# ПРОТОННАЯ РАДИОГРАФИЯ ПЛОТНОЙ ПЛАЗМЫ

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# Proton Radiography of Dense Plasma

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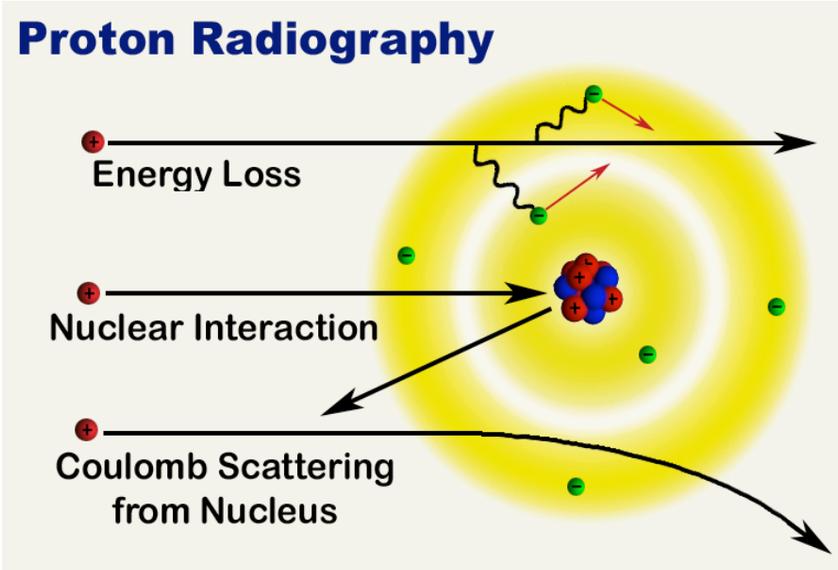
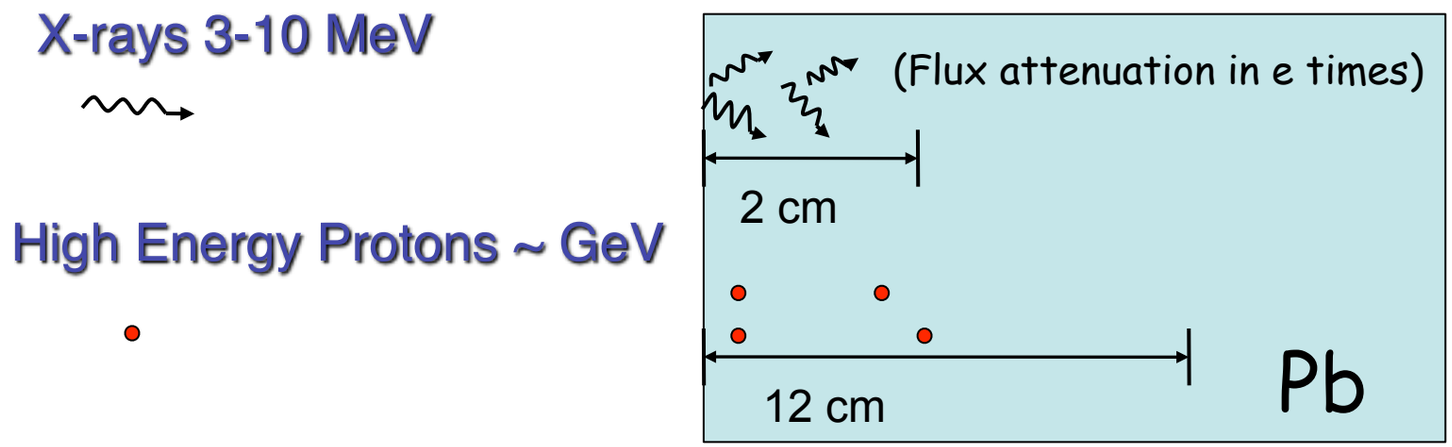
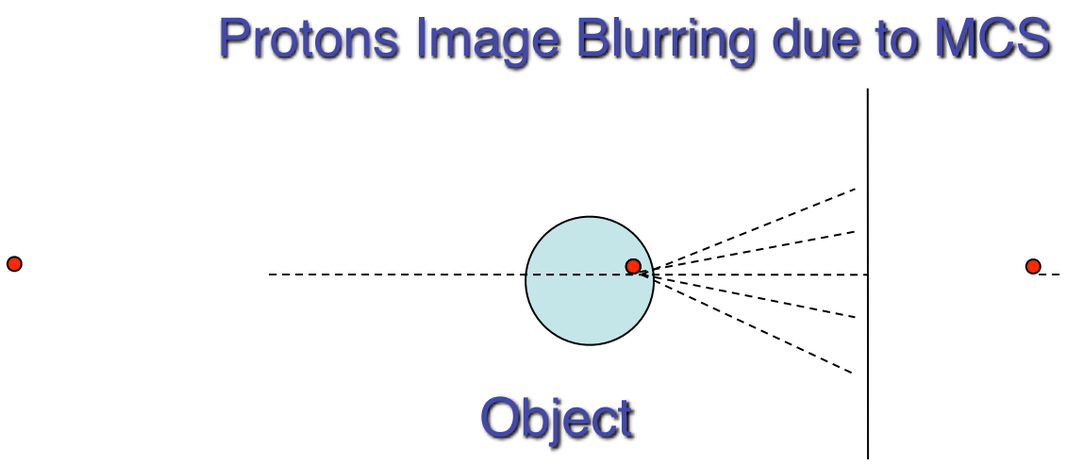
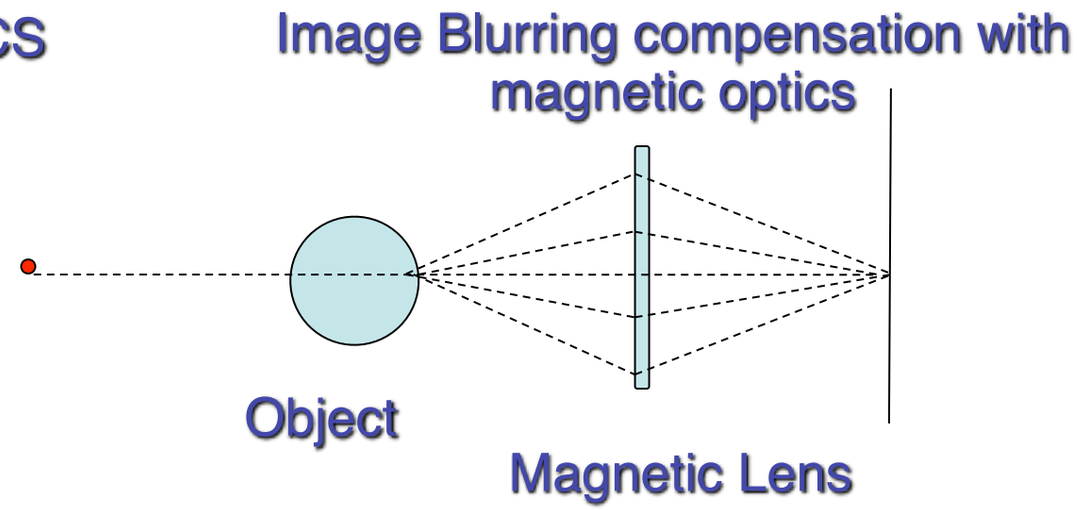
# Proton Radiography Basics




## X-rays and protons ranges in matter



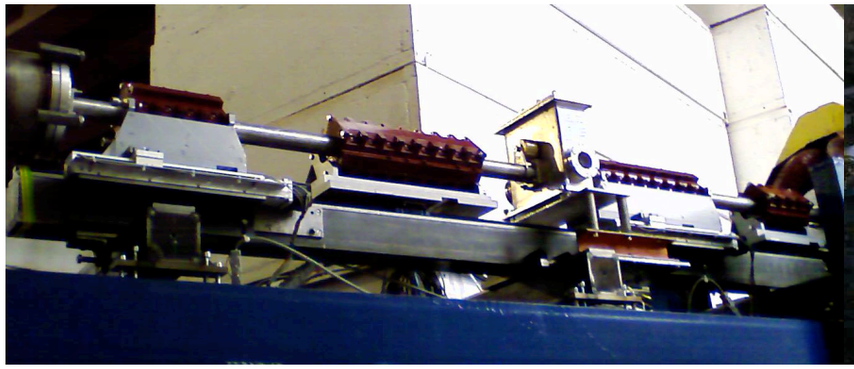



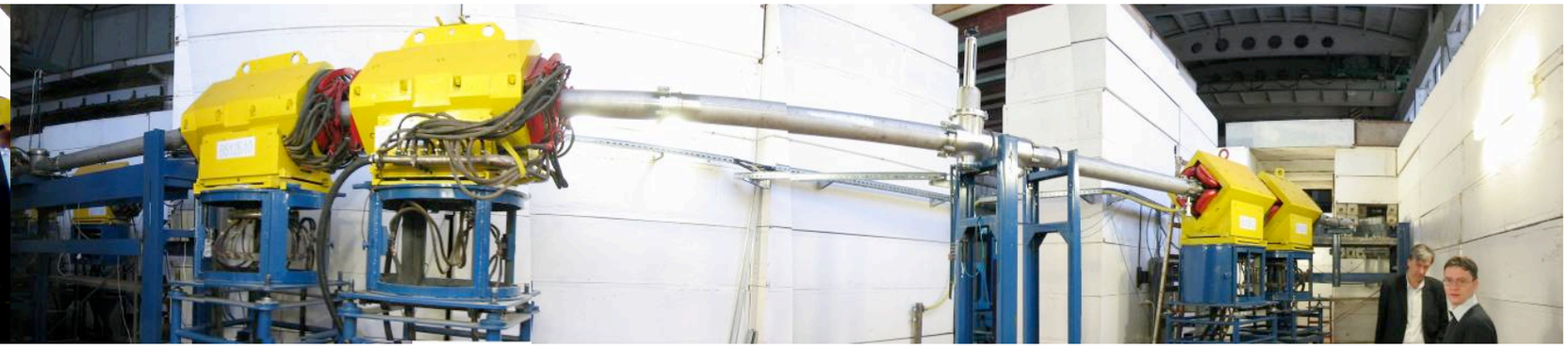

A. M. Koehler, *et al.* *Science* **160**, 303 (1968).

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

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

# Proton Radiography Set-up at ITEP-TWAC Facility



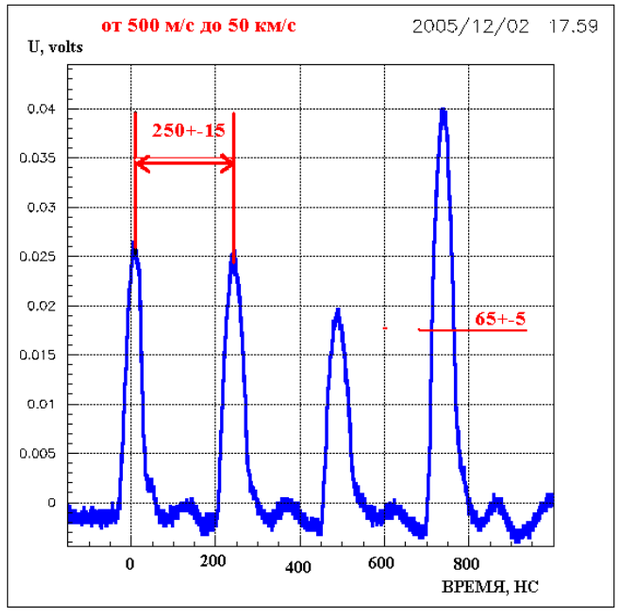


## ITEP Proton Microscope

E = 800 MeV
Beam structure – 4 bunches
$10^{11}$ protons
Magnification X = 7.82
Field of view < 10mm
Spatial resolution σ = 50um

Magnification X = 3.65
Field of view < 22 mm
Spatial resolution σ = 60um

Density resolution ~ 6%




## Explosion Protective Chamber

HE mass (TNT) – up to 70 g
Pumped down to $10^{-3}$ Torr
Active ventilation system
Optical diagnostics - VISAR

<u>Under design:</u>
target angular positioning system (±10°)
cryogenic target system

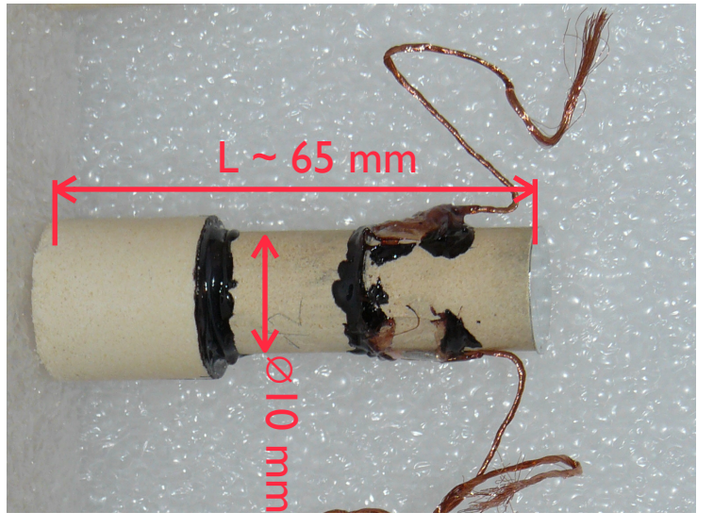
## Image Registration System

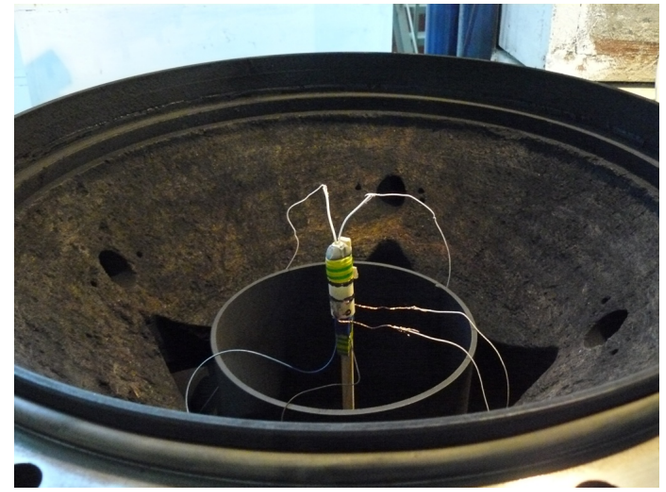
LSO (40 ns) scintillating converter ∅78 mm

14 bit CCD camera with fast shutter (100 ns) matched to beam bunch

Fast Current Transformer (FCT) - beam intensity measurements; beam bunch matching

# Detonation studies in pressed TNT charge



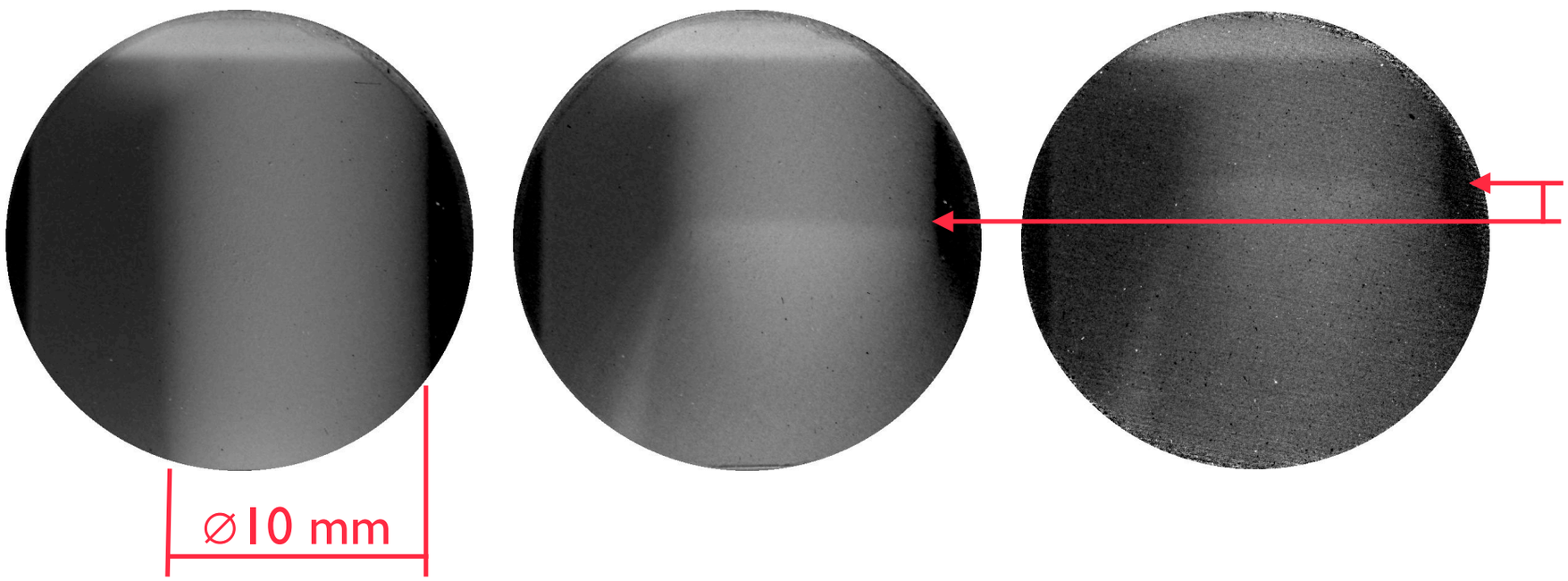



| | |
|---|---|
| total HE charge weight | 25g |
| initial density | 1.32 - 1.65 g/cc |
| charge diameter | 10; 15; 20 mm |
| charge length | 30-56 mm |

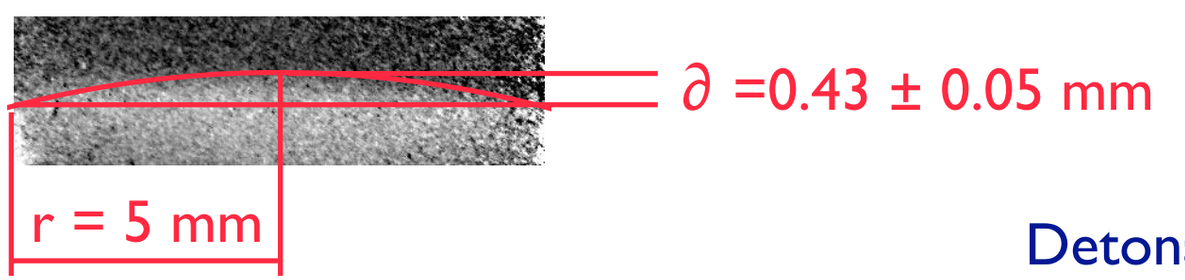
Static image | Bunch 2 image ($T_2$) | Bunch 3 image ($T_3$)

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

$\delta T = 70$ ns




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




Detonation front curvature radius $R = 58 \pm 7$ mm

# Detonation studies in pressed TNT charge

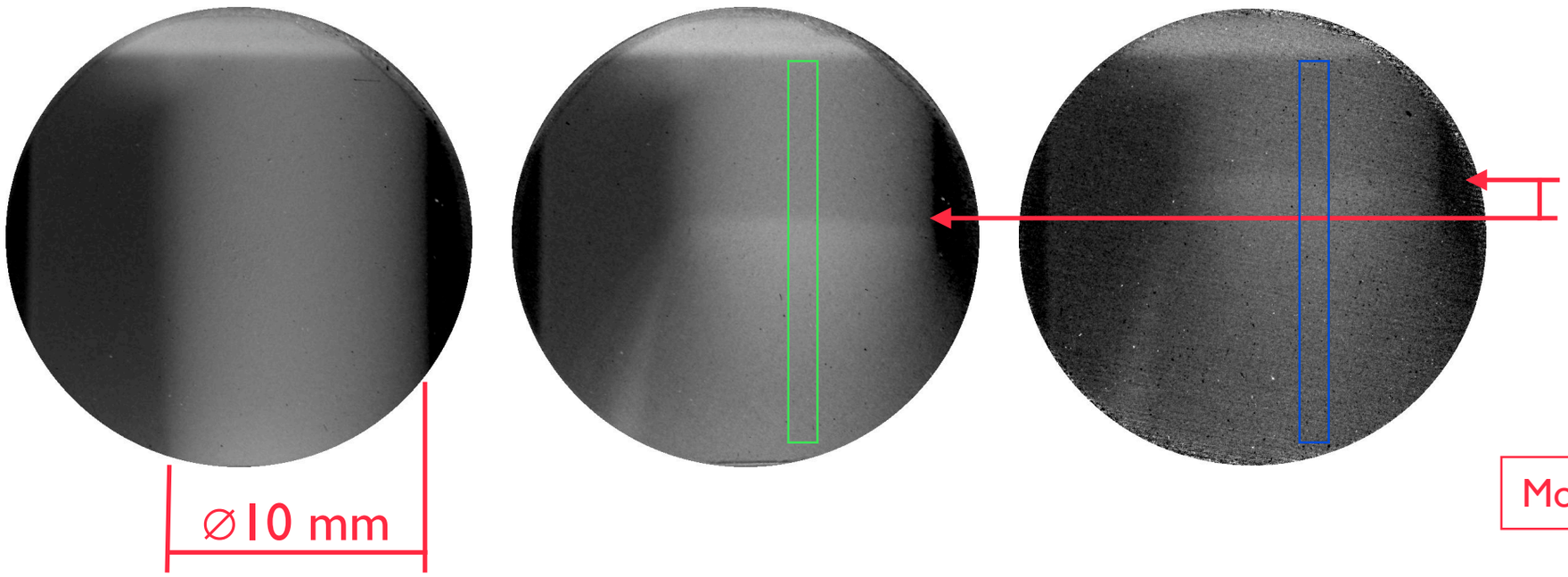
Static image

Bunch 2 image ($T_2$)

Bunch 3 image ($T_3$)

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

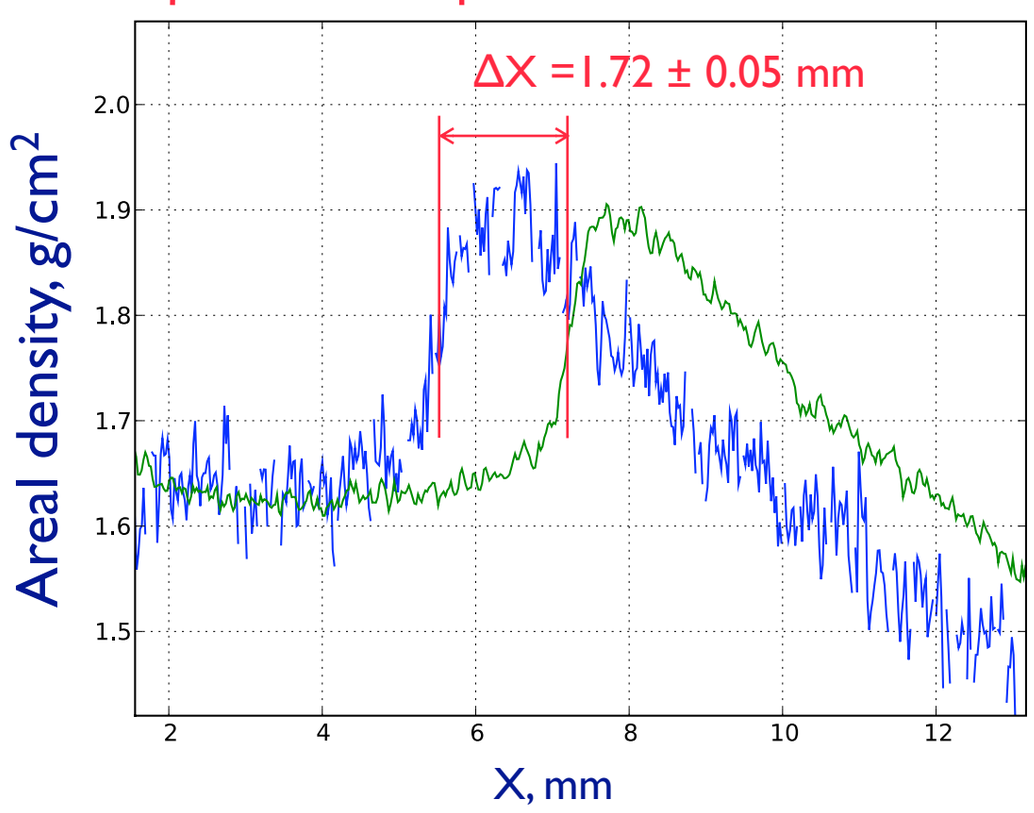
$\delta T = 70$ ns

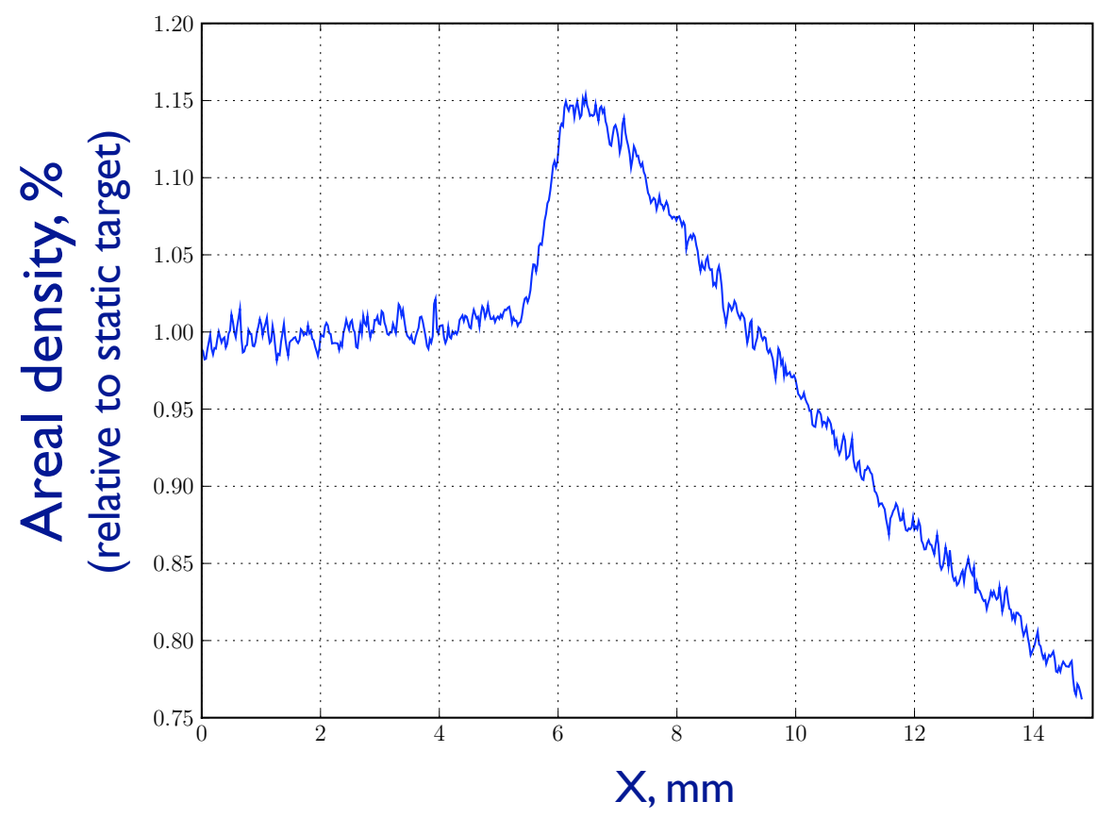



$\Delta X = 1.72 \pm 0.05$ mm

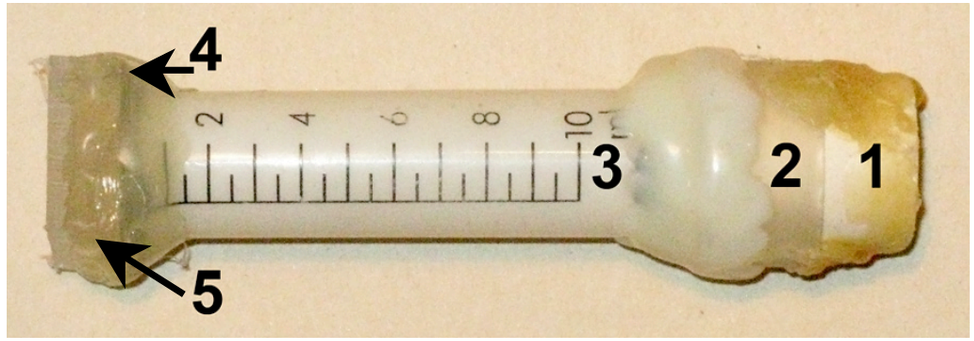
$D = \Delta X/\Delta T = 6.9 \pm 0.2$ km/s

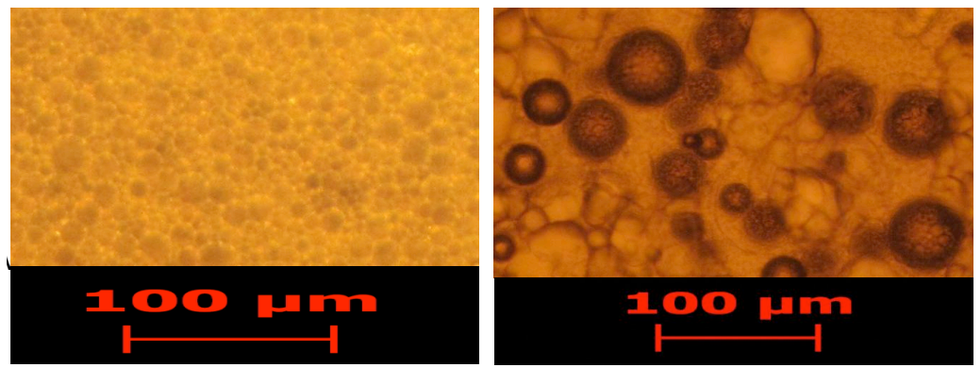
Motion blur $\delta X = D\delta T = 0.48$ mm !



# Detonation studies of Emulsion Explosive




92-95% - oxidizer (ammonium nitrate)
8-5% - fuel (mineral oil)
Hollow glass microballoons (C15-type, 3M)

Weight concentration: 1—4%

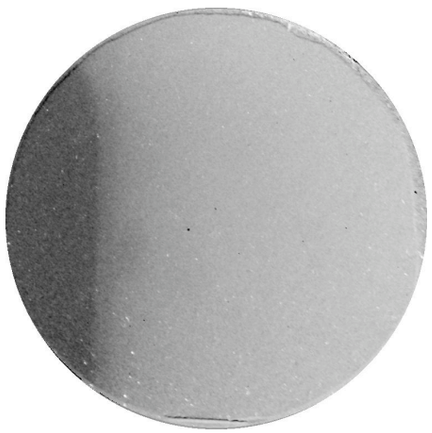
| | |
|---|---|
| density | 1.07 g/cc |
| charge diameter | 15; 20 mm |
| charge length | 30-56 mm |

Radiography Images of EHE

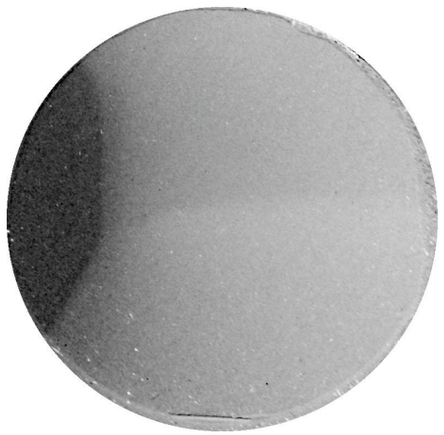
Detonation velocity D = 4.6 ± 0.2 km/s

# Detonation studies of Emulsion Explosive

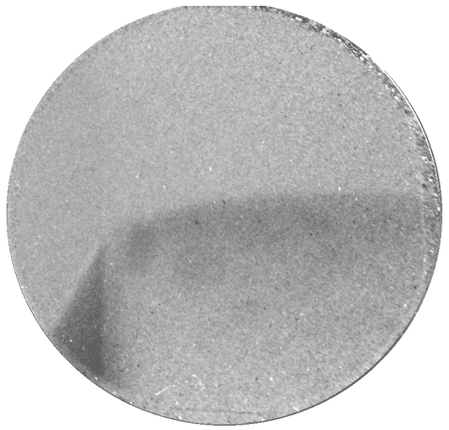
Static image



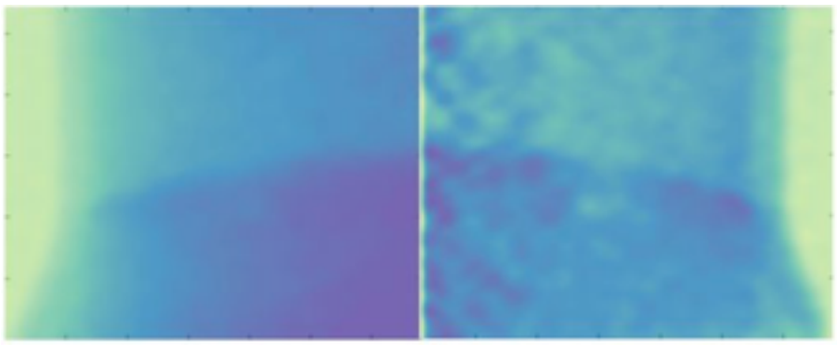
Shot image
(bunch 1)



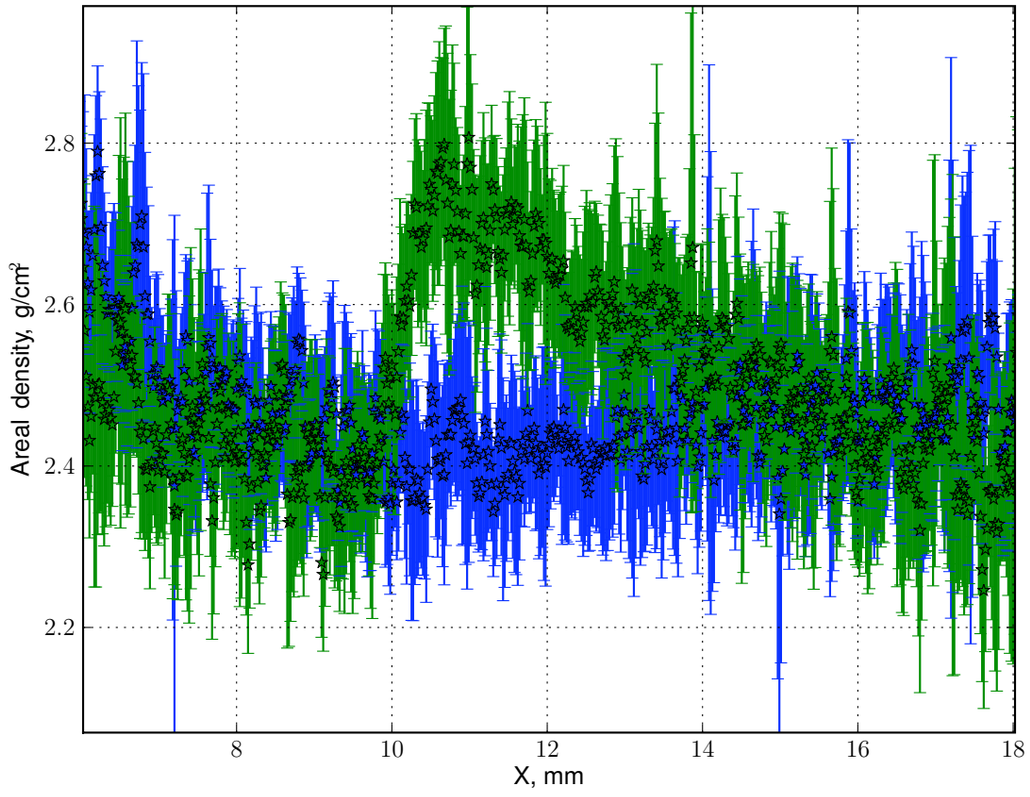
Relative to static
density changes



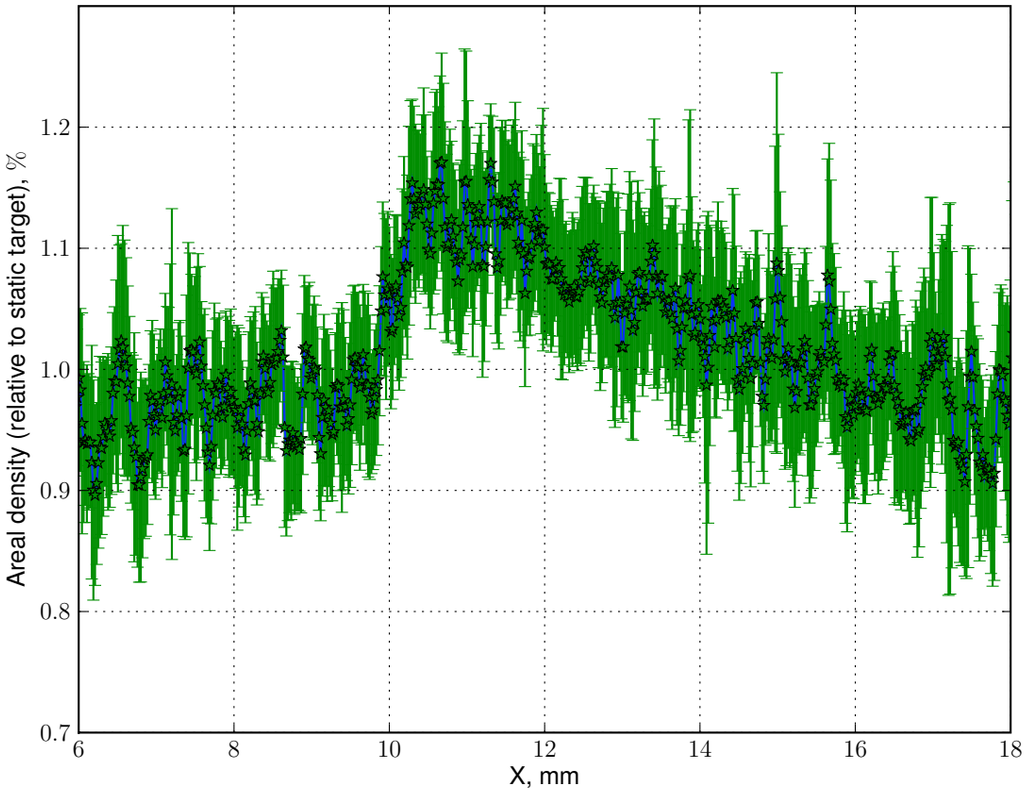
Volume density reconstruction



Areal density profile along charge

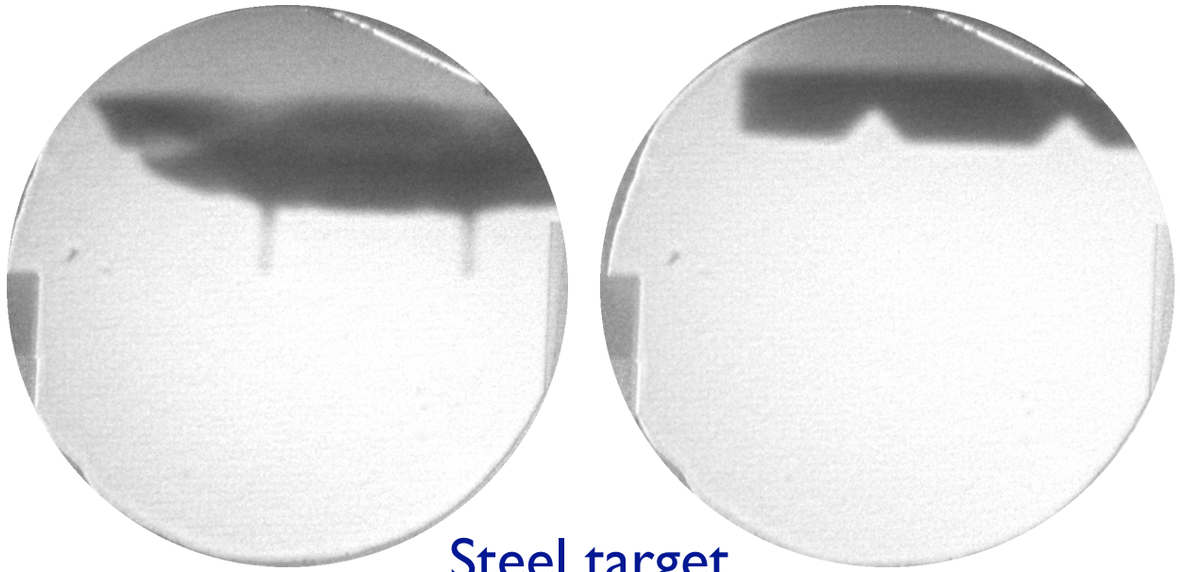



Areal density profile along charge
(relative to static density)

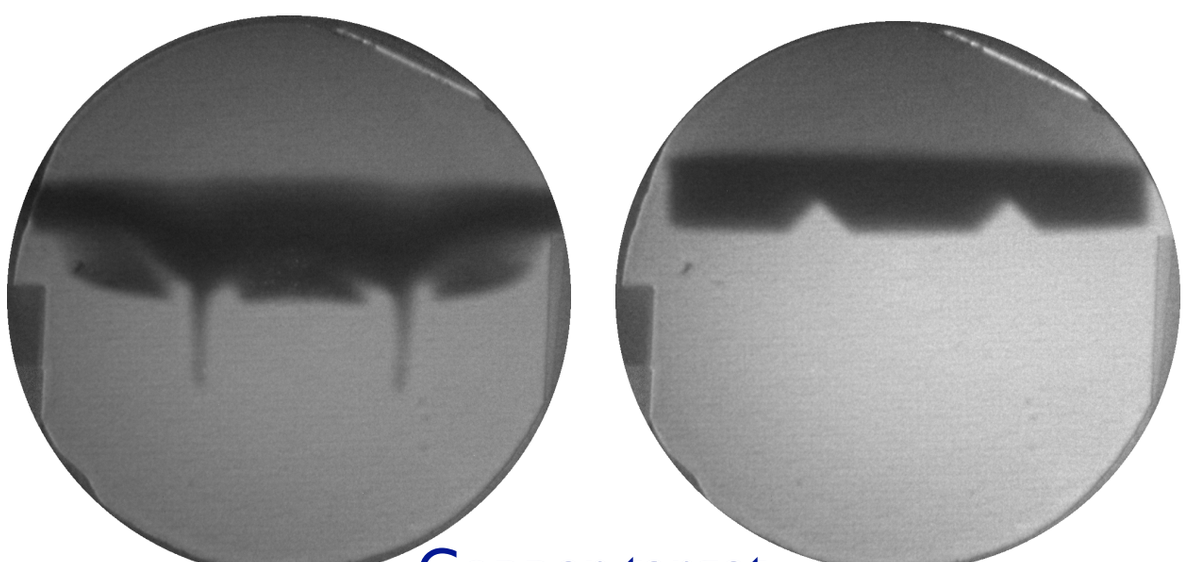


# Dynamic Fracture and Surface Ejecta Formation of Metals under Shock Loading

Proton radiography image of dynamic shot at 2.5 $\mu$s after coming of the shock wave to the free surface of the target

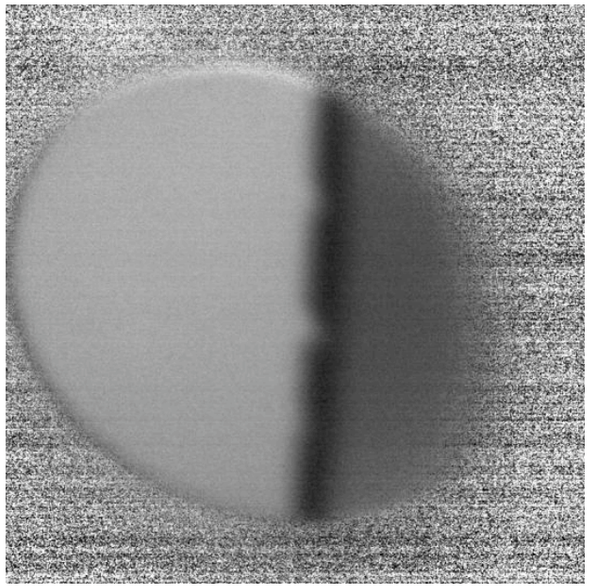


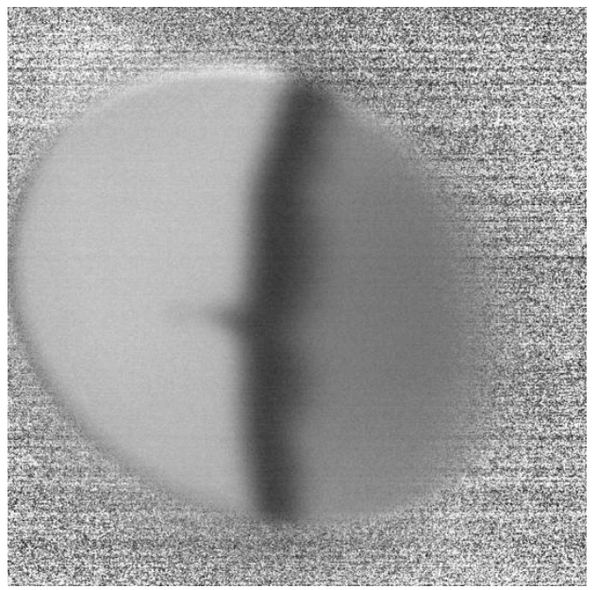
Steel target

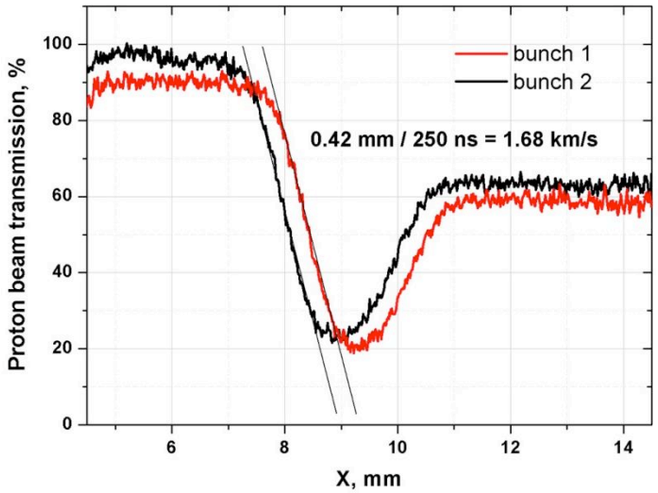


Copper target

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





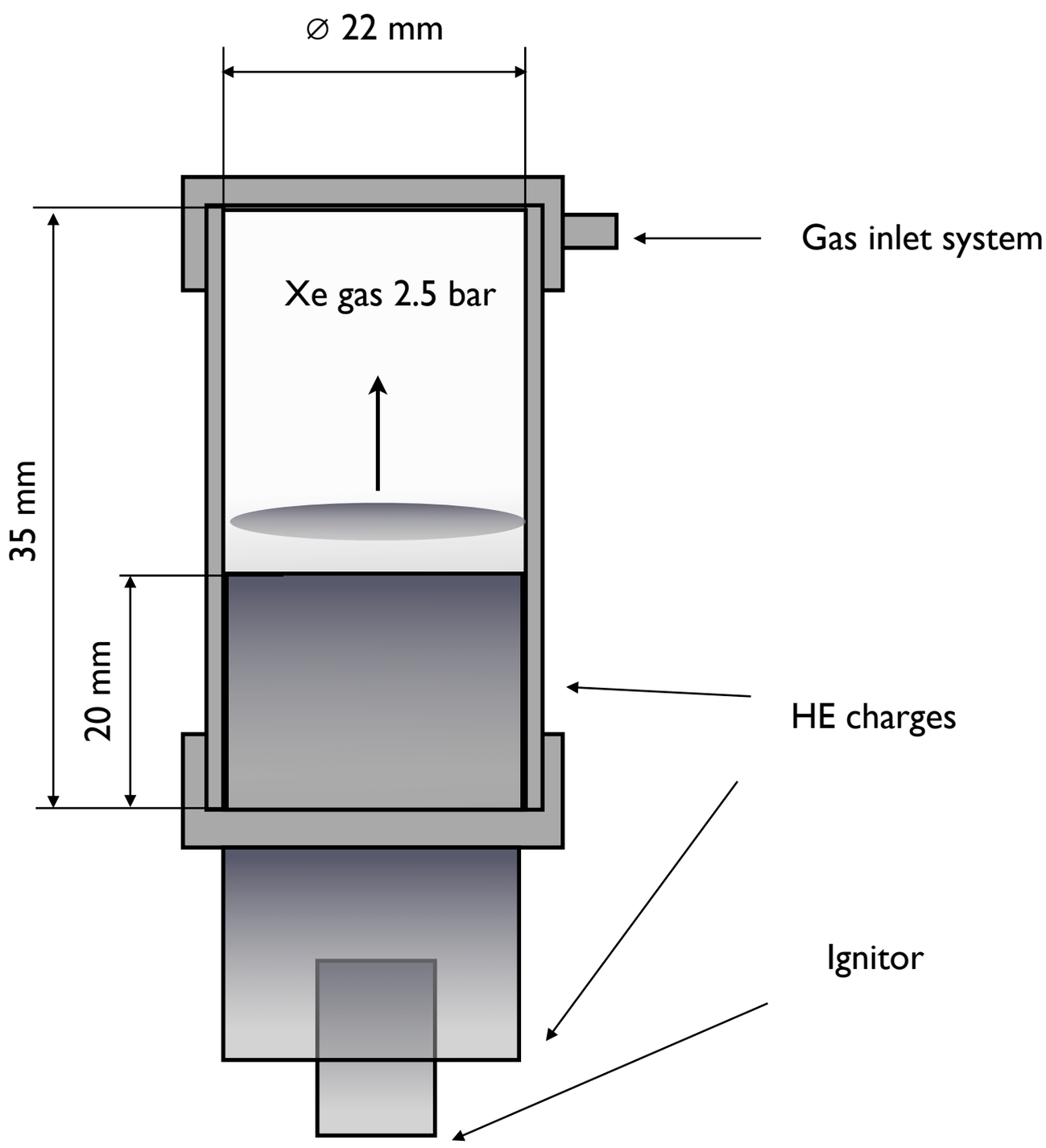



Velocity of the free surface:
**1.68 km/s**

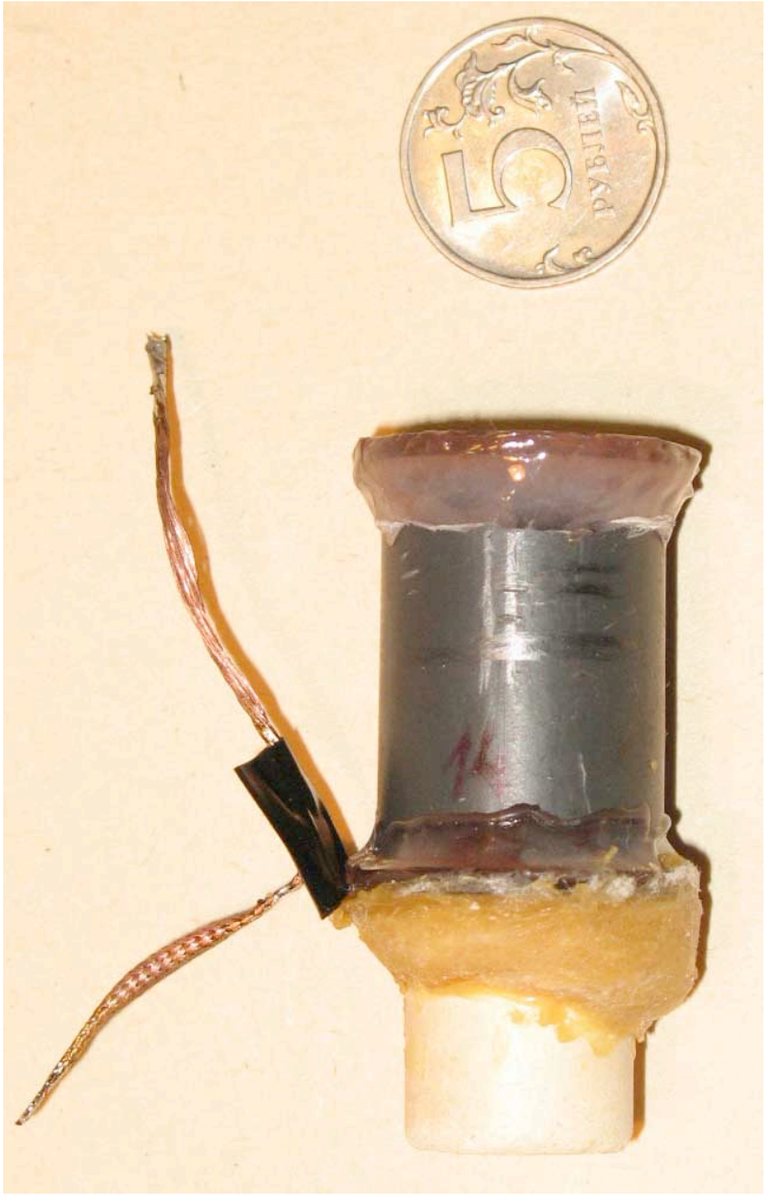
Velocity of the head of the jet:
**4 km/s**

# Shock Compression of Noble Gases

## Target scheme




## Target photo



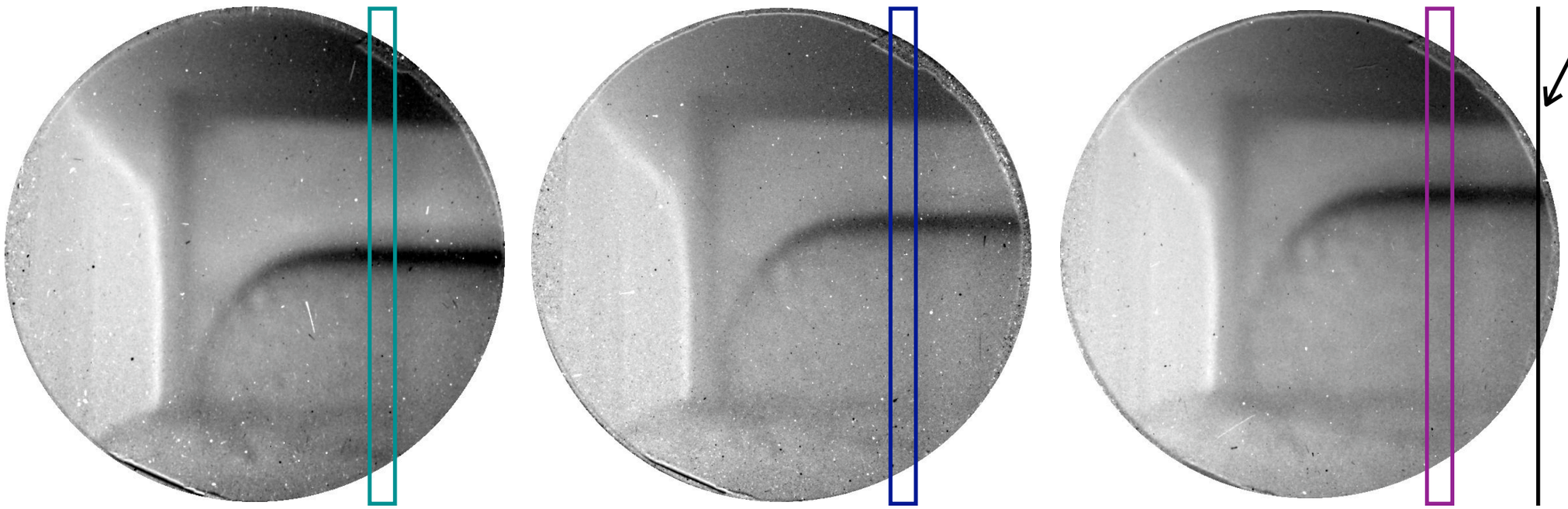
# Shock Compression of Noble Gases

Camera 1
Proton bunch 1 ($t_1$)

Camera 2
Proton bunch 2 ($t_2$)

Camera 3
Proton bunch 3 ($t_3$)

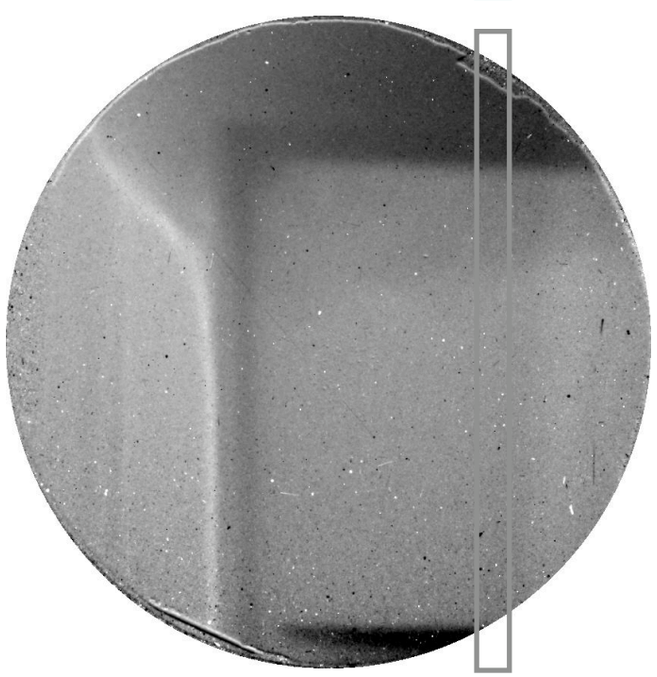
Target axis



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

4.19 mm

1 mm

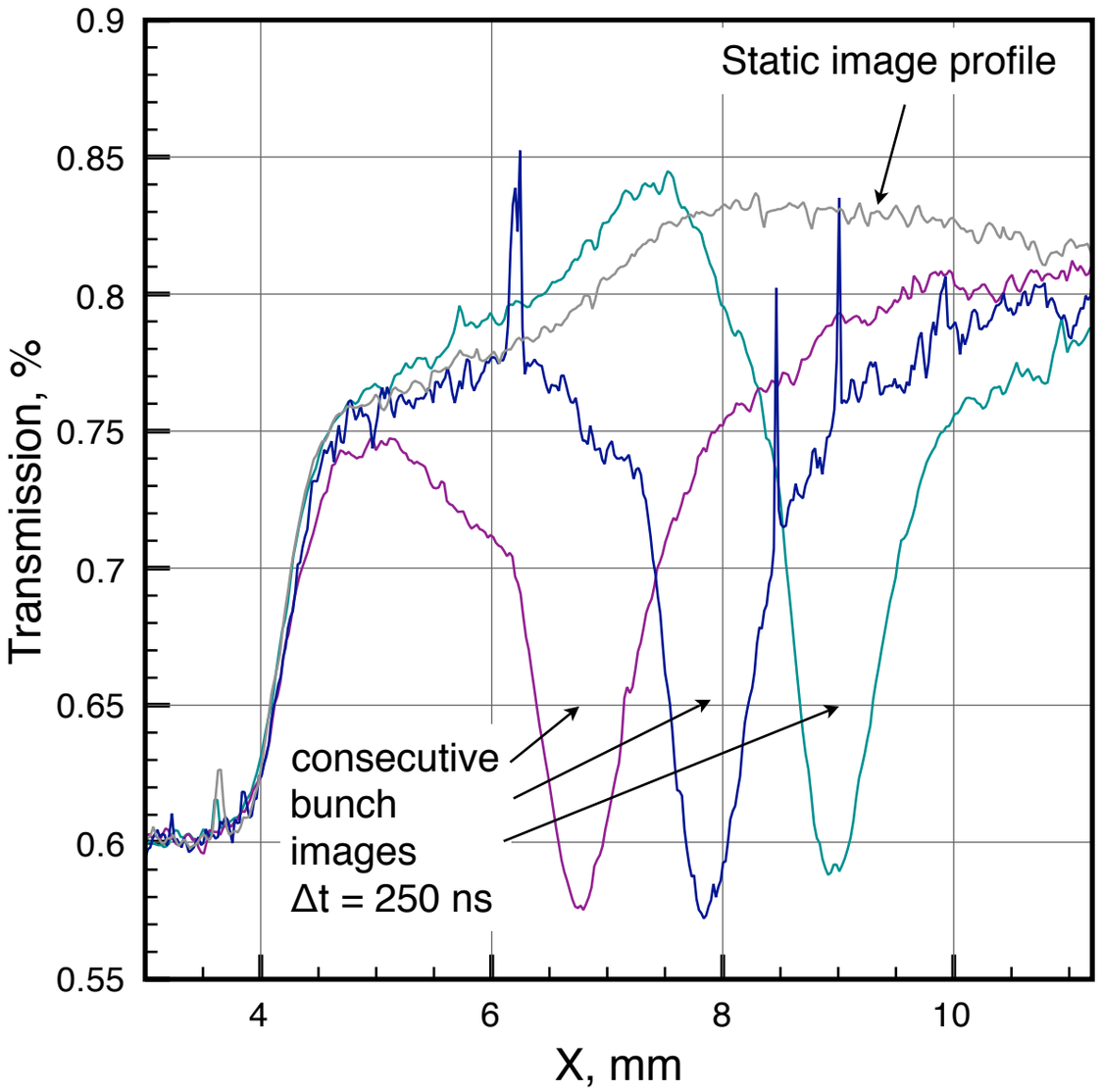


Static image

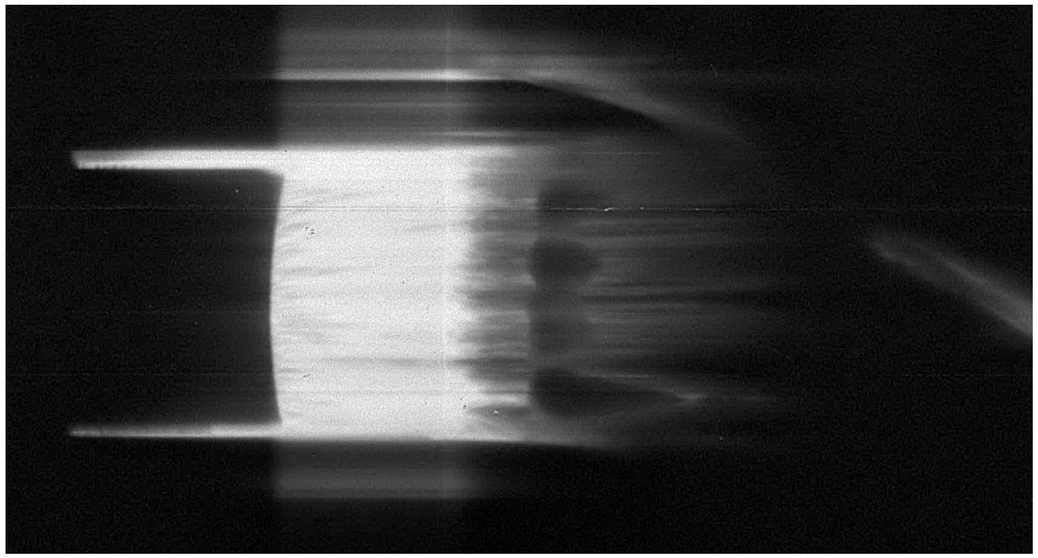
Gas cell thickness - 20.34 mm
Gas pressure - 2.5 Bar
$\rho_0 = 2.5 * 2.034 * 0.00589 = 0.03$ g/cm$^2$

# Shock Compression of Noble Gases

Beam transmission for image profiles



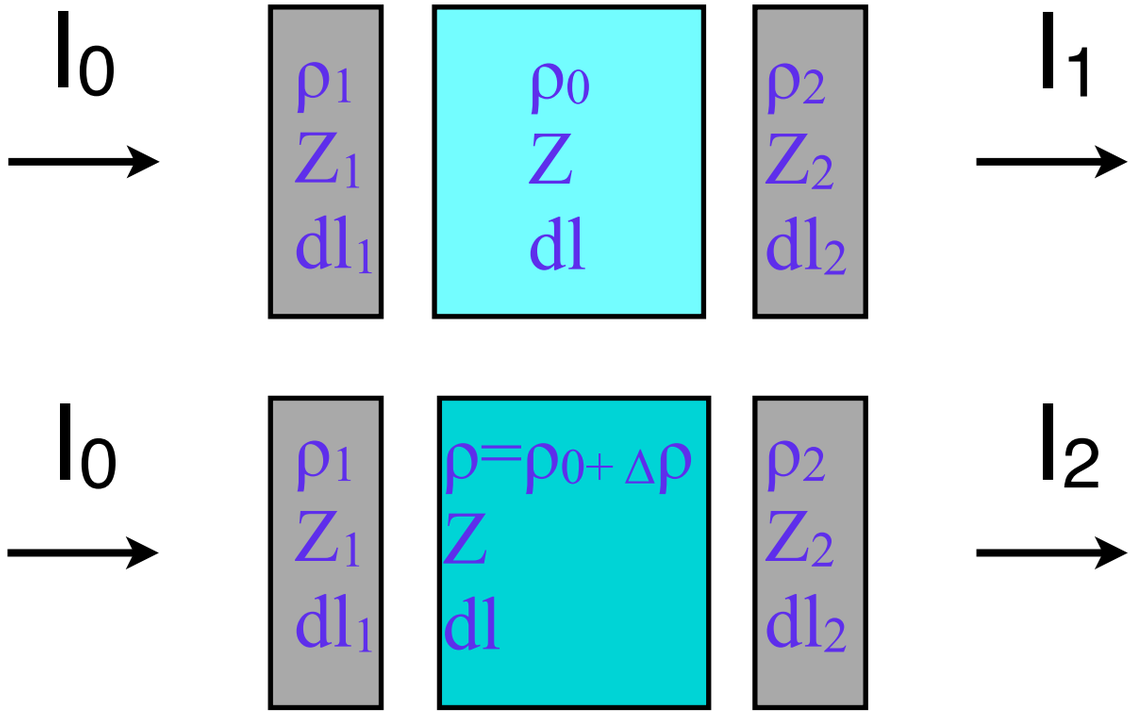

SFR image



U = 4.3 ± 0.2 km/s

# Shock Compression of Noble Gases

Beam transmission for composite target




$T1 = I_1/I_0 = T(\rho_1, Z_1, dl_1)^* T(\rho_0, Z, dl)^* T(\rho_2, Z_2, dl_2)$

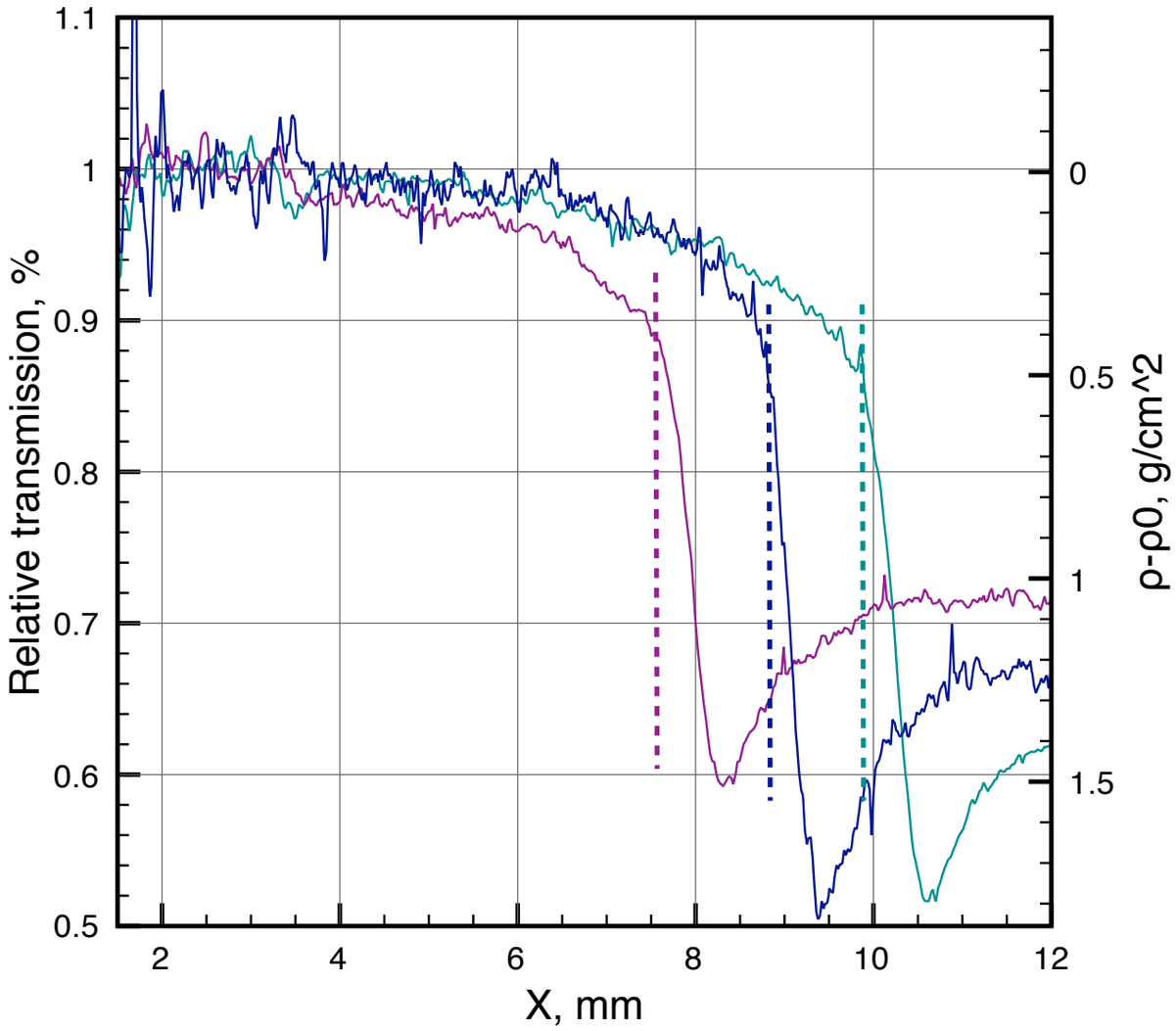
$T2 = I_2/I_0 = T(\rho_1, Z_1, dl_1)^* T(\rho, Z, dl)^* T(\rho_2, Z_2, dl_2) =$
$= T(\rho_1, Z_1, dl_1)^* T(\rho_0, Z, dl)^* T(\Delta\rho, Z, dl)^* T(\rho_2, Z_2, dl_2)$

$T2/T1 = T(\Delta\rho, Z, dl)$

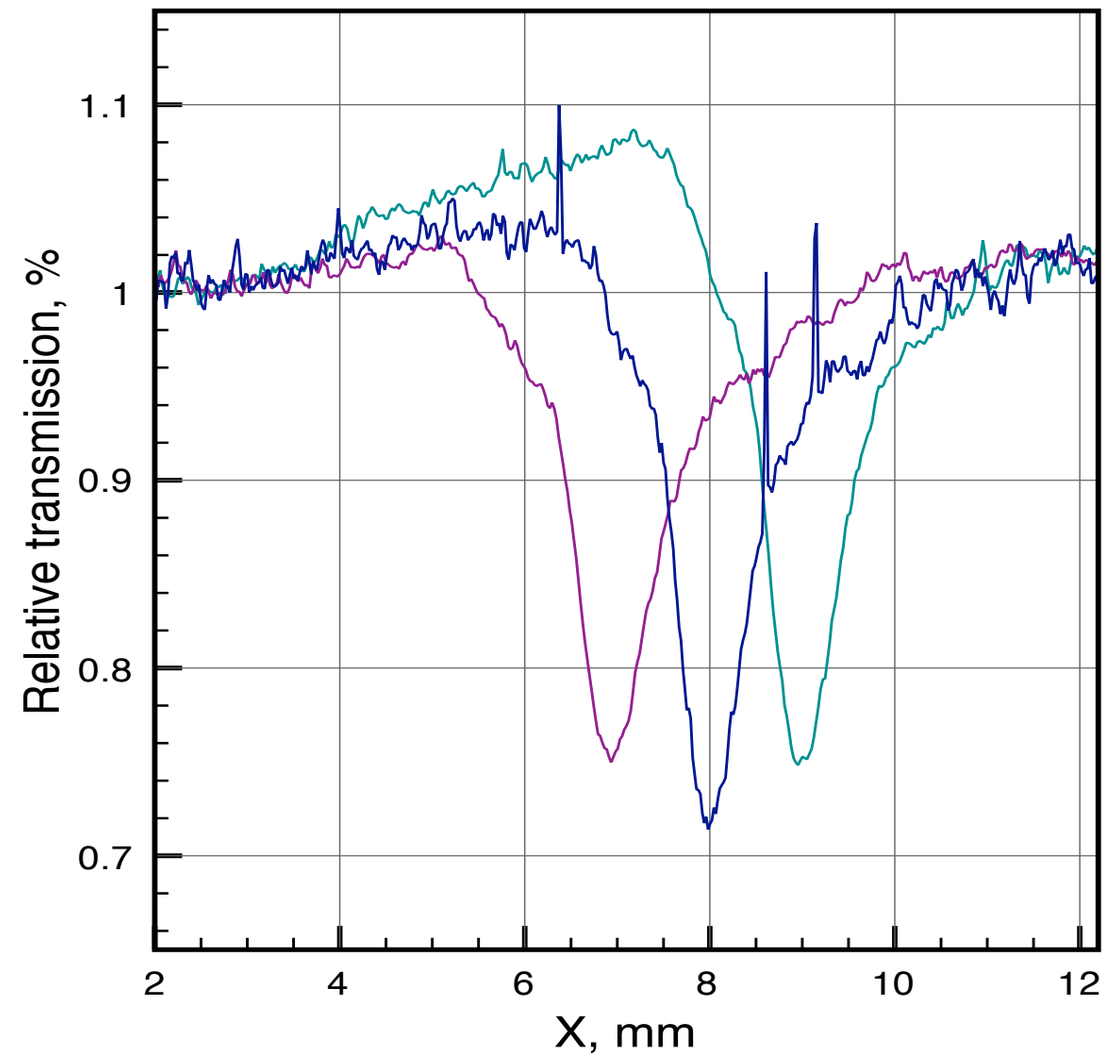
# Shock Compression of Noble Gases

Beam transmission for image profiles (relative to static image)

Ar gas 3.5 Bar



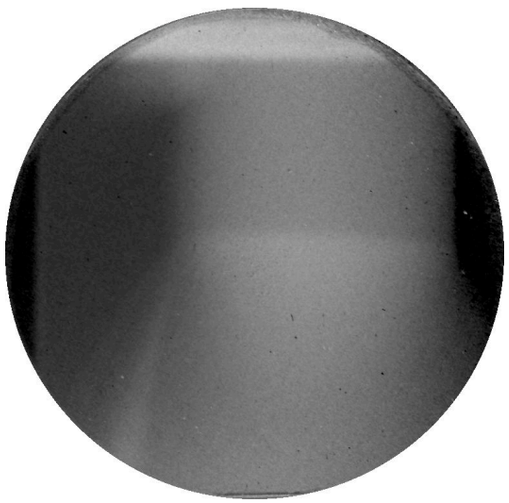

Xe gas 2.5 Bar



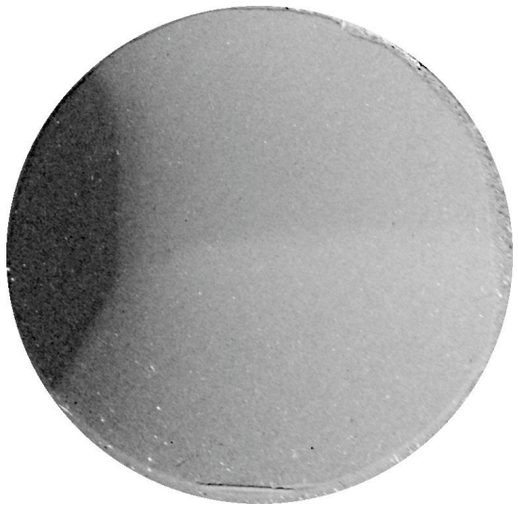
# Proton Radiography of Dense Plasma

Under investigation on ITEP Proton Microscope setup:

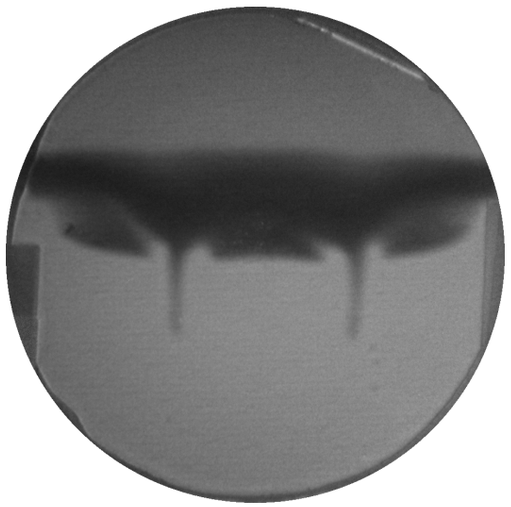
- Detonation of pressed TNT charge
- Detonation of Emulsion Explosive
- Dynamic Fracture and Surface Ejecta Formation
- Shock Compression of Noble Gases



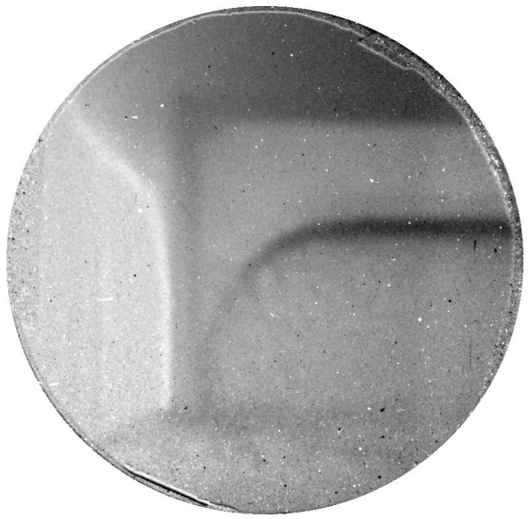
TNT
detonation



EHE
detonation



Ejecta
formation



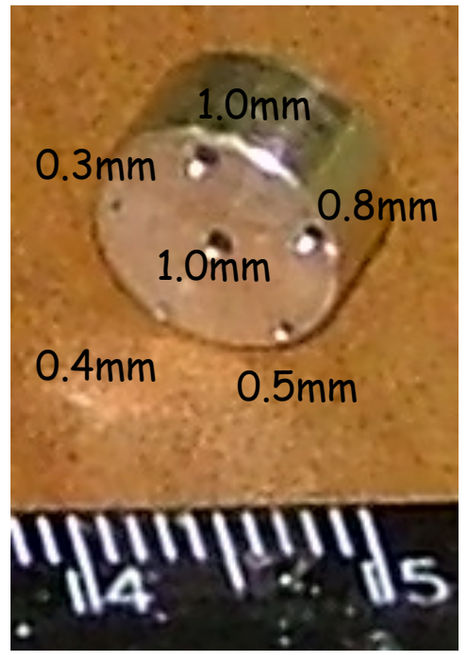
Gas
shock compression

# ITEP Proton Microscope: Static test-objects

## Tomography reconstruction of multi-projection proton microscopy

Targets and SS container

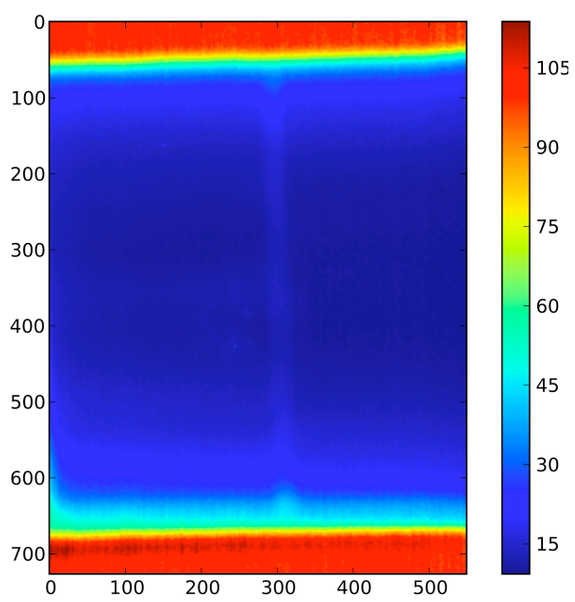

Brass target

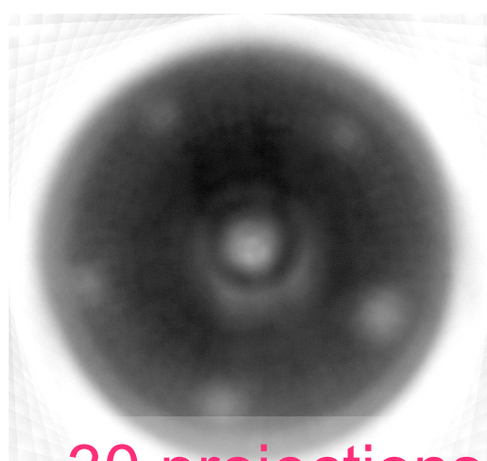



Requirements:

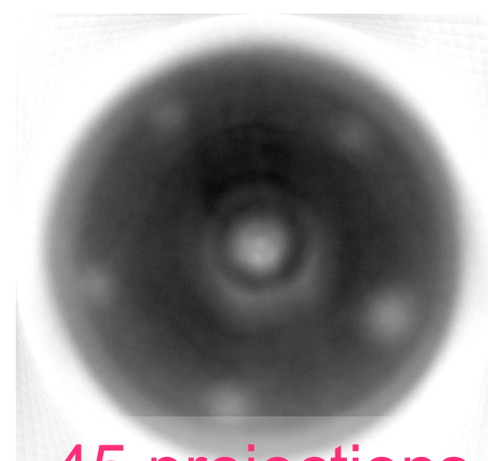
- good spatial and density resolution for projection images
- high precision for target positioning and alignment

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

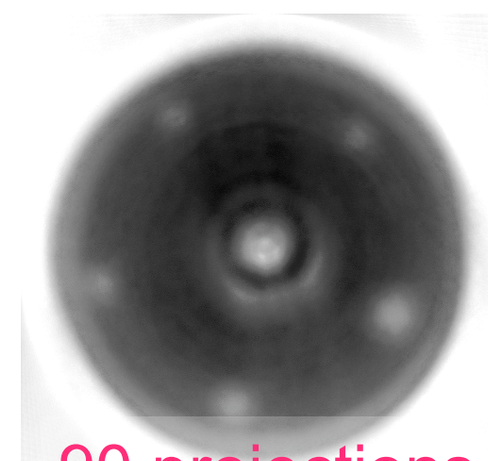


30 projections

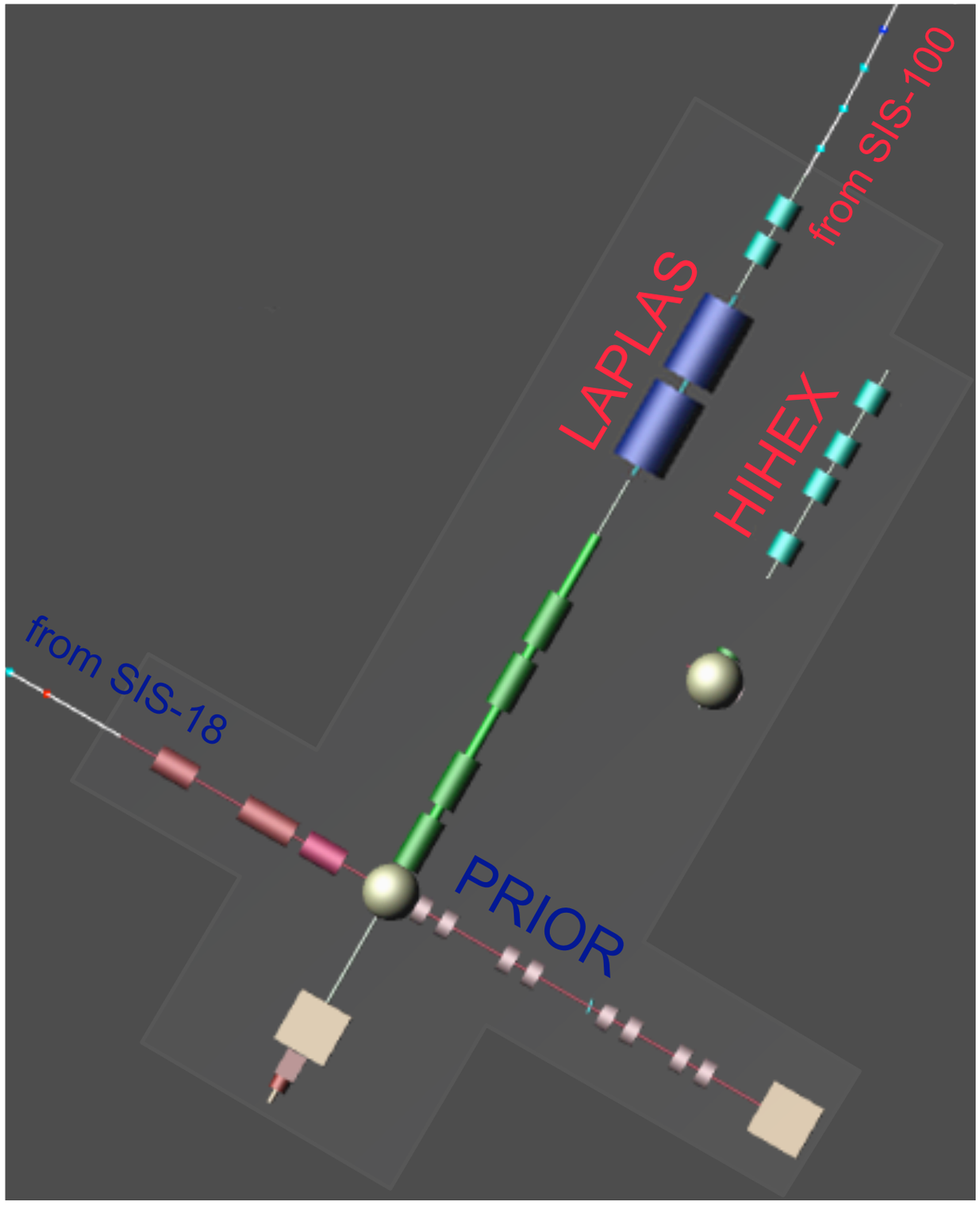


45 projections

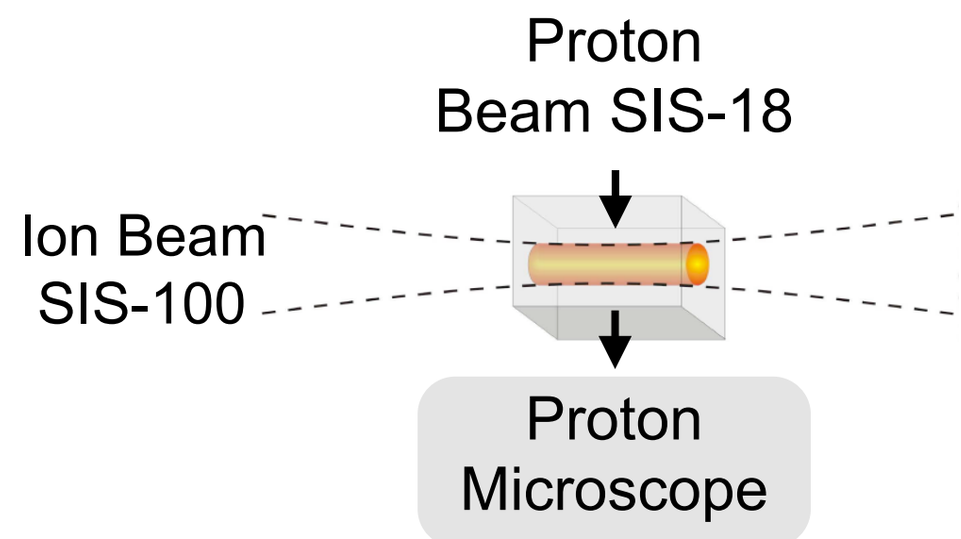


90 projections

# Plasma Physics beam lines and cave at FAIR




**SIS-18:**
a dedicated radiography beam line - density diagnostics for **LAPLAS** and **HIHEX** experiments



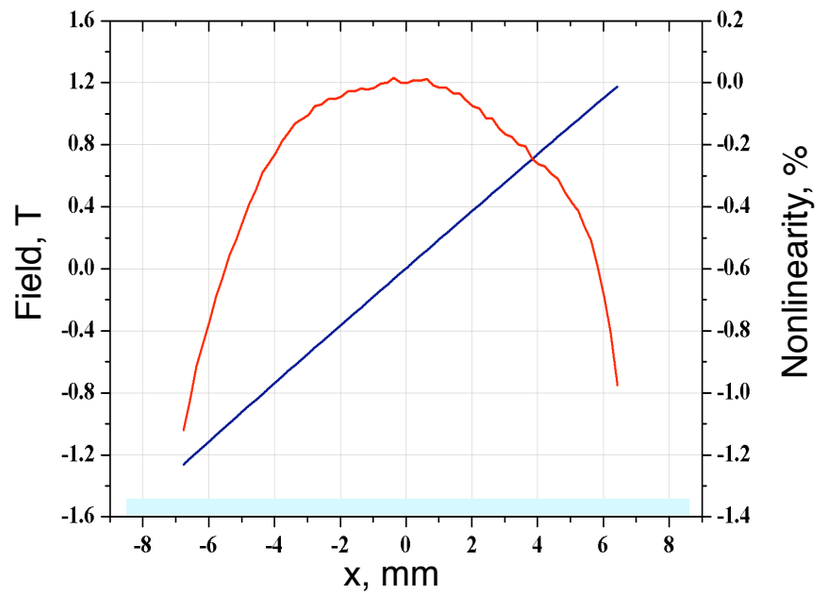

**PRIOR** - **P**roton **M**icrosc**o**pe for FAI**R**:

- proton energy **4.5 GeV**
- up to **~20 g/cm²** (Fe, Pb, Au, etc.)
- **≤10 µm** spatial resolution
- **10 ns** time resolution (multi-frame)
- **sub-percent** density resolution
- proton illumination spot size: **3–15 mm**
- imaging, aberrations correction by magnets

# Permanent Magnetic Quadrupoles (PMQ) - prototype manufacturing

High Gradient
Split-Pole Quadrupole

High Gradient
Split-Pole Quadrupole




Hall Probe
Measurement Bench

- Pole field: ~ 1.6 T
- Final gradient: 211.6 T/m
- Nonlinearity: < 0.9 %
- Two layers with circular 16 sectors
- NdFeB alloy with coercivity on magnetization of 2.7 T in the inner layer of 43 mm diameter

# Permanent Magnetic Quadrupoles (PMQ) - final design for PRIOR

2 x PMQ L =165 mm
2 x PMQ L = 330 mm
All quads have the same cross-section
All quads are of three layers
Each layer contains 24 magnetic elements of prismatic shape. Angle size of all magnetic elements – 15°
All quads are divided longitudinally by modules of the same length of 33 mm. Total number of modules – 30.

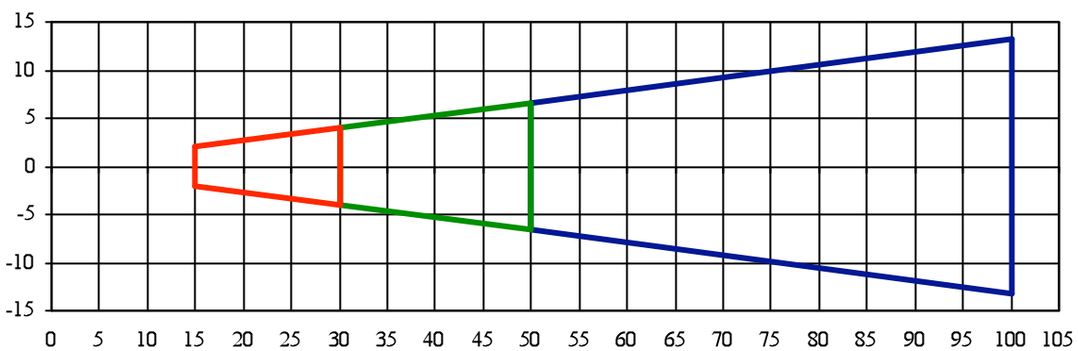



Figure 1. Cross-sections of prismatic elements for three-layer modules.

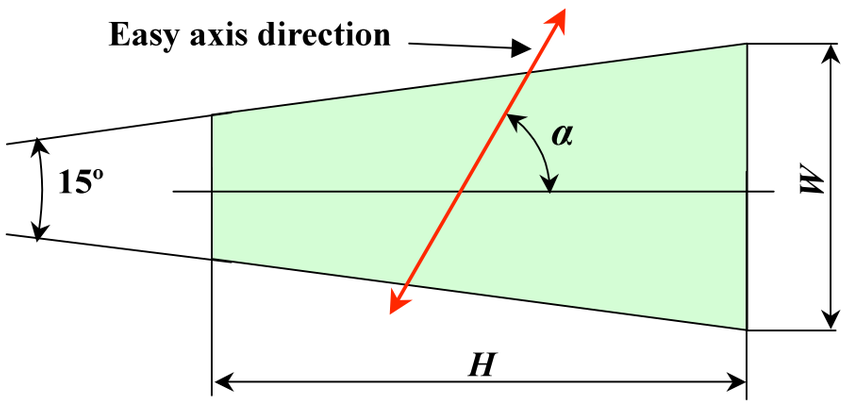



Figure 2. Cross-section parameters of prismatic elements and easy axis slope to the prism's plane of symmetry for three-layer quads

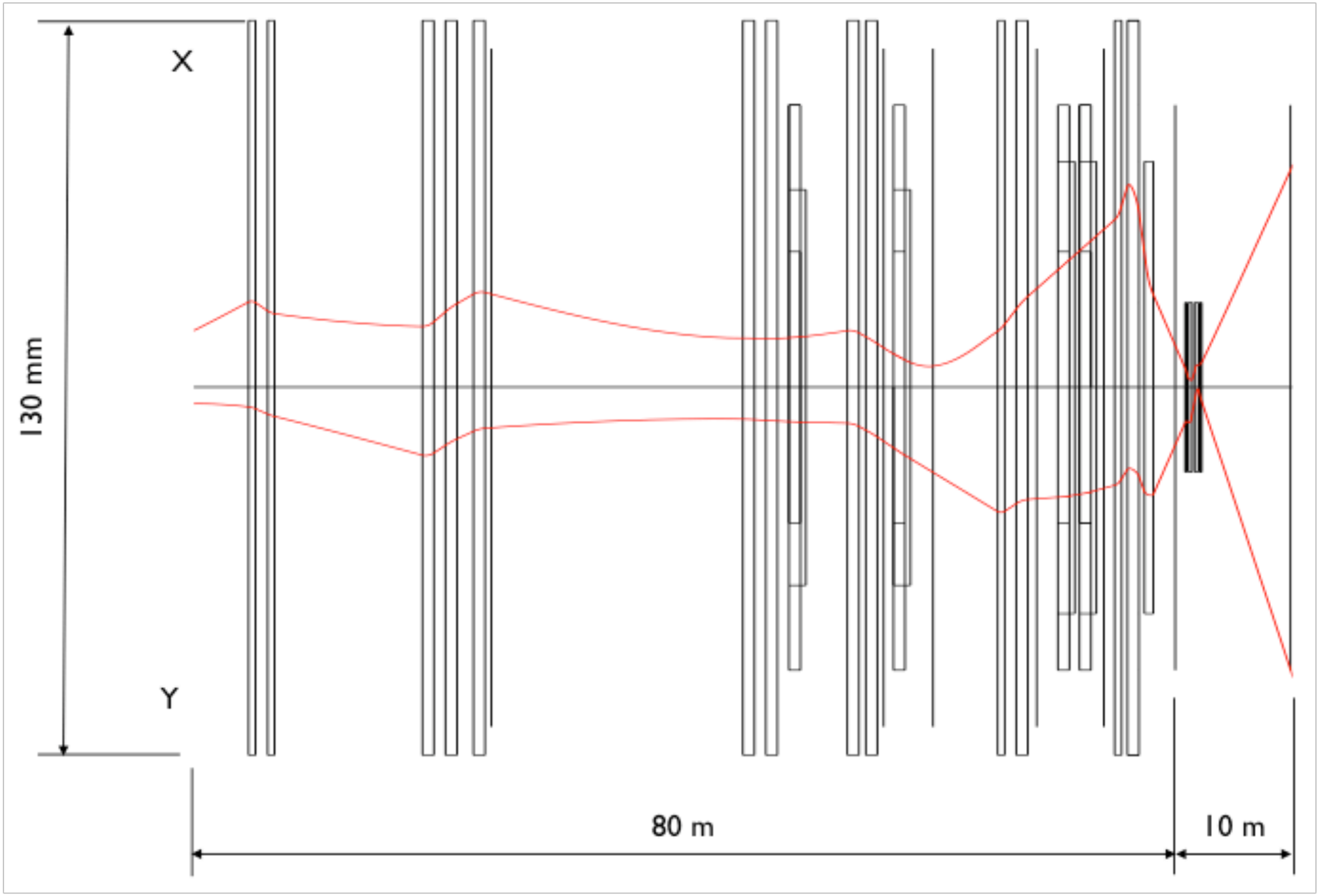
Table 1. Segments dimensions for each layer

| | Layer №1<br>Alloy VACODYM 863<br>TP: Br=1.27 T,<br>μ0·HCJ=2.7 T | Layer №2<br>Alloy VACODYM 854<br>TP: Br=1.32 T,<br>μ0·HCJ=2.2 T | Layer №2<br>Alloy VACODYM 745<br>TP: Br=1.40 T,<br>μ0·HCJ=1.4 T |
|---|---|---|---|
| Segment sizes,<br>W x H x L, mm | $8^{+0.1}\times15^{+0.2}\times33^{+0.1}$ | $13.2^{+0.1}\times20^{+0.2}\times33^{+0.1}$ | $26.5^{+0.1}\times50^{+0.2}\times33^{+0.1}$ |

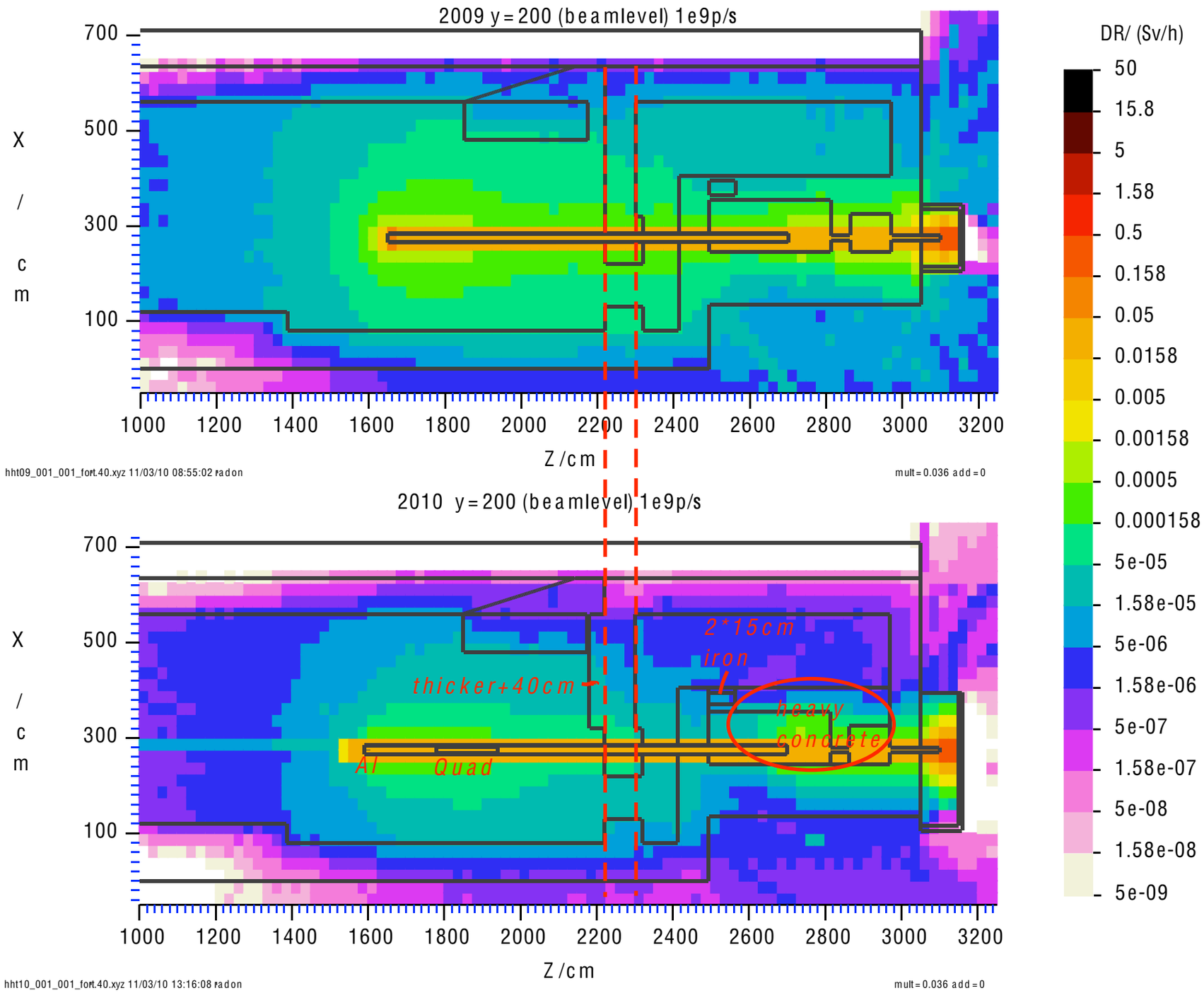
Table 2. Types of segments on easy axis slope

| | Type №1 | Type №2 | Type №3 |
|---|---|---|---|
| α | 15° | 45° | 75° |

# HHT beam line matching to PRIOR optics



# HHT beam line FLUKA simulation



# HHT beam line FLUKA simulation