SCIENTIFIC ACTIVITIES AND PERSPECTIVES AT TWAC

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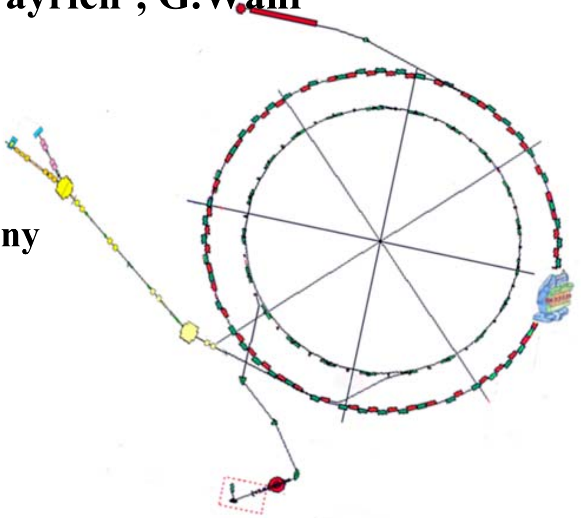
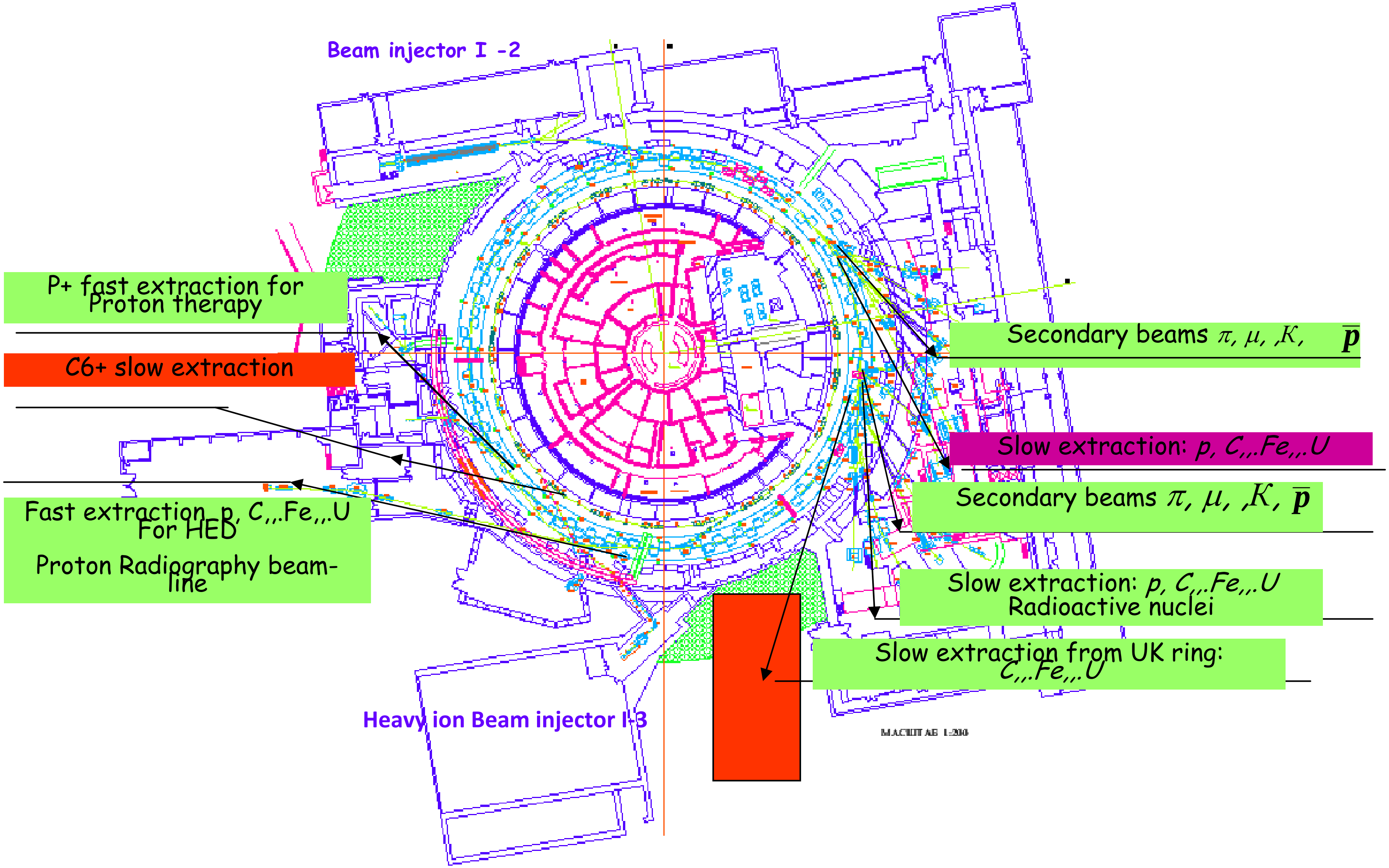


3rd EMMI Workshop on Plasma Physics with Intense Laser and Heavy Ion Beams
Moscow, May 20 – 21, 2010

Contents

- **Status of ITEP-TWAC facility**
- **Plasma lens focusing development.**
- **Proton radiography systems at ITEP**
- **High energy proton microscopy at GSI (PRIOR project)**
- **Wobbler development for LAPLAS experiment.**
- **VISAR development**

ITEP-TWAC Accelerator Facility in Progress



Beam injector I -2

P+ fast extraction for Proton therapy

C6+ slow extraction

Fast extraction p, C,,.Fe,,.U For HED

Proton Radiography beam-line

Heavy ion Beam injector I-3

Secondary beams π, μ, ,K, $\overline{\mathbf{p}}$

Slow extraction: *p, C,,.Fe,,.U*

Secondary beams π, μ, ,K, $\overline{\mathbf{p}}$

Slow extraction: *p, C,,.Fe,,.U*
Radioactive nuclei

Slow extraction from UK ring:
C,,.Fe,,.U

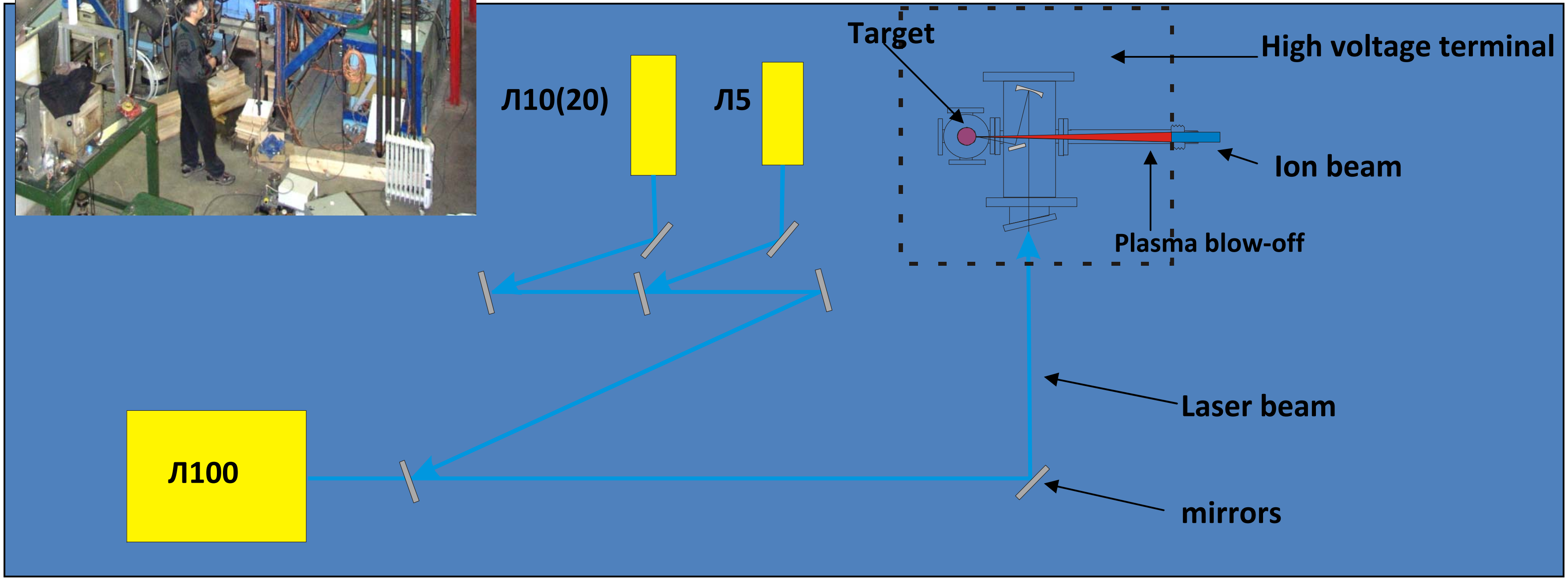
Key element: New triple - laser ion source pre-injection system (L5, L10, L100)

Laser L100

3 mA 80 MeV Fe $^{16+}$ Measured !

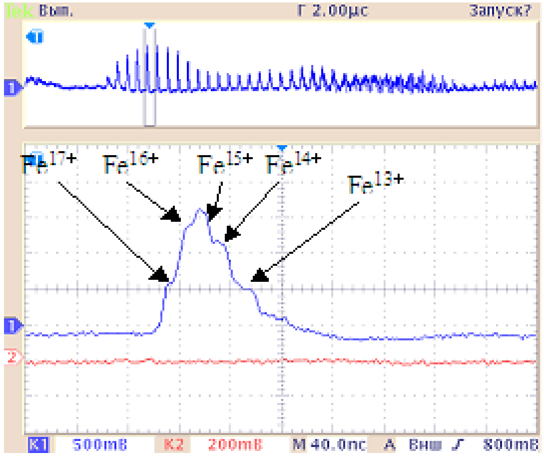
Target with diameter of *150mm* and height of *200mm* for more than *$2*10^6$* shots

Wavelength, μm	**10,6**
Pulse energy, J	**5/20/100**
Pulse duration, ns	**100/80/30**
Repetition rate, Hz	**0,5 /1/1**
Number of shots	**~10^6**

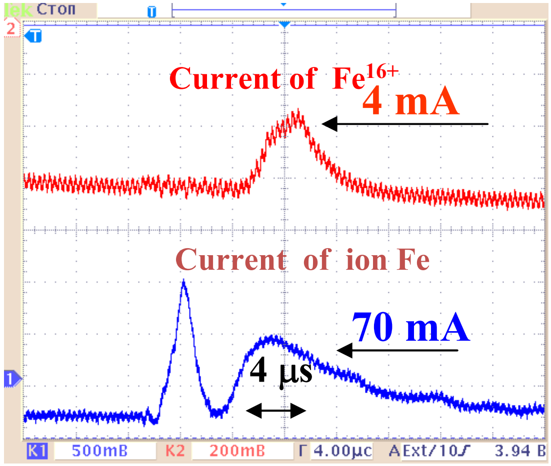


Accelerating of Fe ion up to relativistic energy

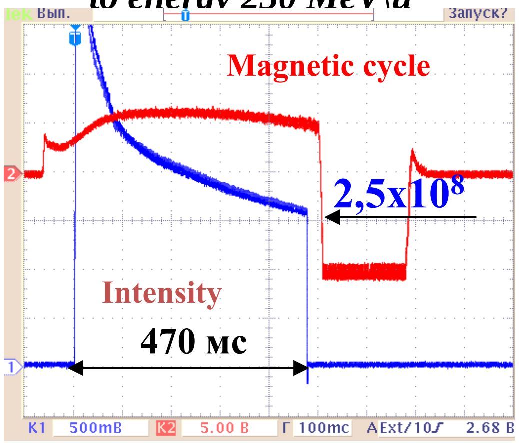
Generation of $_{56}$Fe by laser L100



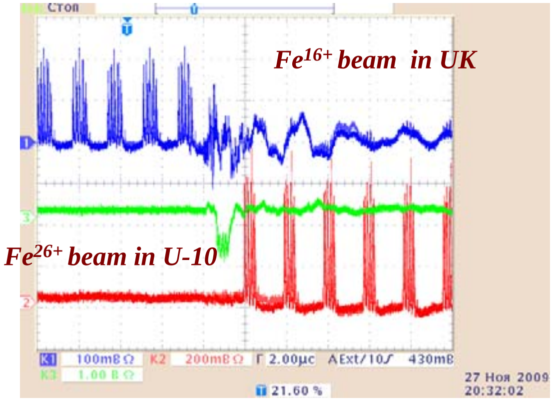
Accelerating Fe^{16+} in I3



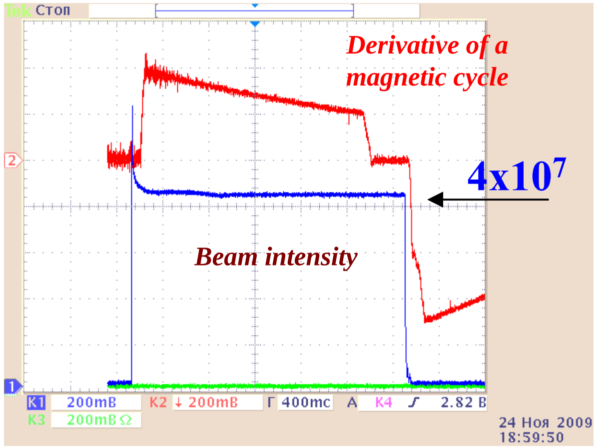
Accelerating Fe^{16+} in booster ring UK up to energy 230 MeV\u



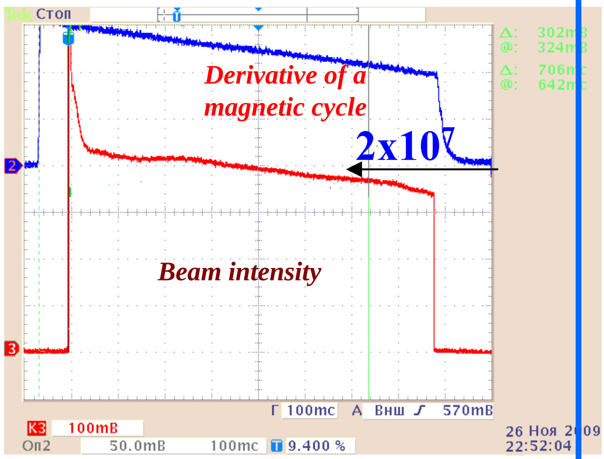
Non-Liouvillian Injection into the accelerate U-10



Accelerating Fe^{26+} in U-10 up to energy 1 GeV/u

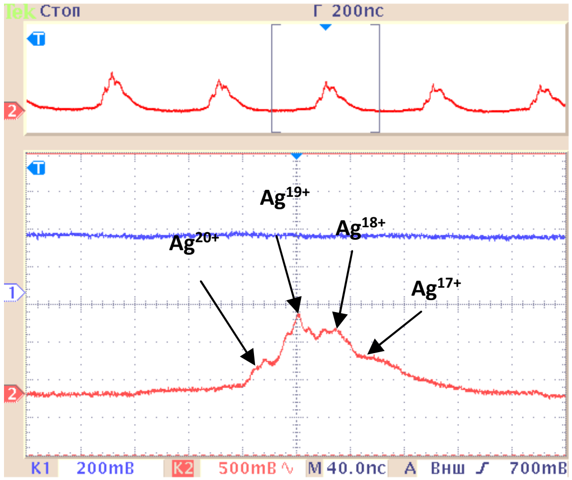


Accelerating Fe^{26+} in U-10 up to energy 3.65 GeV/u

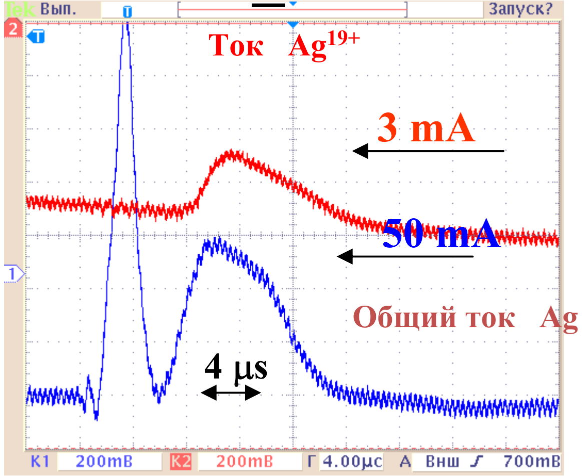


Accelerating of ion beam with atomic mass A~100

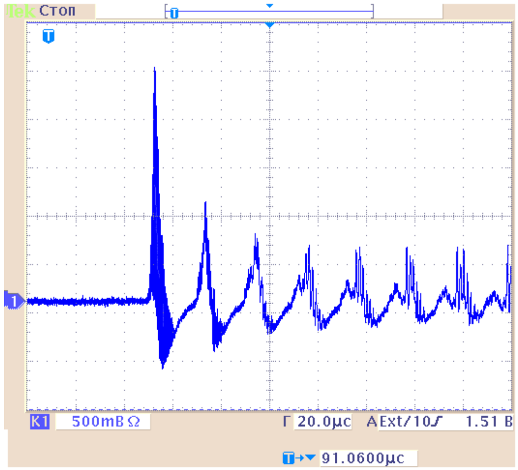
Generation of $_{109}$Ag in L100



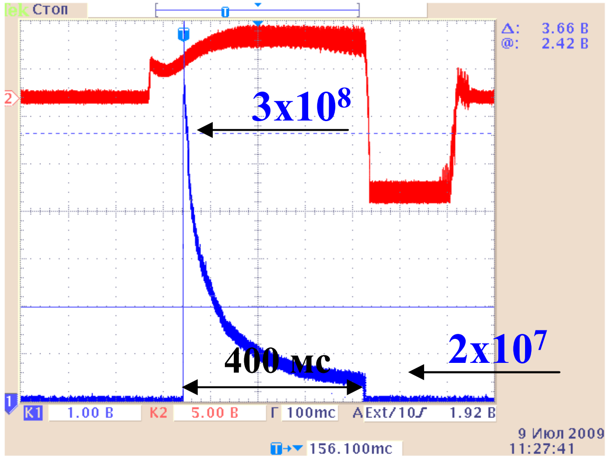
Accelerating of Ag^{19+} in I3

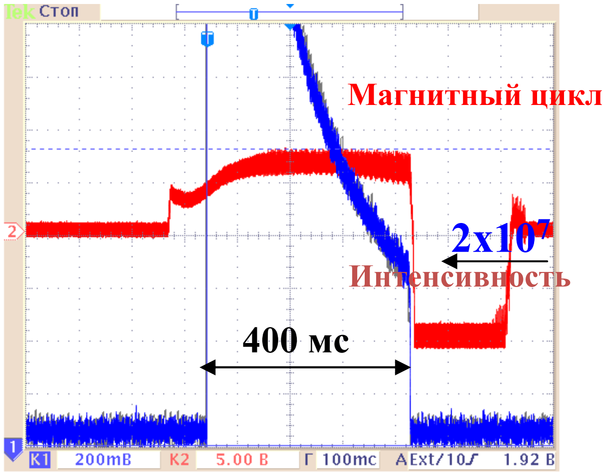


Circutaion of Ag^{19+} in UK



Accelerating of Ag^{19+} in UK up to energy 10,9 GeV

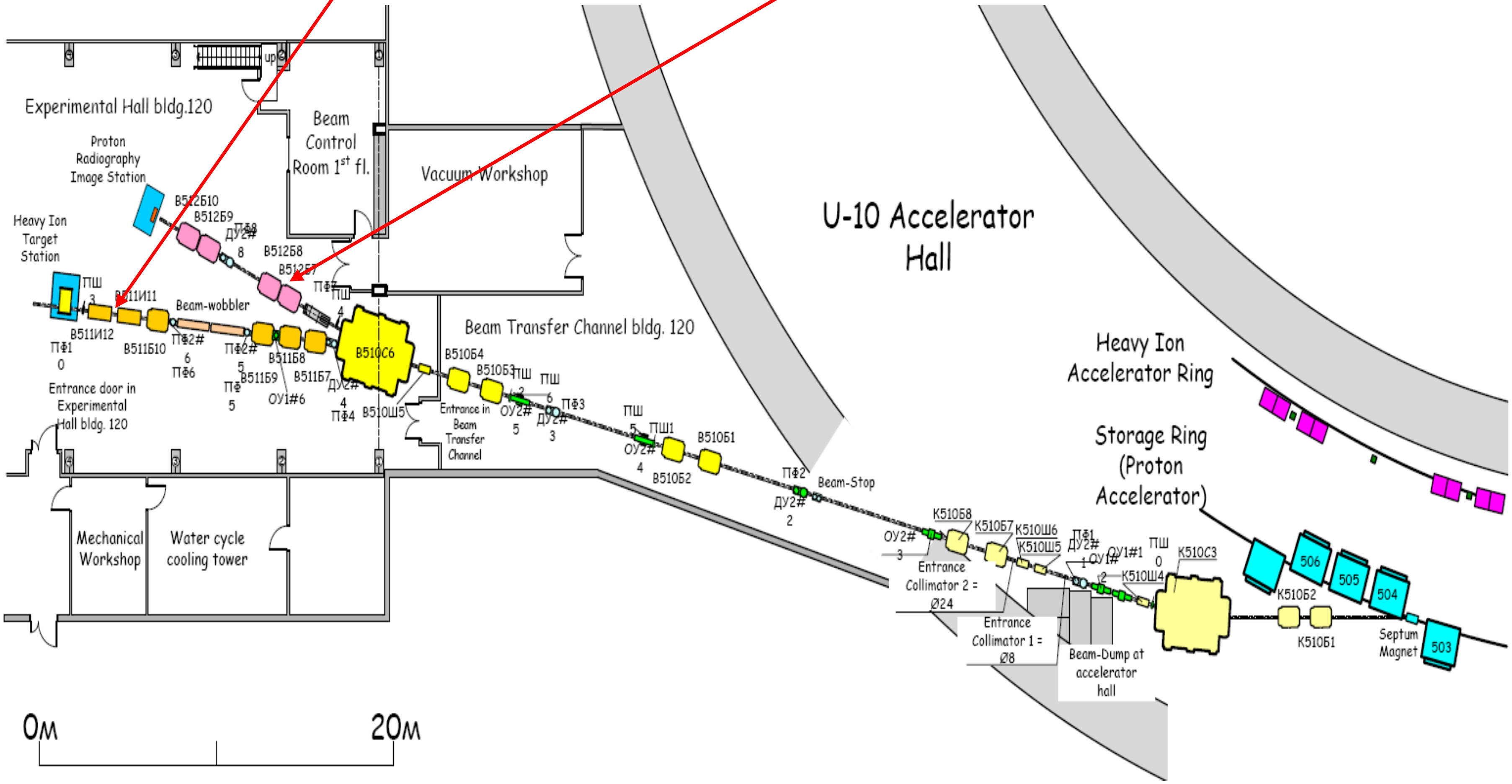




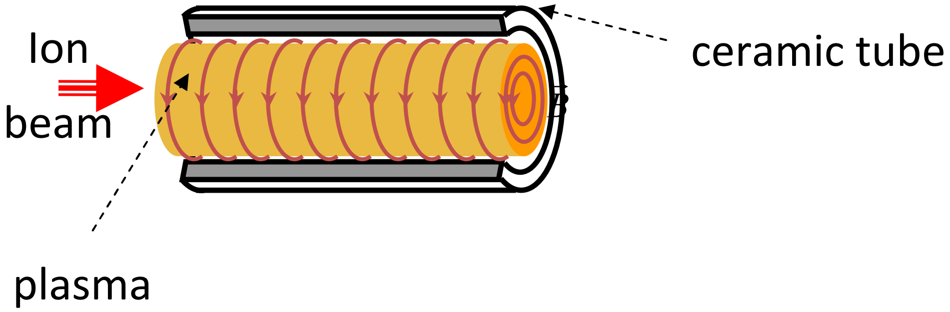
Plasma Physics Experimental Area on TWAC Facility

Heavy ion plasma physics

Proton Radiography



Plasma lens focusing- at GSI



$$F = Zev_z B_\phi(r) \qquad B = \frac{\mu_0}{2} jr$$

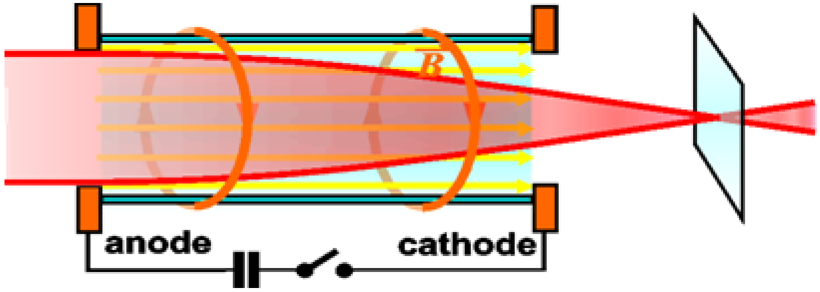
$$d_{min} \sim \varepsilon I^{-1/2}$$

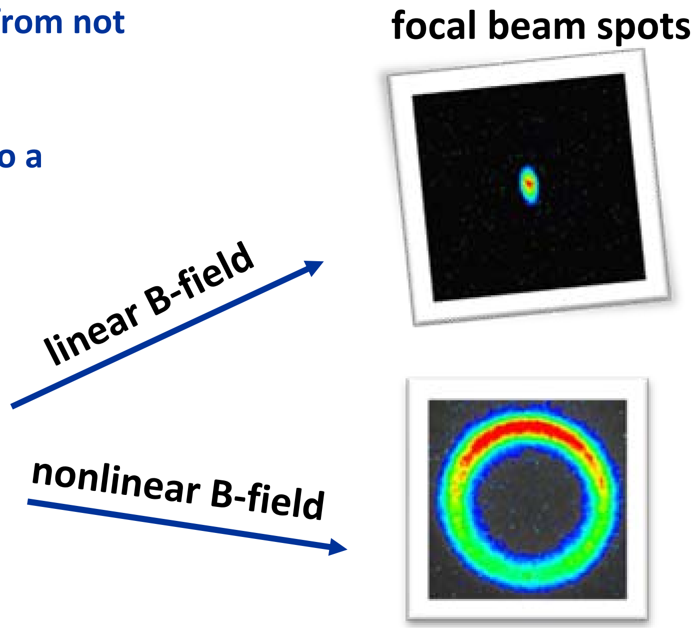
Advantages of plasma lens :

- **focusing area has symmetric first order focusing;**
- **there is no limit for the magnitude of the magnetic field connected with saturation;**
- **charge neutralization of ion beam into the plasma lens ;**
- **beam rigidity decreases by the reason of the stripping of electrons from not fully ionized ions;**

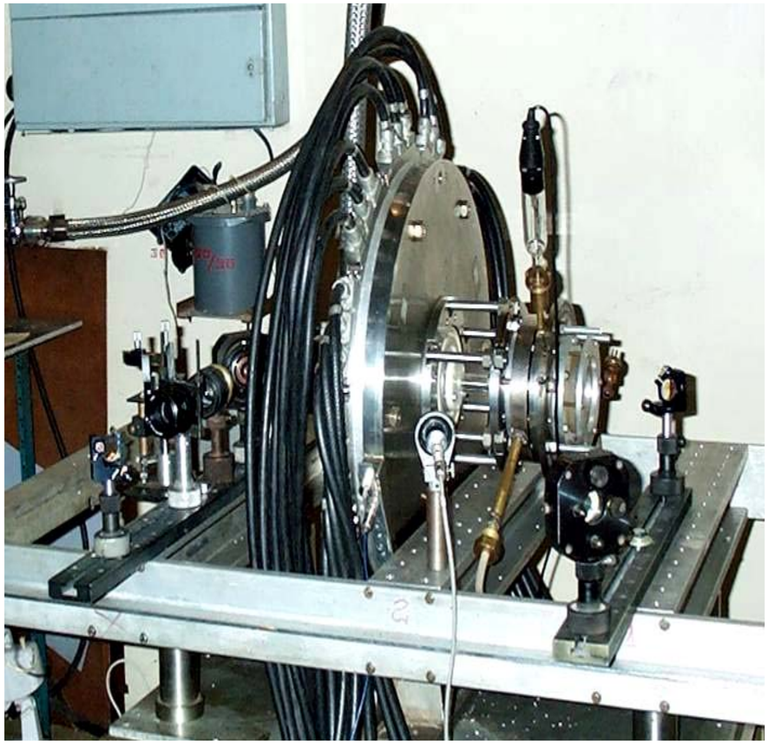
Disadvantages:

- **a plasma lens system doesn’t have necessary stability in contrast to a quadrupole magnetic systems;**
- **very strong electromagnetic noise and inducing .**



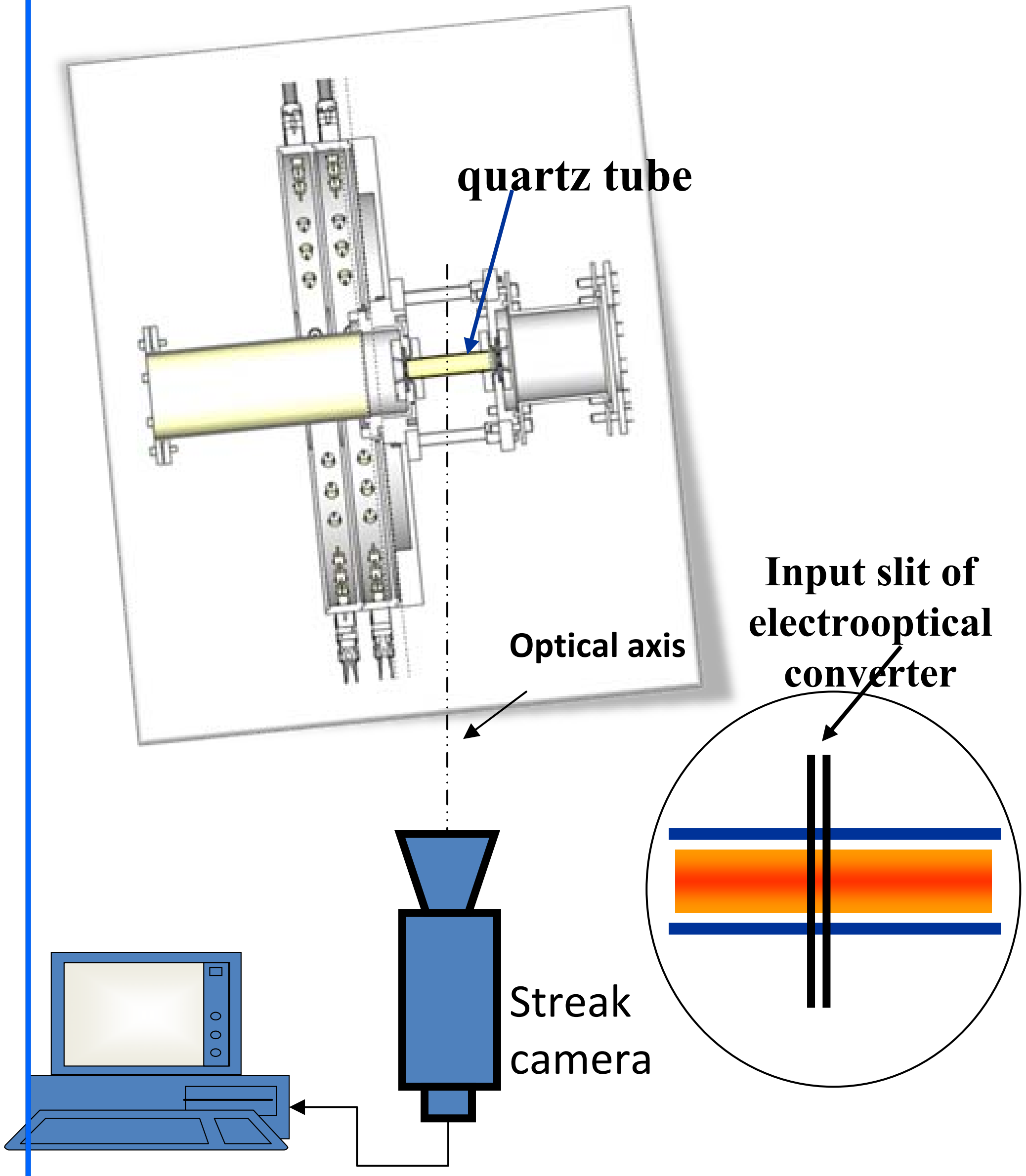


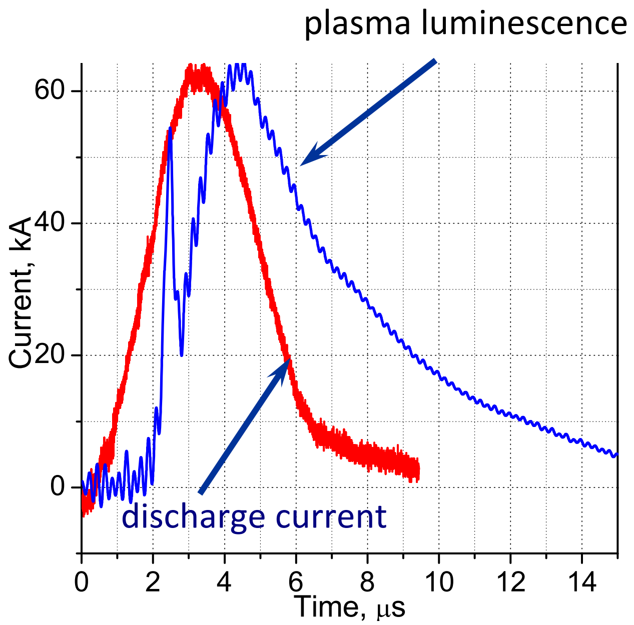
General view and parameters of ITEP plasma lens

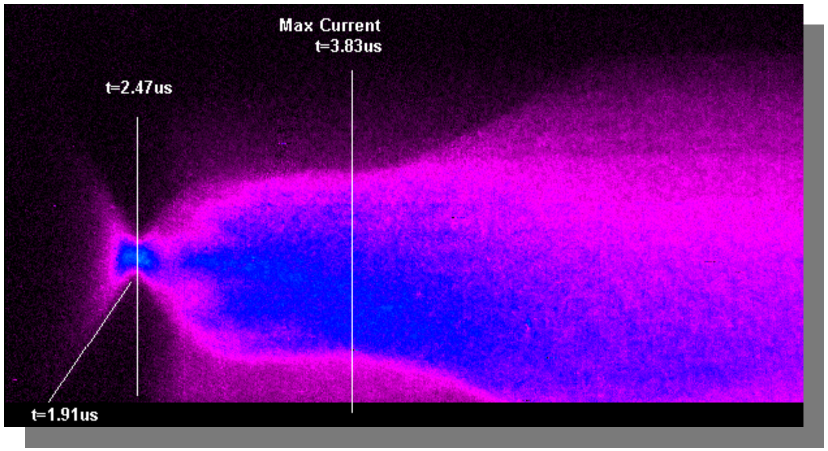


The pulse generator	Capacity C = 25 - 160 μF, Voltage $V_{\text{мах}}$ = 20 kV
The switch	Tiratron TDI1-150k/25
Discharge tube	length – 100 mm, diameter – 20 mm
Half of the period	T = 10 μs при C = 25 μF, T = 40 μs при C = 160 μF
Maximum of the current discharge	I = 200 кA при T = 5 μs, I = 400 кA при T = 200 μs

Investigation of the plasma dynamics by streak-camera

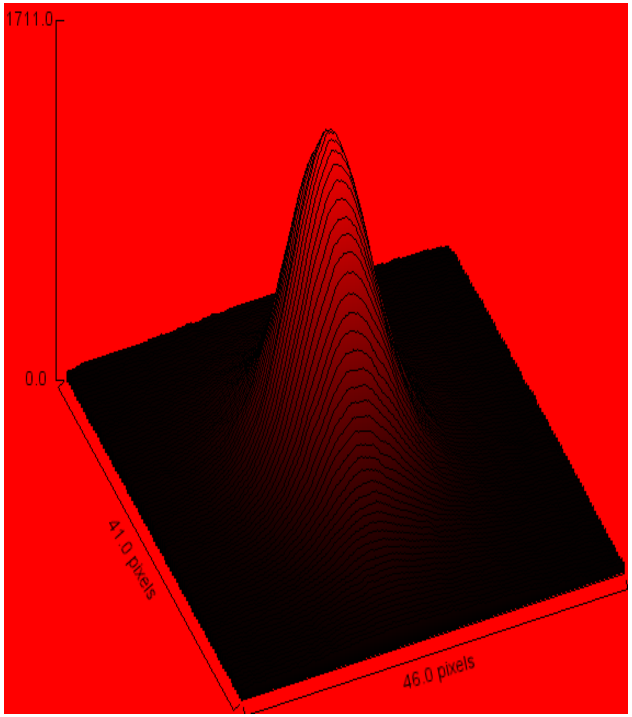


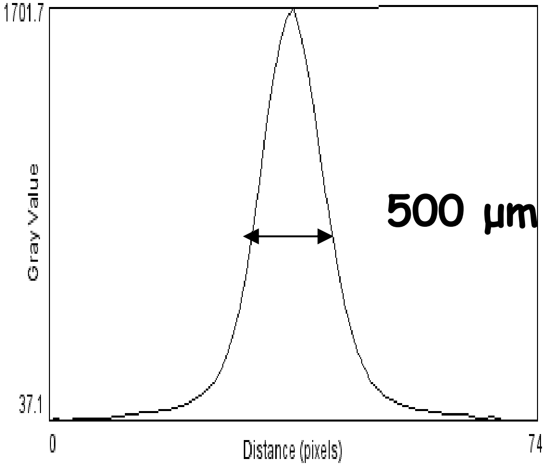




Time scan of plasma luminescence at argon initial pressure 3.5 mbar and discharge current 200kA (full length – 6 ms, cross section size – 2 cm)

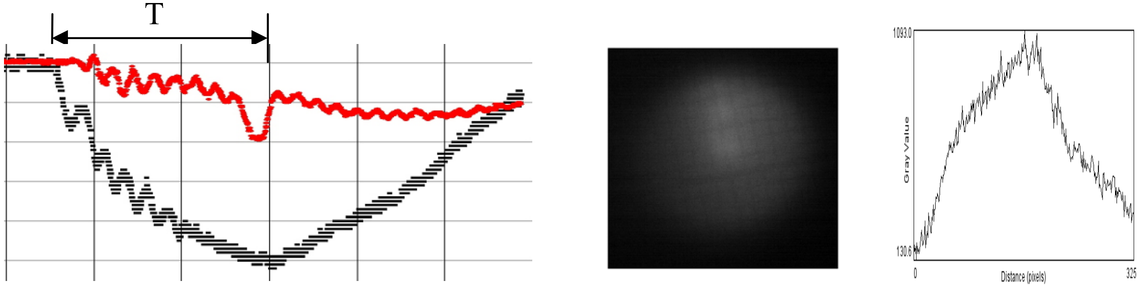
Results of focusing Fe^{+26} ions with energy 200 MeV/u



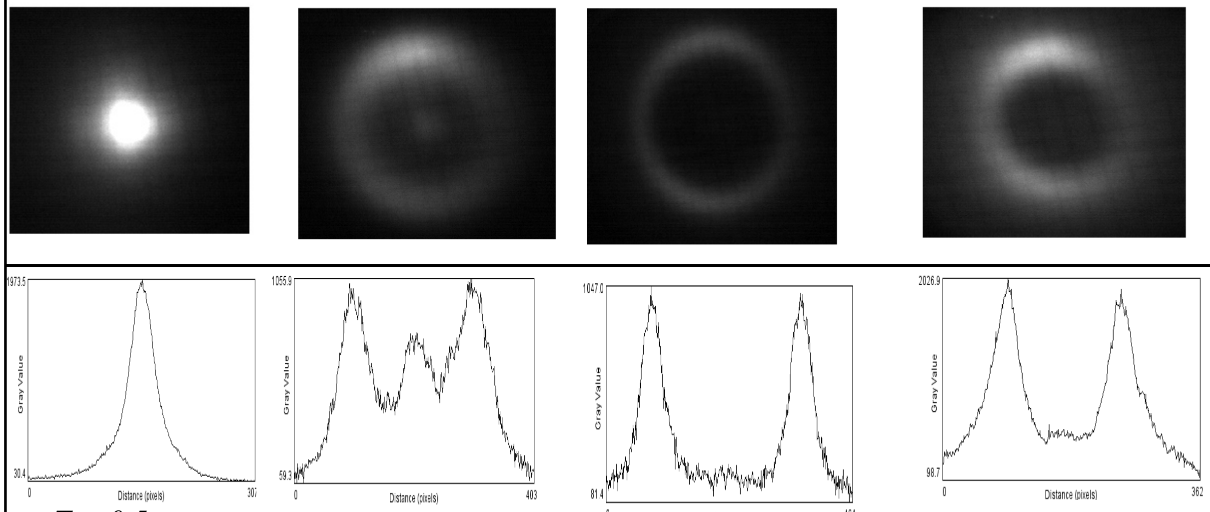


The spot size has been reduced approximately by a factor of 30

Spot shaping of Fe^{+26} ion beam dependence on time discharge



The curves of beam current (the top) and the plasma current discharge; beam spot of ion beam Fe^{+26} at T = 0 μs.



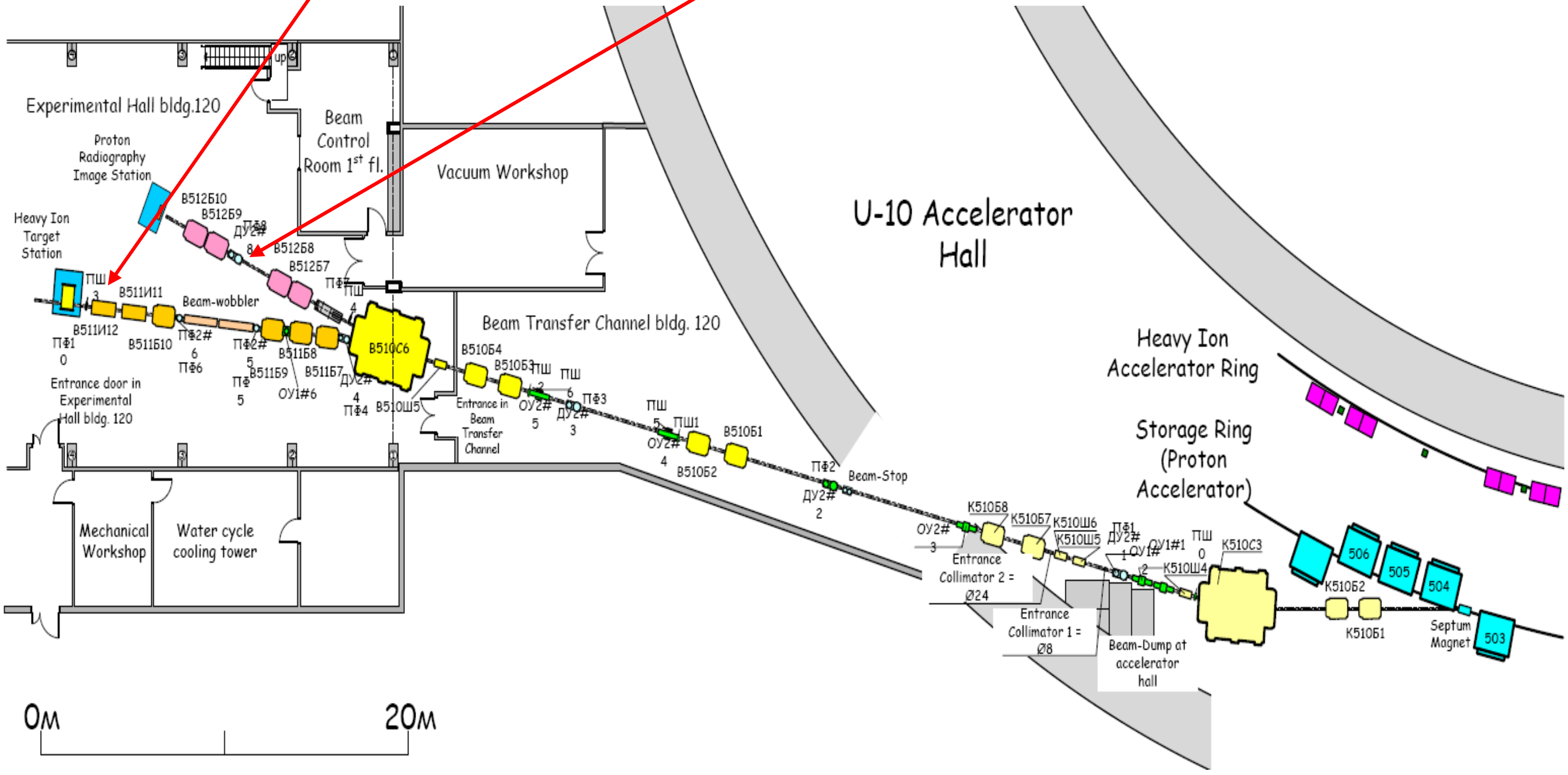
T = 0.5 мкс *T = 1.5 мкс* *T = 1.7 мкс* *T = 2.3 мкс*

Beam spot shaping of Fe^{+26} ion at different time T > 0.

Plasma Physics Experimental Area on TWAC Facility

Heavy ion beam plasma

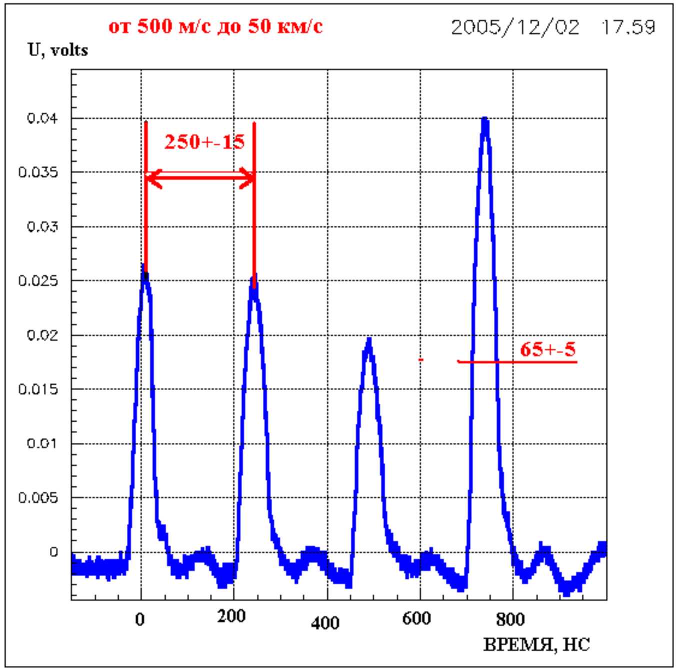
Proton Radiography



Parameters of the p+ radiography set-up

Proton energy 800 MeV

- Field of view on object up to 40 mm
- Investigated objects up to 60 g/cm^2
- Spatial resolution 0.5 p.lines/mm
- Time resolution 4 bunches / 1 µs



Protective Target Chamber designed for:

Up to 80 g TNT

Pumped down to 10^{-3} Torr

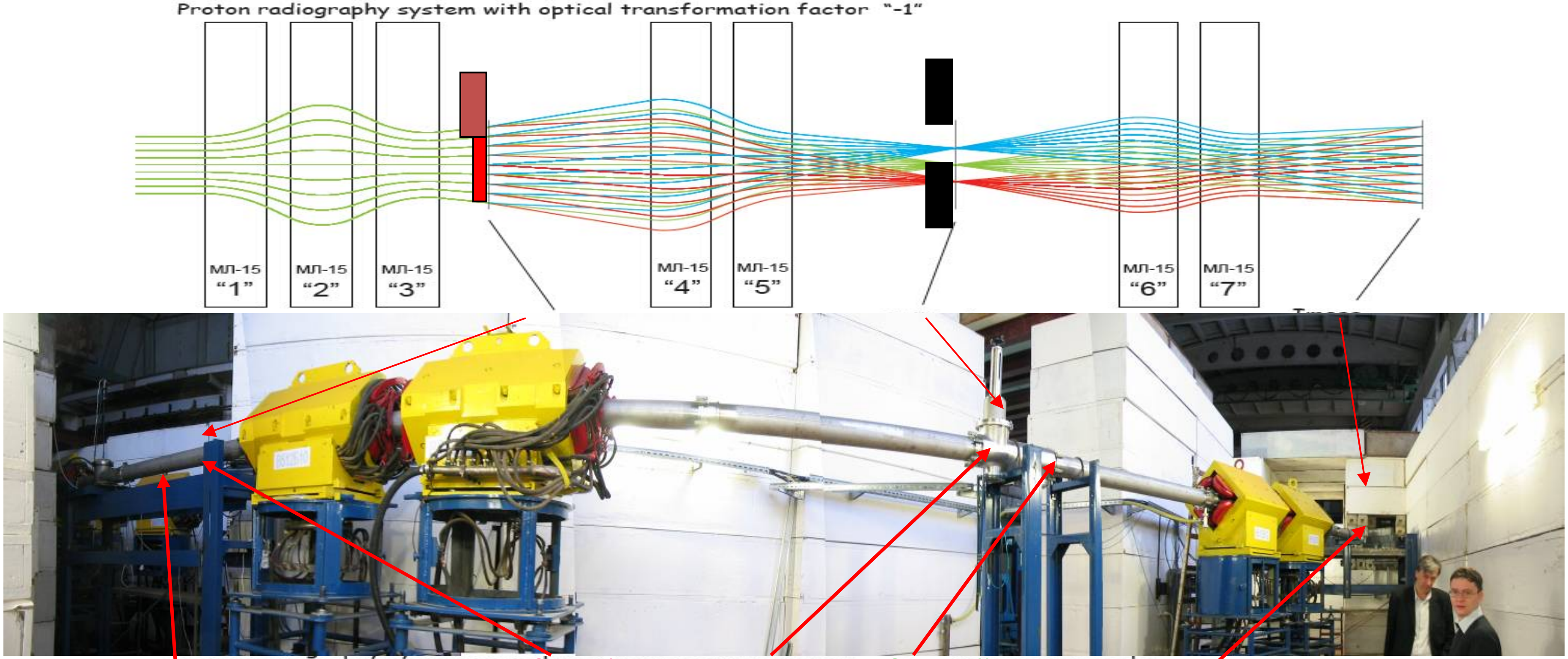
Active ventilation system

Fiber for optical diagnostics (VISAR)

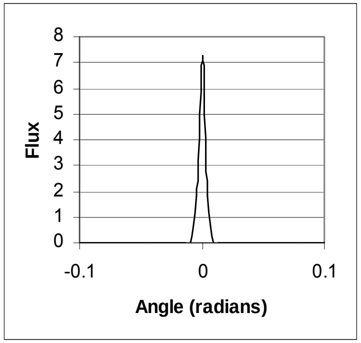
Plasma target parameters (chemical HE generation):

- Electron density up to 10^{23} cm^{-3}
- Pressure ~10 GPa
- Density up to 4,5 g/cm^3
- Temperature 1÷3 eV
- Time scale – microseconds
- HE mass (TNT) – 60 g

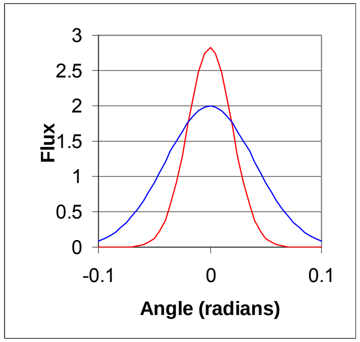
Magnetic optics design for proton radiography set-up image transformation factor “-1”



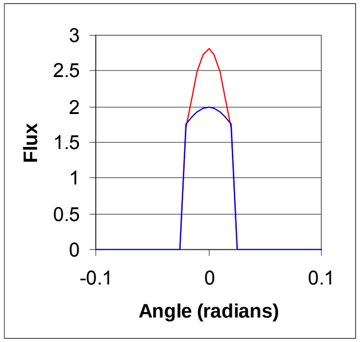
Incident Beam



After Object



After Collimator

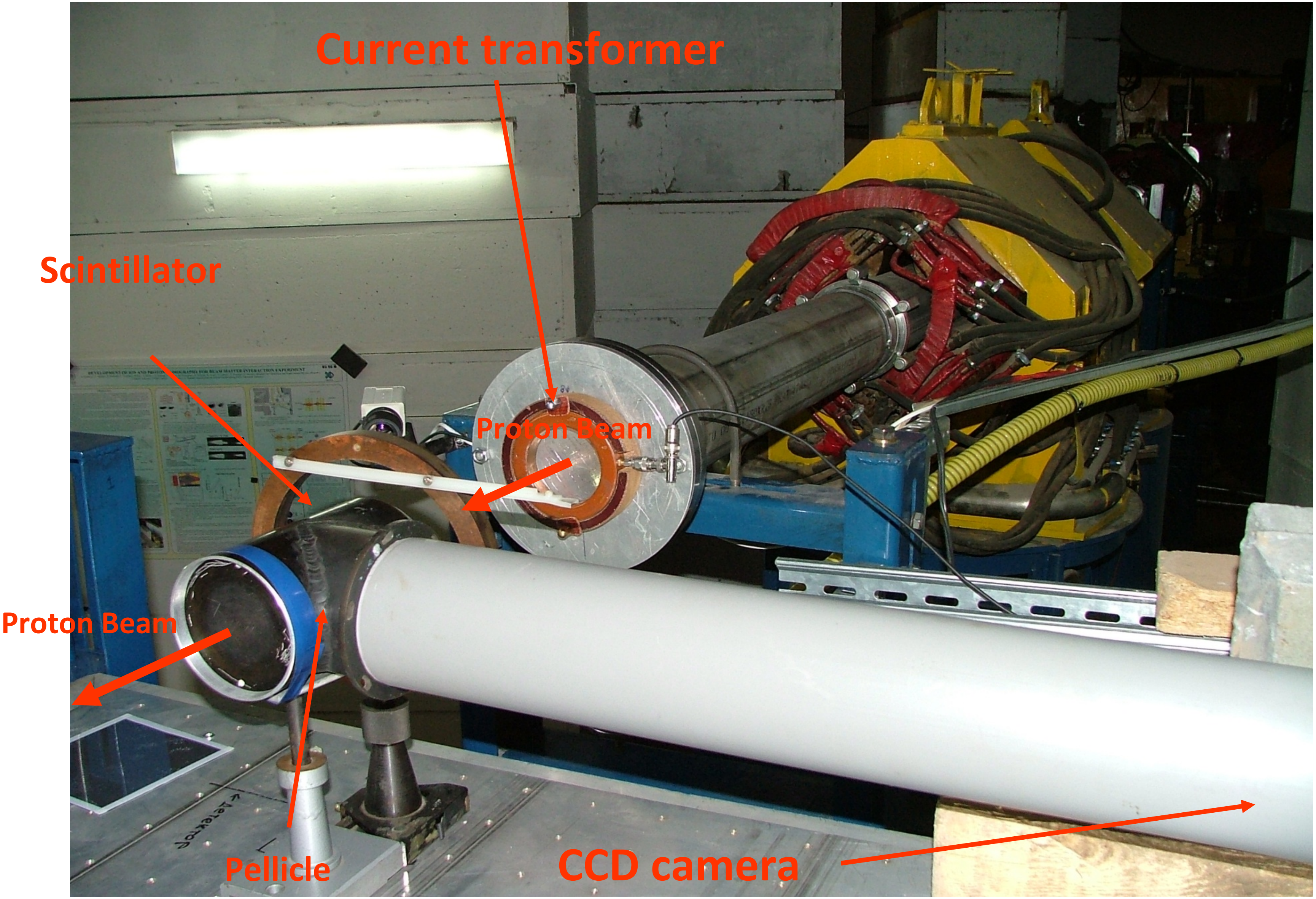


Measured transmission provides information about object thickness

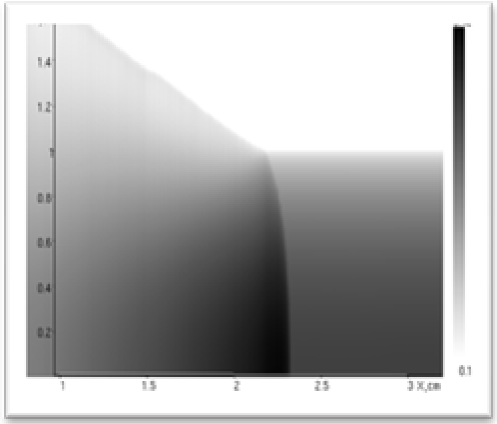
Transmission

$$T_{MCS} = 1 - e^{-\theta_c^2 / 2\theta_o^2}$$

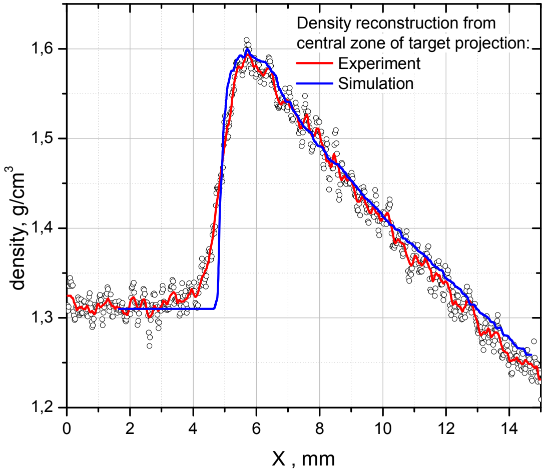
Contrast from Multiple Coulomb Scattering


Current transformer
Scintillator
Proton Beam
Proton Beam
Pellicle
CCD camera

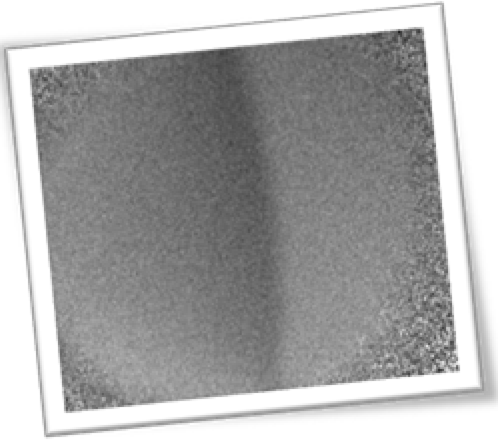
Detonation wave in TNT



Areal density, (g/cm²)
Simulation results – A. Shutov

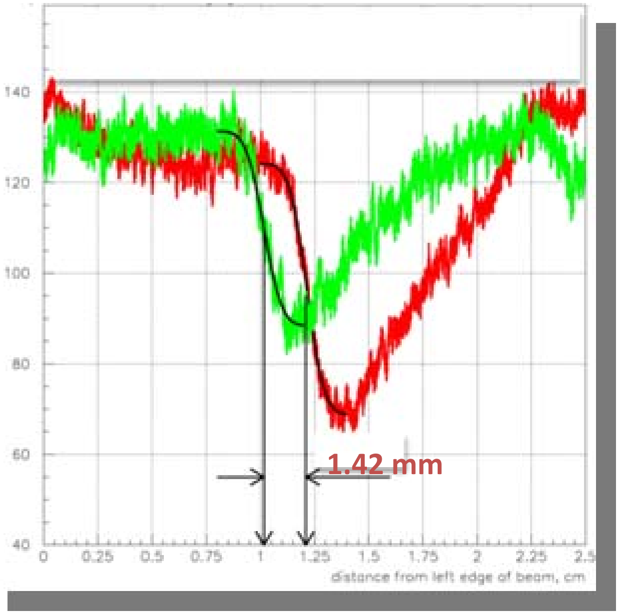


Density profiles on the axis of detonating TNT charge:
solid line - experimental profile for the detonation wave at the transition from the charge with diameter of 20 mm into the charge with diameter of 15 mm; **dashed line** - simulation for a charge with 20 mm diameter.

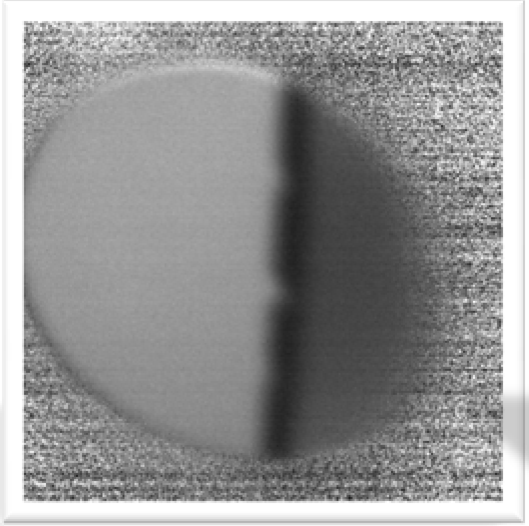


Relative proton beam transmission, (%)

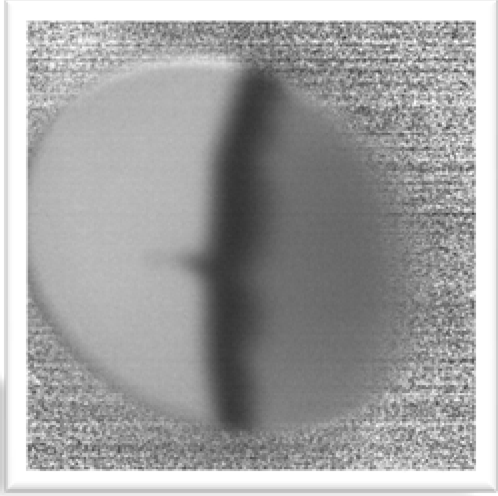
1.42 mm/250ns=(5.7±0.5)km/s



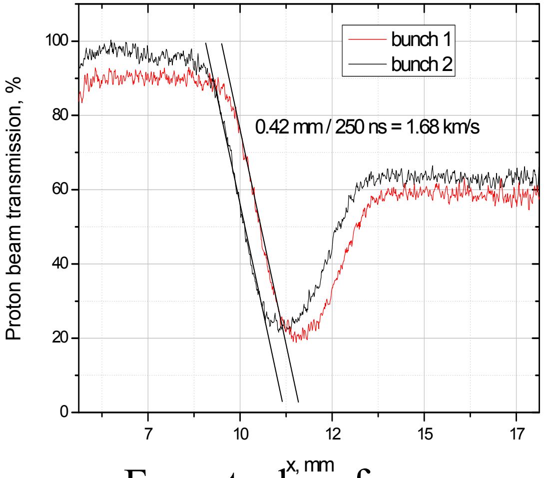
Dynamic dispersion of metals under pulse loading of their free surface.



Proton radiography image of steel plate with notches placed on the face of TNT charge



Target image after 1 μs, after the coming of a shock wave to the free surface of the plate

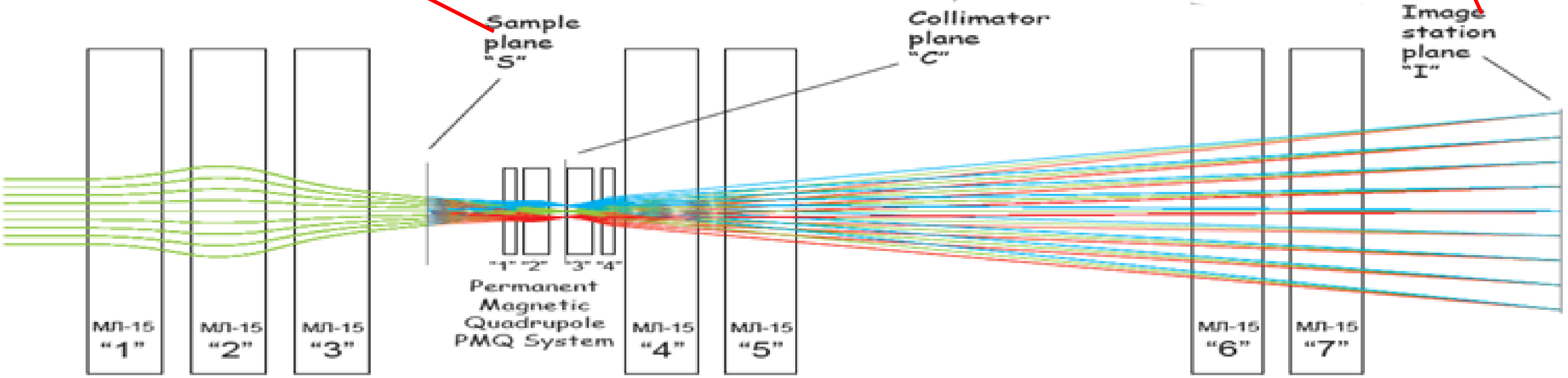


Free steel surface velocity measurements

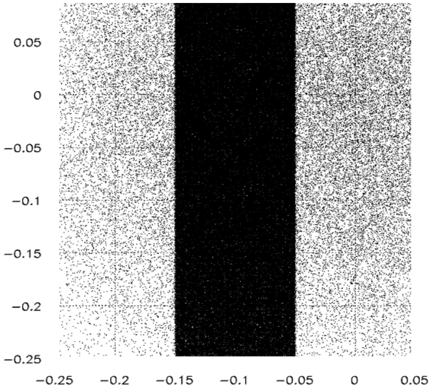
The head of the observed jet moved with 4 km/s
The velocity of the free steel surface 1.68 km/s
At the locations of 0.3 mm cuts jets were not visible

General interest: experiments show that under pulse loading of free surface of metals there is a possibility of formation of a cloud of metal microparticles moving with substantially greater velocity that of the shock wave in gas above the surface. One might have the need to take this ejecta phenomenon into account in laboratory as well as in practical problems involving shock loading of metal surfaces, so there is a question of its nature and its characterization. There is a number of works on qualitative description of this phenomenon, but there is no quantitative description of it on micro-level. In addition, discussions of its mechanism and the possibility of “microcumulation” on natural surface irregularities continue. Therefore the study of surface ejecta formation and dynamics for metals with meso- and microscale natural and artificial surface irregularities under shock-wave loading with the proton radiography technique is supposed.

Proton radiography system with image transformation factor “-8” “Proton microscope”

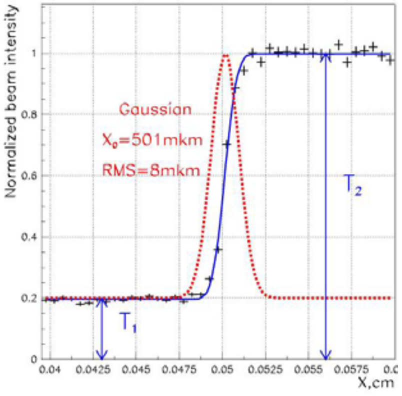


Proton radiography system with optical transformation factor "-8" - "Proton microscope"



GEANT4 simulations for “Proton Microscope”

“Sharp edge” test-object



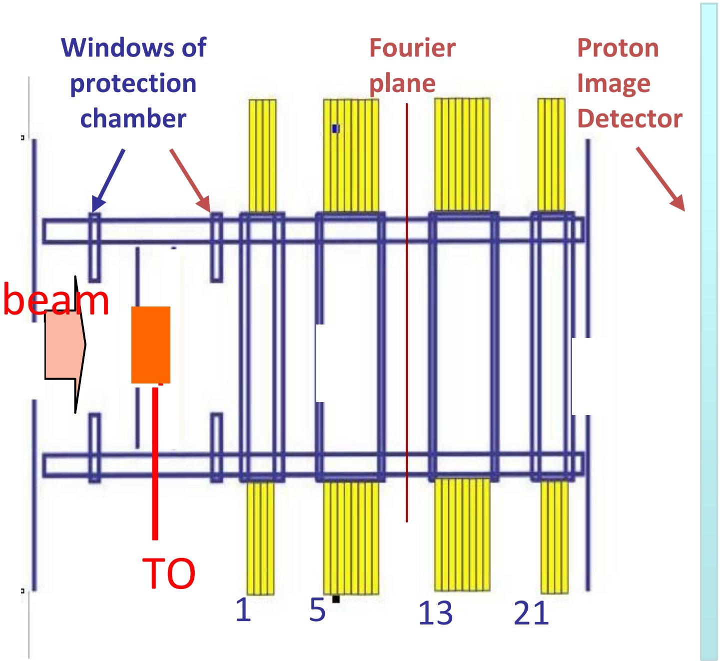
GEANT simulations for Radiography Experiments

Program – GEANT 3.21
Hadron’s code – FLUKA
Magnetic fields – COSY Infinity

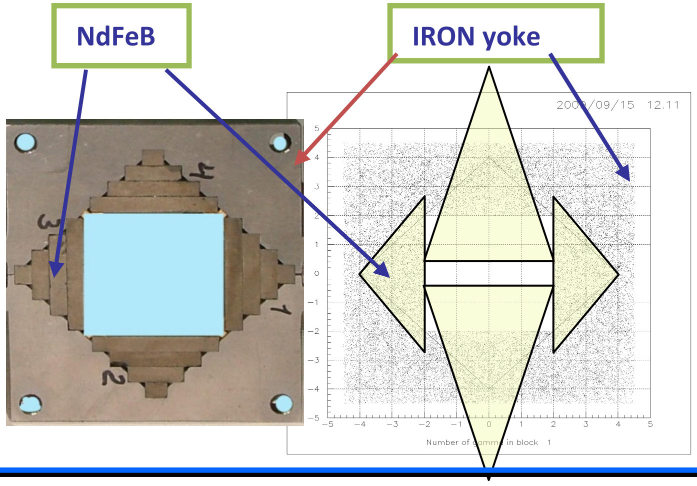
- Simulation of proton beam interaction with object
- Solving of integral equation for proton trajectories in pole of magnetic lenses system
- Simulation of the scintillator detector response

- Radiography set-up parameters optimization:
- Magnetic system parameters;
- Collimator parameters;
- Experimental target parameters
- Photons, electrons, neutrons and protons fluences prediction in microscope PMQs for radiation hardness estimation

GEANT-3.21 model of ITEP proton microscope.

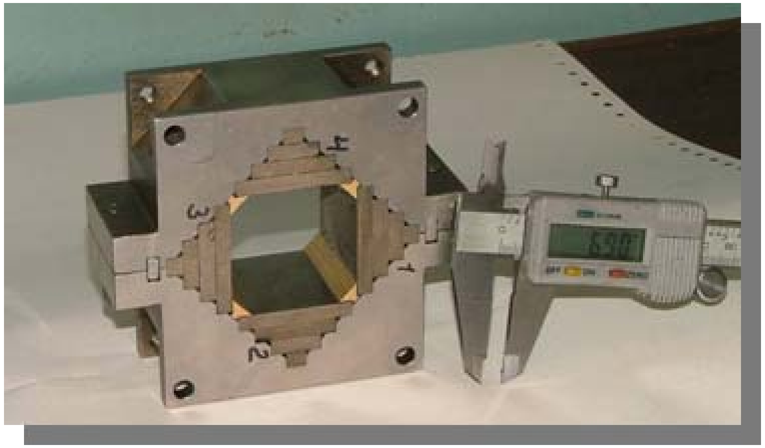


24 blocks of permanent magnets



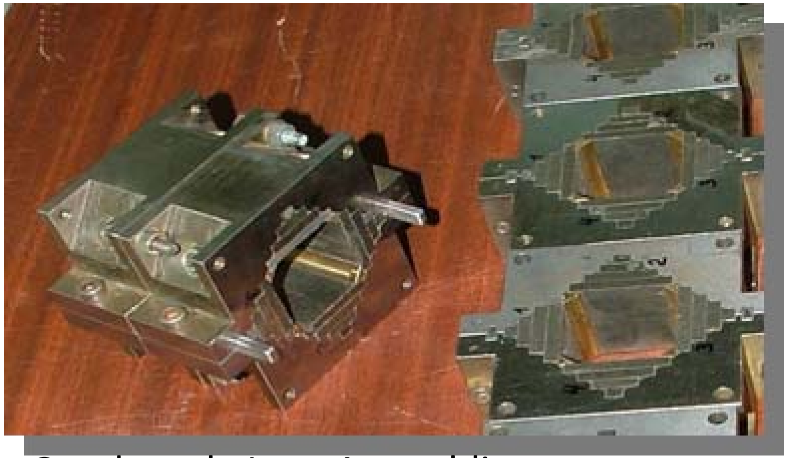
Proton radiography system with image transformation factor “-8” “Proton microscope”

Permanent Magnet Quadrupole lens fabrication for “Proton Microscope”

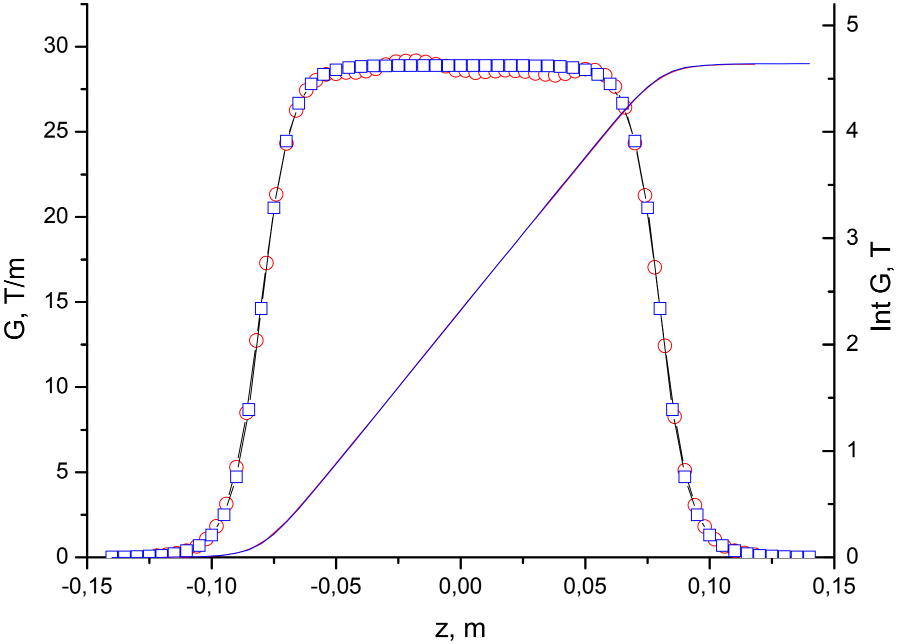


Permanent Magnetic Quadrupole Module

Magnetic alloy Nd-Fe-B



Quadrupole Lens Assembling

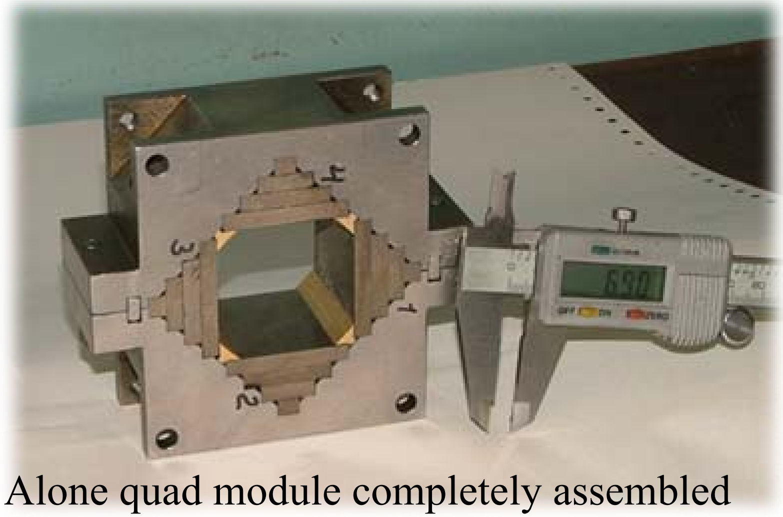


Four Modules Assembly Axis Gradient Distribution

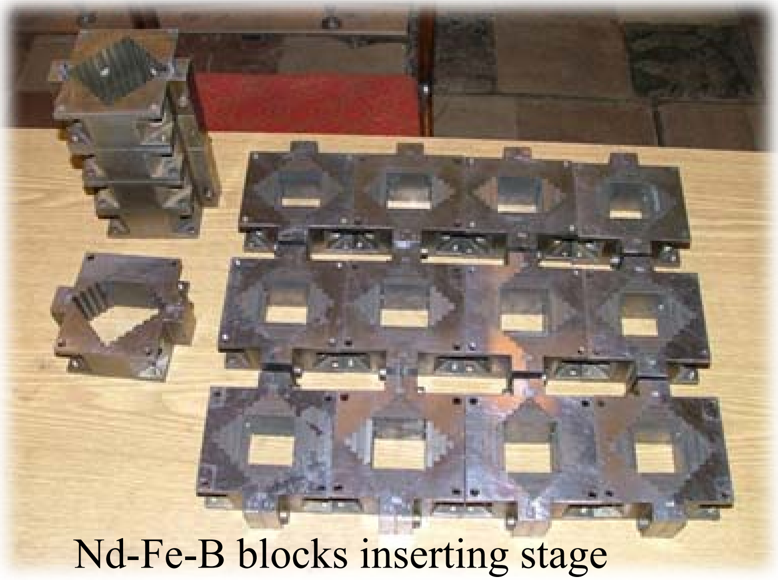
Blue – field simulation

Red – field measurements

REPM QUADS
FOR p+ MICROSCOPE
Manufacturing Stage



Alone quad module completely assembled



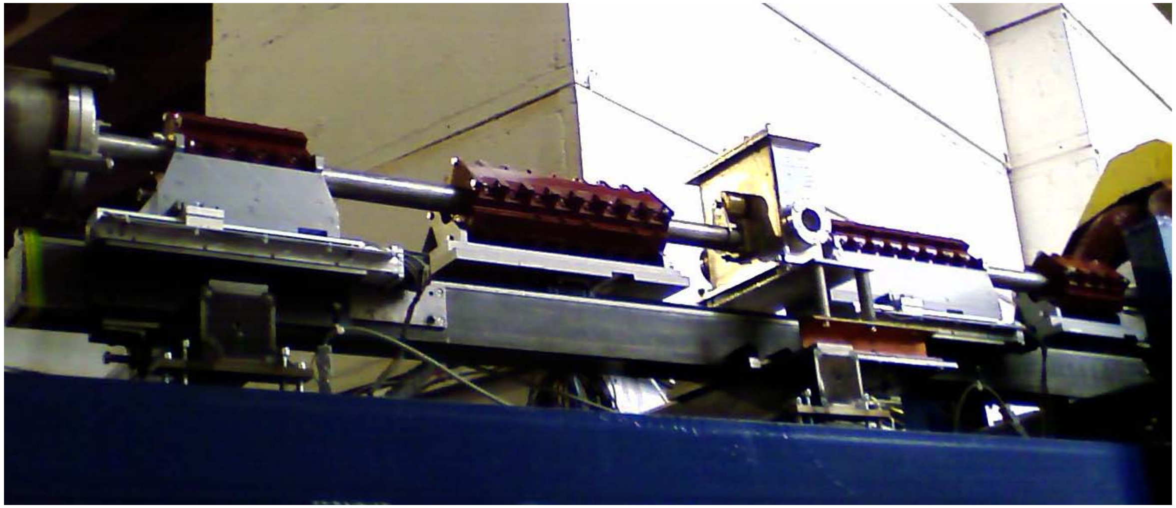
Nd-Fe-B blocks inserting stage

Microscope quadrupole channel mounted to slide on the support girder

- REPM material – Nd-Fe-B alloy with $\mu_0 I = 1.2$ T, $\mu_0 H_{CI} = 1.7$ T
- Aperture – almost square of 40 × 40 mm
- Module length – 40 mm
- Yoke – magnetically soft steel
- Number of identical modules – 24
- Accurate modules assembling

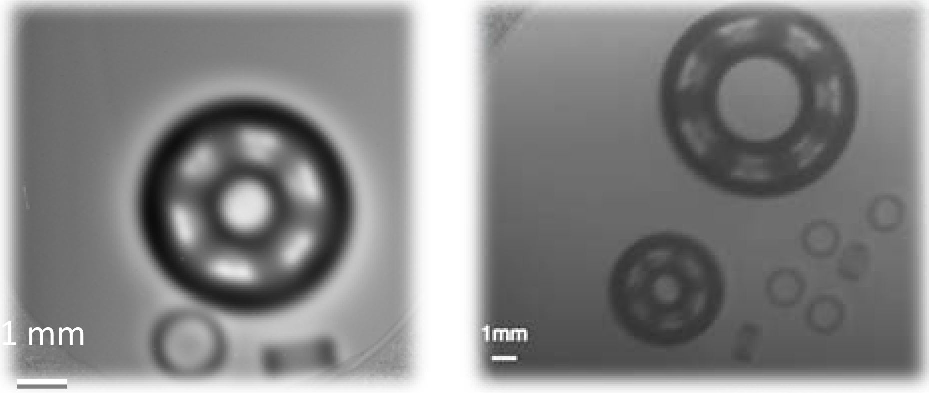
ITEP Proton Microscope

E = 800 MeV
Magnification X = 7.82
Field of view < 10mm
Measured spatial resolution
σ = 50µm
Magnification X = 3.92
Field of view < 22 mm
Measured spatial resolution
σ = 60µm

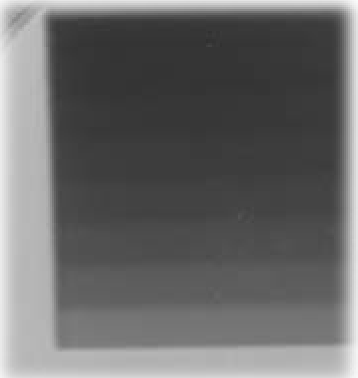


Measured density resolution ~ 6%
Beam structure – 4 bunches
(FWHM=70ns) in 1 µs

Static test-object images



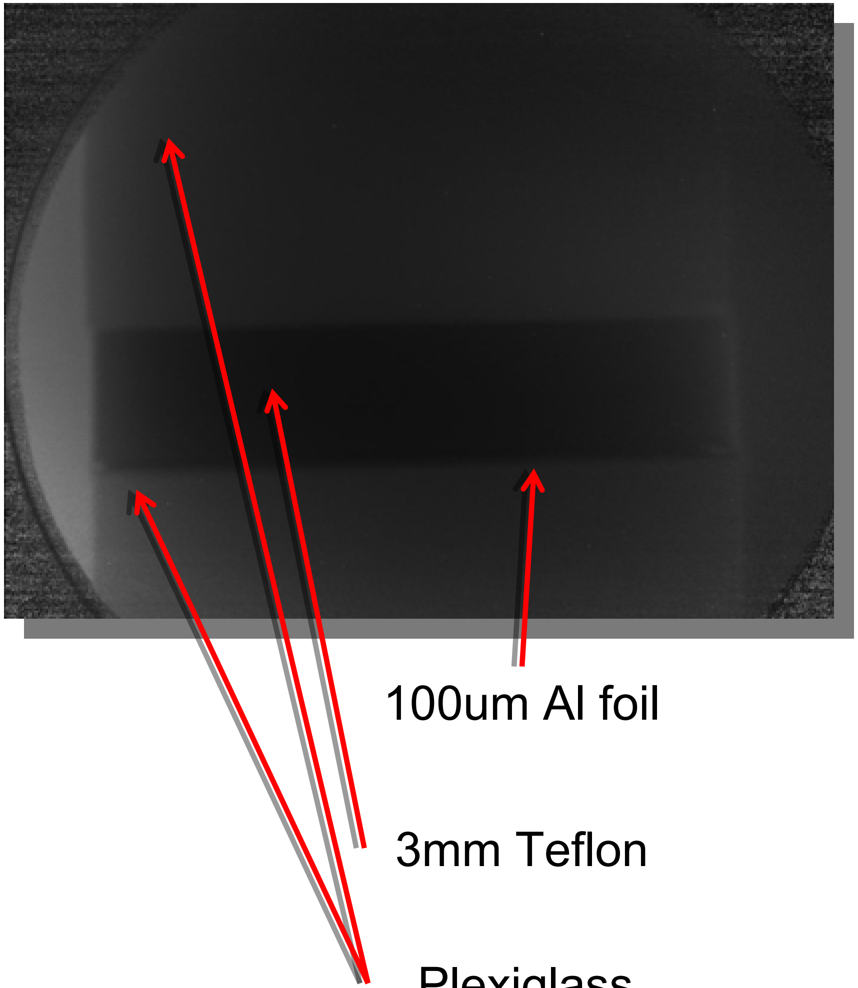
Ball bearing and ferrite ring (X= 7.82 and X=3.92)



Brass stair 1 mm step Δρ=400µm

Detonation wave
imitator d=15mm
σ=100µm

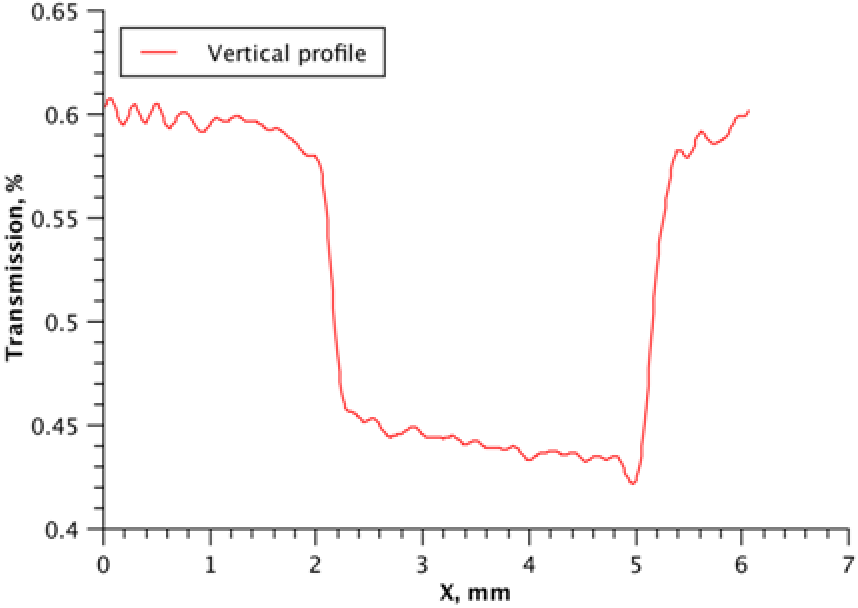
Static imitator of TNT explosion target



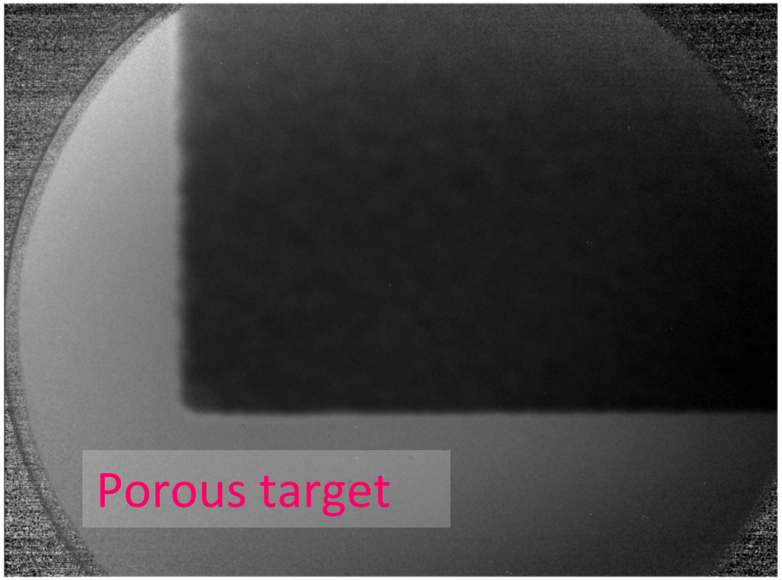
100um Al foil

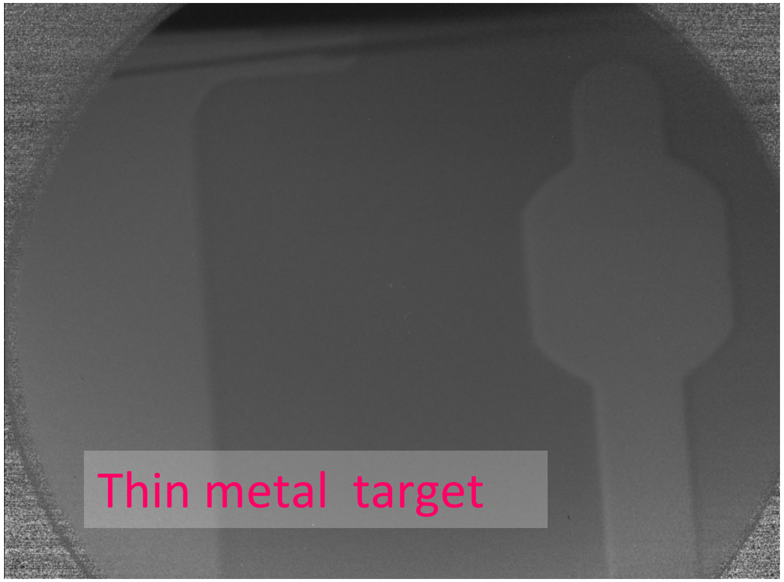
3mm Teflon

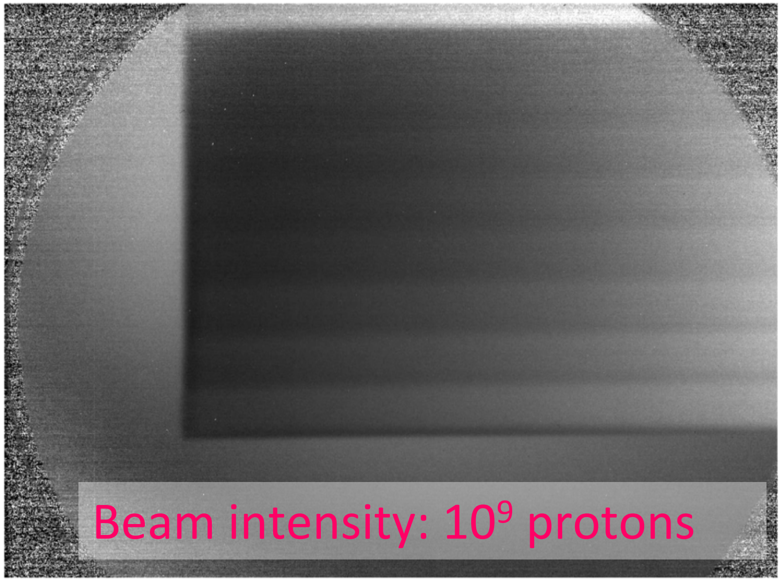
Plexiglass

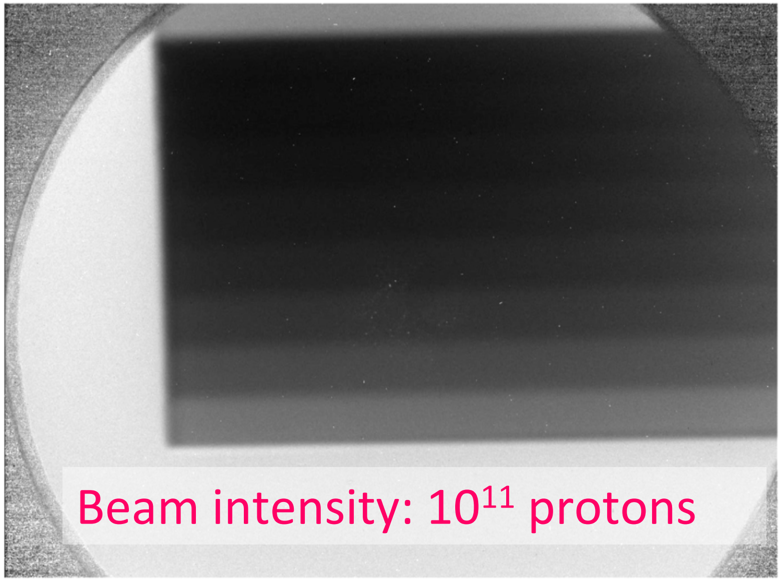


ITEP Proton Microscope: Static test-objects


Porous target


Thin metal target


Beam intensity: 10^9 protons

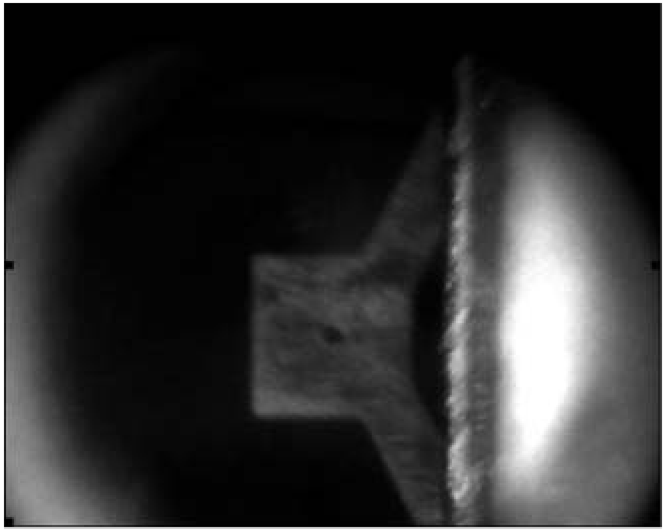

Beam intensity: 10^{11} protons

Brass stair 1 mm, step $\Delta\rho$=0.34 g/cm^2 (400 um)

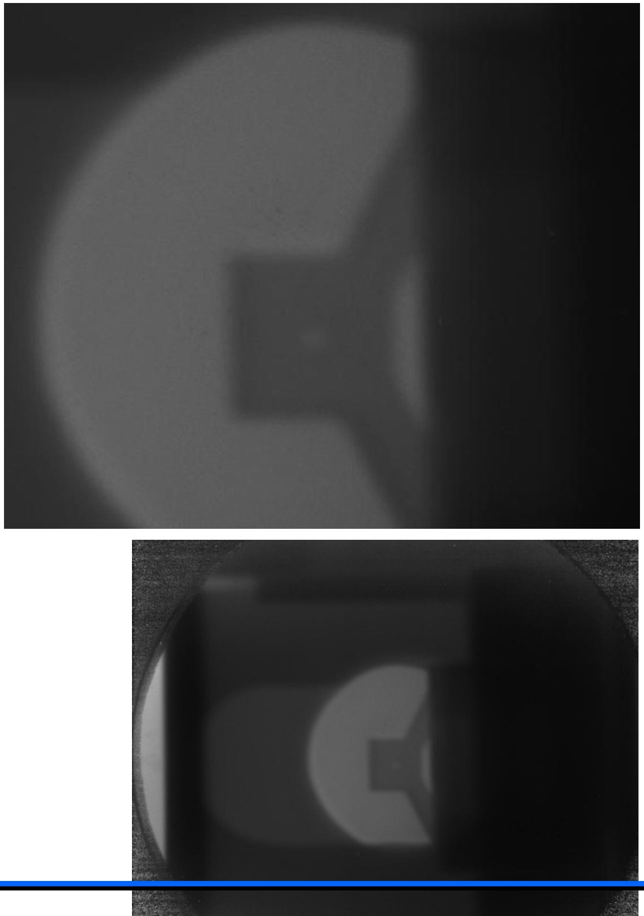
HHT experimental target radiography measurements at ITEP proton microscope

Geometry:
100µm tungsten foil
1.8x1.8 mm with 250 um hole

Photo



Proton radiography

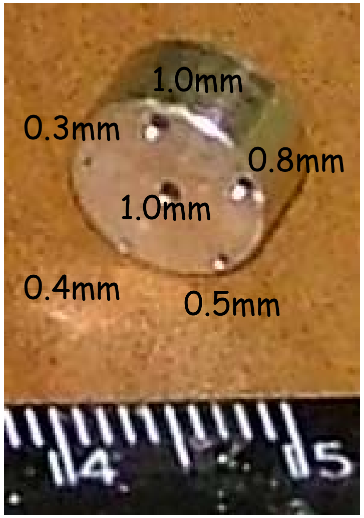


ITEP Proton Microscope: Static test-objects

Tomography reconstruction of multi-projection proton microscopy

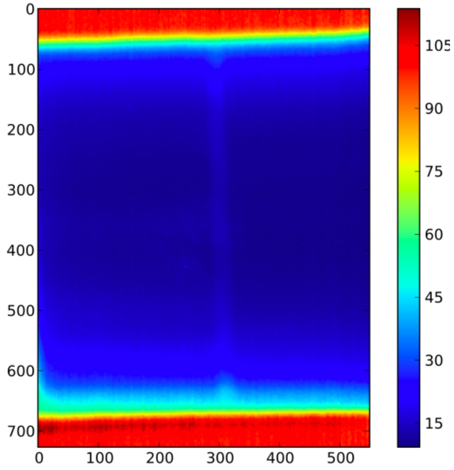
Targets and SS container

Brass target

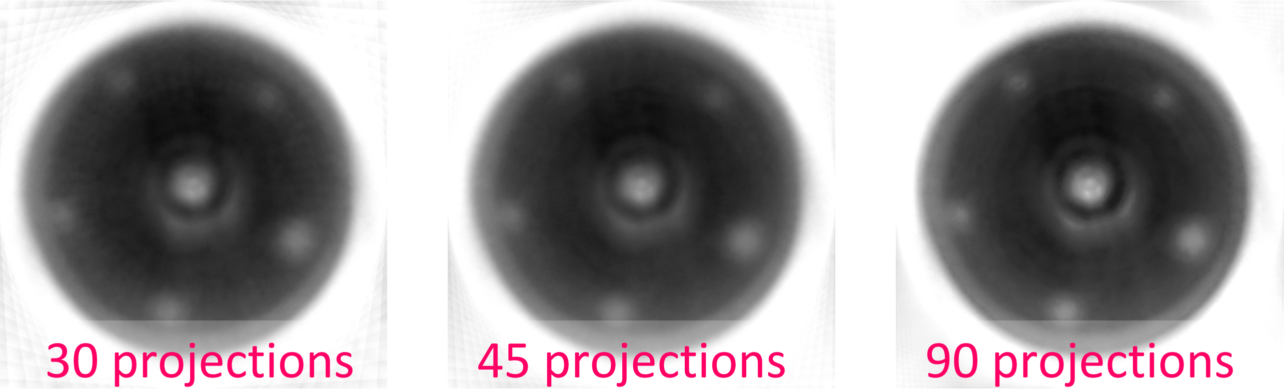


Requirements:

- 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)



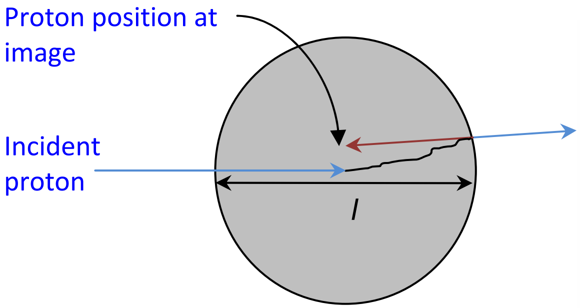
30 projections

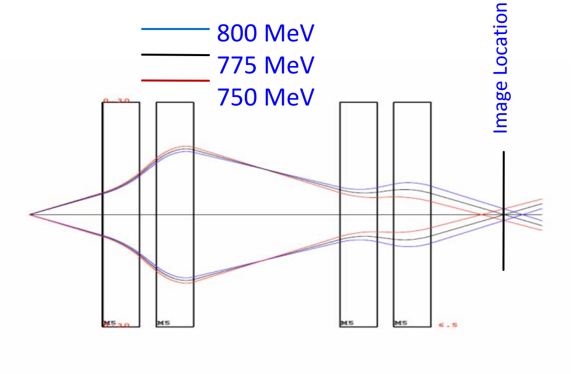
45 projections

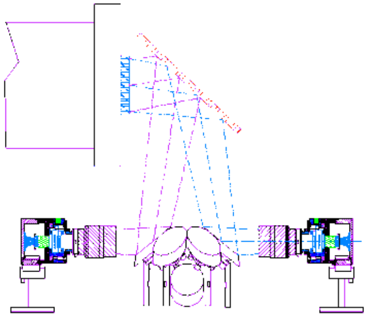
90 projections

Resolution of Proton Radiography

1. **Object scattering** - introduced as the protons are scattered while traversing the object.
2. **Chromatic aberrations**- introduced as the protons pass through the magnetic lens imaging system.
3. **Detector blur**- introduced as the proton interacts with the proton-to-light converter and as the light is gated and collected with a camera system.







Object scattering:

$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \boxed{\frac{l^{\frac{3}{2}}}{P}}$$

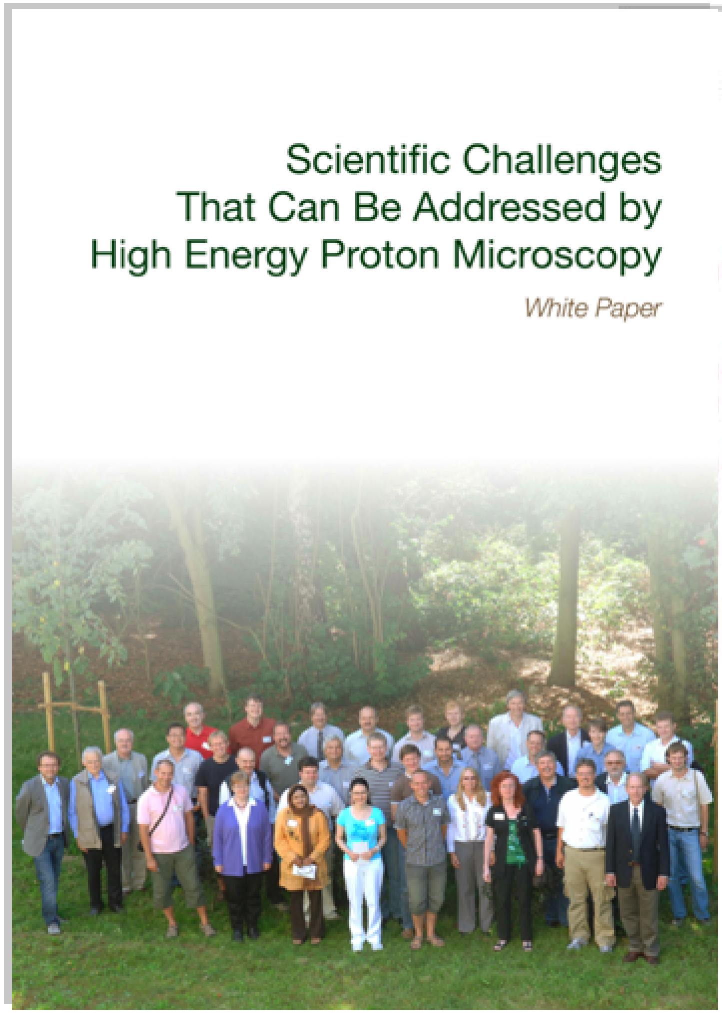
Chromatic aberration:

$$\sigma_c = l_c\theta\frac{\delta P}{P} = c\sqrt{P}\frac{\delta P}{P^2}\frac{14.1}{\beta}\sqrt{\frac{l}{x_o}} \propto \boxed{\sqrt{\frac{l}{P^3}}}$$

Scintillator blur:

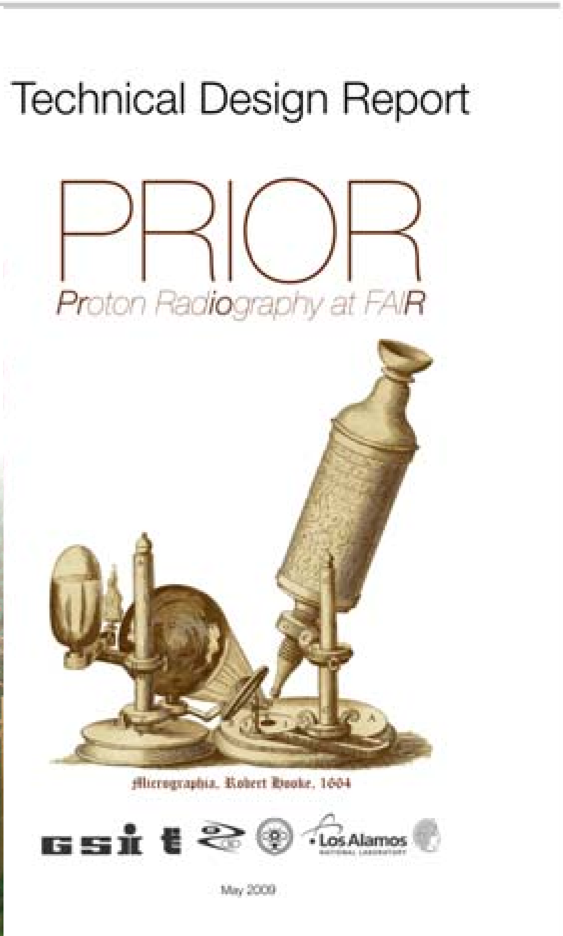
$$\sigma_s = \theta l_s \propto \boxed{\frac{l_s\sqrt{l}}{P}}$$

High energy proton microscopy project



Scientific Challenges
That Can Be Addressed by
High Energy Proton Microscopy

White Paper



Technical Design Report

PRIOR

Proton Radiography at FAIR

Micrographia, Robert Hooke, 1604

May 2009

BMBF grant "Construction of a proton microscope to study matter under transient extreme condition" 01.07.2010 – 30.06.2013 (GSI-ITEP-LANL-IPCP)

Project goal:

Designing and constructing a pRad lens and detector system for **4.5 GeV** protons capable of collecting multiple time radiographs with micron-level resolution, according to the requirements for the FAIR pRad setup.

Lens and detector design goals (in accordance with FAIR pRad specifications):

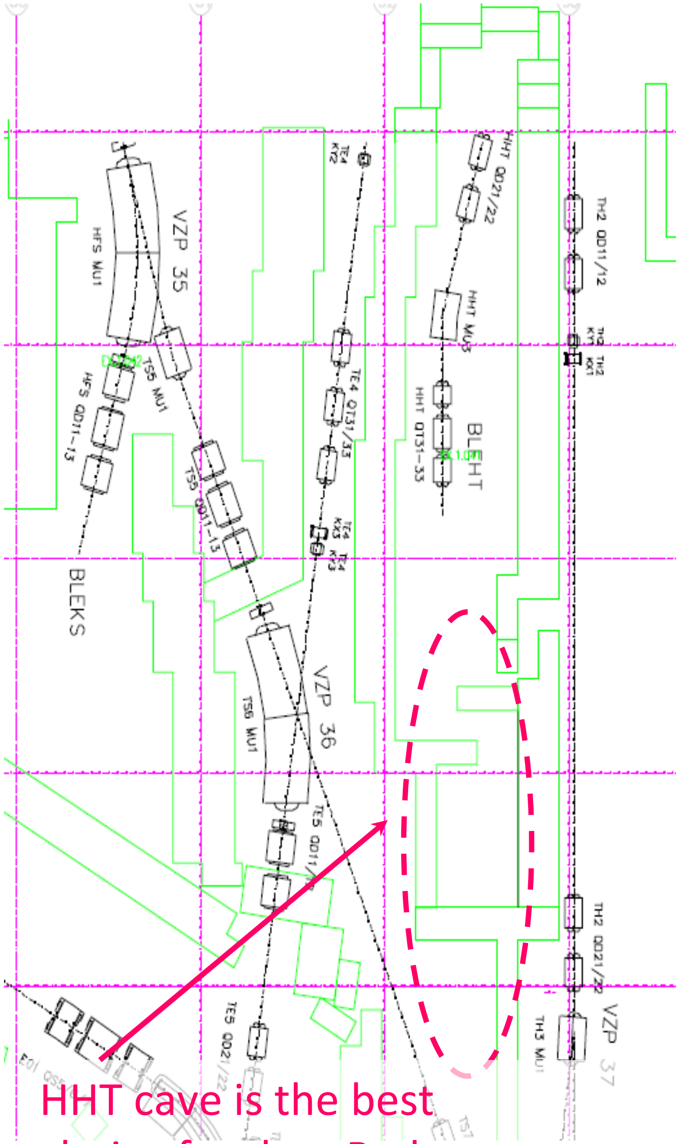
- less than 10 µm spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 50 g/cm^2, high-Z targets;
- temporal resolution <10 ns (for FAIR), <100 ns (for GSI);
- field of view: 20 mm;
- proton illumination spot size: 1 – 20 mm;
- magnifying lens with M = 4 – 8.

Dynamic experiment design goals:

- HE experiments: GSI is certified for up to 100 g TNT loads;
- HE containment: already available at GSI "red Russian" vessel

Beam pipe downstream of the vessel will be a part of the containment system;

- vacuum system capable of achieving < 1 mbar vacuum in containment system.



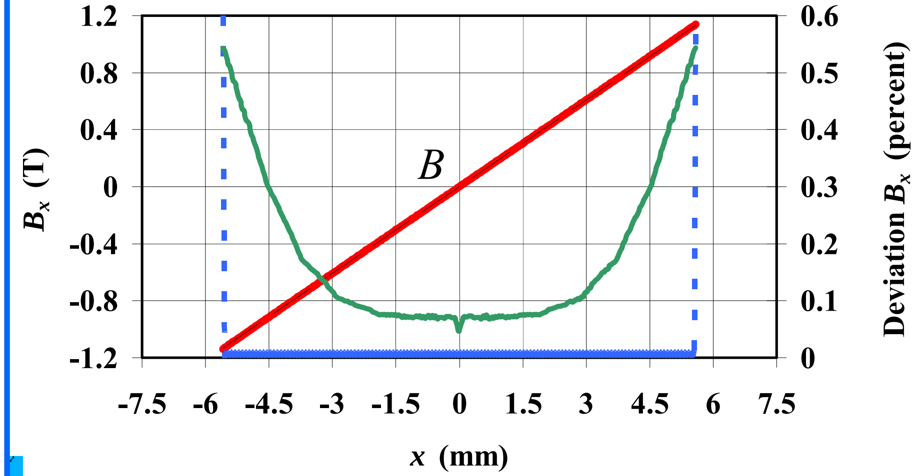
HHT cave is the best choice for the pRad setup

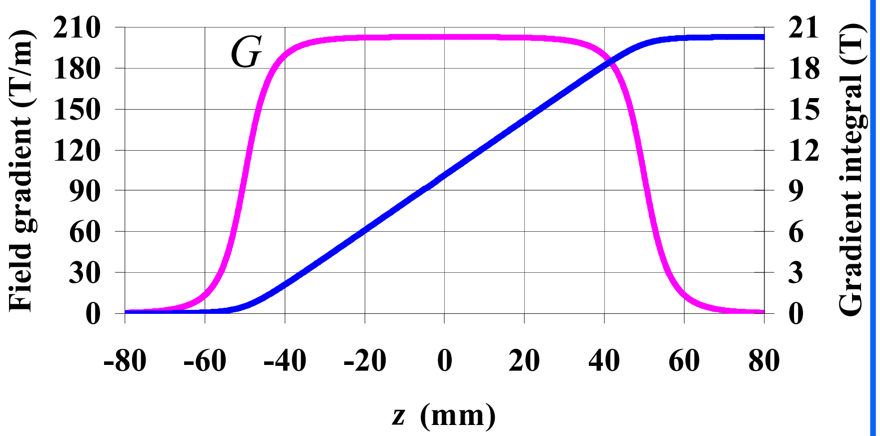
Extremely High Gradient Split-Pole Quad

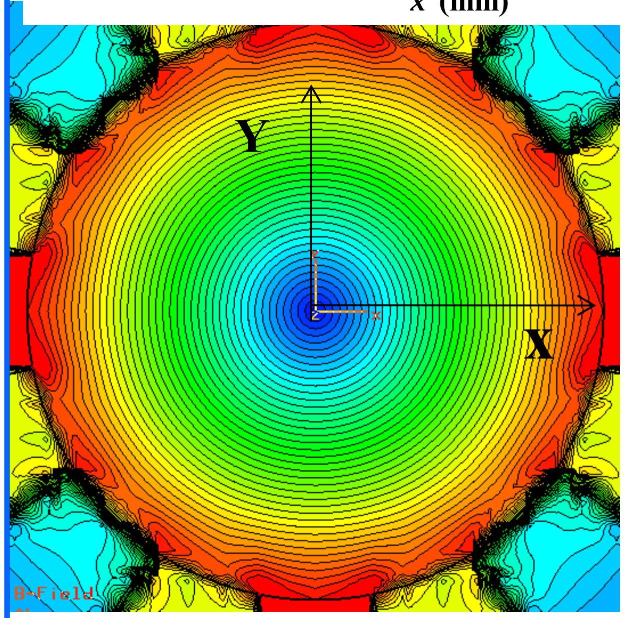
NdFeB Project Calculation parameters

Aperture diameter – 15 mm
Quad geometry – (∅×*L*)= 57 × 100 mm
Quad's segment number – 16

REPM QUADS FOR PROTON MICROSCOPE







Field B_{max} on aperture radius of 7.5 mm	> 1.5 T
Quad field gradient	> 200 T/m
Quad integrated field gradient along *z*-axis	20 T
Field non-linearity within working range	< 1 %
REPM mass (for 100 mm lens length)	1.8 kg

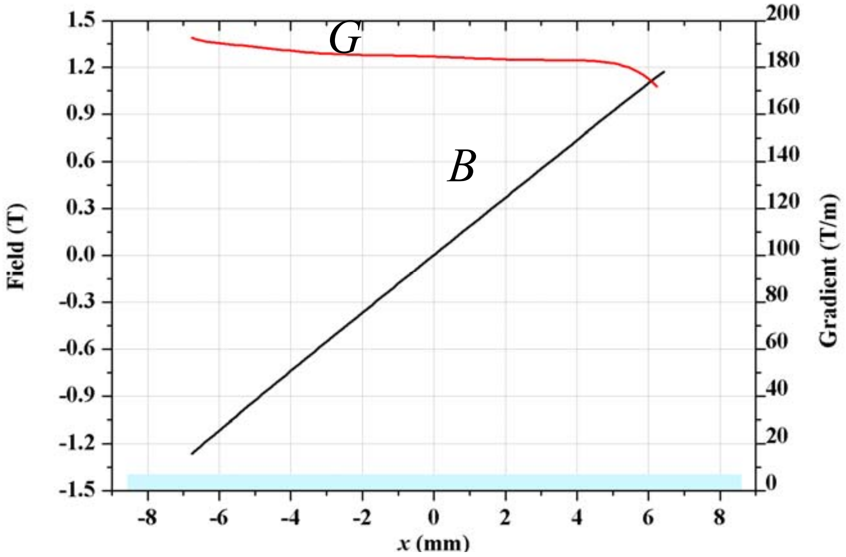
These data promise very good expectations in beam optics and image resolution

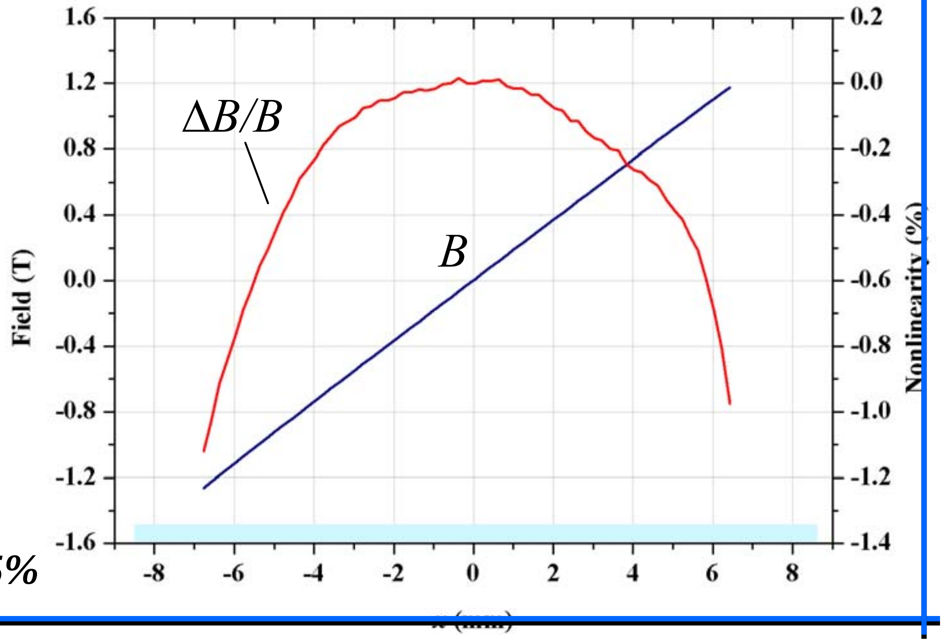
Field profile in the central lens cross-section

Scaled NdFeB experimental quad

Expected parameters:
Aperture – 15 mm
B = 1.7 T (on the aperture radius)
G ≈ 230 T/m
(Ø$_{out}$× *L)* – 80 mm × 50 mm

After a preliminary tuning:
Aperture – 17 mm
B = 1.6 T (on the aperture radius)
G = 185 T/m
Δ*B*/*B* ≤ 0.5 % (within 75 % aperture)

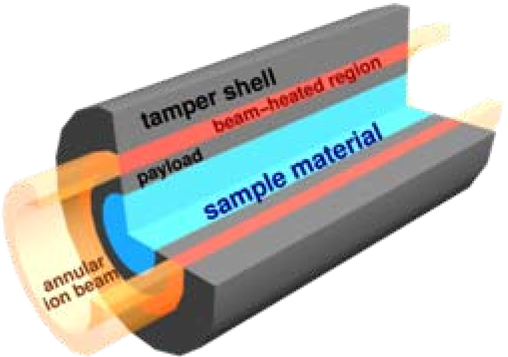




The prototype of the MQL for PRIOR is available.
The main advantage of the developed MQL is :

High magnetic field 1.6 T
High linearity of the magnetic filed less than 0.5%

Wobbler development for experiments at ITEP and LAPLAS (Laboratory Planetary Sciences) FAIR project



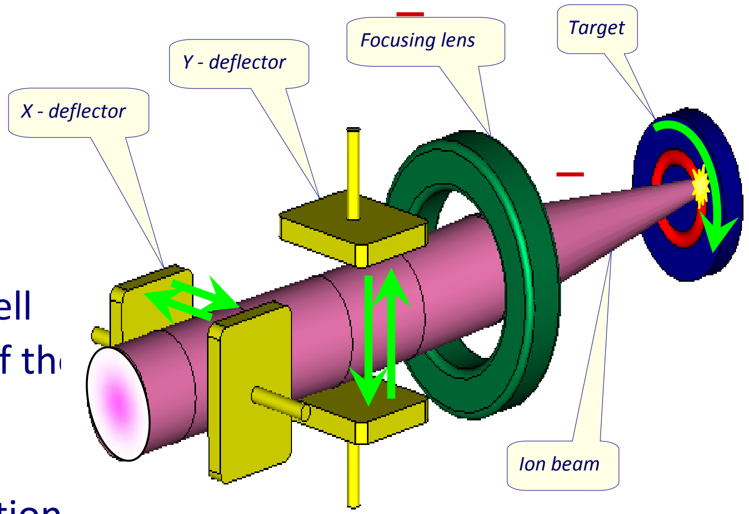
- hollow *(ring-shaped)* beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression of th sample

  ⍰ Mbar pressures @ moderate temperatures

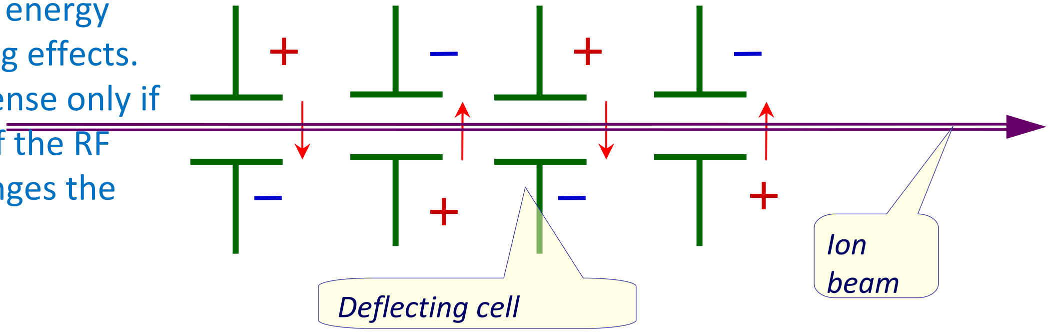
  interior of Jupiter and Saturn, hydrogen metallization

The elementary solution might be realized as a couple of parallel plates where the RF voltage is applied. But such a system can not provide enough deflection for high energy beam because the voltage is limited by the sparking effects. On the other hand, the plate lengthening makes sense only if the particle time-of-flight does not exceed a half of the RF period; otherwise the transverse electric field changes the direction

Mechanism of ring-shaped area illumination



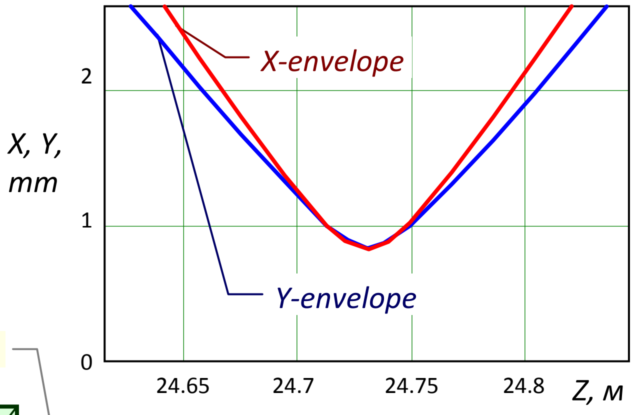
Principle of multi-cell RF deflector

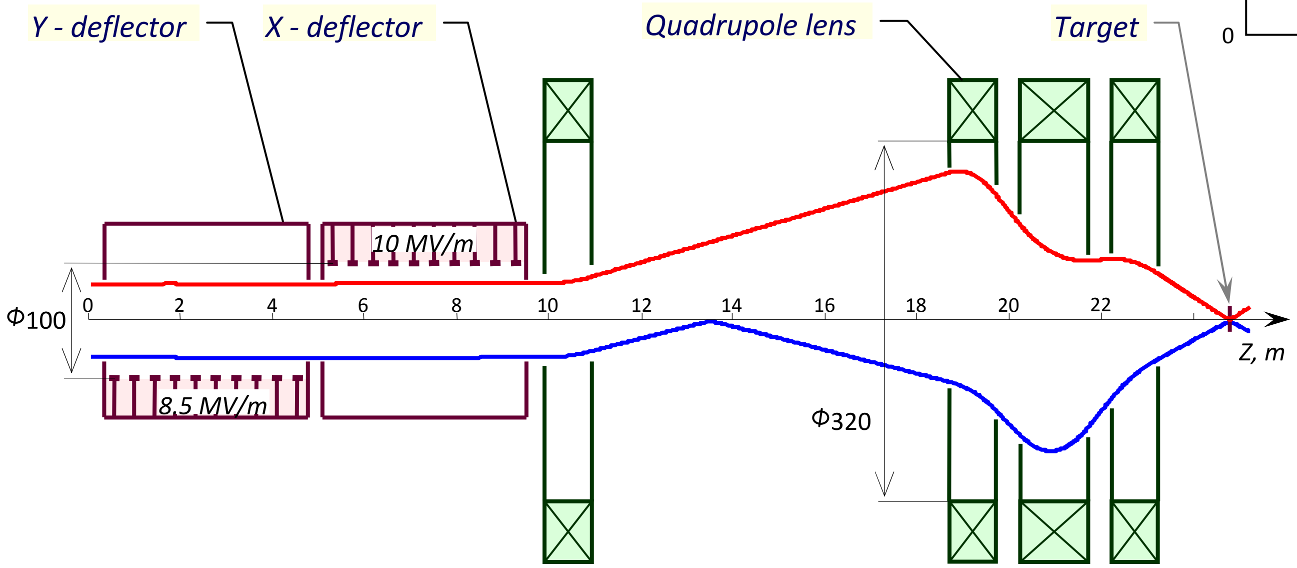


In order to cancel the limitations for high energy beam deflection, a principle of resonant interaction of the beam with multi-cell RF structure may be applied. In particular, every cell must be as long as $D=\beta\lambda/2$, where β is the normalized particle velocity and λ is the RF wavelength. Provided that resonant condition is fulfilled, any particle crosses the cell centers at the constant phase of RF field, regularly increasing the transverse momentum dependently on the phase value.

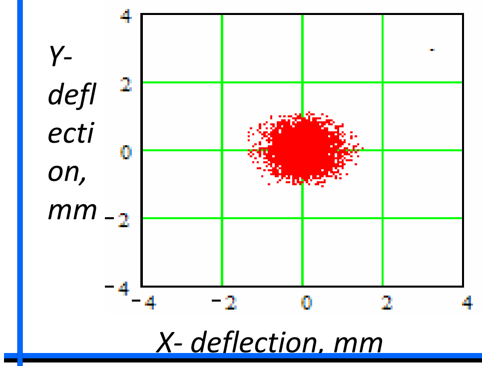
Beam envelope for superconducting triplet

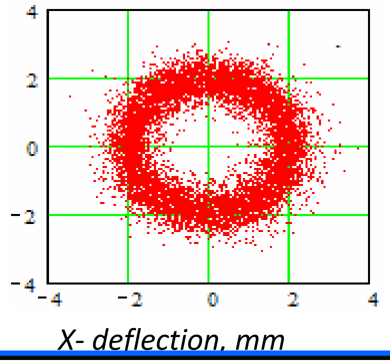
Parameter	Unit	Lens 1	Lens 2	Lens 3	Lens 4
Aperture radius	mm	160	160	160	160
Lenght	mm	1000	1000	1500	1000
Gradient	T/mm	16.5	24.0	27.4	28.0

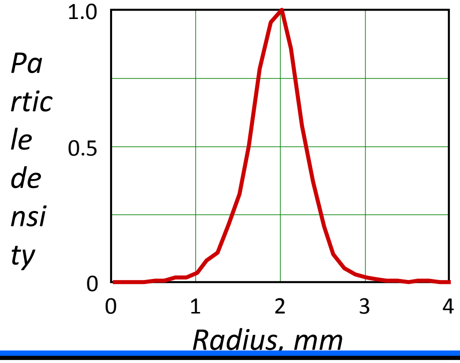




As it is possible to see from presented results, high aperture superconducting lenses allow to reduce noticeably the size of the focused spot and to improve conditions of formation of a hollow beam. At the same time, at the given values emittance and a focal length hardly it is possible to count on the further essential optimization of parameters.

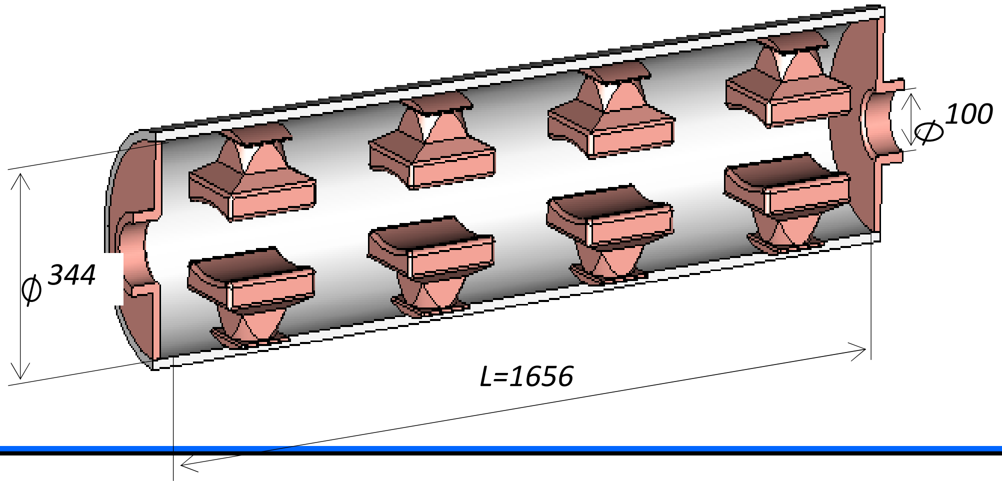


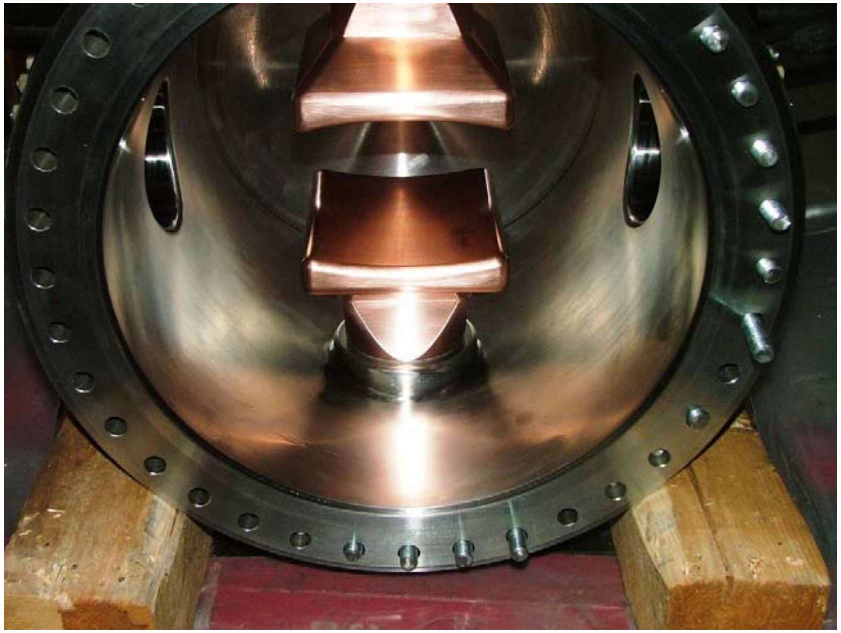


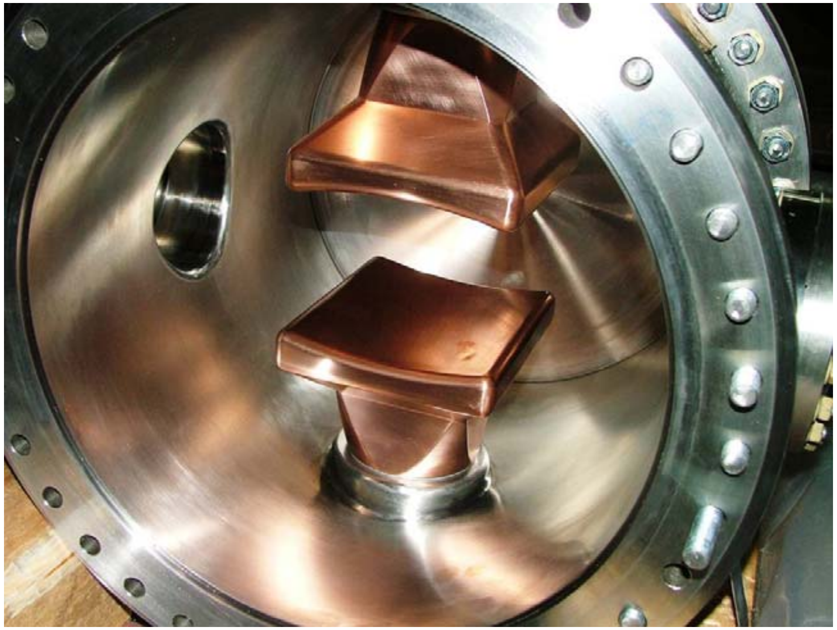


Example of deflecting cavity parameters for 700MeV/u Co+25 beam TWAC facility

Operating frequency	*MHz*	*300*
Number of cells		*4*
Aperture diameter	*mm*	*100*
Cavity diameter	*mm*	*344*
Cavity length	*mm*	*1656*
Plate-plate RF voltage	*MV*	*1*
Quality factor		*1400*
*Maximum **rf** peak power*	*MW*	*1.5*

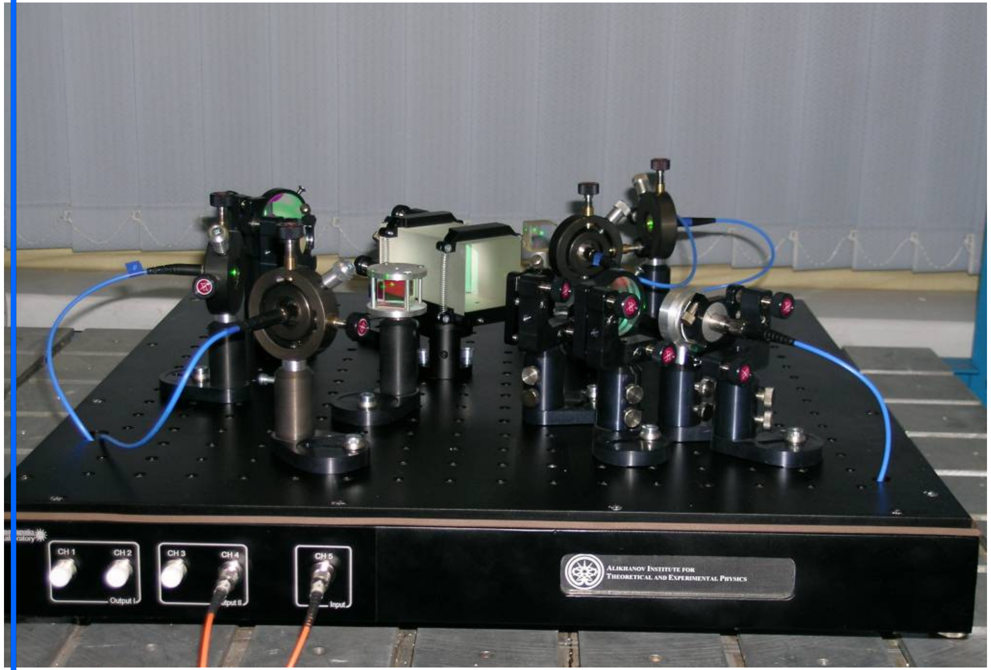


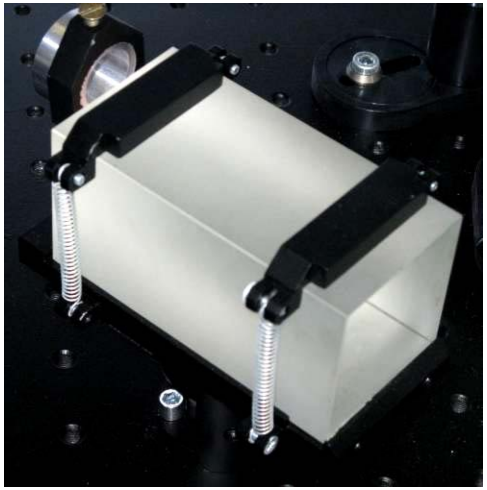




LASER DOPPLER VELOCITY METER IN HIGH ENERGY DENSITY PHYSICS RESEARCH.

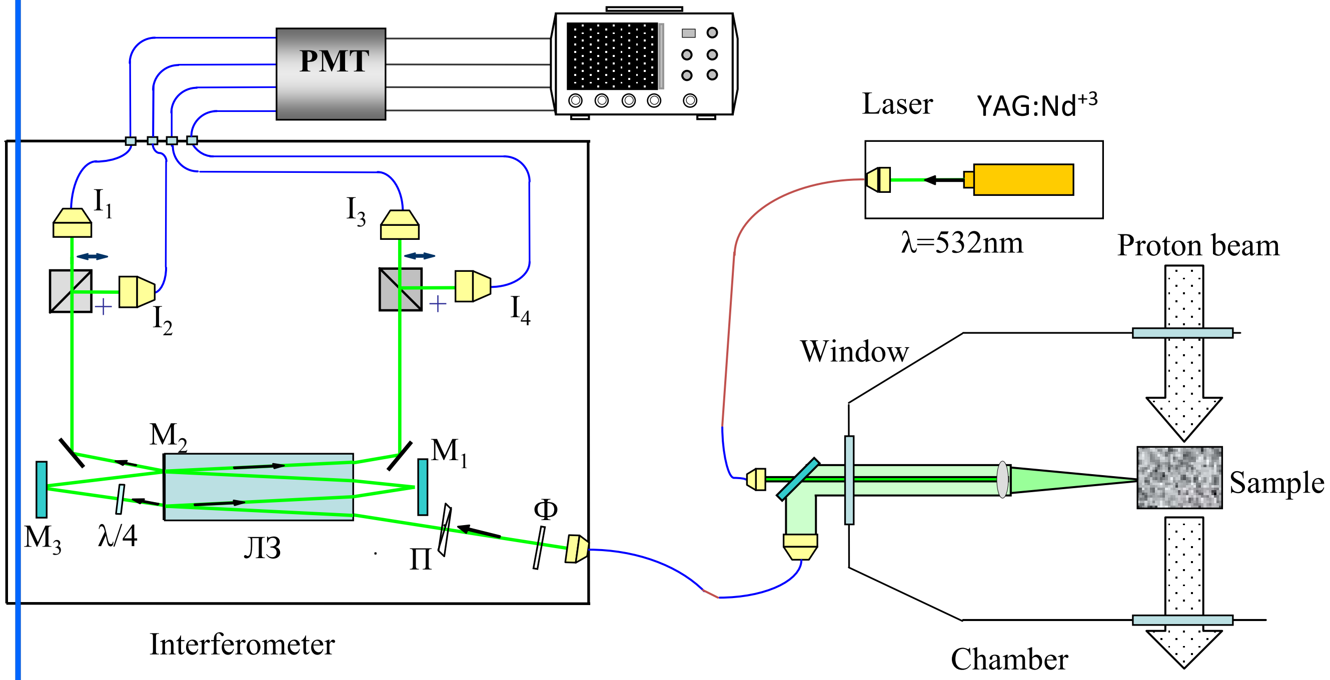
Contactless and remote measurement of target speed under the influence of the intensive dynamic loadings caused by shock waves allows to receive experimental data about elastic-plastic and kinetic properties of materials of various classes.





Main parameters :
Measurement range: 50 -10000 m/s.
Accuracy: 1%
Time resolution: $2 \cdot 10^{-9}$ s.
Spatial resolution: $1 \cdot 10^{-4}$ cm.

Scheme of VISAR
(Velocity Interferometer System for Any Reflector)



1. *Spatial and spectral filtering.*
2. *Protection against mechanical vibrations and electromagnetic noise.*
3. *Measurement range*

   5 m/s< V < 10 km/s.
4. *Compact scheme.*

$$I_1 = I_0 \sin 2\pi N(t) + A(t)$$

$$I_2 = I_0 \cos 2\pi N(t) + A(t)$$

$$I_3 = -I_0 \sin 2\pi N(t) + A(t)$$

$$I_4 = -I_0 \cos 2\pi N(t) + A(t)$$

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

Laser

DTL-317

- Wavelength 532 nm
- Output Power 50 mW (CW)
- TEMoo
- Single Longitudinal Mode
- Linear polarization
- Line Width 0.00001 nm
- Coherence Length 50 m

  Beam
- Divergence (full angle,) 0.6 mrad
- Diameter At Output 1.1 mm
- Noise (10 Hz – 20 MHz) 0.5% RMS (typ. 0.1%) and 2% p-to-p (typ. 0.5%)
- Long Term Stability 2 %/8 hour

Laser-compact group
Laser-export Co.Ltd

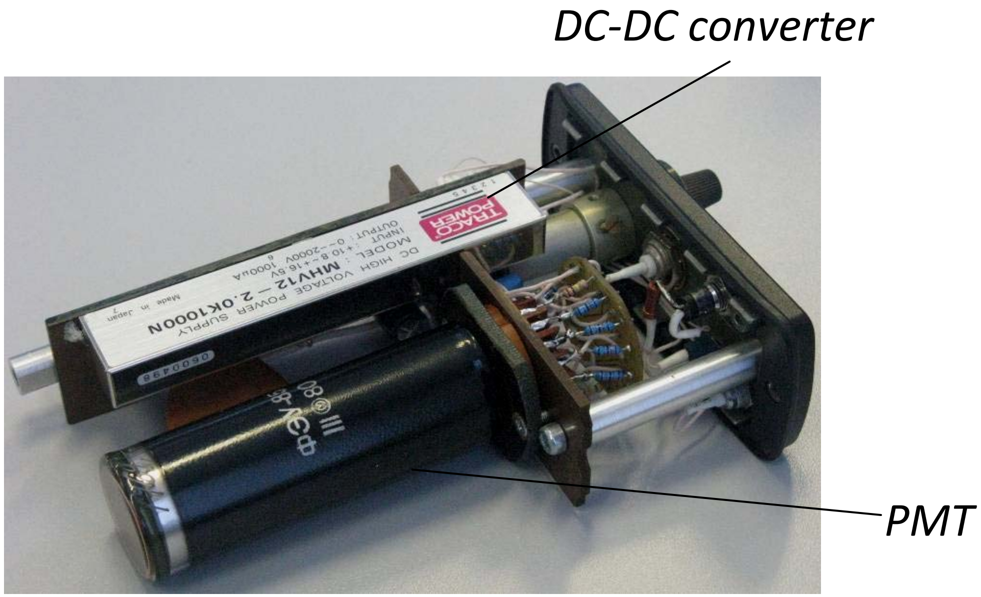
Photomultiplier

Active voltage divider circuit of PMT (having FETs in place of the dividing resistors) was designed to improve the output linearity. It allows to provide measuring of fast processes in continuous regime.

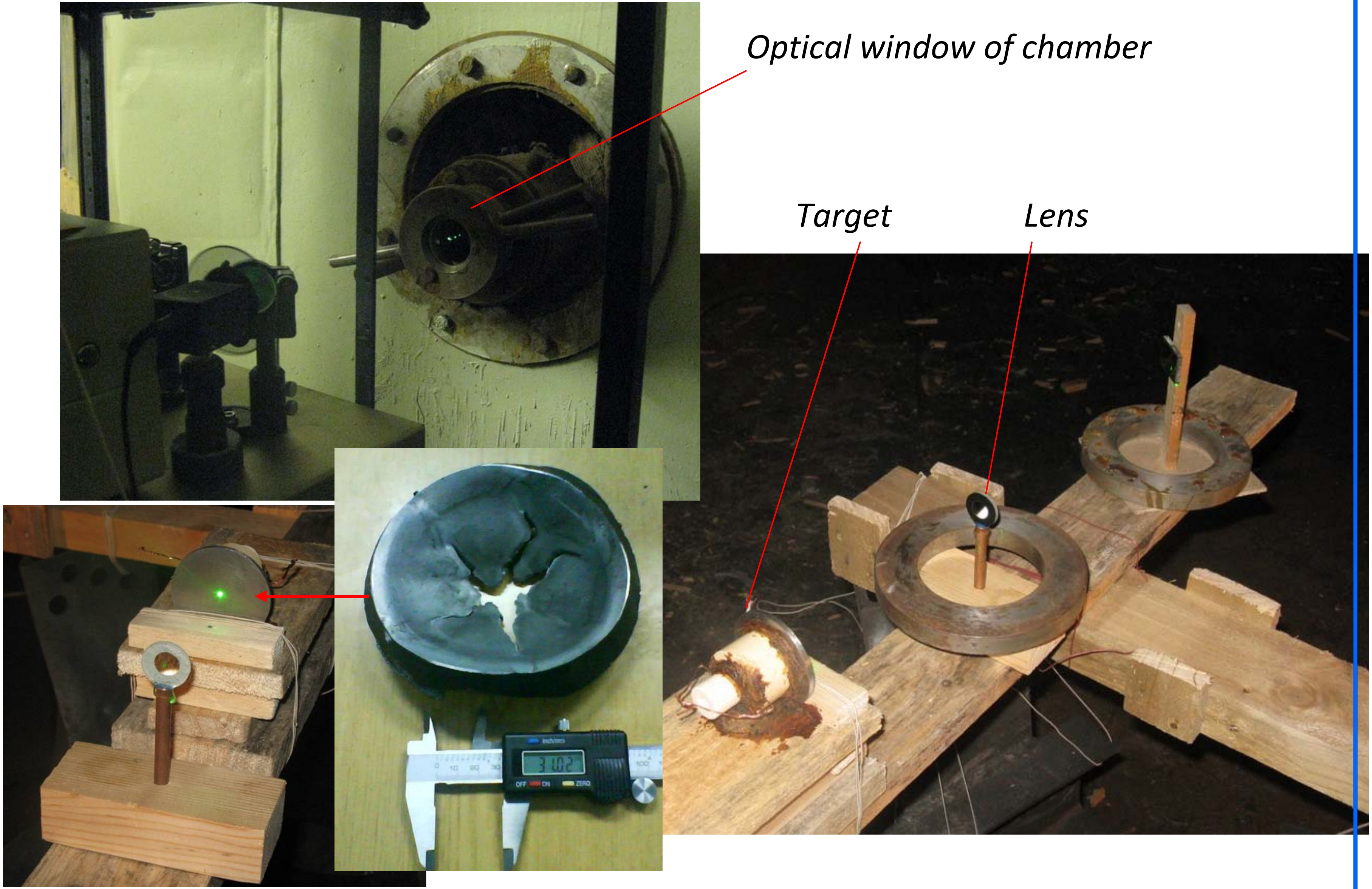
Rise time ~ 2 ns

Fiber input with FC connector

12 V input voltage



Testing experiments in IPCP RAS (Chernogolovka)

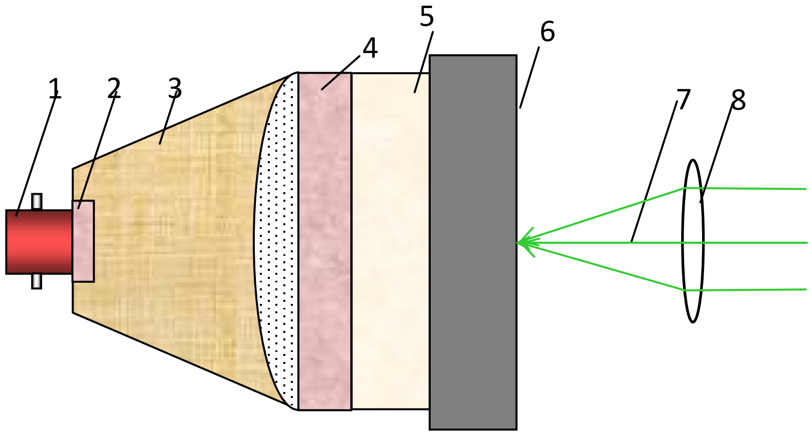


Optical window of chamber

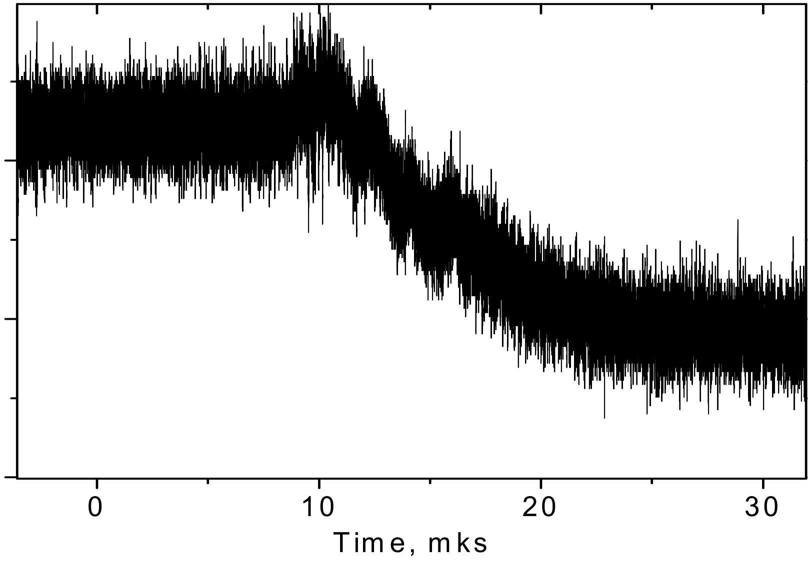
Target

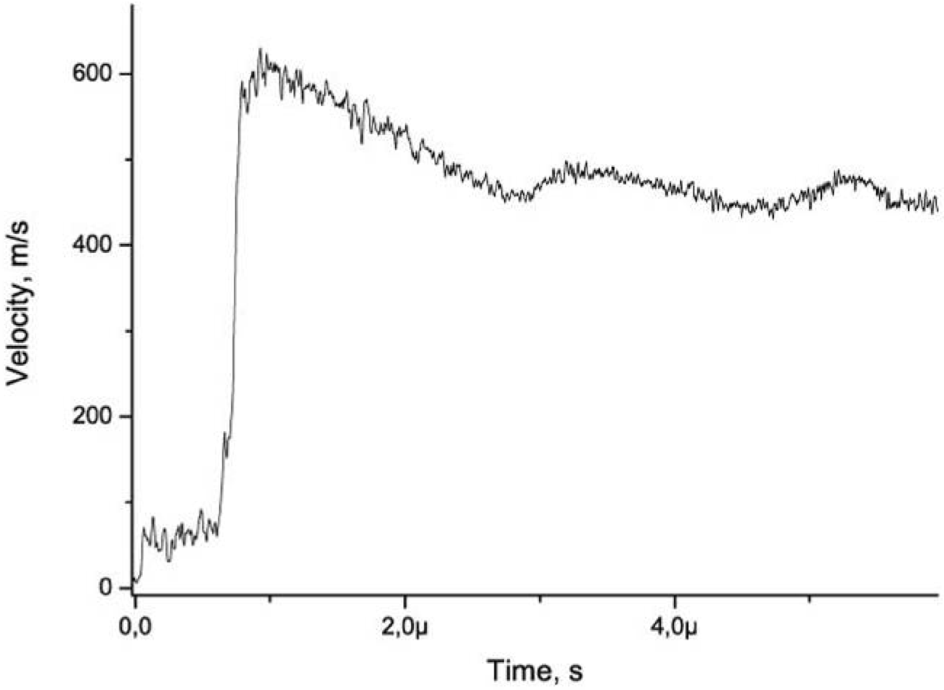
Lens

Registration of a profile of mass speed in steel

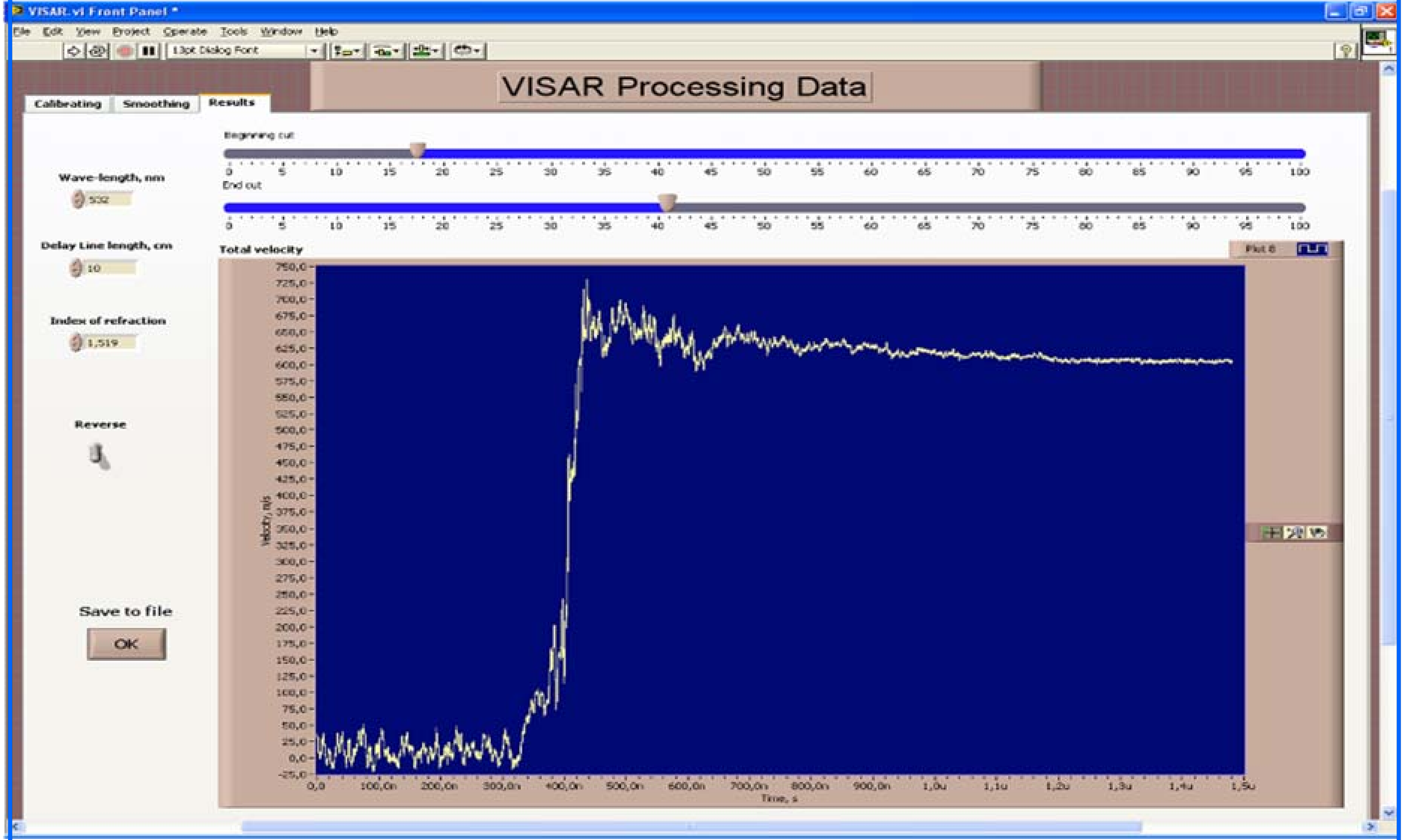


1. **Electrical detonator ЭД АТЭД- 4.000.8;**
2. **Layer П-84 – 4 mm;**
3. **Plane wave generator А36-Л118.880 ∅90;**
4. **П-84 – 10 mm;**
5. **ОЛП-25Т – ∅40x30 mm;**
6. **Steel plate;**
7. **Probing laser radiation λ=532 nm;**
9. **Focusing lens.**





Data processing

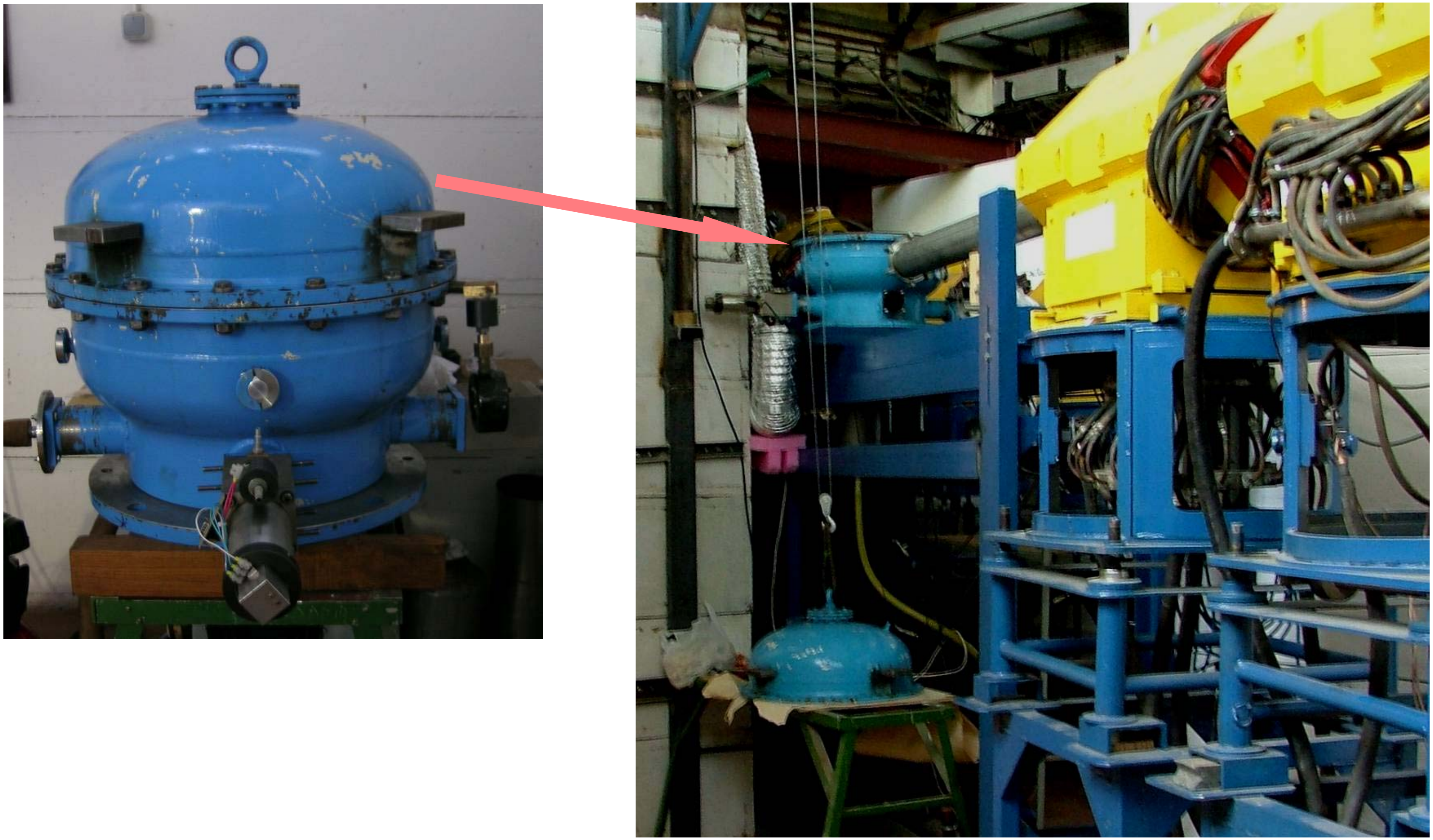


Wave-length, nm: 532

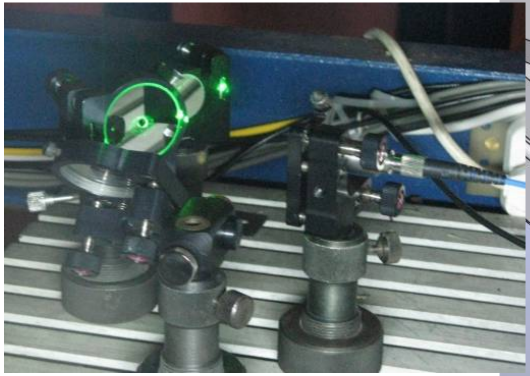
Delay Line length, cm: 10

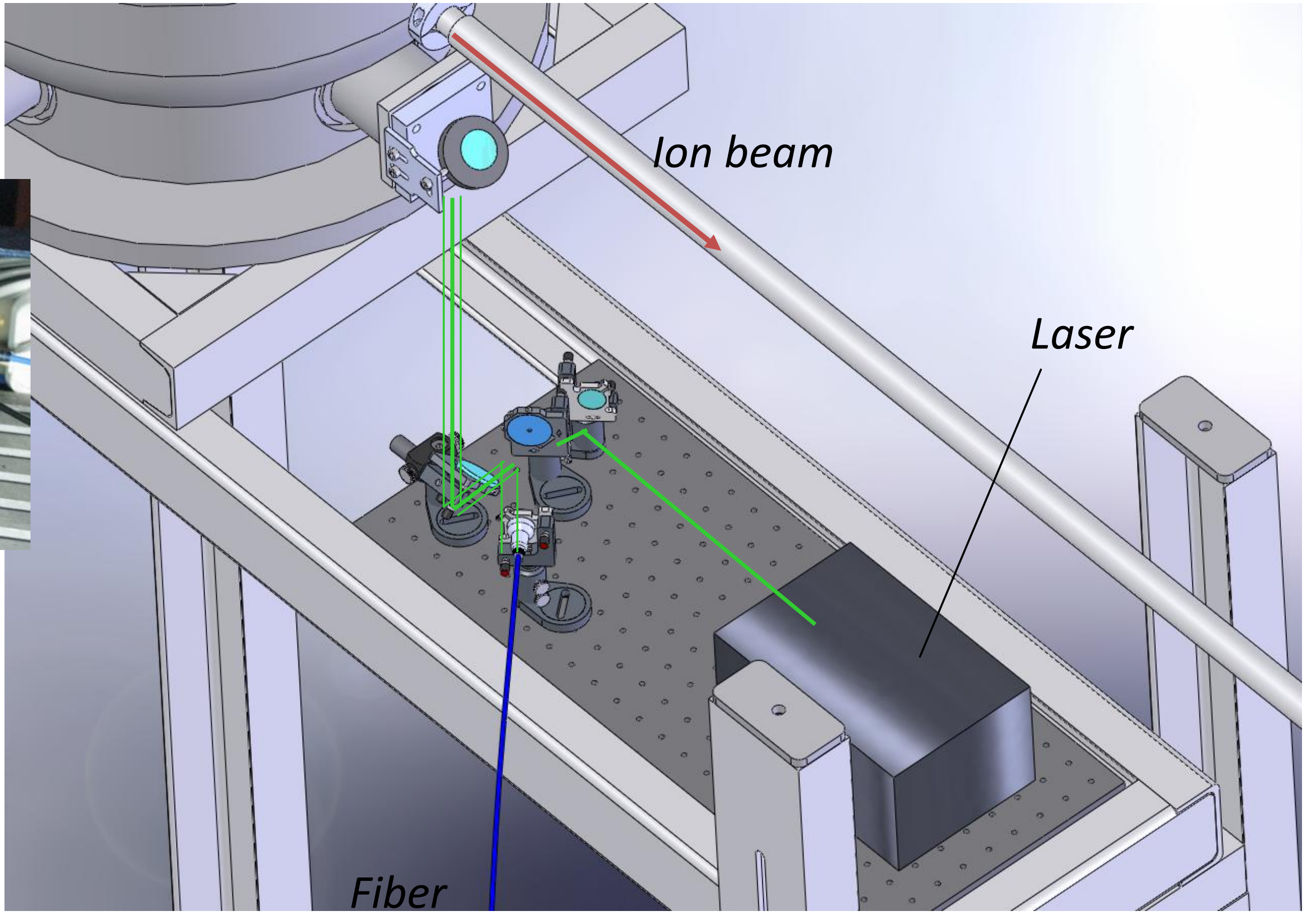
Index of refraction: 1,519

Protective Target Chamber

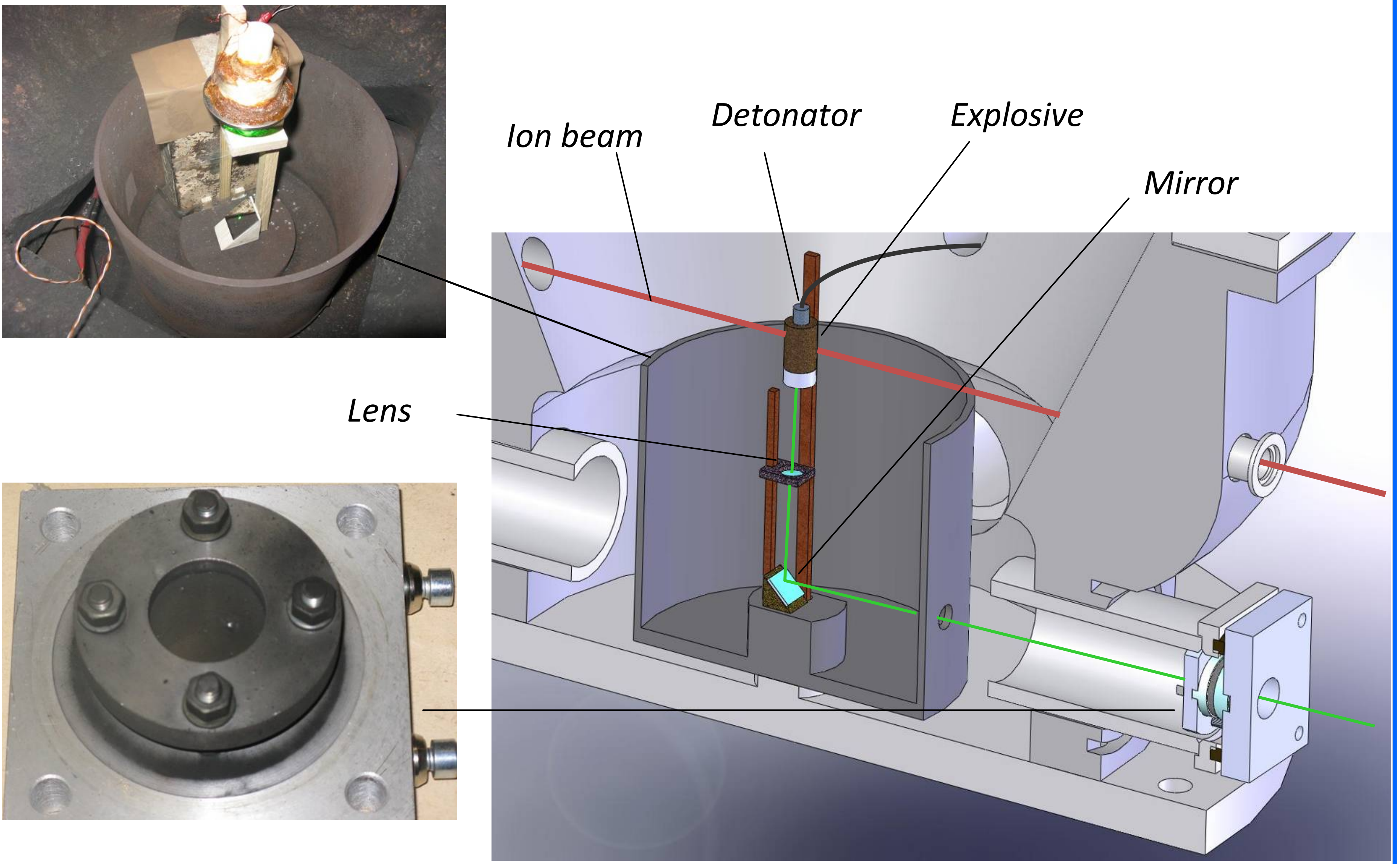


External part of the optical scheme





Internal part of the optical scheme



Conclusion

- ***ITEP-TWAC project is well in progress:***
  - ***The Fe ions accelerated up to relativistic energy.***

- ***The focusing plasma lens are optimized for different application.***

- ***Dynamic experiments are performed on ITEP-TWAC Proton Radiography Facility.*** **The next gain in radiographic capability will come from combining multi-GeV protons with magnifying lens systems.**

- ***The prototype of the MQL for PRIOR manufactured. The main advantage of the developed MQL :***
  - ***High magnetic field 1.6 T***
  - ***High linearity of the magnetic filed less than 0.5%***

- ***Prototype of wobbler beam for ITEP and LAPLAS experiments are started to manufacture. A prototype cell was constructed and manufactured.***

- ***Mass speed measuring system allows to work with diffuse reflecting surfaces of objects. The system consists of unifrequent solid-state laser, the optical block, system of photoregistration of small optical signals***