Design of proton radiography diagnostic system for HEDgeHOB experiment

High Energy Density Matter Generated by Heavy Ion Beams

V. Turtikov
ITEP, Moscow

First seminar of FRRC Fellows FAIR – Russia Research Center
FRRC, Moscow June, 9 - 10, 2009

Intense heavy ion beam is an excellent tool to generate large-volume uniform HED samples

High Energy Density Matter

Warm Dense Matter

T ~ 0.2 - 20 eV

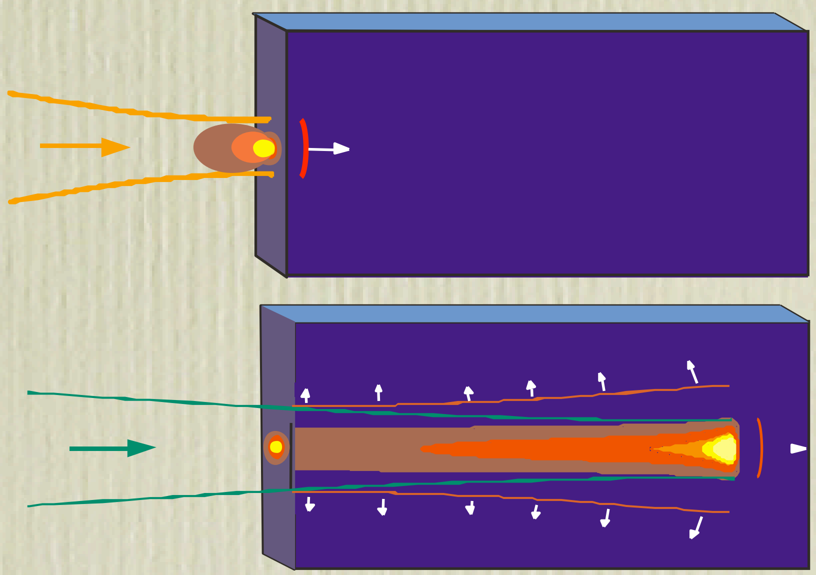
ρ ~ solid density (x$10^{\pm 2}$)

P ~ kbar, Mbar

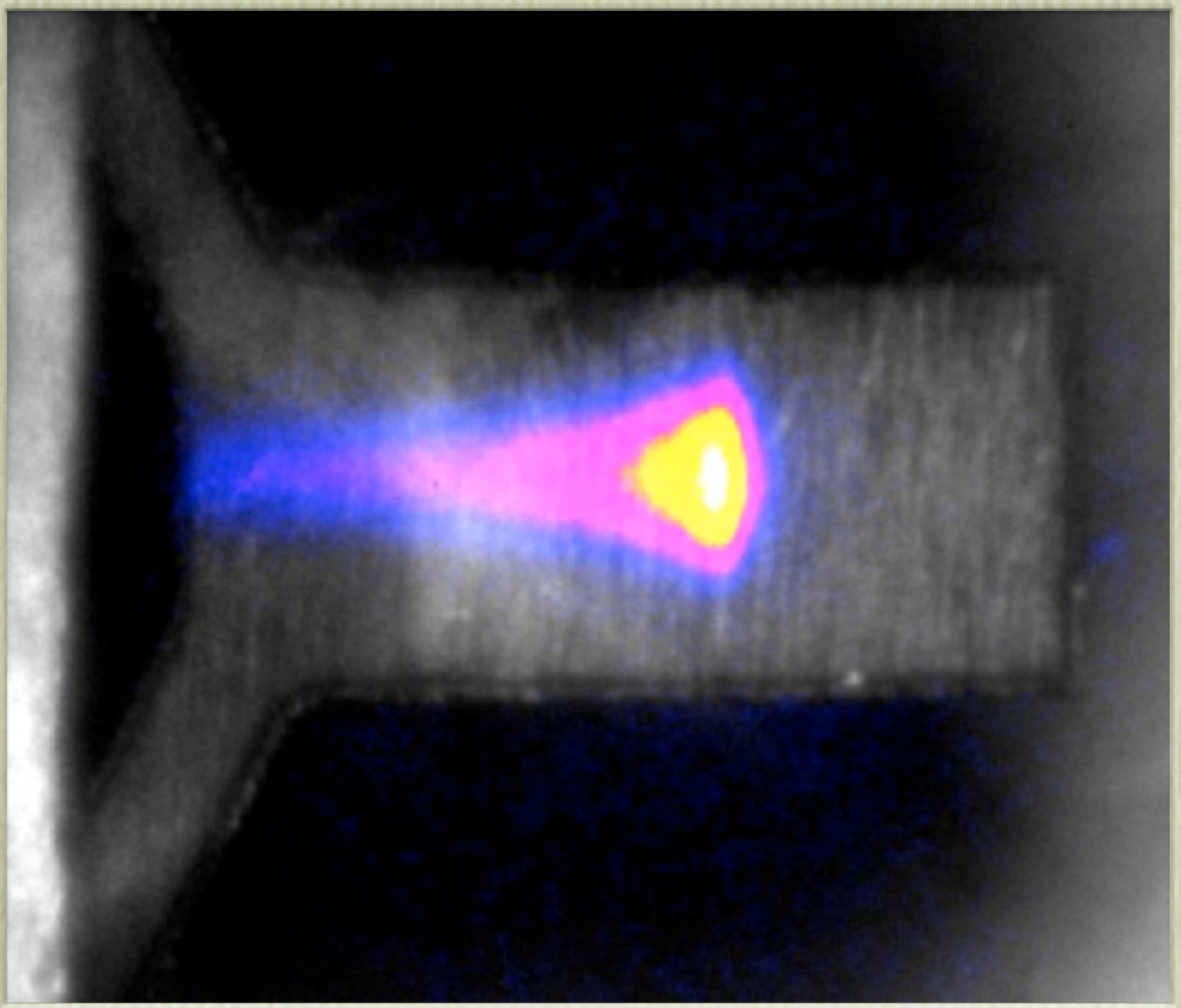
Intense heavy ion beams:

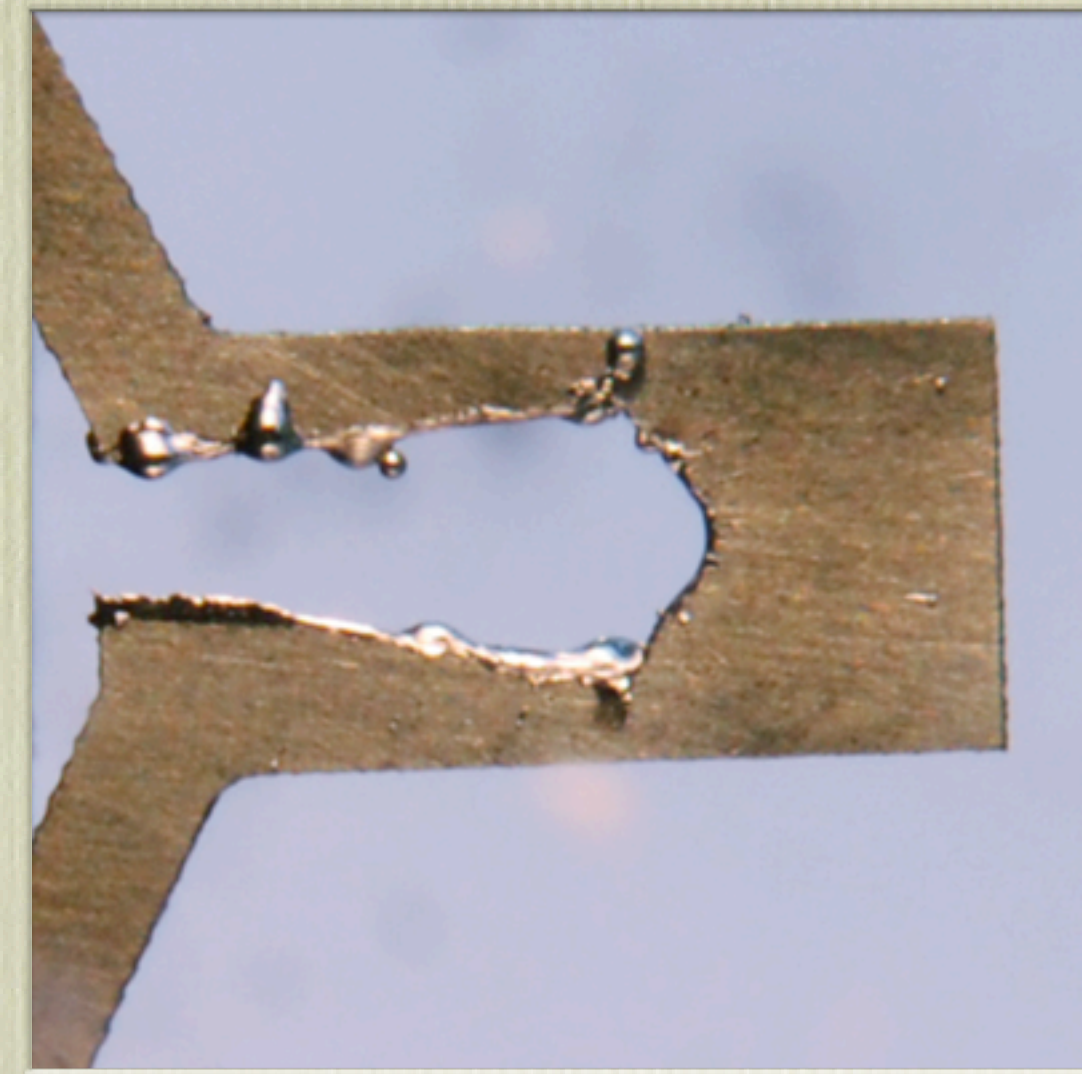
volumetric character of heating

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



Tantalum foil of "long-Y" target before and after a shot





Accelerator laboratories worldwide performing HEDP experiments with intense ion beams

FAIR: Facility for Antiproton and Ion Research

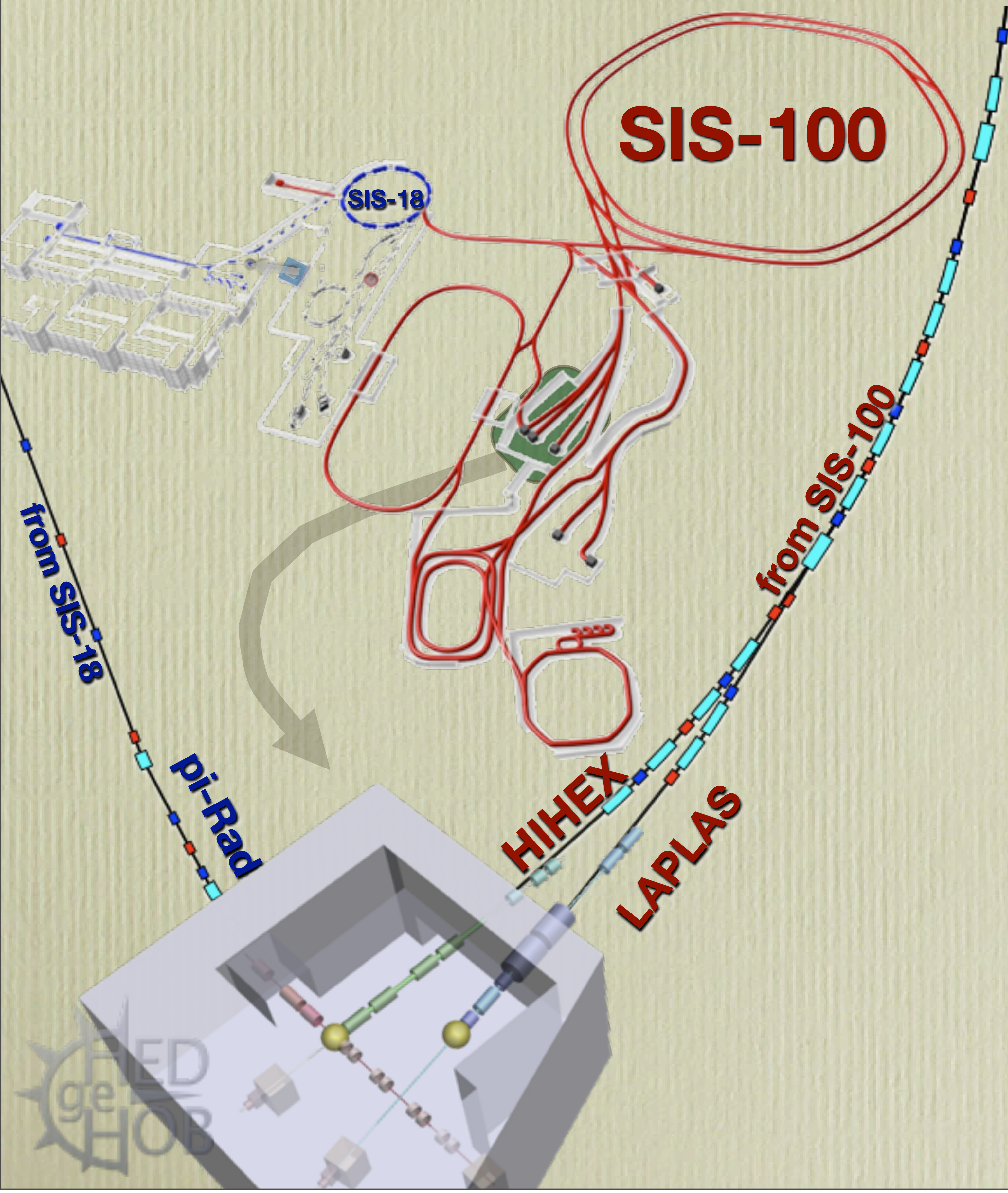
- ~1.2 billion €
- 14+ countries

- **2008**
- starting construction

- **2013**
- first experiments

- **2016**
- completing construction

Parameters of intense uranium beams for generation of extreme states in matter at GSI and at FAIR



URANIUM BEAM	GSI	FAIR
E_o	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 mm^2	~1 mm^2
	Lead target	
E_s	~1 kJ/g	600 kJ/g
P_s	5 GW/g	12 TW/g

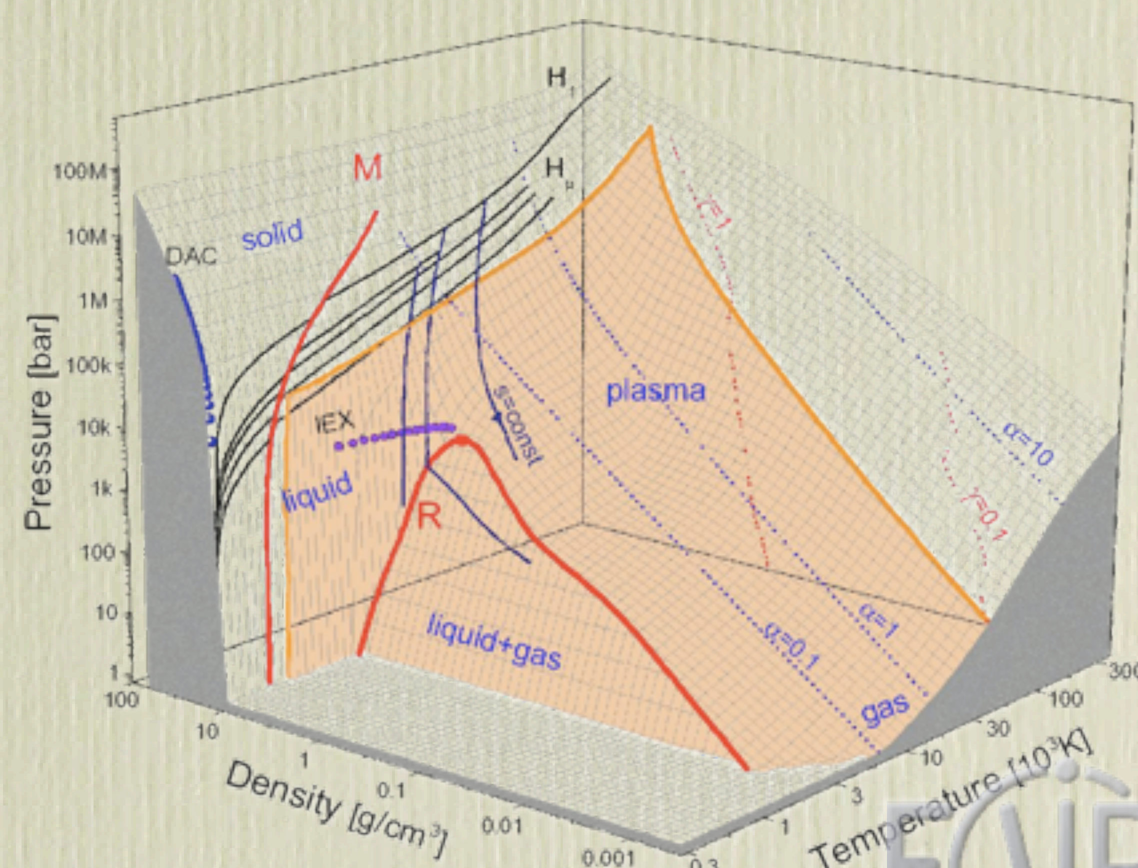
FAIR will open a new route for HEDP research

Intense heavy ion beams at FAIR provide unique capabilities for generating and studying HED states in matter:

- SIS-100 intense beam can generate large volume (mm³) homogeneous WDM samples
  - specific energy of 0.6 MJ/g and deposition power of 12 TW/g at high densities
- unique diagnostic tools: multi-GeV proton / ion beams and high-energy PW laser (ion, proton or x-ray radiography, Thomson scattering)
  - high rep. rate, any target material

Physics program – fundamental properties of matter under extreme conditions:

- **Equation-of-state of HED mater**
  basic thermodynamic properties of matter in unexplored regions of the phase diagram (two-phase regions, critical points, non-ideal plasmas)
- **Phase transitions and exotic states of matter**
  metal-to-insulator or plasma phase transition, hydrogen metallization problem, etc.
- **Transport and radiation properties of HED matter**
  electrical and thermal conductivity, opacity, etc.
- **Stopping properties of non-ideal plasma**
  anomalous temperature and density dependence heavy ion stopping and charge-exchange cross sections

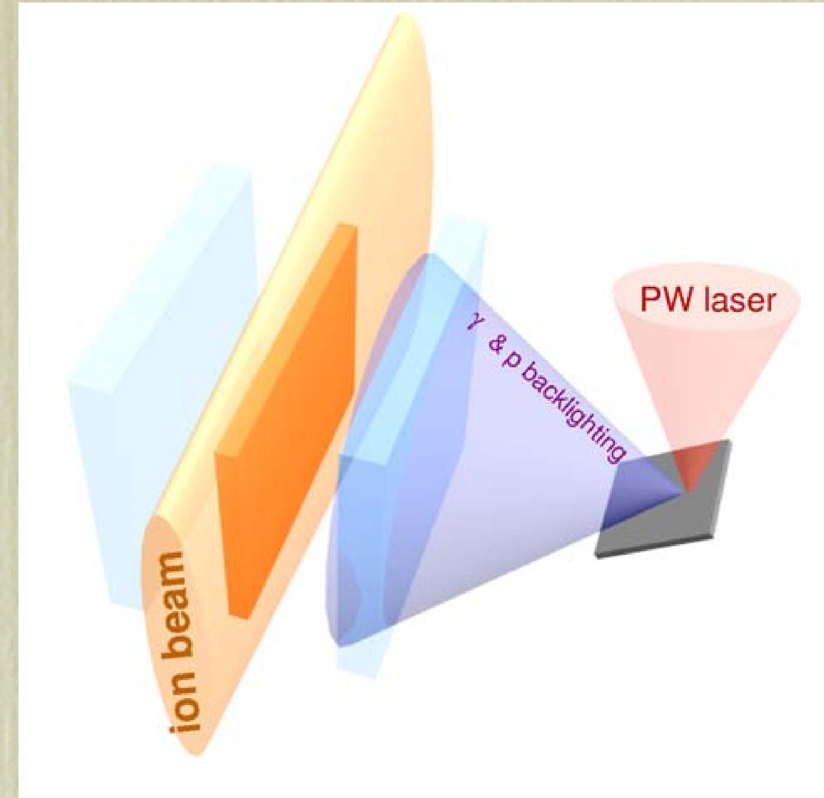


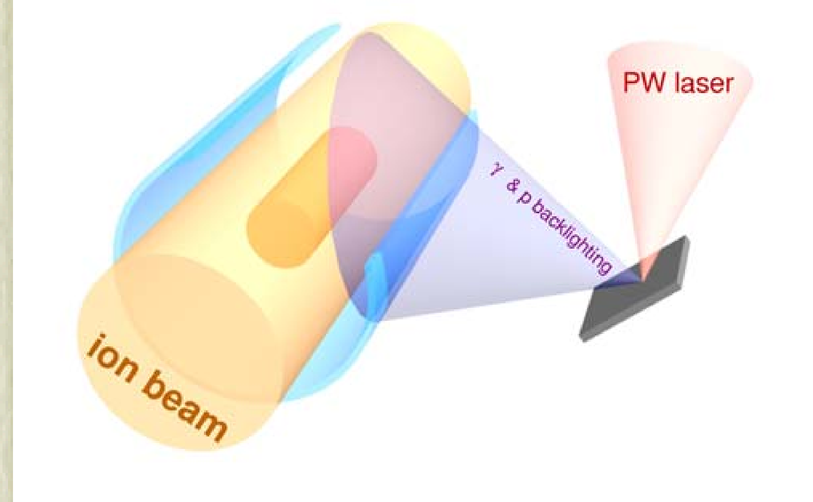
HED regions of Pb EOS accessible at FAIR

HEDgeHOB experiments @ FAIR

HIHEX: heavy ion heating and expansion

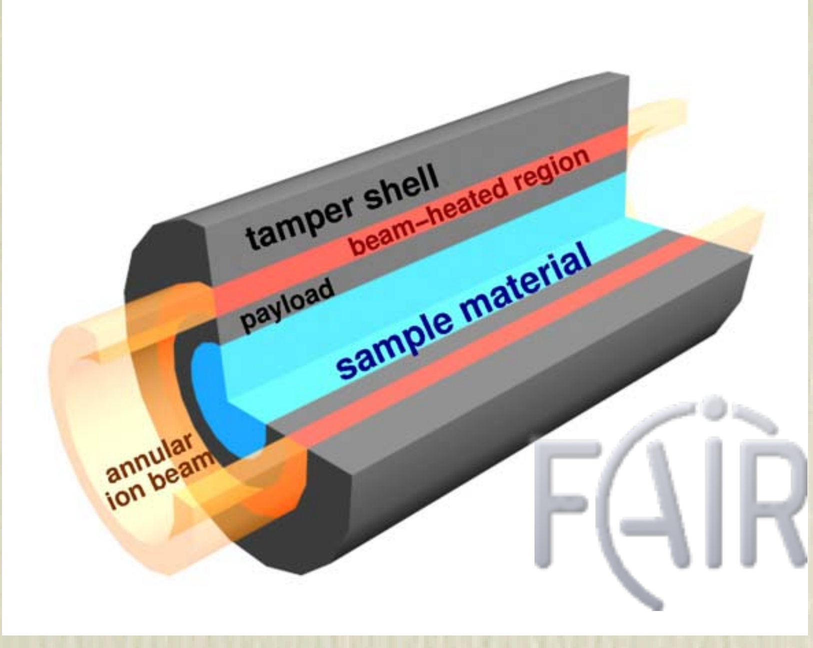
- volumetric character of heating, in contrast to generating a shock wave
- heated material expand isentropically, passing through many interesting physical states
- expansion of the target material can be limited by a surrounding container that can also be filled with a buffer gas at different initial pressures
- measurements of the target physical properties are done during the heating as well as the expansion phase
- plane as well as cylindrical beam-target configurations





LAPLAS: low-entropy compression

- low-entropy implosion of a test material in order to achieve a high degree of compression while keeping the temperature in the sample relatively low
- target consists of a cylinder of frozen hydrogen that is surrounded by a thick shell of a heavy material (Au, Pb)
- target is irradiated with an intense heavy ion beam that has an annular (ring-shaped) focal spot
- outer shell known as "payload", will be created between the sample material and the beam-heated region. The payload plays an important role in placing the compression on the desired adiabat



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/cm2
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:

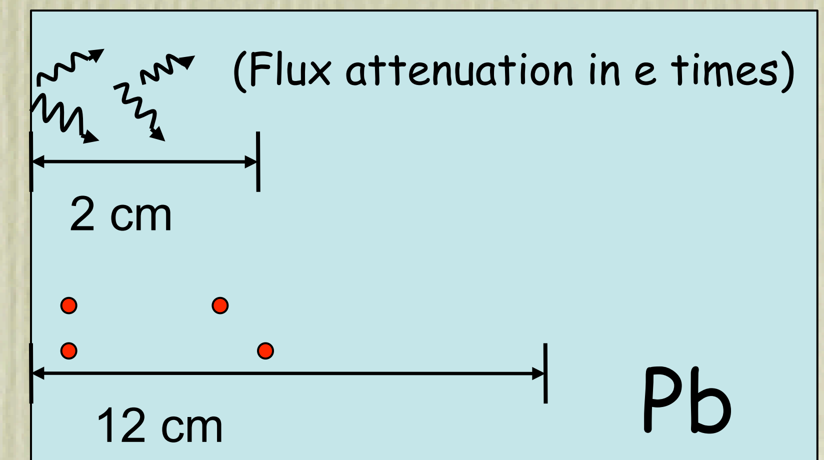
Up to 80 g TNT
Pumped down to 10^{-3} Torr
Active ventilation system
Fiber for optical diagnostics (VISAR)

Proton Radiography Basics

X-rays and protons ranges in matter

X-rays 3-10 MeV

High Energy Protons - GeV



Protons Image Blurring due to MCS

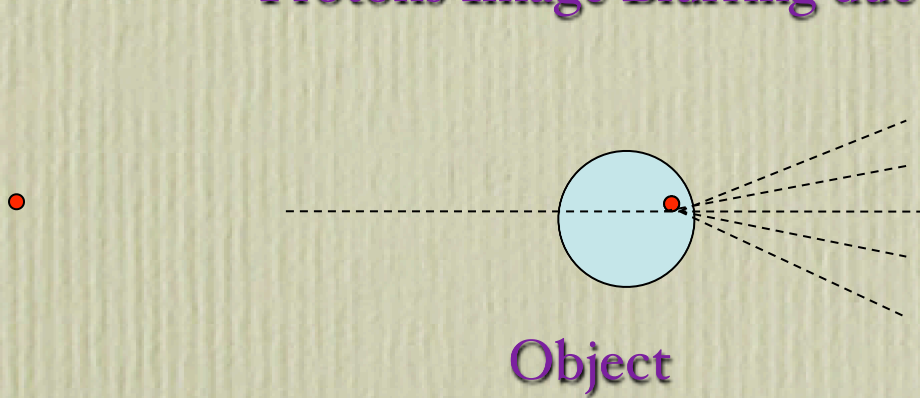
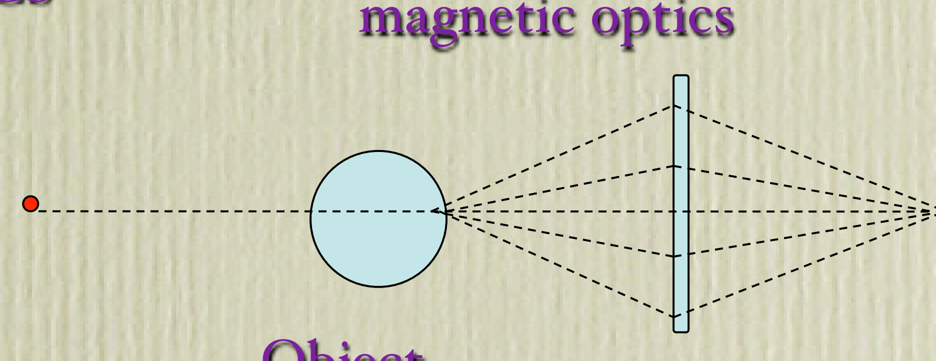


Image Blurring compensation with magnetic optics

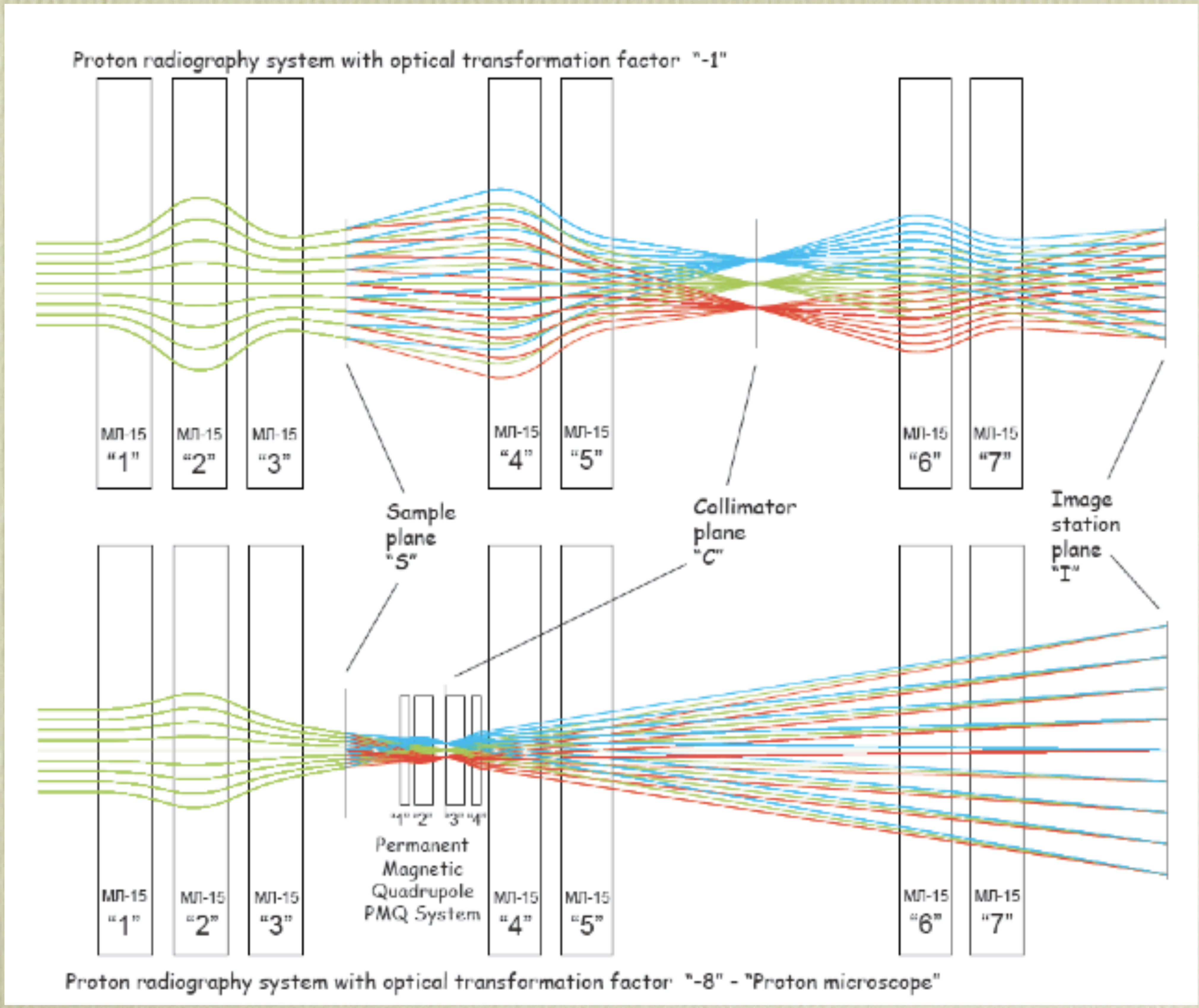


A. M. Koehler, *et al.* *Science* **160**, 303 (1968)

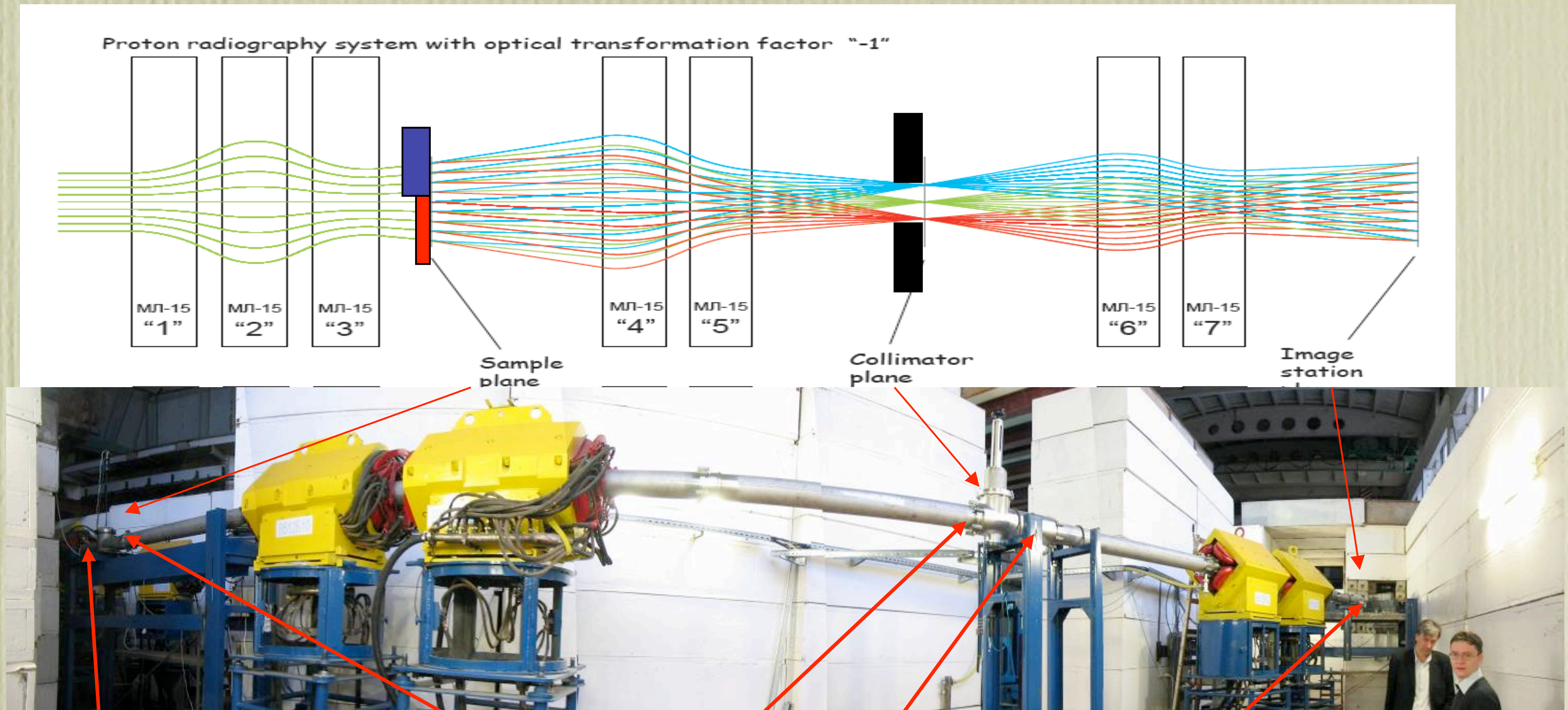
J. A. Cookson Naturwissenschaften 61, 184—191 (1974)

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

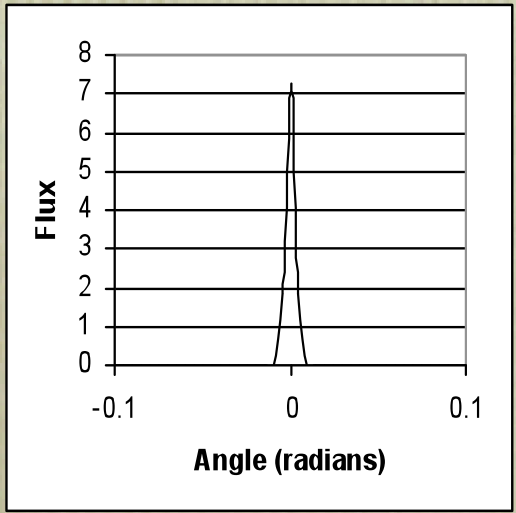
Magnetic optics design for proton radiography set-up



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



Incident Beam | After Object | After Collimator



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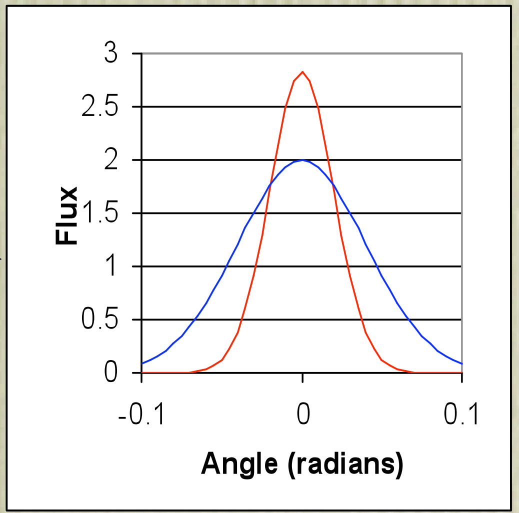

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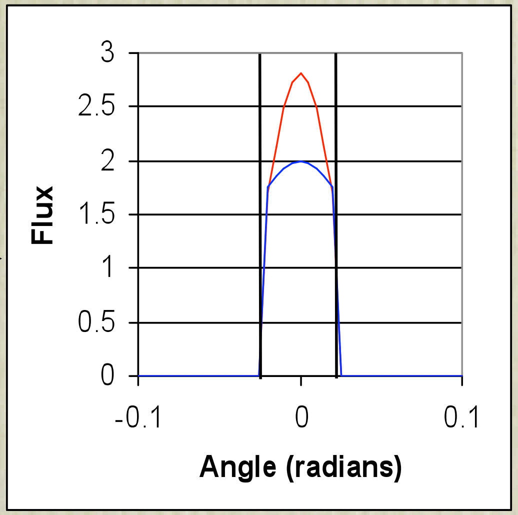
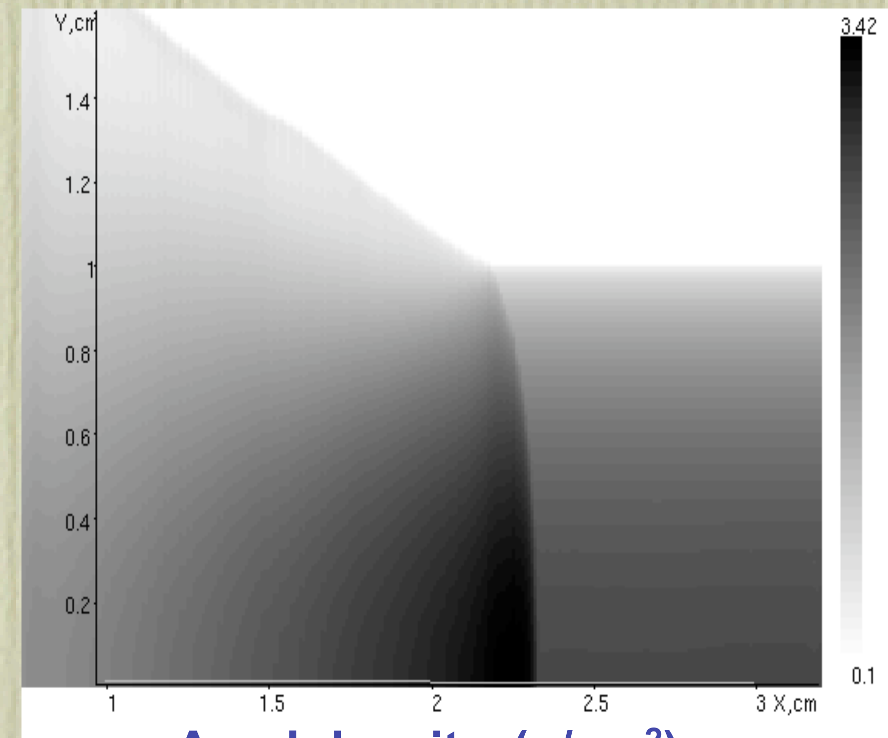
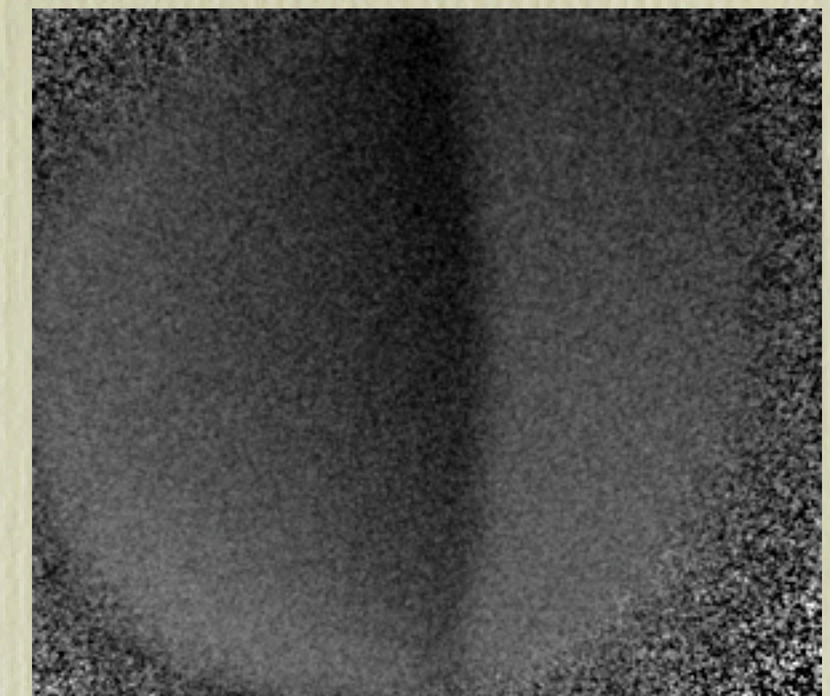


→ Measured transmission provides information about object thickness

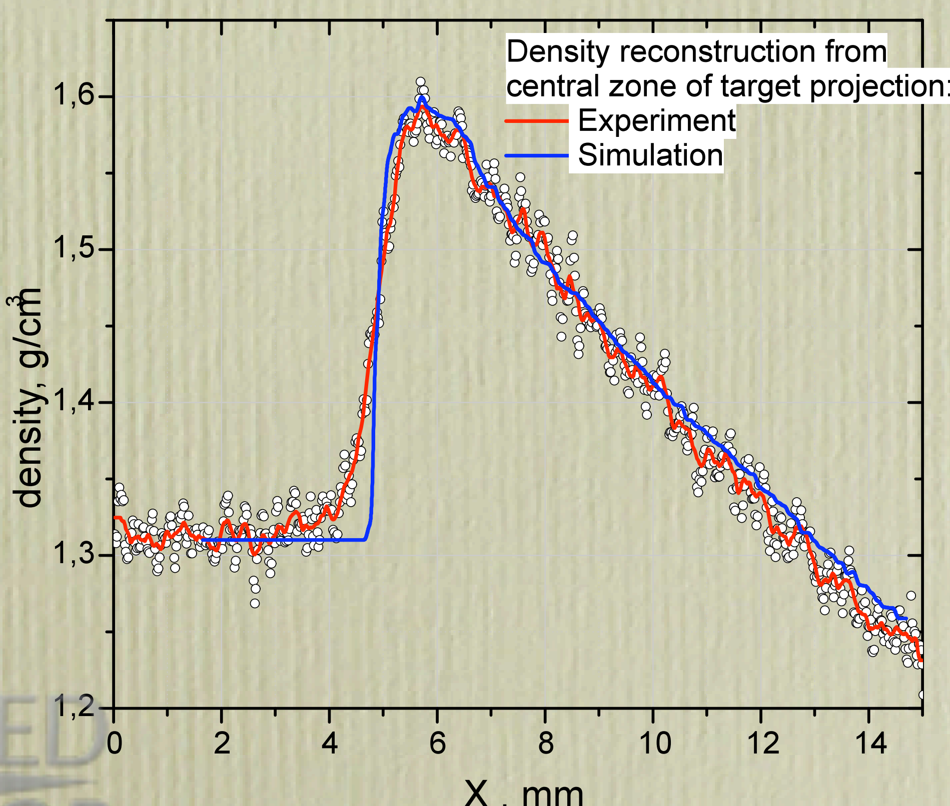
First results of dynamic experiments: Detonation wave in TNT

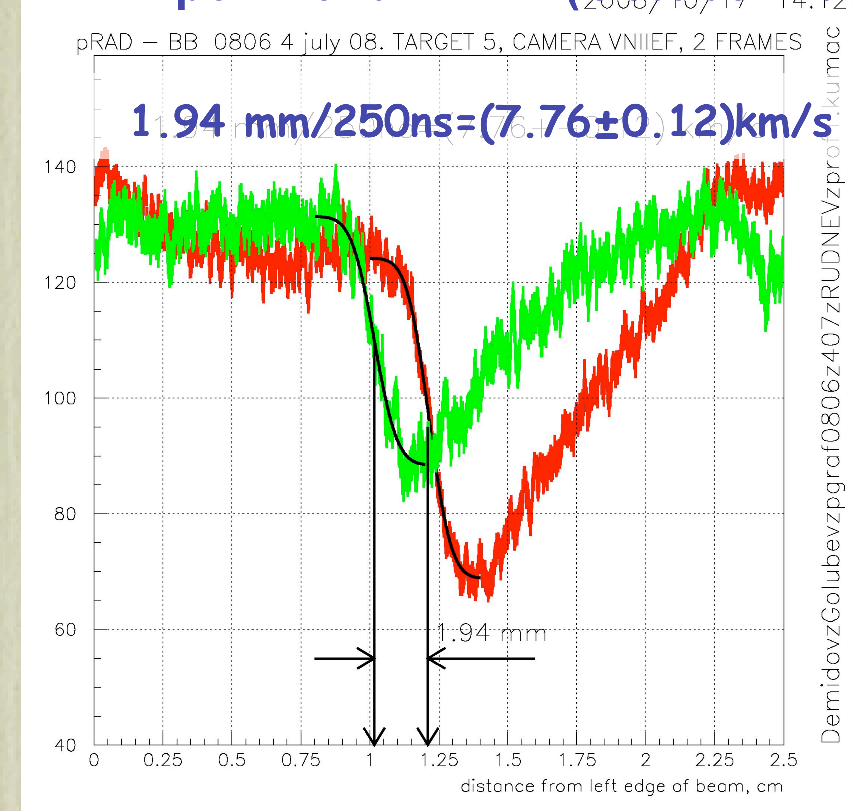


Areal density, (g/cm^2)
Simulation results – A. Shutov



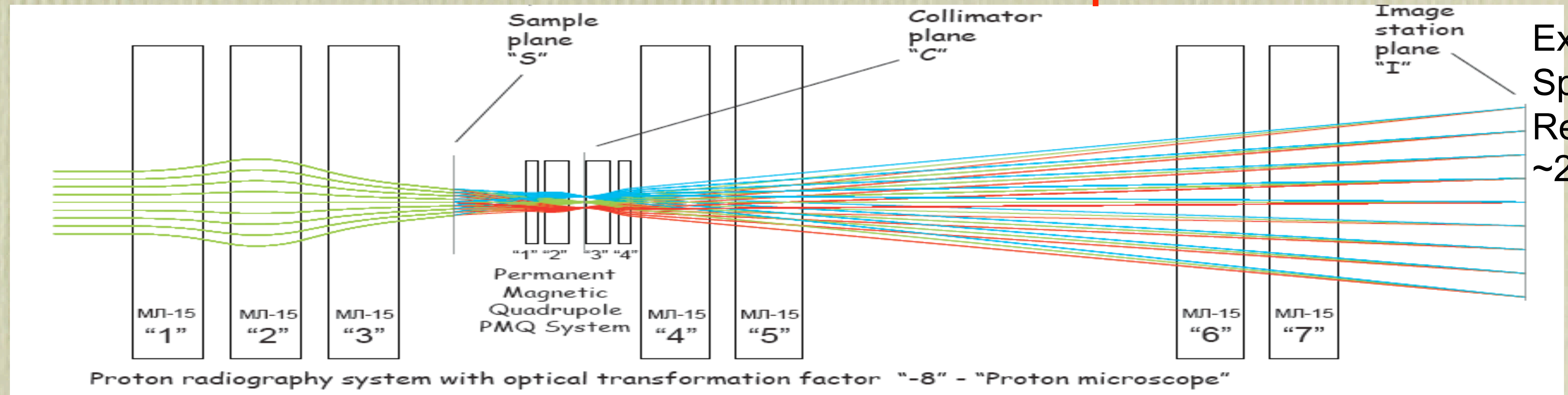
Relative proton beam transmission, (%)
Experiment – ITEP (October 2008)





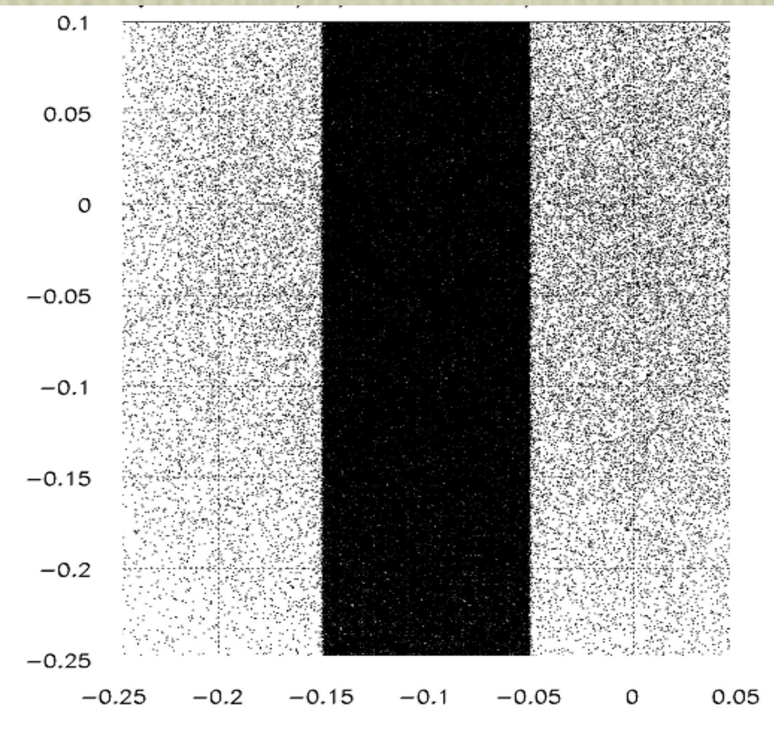
Magnetic optics design for proton radiography set-up image transformation factor -8

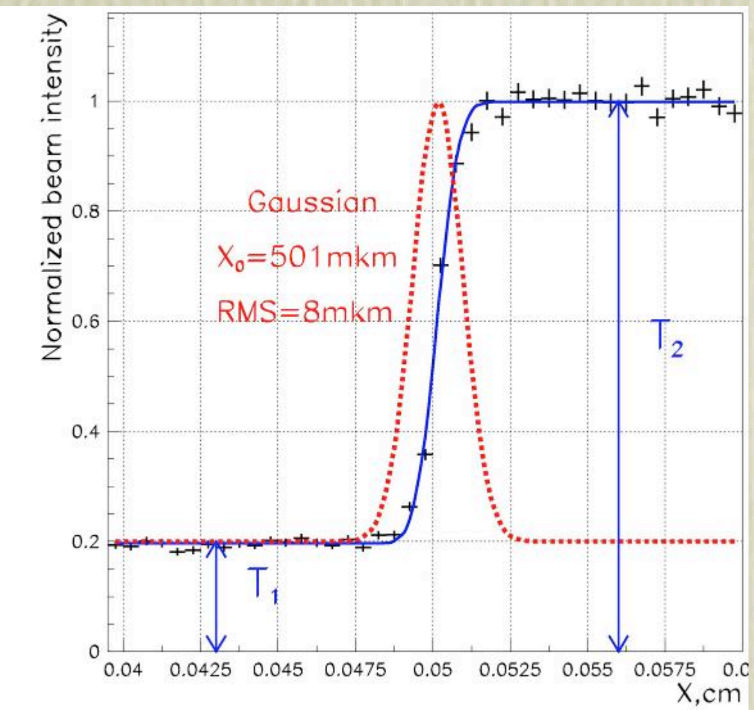
COSY simulation for "Proton Microscope"



Expected Spatial Resolution ~20 μm

GEANT4 simulations for "Proton Microscope"

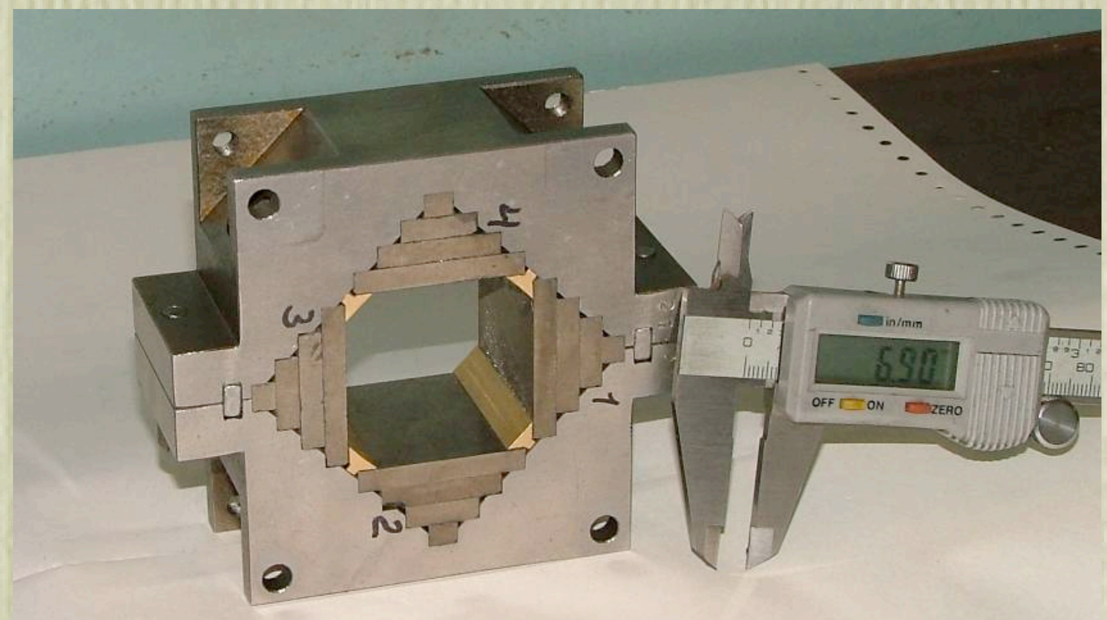




"Sharp edge" test-object

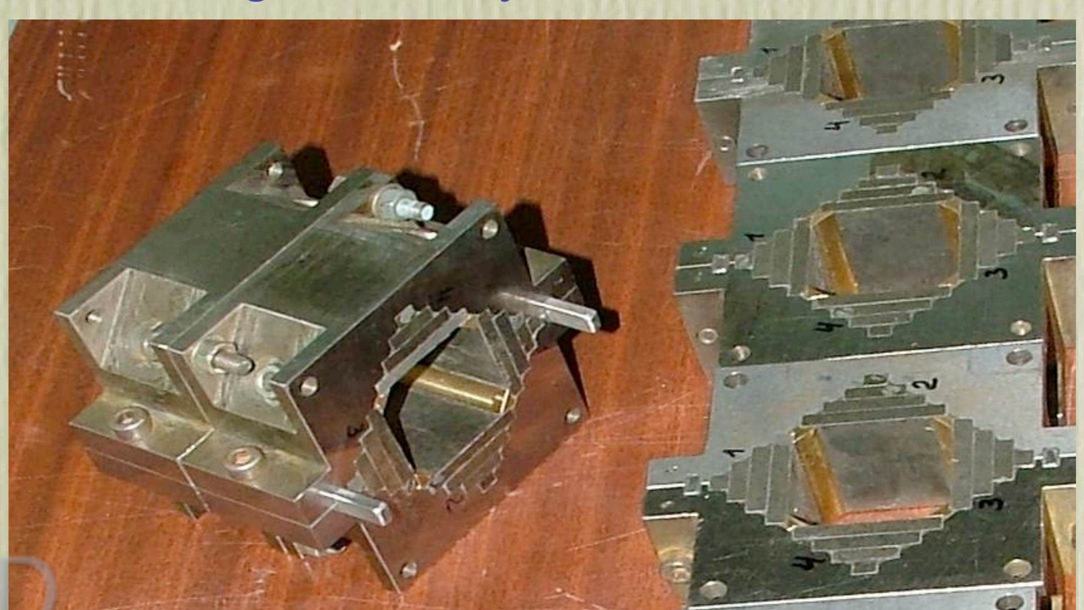
Magnetic optics design for proton radiography set-up image transformation factor -8

Permanent Magnet Quadrupole lens fabrication for “Proton Microscope”

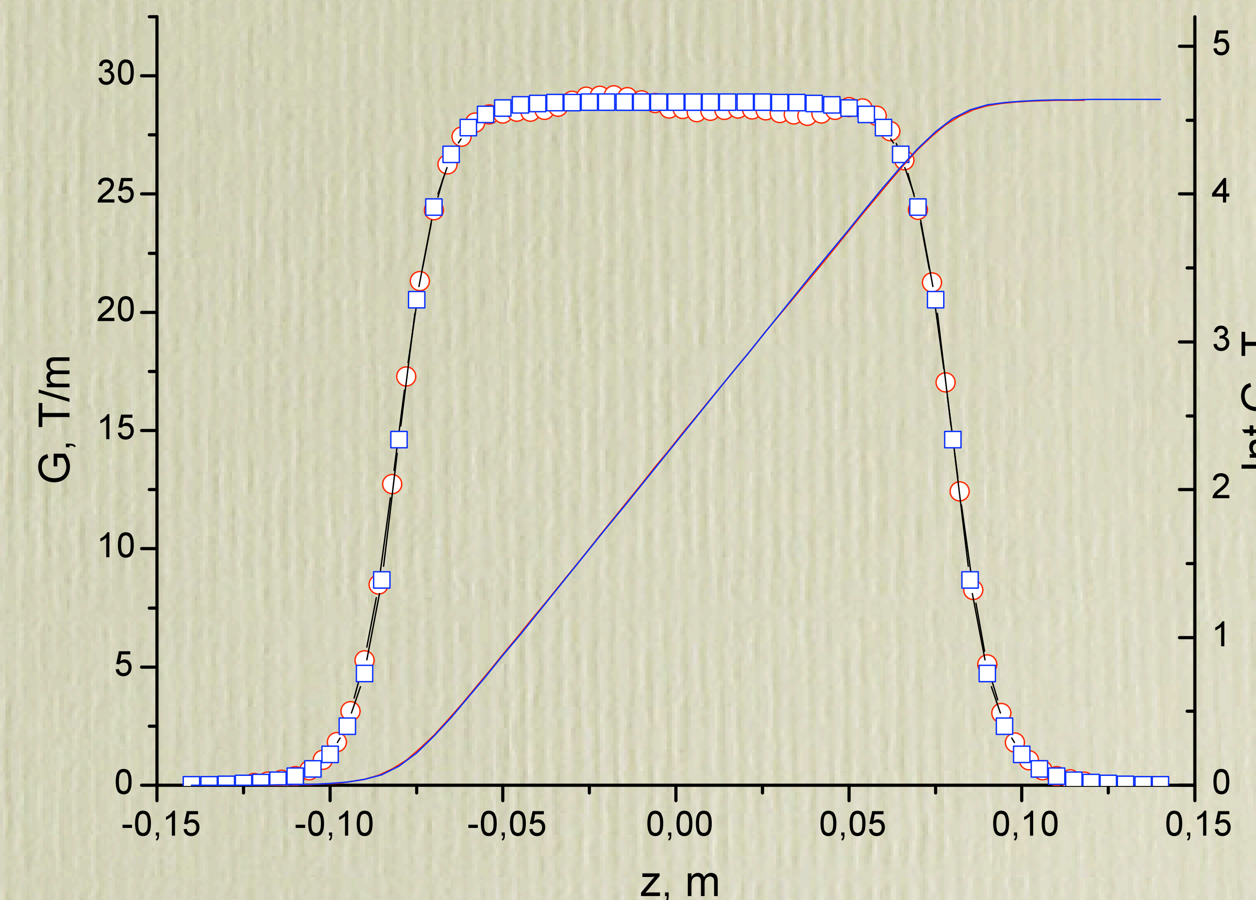


Permanent Magnetic Quadrupole Module

Magnetic alloy Nd-Fe-B



Quadrupole Lens Assembling



Four Modules Assembly Axis Gradient Distribution

Blue – field simulation

Red – field measurements

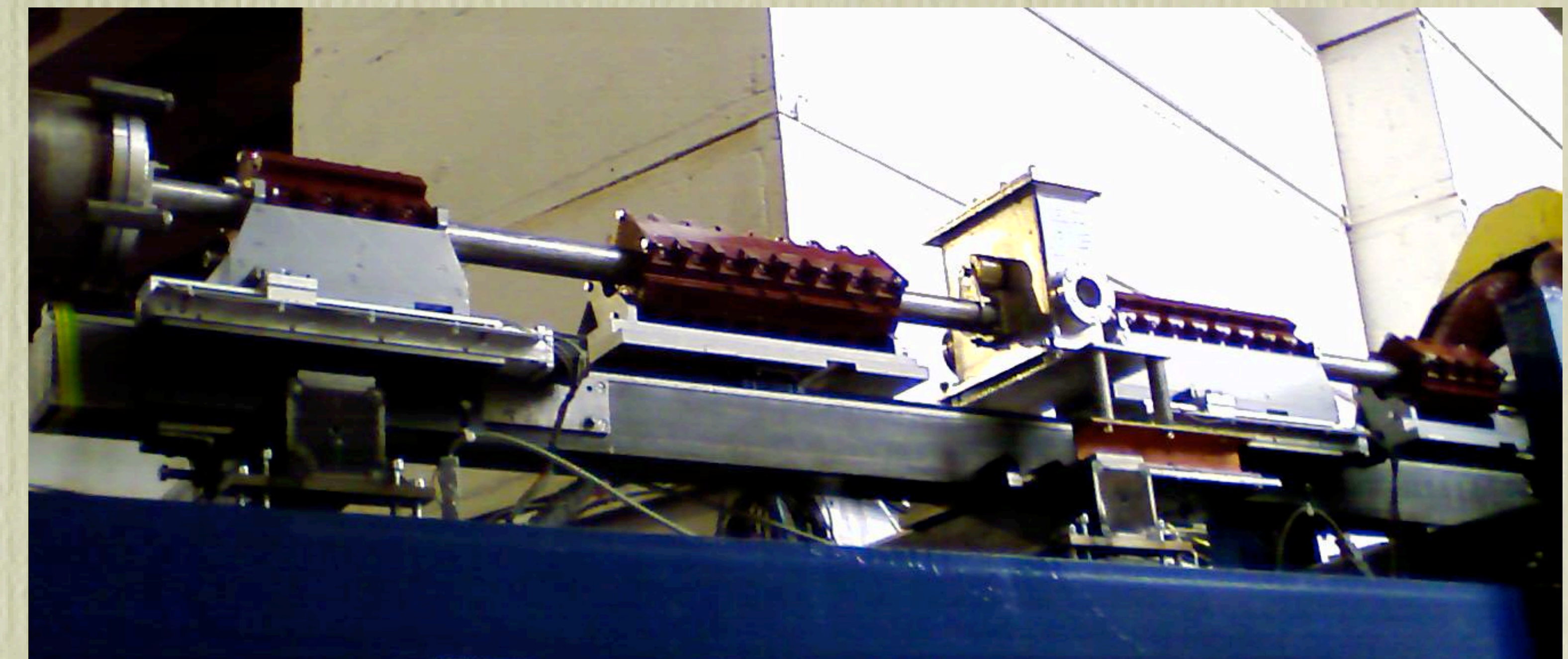
ITEP Proton Microscope commissioning in 2008

E = 800 MeV
Magnification X = 7.82
Field of view < 10mm
Spatial resolution σ = 50um

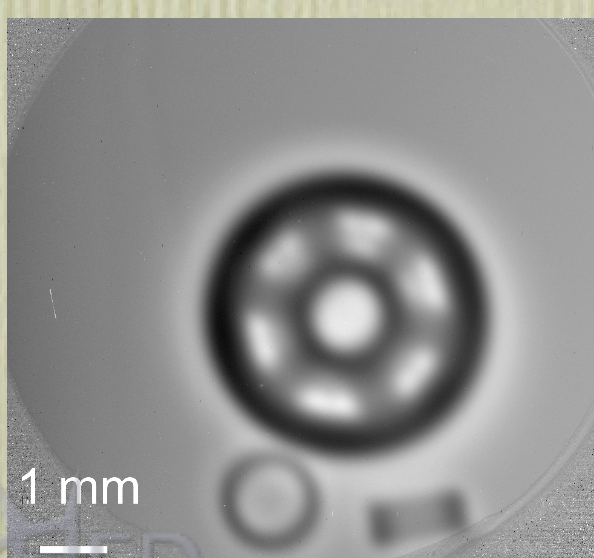
Magnification X = 3.92
Field of view < 22 mm
Spatial resolution σ = 60um

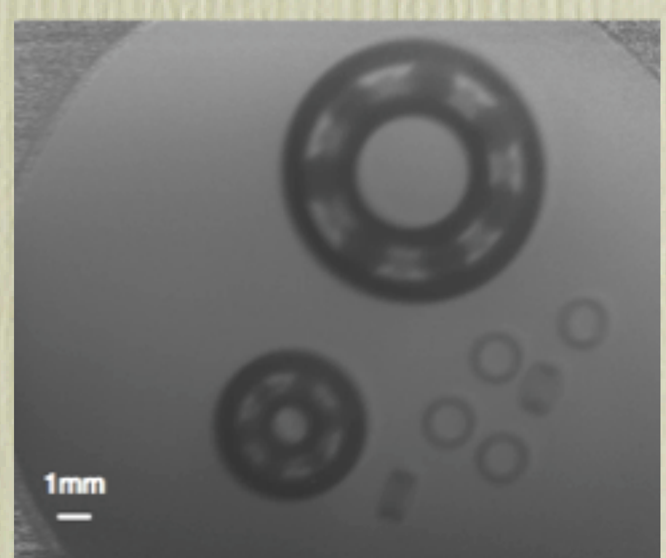
Density resolution ~ 6%

Beam structure – 4 bunches (FWHM=70ns) in 1 us

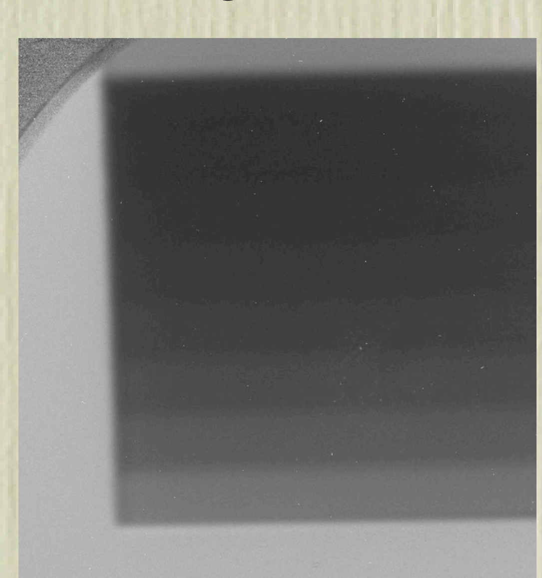


Static test-object images





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

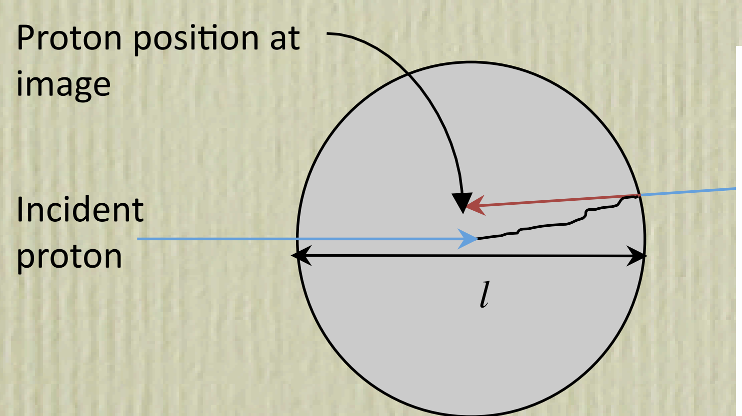


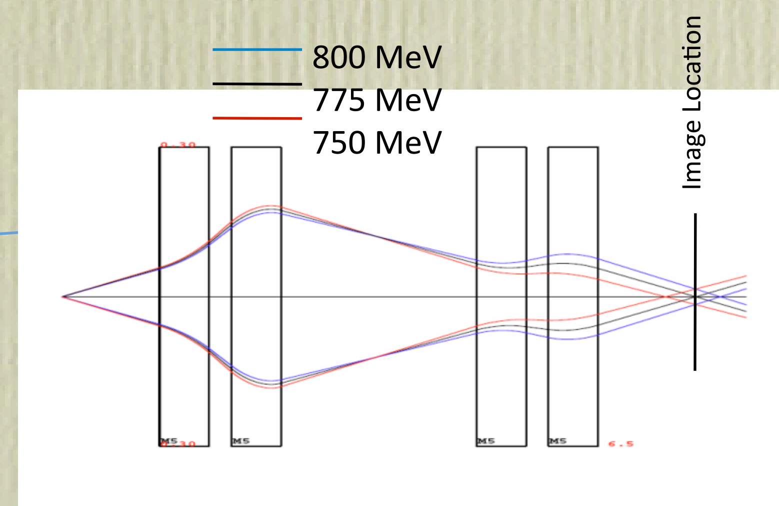
Brass stair 1 mm step Δρ=400um

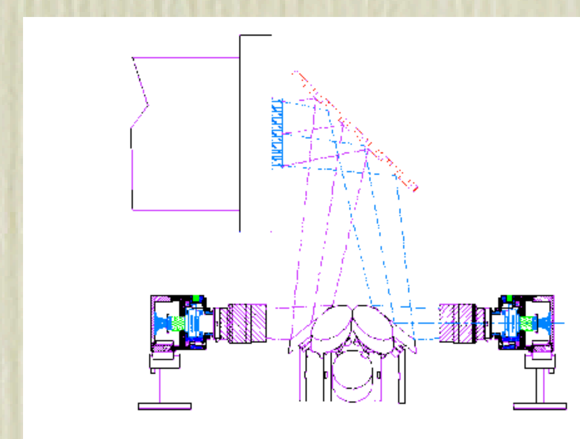
Detonation wave immitator d=15mm σ=100um

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:

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

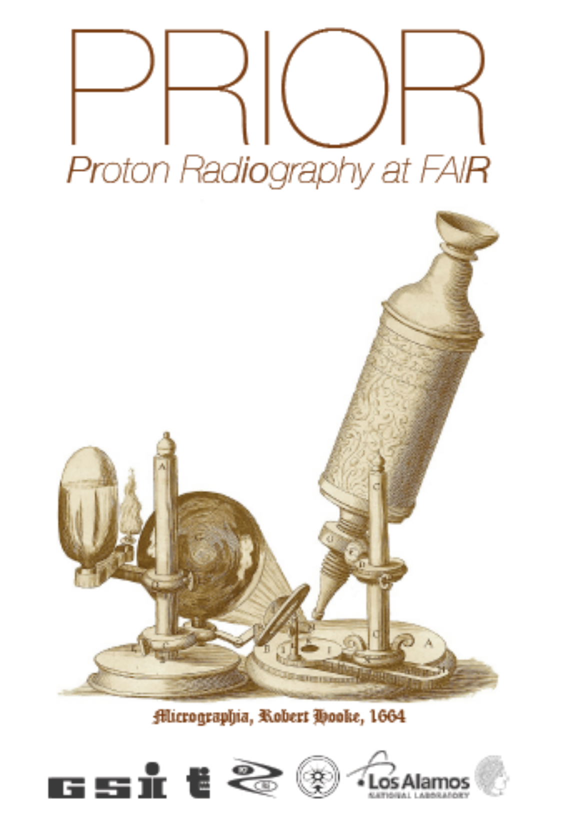
Chromatic aberration:

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

Scintillator blur:

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

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

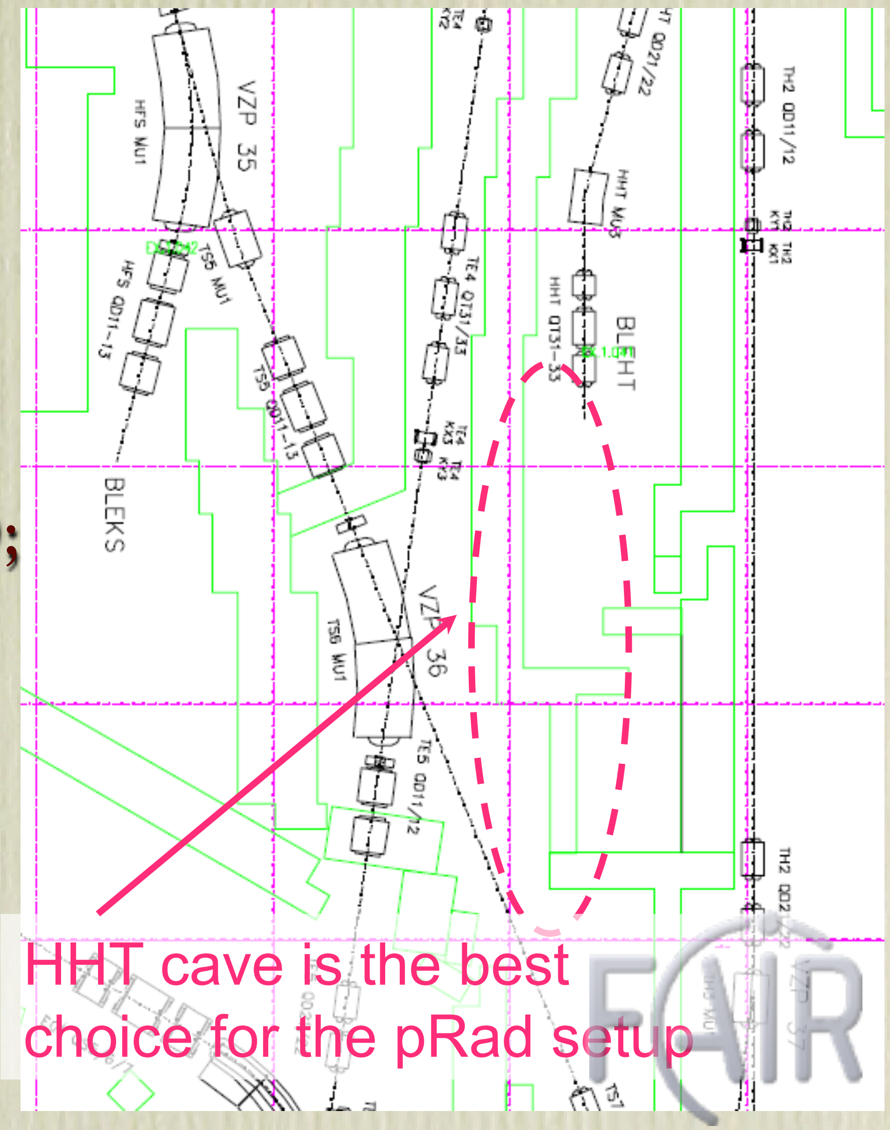


<u>Project goal:</u>

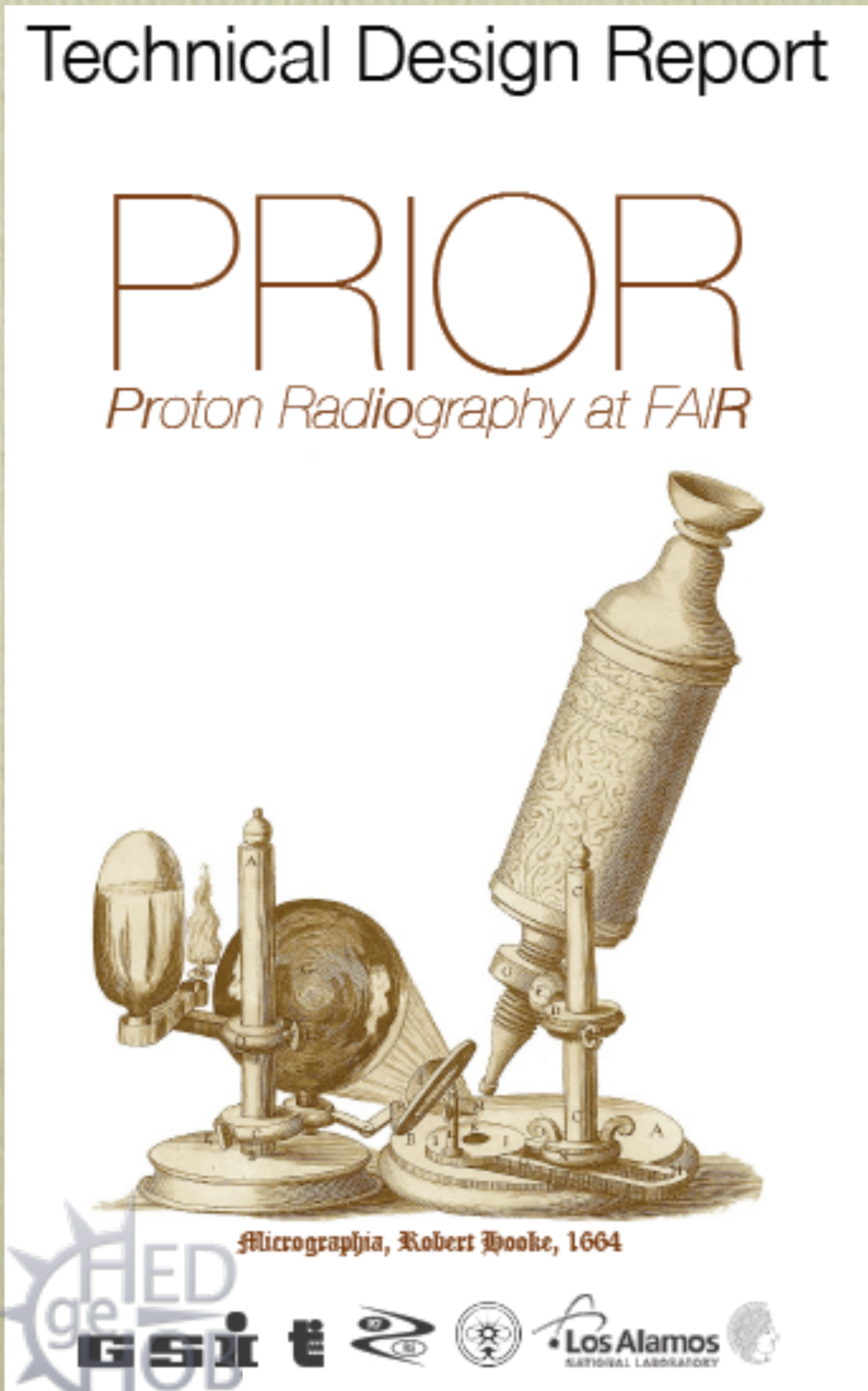
Designing and constructing a pRad lens and detector system for 4.5 GeV protons capable of collecting multiple time radiographs with micron-level resolution, according to the requirements for the FAIR pRad setup.

<u>Lens and detector design goals</u>
<u>(in accordance with FAIR pRad specifications):</u>

- less than 10 μm spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 10 g/cm2, high-Z targets;
- temporal resolution <10 ns (for FAIR), <100 ns (for GSI);
- field of view: 10 mm;
- proton illumination spot size: 1 – 10 mm;
- magnifying lens with M = 4 – 8.



PRIOR: Proton Microscope at FAIR
Time schedule and milestones

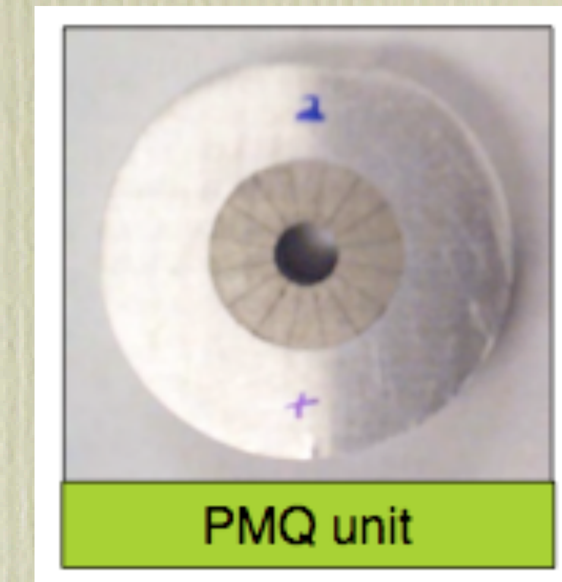


- approval of the project by GSI management – Q2 2009
- optical design of the proton microscope – Q2-Q3 2009
- engineering design of the whole system – Q3-Q4 2009
- completion of the HHT reconstruction – Q4 2009
- ordering the production of main components – Q3-Q4 2009
- assembling the setup at HHT – 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

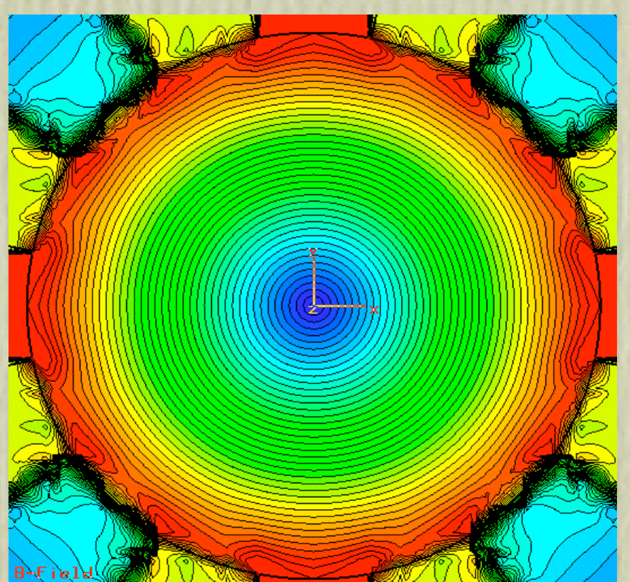
PRIOR: Proton Microscope at FAIR

High Gradient Small Aperture Split-pole REPM quadrupole

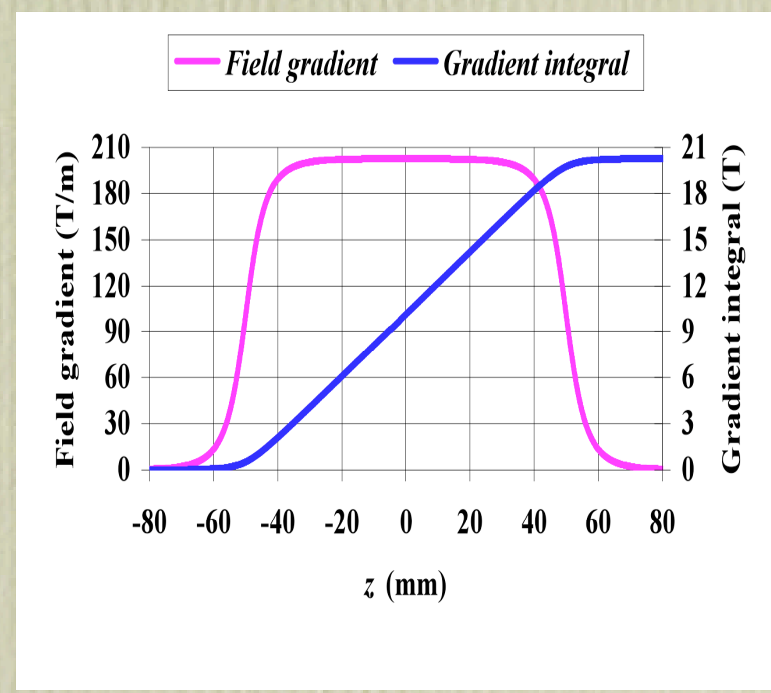
Magnetic aperture diameter	15 mm
Pole tip field	1.5 T
Lens length	100 mm
Quad’s segment number	16
Sector gap	0.1 mm



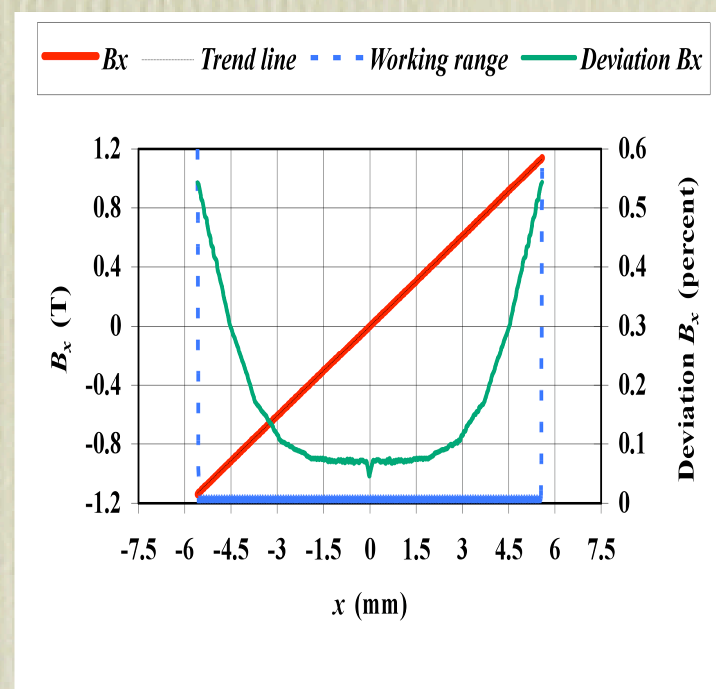
CST EMS calculations results



Field B_{abs} in the central lens cross-section z = 0 mm

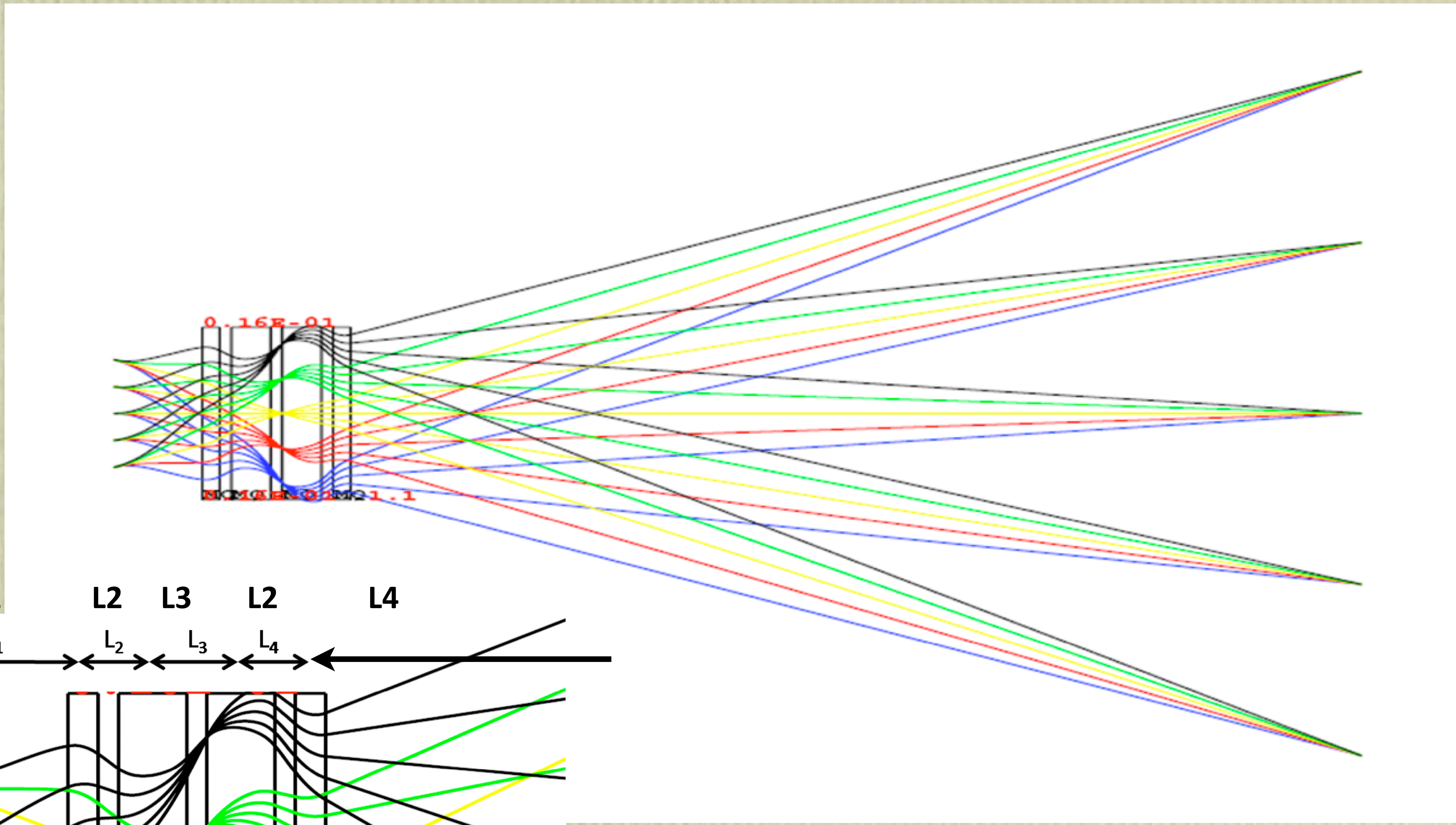


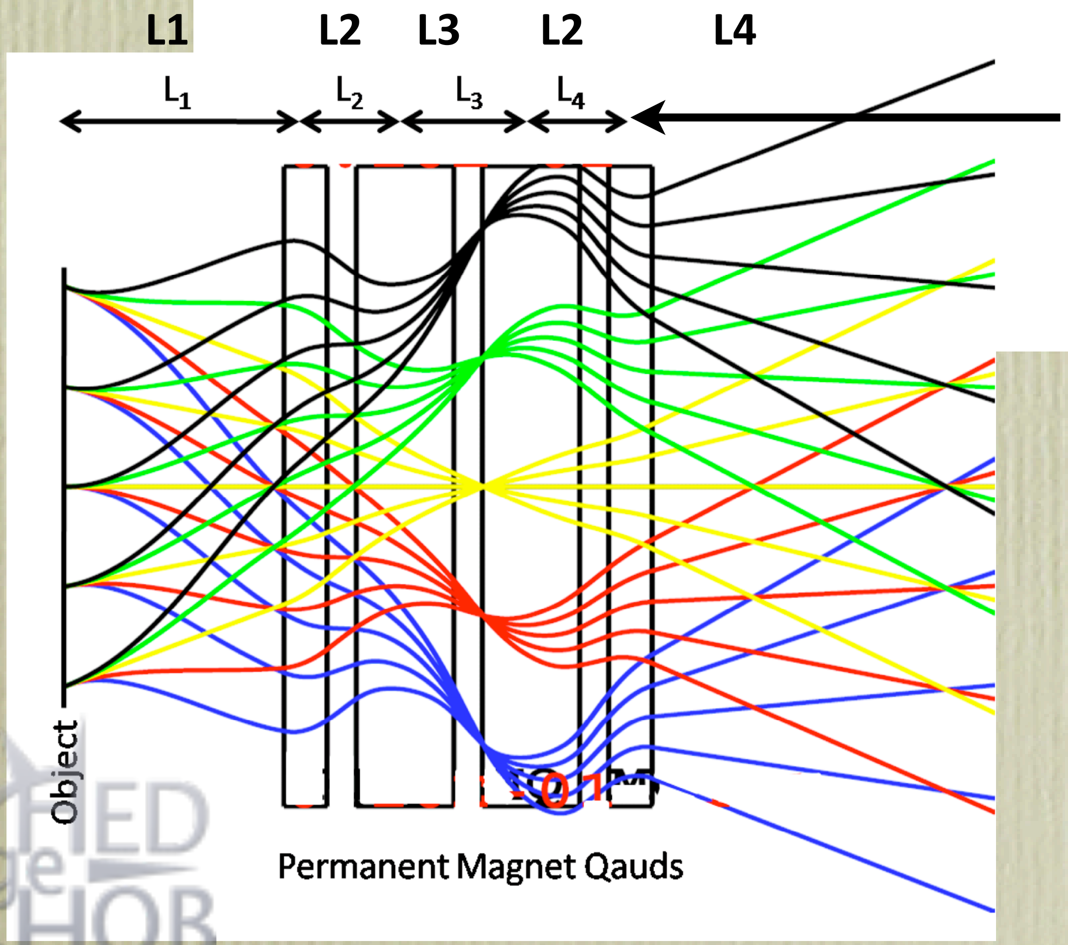
Field gradient and gradient integral along lens z-axis



Field B_x and non-linearity in the segmented split-pole quad

PRIOR: Proton Microscope at FAIR

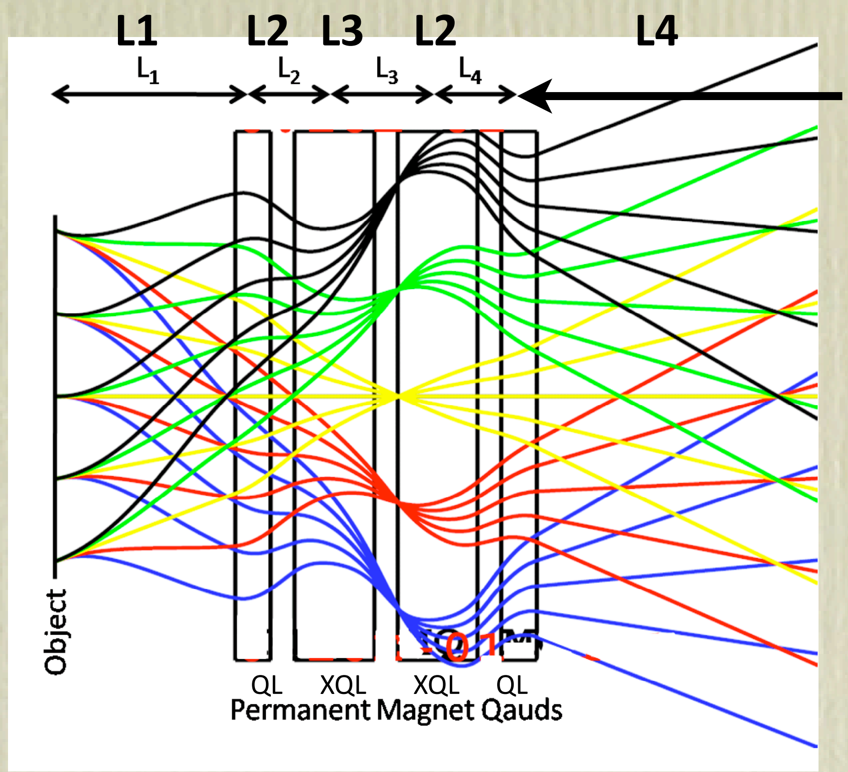




COSY simulation of magnetic optics

PRIOR: Proton Microscope at FAIR

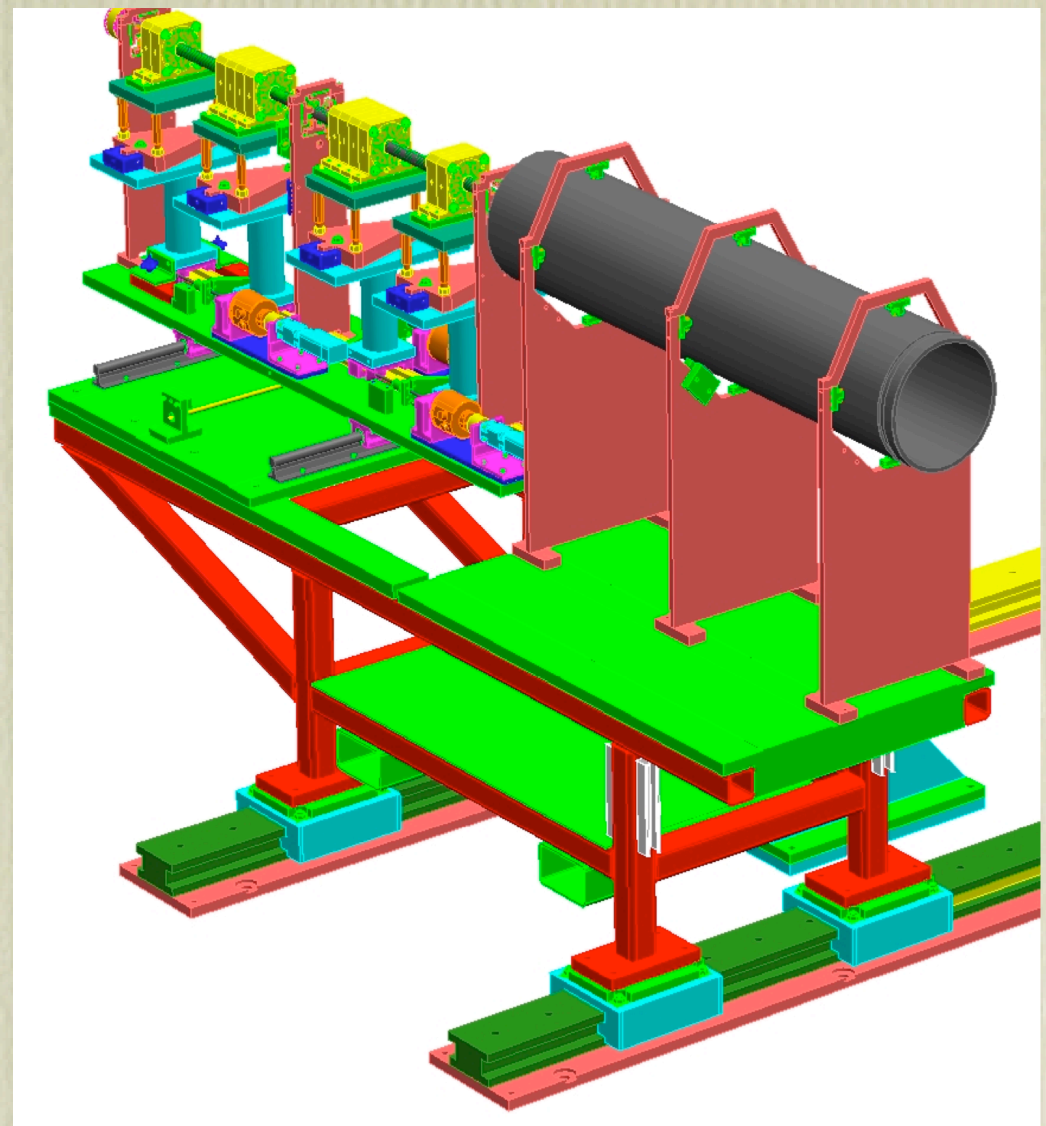
optical design topics:
- min L1, L2, L3
- max L4 and total length X=L1+L2+L3+L4
- min allowed (from PMQ construction):
  d1=delta(PMQ1-PMQ2, PMQ3-PMQ4)
  and d2=delta(PMQ2-PMQ3)
- max PMQ gradient T/m
- optimized k=XQL/QL for min d1, d2



HHT beam line matching:
- beam parameters: vertical and horizontal emittance
- matching section - as option PMQ

PRIOR: Proton Microscope at FAIR

Parameter	Value
Beam energy	4.5 GeV
Inner aperture R_i	0.008 m
Out aperture R_o	0.020 m
B_p "pole tip" field	1.4 T
Gradient	200 T/m
"short" quad length	0.12 m
"Long" quad length	0.27 m
L_1 Object to first Qaud	0.7 m
L_2 (first to second and third to fourth quad spacing)	0.28 m
L3 (second to third quad spacing)	0.36 m
L4 (last quad to image)	7.38 m
Total length	9 m
Magnification	6.5
C_x horizontal Chromatic length	2.43 m
C_y vertical chromatic length	1.89 m
Angular Acceptance	5 mrad
Gaussian line spread function (RMS)	5 um



Conclusions:

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

- New magnet optical system of "Proton Microscope ITEP" developed
first experiment with proton beam was in November 2008

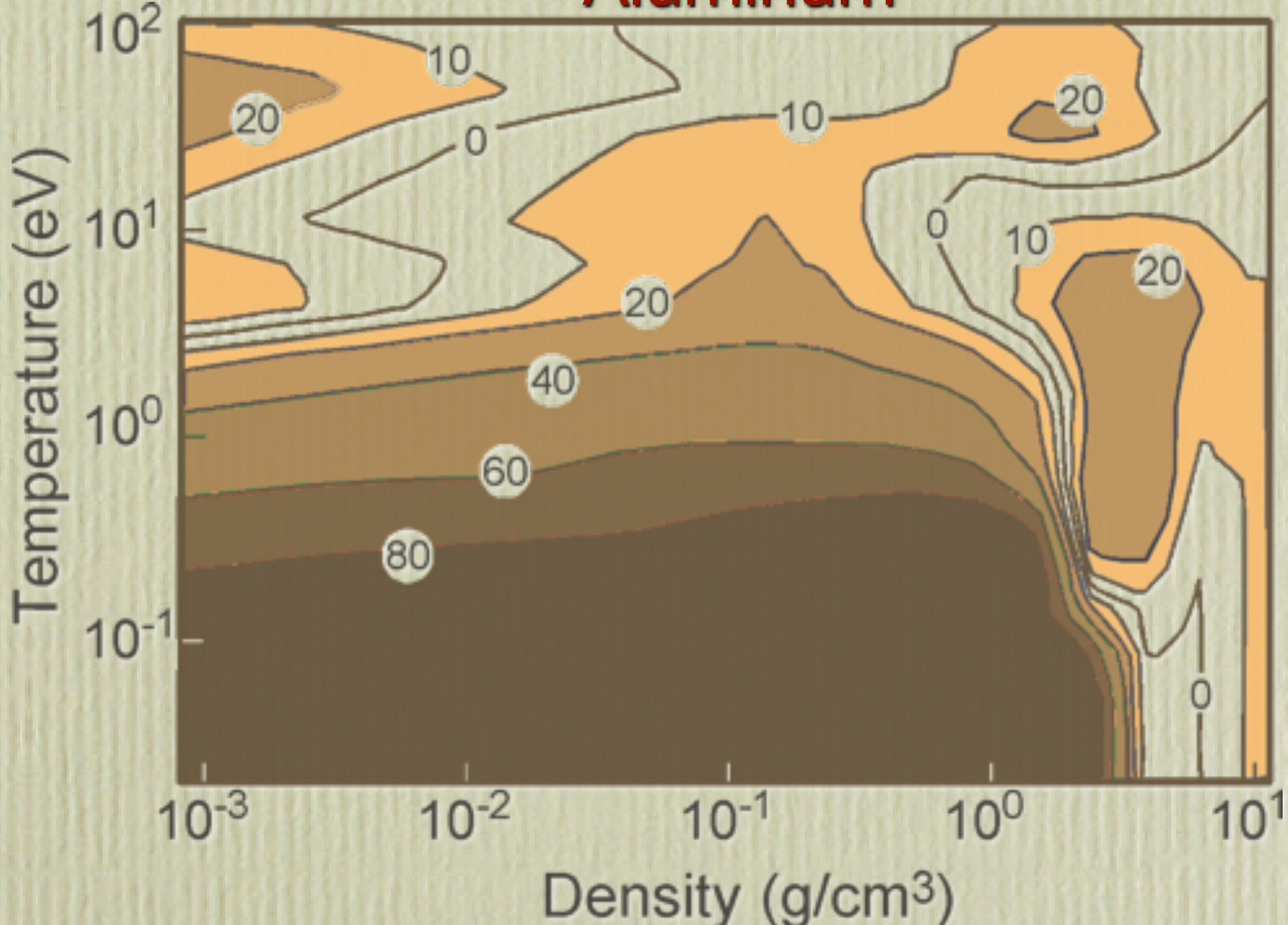
- Proton and Ion Radiography developed as one of the main diagnostic tool for HEDgeHOB collaboration at FAIR project

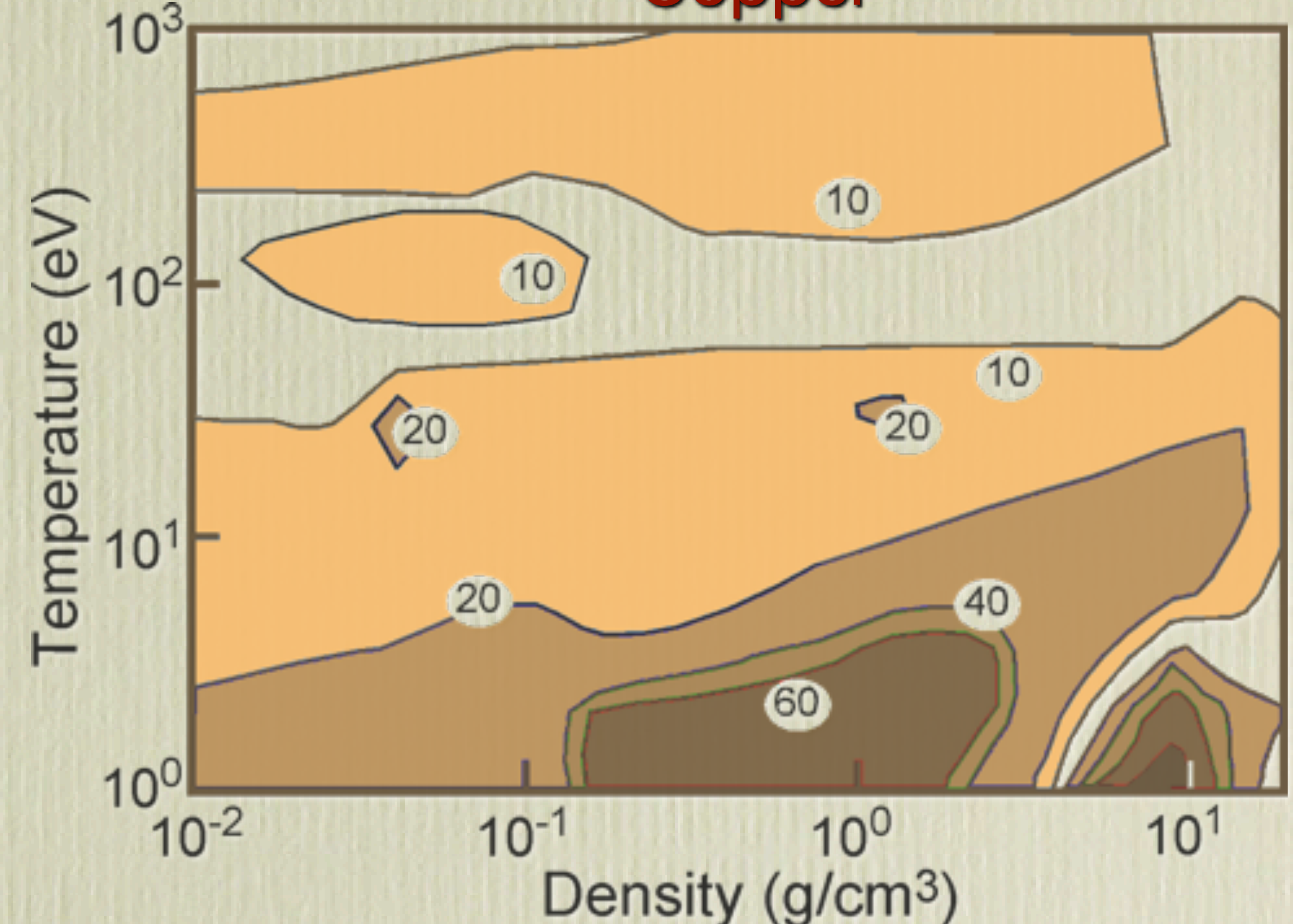
- PRIOR: Proton Microscope at FAIR -
TDR is under preparation

BackUp

Comparison between theoretical EOS models

Contours of % pressure difference between two advanced wide-range semi-empiric EOS models

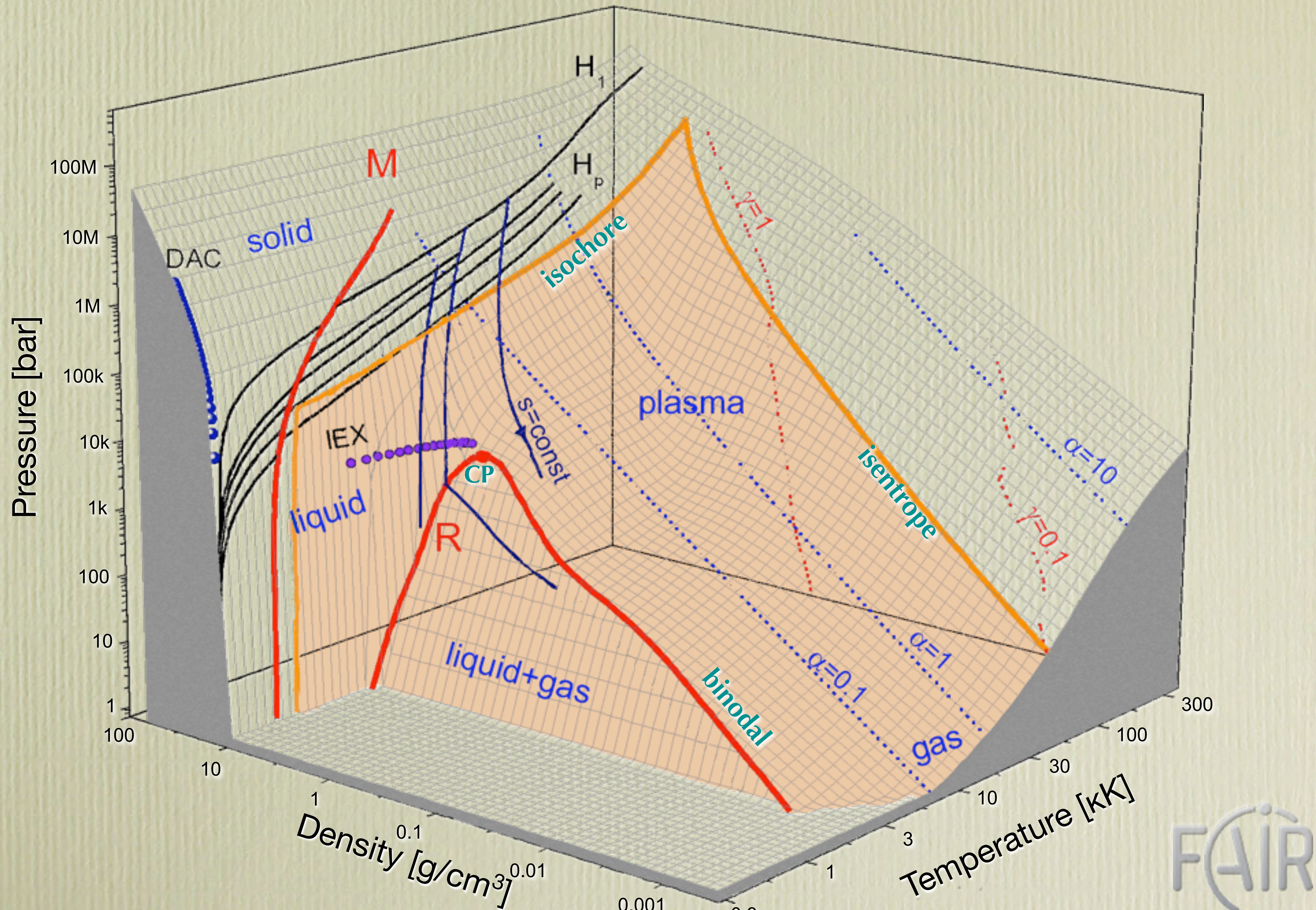




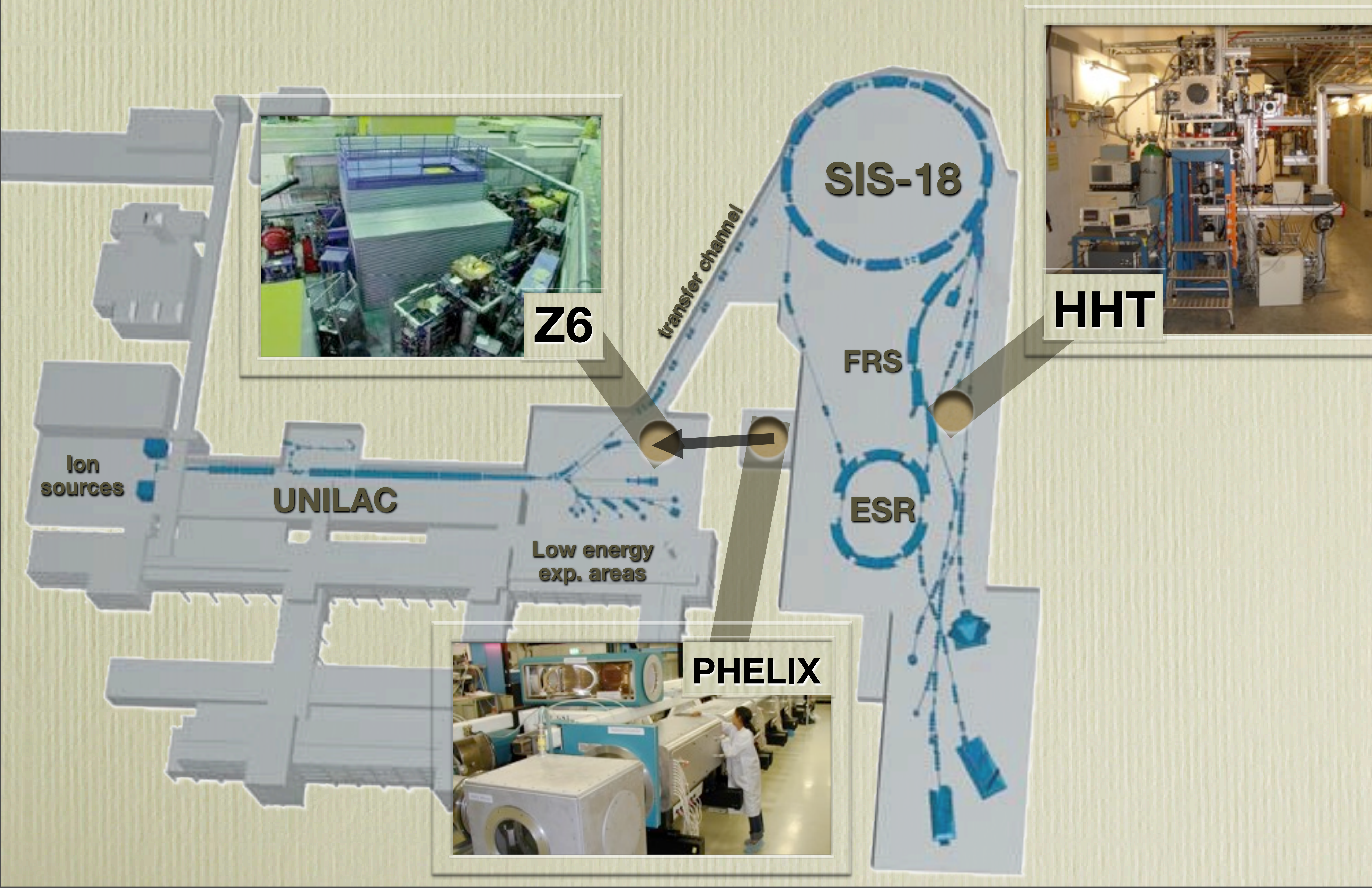
- 80 % or bigger differences between EOS model predictions is easily possible
- theories are in a good agreement in the regions where experimental data exists
- lack of experimental data in the WDM region: **ρ = (0.01 – 1) · ρ_o, T = 0.3 – 3 eV**

courtesy of Richard Lee, LLNL

HED phase diagram and available experimental data



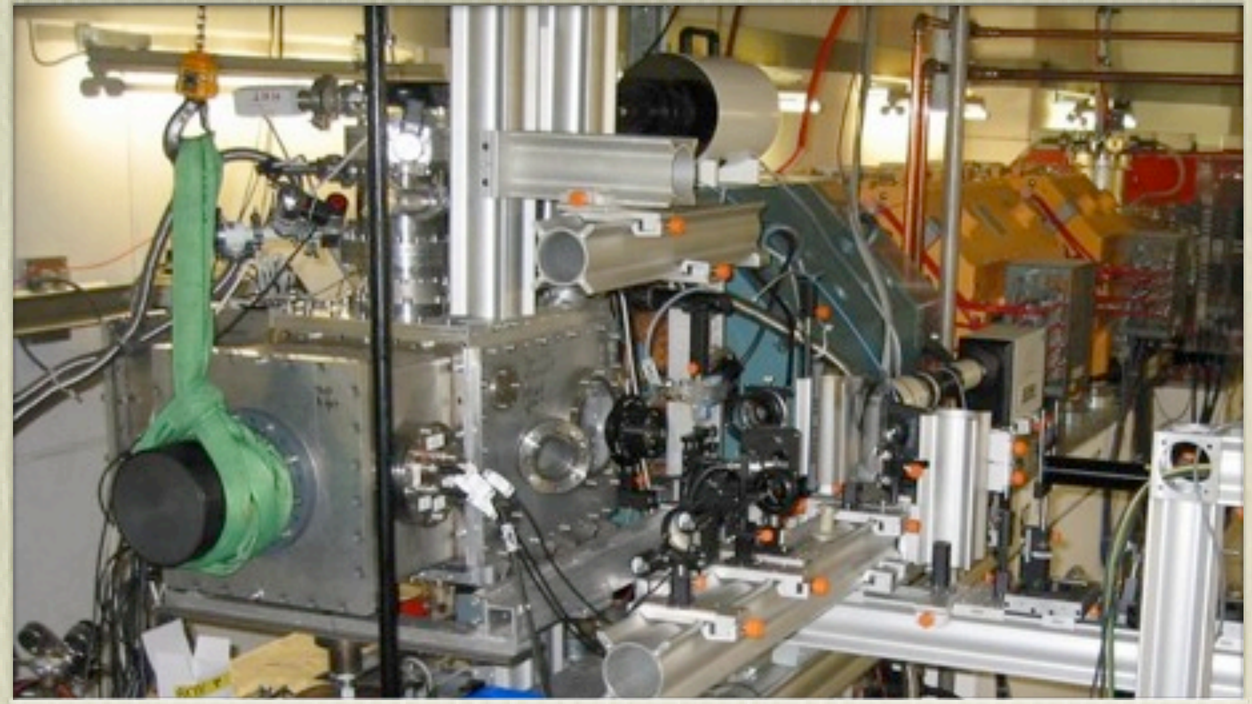
Plasma physics experimental areas at GSI



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

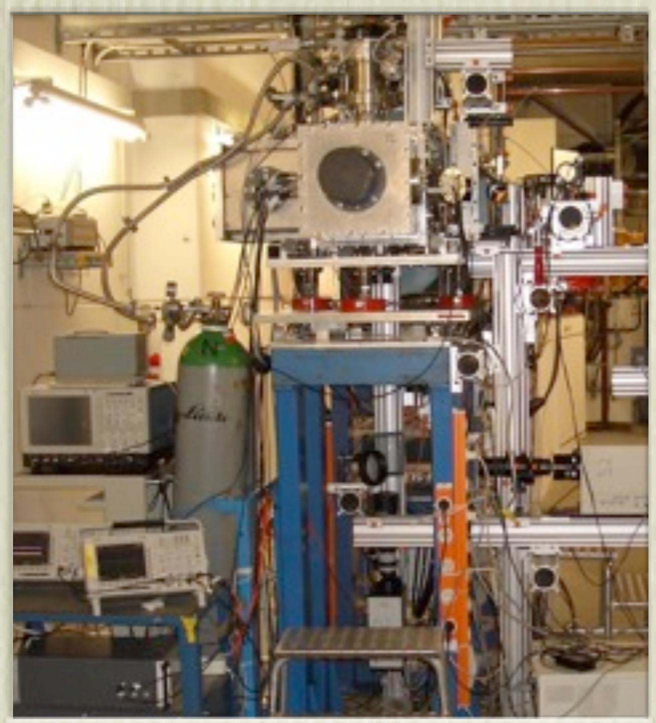
HHT: High energy **H**igh **T**emperature:

- 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

Mission of HEDP / WDM experiments at GSI

Mission:

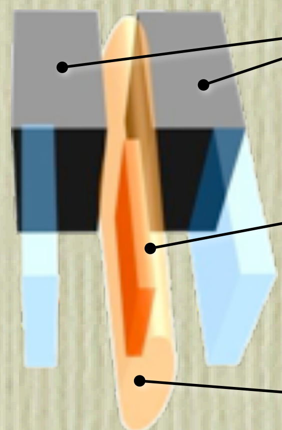
- development and commissioning of essential diagnostic instruments and methods for future HEDP experiments at FAIR (T, P, ρ, E_s, ρ_{el}, C_s, ..., ion beam diagnostics)
- research on new beam-target configurations for HEDP studies using intense heavy ion beam as a driver: find a way for direct measurements of EOS / transport properties without need for intermediate (hydro) re-calculations
- obtaining new data on thermodynamic, transport and optical properties of various materials in HED states near melting and boiling curves, two-phase liquid-gas and the critical point regions, non-ideal plasmas (Pb, W, Cu, C, Al, Au, Ta, Sn, UO_2, SiO_2, Al_2O_3, LiF)

Tools and resources:

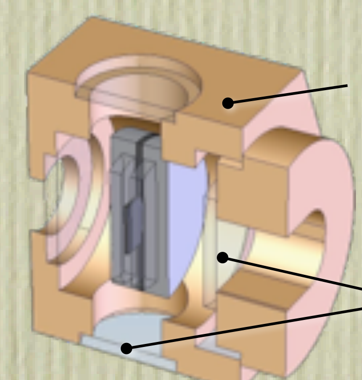
- HHT – unique experimental area and setup for HEDP experiments with intense ion beams
- worldwide most intense heavy ion beams from SIS-18 synchrotron
- more than 10 institutes and universities collaborating (Germany, Russia, ...)
- about 20 scientists and students continually involved in experiment

WDM experimental setup at GSI

Physics package

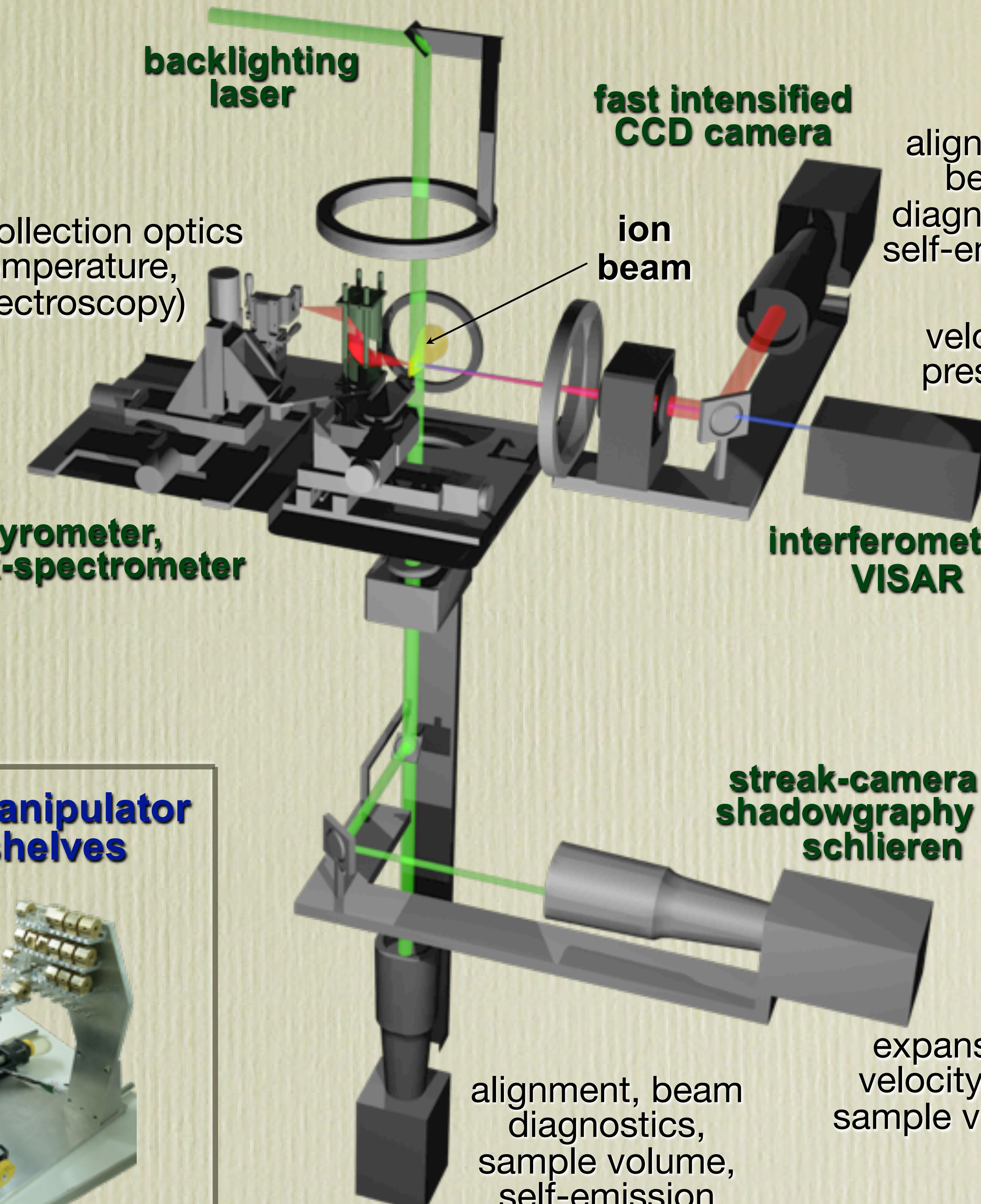


Package in container



Container no the target table

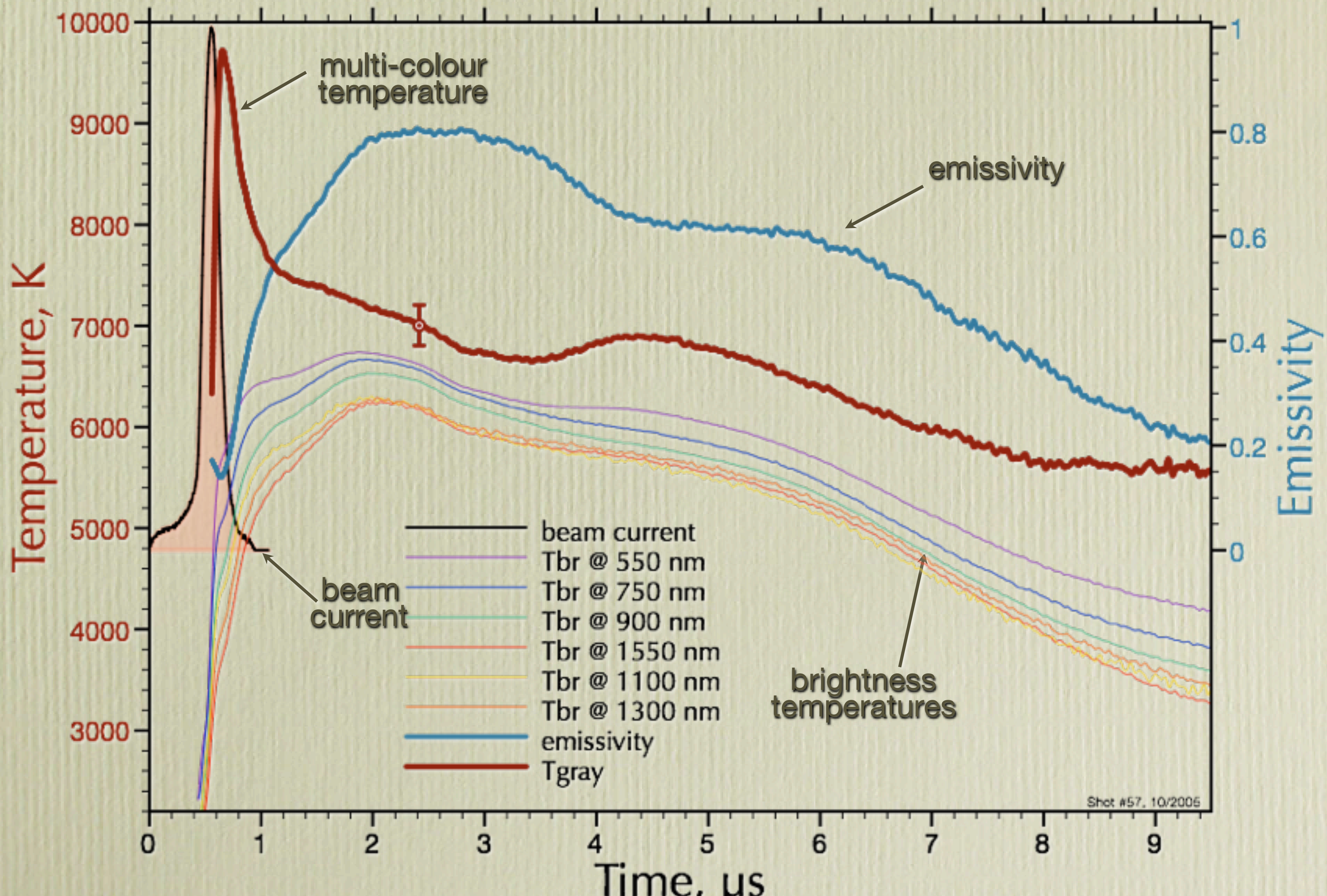
6-axis target manipulator and target shelves



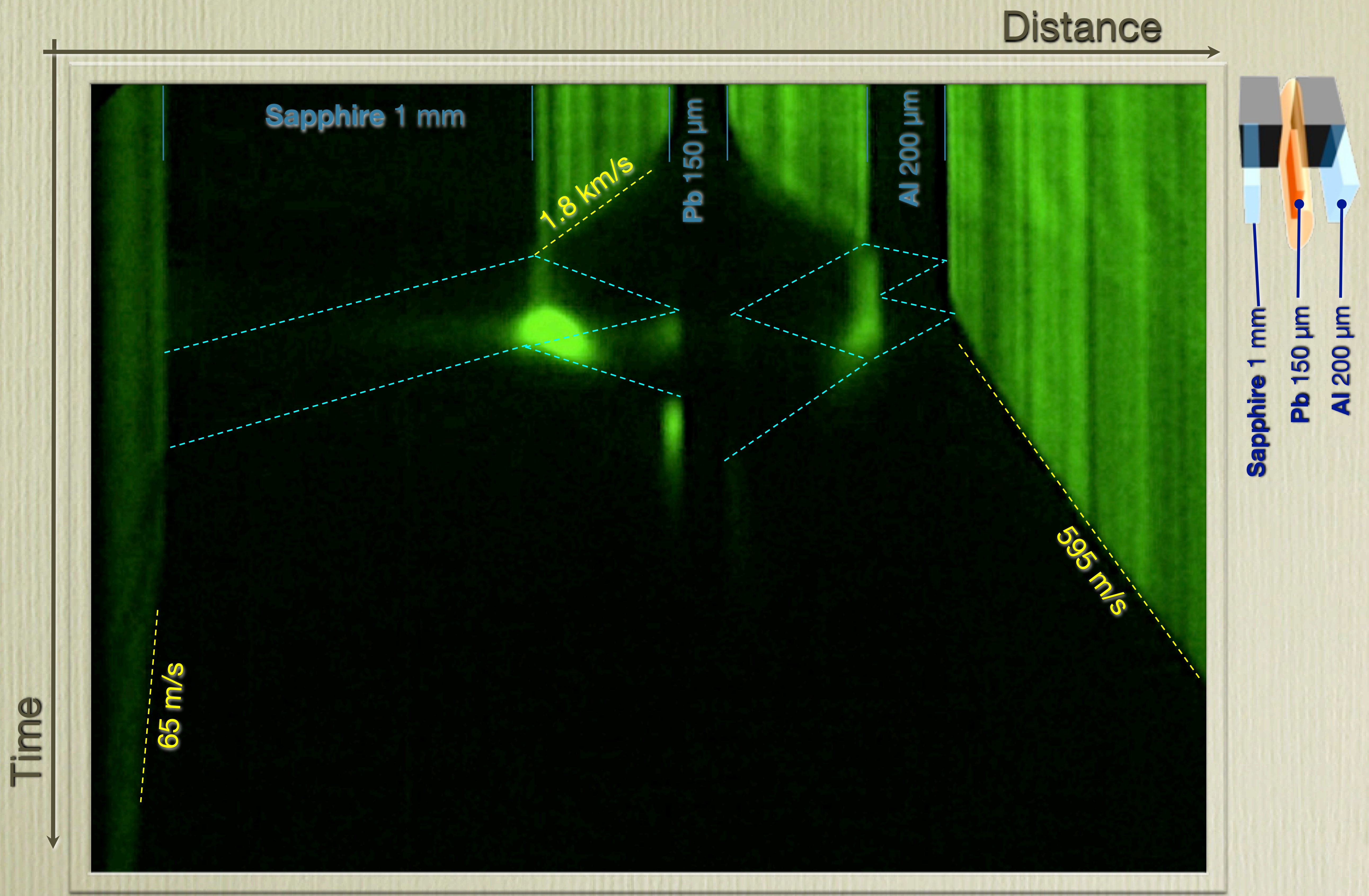
WDM experimental setup at GSI

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

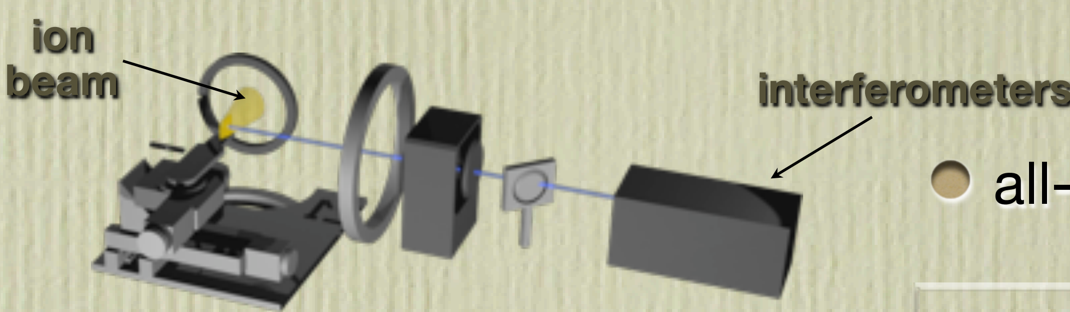
Beam: ^{238}U, 350 MeV/u, 120 ns, $2 \cdot 10^9$ Target: 100 μm W foil



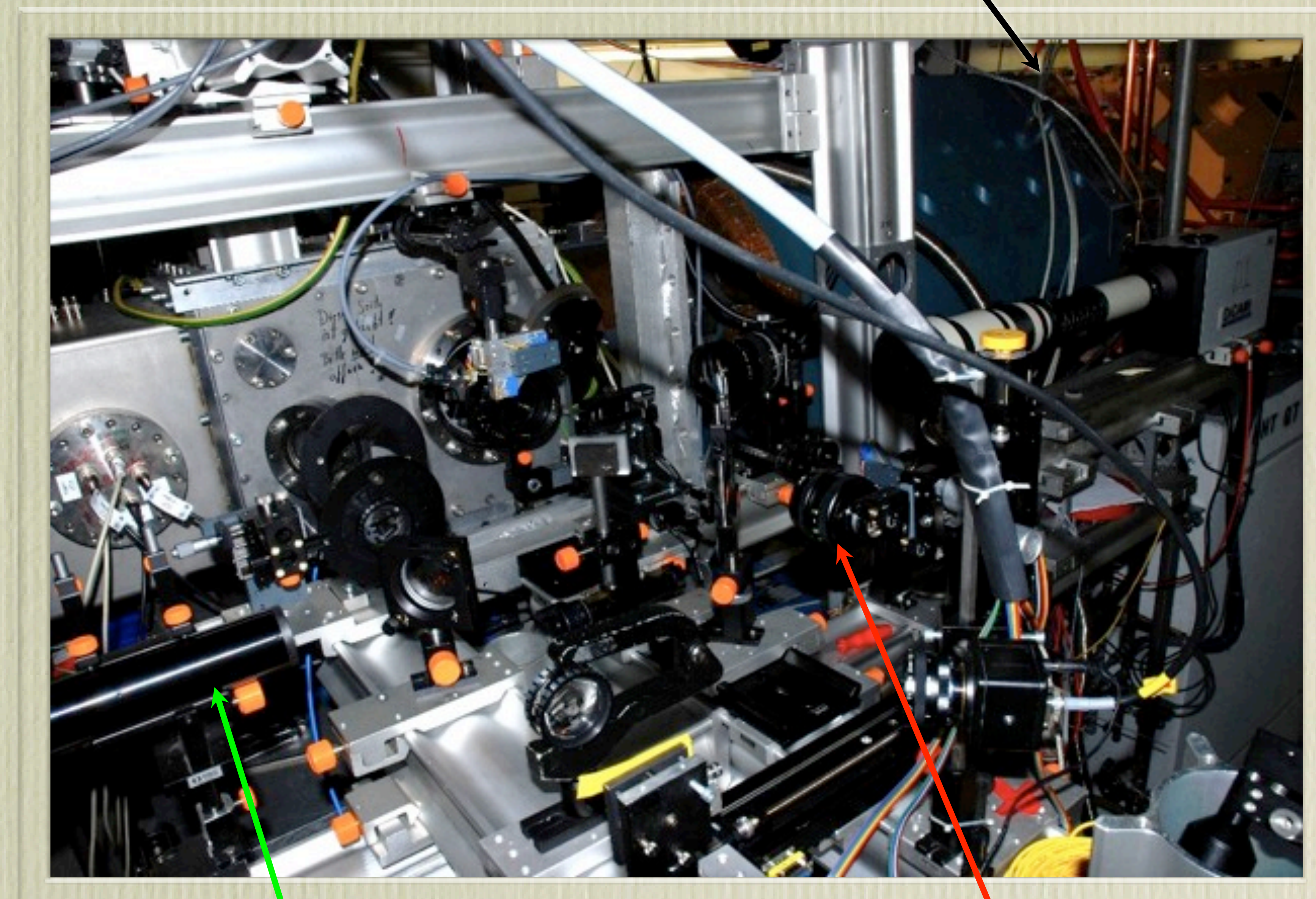
Visible laser shadowgraphy: impact acceleration of cold metallic foils to km/s velocities



Laser interferometers for pressure measurements



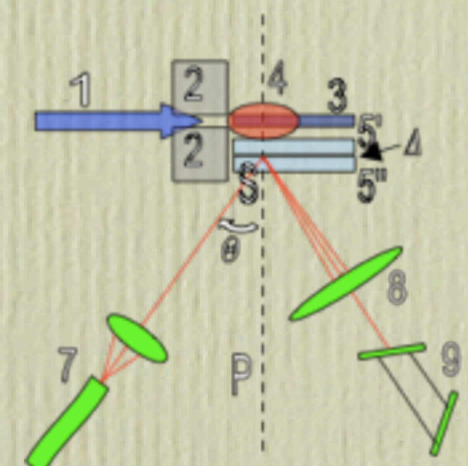
- all-fiber laser-Doppler interferometer (VISAR)



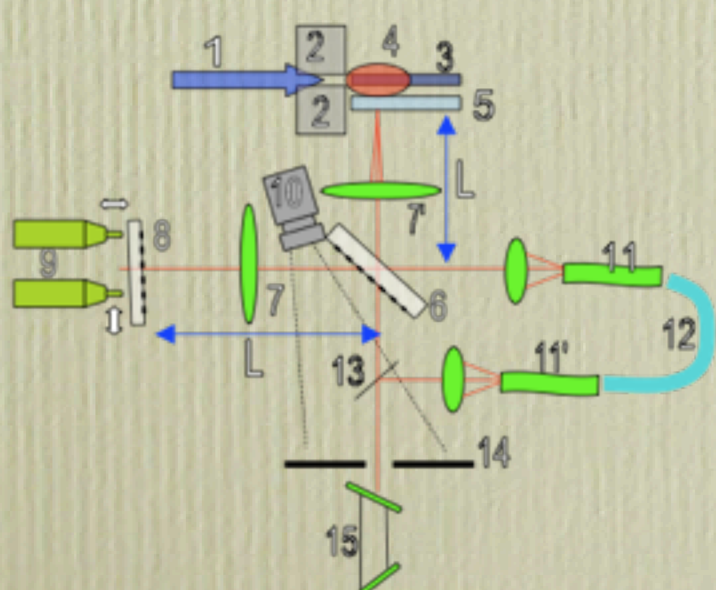
HeNe laser of the Michelson interferometer

motorized optics of the VISAR system

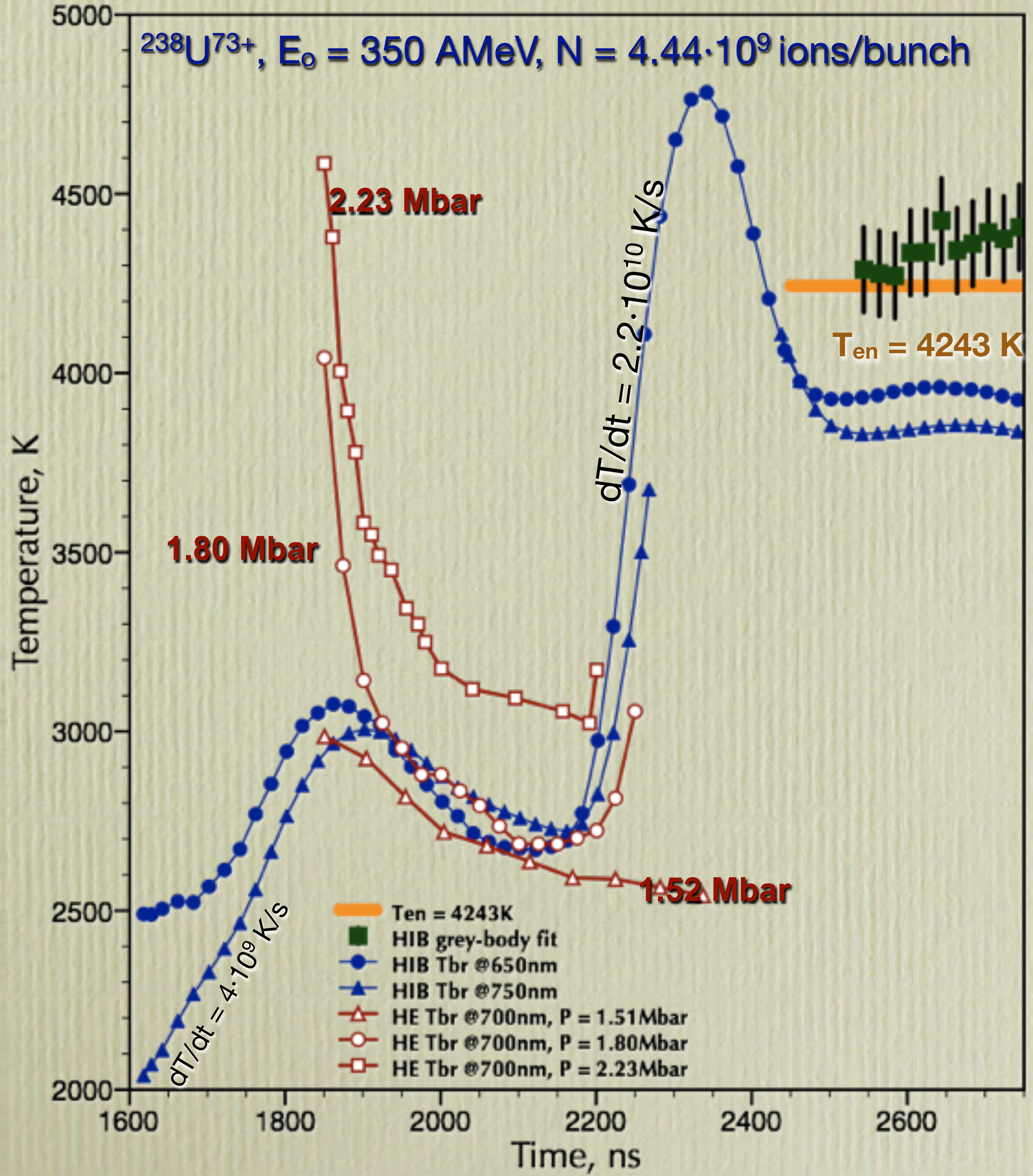
- 15° displacement interferometer



- Michelson interferometer

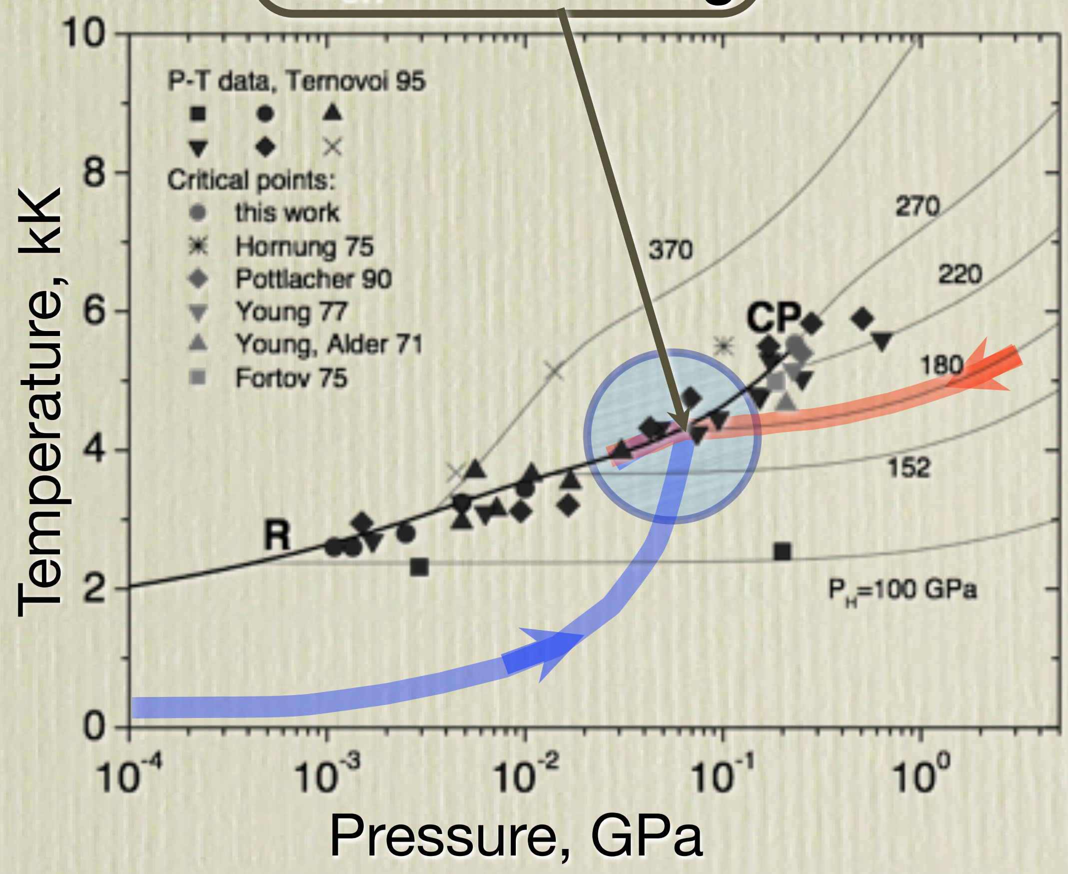


Expansion dynamics of boiling lead: comparing release isentropes after ion beam heating and high-explosive loading



Expansion dynamics of evaporating lead into helium (~ 1 bar): comparison of HIHEX expansion isentropes after ion-beam heating (GSI, Darmstadt, 2006) and release isentropes from shock-compressed states in high-explosive experiments (IPCP, Chernogolovka, 1995)

T_{en} = 4243 K
P_{en} = 0.5 kbar
E_{en} = 0.727 kJ/g



D. Varentsov et al., Nucl. Instr. Meth A577 (2007) 262

HHT experiments in 2008: R&D on essential diagnostics

- Reflectivity / emissivity measurements
- new laser-diode reflectometer embedded into pyrometer setup
- flat-hohlraum targets

- Beam diagnostics: gas fluorescence
- detailed spectroscopic study for Ar and N; time-resolved emission
- better statistics, systematics
- schlieren measurements of induced shock waves

- Integrated conductivity measurements
- improved 4-point scheme
- fully integrated with T/D measurements
- first tests of non-contact techniques

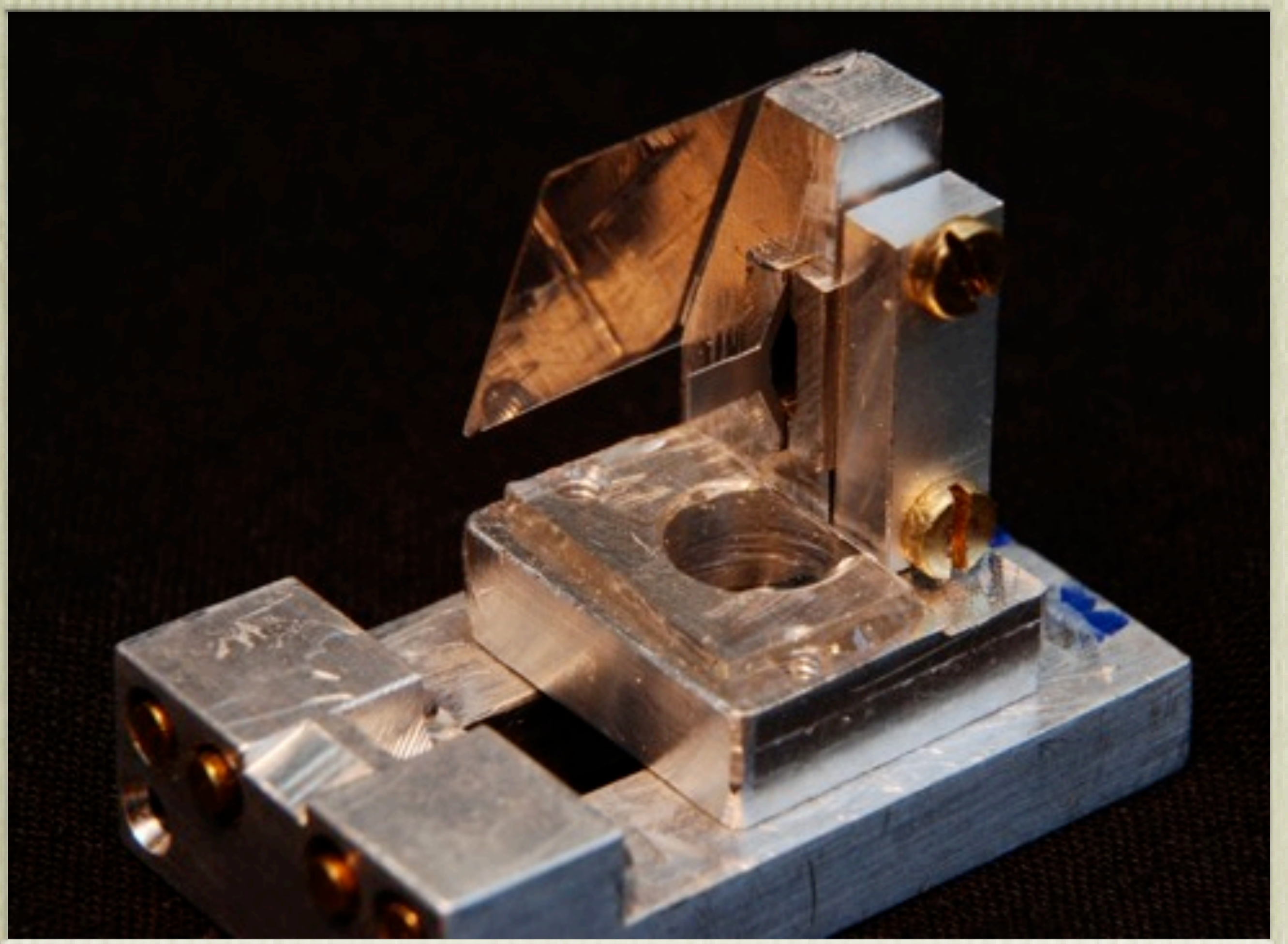
- Opacity of thin WDM layers
- semi-transparent (in UV/VIS) thin films (Au, C, Al)
- time-resolved spectral absorption
- time-resolved thermal emission

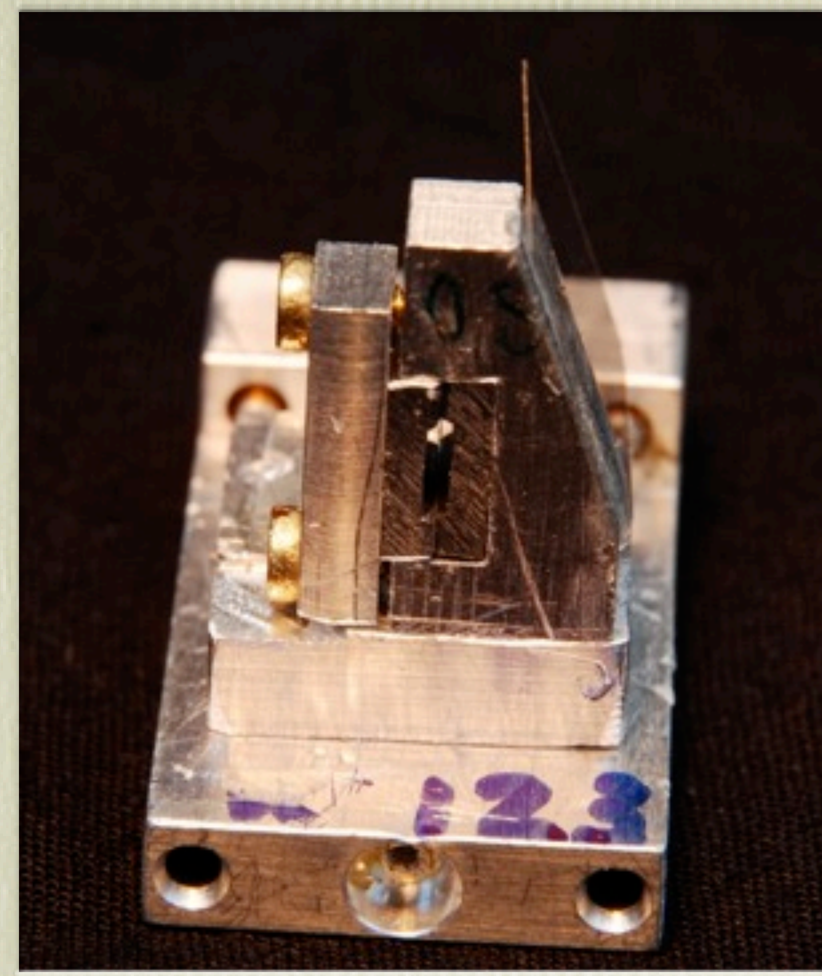
HHT experiments in 2008: focused physics program

- Reflectivity / emissivity and electrical conductivity of refractory metals (tungsten, tantalum) at melting and in hot liquid states
- only two runs were available at HHT in 2008:
  U, $1\text{-}1.3 \cdot 10^9$ (May),   Xe, $5 \cdot 10^9$ (July)
- avoid boiling: well-defined surface, no fast expansion
- reliable and rigid benchmarks for simulation codes

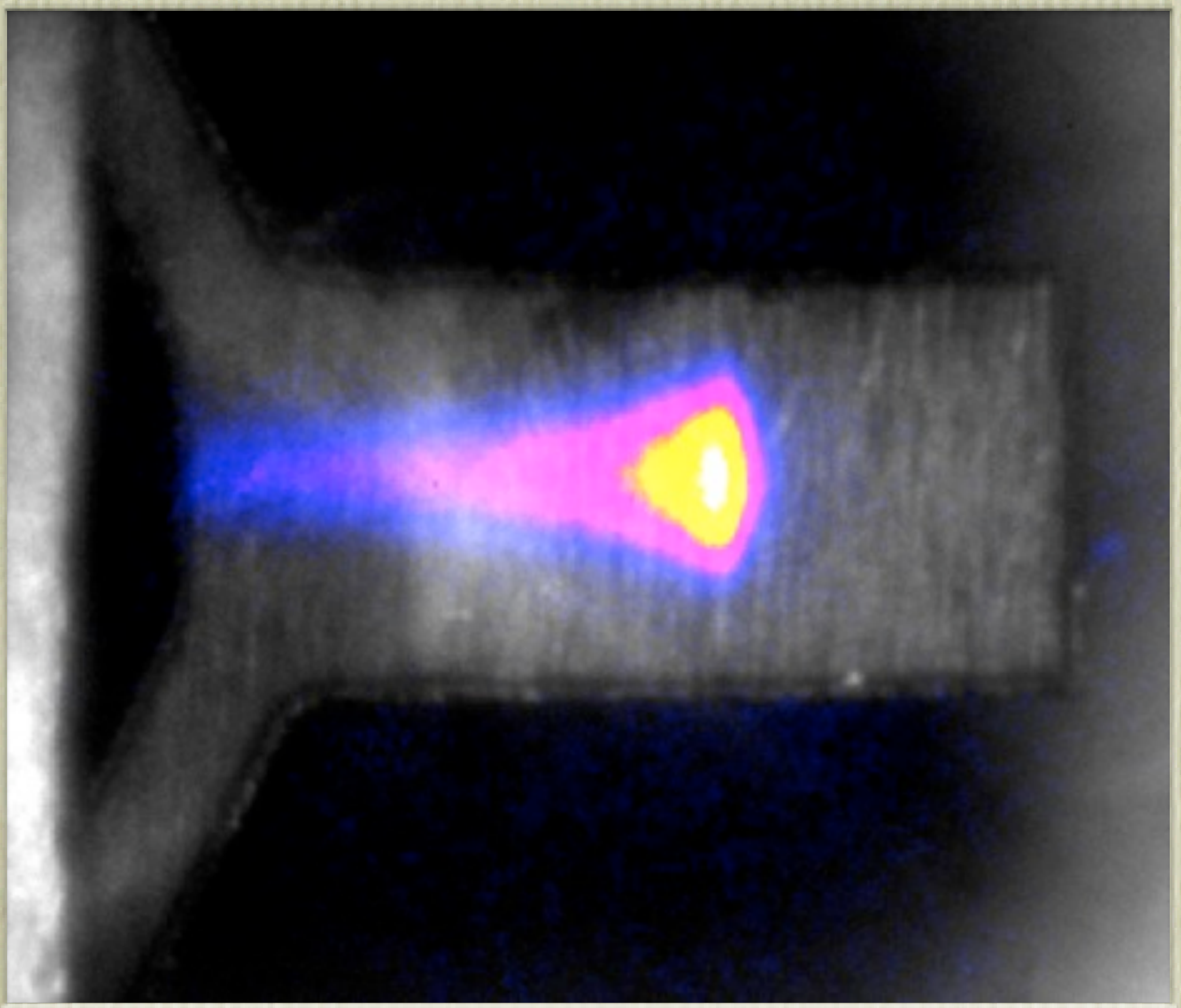
- No more "record-breaking" but data quality
- defocused beam for better uniformity and precision
- long coasting (flat-top) ion beam pulses for easier interpretation of results
- from "single-shot" philosophy towards reproducibility and statistics

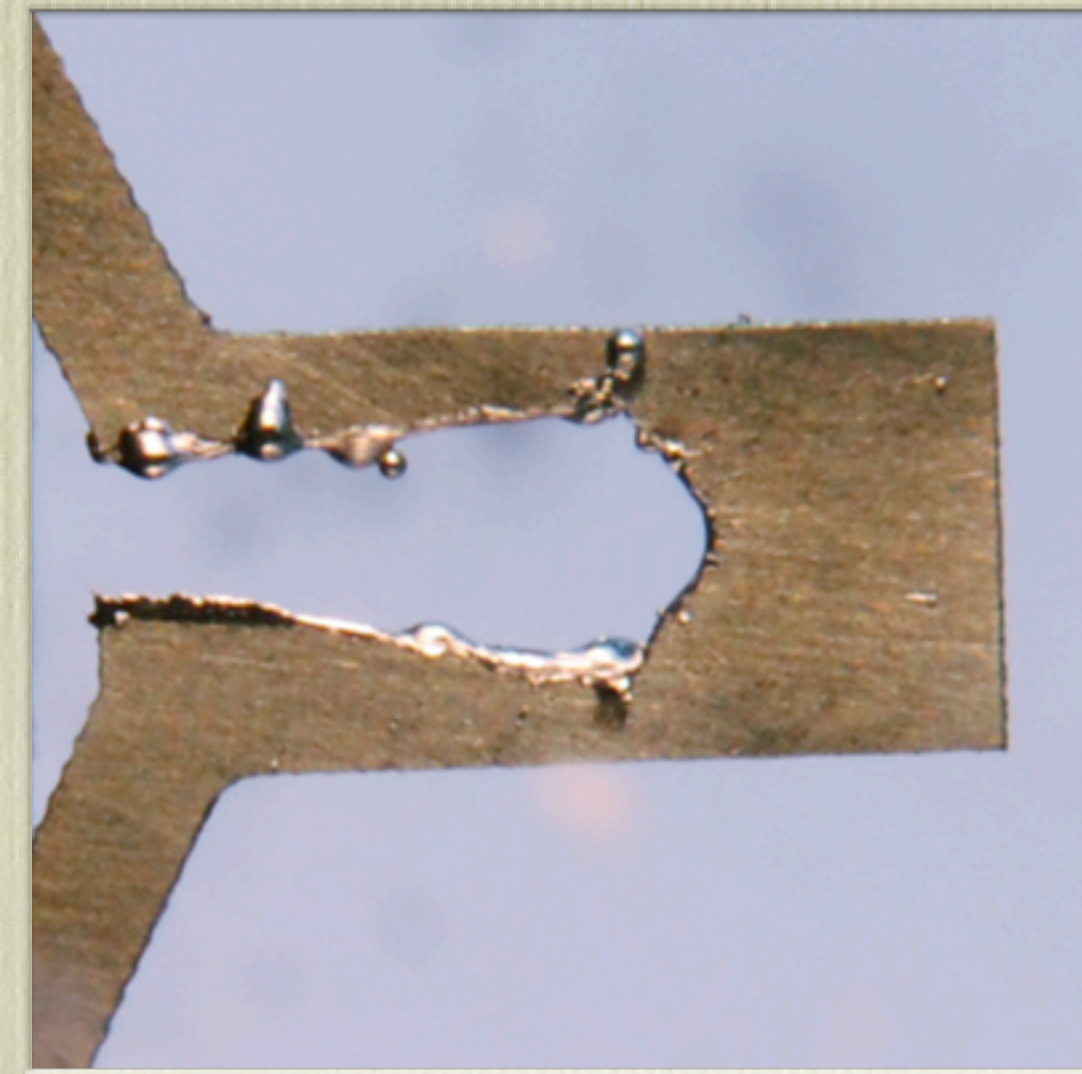
“Y”-type plain targets



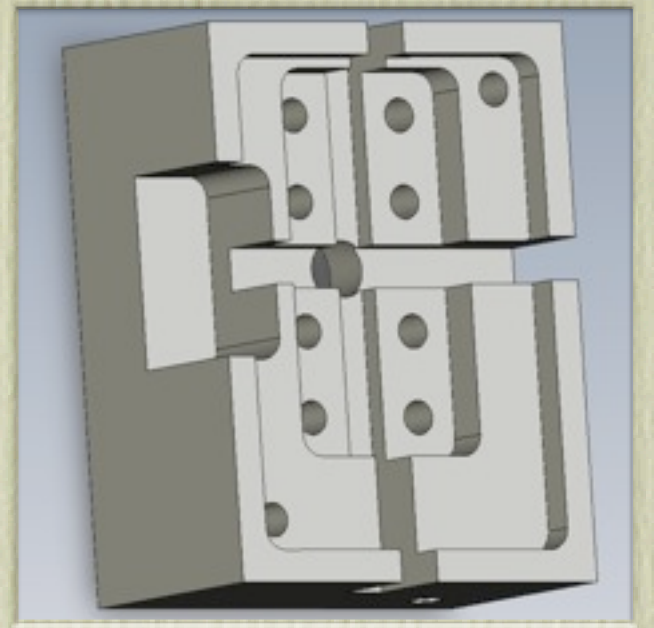


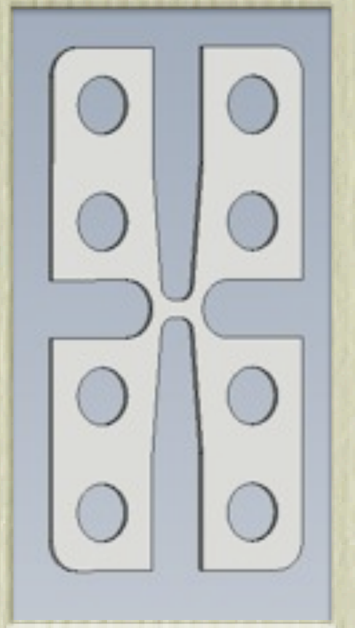
Tantalum foil of "long-Y" target before and after a shot

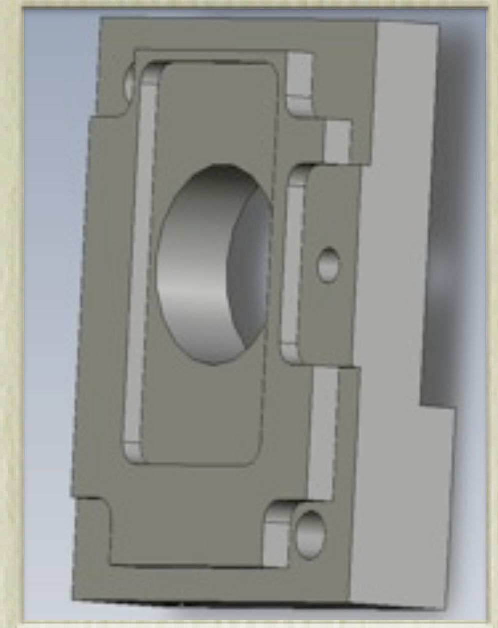


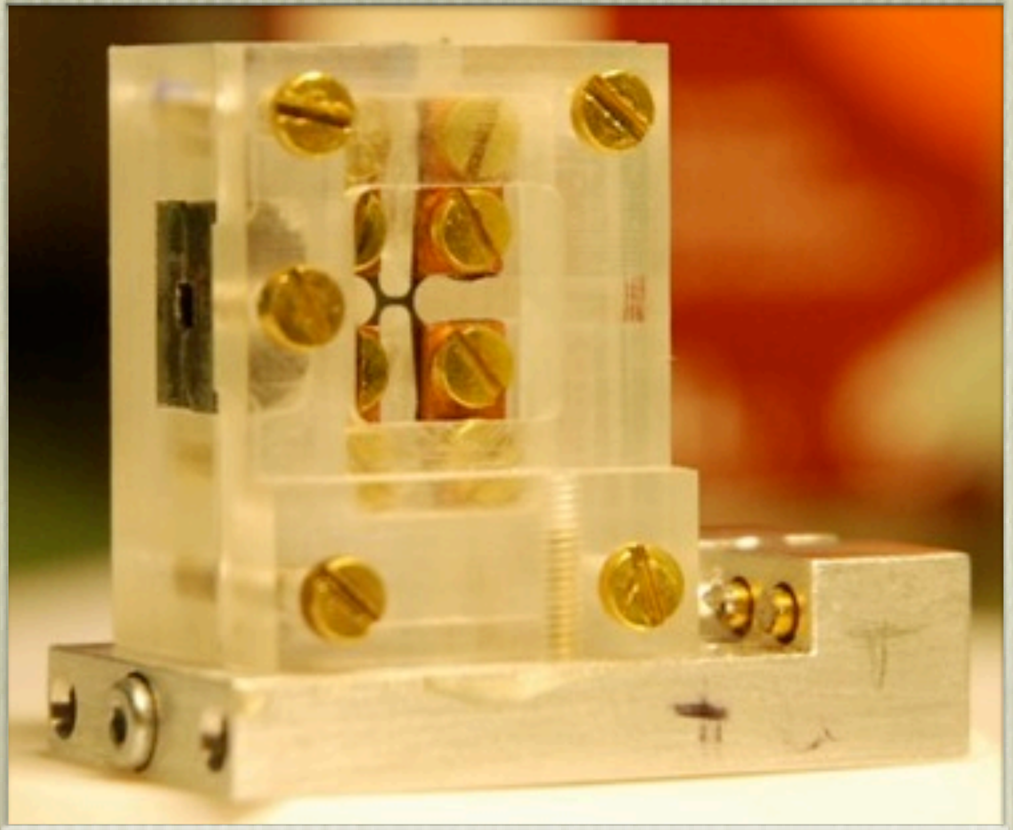


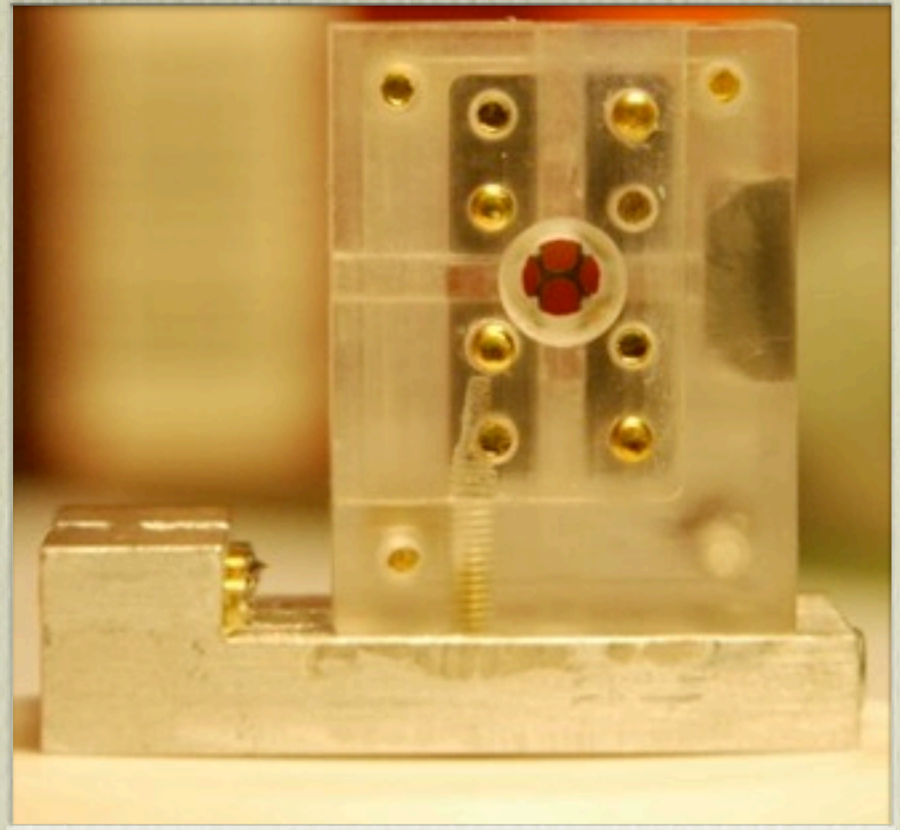
Targets for contact conductivity measurements



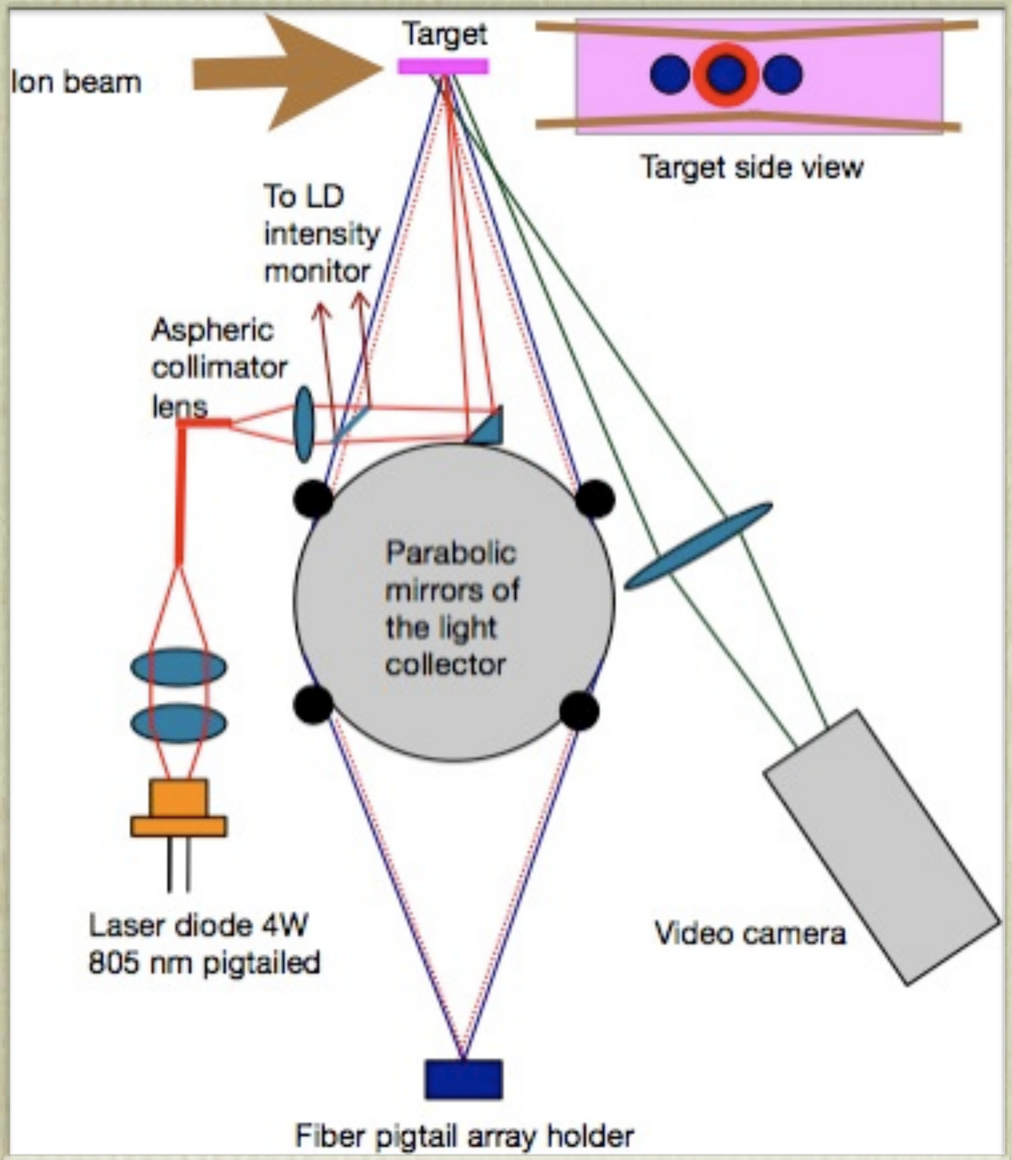


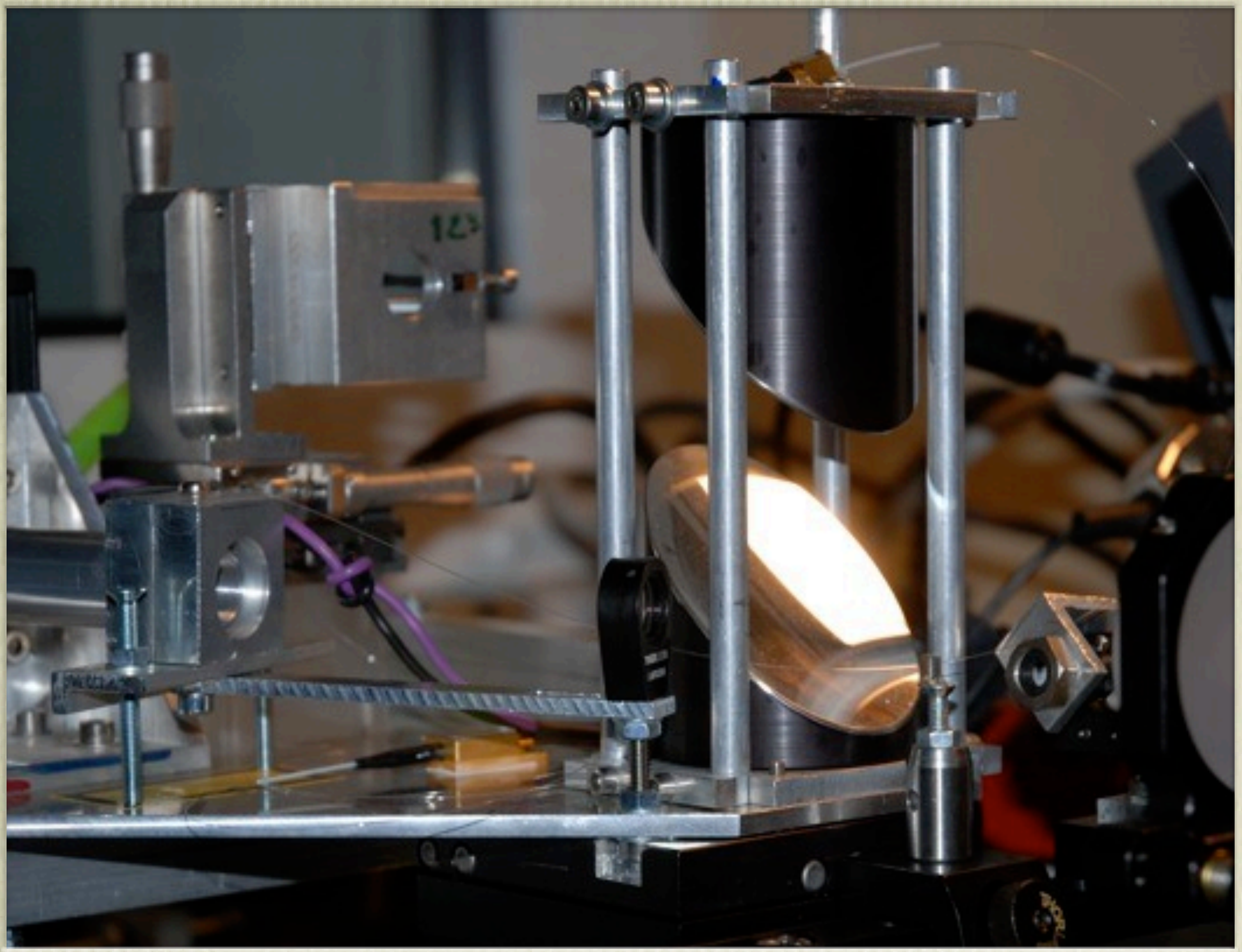




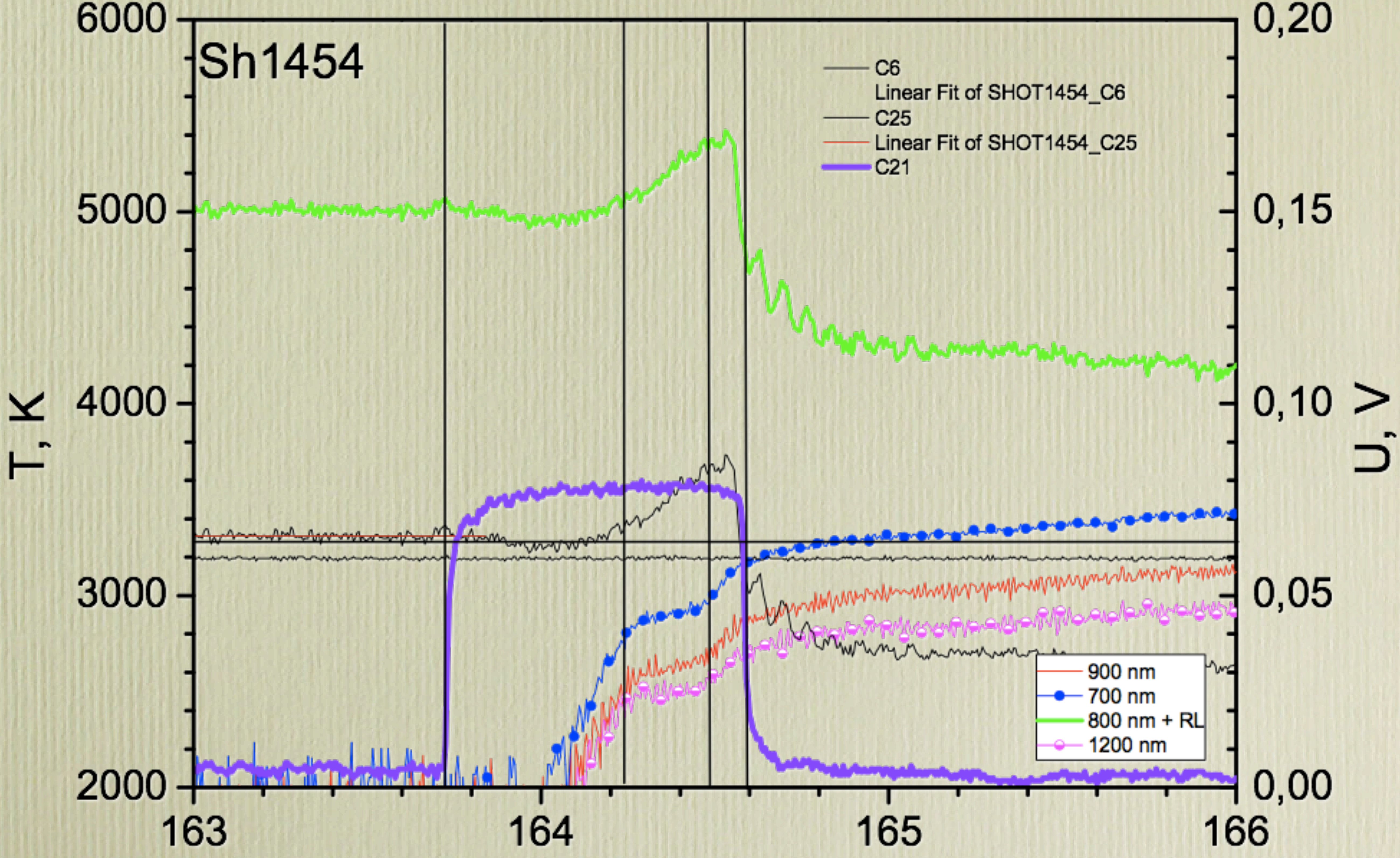


Embedded laser-diode (800 nm) reflectometer

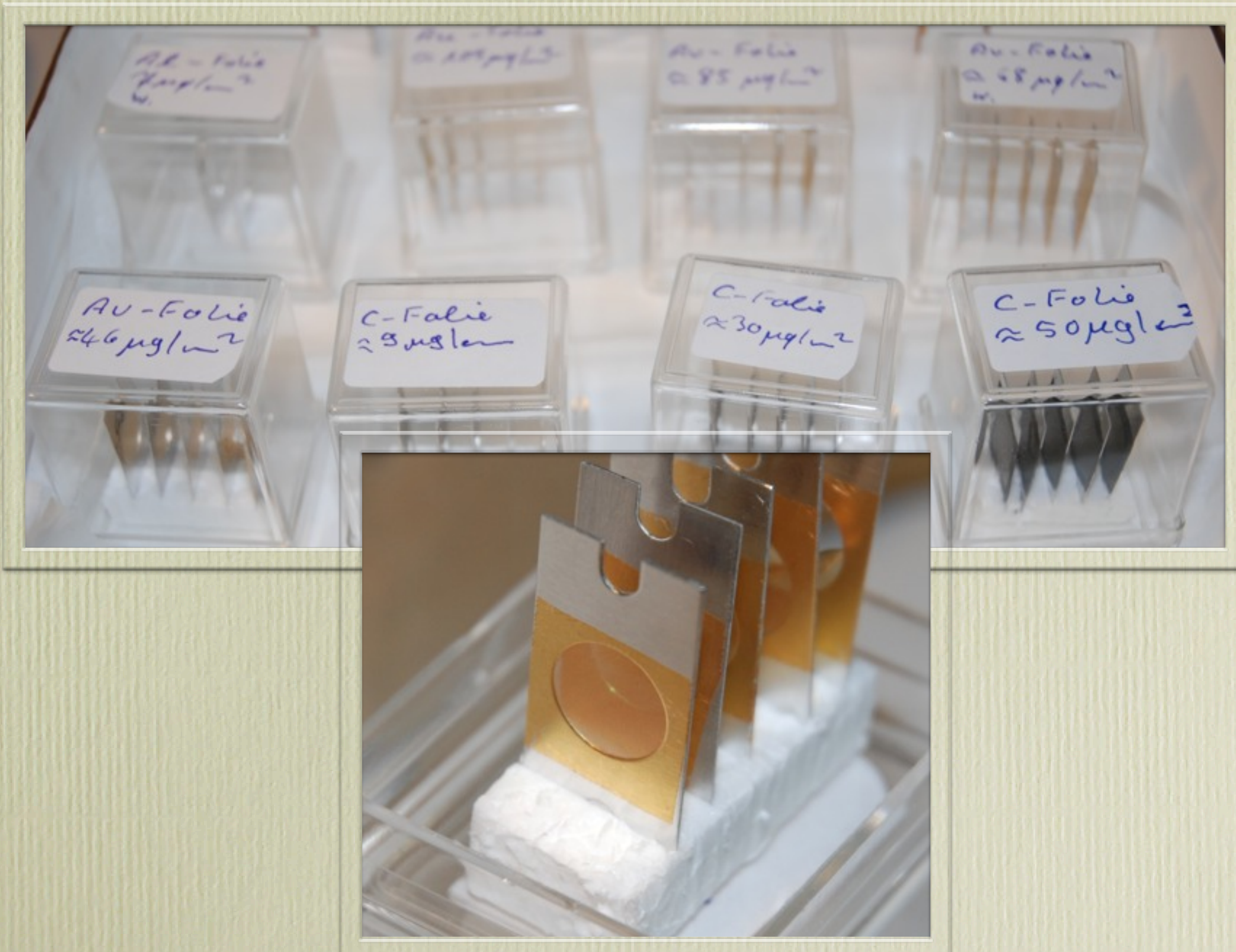




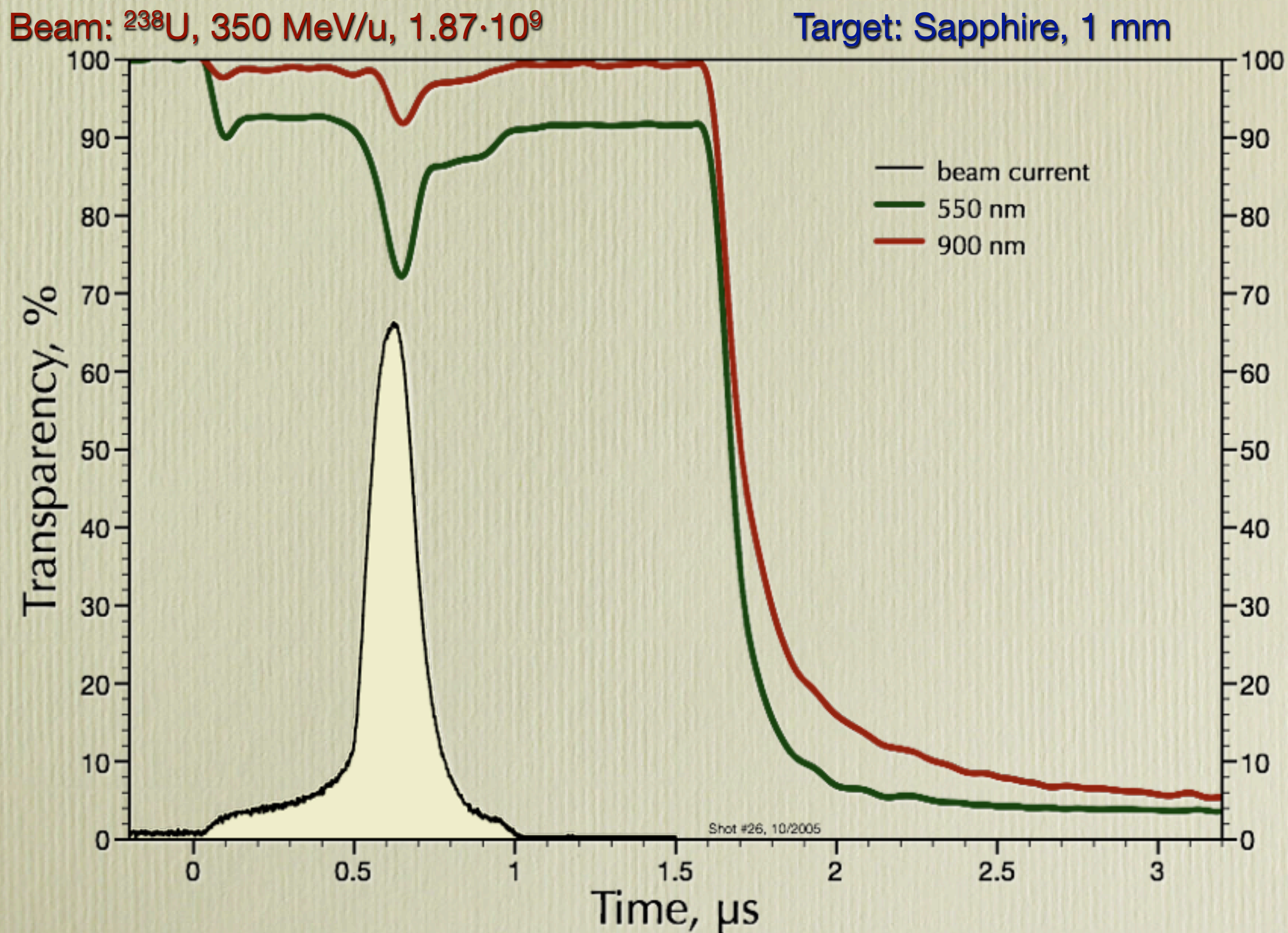
Pyrometer/reflectometer record: Ta melted by U beam



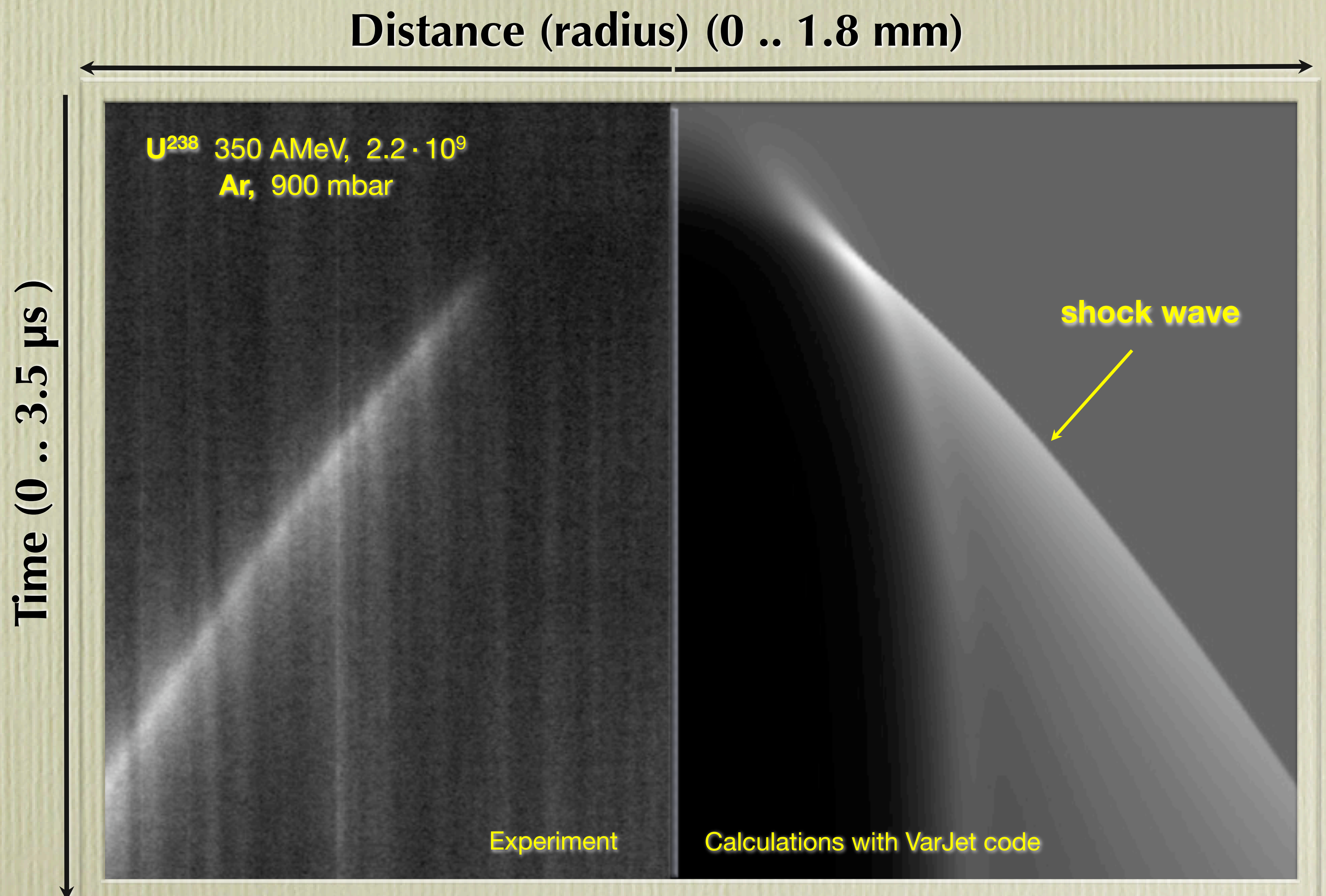
Opacity of thin WDM layers



Abnormal optical transmission of sapphire under intense heavy ion beam irradiation

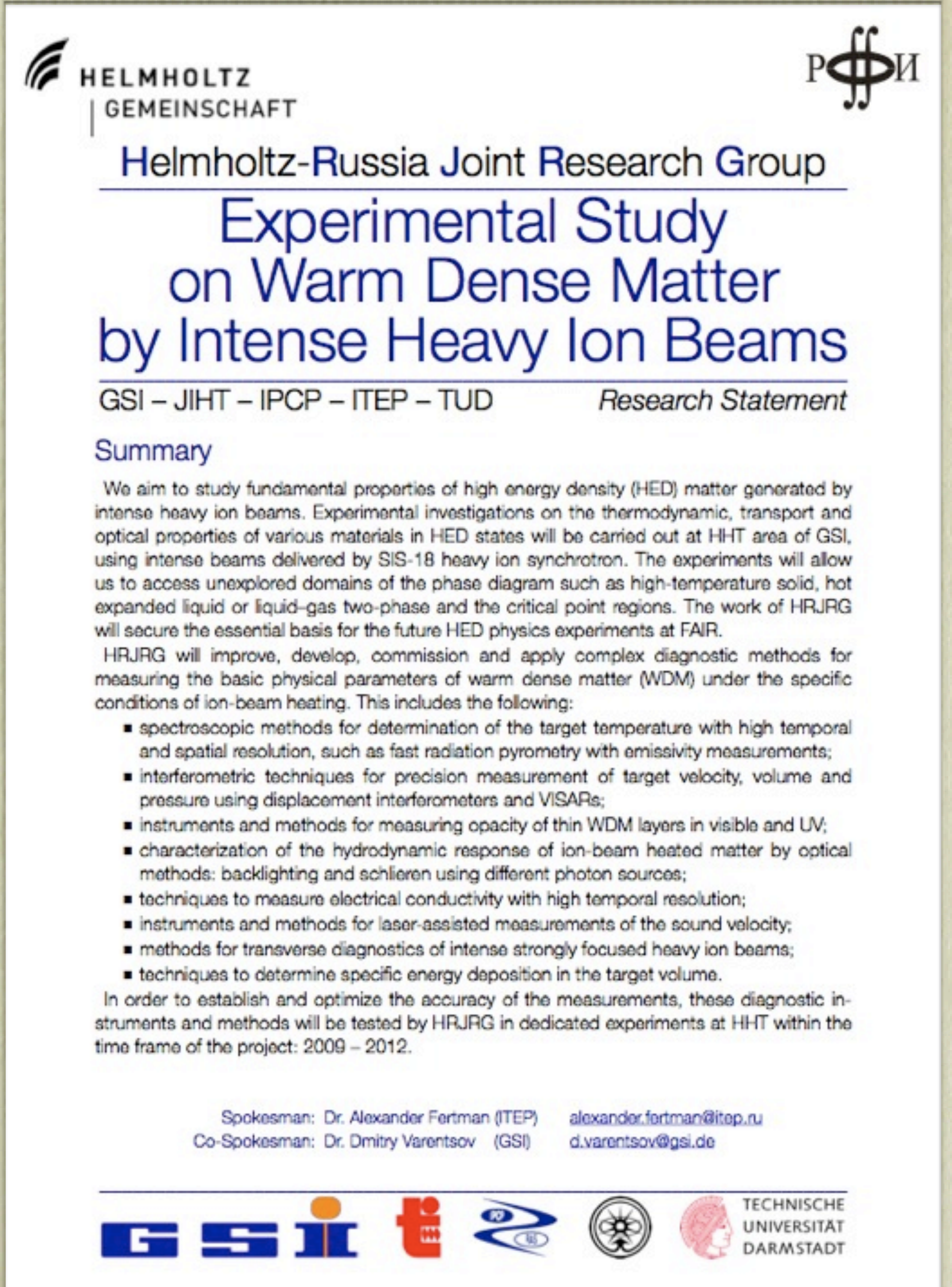


Streak-Schlieren measurements of beam-induced shock in argon and corresponding gasdynamic simulations



Experimental streak-schlieren record

Simulated evolution of density distribution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РФФИ

Helmholtz-Russia Joint Research Group

Experimental Study on Warm Dense Matter by Intense Heavy Ion Beams

GSI – JIHT – IPCP – ITEP – TUD *Research Statement*

Summary

We aim to study fundamental properties of high energy density (HED) matter generated by intense heavy ion beams. Experimental investigations on the thermodynamic, transport and optical properties of various materials in HED states will be carried out at HHT area of GSI, using intense beams delivered by SIS-18 heavy ion synchrotron. The experiments will allow us to access unexplored domains of the phase diagram such as high-temperature solid, hot expanded liquid or liquid-gas two-phase and the critical point regions. The work of HRJRG will secure the essential basis for the future HED physics experiments at FAIR.

HRJRG will improve, develop, commission and apply complex diagnostic methods for measuring the basic physical parameters of warm dense matter (WDM) under the specific conditions of ion-beam heating. This includes the following:

- spectroscopic methods for determination of the target temperature with high temporal and spatial resolution, such as fast radiation pyrometry with emissivity measurements;
- interferometric techniques for precision measurement of target velocity, volume and pressure using displacement interferometers and VISARs;
- instruments and methods for measuring opacity of thin WDM layers in visible and UV;
- characterization of the hydrodynamic response of ion-beam heated matter by optical methods: backlighting and schlieren using different photon sources;
- techniques to measure electrical conductivity with high temporal resolution;
- instruments and methods for laser-assisted measurements of the sound velocity;
- methods for transverse diagnostics of intense strongly focused heavy ion beams;
- techniques to determine specific energy deposition in the target volume.

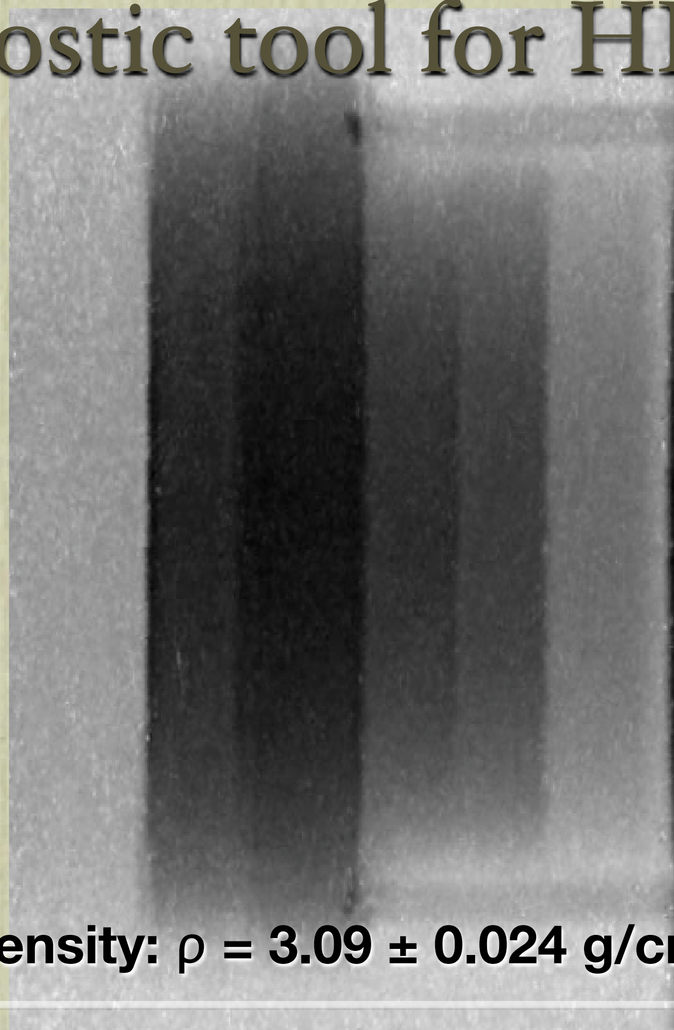
In order to establish and optimize the accuracy of the measurements, these diagnostic instruments and methods will be tested by HRJRG in dedicated experiments at HHT within the time frame of the project: 2009 – 2012.

Spokesman: Dr. Alexander Fertman (ITEP) alexander.fertman@itep.ru
Co-Spokesman: Dr. Dmitry Varentsov (GSI) d.varentsov@gsi.de

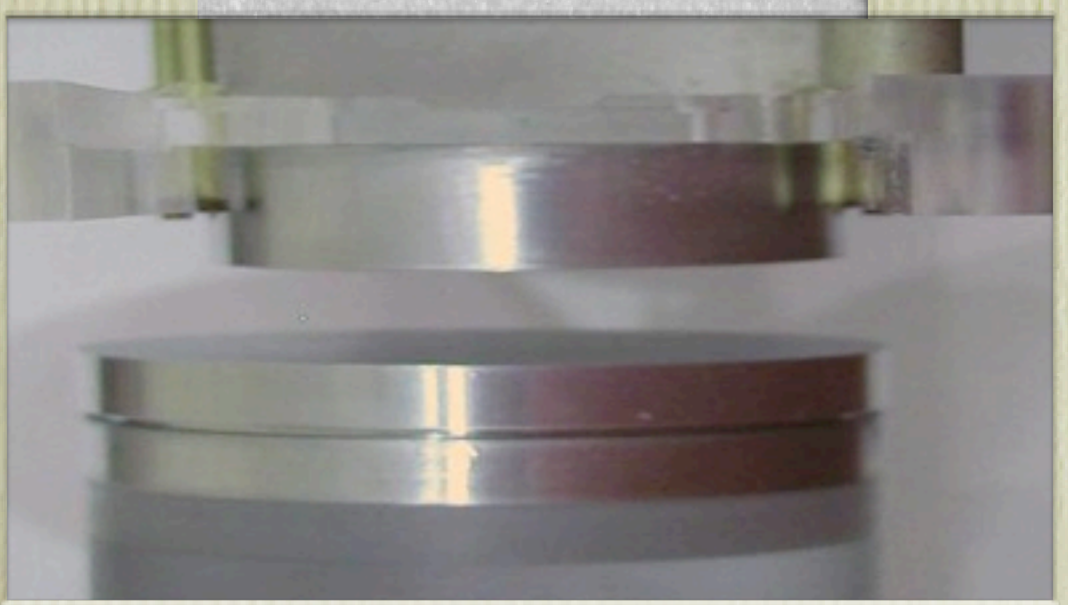
TECHNISCHE UNIVERSITÄT DARMSTADT

- for HEDP experiments with intense heavy ion beams at HHT
- GSI, JIHT, IPCP, ITEP, TUD
- jointly funded by Helmholtz Association and RFBR
- 2009 – 2012

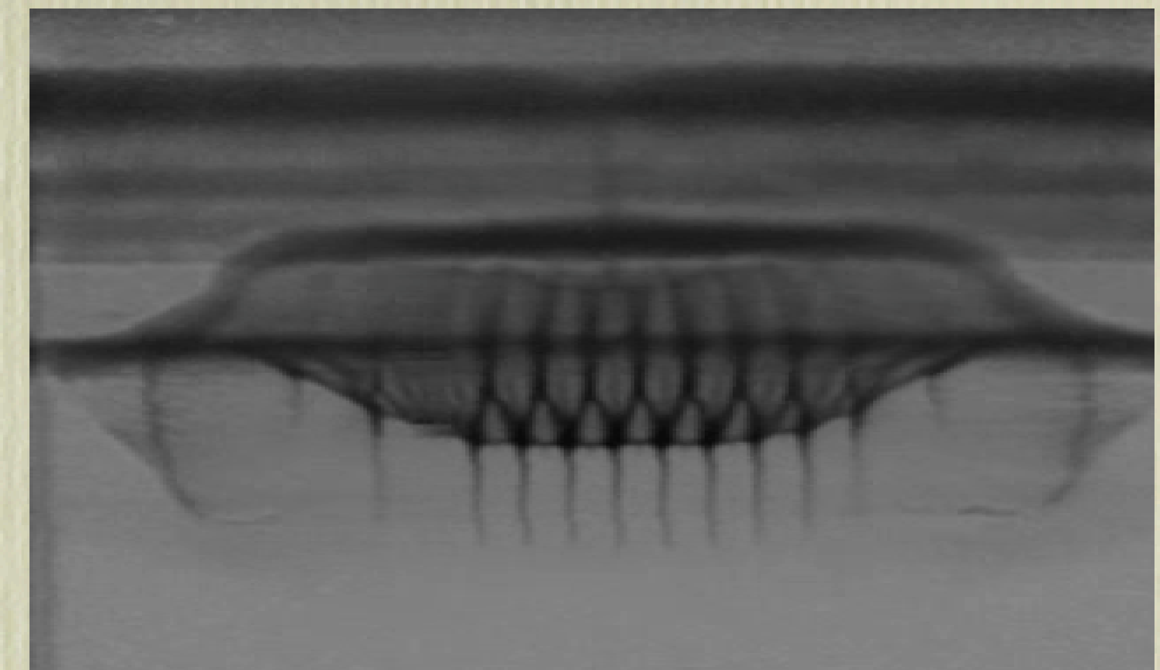
Radiography by 4.5 GeV protons is an indispensable diagnostic tool for HEDP experiments at FAIR

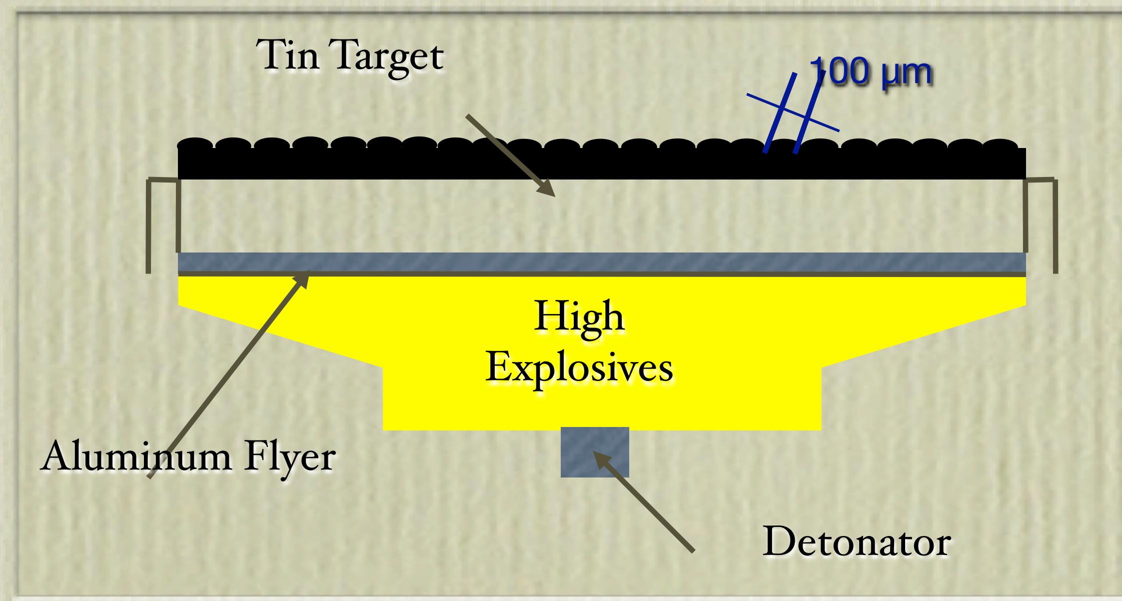


Density: ρ = 3.09 ± 0.024 g/cm^3



Two independent ways to determine Al EOS in one shock wave experiment by proton radiography only





Experiments on Richtmyer-Meshkov instability (formation and grow rate) in Sn

courtesy of Kurt Schoenberg, LANL

Summary

- intense heavy ion beams available at GSI and later at FAIR bring up unique capabilities for high-energy-density physics / warm dense matter research

- at GSI:
- continuing experiments on thermophysical properties and hydrodynamic response of various materials in the states near the boiling curve, two-phase liquid-gas and the critical point region until moving to FAIR
- new Helmholtz-Russia Joint Research Group for HEDP/WDM experiments with intense ion at HHT
- R&D and commissioning of essential diagnostic instruments and methods for HEDgeHOB experiments at FAIR:
  proton radiography with 4.5 GeV SIS-18 proton beam