ITEP activities in physics of intense ion and laser beams

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ITEP, Moscow

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Participations

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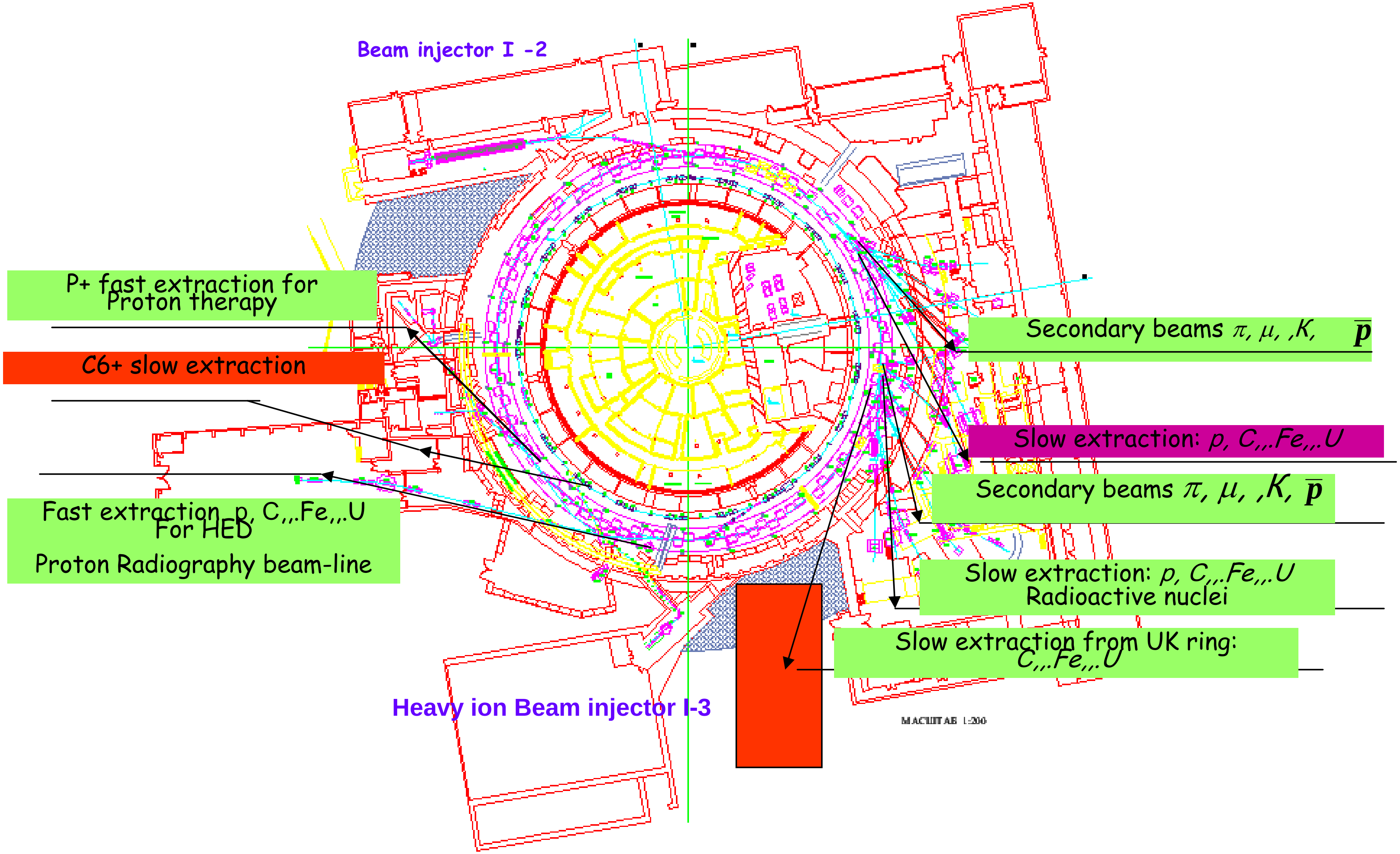
Contents

- Status of ITEP-TWAC facility
- Plasma lens focusing development.
- Proton radiography systems for dynamic processes
- Wobbler development for LAPLAS experiment.
- Stopping range measurement of ion beam in porous targets.

ITEP-TWAC Accelerator Facility in Progress



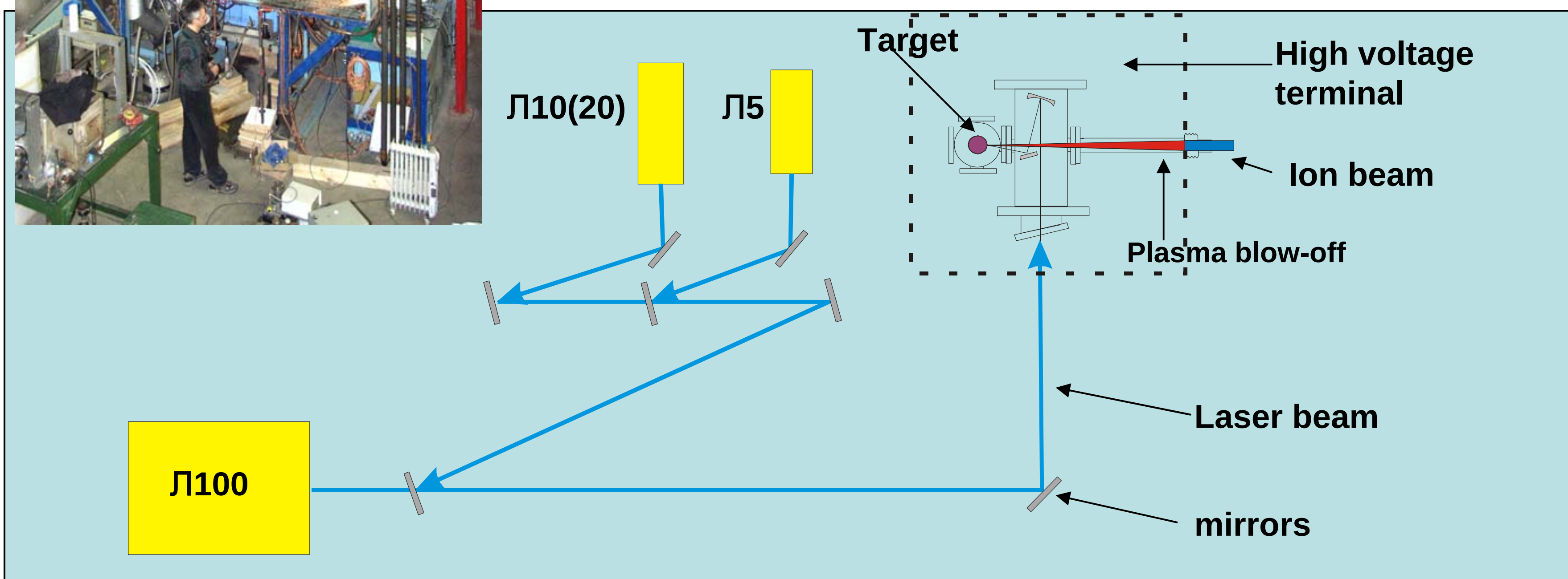
Key element: New triple - laser ion source pre-injection system (L5, L10, L100)

Laser L100

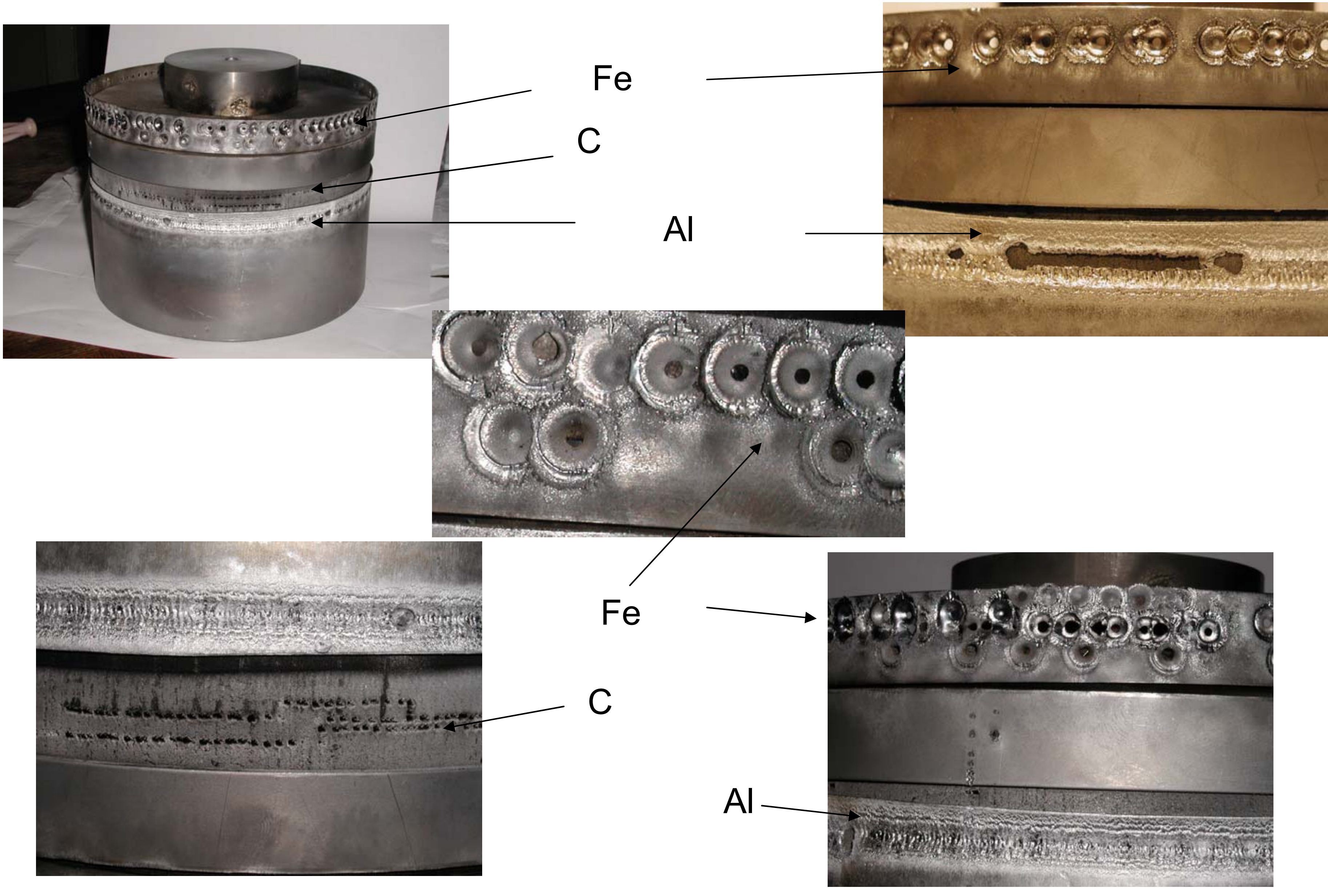
3 mA 80 MeV Fe^{16+} Measured !

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

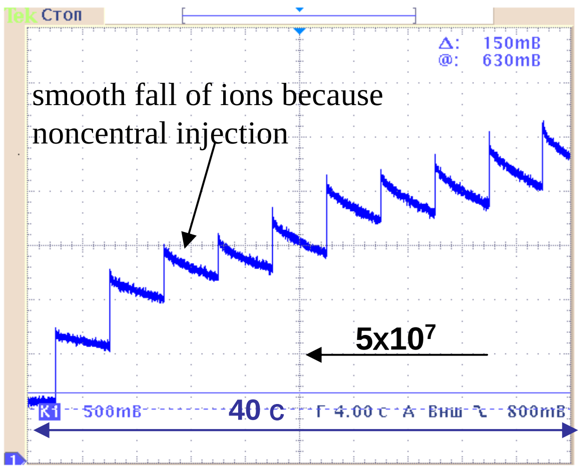


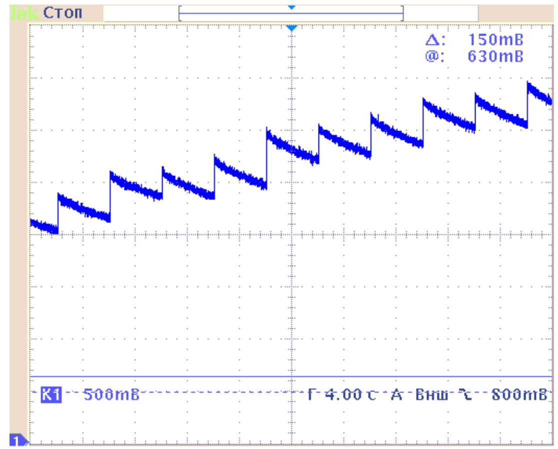
Target assembly after 3-weeks operation cycle



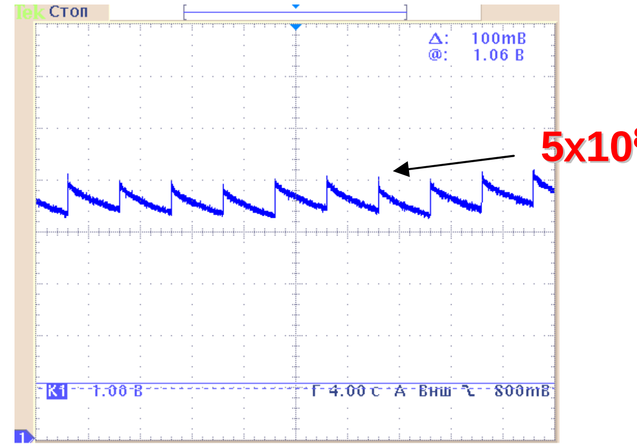
First experience with $Fe^{16+} \Rightarrow Fe^{26+}$ stacking

Stacking of the $Fe^{16+} \Rightarrow Fe^{26+}$ beam in U-10 Ring



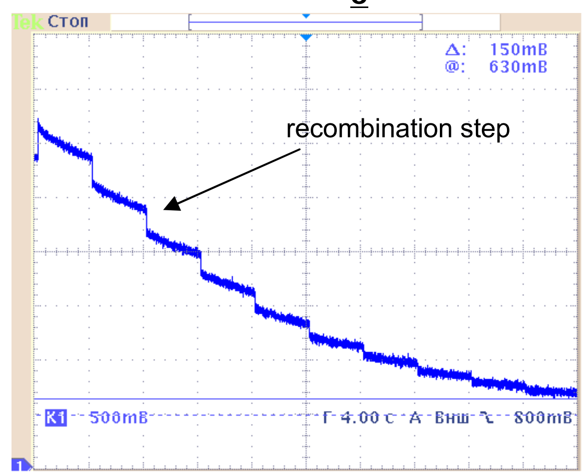


Maximum intensity of Fe^{26+} stacked beam $k_{\propto} \Rightarrow 10$

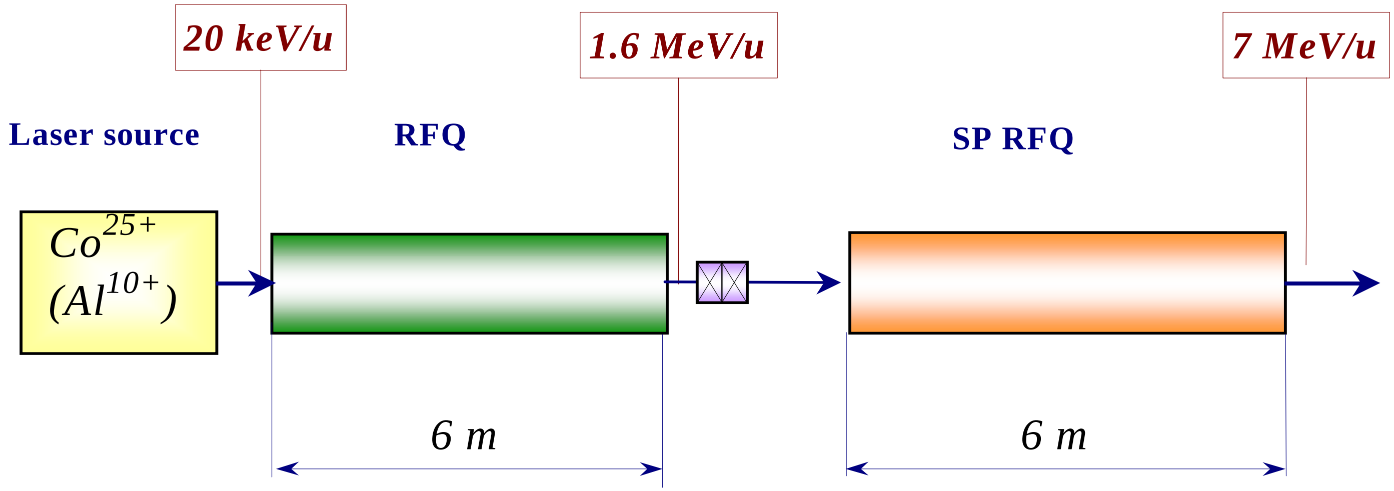


Beam energy	165 MeV/u
Target material	Mylar
The thickness of the target	1,5 mg/cm^2
The target size	10x20 mm^2
The cross section of ionization	~3x10^{-21} cm^2
The cross section of recombination	~7x10^{-23} cm^2
The frequency of injection	0,25 Hz

Stacked beam life time in the U-10 Ring at kickers on, τ_0=16 s

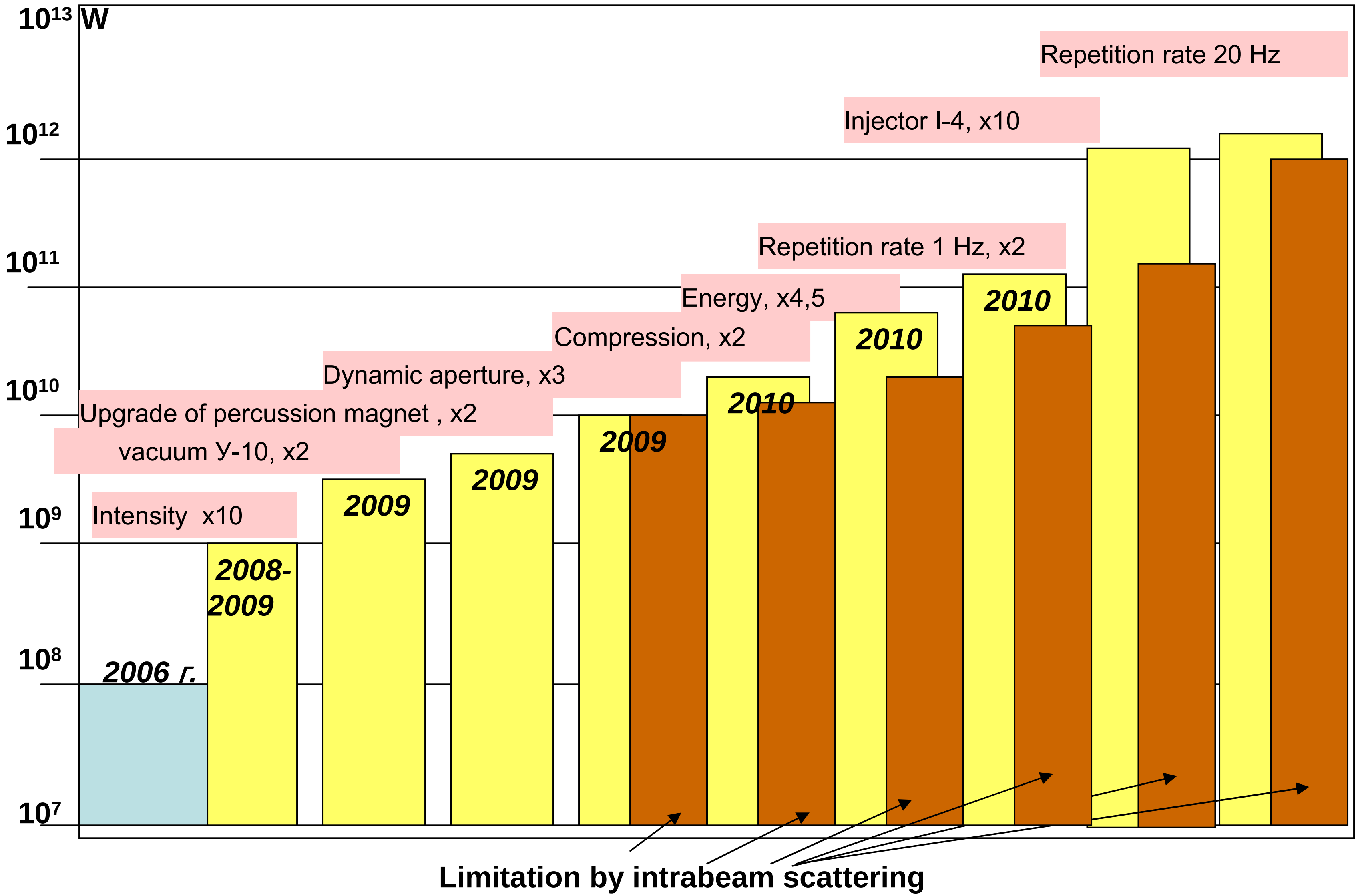


Layout of the new injector Linac

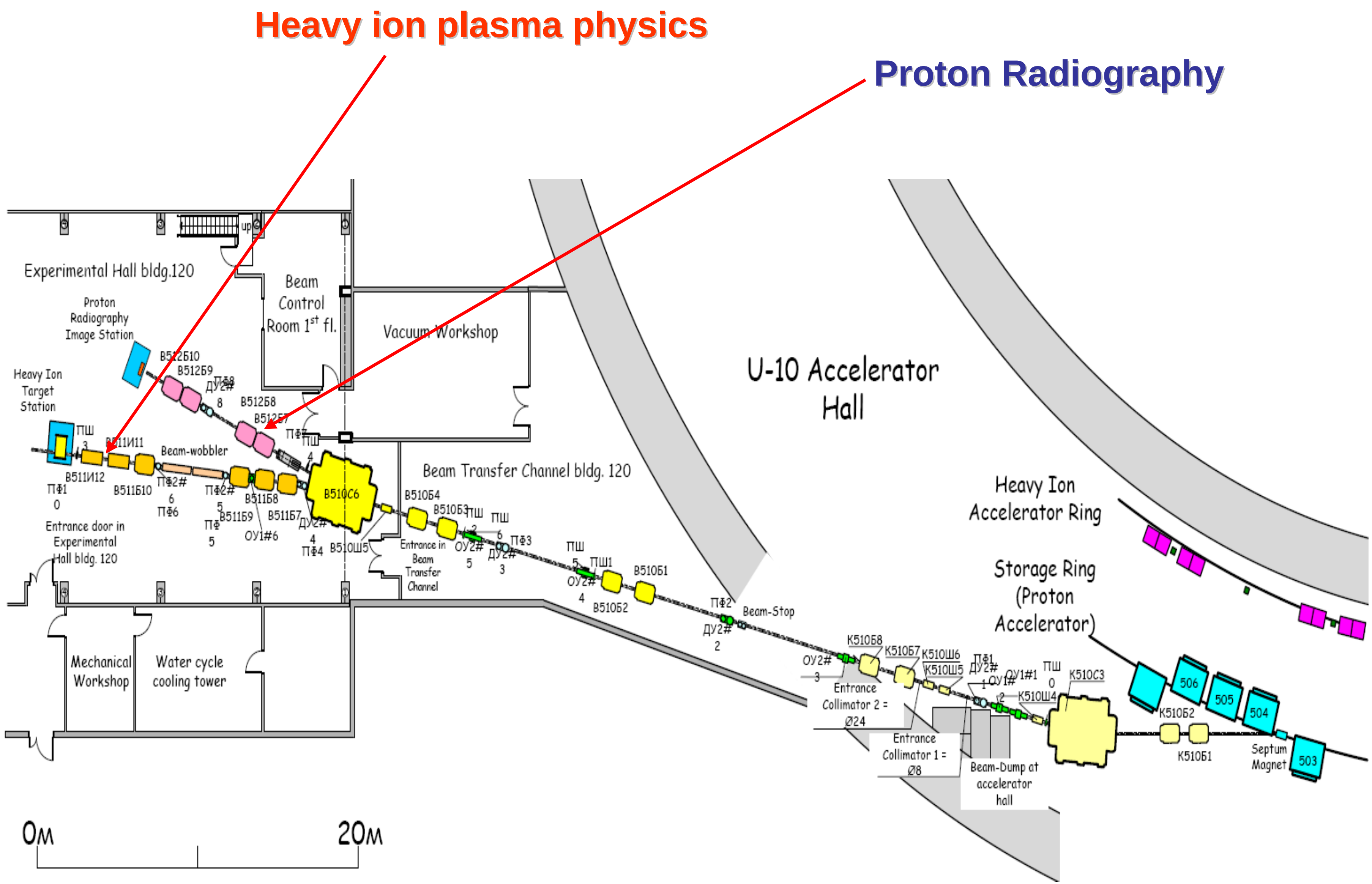


Output energy	*7 – 8 MeV/u*
Beam pulse duration	*15 μs*
Beam current of the main component	*16 mA*
Beam emittance	*4π mrad*mm*
Operation frequency	*81.4 MHz*

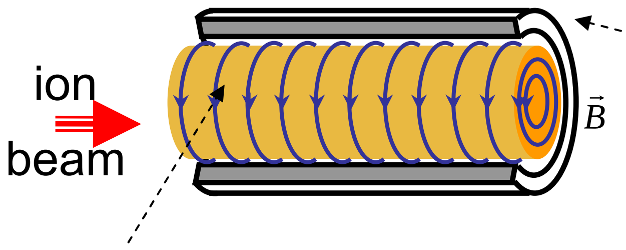
Road map to beam intensity upgrade



Plasma Physics Experimental Area on TWAC Facility



Plasma lens focusing- at GSI



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

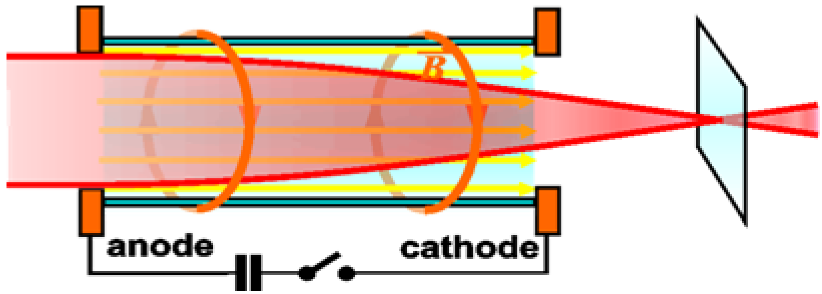
$$d_{min} \sim \varepsilon I^{-1/2}$$

Advantages of plasma lens :

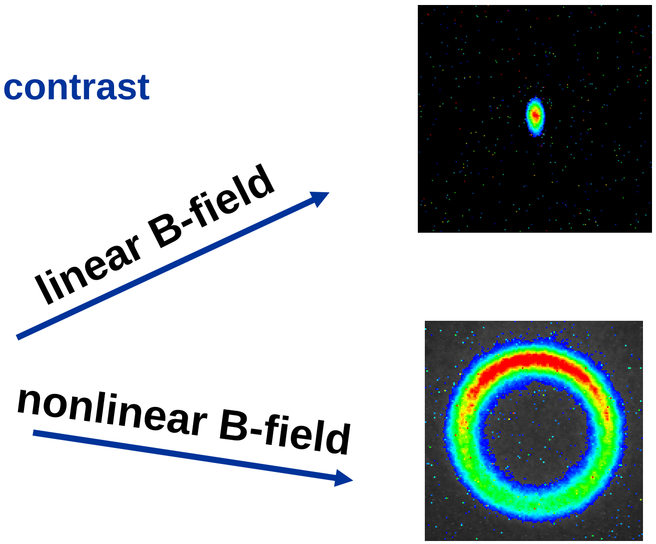
- **focusing area has symmetric first order focusing;**
- **there is no limit for the magnitude of the magnetic field connected with saturation;**
- **charge neutralization of ion beam into the plasma lens ;**
- **beam rigidity decreases by the reason of the stripping of electrons from not fully ionized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

Disadvantages:

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

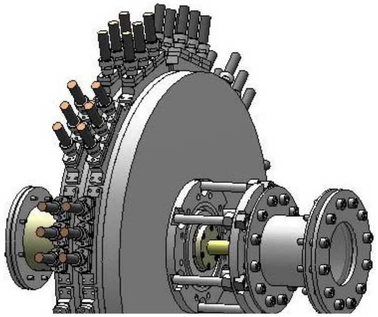


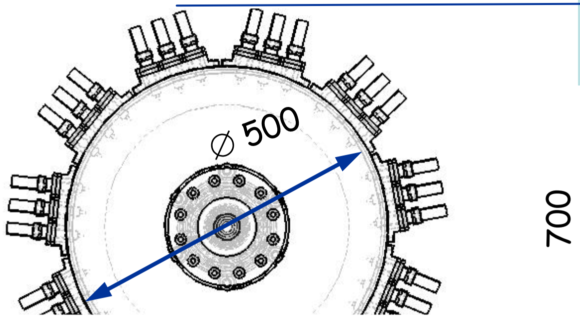
focal beam spots

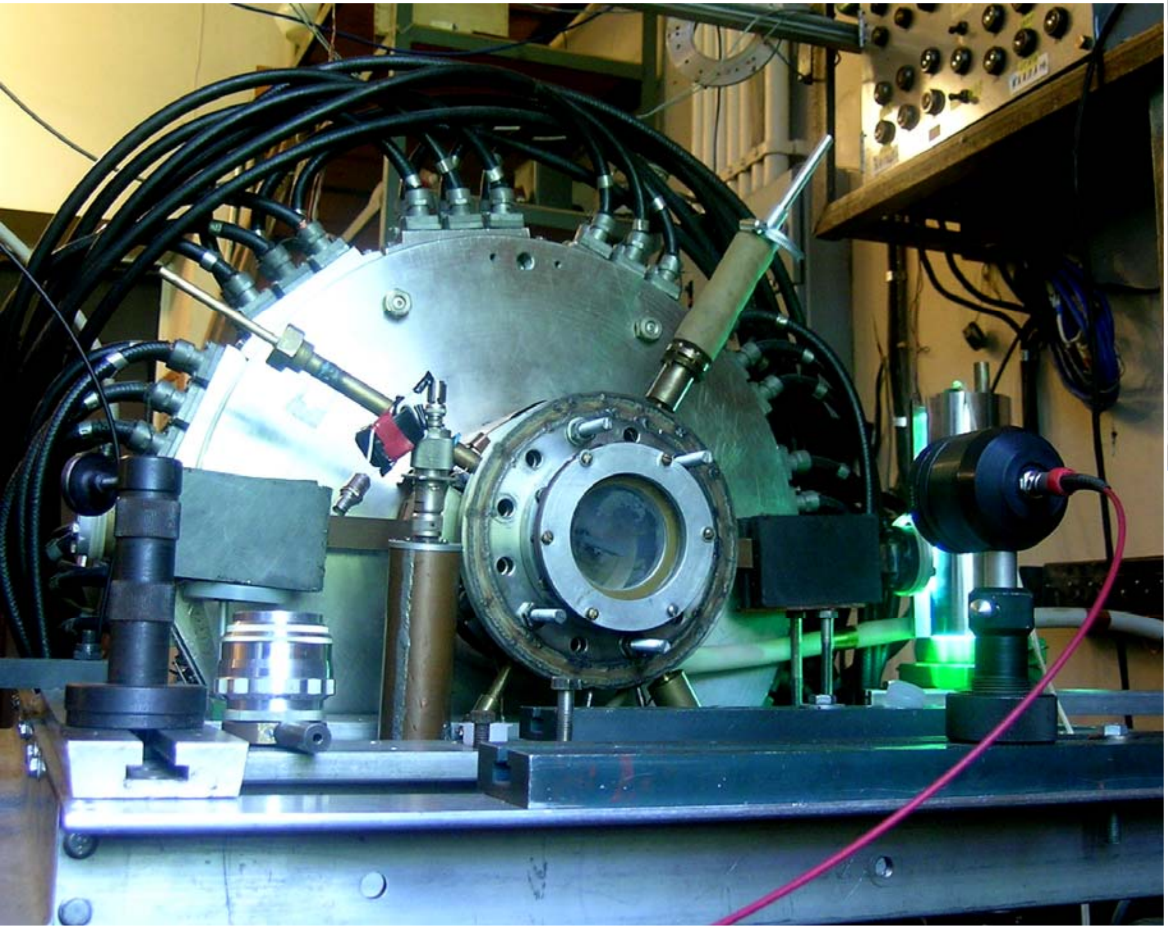


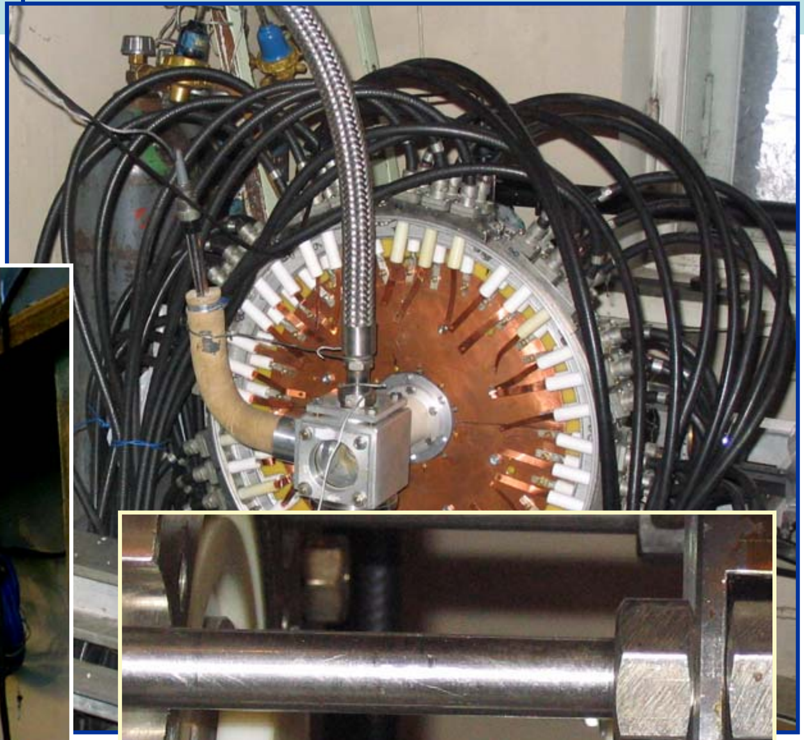
General view of ITEP plasma lens

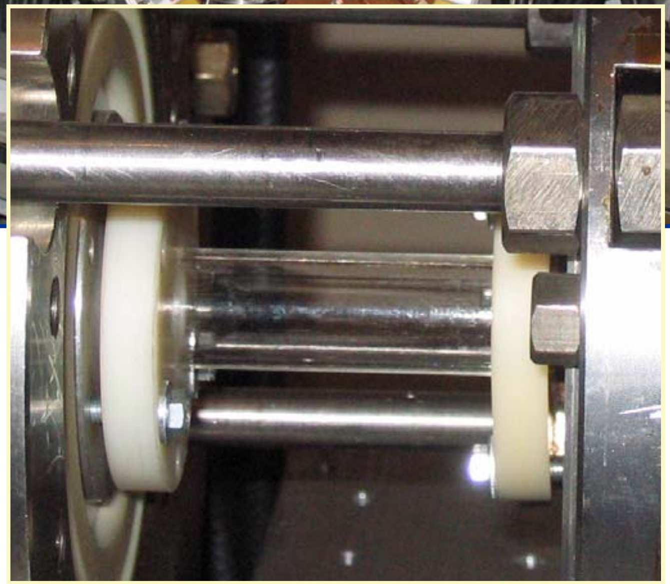
I_{max}= 300 кA, R = 10 mm, L = 100mm.









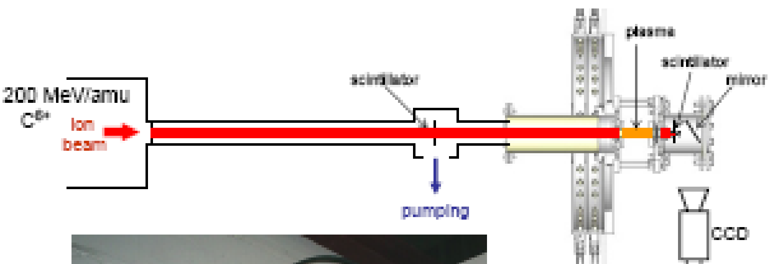


ITEP 300 kA plasma lens: experiments and results

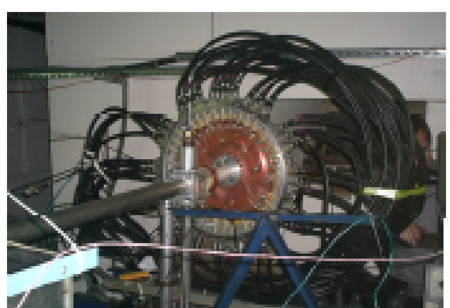
plasma lens at experimental area

At present time the plasma lens have been designed and fabricated. Study of dynamics of the R-T behavior of the plasma discharge has been started. Investigation of plasma discharge formation has been conducted and the range of parameters has been determined where the spatial distribution of the current density may be homogeneous.

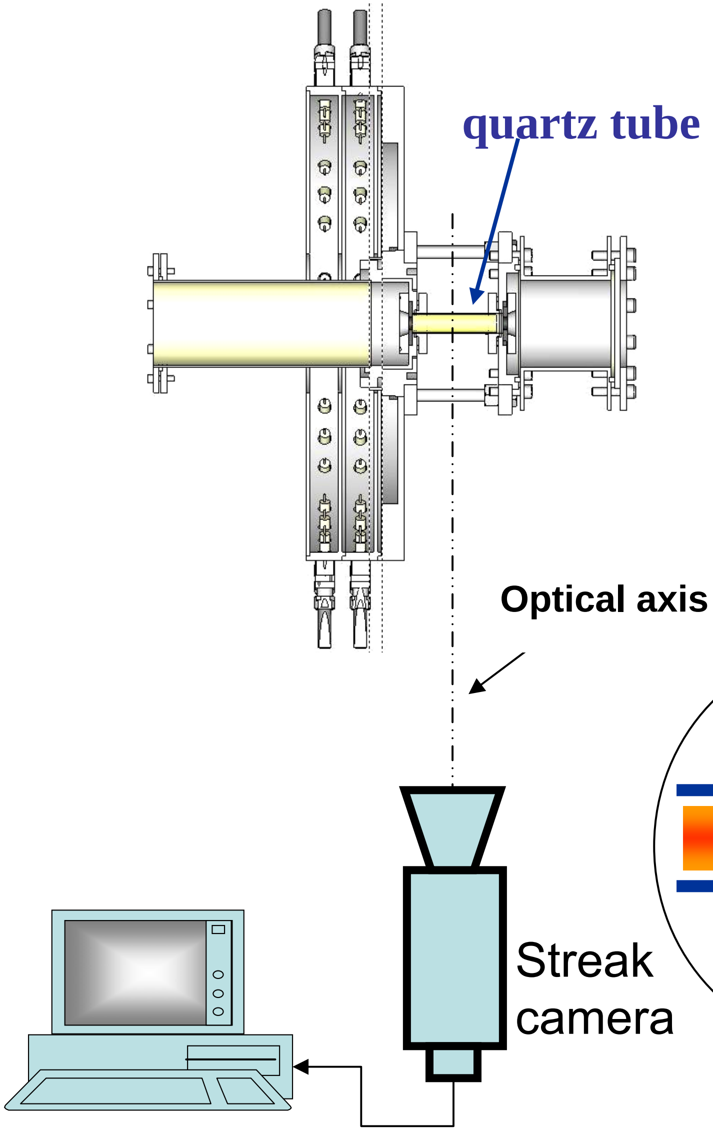
Next stage of optimization efforts aimed at reaching the required focusing ability of the plasma lens. It has been began lens testing by focusing of a carbon ion beam.

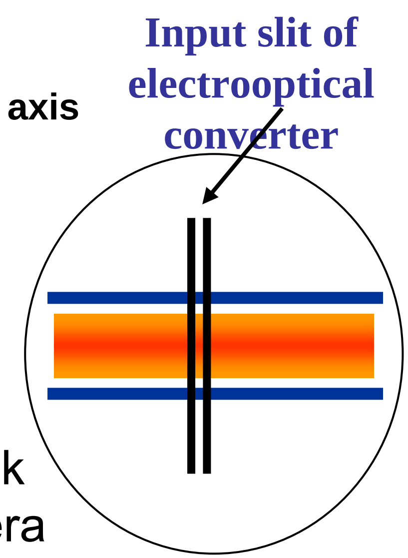


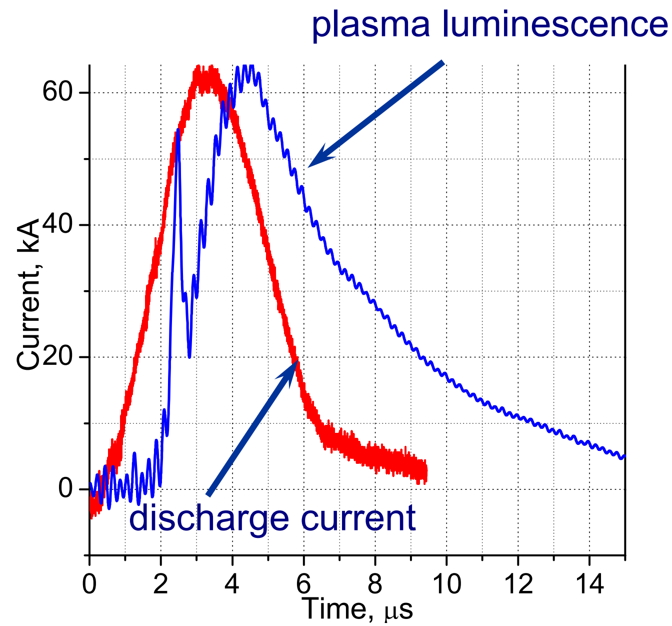
The beam spot was observed downstream of the plasma using a quartz scintillator which was positioned at 50mm behind the end of discharge tube. The emitted scintillator light was monitored using CCD framing photography.

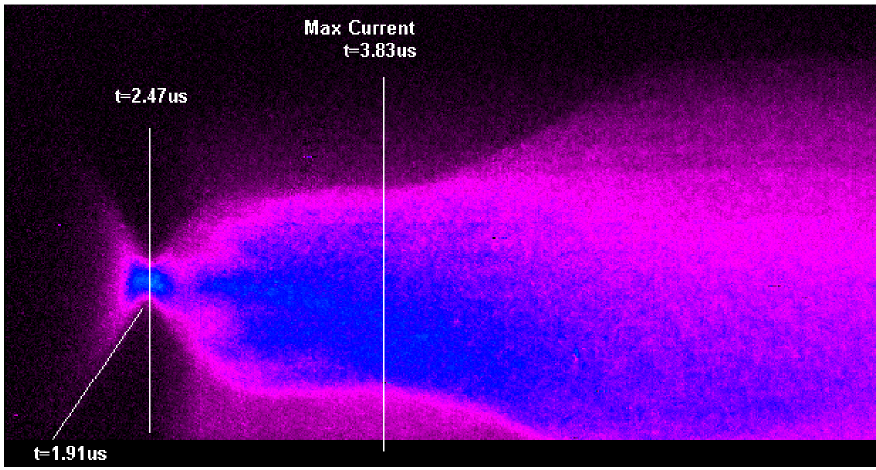


Investigation of the plasma dynamics by streak-camera



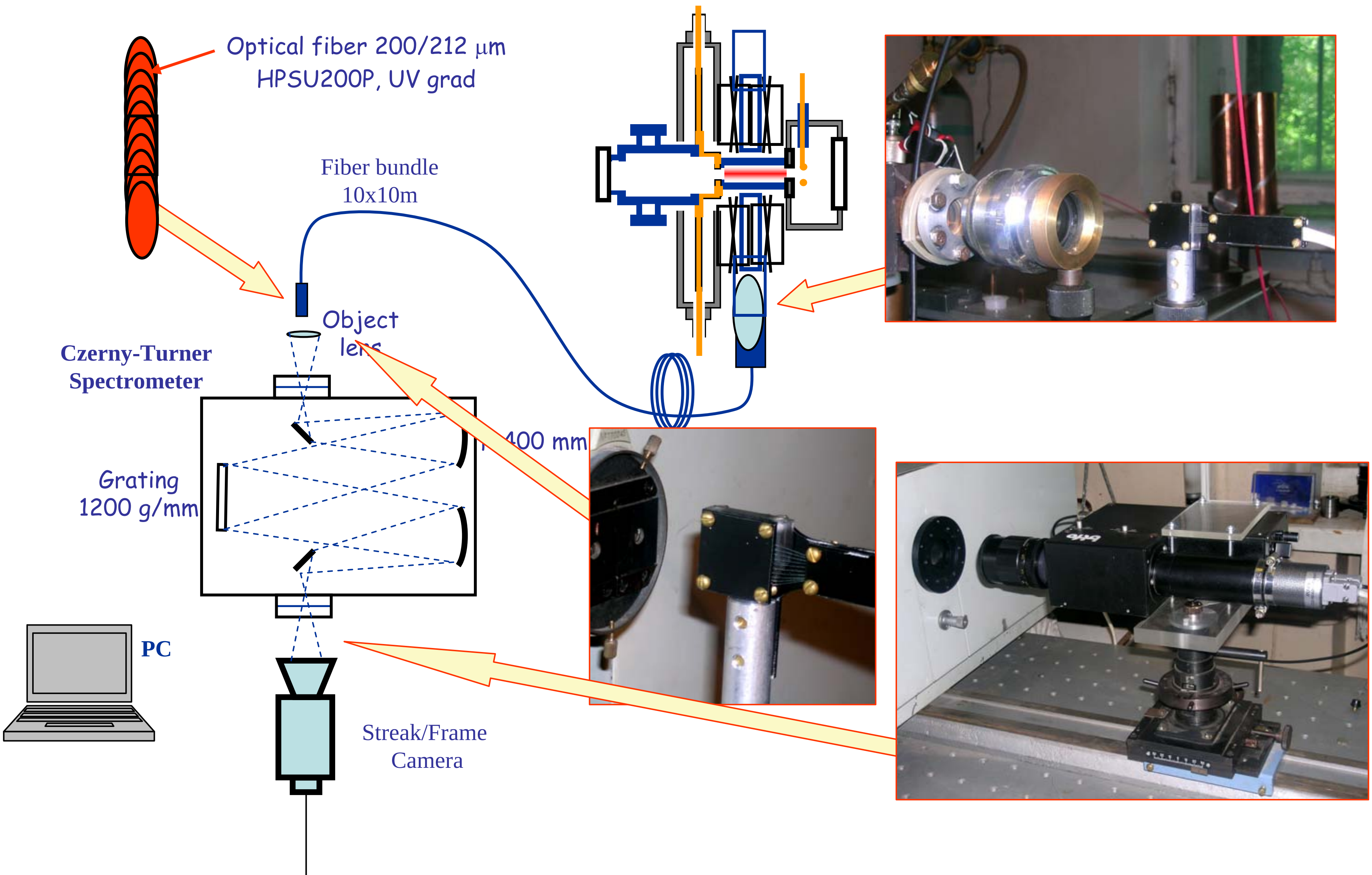




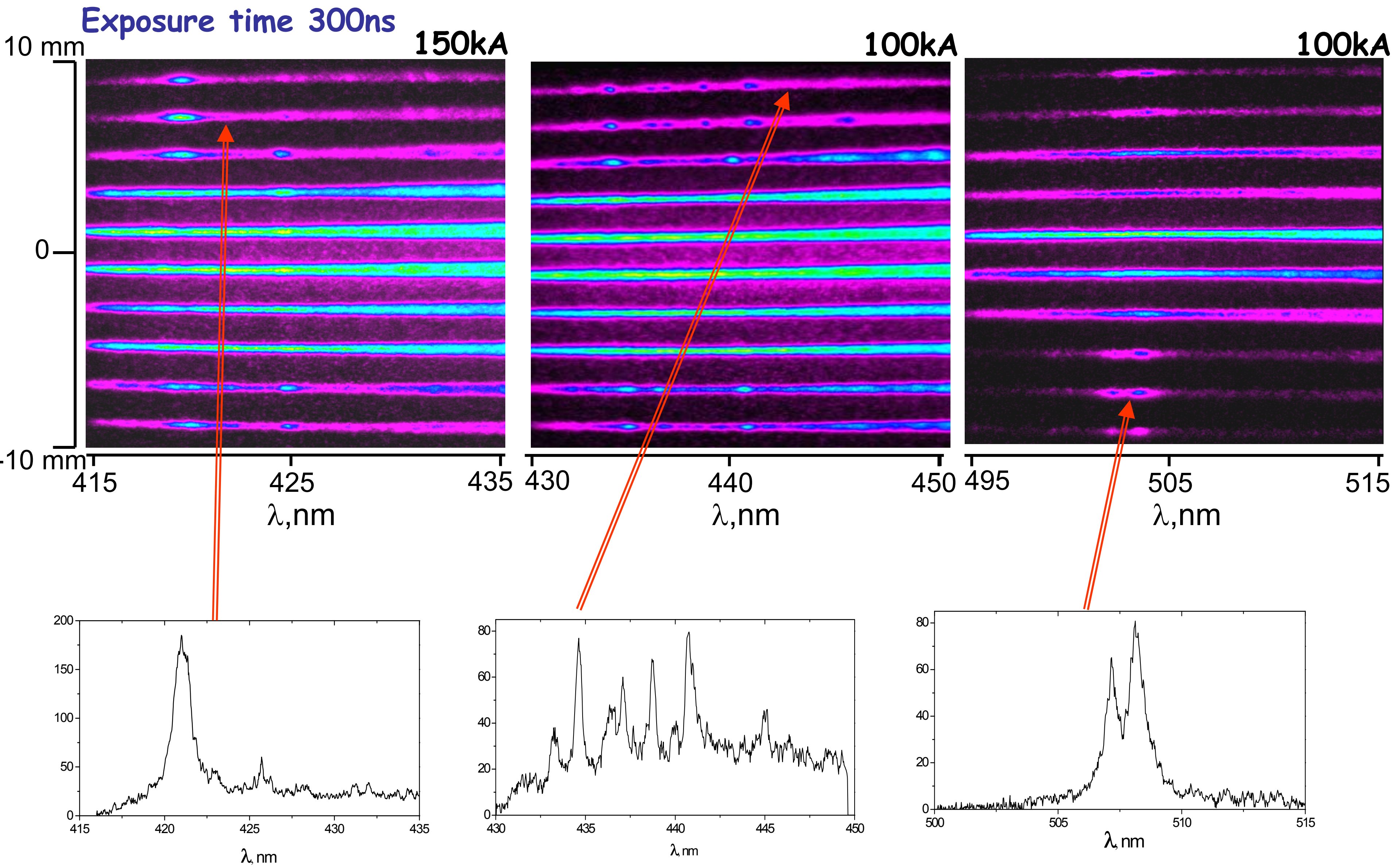


Time scan of plasma luminescence at argon initial pressure 3.5 mbar and discharge current 200kA (full length – 6 ms, cross section size – 2 cm)

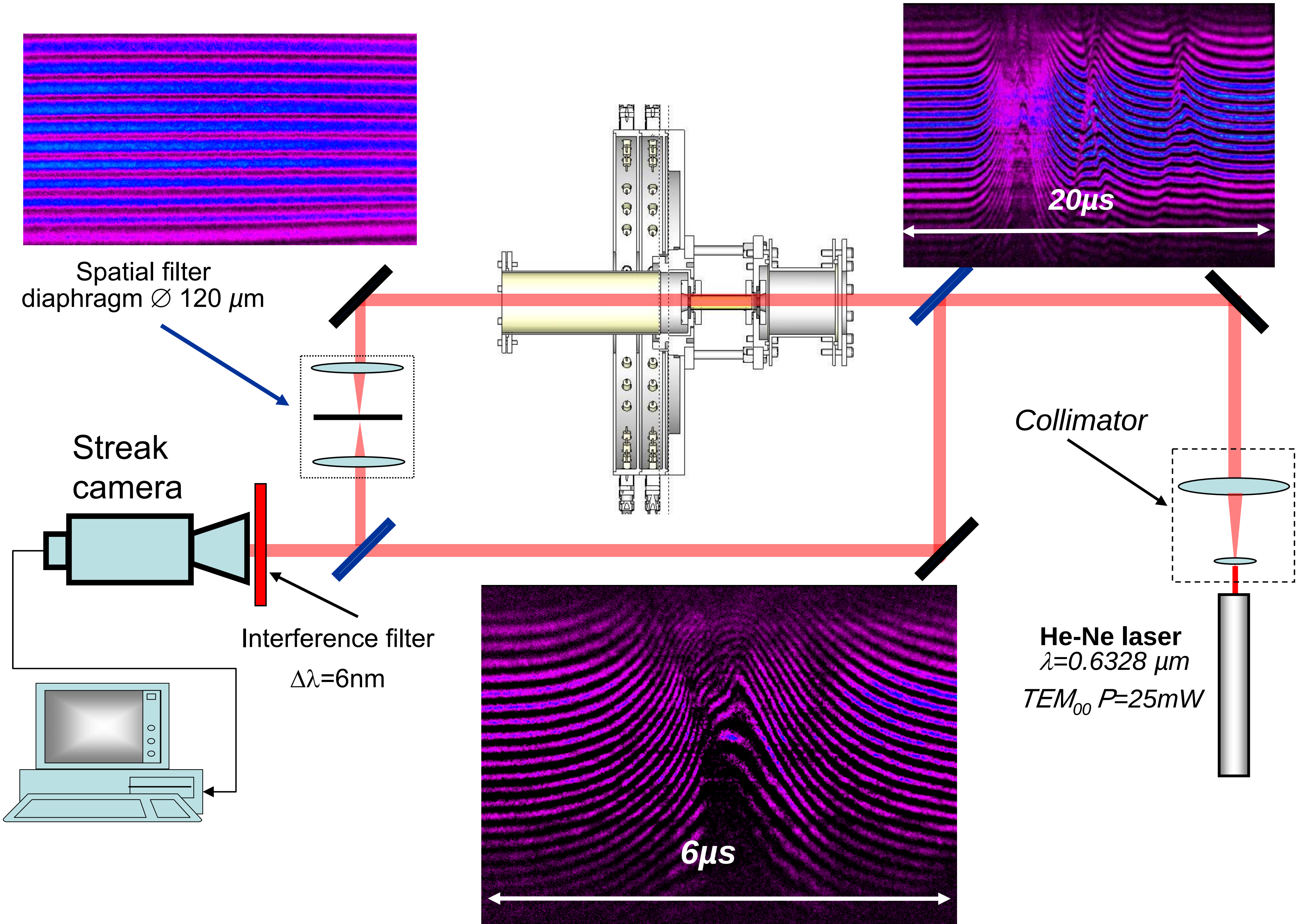
Emission spectroscopy in the wavelength range (360-600 nm) with spatial and time resolution



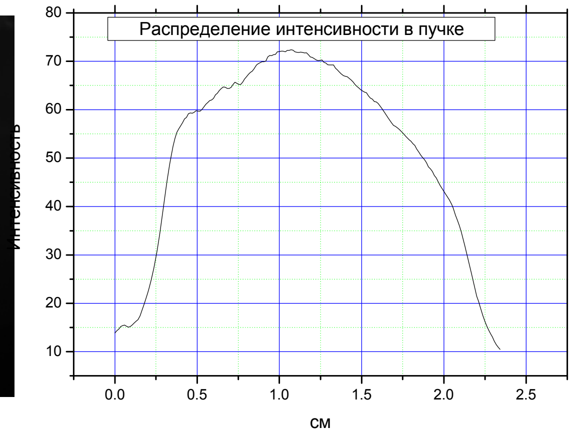
Emission plasma spectra with spatial resolution (maximum current, t=4μs, Ar pressure=5 torr)

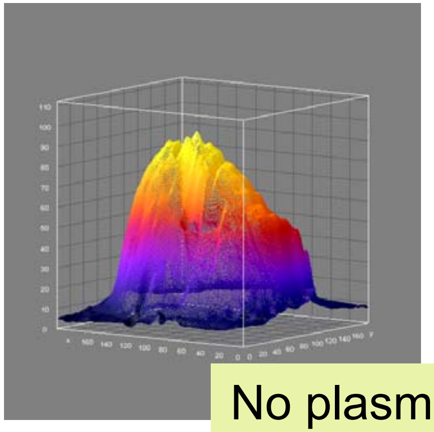


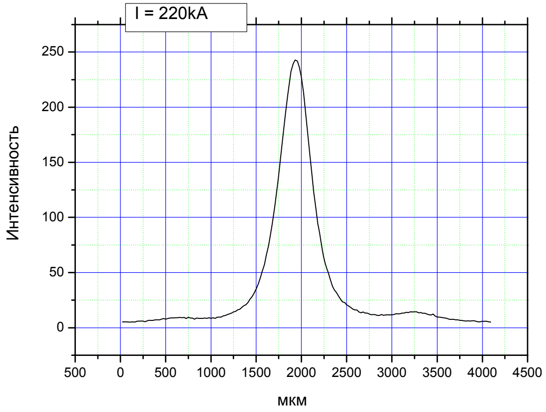
Plasma lens interferometry

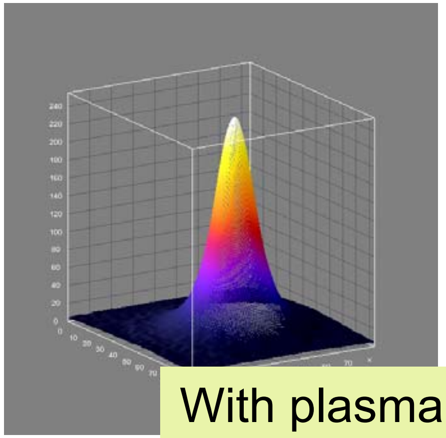


Beam Focusing by Plasma Lens ITEP







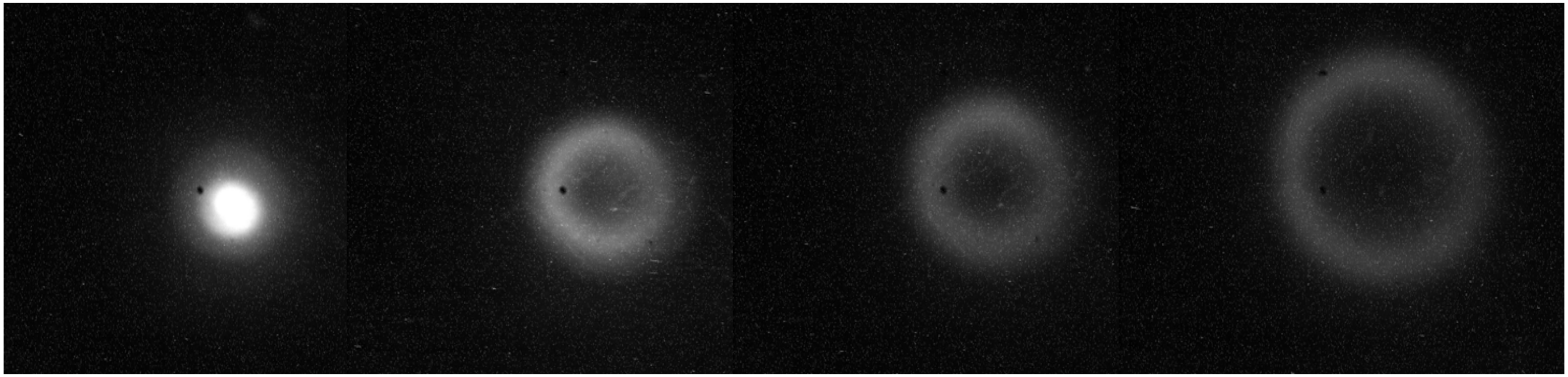


Изображение пучка ионов C^{6+} с энергией **200** МэВ/н и поперечное распределение плотности частиц без фокусировки и с фокусировкой при помощи плазменной линзы: ток в линзе **220** кА, фокусное расстояние **30** мм, размер пятна (на полувысоте) **350** мкм

C^{6+} E = 200 MeV/u, F = 300 mm, D (FWHM = 350 μm)

Plasma lens - Hollow beam

Beam Radius



Distance from the end of the discharge tube to scintillator →

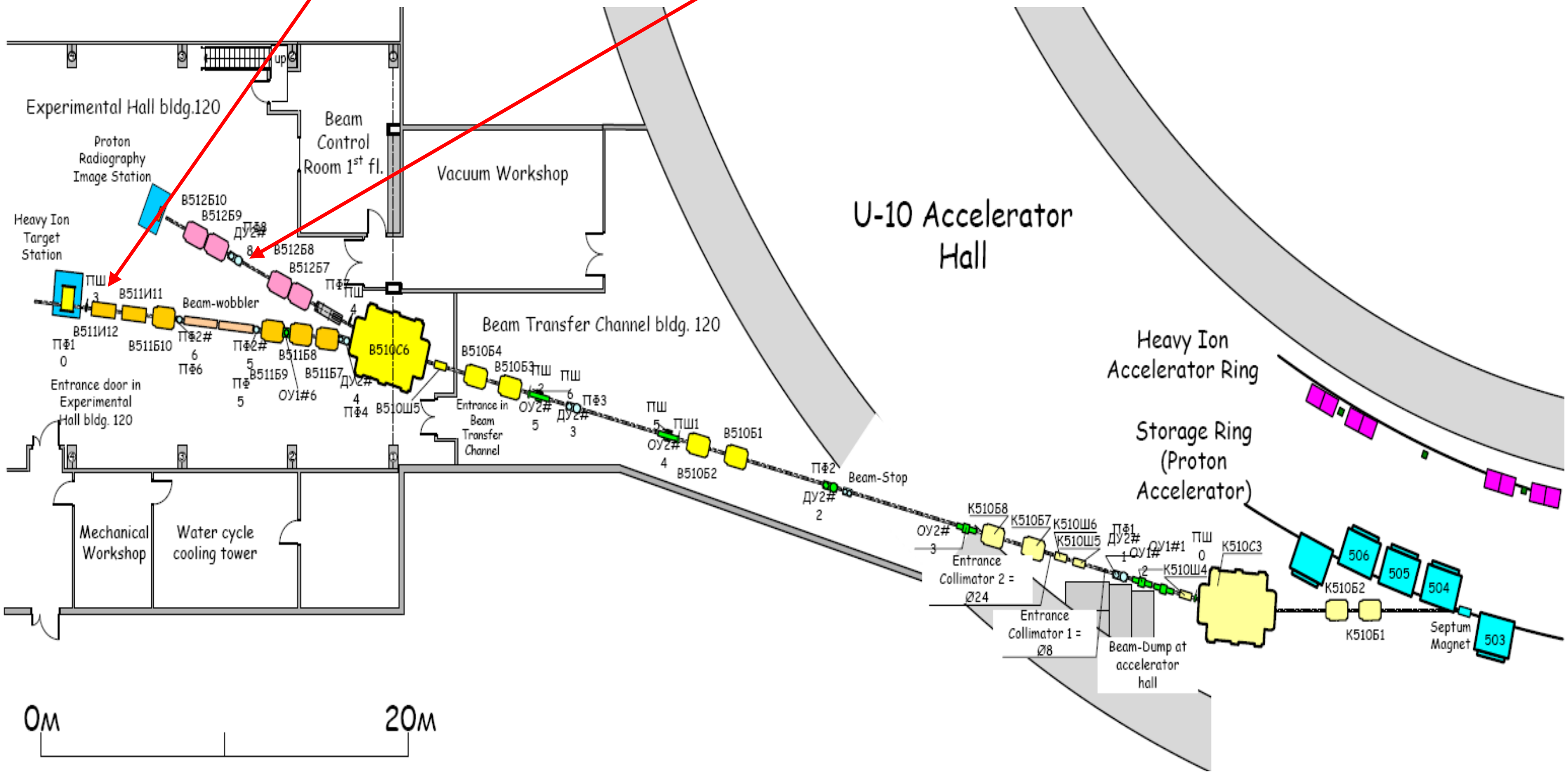
Plasma lens parameters:

I_{max} = 130 kA, p_{Ar} = 6.8 mbar

Plasma Physics Experimental Area on TWAC Facility

Heavy ion beam plasma

Proton Radiography



Proton Radiography Set-up at ITEP-TWAC Facility

ITEP + IPCP RAS + GSI collaboration

Diagnostics of optically thick dynamical objects

Parameters:

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	

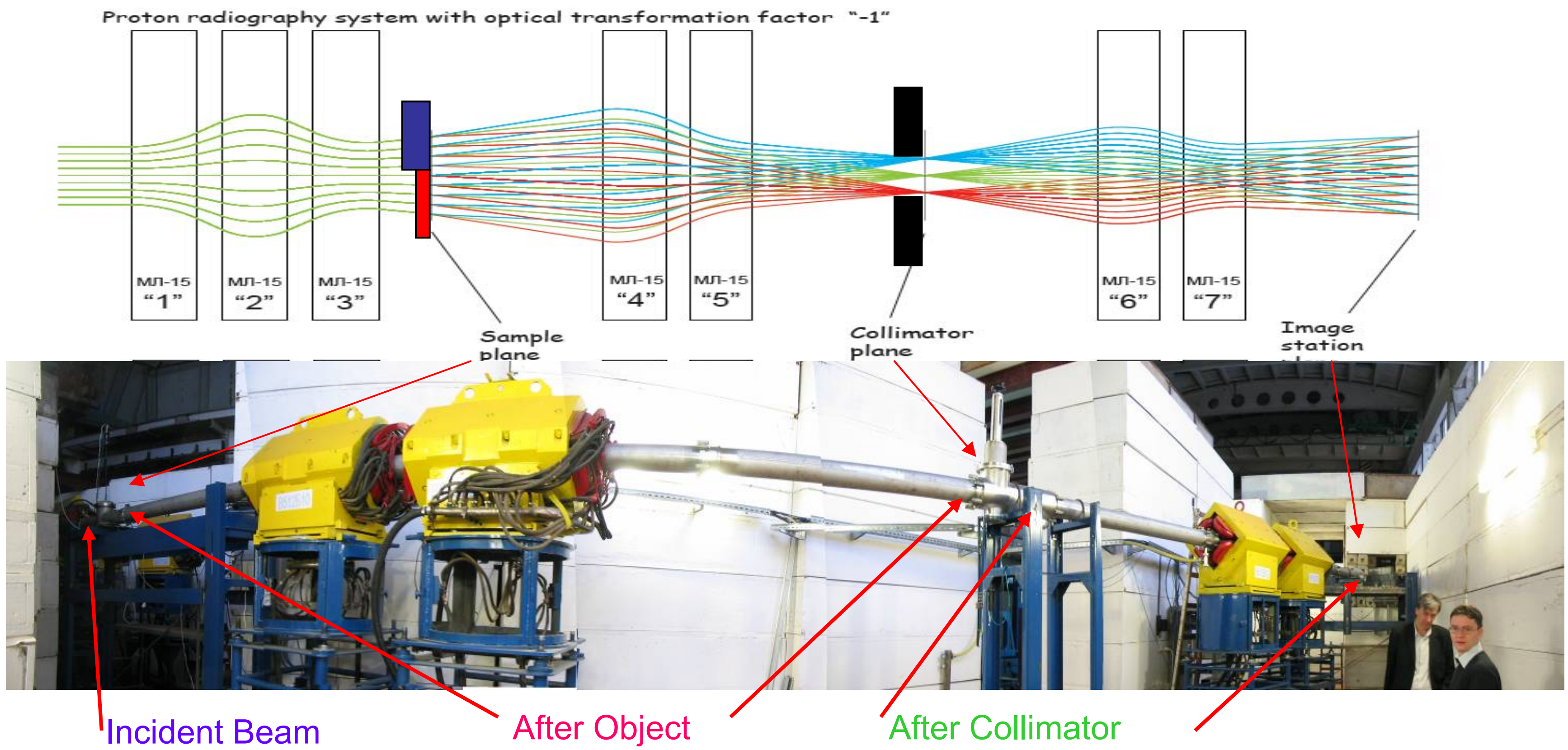
Plasma target parameters (chemical HE generation):

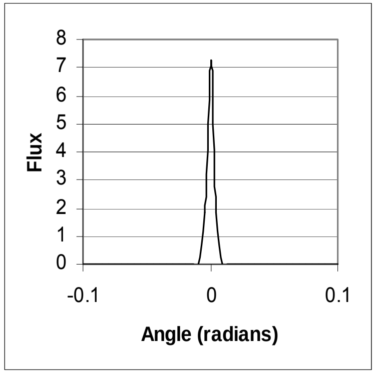
- Electron density up to 10^{23} cm^{-3}
- Pressure ~10 GPa
- Density up to 4,5 g/cm^3
- Temperature 1÷3 eV
- Time scale – microseconds
- HE mass (TNT) – 60 g

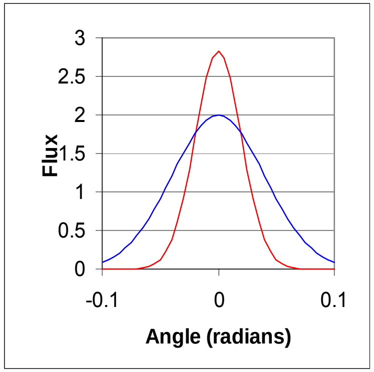
Protective Target Chamber designed for:
Up to 80 g TNT
Pumped down to 10^{-3} Torr
Active ventilation system
Fiber for optical diagnostics (VISAR)

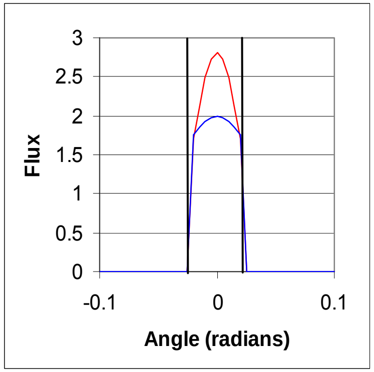
Magnetic optics design for proton radiography set-up

image transformation factor “-1”



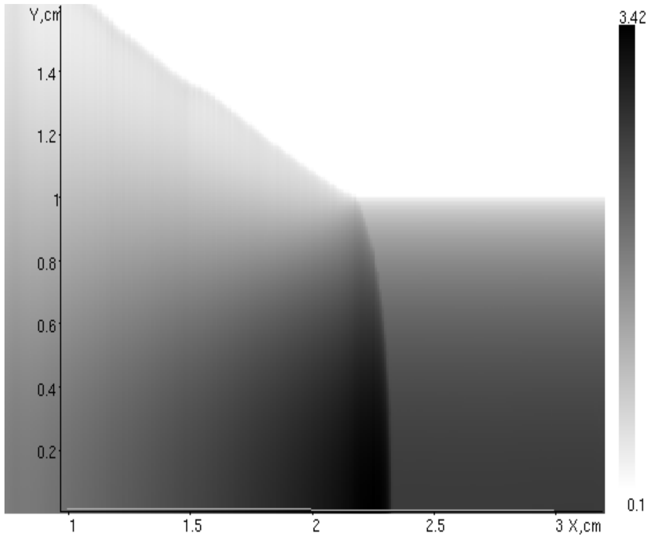




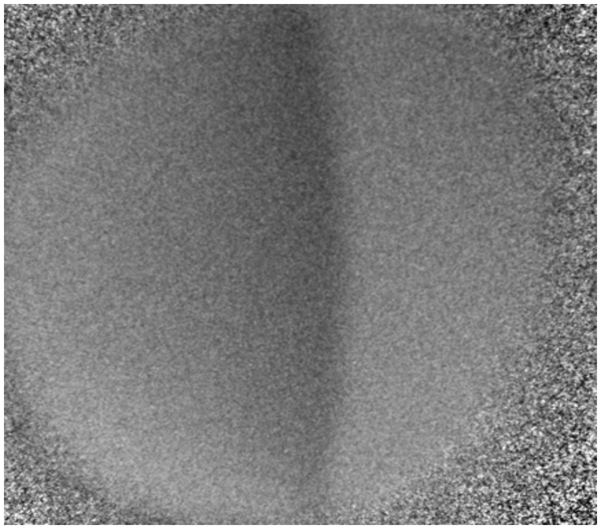


Measured transmission provides information about object thickness

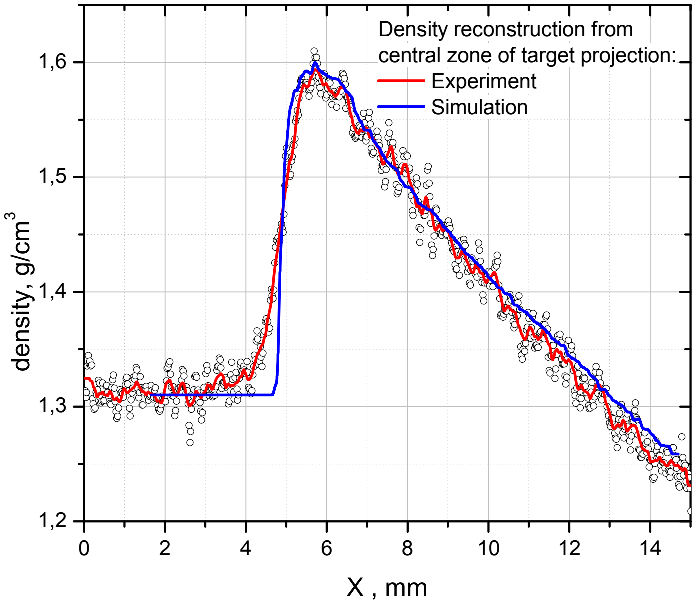
First results of dynamic experiments : Detonation wave in TNT

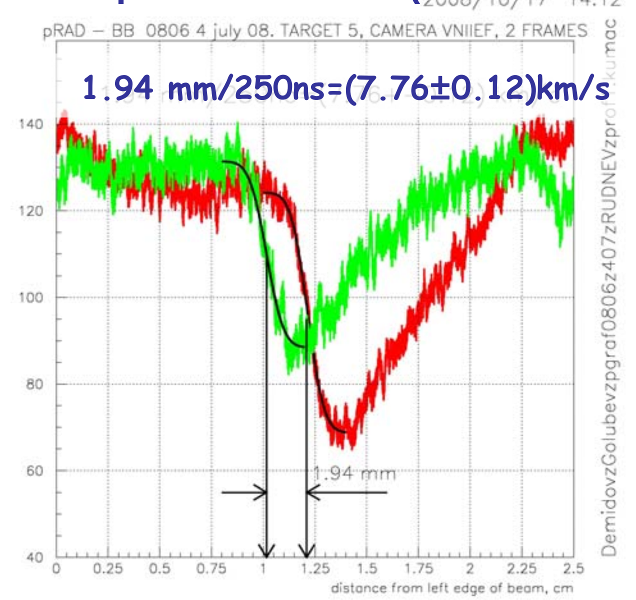


Areal density, (g/cm²)
Simulation results – A. Shutov



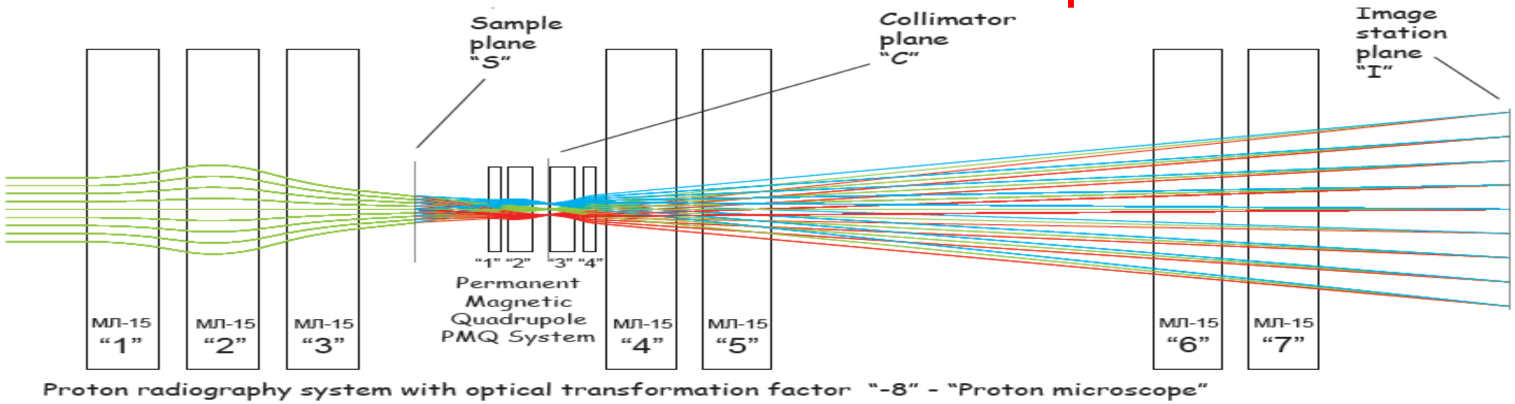
Relative proton beam transmission, (%)
Experiment – ITEP (October 2008)





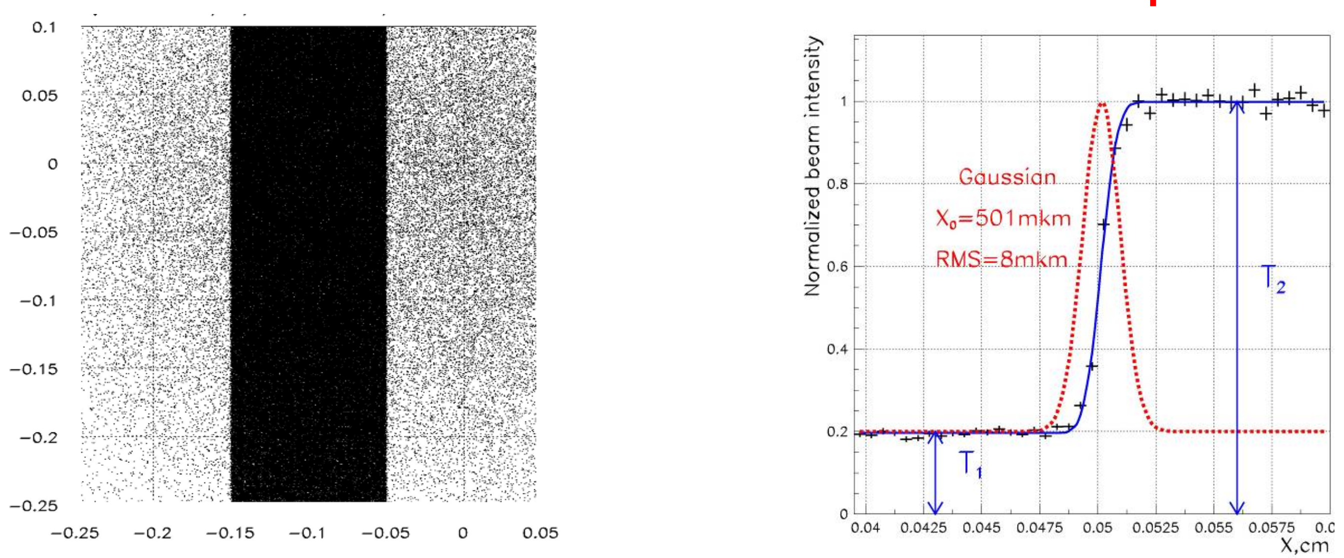
Proton radiography system with image transformation factor “-8” “Proton microscope”

COSY simulation for “Proton Microscope”



Expected Spatial Resolution ~20 µm

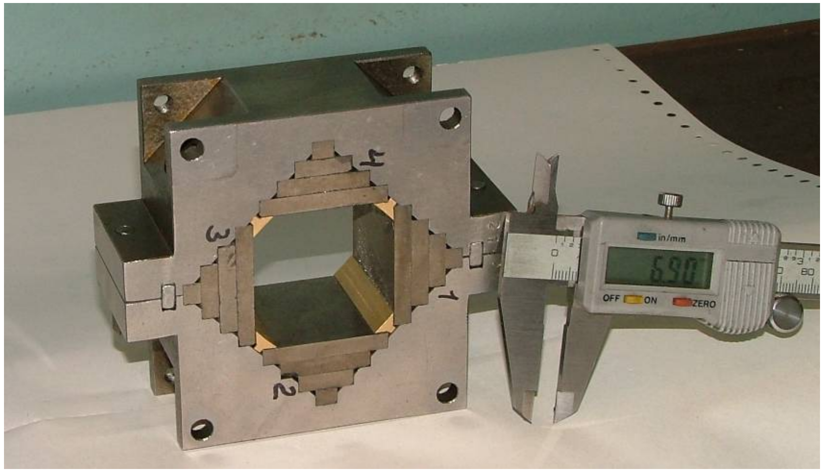
GEANT4 simulations for “Proton Microscope”



“Sharp edge” test-object

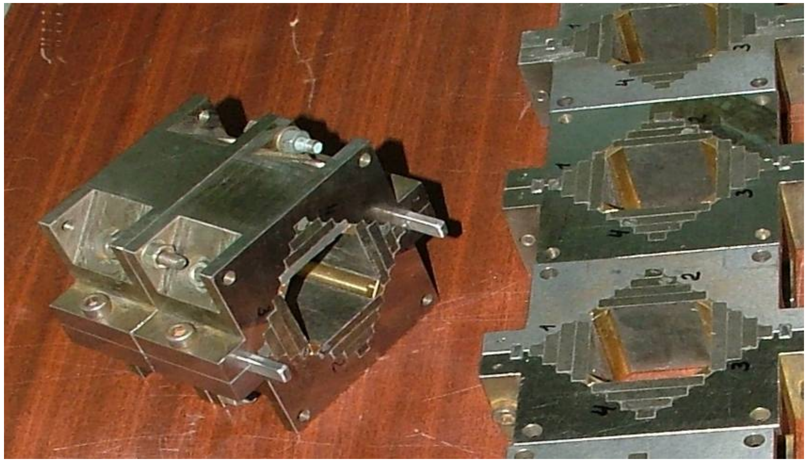
Proton radiography system with image transformation factor "-8" "Proton microscope"

Permanent Magnet Quadrupole lens fabrication for "Proton Microscope"

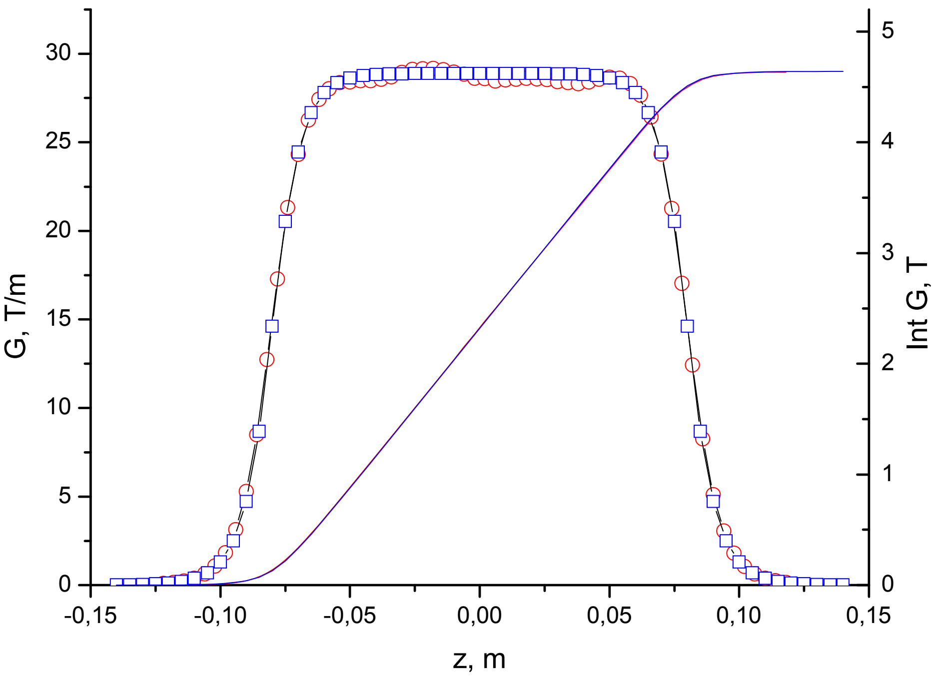


Permanent Magnetic Quadrupole Module

Magnetic alloy Nd-Fe-B



Quadrupole Lens Assembling



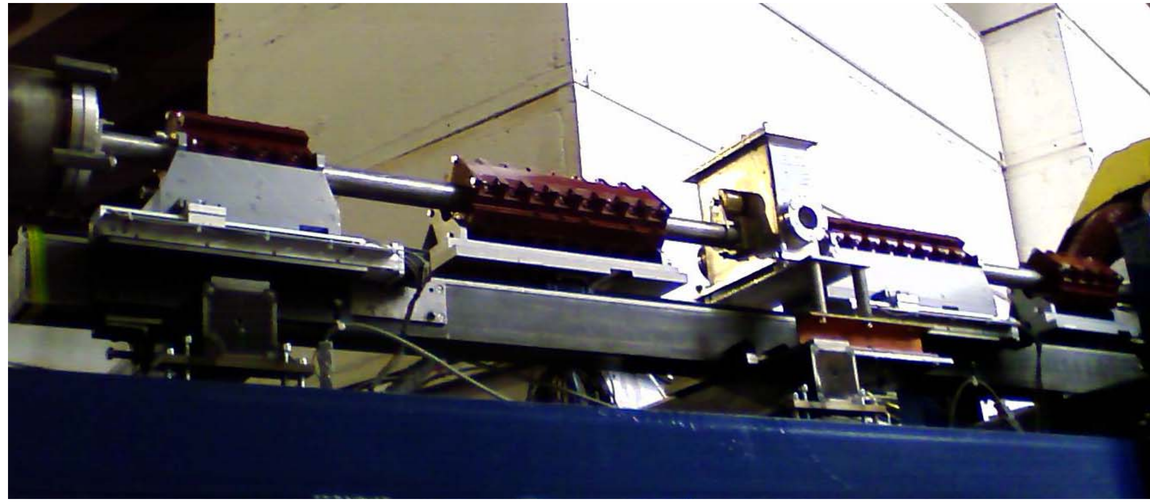
Four Modules Assembly Axis Gradient Distribution

Blue – field simulation

Red – field measurements

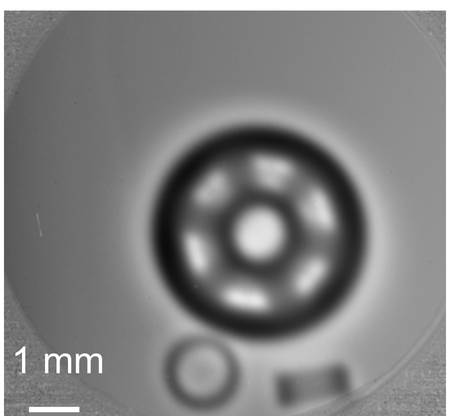
ITEP Proton Microscope commissioning at 2008

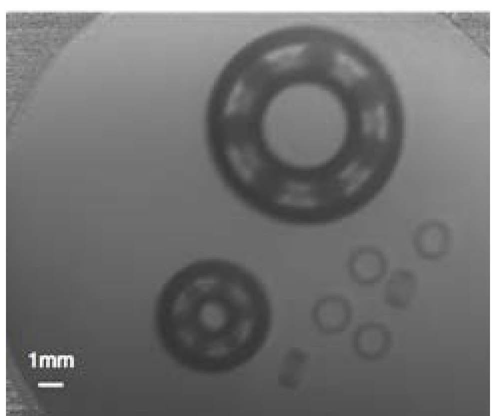
E = 800 MeV
Magnification X = 7.82
Field of view < 10mm
Measured spatial resolution
σ = 50μm
Magnification X = 3.92
Field of view < 22 mm
Measured spatial resolution
σ = 60μm

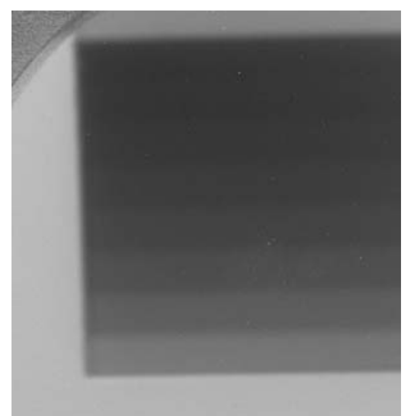


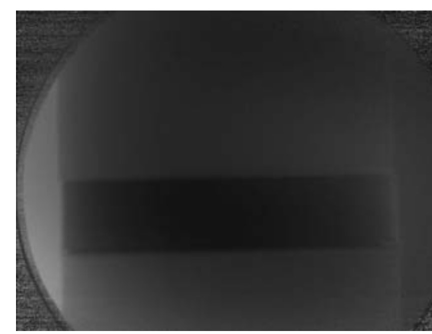
Measured density resolution ~ 6%
Beam structure – 4 bunches
(FWHM=70ns) in 1 μs

Static test-object images









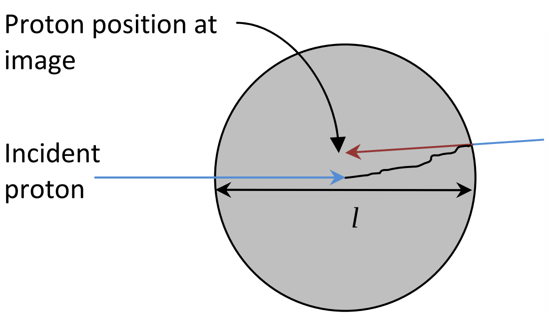
Ball bearing and ferrite ring (X= 7.82 and X=3.92)

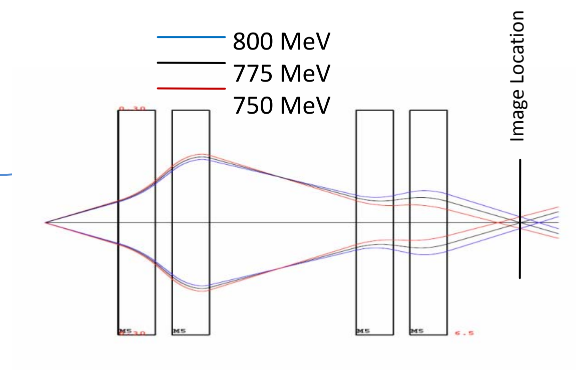
Brass stair 1 mm step Δρ=400μm

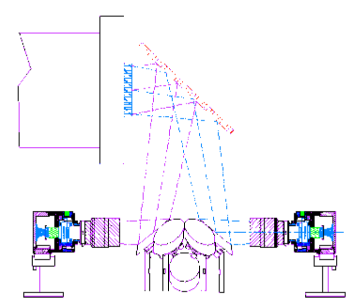
Detonation wave
immitator d=15mm
σ=100μm

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:

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

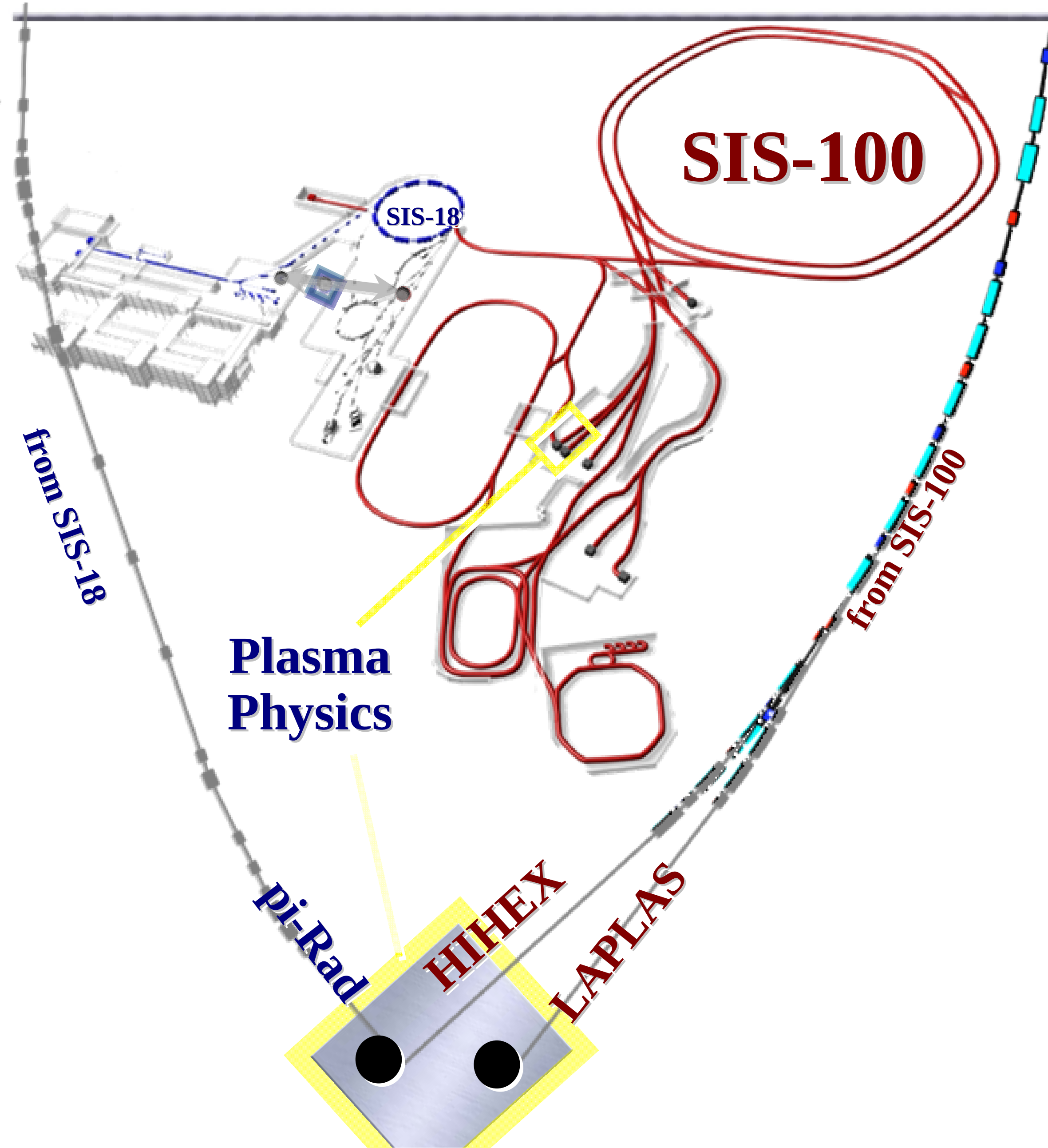
Chromatic aberration:

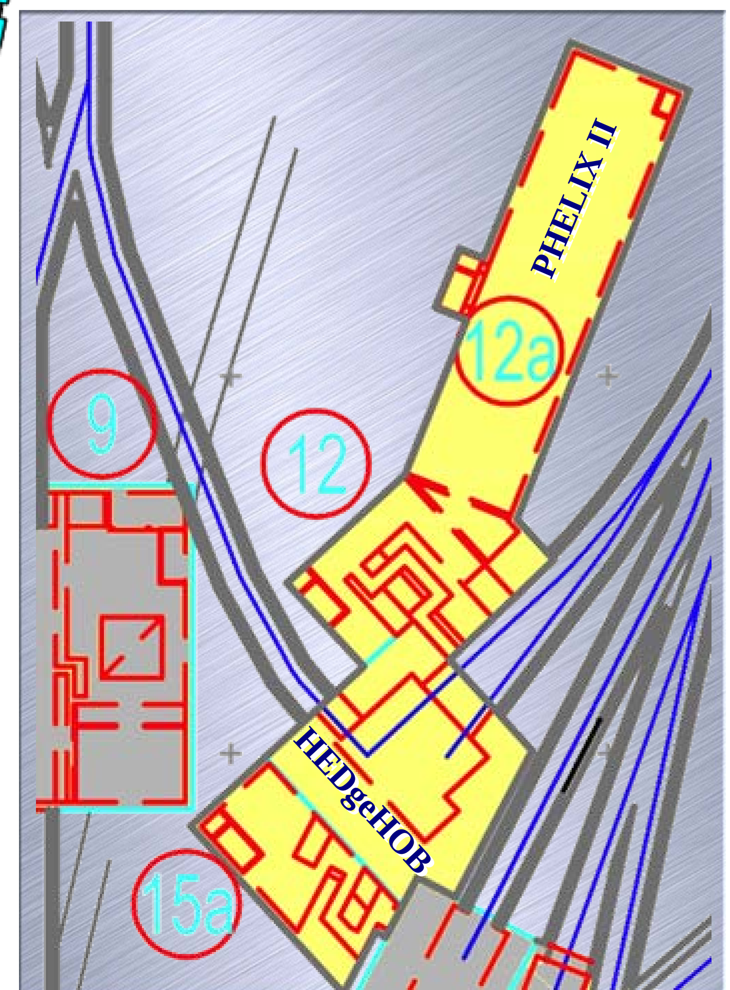
$$\sigma_c = l_c\theta\frac{\delta P}{P} = c\sqrt{P}\frac{\delta P}{P^2}\frac{14.1}{\beta}\sqrt{\frac{l}{x_o}} \propto \sqrt{\frac{l}{P^3}}$$

Scintillator blur:

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

HEDgeHOB beam lines and cave





New pRad facility for FAIR project (GSI-ITEP-LANL-IPCP)

PRIOR
Proton Radiography at FAIR

Micrographia, Robert Hooke, 1664

Project goal:

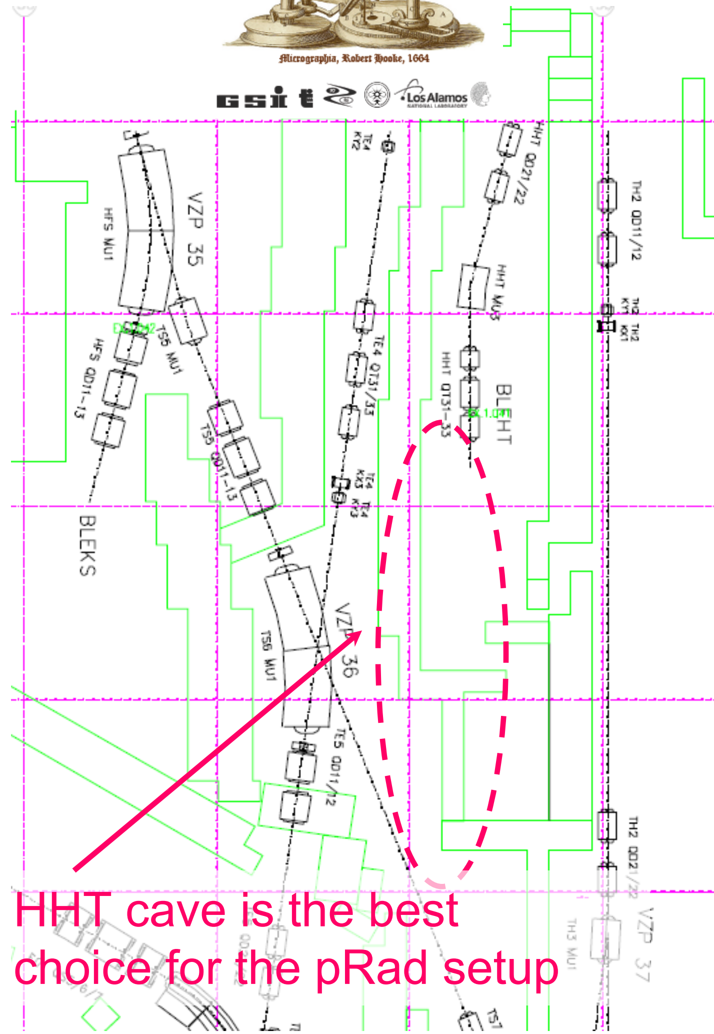
Designing and constructing a pRad lens and detector system for **4.5 GeV** protons capable of collecting multiple time radiographs with micron-level resolution, according to the requirements for the FAIR pRad setup.

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.



Technical Design Report

Time schedule and milestones

- ✓approval of the project by GSI management – Q2 2009
- ✓optical design of the proton microscope – Q2-Q3 2009
- ✓engineering design of the whole system – Q3-Q4 2009
- ✓completion of the HHT reconstruction – Q4 2009
- ✓ordering the production of main components – Q3-Q4 2009
- ✓assembling the setup at HHT – Q3 2010
- ✓off-lines tests, measurements and alignment - Q3-Q4 2010
- ✓application of beam time proposals to GPAC – Q2 2010
- ✓commissioning with static objects – Q4 2010 - Q1 2011
- ✓commissioning with dynamic objects – Q2 2011

New HRJRG project

HELMHOLTZ
GEMEINSCHAFT

Helmholtz-Russia Joint Research Group

Experimental Study on Warm Dense Matter by Intense Heavy Ion Beams

Project goal:

HED physics experiments with intense heavy ion beams at HHT during 2009 – 2012

Collaborative institutions:

GSI, JIHT, IPCP, ITEP, TUD

Supported by:

jointly funded by Helmholtz Association and RFBR

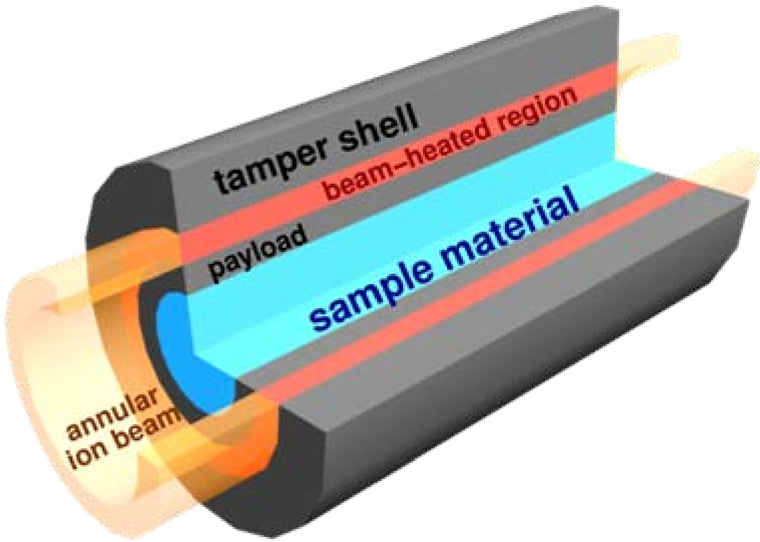
Scientific programm:

• thermodynamic, transport and optical properties of ion-beam generated HED states in matter

• R&D and commissioning of essential diagnostics for FAIR:

- * spectroscopy, pyrometry
- * interferometry
- * opacity in UV, VIS, NIR
- * backlighting and schlieren
- * electrical conductivity
- * sound velocity
- * beam diagnostics

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



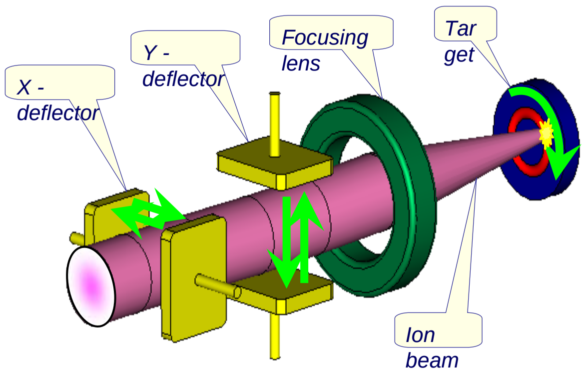
- hollow *(ring-shaped)* beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression of the sample
  - Mbar pressures @ moderate temperatures
    interior of Jupiter and Saturn, hydrogen metallization

An intense ion beam can be used very efficiently to achieve low-entropy compression of a sample material like hydrogen or ice that is enclosed in a heavy cylindrical tamper shell. Such a target will be driven by a hollow beam with a ring shaped (annular) focal spot. In this experiment it will be possible to achieve physical conditions that exist in the interior of giant planets, Jupiter and Saturn. Another goal of the LAPLAS experiment will be to study the problem of hydrogen metallization.

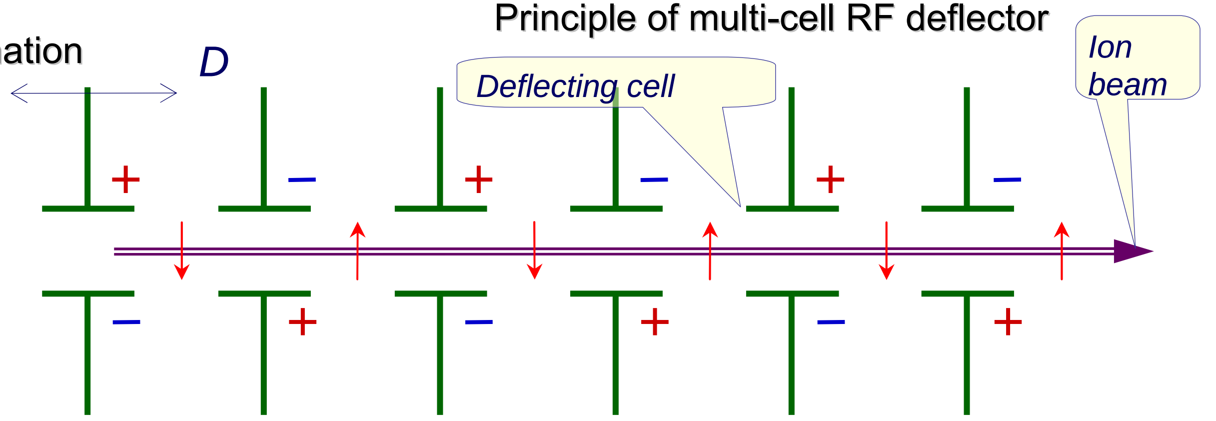
Implosion asymmetries induced by a rotating ion beam

Cylindrical implosions with high radial convergence require high degree of azimuthally uniformity of the beam irradiation, especially when a cold pusher is used to compress the sample material in the central cavity. To ensure the required symmetry of beam irradiation, it was proposed to rotate the ion beam around the cylindrical target axis by means of a corresponding beam wobbler. An idea is to deflect the parallel beam by RF electric field in both transverse directions and then to focus it to the small rotating spot, illuminating the ring-shaped area on the target.

Mechanism of ring-shaped area illumination



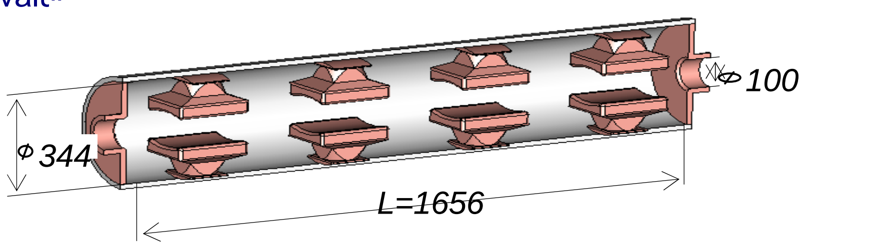
Principle of multi-cell RF deflector



Example of deflecting cavity parameters
for 700MeV/u Co+25 beam TWAC-ITEP 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*

In order to keep the resonant interaction of the beam with the electric field, every cell must be as long as $\beta\lambda/2$, where β is the normalized beam velocity and λ is the ***rf*** wavelength. When this condition is satisfied, particle crosses all the cell centers at the same phase, regularly increasing the transverse momentum dependently on the phase value

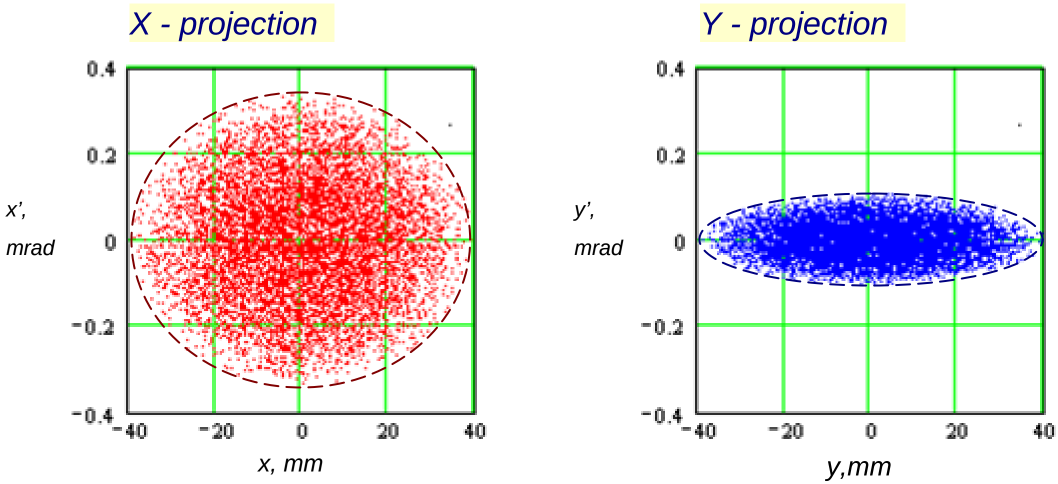


Two resonant multi-cell deflecting rf cavities are proposed to obtain the necessary beam deflection in both directions. Rotation frequency of 300 MHz is the minimum possible value allowed by the experiment requirements.

Ion beam parameters for LAPLAS experiment

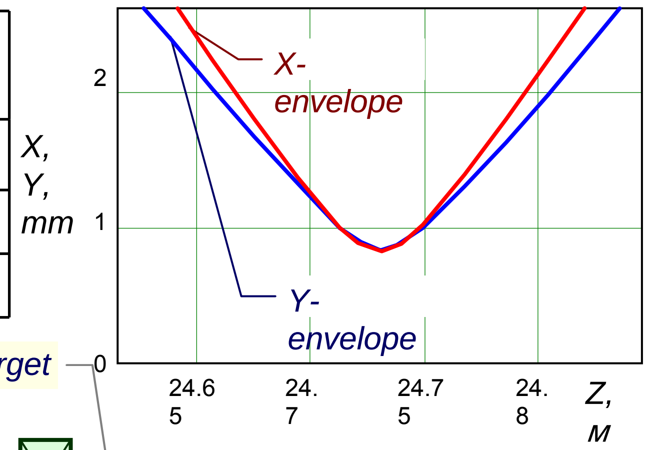
Ions		$_{238}U^{28+}$
Beam energy	*GeV/u*	*1.0*
Horizontal / vertical emittance (normalized)		$25\pi / 8\pi$
Energy spread	*%*	*1*
Rotation frequency	*MHz*	*300*

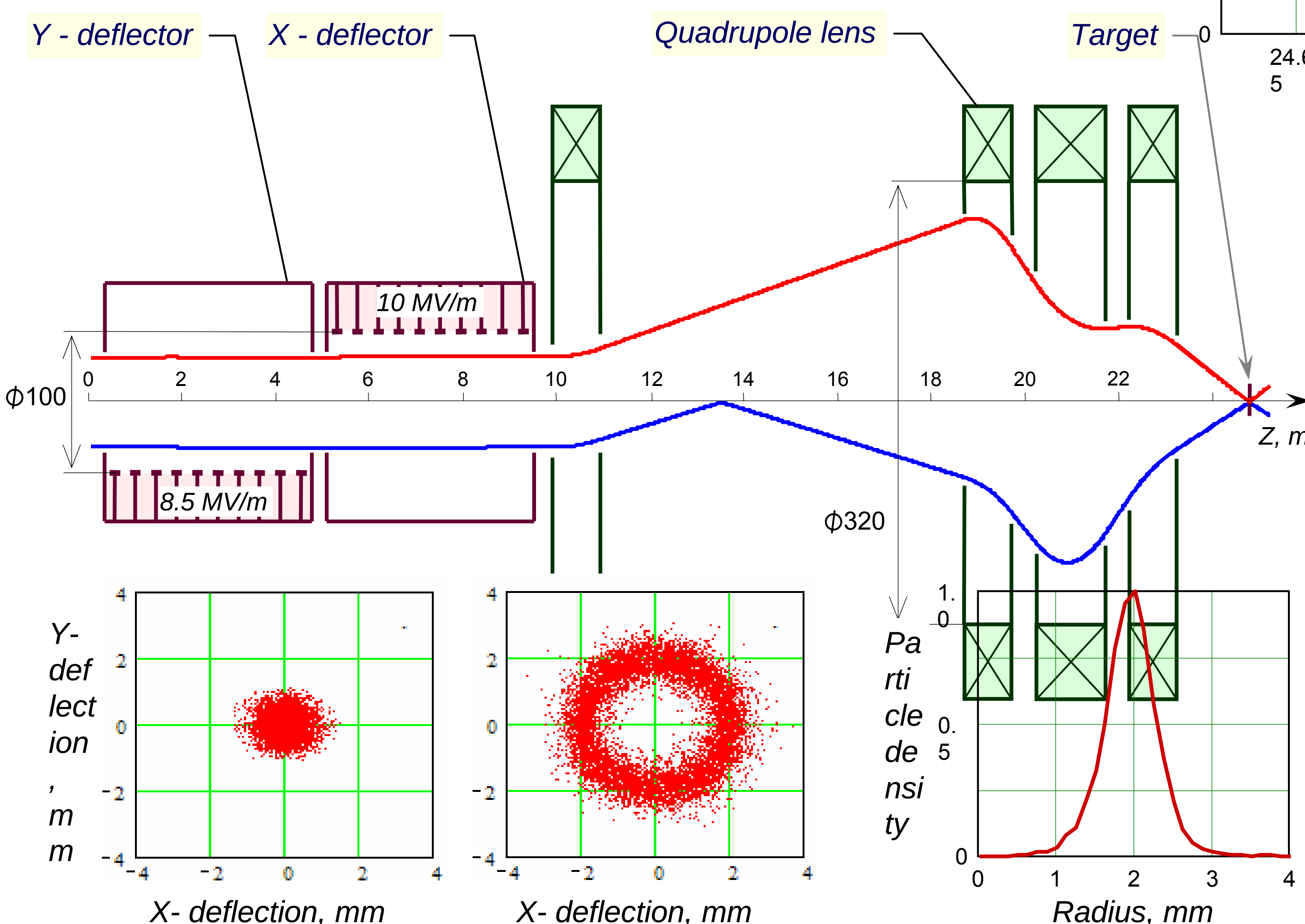
Emittance projections to the transverse planes



Beam envelope for superconducting triplet

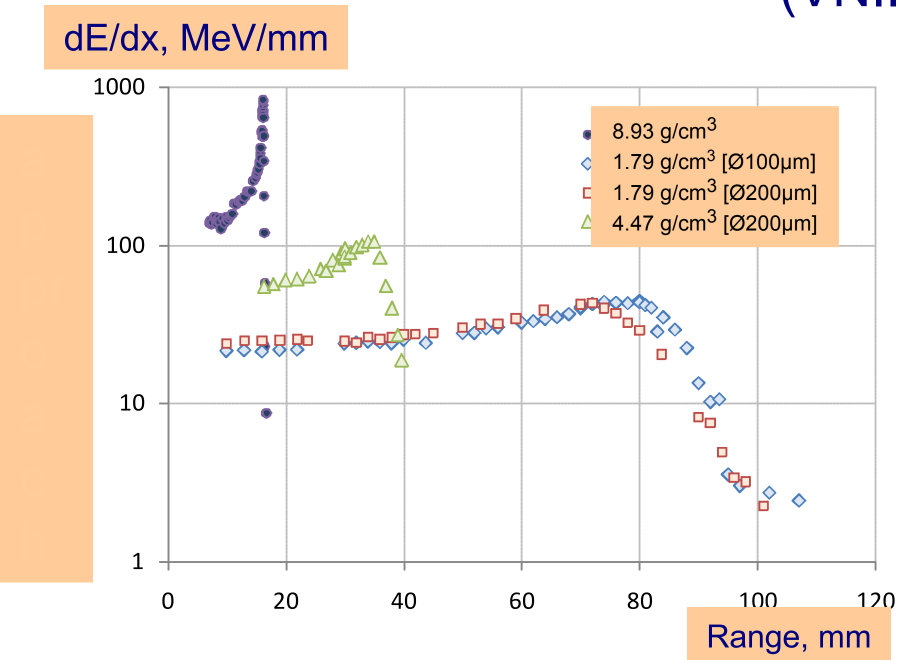
Parameter	Unit	Lens 1	Lens 2	Lens 3	Lens 4
Aperture radius	mm	160	160	160	160
Lenght	mm	1000	1000	1500	1000
Gradient	T/mm	16.5	24.0	27.4	28.0

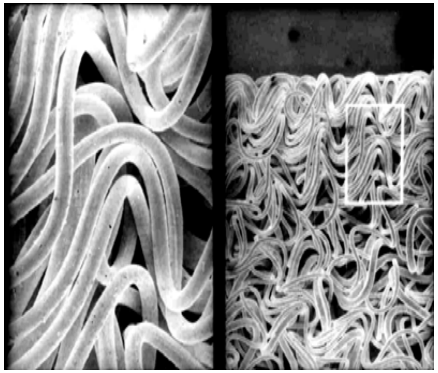


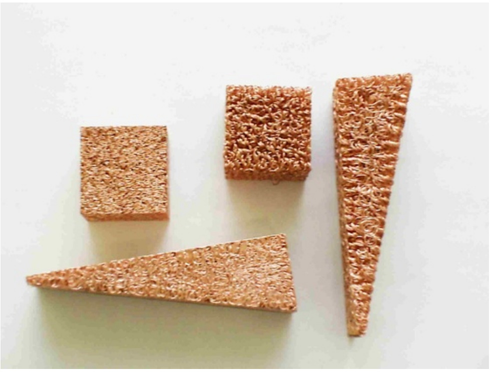


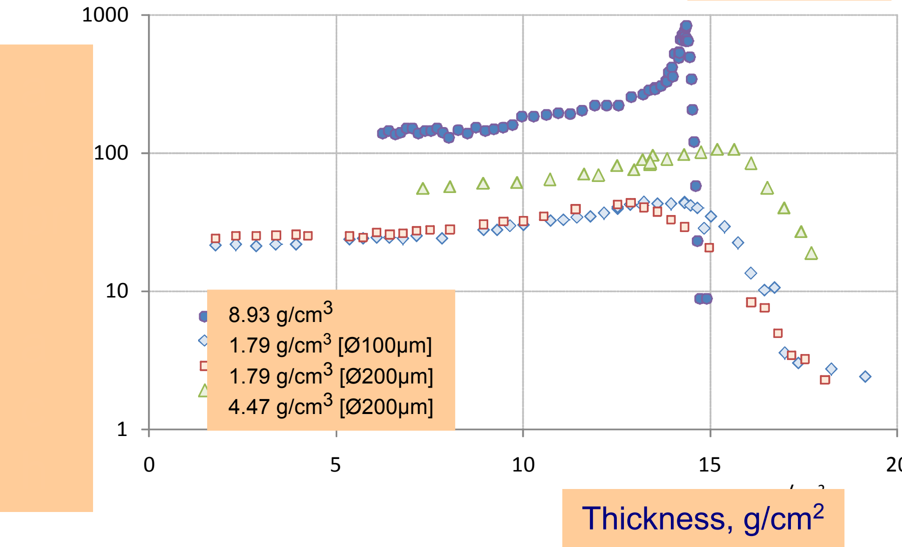
As it is possible to see from presented results, high aperture superconducting lenses allow to reduce noticeably the size of the focused spot and to improve conditions of formation of a hollow beam. At the same time, at the given values emittance and a focal length hardly it is possible to count on the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

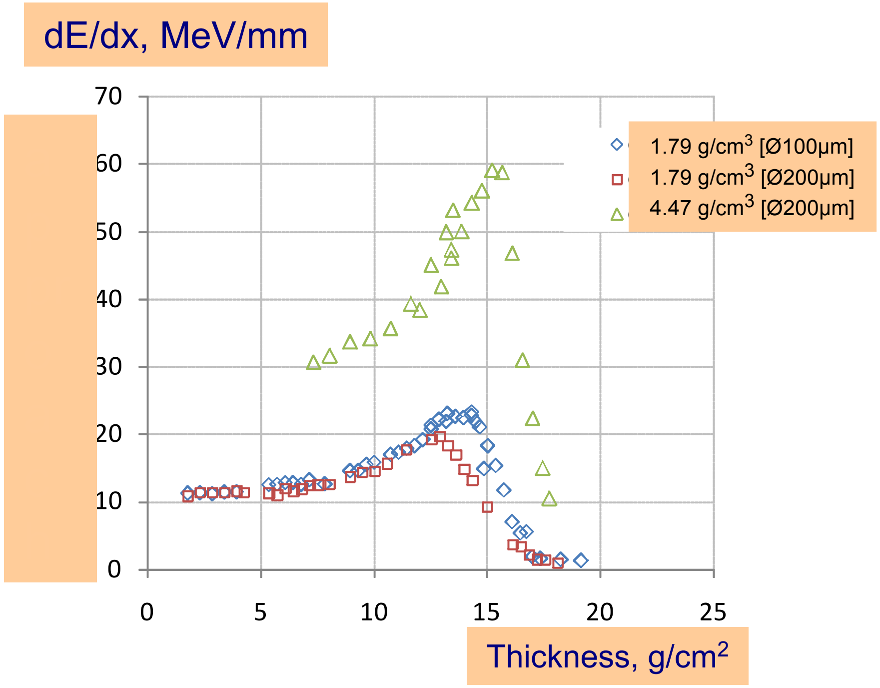
Stopping range measurement and the energy deposition profile of 216 MeV/u C beam in porous Cu targets by “thick target” approach (VNIIEF&ITEP)







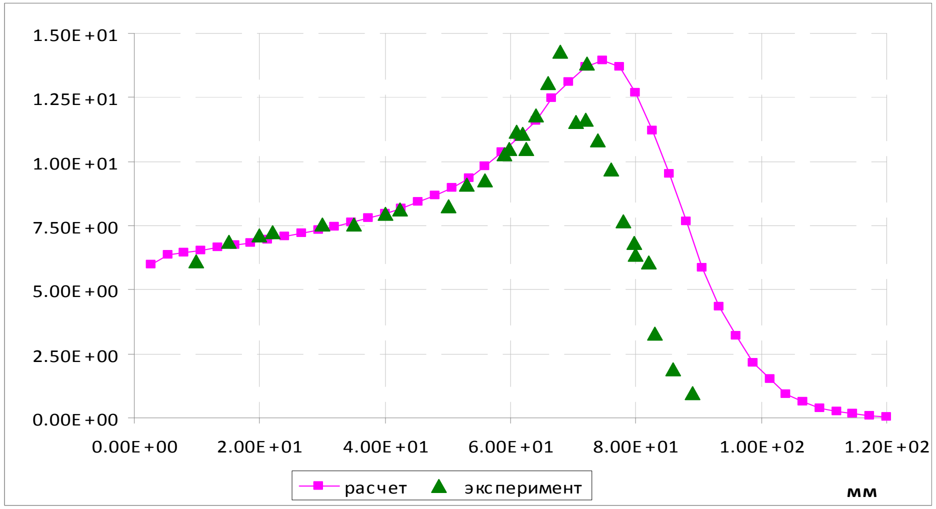


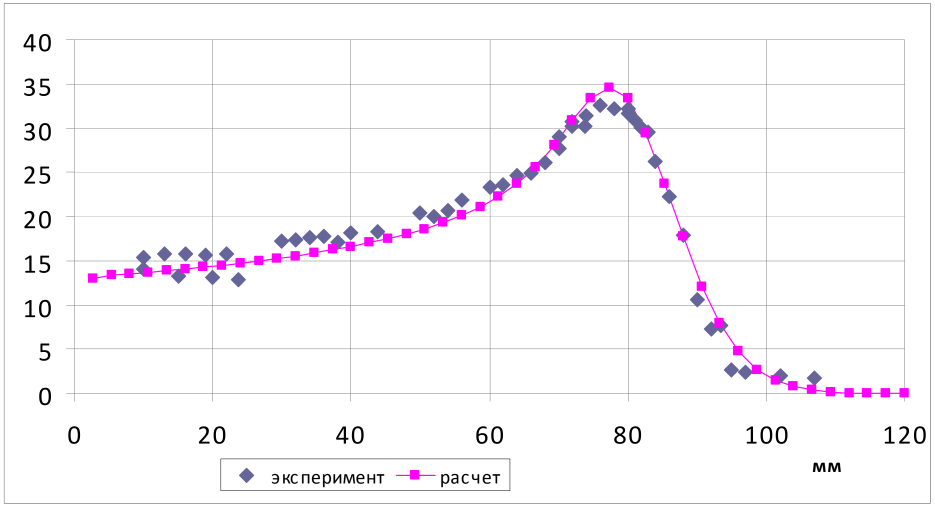


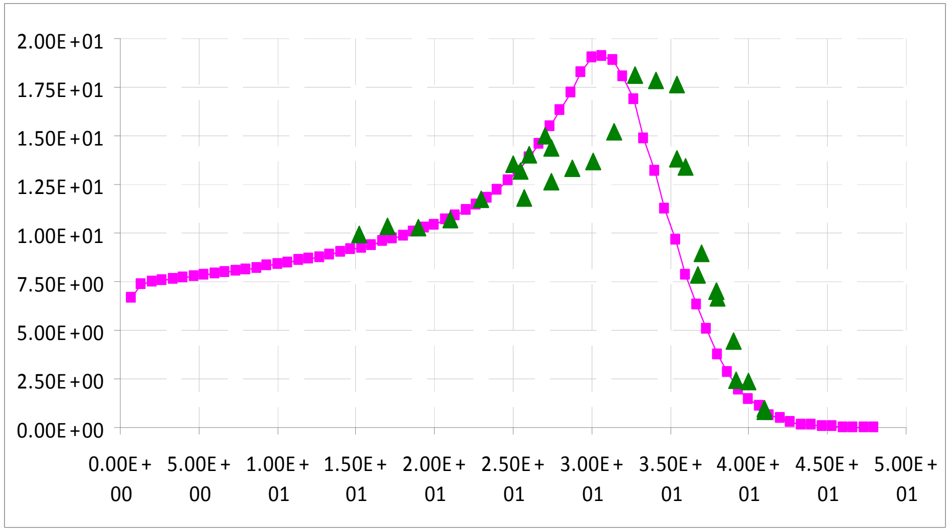
Numerical simulation & experimental data
dE/dx for C ion with E= 216 MeV/u in Cu porous target

ρ=1.79 g/см³ Ø200μm

ρ=1.79 g/см³ Ø100μm







ρ=4.47 g/см³ Ø200μm

V.V.Vatulin, A.Gnutov

Summary

- **ITEP-TWAC project is well in progress:**
  - **New laser ion source in operation**
  - **The Al and Fe ions accelerated and stored.**
  - **The construction of a high-current ion injector for energy of 7–8 MeV/u will allow a substantial increase (by an order of magnitude and up) of the intensity of accelerated ion beams.**

- **The focusing plasma lens are developed**

- **First dynamic experiments were performed on *ITEP-TWAC Proton Radiography Facility***

- ***N*ew magnet optical system of "Proton Microscope" constructed and commission**

- **Proton Radiography developed as one of the main diagnostic tool for HEDgeHOB collaboration at FAIR project (new project GSI-ITEP-LANL-IPCP)**

- **Prototype of wobbler for ITEP and LAPLAS experiments are started to manufacture.**