Activities on Proton radiography at ITEP

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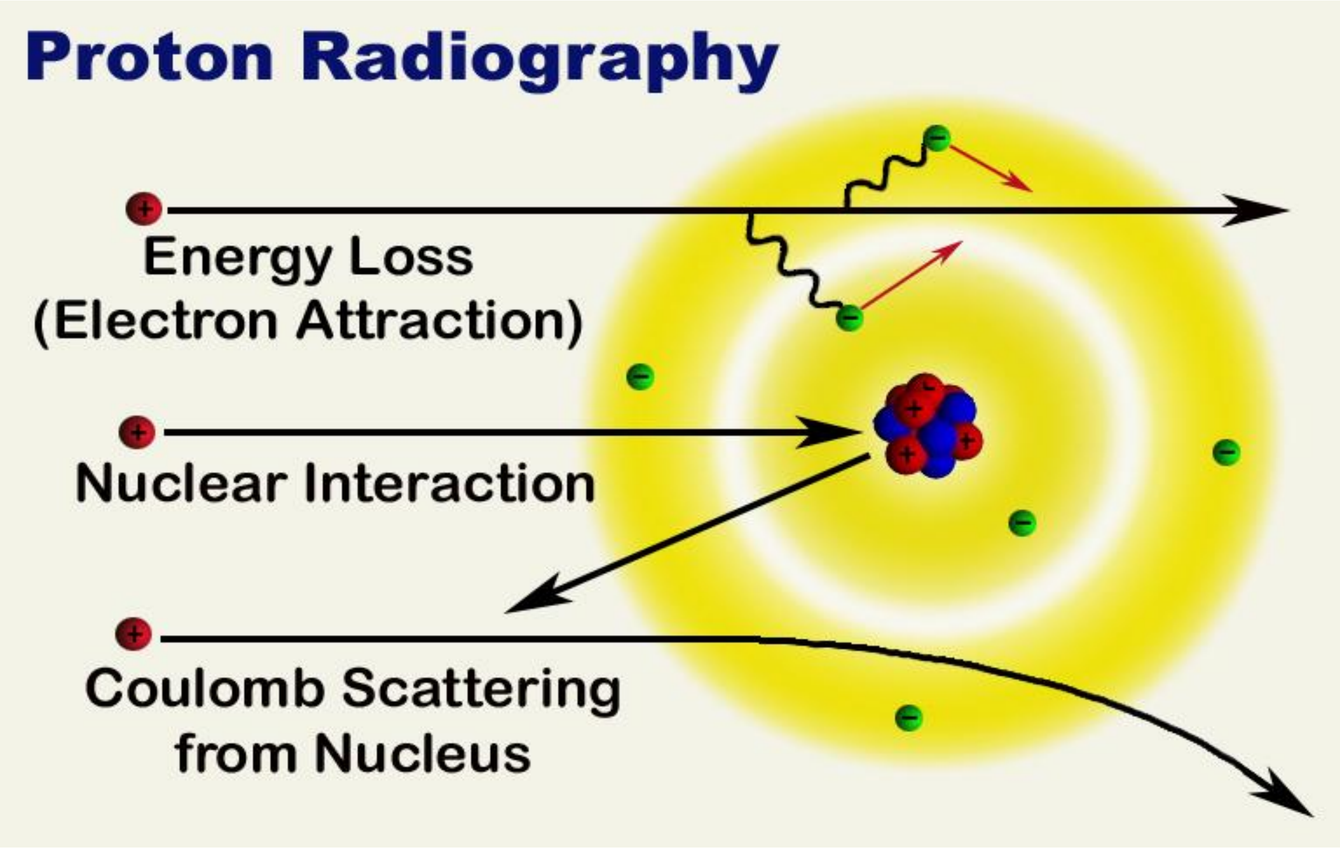
Los-Alamos National Laboratory, USA
Frank Merrill

Proton Radiography Principle



Protons passing through a matter undergo:

- *Coulomb* multiple *scattering* (cross-section pro rata Z^2/A, Z – nuclear charge)
- Nuclear scattering (loss particle pro rata atomic weight $A^{2/3}$)
- Energy loss

Marginal Range Proton Radiography

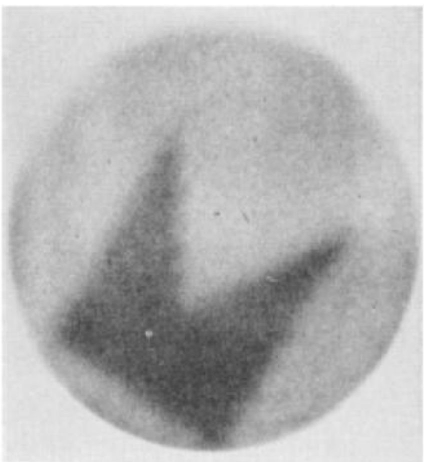
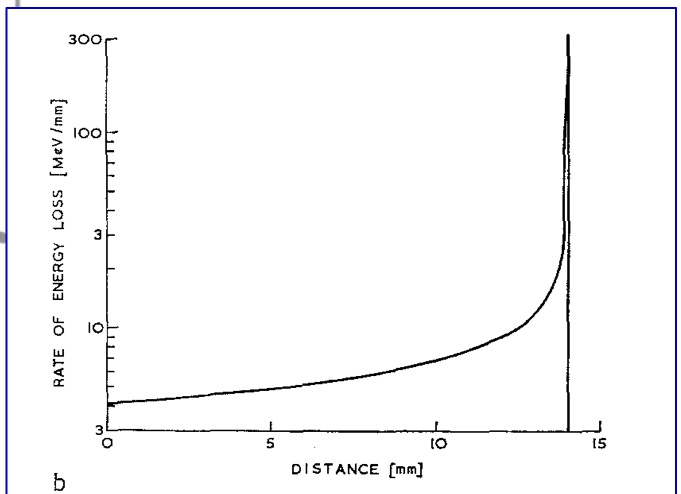


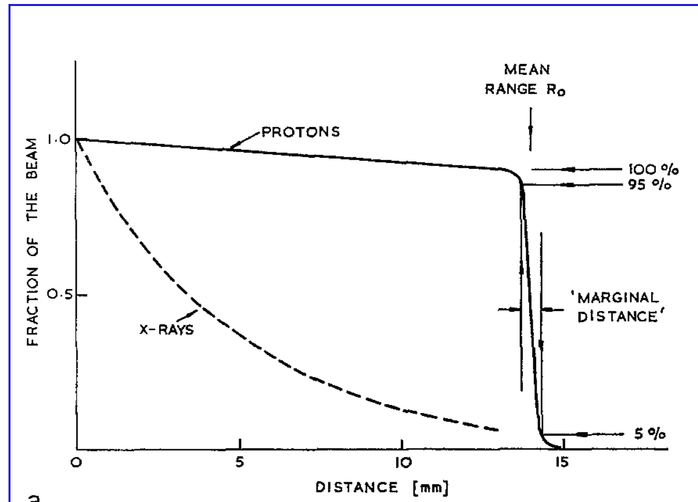
Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035-g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the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

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

- Reduce proton beam energy to near end of range.
- Use steep portion of transmission curve to enhance sensitivity to areal density variations.
- Coulomb scattering at low energy results in poor resolution >1.5 mm.
- Contrast generated through proton absorption.



The energy lost per mm for a typical proton as a function of the distance it has travelled in iron.



The proportion of protons (solid line) or X-rays (dotted line) at different distances in iron.

Scattering Proton Radiography

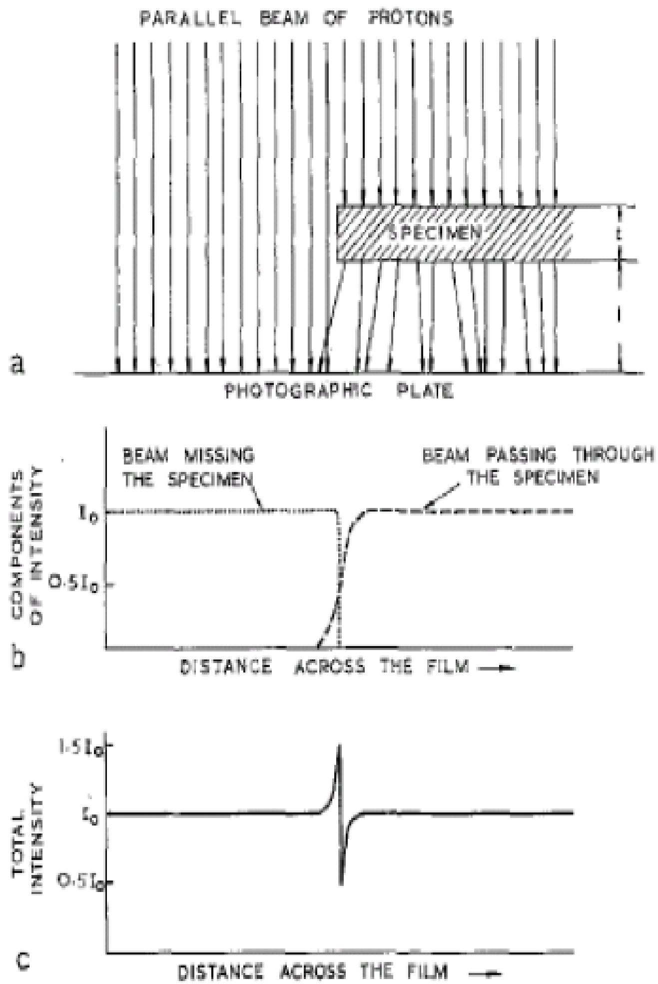


Fig. 7. Illustration of how multiple scattering produces its characteristic edge pattern

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

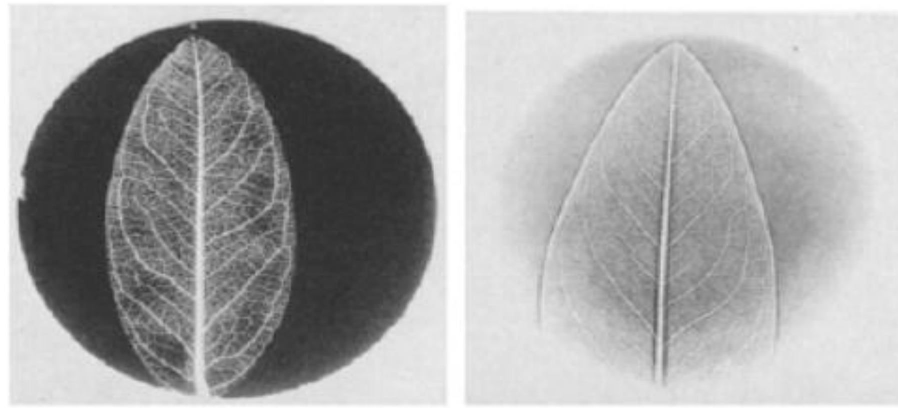


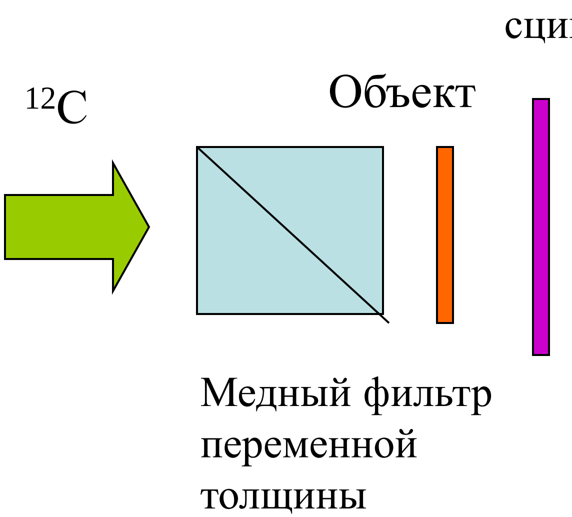
Fig. 6a and b. Radiographs of leaves by a) marginal range radiography with 196 mg/cm² of extra Al absorber, and b) scattering radiography with leaf sandwiched between two 6.9 mg/cm² Al layers and 14 mm from the film

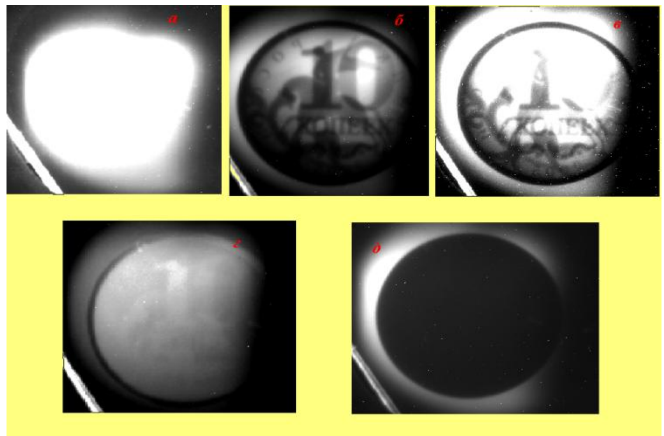
<u>Scattering Radiography</u>

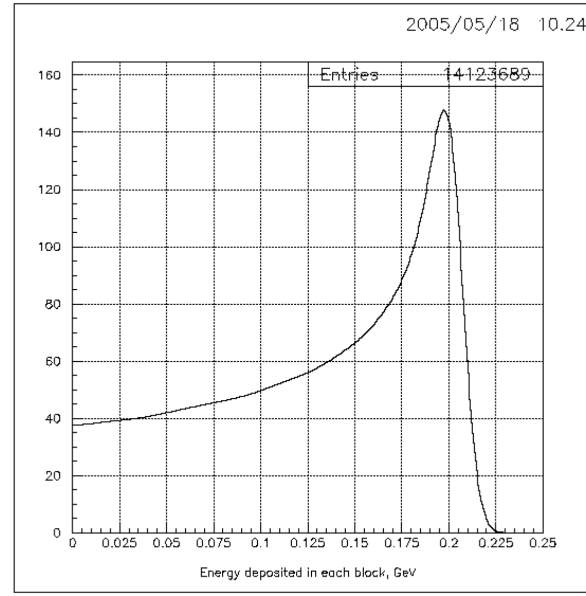
- Edge detection only
- Limited to thin objects
- Contrast generated through position dependent scattering

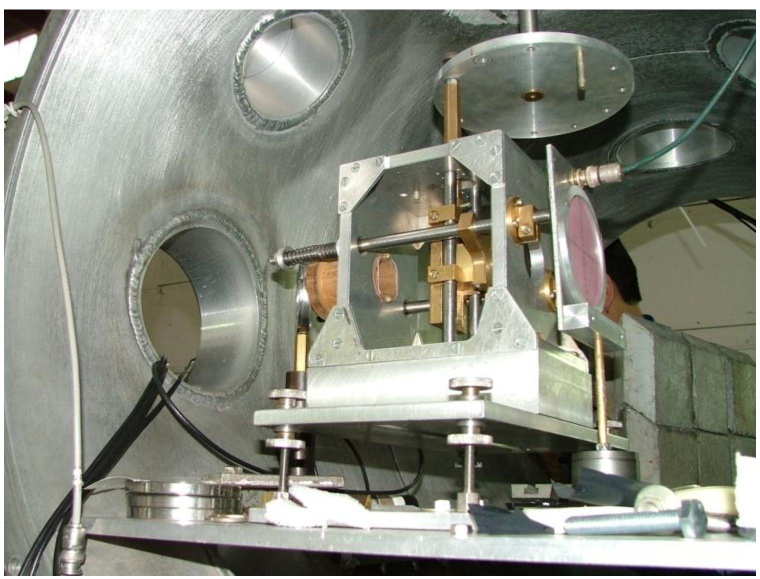
Illustration of how multiple scattering produces its characteristic edge pattern

Ion Radiography



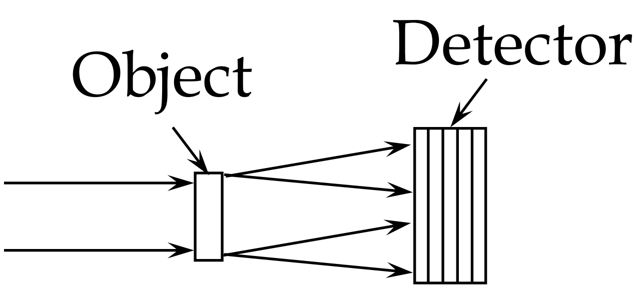


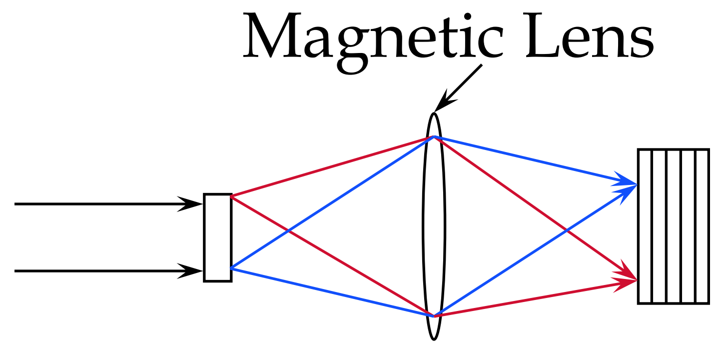




1st LANL Proton Radiography (1995)

188 MeV secondary proton beamline at LANSCE





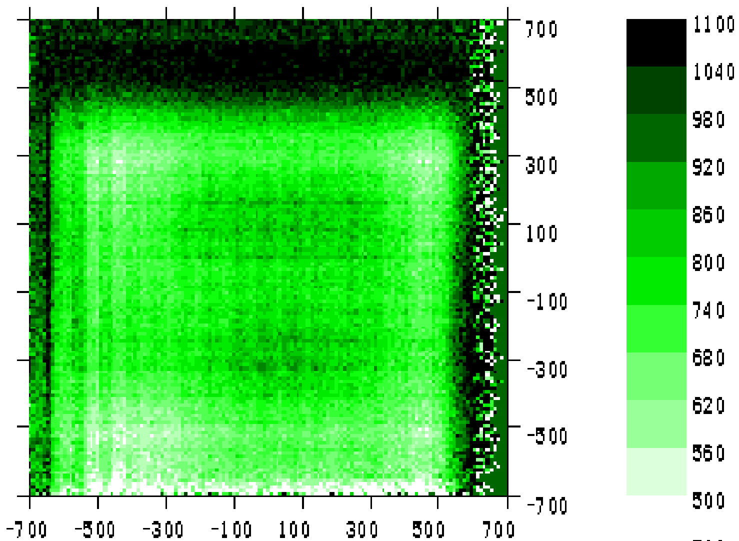
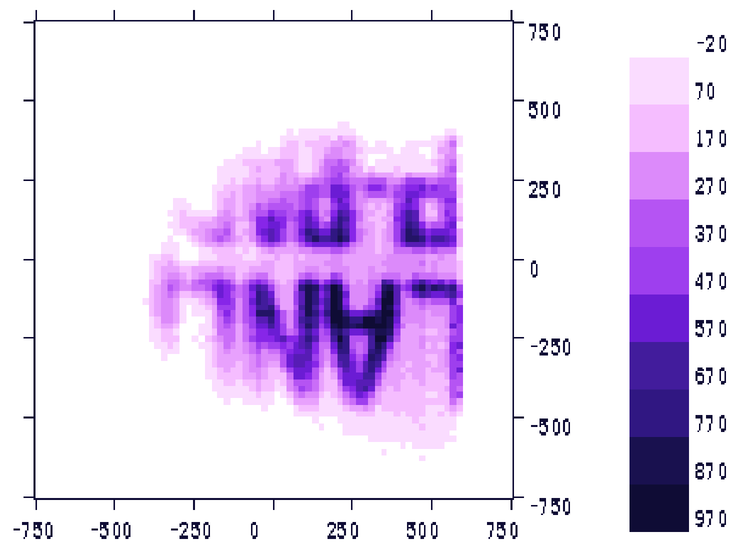
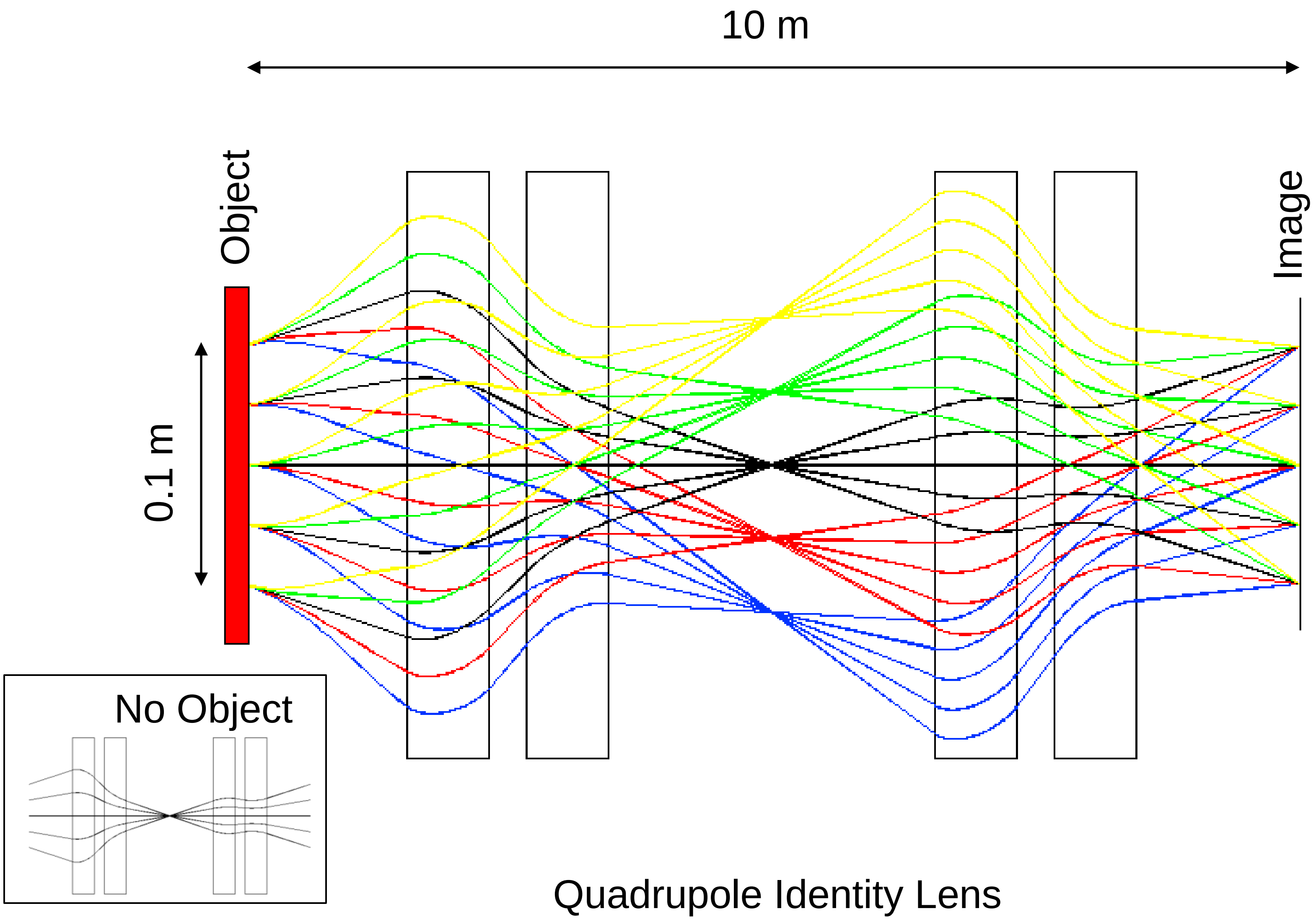


Image at the detector is substantially blurred.



Magnetic imaging lens preserves image with high resolution.

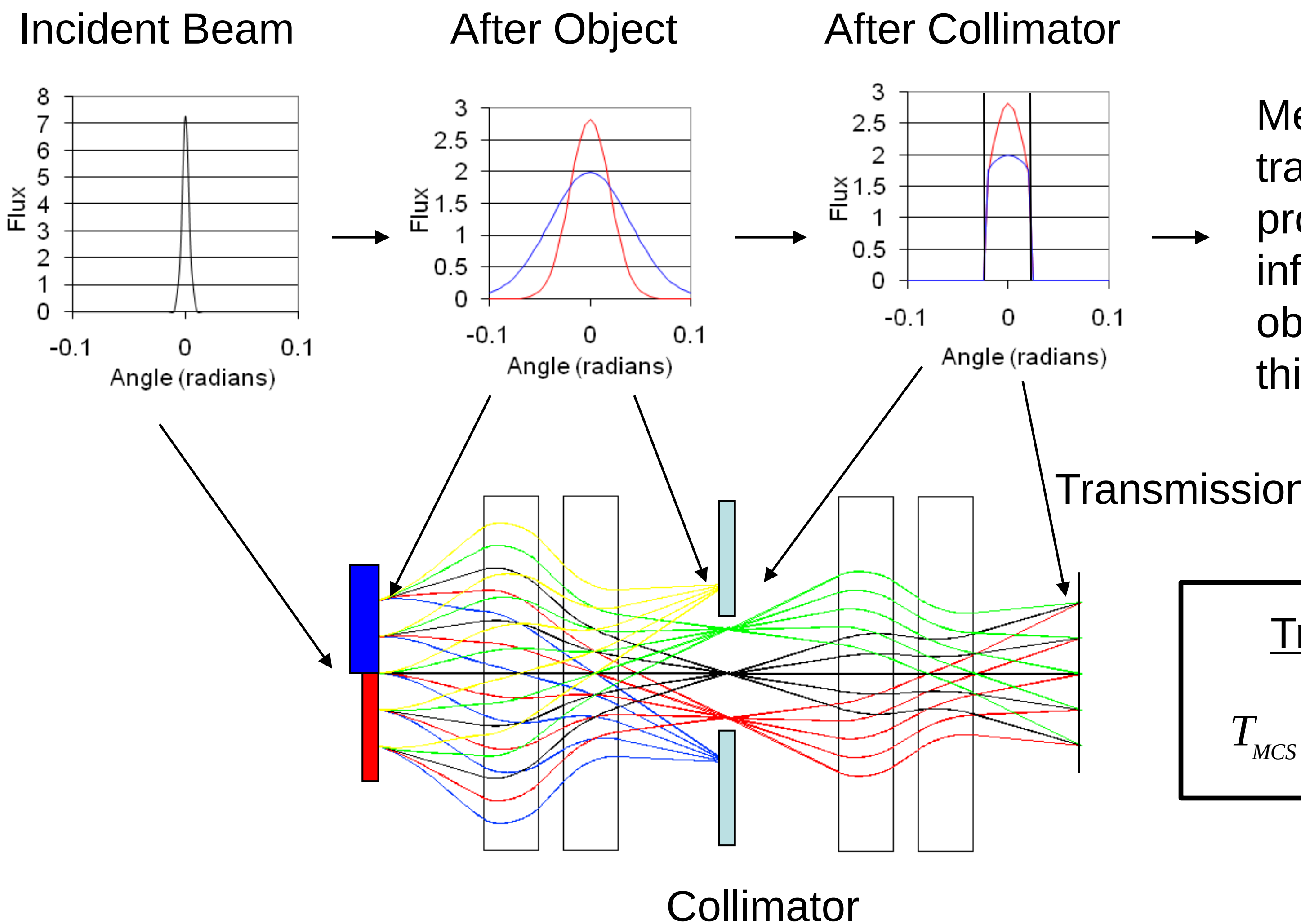
Magnetic Imaging Lens



Quadrupole Identity Lens

Images courtesy of Frank Merrill, LANL

Contrast from Multiple Coulomb Scattering



Measured transmission provides information of object thickness

$$\frac{\text{Transmission}}{} \quad T_{MCS} = 1 - e^{-\theta_c^2 / 2\theta_o^2}$$

Images courtesy of Frank Merrill, LANL

Areal Density Reconstruction

$$T_{nuclear} = e^{-x/\lambda}$$

Nuclear removal processes

$$T_{MCS} = 1 - e^{-\theta_c^2 / 2\theta_o^2}$$

$$\theta_o = \frac{14.1 MeV}{p\beta} \sqrt{\frac{x}{x_o}}$$

Multiple Coulomb Scattering with collimation:

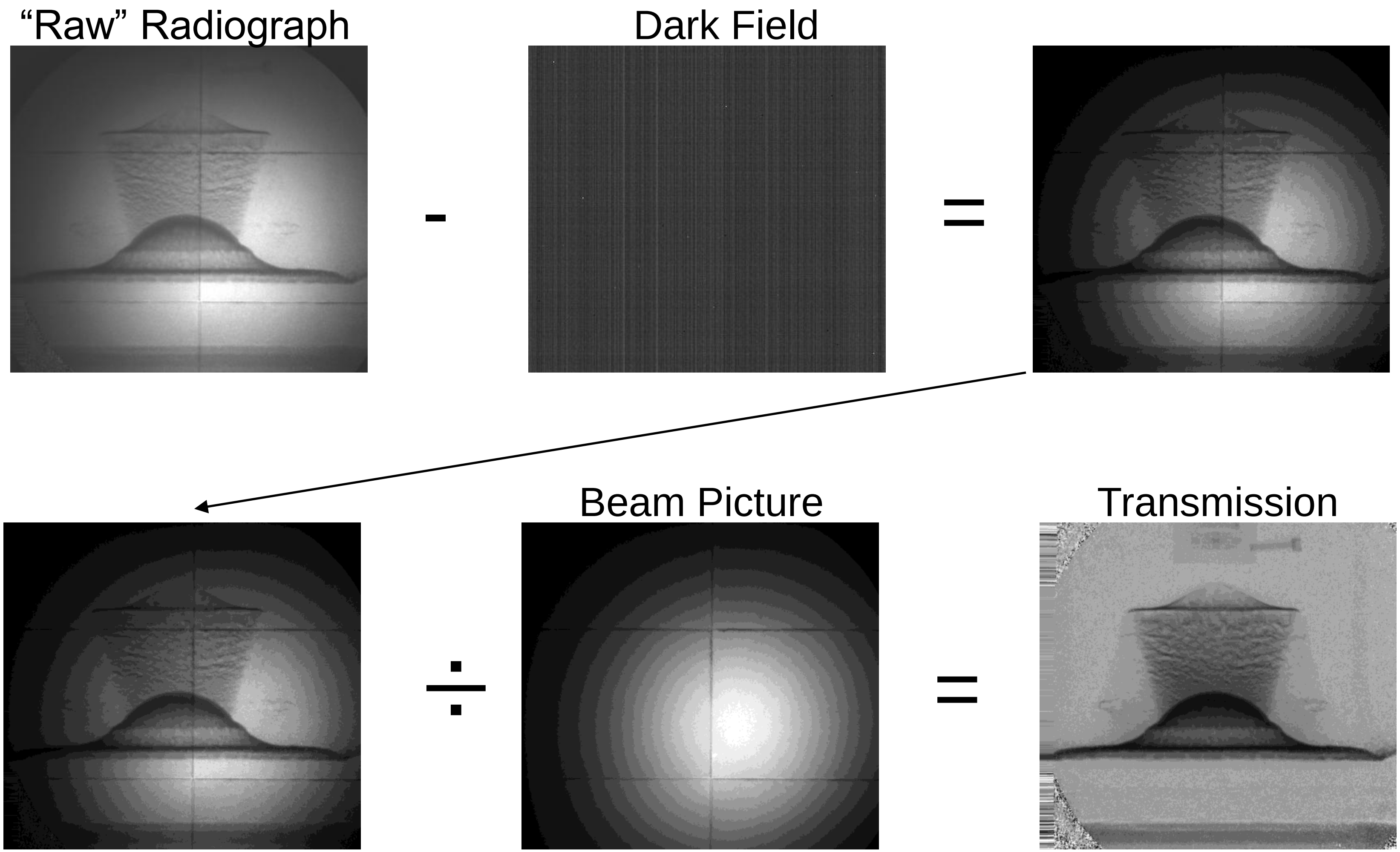
θ_o - scattering angle (radians)
x - areal density
x_o - radiation length
p - momentum (MeV)
β - relativistic velocity

$$T = e^{-x/\lambda} \left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1 MeV}\right)^2 \frac{x_o}{2x}} \right)$$

Total Transmission

- inverted to determine areal density, x

Radiographic Analysis

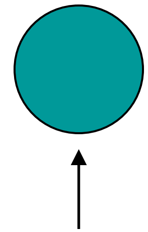


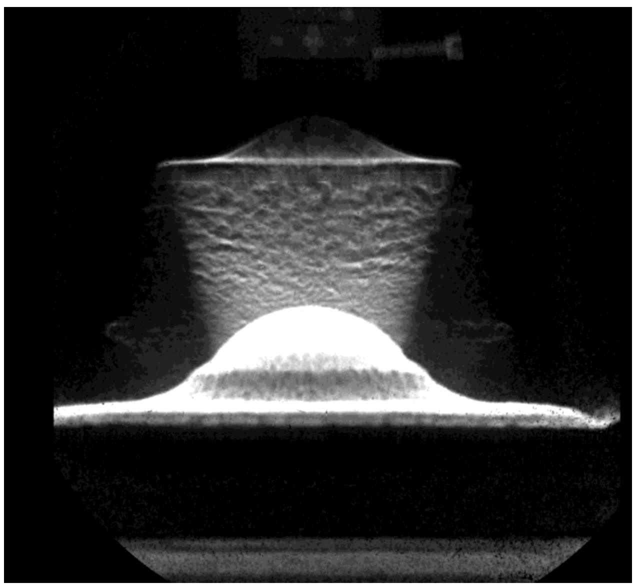
Density Reconstruction

Invert to calculate Areal Density

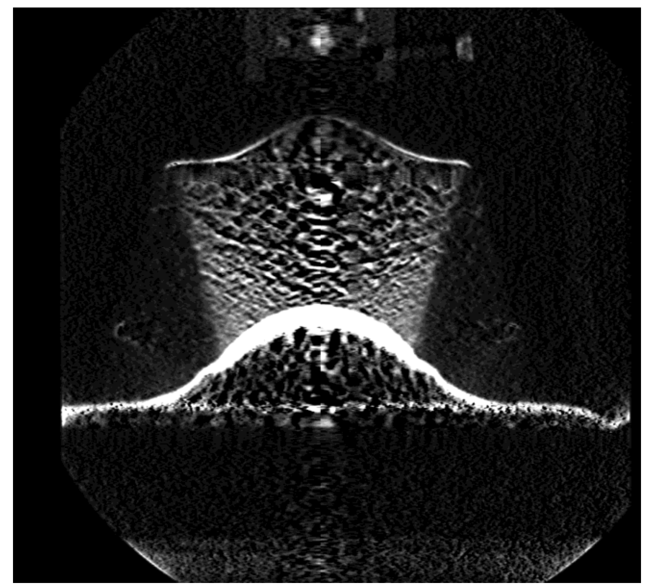
$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p \beta}{14.1\,MeV}\right)^2 \frac{x_o}{2x}}\right)$$

Use assumption of cylindrical symmetry to determine volume density (Abel inversion)



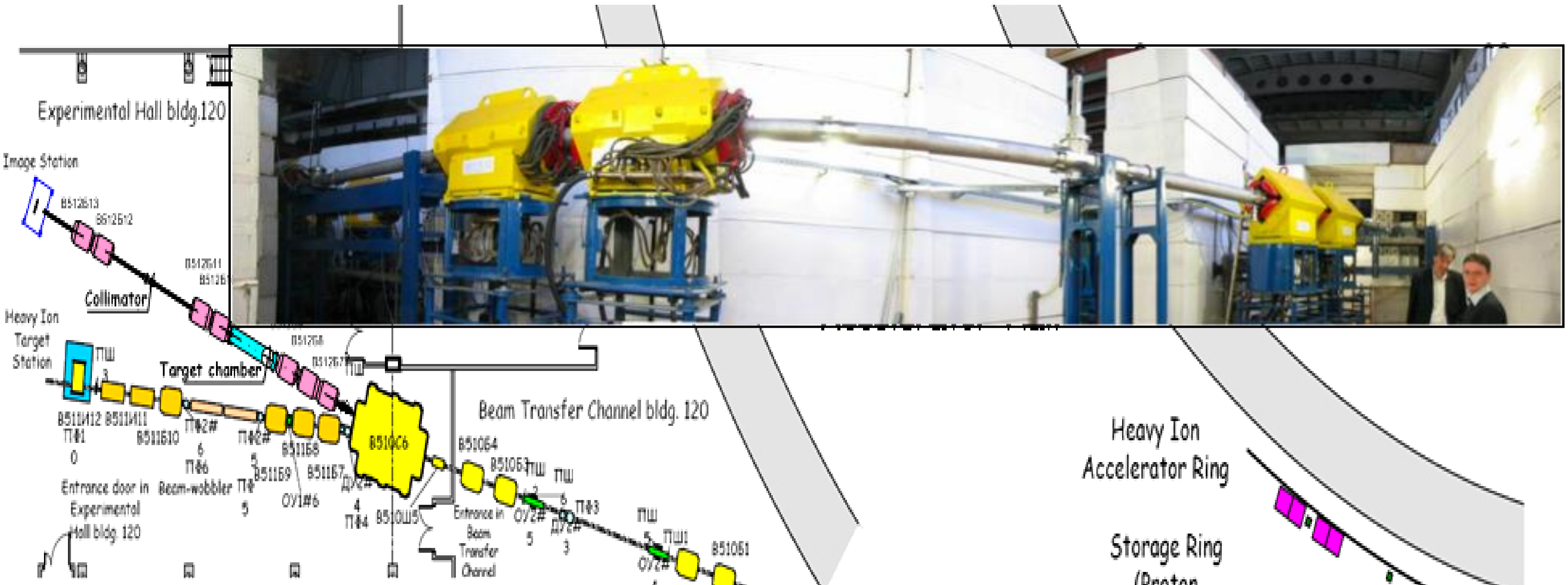


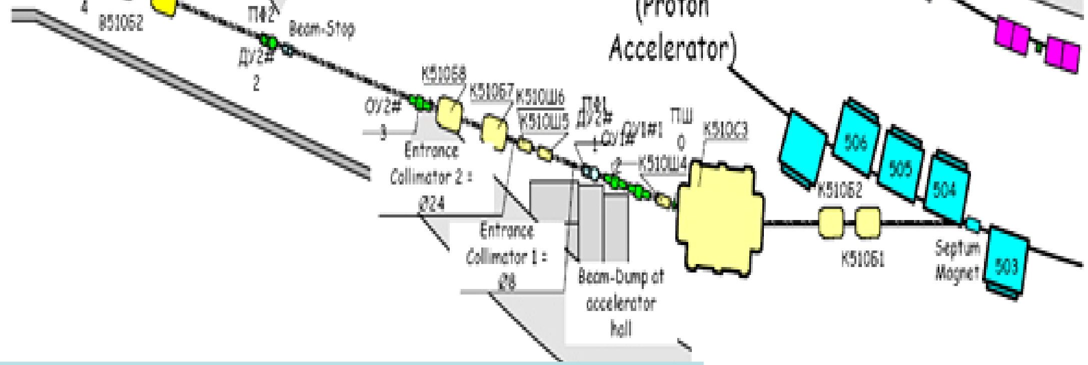
Areal Density (g/cm^2)

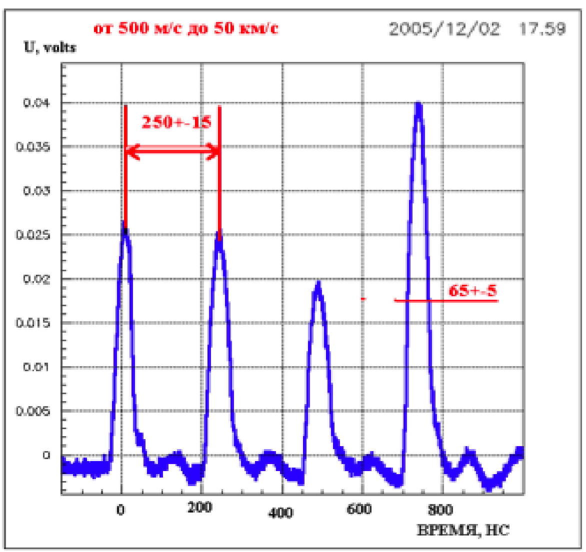


Volume Density (g/cm^3)

pRad at ITEP-TWAC facility

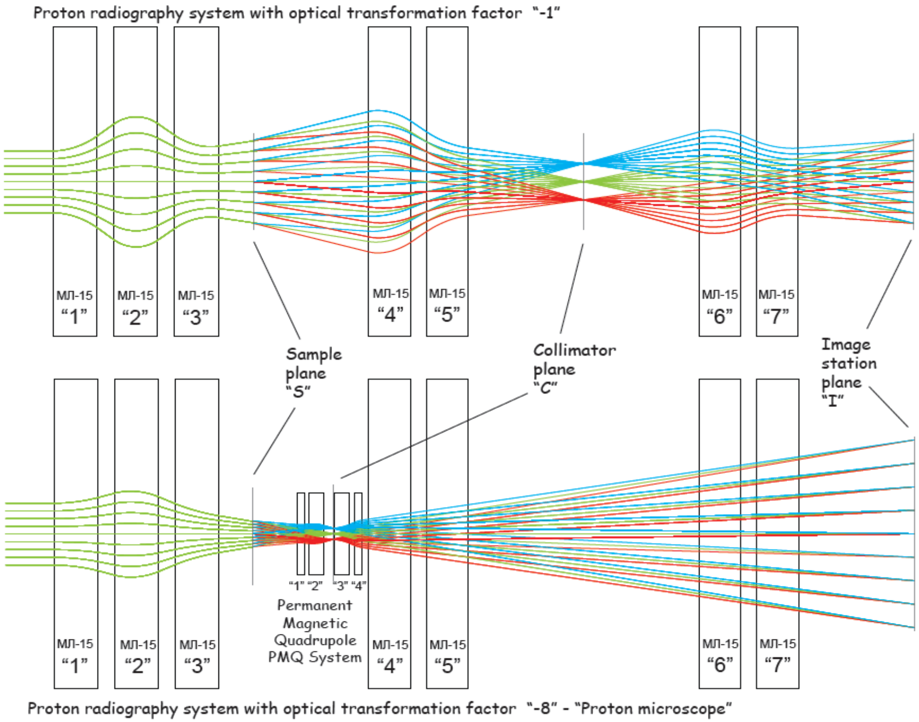






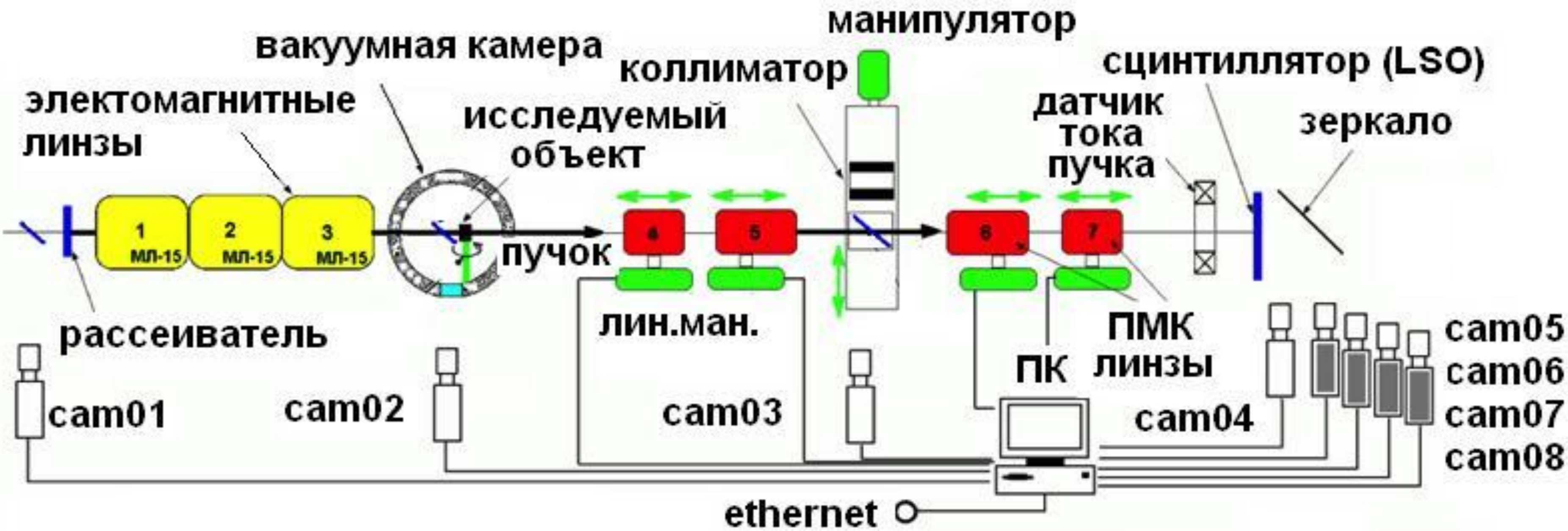
Beam structure – 4 bunches
Duration of single bunch: **70 ns**
Interval between bunches: **250 ns**
Beam intensity: up to **10^{11}** protons

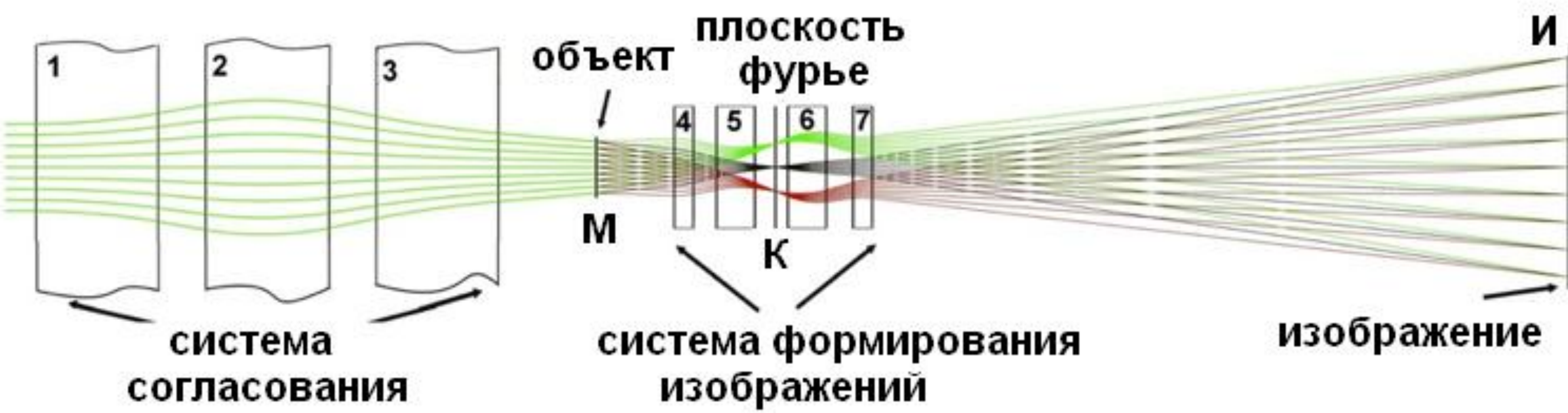
Proton Microscope



- 4 permanent high gradient quadruple lens
- Magnification **X = 3.92**
- Field of view < **19 mm**
- Density resolution ~ **6%**
- Best spatial resolution on object: **50 μm**

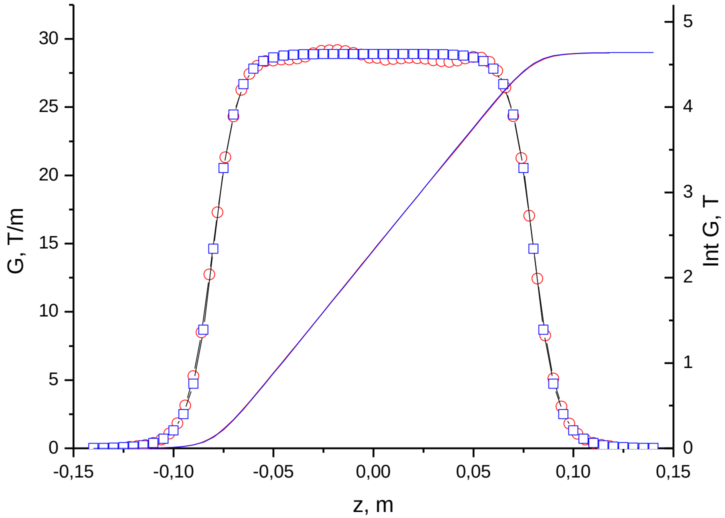
Proton Microscope





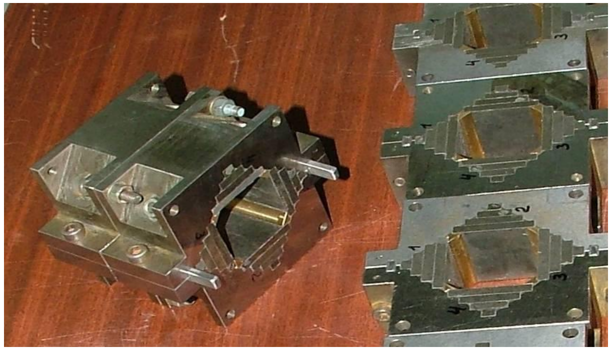
A. V. Kantsyrev et al., Instruments and Experimental Techniques, (2014), No. 1, pp. 5-14.

Permanent Magnet Quadrupole lens for “Proton Microscope”



Blue – field simulation
Red – field measurements

- REPM material – Nd-Fe-B alloy
- Magnetic field – 0.6 T (gradient 28 T/m)
- Nonlinearity - <0.75%
- Length – (Q4,Q7) 160mm и (Q5,Q6) 320mm
- Aperture – 40 mm



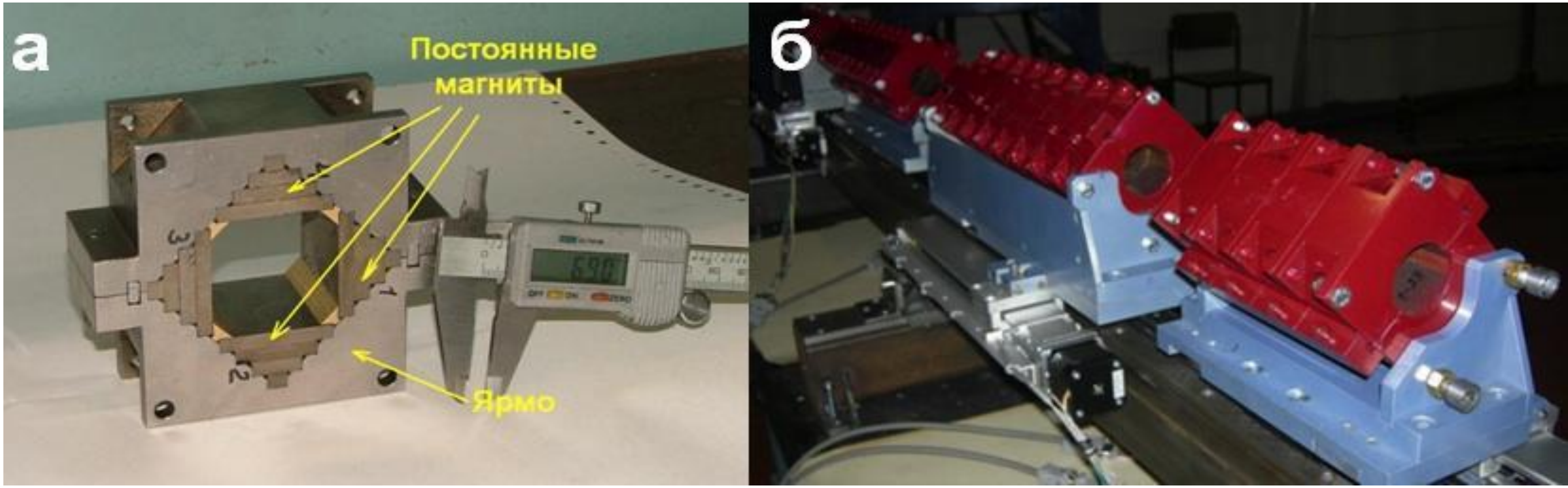
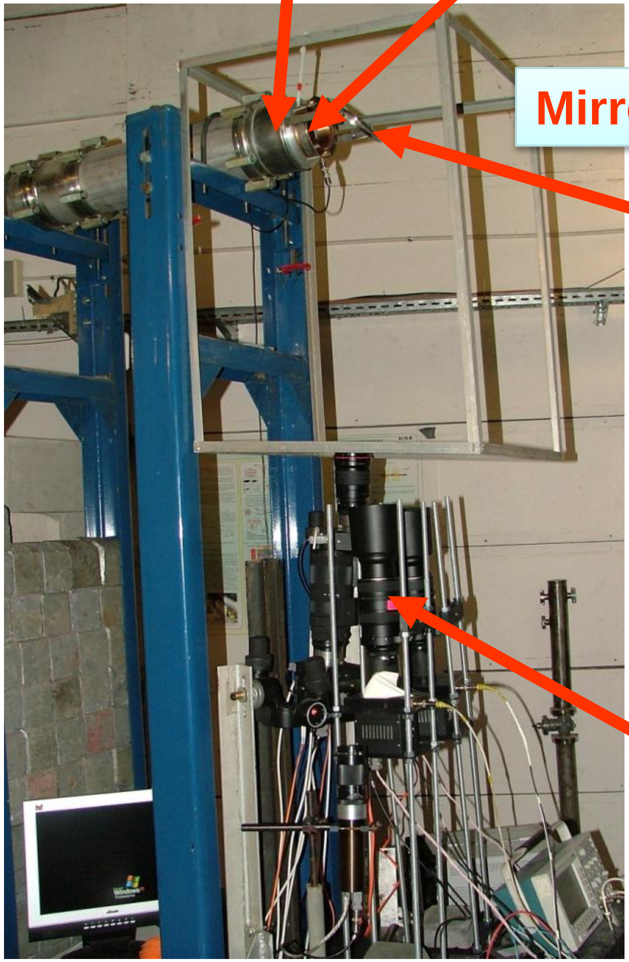


Image Registration System



Optical convertor:
LSO scintillator (40 ns), ∅78 mm

14 bit CCD cameras, fast shutter (100 ns), matched to beam bunch;

Temporal resolution = Bunch duration = **70 ns**

Allows to take 4 images of dynamic processes within 1 μs

Target Chamber



- HE mass (TNT) – up to **70 g**
- Pumped down to 10^{-3} Torr
- Active ventilation system
- Optical diagnostics - VISAR
- Target angular positioning ($\pm 10^{o}$)
- Static target positioning system
- Cryogenic target system

pRad for High Energy Density Physics Research

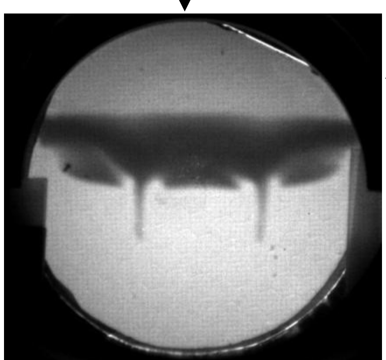
The higher spatial and density resolution should provide a new and unique window into the processes underlying dynamic materials science.

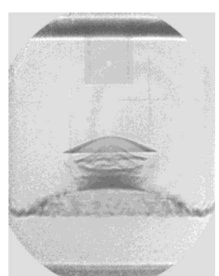
High Energy Density Physics

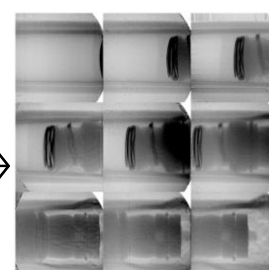
Hydrodynamics of HED flows (shock wave, detonation, hydrodynamic instabilities, ejecta formation)

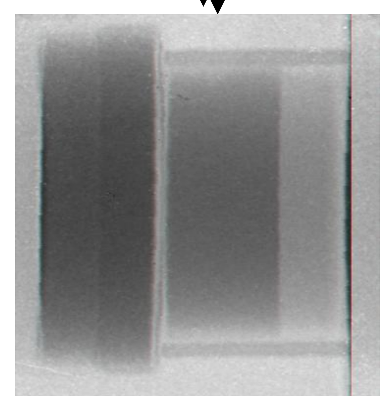
EOS and phase transitions (strongly coupled plasma, extreme state of matter, Warm Dense Matter.)

Material Strength and Damage (dynamic fracture of materials)









The definition of the parameters detonation wave by proton radiography method

Which is parameter of the detonation wave may direct measurement by proton radiography method?

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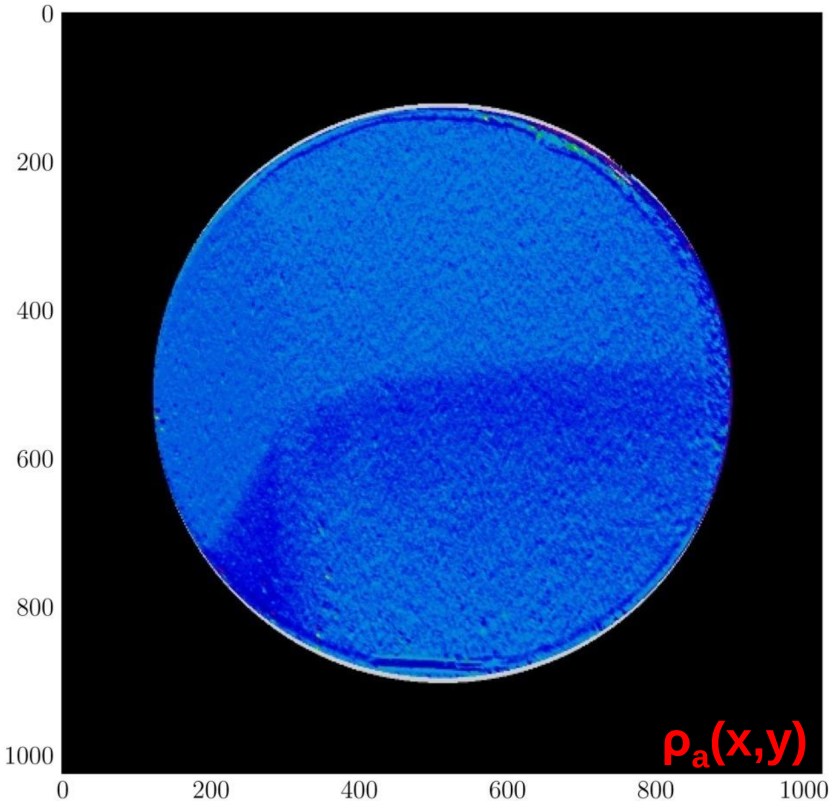
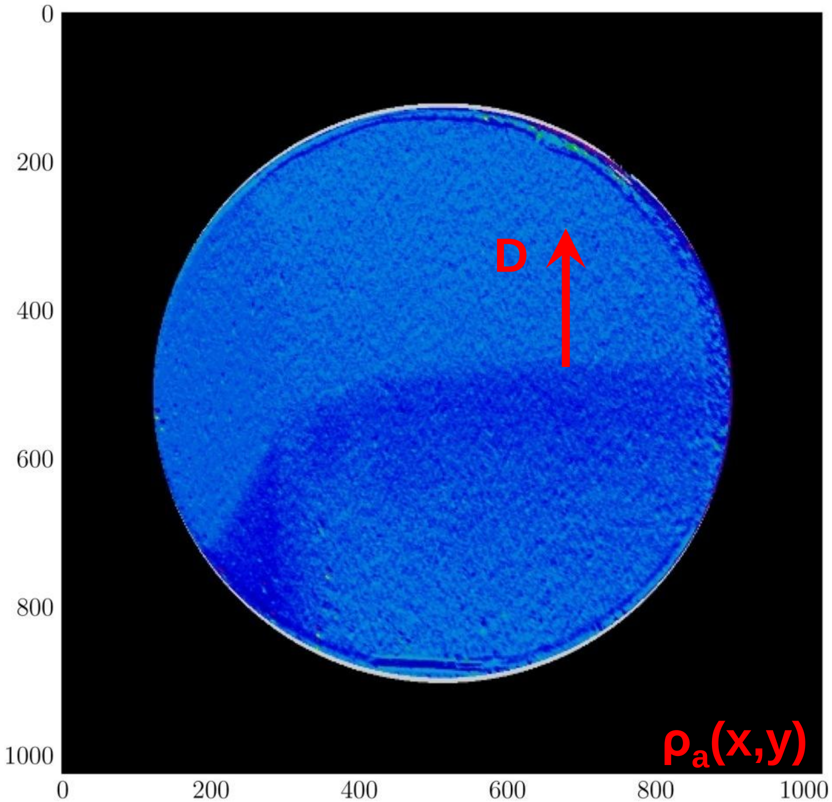


- Density distribution (linear and, after mathematic development, volume) ***$\rho_a(x,y)$, $\rho(r,z)$***

The definition of the parameters detonation wave by proton radiography method

Which parameter of the detonation wave may direct measurement by proton radiography method?



- *Density distribution (linear and, after mathematic development, volume)* ***$\rho_a(x,y)$, $\rho(r,z)$***

- *Detonation wave* ***D*** *by multi frame registration*

The definition of the parameters detonation wave by proton radiography method

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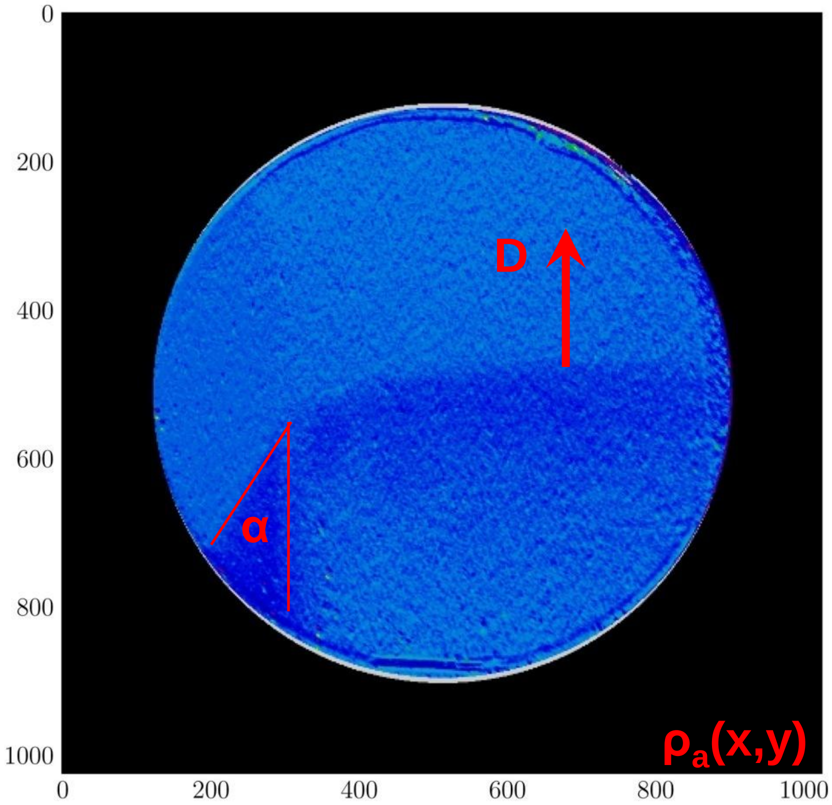

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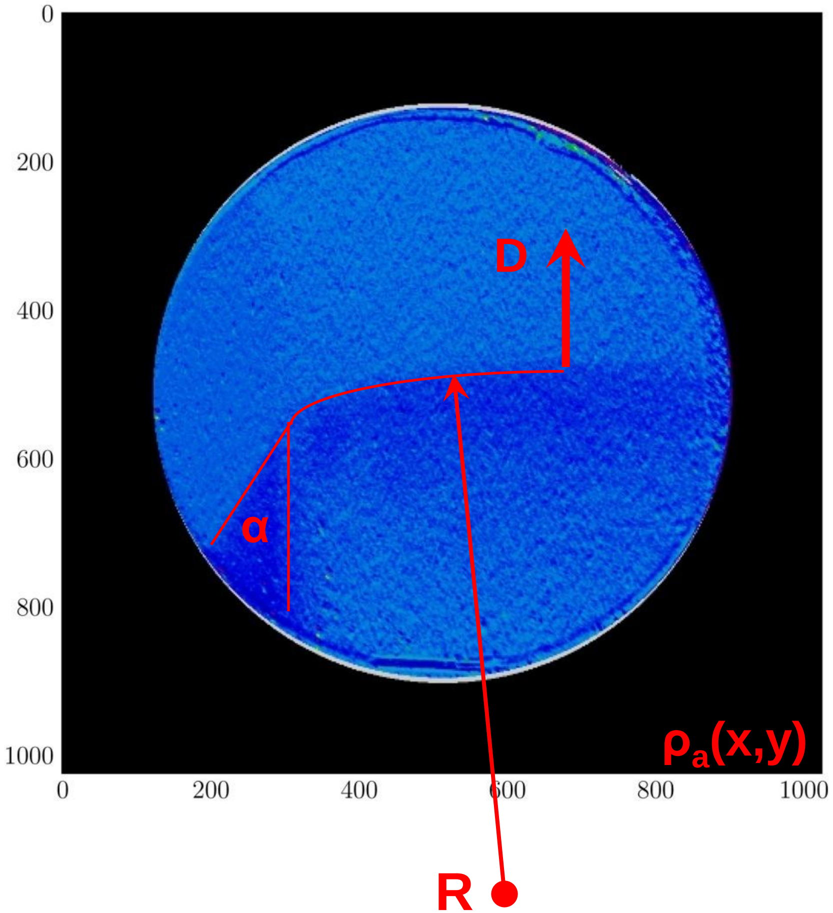


- *Density distribution (linear and, after mathematic development, volume)* $\rho_a(x,y)$, $\rho(r,z)$

- *Detonation wave* ***D*** *by multi frame registration*

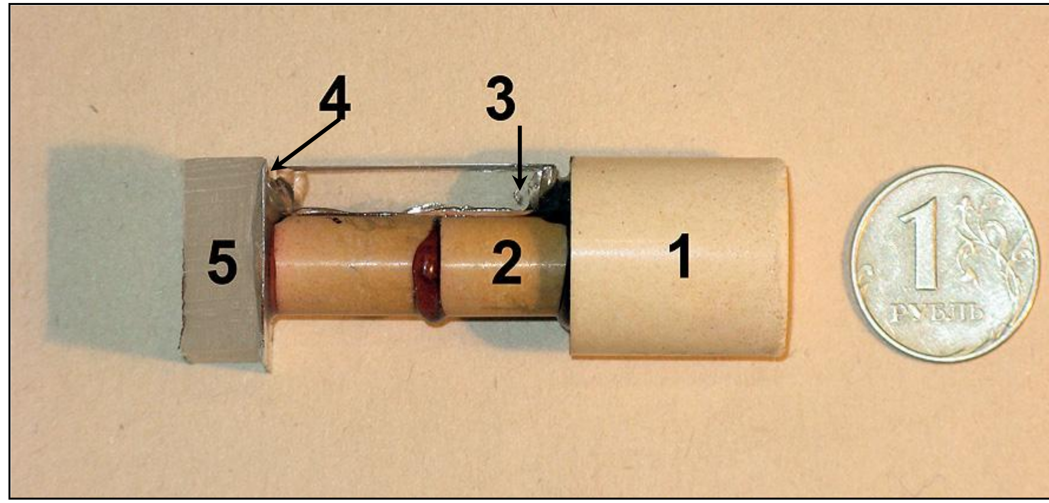
- *expansion cone parameters of the product detonation* ***α***

- *Detonation front curvature radius* ***R***

These parameters will be enough to reconstruct the full picture of hydrodynamic flow on the basic experimental data of one shot!

Detonation of Pressed TNT

(the results from June 2010)

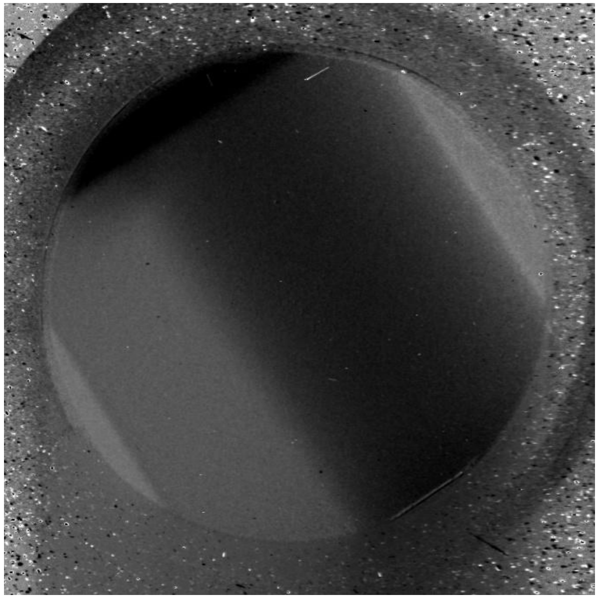


The photo of the target, charge TNT with diameter 10mm.
1 – detonator charge TNT (ТГ 50/50), 2 – investigation charge, the density 1.63 g/cm^3, 3 – 2 mm Plexiglas plate, 4 – 7μm Al-foil for VISAR diagnostic, 5 – the Plexiglas window.

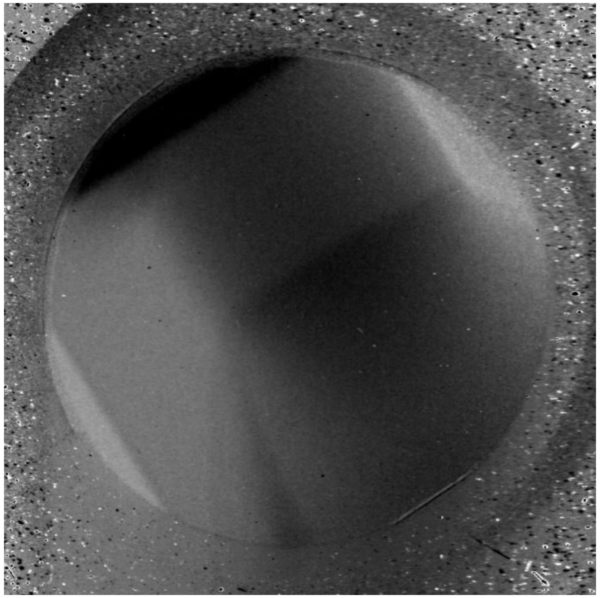
The experimental area

Detonation of Pressed TNT

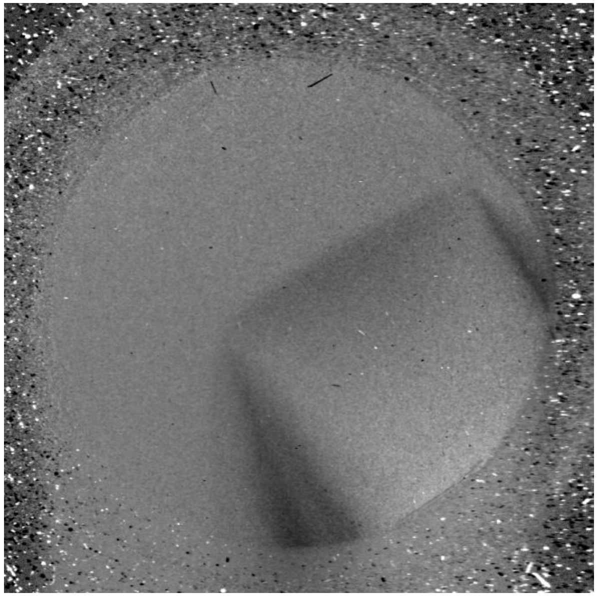
(the results from June 2010)



The proton radiography image of the static target



The proton radiography image of the detonation process



The relative density between dynamic and static target.

The numerical simulation of the expansion cone: ***23.8°***

The expansion cone of the product detonation (on the right wall): ***25.0 ± 3.0°***

The expansion cone of the product detonation (on the left wall): ***22.5 ± 3.0°***

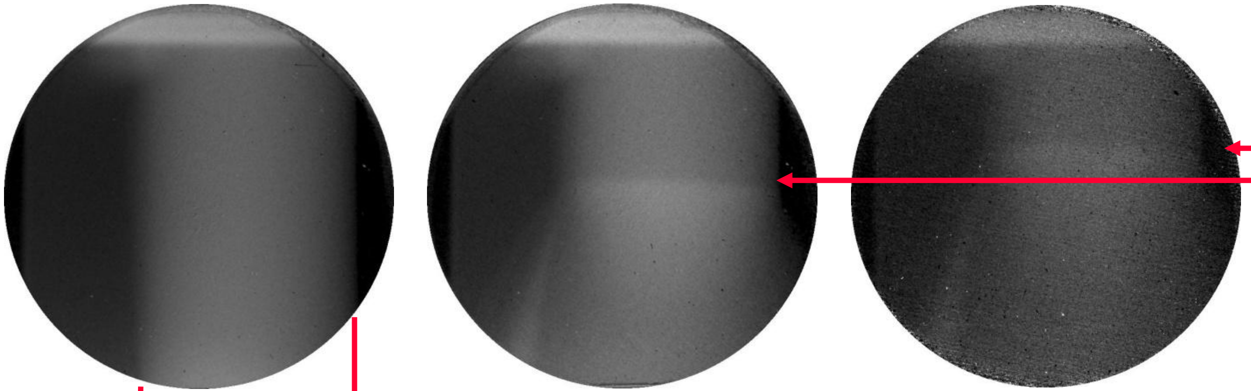
The cone in the Plexiglas plate: ***35.0 ± 2.0°***

Detonation of Pressed TNT

Static image | Bunch 2 image (T_2) | Bunch 3 image (T_3)

$\Delta T = T_3 - T_3 = 250$ ns

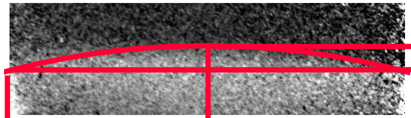
$\delta T = 70$ ns



$\Delta X = 1.72 \pm 0.05$ mm

ø10 mm

Detonation velocity $D = \Delta X/\Delta T = 6.9 \pm 0.2$ km/s



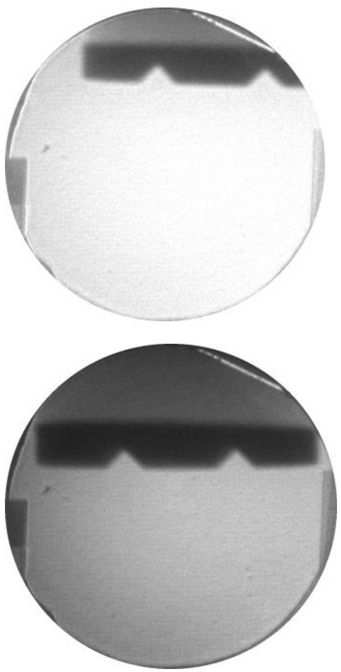
$\partial = 0.43 \pm 0.05$ mm

r = 5 mm

Detonation front curvature radius R = 58 ± 7 mm

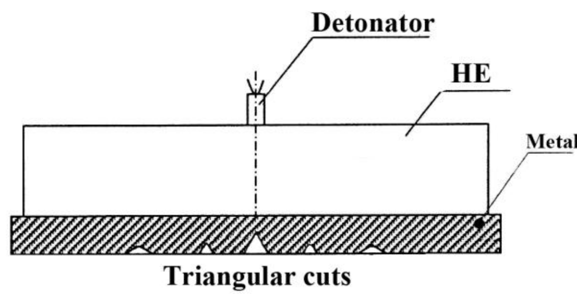
Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

Proton radiography images of static targets



Steel target

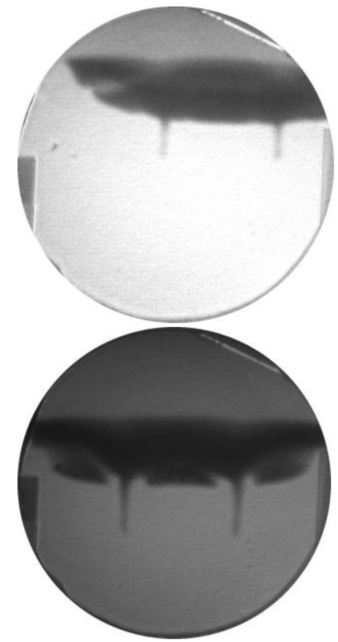
Diameter – 15 mm
Thickness – 2 mm
Depth of cuts – 1 mm



Copper target

Similar to steel one

Proton radiography images of dynamic shots at 1.5 μs after shocking the free surface of a target

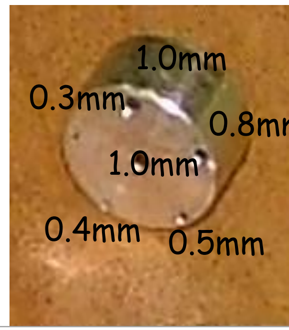


The radiographic images of shock loading of irregular free surfaces of 2 mm thick steel and copper plates attached to detonating TNT charges were registered. Loaded surfaces had various triangular cuts, and radiographic images clearly showed the formation of jets of ejected target material above them, while at the same time a spallation and fracture of initial plates was observed. Jets in copper targets formed faster and contained more material than in similar steel targets, while observed fracturing of targets with different materials occured by different mechanisms.

ITEP Proton Microscope: Static test-objects

Tomography reconstruction of multi-projection proton microscopy

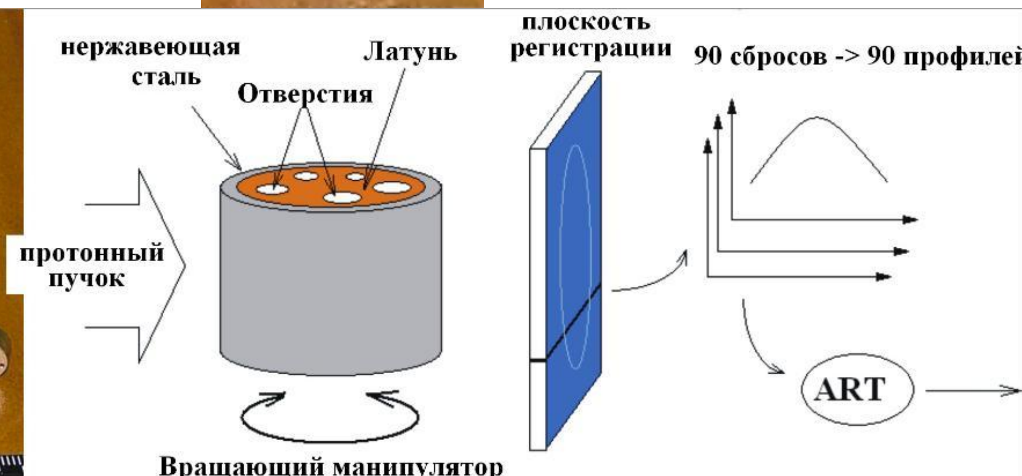
Brass target

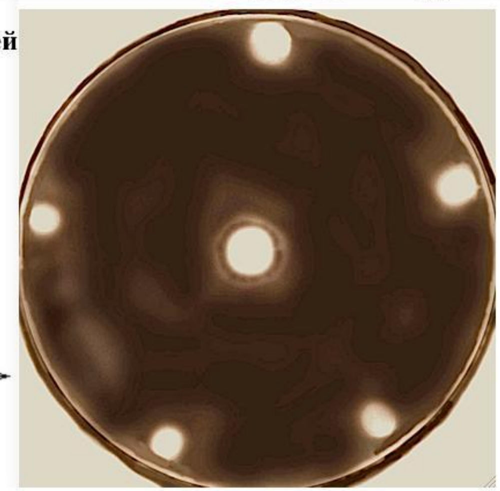


Requirements:

- good spatial and density resolution for projection images
- high precision for target positioning and alignment

Targets and SS container

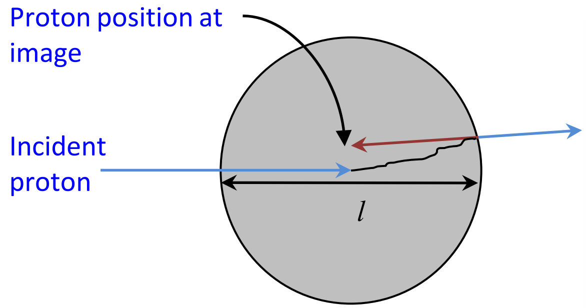


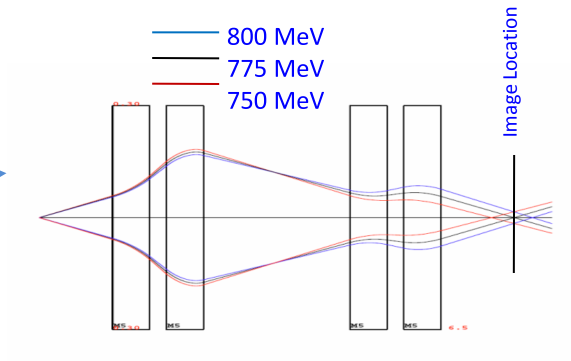


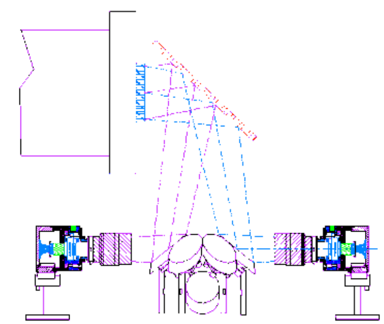
Reconstructed two-dimensional target density distribution by Algebraic Reconstruction Technique (ART). Special resolution 220±80μm

Resolution of Proton Radiography

1. ***Object scattering*** - *introduced as the protons are scattered while traversing the object.*
2. ***Chromatic aberrations***- *introduced as the protons pass through the magnetic lens imaging system.*
3. ***Detector blur***- *introduced as the proton interacts with the proton-to-light converter and as the light is gated and collected with a camera system.*







Object scattering:

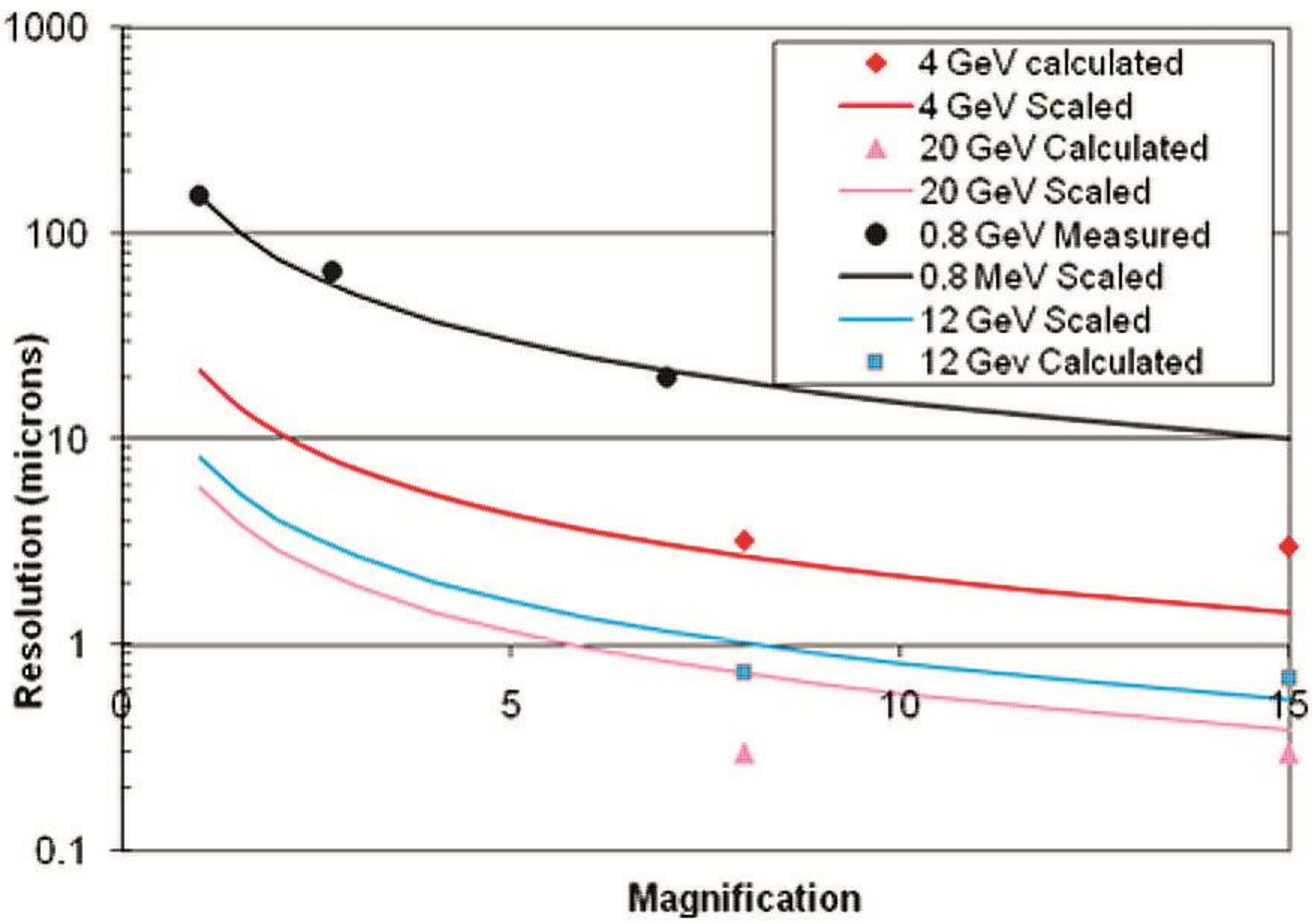
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{\frac{3}{2}}}{P}$$

Chromatic aberration:

$$\sigma_c = l_c\theta\frac{\delta P}{P} = c\sqrt{P}\frac{\delta P}{P^2}\frac{14.1}{\beta}\sqrt{\frac{l}{x_o}} \propto \sqrt{\frac{l}{P^3}}$$

Scintillator blur:

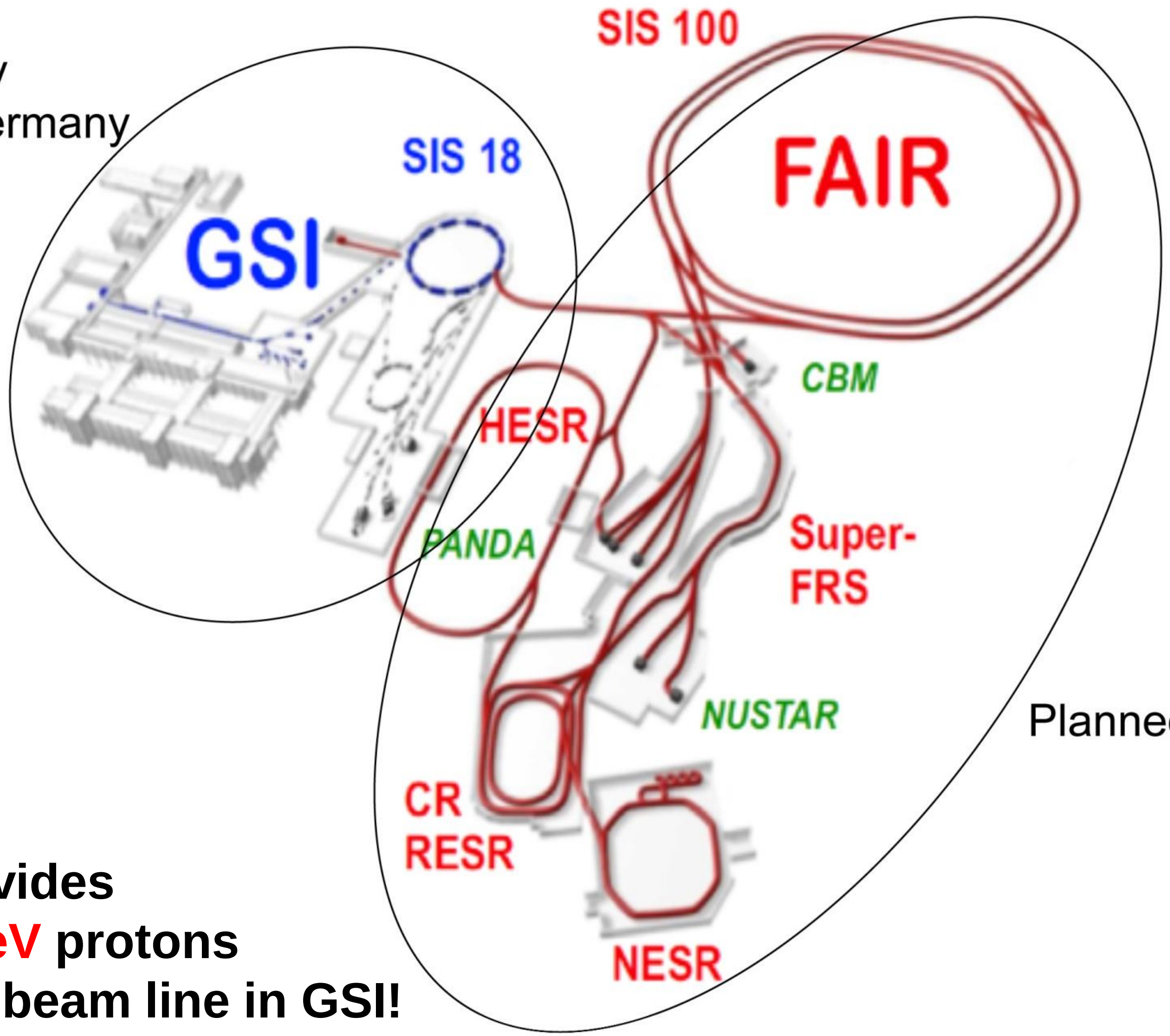
$$\sigma_s = \theta l_s \propto \frac{l_s\sqrt{l}}{P}$$



At higher proton beam energies a <u>sub-micron</u> range of spatial resolution can be reached!

GSI / FAIR

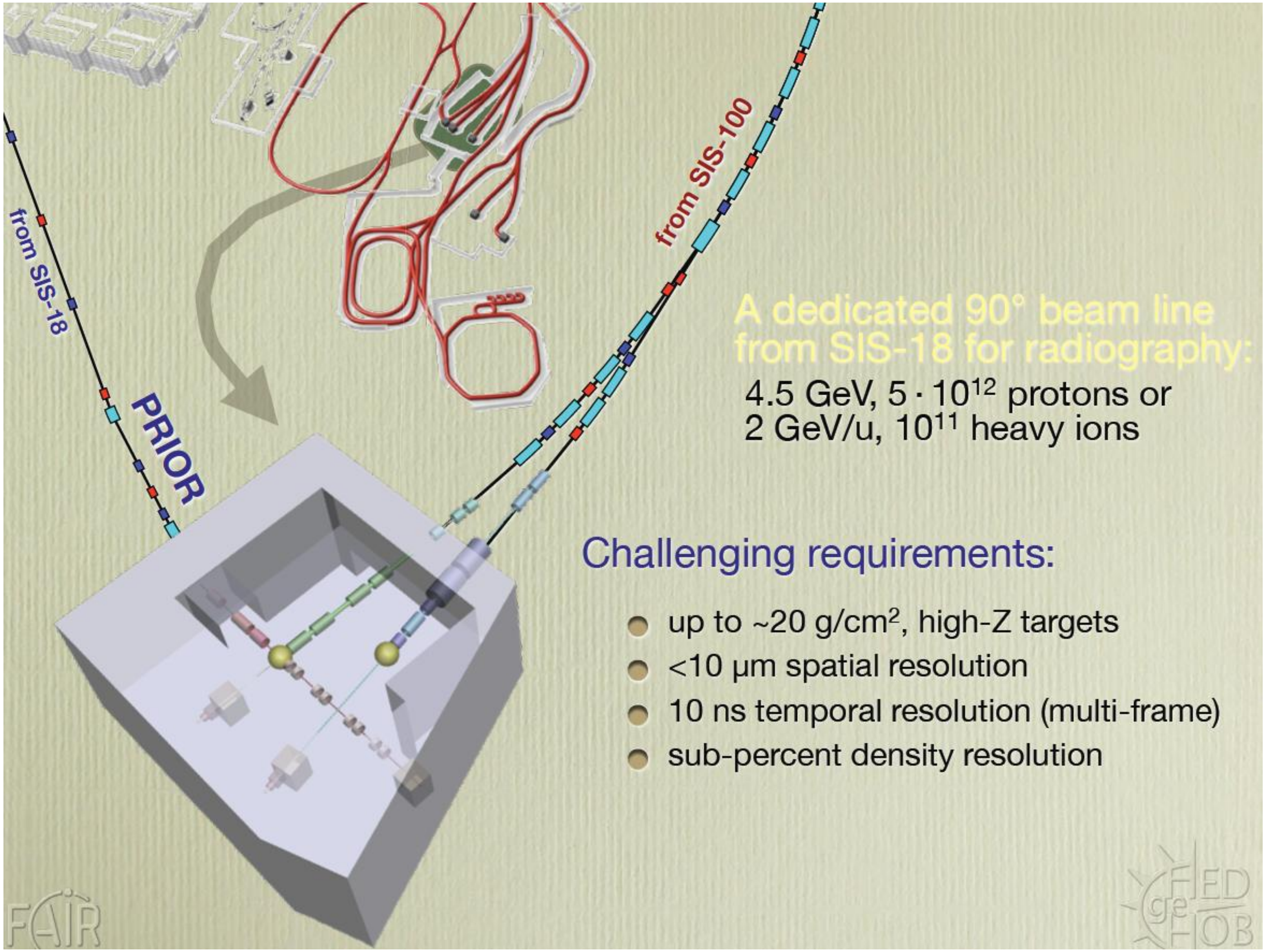
Existing facility
Darmstadt, Germany



Planned Upgrade

Already provides
$5 \cdot 10^{12}$ 4.5 GeV protons
from SIS-18 beam line in GSI!

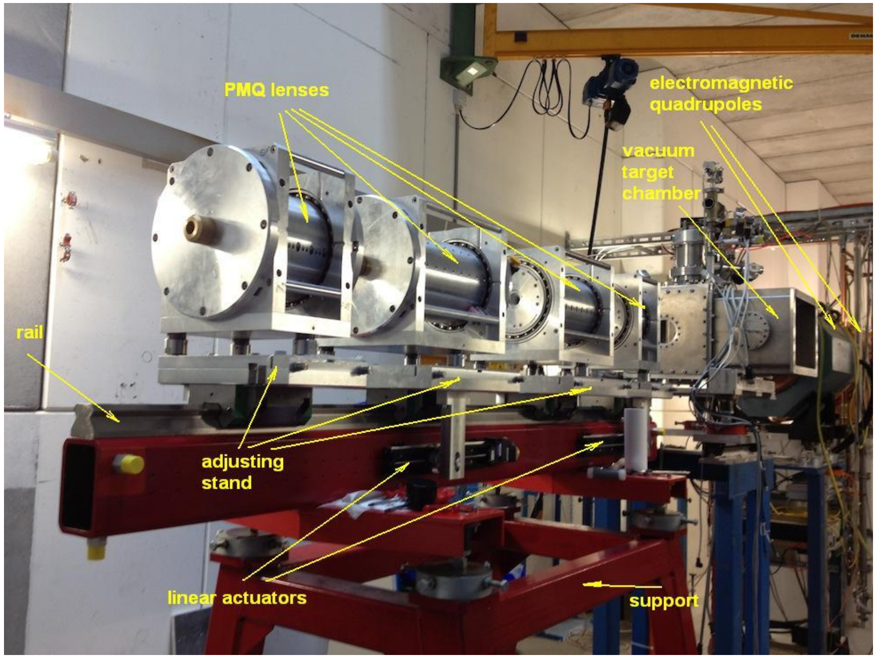
Ion Driven HEDP Studies at FAIR

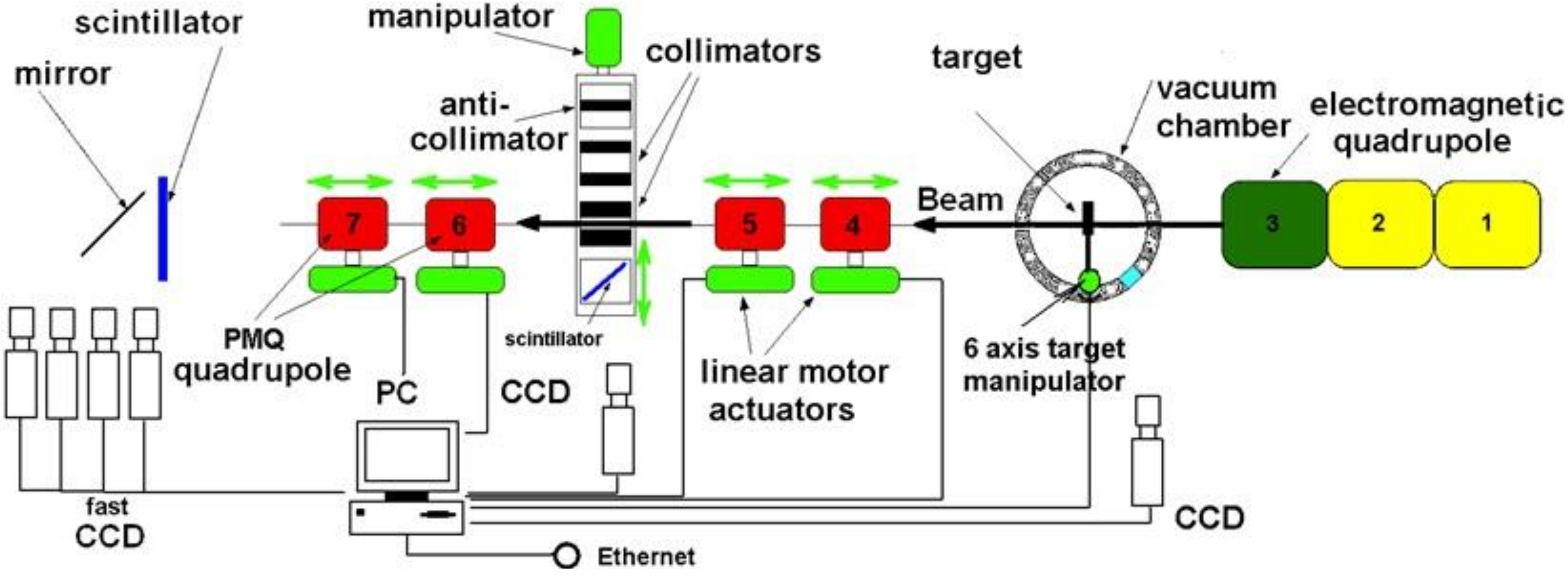


PRIOR (Proton microscope for FAIR)

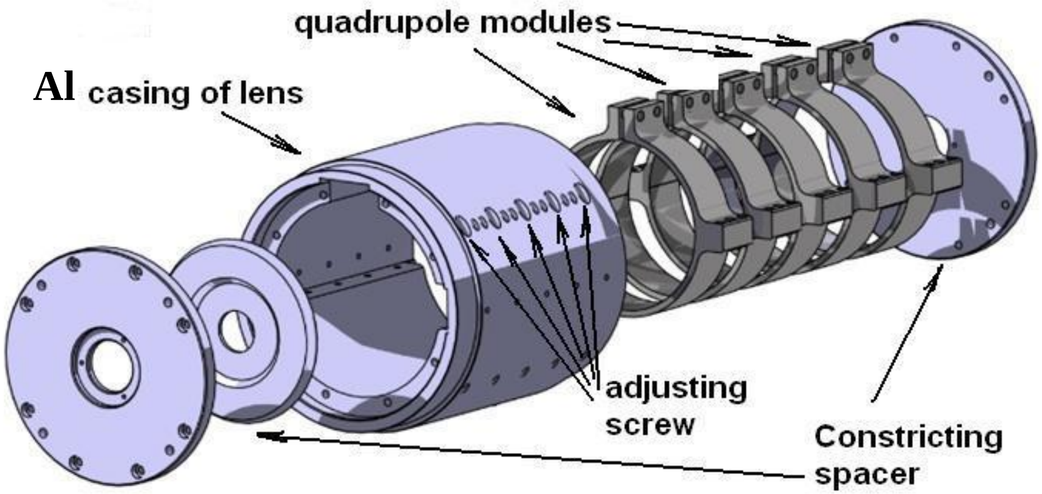
Main parameters:
•proton energy: up to **4.5 GeV**;
•areal density of target: up to **10-20 g/cm²**;
•areal density reconstruction: sub-percent level;
•spatial resolution: less than **10 μm**;
•temporal resolution: **10 ns**;
•multi-framing capability: up to **4** frames per dynamic event (at GSI), 16 frames at FAIR ;
•field of view: 10 – **15** mm;
•length of setup ~ 25 m
•proton beam intensity: $5*10^{10}$ (at GSI),

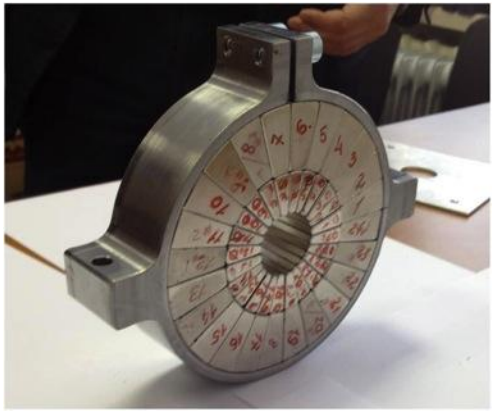
•chromatic length: ~3 m



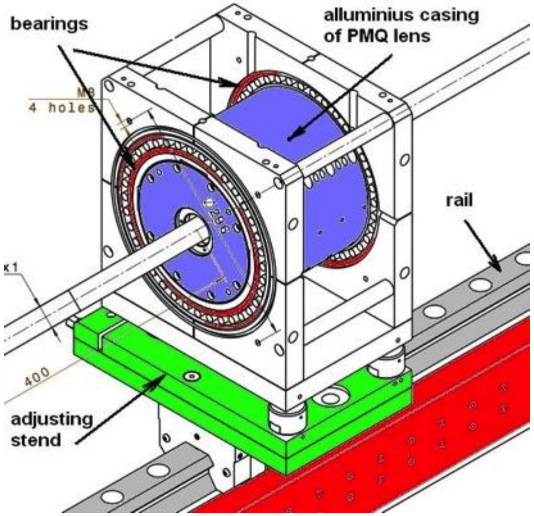


Permanent Magnet Quadrupole lens



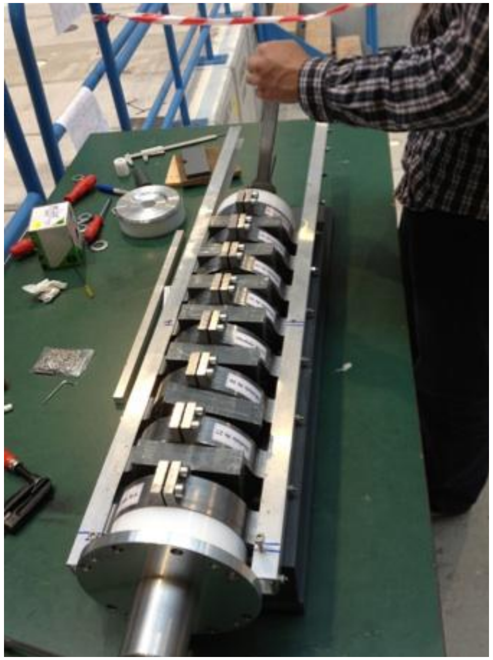


One quadrupole module
in metal case



Main parameters of PMQ lenses:

PMQ quantity: 4
Pole tip field: 1.83 T
Field gradient: 122 T/m
Nonlinearity: <0.9%
Two layer structure with trapezoidal sectors
Magnetic element material: NdFeB
Aperture diameter: 30 mm ;Outer diam. 210 mm
PMQ Length: 180mm (144 mm) (4 modules+1 dummy)
360mm (288 mm) (8 modules +2 dummy)
Possibility to use same lenses at FAIR (10 GeV proton beam) with addition modules

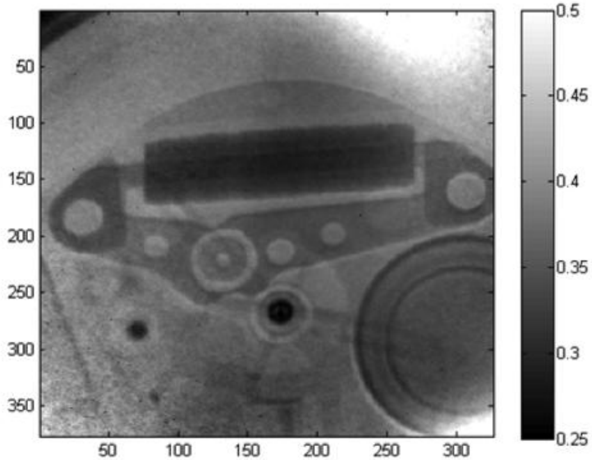


Stand for pull together of
quadrupole modules

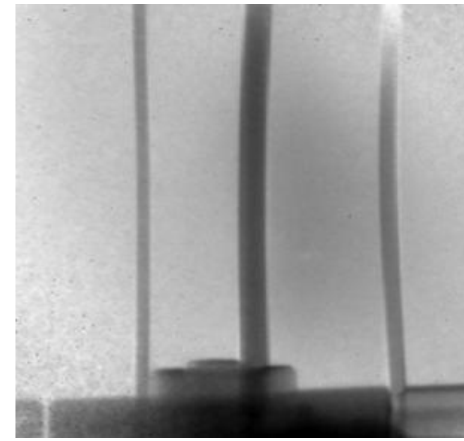
Static commissioning of PRIOR

(April 2014, GSI, SIS-18, proton beam energy 3.6 GeV)

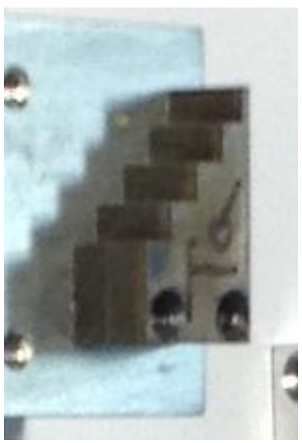
Quartz watch

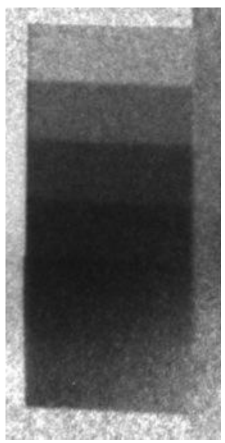


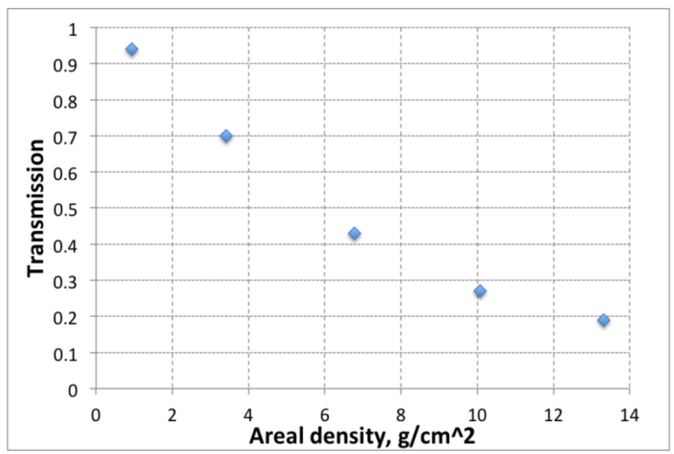
Ta wire 0.8 mm

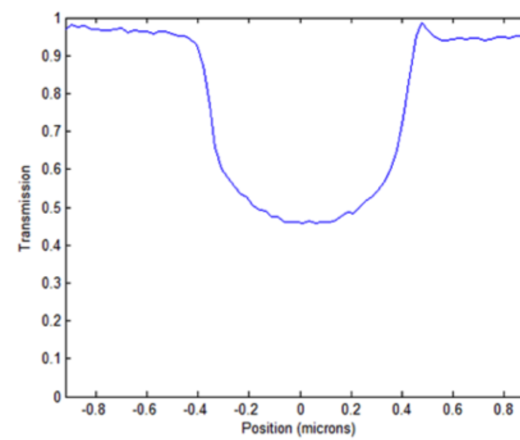


Thickness of Ta steps (0.56 mm, 2.06 mm, 4.07 mm and 6.05 mm)



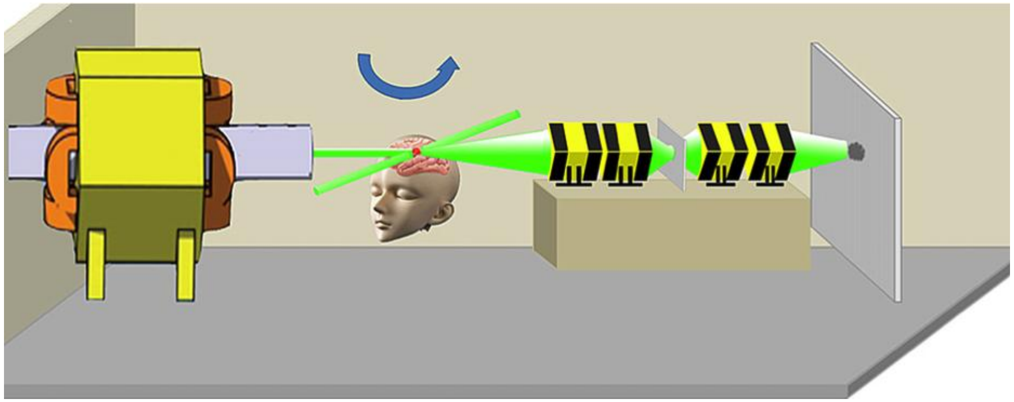






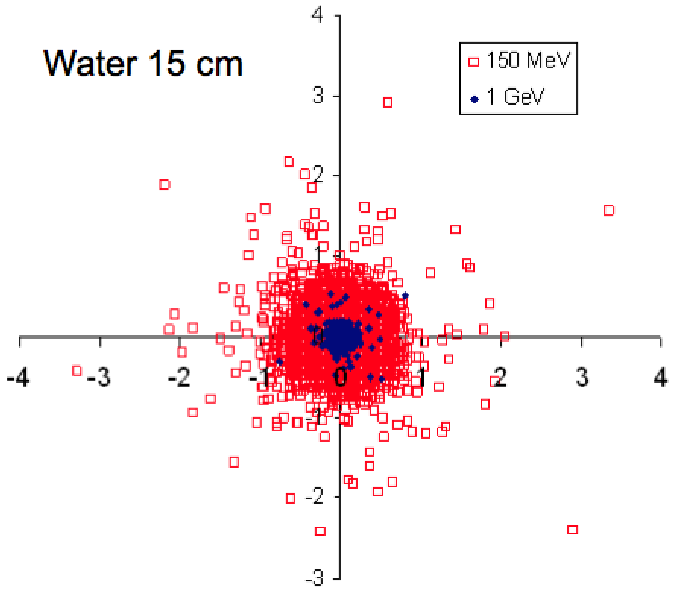
Best spatial resolution of 30 µm was obtained with target - tungsten rolled edge with a radius of 500 mm, resulting in an effective width of ~ 10 mµ.

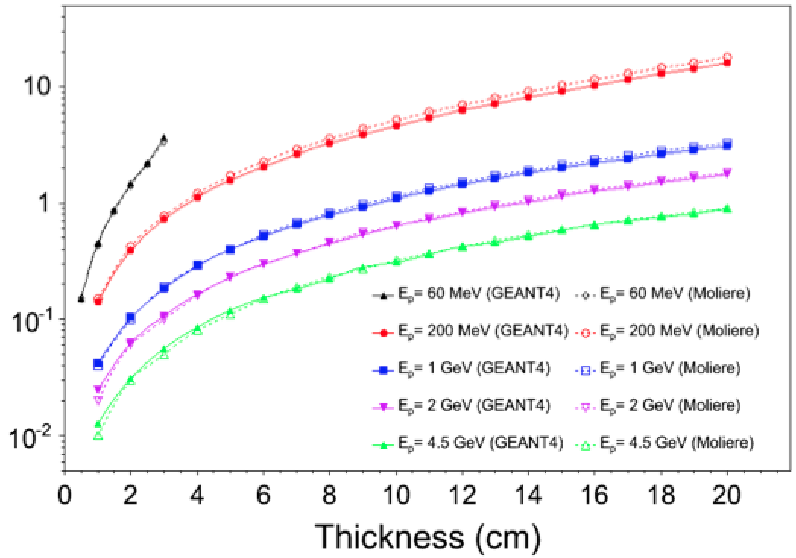
Experiment PaNTERA – ProtoN ThErapy and Radiography (image-guided stereotactic particle radiosurgery IGSpRS)



Advantages with high energy protons and proton radiography:
Online imaging and low lateral scattering allow reduction of margins, treatment of moving targets and dose escalation

Lateral scattering for high energy protons



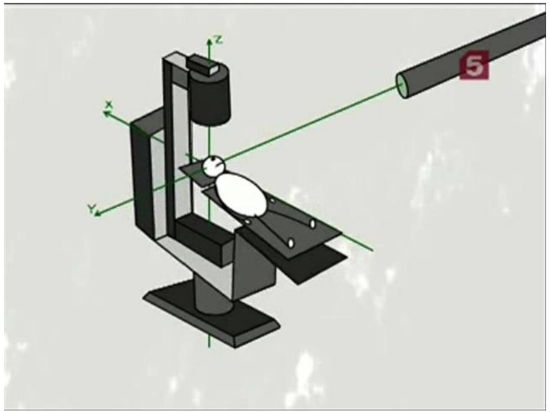


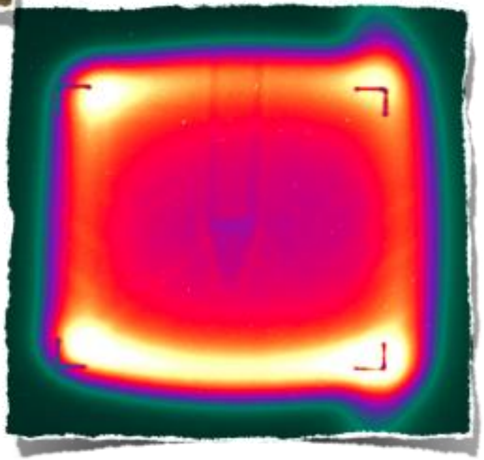
The only facility where 1 GeV protons are used for therapy

St.-Petersburg Nuclear Physics Institute (PNPI), Russia

Since 1975 a total of 1,362 patients treated:

- pituitary adenoma
- breast and prostate cancer
- AVM
- aneurysm
- endocrine ophtalmopathy
- epilepsy



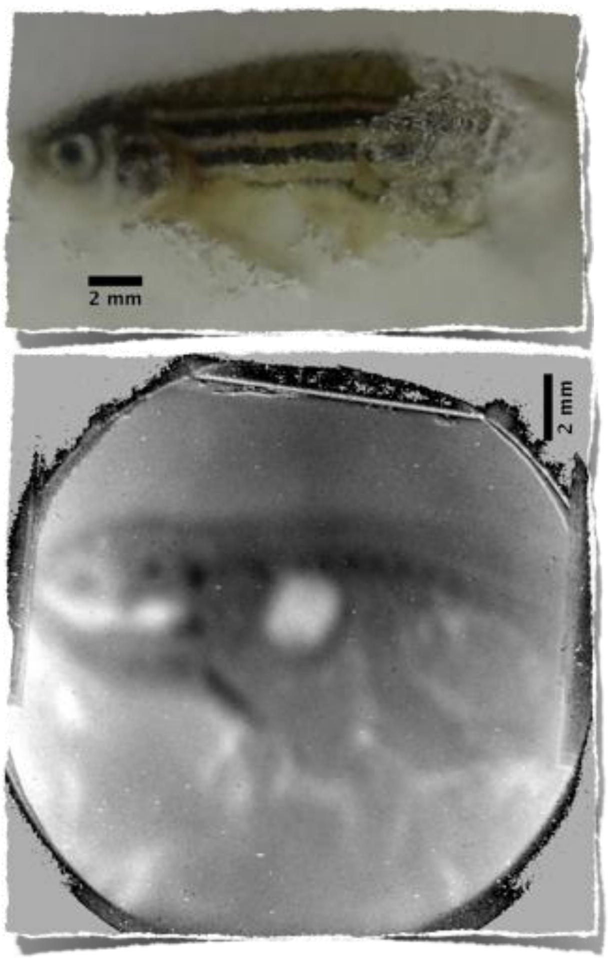


A 10 cm diameter 1 GeV proton beam used to expose blood cells in a plastic tube – visible in scattering proton radiogram

First biological images with HEPM

- ITEP-Moscow, December 2011, 800 MeV protons, pRad microscope

Zebrafish (*Danio rerio*) embedded in 1cm-thick paraffin



8 mm-thick PMMA phantom with 1mm-thick, 1mm-deep letters milled on the surface

Conclusions

- Proton radiography facility is the unique new tool for studies of dynamic materials science.

- Multi-pulse proton radiography has turned into a useful radiographic probe for dynamic as well as static measurements.

- There are new applications every year.

- The higher spatial and density resolution should provide a new and unique window into the processes underlying dynamic materials science.
    - Warm Dense Matter, Equations of state and Phase transitions.
    - Material damage process, void formation and coalescence and failure.
    - …