The Abdus Salam International Centre for Theoretical Physics

2370-14

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

High Energy Density in Matter Produced by Intense Heavy Ion Beams

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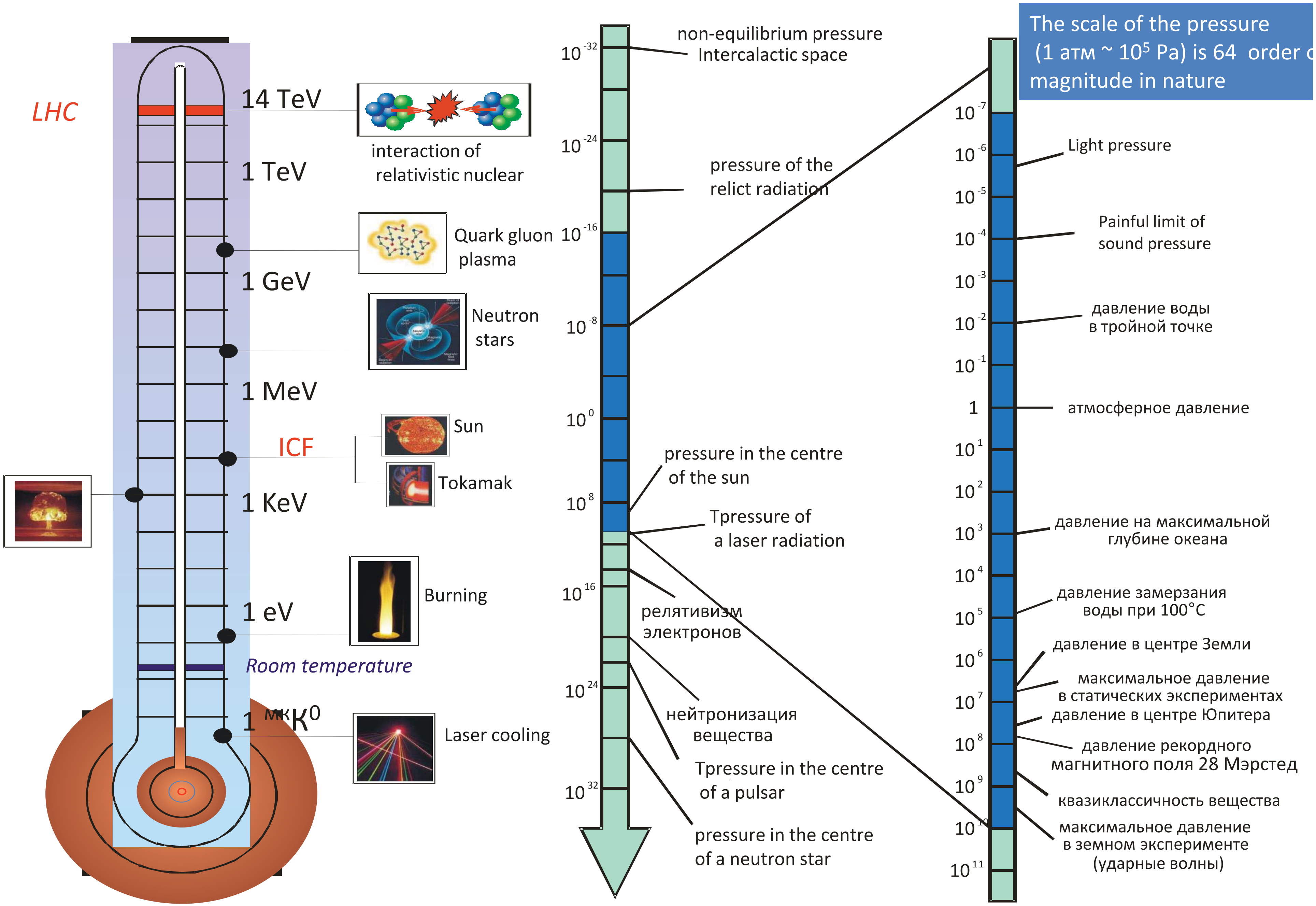
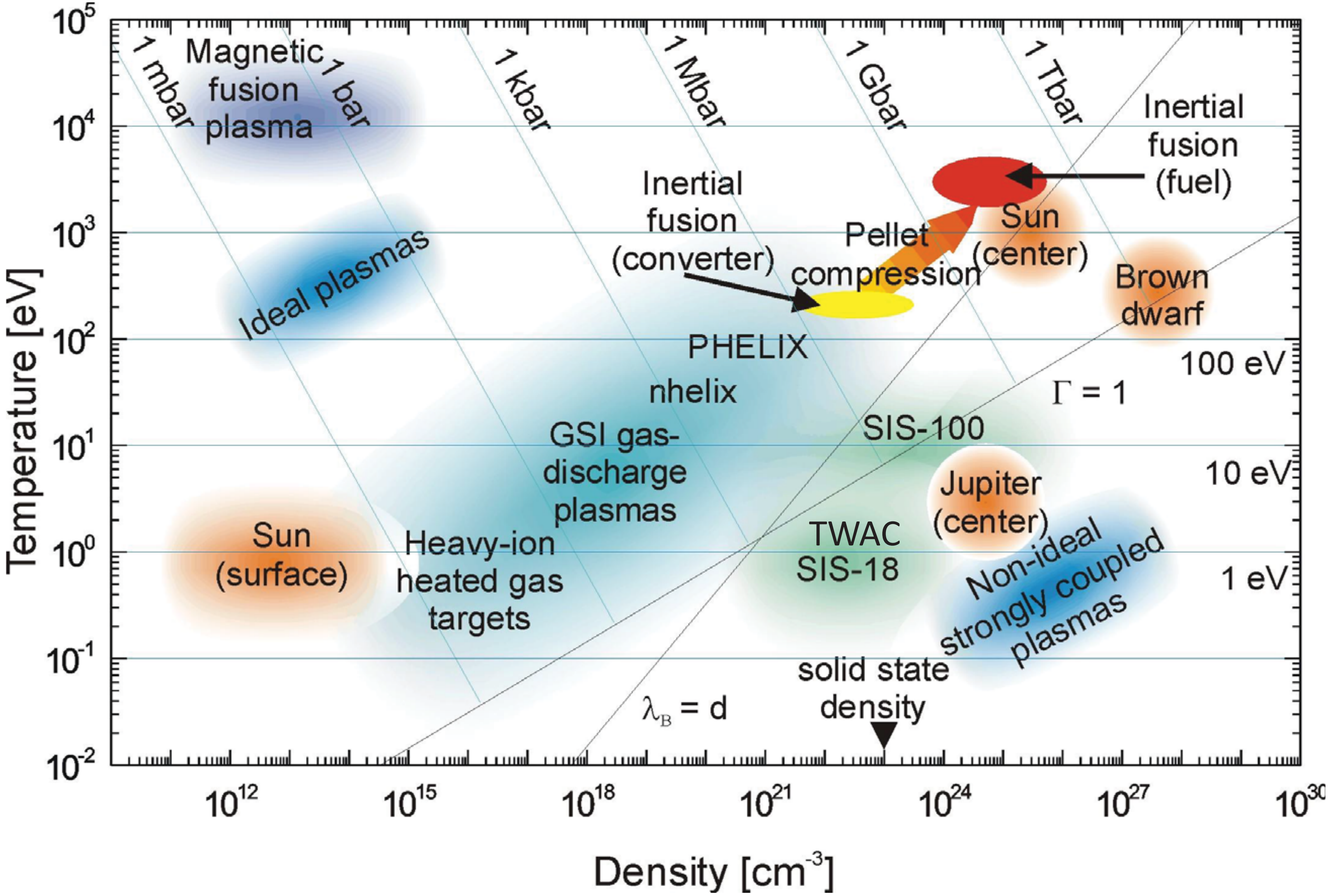
School &Training Course on Dense Magnetized Plasma
Trieste, 8-12 October


EXSTREME STATES OF MATTER
98% of VISIBLE MATTER
SUPERNOVA EXPLOSION
NE
"Today we understand all the physical processes in the Universe except extreme ones."
S.Hawking, A Briefer History of Time
ICF

TEMPERATURE AND PRESSURE SCFLES IN NATURE

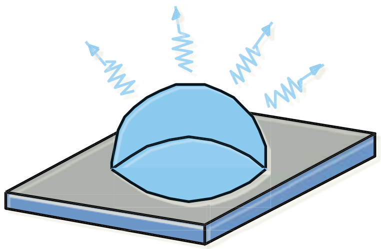


High Energy Density in Matter Physics



High Energy Density in Matter

The collective interaction of the matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called High Energy Density Physics.
It is a field characterized by *extreme states* of matter previously unattainable in laboratory experiments (high concentration of energy: high temperatures and high pressures)



T ~ 2,000 – 500,000 K

ρ ~ 0.1 – 100 g/cm^3

P ~ kbar, Mbar, ...

Extreme states of matter: basic physics and applications

- **Plasma physics, atomic physics, thermophysics**
  fundamental properties of matter in unexplored regions of the phase diagram: equation-of-state, exotic phase transitions, transport and optical properties, effects of strong inter-particle interaction, ...

- **Astrophysics and planetary sciences**
  brown dwarfs, pulsars, supernova explosions, structure of the earth and sun interior, giant and extra-solar planets

- **Energy research and inertial confinement fusion**
  fusion energy, portable nuclear and MHD reactors, safety of power plants

- **Technologies**
  material research, pulsed and high-temperature technologies, dynamic synthesis of new materials, space technologies, defence applications

High Energy Density matter is interesting because it occurs frequently in Nature

Experimental methods in HED physics research

- **Static methods (diamond anvil cell)**
  isotherms P(V, T=const~T_k), melting curve, volume and enthalpy changes at melting, binding energy, heat capacity, crystal structure;
  low temperatures, P < 5 Mbar

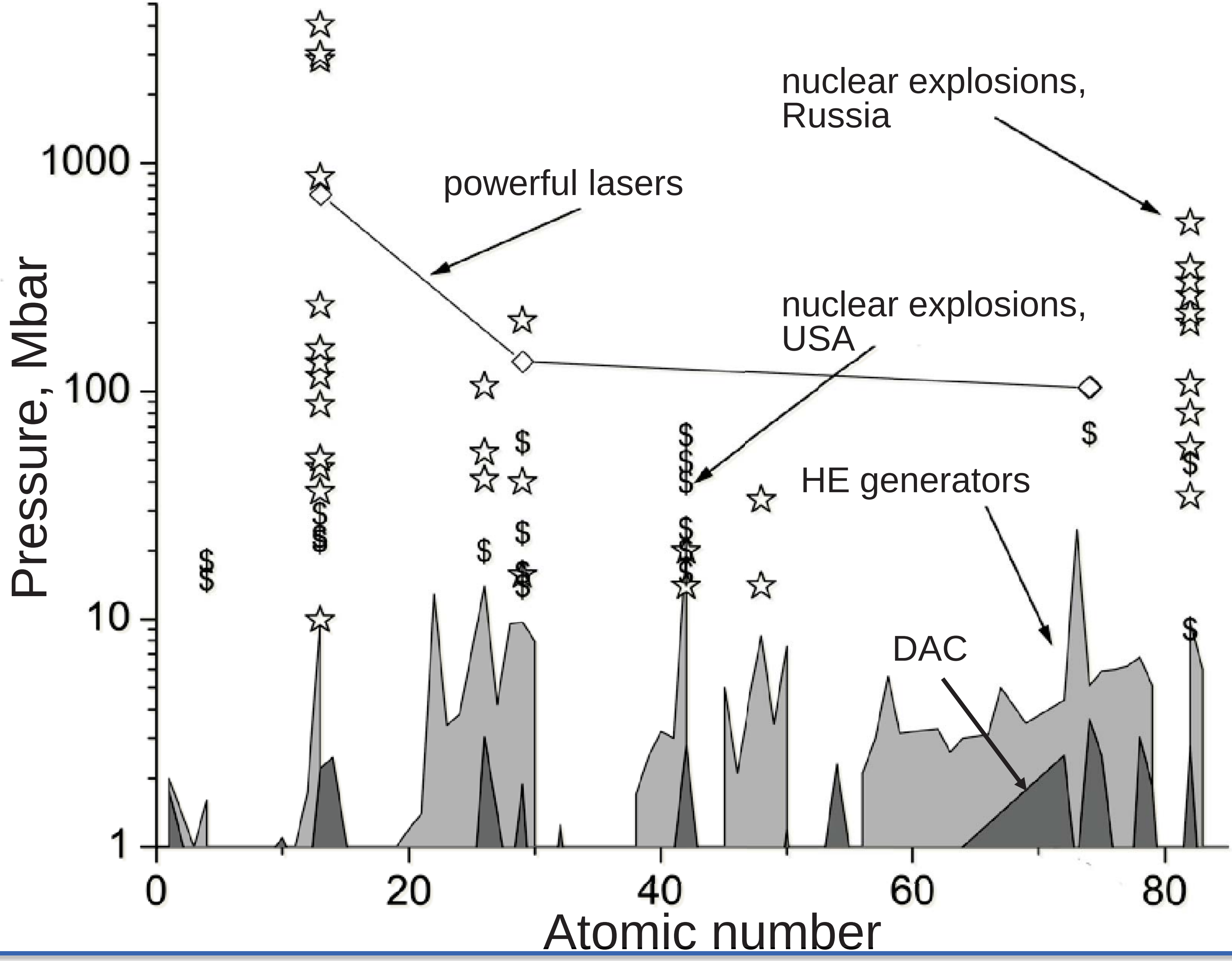
- **Shock wave compression**
  shock adiabats of solid and porous samples H_1, H_m, E(P,V), extremely high pressures; **max. temperature and density; data only along Hugoniots**

- **Isentropic release from shock-compressed state**
  isentropes near boiling curve and critical point, evaporation kinetics, P, U, (T), s=const; **complexity and accuracy of data**

- **Quasi-adiabatic compression**
  adiabatic compressibility at ultra-high densities, dynamic structural phase transitions, dielectric-metal transition, etc.

- **Fast electric heating (“wire explosion”)**
  isobaric or isochoric heating, H, E, T, V, P, σ; **max, pressure, instabilities in two-phase region, radial uniformity**

Highest pressures achieved in shock wave experiments



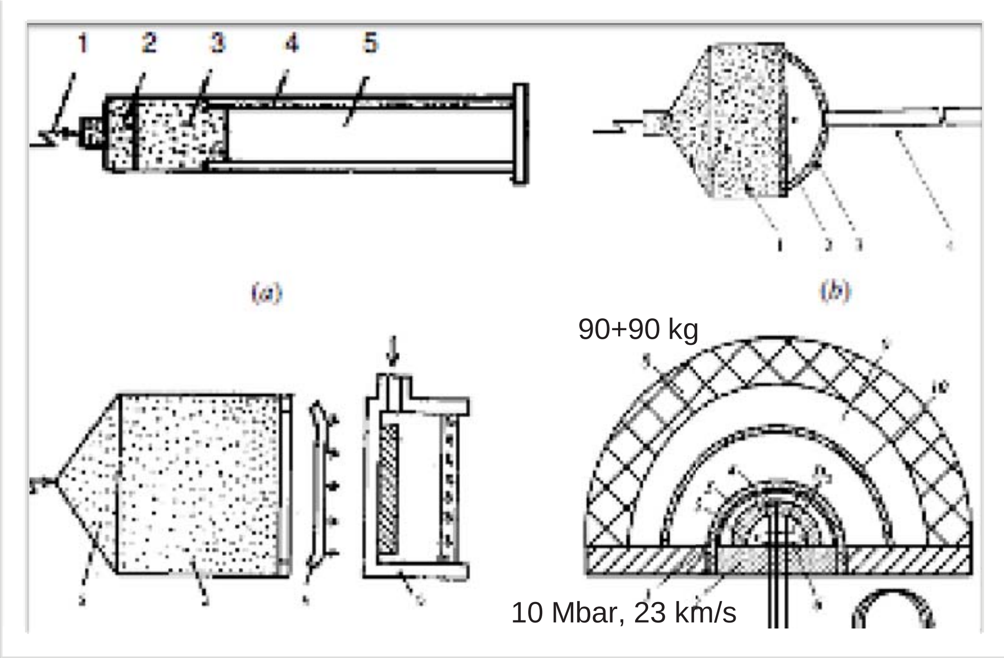
How much is one Gbar?

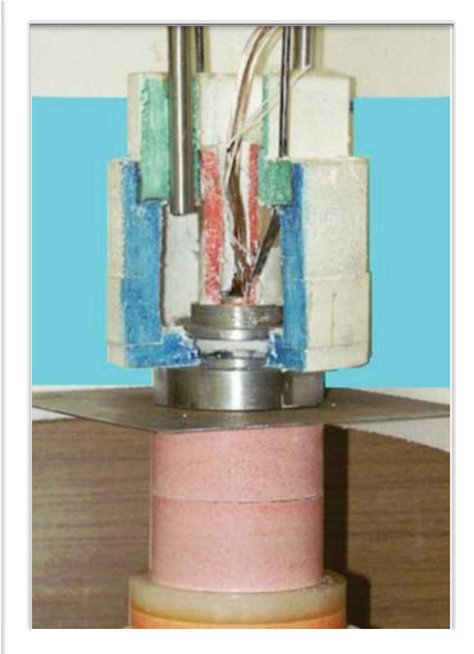
pressure on the tip of your thumb holding 10 fully loaded aircraft carriers

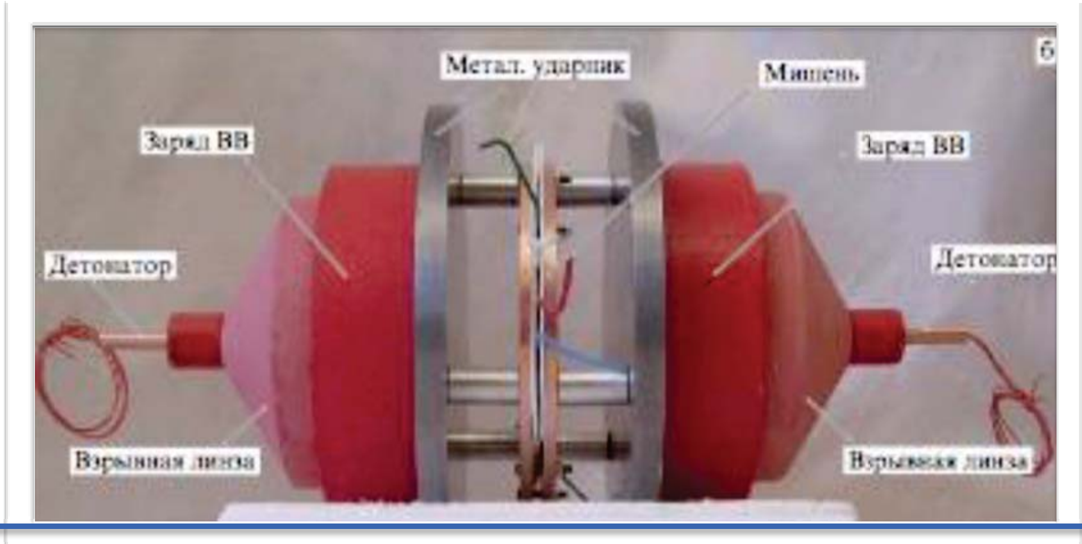
about energy density inside a bier bottle where ~1.3 ton of gasoline have burned

courtesy of D.Varentsov, GSI, Darmstadt

High explosive shock wave generators

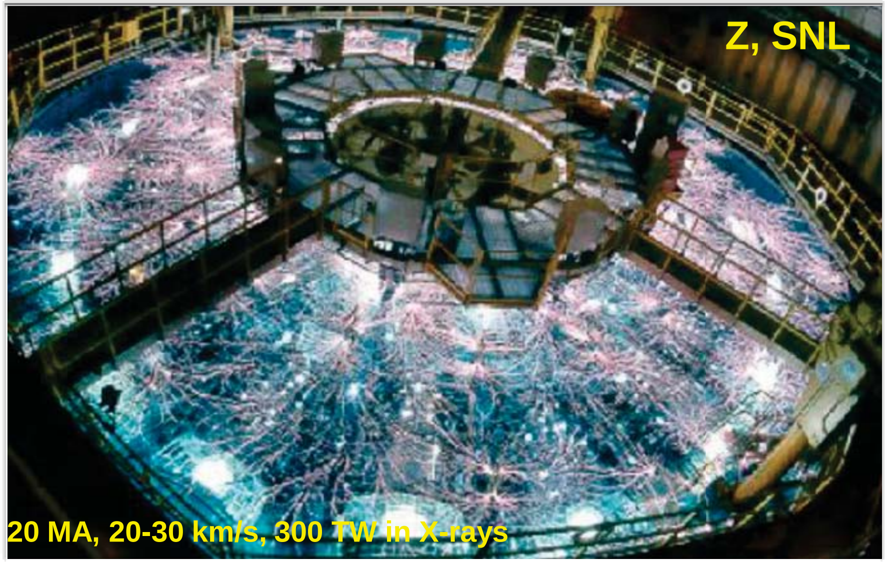


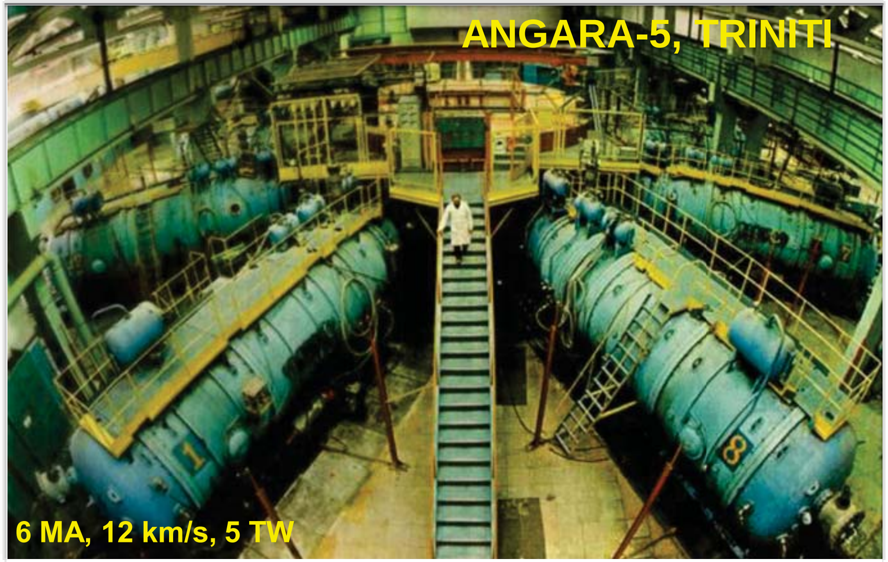


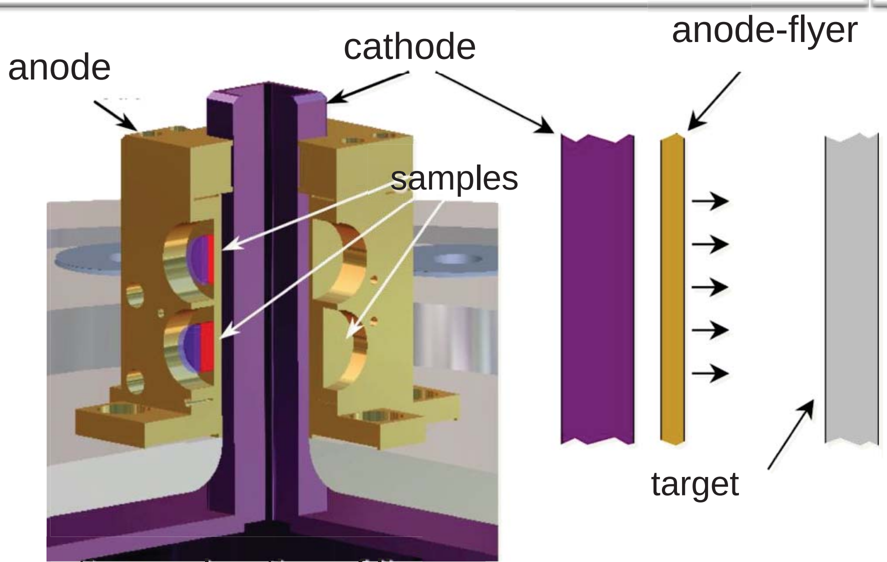


Experimental explosive areas at IPCP-Chernogolovka, Russia

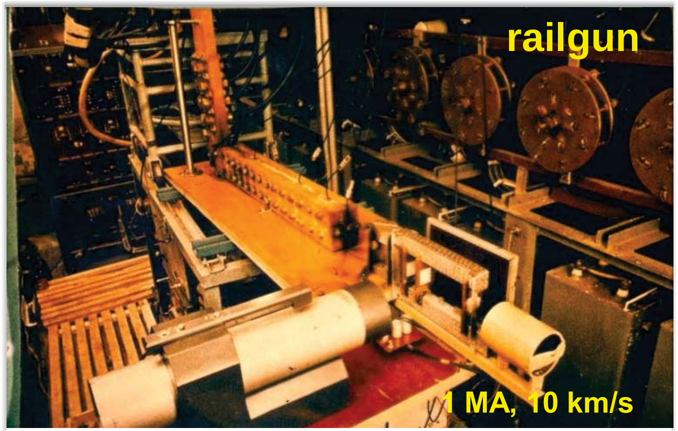
High current pulsed power generators



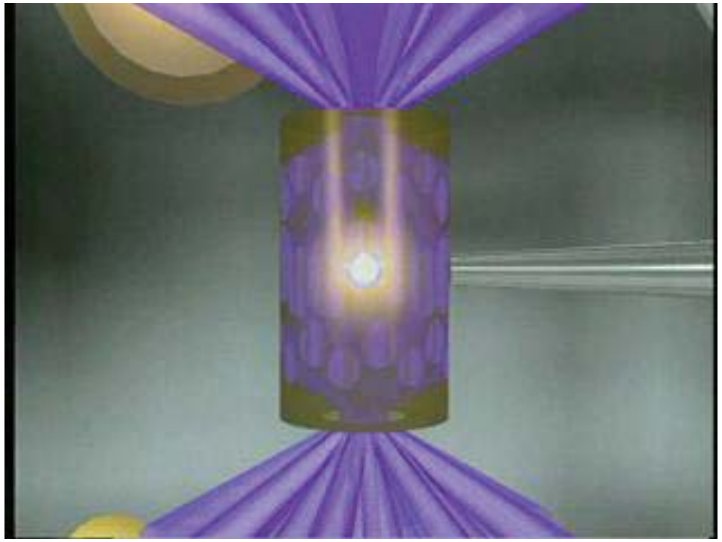




Magnetic acceleration of liner



High power high energy lasers: NIF



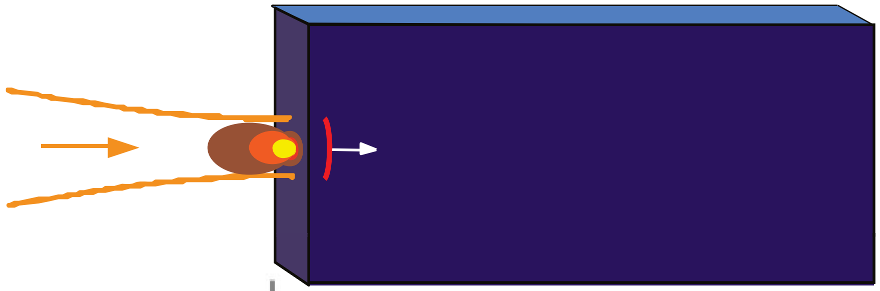
- 21 kJ (10 kJ @ 350 nm) x 192 lasers = 4 MJ (2 MJ, 500 TW)
- > 3000 m² high-precision optics
- vacuum target chamber: 10 m, 500 t

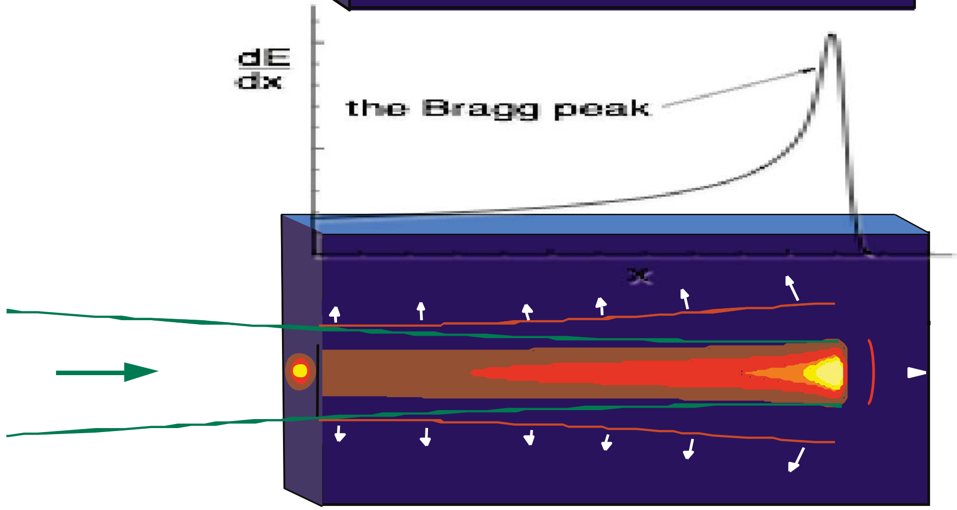
Energy deposition by a laser and by relativistic ions

Powerful lasers:

energy is absorbed on the target surface (critical density)

=> **shock wave, high gradients**



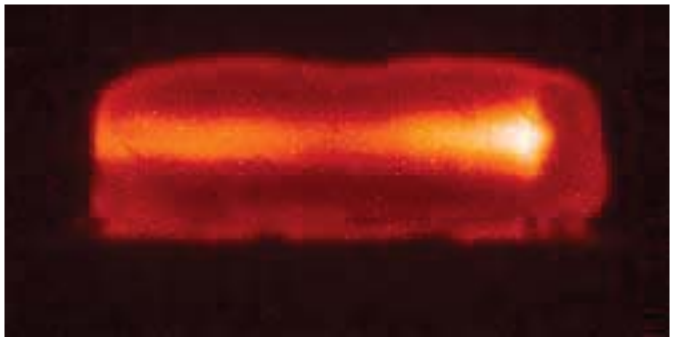


Intense ion beams:

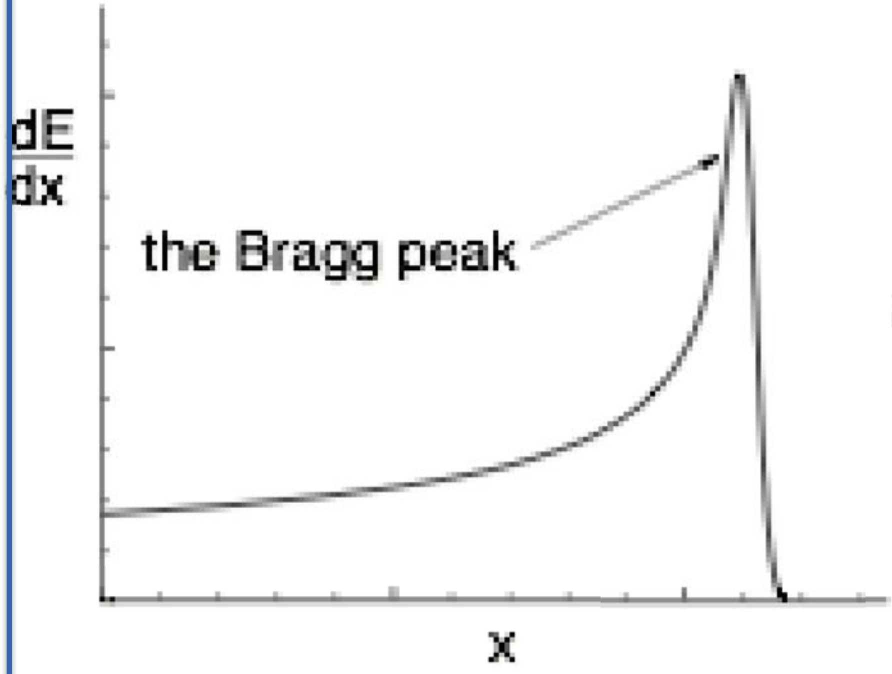
energy is deposited in the bulk of the target

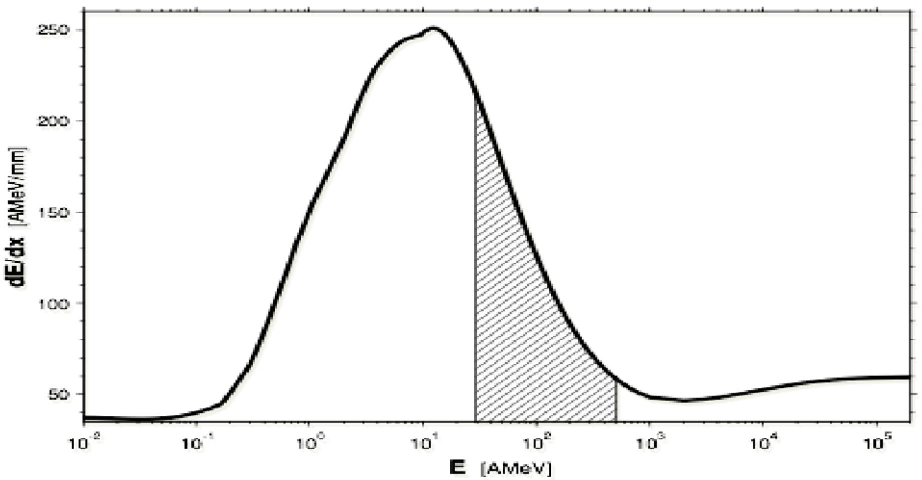
=> quasi-isochoric heating

- large volume of sample (mm^3)
- fairly uniform physical conditions
- high entropy @ high densities
- high rep. rate and reproducibility
- any target material

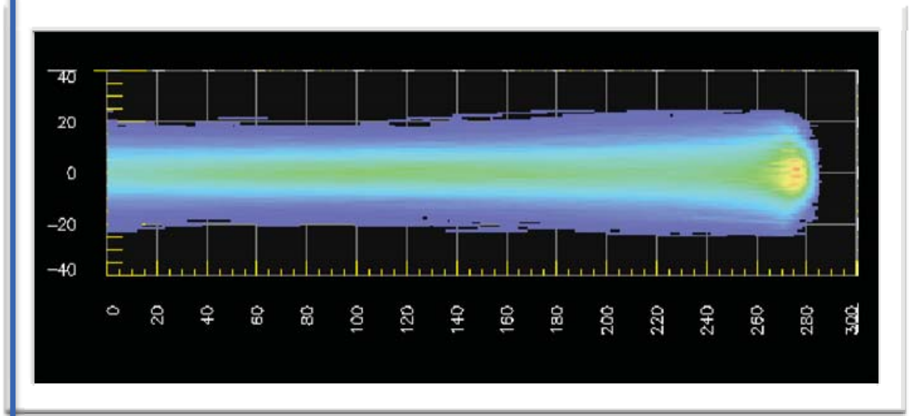


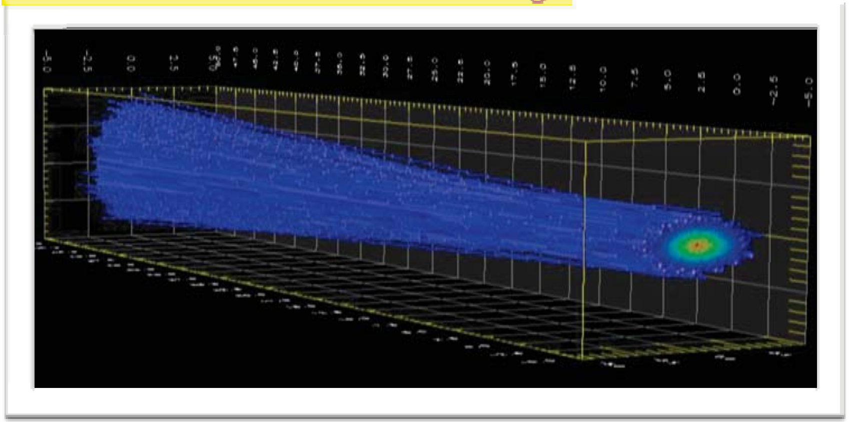
Specific energy deposition by intense focused ion beam





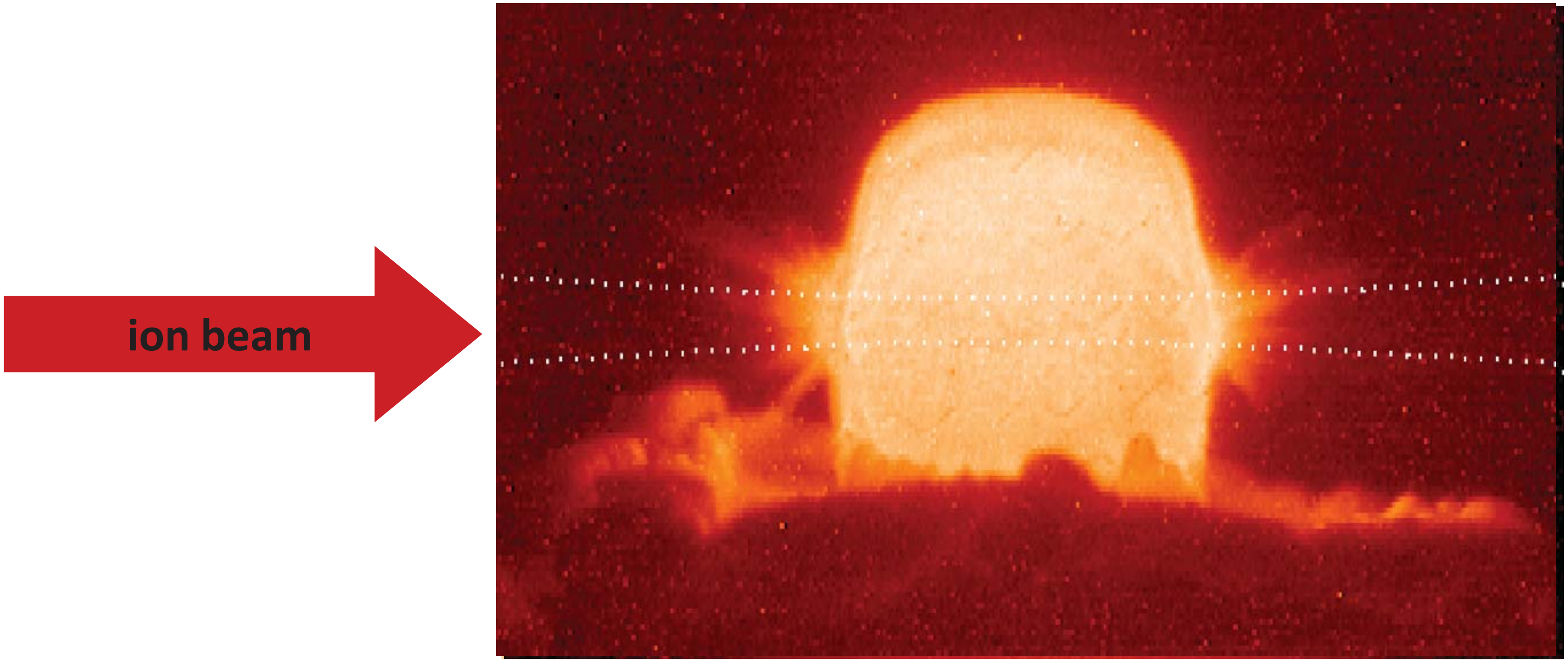
$$E_s \propto \frac{1}{\rho} \cdot \frac{dE}{dx} \cdot \frac{N}{r_b^2}$$ **[kJ/g]**



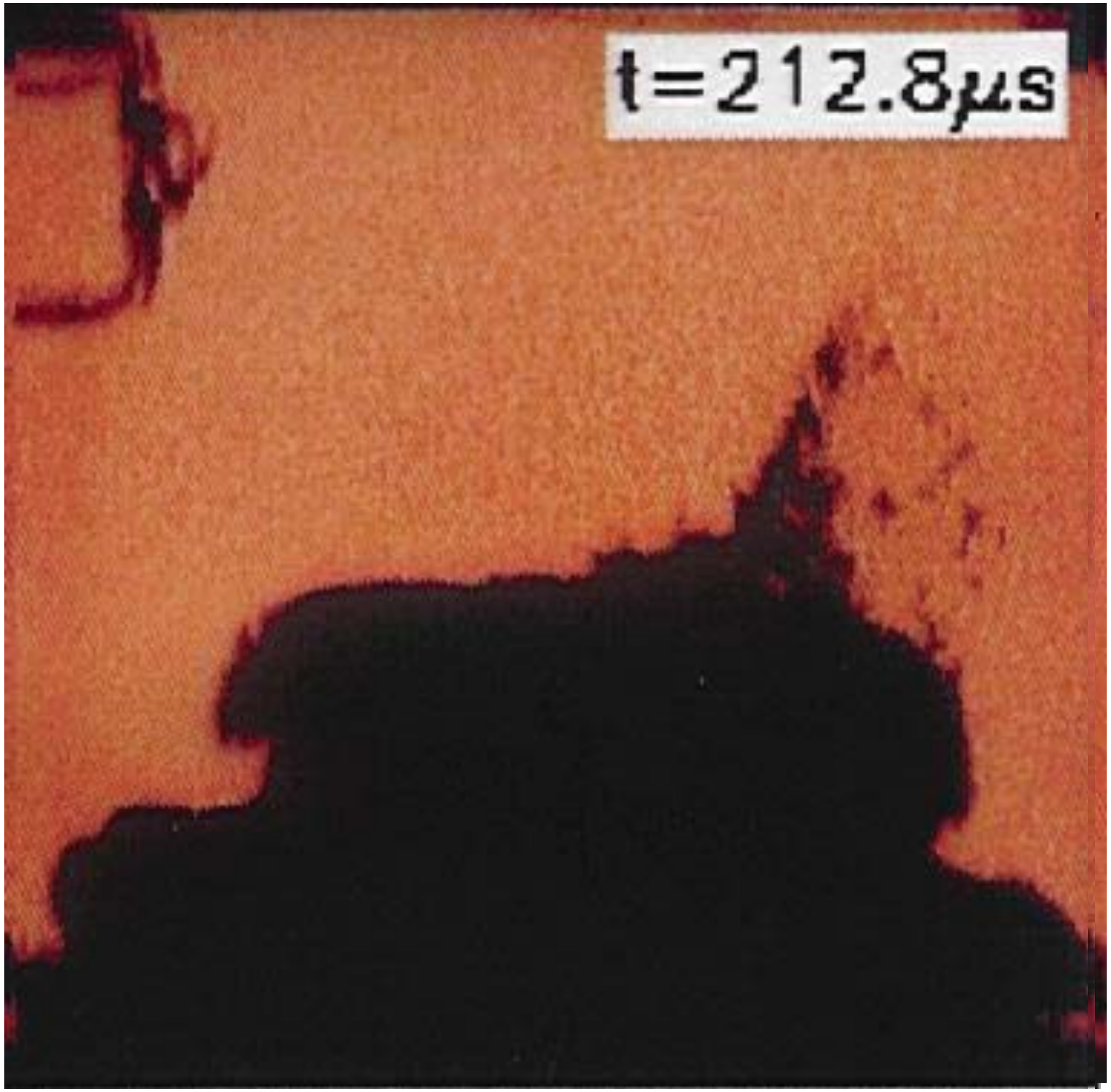


Intense Ion beam interaction with matter

Ne^{10+} ion beam with energy E_0 =300MeV/u, the target Kr kristal



Hydrodynamic motion



Frame camera

Ideal ion beam as a driver for HEDP experiments

$$E_s \propto \frac{1}{\rho} \cdot \frac{dE}{dx} \cdot \frac{N}{r_b^2}$$

- heavy ions (dE/dx ~ Z^2), Z_U = 92
- ion energy 200 – 1500 MeV/u (50 – 350 GeV for U)
- maximum beam intensity (number of ions per pulse) N ~ 10^9 – 10^{12}
- minimum pulse duration τ ~ 10 – 100 ns => bunch compression
- minimum focal spot size at the target r_b
  √ reducing transverse emittance – electron cooling
  √ special final focus system
- The important condition, which is not absolutely necessary but which would ensure much “cleaner” experiments, the pulse duration of the ion beam should be much smaller than the time of the hydrodynamic motion of the plasma This condition ensures that all the beam energy is deposited before the hydrodynamic expansion sets in.

Accelerator laboratories worldwide currently performing HEDP experiments with intense ion beams

Neutralized Drift Compression Experiment (NDCX-I and NDCX-II)

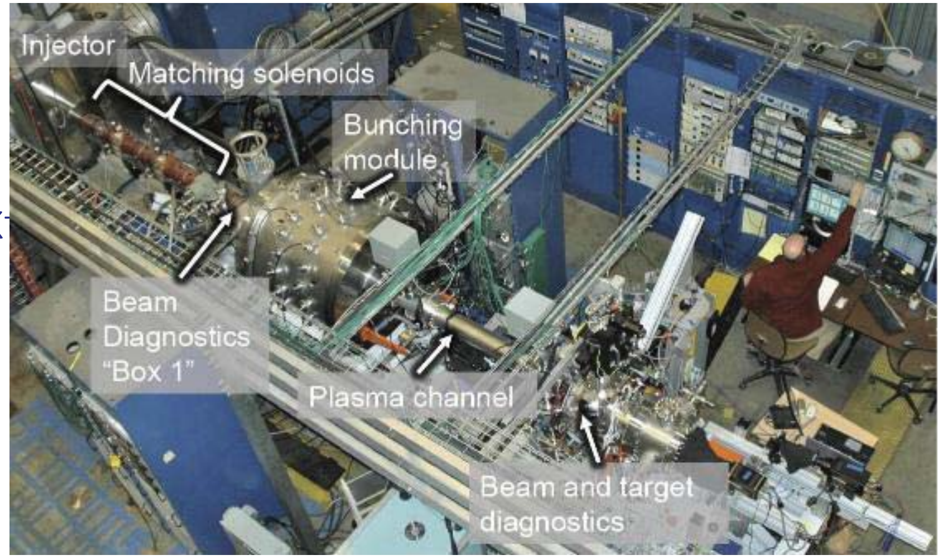
NDCX I

0.3 MeV, K+

0.01 μC

2 ns

Now



- Explore liquid/vapor boundaries at T ~ 0.4 eV
- Evaporation rates and droplet formation
- Test beam compression physics
- Develop diagnostics

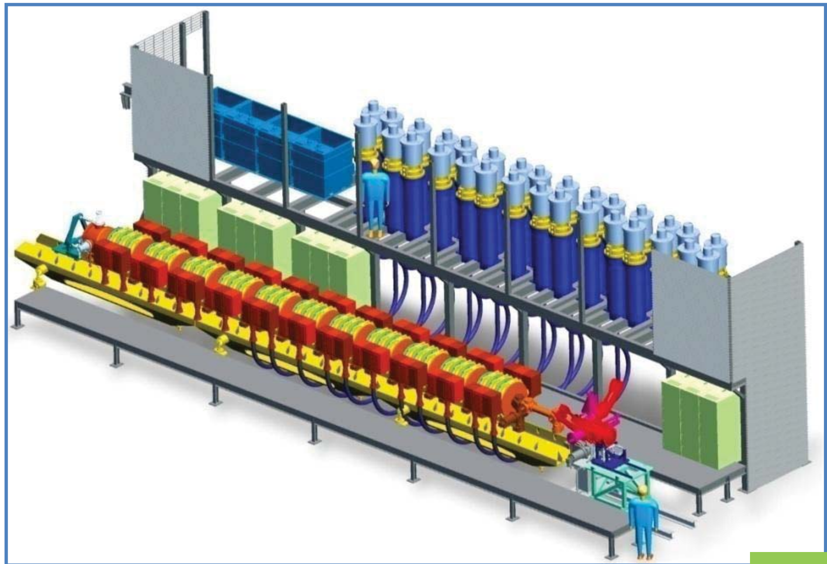
NDCX II

2 - 3 MeV, Li^+

0.03 μC

<1 ns

Completion date: 2012



- Bragg peak heating
- T ~1-2 eV in planar targets
- Ion^+/Ion^- plasmas
- Critical point; complete liquid/vapor boundary
- Transport physics
- HIF coupling and beam physics

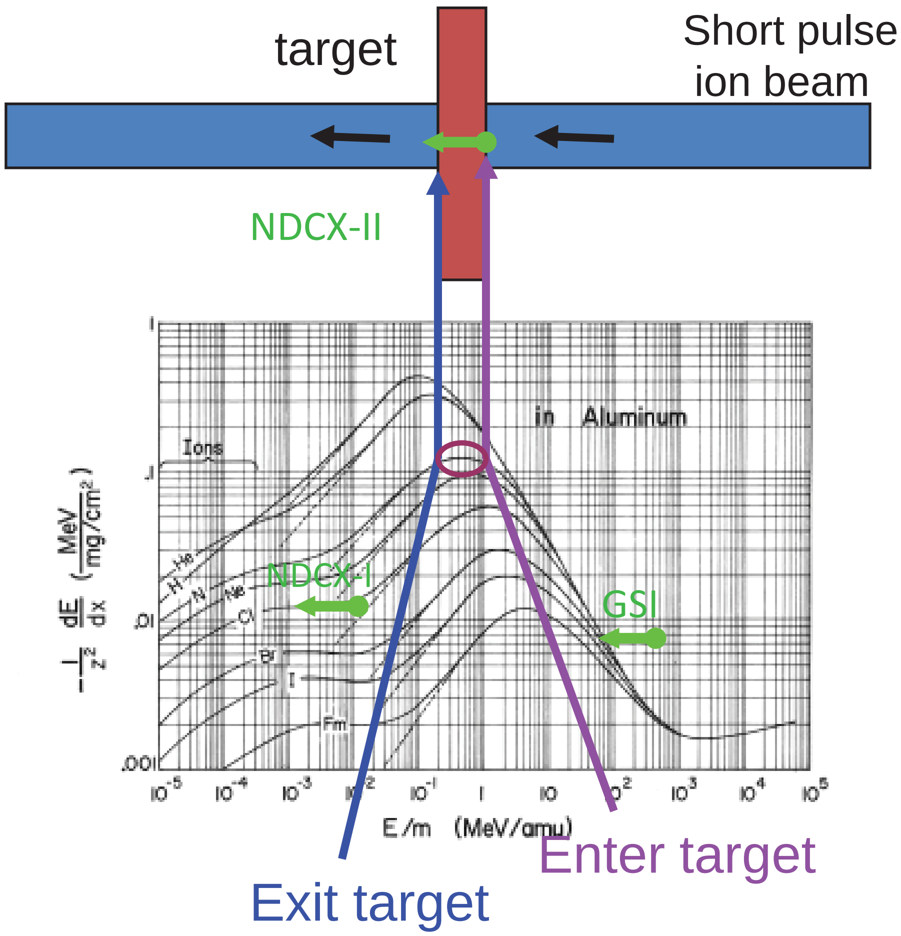
courtesy of F. M. Bieniosek, Berkeley

Ion beams provide a tool for generating homogeneous warm dense matter.

- Warm dense matter (WDM)
  - T ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * solid density

- Uniform energy deposition near flat portion of dE/dx curve, e.g. nuclear stopping plateau (NDCX-I); Bragg peak (NDCX-II)

- Other favorable characteristics include
  - Precise control of energy deposition
  - Large sample size ~micron depth, 1 mm diameter → easy to diagnose
  - Ability to heat any target material → broad industrial applications
  - Not sensitive to 'bleaching'
  - Benign environment for diagnostics
  - Immune to blowoff plasma
  - High rep rate and reproducibility



L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

courtesy of F. M. Bieniosek, Berkeley

Overview of HIFS-VNL target experiment program

- HIFS-VNL is a heavy ion fusion science program but main experimental effort is in the area of ion beam driven high energy density physics (HEDP).

- We have recently held a workshop on ion beam driven HEDP.
  - -2010 Ion Beam Driven High Energy Density Workshop, June 22-24, 2010
  - http://hifweb.lbl.gov/public/BeamHEDP2010/Presentations.html

- NDCX-I (0.3-MeV K^+) is a test bed for beam manipulation, target physics and diagnostic development.

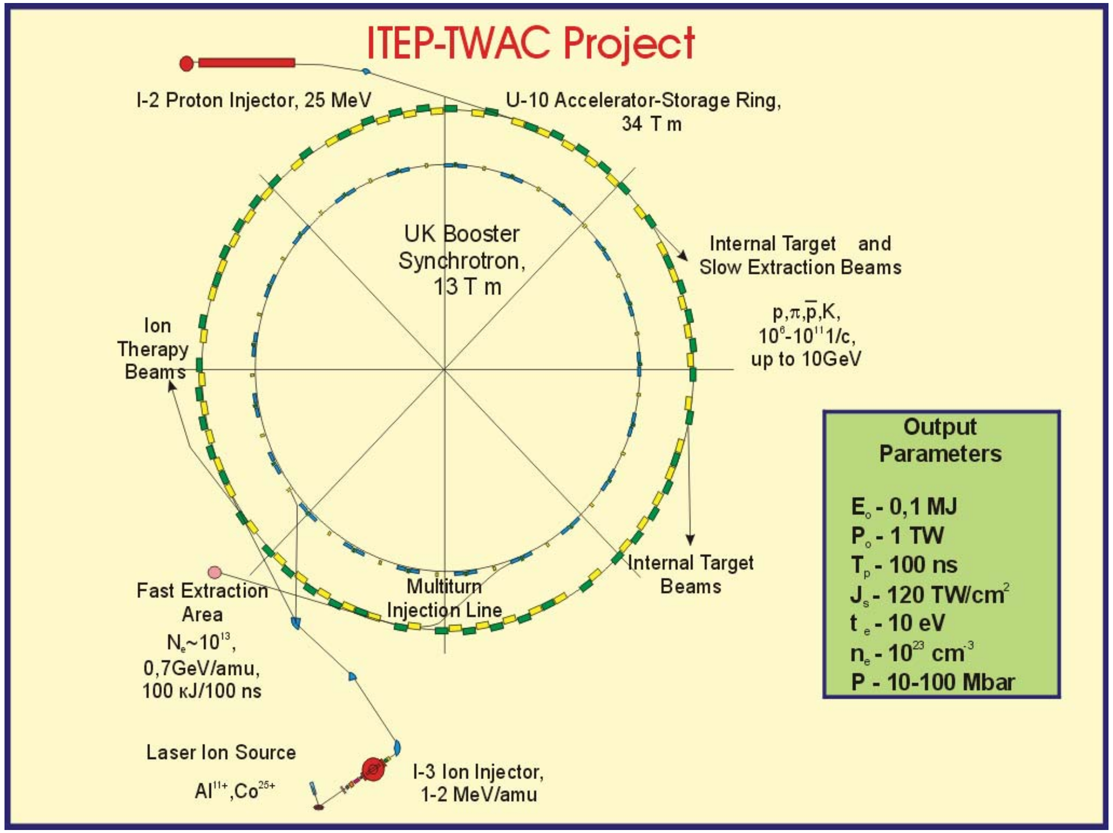
- NDCX-II (2-3 MeV Li^+) is a linear induction accelerator, under construction. It will be an ion beam driven user facility, to be available for target experiments after beam commissioning, in 2012.

- New target chamber with enhanced capability for diagnostics to be designed for installation on NDCX-II; *e.g.* high power lasers, cryo-targets, x-ray diagnostics.

- This presentation focuses on target chamber HEDP experiments in NDCX-I and NDCX-II.

courtesy of F. M. Bieniosek, Berkeley

TERRA-WATT ACCELERATOR *TWAC-ITEP*

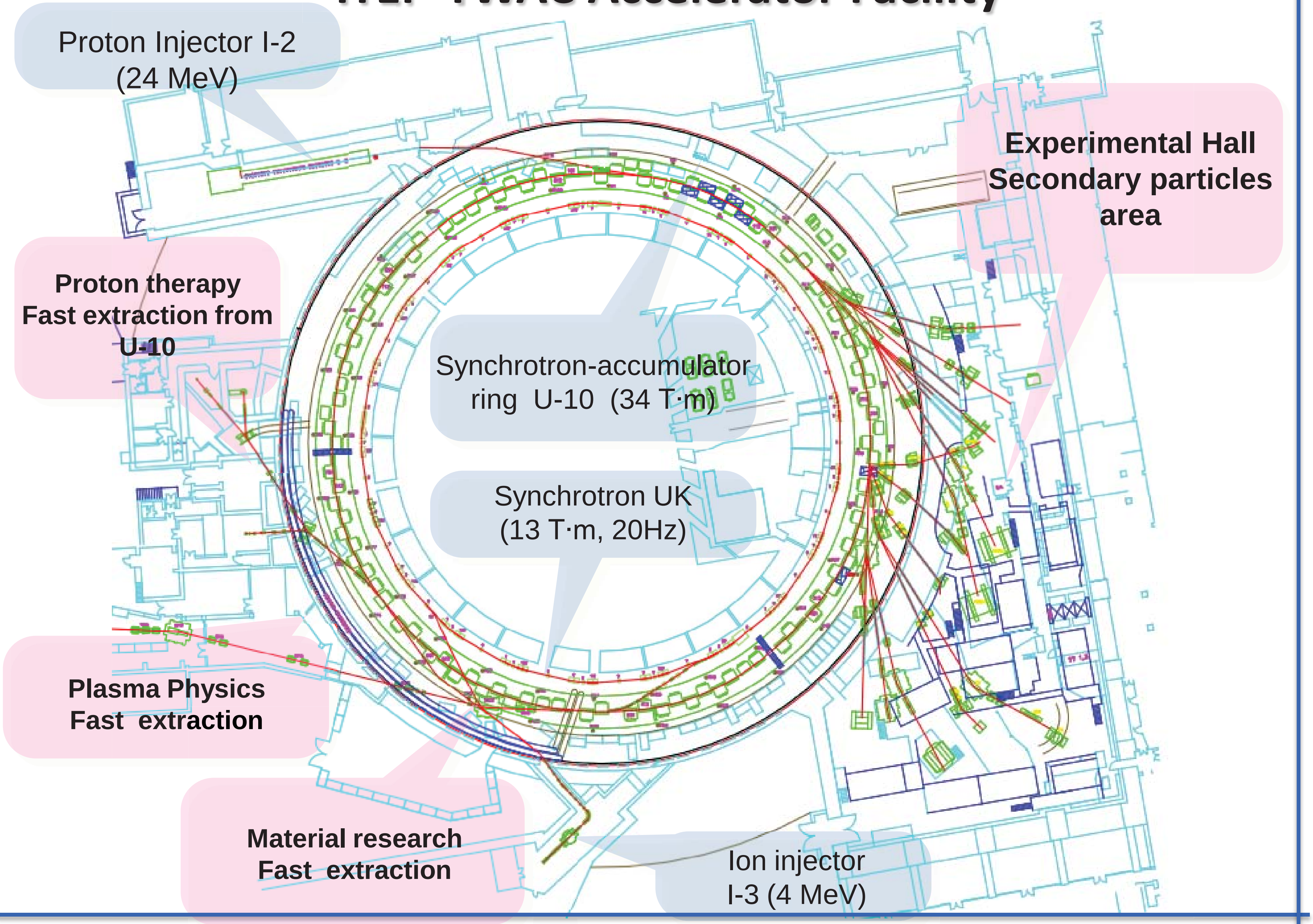


- High energy density in matter Physics
- Relativistic nuclear Physics
- Charge particle accelerators Physics
- Proton and heavy ion Therapy
- Nuclear Fluel cycle Problems
- Radiation Science of Materials

The goal of the project is to take advantage of existing accelerator facility based on two heavy ion synchrotron rings for high current HIFE related experiment. Non-Liouvillian stripping technique is applied for stacking of many pulses accelerated in synchrotron UK into the storage ring U-10. Full stripping of He –like medium atomic mass ions is used to provide high efficiency of the non-Liouvilian stacking process.

The whole acceleration – accumulation scenario looks as follows. A laser ion source produced about 10^{10} ions, which are accelerated in the pre-injector U-3 up to 1.6MV/u, then injected into the booster ring UK. After acceleration up to 0.7 GeV/u, a 250ns long bunch is injected in a single turn mode to the synchrotron ring U-10 using a non-Liouvilian stripping process. The charge state of the ions changes from He-like to fully stripped by passing through a solid foil of about 5mg/cm^2. Repeating this process several hundred times provides accumulation in the coasting beam until the space-charge limit is reached in the synchrotron ring. A rapid switch on the RF in the synchrotron ring caused ballistic compression of the accumulated bunch from a length of 1000ns down to 100ns. After compression, the bunch is extracted, transported and focused onto the target.

ITEP-TWAC Accelerator Facility



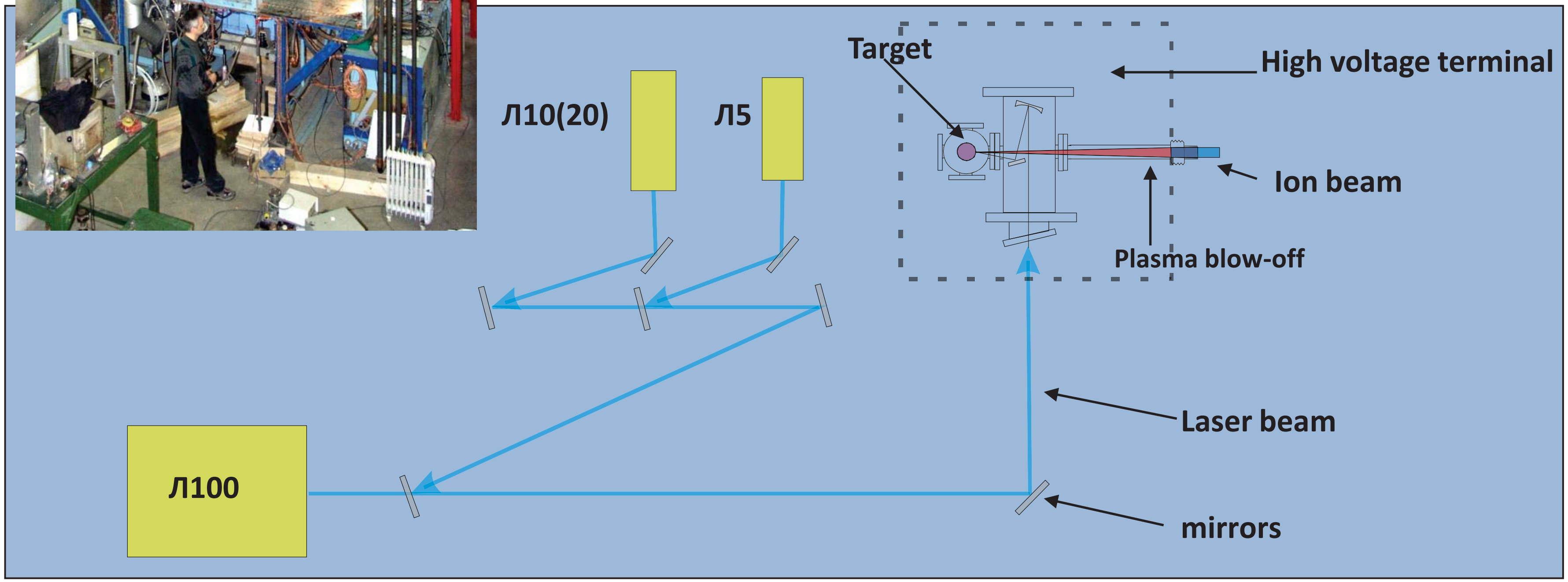
Key element: New triple - laser ion source pre-injection system (L5, L10, L100)

Laser L100

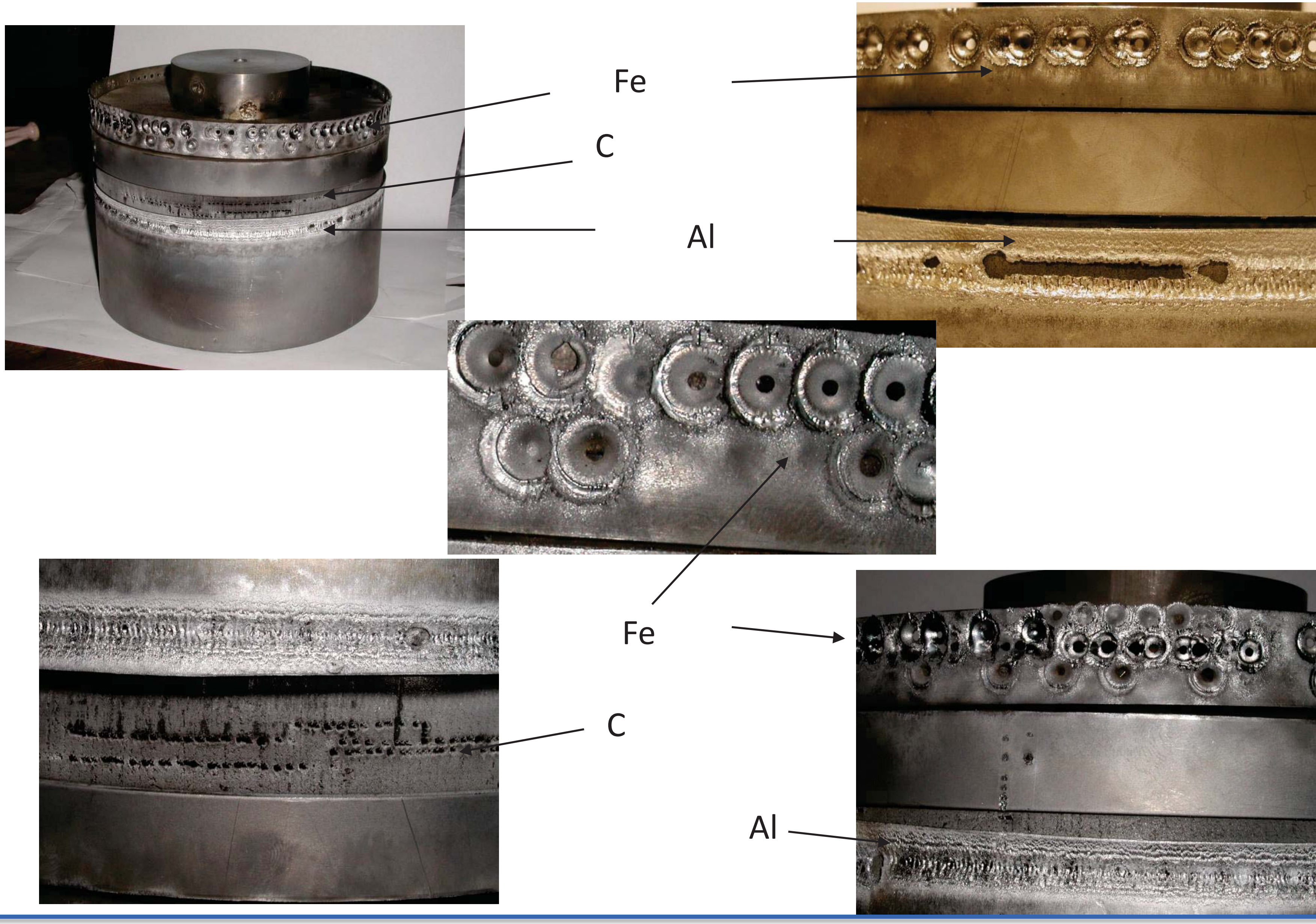
3 mA 80 MeV Fe^{16+} Measured !

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

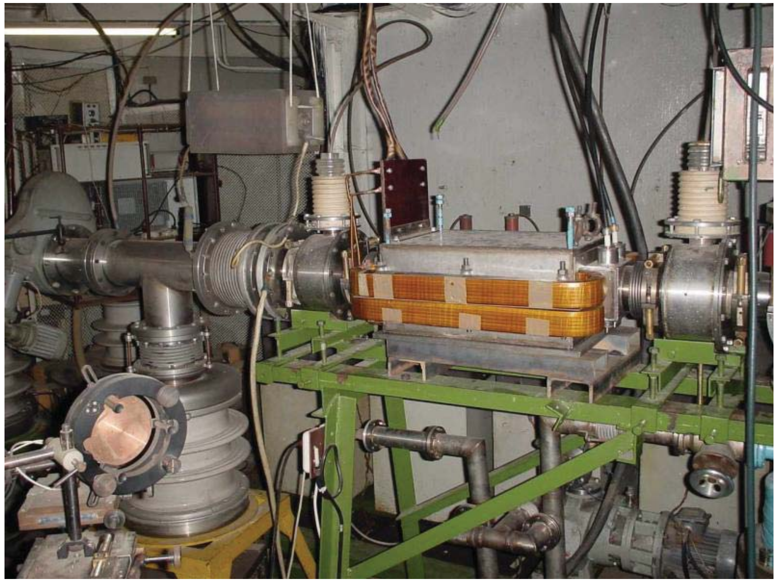
Wavelength, μm	10,6
Pulse energy, J	5/20/100
Pulse duration, ns	100/80/30
Repetition rate, Hz	0,5 /1/1
Number of shots	~10^6

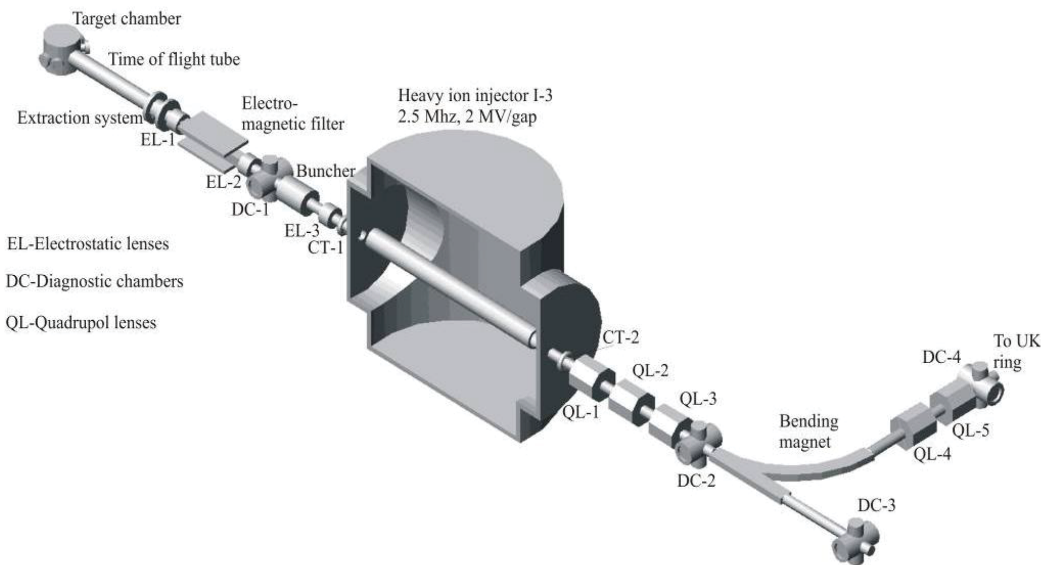


Target assembly after 3-weeks operation cycle

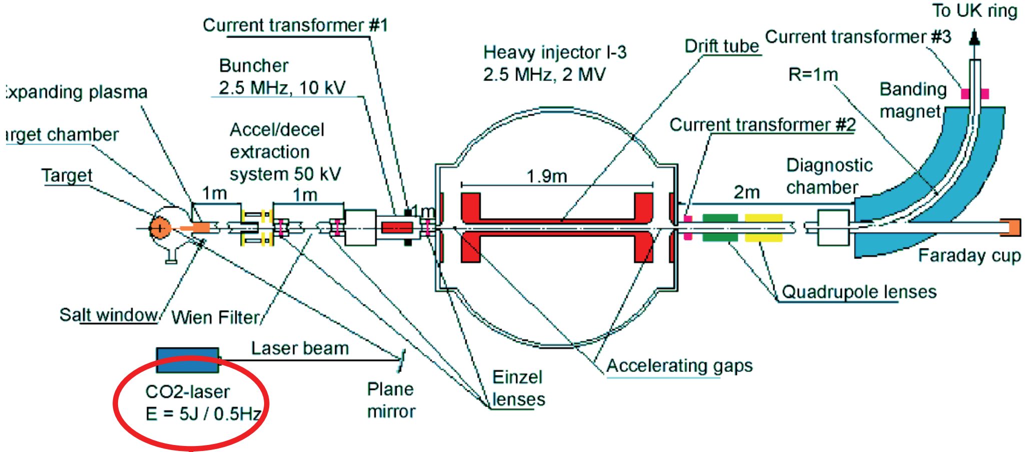


Heavy ion injector line layout and laser ion source



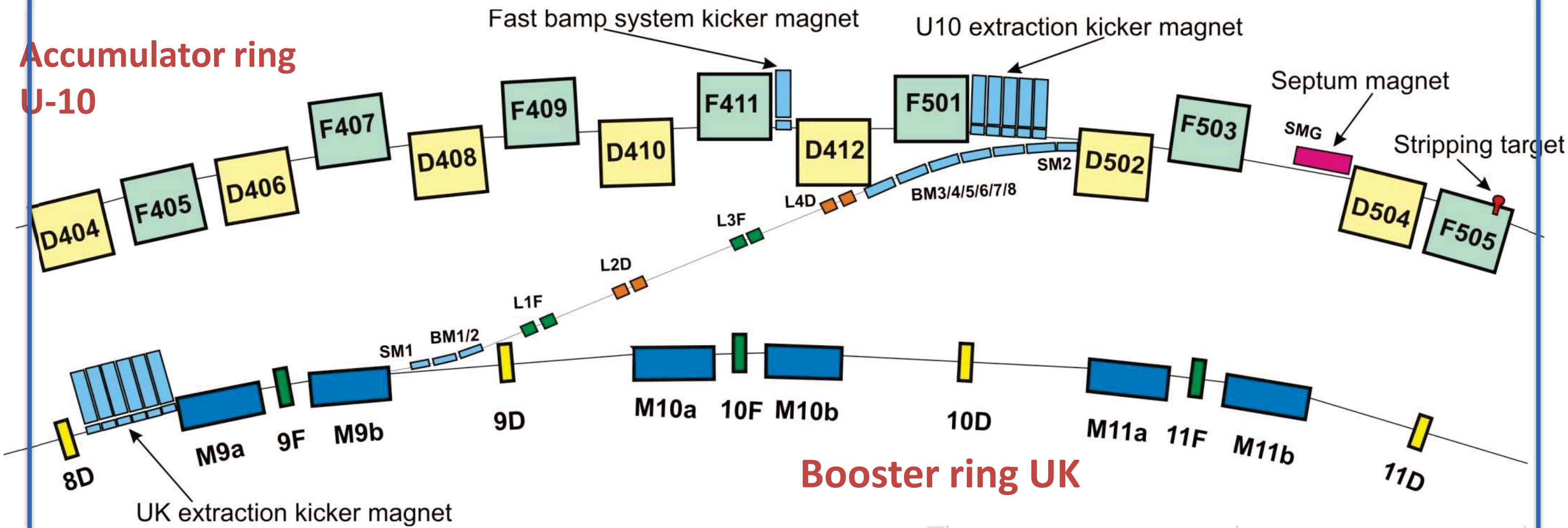


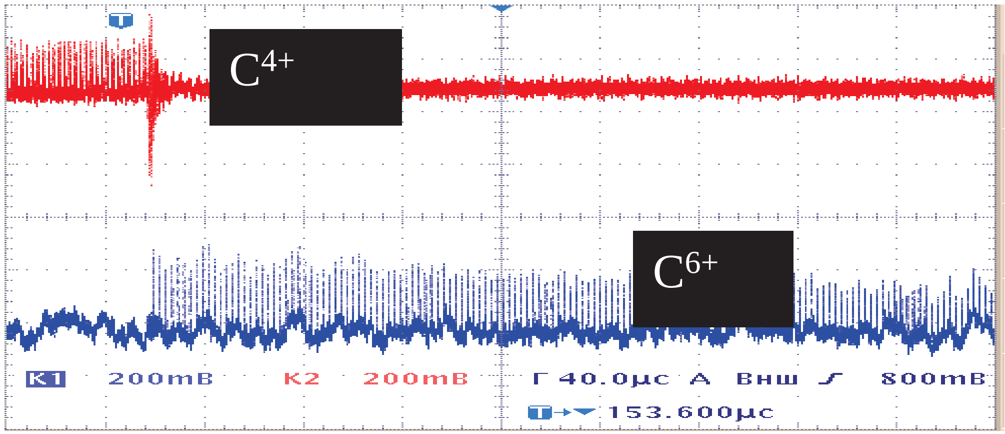
•Laser ion source, based on 5J/0.5Hz TEA CO2 –laser, has been set in operation and installed in U3 pre-injector area. The 20 mA/20μs Carbon ion beam was matched to the 2MV/2.5MHz U3 pre-injector.
•Powerful CO2 –laser with output parameters ~ 100J/20ns and rep-rate of ~1Hz is under install.



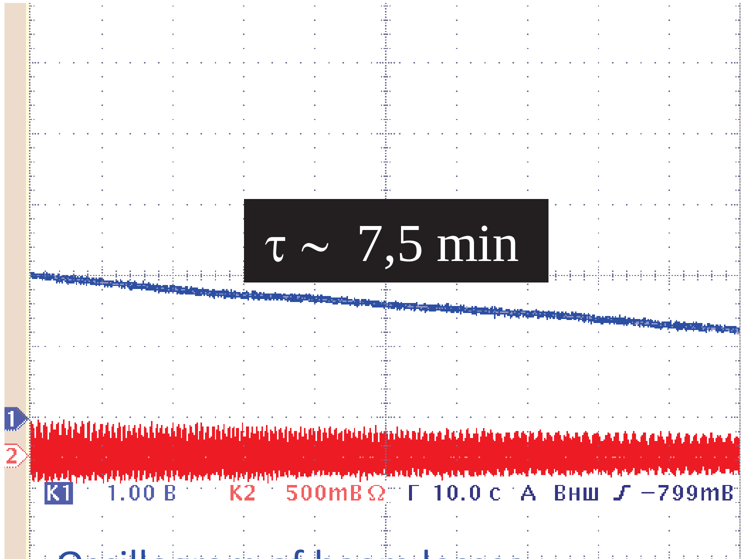
100J/1Hz laser is being mounted

Non-Liouvillian Injection into the storage ring





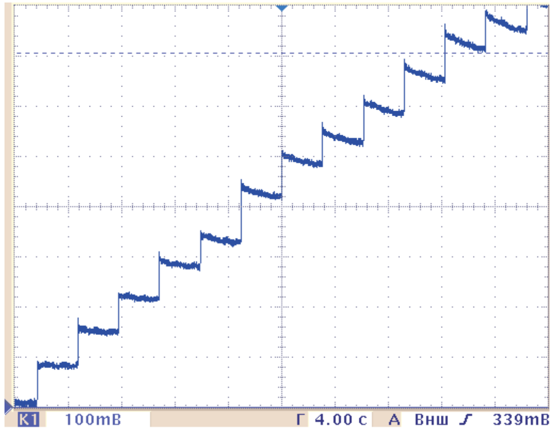
Oscillogram of injection in a single turn mode to the storage ring U-10 using a non-Liouvilian stripping process

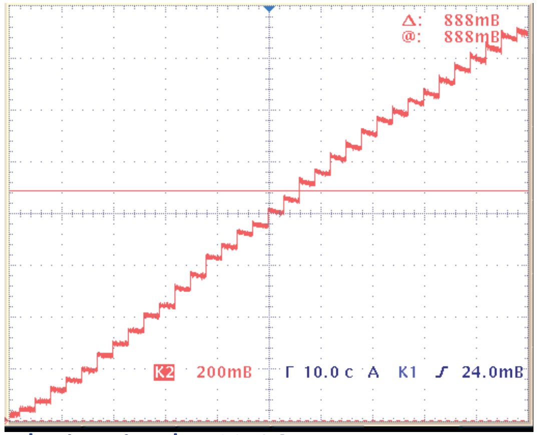


Oscillogram of beam losses

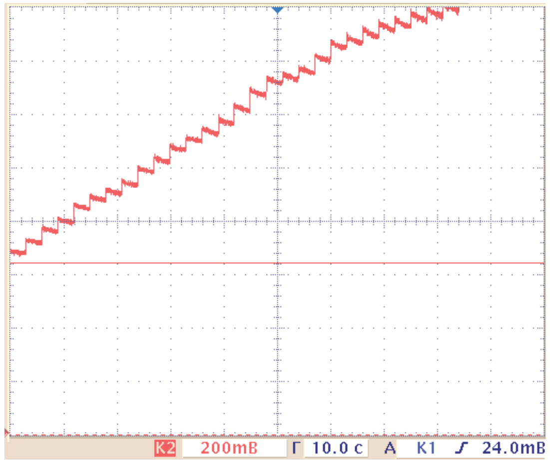
Ion accumulation C^{6+} in U-10 (213 MeV/u)

Linear intensity growth ~ 100 s (> 40 cycles)

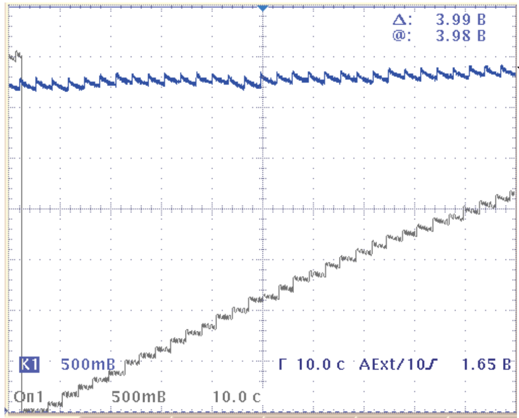




Oscillograms for the intensity of the C^{+6} during accumulation in the U-10



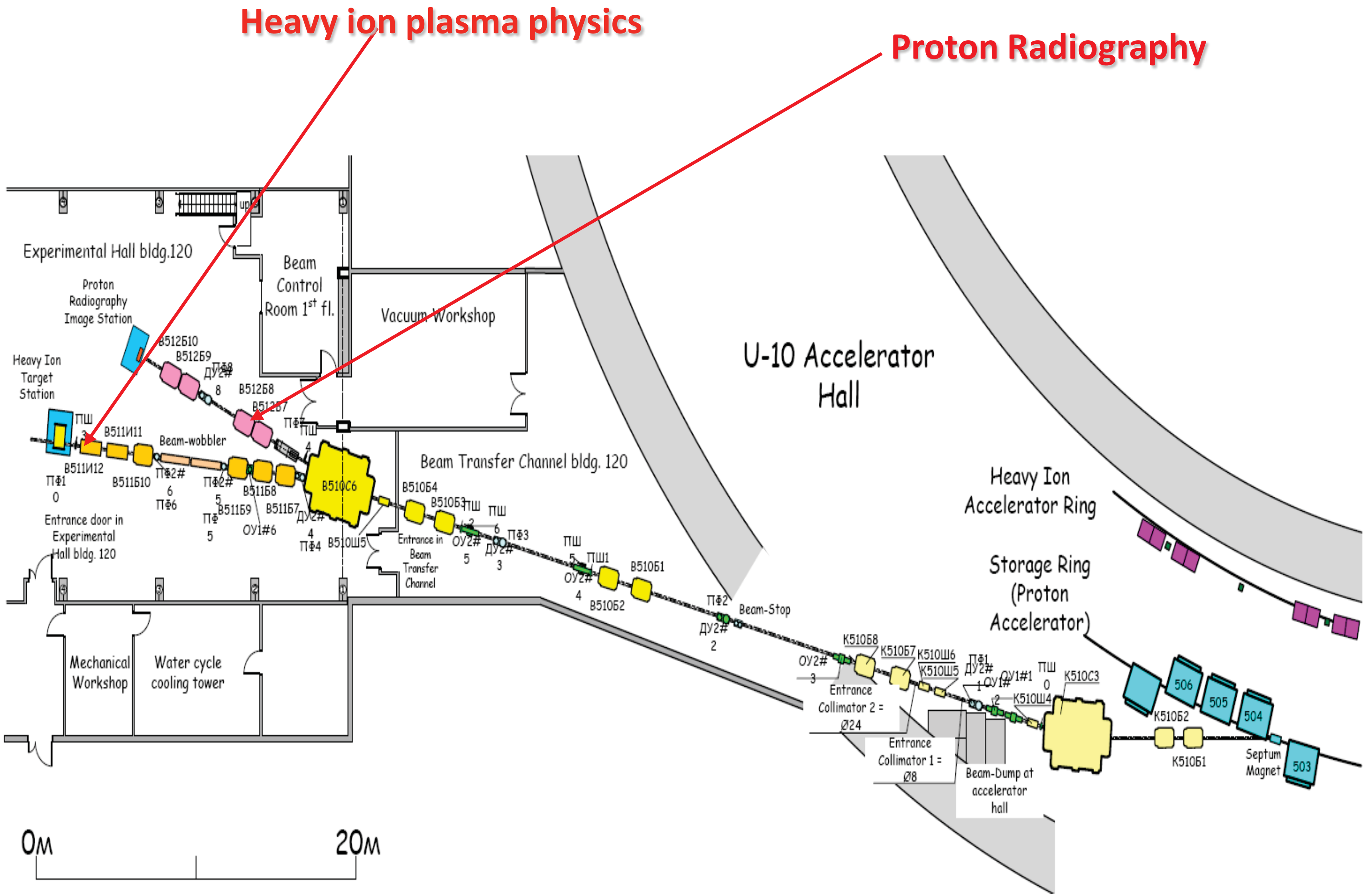
Accumulation drawdown



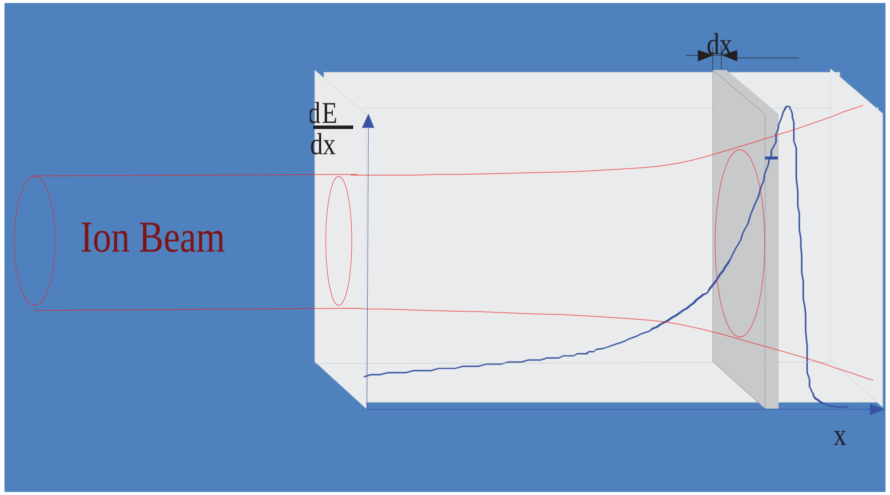
$4 \cdot 10^{10}$

Maximum intensity of accumulated beam

HED Experimental Area on TWAC Facility



Experimental method of Stopping range measurement and the energy deposition profile



Why

is needed to use 'thick target' approach for a precise measurement of total stopping range and energy deposition profiles of ion beam in solids?

Because:

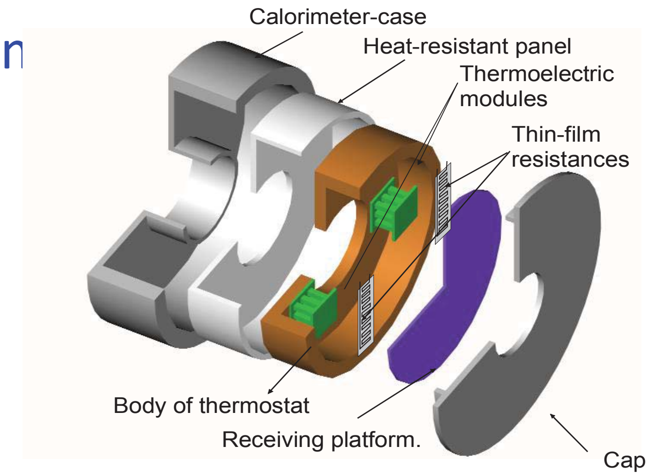
it provides direct measurement of the energy deposition range ion beam, rather than its reconstruction from measured differential energy loss of ion;

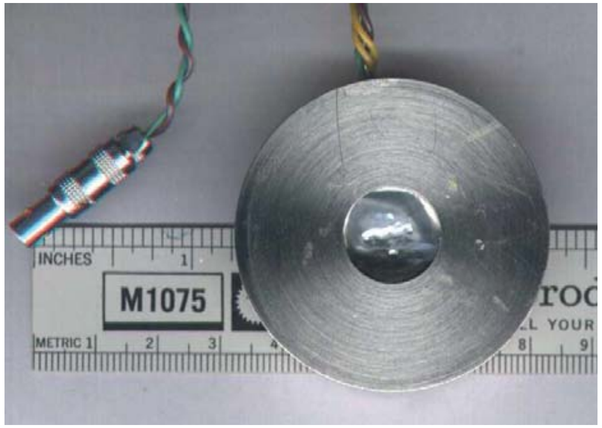
it enables to eliminate the 'edge effects', as compared to 'thin foil' approach;

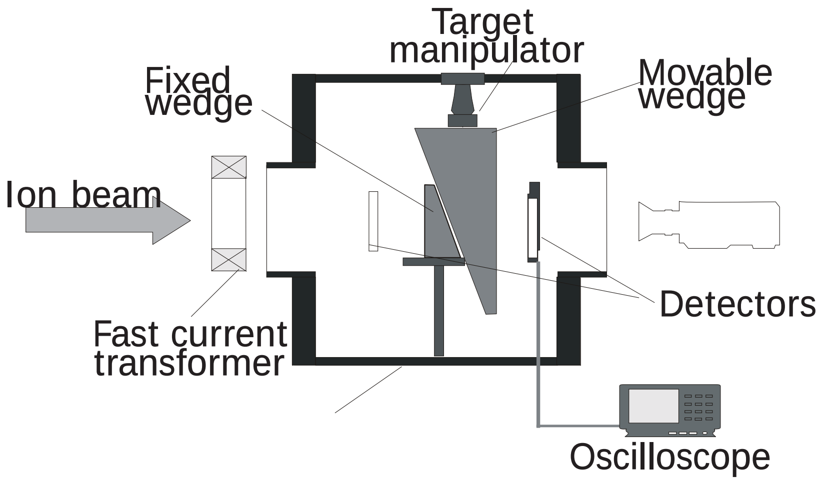
it takes into account of the ion beam straggling and fragmentation, secondary particles etc.

- This method using thick targets of variable thickness, determined with high precision and registrate of the energy deposition along the ion stopping range by thin detectors.
- The precision of the method is determined by the detector parameters (energy resolution, registration efficiency, detection threshold, etc. depending on a detector type) and the target parameters (precision with which the target thickness, density, purity, are known). In order to get accurate and reliable results the ion beam parameters should also be well controlled.

The scheme of the experin setup



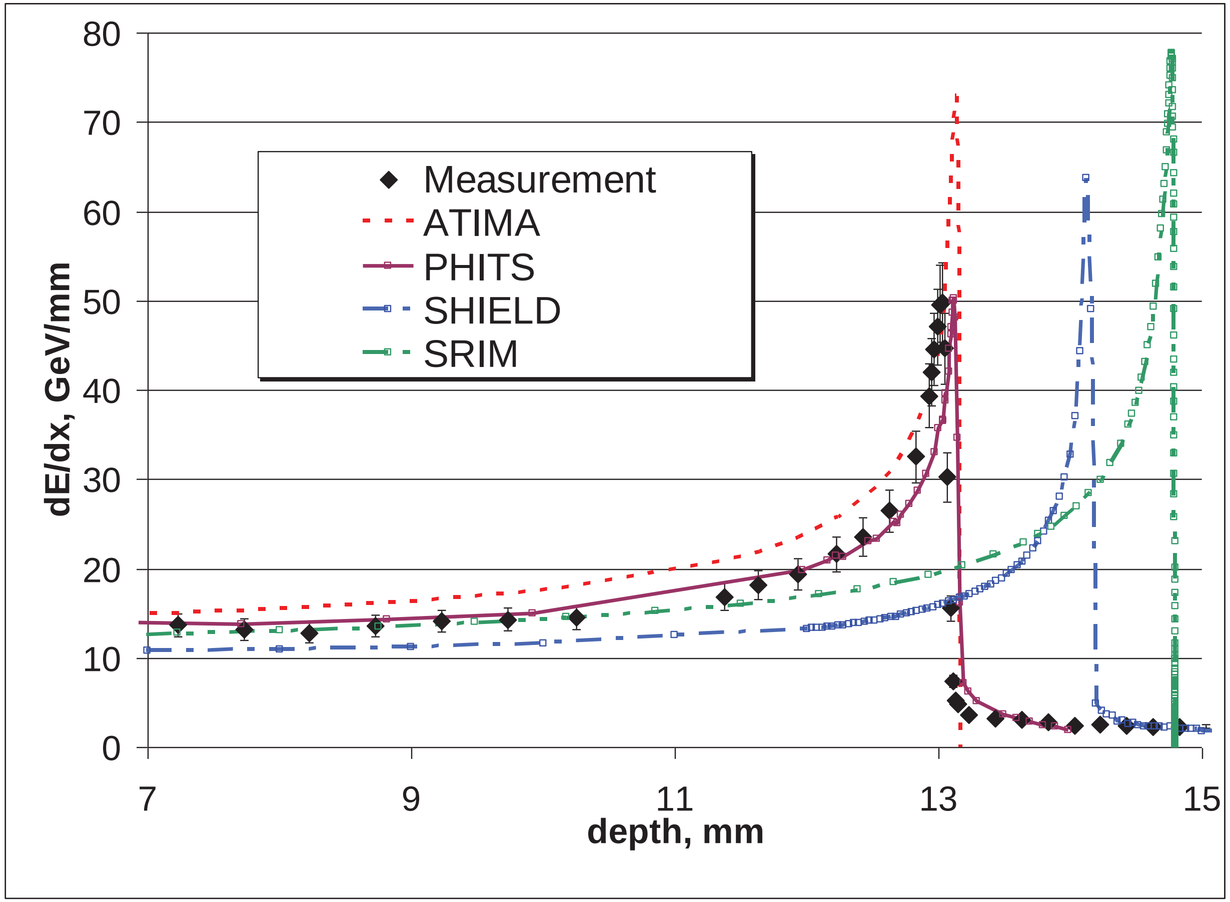




The calorimeter measures the change of temperature in a thin layer of material due to its heating by the passing ion beam. The calorimeter is enclosed in a metal case and consists of a receiving platform made of a foil attached to thermo-modules, which are fixed on a massive thermostat, serving as a massive heat sink. Two thin-film resistances (thickness 0.05mm) are glued to the surface of the foil out of direct exposure to the beam for absolute calibration for heating. Up to four receiving platform one from other may be installed in one calorimeter metal case. The size of the device is Ø50x11mm. The aperture of the calorimeter is Ø15 mm. The detector sensitivity is 5.0±0.4mV/J. The error of the specific deposited energy measurement is 7%.

- **The first design represents two wedges, the larger one sliding along the fixed smaller one to vary the target thickness. Such targets manufacture of high purity matter with precise control of the angle and surfaces of optical quality. The distance between the two wedges few tenth μm. Axial resolution of the manipulator mounted at the experimental area, where the experiments were performed, was 20μm. That allowed going through the bulk of the target with the minimum step 8μm.**
- **The second design is an assembly of foils of different thickness. The thinnest foils place at the rear of the target (end of the stopping range) in order to provide higher spatial resolution near the Bragg peak.**

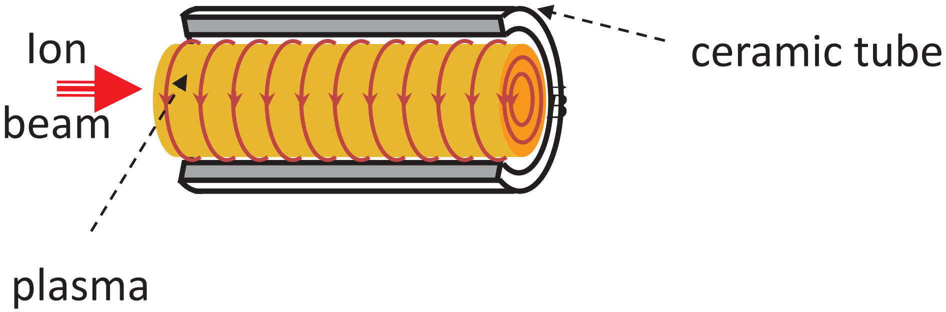
Comparison of the measured and calculated energy-deposition profiles dE/dx for the case of 950 MeV/u U ions in Cu target.



The Monte-Carlo codes PHITS and SHIELD include nuclear reactions and straggling effects, while ATIMA and SRIM are deterministic stopping power codes without nuclear reactions. The dE/dx calculation module of the PHITS code is based on the ATIMA code, whereas the SHIELD code uses the basic Bethe formula.

The PHITS calculation shows best agreement with the experimental data and produces the peak position as well as the peak shape and peak height rather well.

Plasma lens focusing



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

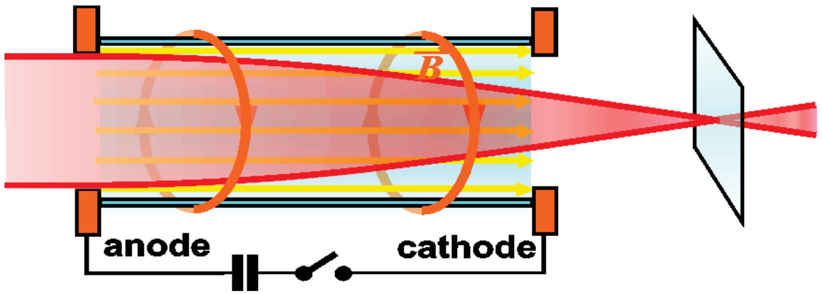
$$d_{min} \sim \varepsilon I^{-1/2}$$

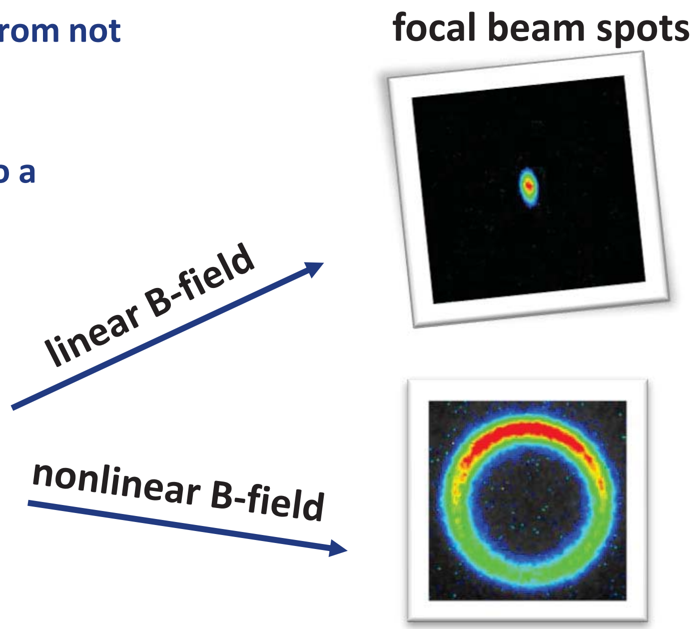
Advantages of plasma lens :

- 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;

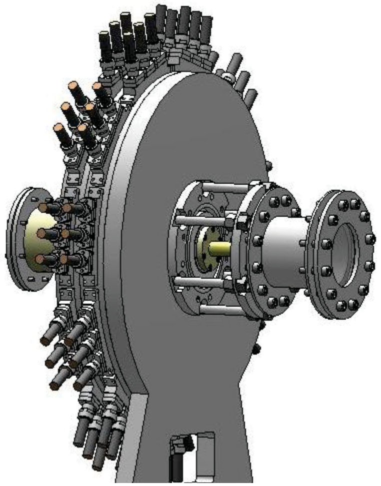
Disadvantages:

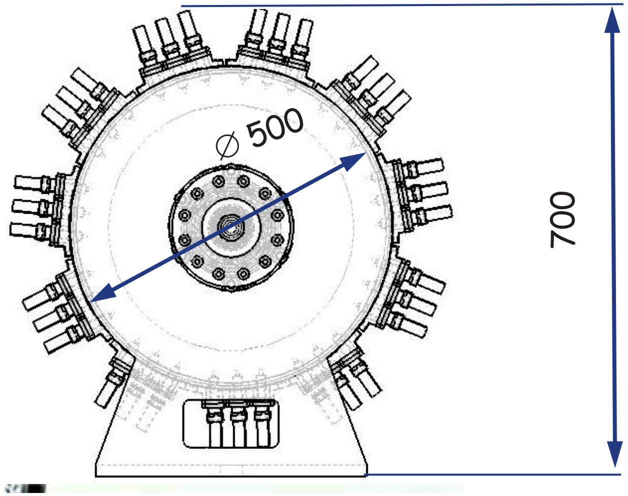
- a plasma lens system doesn't have necessary stability in contrast to a quadrupole magnetic systems;
- very strong electromagnetic noise and inducing .

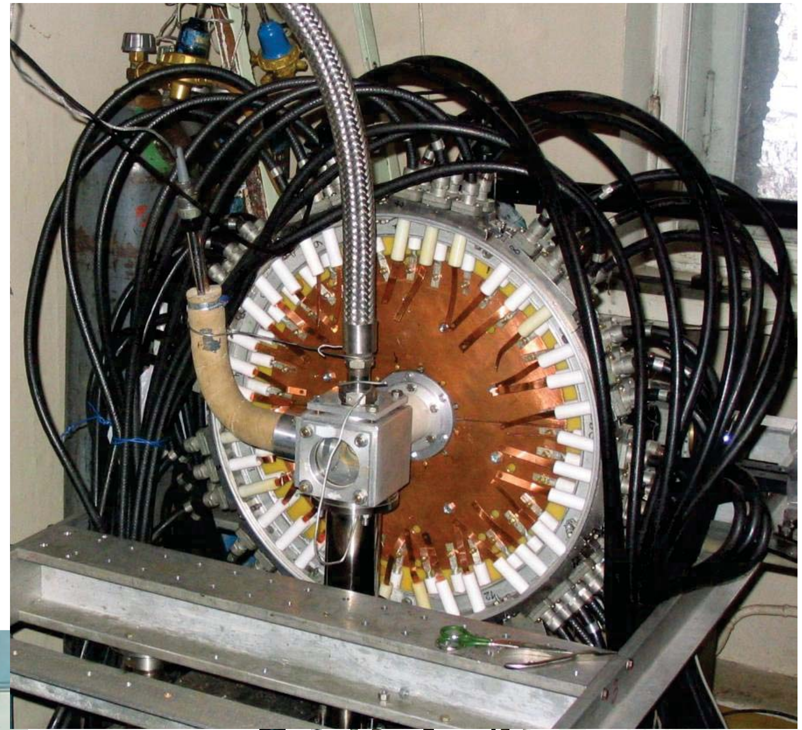


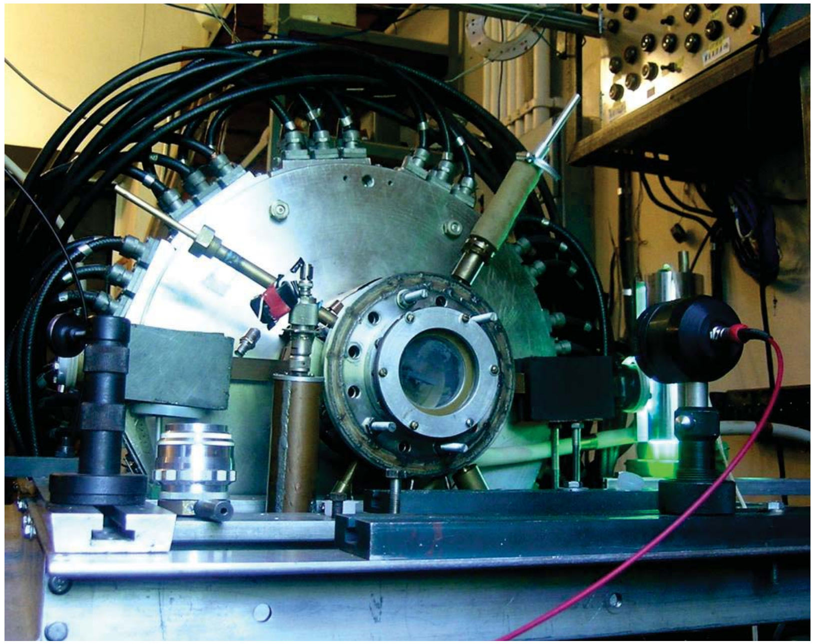


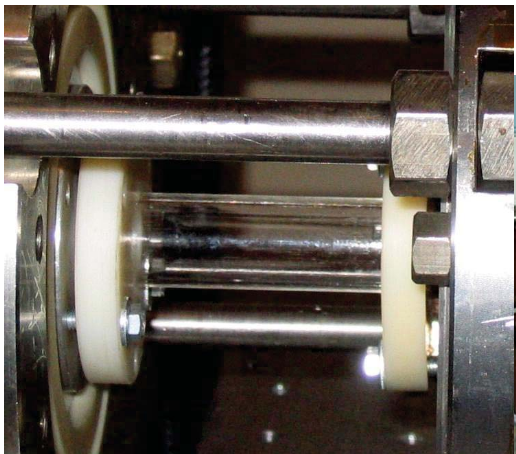
General view of ITEP plasma lens

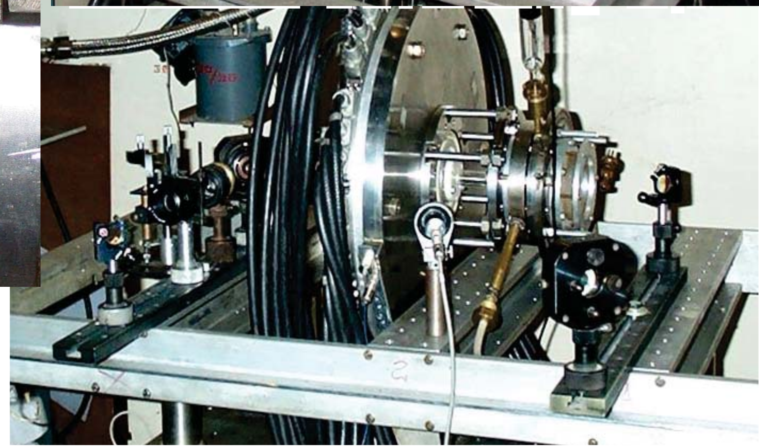




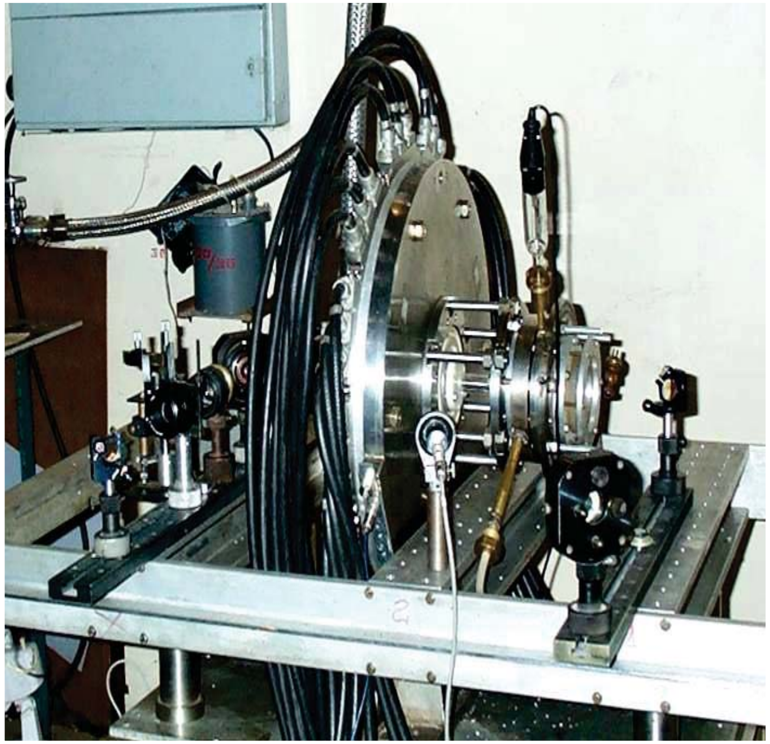






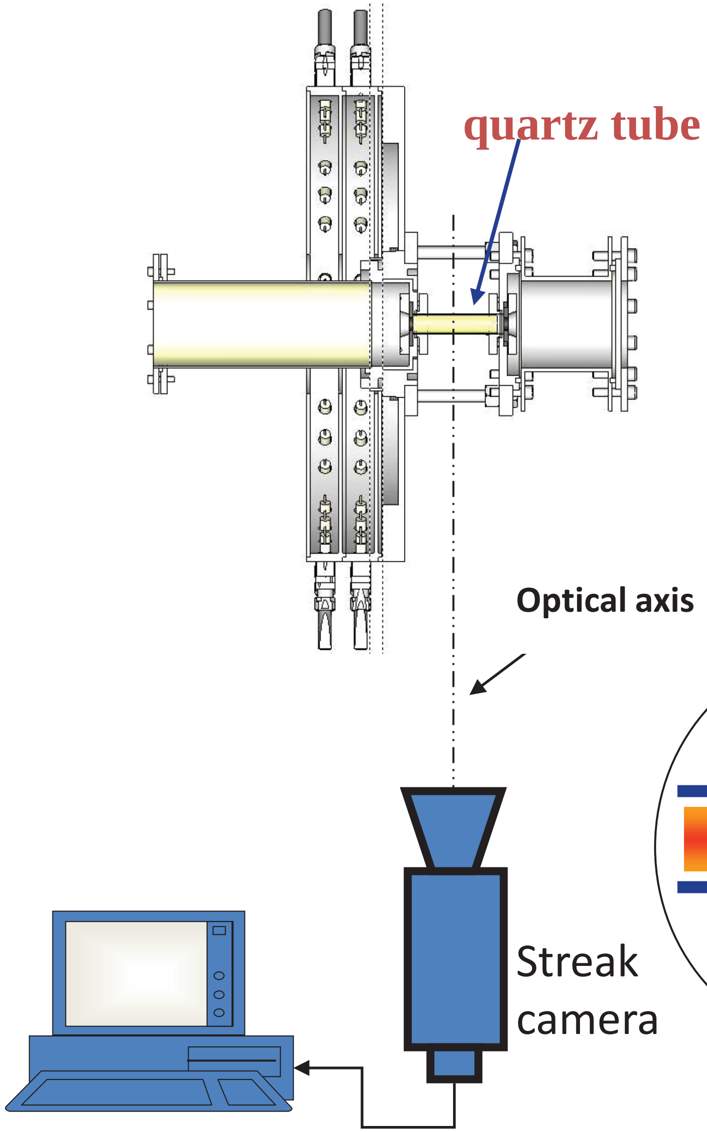


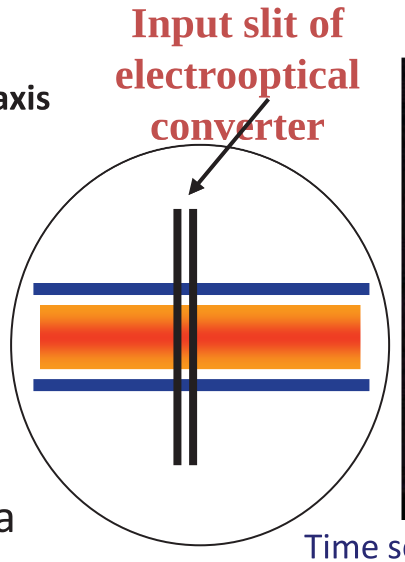
General view and parameters of ITEP plasma lens

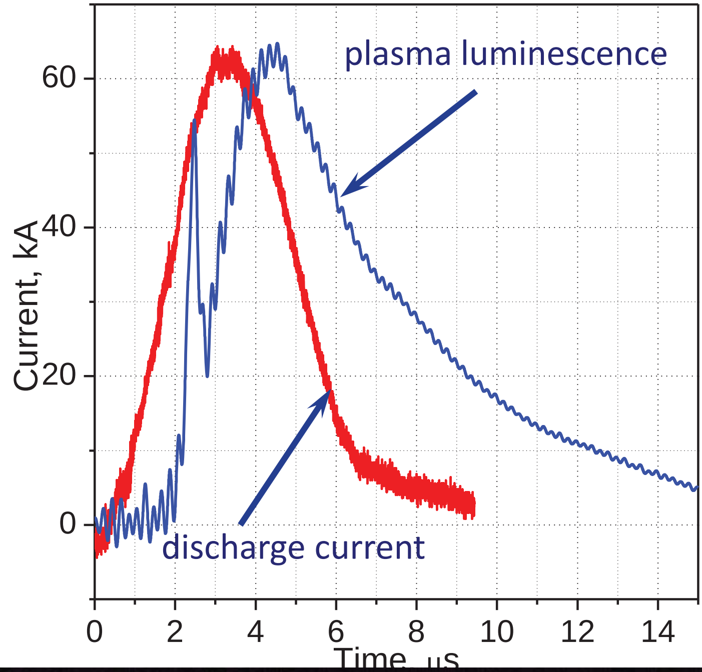


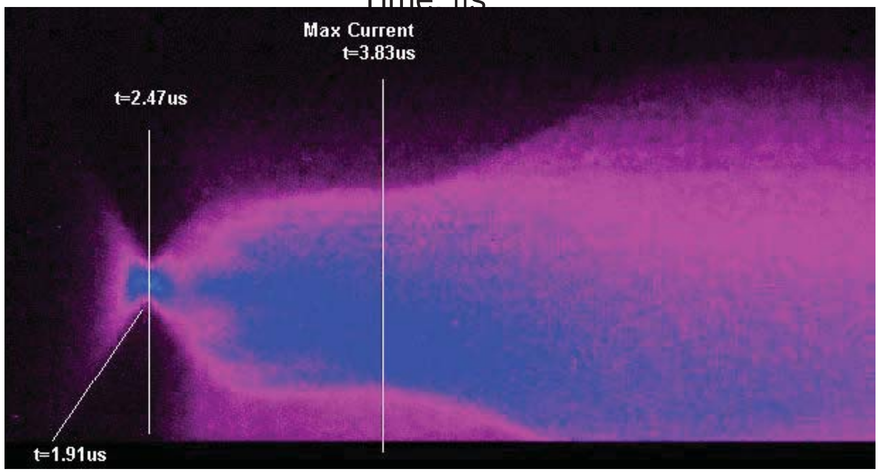
The pulse generator	Capacity C = 25 - 160 μF, Voltage $V_{мах}$ = 20 kV
The switch	Tiratron TDI1-150k/25
Discharge tube	length – 100 mm, diameter – 20 mm
Half of the period	T = 5 μs при C = 25 μF, T = 40 μs при C = 160 μF
Maximum of the current discharge	I = 200 кА при T = 5 μs, I = 400 кА при T = 200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

Investigation of the plasma dynamics by streak camera



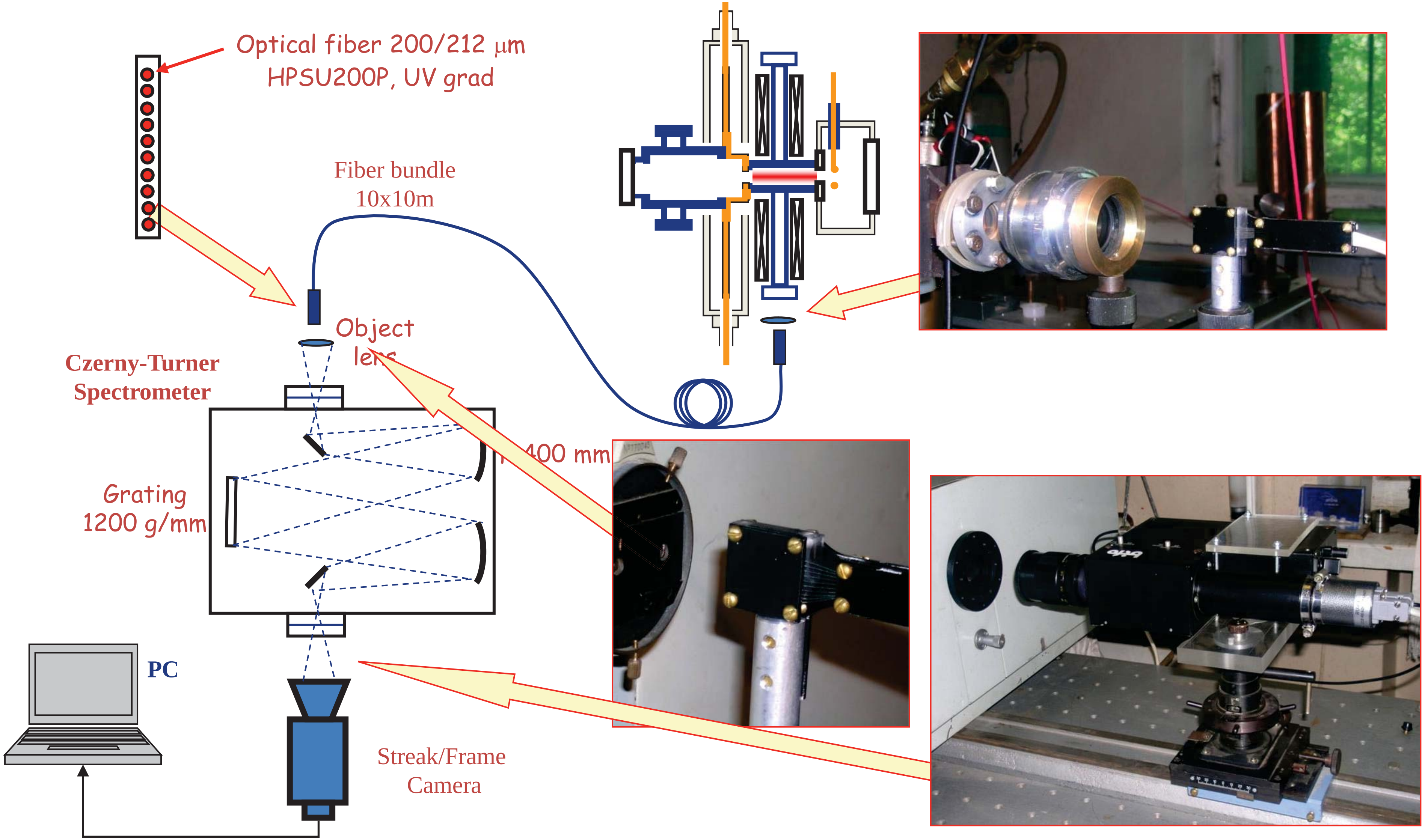




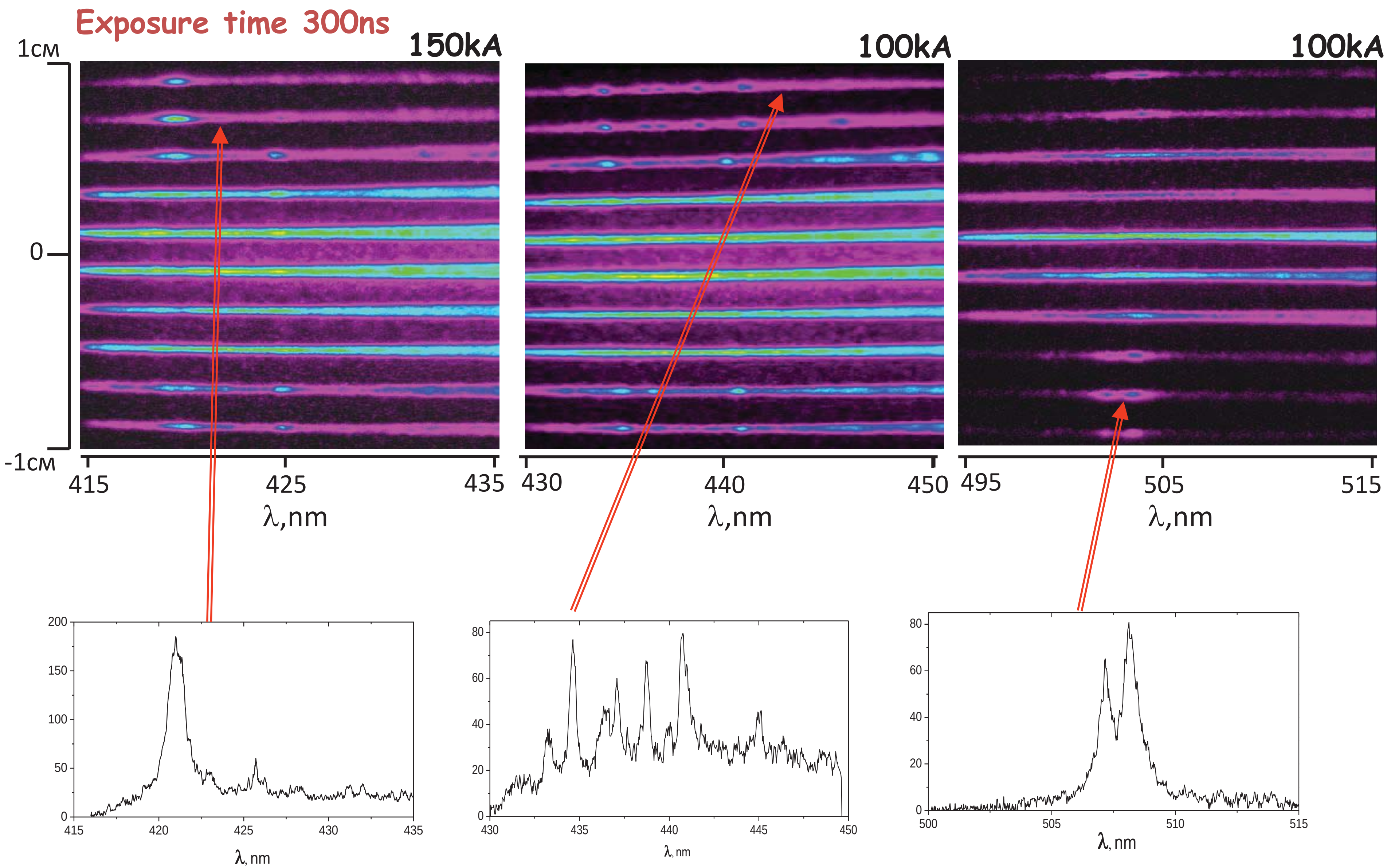


Time scanning of plasma luminescence at argon initial pressure 3.5 mbar and discharge current 200kA (full length – 6 ms, cross section size – 2 cm)

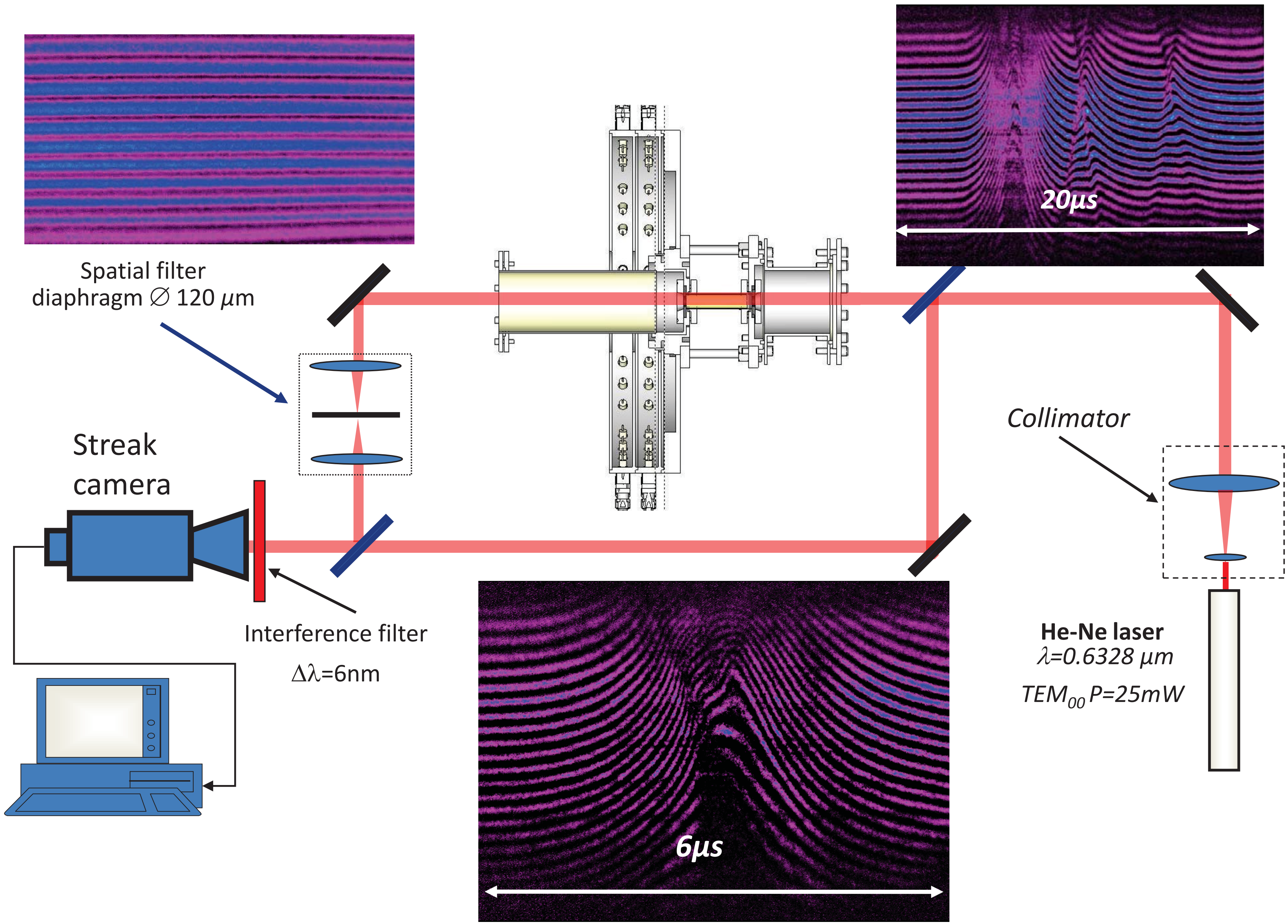
Emission spectroscopy in the wavelength range (360-600 nm) with spatial and time resolution



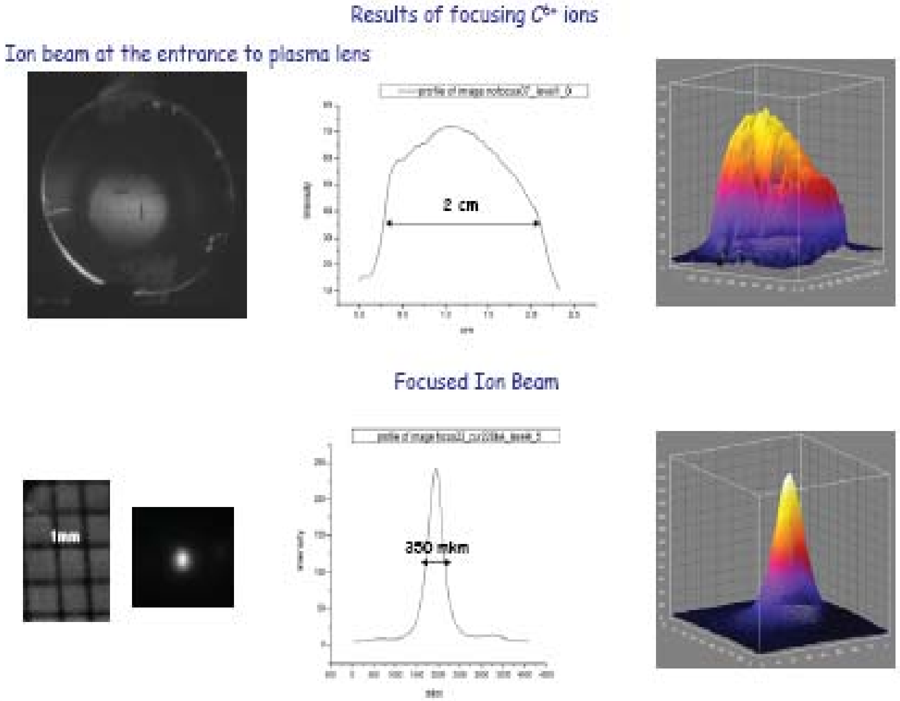
Emission plasma spectra with spatial resolution
(maximum current, t=4mks, Ar pressure=5 torr)

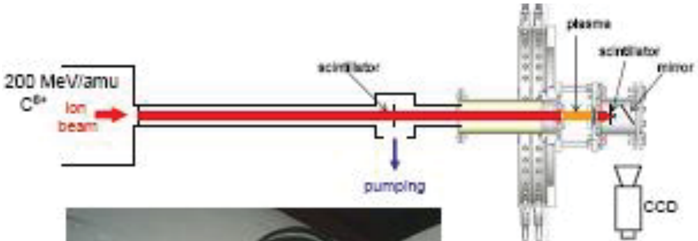


Plasma lens interferometry



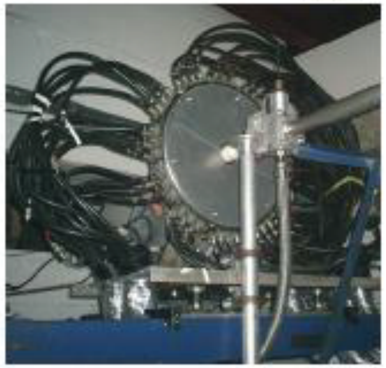
Experiments and results





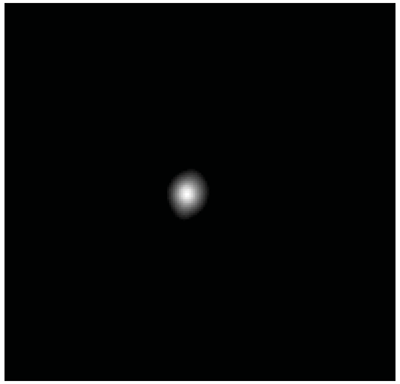
The beam spot was observed downstream of the plasma using quartz scintillator which was positioned at 50mm behind the e of discharge tube. The emitted scintillator light was monitored using CCD framing photography

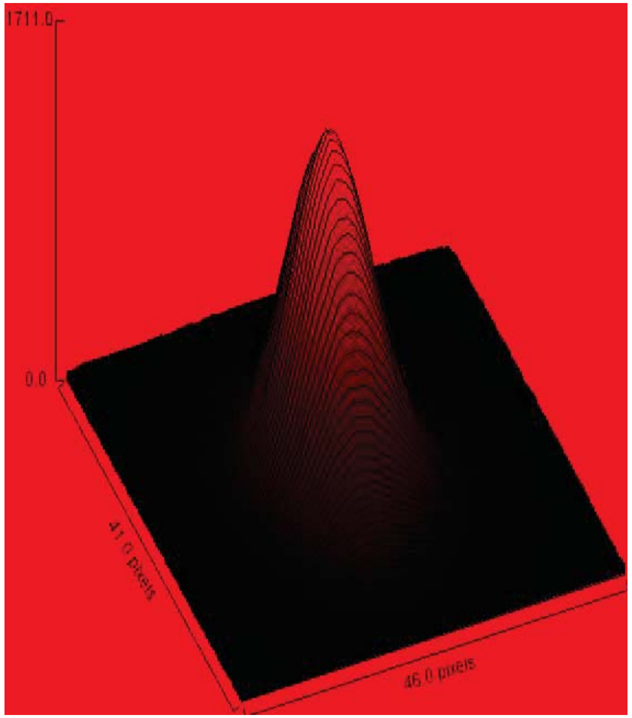
Frame images taken at d=50 mm show that the spot size has been reduced approximately by a facto of 60 to about 350 mkm (FWHM) from its initial value of 20mm. Pinch current was 220 kA, however, the pinch current has to be maximized to achieve sufficiently high magnetic-field gradients.
Further measurements with the present z-pinch device are scheduled, to perform a thorough investigation of the focusing behavior.

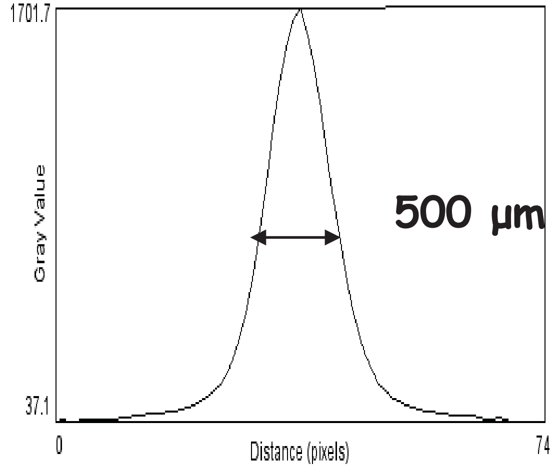


At present time the plasma lens have been designed and fabricated. Study of dynamics of the space-time behavior of the plasma discharge has been started. Investigation of plasma discharge formation has been conducted and the range of parameters has been determined where the spatial distribution of the current density may be homogeneous. Accomplished investigation lens performance allow transition to the 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.

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

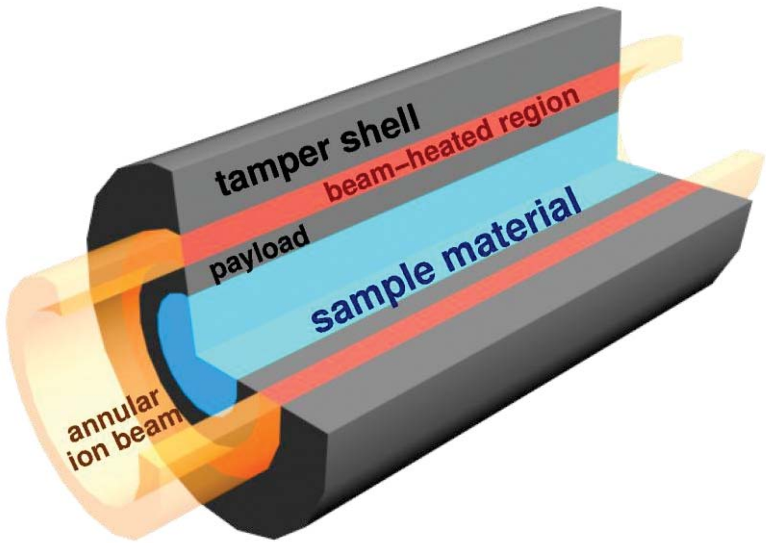






The spot size has been reduced approximately by a factor of 30

Wobbler development for LAPLAS (Laboratory Planetary Sciences) experiments



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

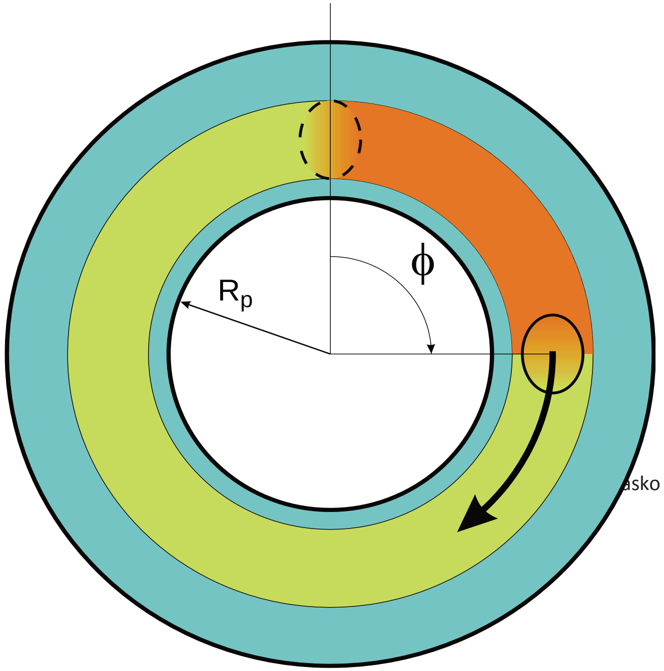
  ? Mbar pressures @ moderate temperatures

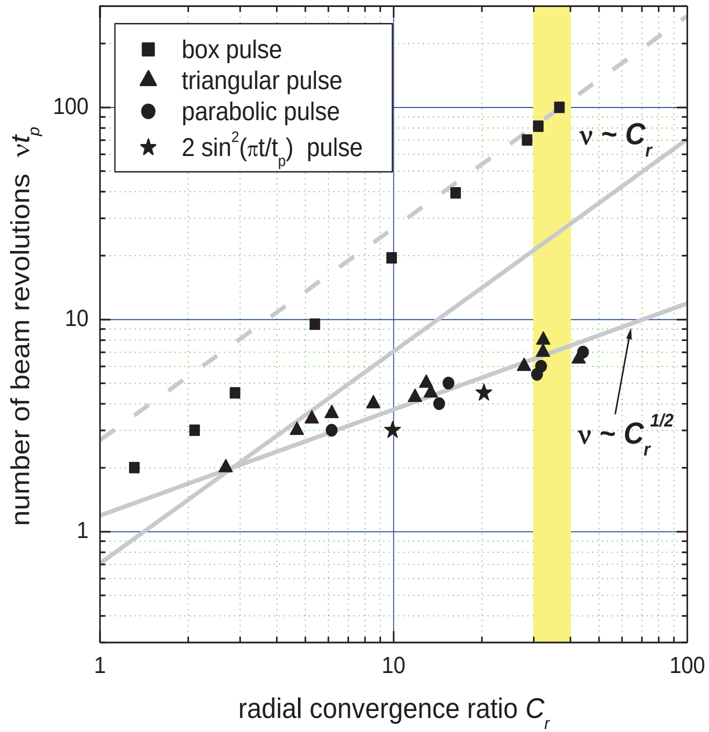
  interior of Jupiter and Saturn, hydrogen metallization

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

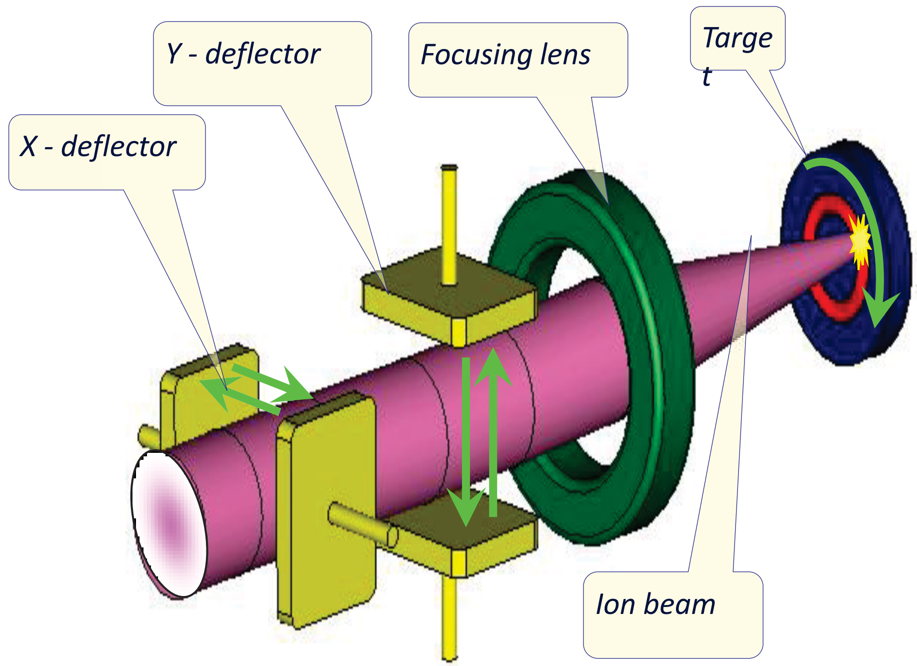
Cylindrical implosions with high radial convergence require high degree of azimuthal uniformity of the beam irradiation, especially when a cold pusher is used to compress the sample material in the central cavity. To ensure the required symmetry of beam irradiation, it was proposed to rotate the ion beam around the cylindrical target axis by means of a corresponding beam wobbler. One of the key parameters that has to be determined before laying out the wobbler design is the frequency of the beam rotation (revolutions per second).





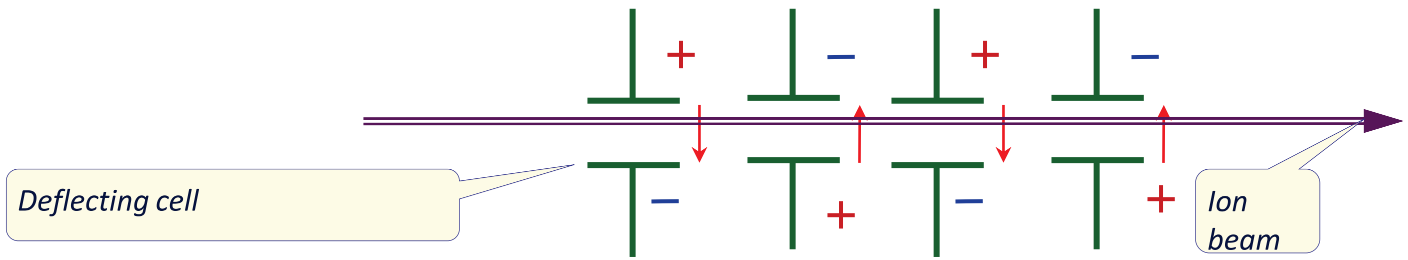
M.Basko, T.Schlegel and J.Maruhn. Physics of Plasma v.11, N.4 2004.
A.Piriz, N.Tahir, D.Hoffmann, M.Temporal. Phys.Rev. E 67, 2003.

Mechanism of ring-shaped area illumination



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.

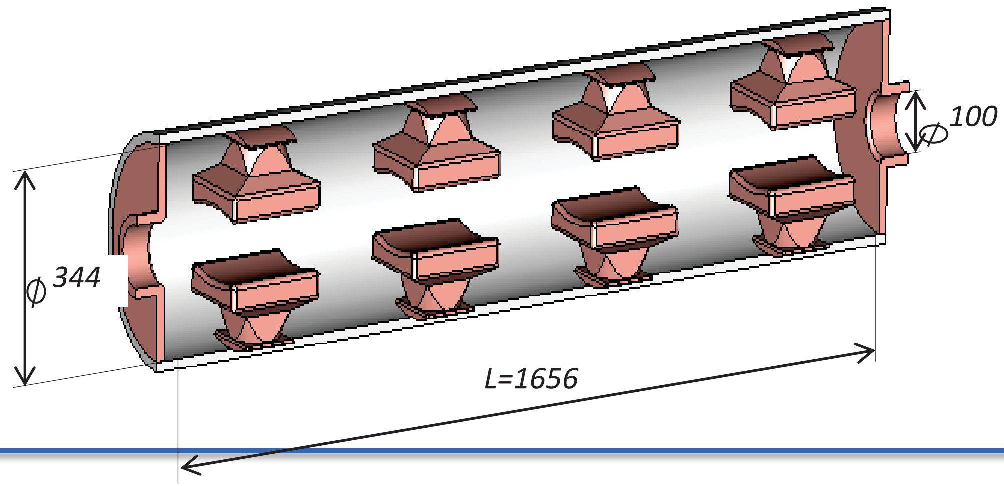
Principle of multi-cell RF deflector



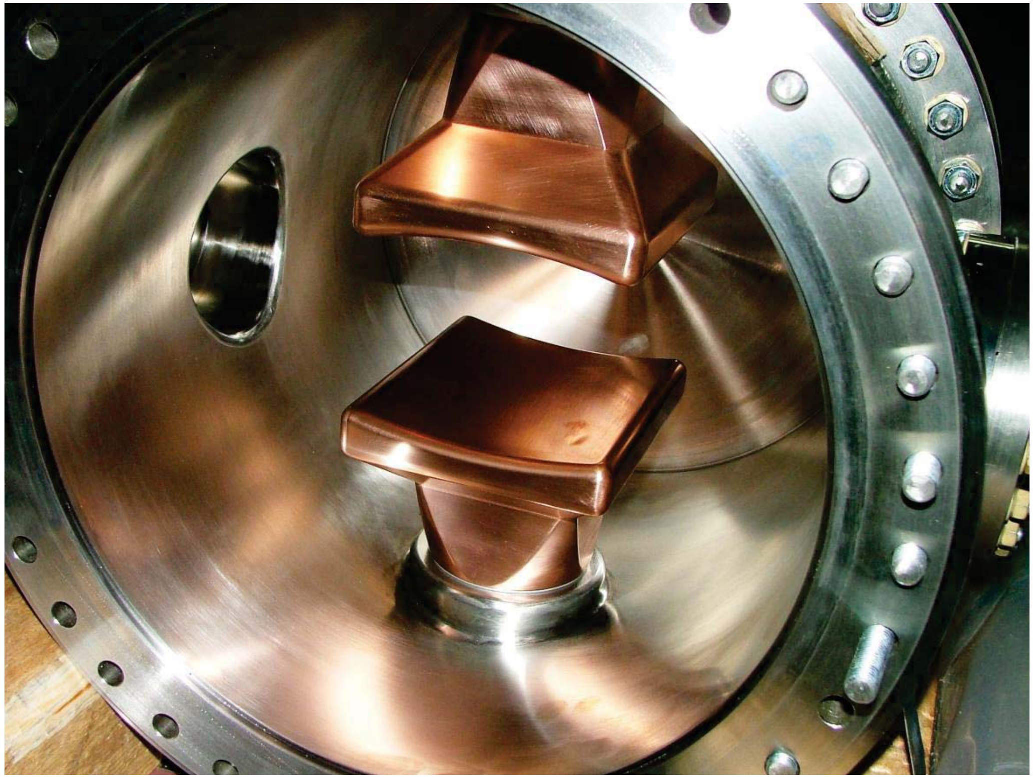
In order to keep the resonant interaction of the beam with the electric field, every cell must be as long as **D=** $\boldsymbol{\beta\lambda/2}$, where $\boldsymbol{\beta}$ is the normalized beam velocity and $\boldsymbol{\lambda}$ is the ***rf*** wavelength. When this condition is satisfied, particle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

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*



Measurement of the electrodynamics characteristics of the wobbler cell

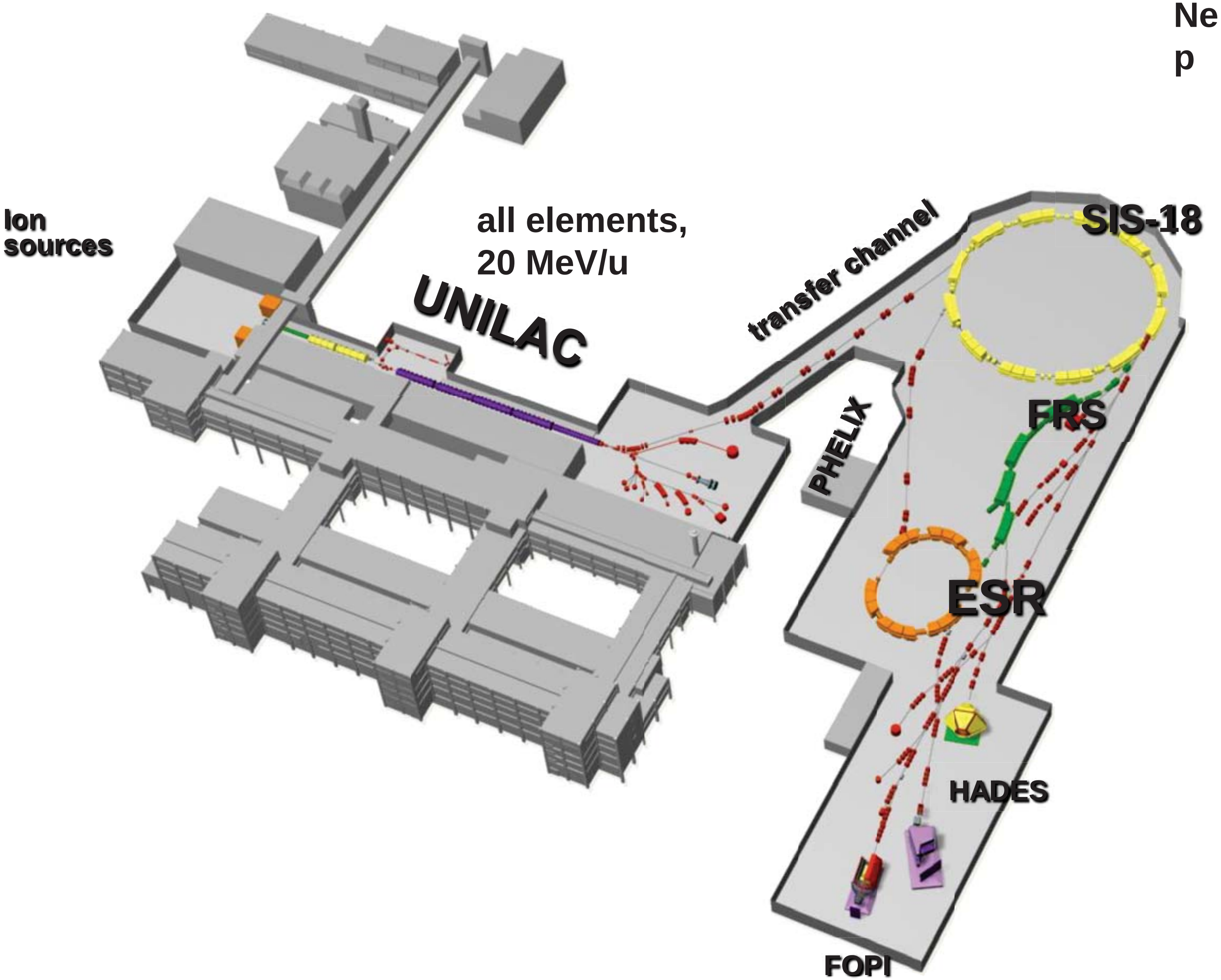


Parameter	Calculated value	Measured value
f_0, MHz	296.6	**296.96**
Q_0-quality	12000	11150

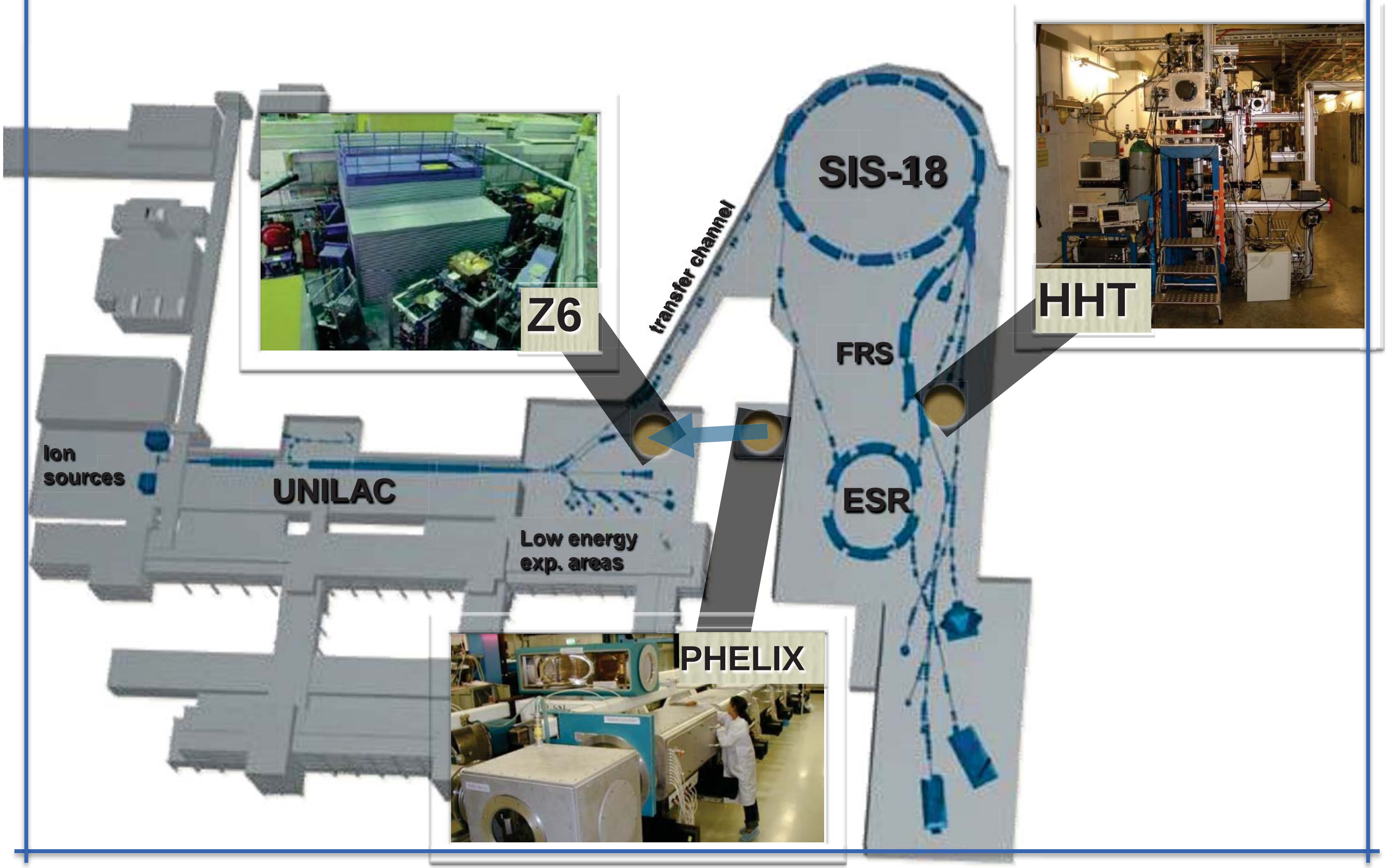
The measurement of the electrodynamics characteristics was carried out by using Agilent Technologies E5061A

GSI accelerator facility

U 1 GeV/u
Ne 2 GeV/u
p 4.5 GeV



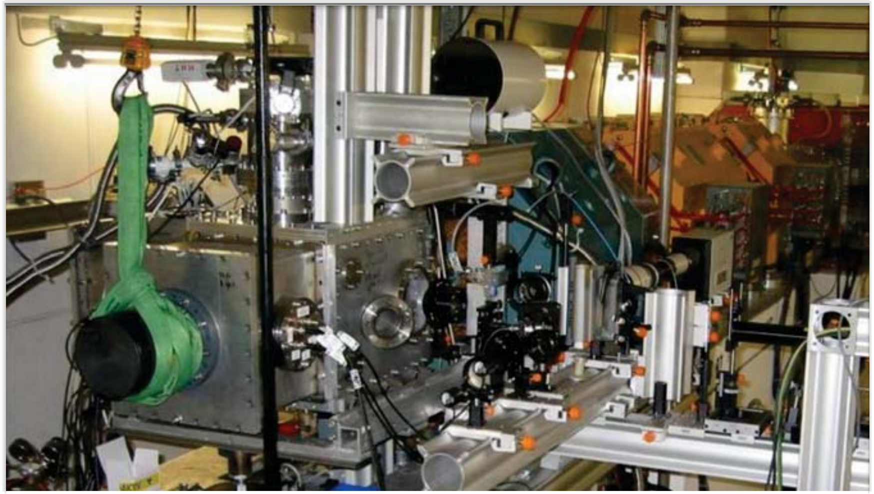
Plasma physics experimental areas at GSI



HHT is unique experimental area at GSI designed for HED physics experiments with intense heavy ion beams

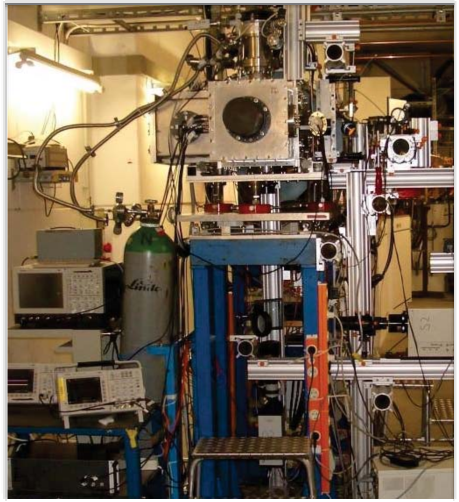
HHT: High energy High Temperature:

- strong Final Focus System
- ions up to U, 50 – 450 AMeV (18 Tm)
- pulse duration 100 – 1400 ns
- focal spot size 150 μm – 1.5 mm
- diagnostics for intense, short ion pulses in the beam line



Beams for WDM experiments:

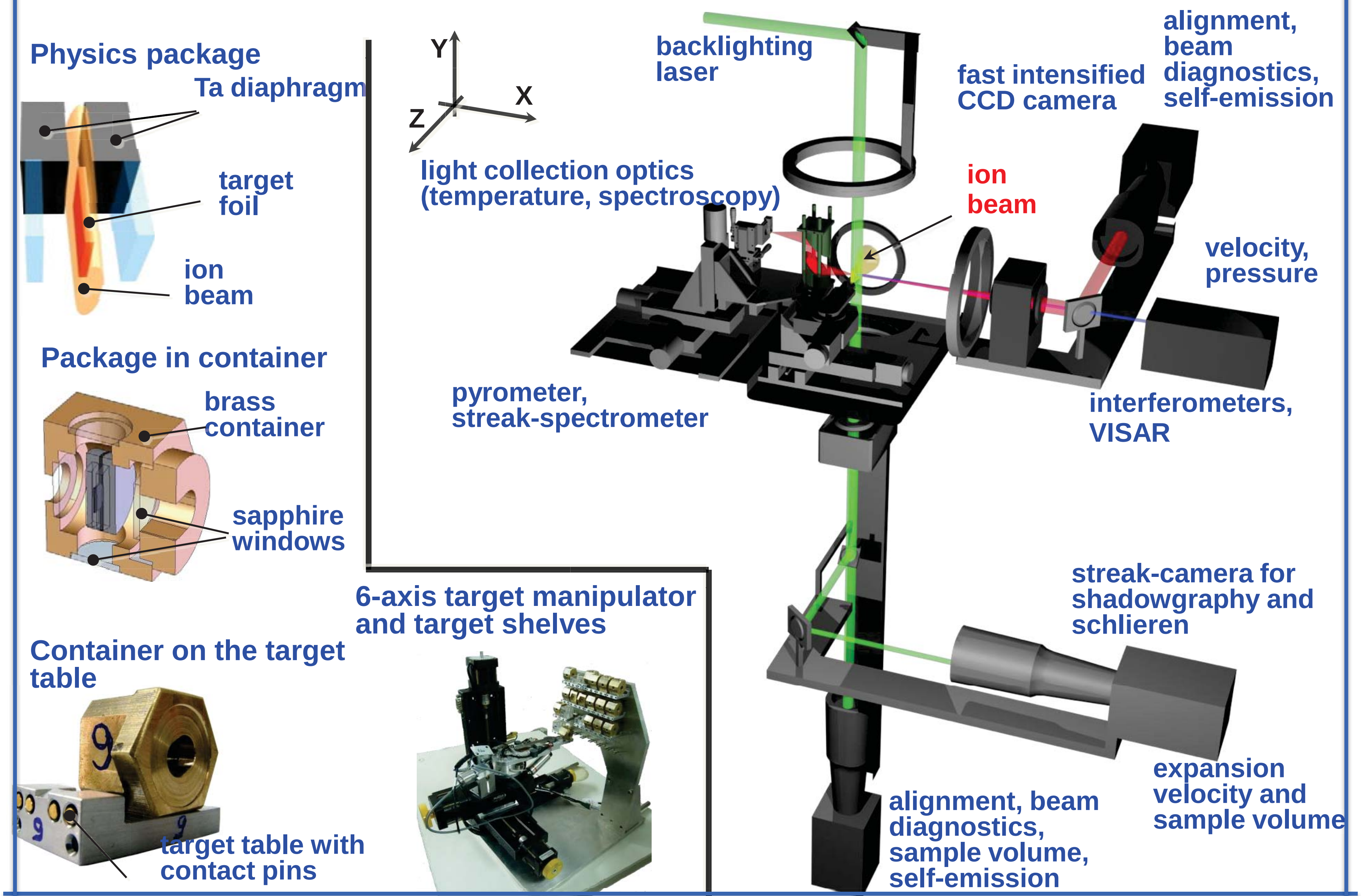
- $^{238}U^{73+}$, 80 GeV, e-cooled
- up to $5 \cdot 10^9$ ions, 100 – 300 ns bunch
- ≤ 300 μm spot at the target



Solid metallic targets:

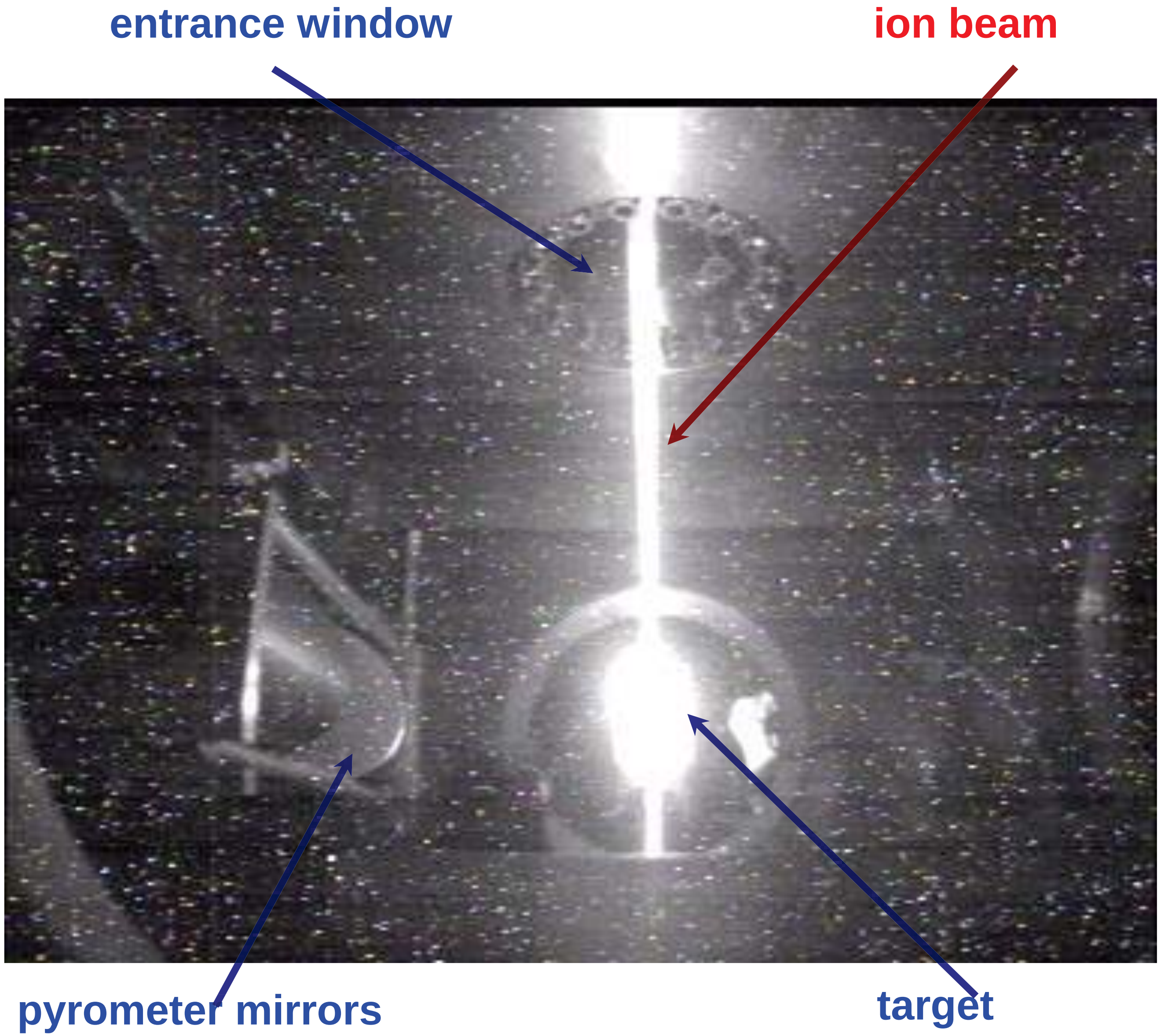
- specific energy: 1 – 5 kJ/g
- temperature: up to 2 eV
- pressure: in multi-kbar range

WDM experimental setup at HHT

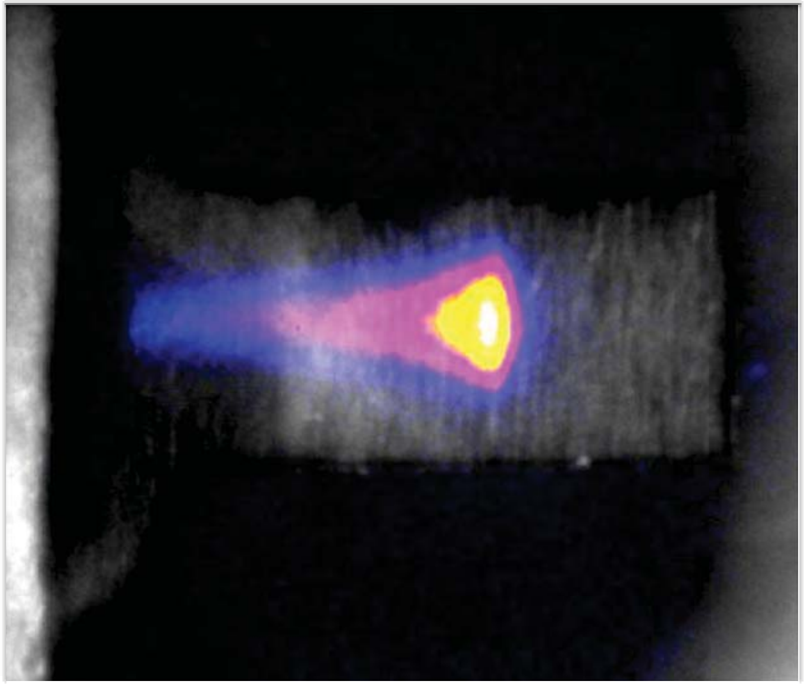


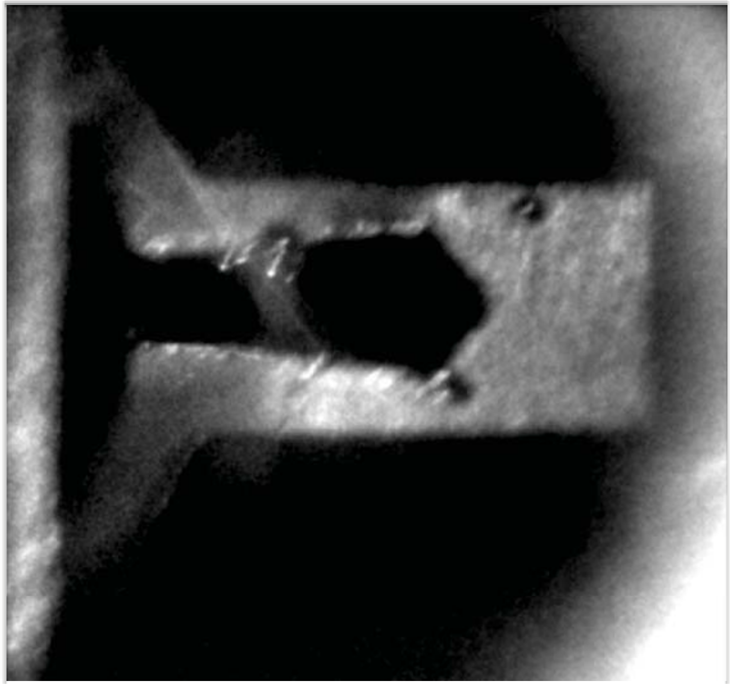
WDM experimental setup at HHT

Video camera watching the target chamber from top: intense uranium beam boils a lead foil

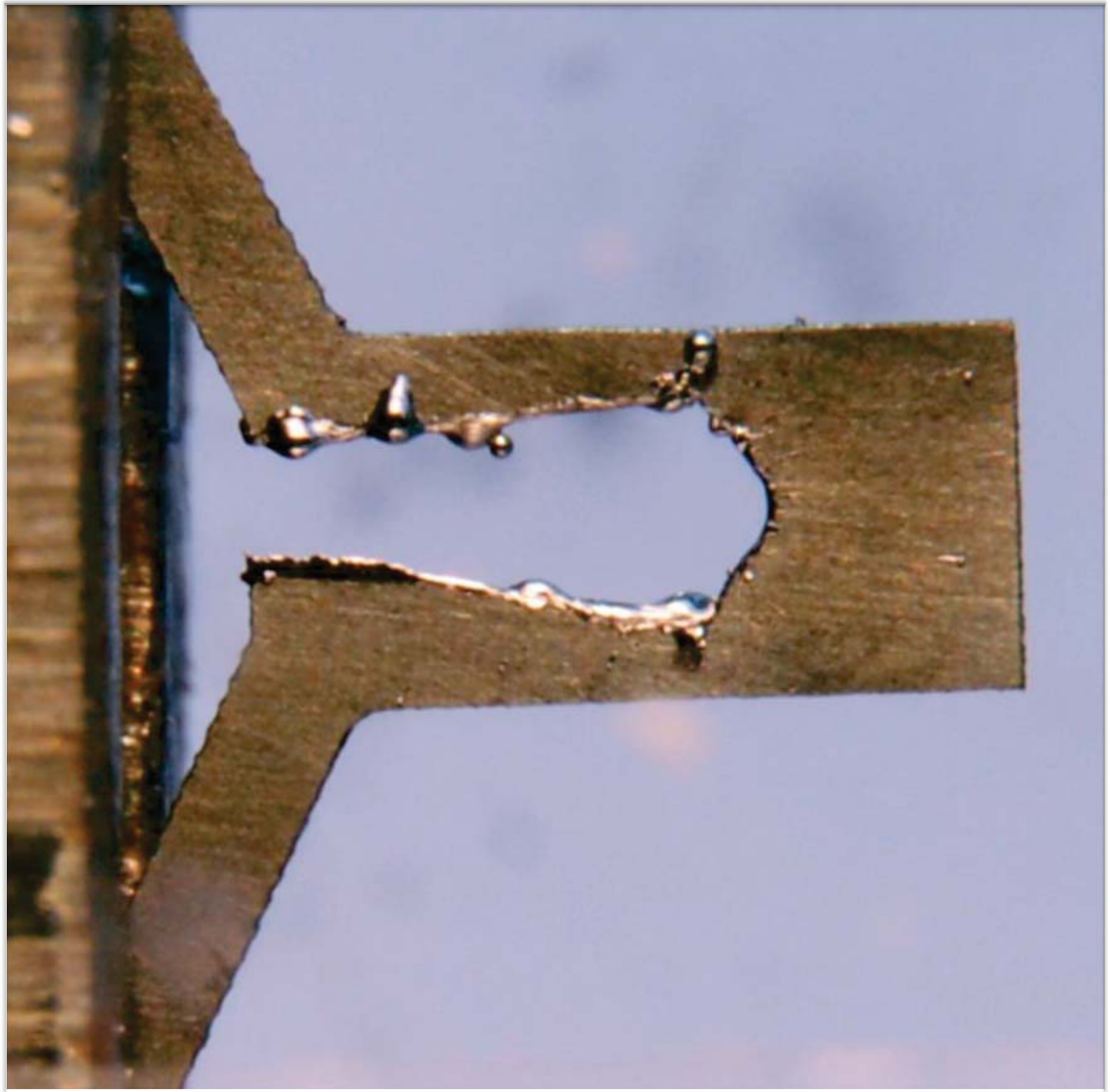


Tungsten foil before, during and after the shot

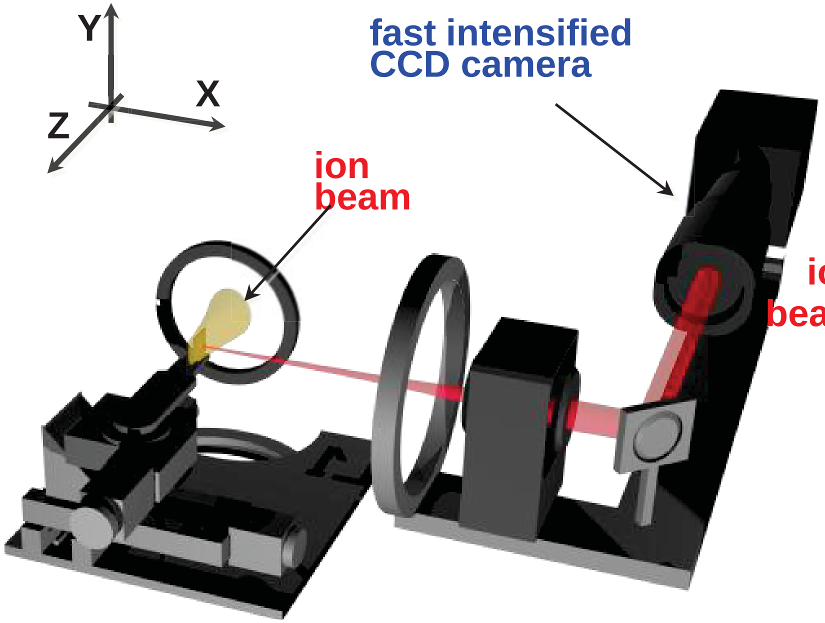




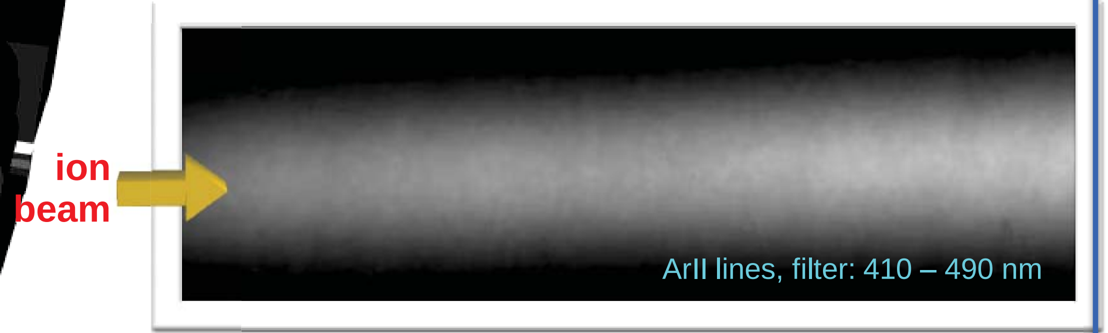
post mortem (melting only)

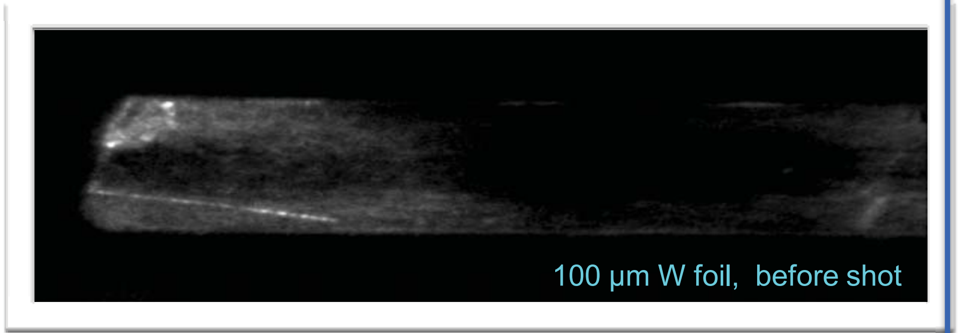


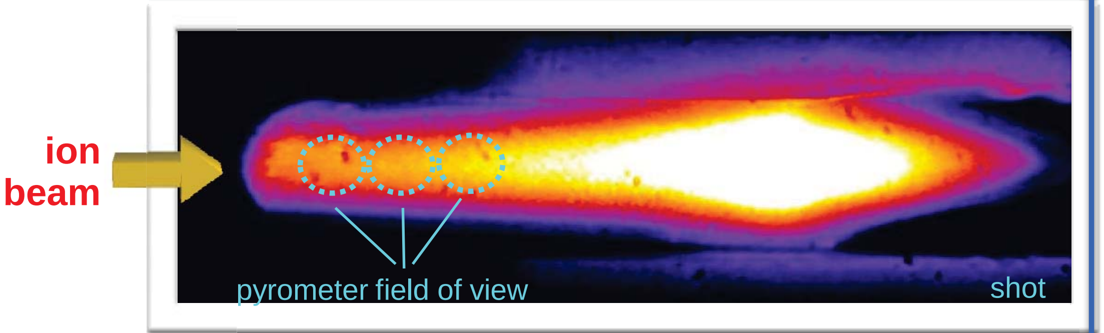
Beam-target alignment and transverse beam diagnostics



beam-induced light emission from Ar^{+}

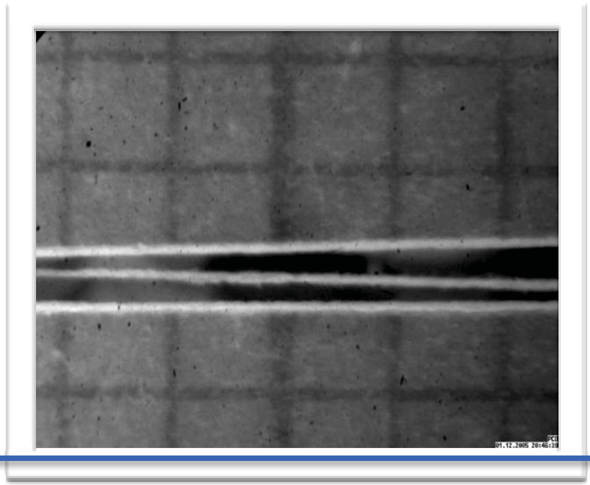






thermal light emission from the target

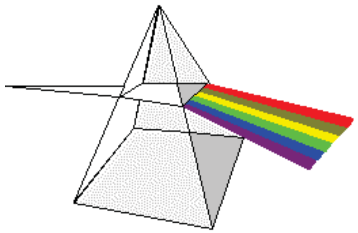
scale-paper “target”



Temperature measurements:
fast multi-channel radiation pyrometer

Pyrometer records thermal light emitted by heated target at several wavelengths in a wide spectral range (400 – 1500 nm) simultaneously, and with high temporal (~ns) and spatial (<50 µm) resolution.

light collector

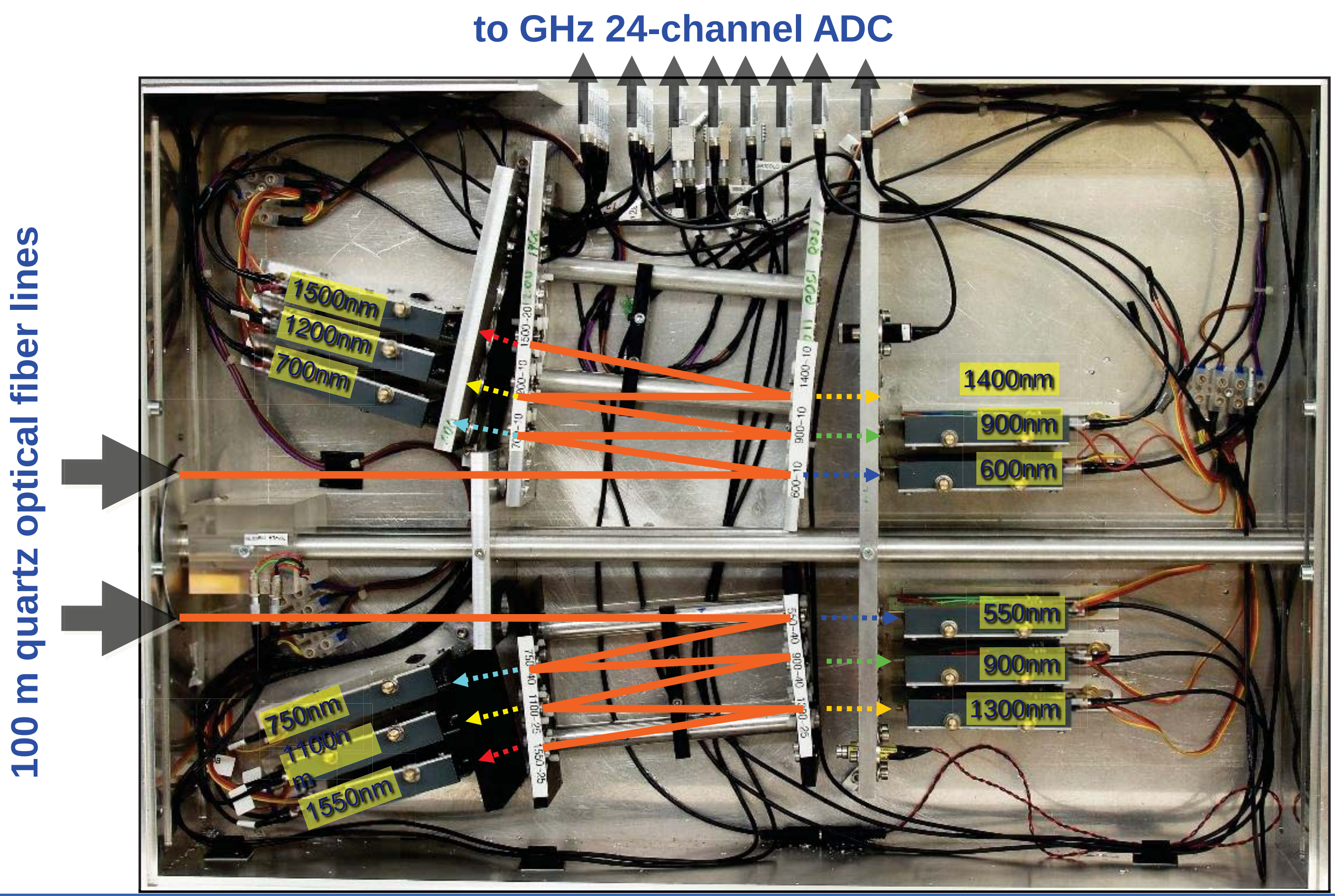


spectral analyser

recording unit

Fast multi-channel pyrometer

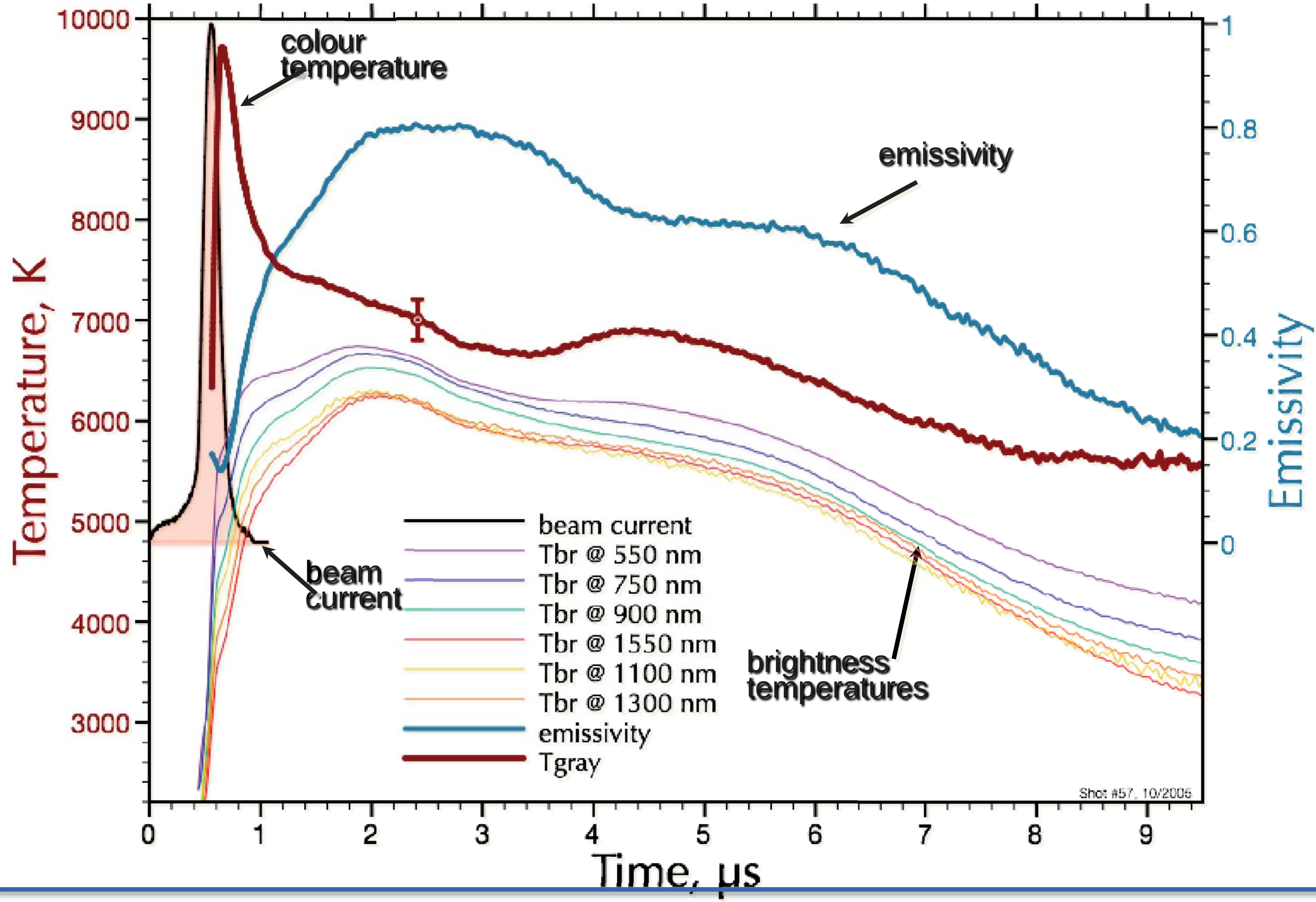
- no beam splitters
- 12+ channels (500 – 1500 nm)
- narrow (10-20 nm) channels
- fast amplifies and photodiodes
- high sensitivity and dynamic range
- time resolution ≤ 5 ns
- each channel is absolutely calibrated
- modular construction



Temperature measurements in WDM experiments: tungsten foil heated up to 10,000 K and expanding

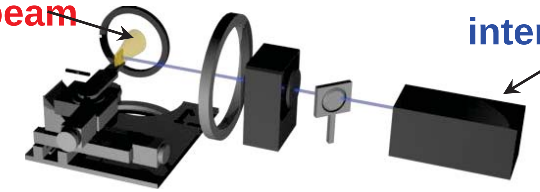
Beam: ^{238}U, 350 MeV/u, 120 ns, $2\cdot10^9$

Target: 100 µm W foil



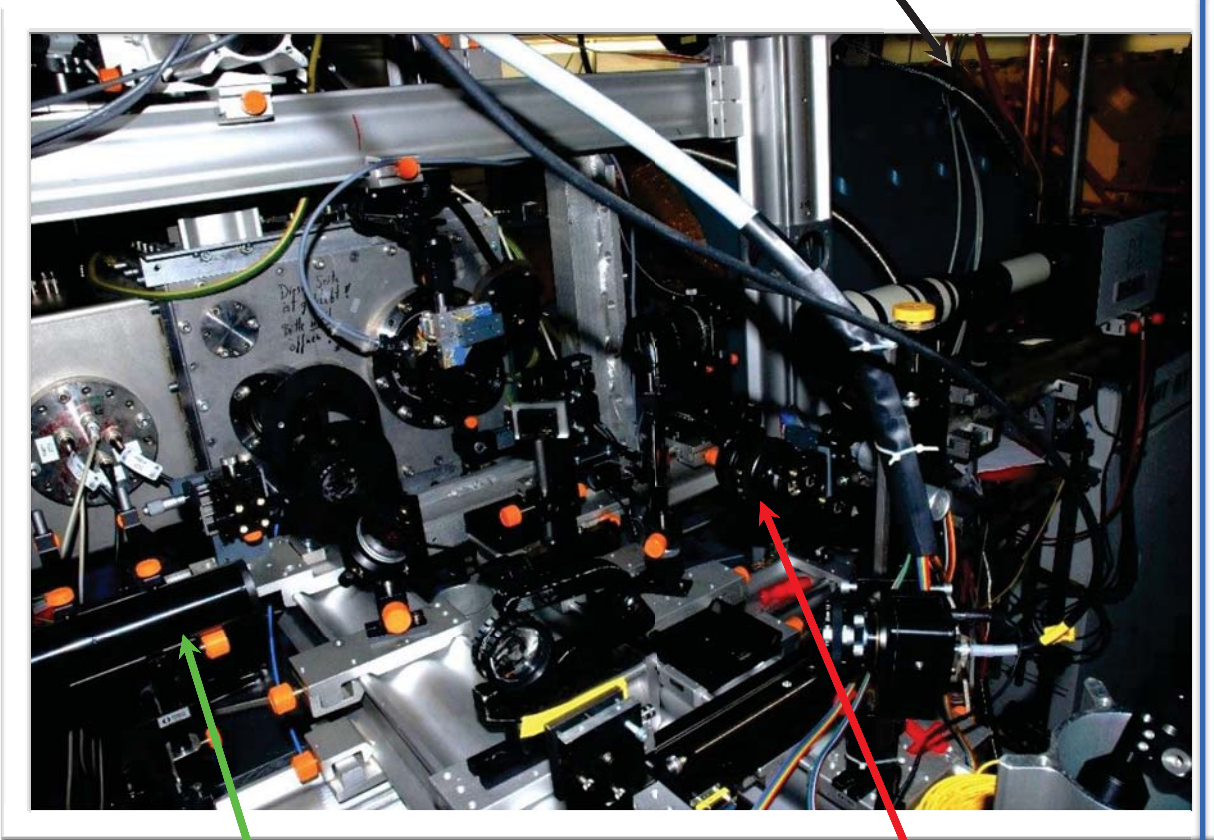
Laser interferometers for pressure measurements

ion
beam

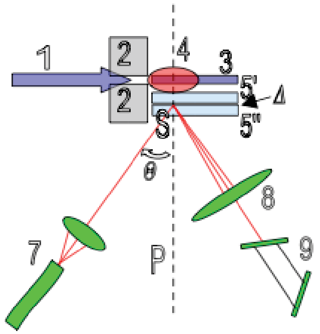


interferometers

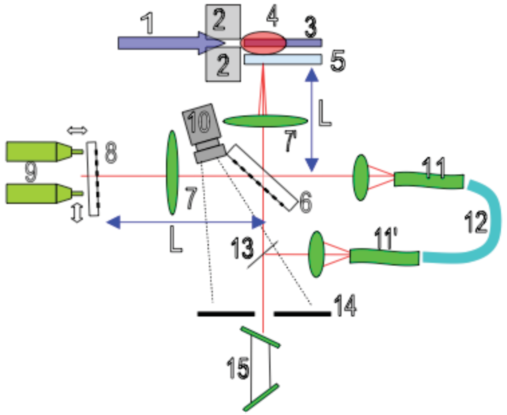
- all-fiber laser-Doppler interferometer (VISAR)



- 15º displacement interferometer



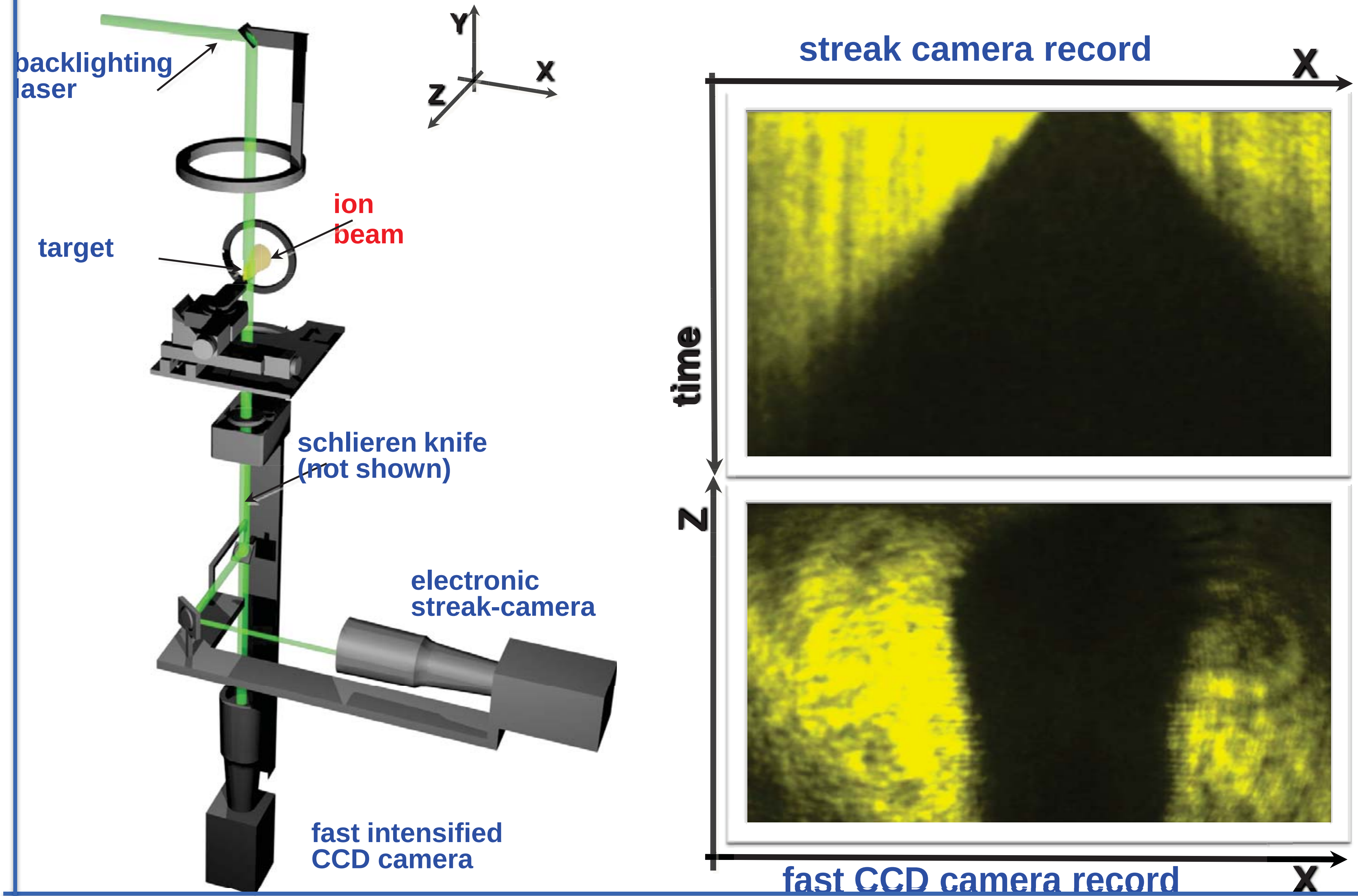
- Michelson interferometer



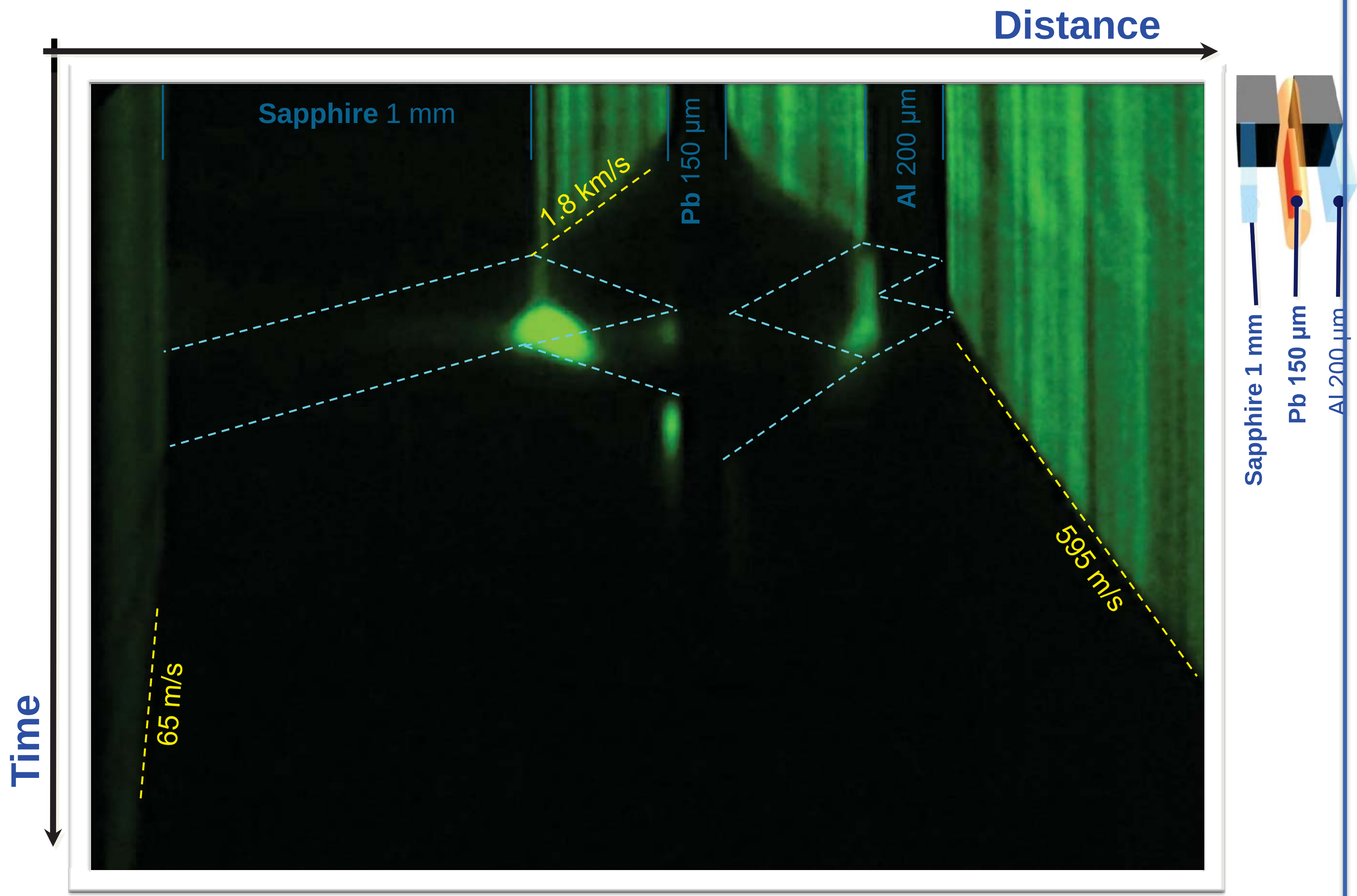
HeNe laser of
the Michelson
interferometer

motorized optics of
the VISAR system

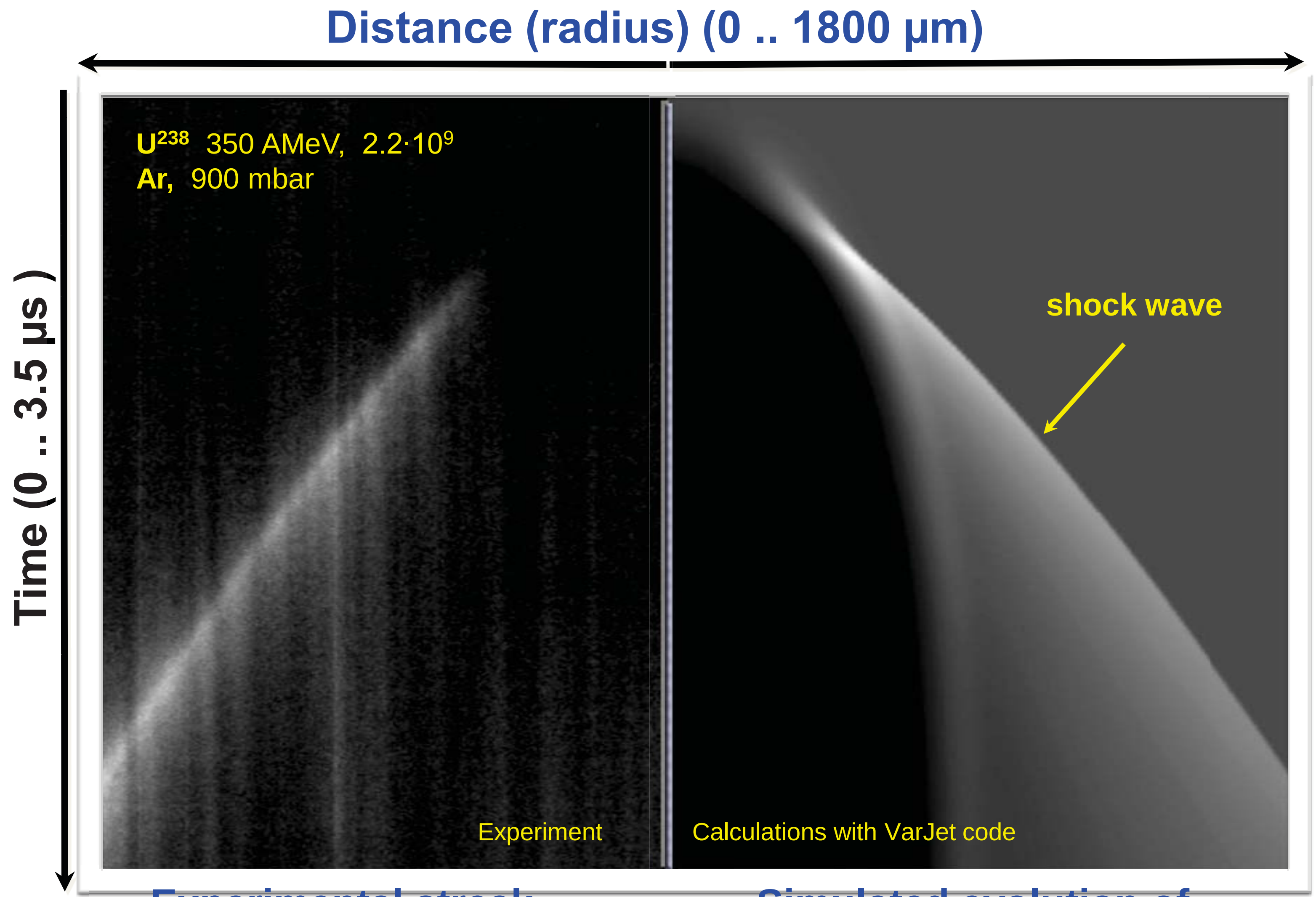
Fast shadowgraphy with laser backlighting: measurements of expansion velocity and target volume



Visible shadowgraphy with 532 nm laser: impact acceleration of metallic foils to ~km/s velocities



Shock wave in Ar induced by intense uranium beam: simulations and schlieren measurements



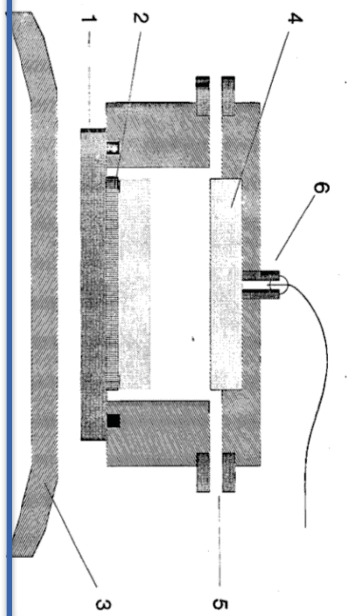
Experimental streak-schlieren record

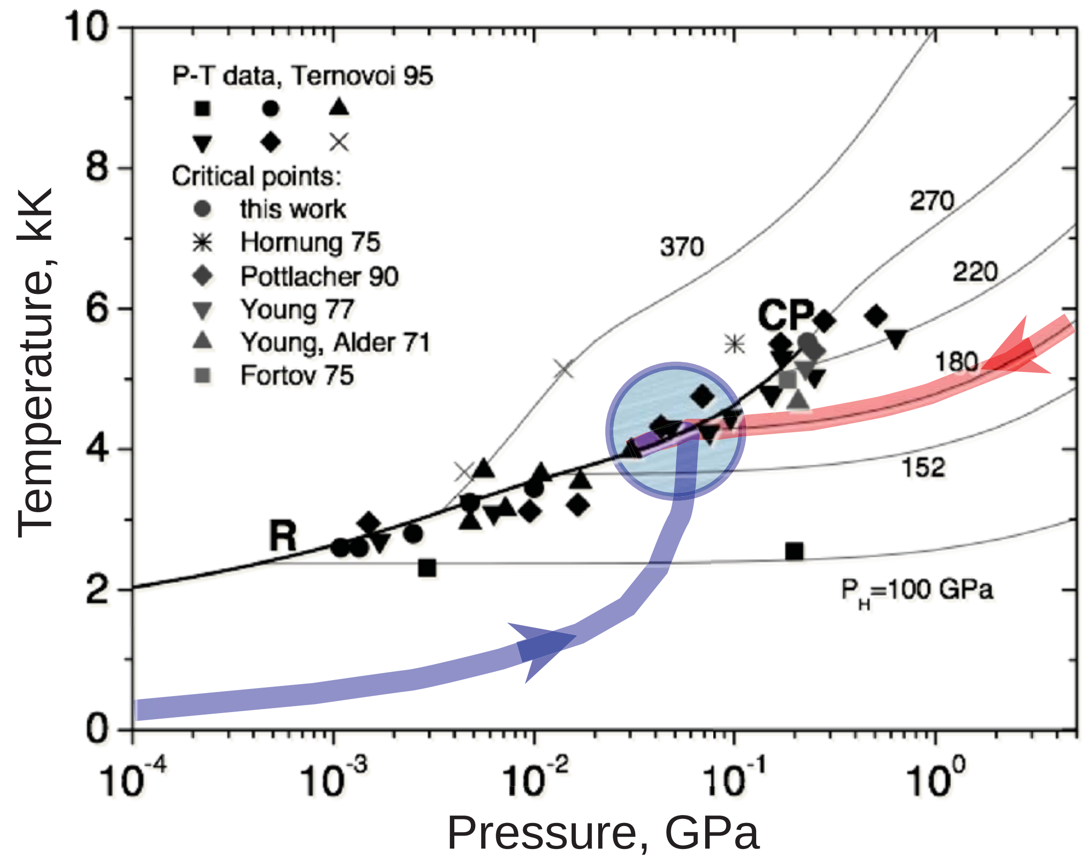
Simulated evolution of density distribution

Expansion dynamics of boiling lead: comparing heavy-ion beam and high-explosive release isentropes

Expansion dynamics of evaporating lead into helium buffer gas (~ 1 bar): comparison of HIHEX expansion isentropes after ion-beam heating (GSI, Darmstadt) and release isentropes from shock-compressed states in high-explosive experiments (IPCP, Chernogolovka)

Shock-wave experiments, IPCP, 1995





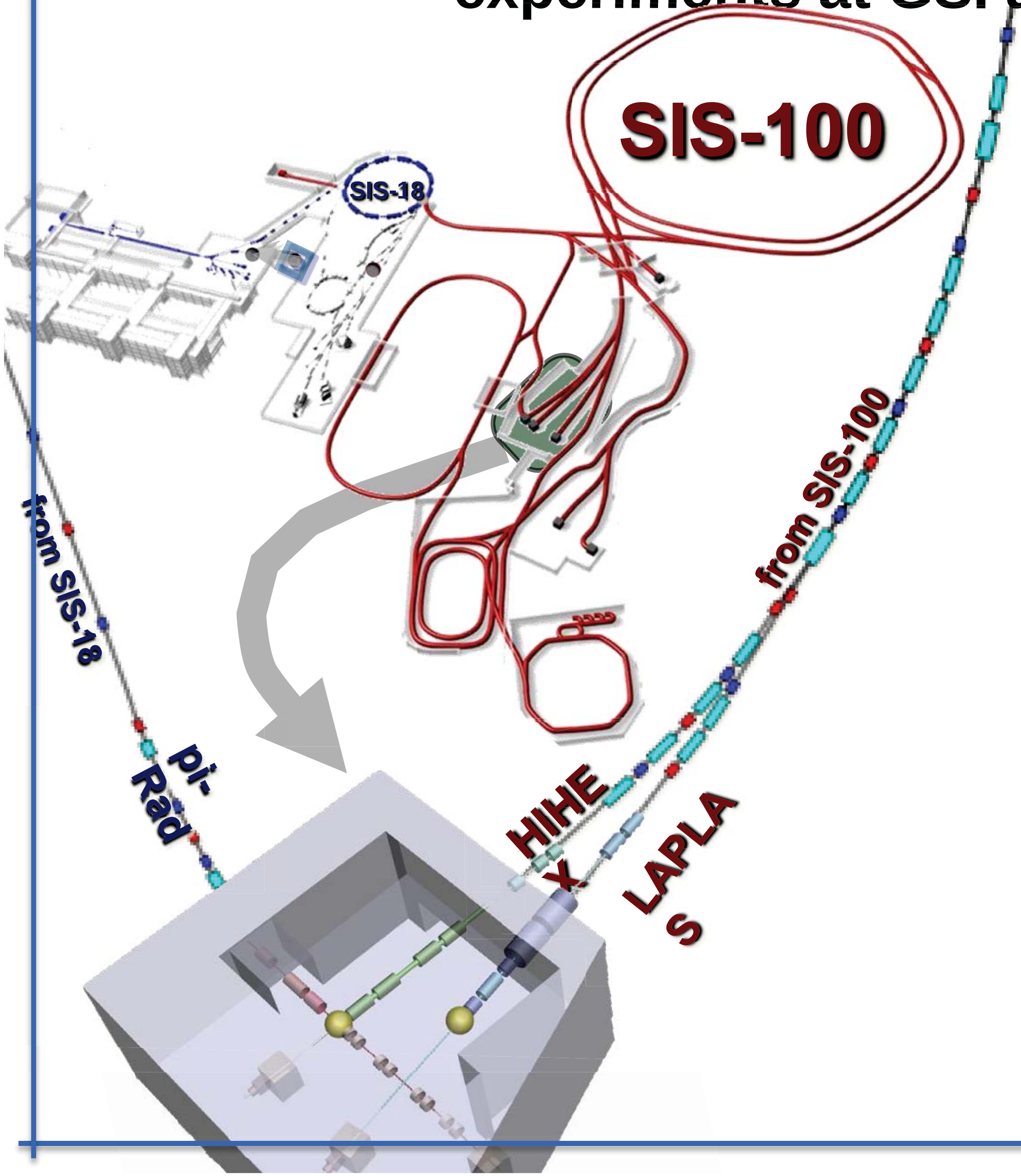
Experiments with uranium beams, GSI, 2006

FAIR: Facility for Antiproton and Ion Research

- ~1.2 billion €
- 14 countries

- **2011**
- starting construction
- **2017**
- first experiments

Parameters of intense uranium beams for HED physics experiments at GSI and at FAIR



uranium beam	GSI	FAIR
E_0	400 AMeV	2700 AMeV
N	$4 \cdot 10^9$ ions	$2 \cdot 10^{12}$ ions
E_{beam}	0.06 kJ	76 kJ
τ	130 ns	50 ns
P_{beam}	0.5 GW	1.5 TW
S_f	~1 mm²	~1 mm²

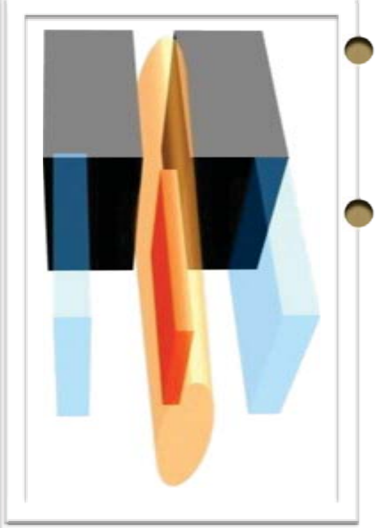
Lead target

E_s	few kJ/g	600 kJ/g
P_s	5 GW/g	12 GW/g

HEDgeHOB collaboration will construct and run at FAIR two main HEDP experiments: HIHEX and LAPLAS

HIHEX

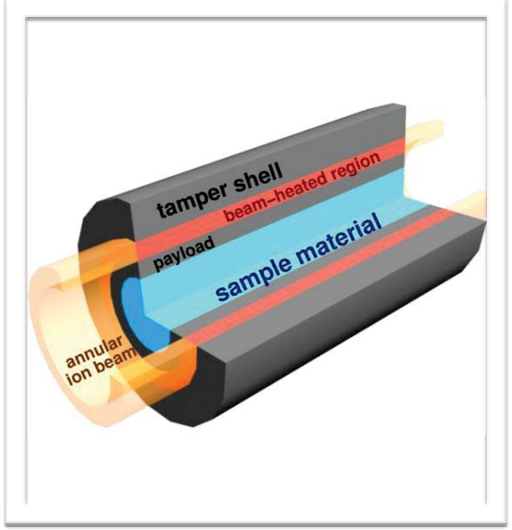
***H**eavy **I**on **H**eating and **Ex**pansion*



- uniform quasi-isochoric heating of a large-volume dense target
- quasi-isentropic expansion in 1D (plane or cylindrical) geometry

LAPLAS

***La**boratory **Pla**netary **S**ciences*

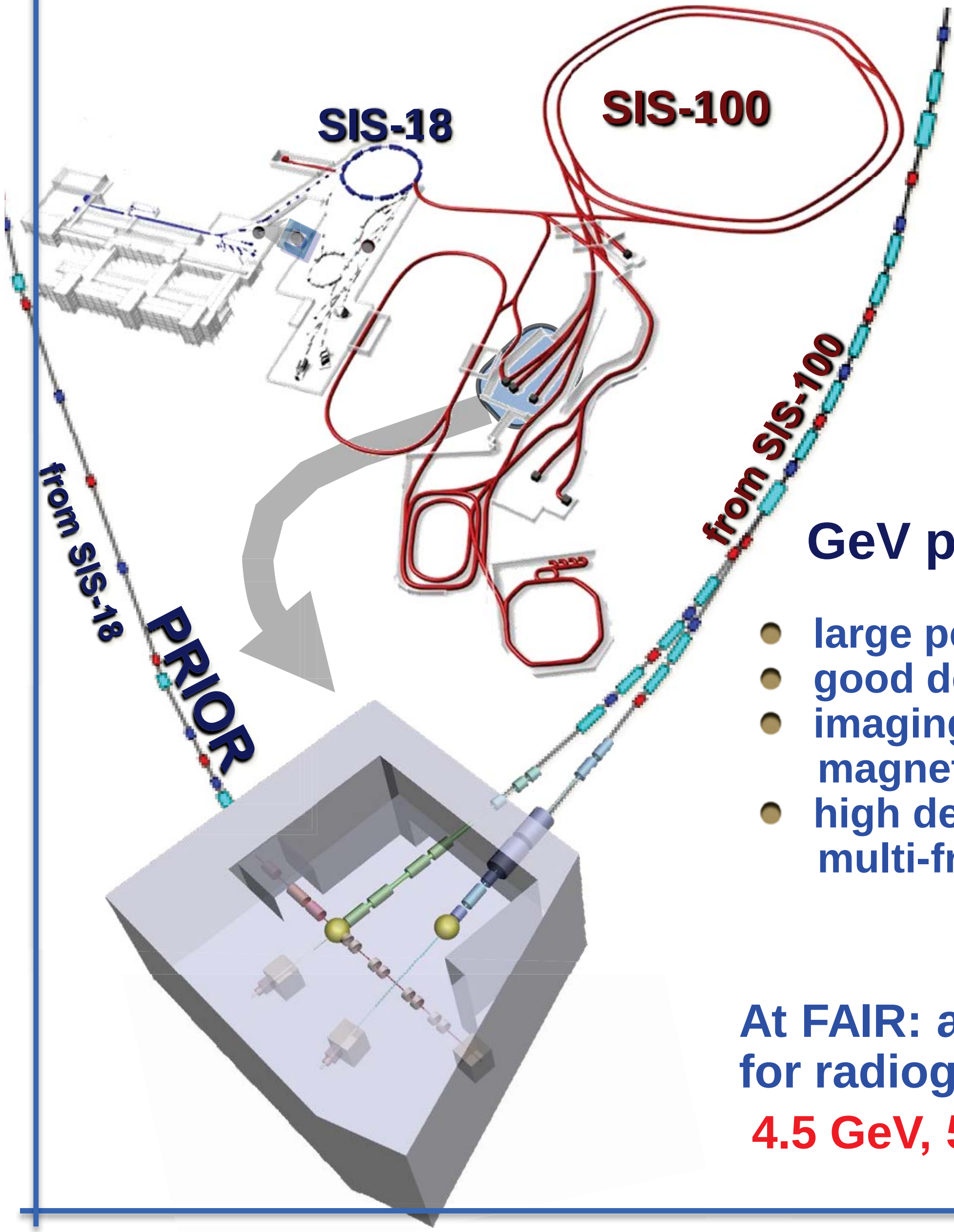


- hollow (ring-shaped) beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression

- **Numerous high-entropy HED states:** EOS and transport properties of e.g., non-ideal plasmas, WDM and the critical point regions for various materials

- **Mbar pressures @ moderate temeperatures:** ultra-high density HED states, e.g. hydrogen metallization problem, interior of Jupiter, Saturn and Earth

PRIOR – Proton Radiography at FAIR



Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 µm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

GeV protons:

- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets high spatial resolution (microscopy)
- high density resolution and dynamic range multi-frame capability for fast dynamic events

At FAIR: a dedicated beam line from SIS-18 for radiography

4.5 GeV, 5·10^{12} protons

Conclusion

- Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of matter in reproducible experimental conditions

- Powerful accelerator facilities based on the use of heavy ion synchrotrons at ITEP-Moscow, HIFS-VNL - Berkeley, GSI-Darmstadt and future FAIR are in progress, attracting experimental groups from all over the world

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