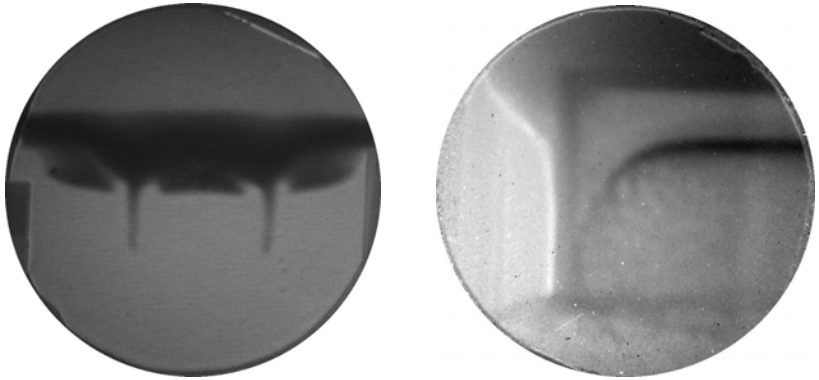
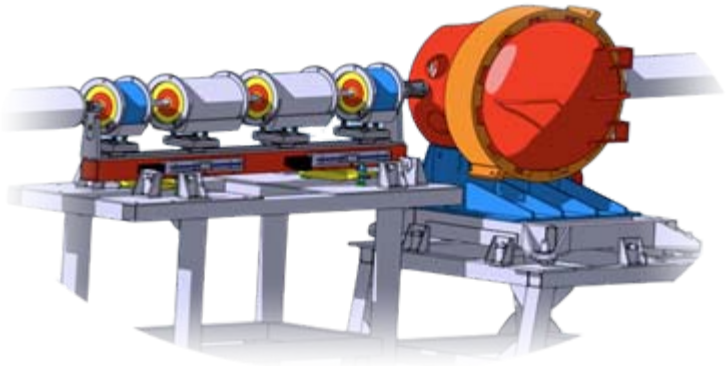
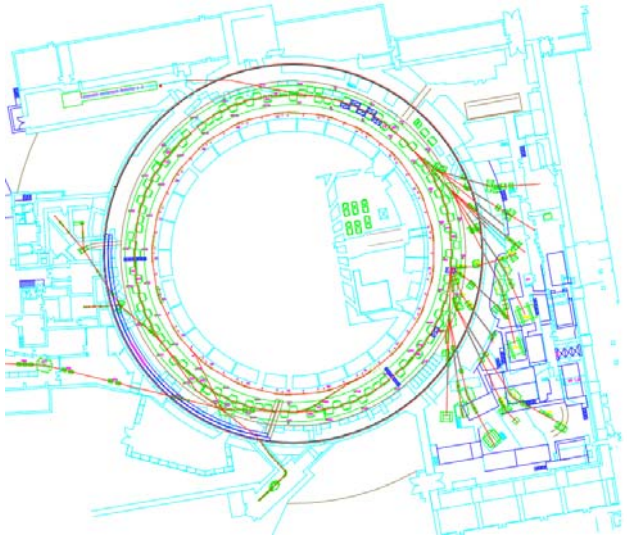
PROTON RADIOGRAPHY OF DENSE PLASMA

Introduction
ITEP-TWAC Facility
Detonation Studies
Dynamic Surface Ejecta Formation
Development of Compact Explosive Generators
Shock Compression of Noble Gases
Conclusions



Scientific-coordination session
"Non-Ideal Plasma Research"
November 23-24, 2011, Moscow





IPCP RAS, Chernogolovka, Russia
JIHT, Moscow, Russia

V.B. Mintsev, S.A. Kolesnikov, S.V. Dudin, V.V.Lavrov, D.N.Nikolaev, A.V. Savchenko, V.Ya.Ternovoi, A.V.Utkin, N.S. Shilkin, D.S.Yuriev, V.E. Fortov

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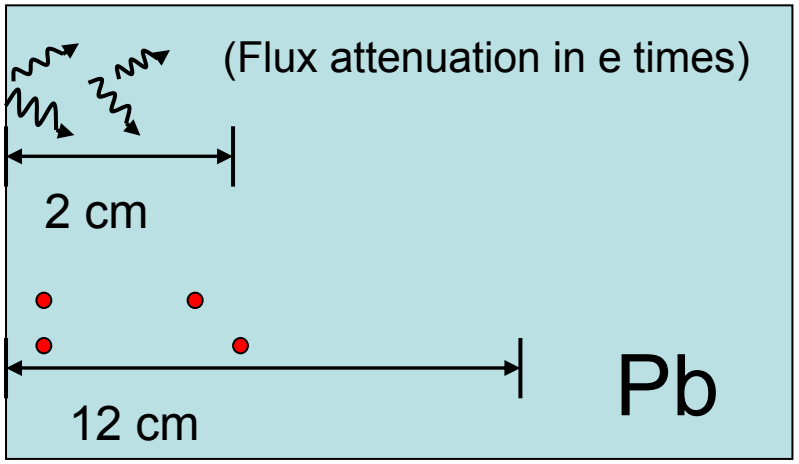
Radiography Basics

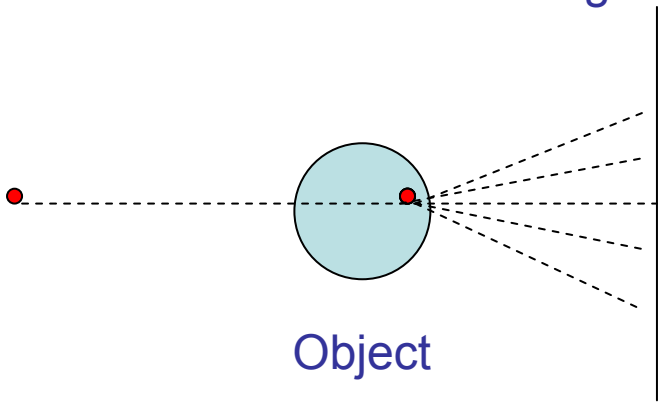
Photons and charged particles in matter

X-rays 3-10 MeV

High Energy Protons ~ 1 GeV

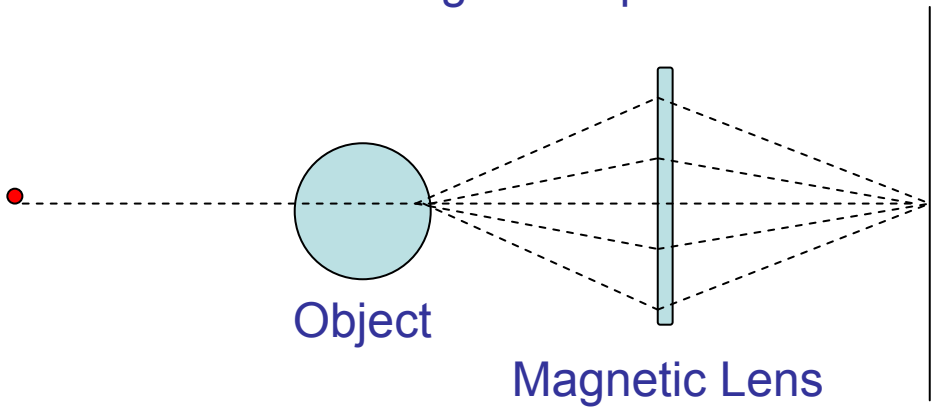


Protons Image Blurring Due to Multiple Coulomb Scattering



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.

Advantages of Proton Radiography

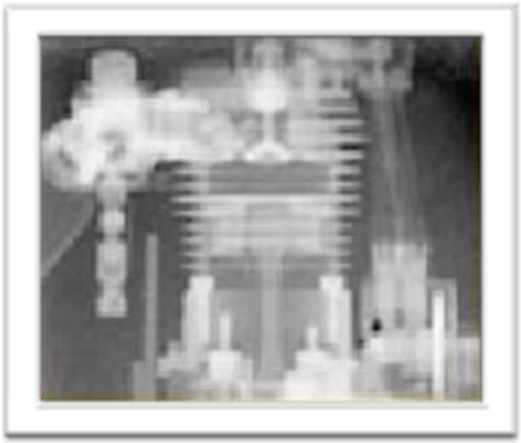
as compared with X-rays

- magnetic lenses for correcting imaging aberrations
- high resolution and dynamic range to both density and material composition
- better signal-to-noise ratio and detection efficiency
- higher penetrating depth (targets with high areal density)
- multi-framing capability

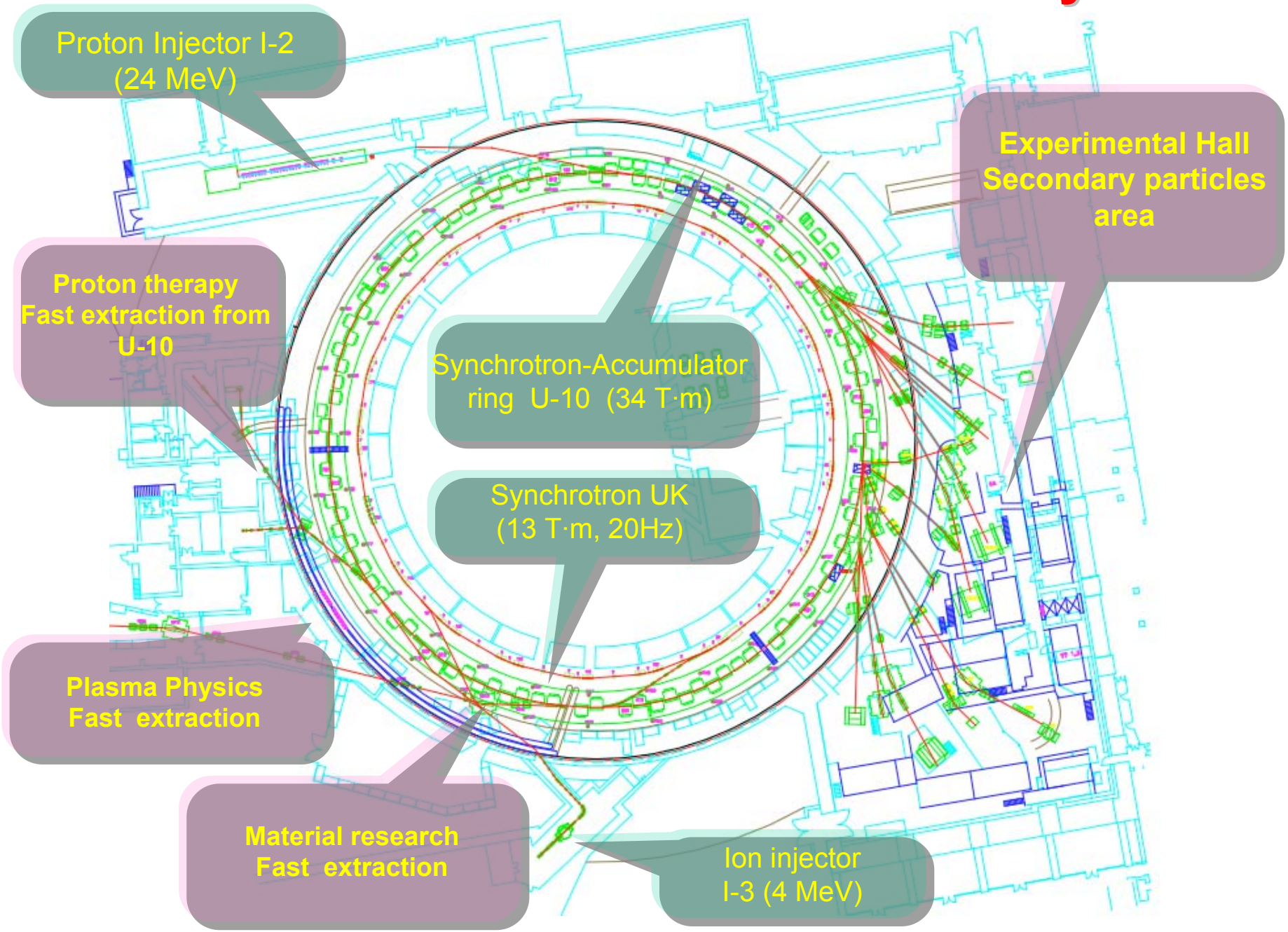
photo

100 keV X-rays

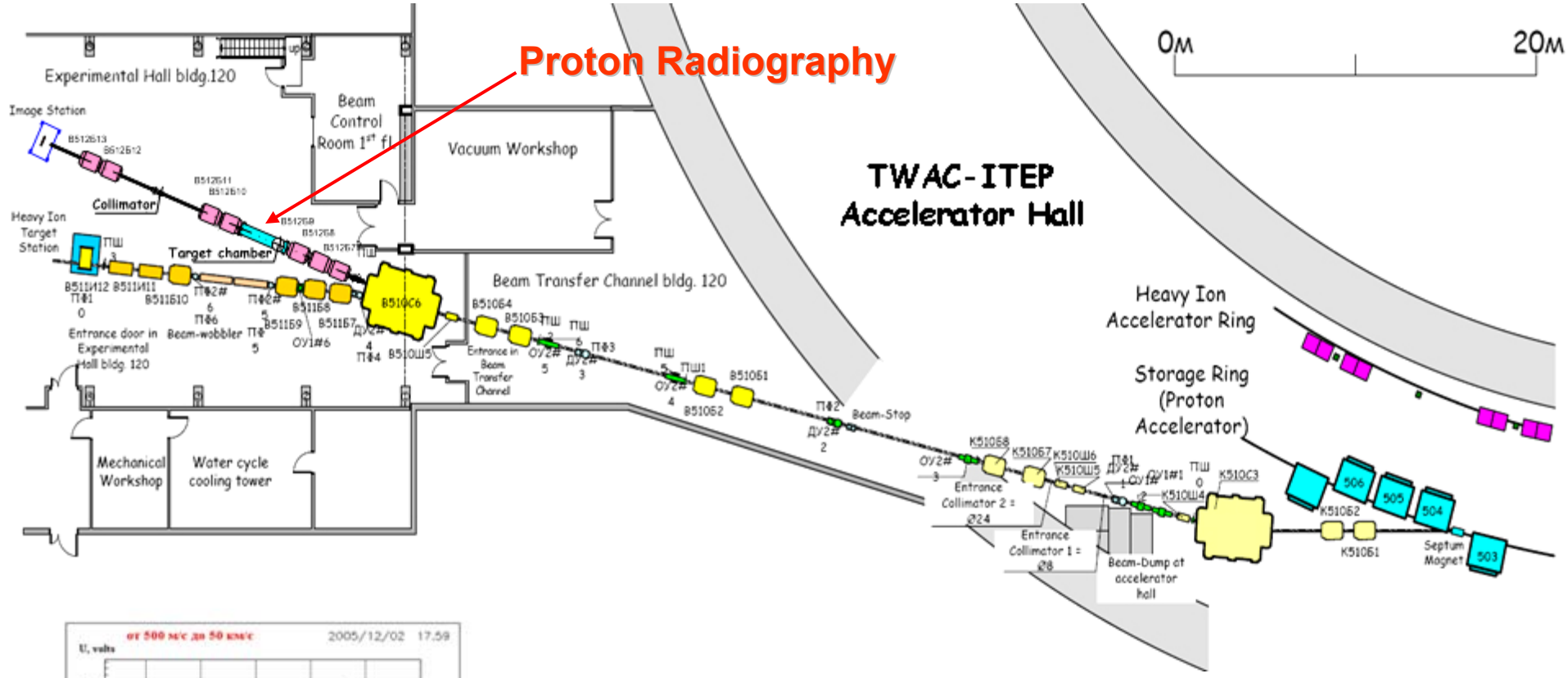
800 MeV protons

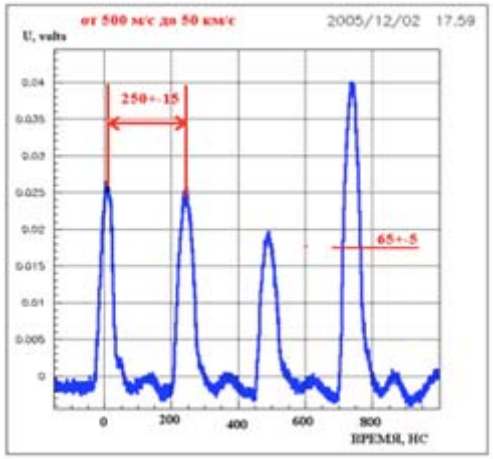


ITEP-TWAC Accelerator Facility



Proton Radiography Facility at ITEP-TWAC Accelerator





800 MeV Proton Beam Line

Beam structure – 3-4 bunches (See image on the left)
Duration of single bunch (FWHM): **70 ns**
Interval between bunches: **250 ns**
Beam intensity: up to **10^{11}** protons

Proton Radiography Facility at ITEP-TWAC Accelerator

ITEP Proton Microscope

4 permanent quadruple magnets
Magnification X = 3.92
Field of view < **19 mm**
Spatial resolution on sharp contrast object: **σ = 50 μm**
Density resolution ~ **6%**

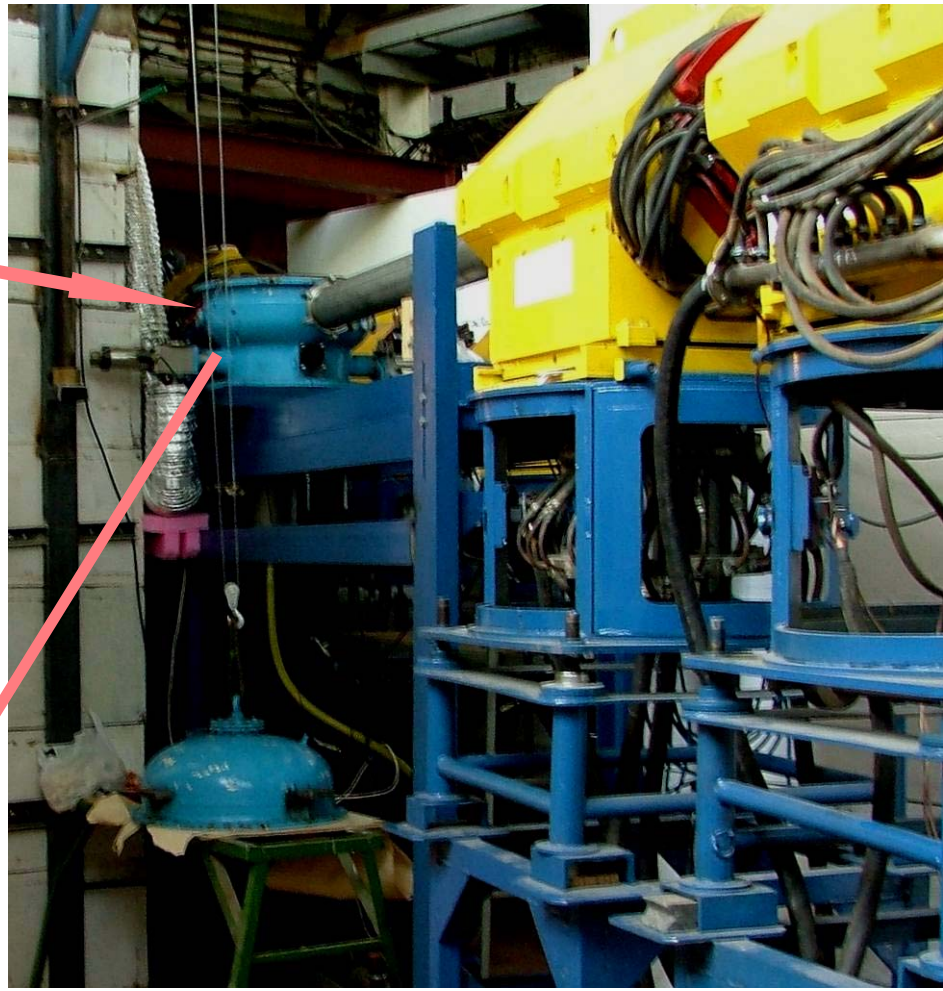
Image Registration System

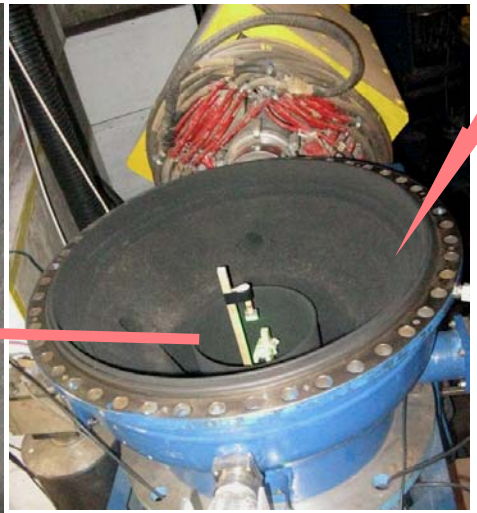
Optical convertor: LSO scintillator (40 ns), ⌀78 mm
3-6 14 bit CCD cameras, fast shutter (100 ns), matched to beam bunch;
Temporal resolution = Bunch duration = **70 ns**

Explosion Confinement Chamber

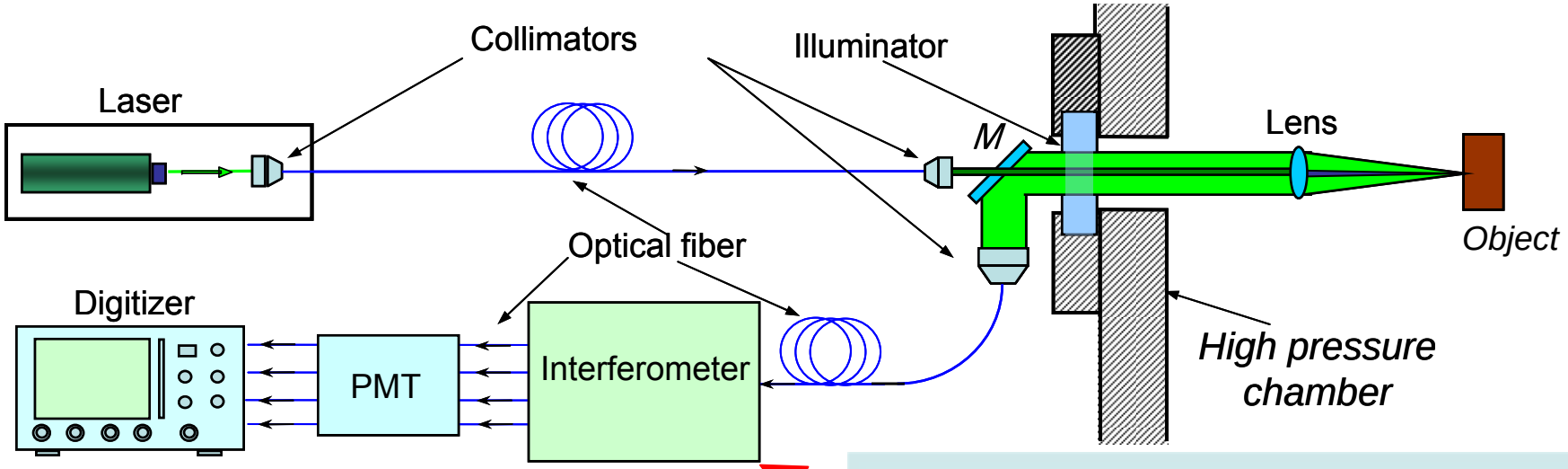
Volume – 50 liters
HE mass (TNT) – up to **70 g**
Pumped down to 10^{-3} Torr
Active ventilation system
Optical diagnostics - VISAR
Target angular positioning (±10°)
Cryogenic target system

Experimental Area





Push-Pull VISAR for Proton Radiography at ITEP

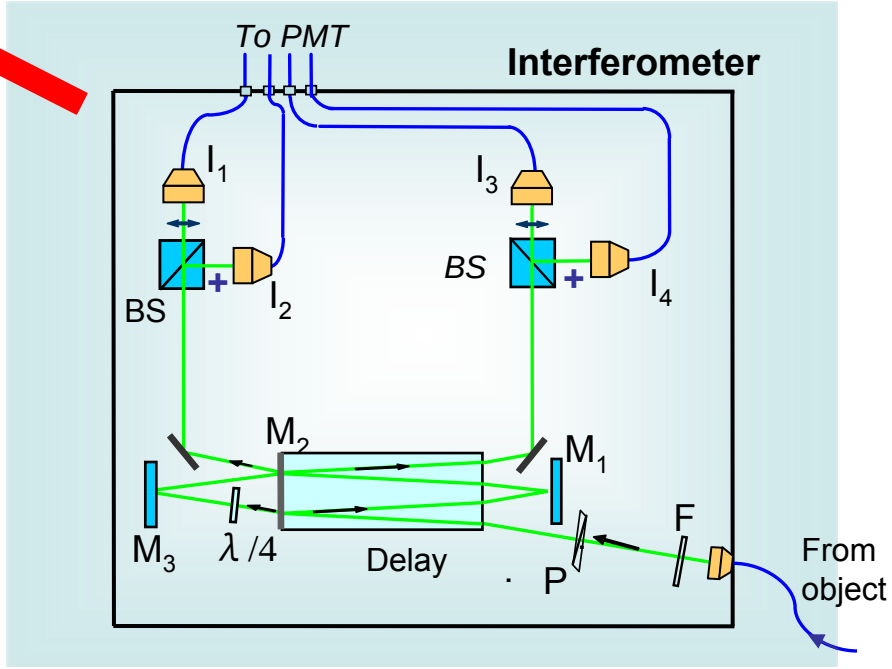


Laser

Wavelength 532 nm
Line width <5 MHz
Power 50 mW

$$I_1 = I_0 \sin 2\pi N(t) + A(t)$$
$$I_2 = I_0 \cos 2\pi N(t) + A(t)$$
$$I_3 = -I_0 \sin 2\pi N(t) + A(t)$$
$$I_4 = -I_0 \cos 2\pi N(t) + A(t)$$

$$V(t) = \frac{c\lambda}{8\pi l_d (n - 1/n)(1+\delta)} arctg \frac{I_1 - I_3}{I_2 - I_4}$$



by A. Kuznetsov, K. Gubsky

Proton Radiography for High Energy Density Physics

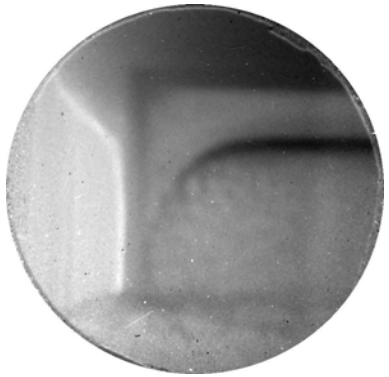
HEDP

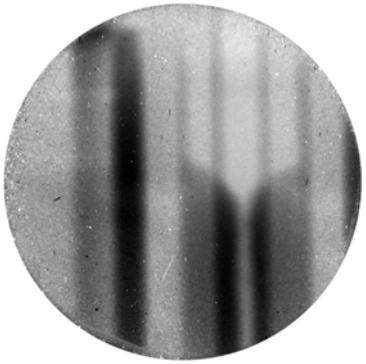
Research areas that can be addressed by Proton Radiography

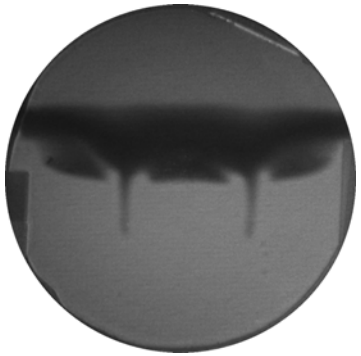
EoS and Phase Transitions
in materials in extreme conditions

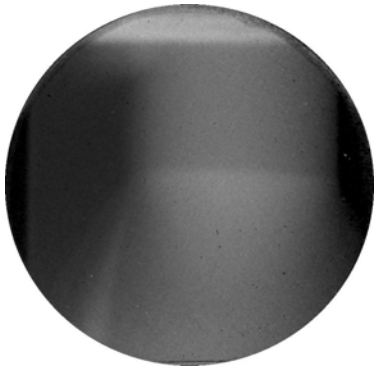
Hydrodynamics of HED Flows
Shock and Detonation Waves,
Hydrodynamic Instabilities

Material Strength and Damage
Dynamic Fracture of Materials



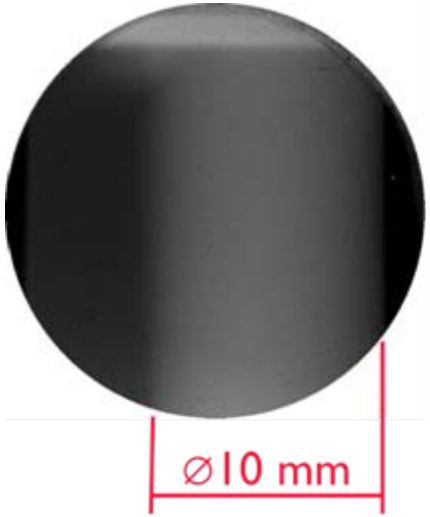




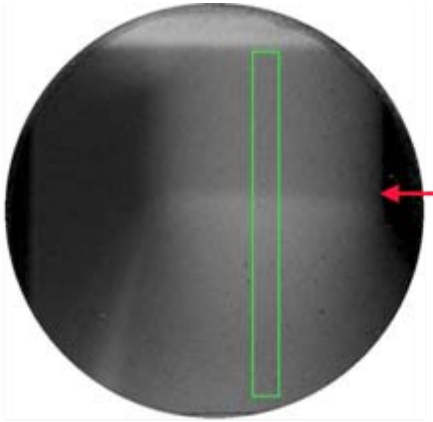


Detonation of Pressed TNT

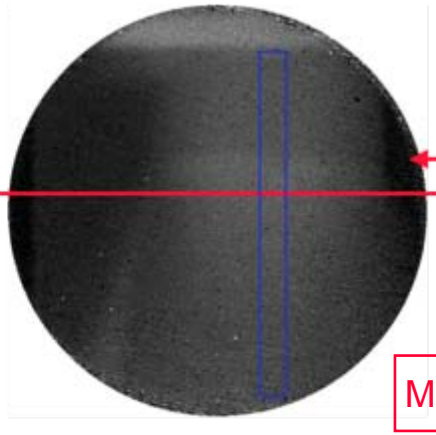
Static image



Bunch 2 image (T_2)



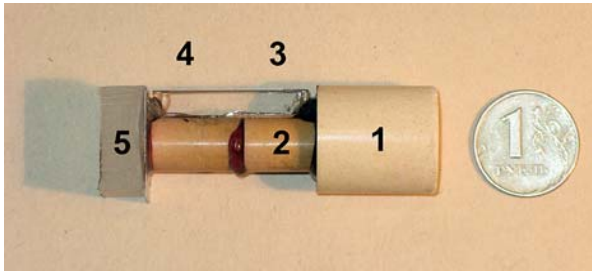
Bunch 3 image (T_3)



$\Delta T = T_3 - T_2 = 250$ ns
$\delta T = 70$ ns
$\Delta X = 1.72 \pm 0.05$ mm
$D = \Delta X / \Delta T = 6{,}9 \pm 0{,}2$ km/s
Front curvature radius:
$R = 58 \pm 7$ mm

Motion blur $\delta X = D\delta T = 0.48$ mm!

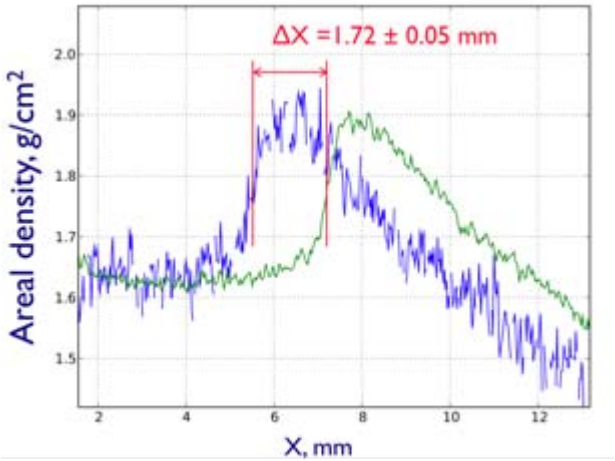
Total HE weight	25g
Initial density	1.32 - 1.65 g/cc
Charge diameter	10; 15; 20 mm
Charge length	30-56 mm

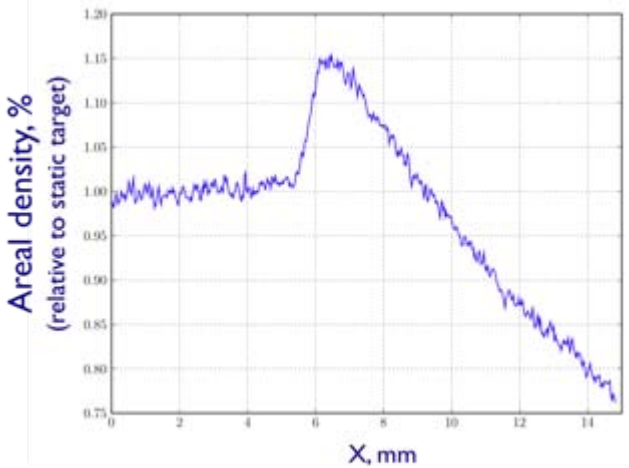


Above: proton radiography images of static (left) and dynamic detonating 10 mm TNT charge with initial density of 1.63 g/cc.

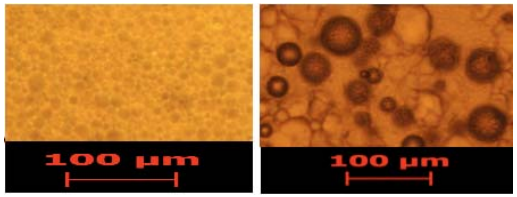
Below, left: photo of experimental target. 1 – initiating HE charge, 2 – target charge, 3 – reference plastic plate, 4,5 – VISAR reflective Al surface and diagnostic window.

Below: absolute (center) and relative (left) areal density profiles for the TNT charge.





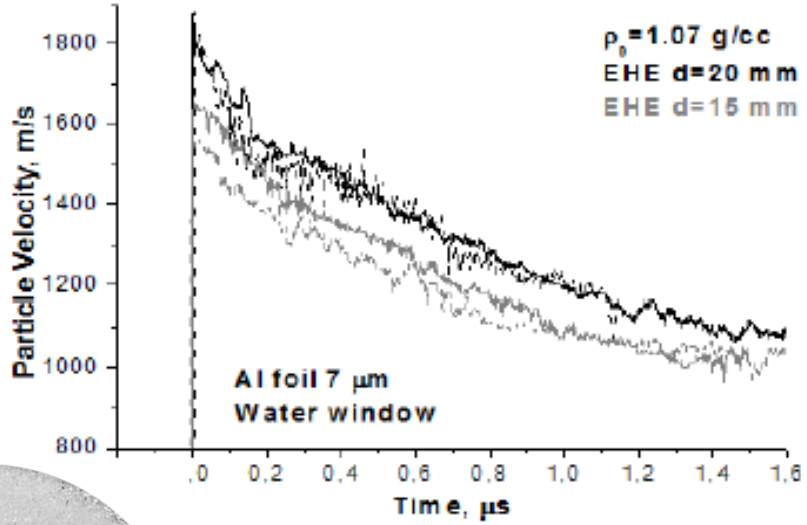
Detonation of Emulsion Explosive

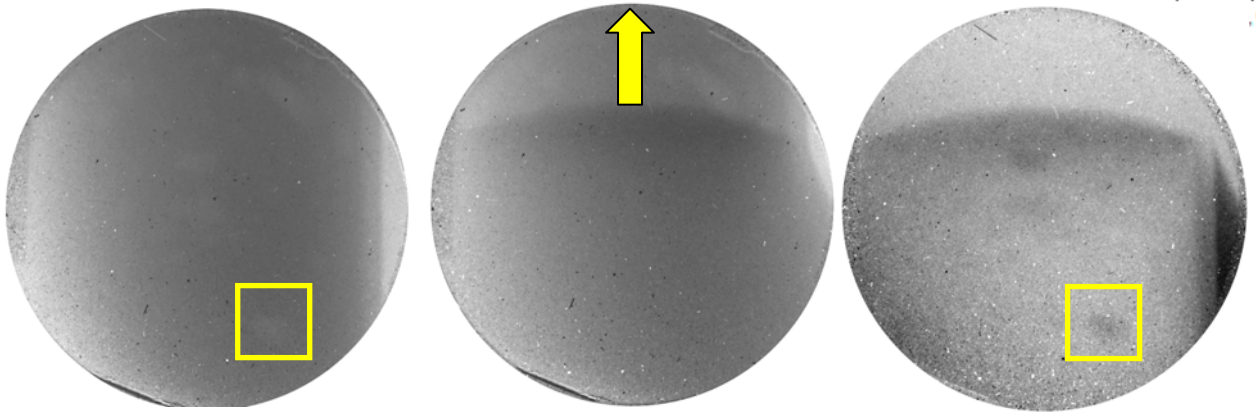


Emulsion Explosive
92-95% - oxidizer (ammonium nitrate)
8-5% - fuel (mineral oil)
+ 3 wt.% - hollow glass microballoons

Density	1.07 g/cc
Charge diameter	15; 20; 36 mm
Charge length	60-150 mm

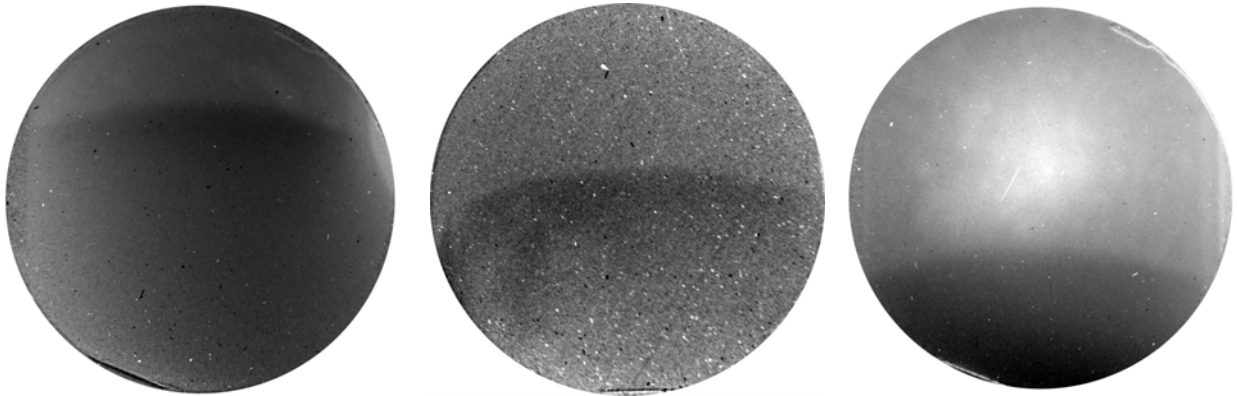
Experimental target
1 – initiating HE charge, 2 – plastic flange
3 –polyethylene tube with studied emulsio
explosive, 4,5 – VISAR reflective 7 μm A
surface and plastic diagnostic window.





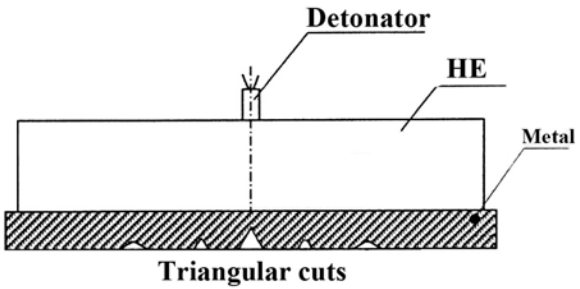
Static, dynamic and relative proton radiography images of 20 mm emulsion explosive charge. Yellow arrow points to the direction of wave propagation. Yellow frame points to one of the inhomogeneities of the initial charge.

Detonation velocity D = 4.6 ± 0.2 km/s



Dynamic proton radiography images for different 15 mm emulsion explosive charges: left – steady-state detonation (D=4.4 km/s), center – non-steady detonation-like wave (D=4.4 km/s), right – fading shock wave (D~4.0 km/s)

Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

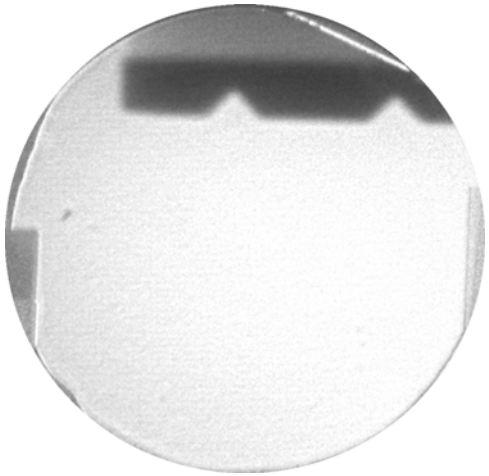


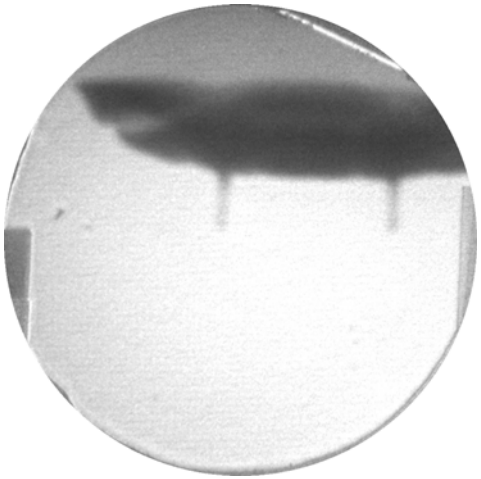
Proton radiography images of static targets

Proton radiography images of dynamic shots at 2.5 μs after shocking the free surface of a target

Steel target

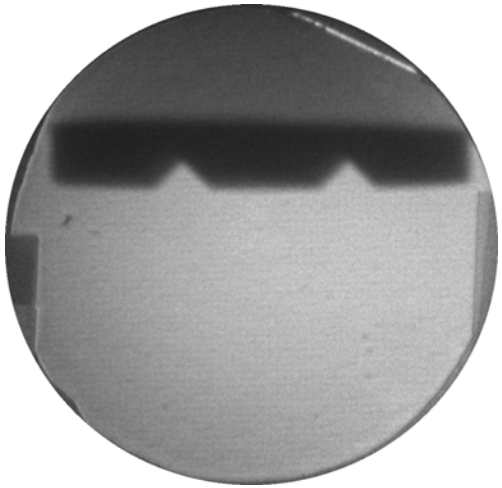
Diameter – 15 mm
Thickness – 2 mm
Depth of cuts – 1 mm

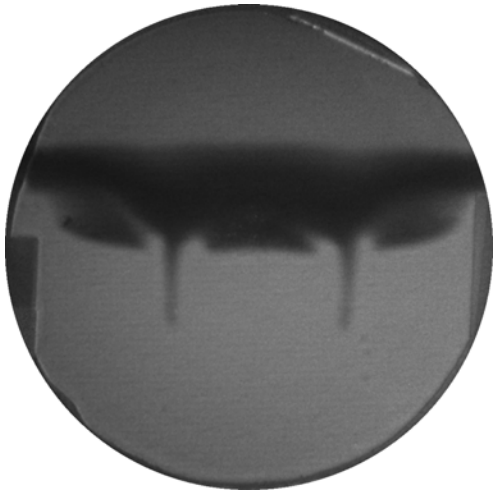




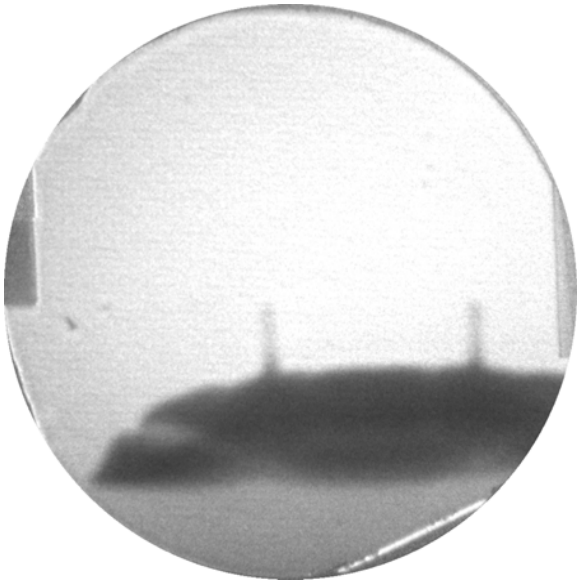
Copper target

Similar to steel one

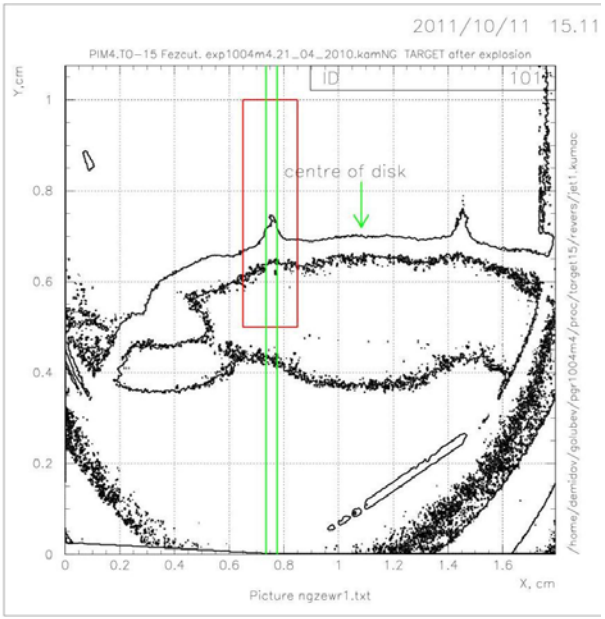




Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

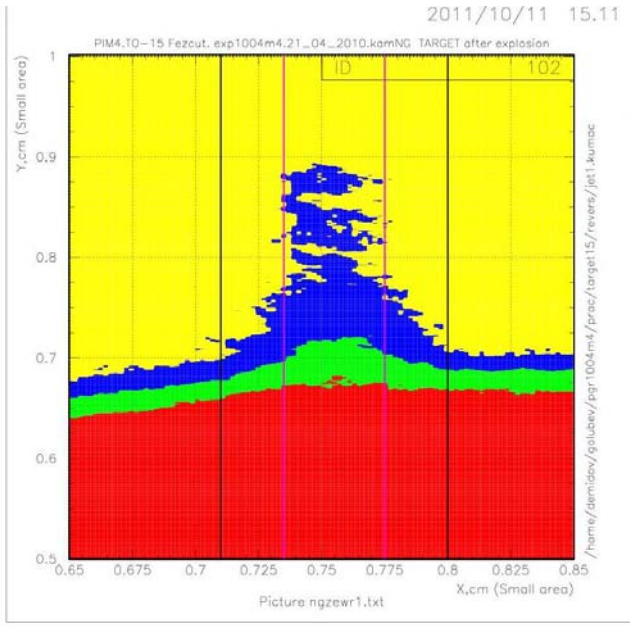


Dynamic proton radiography image shot at 2.5 μs after shocking the free surface of the steel target



Linear density map reconstructed from radiographic image

Velocity of jet tip: 2.8 km/s



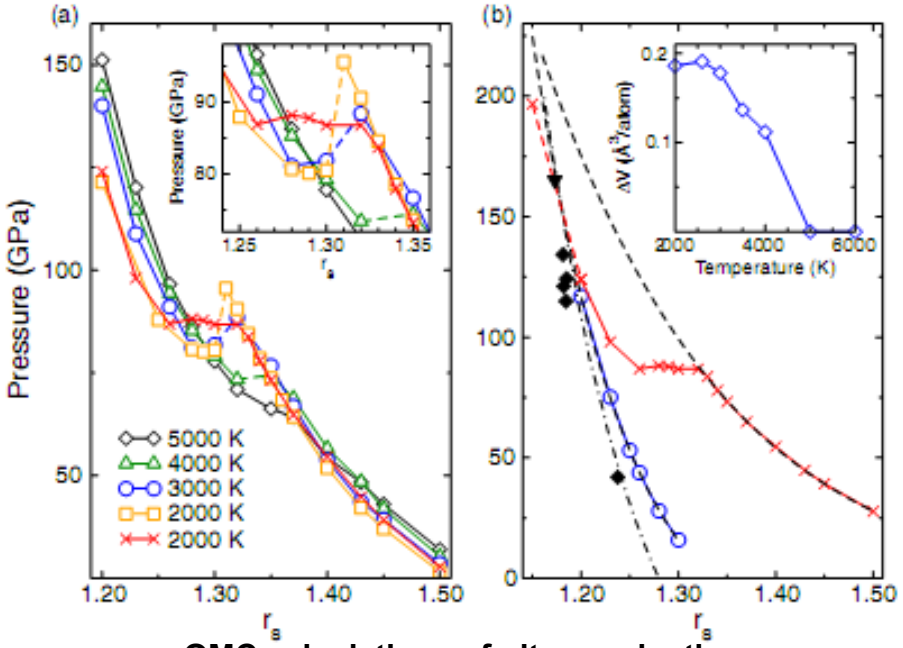
Close-up of the area inside the red frame on the left image

Mean volume density of jet material: 0.08 g/cc

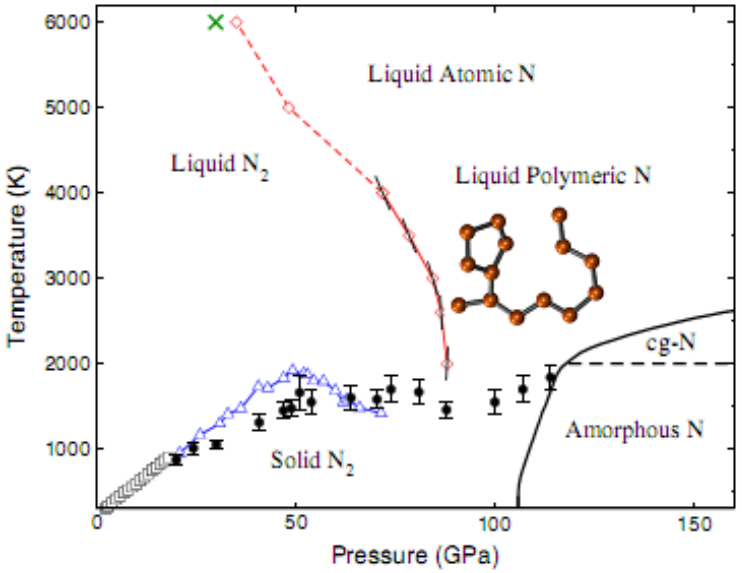
Development of Compact Explosive Generators

for Studies of First-Order Liquid-Liquid Phase Transition in Compressed Nitrogen

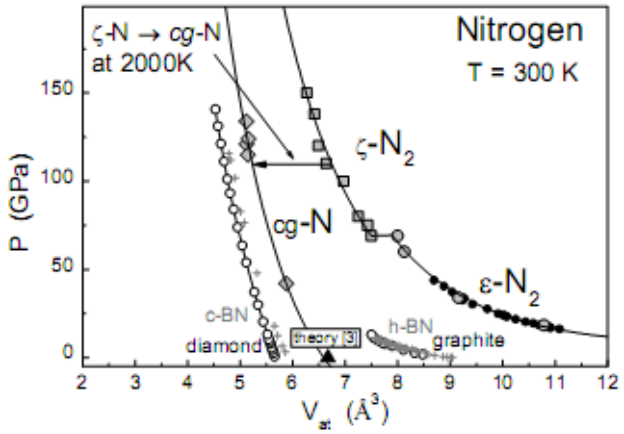
B. Boates, S. Bonev. PRL 102, 015701 (2009)



QMC calculations of nitrogen isotherms: X – liquid phase, O – solid phase



Proposed nitrogen phase diagram in P-T coordinates. Region of possible existence of liquid polymeric phase is shown.



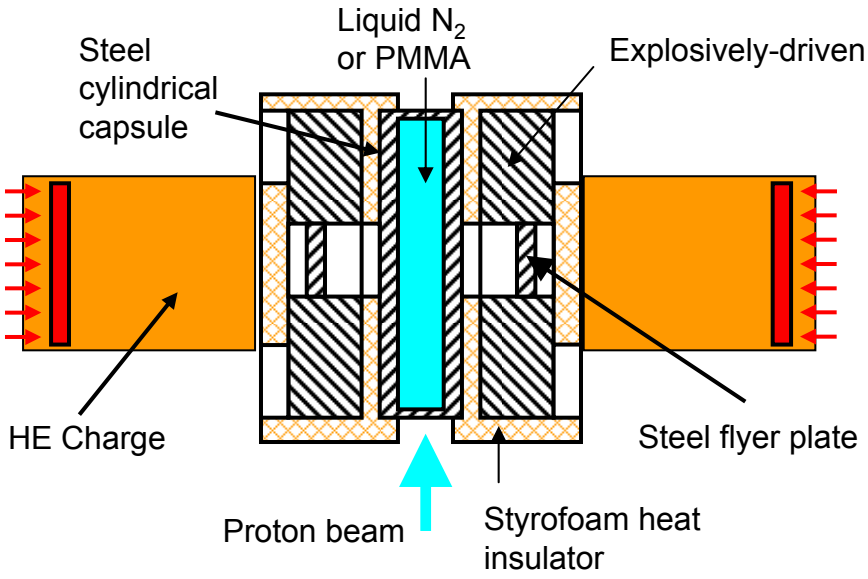
Experiment: nitrogen compression and heating in DAC

Structural transformation of milecular nitrogento a single-bondedatomic state at high pressures. M. Eremets, A. Gavriliuk et.al. J Chem Phys. 2004 121(22):11296

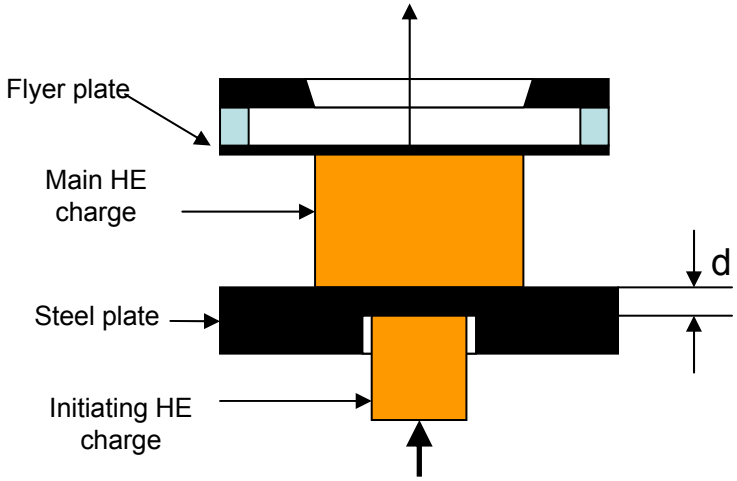
Transition of nitrogen to liquid polymeric phase is expected at compression of 75-100 GPa, temperature 2000 K and density jump of about 20-24%. This jump is very large for structural phase transition, which makes it a good object for proton radiography studies.

Development of Compact Explosive Generators

for Studies of First-Order Liquid-Liquid Phase Transition in Compressed Nitrogen

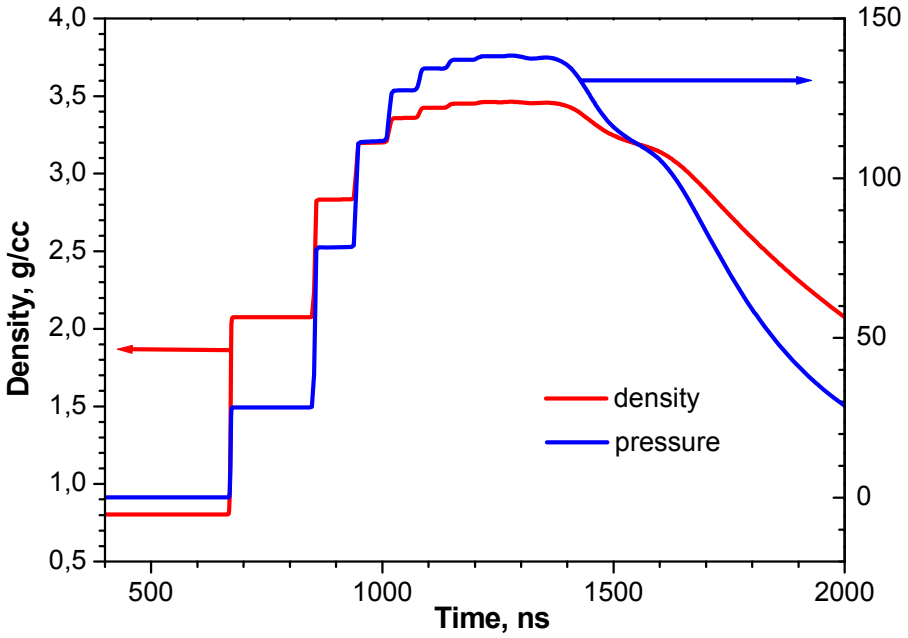


Scheme of experiment



Scheme of compact explosively-driven gun

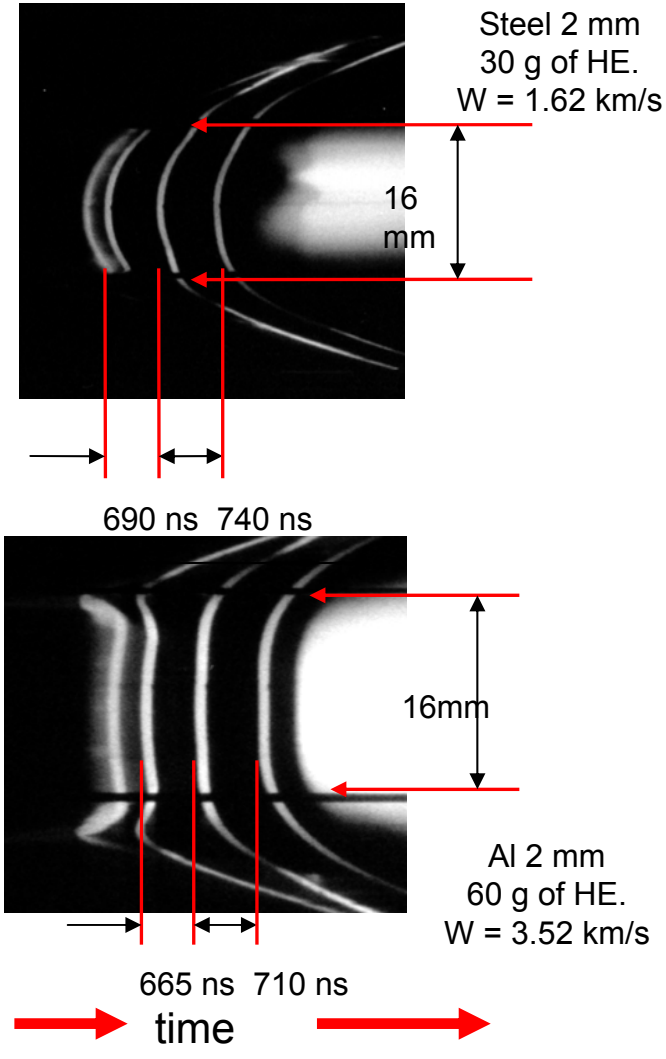
Problem: limited HE capacity of existing explosive confinement chamber (70 g of TNT), which requires the development of new compact explosive generators.



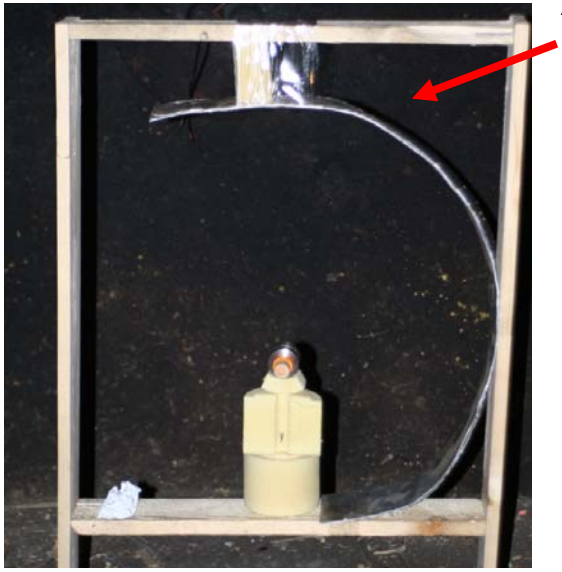
Pressure and density calculations for liquid N_2; flyer plate velocity - 2.2 km/s

Development of Compact Explosive Generators

for Studies of First-Order Liquid-Liquid Phase Transition in Compressed Nitrogen

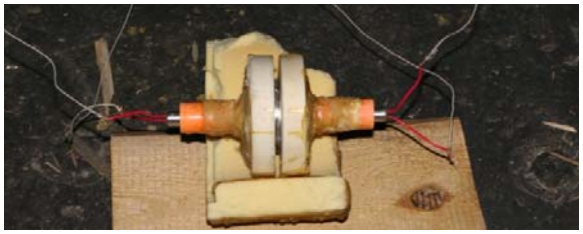


Flyer plate shape testing and mitigation development

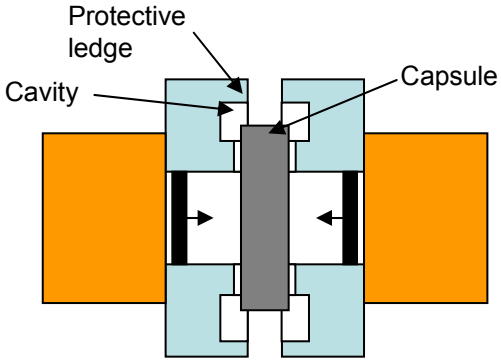


Al 0.75 mm sheet

Penetration of fragments through sheet



Cavity for capturing the fragments is required within the developed “gun”

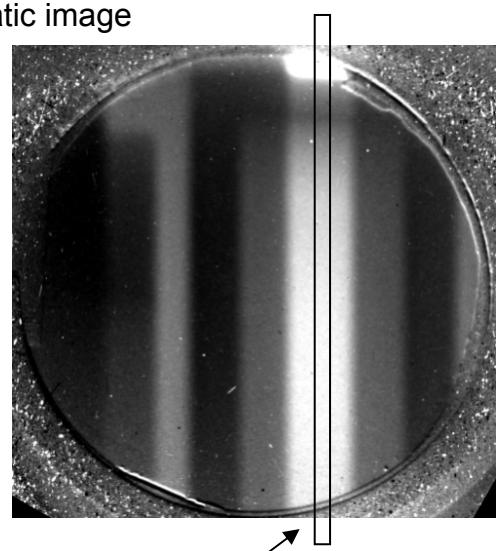


Scheme of improved compact explosive generator

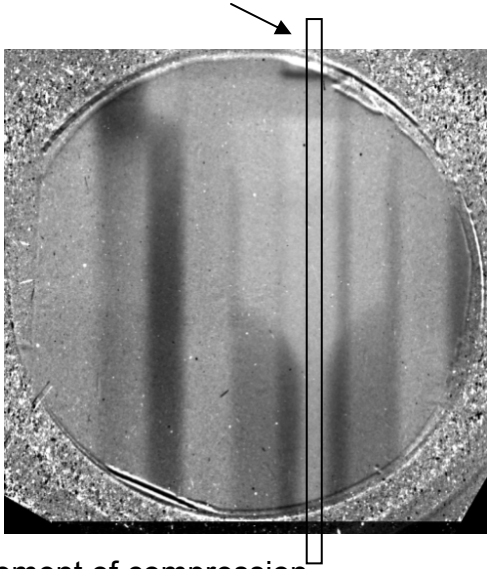
Development of Compact Explosive Generators

for Studies of First-Order Liquid-Liquid Phase Transition in Compressed Nitrogen

Static image

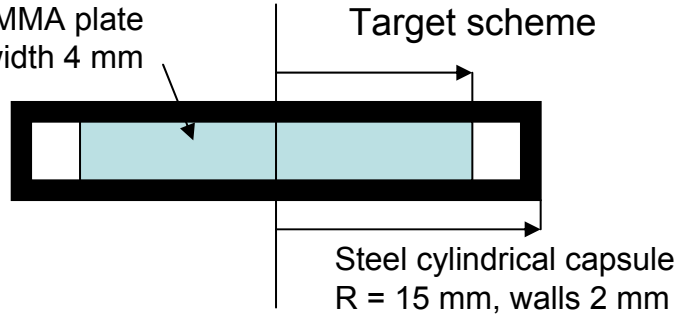


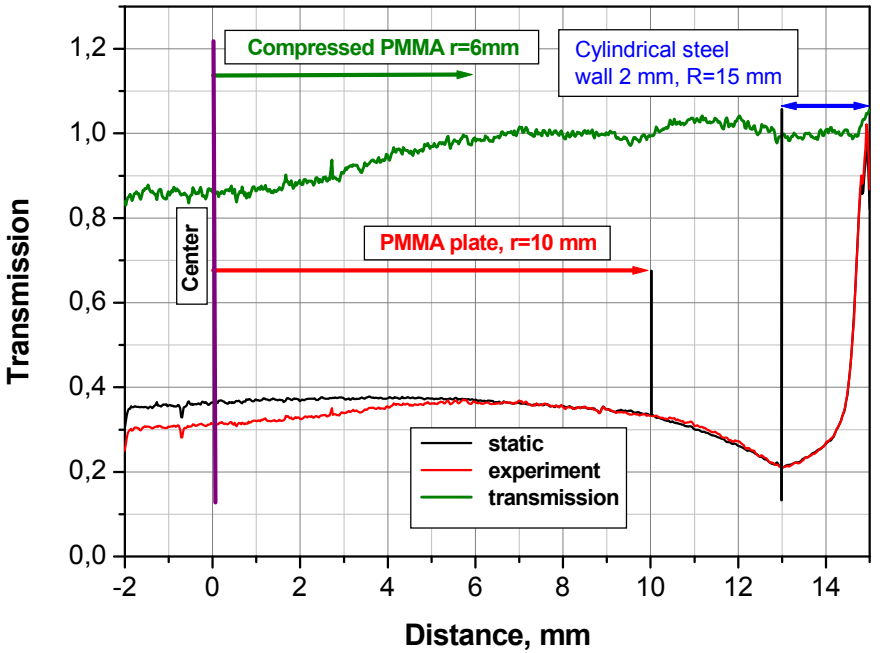
Cross-section where the density profile is taken



Moment of compression

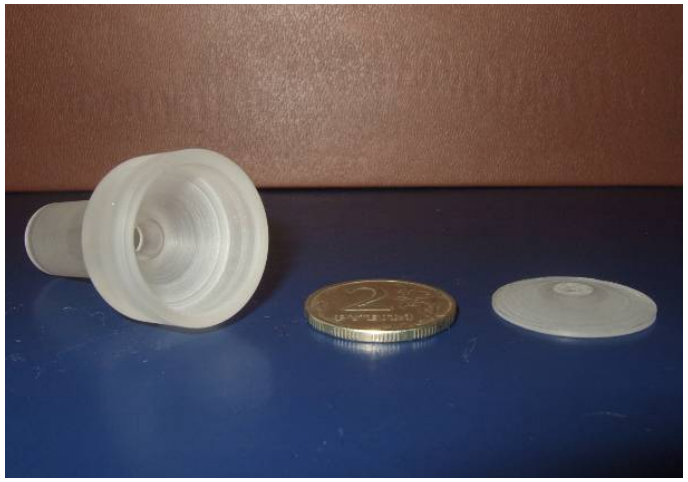
Proton radiography registration of bilateral compression of test PMMA target





Transmission profiles (relative to the “white field” intensity) for static and 1st dynamic proton radiography shots. Relative transmission profile (divided by static profile) for compressed PMMA is also presented.

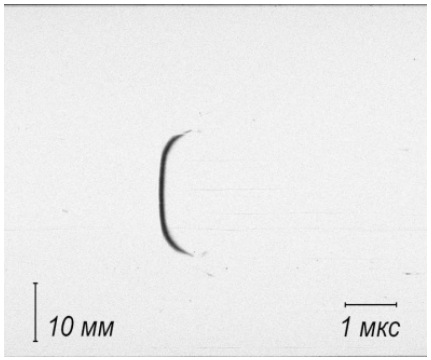
Development of Compact Explosive Generators

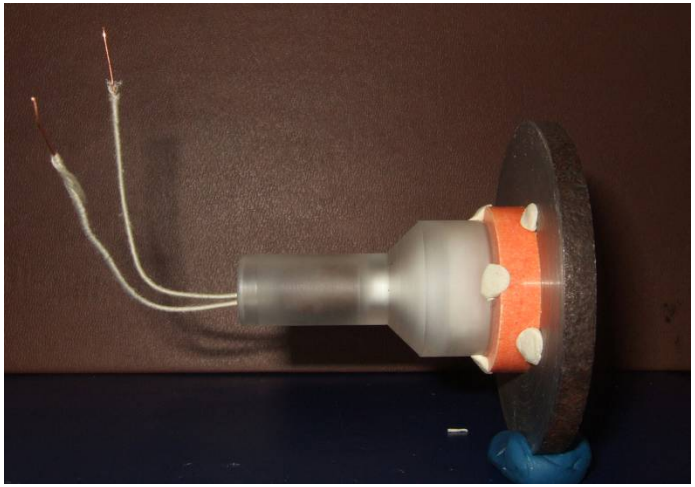


Plexiglass components of compact explosive generator

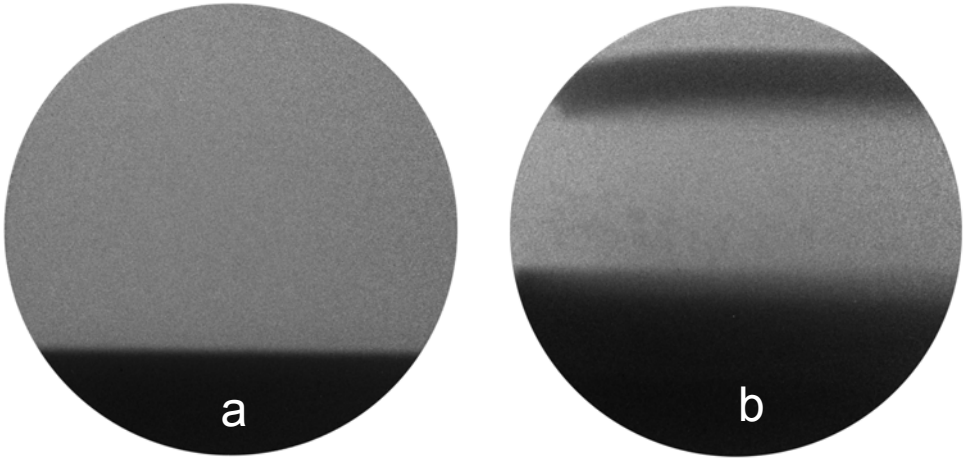
Total amount of explosive	**< 15 g of TNT**
Flyer plate	**⌀20, 1-2 mm thick**
Flyer plate material	**Al, Steel**

To the right: high-speed photoregistrator image of shock wave from 1 mm Al flyer plate accelerated with compact explosive generator



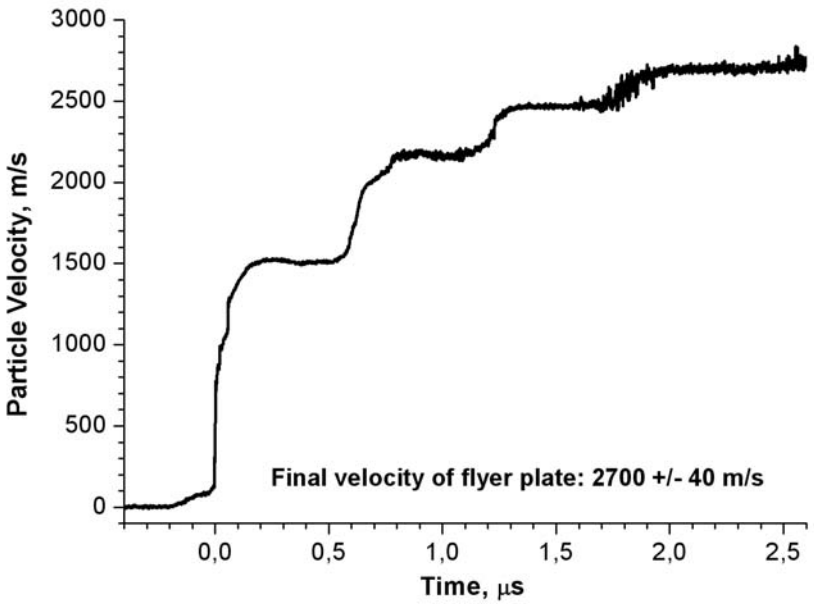


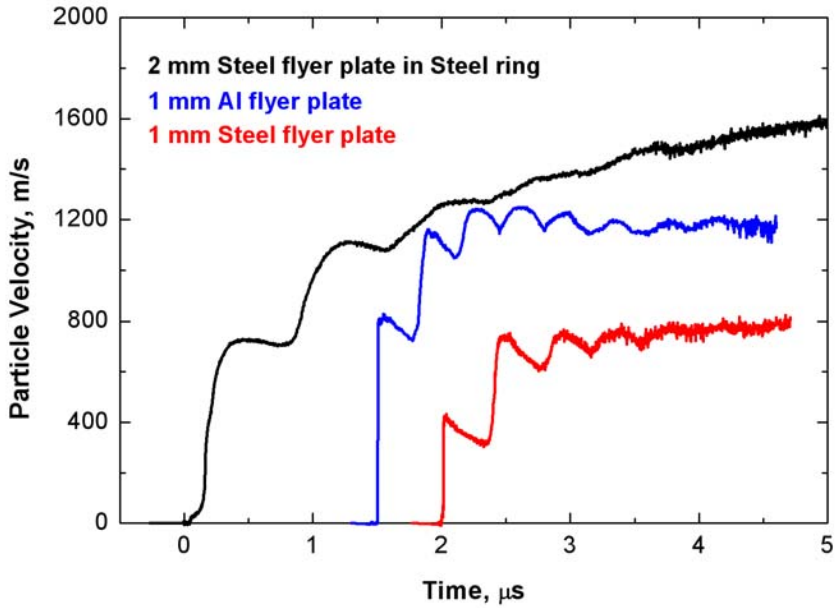
Experimental assembly for accelerating flyer plate with compact explosive generator



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

Development of Compact Explosive Generators



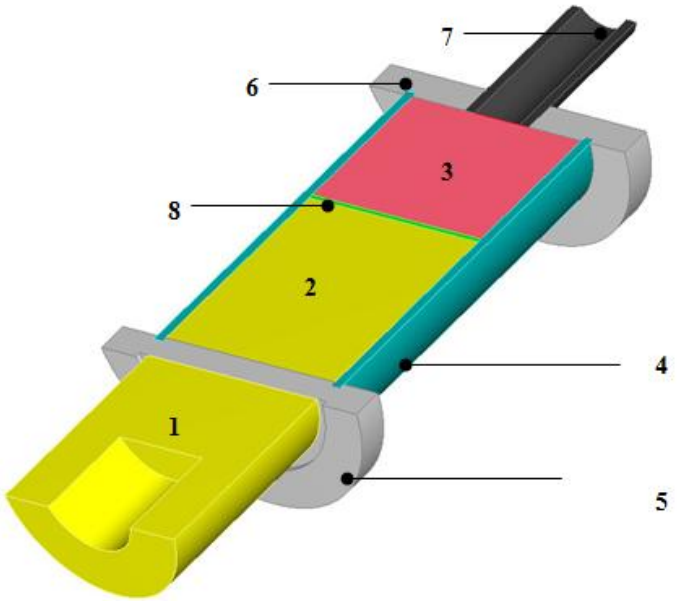


VISAR flyer plate free surface profiles: *left* – for 2 mm Al flyer plate,
right – for 1 mm Al and 1 & 2 mm Steel flyer plates

Flyer plate	Velocity after full acceleration, km/s	Base of flight, mm	Diameter of plane region, mm
2 mm Al in Steel ring	**2.8**	10	13
2 mm Steel in Steel ring	**1.6**	6	
1 mm Al	**1.2**	3	13
1 mm Steel	**0.8**	2	

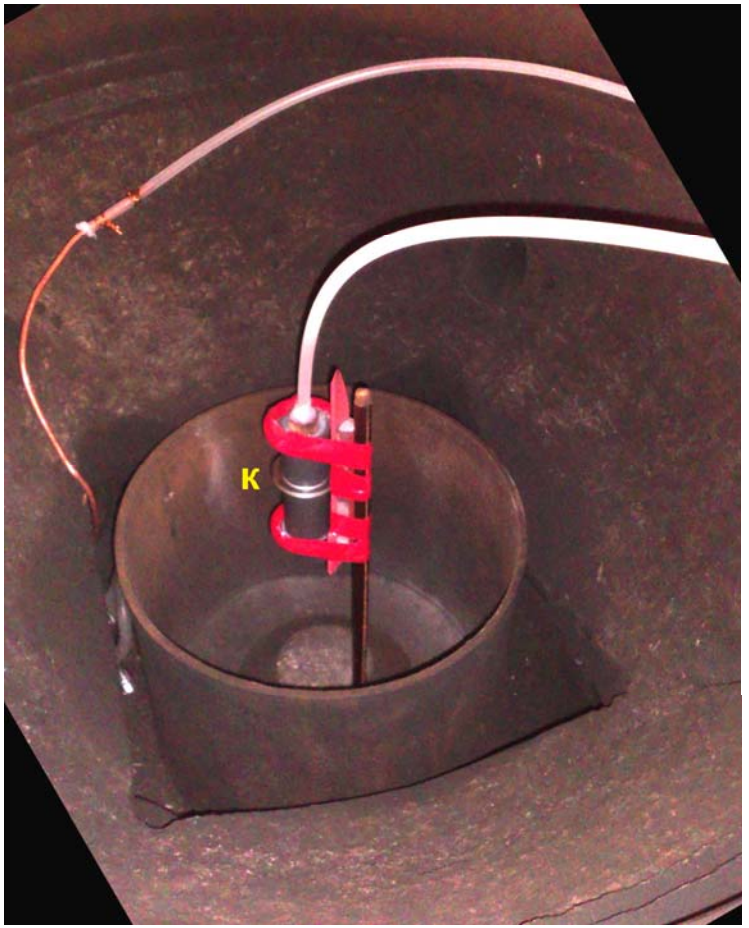
Shock Compression of Noble Gases

Target scheme



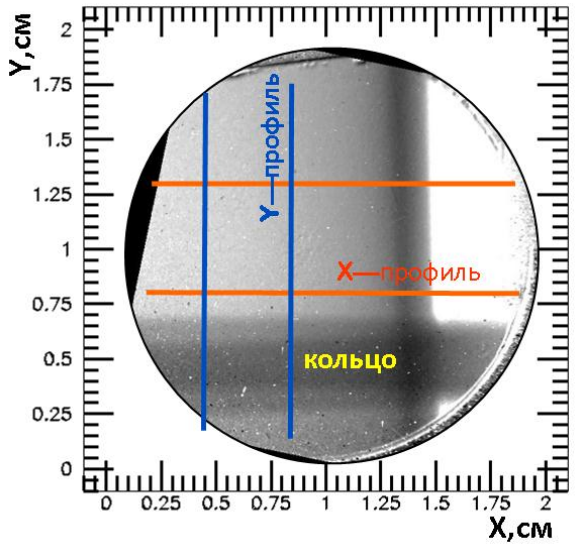
1,2 – HE tablets,
3 – investigated noble gas,
4 – generator canal,
5, 6 – leak-proof flanges,
7 – tube for gas system

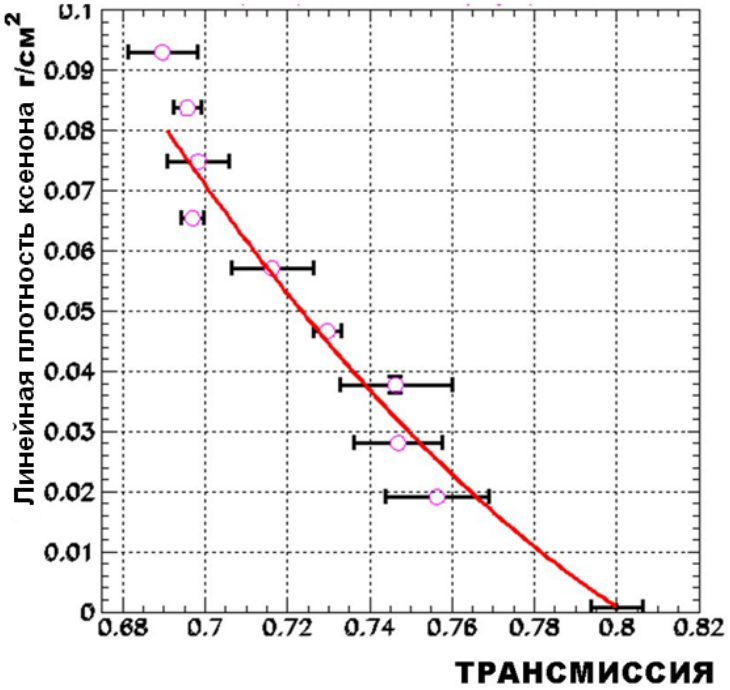
Studied gases: Ar, Xe
Initial pressure: ~ 1-5 Bar
Shock wave velocities: ~ 4-6 km/s

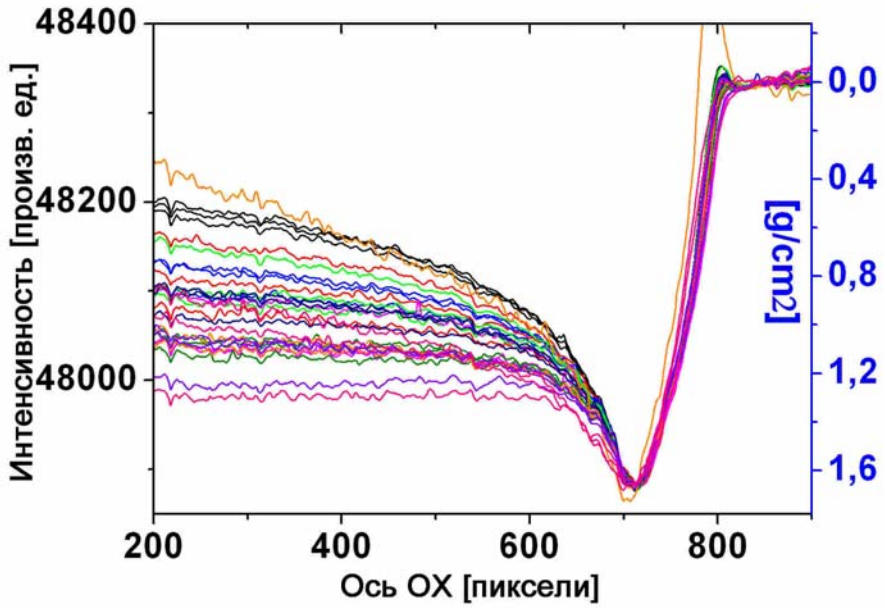


Shock Compression of Noble Gases

Calibration of Density vs Transmission for Static Targets with Xe for Pressures 0-10 Bar







Above, left: static proton radiography image of gas container with Xe

Left: normalized light intensity profiles for different initial densities from 0 to 10 Bars, taken between horizontal red lines on static image

Above: calibration dependence of linear density vs proton beam transmission, calculated from the image on the left

Shock Compression of Noble Gases

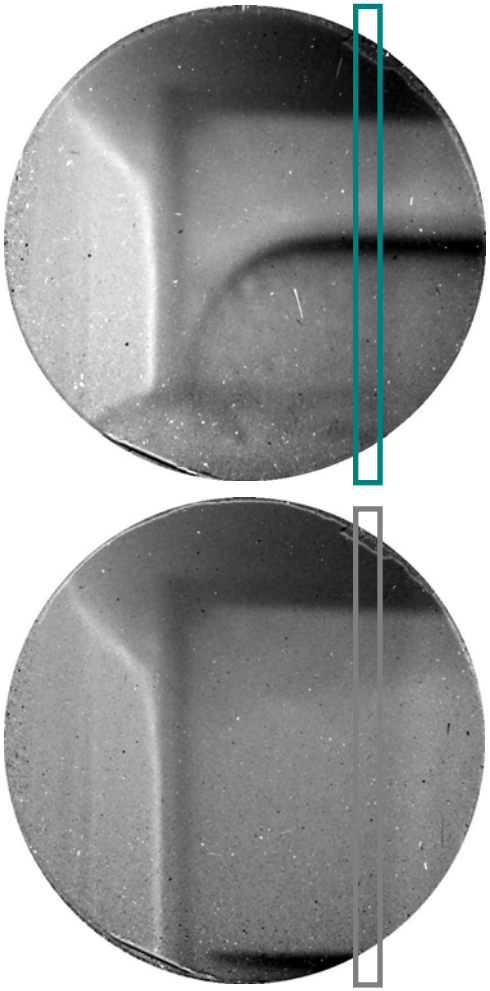
Xenon P_0 = 2.5 Bar

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
δt(FWHM) = 70 ns

4.19 mm

1 mm

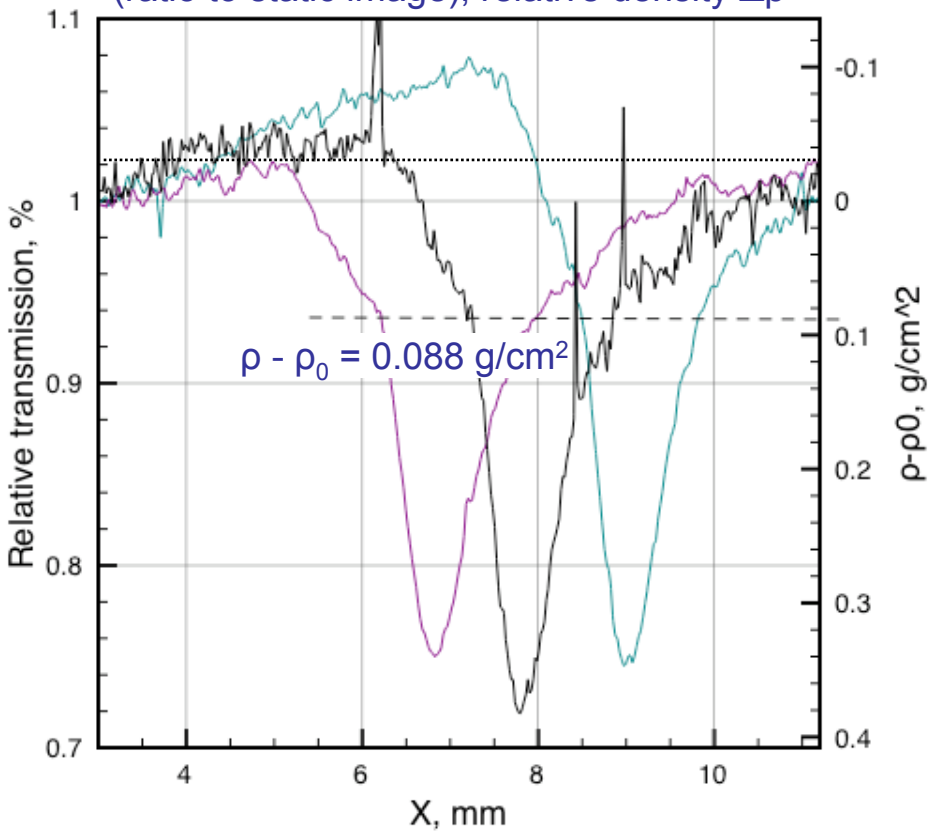
Gas cell thickness - 20.34 mm
Gas pressure - 2.5 Bar
$\rho_0 = 2.5 * 2.034 * 0.00589 = 0.03$ g/cm^2

Static image

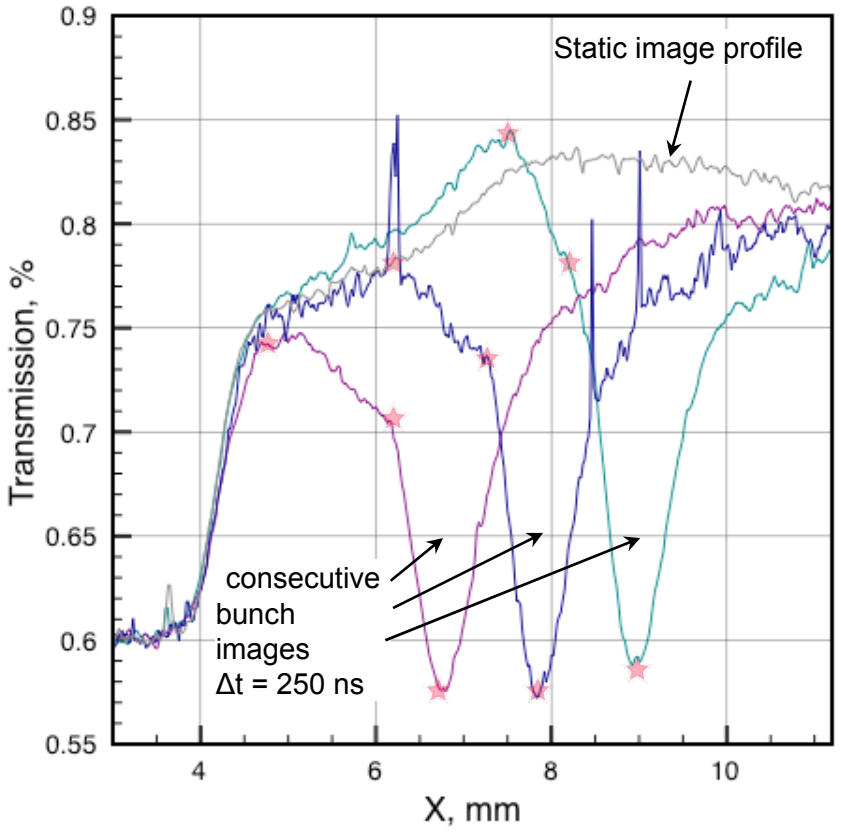
Shock Compression of Noble Gases

Xenon P_0 = 2.5 Bar

Beam transmission for image profiles
(ratio to static image), relative density Δρ



Beam transmission for image profiles



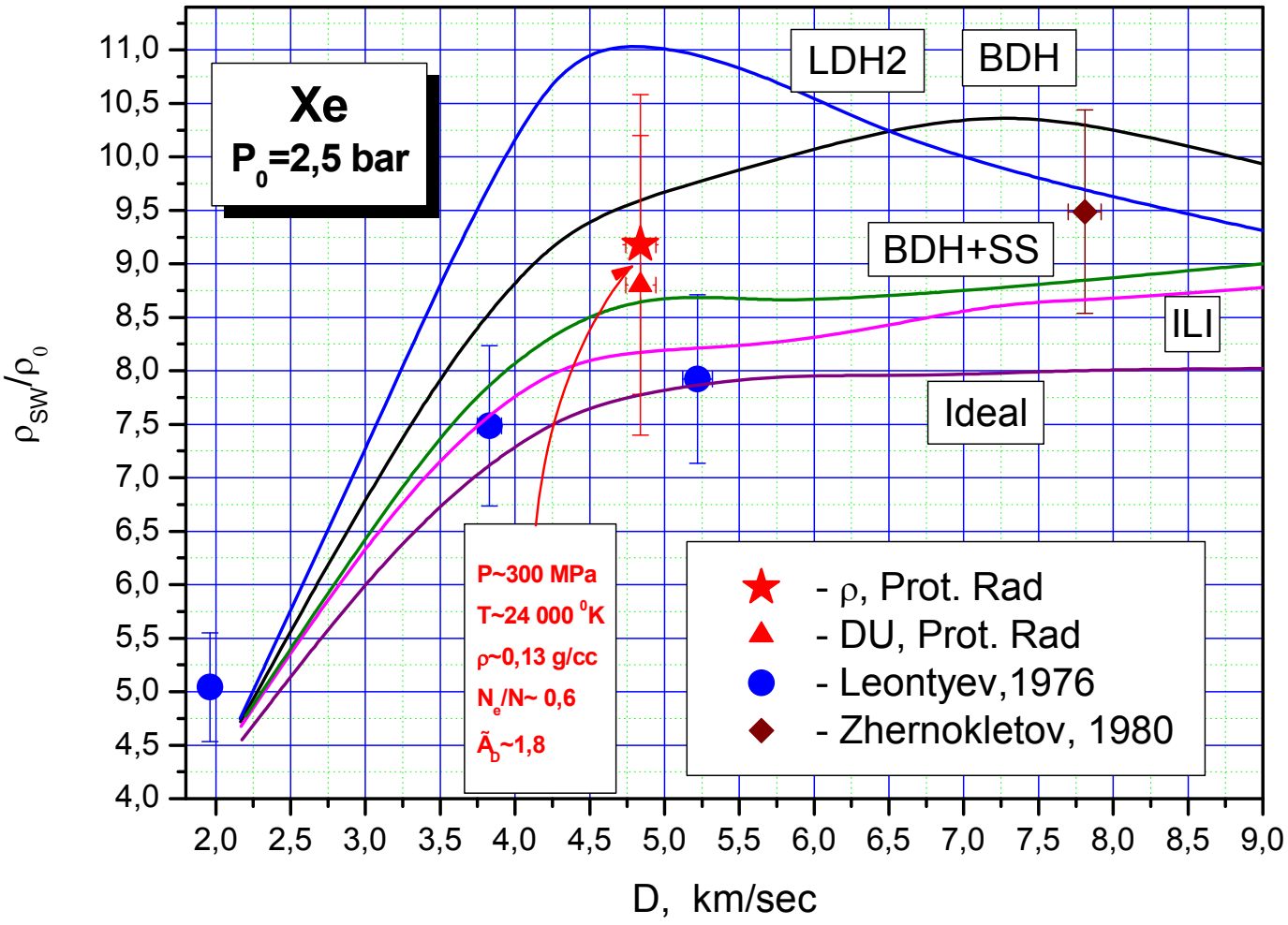
Δρ - ρ_0 = 0.088 g/cm²
ρ_0 = 0.030 g/cm²

$$H \sim \frac{(\rho - \rho 0)\, d}{\rho 0\ D\tau} + 1 = 9.38 \quad (d > D\tau)$$

D = 4.84 ± 0.09 km/s
U = 4.29 ± 0.09 km/s

$$H \sim \frac{D}{D - U} = 8.8$$

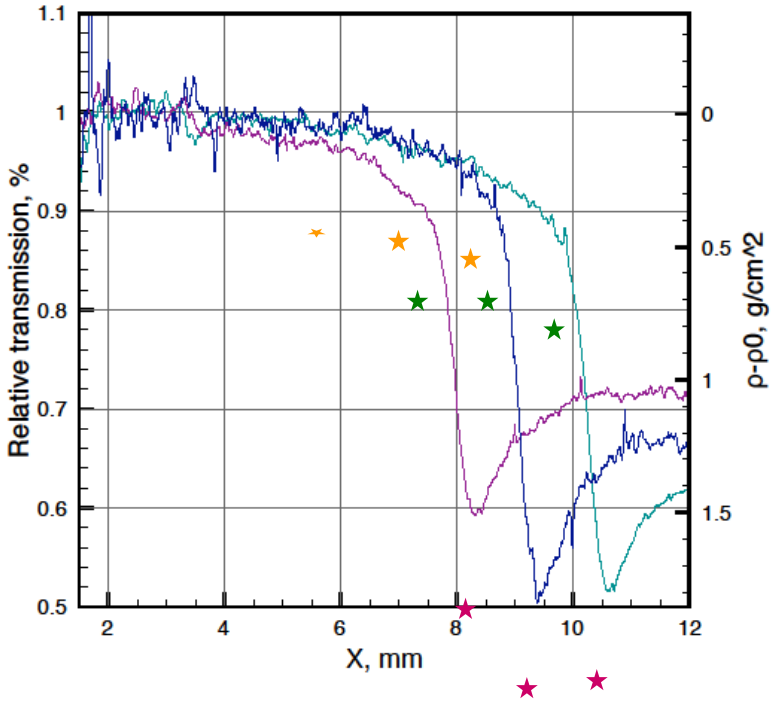
Shock Hugoniot of Xenon at P_0 =2.5 Bar



Shock Compression of Noble Gases

Argon

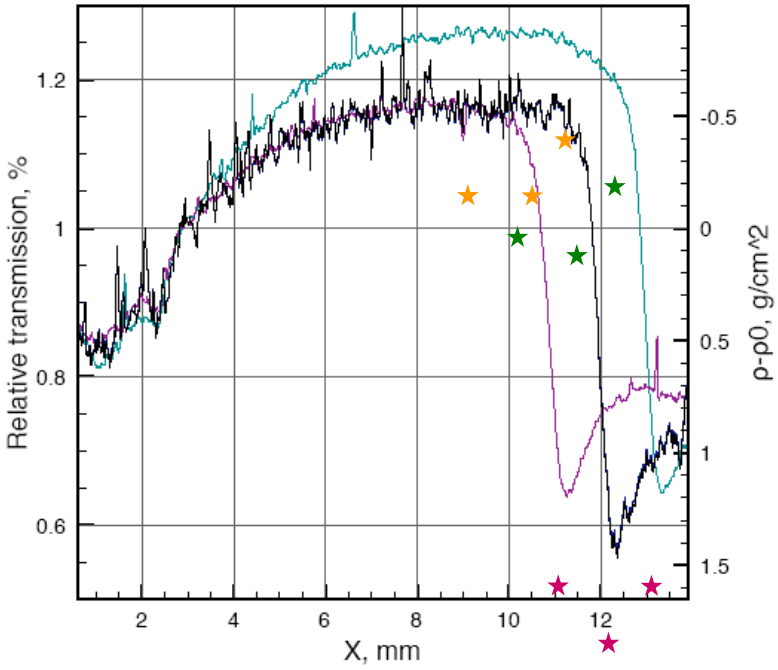
P_0 = 3.5 Bar



D = 5.4 km/sec

U = 4.5 km/sec

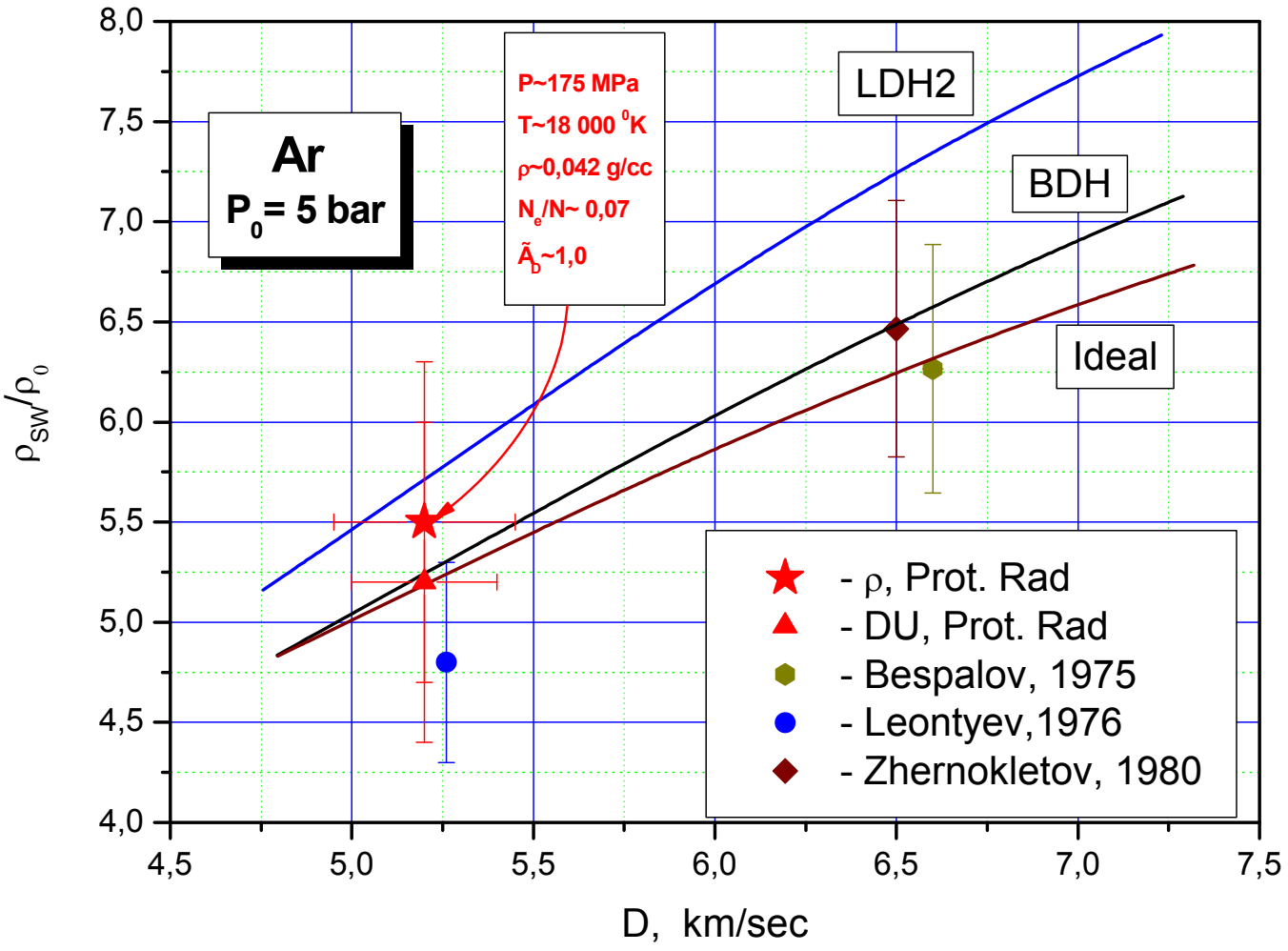
P_0 = 5 Bar



D = 5.2 km/sec

U = 4.2 km/sec

Shock Hugoniot of Argon at P_0 = 5 Bar

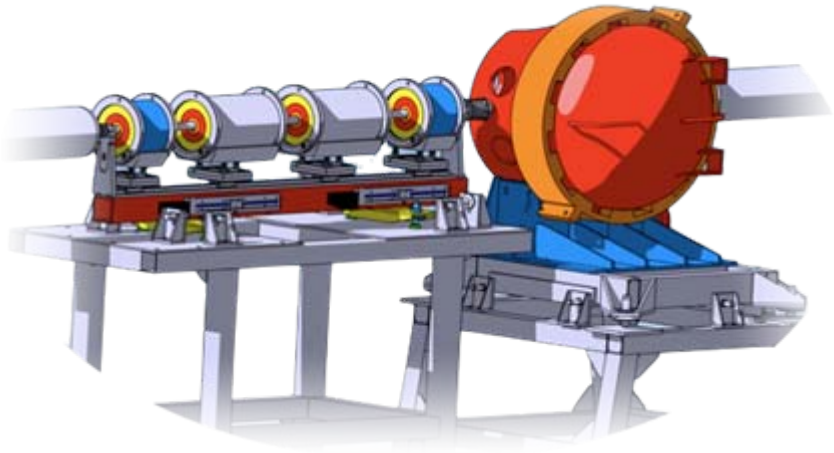


PRIOR Project

PRIOR = Proton Microscope for FAIR

4.5 GeV Proton Microscopy:

- **$5 \cdot 10^{12}$** 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



Collaborators:

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

Conclusions

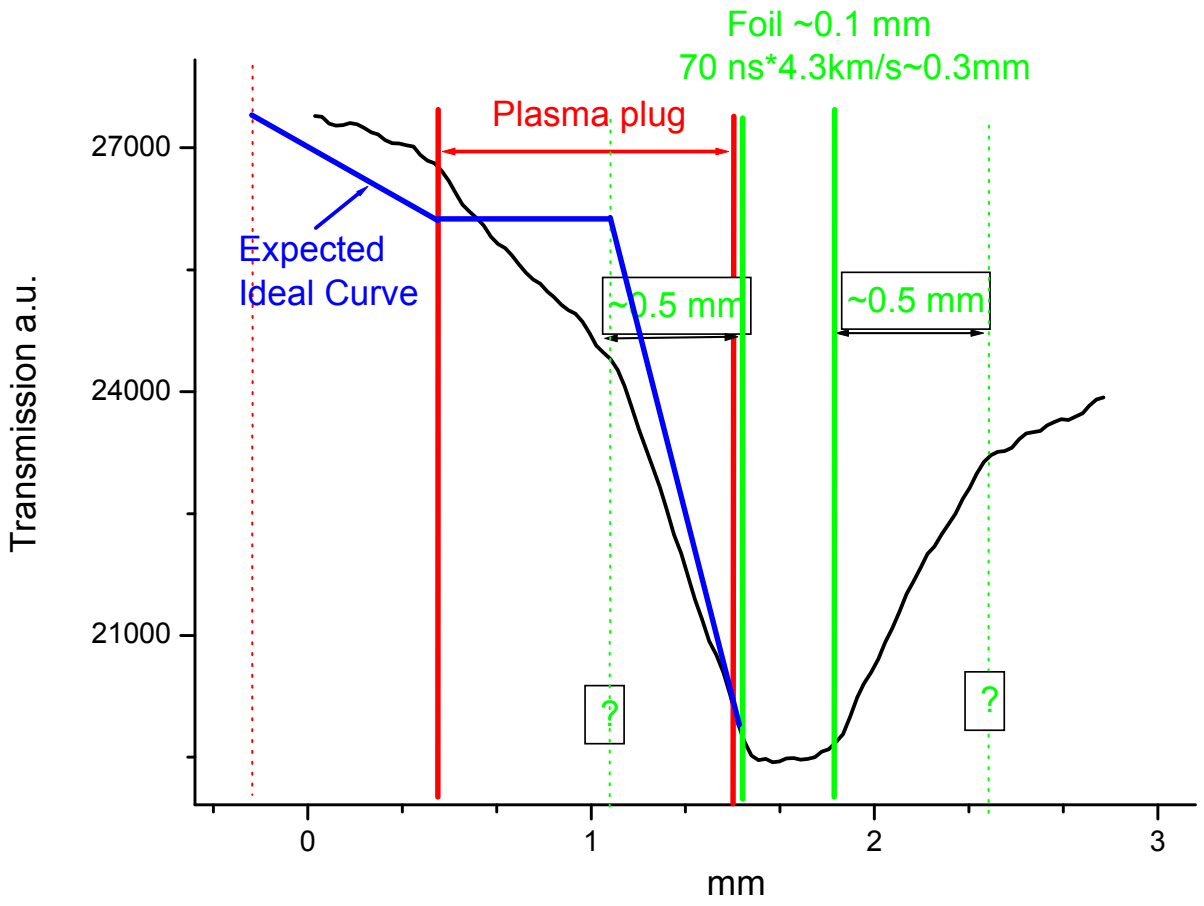
Current fields of research at ITEP-TWAC Proton Radiography Facility:

- Detonation of solid and emulsion explosives;
- Surface ejecta formation in metals under shock loading;
- Shock-compressed plasma of noble gases;
- Development of new compact explosive generators.

What's Next:

- Phase transitions in shock-compressed materials (metals, liquid nitrogen…);
- Experiments with noble gases at higher initial pressures;
- Experiments with cryogenic targets;
- Development of PRIOR facility at GSI/FAIR.

Transmission Profile for Xe at 2.5 Bar



Possible explanation : misalignment 2.5˚