High Energy Density Physics at ITEP-TWAC Proton Microscope

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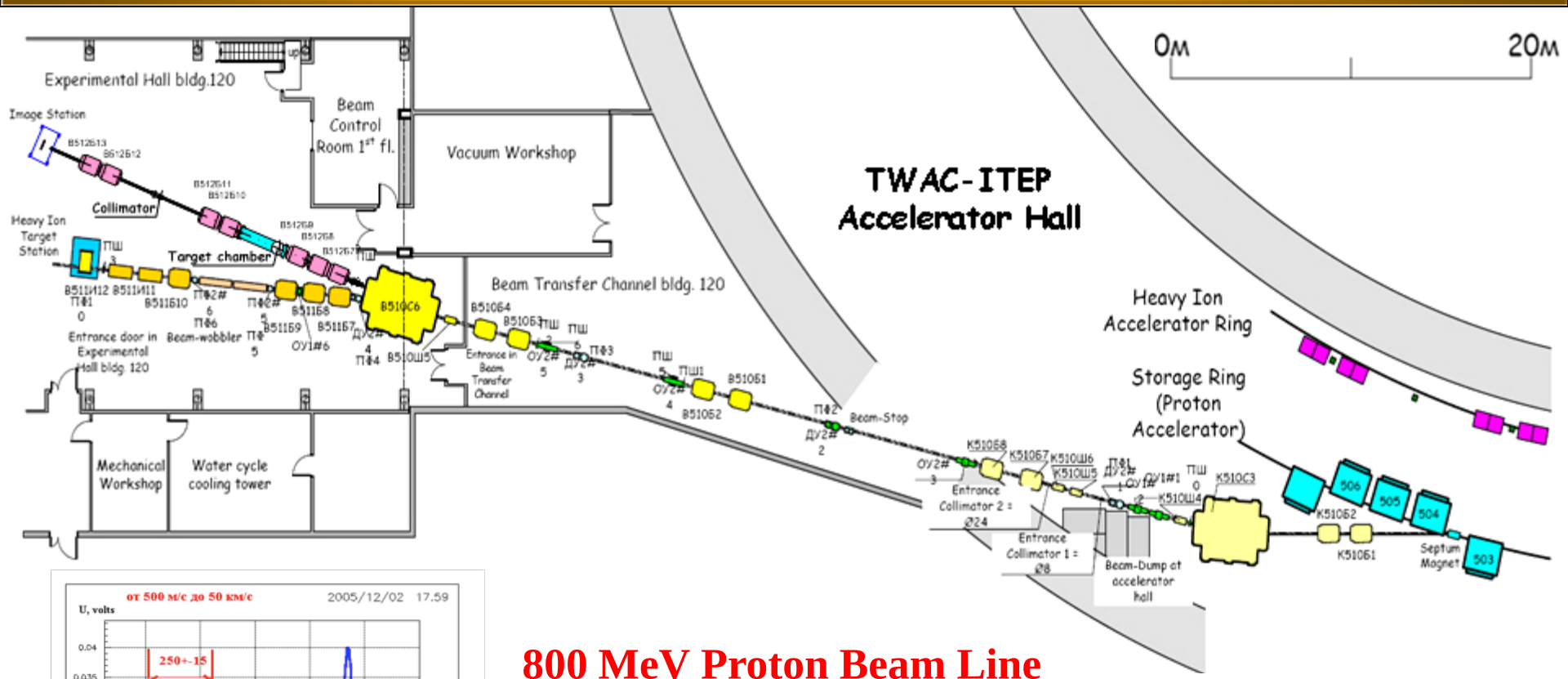
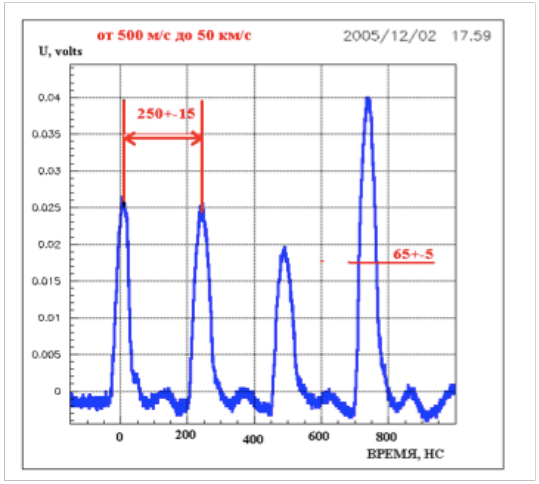
Proton Radiography at ITEP-TWAC Accelerator

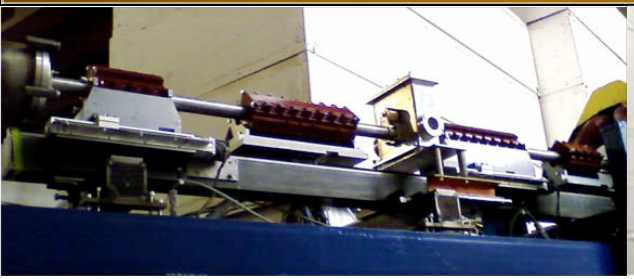




800 MeV Proton Beam Line

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

Proton Radiography 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: up to **50 μm**
Density resolution ~ **6%**

Image Registration System

Optical convertor: LSO scintillator (40 ns), ø78 mm
3-6 14 bit CCD cameras, fast shutter (100 ns), matched to beam bunch;
Temporal resolution = Bunch duration = **70 ns**

Explosion Confinement 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

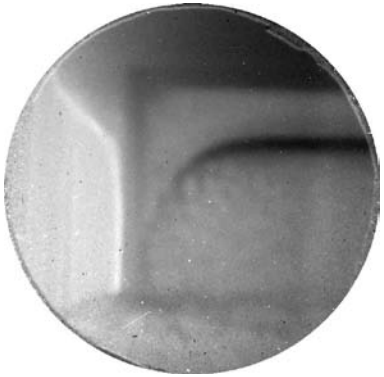
Proton Radiography in High Energy Density Physics

HEDP

research areas that can be addressed by Proton Radiography

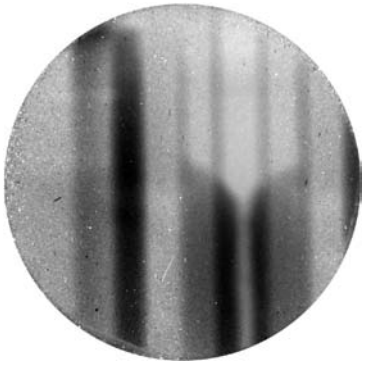
EoS and Phase Transitions

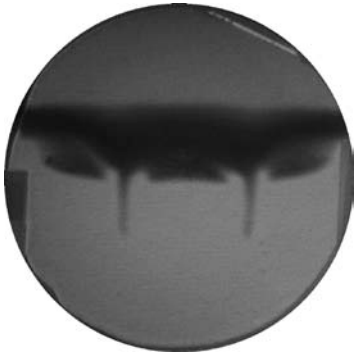
in materials in extreme conditions



Material Strength and Damage

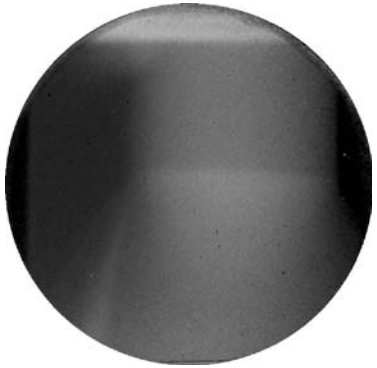
(Dynamic Fracture of Materials)





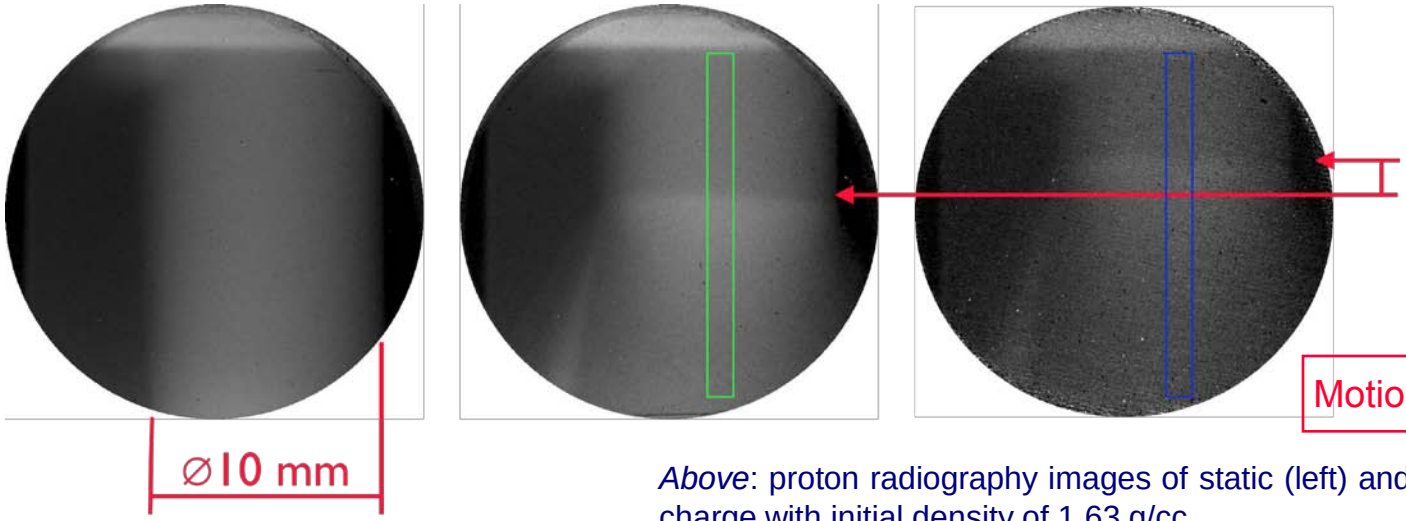
Hydrodynamics of HED Flows

(Shock and Detonation Waves, Cumulation, Hydrodynamic Instabilities)



Detonation in 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

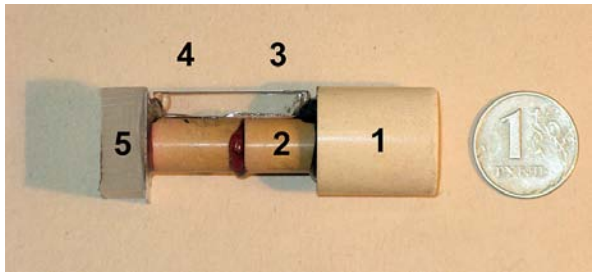
Motion blur $\delta X = D\delta T = 0.48$ mm!

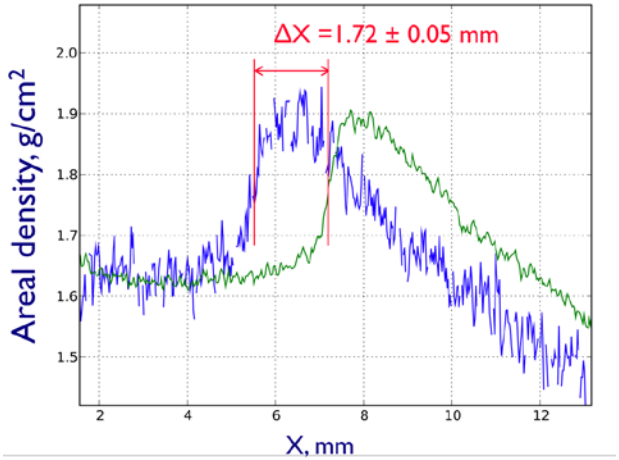
Above: proton radiography images of static (left) and dynamic detonating 10 mm TNT charge with initial density of 1.63 g/cc.

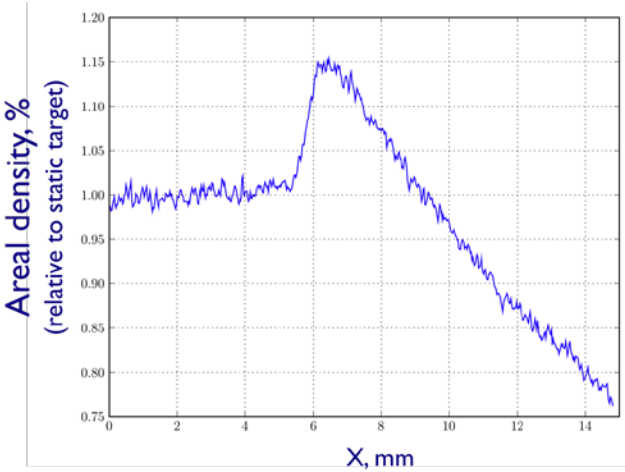
Below, left: photo of experimental target. 1 – initiating HE charge, 2 – target charge, 3 – reference plastic plate, 4,5 – VISAR reflective Al surface and diagnostic window.

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

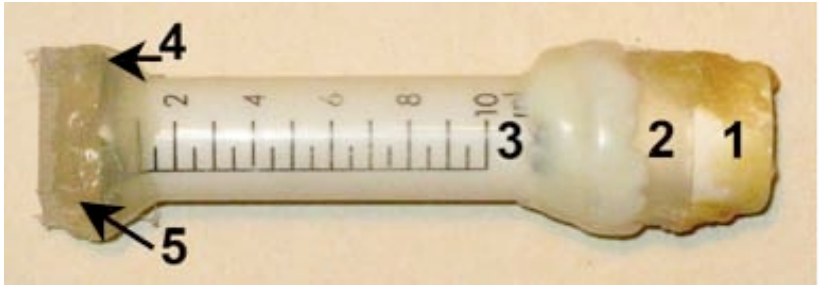
Total HE weight	25g
Initial density	1.32 - 1.65 g/cc
Charge diameter	10; 15; 20 mm
Charge length	30-56 mm

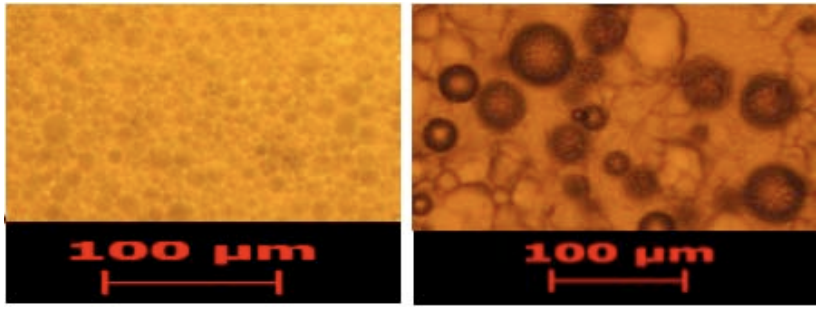






Detonation in Emulsion Explosive





Emulsion Explosive

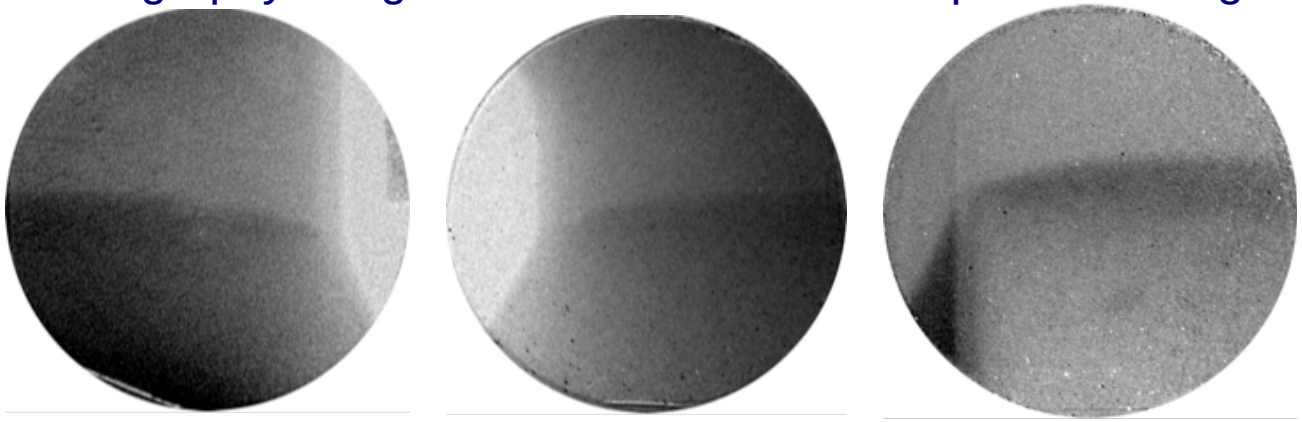
92-95% - oxidizer (ammonium nitrate)
8-5% - fuel (mineral oil)
+ 3 wt.% - hollow glass microballoons

Density	1.07 g/cc
Charge diameter	15; 20 mm
Charge length	60-80 mm

Experimental target

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

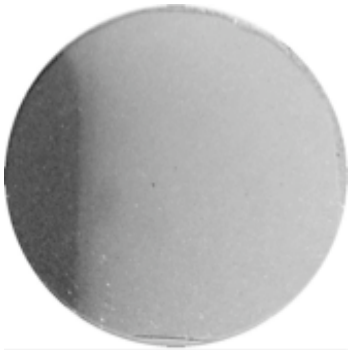
Radiography Images of 20 mm Emulsion Explosive Charges



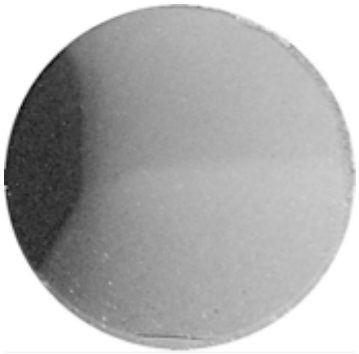
Detonation velocity D = 4.6 ± 0.2 km/s

Detonation in Emulsion Explosive

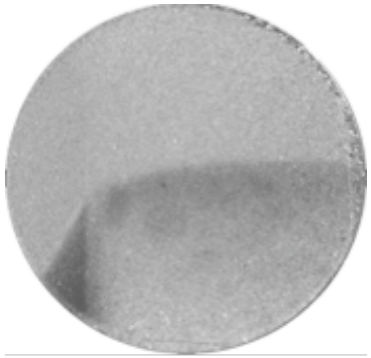
Inverted static image



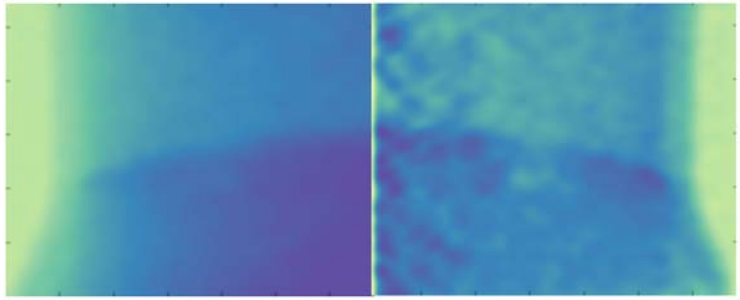
Inverted shot image (Bunch 1)



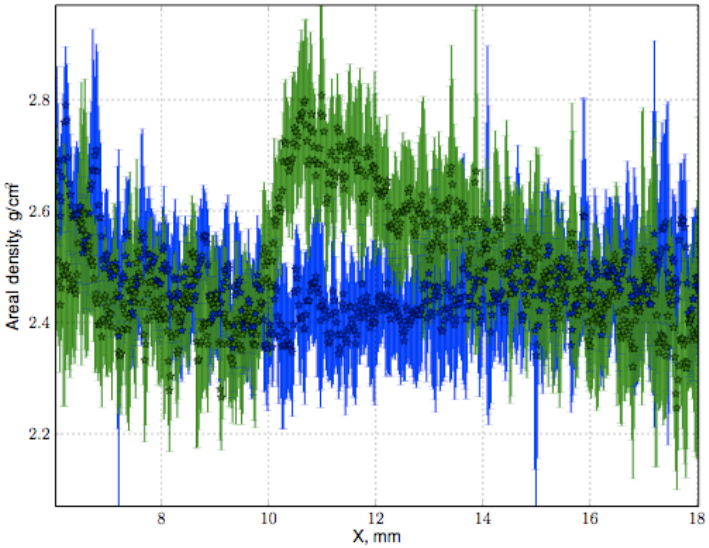
Relative to static density changes



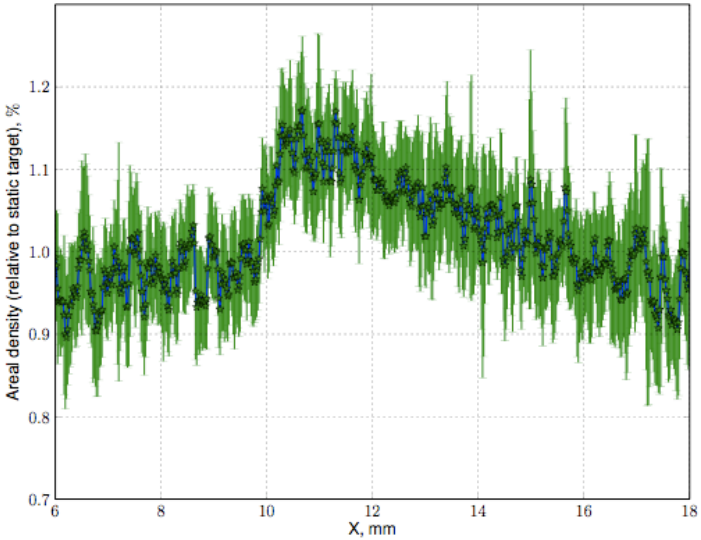
Volume density reconstruction



Absolute areal density profile along the axis of charge



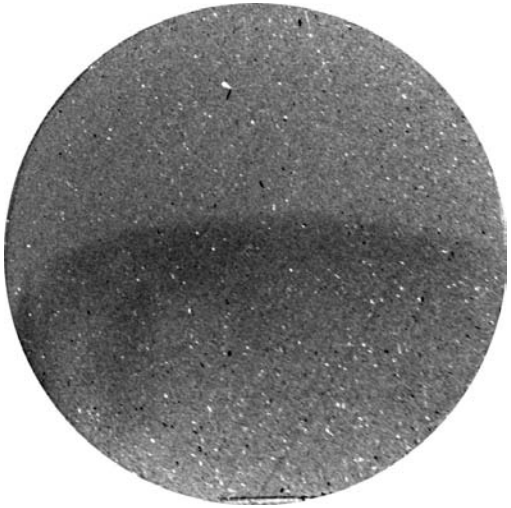
Areal density profile along the axis of charge (relative to static density)



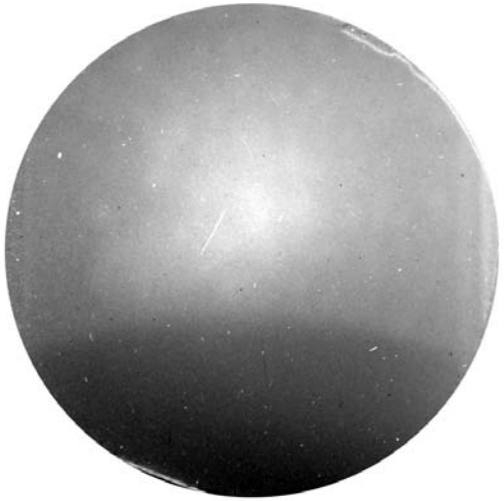
Detonation in Emulsion Explosive

Proton radiography images of 15 mm Emulsion Explosive charges

Steady-state
Detonation wave
D = 4.4 km/s



Non-steady
Detonation-like wave
D = 4.4 km/s



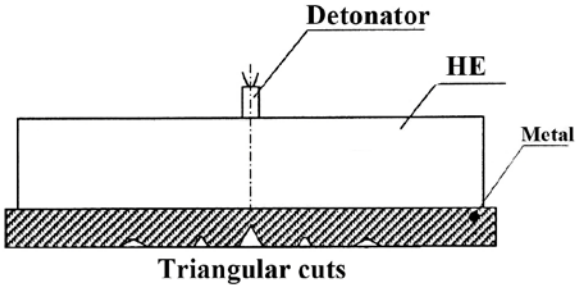
Fading shock wave
(Detonation failure?)
D ~ 4.0 km/s

-> Stochastic character and behaviour of explosive process was found for 15 mm emulsion explosive charges

-> 15 mm is near to a critical diameter for emulsion explosive detonation

-> Study of macrokinetics of chemical reaction for emulsion explosive at different diameters is being conducted at the moment

Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

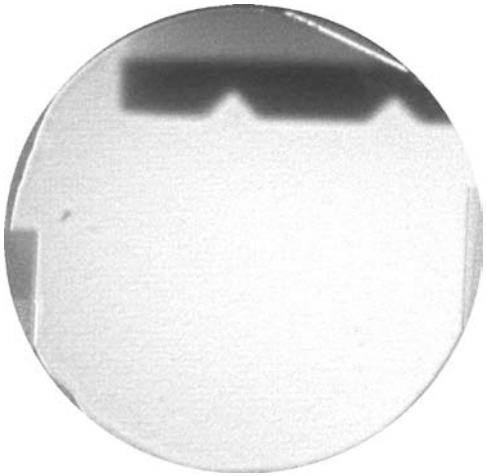


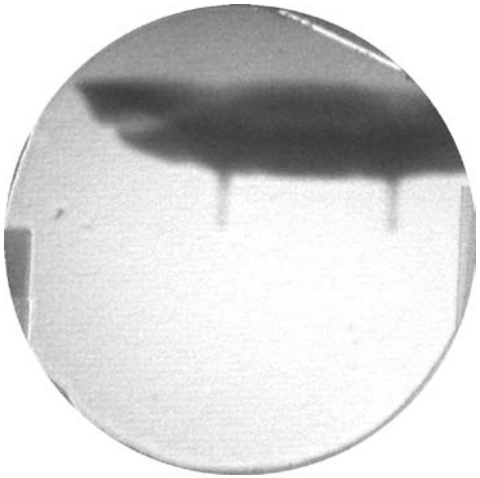
Proton radiography images of static targets

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

Steel target

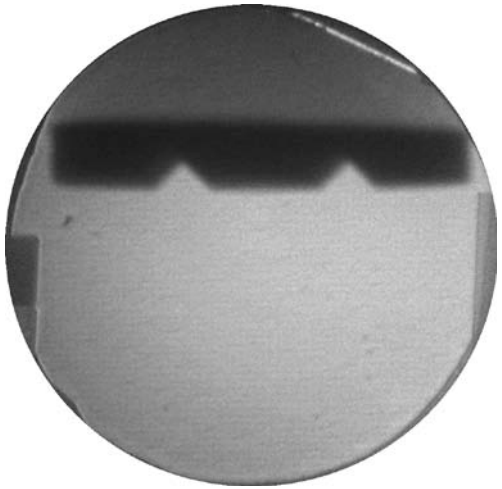
Diameter – 15 mm
Thickness – 2 mm
Depth of cuts – 1 mm



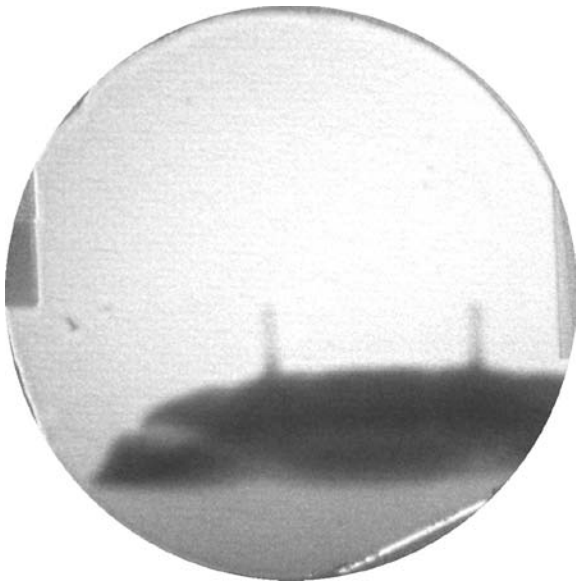


Copper target

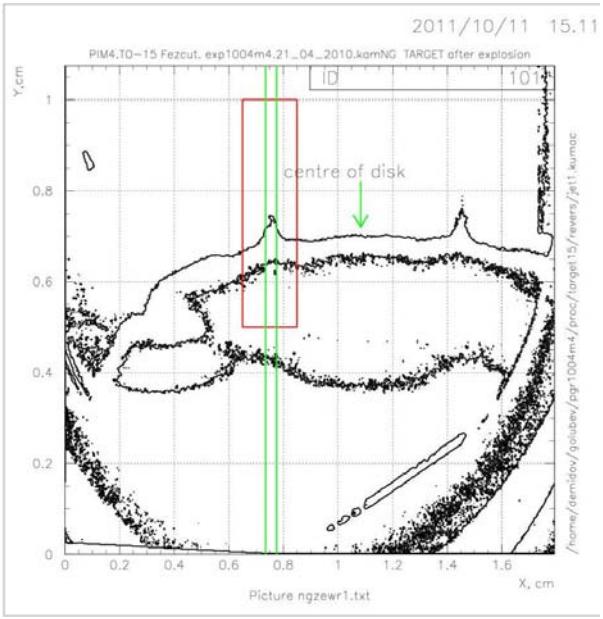
Similar to steel one



Dynamic Fracture and Surface Ejecta Formation in Metals under Shock Loading

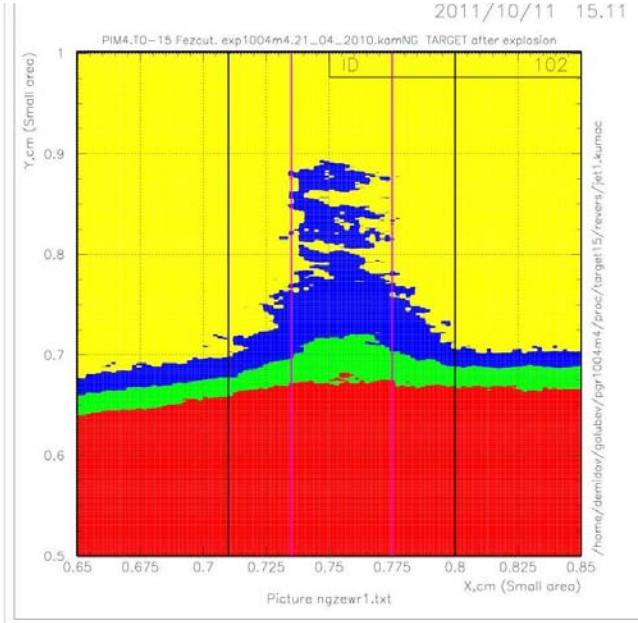


Dynamic proton radiography image shot at 2.5 µs after shocking the free surface of the steel target



Linear density map reconstructed from radiographic image

Velocity of jet tip: 2.8 km/s

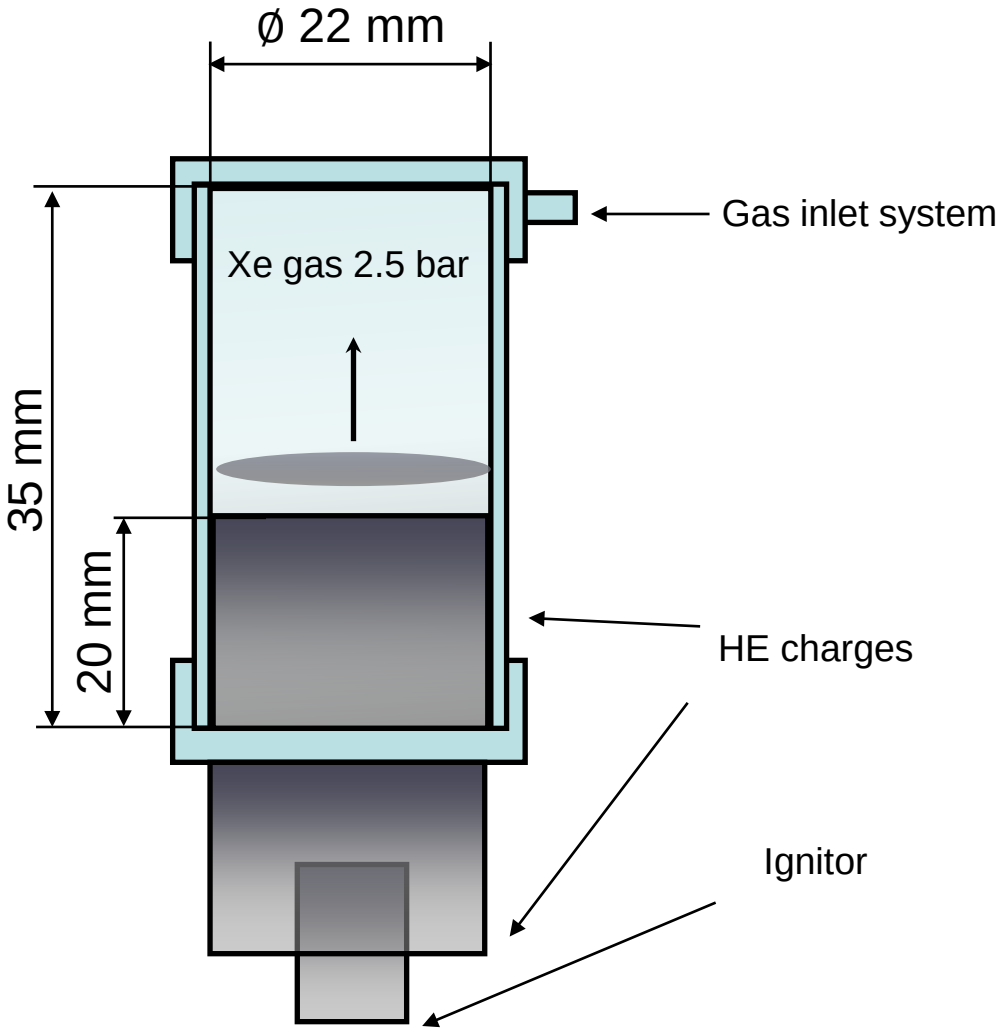


Close-up of the area inside the red frame on the left image

Mean volume density of jet material: 0.08 g/cc

Shock Compression of Noble Gases

Target scheme



Target photo

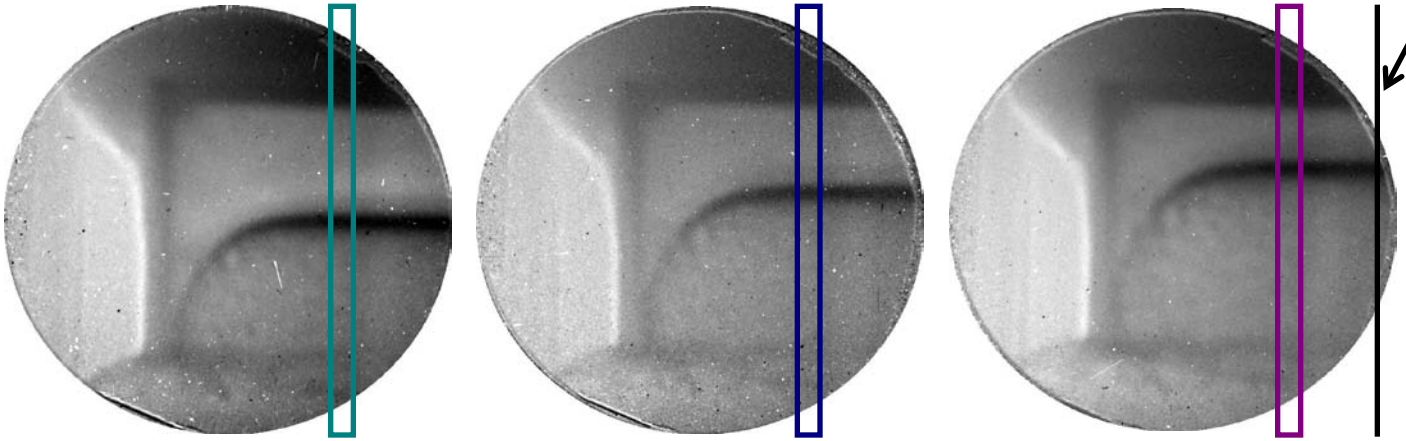
Shock Compression of Noble Gases

Camera 1
Proton bunch 1 (t_1)

Camera 2
Proton bunch 2 (t_2)

Camera 3
Proton bunch 3 (t_3)

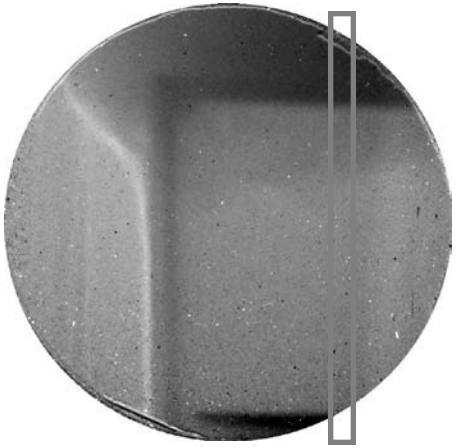
Target axis



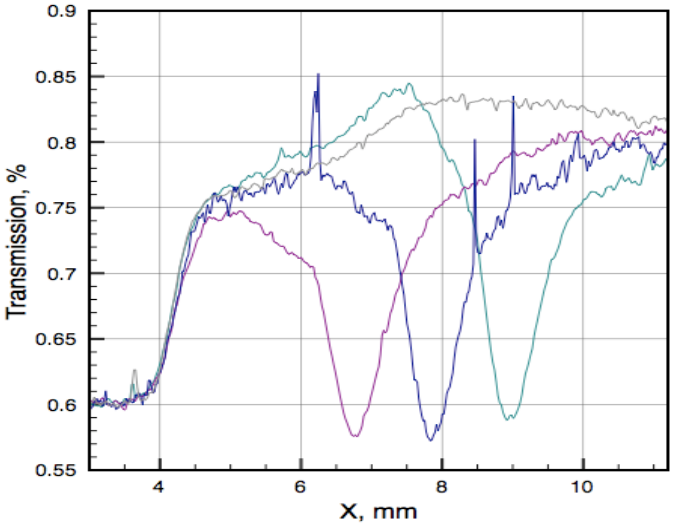
$\Delta t = t_2 - t_1 = t_3 - t_2 =$
$= 250$ ns
$\delta t(FWHM) = 70$ ns

4.19 mm

1 mm



Static image

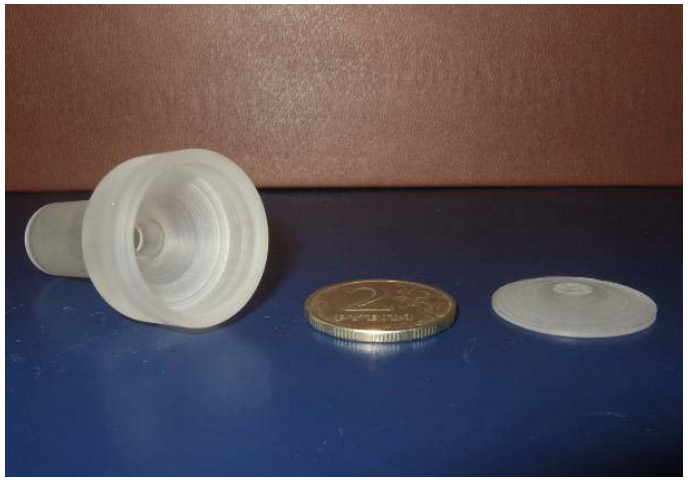


Beam transmission for image profiles

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

$U = 4.3 \pm 0.2$ km/s

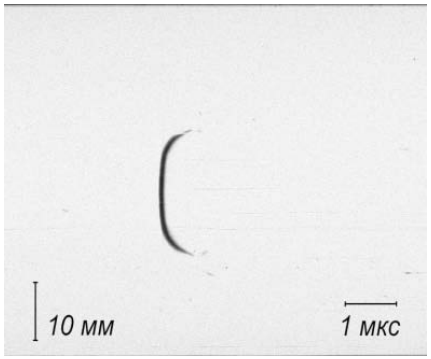
Development of Compact Explosive Generators

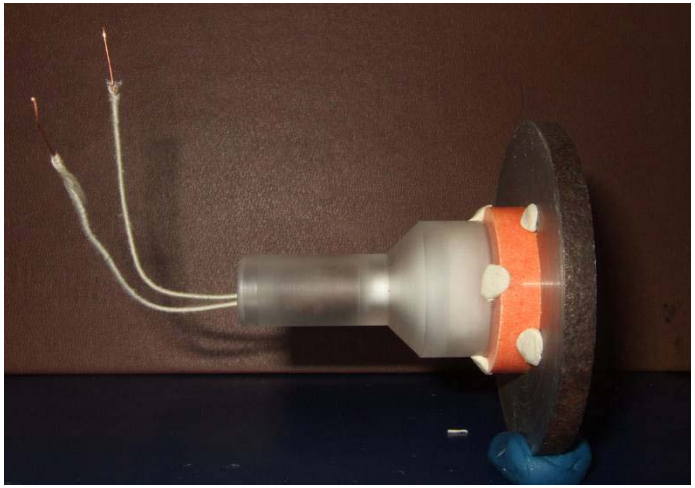


Plexiglass components of compact explosive generator

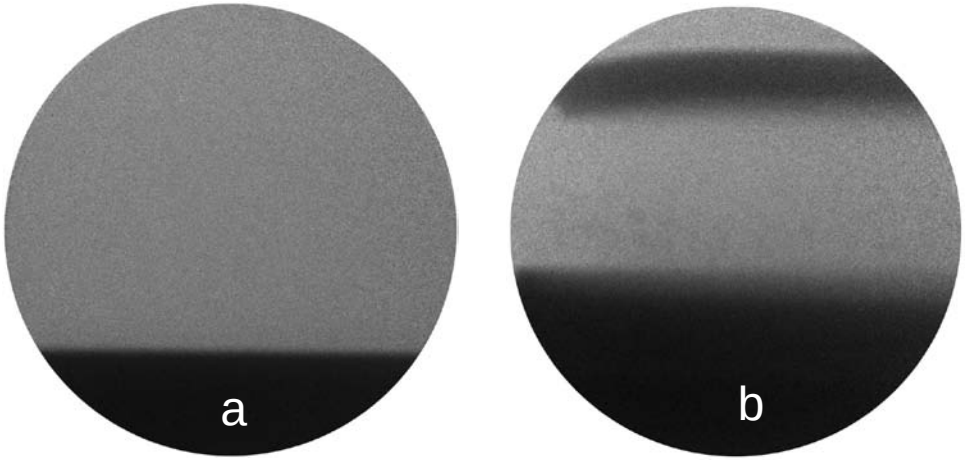
Total amount of explosive	**< 15 g of TNT**
Flyer plate	**∅20, 1-2 mm thick**
Flyer plate material	**Al, Steel**

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



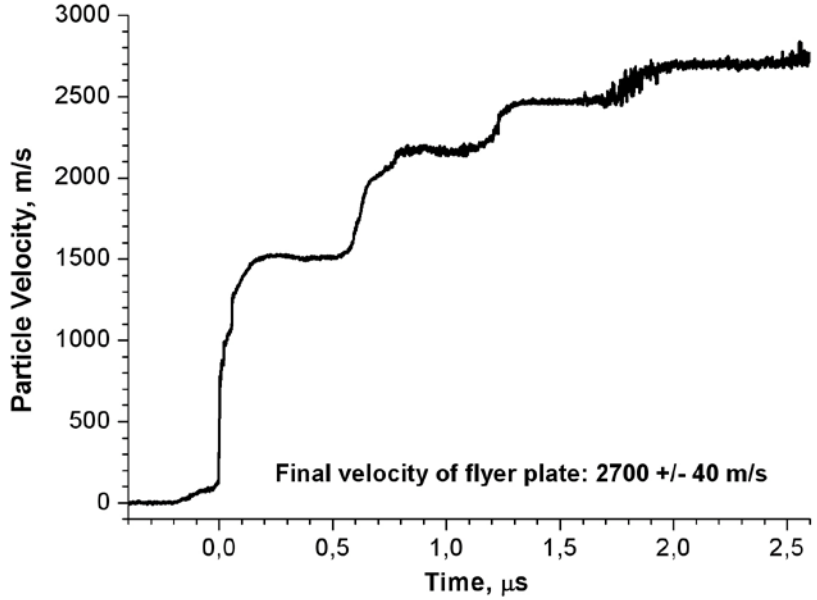


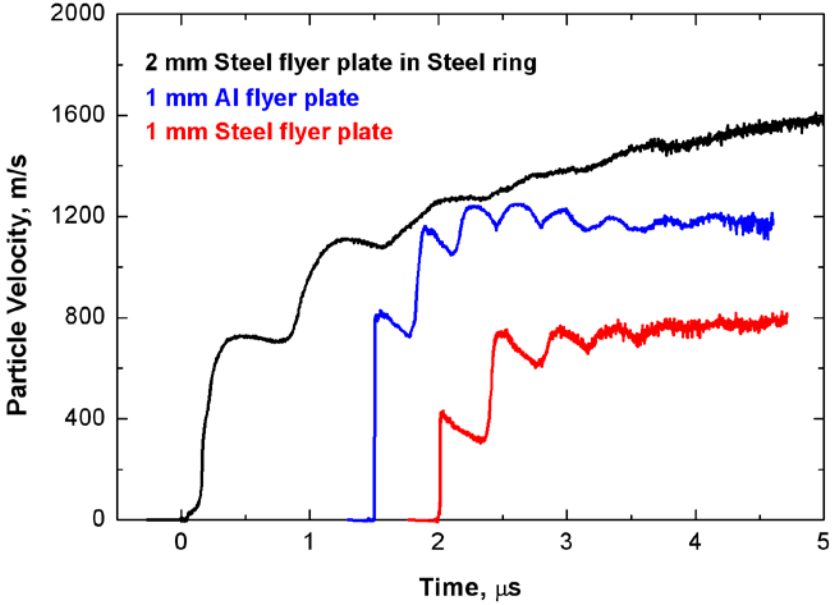
Experimental assembly for accelerating flyer plate with compact explosive generator



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

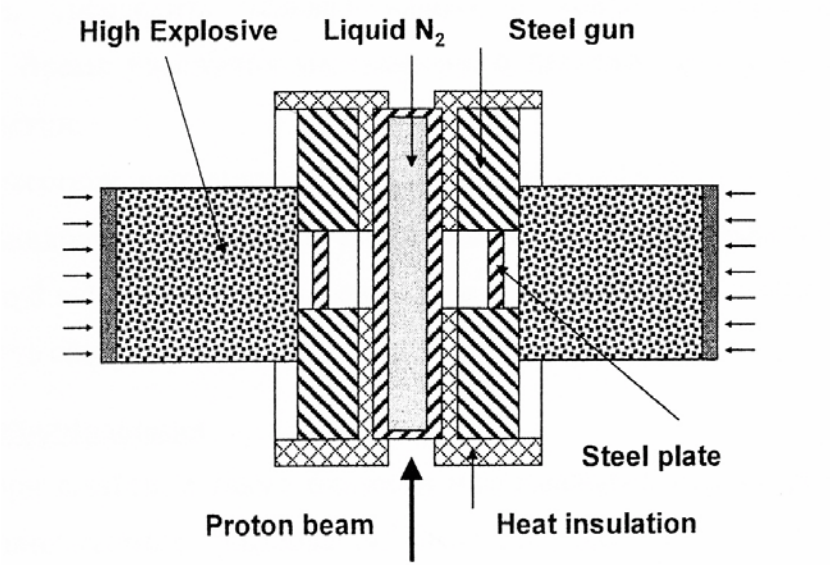


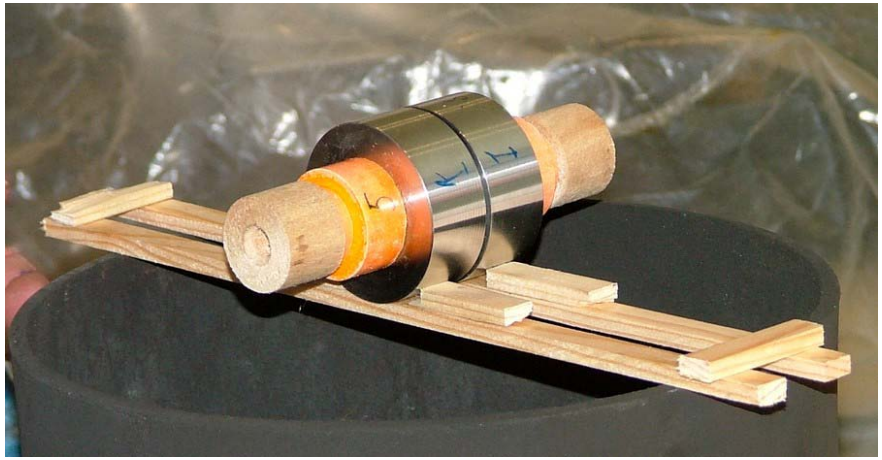


VISAR flyer plate free surface profiles: *left* – for 2 mm Al flyer plate, *right* – for 1 mm Al and 1 & 2 mm Steel flyer plates

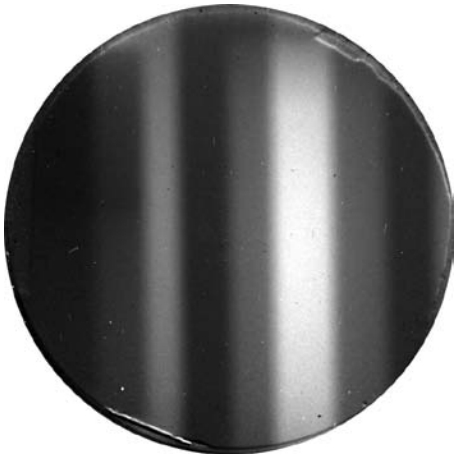
Flyer plate	Velocity after full acceleration, km/s	Base of flight, mm	Diameter of plane region, mm
2 mm Al in Steel ring + 12 g HE booster	**2.8**	10	13
2 mm Steel in Steel ring + 12 g HE booster	**1.6**	6	
1 mm Al	**1.2**	3	13
1 mm Steel	**0.8**	2	

Development of Compact Explosive Generators

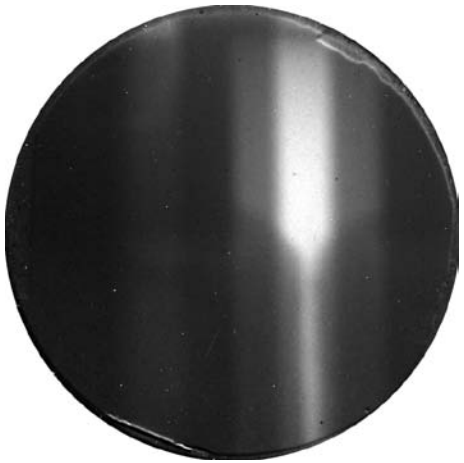




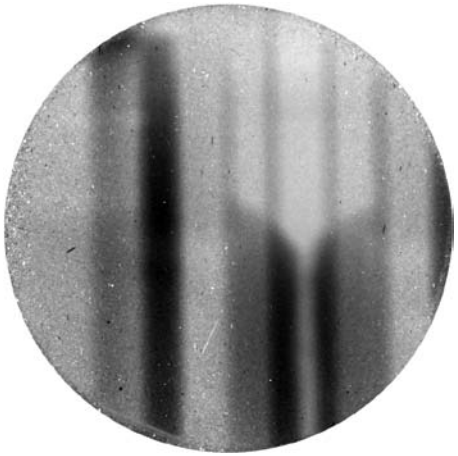
Compact explosive generator for symmetric bilateral compression of condensed matter up to 150 GPa



Static image



Dynamic image



Relative to static density changes

Summary

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

- Detonation of solid and emulsion explosives;
- Dynamic fracture of metals;
- 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 condensed matter;
- Experiments with cryogenic targets (including liquid nitrogen);
- Development of possible future targets for PRIOR facility.

Details on our proposed study of phase transitions in shock-compressed liquid nitrogen and shock compression of porous materials will be given in a talk by Dmitry Nikolaev