The Abdus Salam International Centre for Theoretical Physics

2370-15

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

Proton radiography

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Proton radiography

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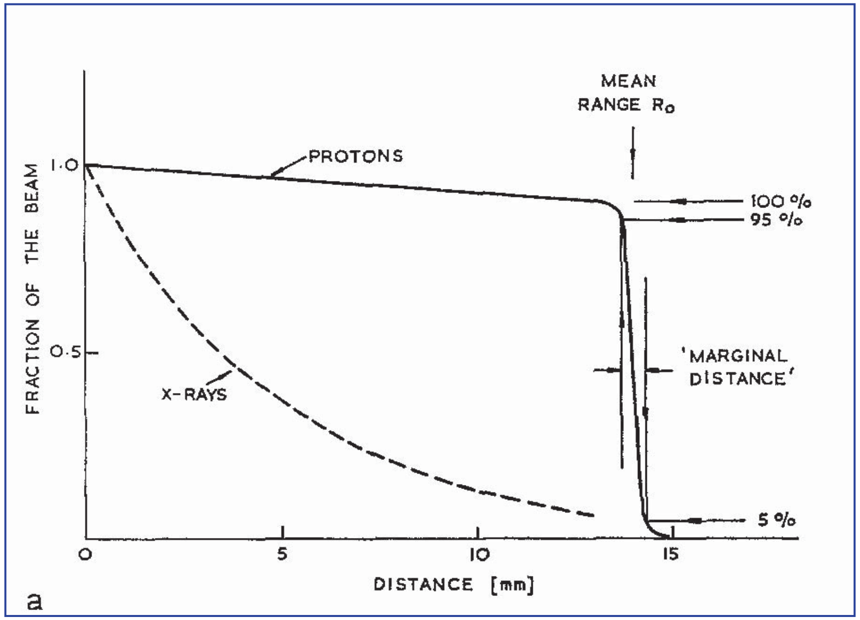
School &Training Course on Dense Magnetized Plasma

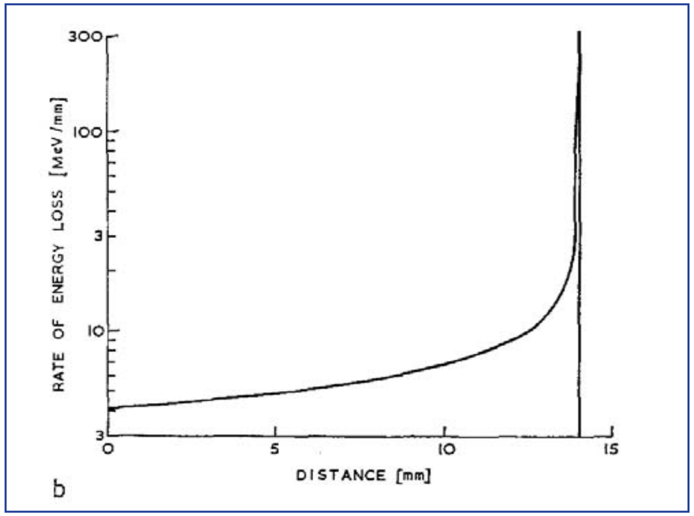
Trieste, 8-12 October

Basic physics of the «Marginal Range» Proton Radiography

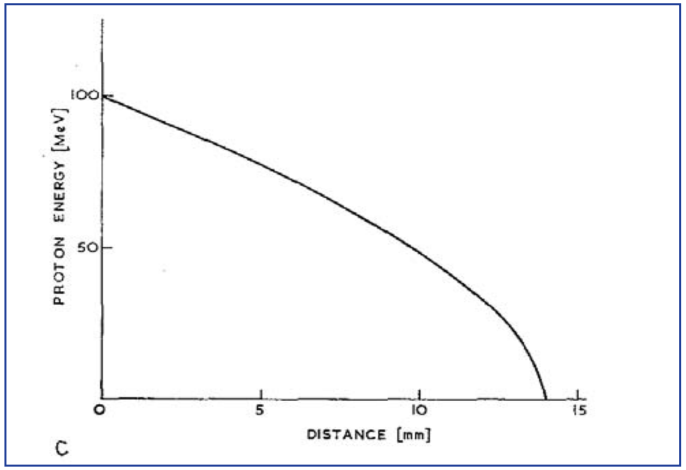
- Reduce proton beam energy to near end of range.
- Use steep portion of transmission curve to enhance sensitivity to areal density variations.
- Coulomb scattering at low energy results in poor resolution >1.5 mm.
- Contrast generated through proton absorption.



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

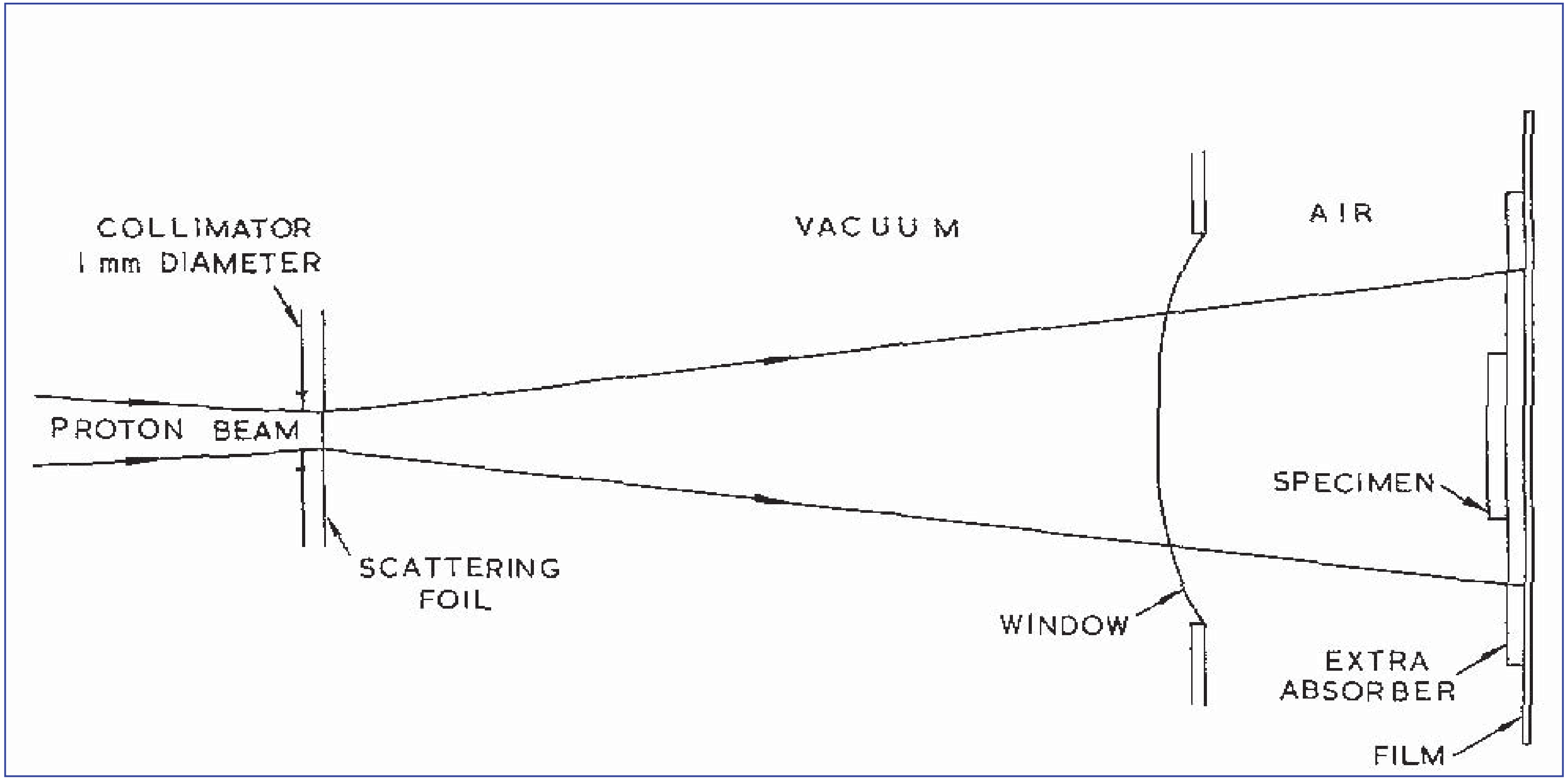


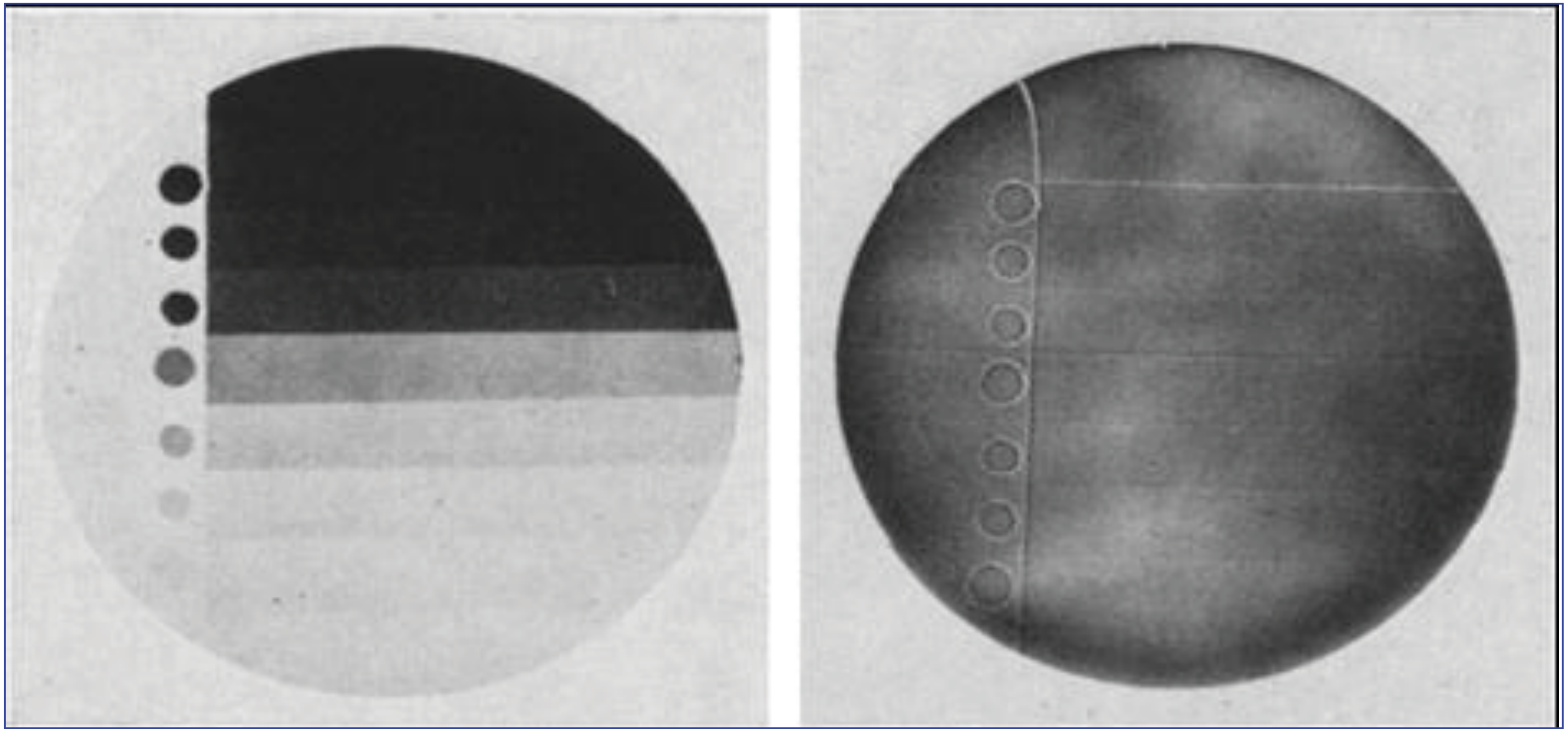
The energy lost per mm for a typical proton as a function of the distance it has travelled in iron.



The residual energy of an individual proton as a function of the distance it has travelled in iron

Typical system for Marginal Range Proton Radiography.



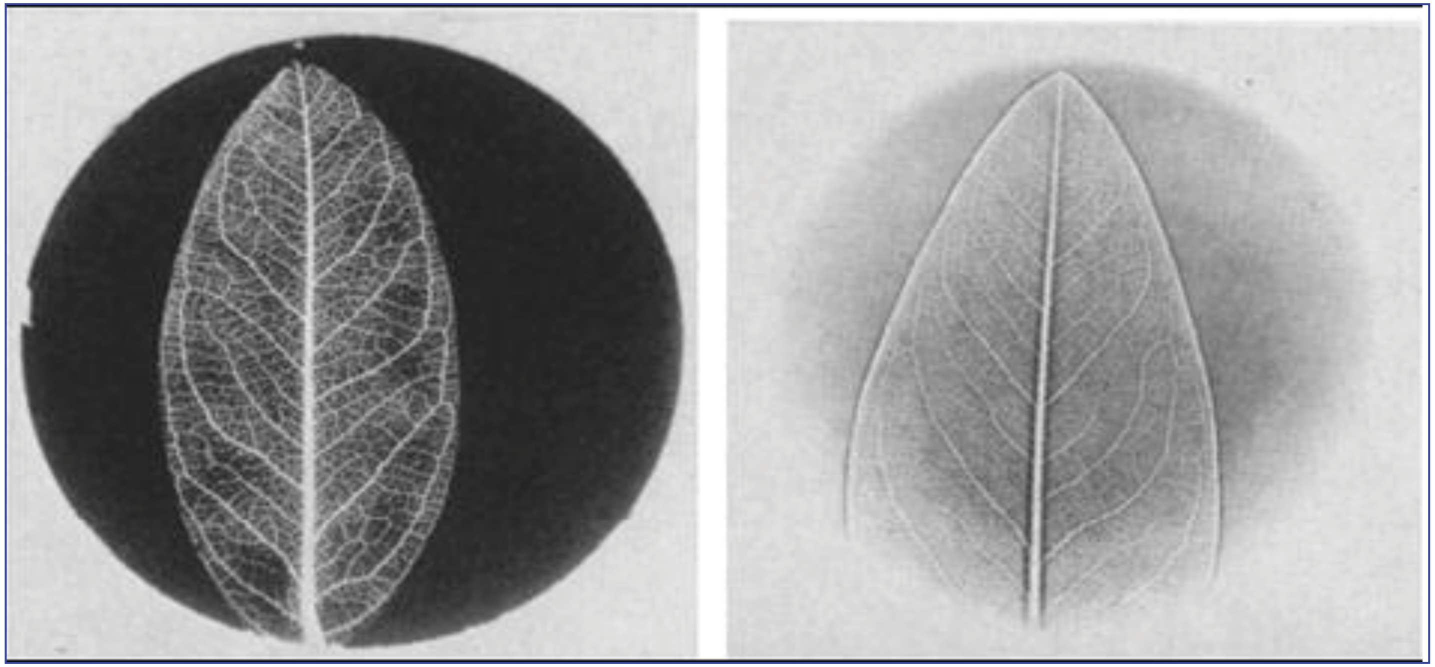


Radiographs of a wedge with steps of 2.1 mg/cm ^{2} Al. The pattern of dots identifies the position of the wedge.

a) Marginal range technique. 213 mg/cm^2 extra Al absorber. Ni strips of 0.29 mg/cm^2 and 0.26 mg/cm^2 give vertical lines on the left and right sides of the wedge,

b) Multiple scattering technique. Wedge-to-film distance 14 mm

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



Radiographs of leaves by
a) marginal range radiography with 196 mg/cm^2 of extra Al absorber.
b) scattering radiography with leaf sandwiched between two 6.9 mg/cm^2 Al layers and 14 mm from the film

12.10.2012

Scattering Proton Radiography

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

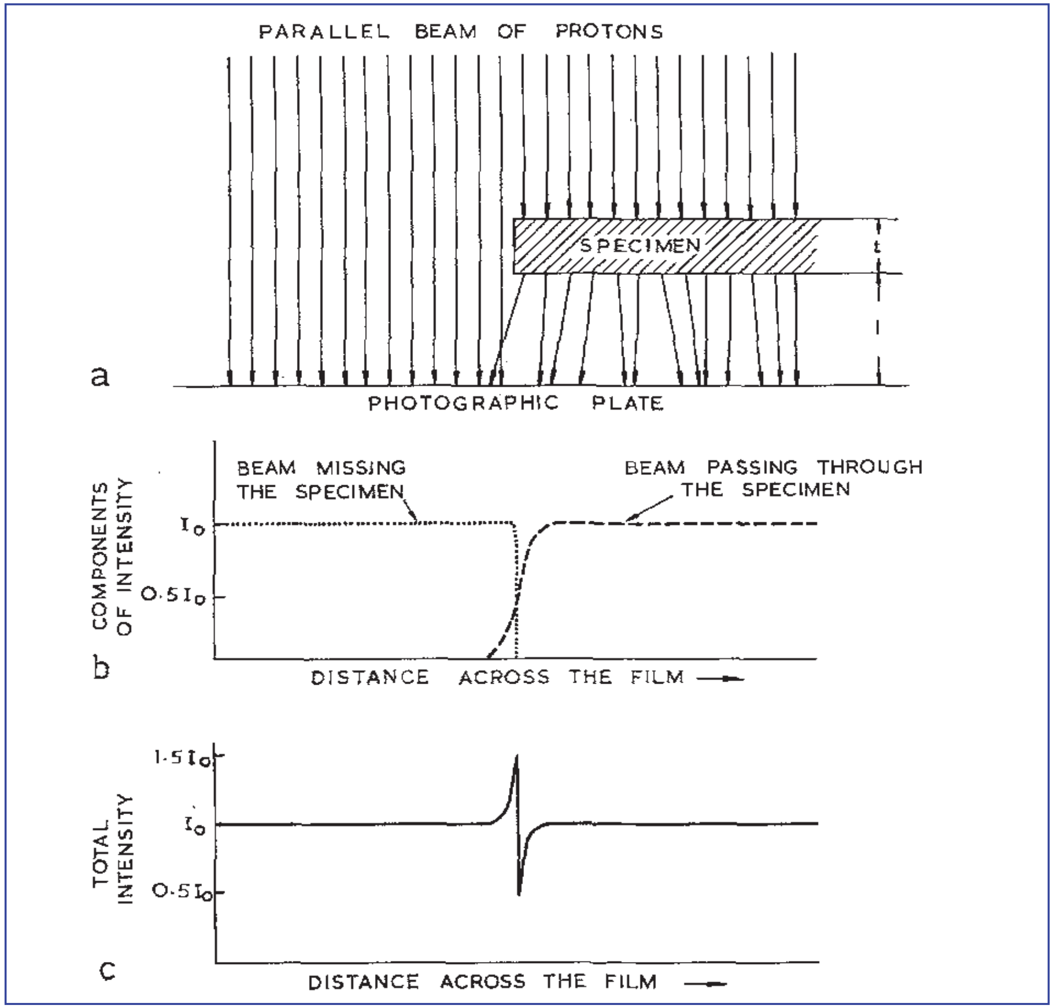
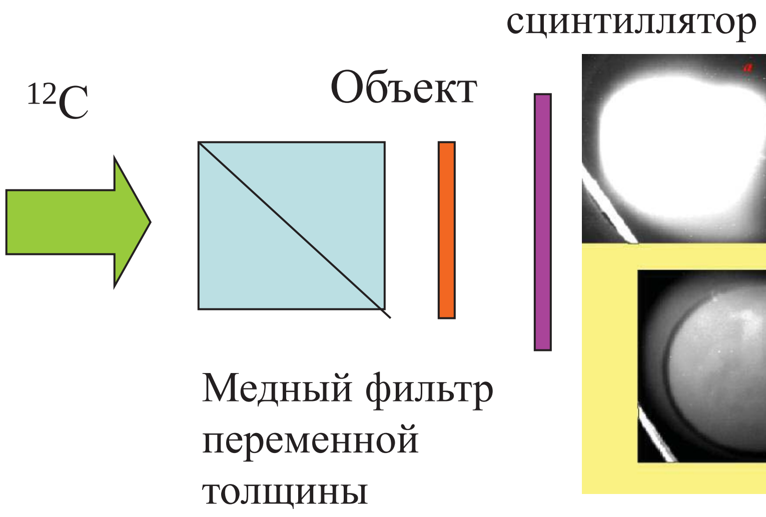
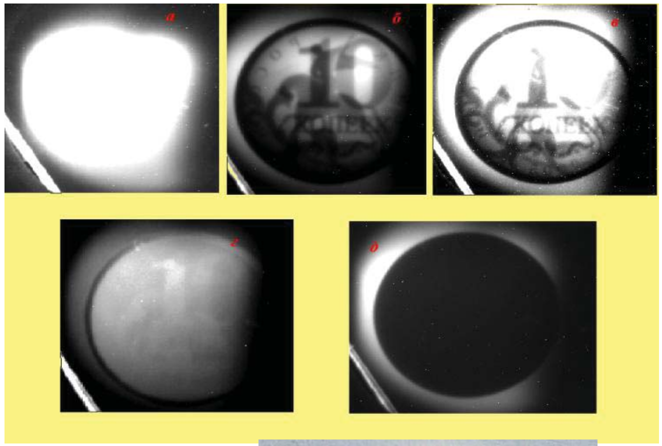
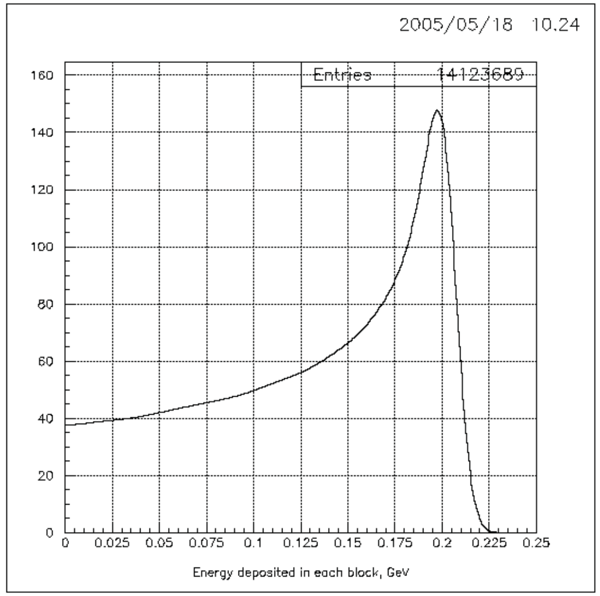


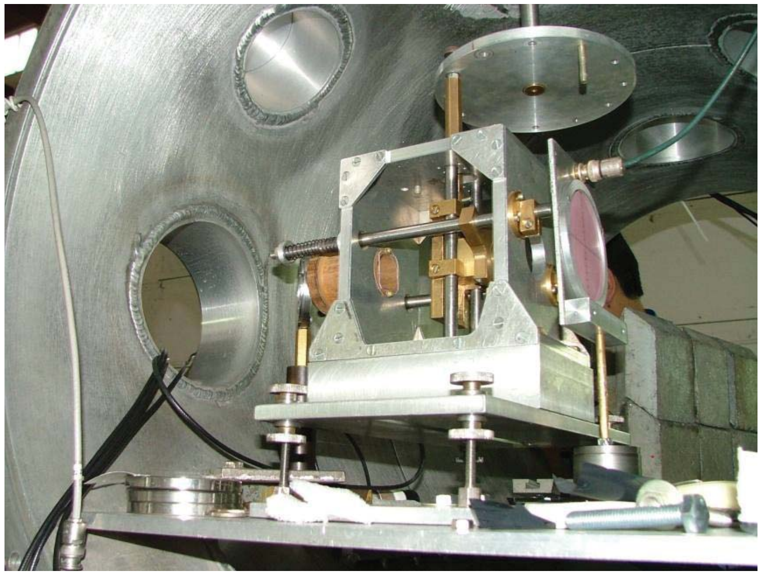
Illustration of how multiple scattering produces its characteristic edge pattern

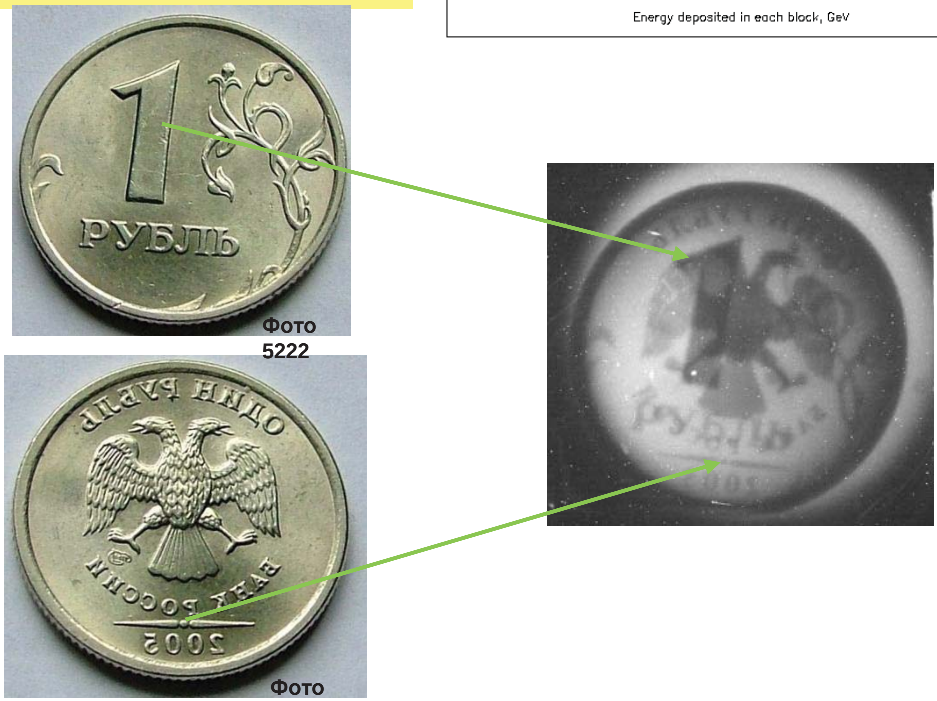
Ion Radiography



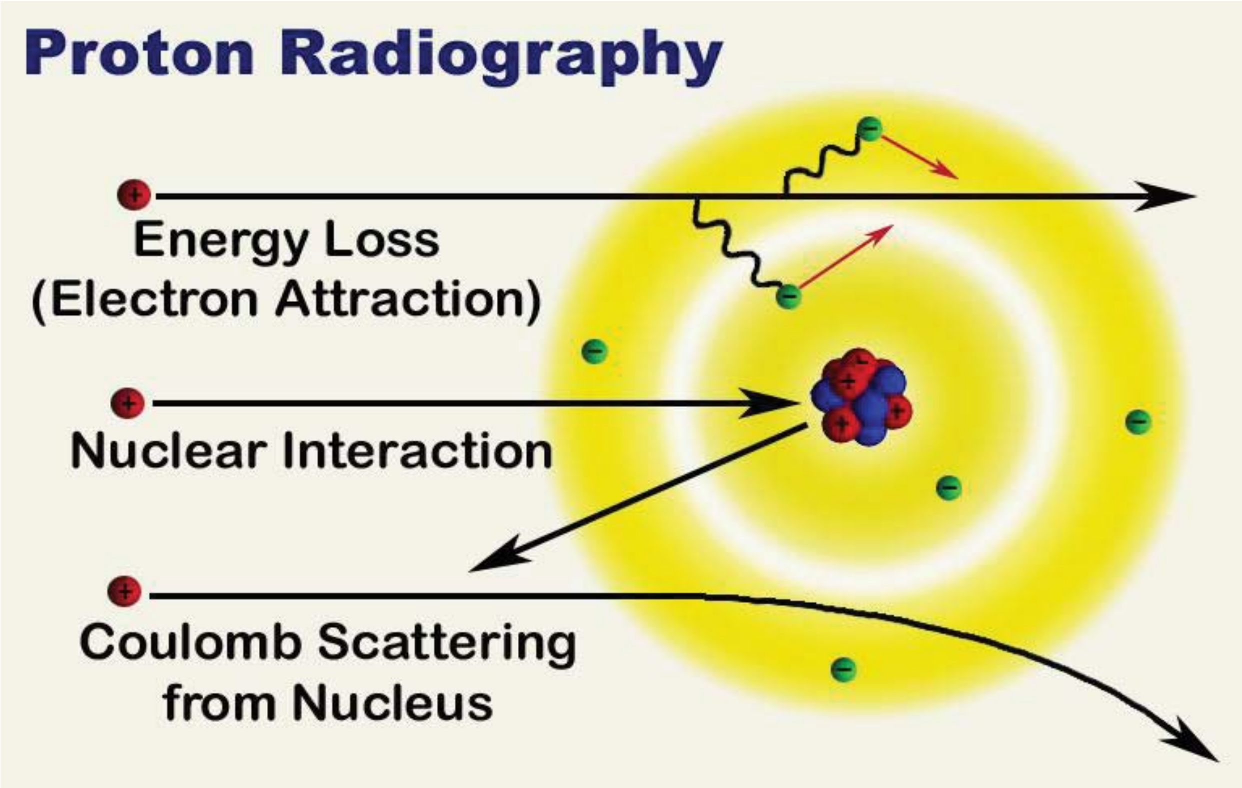








Proton Radiography Principle



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

1st LANL Proton Radiography (1995)

188 MeV secondary proton beamline at LANSCE

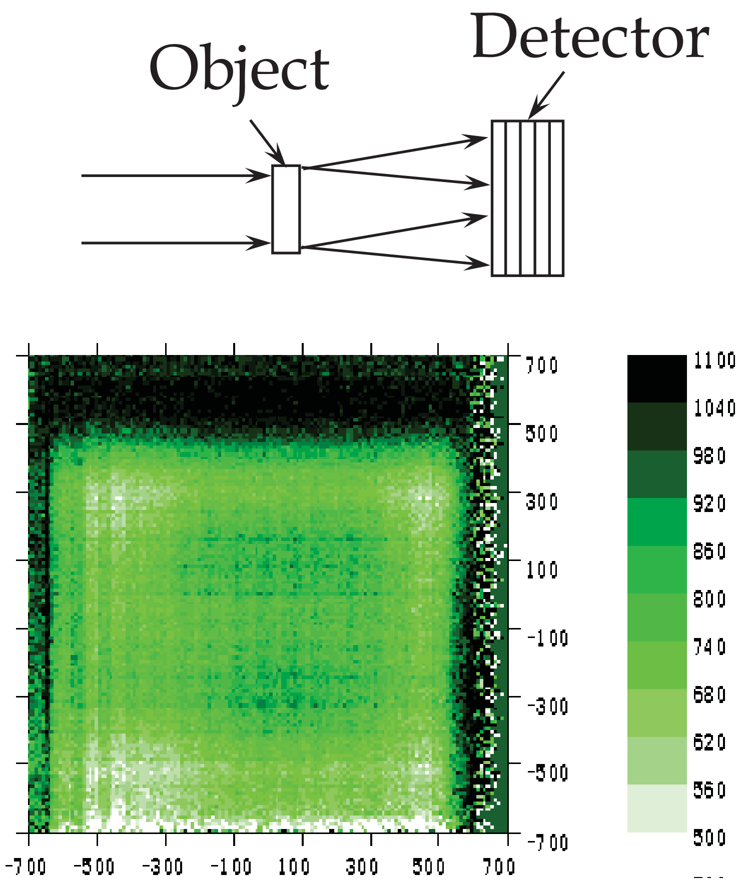
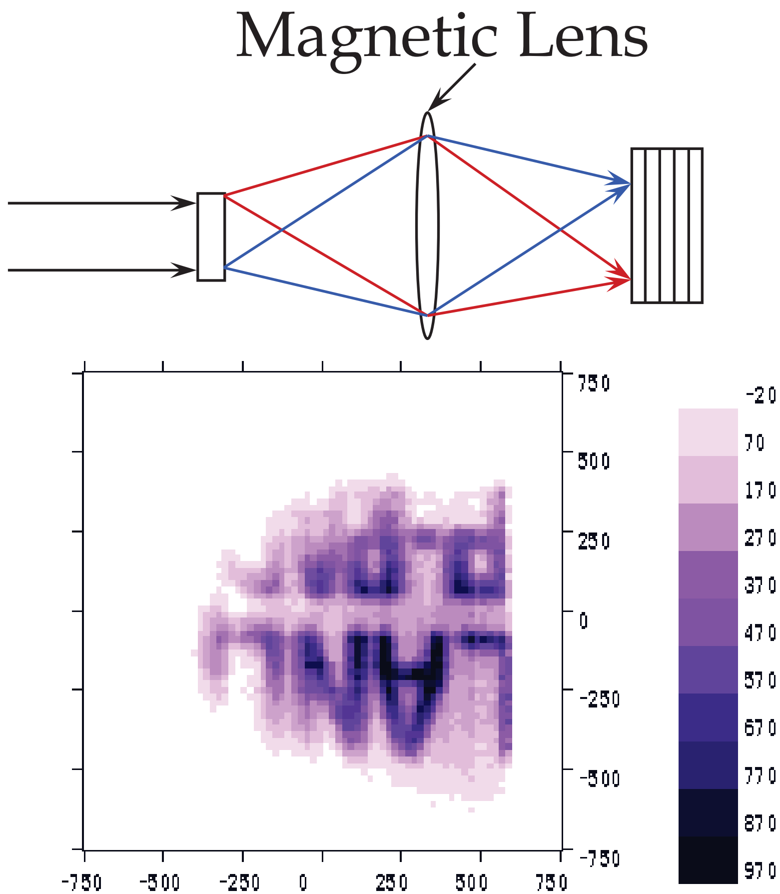
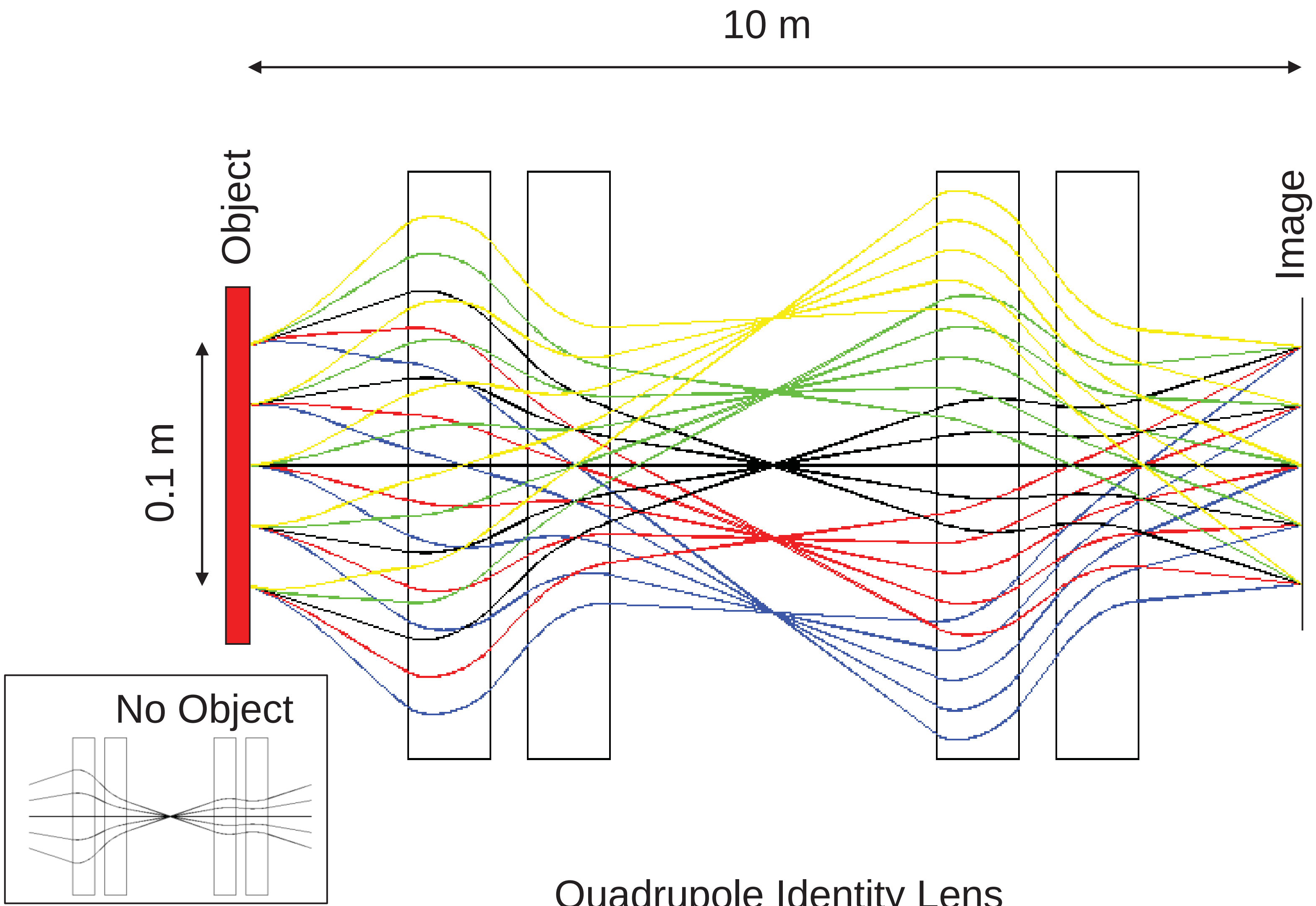


Image at the detector is substantially blurred.



Magnetic imaging lens preserves image with high resolution.

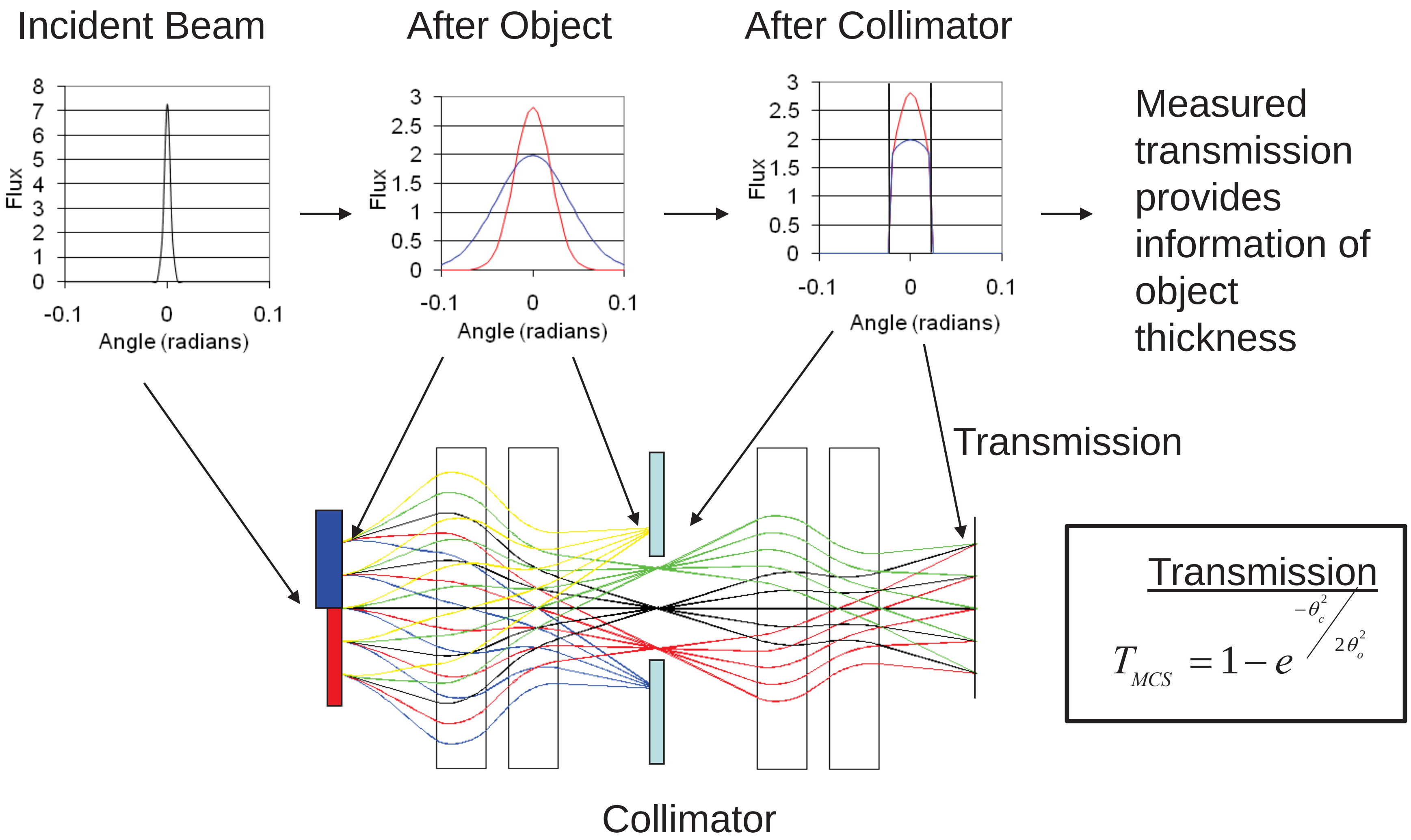
Magnetic Imaging Lens



Quadrupole Identity Lens

Images courtesy of Frank Merrill, LANL

Contrast from Multiple Coulomb Scattering

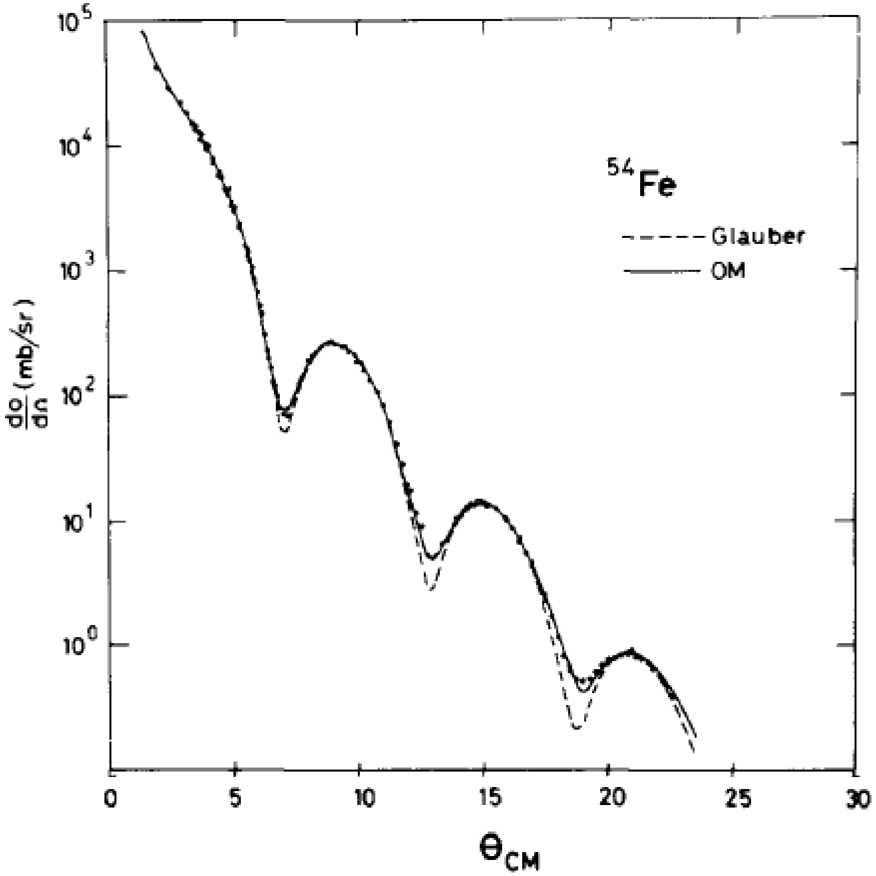


$$T_{MCS} = 1 - e^{-\theta_c^2 / 2\theta_o^2}$$

Images courtesy of Frank Merrill, LANL

Nuclear Interactions

Angular distribution of 800 MeV proton nuclear elastic scattering from Iron.



Simple Approximation for Modeling Proton Radiography

- Characteristic Nucleamr Collision Length: λ_c
- Approximate that each interaction removes the proton fro the acceptance of the imaging lens.
- Measure the collision Length at 800 MeV

The “true” nuclear interactions are more complicated than this simple assumption and these interactions are reasonably well understood. This can all be simulated, but it is typically not worth the effort for designing small scale experiments.

Transmission

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

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:

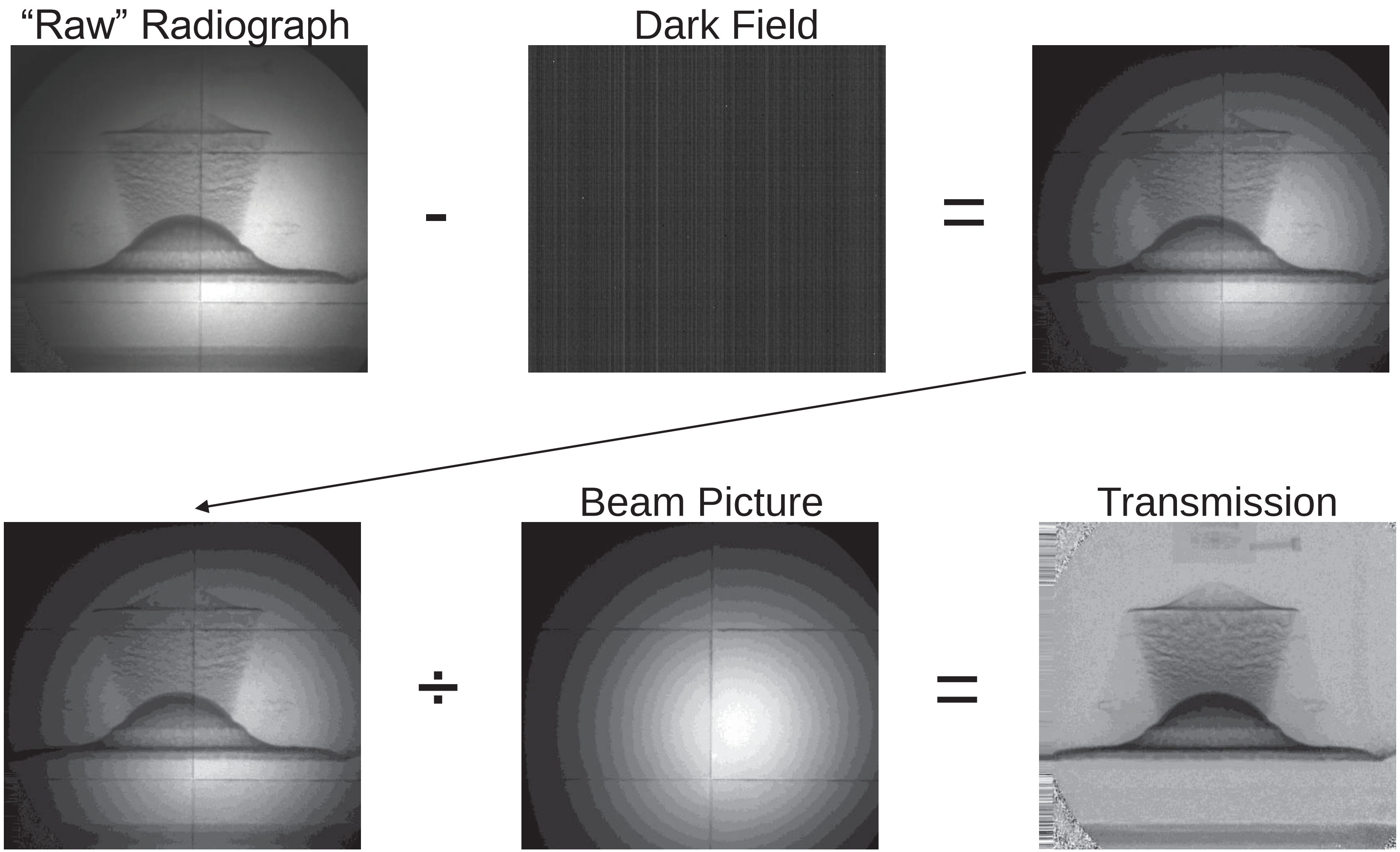
θ_o - scattering angle (radians)
x - areal density
x_o - radiation length
p - momentum (MeV)
β - relativistic velocity

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

Total Transmission
- inverted to determine areal density, *x*

Images courtesy of Frank Merrill, LANL

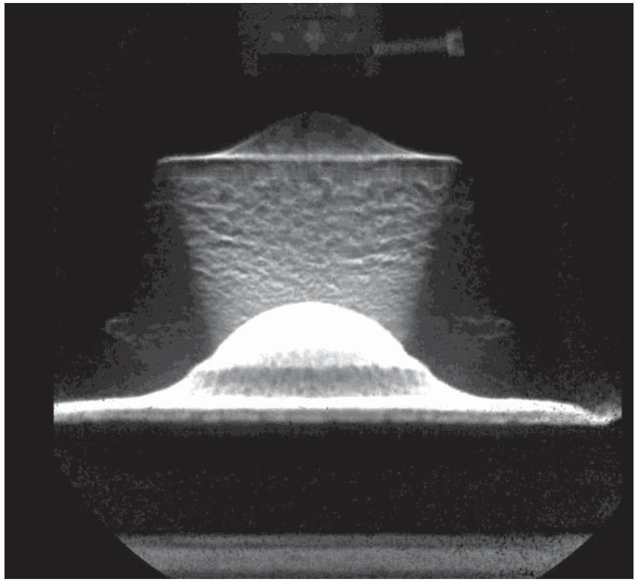
Radiographic Analysis



Density Reconstruction

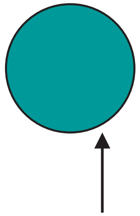
Invert to calculate Areal Density

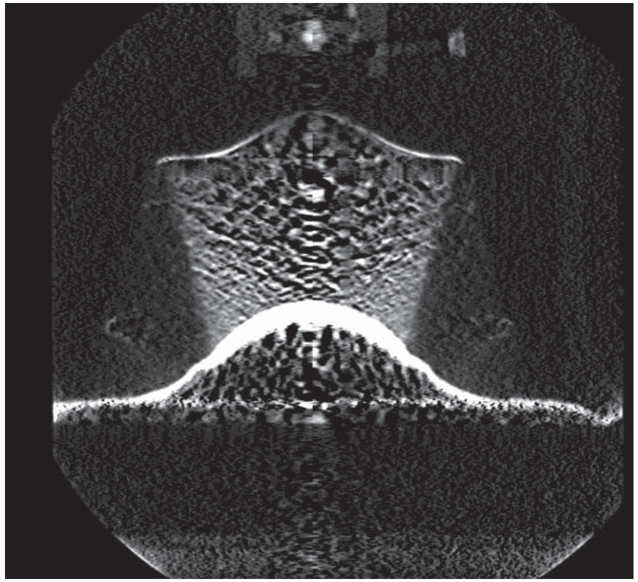
$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1MeV}\right)^2 \frac{x_o}{2x}}\right)$$



Areal Density (g/cm^2)

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





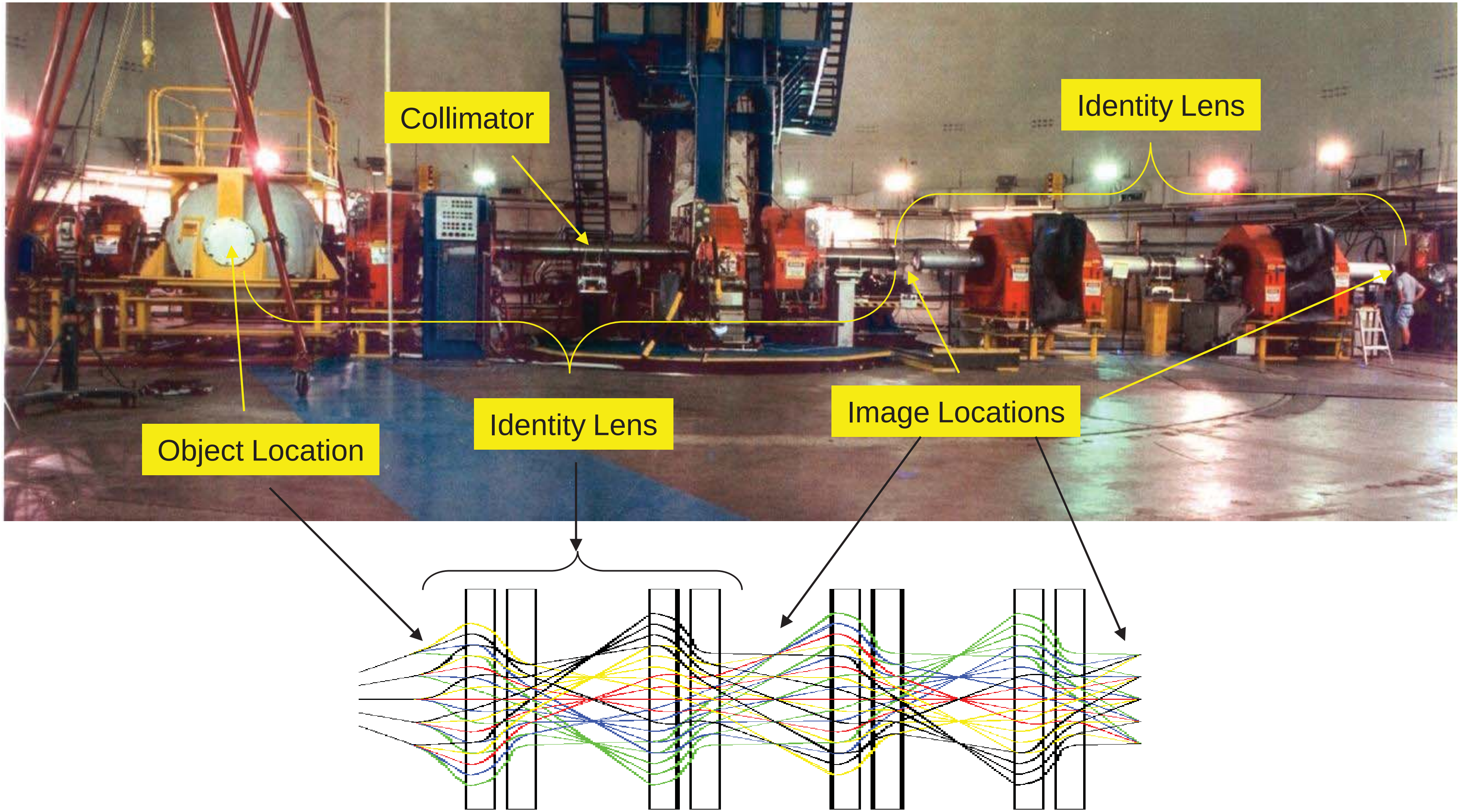
Volume Density (g/cm^3)

LANSCE Experimental Areas

- Lujan Center
  - ***Materials, bio-science, and nuclear physics***
  - ***National user facility***
- WNR
  - ***Nuclear Physics***
  - ***Neutron Irradiation***
- Proton Radiography
  - ***Dynamic Materials science,***
  - ***Hydrodynamics***
- Isotope Production Facility
  - ***Medical radioisotopes***

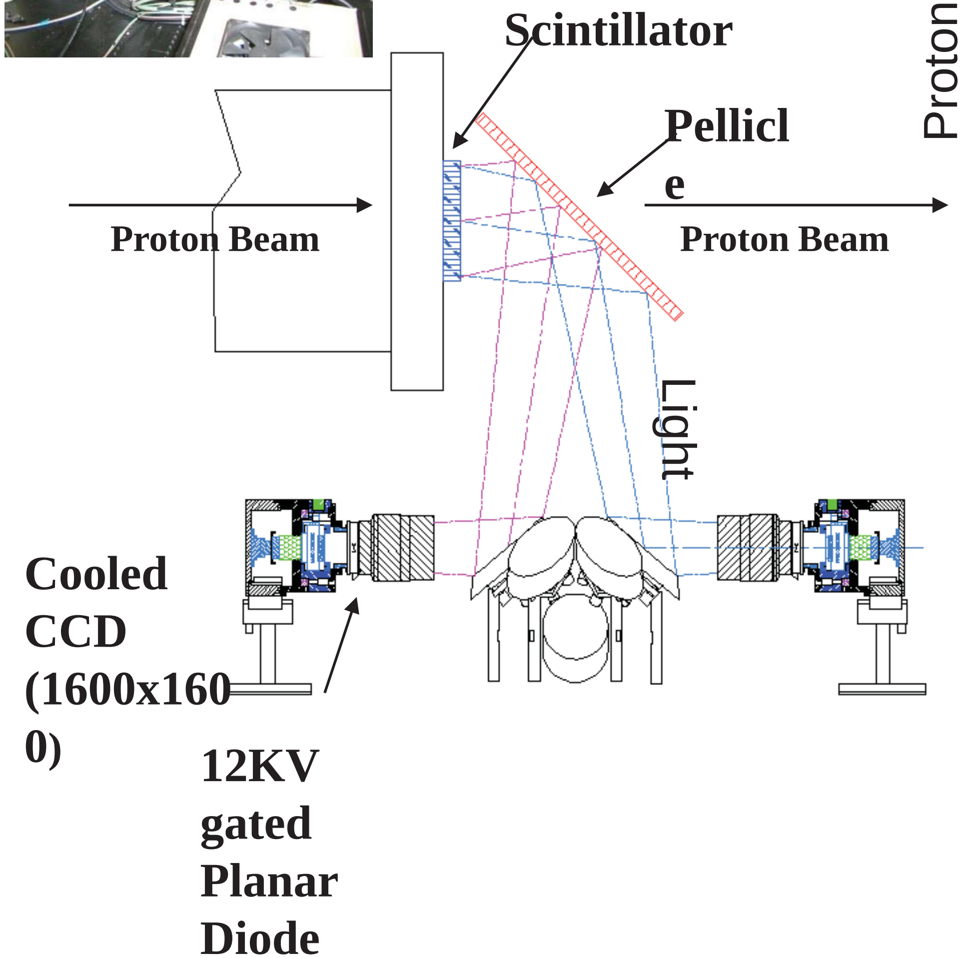
Images courtesy of Frank Merrill, LANL

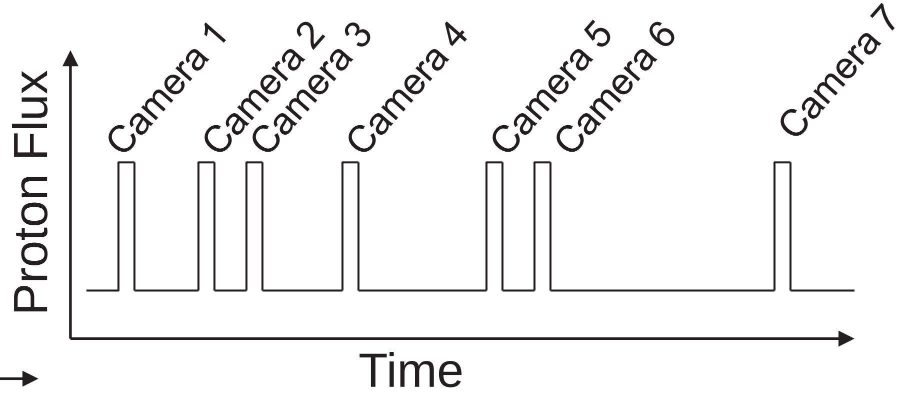
800 MeV pRad Facility at LANSCE



Images courtesy of Frank Merrill, LANL

Temporal Resolution





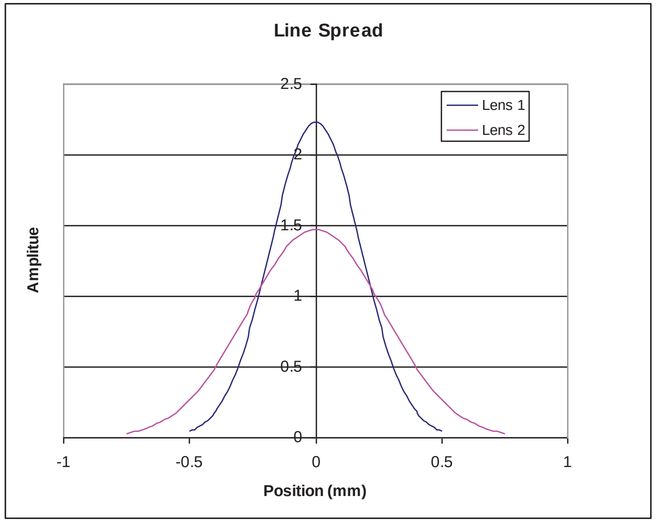
- 19 images at first station
- 22 images at second station
- Typically 100 ns exposure times
- 180 ns inter frame spacing
- Beam available for1000 μs

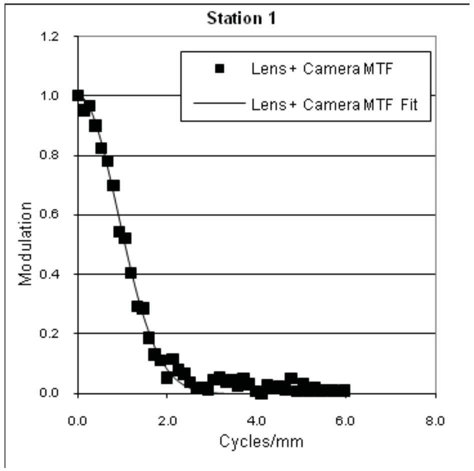
Images courtesy of Frank Merrill, LANL

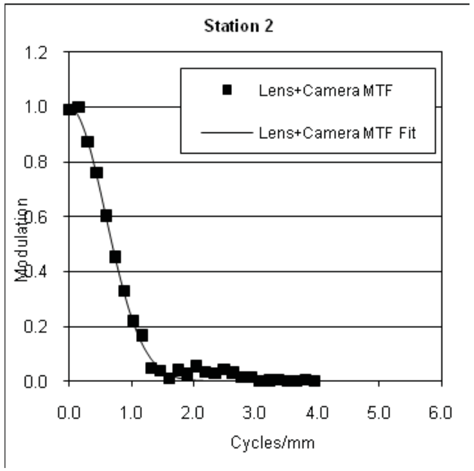
Resolution of 12" Lens

- Bare resolution (rms)
  - Station 1: 178 μm
  - Station 2: 280 μm

Gaussian Line Spread Function

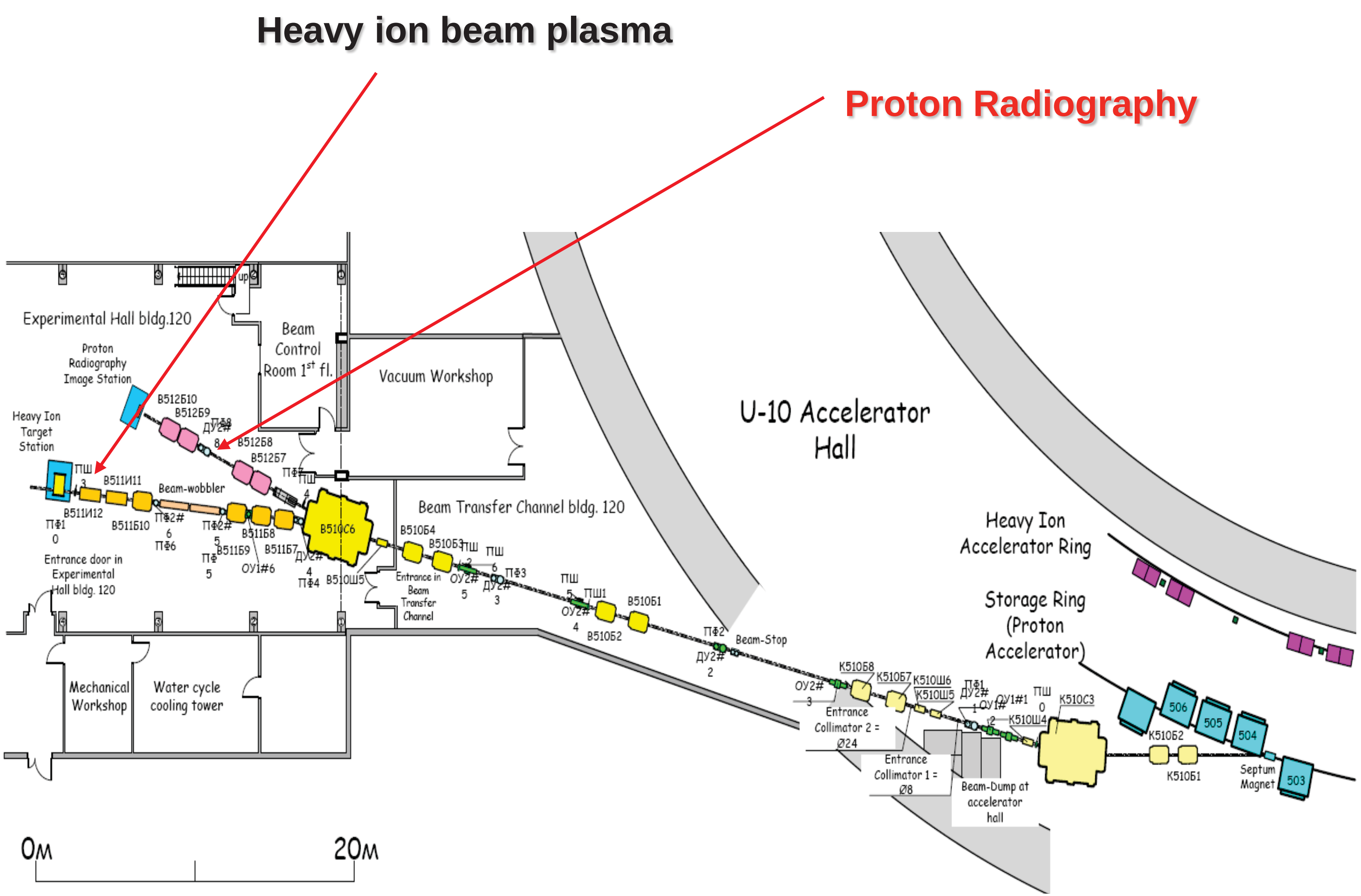




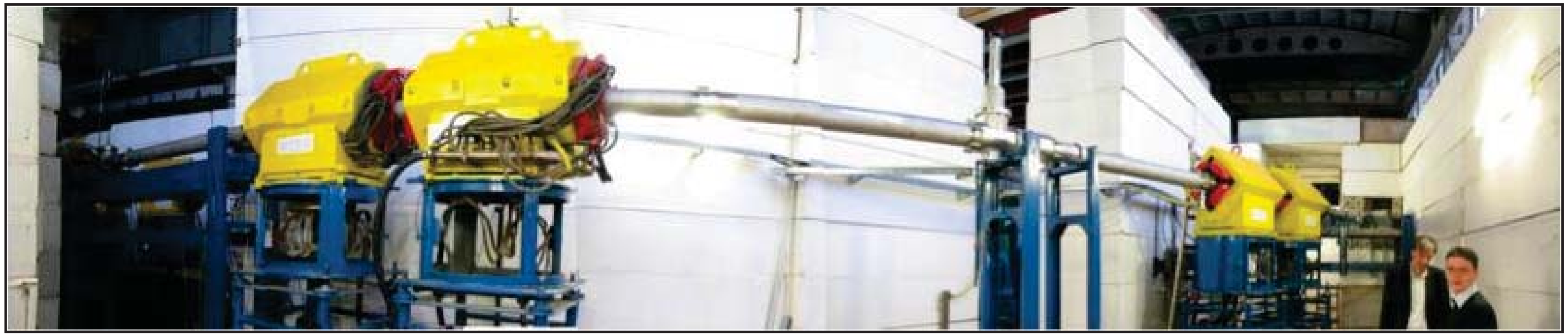


Images courtesy of Frank Merrill, LANL

Plasma Physics Experimental Area on TWAC Facility



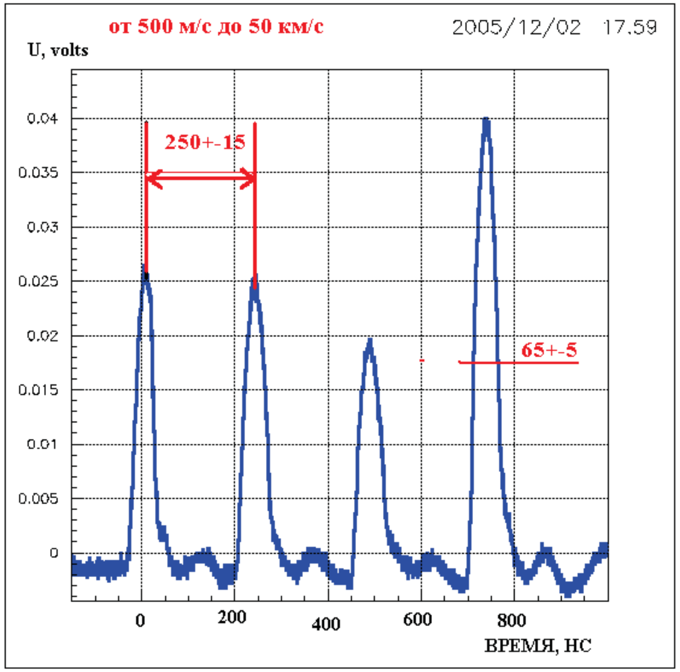
Proton Radiography Facility



Parameters of the proton radiography set-up

Proton energy 800 MeV

- Field of view on object up to 40 mm
- Investigated objects up to 60 g/cm^2
- Spatial resolution 0.5 p.lines/mm
- Time resolution 4 bunches / 1 μs



Protective Target Chamber designed for:
Up to 80 g TNT equivalent
Pumped down to 10^{-3} Torr
Active ventilation system
Inlets for VISAR diagnostics

Plasma target parameters (chemical HE generation):

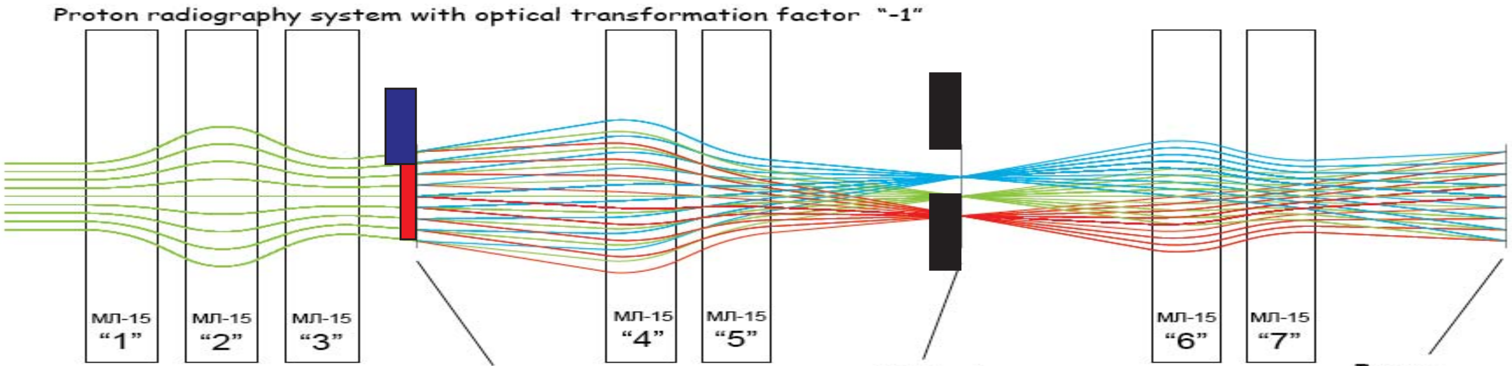
- Electron density up to 10^{23} cm^{-3}
- Pressure ~10 GPa
- Density up to 4,5 g/cm^3
- Temperature 1÷3 eV
- Time scale – microseconds
- HE mass (TNT) – 60 g

Target Chamber

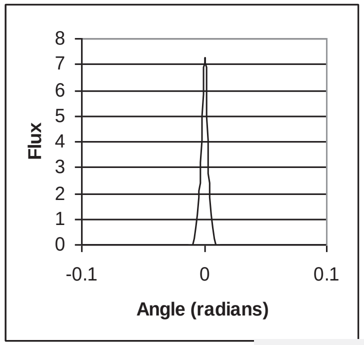


- HE mass (TNT) – up to **70 g**
- Pumped down to 10^{-3} Torr
- Active ventilation system
- Optical diagnostics - VISAR
- Target angular positioning (±10°)
- Static target positioning system
- Cryogenic target system

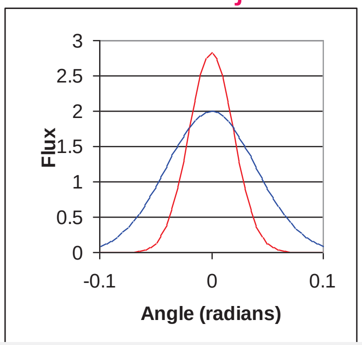
Magnetic optics design for proton radiography set-up image transformation factor "-1"



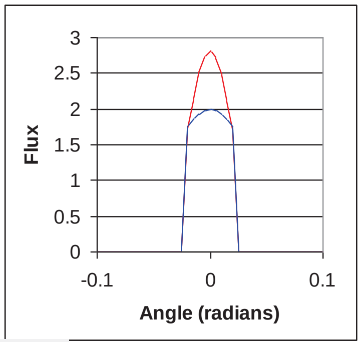
Incident Beam



After Object



After Collimator



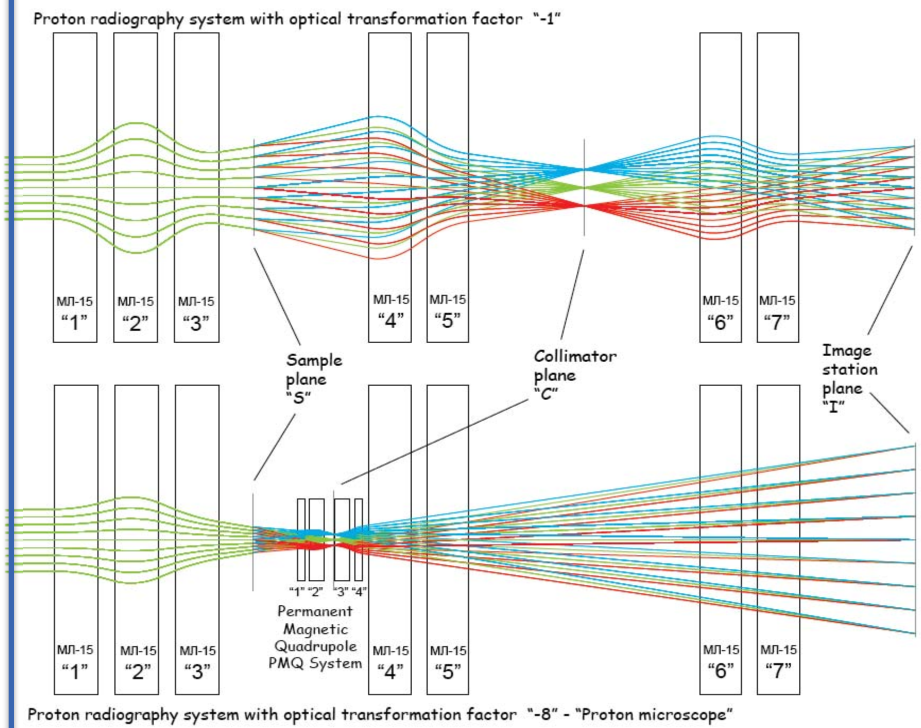
Measured transmission provides information about object thickness

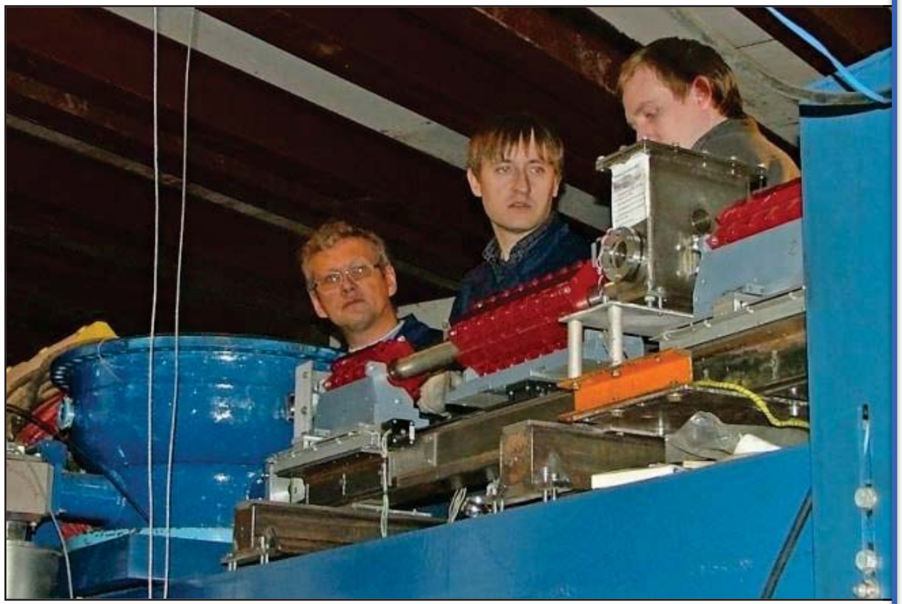
Transmission

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

Contrast from Multiple Coulomb Scattering

Proton Microscope

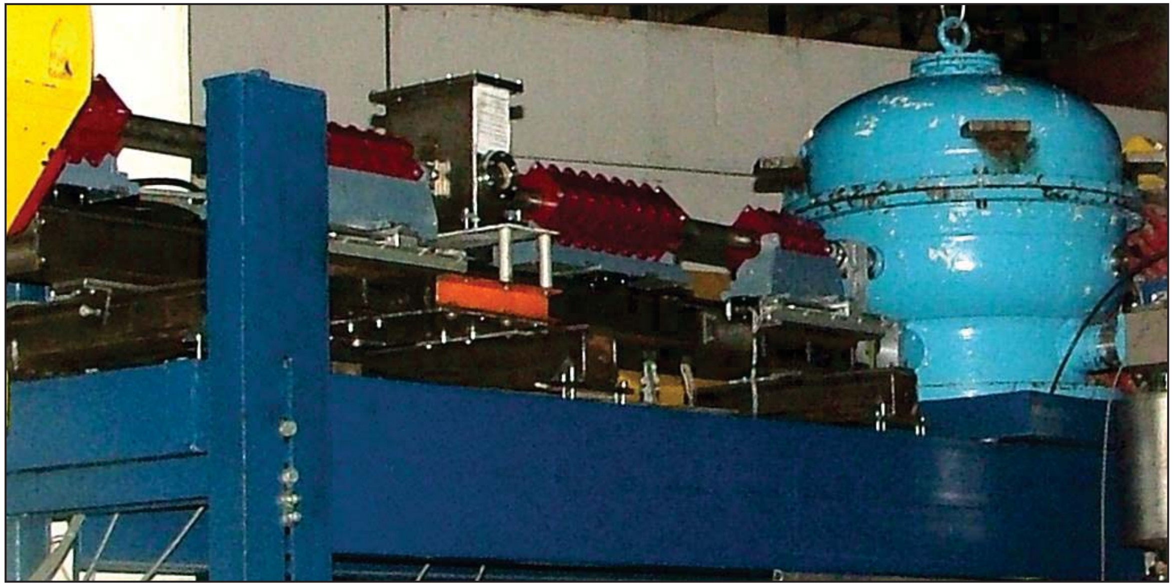




- 4 permanent high gradient quadruple lens
- Magnification **X = 3.92**
- Field of view < **19 mm**
- Density resolution ~ **6%**
- Best spatial resolution on object: **50 μm**

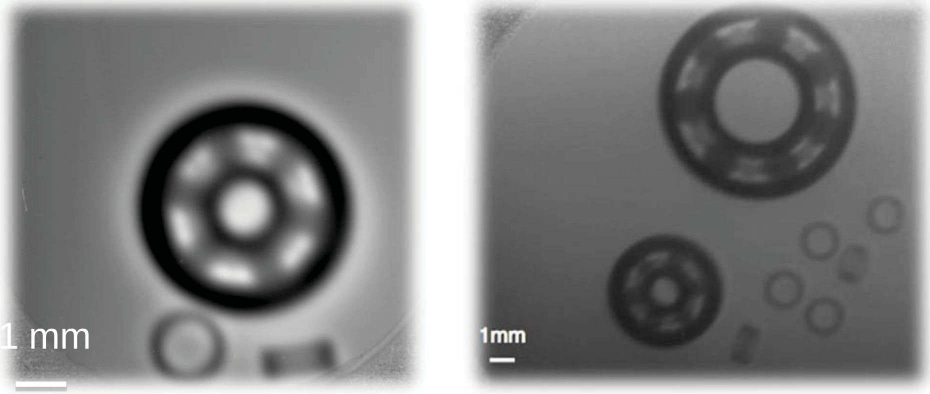
Proton Microscope

E = 800 MeV
Magnification X = 7.82
Field of view < 10mm
Measured spatial resolution
σ = 50μm
Magnification X = 3.92
Field of view < 22 mm
Measured spatial resolution
σ = 60μm

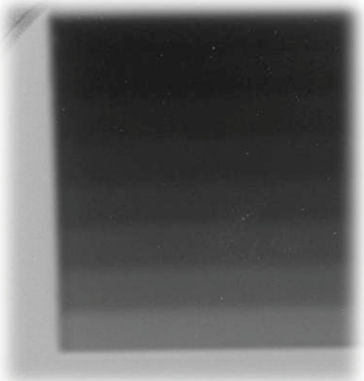


Measured density resolution ~ 6%
Beam structure – 4 bunches
(FWHM=70ns) in 1 μs

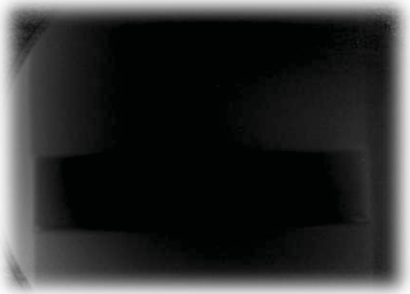
Static test-object images



Ball bearing and ferrite ring (X= 7.82 and X=3.92)



Brass stair 1 mm step Δρ=400μm



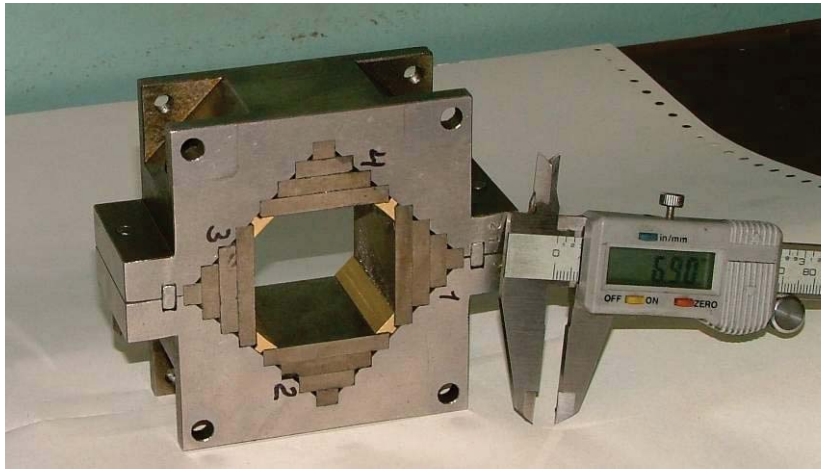
Detonation wave imitator d=15mm σ=100μm

REPM QUADS FOR p+ MICROSCOPE

- Rare-Earth Permanent Magnet Material (REPM) – Alloy of Sm-Co and Nd-Fe-B Groups With Highest Magnetic Parameters: $\mu_0 \square = 1.1 \div 1.3$ T, $\mu_0 \square_{CI} = 1.3 \div 3.3$ T
- Basic Designs
  - Split-pole Multipole (Developed at ITEP since mid 70s)
    - High-level Gradient
  - Quasi-Sheet Multipole (QSM) (V. Skachkov, NIM A 500, 2003, p.43)
    - Quadrupole – of Identical Module Construction
    - ITEP Symmetrical Channel Structure – FDFD (160 mm – 320 mm – 320 mm – 160 mm)
    - Gradient Integral – (4.6 T – 9.2 T – 9.2 T – 4.6 T)
    - Low-Level Gradient but Technological Advantages
    - No Limitations on the Working Region Shape
- Engineering Approach to Channel Structure:
  - Gradient – Fixed
  - Longitudinal Lens Alignment – Remotely Driven Adjustable

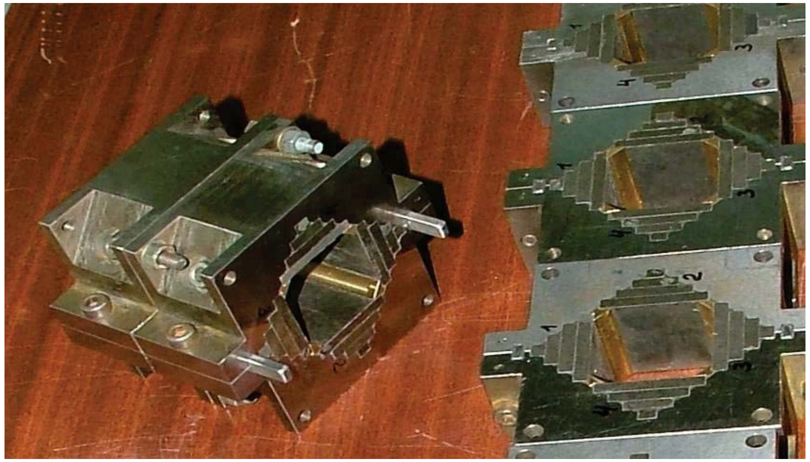
Vladimir Skachkov
ITEP, Moscow

Permanent Magnet Quadrupole lens fabrication for “Proton Microscope”

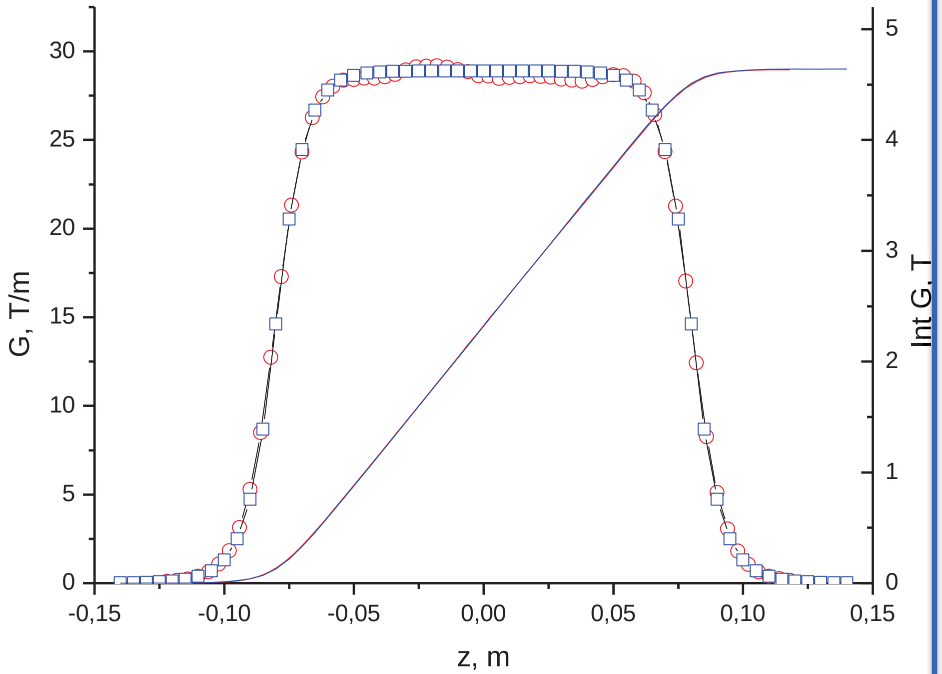


Permanent Magnetic Quadrupole Module

Magnetic alloy Nd-Fe-B



Quadrupole Lens Assembling

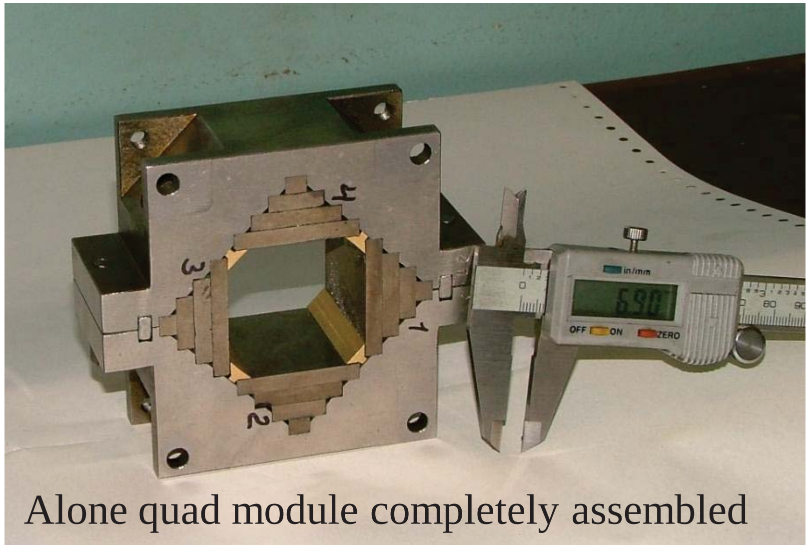


Four Modules Assembly Axis Gradient Distribution

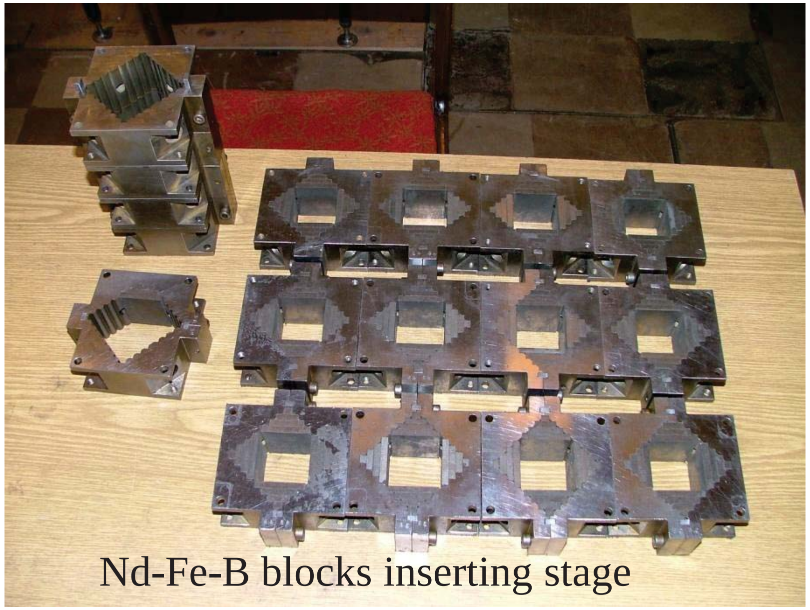
Blue – field simulation

Red – field measurements

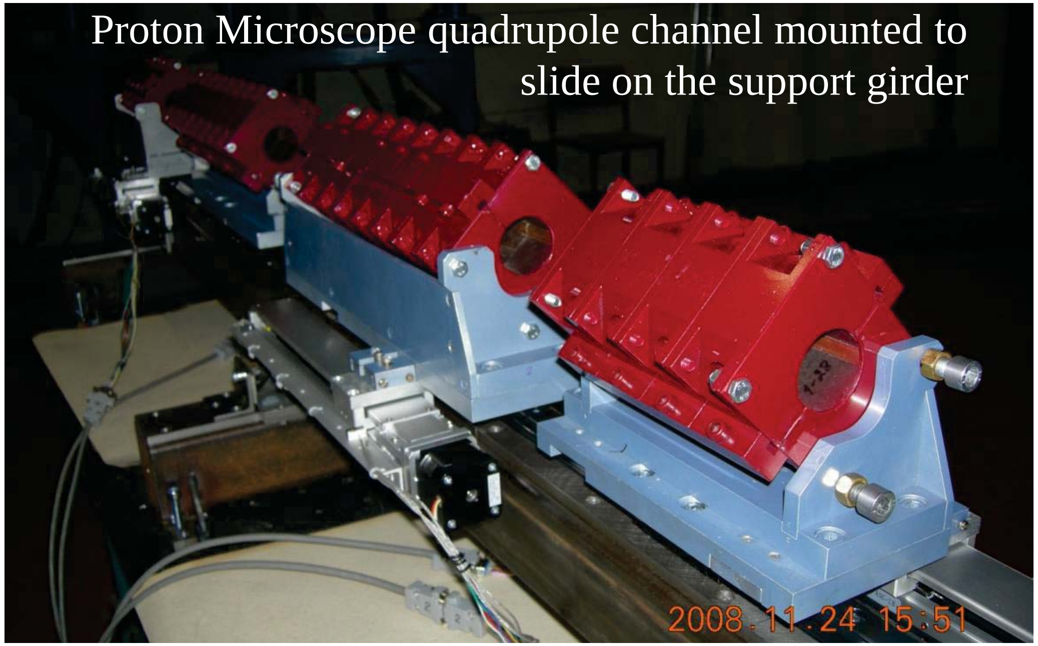
REPM QUADS
FOR p+ MICROSCOPE
QSM Quads Manufacturing Stage



Alone quad module completely assembled



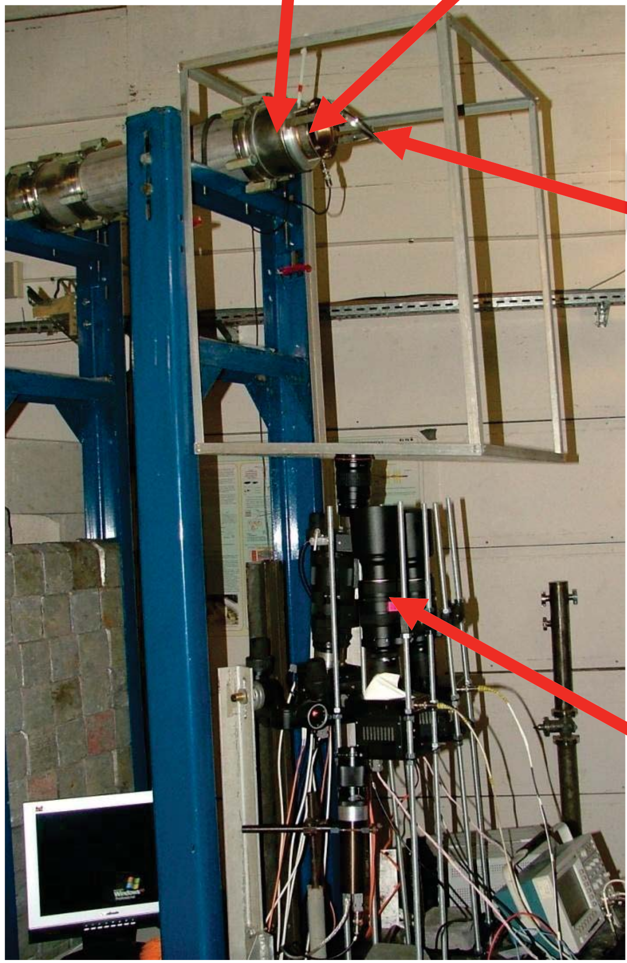
Nd-Fe-B blocks inserting stage



Proton Microscope quadrupole channel mounted to slide on the support girder

- REPM **material** – Nd-Fe-B alloy
  with $\mu_0 \square = 1.2$ T, $\mu_0 \square_{CI} = 1.7$ T
- **Aperture** – almost square of 40 × 40 mm
- **Module** length – 40 mm
  - Yoke – magnetically soft steel
  - Number of identical modules – 24
  - Accurate modules assembling

Image Registration System



Optical convertor:
LSO scintillator (40 ns), Ø78 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

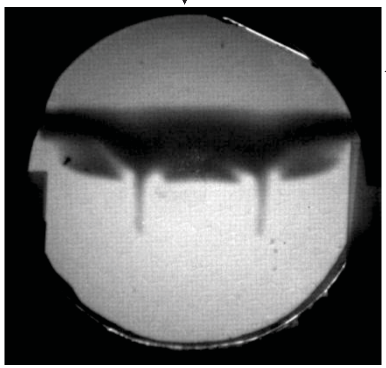
Proton Radiography for High Energy Density Physics Research at ITEP

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

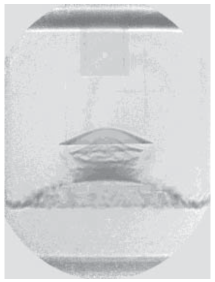
High Energy Density Physics

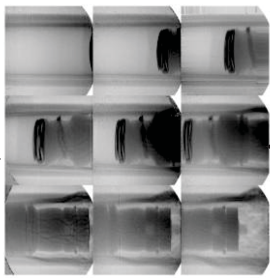
Hydrodynamics of HED flows (shock wave, detonation, hydrodynamic instabilities, ejecta formation)

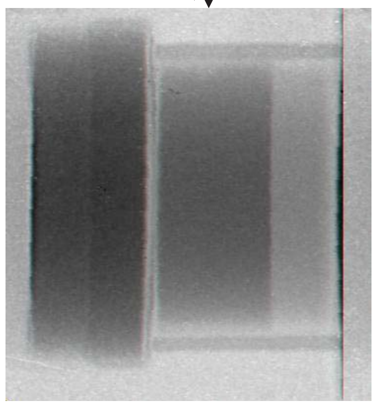
EOS and phase transitions (strongly coupled plasma, extreme state of matter, Warm Dense Matter.)



Material Strength and Damage (dynamic fracture of materials)

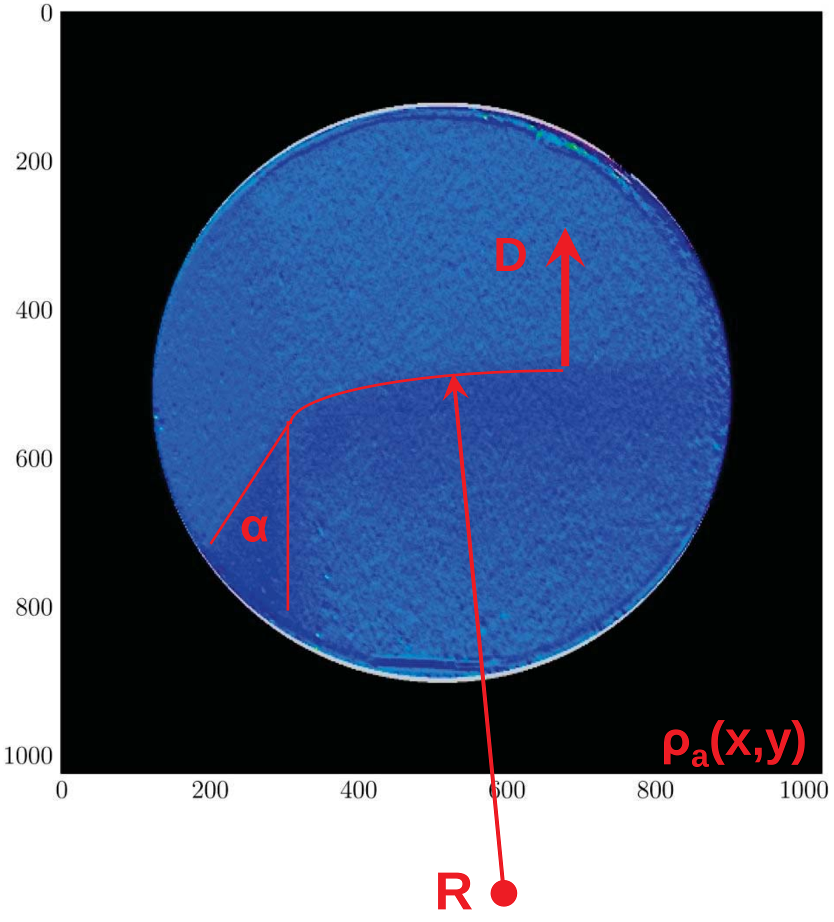






The definition of the parameters detonation wave by proton radiography method

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



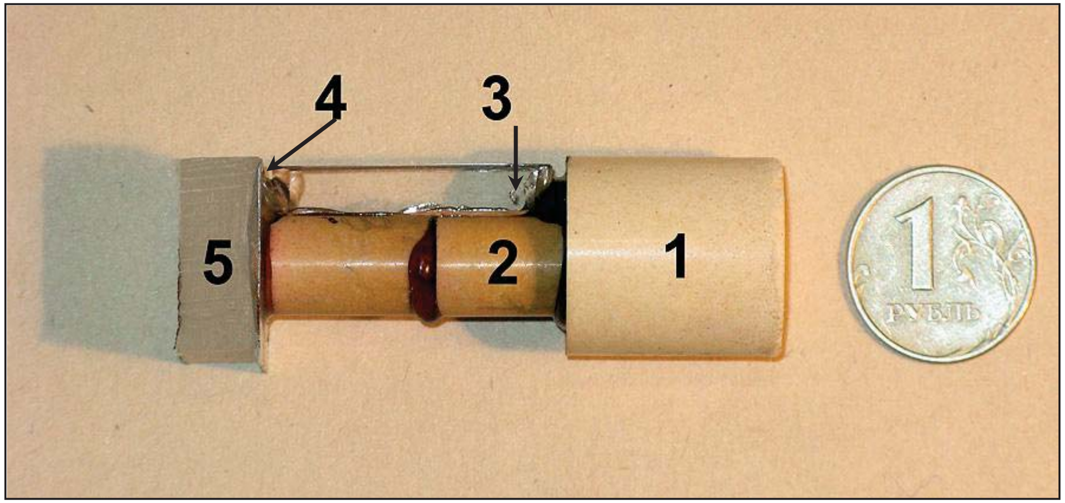
- *Density distribution (linear and, after mathematic development, volume)* $\rho_a(x,y)$, $\rho(r,z)$
- *Detonation wave* ***D*** *by multi frame registration*
- *expansion cone parameters of the product detonation* ***α***
- *Detonation front curvature radius* ***R***

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)

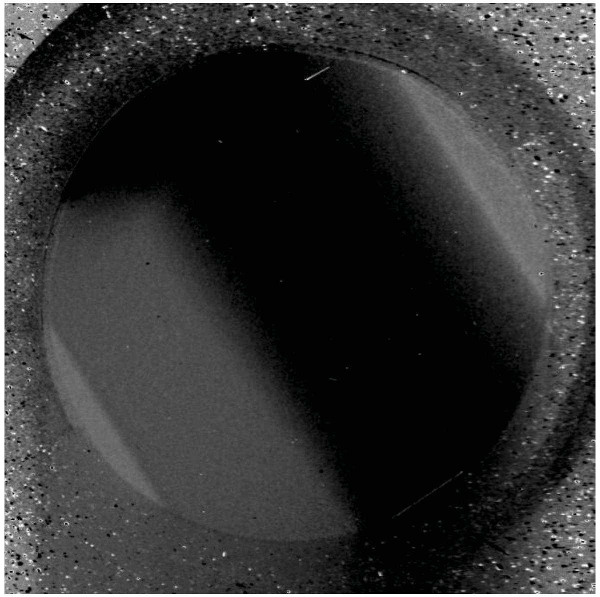
The experimental area



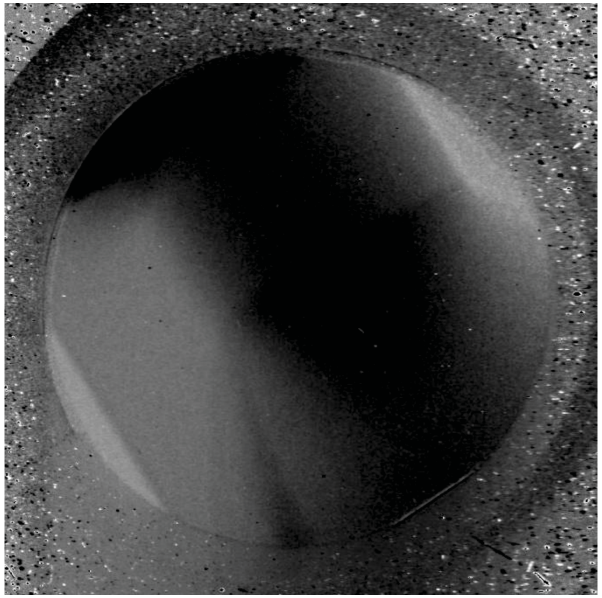
The photo of the target, charge TNT with diameter 10mm.
1 – detonator charge TNT (ТГ 50/50), 2 – investigation charge, the density 1.63 g/cm^3, 3 – 2 mm Plexiglas plate, 4 – 7μm Al-foil for VISAR diagnostic, 5 – the Plexiglas window.

Detonation of Pressed TNT

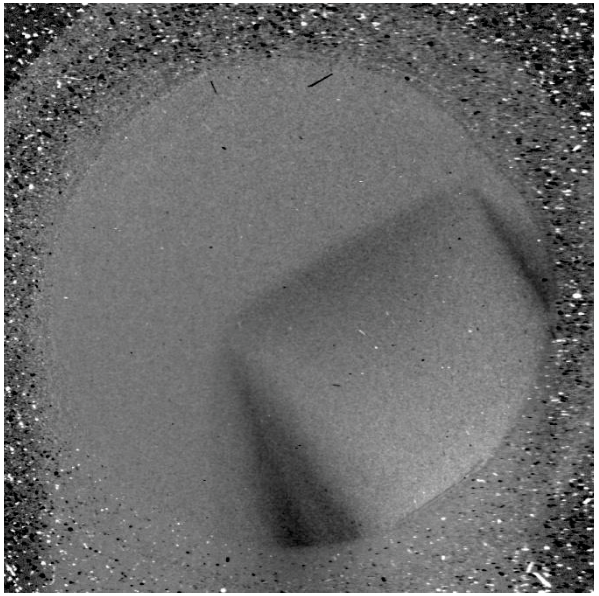
(the results from June 2010)



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°***

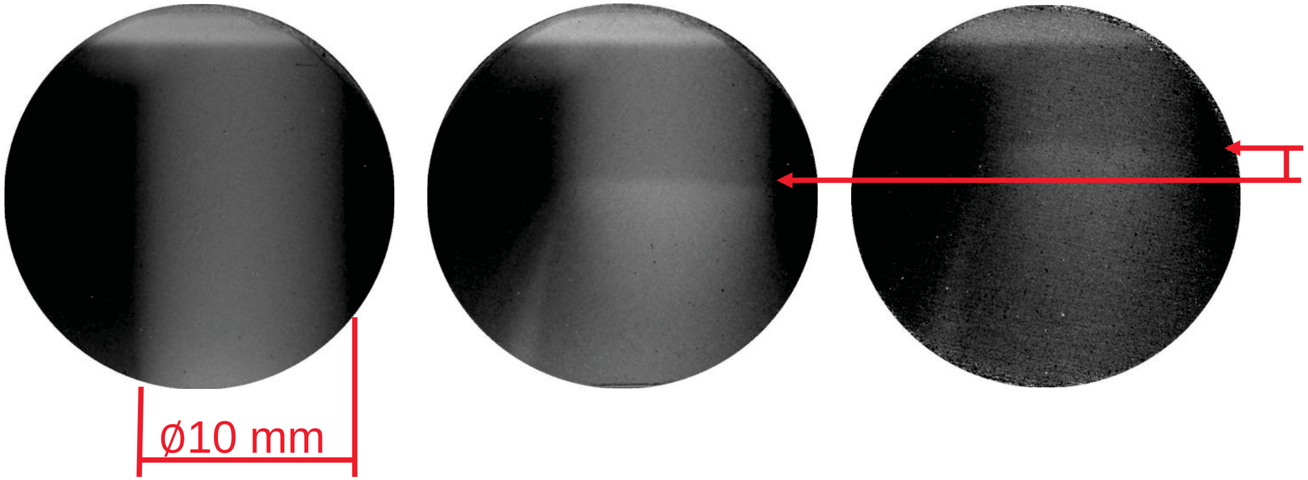
The cone in the Plexiglas plate: ***35.0 ± 2.0°***

Detonation of Pressed TNT

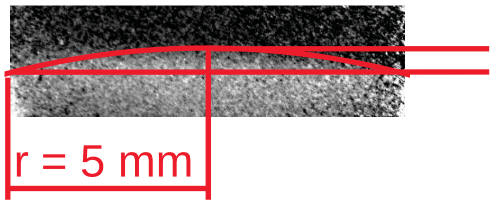
Static image | Bunch 2 image (T_2) | Bunch 3 image (T_3)

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

$\delta T = 70$ ns



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



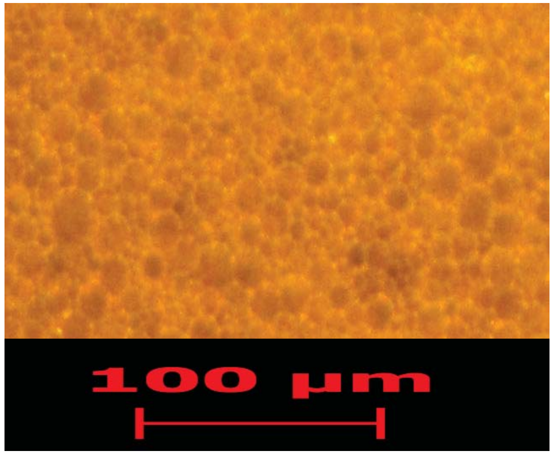
Detonation front curvature radius R = 58 ± 7 mm

Detonation of Emulsion Explosive

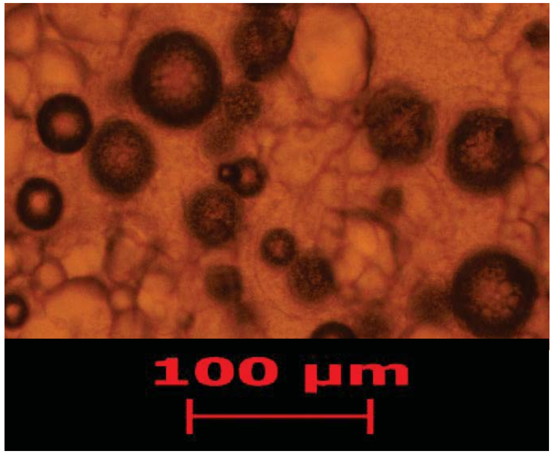
Emulsion explosive is an emulsion of — water in oil — type where droplets of oxidizer solution are surrounded by a thin film of liquid fuel, and is sensitized by a porous additions.

Emulsion matrix:

-92-95% -oxidizer (ammonium nitrate)
-8-5%-fuel (mineral oil)
• Sensitizer –Hollow glass microballoons (C15-type,3M)
• Weight concentration: 1—4%-

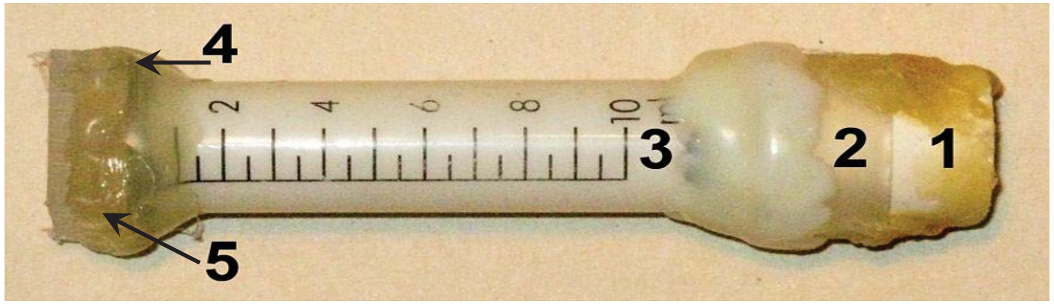


Emulsion matrix photo



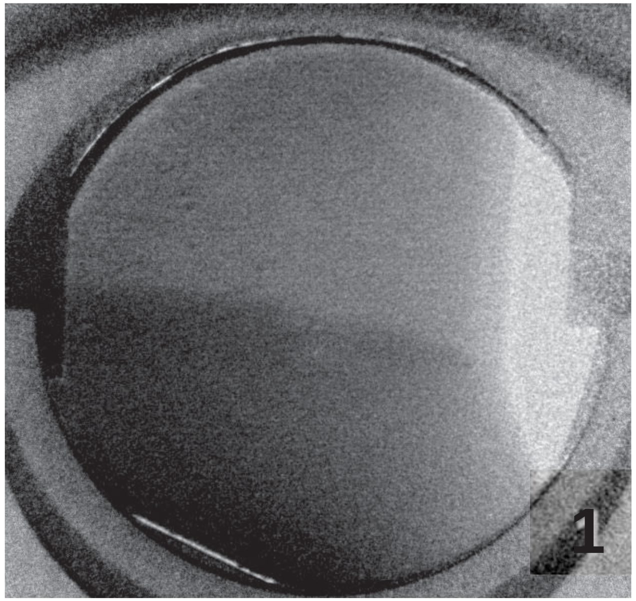
Emulsion explosive (emulsion matrix + 3% of sensitizer)

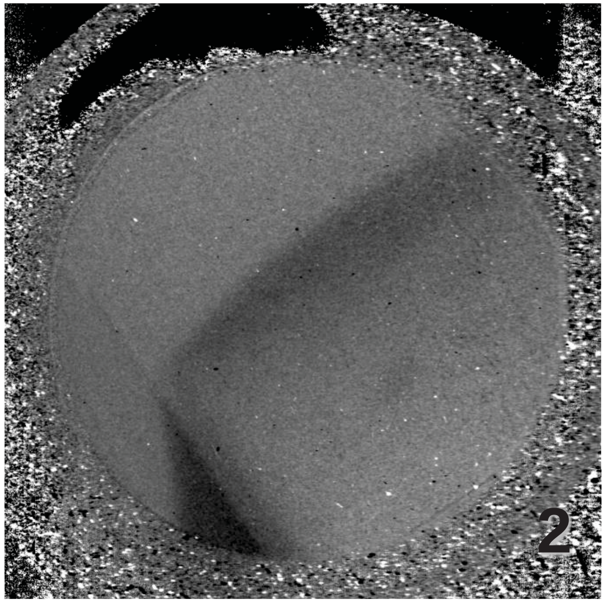
The initial density of the EE charge ***1.07g/cm³*** *(3% microballoons) diameter* ***15*** *и* ***20 mm***
The оболочка – 0.6 and 0.8 mm polyethylene
The length of the charge – ***60*** *and* ***80*** *mm*

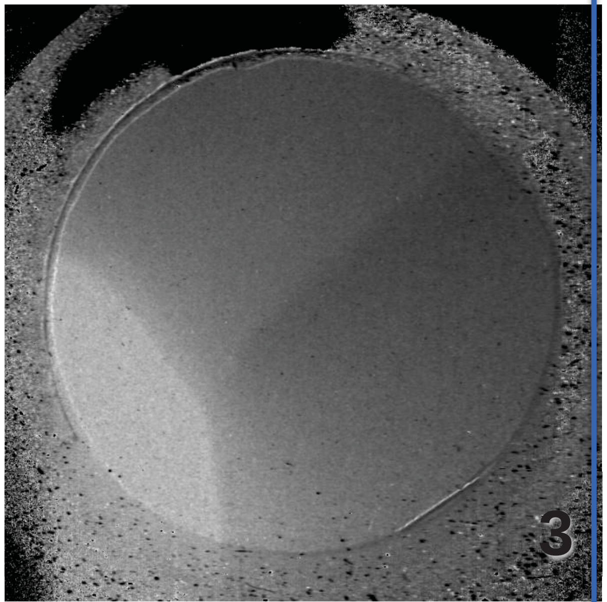


The EE charge target 20mm diameter. 1 – detonator charge 2 – Plexiglas flange , 3 – housing of the EE charge, 4 – 7µm Al-foil for VISAR diagnostic , 5 – Plexiglas window.

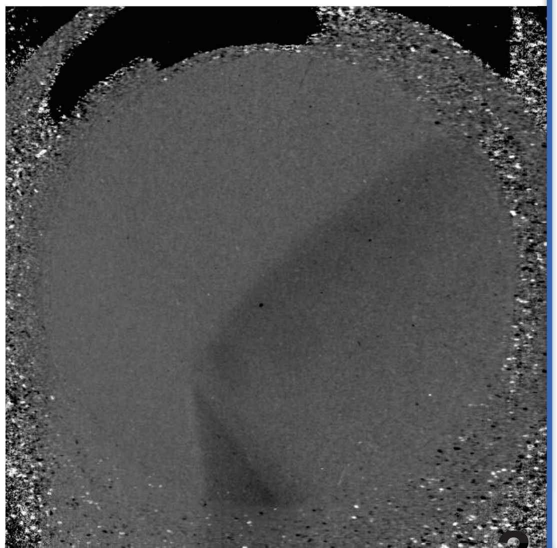
Detonation of Emulsion Explosive
(the diameter charge 20 mm)





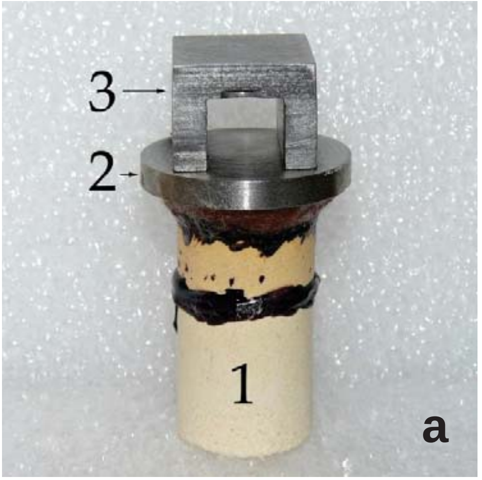


The proton radiography image and relative density distribution for three type of the detonation EE charge 20 mm diameter



The detonation velocity ***D = 4.64 km/s***
The duration of the reaction zone (VISAR) – ***0.94 μs***
The duration of the reaction zone(СИ) – ***0.6 μs***

Dynamic Dispersion and Surface Ejecta Formation of Metals under Shock Loading

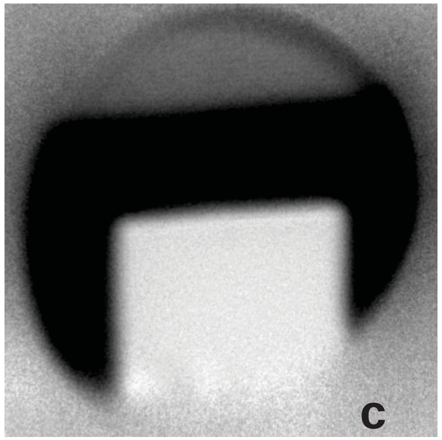


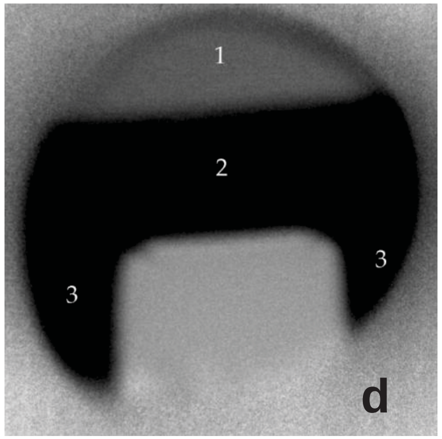
Shock loading of П-shaped steel profile :

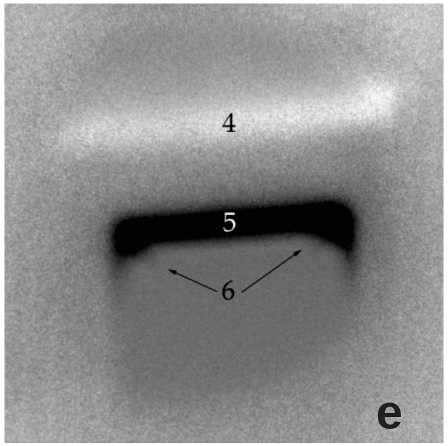
a) experimental setup;
b) fractured sample after the experiment;
c) proton radiographic image of static target;
d) the same at 2.5 μs after coming of a shock wave to the free surface of the steel plate;
e) Relative change of density between d) and c) images.

1–TNT charge, d=20mm;2–4 mm thick steel disk; 3–5 mm thick П-shaped steel profile; 4,5–displacement strips;6–steel microparticle jets.

Free surface velocity - **530±120 m/s. Jet velocity-1130±120 m/s.**

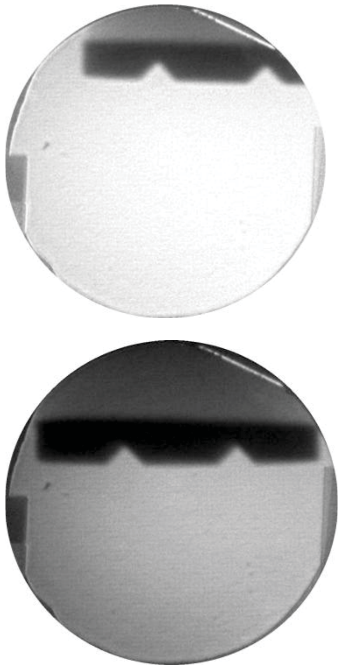






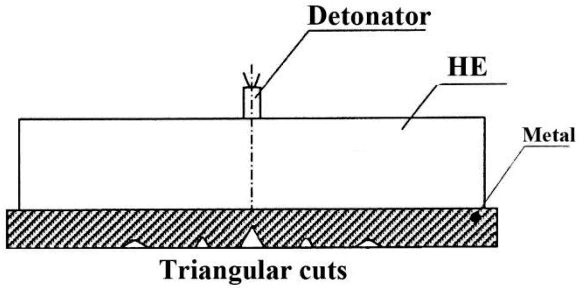
Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

Proton radiography images of static targets



Steel target

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



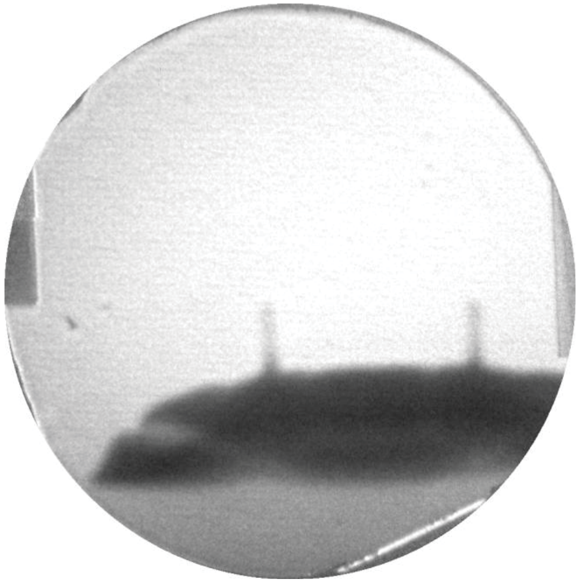
Copper target

Similar to steel one

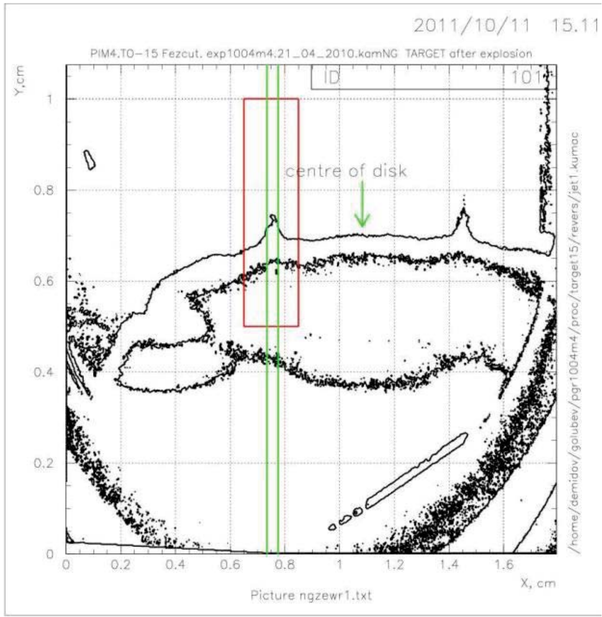
Proton radiography images of dynamic shots at 1.5 μs after shocking the free surface of a target

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.

Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

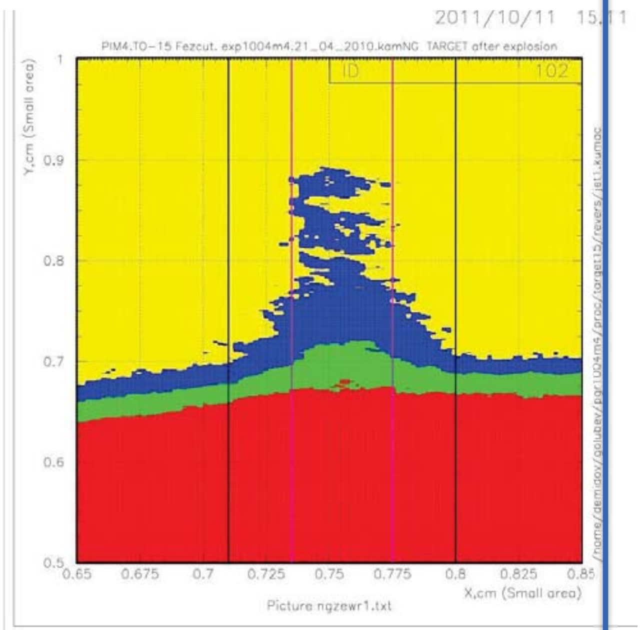


Dynamic proton radiography image shot at 1.5 μs after shocking the free surface of the steel target



Linear density map reconstructed from radiographic image

Velocity of jet tip: 2.8 km/s

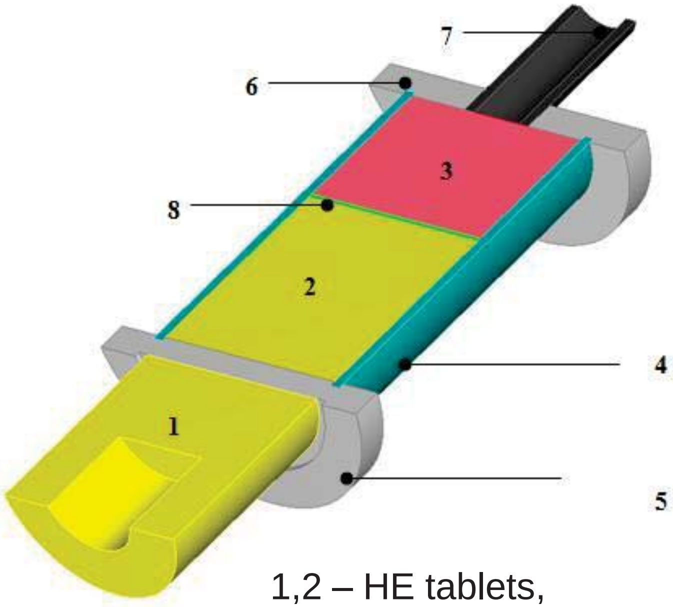


Close-up of the area inside the red frame on the left image

Mean volume density of jet material: 0.08 g/cc

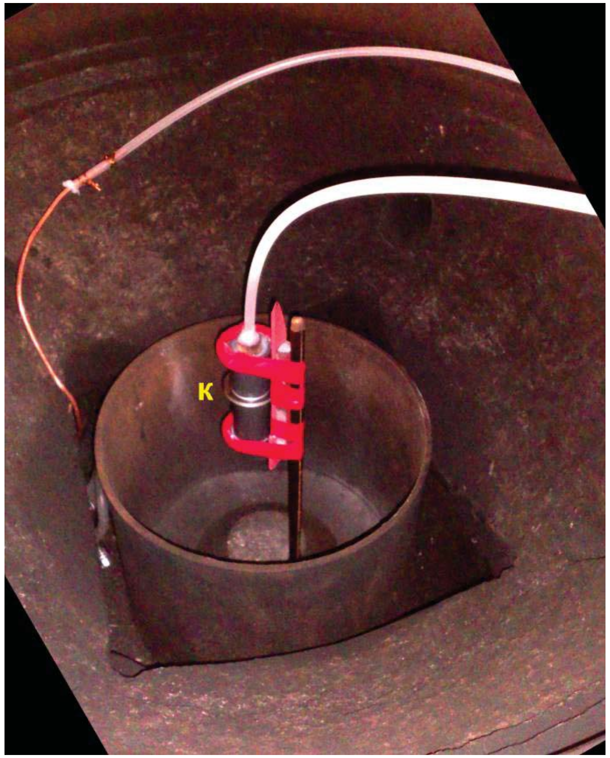
Shock Compression of Noble Gases

Target scheme



1,2 – HE tablets,
3 – investigated noble gas,
4 – generator chanal,
5, 6 – leak-proof flanges,
7 – tube for gas system

Studied gases: Ar, Xe
Initial pressure: ~ 1-5 Bar
Shock wave velocities: ~ 4-6 km/s



Shock pressure *P obtained in* Ar tests was 0.1-1kbars, temperature *T* = *8*-20 kK with non-ideality parameter *Γ~1. In similar* Xe tests *P=4-6.5 kbar, T=20-25 kK and Γ=1-2.5* values were reached.

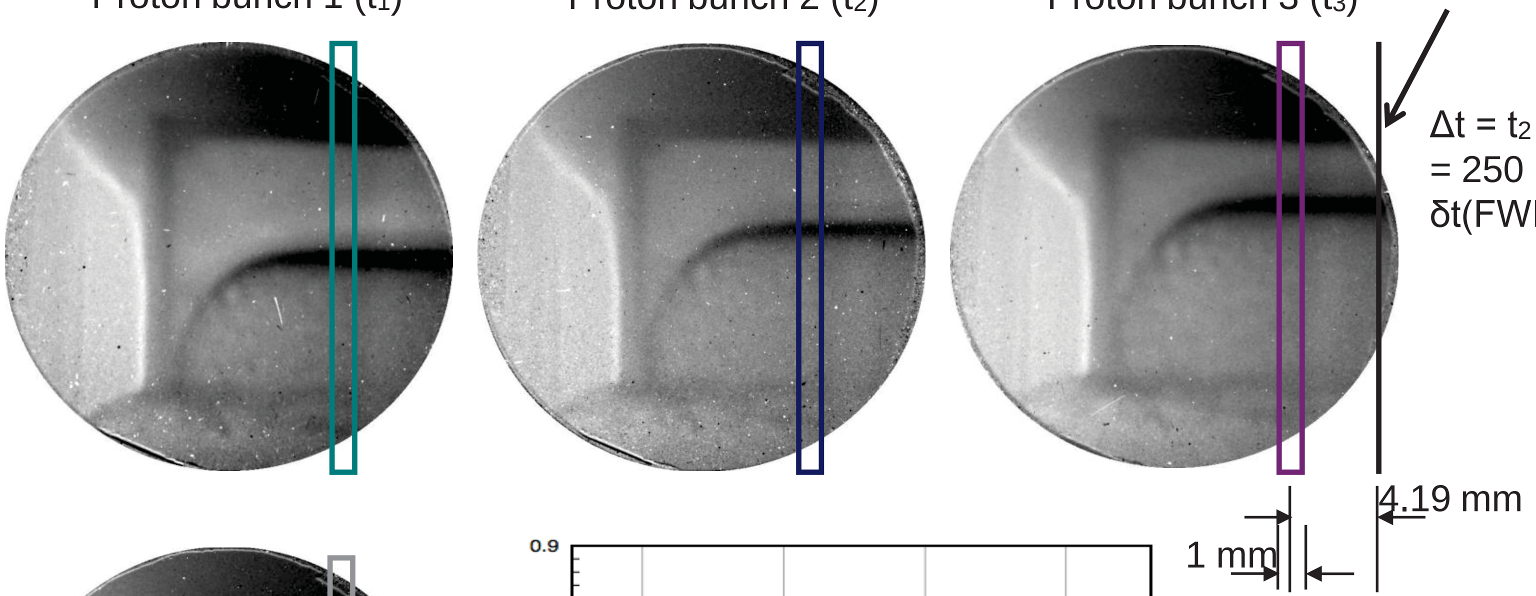
Shock Compression of Noble Gases

Camera 1
Proton bunch 1 (t_1)

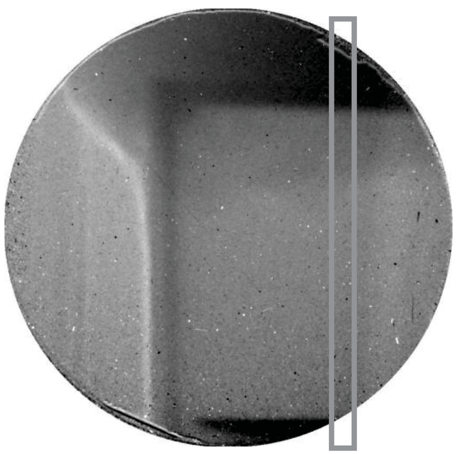
Camera 2
Proton bunch 2 (t_2)

Camera 3
Proton bunch 3 (t_3)

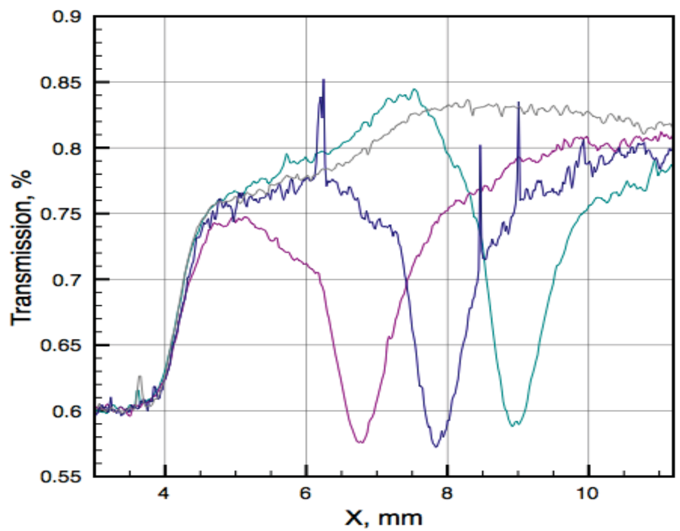
Target axis



$\Delta t = t_2 - t_1 = t_3 - t_2 =$
$= 250$ ns
$\delta t(FWHM) = 70$ ns



Static image



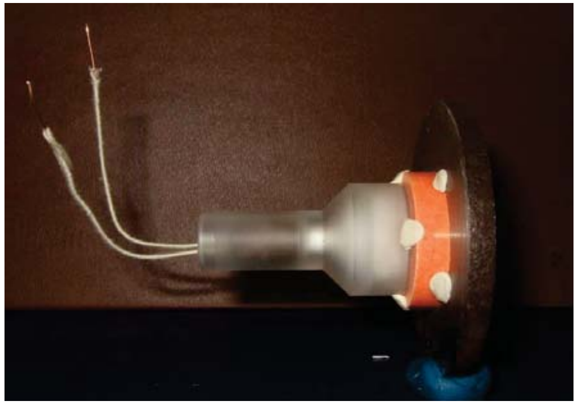
Beam transmission for image profiles

Gas cell thickness - 20.34 mm
Gas pressure - 2.5 Bar
$\rho_0 = 2.5 * 2.034 * 0.00589 =$
$= 0.03$ g/cm^2

U = 4.3 ± 0.2 km/s

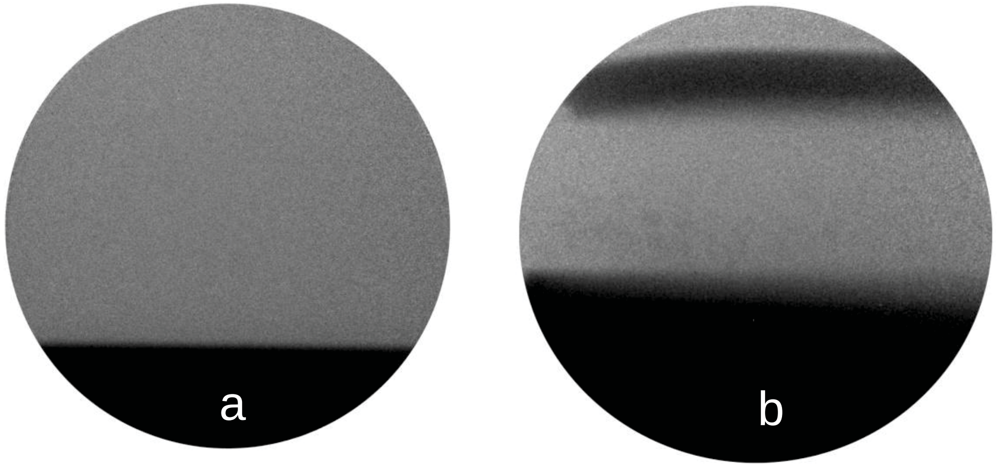
Development of Compact Explosive Generators

Plexiglass components of compact explosive generator



Experimental assembly for accelerating flyer plate with compact explosive generator

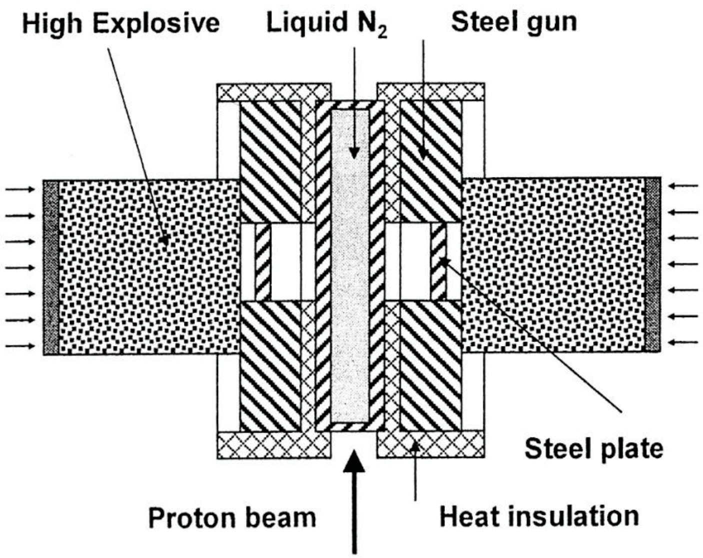
Total amount of explosive	**< 15 g in TNT**
Flyer plate	**∅20, 1-2 mm thick**
Flyer plate material	**Al, Steel**
Velocity	**0.8 -2.8 km/s**



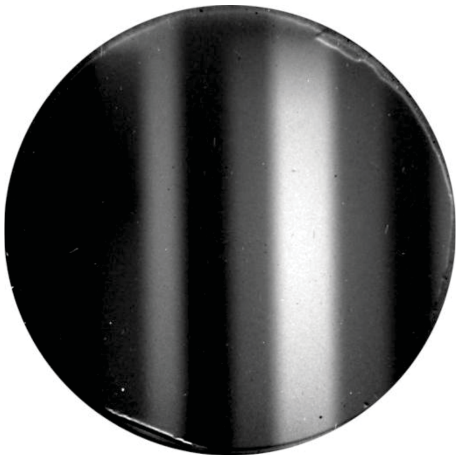
Proton radiography images of 2 mm thick ∅20 Al flyer plate acceleration: a) static image; b) dynamic shot at 4.75 μs after start

HE capacity of explosive confinement chamber which is being used at the facility is only 70 g of TNT, so it substantially limits the upper range of physical parameters which can be achieved in it using common explosive generators. To improve this range a new family of compact explosive generators aimed specifically for a use with proton radiography technique was developed and tested.

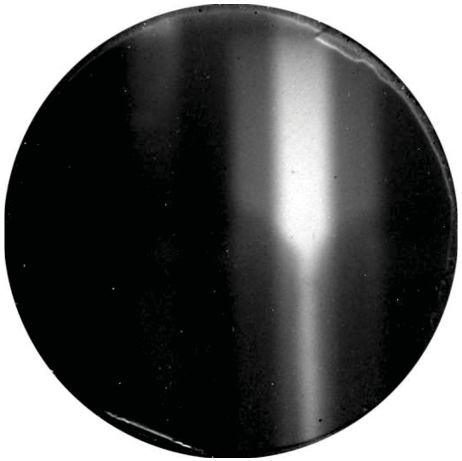
Development of Compact Explosive Generators



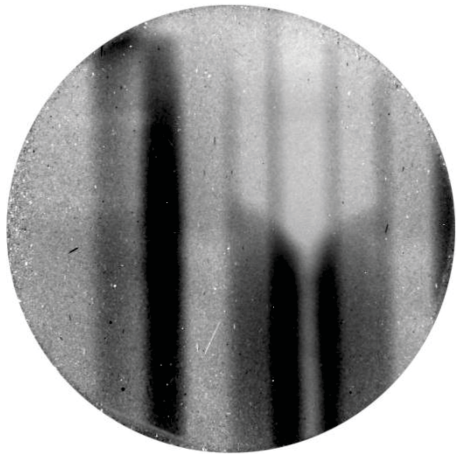
Compact explosive generator for symmetric bilateral compression of condensed matter up to 150 GPa



Static image

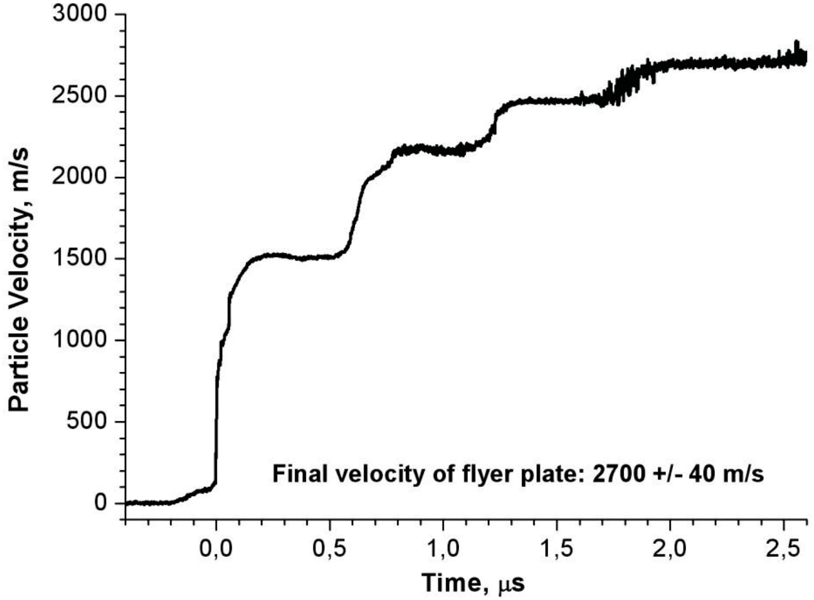


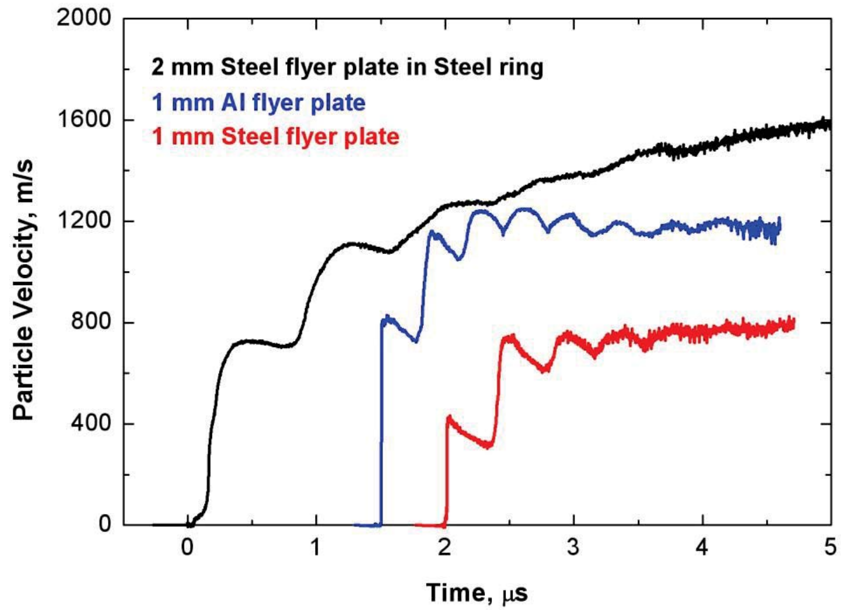
Dynamic image



Relative to static density changes

Development of Compact Explosive Generators





VISAR flyer plate free surface profiles: *left* – for 2 mm Al flyer plate,
right – for 1 mm Al and 1 & 2 mm Steel flyer plates

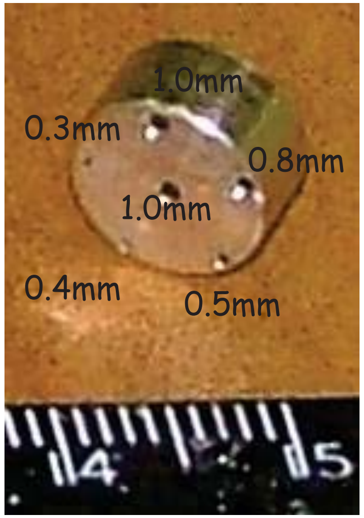
Flyer plate	Velocity after full acceleration, km/s	Base of flight, mm	Diameter of plane region, mm
2 mm Al in Steel ring + 12 g HE booster	**2.8**	8	13
2 mm Steel in Steel ring + 12 g HE booster	**1.6**	6	
1 mm Al	**1.2**	3	13
1 mm Steel	**0.8**	2	

ITEP Proton Microscope: Static test-objects

Tomography reconstruction of multi-projection proton microscopy

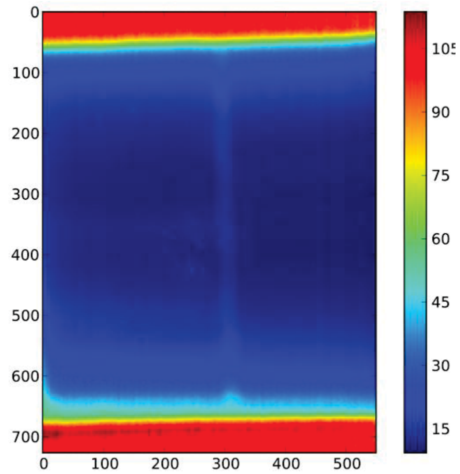
Targets and SS container

Brass target

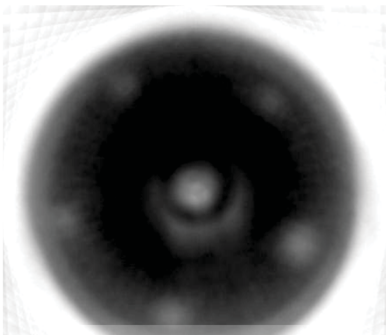


Requirements:

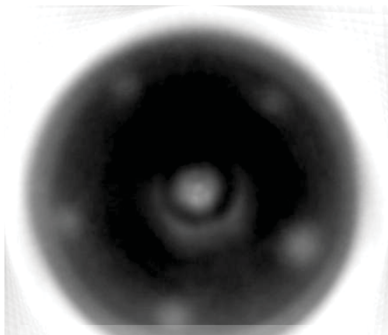
- good spatial and density resolution for projection images
- high precision for target positioning and alignment



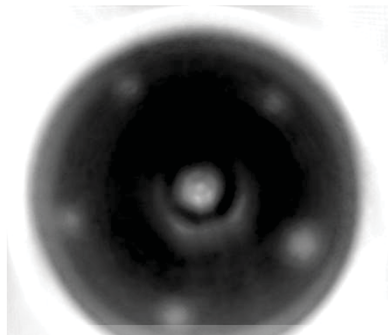
Reconstructed two-dimensional target density distribution by Algebraic Reconstruction Technique (ART)



30 projections

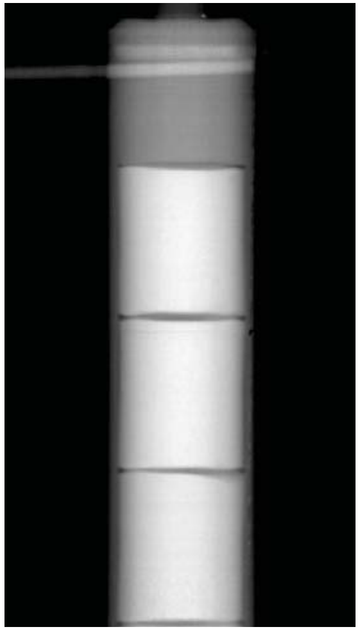


45 projections

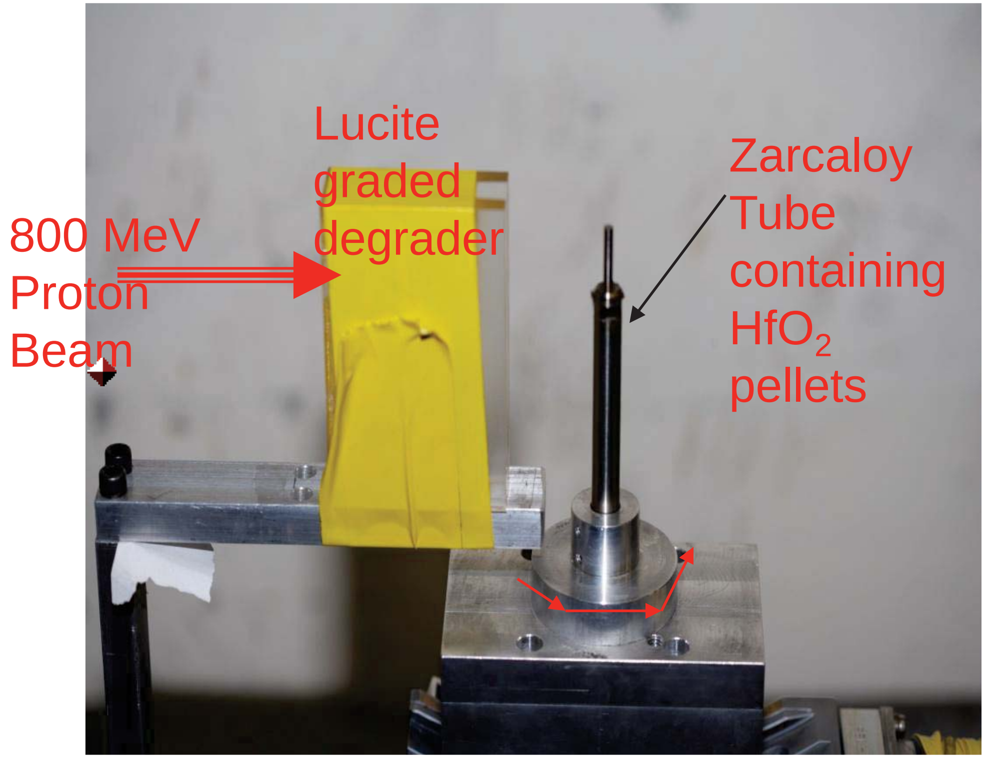


90 projections

Static Objects: Surrogate Nuclear Fuel Rods



Hafnium Oxide surrogate fuel rod.

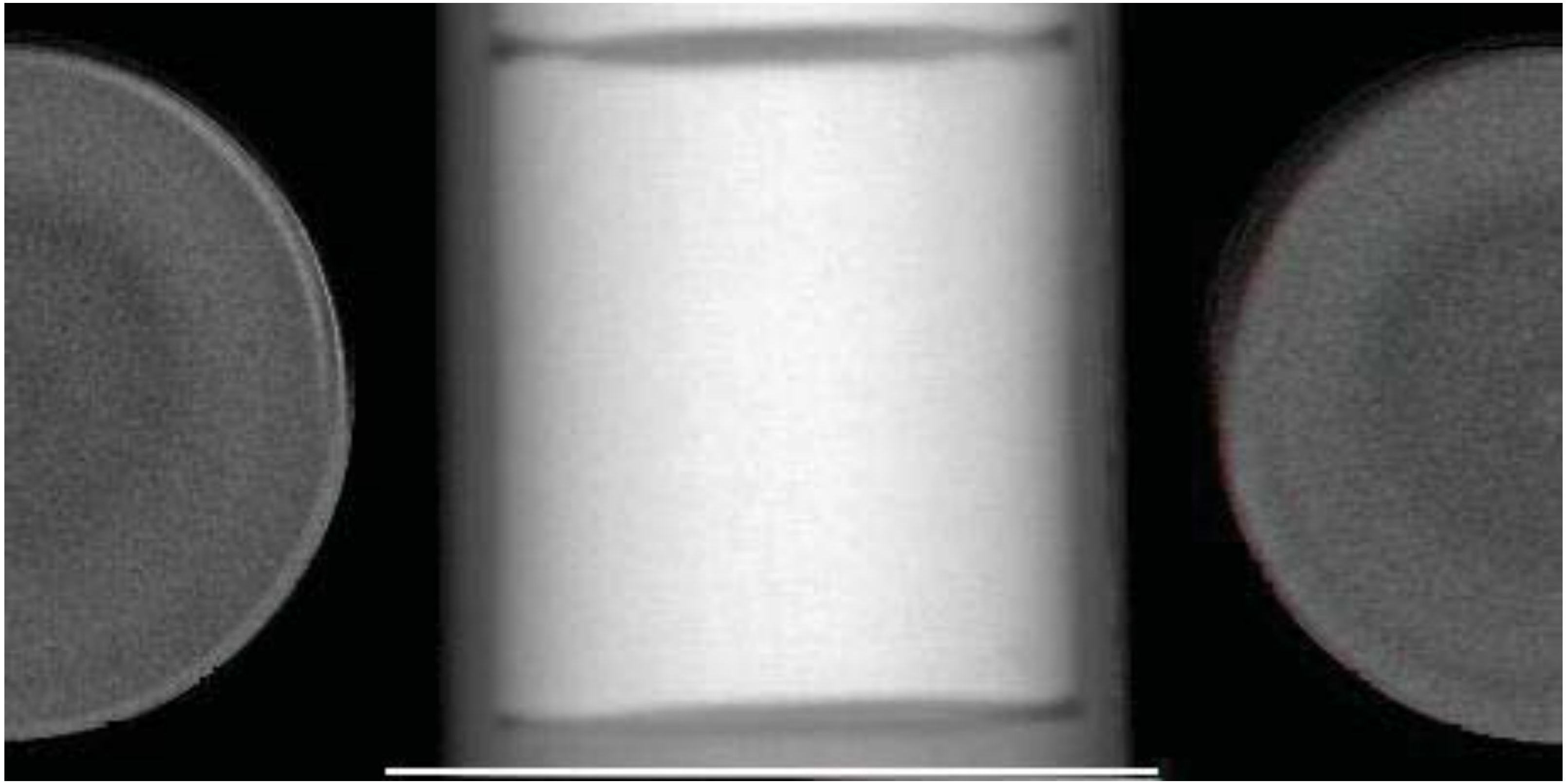


Zarcaloy tube was aligned on the graded degrader. Radiograph pictures were taken at 181 rotational positions

Images courtesy of Frank Merrill, LANL

CT Reconstructed Slices:

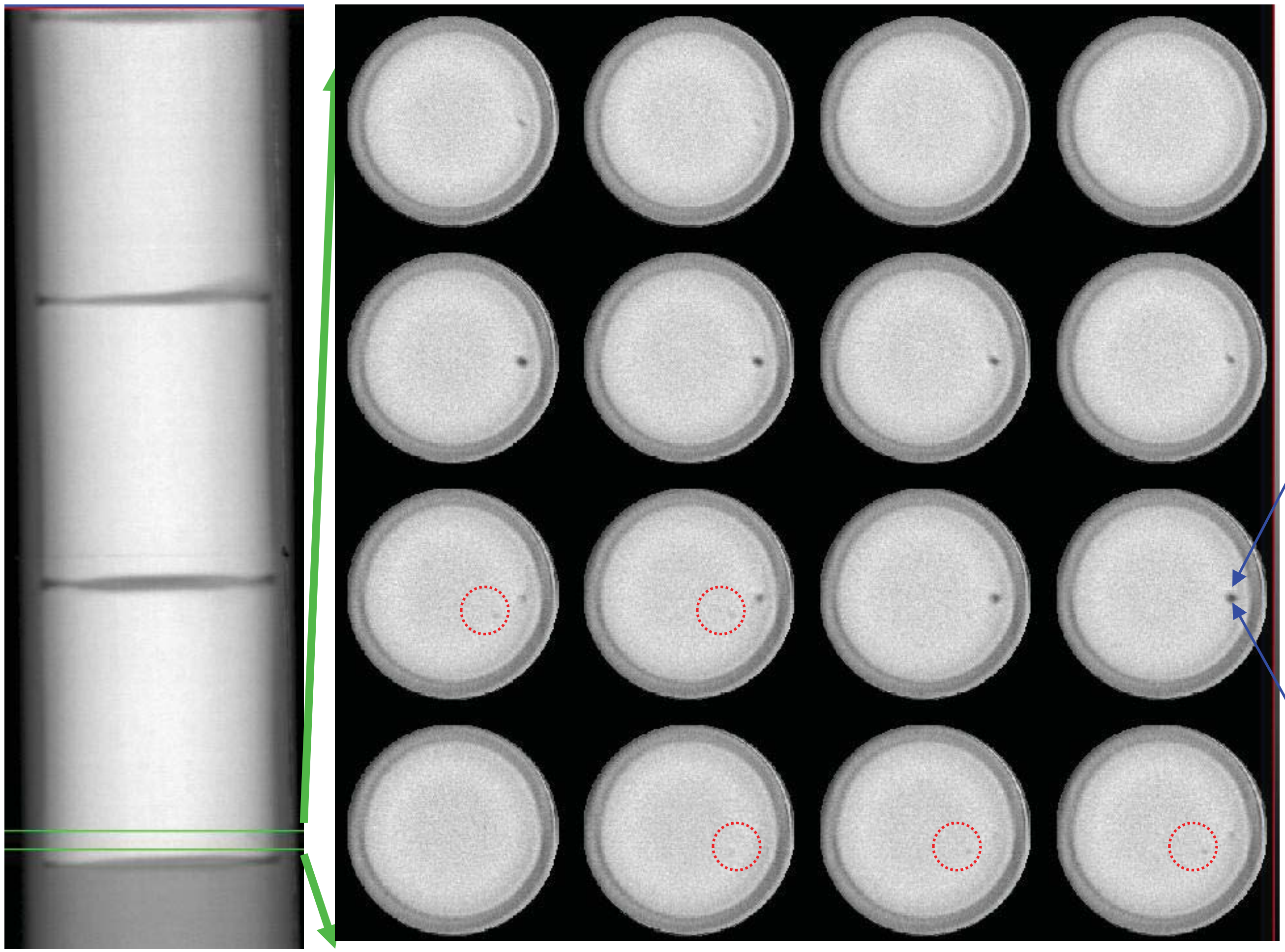
Interesting Regions: Part of Zarcaloy portion, all of Pellet#4, Part of Pellet#3

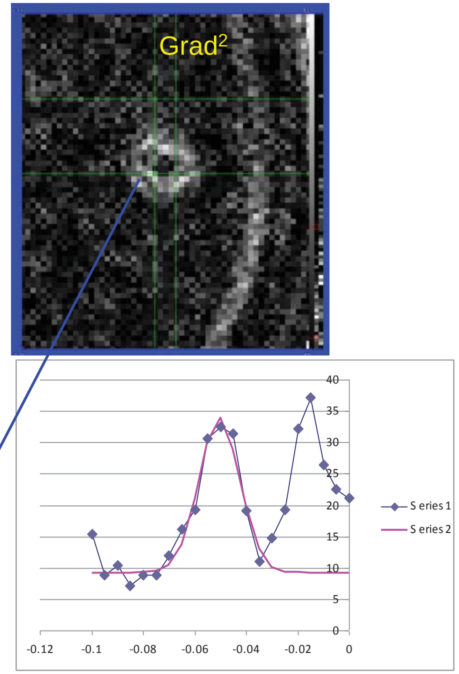


Images courtesy of Frank Merrill, LANL

Filtered Back Projection:

Defects in Pellet #4, Slices 78 to 93





Resolution ~ 80 μm

$Diameter_{Inclusion}$ ~ 350 μm

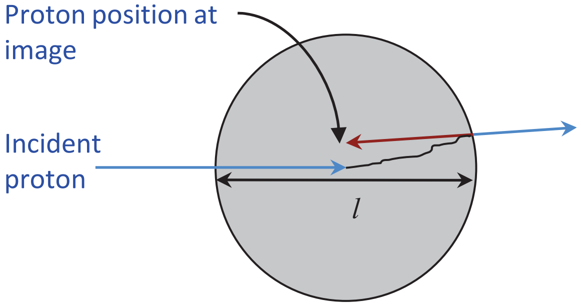
$Length_{Inclusion}$ ~ 550 μm

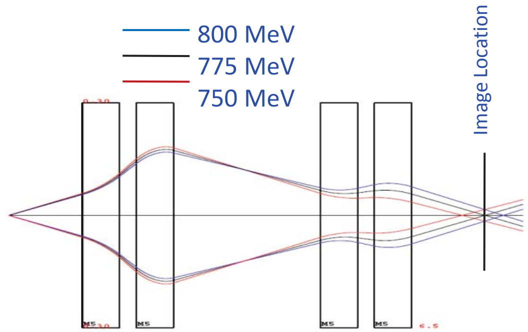
Fainter 250 μm long by ~150 to 200 μm diameter inclusions are shown in the circles

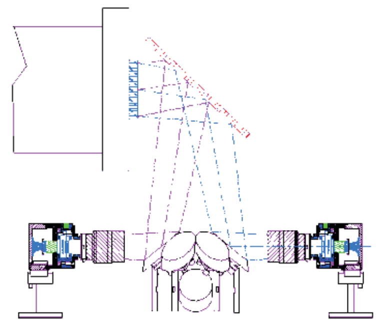
What is Next for Proton Radiography?..

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:

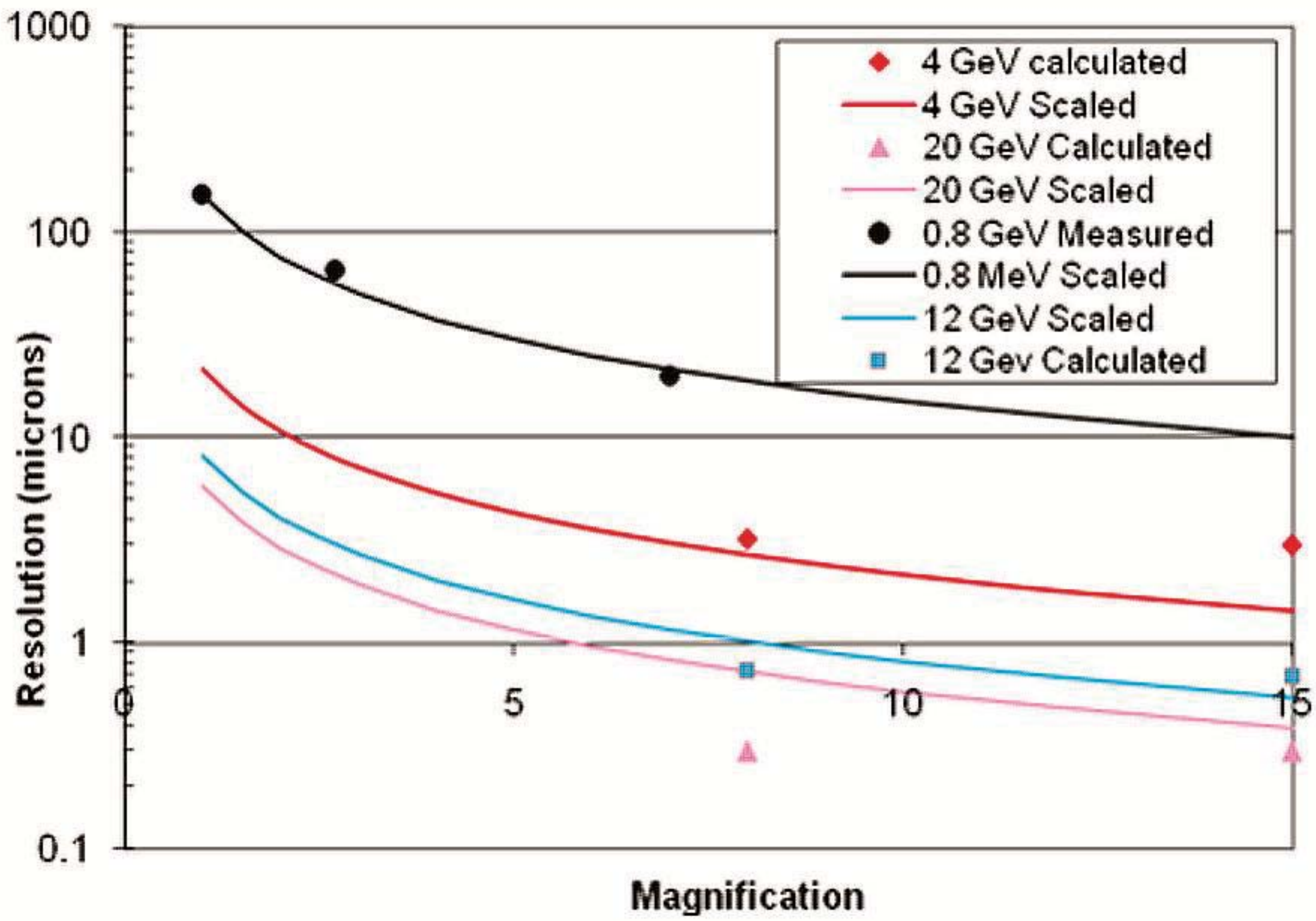
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{\frac{3}{2}}}{P}$$

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:

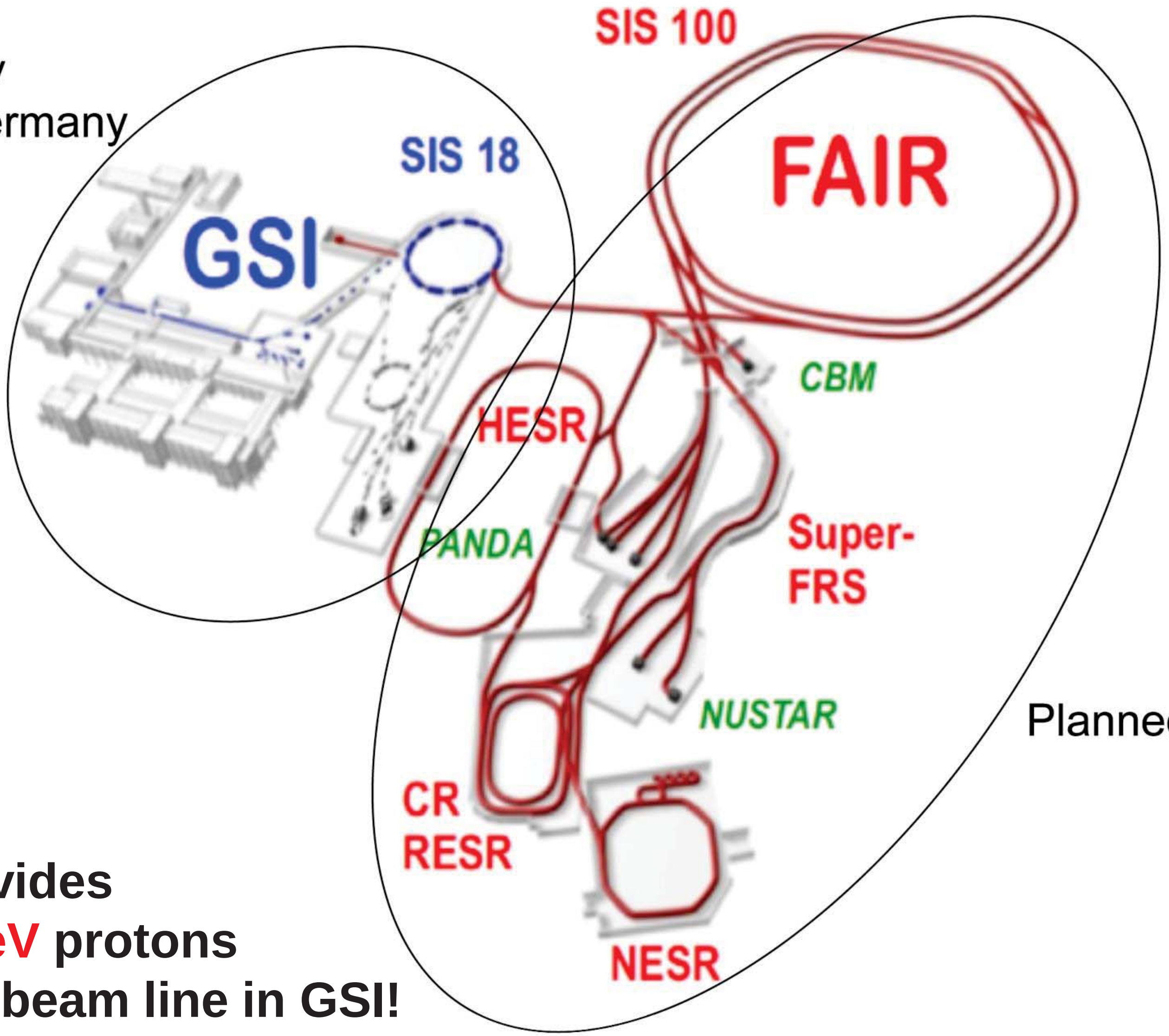
$$\sigma_s = \theta l_s \propto \frac{l_s\sqrt{l}}{P}$$



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!

Proton M**i**cr**o**scope at Ext**r**emes
(PRIOR Project)

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:

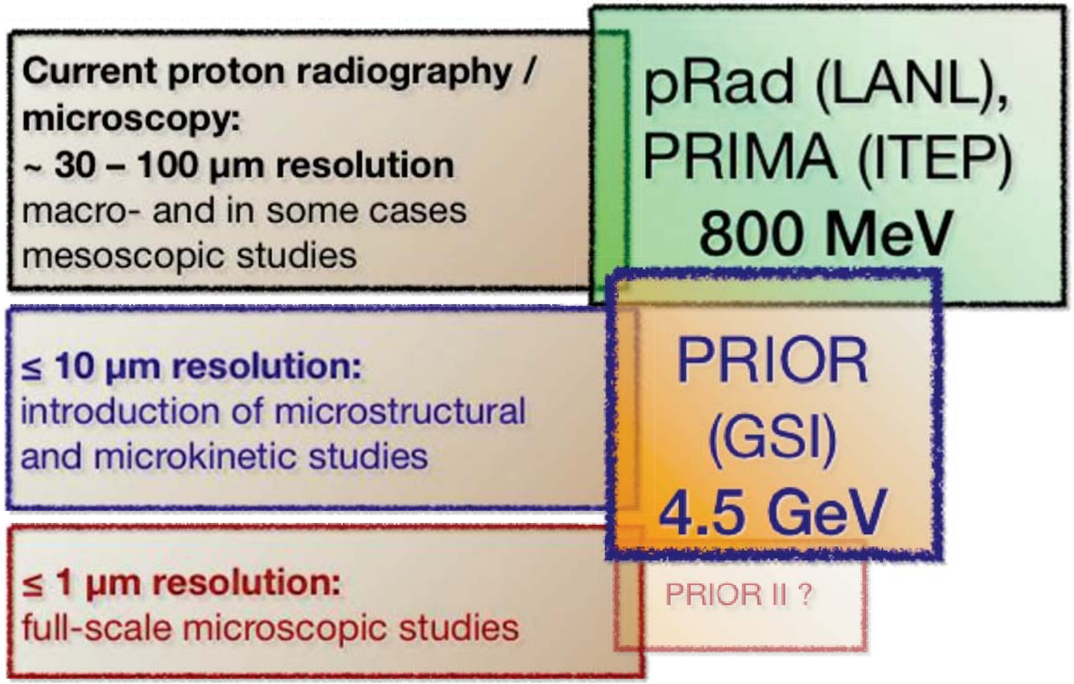
- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets high spatial resolution (microscopy)
- high density resolution and dynamic range multi-frame capability for fast dynamic events

PRIOR project will accomplish two main tasks:

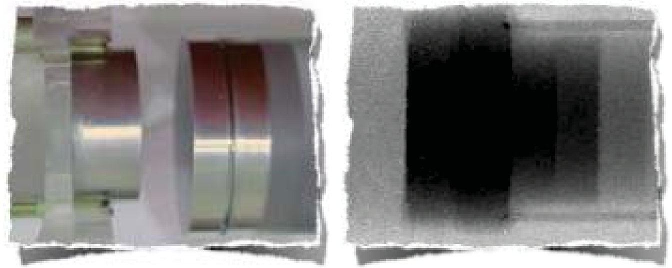
- FAIR proton radiography system which a **core FAIR installation** will be **designed, constructed and commissioned** in full-scale dynamic experiments with 4.5 GeV proton beam prior to FAIR using the same SIS-18 proton beam,
- **a worldwide unique radiographic facility** may become operational **at GSI** that would provide a capability for **unparalleled high-precision experiments** with great discovery potential at the leading edges of **plasma physics, high energy density physics, biophysics, and materials research**

Proton microscopy for HEDP, material sciences and beyond

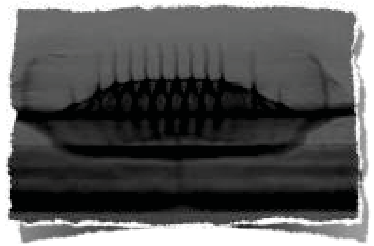
- **materials in extremes** (EOS, dynamic phase transitions, hydrodynamics of HED flows, instabilities, material strength and damage, ...)
- **new materials synthesis and process-aware manufacturing**
- **biophysics, medical applications**
- **industrial applications**



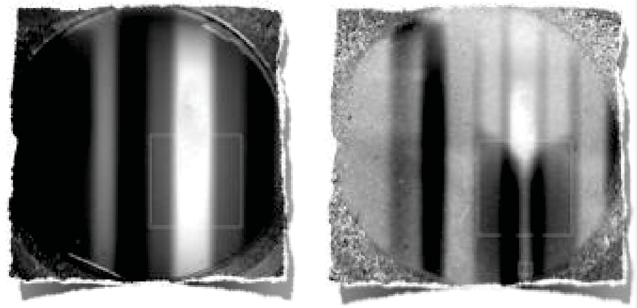
Al EOS in a shock wave experiment by proton radiography only (LANL)



Experiments on Richtmyer-Meshkov instability (LANL)

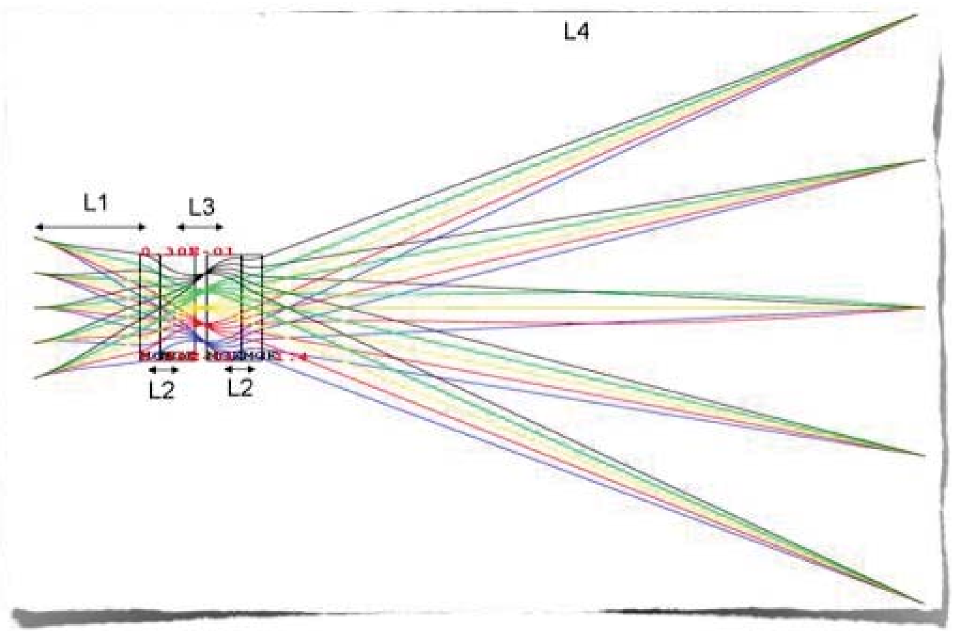


Phase transition of molecular nitrogen (IPCP, ITEP)



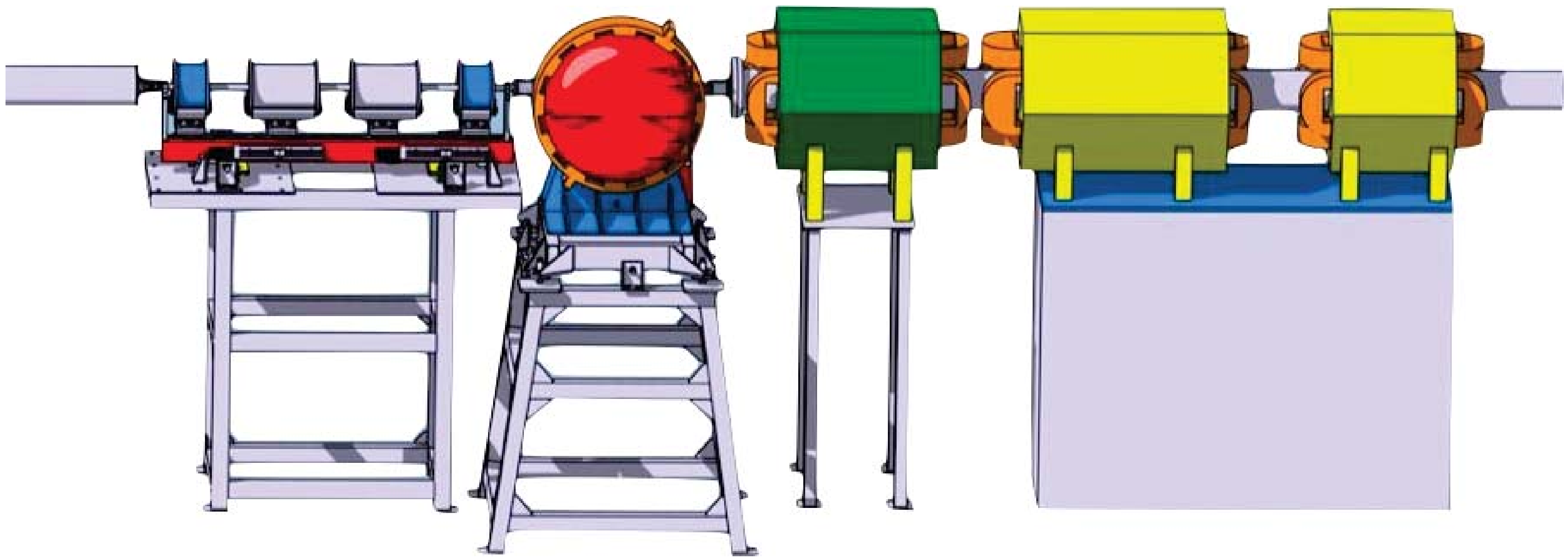
PRIOR ion optical design – 30 mm PMQ aperture

Parameter	Value
Proton energy	4.5 GeV
PMQ inner aperture, $2 \cdot R_i$	30 mm
PMQ outer aperture, $2 \cdot R_o$	100 mm
REPM remanent field	1.16 T
Field gradient	115 T/m
"Short" quadrupole length	165 mm
"Long" quadrupole length	330 mm
L_1 (object to first quad)	1.3 m
L_2 (first to second)	0.307 m
L_3 (second to third)	0.515 m
L_4 (last to image)	7.576 m
Total length	10.000 m



Parameter	Value
Magnification	4.1
Spatial resolution	8 – 10 μm
Horizontal chromatic length, C_x	3.99 m
Vertical chromatic length, C_y	3.41 m
Angular acceptance	5 mrad
Horizontal matching correlation, M_x	-0.45 mrad/mm
Vertical matching correlation, M_y	-0.55 mrad/mm

PRIOR additional features

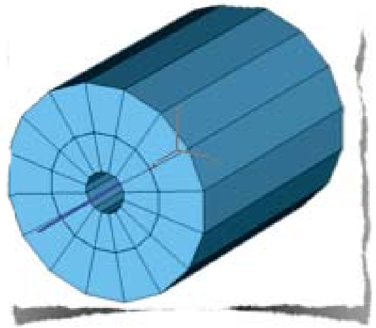


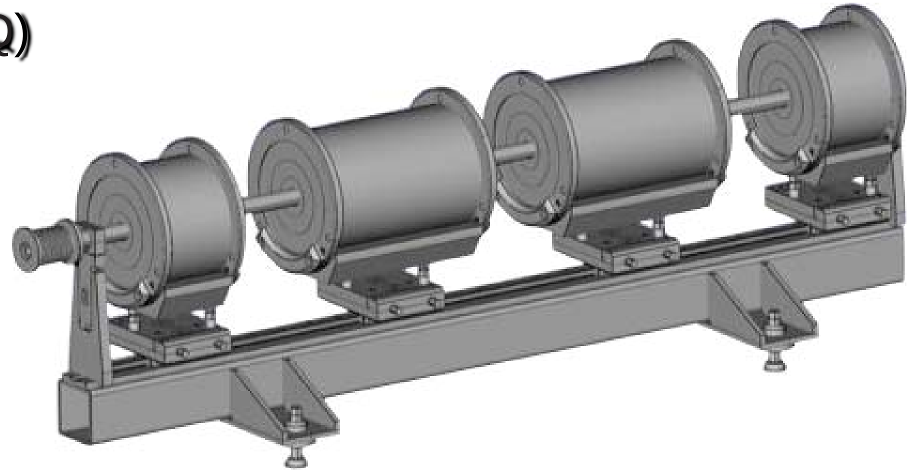
- **flexibility**: setup can be optimized for a particular experiment:
- proton energy can be adjusted
- standoff can be changed
- magnification can be increased

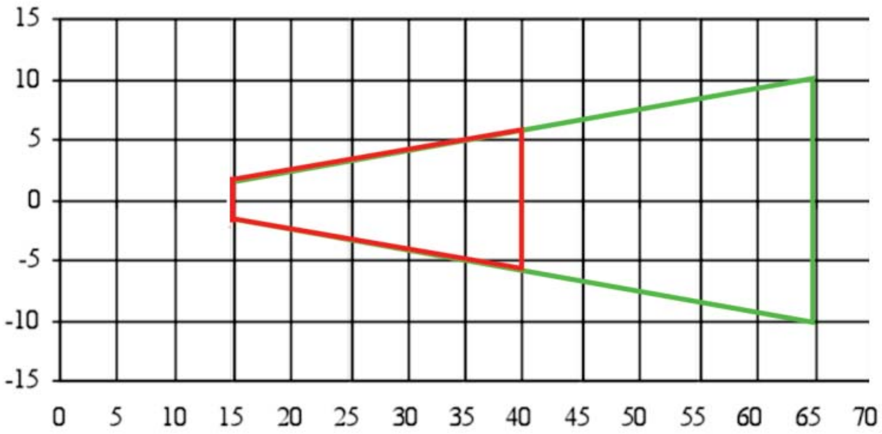
- **SIS-18 electron cooler**: both transverse (⇒ density resolution) and longitudinal (⇒ spatial resolution) emittances of the beam can be reduced by an order of magnitude or more

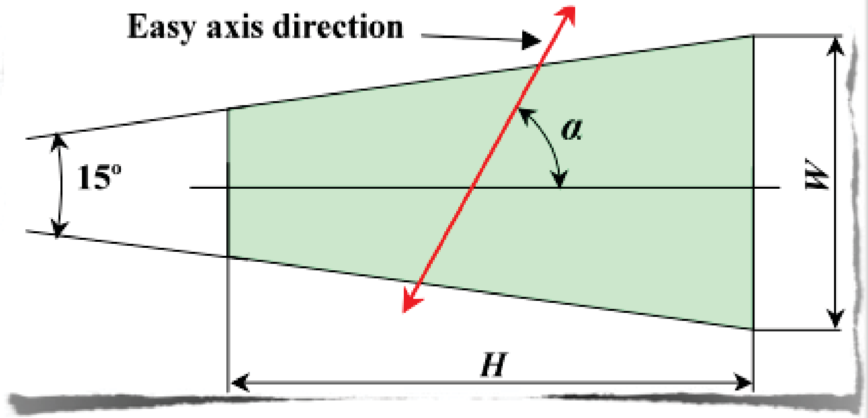
Permanent Magnetic Quadrupoles (PMQ)

- aperture: **30 mm**
- B_p: **1.7 T**
- 2xQ1: **165 mm**
  2xQ2: **330 mm**

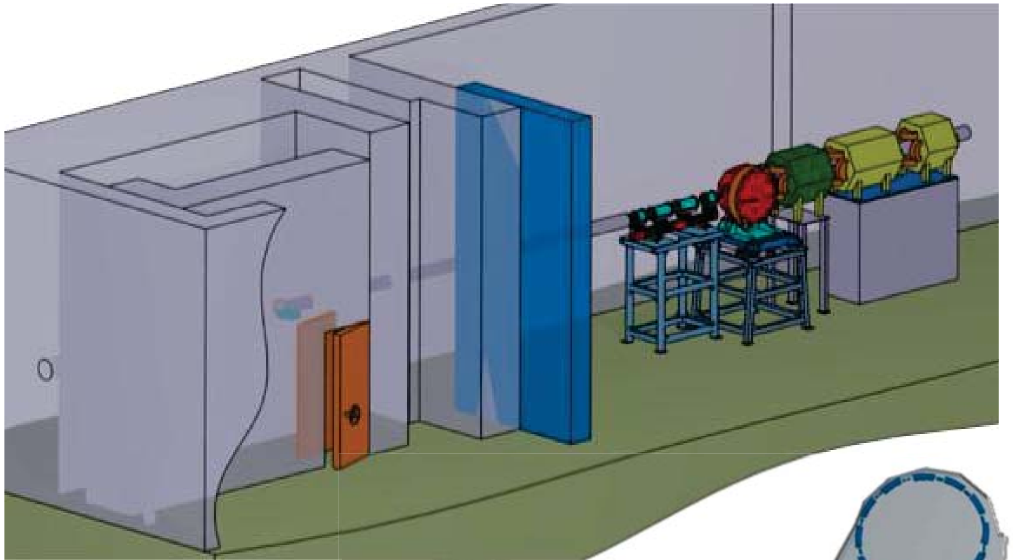


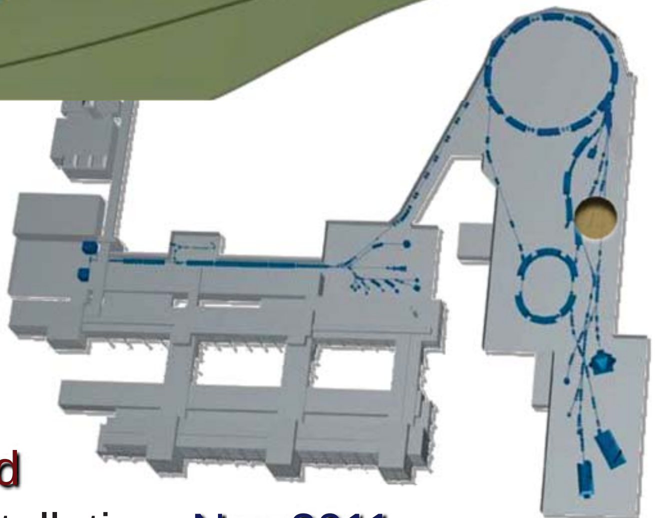


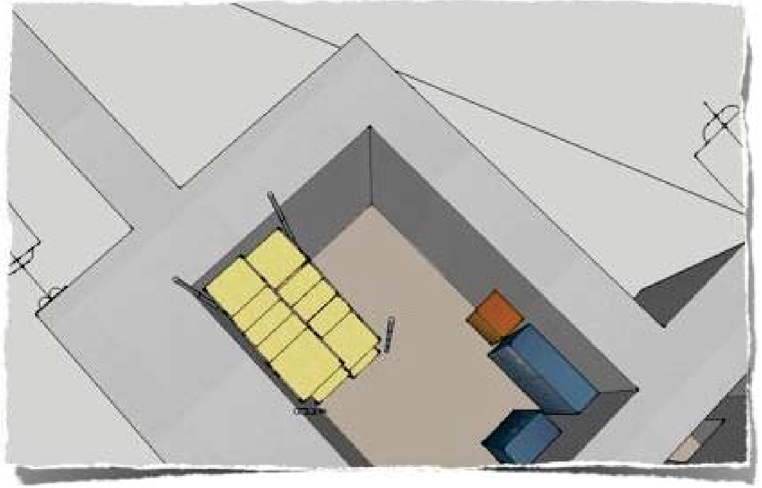




Fielding at GSI – a reconstruction of the HHT cave

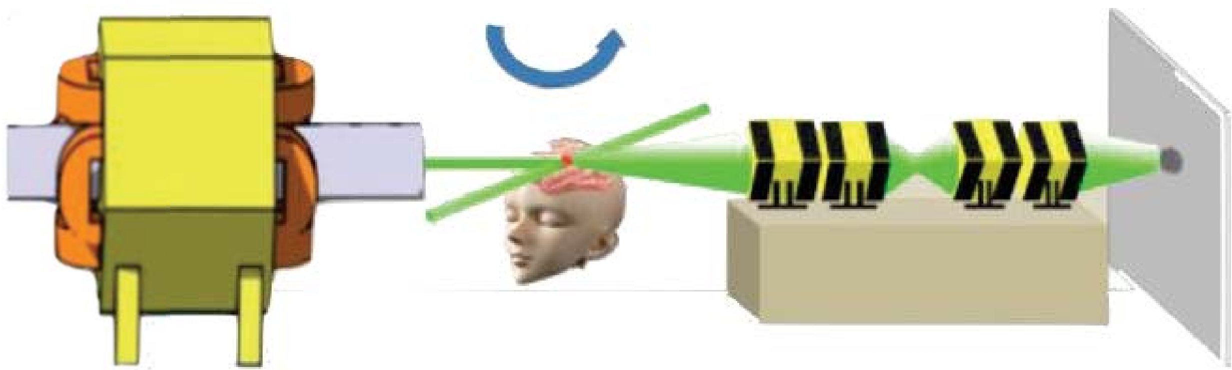






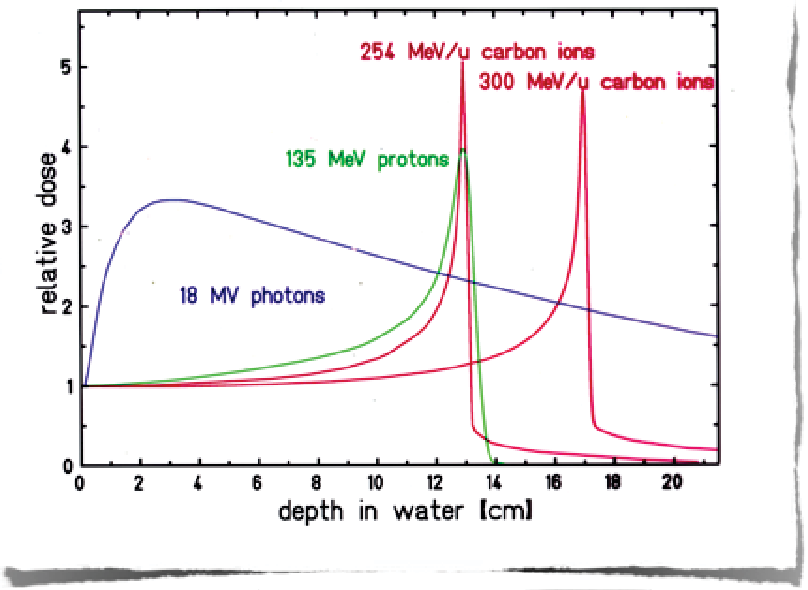
- area is prepared
- beam dump installation: Nov 2011
- walls, roof & staircase: Jan/Feb 2012

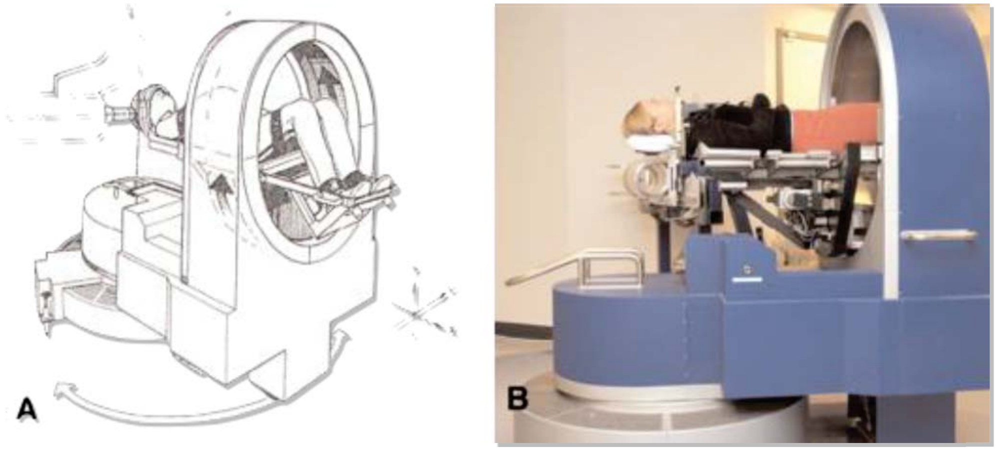
PaNTERA
Proton Therapy and Radiography



Marco Durante, GSI

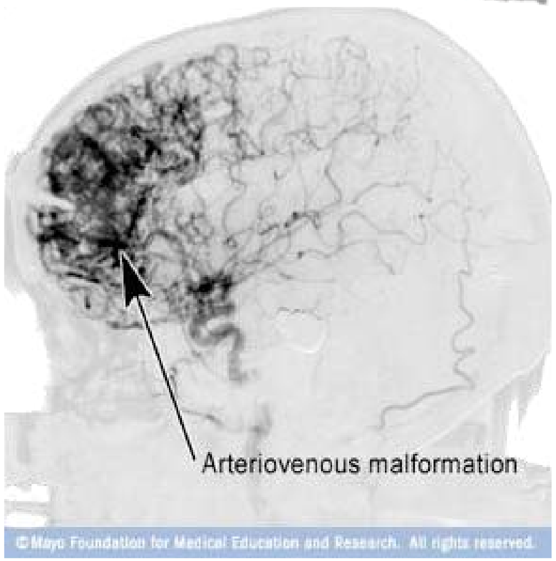
"Bragg peak" radiosurgery in neurosurgery





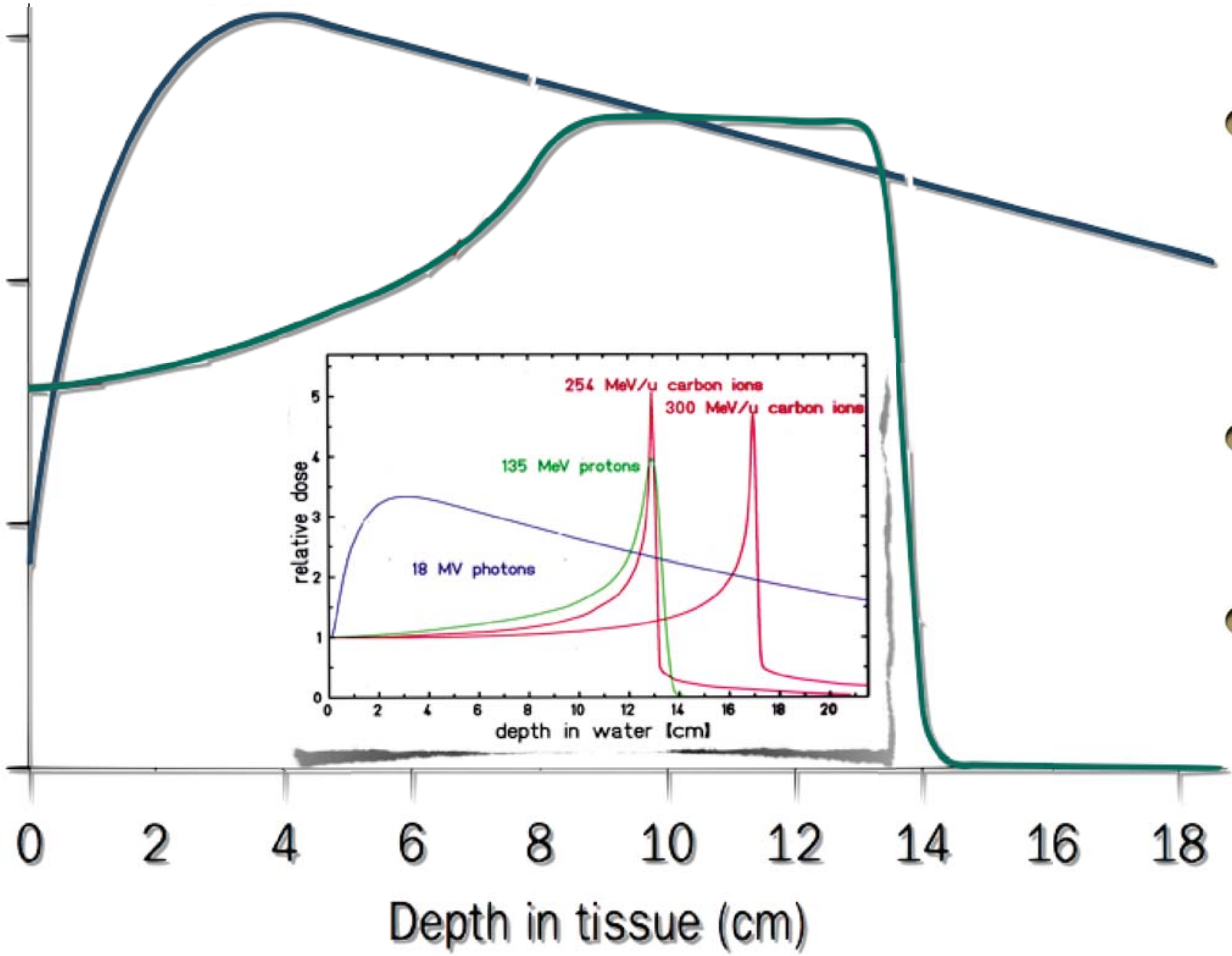
STAR System at Massachusetts General Hospital
Northeast Proton Therapy Center

"... AVM obliteration rate are more than 70% for V < 15 ml, but less than 40% for V > 15 ml." Chen et al., *Neurosurg. Focus 2007*



- no significant improvement over X-rays for large malformations

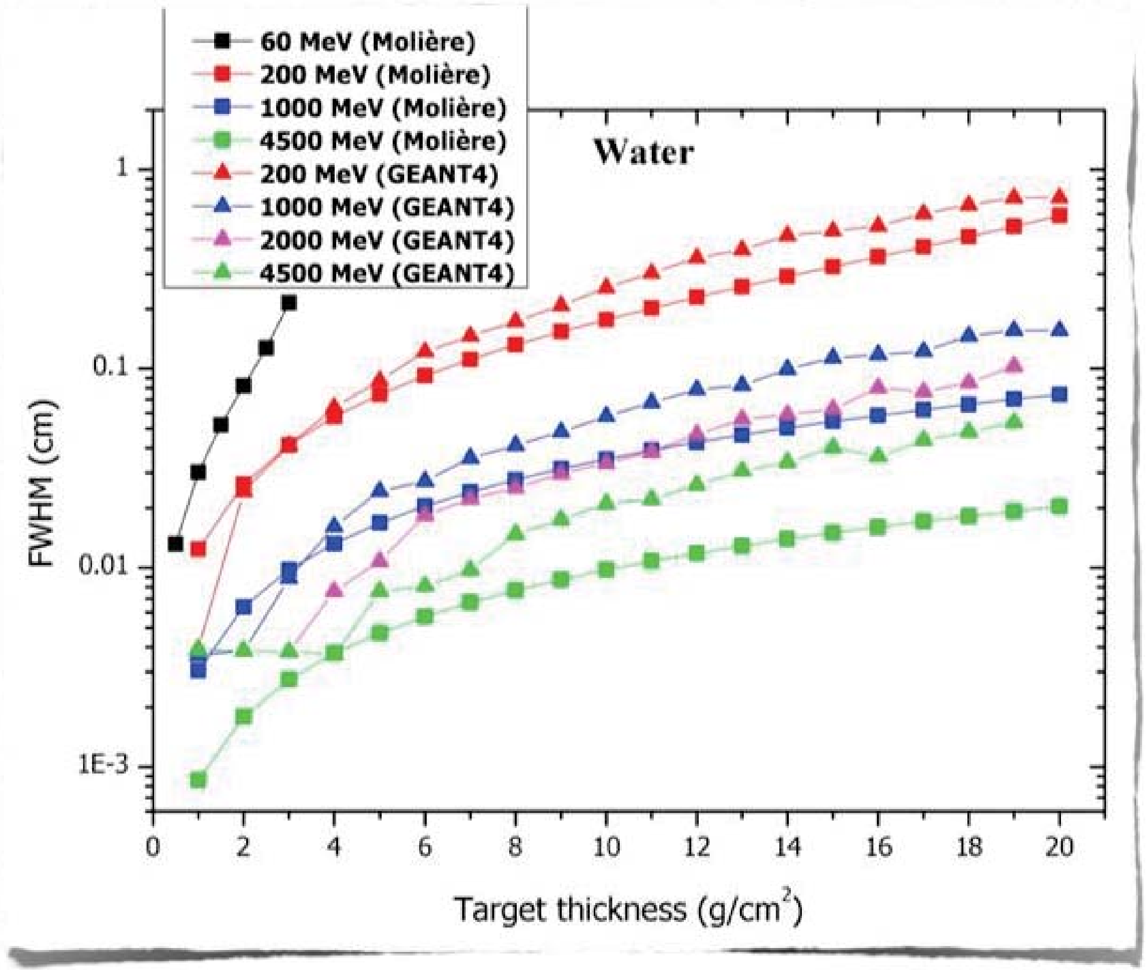
"Bragg peak" particle therapy / radiosurgery



- the spread-out-Bragg-peak dose profile may be not that different from X-rays profile: sparing of a normal tissue is not significant
- ablation of a vascular malformation may require too high doses
- precision of the dose distribution is much more important!

- **sharp edges of the energy deposition zone would allow to spare critical structures in the vicinity and consequently to increase the dose in the tumor**

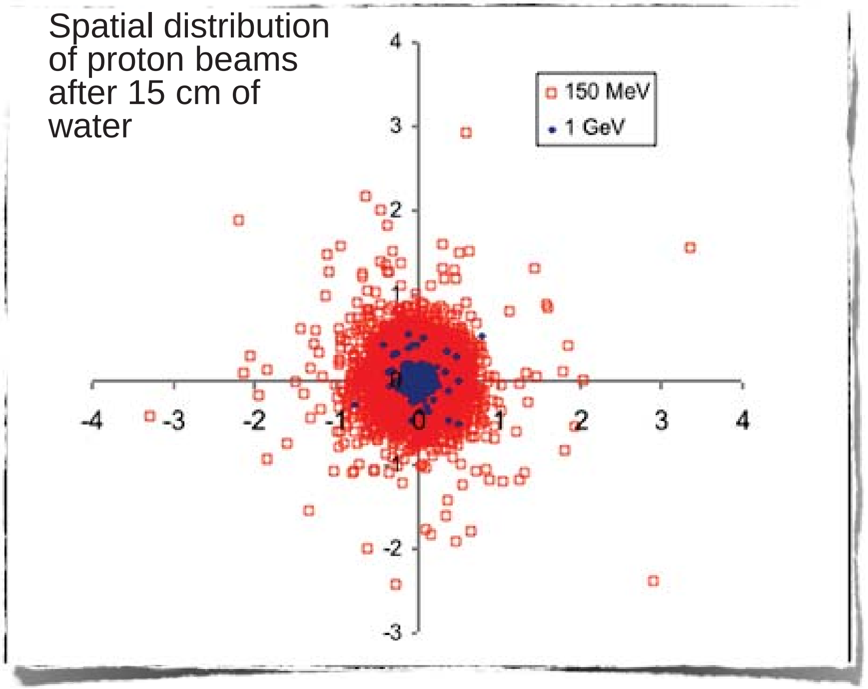
“Bragg peak” vs. “Plateau”: scattering and precision

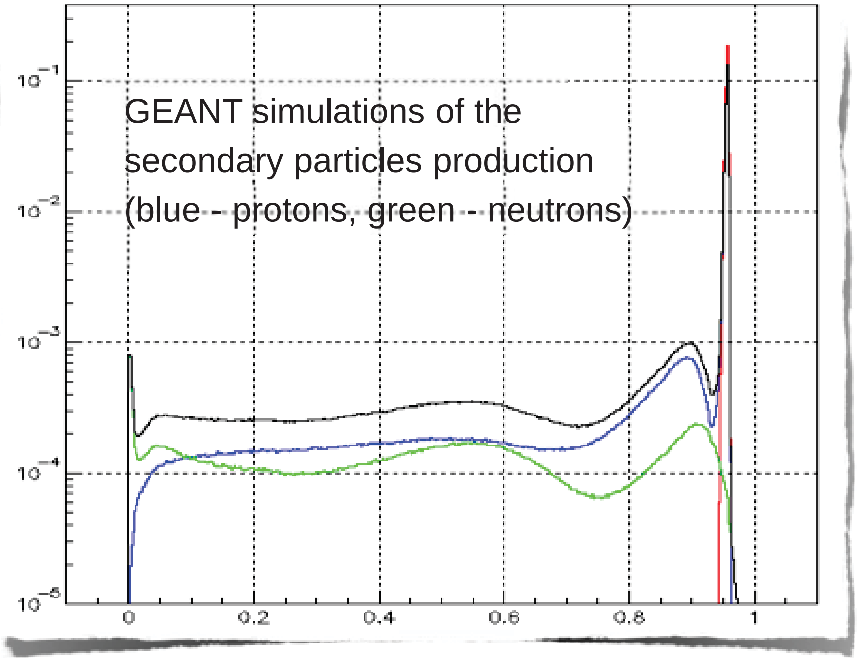


after 16 cm of water:

- FWHM(150 MeV) ≈ 7.5 mm ⇒ cm-scale precision
- FWHM(4.5 GeV) ≈ 0.4 mm ⇒ sub-mm precision

IGSpRS – Image-Guided Stereotactic Particle Radiosurgery



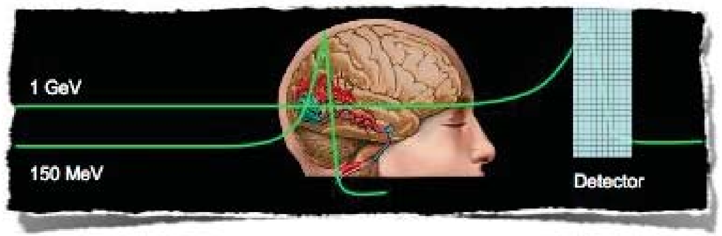


"+" very small lateral scattering (remote scalpel)

"+" simultaneous imaging (on-line radiography) with the same beam (PRIOR)

"-" not sparing tissue behind the tumor

"**-**"/"**+**"? modification of the dose distribution due to production of secondaries

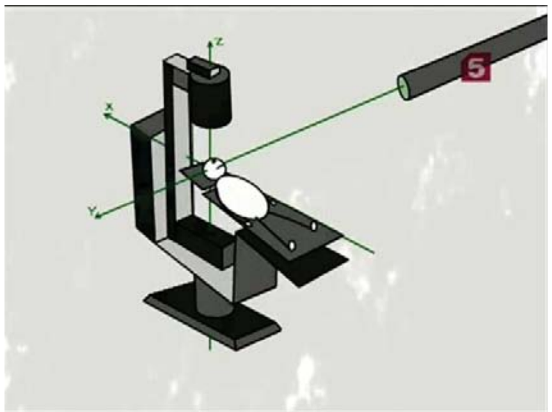


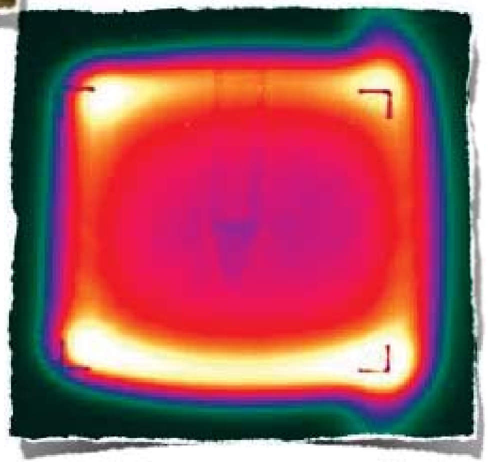
The only facility where 1 GeV protons are used for therapy

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



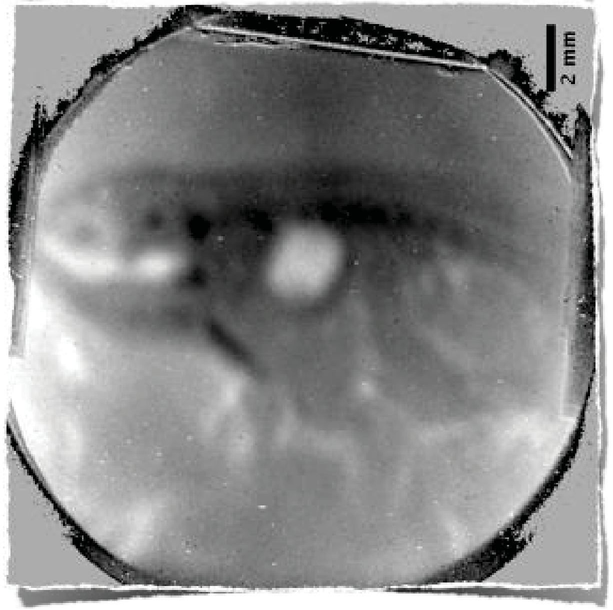


A 10 cm diameter 1 GeV proton beam used to expose blood cells in a plastic tube – visible in scattering proton radiogram

First biological images with HEPM

- ITEP-Moscow, December 2011,
  800 MeV protons, PUMA x4 microscope

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



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