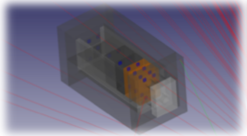
High energy density science laboratory (NRC *"Kurchatov Institute"*)

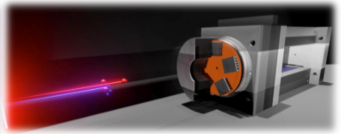
Laboratory of High Energy Density in Matter Physics

Kurchatov Complex of Theoretical and Experimental Physics, Moscow, Russia

Full scale numerical simulation:

-Monte-Carlo with Geant4 code (proton radiography, experiments with x-ray diagnostics, laser acc. electrons)
- Monte-Carlo of X-Ray Grazing-incidence spectrometers
- Monte-Carlo with FLUKA code
- COSY infinity – ion beam dynamic calculation
- CST Studio – charge particle diagnostic devices, ion optic. el.
- 2D3V PICSIS code for plasma simulation





Development of scientific devices and targets:

- Quadrupole lenses on Permanent Magnets (PM)
- Charge particle spectrometers on PM
- Plasma target on gas discharge
- High cur. electron beam gun (up to 300 keV)

Experience in experimental work:

-High energy proton radiography incl. expl. exp.
- X-Ray and particle diagnostic at Z-pinch setup (Angara at TROITSK (Russia))
- Participation in experiments at PHELIX laser – electron acceleration experiments
- Heavy ions energy loss measurements at TIPr (ITEP), UNILAC and SIS-18

Diagnostics:

- Proton radiography: PRIOR at FAIR
- Charge particle diagnostic of pulsed plasma (high power Z-pinch and lasers)
- X-Ray Grating Spectroscopy
- XCOT (Xray Conversion to Optical radiation and Transport) – in collaboration with GSI and GU-Frankfurt
- VISAR interferometry for experiments with shock wave
- Plasma diagnostic with laser interferometry and optical spectroscopy
- TOF heavy ions energy loss measurements in plasma

Laboratory of
High energy density in matter physics

Golubev A., Kantsyrev A., Skobliakov A., Gavrilin R., Bogdanov A., Panyushkin V., Khurchiev A., Kolesnikov D., Savin S., Roudskoy I., Visotskiy S. , Drozdovski A., Panyushkina A.,

Experimental data processing:

-Image processing for proton radiography
-X-Ray spectrum reconstruction for Z-pinch experiments (Angara)
-Tomography reconstruction (ART)
-RF signals analysis for ion energy loss in plasma experiments

Data acquisition system:

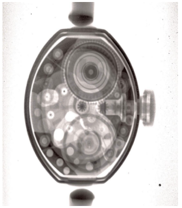
-Complex system for PRIOR at HHT (GSI)
-Synchronization units
-CCD cameras (PCO Edge 5.5, ..)
-Robots (target manipulator)
-High voltage generators and plasma target
-Software for complex system

In collaboration with:

GSI/FAIR
(Darmstadt)
Rosmej O.,
Varentsov D.,
Zaahter S.,
Gyrdymov M....

IPCP
(Chernogolovka)
Lomonosov I.,
Mintsev V.,
Shilkin N.,
Nikolaev D.,
Dudin S.....

TRINITI
(Troitsk)
Grabovski E.,
Gritsuk A. .....

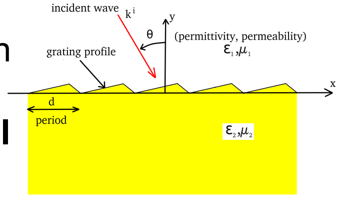


Monte-Carlo Numerical simulation of experiments on X-ray Diagnostics of Pulsed Plasma

Problem for X-Ray spectrum reconstruction for grating spectrometers: superposition of signals from different diffraction orders and the complex form of the instrumental function of the spectrometer

Goal: construction of a full-scale model of an X-ray spectrometer makes it possible to calculate the instrumental function of the device used to reconstructing the initial X-ray spectrum

Intensity distribution of radiation after grating (**differential** method*)



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Model

Monte-Carlo model of radiation tracking in spectrometer

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Instrumental function of spectrometer

This new code was also tested in compare with PCGrate code

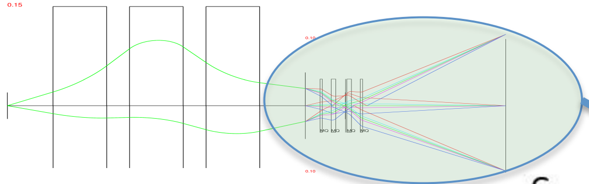
Experimental data on registration plane → Reconstruction procedure

Instrumental function of spectrometer → Reconstruction procedure → Reconstructed x-ray spectrum

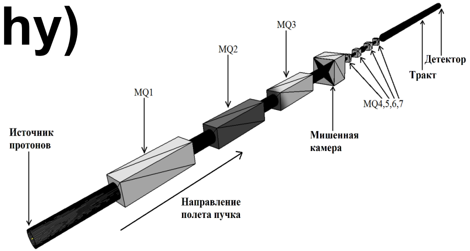
*Michel Neviere, Evgeny Popov, Light Propagation in Periodic Media Differential Theory and Design, ISBN 9780824708931, Published November 6, 2002 by CRC Press

Beam position instability correction with addition image plane in front of target position (proton radiography)

Scheme of beam line of proton radiography setup PUMA (ITEP)



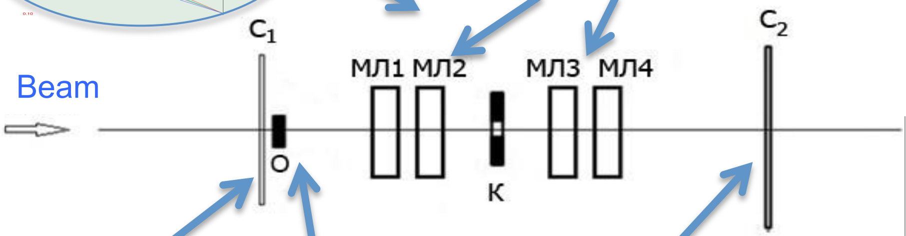
Beam dynamic calculation with COSY Infinity code



Geant4 Monte-Carlo model

Quadrupole lenses on permanent magnets

Beam

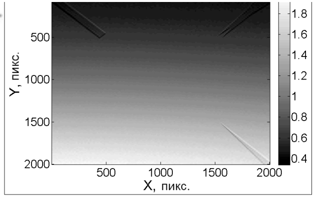


Addition image plane scintillator (1 mm BC408)

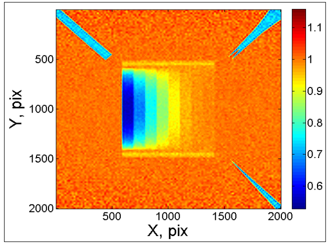
Target position

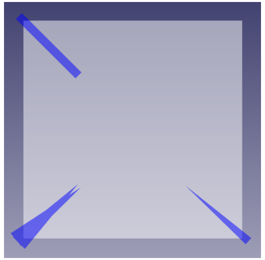
Main image plane

Not corrected image of white field image

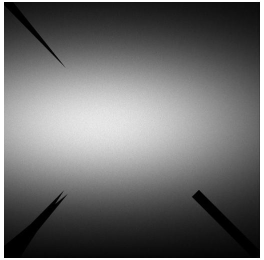


Test with step target

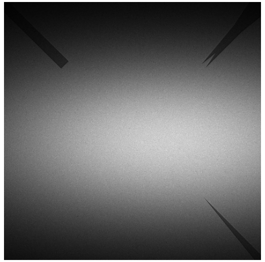




Model of addition scintillator with Cu markers

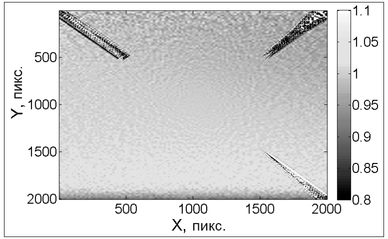


Model image C1



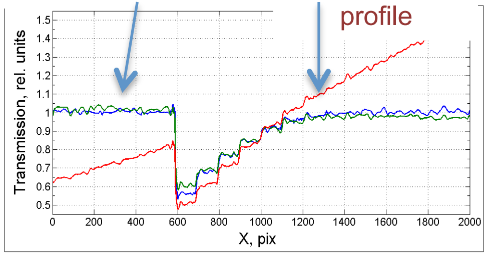
Model image C2

Corrected image of white field image



Corrected profile

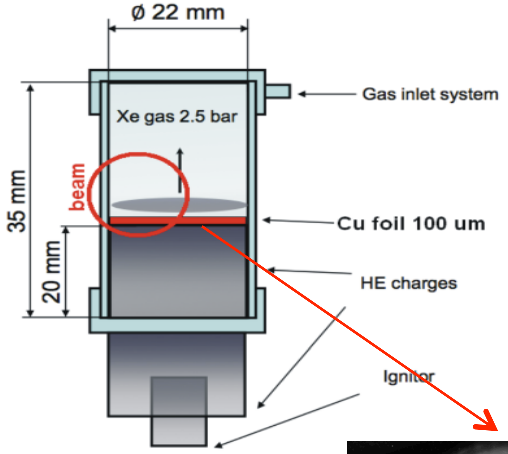
Not corrected profile

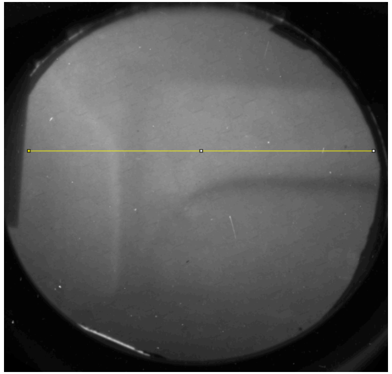


Experimental data processing

Investigation of non-ideal plasma
of shock-compressed Xe-gas with 800 MeV protons (PUMA at ITEP)

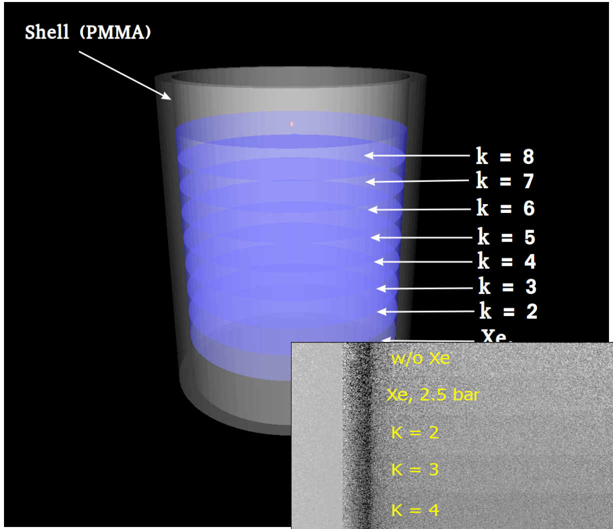
Scheme of the target

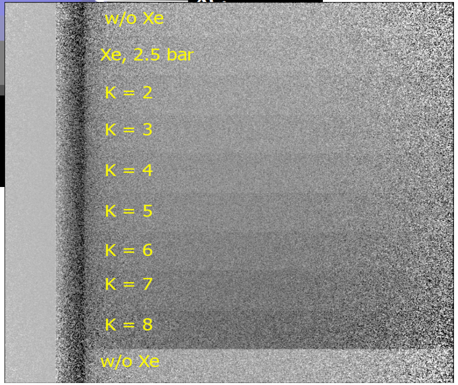




Experimental proton-radiographic image obtained at PUMA (ITEP) proton microscope with 800 MeV protons

3D model of the target at Monte-Carlo Geant4 code



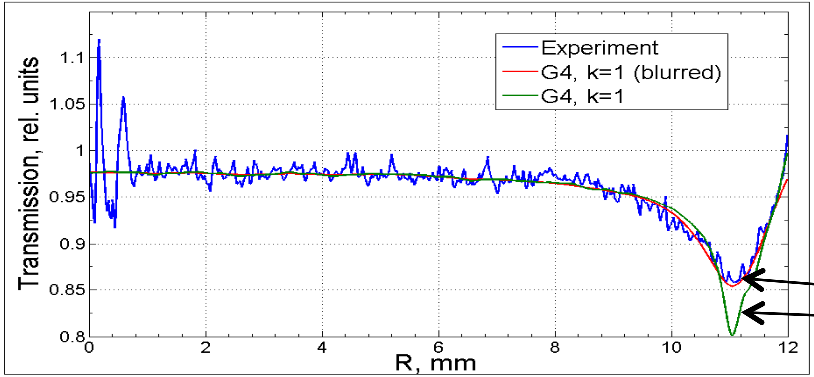


Simulated proton-radiographic image with different compression rations of Xe gas

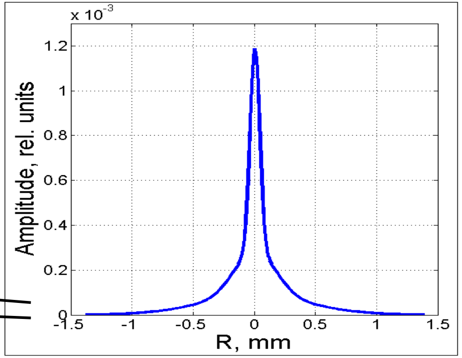
Proton radiography experimental data processing

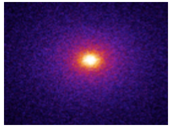
Investigation of non-ideal plasma
of shock-compressed Xe-gas with 800 MeV protons

Comparison of Geant4 profile with experiment (static)

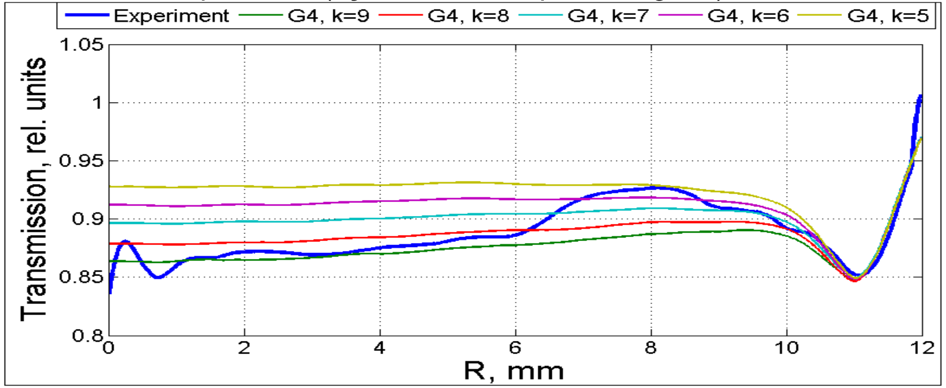


Point Spread Function (PSF)

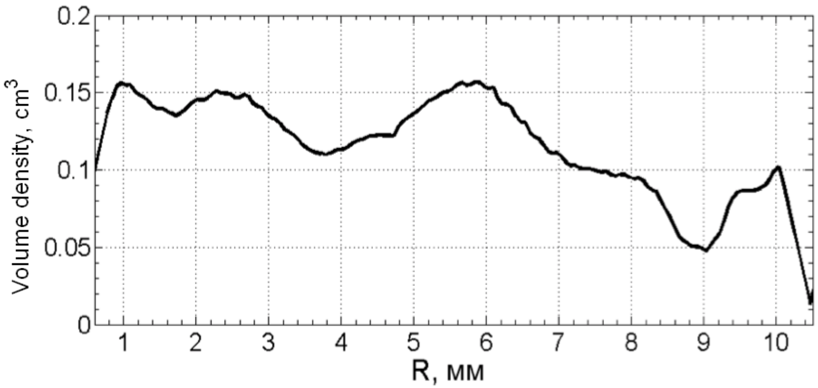




Comparison of simulated profile (different compression ration) with experiment (**dynamic** – compressed gase)

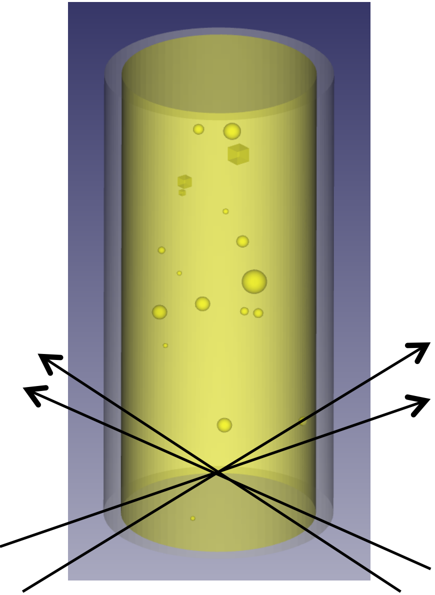


Reconstructed volume density radial distribution
in gas cylindrical target



Experimental data processing

Target model
of nuclear reactor cell

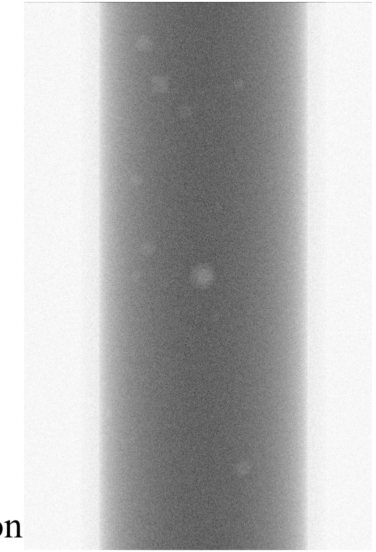


Beam energy: 4 GeV
Number of protons: $5 \cdot 10^8$ per projection
Pores from 100 to 500 microns

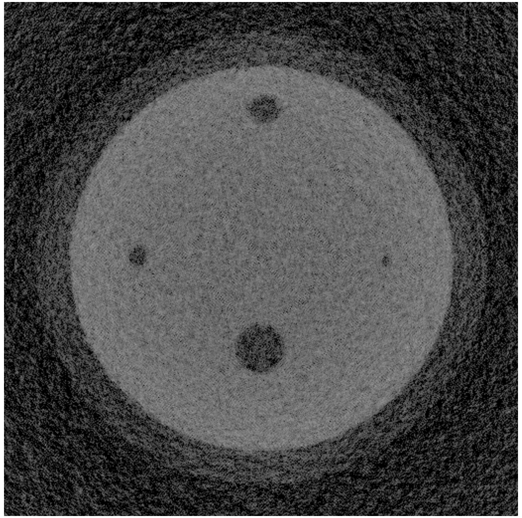
Shell:
outer radius - 4.55 mm
inner radius - 3.86 mm
material - stainless steel

Development of tomography reconstruction software

Simulated (at Geant4 model of PRIOR) image
One of multiples projection



Result of reconstruction by modified ART (Algebraic Reconstruction Technic – Python code)



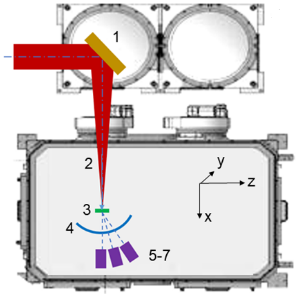
Tablet:
Radius - 3.86 mm
Density - 10.97 g / cm^3

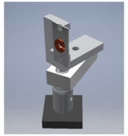
Numerical simulation (Geant4) of experiments on laser-driven neutron and gamma generation

Laser-driven relativistic electron beams are excellent tools for the generation of ultrashort MeV gamma and neutron sources, THz and betatron radiation [1]. In the case of well-directed high current beams of relativistic electrons one can reach extreme high luminosity of gamma and neutron sources and use them for radiographic applications, laser driven nuclear physics, and production of radioisotopes for nuclear medicine.

PHELIX experimental setup

1 - off-axis focusing parabola
2 - laser beam
3 - target position
4 - stack of cylinders
5-7 - three magnetic spectrometers



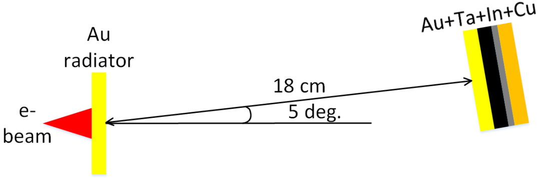


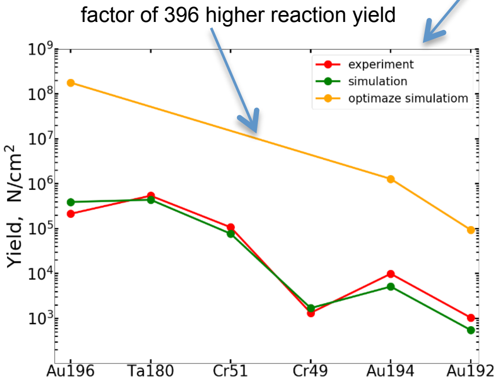
target holder

Nd:glass laser: wavelength: 1.053 mm, duration: 750 fs, focal spot FWHM diameters: 12 ± 2 µm
Pre-pulse: laser intensity: 5x10^{13} Wcm^{-2}
Main pulse: laser intensity: (1 ÷ 2.5) ×10^{19}Wcm^{-2} , laser energy: 90 ± 10 J
Target: cellulose triacetate (TAC, $C_{12}H_{16}O_8$), volume density: 2 mg cm^{-3} ,thickness: 300 ÷ 400 mm

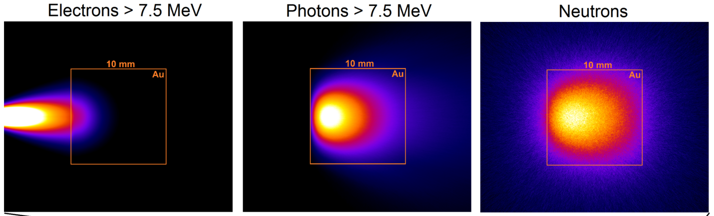
Secondary targets scheme

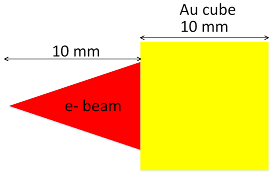
In the experiment and in simulations, the electron beam propagates through 1mm thick Au-radiator producing MeV bremsstrahlung radiation. 1 mm-thick activation samples of Au, Ta, Cr and 0.25 mm thin In-foil of 15x15 mm² area were placed at 5°to the laser pulse propagation direction 180 mm away from the target position.

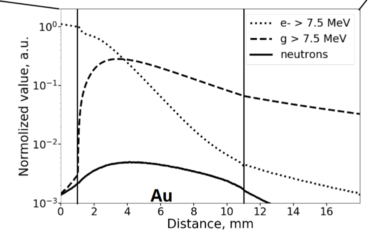




Optimized setup of secondary target







Calibration of Imaging Plates with radioactive sources

Several types of detectors exist in order to diagnose high-energy ions and electrons of pulse plasma: CR-39, radiochromic films (RCF), scintillators and image plates (IP). Although an IPs is passive detectors and cannot be used in high repetition rate experiments, IPs has several advantages over other particle detectors: persistency to electromagnetic pulse, high dynamic range (up to 10^5), high spatial resolution (usually 10 – 50 μm). In addition, IP can be erased with white light, allowing for reuse. In this work, the BAS-MS and BAS-TR image plates were calibrated for electrons and alpha particles in case of using the medical scanner **VistaScan Mini (Durr Dental).**

Calibration with α particles provide to calculate BAS-TR absolute sensitivity (in dependence of ions energy) for any type of heavy ions like Pb, W, Cu …

Absolute calibration IP BAS-MS for electrons

Isotope Sr^{90}/Y^{90} emits the continuous spectrum with a maximum energy of 2.28 MeV.

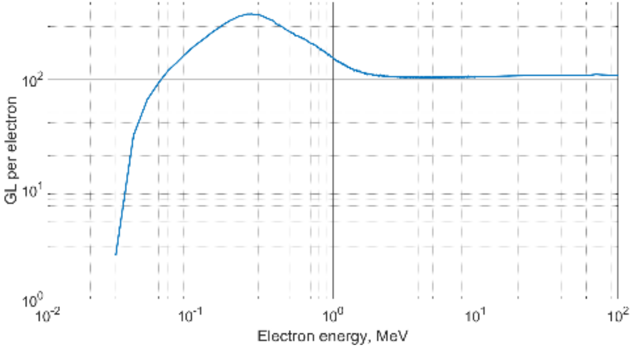
$$GL(E) = \alpha \int_0^W \frac{dE_{dep}}{dz}(E,z) e^{-z/L}\, dz = \alpha dE_{dep}^{eff}$$

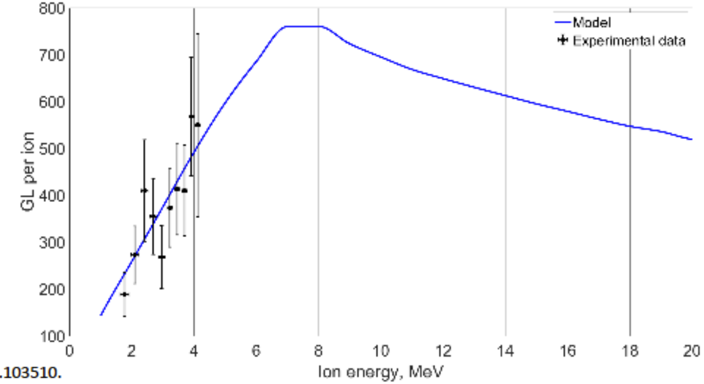
Absolute calibration IP BAS-TR for α particles

Isotope Pu^{239} emits α particles with energy of 5.1 MeV.

$$GL(E) = A \int_0^W \frac{{dE_{dep}}/{dz}(E,z)}{1 + B\left|{dE_{dep}}/{dz}\right|} e^{-z/L} dz$$

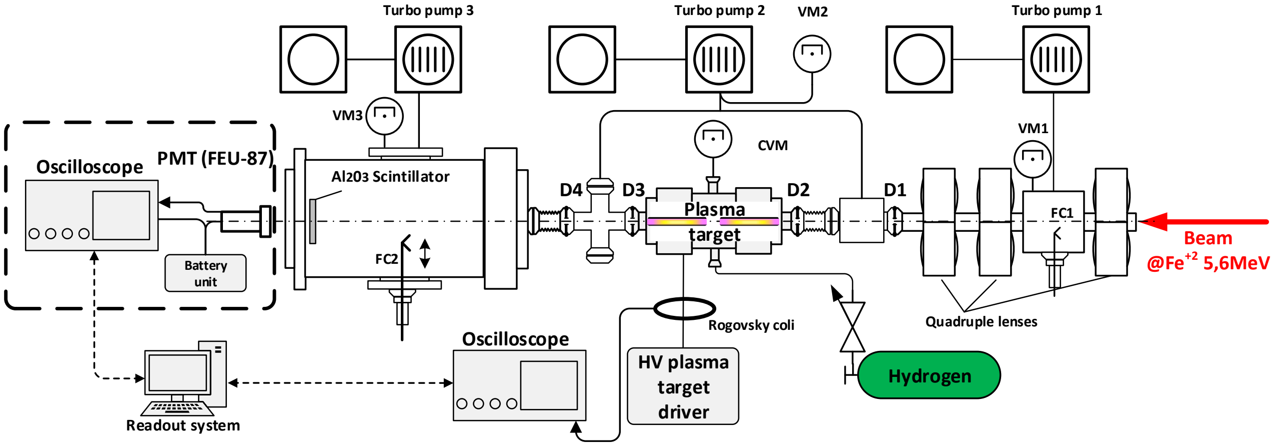
where dE_{dep}/dz is amount of energy deposited by the incident and all the secondary particles in the phosphor layer between z and z+dz;
W is the thickness of the phosphor layer; L is the absorption lengths; A, B, α – coefficients.





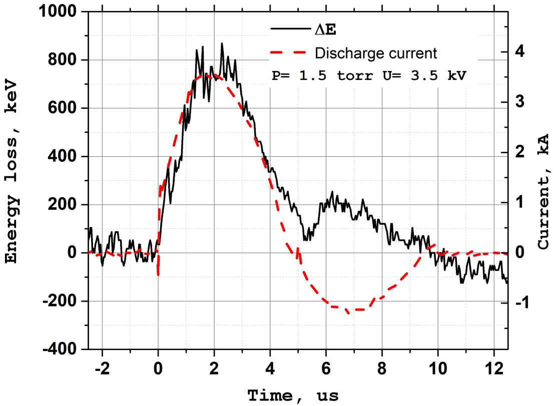
Bonnet T. et. al., Response functions of imaging plates to photons, electrons and 4He particles // Review of Scientific Instruments – 2013. – 84. Art.103510.
Lelasseux V., Fuchs J. Modelling energy deposition in TR image plate detectors for various ion types // Journal of Instrumentation – 2020. – V.15. Art.P04002.

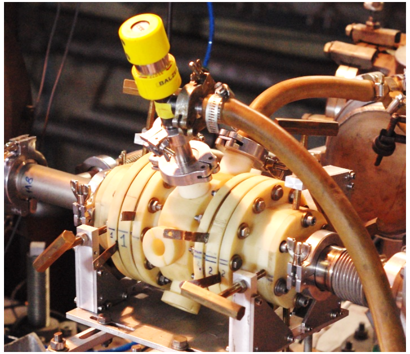
Stopping power measurement for 100 keV/u Fe^{+2} ions in hydrogen plasma (TIPr linear accelerator at ITEP)



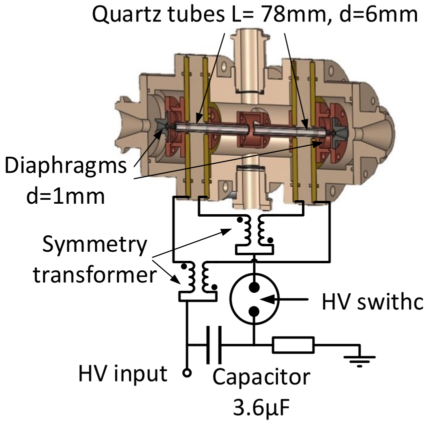
- Projectiles: @Fe 100 KeV/u
- Plasma linear density: $2.9\cdot10^{17}$ cm^{-2} to $1.19\cdot10^{18}$ cm (~)
- Maximal beam pulse : 450us
- Maximal repetition rate: 0.25 Hz

Time dependence of energy losses of Fe^{+2} ions in the plasma and discharge current



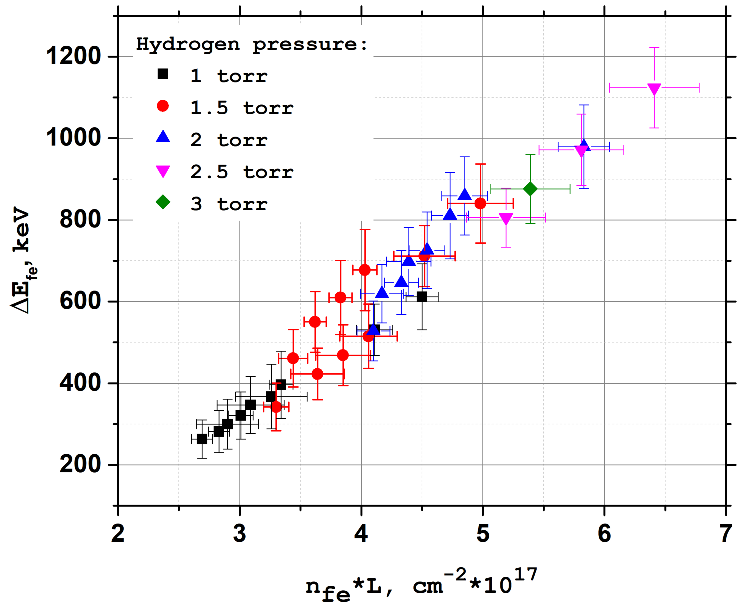


Scheme of a gas-discharge plasma target and the main elements of the electrical circuit

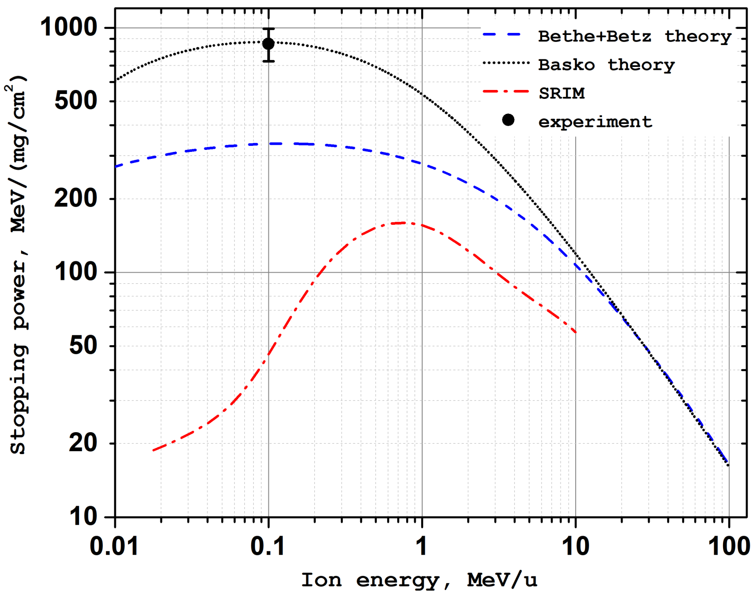


Results

Ion beam energy loses caused by free electrons of plasma



Comparison of experimental result for the hydrogen plasma stopping power with theory calculations



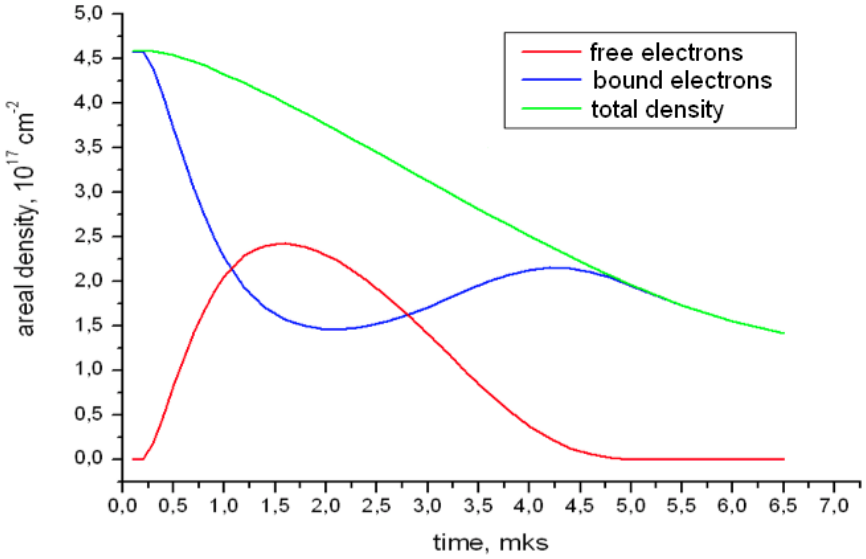
The obtained average stopping power value of hydrogen plasma is S_{fe}= (**860±130**)MeV/(mg/cm²)

Numerical simulation of plasma processes

The PICSIS (2D3V) numerical code was developed to simulate physical processes in gas discharges, plasma, as well as in various kinds of electron and ion sources, including extraction systems and channels for transporting charged particles in stationary electric and magnetic fields.

Recently the code was moved to CUDA C++ for using of graphic card GPU multiple calculation technic

Distribution of electric fields in a plasma target at different times with an initial pressure of 2 mbar, (hydrodynamic code)



Extraction and transportation of C^{+4} ions from a laser source (ITEP, I-4) using an electrostatic lens in the transport channel at various values of the extraction current. U_b=0, U_g=60kV, U_c=-10kV, U_r=-70kV