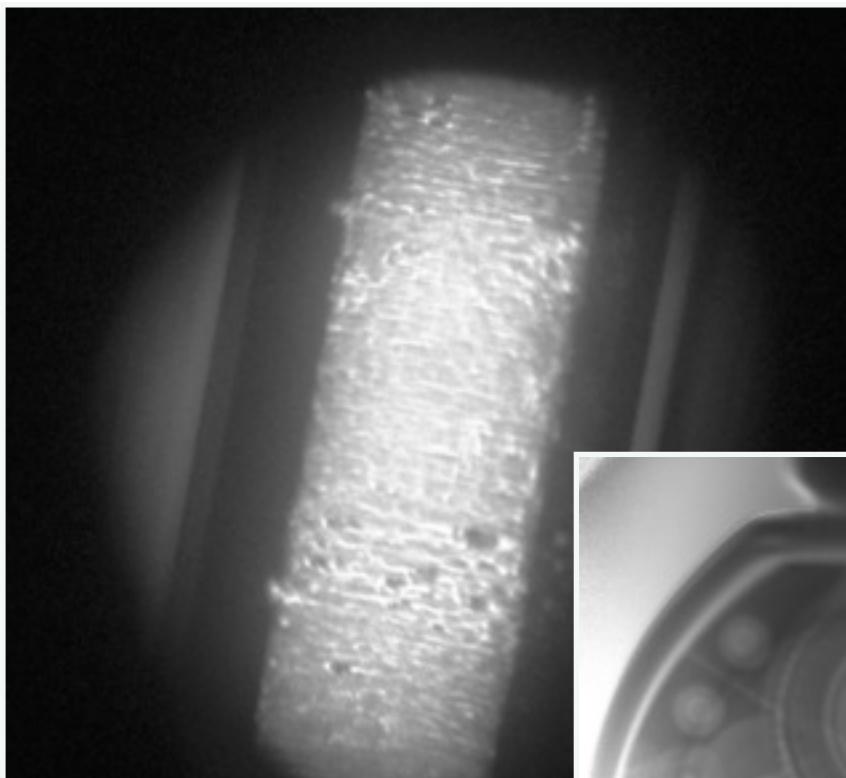
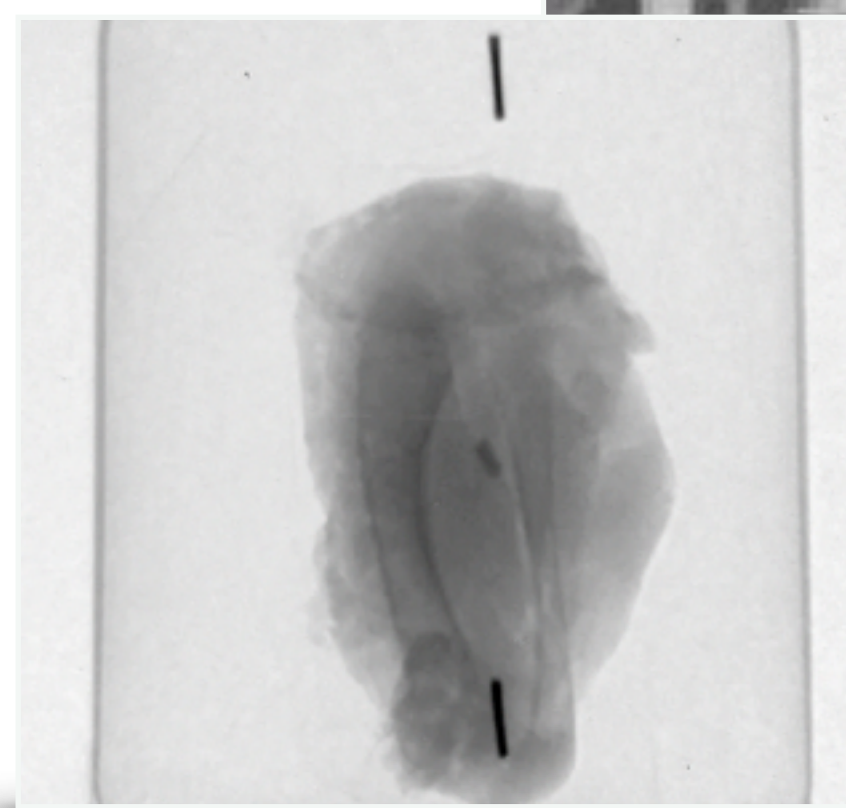
PRIOR

Proton Microscope for FAIR



Lev Shestov

GSI/TUD



FAIRNESS 2014

The HEDgeHOB collaboration:

High Energy Density Matter Generated by Heavy Ion Beams

Studies on high energy density matter with intense heavy ion and laser beams at FAIR

(officially inaugurated: June 2005)

HEDgeHOB

- >170 scientists
- 44 institutes
- 14 countries

http://hedgehob.physik.tu-darmstadt.de

HEDgeHOB experiments

HIHEX

***H**eavy **I**on **H**eating and **Ex**pansion*

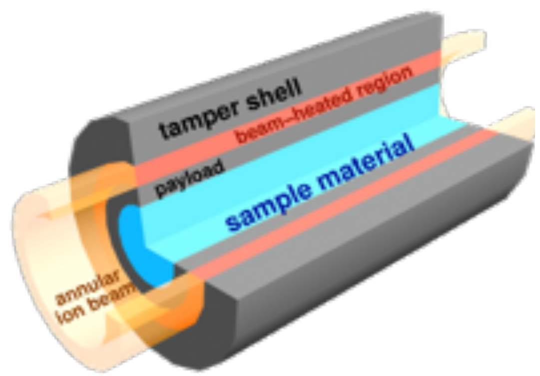
U^{28+}, 2 GeV, $5 \cdot 10^{11}$, SC FFS

- uniform quasi-isochoric heating of a large-volume dense target and isentropic expansion
- **numerous high-entropy HED states:** EOS and transport properties of non-ideal plasmas / WDM for various materials

LAPLAS

***La**boratory **Pla**netary **S**ciences*

U^{28+}, 1 GeV, $5 \cdot 10^{11}$, Wobbler

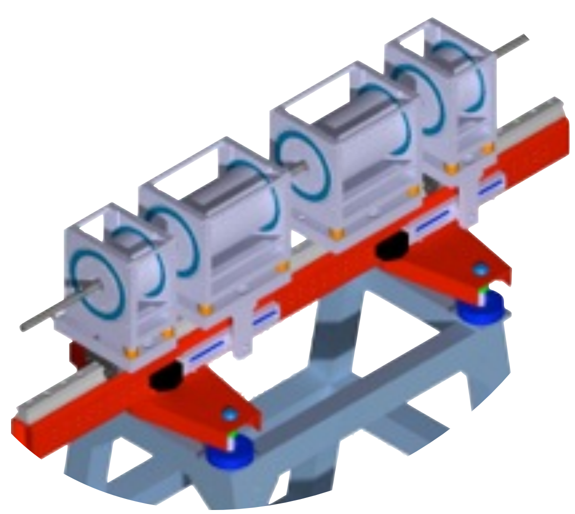


- ring-shaped beam implodes a heavy tamper shell, low-entropy compression of hydrogen
- **Mbar pressures @ moderate temperatures:** hydrogen metallization, interior of Jupiter, Saturn or Earth

PRIOR

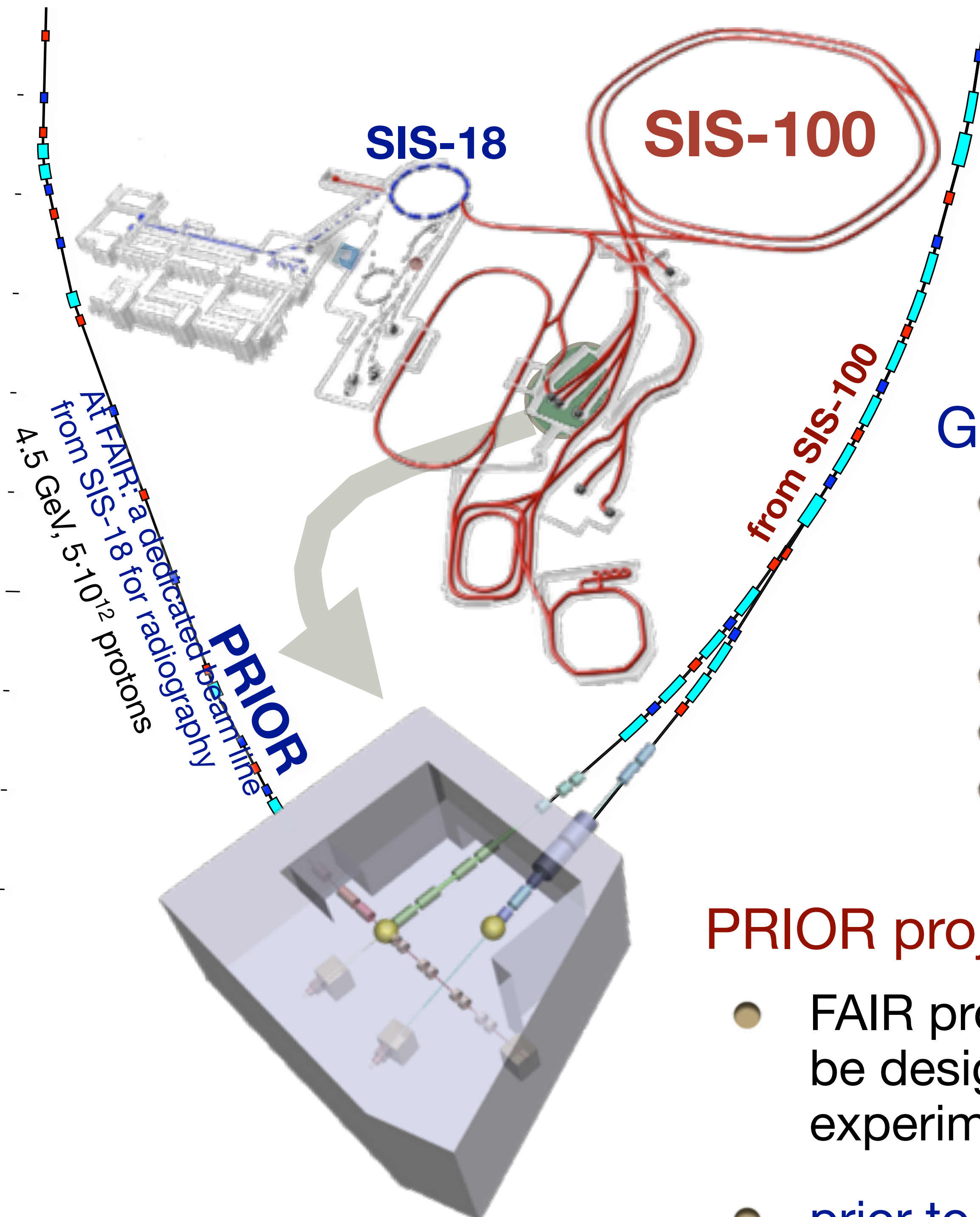
Pr**oton M**i**crosc**o**pe for FAI**R

p, 5 – 10 GeV, $2.5 \cdot 10^{13}$, PRIOR



- worldwide unique high-energy proton microscopy setup with SIS-100 proton beam
- **dynamic HEDP experiments and PaNTERA, jointly with BIOMAT collaboration:** unparalleled density distribution measurements and Proton Therapy and Radiography (PaNTERA) project

PRIOR motivation – Proton Microscope for FAIR



Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 μm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

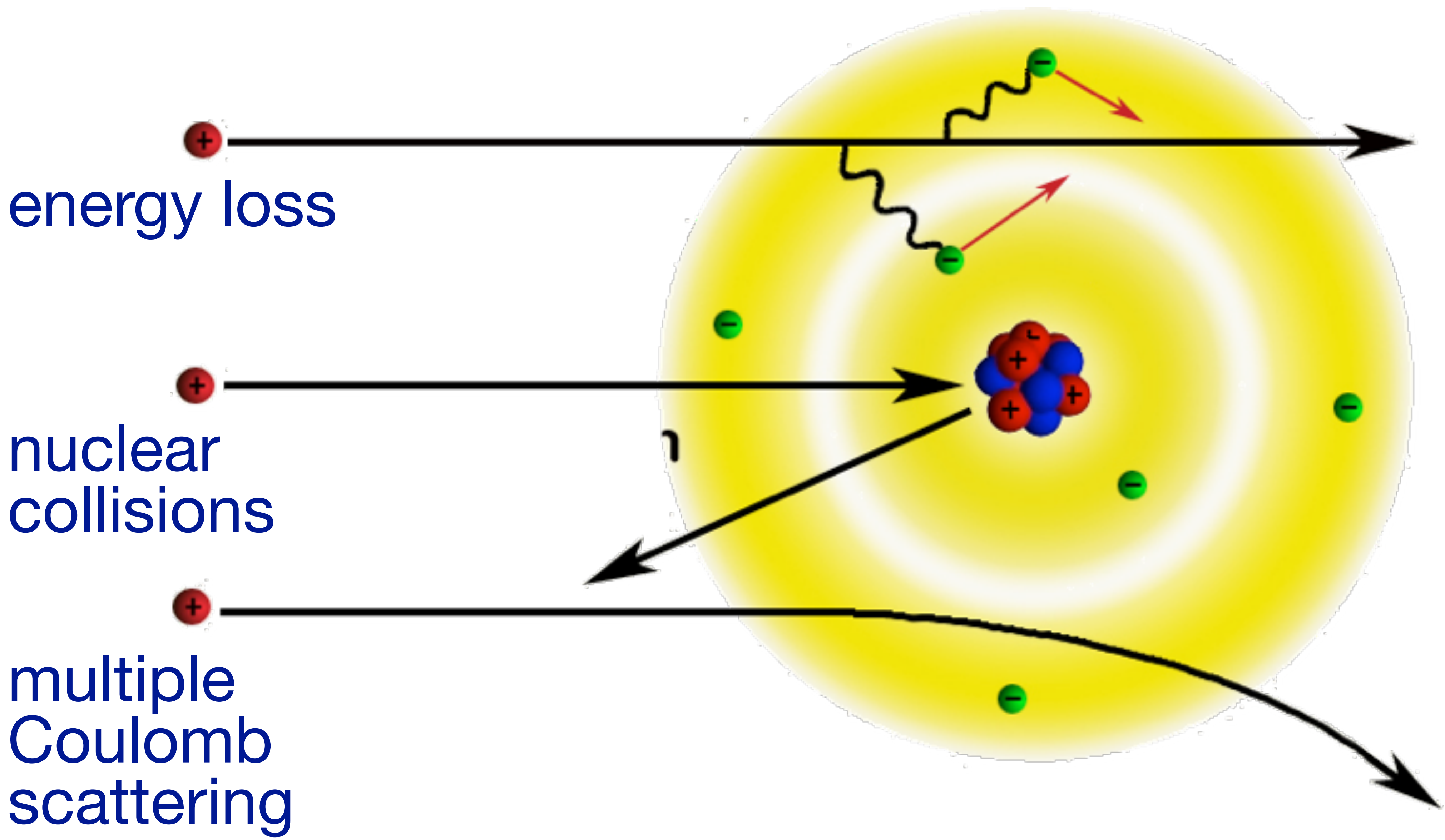
GeV protons:

- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets
- high spatial resolution (microscopy)
- high density resolution and dynamic range
- multi-frame capability for fast dynamic events

PRIOR project will accomplish two main tasks:

- FAIR proton radiography system which a core FAIR installation will be designed, constructed and commissioned in full-scale dynamic experiments with 10 GeV proton beam from SIS-100
- prior to FAIR, a worldwide unique radiographic facility will become operational at GSI providing a capability for unparalleled high-precision experiments in plasma physics, high energy density physics, biophysics, and materials research

High energy proton interactions for radiography



Early proton radiography: known since 1960s

M.A. Koehler et al., Science 160 (**1968**) 303

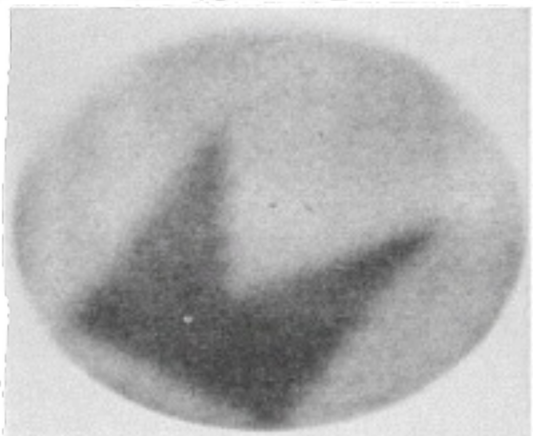


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035-g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the film.

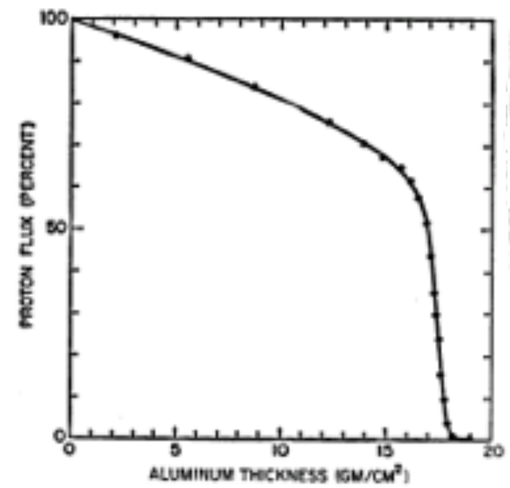


Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm² is used to obtain the high contrast of Fig. 1.

Marginal range radiography

- reduce proton energy to near end of range
- use steep portion of transmission curve to enhance sensitivity to areal density variations
- contrast generated through proton absorption (stopping)
- Coulomb scattering at low energy results in poor resolution > 1.5 mm
- poor density reconstruction and small dynamic range

J.A. Cookson, Naturwissenschaften 61 (**1974**), 184-191

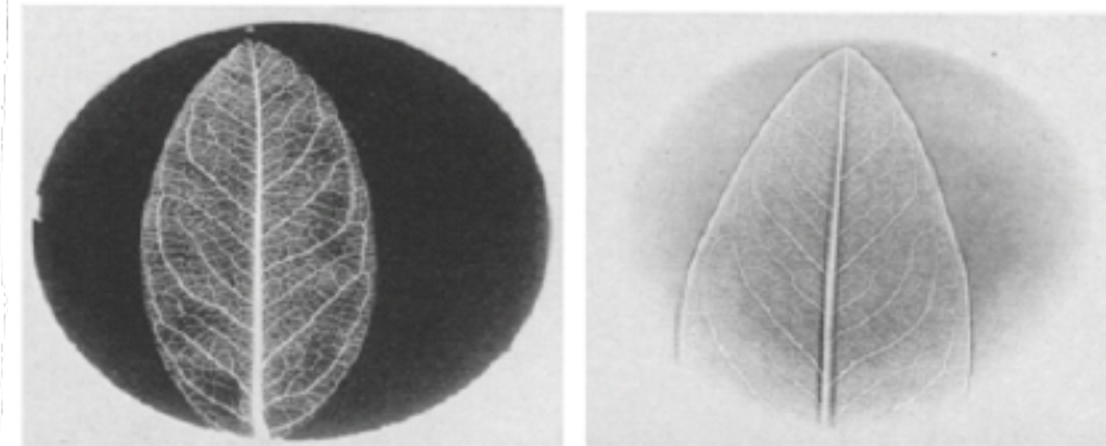


Fig. 6a and b. Radiographs of leaves by a) marginal range radiography with 196 mg/cm² of extra Al absorber, and b) scattering radiography with leaf sandwiched between two 6.9 mg/cm² Al layers and 14 mm from the film

Scattering radiography

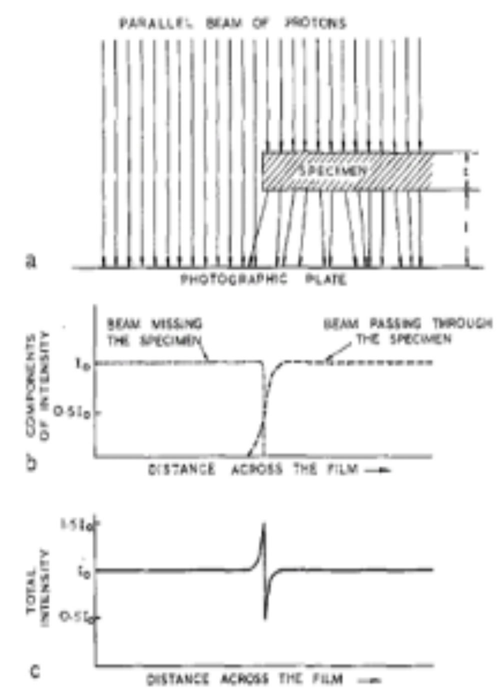
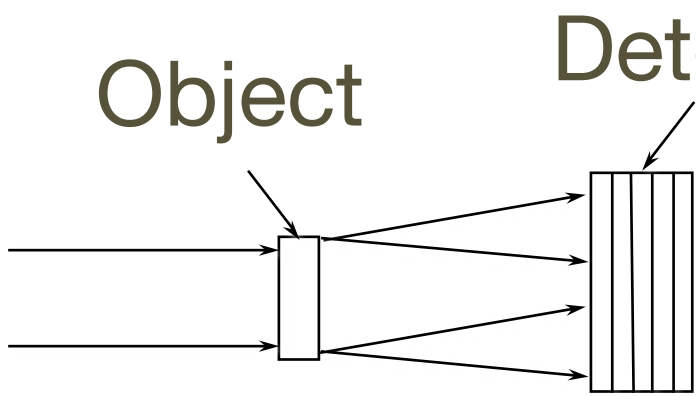


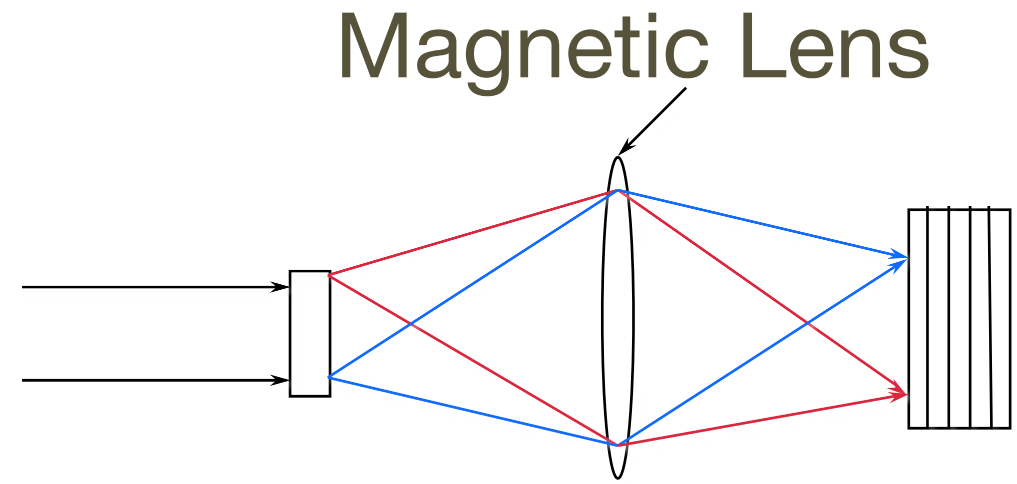
Fig. 7. Illustration of how multiple scattering produces characteristic edge pattern

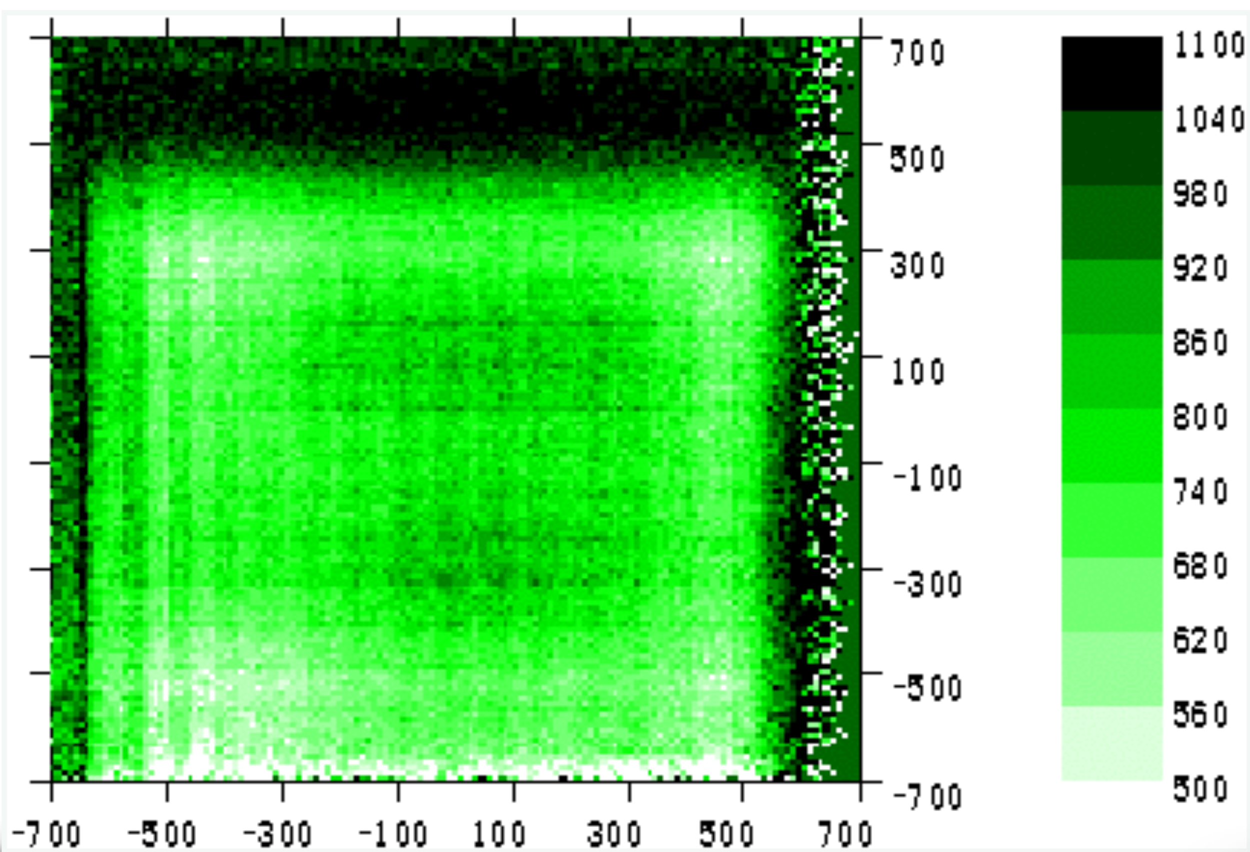
- similar to phase contrast imaging
- contract through position dependent scattering
- very sensitive for identifying boundaries within thin objects
- edge detection only (no density reconstruction)
- limited to thin objects

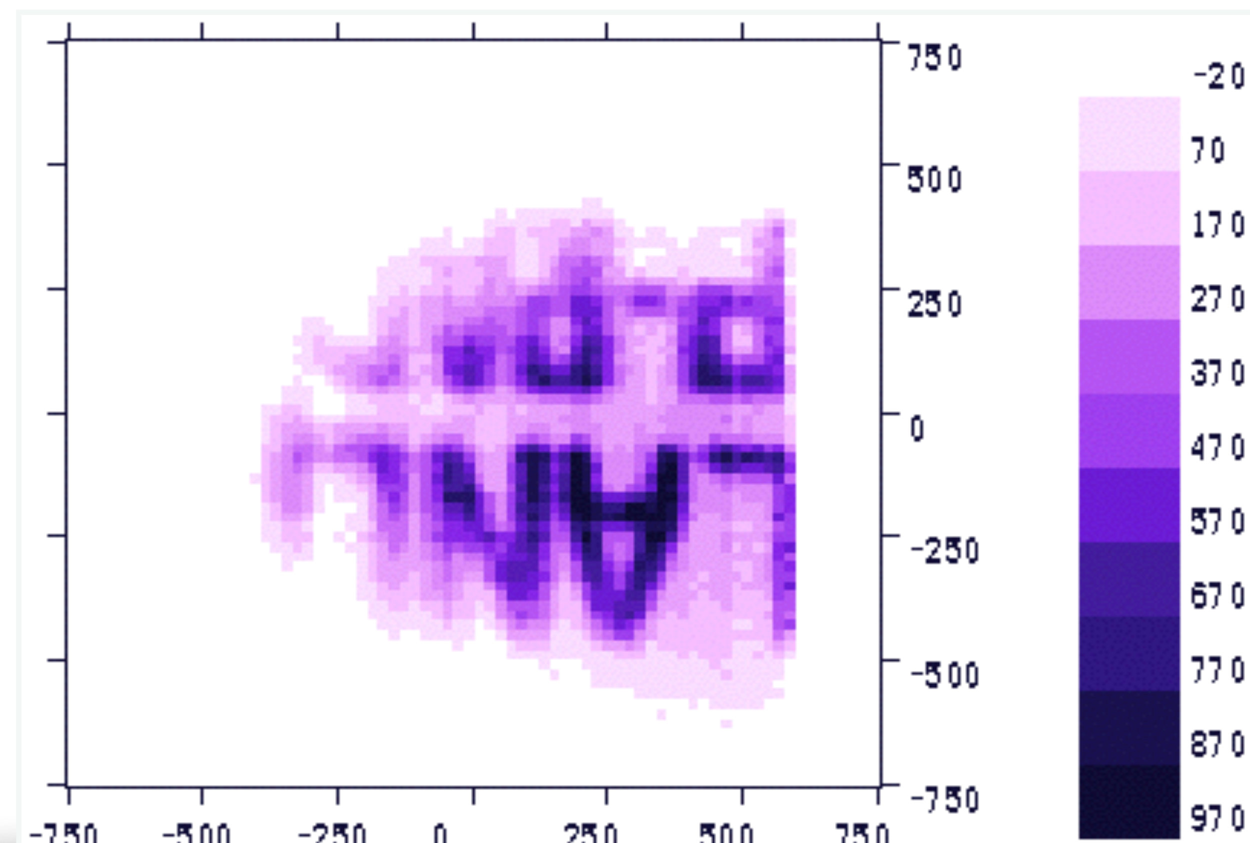
Transmission radiography with magnetic lens (LANL, 1995)

188 MeV secondary proton beam line at LANSCE





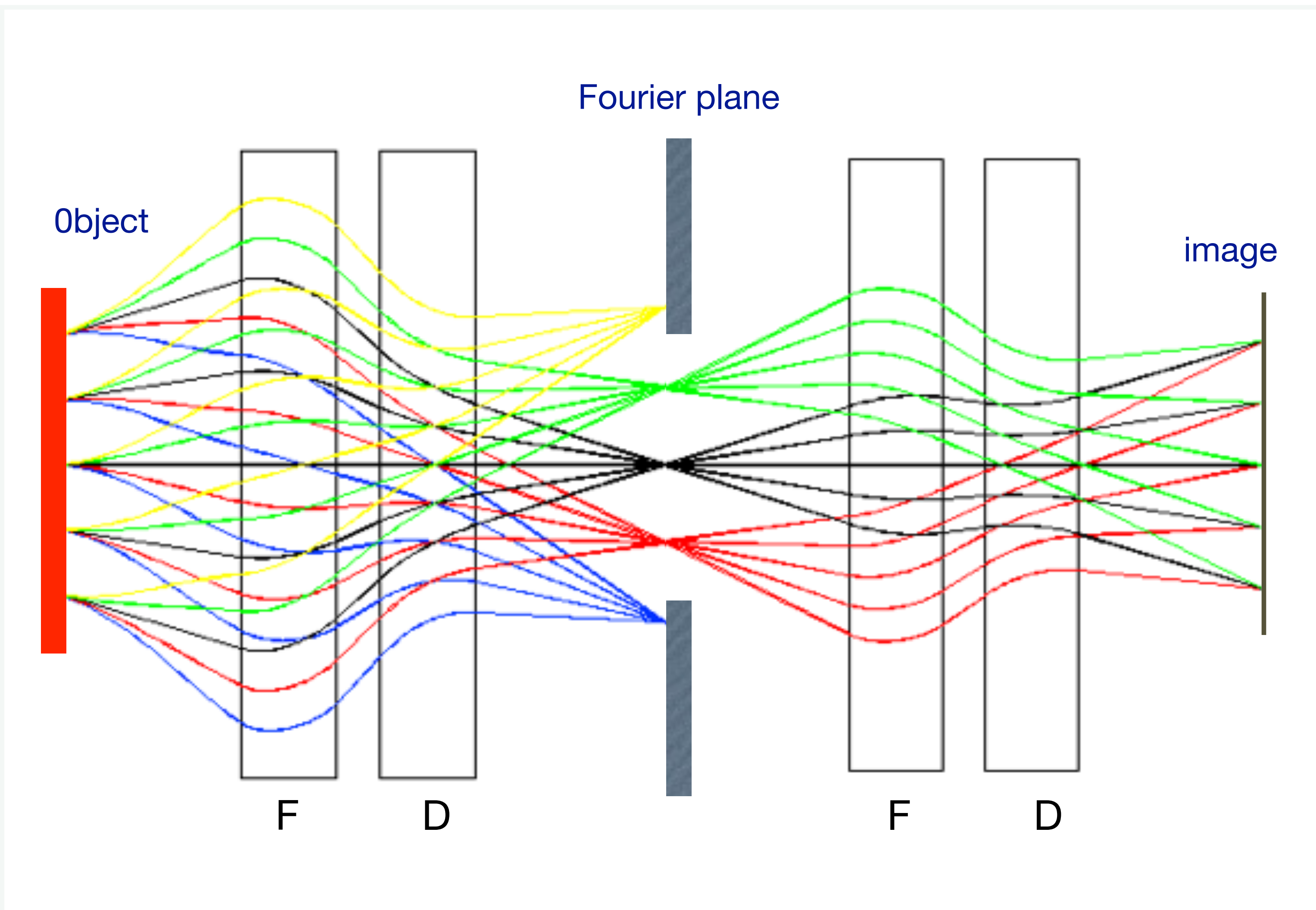




- image at the detector is substantially blurred due to MCS
- magnetic imaging lens preserves image with high resolution

Nowadays imaging is done with more sophisticated lenses

Quadrupole Identity Lens (Russian Quadruplet): imaging and correcting chromatic aberrations



- stigmatic imaging lens
- initial beam is matched to have certain position-angle correlation
- same position-angle correlation which forms a Fourier plane

$$\Delta x \propto C_x \cdot \theta_c \cdot \delta E(\ell)$$

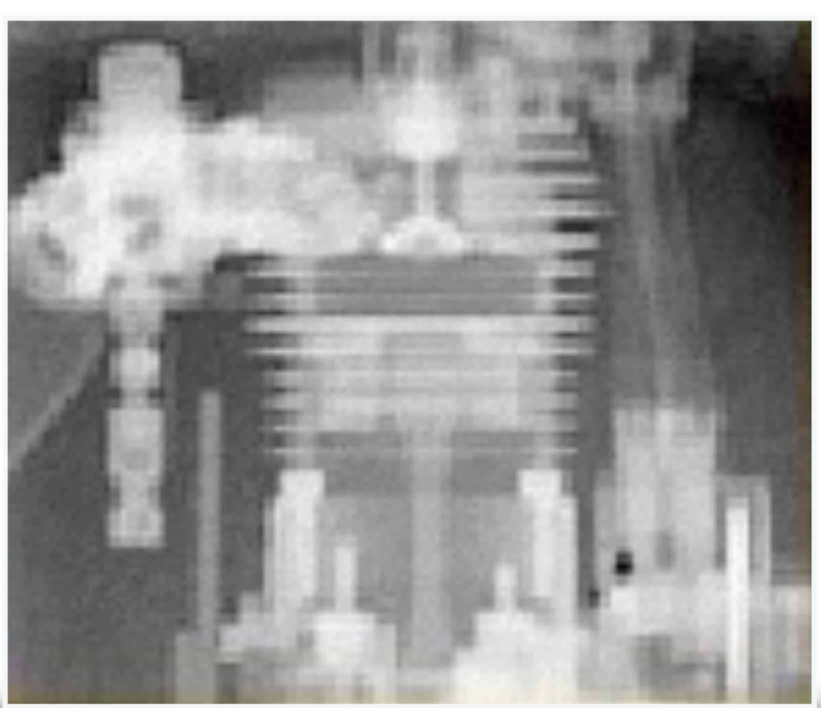
Advantages of proton radiography (vs X-rays)

- (magnetic) lenses for imaging and aberration correction
- high resolution and dynamic range to both density and material composition
- better signal-to-noise ratio and detection efficiency
- higher penetrating depth (thick targets: 800 MeV p ⟷ 5 MeV X-rays)
- multi-frame capability

photo

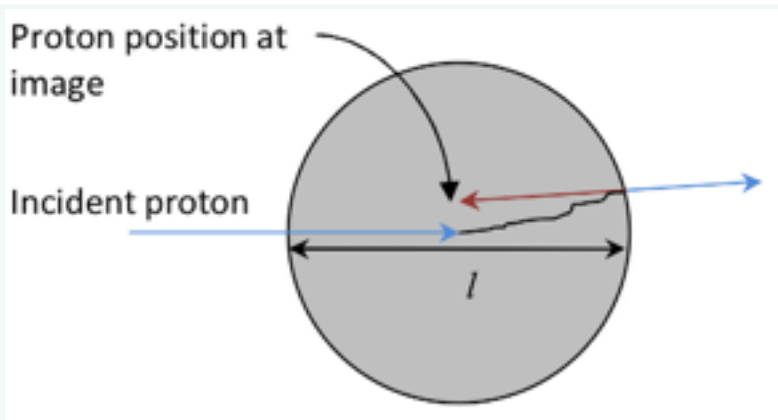
100 keV X-rays

800 MeV protons



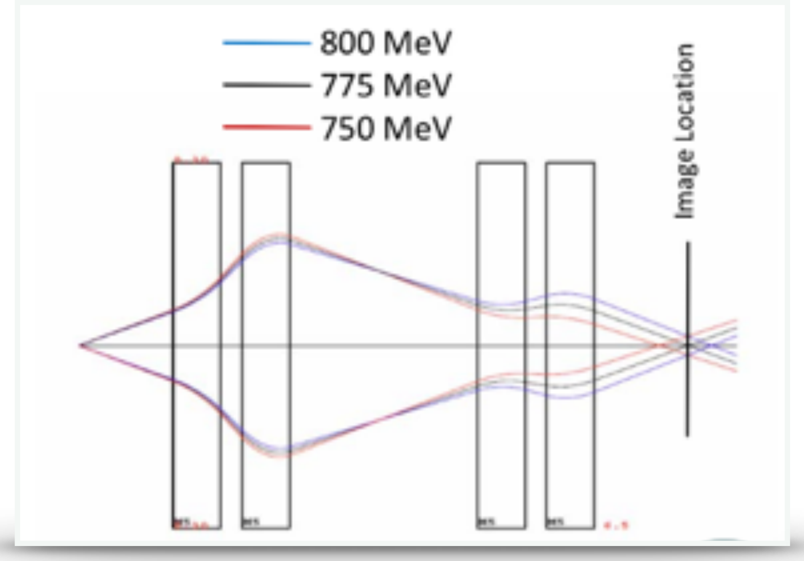
There are three resolution limitation of proton radiography

Object scattering



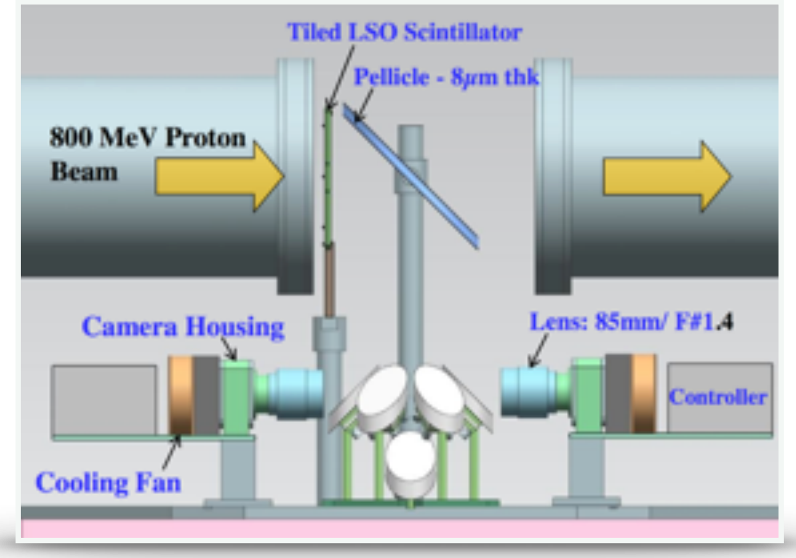
- introduced as the protons are scattered while transversing the object
- increase proton energy
- reduce the amount of material downstream the object

Chromatic aberrations



- introduced as the protons pass through the magnetic lens imaging system
- the dynamic range is often limited by energy loss rather than object thickness
- increase proton energy

Detector blur

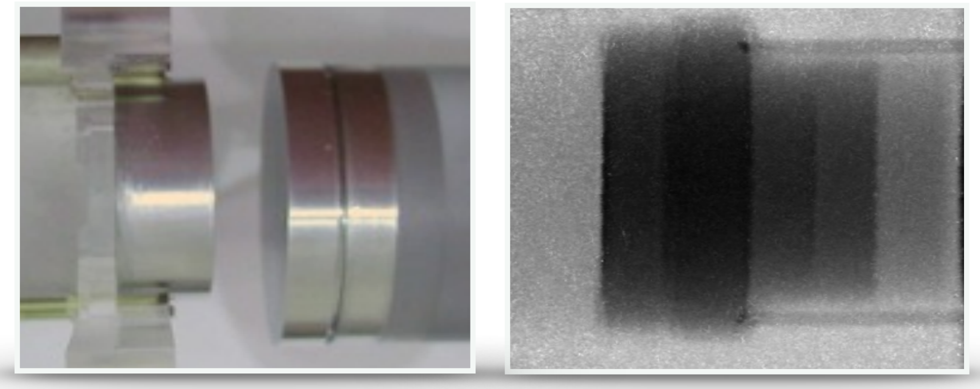


- introduced as the proton interacts with the proton-to-light converter and as light is collected with a camera system
- increase proton energy
- increase number of pixels, light collection efficiency, search for proper scintillators

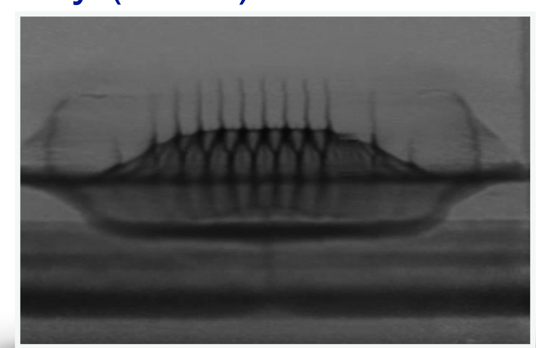
Proton microscopy for HEDP, material sciences and beyond

- **materials in extremes** (EOS, dynamic phase transitions, hydrodynamics of HED flows, instabilities, material strength and damage, ...)
- **new materials synthesis and process-aware manufacturing**
- **industrial applications**
- **biophysics, medical applications**

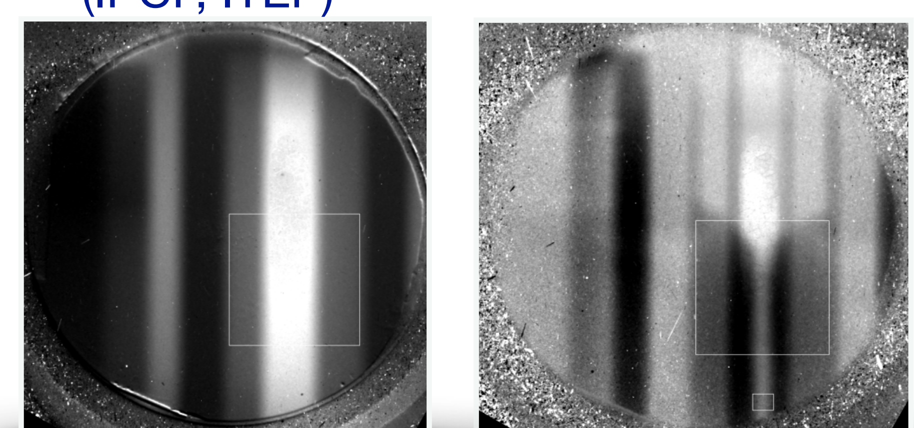
Al EOS in a shock wave experiment by proton radiography (LANL)



Experiments on Richtmyer-Meshkov instability (LANL)



Phase transition of molecular nitrogen (IPCP, ITEP)



Current proton radiography / microscopy:
~ 50 – 200 μm resolution
macro- and in some cases mesoscopic studies

≤ 10 μm resolution:
introduction of microstructural and microkinetic studies

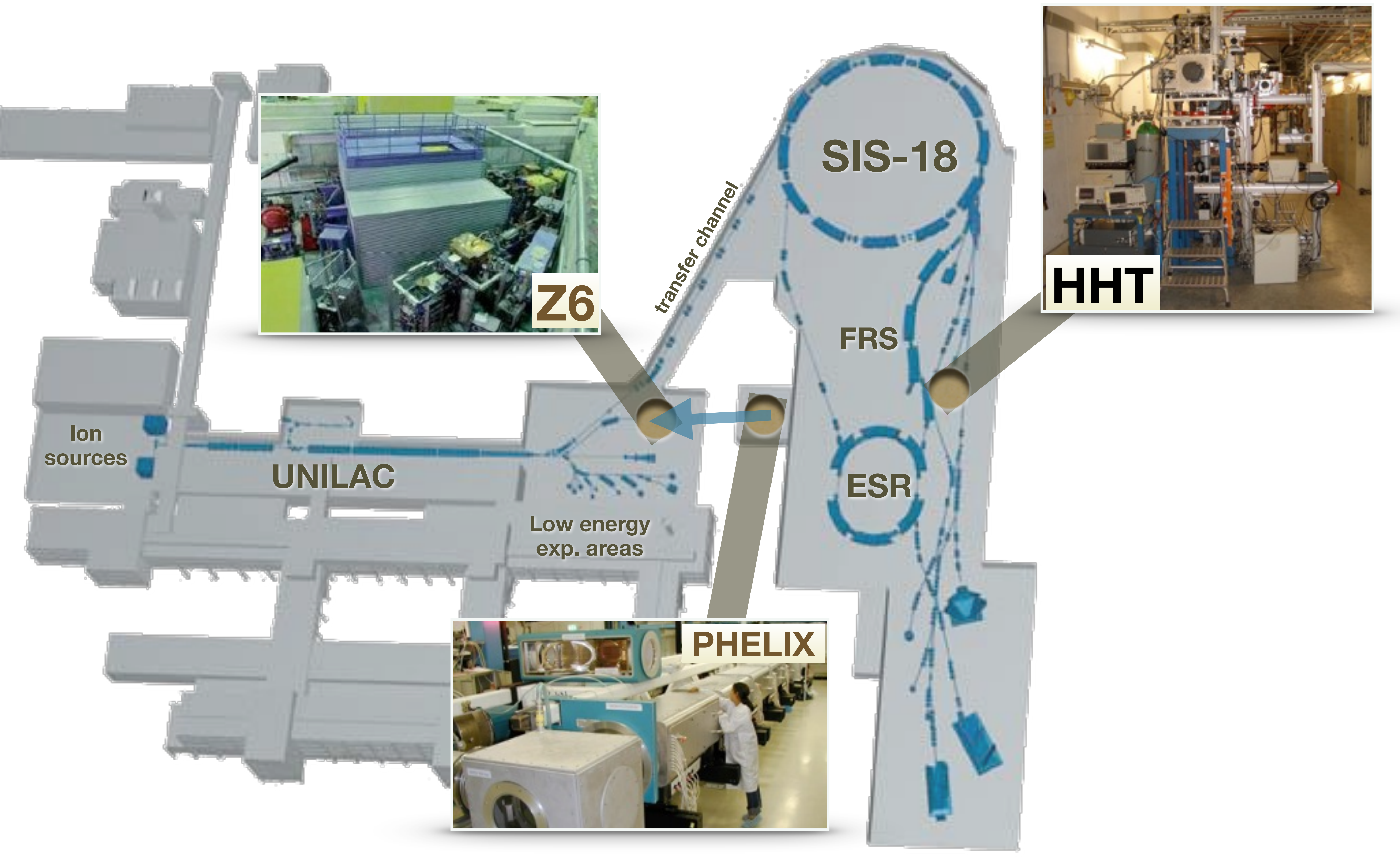
≤ 1 μm resolution:
full-scale microscopic studies

pRad (LANL),
PUMA (ITEP)
800 MeV

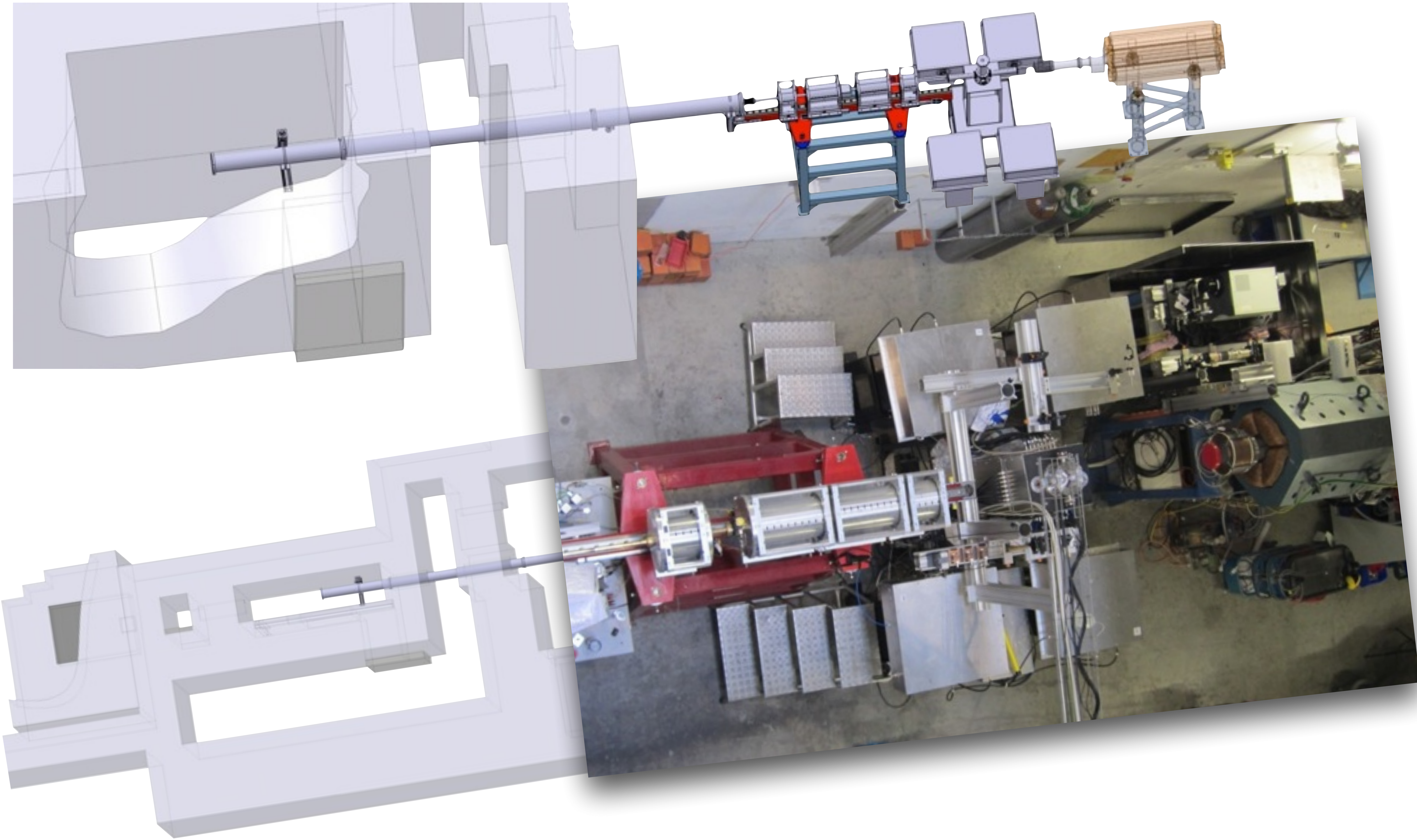
PRIOR
(GSI)
4.5 GeV

PRIOR
(FAIR)
10 GeV

Plasma physics experimental areas at GSI



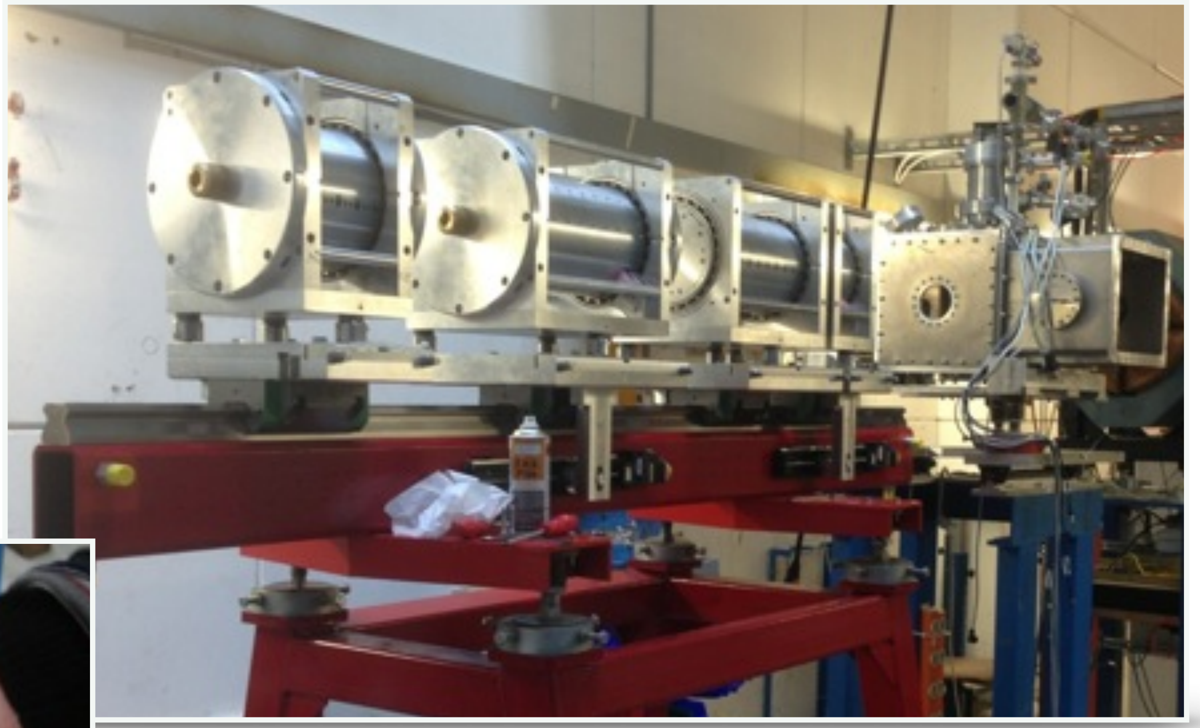
Fielding at the HHT experimental area of GSI

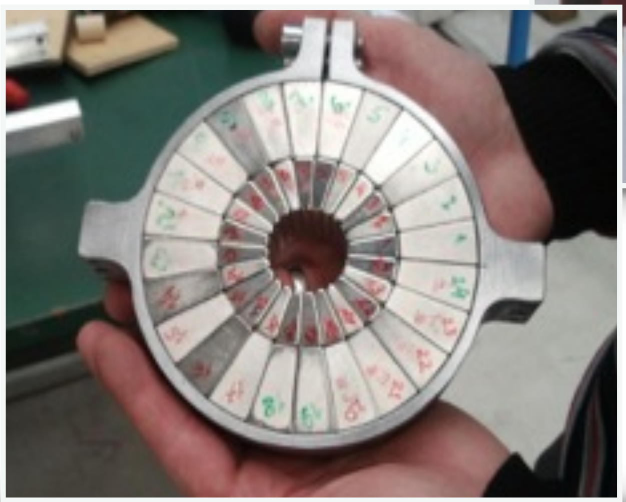


- a compact system but long drift is needed for the microscope

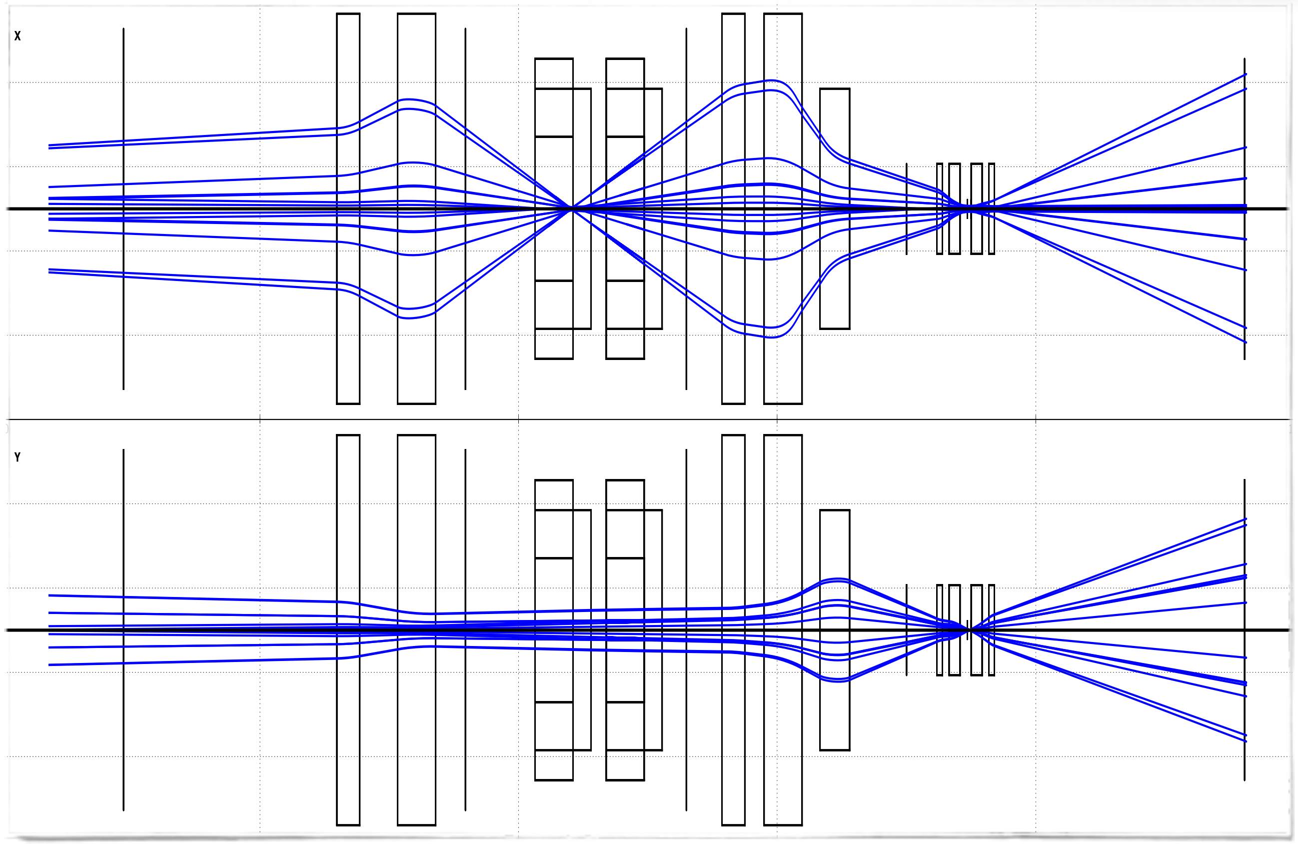
PRIOR PMQ and optical design

Parameter	Value
Proton energy	4.5 GeV
PMQ inner aperture	30 mm
B	1.83 T
Field gradient	122 T/m
"Short" quad length	144.4
"Long" quad length	288.8

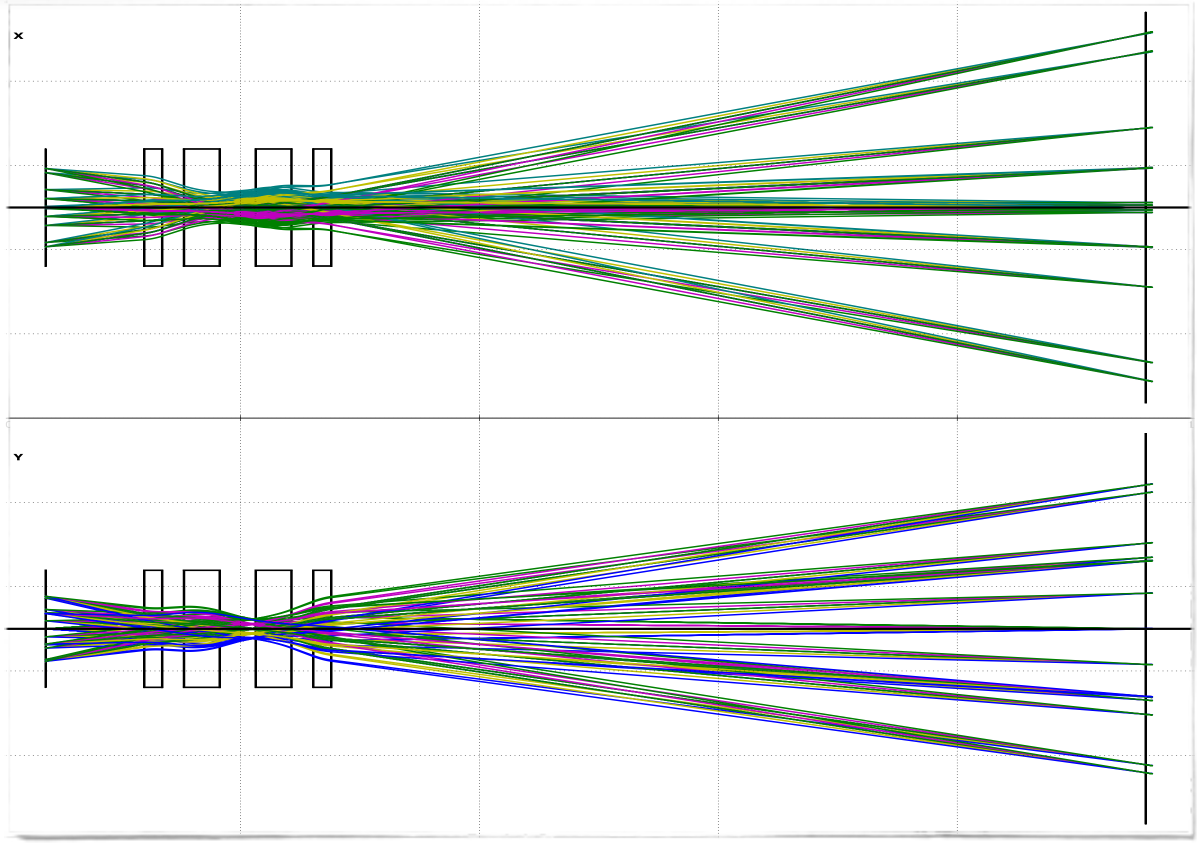




matching

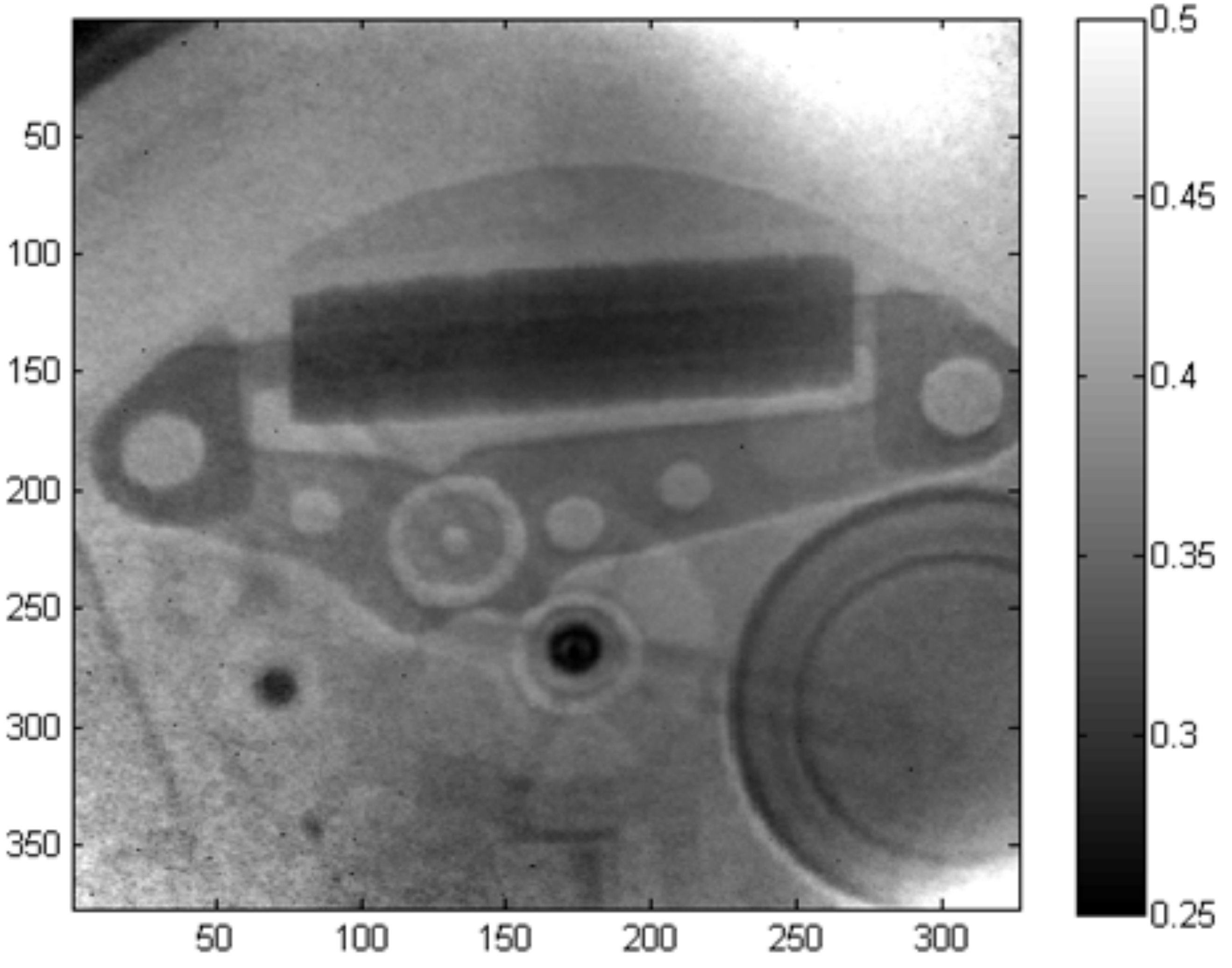


imaging



Beam time commissioning of PRIOR microscope

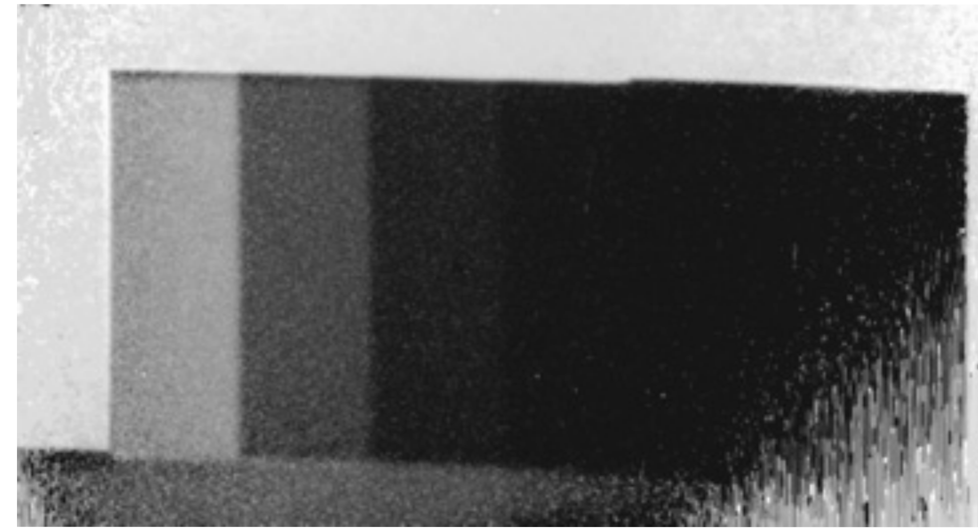
The PRIOR prototype has been constructed and successfully commissioned in static experiments with 4.5 GeV proton beam of SIS-18 in April 2014

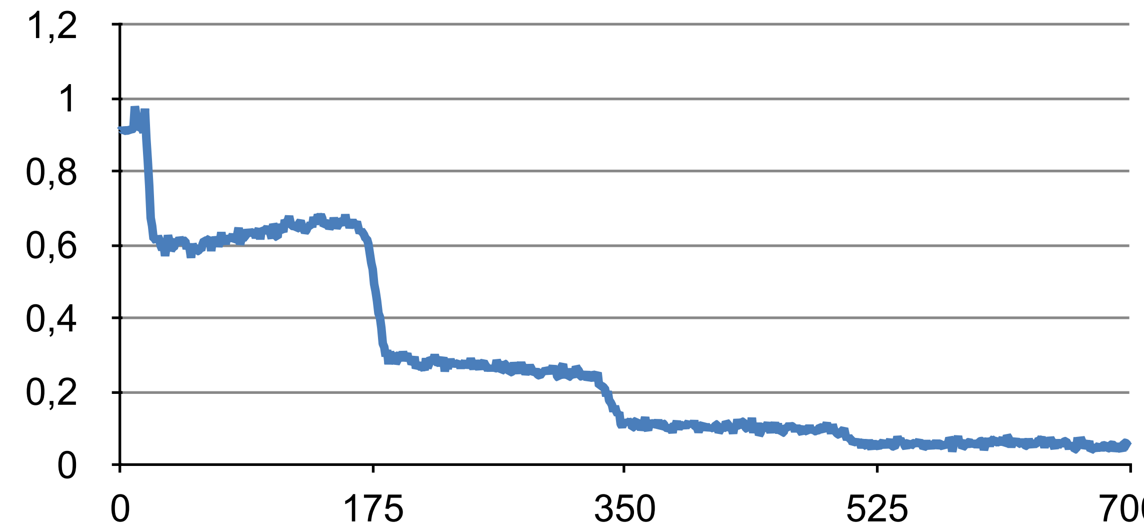


Static experiment with PRIOR

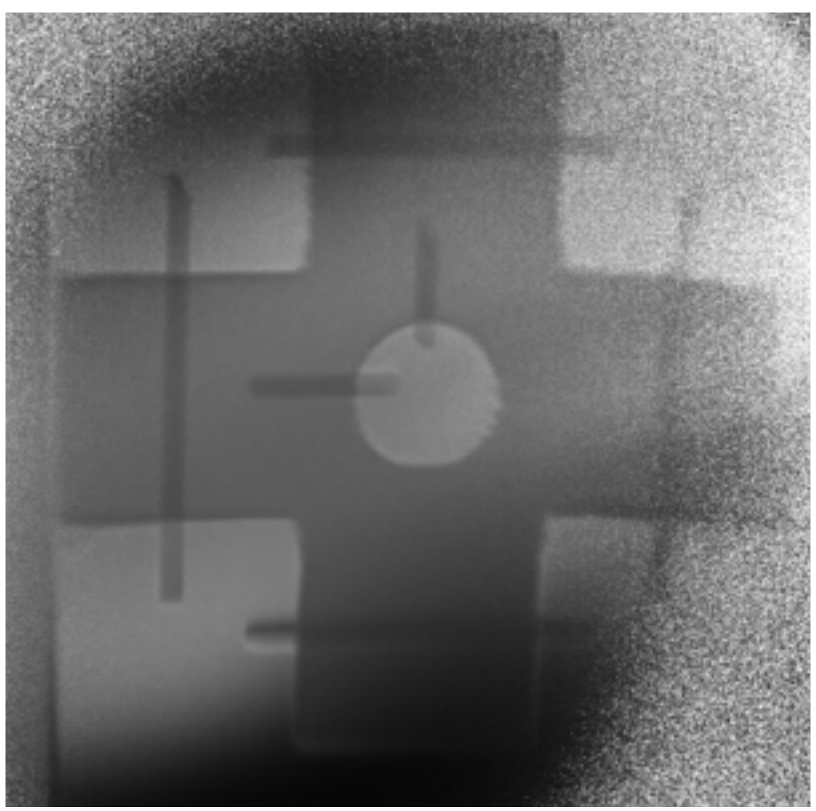
Hand watch

Ta steps



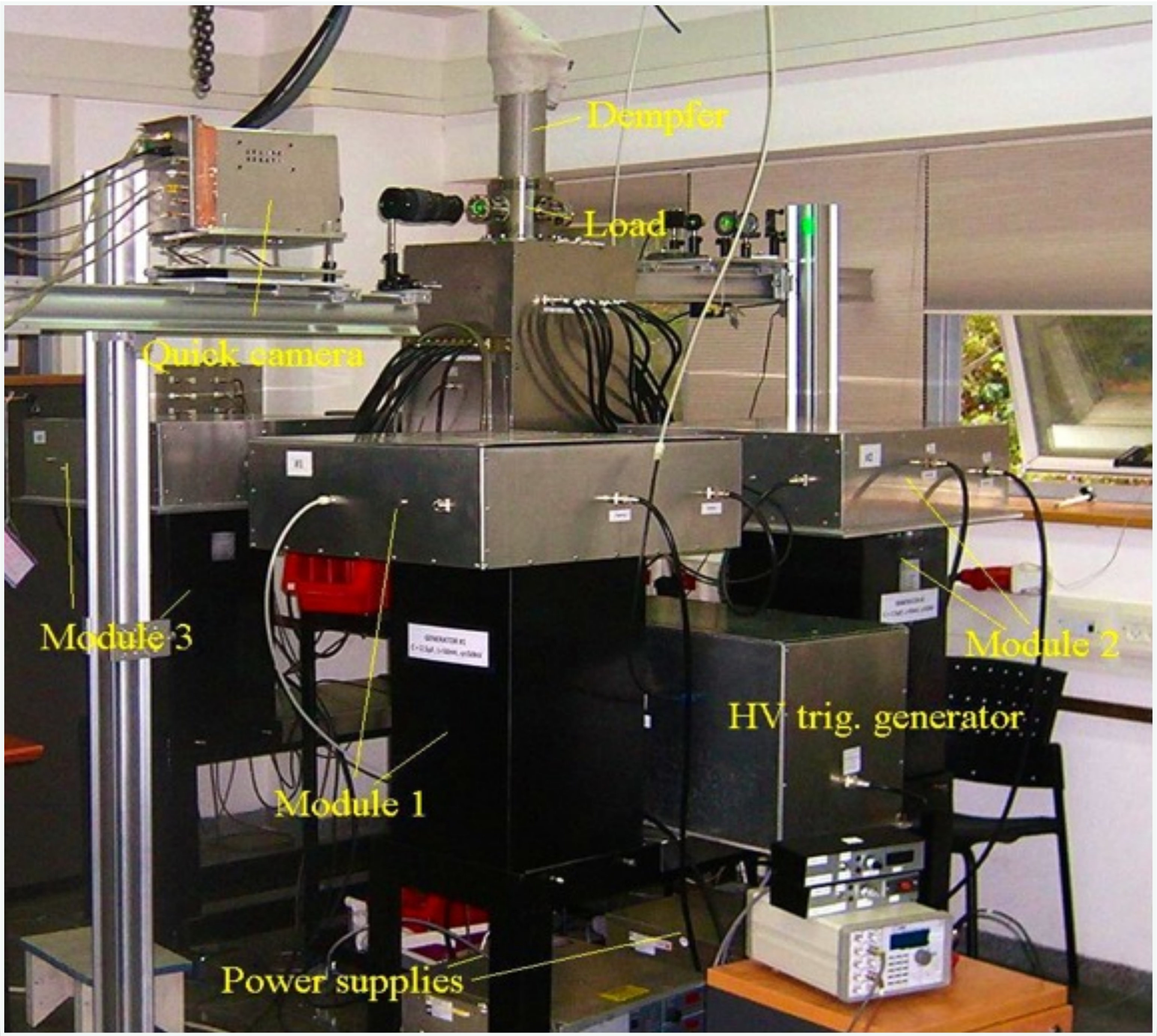


Maltese cross



- Ta steps: 25μm
- Maltese cross: 40 μm - 60 μm

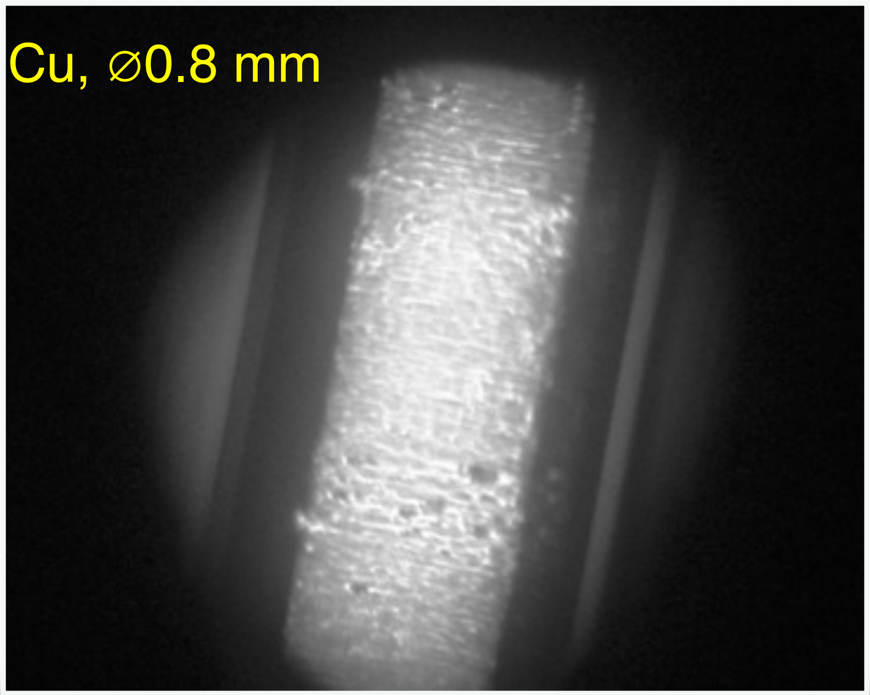
Dynamic experiment with PRIOR

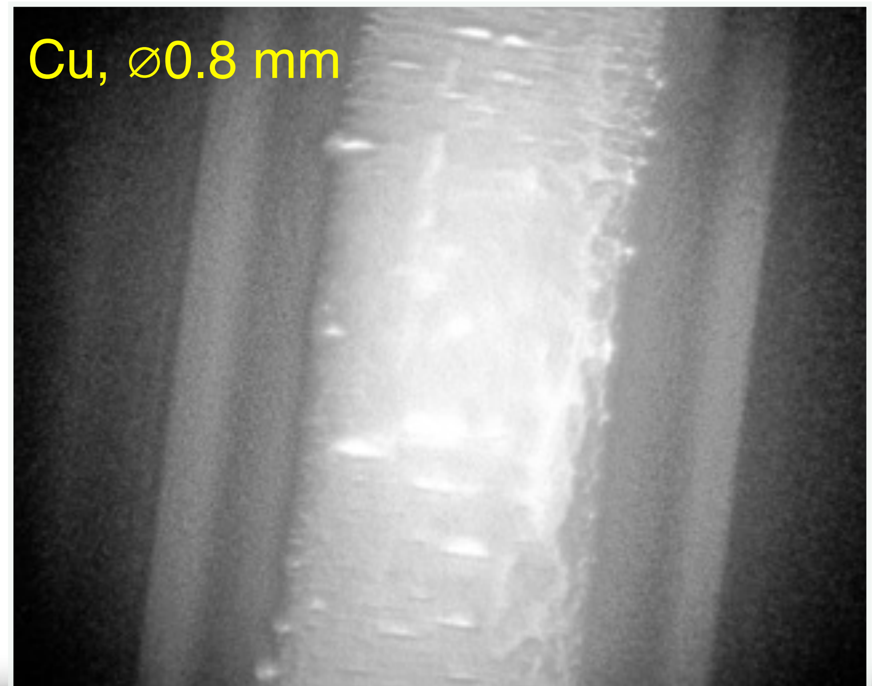


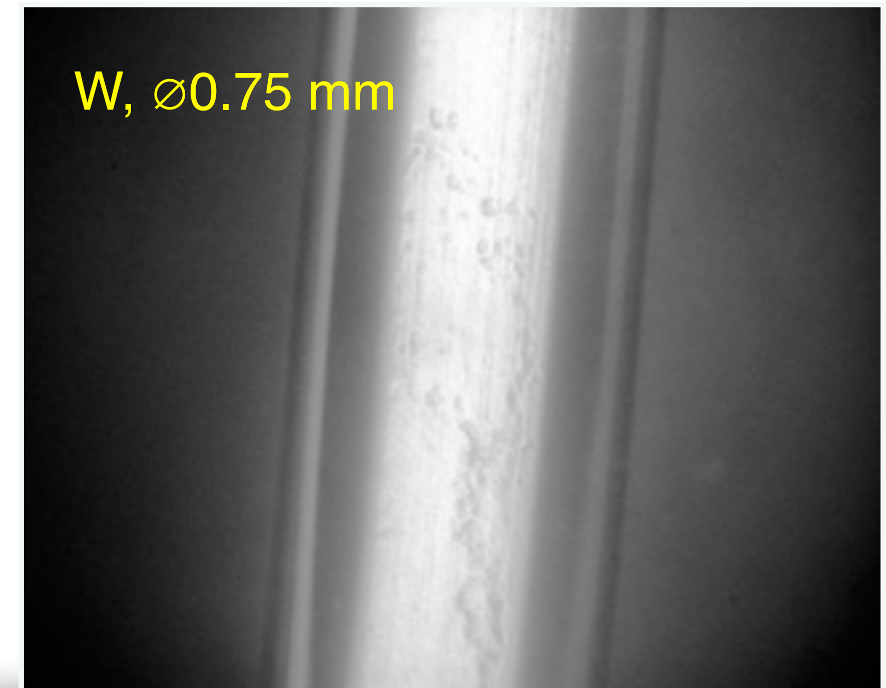
- Marx (50 kV, 2.5 μF, 40 nH) **x4** multichannel spark gap switches
- 12.5 kJ stored
- **200 – 300 kA, 1–2 μs**
- chamber filled with water
- 0.1–1 mm diam., 4–5 cm long wires (Cu, W, ...)
- **T ~ few eV, ε ~ 50 – 150 kJ/g, ~ 10^{11} – 10^{12} A / cm^2 / s**

Technion (Haifa) <-> GSI (Darmstadt)

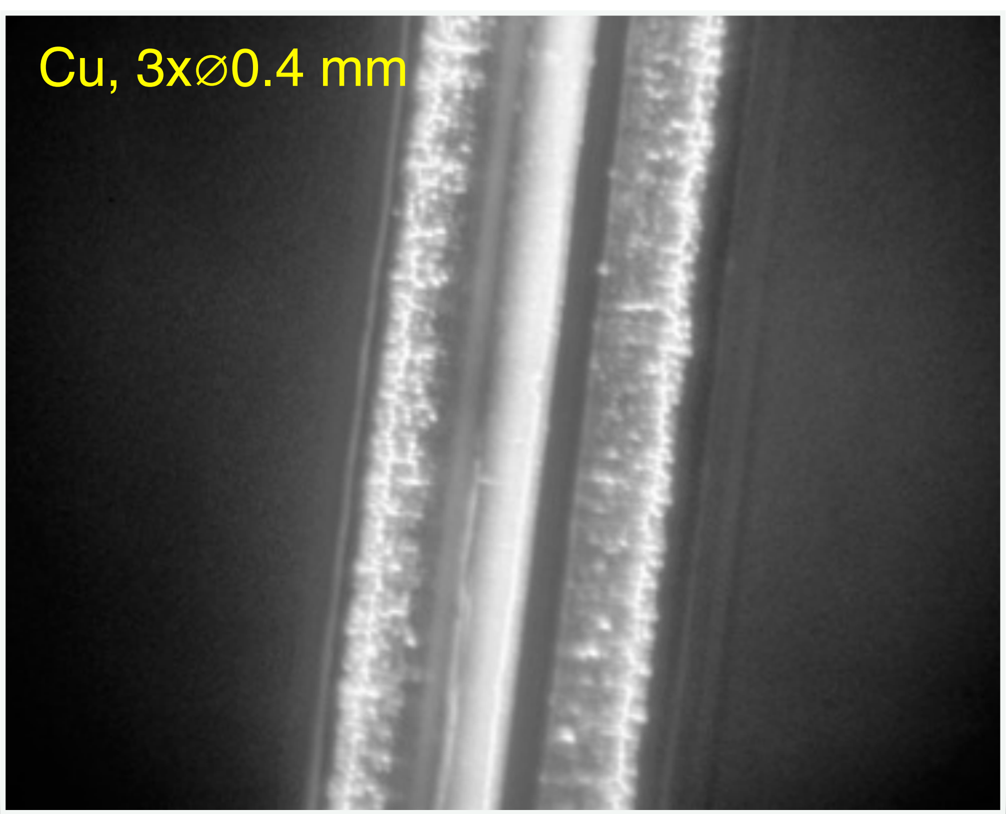
Fast self-emission images of exploding wires (P_{max} ~ 5 GW)



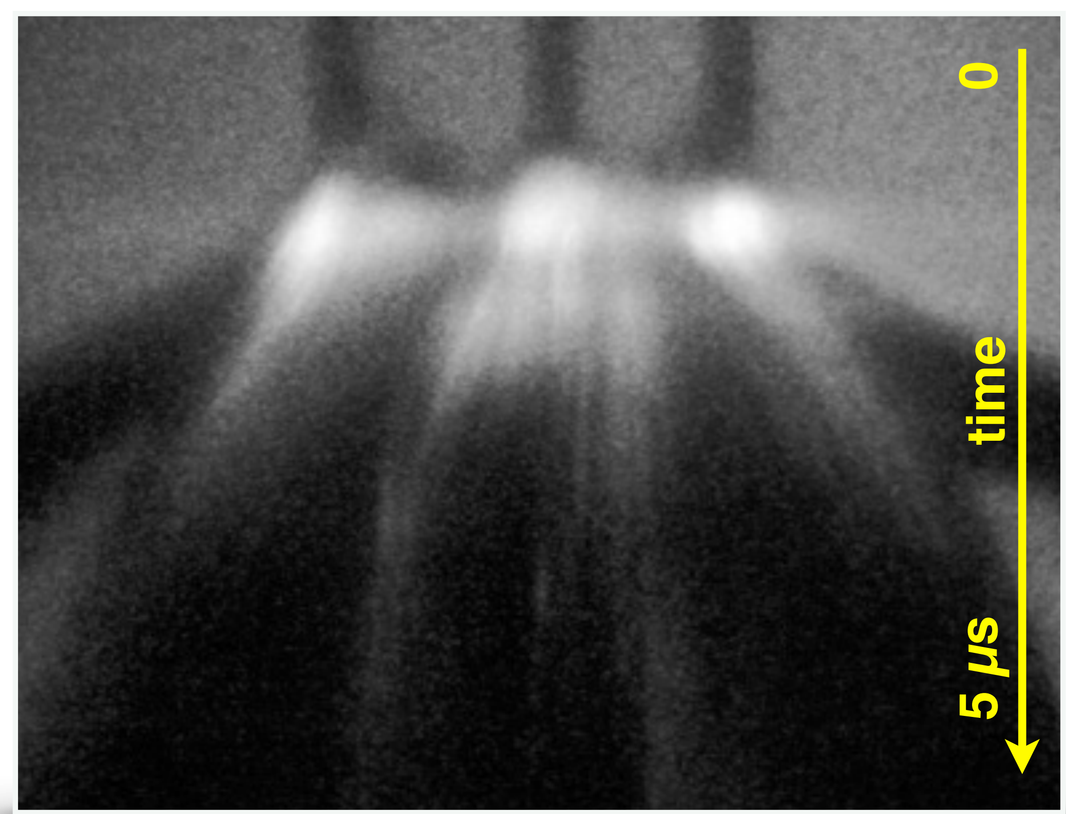




Explosion of a wire array

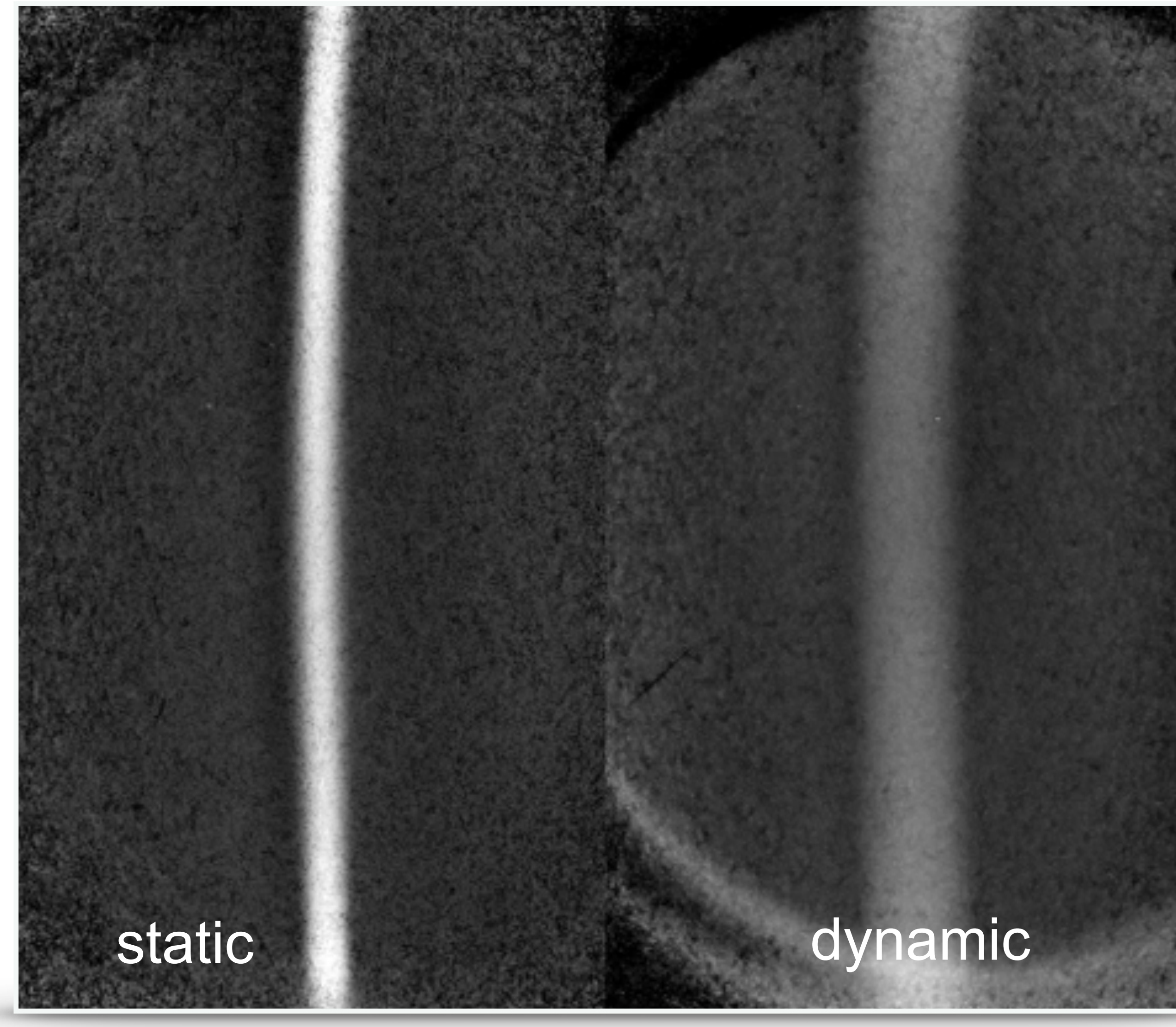


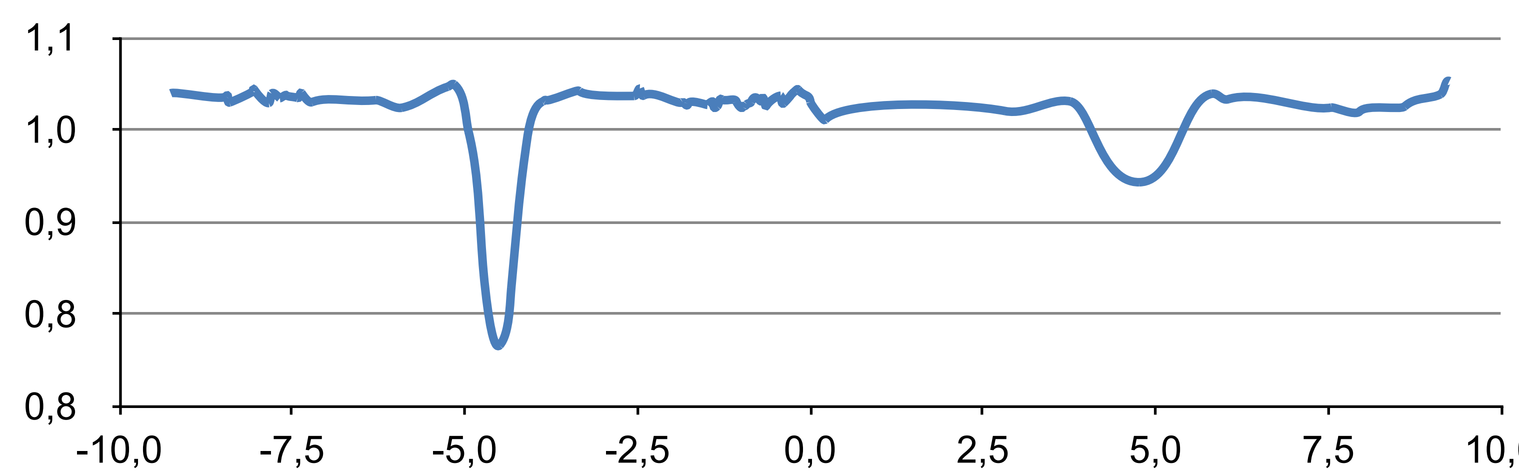
Streak camera image



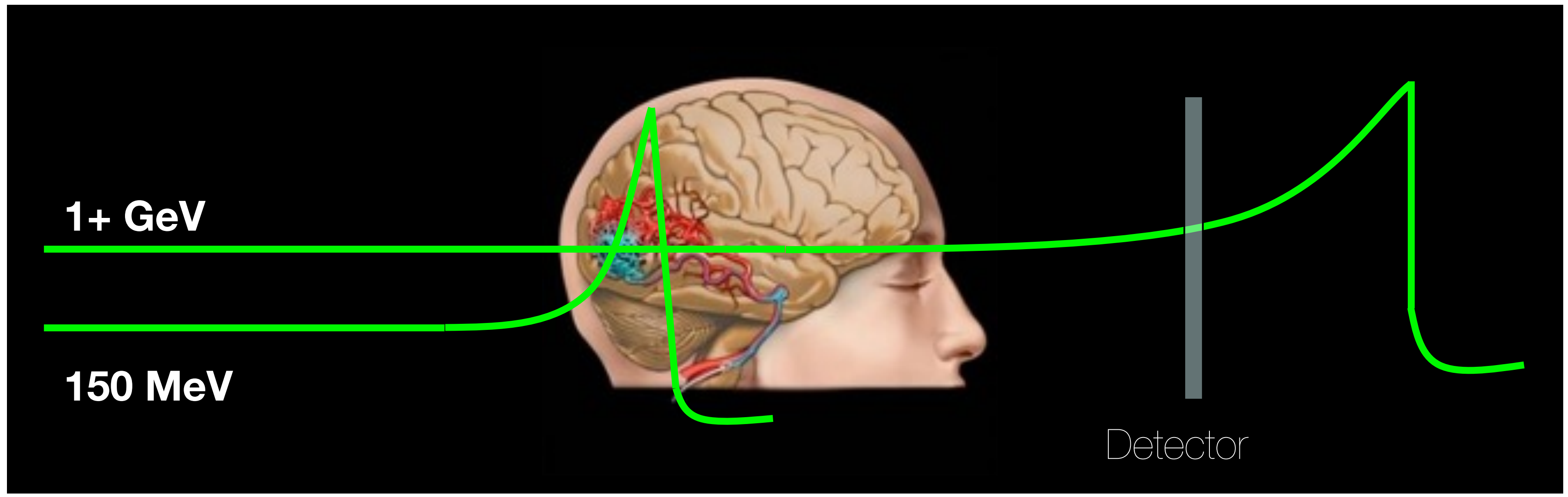
Dynamic experiments with PRIOR

- 0.8 mm Ta wire in 2 cm of water.
- Current density is about 40 MA/cm^2
- Energy density deposition is around 10 kJ/g
- ~2 eV
- mm/μs expansion velocity.
- Several dynamic experiment experiments were performed to build a time history of the expansion.
- Main goal: to measure internal structure of expanding Ta was readily achieved.





PaNTERA
Proton Therapy and Radiography



Relativistic plateau (non-Bragg-peak) protons

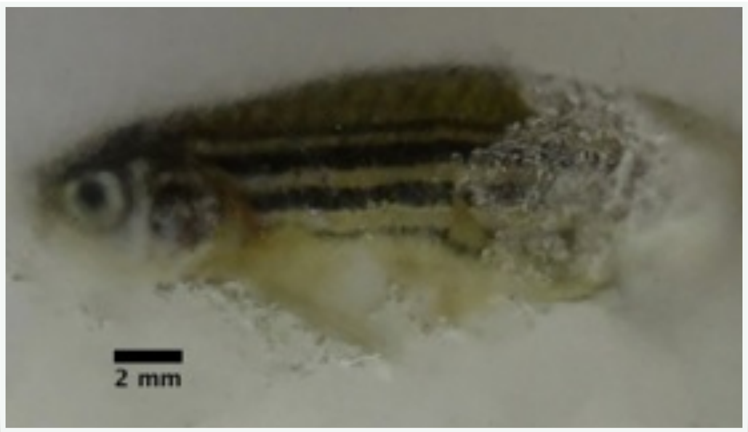
- simultaneous imaging (on-line radiography) with the same beam
- very small lateral scattering

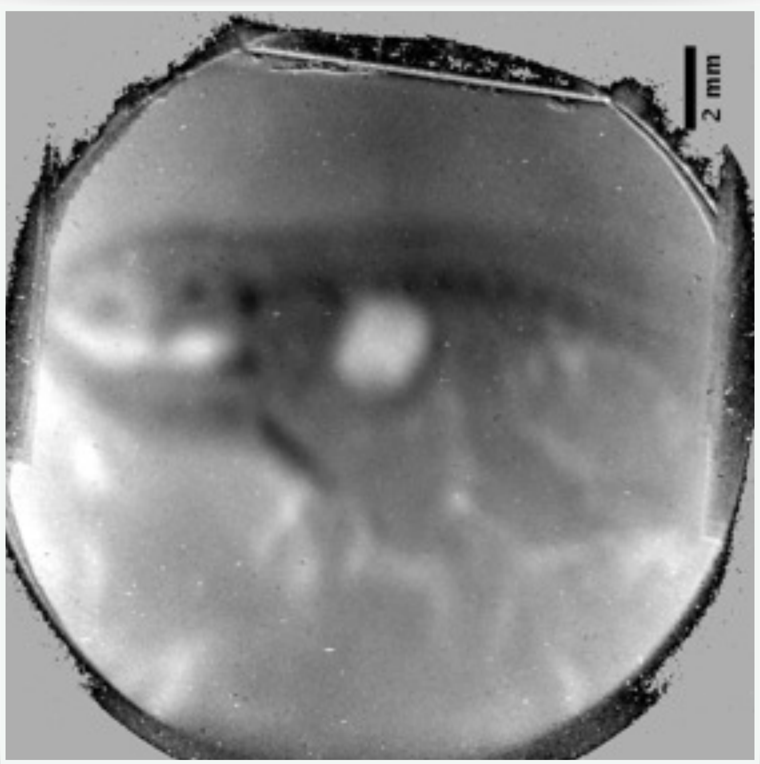
- not sparing tissue behind the tumor
- modification of the dose distribution due to production of secondaries

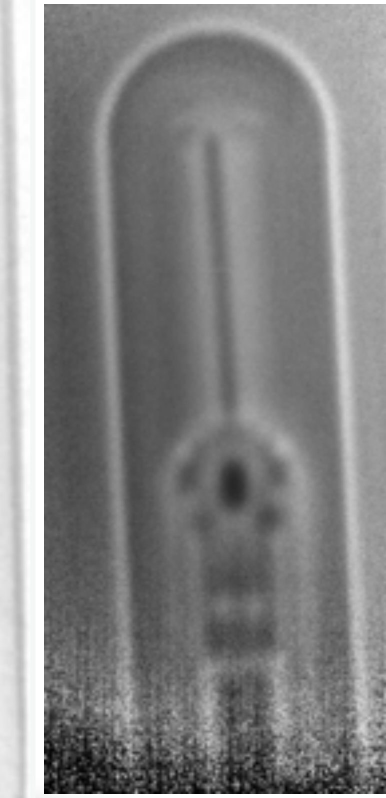
Image-guided stereotactic particle radiosurgery (IGSpRS) is in competition with X-ray SRS, but online imaging and low lateral scattering allow reduction of margins, treatment of moving targets and dose escalation

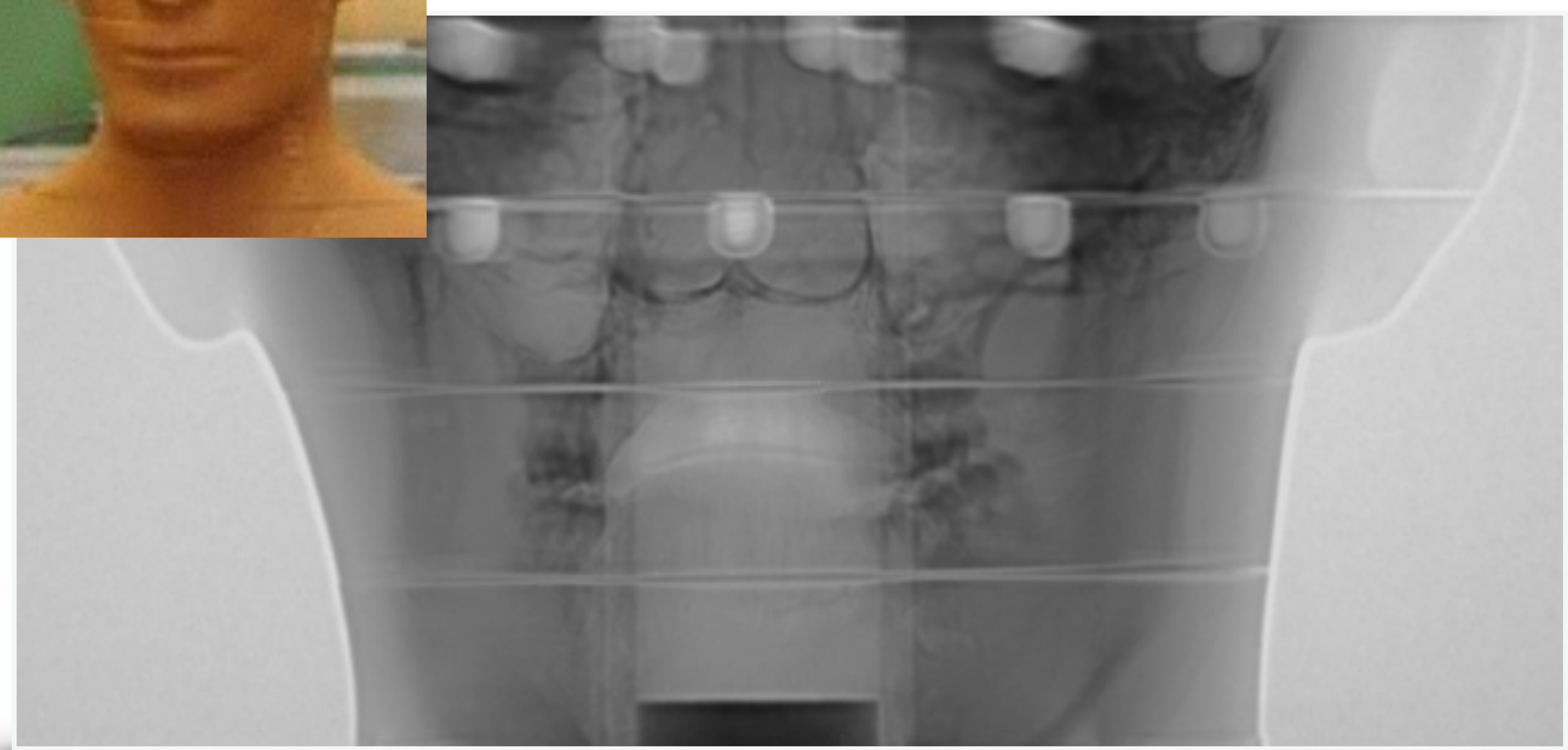
Biological images with HEPM

Zebrafish in 1cm-thick paraffin
ITEP







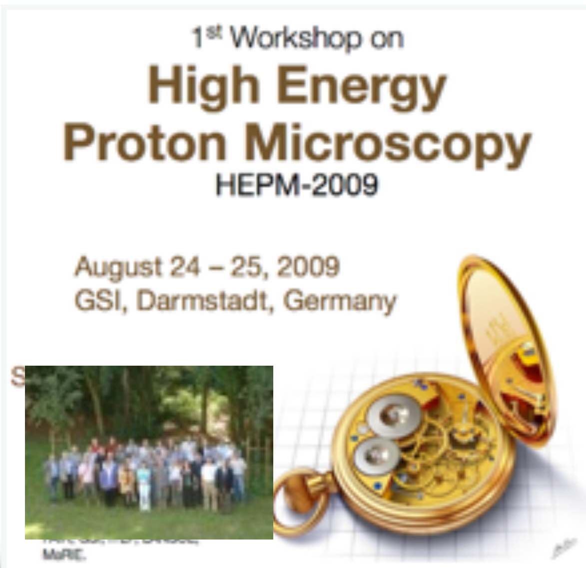


Human phantom - ‘Matroshka’, LANL

PANTERA in details:
Next talk by Matthias Prall

- High Energy Proton Microscopy (HEPM):
  - provides unique capabilities for unparalleled high-precision experiments in plasma physics, materials research, biophysics and medicine
- PRIOR prototype @GSI:
  - commissioned in April 2014
  - 20 μm spatial resolution was achieved
  - off-line tests of exploding wire experiment at GSI have been completed in 2013
  - first dynamic experiments with 4.5 GeV protons
- PRIOR @FAIR:
  - x500 beam intensity
  - x2 proton energy
  - SC or PMQ imager options
  - probably the first HEDgeHOB experiment at FAIR

High Energy Proton Microscopy workshops series



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conferences/HEPM2009

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proton%20microscopy

http://www-aix.gsi.de/
conferences/HEPM2013/

HEPM - 2015
Moscow, Russia