Application of Proton Radiography to High Energy Density Research

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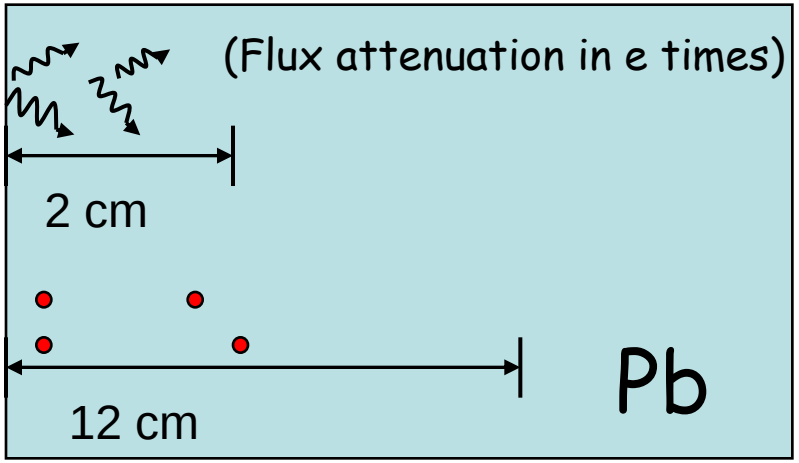
Radiography Basics

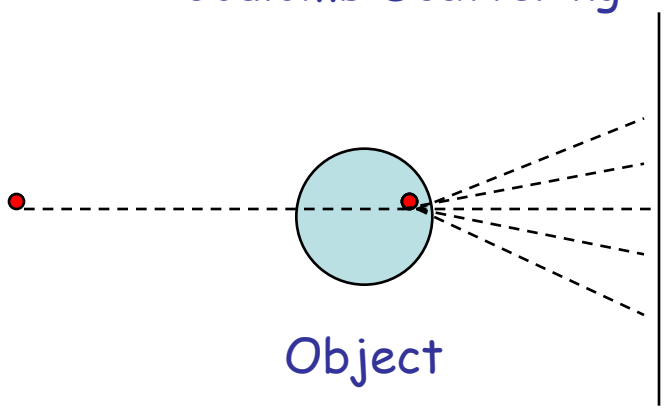
Photons and protons in matter

X-rays 3-10 MeV

High Energy Protons ~ 1 GeV

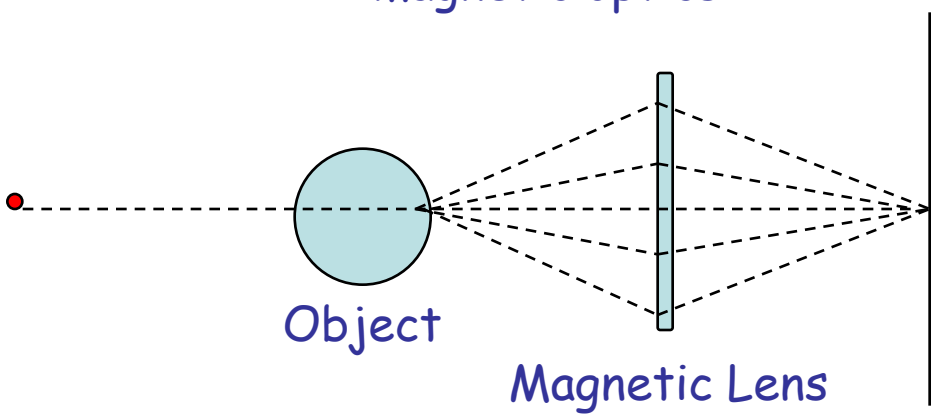


Protons Image Blurring due to Multiple Coulomb Scattering



A. M. Koehler, et al. *Science* **160**, 303 (1968).
J. A. Cookson Naturwissenschaften 61, 184—191 (1974)

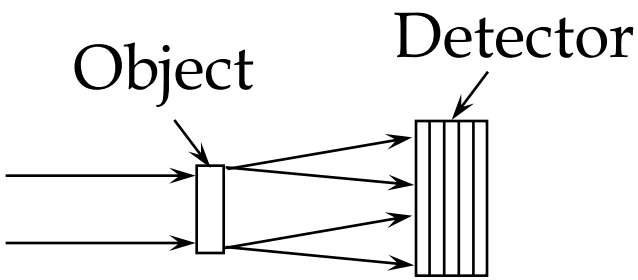
Image Blurring compensation with magnetic optics



C.L. Morris, J.D. Zumbro, Overview of proton radiography—concepts and techniques, Technical Report LA-UR-97-4172, Los Alamos National Laboratory, 1997.

First Experiments on Proton Radiography with Magnetic Optics (Los Alamos, 1995)

188 MeV secondary proton beamline at LANSCE



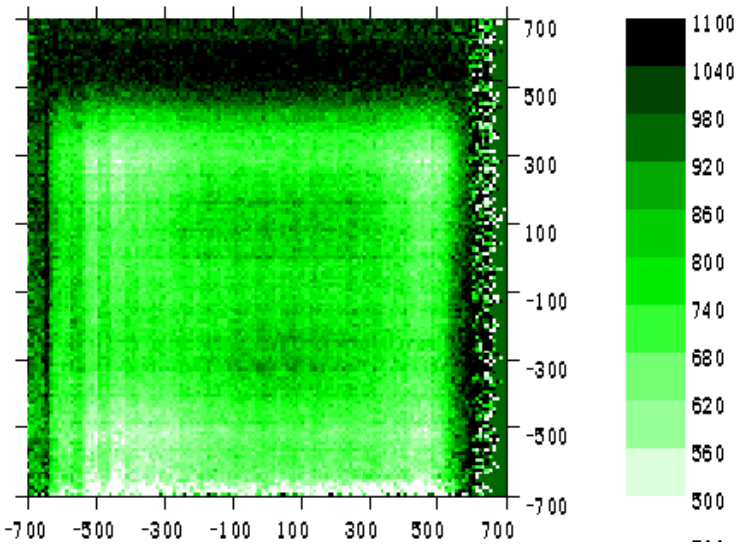
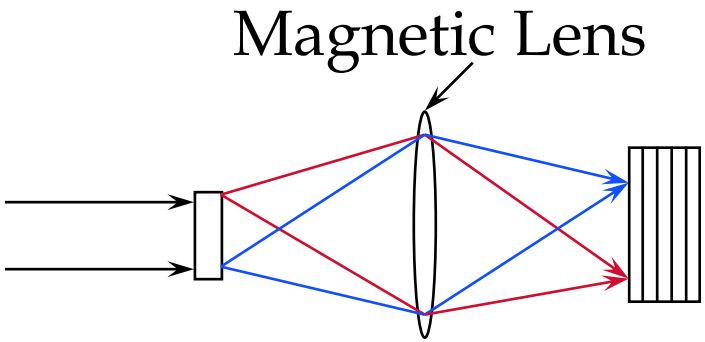
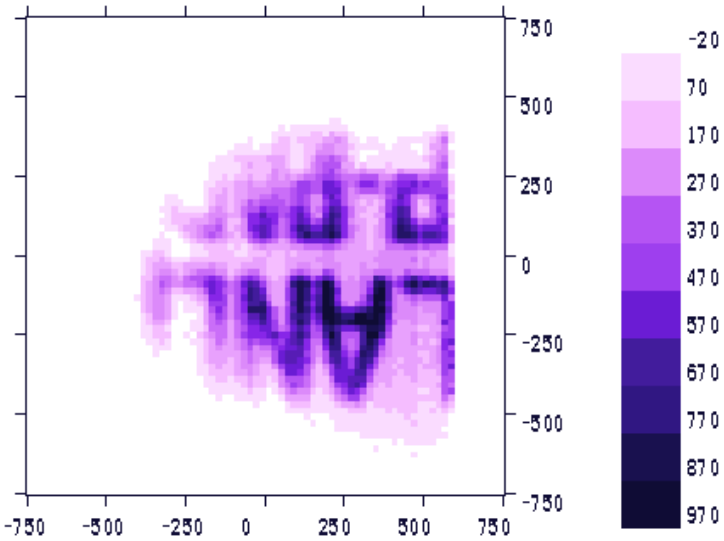


Image at the detector is substantially blurred

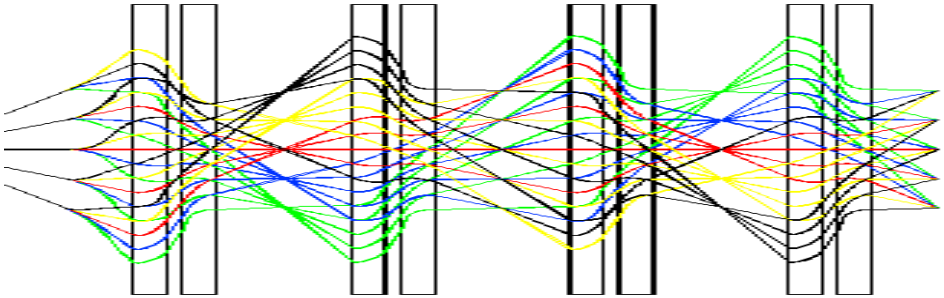




Magnetic imaging lens preserves image with high resolution

Capabilities and Applications

Proton radiography @ LANSCE:
- up to **30 frames**
- density range - **0.05 to 50 g/cm^2**
- spatial resolution **~100 μm**
- temporal resolution **~100 ns**



Capabilities for both the **visualization** of fast processes and absolute ***in situ*** **measurements** of important material and microstructural characteristics (including density distribution) that are especially useful for **dense optically non-transparent media** studies.

High Energy Density Research

HED & WDM
(EOS, phase transitions…)

Hydrodynamics of HED flows
(shock compression of reacting and non-reacting media, hydrodynamic instabilities)

Material Strength and Damage
(dynamic fracture of materials)

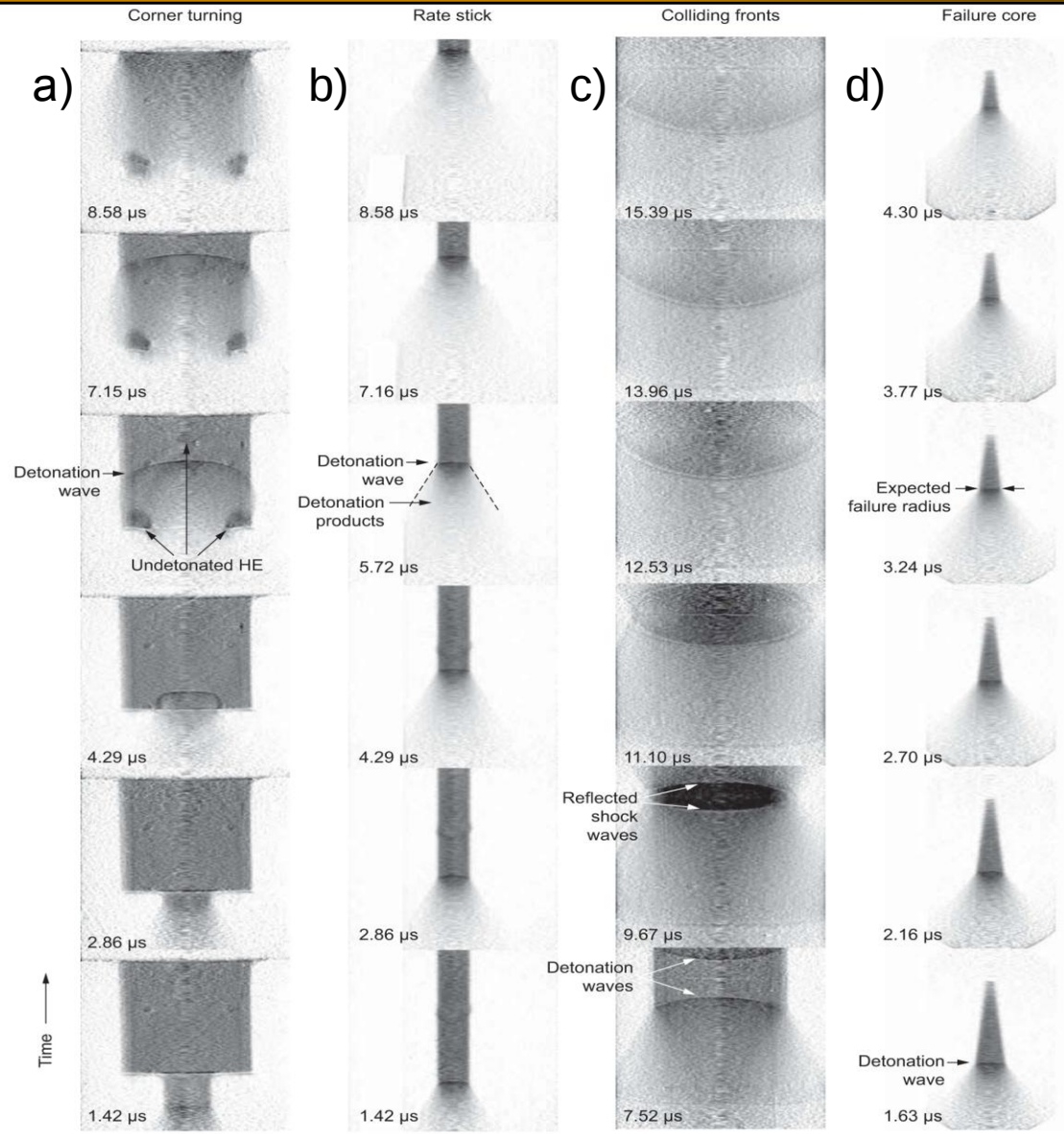
Detonation Waves in High Explosives

a) Detonation wave corner turning experiments.

b) Rate stick test for PBX-9502.

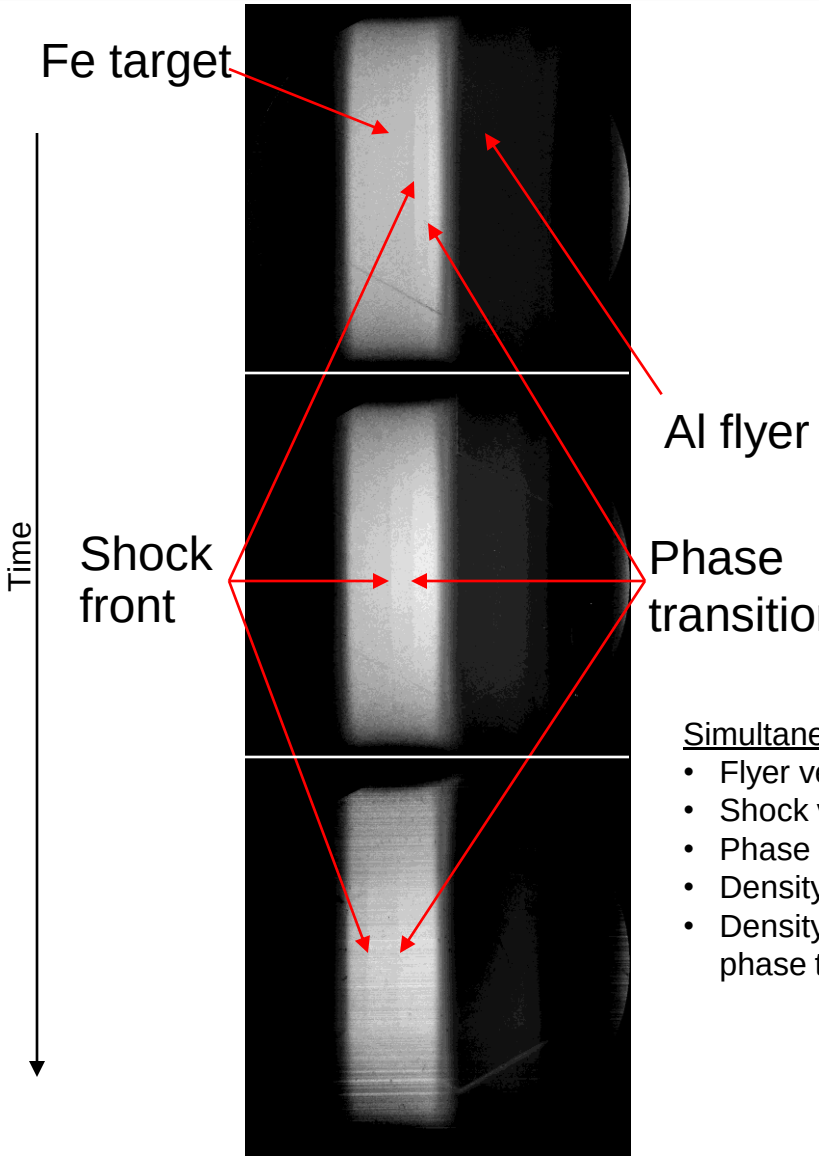
c) Collision of detonation waves.

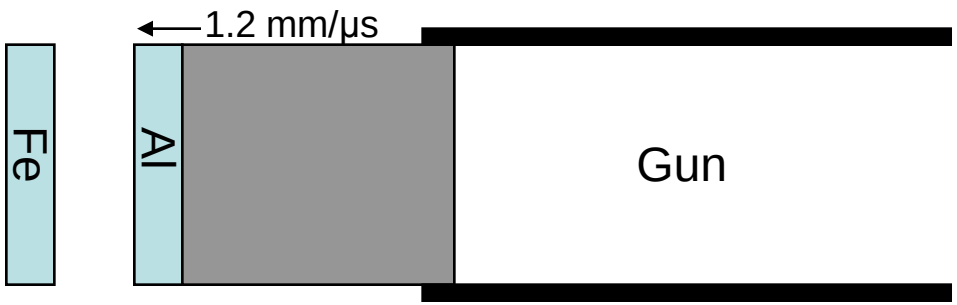
d) Failure cone test.

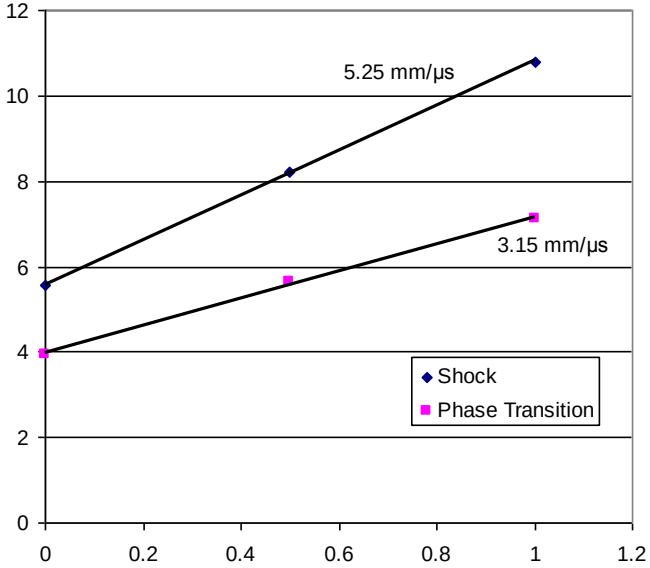


Source: C. Morris, J.W. Hopson, P. Goldstone, "*Proton radiography*". Los Alamos Science, N30, 2006.

Phase Transition in Shocked Iron





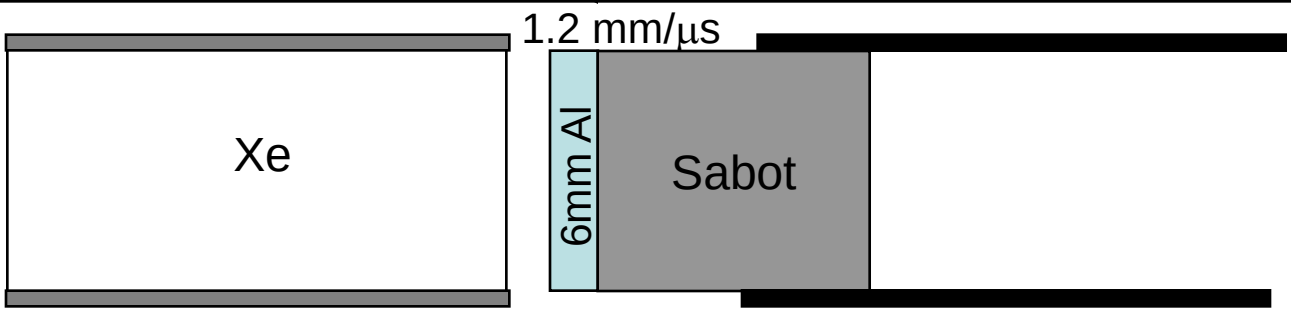


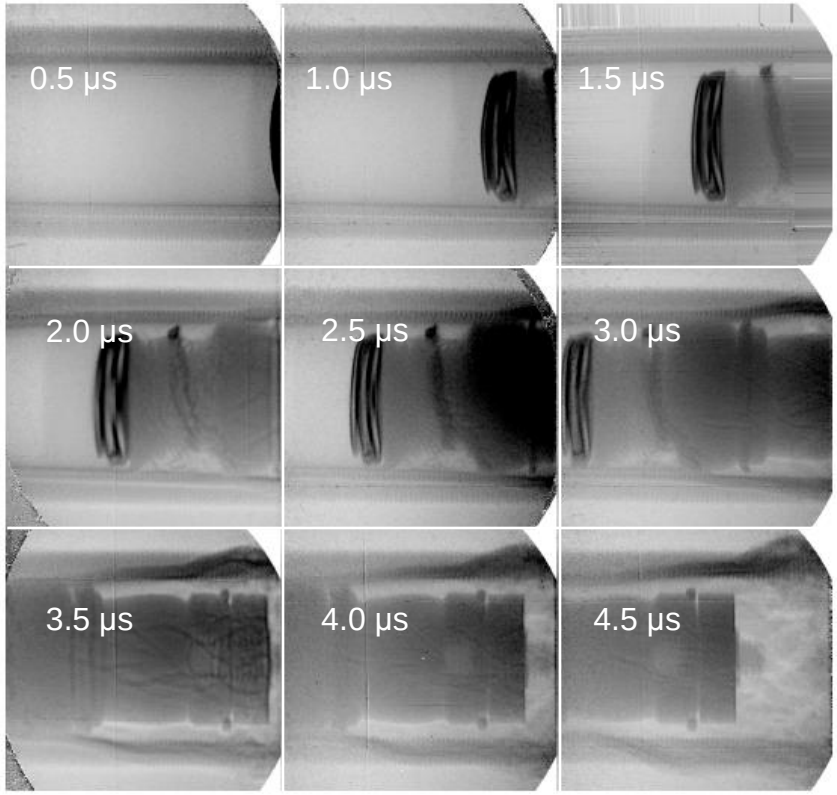
<u>Simultaneous measurement of:</u>

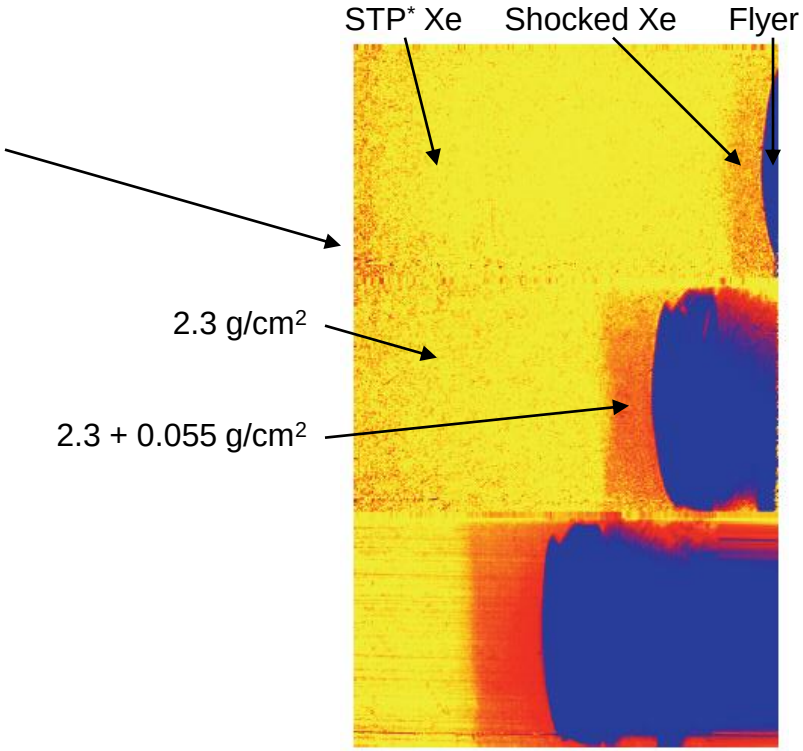
- Flyer velocity
- Shock velocity
- Phase boundary velocity
- Density of shocked material
- Density change in solid-solid phase transition

Images courtesy of Frank Merrill, *LANL*

Shock Waves in Gaseous Xenon





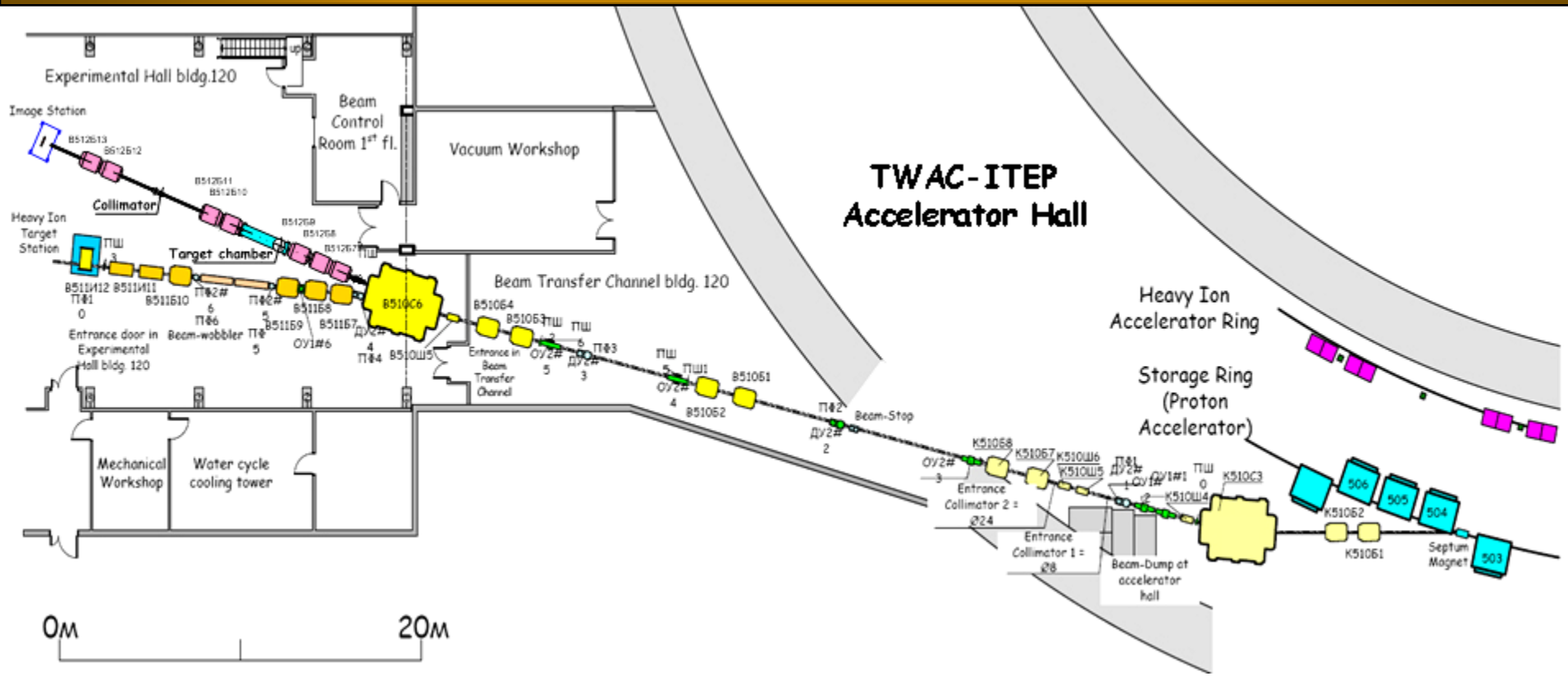


* Standard Temperature and pressure

Images courtesy of Frank Merrill, *LANL*

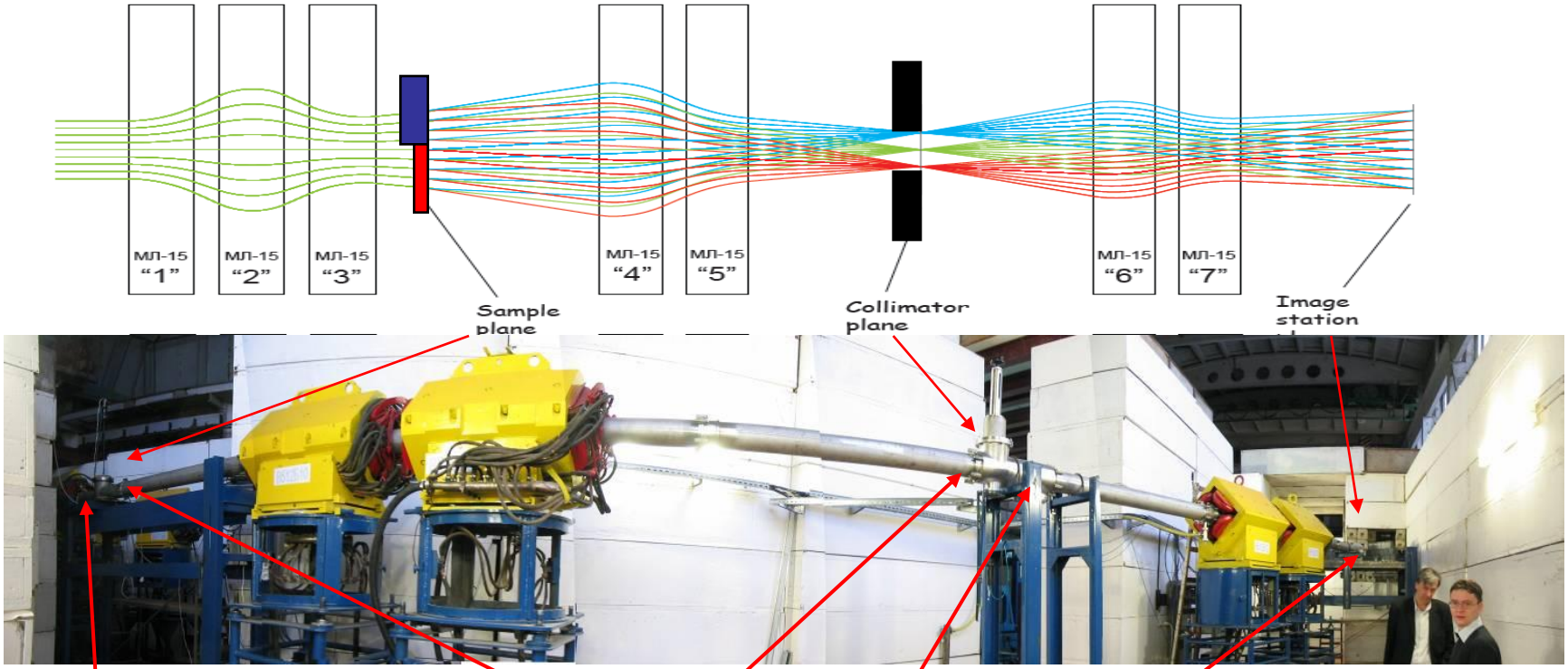
Proton Radiography at ITEP

800-MeV Proton Radiography Facility at TWAC-ITEP Accelerator (Moscow)



- Field of view — **20 mm**;
- Target density range — **< 60 g/cm^2**;
- Spatial resolution — basic magnetic optics system: **300 μm**; "proton microscope": **~ 50 μm**;
- Time structure of proton beam: — four **70 ns** long bunches with **250 ns** interval between them;
- Temporal resolution: — is defined by the length of a bunch – **70 ns**

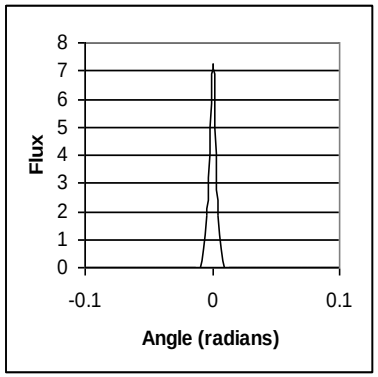
Magnetic Optics System

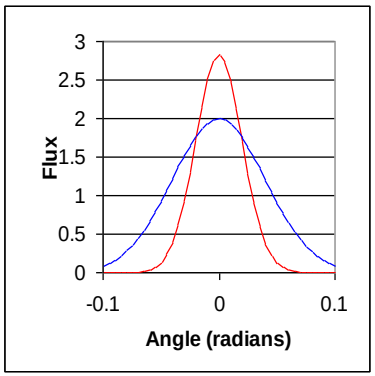


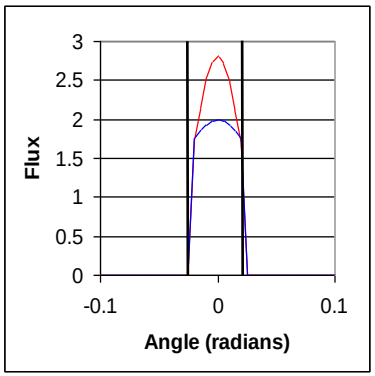
Incident Beam

After Object

After Collimator



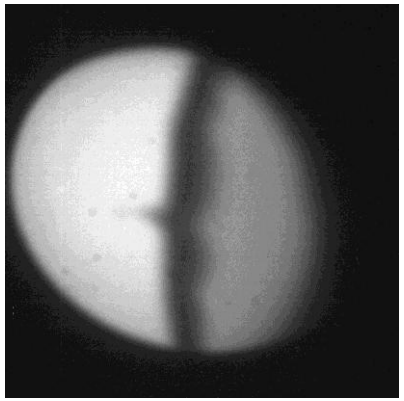




Measured transmission provides information about object's areal density

Proton Radiography Image Analysis

"Raw" Proton Radiography Image



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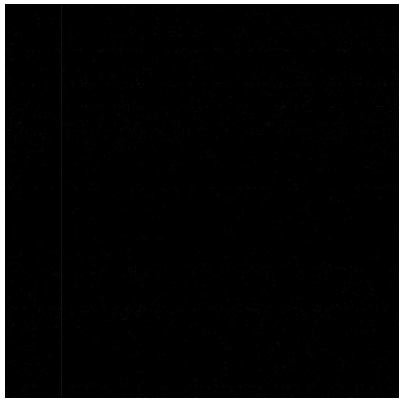
"Dark Field" Image



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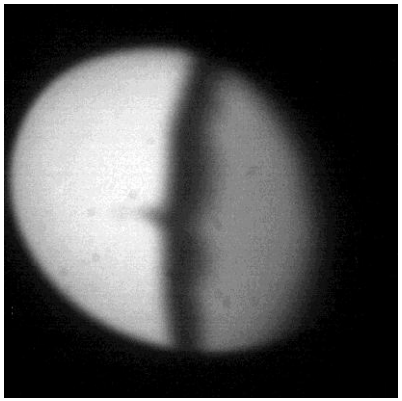
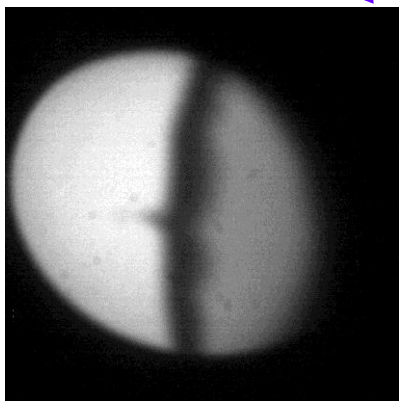
Proton Radiography Image with subtracted "Dark Field"





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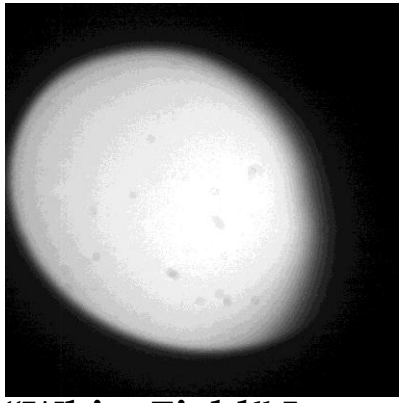

"White Field" Image (Beam Image)

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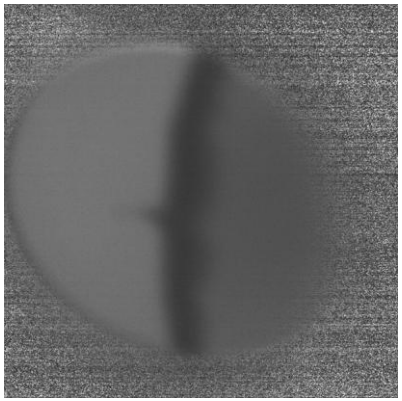


Proton Transmission – object areal density information

Reconstruction of volume density with the use of Abel inversion is based on the assumption of cylindrical symmetry

Explosive Confinement Chamber

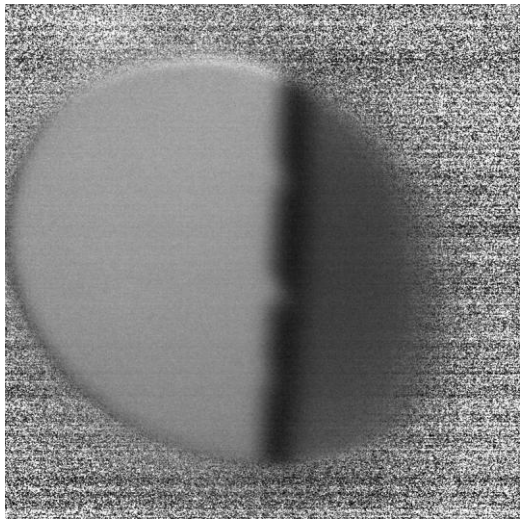
- Certified for HE charges of up to **60 g** in TNT equivalent
- Pumped down to **10^{-3} Bar**
- Active ventilation system
- Replaceable beam entrance windows (**Al, Fe 0.2-1.5 mm**)
- Fibers for optical diagnostics (**VISAR**)

First Dynamic Experiments (2008)

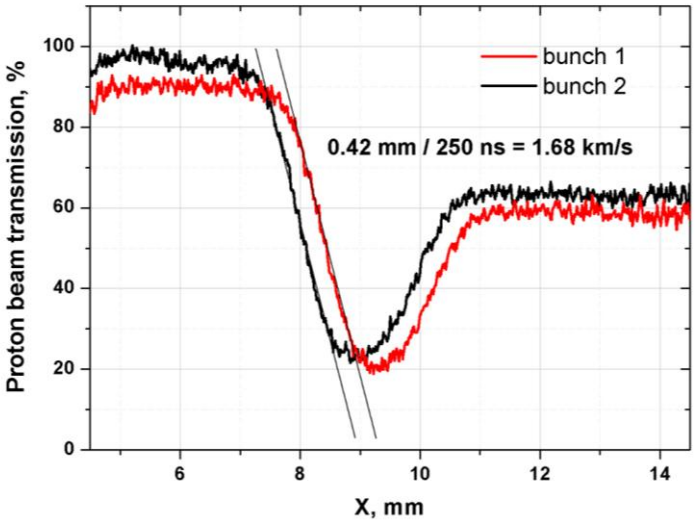
Explosively driven techniques using small pressed TNT charges:

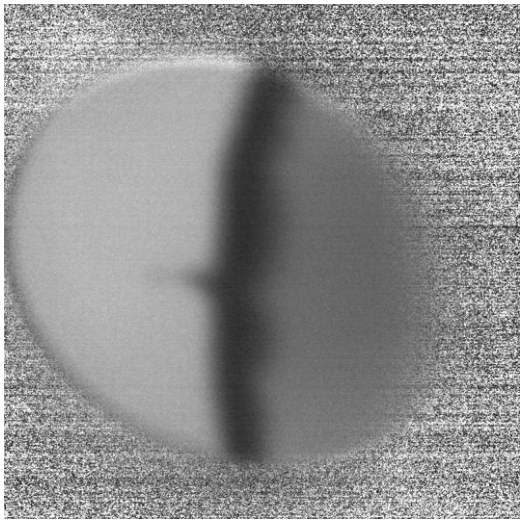
- **total weight of charge** – 25 g
- **initial density** – 1.32-1.35 g/cc
- **diameter** – 15-20 mm
- **length** – 32-40 mm

First Dynamic Experiments:
Shock Loading of Steel Plate Surface



Static target image:
1 mm thick steel plate with 0.3 and 0.5 mm deep triangular cuts placed on the face of the TNT charge





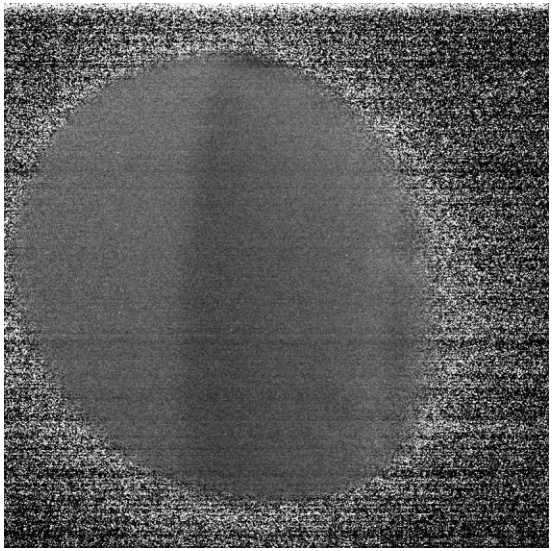
Dynamic target image:
shot after 1 μs after the shock wave had come to the free surface of the plate.

Velocity of the free surface:
1.68 km/s

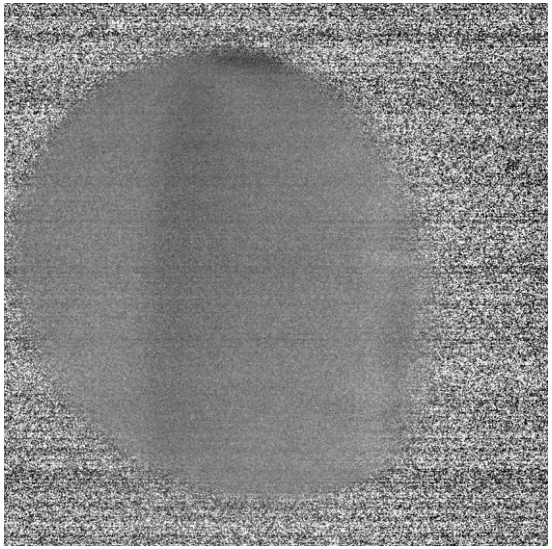
Velocity of the head of the jet:
4 km/s

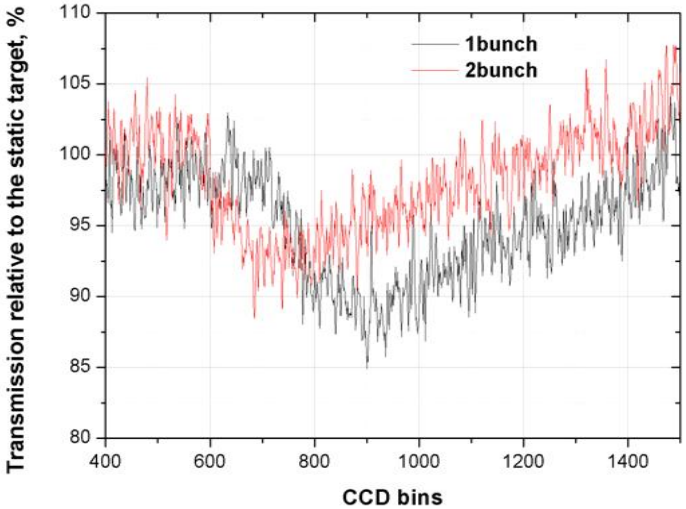
First Dynamic Experiments:
Detonation Wave in Pressed TNT

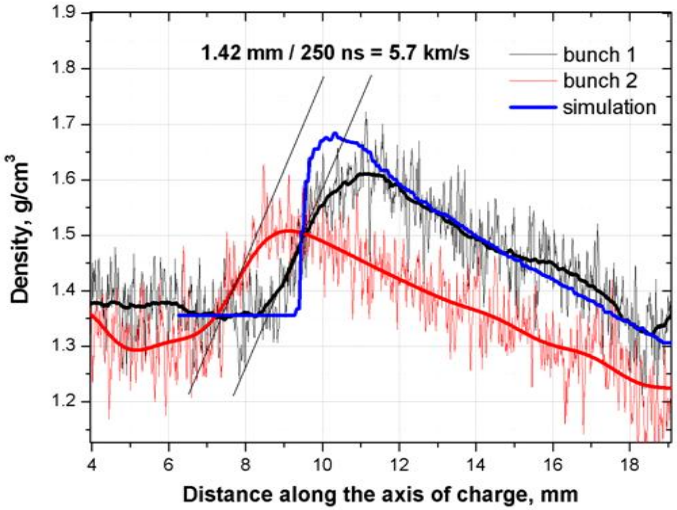
1st proton bunch



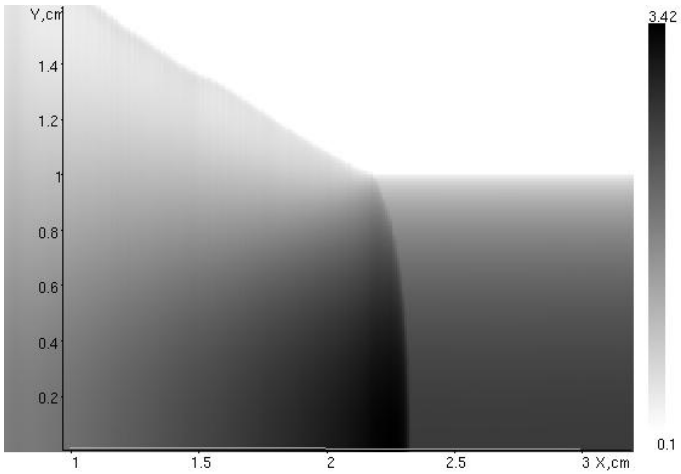
2nd proton bunch



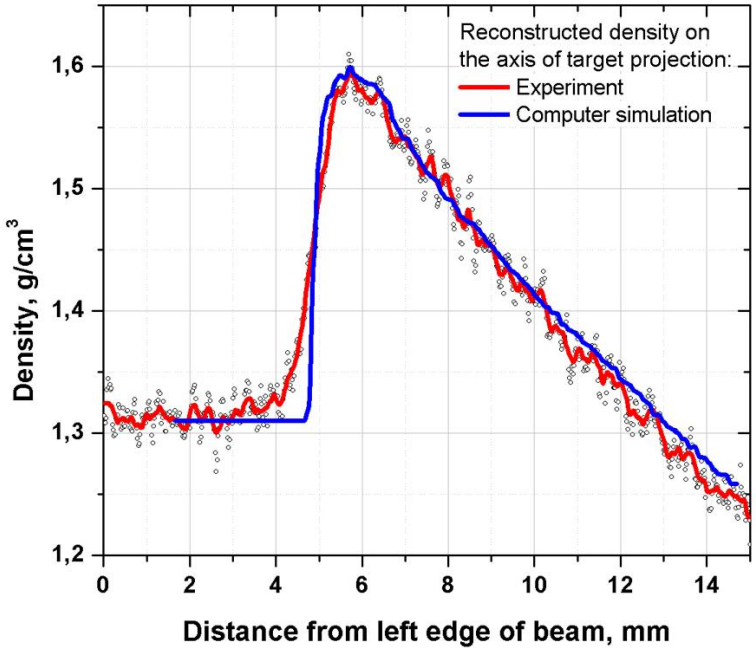




Comparison of Experimental and Simulation Data



2D simulation of detonation of TNT charge with diameter of 20 mm and initial density of 1.32 g/cc. Simulation by A. Shutov.



Density profiles on the axis of detonating TNT charge: **blue** – computer simulation for the charge with 20 mm diameter; **red** – experimental profile for the detonation wave at the transition from the charge with 20 mm diameter into the charge with 15 mm diameter.

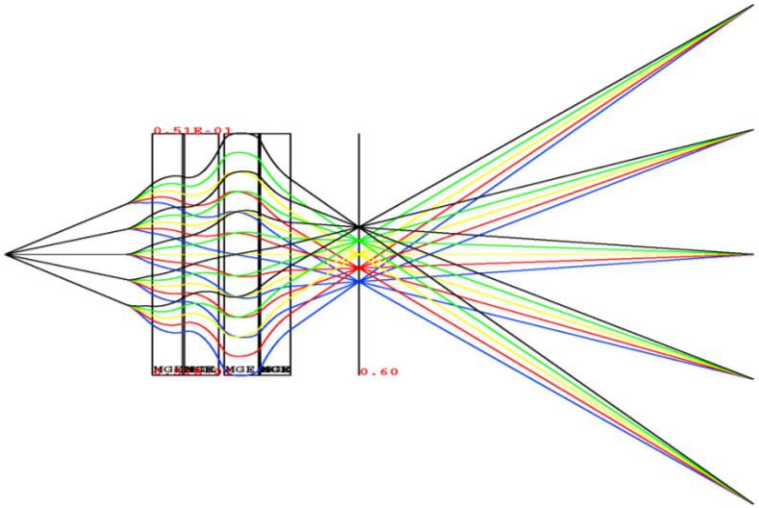
Summary

- The 800-MeV proton radiography facility for HED research has been commissioned at the TWAC-ITEP accelerator.

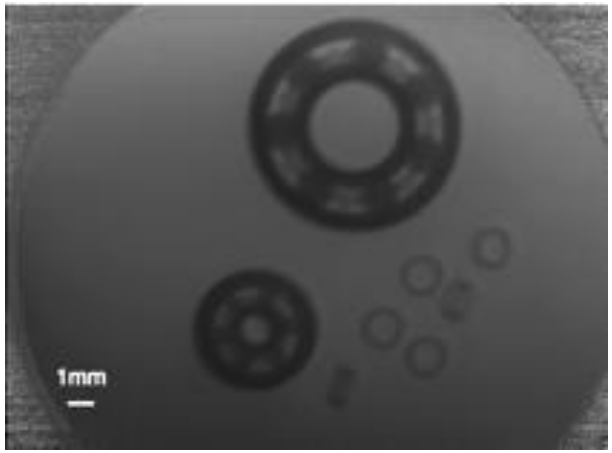
- First dynamic experiments on the observation of a shock loading of metal surface and a propagation of the detonation wave in a high explosive charge showed good quantitative agreement of the reconstructed density profiles with the known data and simulation results. Both sets of experiments showed good capabilities of high energy proton radiography as a visualization instrument, as well as a technique for absolute *in situ* density measurements in the field of HED & WDM research.

Next Steps

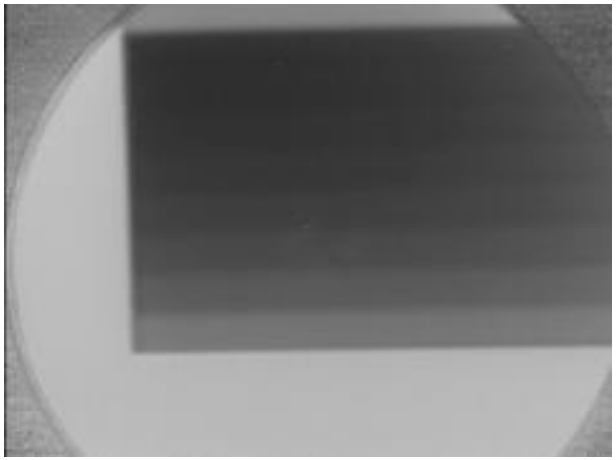
- The construction of 3,7X / 8X “Proton Microscope” magnetic optics system (Spring 2009). The spatial resolution of it was measured in static experiments to be **~50 µm**.
- First dynamic experiments with Proton Microscope @ ITEP are expected in October, 2009.



Static shots with Proton Microscope:



Ball bearing and ferrite ring



Brass stairs

PRIOR = Proton Microscope for FAIR

4.5 GeV Proton Microscopy Goals:

- $5 \cdot 10^{12}$ protons from SIS-18 beam line in GSI (Darmstadt, Germany);
- less than **10 μm** spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 50 g/cm^2;
- high-Z targets;
- temporal resolution < **20 ns**;
- multi-frame capability;
- heavy ion beams and/or explosives as a driver for a generation of extreme states in matter.

Collaborators:

- GSI Helmholtzzentrum für Schwerionenforschung (Germany)
- Institute for Theoretical and Experimental Physics (Russia)
- Institute of Problems of Chemical Physics RAS (Russia)
- Los Alamos National Laboratory (USA)
- Technische Universität Darmstadt (Germany)

Conclusions

- Proton Radiography at existing facilities (LANSCE, ITEP…) is providing multi-frame image shots of HED processes with ~100 μm spatial resolution;
- Next improvement in spatial resolution will come from magnetic optic magnifiers used at higher energy proton facilities (GSI, FAIR…);
- Multiple drivers (explosives, pulsed power, heavy ions…) in combination with high resolution proton microscopy will provide a unique facility for the study of material properties at extreme temperatures and pressures.
- PRIOR Collaboration is very young and welcoming of participation from all communities.