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

Image Blurring compensation with magnetic optics

(A Flux attenuation in e times)

Object

Object

Magnetic Lens

Flux attenuation in e times

2 cm

12 cm

Pb

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

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
Proton radiography @ LANSCE:
- up to 30 frames
- density range - 0.05 to 50 g/cm²
- 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.

Phase Transition in Shocked Iron

Images courtesy of Frank Merrill, LANL

Simultaneous measurement of:
- Flyer velocity
- Shock velocity
- Phase boundary velocity
- Density of shocked material
- Density change in solid-solid phase transition
Shock Waves in Gaseous Xenon

Images courtesy of Frank Merrill, LANL

* Standard Temperature and pressure

1.2 mm/µs

6mm Al

Sabot

Xe

2.3 g/cm²

2.3 + 0.055 g/cm²

STP* Xe  Shocked Xe  Flyer

0.5 µs  1.0 µs  1.5 µs

2.0 µs  2.5 µs  3.0 µs

3.5 µs  4.0 µs  4.5 µs
Proton Radiography at ITEP
800-MeV Proton Radiography Facility at TWAC-ITEP Accelerator (Moscow)

- Field of view: 20 mm;
- Target density range: < 60 g/cm²;
- 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

“Dark Field” Image

Proton Radiography Image with subtracted “Dark Field”

“White Field” Image (Beam Image)

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

Graphs showing transmission relative to the static target and density along the axis of the charge.
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.
• 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 \textit{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 \(~50\ \mu m\).

• 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 $10 \ \mu m$ 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.