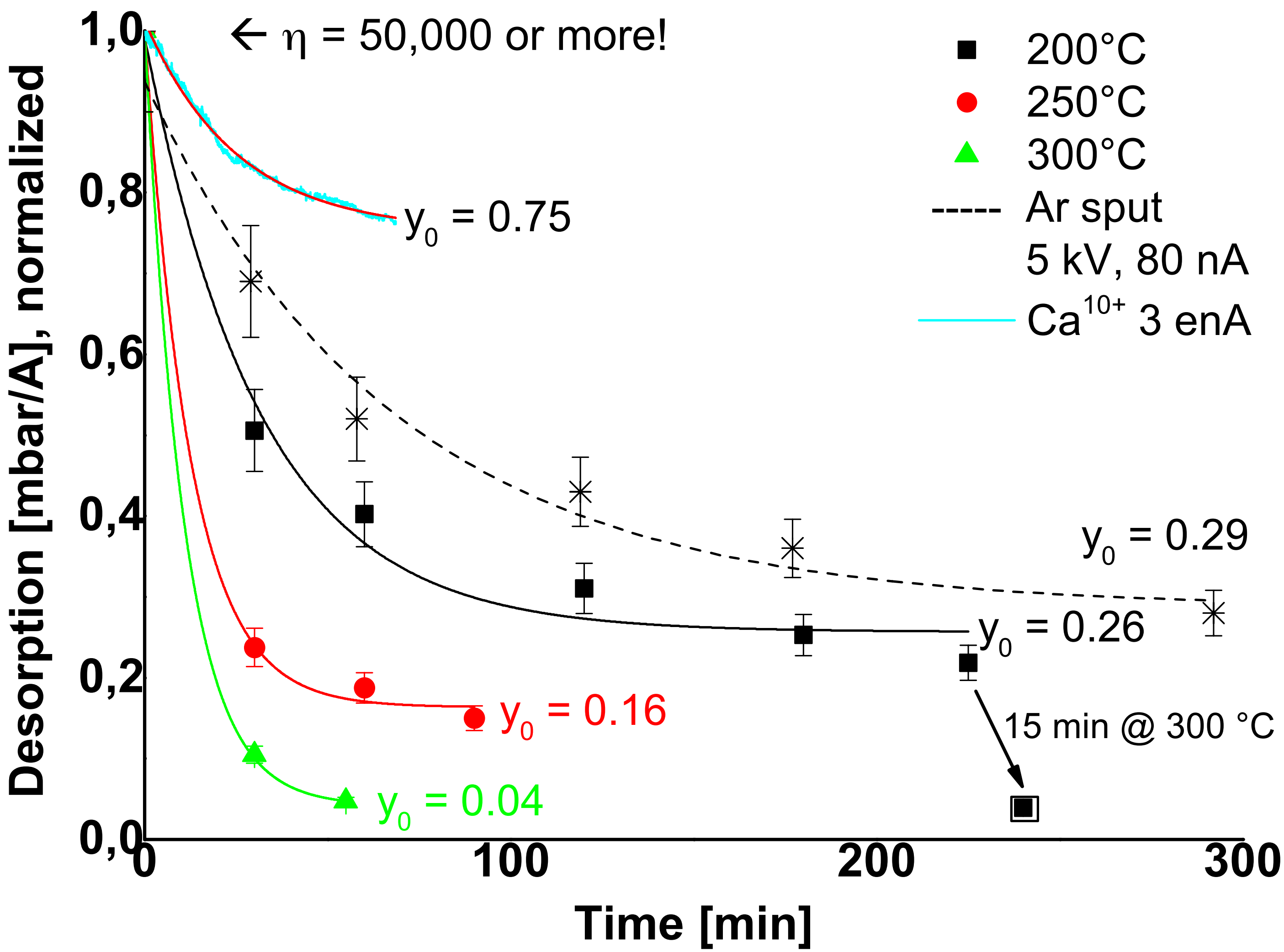


Dramatic consequences for:

- Heavy ion synchrotrons at RT (partially cured)
- Heavy ion synchrotrons and surfaces at cryo temperatures
- Production targets
- Examples: FAIR, Spiral2, HIAF

Surface phenomena: gas desorption

Target- / surface- / beam pipe-conditioning to minimize the outgassing yield



Surface phenomena: gas desorption

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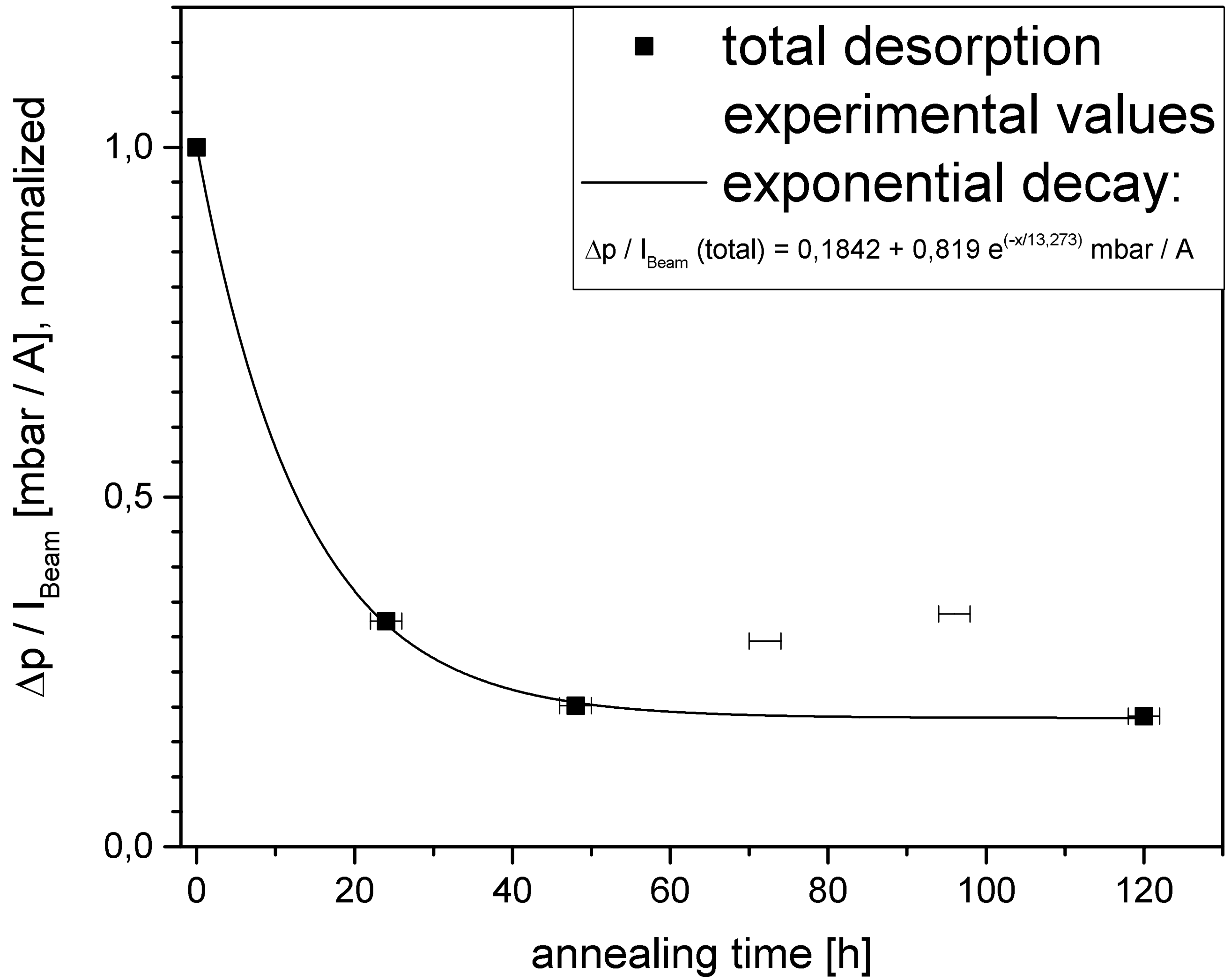

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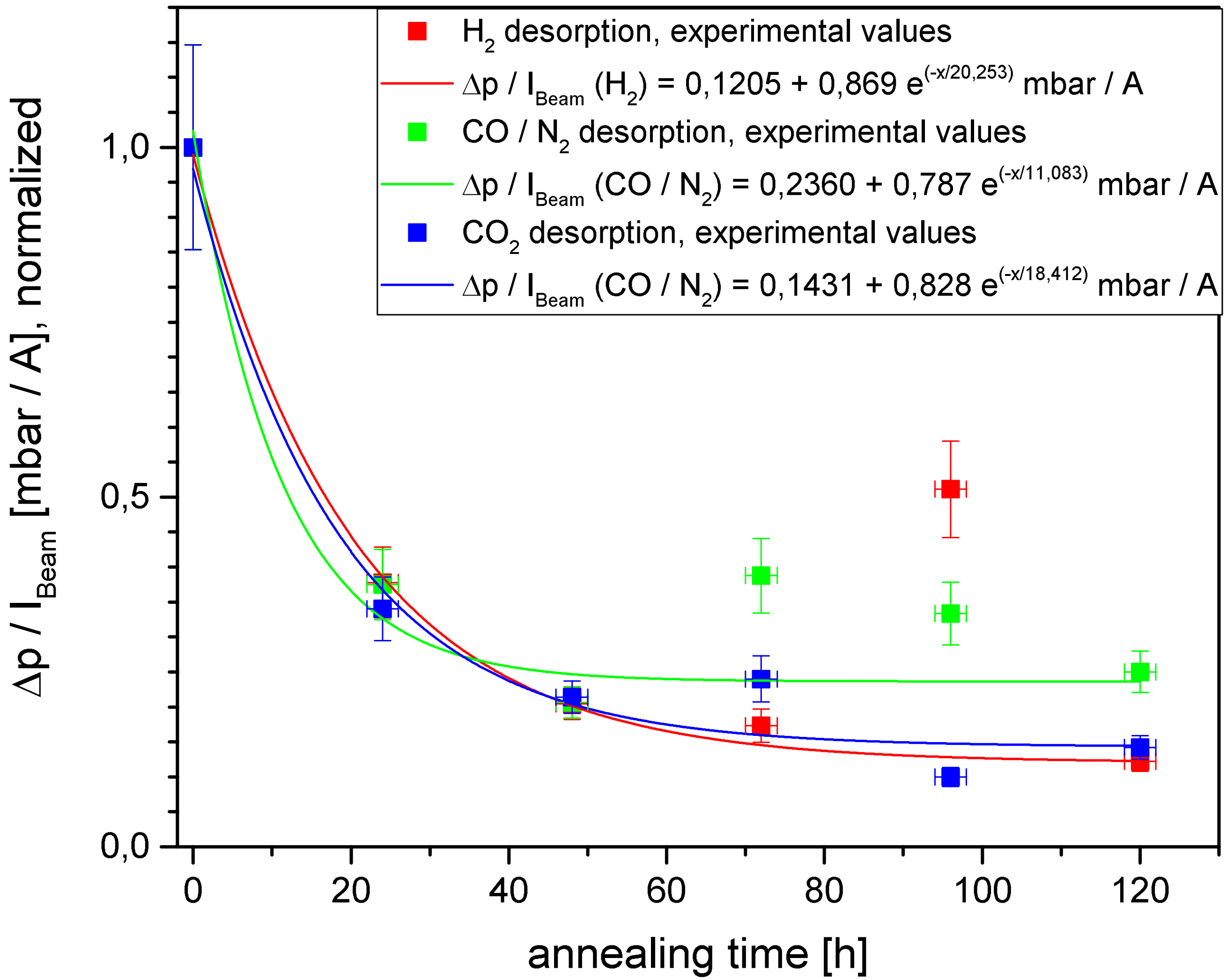

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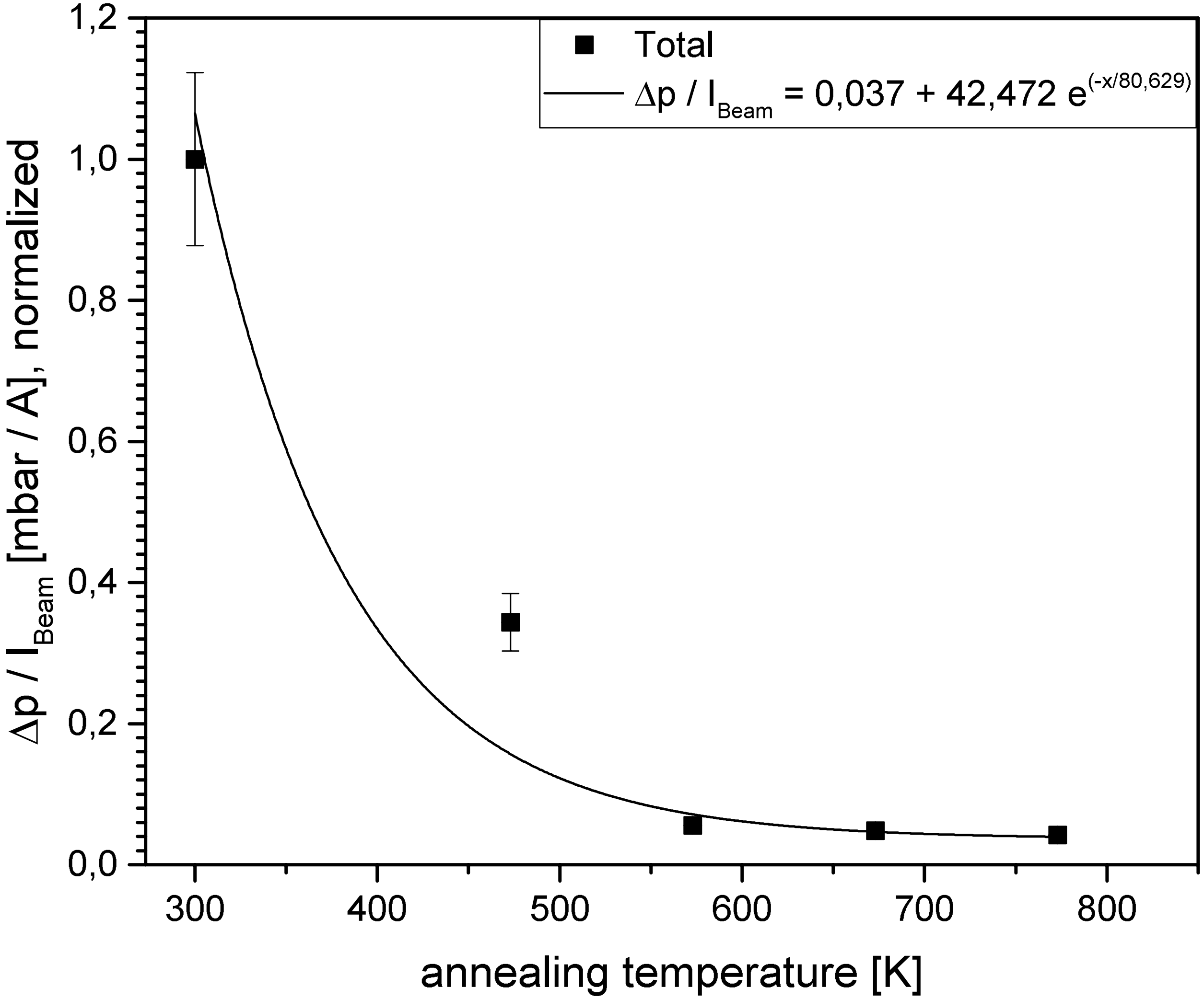

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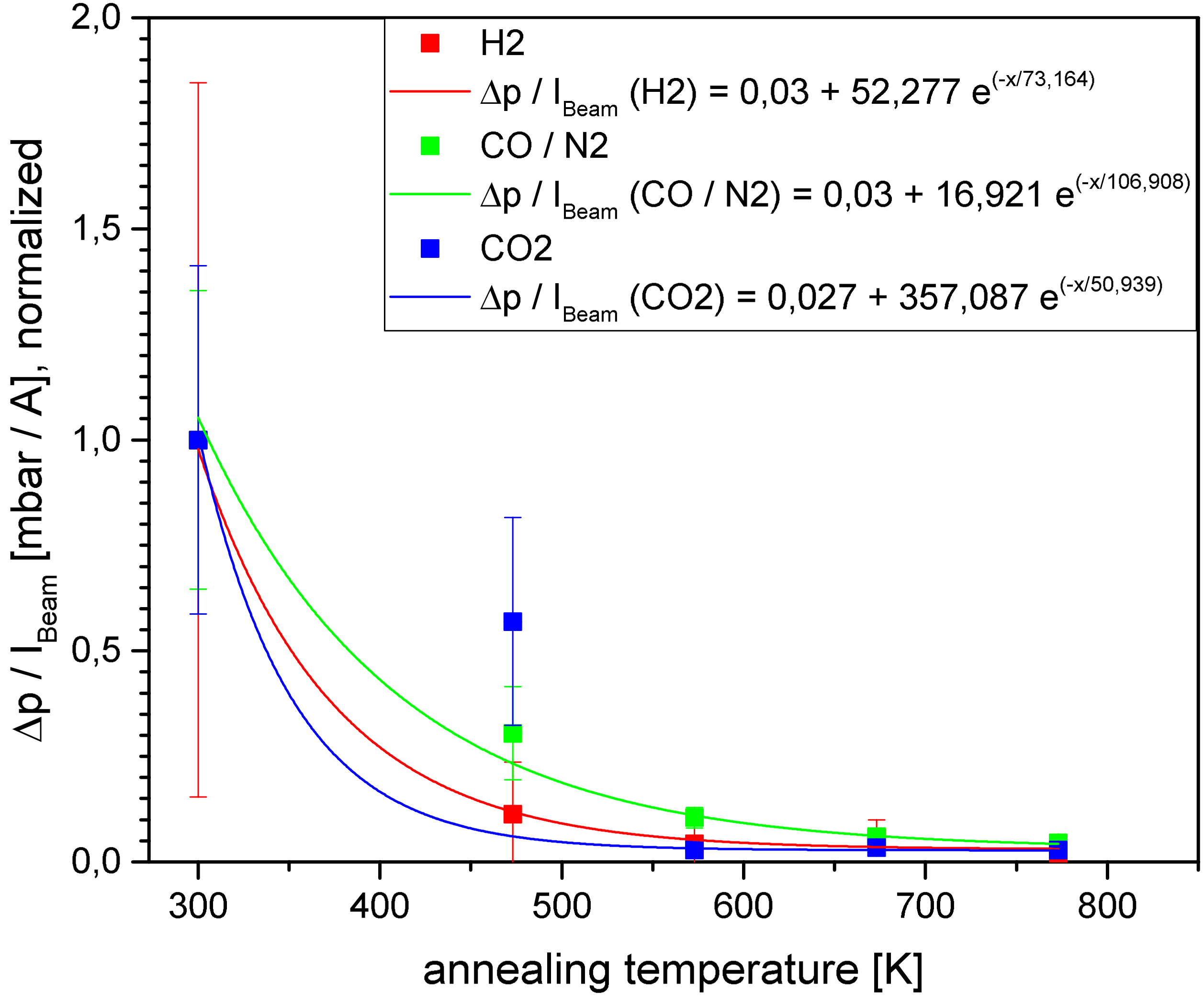
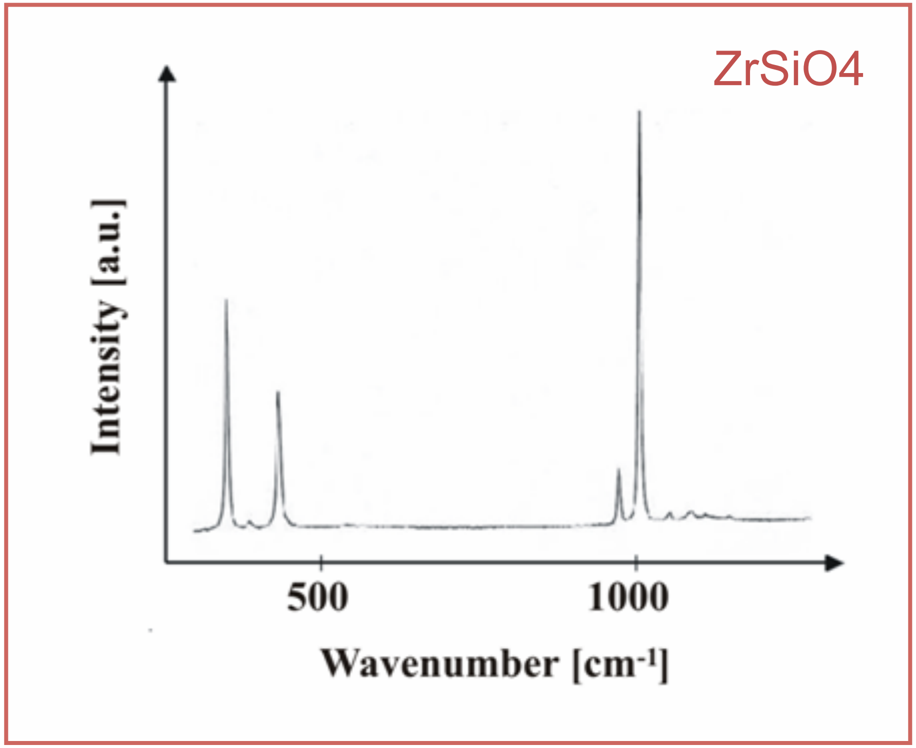


Materials under extreme conditions: opportunity

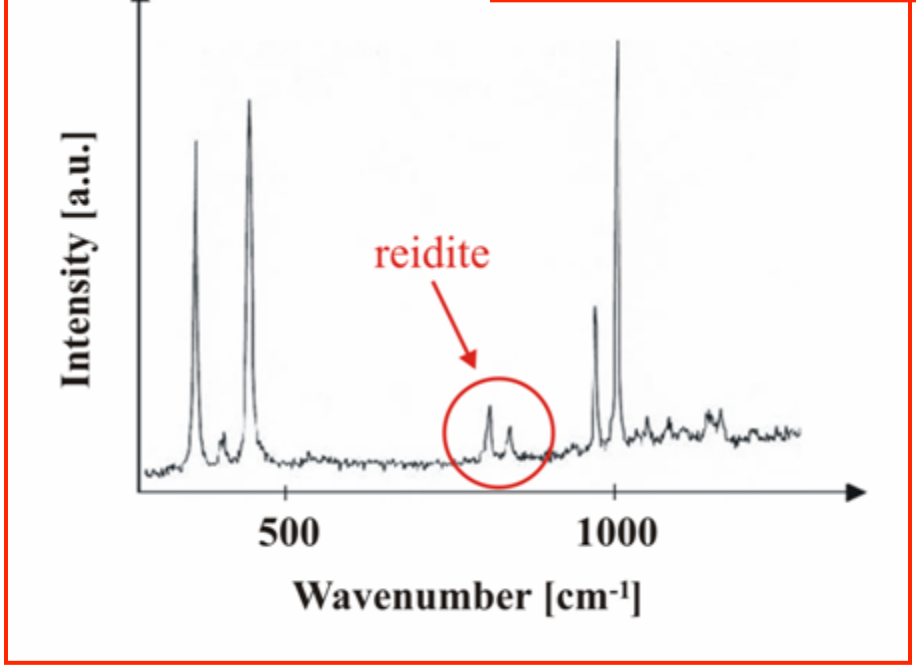
High pressure irradiation of Zircon

P = 14.2 GPa
U (E_f = 60 MeV/u)
dE/dx = 24.5 keV/nm
$2{\times}10^9$ ions/cm^2

before irradiation



after irradiation



Materials under extreme conditions: challenge

Courtesy: M. Tomut

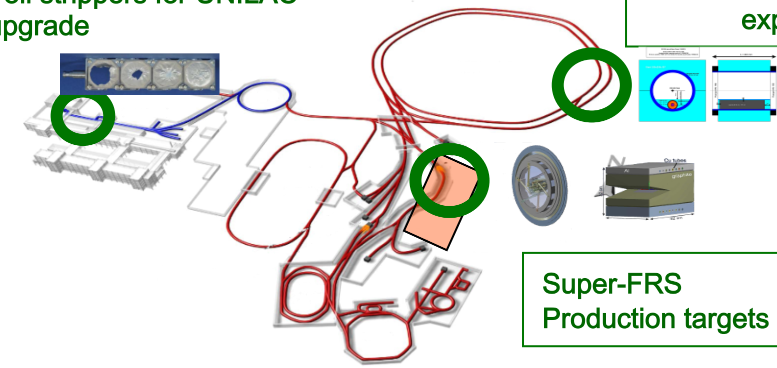
intensity of primary beam

x 100 – 1000

Intensity of future beam halo ~ existing GSI beam

Foil strippers for UNILAC upgrade

Beam dumps - SIS100 exp. caves



Super-FRS
Production targets & beam catcher

Reliability of functional properties

- dimensional stability
- mechanical stability
- fatigue
- electrical stability
- response at low/high T
- defect recovery

Lifetime of beam-exposed components

- targets, stripper foils, beam catchers
- beam dumps for experimental caves
- beam window, collimators
- diagnostic screens

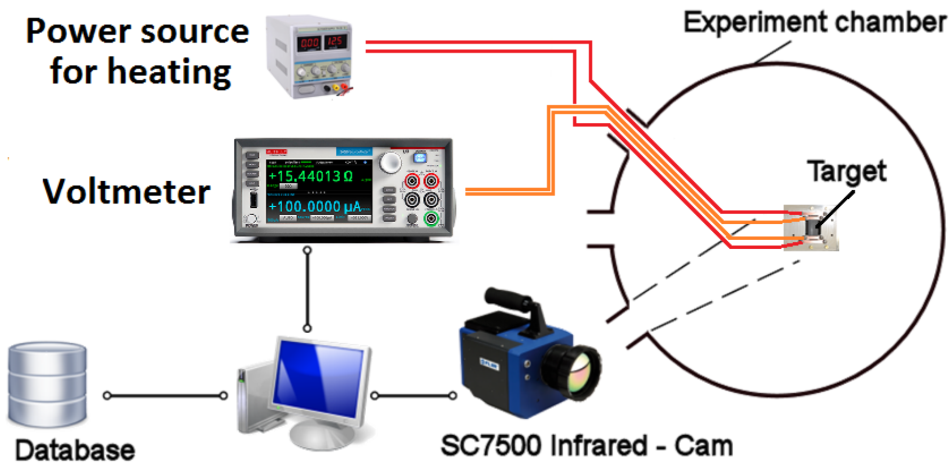
Lifetime of components seeing secondaries

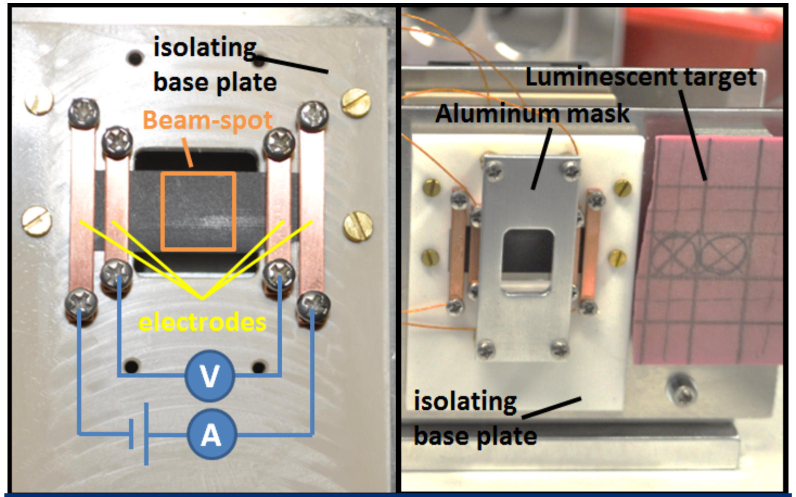
- electronics, insulators, superconducting cables, magnetic cores, permanent magnets

Materials under extreme conditions: challenge

Courtesy: M. Tomut

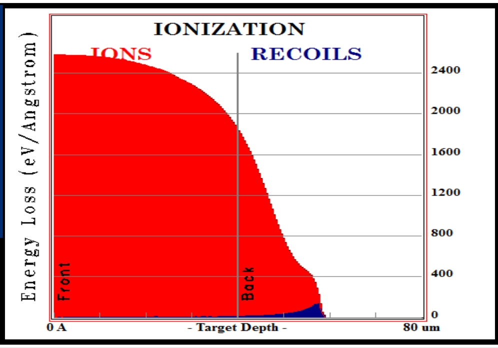
Online experiments: in situ 4-probe electrical resistivity measurements

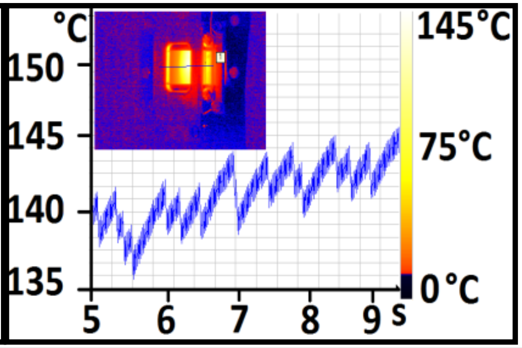




stack of 2 samples (front and back) with Al-mask

Stopping power evolution in the front and in the back samples (SRIM2013)

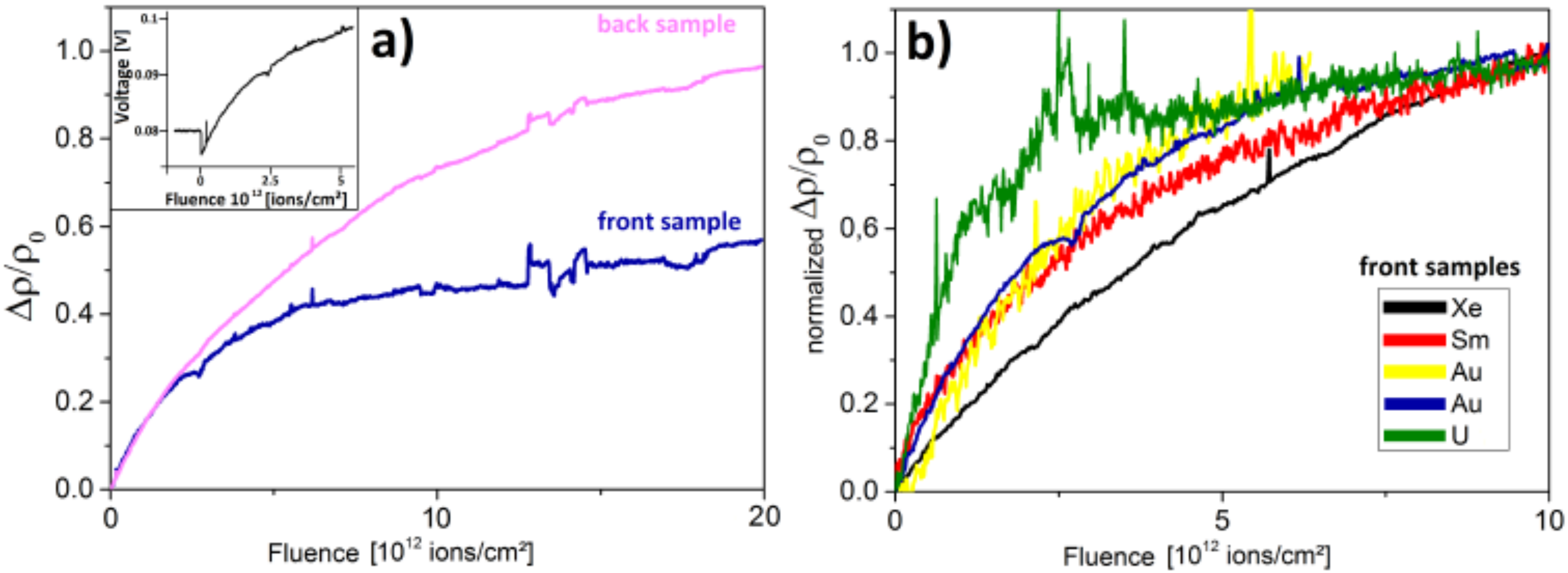




IR sample monitoring

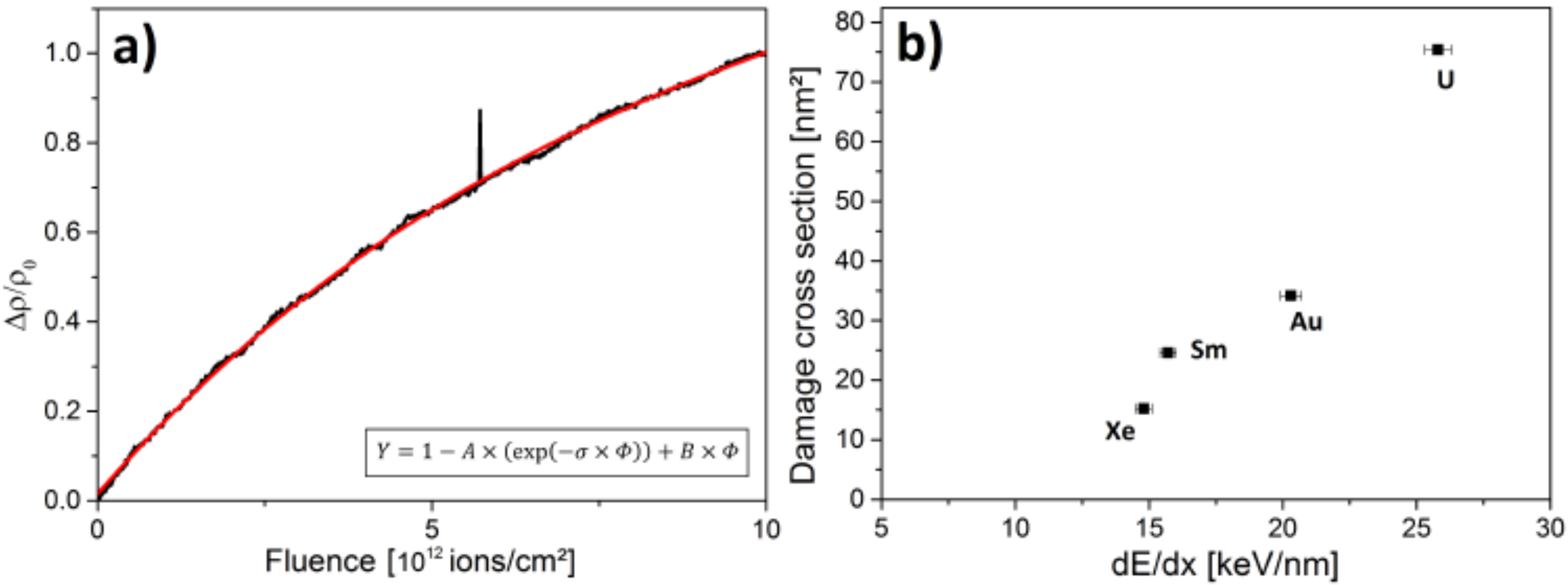
Materials under extreme conditions: challenge

Courtesy: M. Tomut



Materials under extreme conditions: challenge

Courtesy: M. Tomut

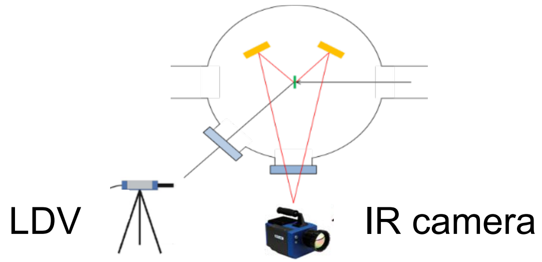


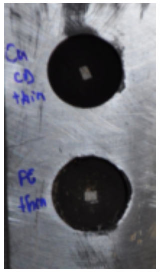
Materials under extreme conditions: challenge

Courtesy: M. Tomut

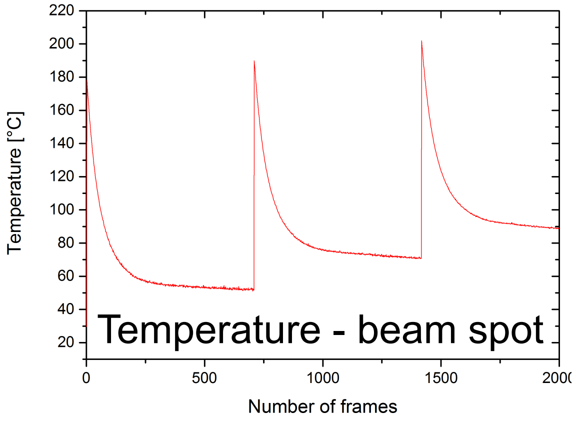
UNILAC, GSI- short pulse

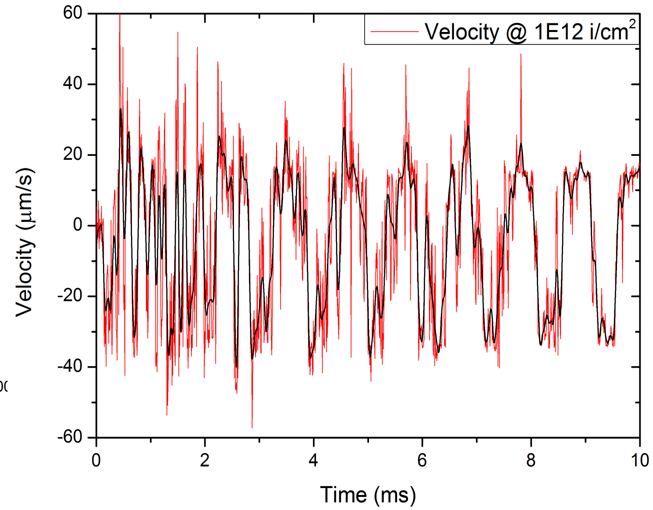
- **4.8 MeV/u U^{28+}**
- **150 µs pulse length; 1 Hz**
- **Up to 1.5×10^{10} i/cm^2 per pulse**
- **Up to fluences of 1×10^{14} i/cm^2**

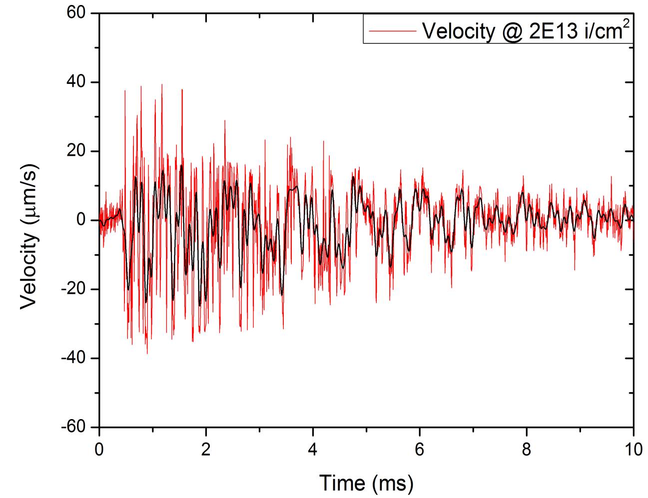




Iso-graphite response to beam-induced stress waves with radiation damage accumulation







Isotropic graphite - 140 µm

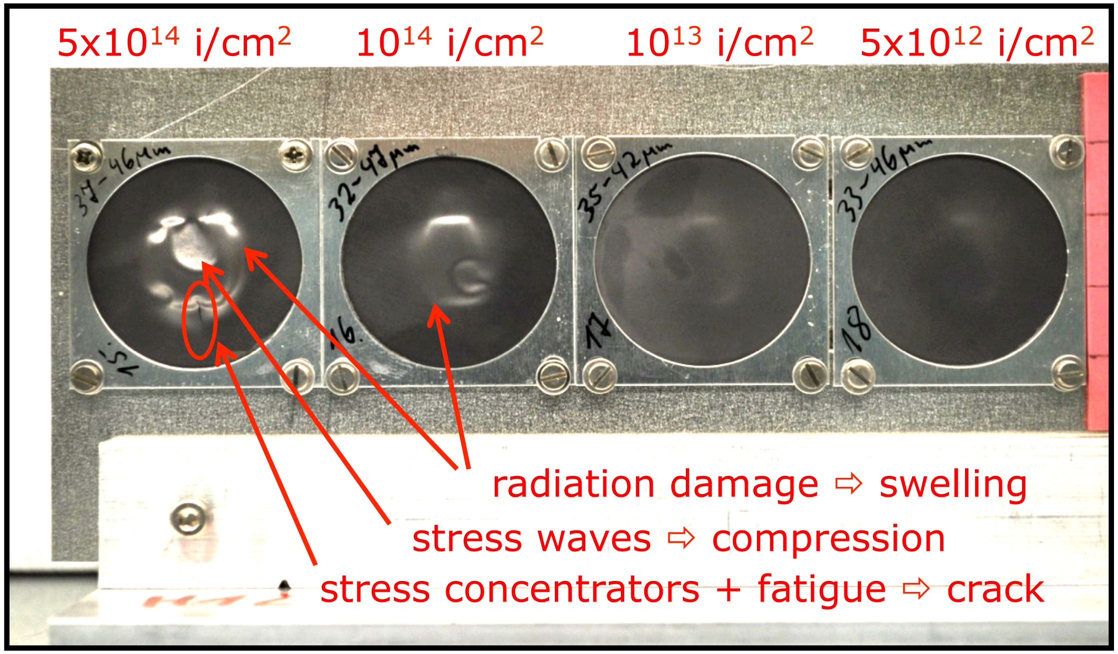
Additional reflection at irradiated / non-irradiated interface

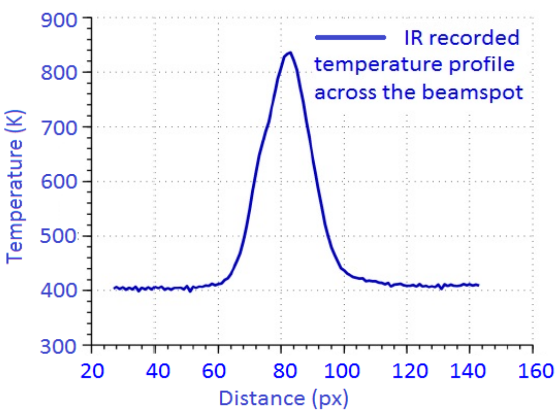
- **increase of frequency**
- **increase of damping**
- **decrease of velocity**

Materials under extreme conditions: challenge

Courtesy: M. Tomut

Experiment





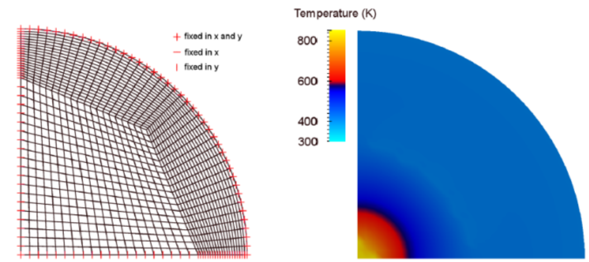
^{238}U, 4.8 MeV/u

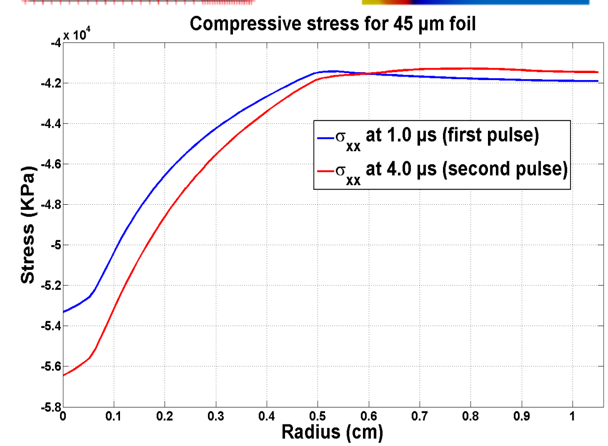
1.5 x10^{10} i/pulse

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





Experiments and results: conclusion

- Opportunities:
  - Behavior of graphene
  - Tracks in silicon
  - Astrophysical ice and dust
  - Materials under extreme conditions
  - Nano structuring, bio and electronic tests with 1 … 1e12 ions, etc…

- Challenges:
  - Vacuum instabilities
  - → develop annealing methods
  - Radiation damage with fluence or from short, high intensity pulses
  - → in situ investigations to predict life time → develop new materials
  - → development of online monitoring of damage creation

Thank you for your attention!