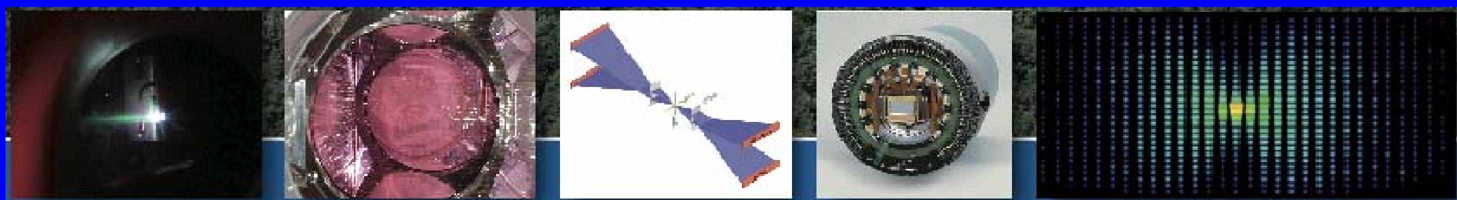
ExtreMe Matter Institute EMMI

Physics Days

Indirectly heated plasma targets for combined PHELIX laser - heavy ion beam experiments

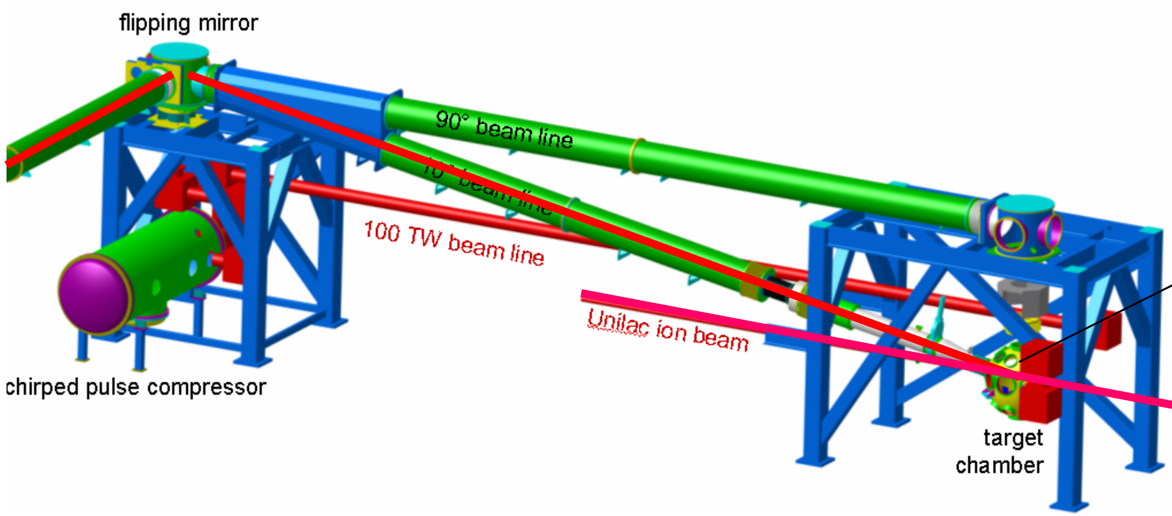
Olga Rosmej
Plasma physics, GSI



November 4-5, 2010, Darmstadt

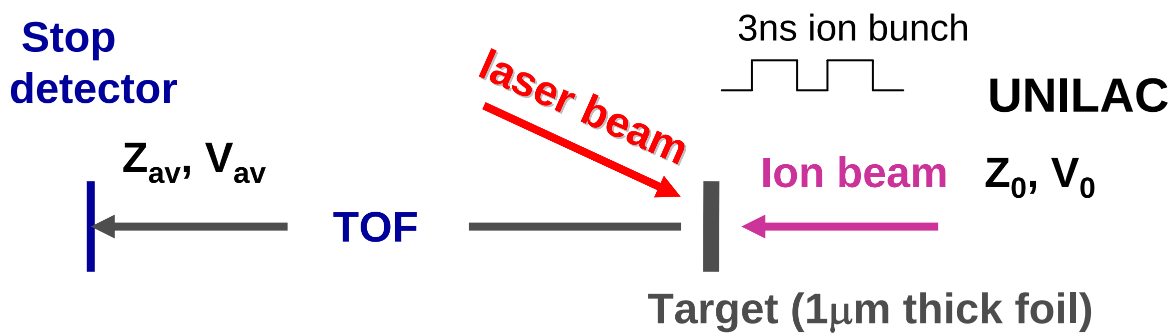
Laser-heavy ion beam combined experiments at GSI

PHELIX-laser : 0.3 kJ @ 1-15 ns, 1ω,
0.15 kJ 1ns 2ω (October 2010)

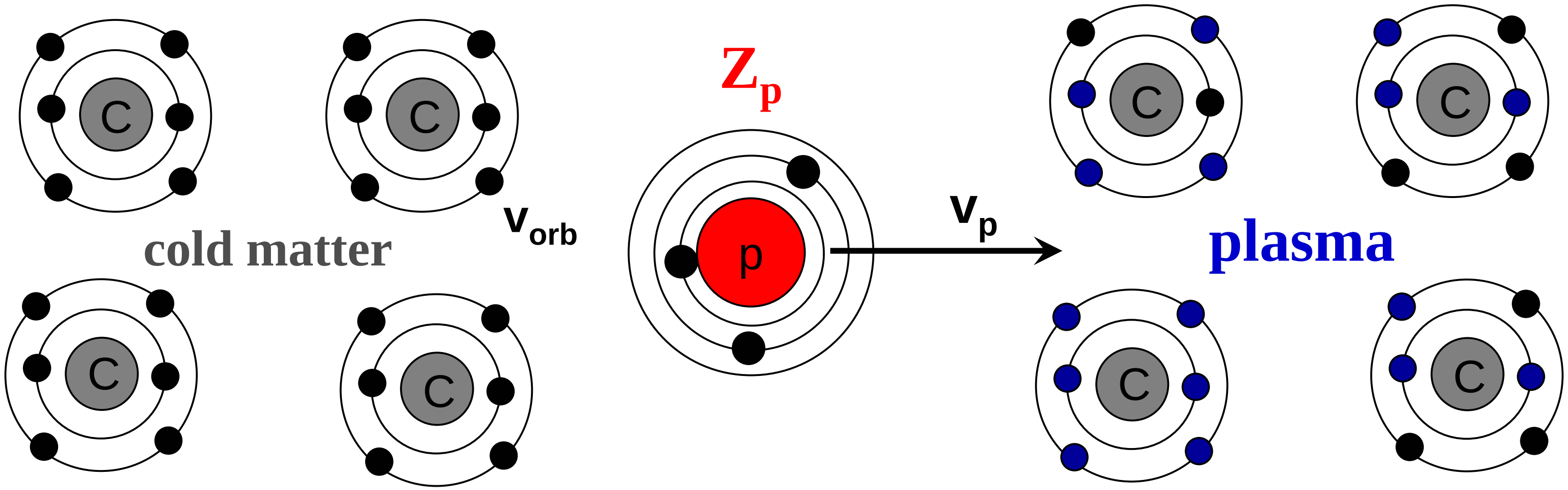


Heavy ion beam (UNILAC)
$1<Z<92$, E=3–13 MeV/u,
RF: 108/36 MHz

Interaction of heavy ions with ionized matter : increased plasma stopping power



Projectile ion energy loss in ionized matter



1. Increased energy transfer from the projectile ion to free plasma electrons
2. Increased projectile charge state due to suppression of the BEC in plasma

Projectile energy loss in partially ionized matter

$$-\frac{dE_S}{dz} = \frac{16\pi a_0^2 I_H^2 Z_{eff}^2}{m_e v_S^2}\left[\underbrace{\sum_{Z=0}^{Z_K}(Z_K - Z)\, n_Z \ln\left(\frac{2m_e v_S^2}{I_Z}\right)}_{\text{bound electrons}} + \underbrace{n_e \ln\left(\frac{2m_e v_S^2}{\hbar\omega_p}\right)}_{\text{free electrons}}\right]$$

Bethe-Bohr--Bloch

Increased ion energy loss in plasma

PHYSICAL REVIEW A VOLUME 42, NUMBER 4 15 AUGUST 1990

Energy loss of heavy ions in a plasma target

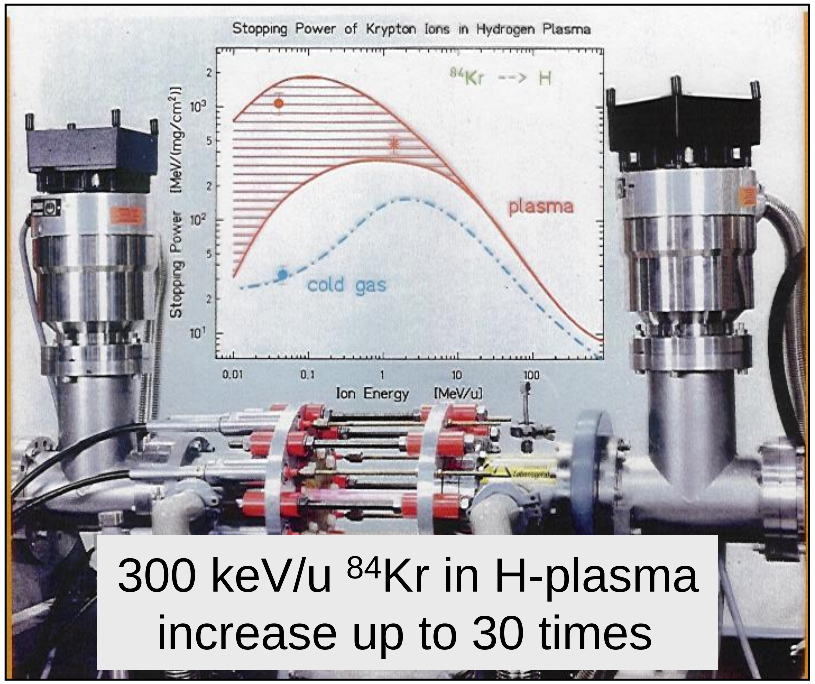
D. H. H. Hoffmann,* K. Weyrich, and H. Wahl

Max-Planck-Institut für Quantenoptik, Garching, Federal Republic of Germany

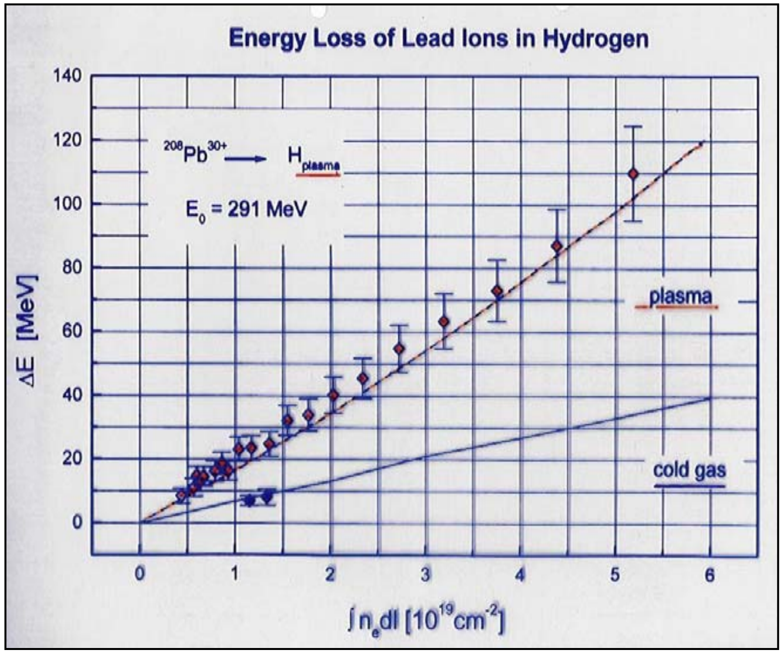
and Gesellschaft für Schwerionenforschung Darmstadt m.b.H., P.O. Box 110552, D-6100 Darmstadt, West Germany

H-plasma: N_e~10^{17} cm^{-3}, T_e ~1-2 eV

Ca-U; 1.4 MeV/u



300 keV/u ^{84}Kr in H-plasma increase up to 30 times

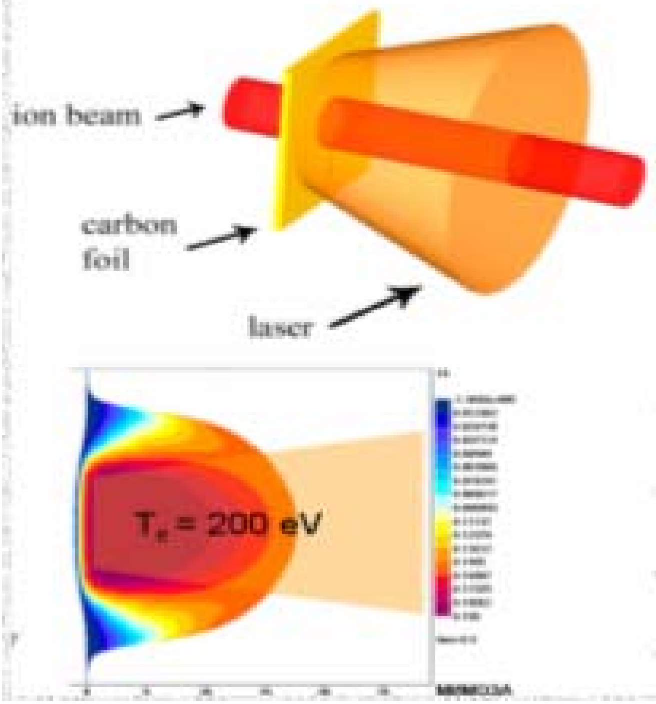


Laser produced plasma: N_e~10^{21} cm^{-3}, T_e ~ 0.1-1 keV

Current schemes of the plasma target production

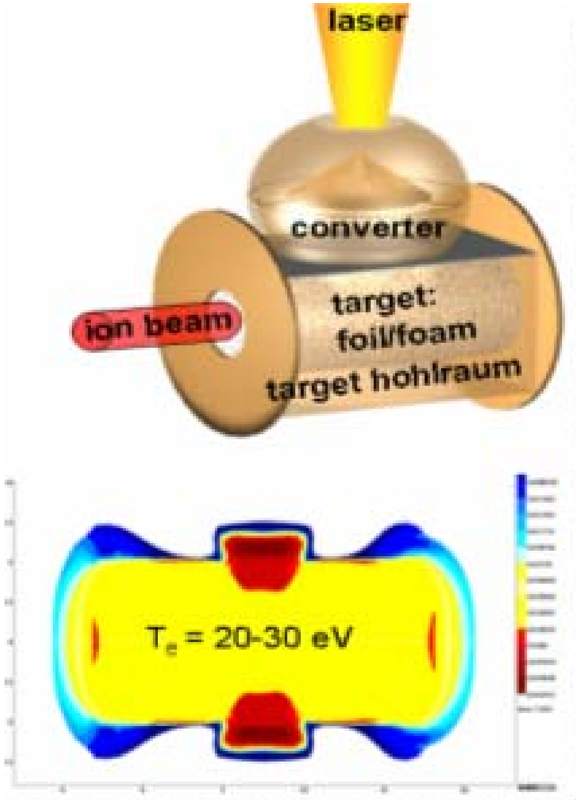
Direct laser heating

Ideal , non-uniform plasma:
Te~ 200 eV, $n_e < 10^{21} cm^{-3}$
fully ionized



Heating with hohlraum radiation

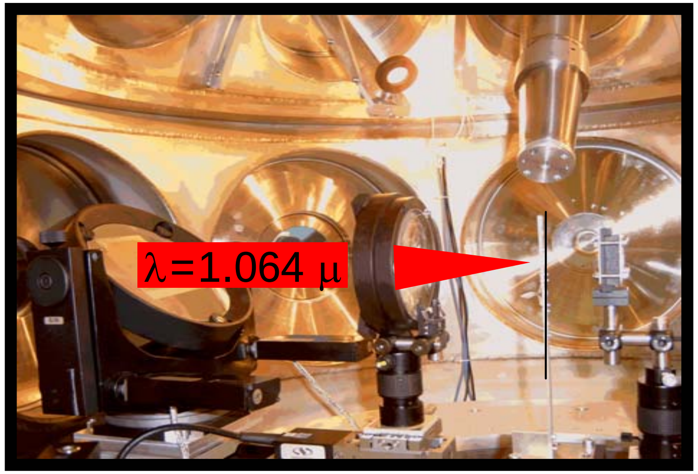
homogeneous plasma:
Te~ 30 eV, ne~$10^{21} cm^{-3}$
partially ionized



Expansion of the laser heated foil target

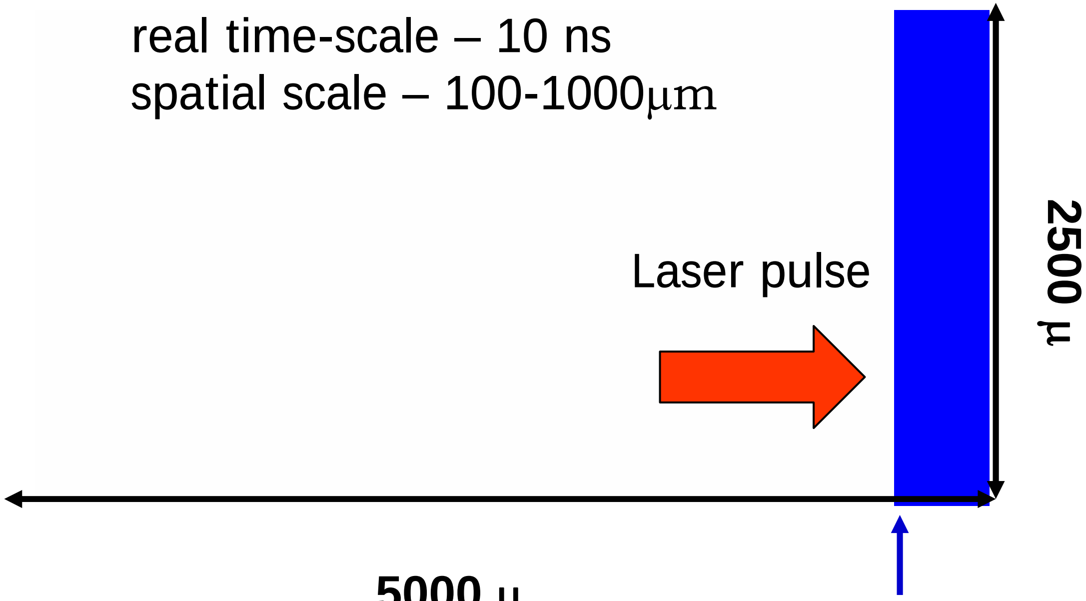
In experiments on laser generated plasma, the energy is focused on to the target into a small spot of 10-100μm :

High energy density plasma : 5 MJ/mm^3



E=50J, t=10 ns, d=100μ I=5.10^{13} Wt/cm^2

real time-scale – 10 ns
spatial scale – 100-1000μm

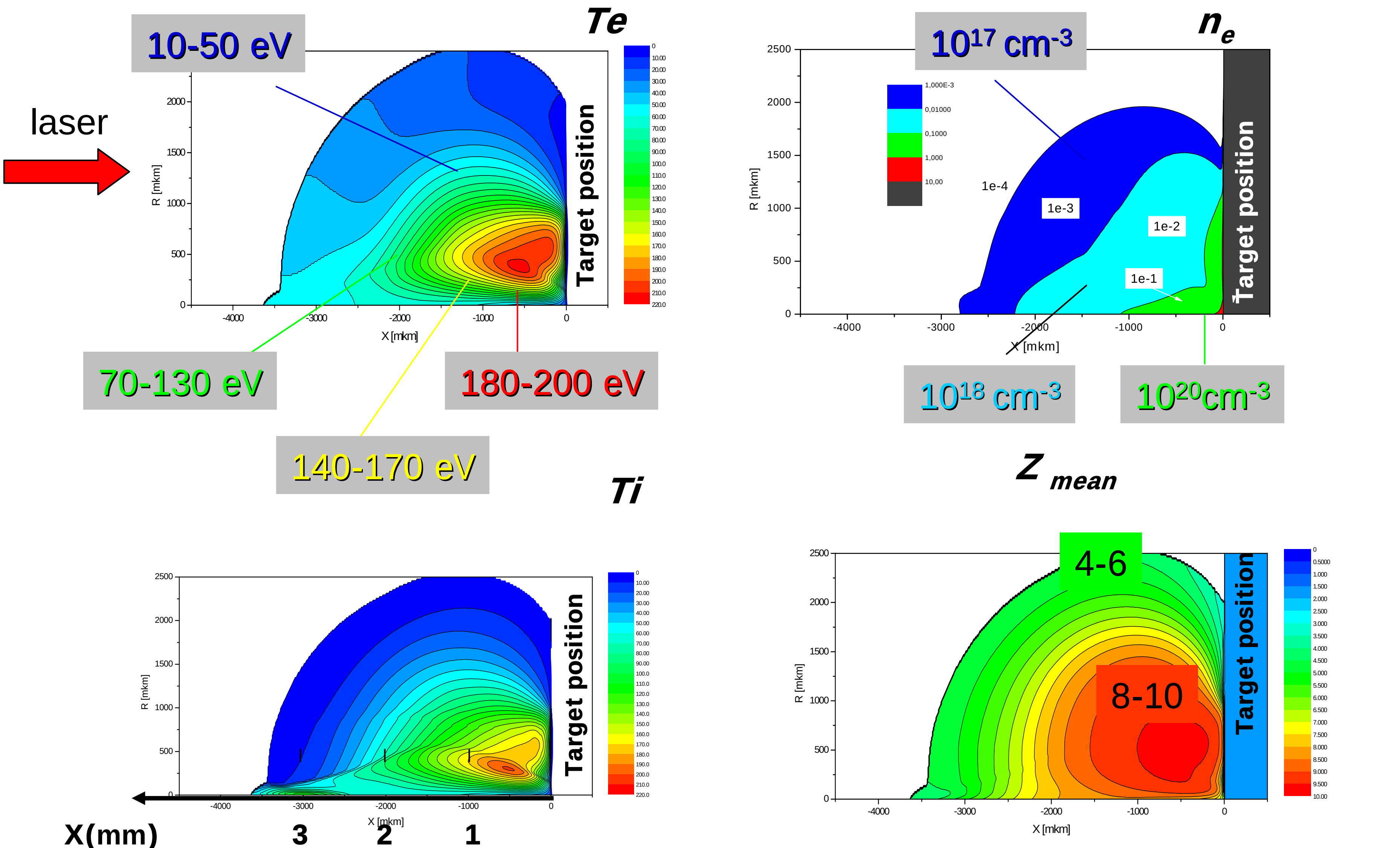


ion temperature

Red ~ 250 eV
Green ~ 125 eV
Blue ~ 50 eV

2D –HD, M. Povarnitsin, JIHT, Moscow

Strong gradients of the directly heated plasma

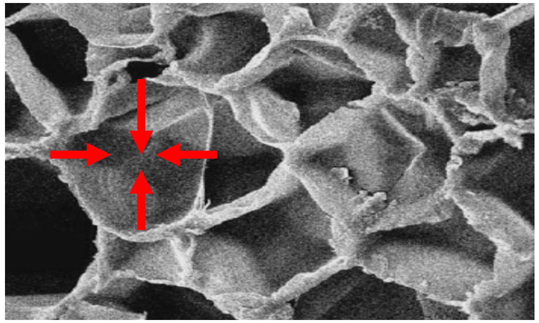


2D –hydrodynamics, M. Povarnitsin , JIHT, Moscow

Why foams?

Properties under the ion and laser beams:

1. Higher conversion of laser energy in to the plasma temperature compared to the solid foils

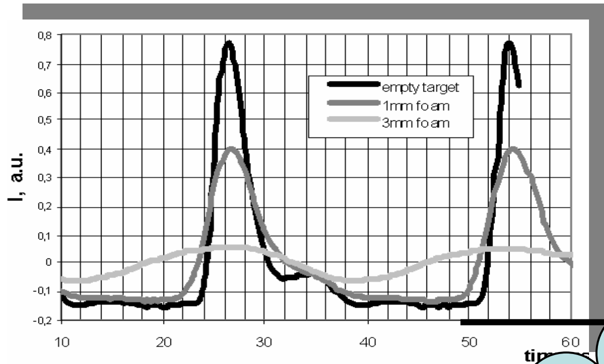


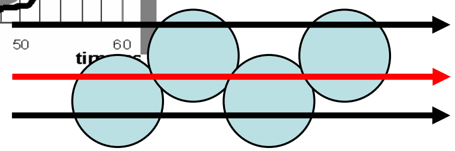
2. Slow expansion dynamics
   (ρ, T ~ constant during nanoseconds)

3. Fast (~sub ns) homogenization after laser heating

$$mv_i^2 \Rightarrow T_i \Rightarrow T_e$$

4. Energy broadening of the ion bunch caused by the porous structure has to be acceptable (no merging of the subsequent ion bunches)





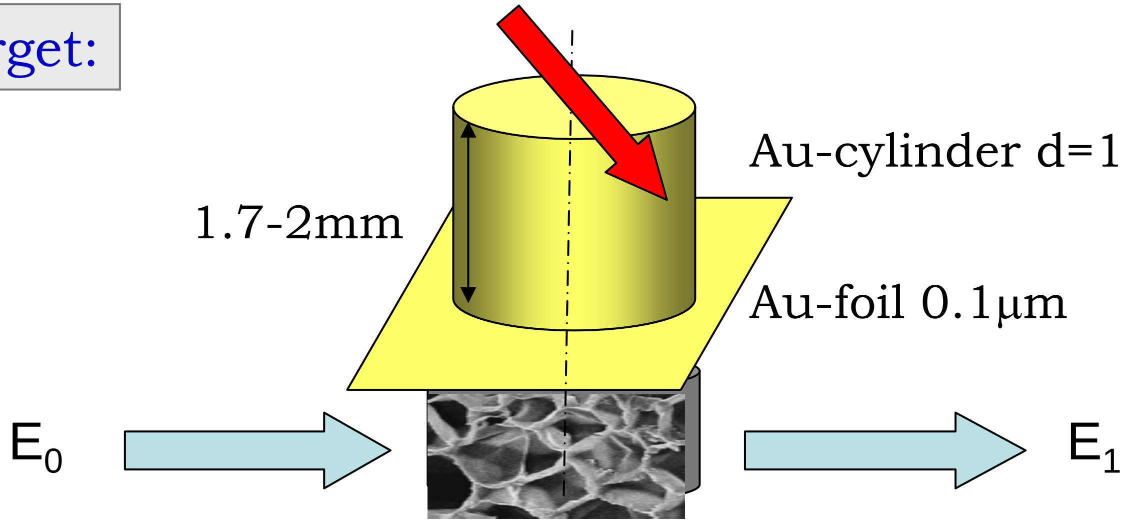
Small pore size is important!

Heating of low Z foams by means of hohlraum radiation

Project goal:
creation of large (1mm x 1mm), homogeneous, long leaving (>3 ns - length of the ion bunch) partially ionized plasma of $n_e \sim 10^{20}-10^{21} cm^{-3}$

PHELIX Laser: λ=1,056 µm, τ =1.4 ns, E= 200-270 J, d~200-300µm, $I>10^{14} W/cm^2$, contrast 10^{-6}

Target:



Heavy ion beam
4-6 MeV/u
d~500µm
τ=3ns

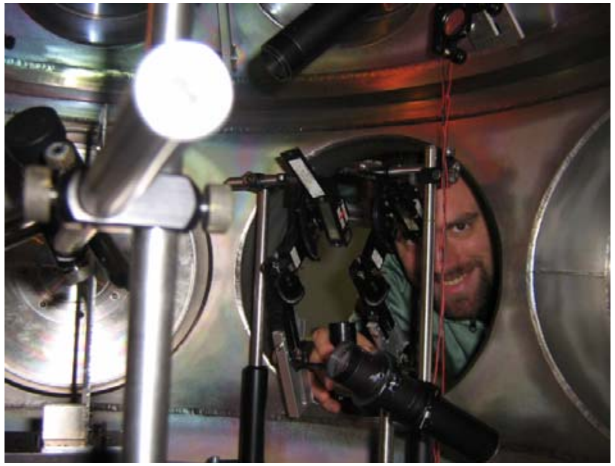
CHO-foam 2-20 mg/cm³
areal density ρx~ 150-500 mg/cm²

International collaboration

- VNIIEF-Sarov, Russia (ISTC 2264);
  Numerical optimization of the target design, experimental support
- Rhein-Ahr-Campus Remagen, University of Applied Sciences, Germany
  experimental support (absolute calibrated transmission grating spectrometer)
- Goethe University, Frankfurt am Main, Germany
  experimental support (X-ray diagnostics)
- Joint Institute for High Temperatures, Moscow, Russia
  carbon plasma opacities calculations
- Lebedev Physical Institute, Moscow, Russia
  foam target production, calculations of the foam hydrodynamics
- Institute of Modern Physics, Lanzhou, China
  experimental support (X-ray diagnostics)
- Plasma Physics Division GSI
  project leading, PHELIX-laser, diagnostics, infrastructure

Last experimental campaign on February-March 2010






Conferences and workshops 2010

1. EMMI workshop on Plasma Physics with Intense Heavy Ion and Laser Beams, May 20-21,2010, Moscow, Russia
"Experiments on the indirect heating of low Z foam targets"

2. EMMI workshop on "X-rays as a Tool for Probing Extreme States of Matter", June 7-9, 2010, GSI-Darmstadt
" Properties of combined hohlraum targets for probing with heavy ion beams"

3. Heavy Ion Fusion Conference (HIF 2010), 31.08-3.09.2010 , Darmstadt,Germany
"Properties of combined hohlraum targets for probing with heavy ion beams"

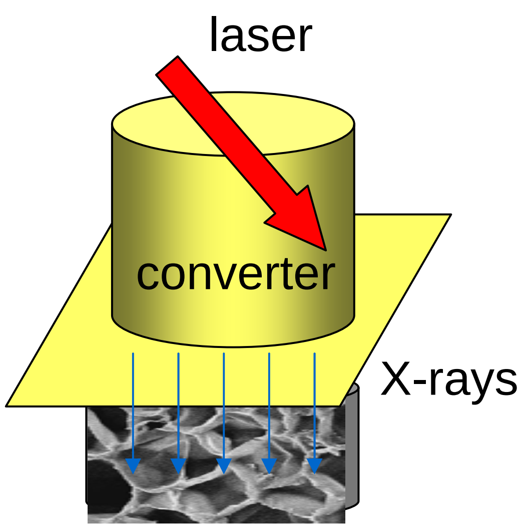
4. 31th European Conference on Laser Interaction with Matter (ECLIM), September 6-10, 2010 , Budapest, Hungary
"Experiments on indirect heating of low density aerogels for applications in heavy ion stopping in plasma"

5. 4th International conference "Supers strong fields in plasma", October 3-9, 2010, Varenna, Italy
Nanostructures irradiated by fs and ns laser pulses: latest advances on X-ray sources and high energy density plasmas

6. EMMI Physics Days, November 4-5, 2010, GSI-Darmstadt

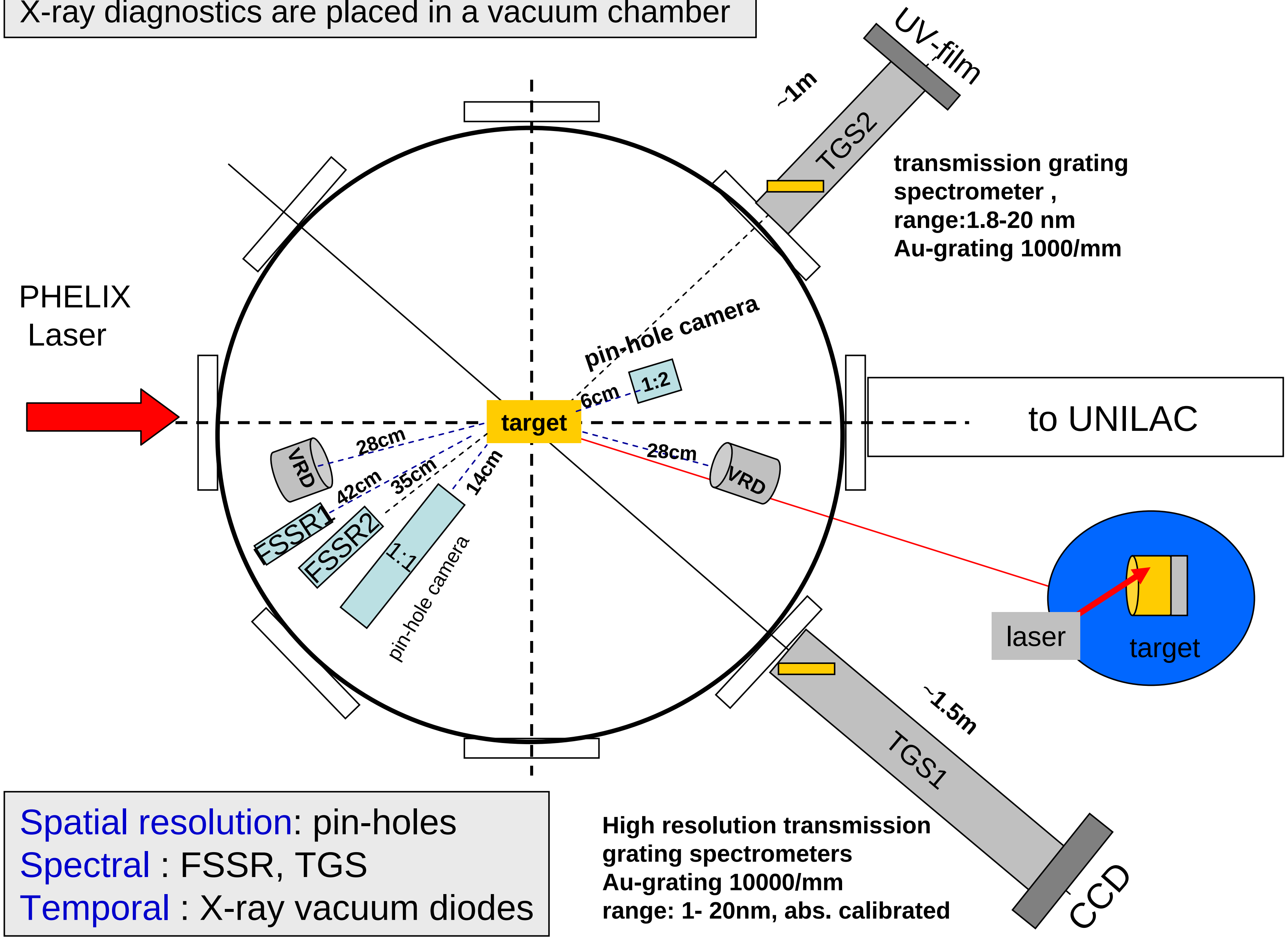
What we would like to know?

1. Radiation field of the primary hohlraum (converter)
2. Conversion efficiency of the laser energy into soft X-rays
3. Absorption properties of CHO-foams
4. Temperature and ionization degree of heated by X-rays CHO-plasma



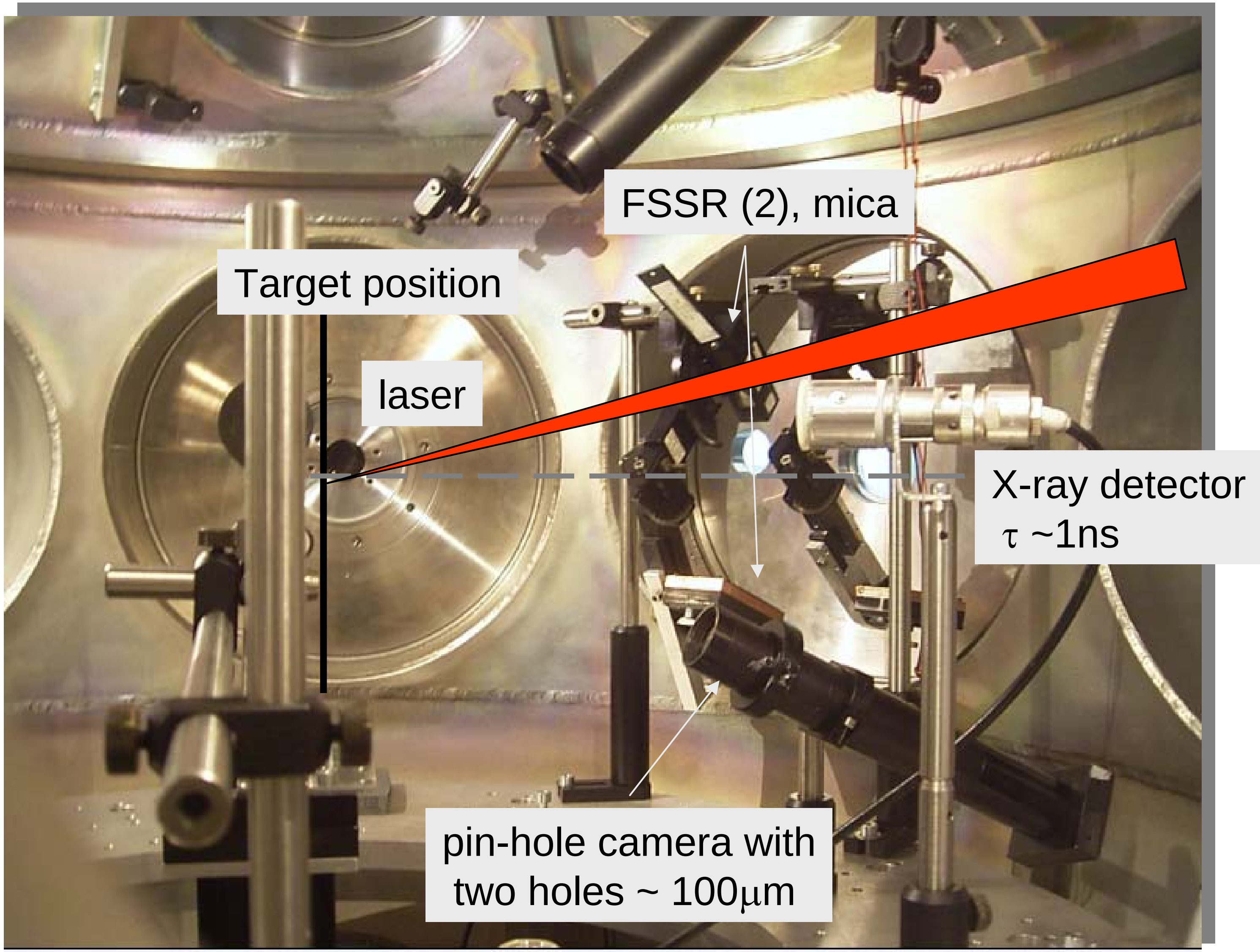
X-ray diagnostics set-up

X-ray diagnostics are placed in a vacuum chamber

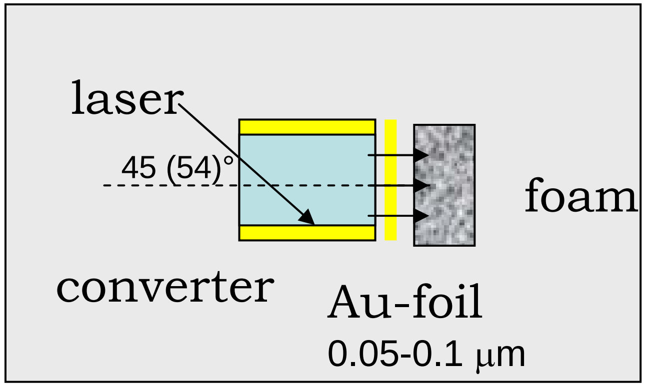


Spatial resolution: pin-holes
Spectral : FSSR, TGS
Temporal : X-ray vacuum diodes

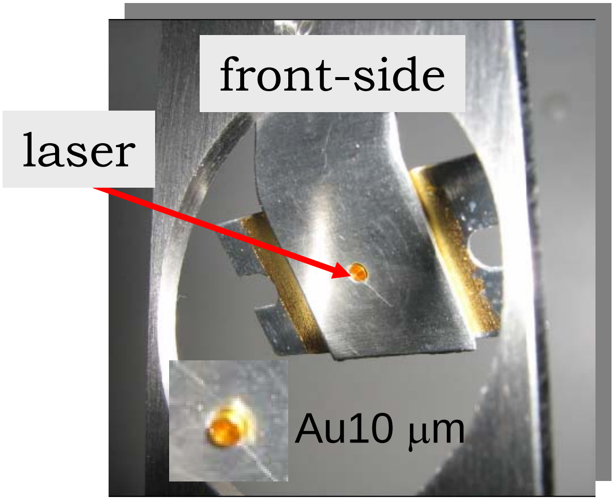
Front side diagnostics of the converter radiation



Combined targets: converter + foam/foil

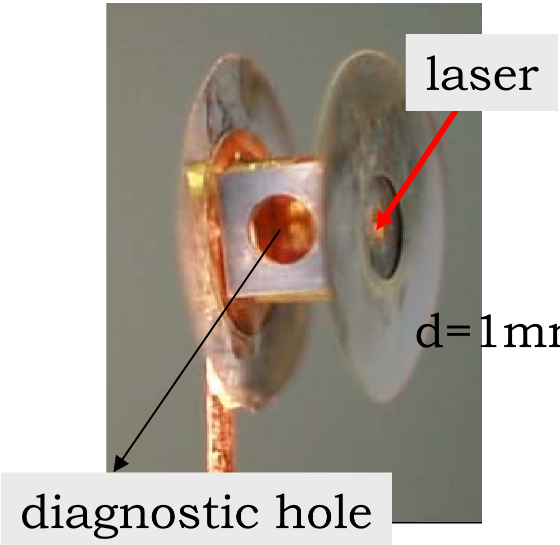


GSI-converter



GSI-converter+foam

Sarov-converter



cellulose triacetate

3-D regular network
with opened cell
structure, the most
fine pores (~ 1μm)
remains stable up to
220C,
used at PALS, LIL, GSI

TAC(C12$H_{16}O_8$)

2mg/cc 800-1000μm

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Hohlraum targets after shots

Converter, shot 32, E $_{las}$=228J

target front side

HED in the laser focal spot during 1 ns laser pulse

$$\frac{E(J)}{V(mm^3)} = \frac{200J}{(0.3mm)^2 \cdot 10^{-3}mm} = 2MJ/mm^3$$

plasma generation

target back side

After the interaction, at later times, deposited energy is redistributed over the whole hohlraum

$$\frac{E(J)}{V(mm^3)} = \frac{200J}{(1.7mm)^2 \cdot 1.7mm} = 20J/mm^3 \sim 0.2Mbar$$

phase transitions, shock wave generation

Main results: Converter (primary hohlraum)

By irradiation of the primary hohlraum with 230-270J laser energy (1.4ns, λ=1.054 μm) we create

uniform 1.7 mm soft X–ray source

Soft X-ray pulse duration

$\tau_{x\text{-}rays}$ = 5-7 ns

Hohlraum equivalent radiation temperature

T_{rad} = 30-40eV

Conversion efficiency of laser energy into X-rays

up to 17% (1ω)
40J in soft X-rays

Main results

Amount of X-ray energy absorbed in foam targets

75-90%

This corresponds up to 10-30 J energy in soft X-rays

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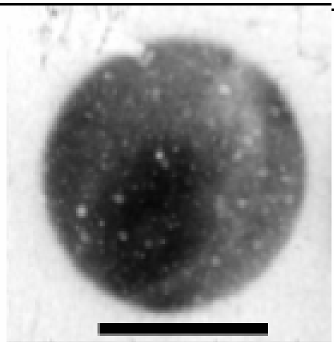
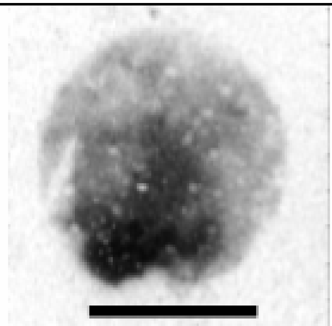
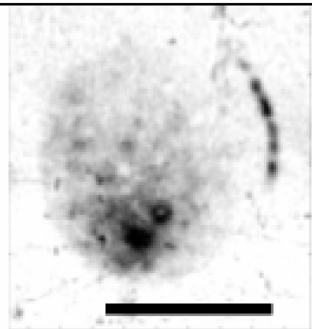
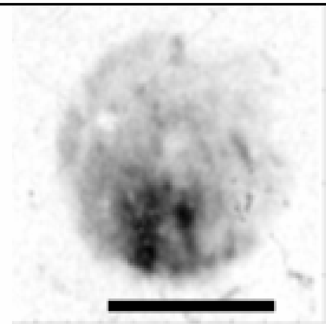
Main results: Absorption of soft-X-rays in foam targets

Hohlraum X-ray image (back) in 0.2-0.28 keV photon energy

E_{las}~100J		E_{las}>200J	
24.02 (1) E=127J	25.02 (2) E=116J	24.02 (3) E=218J	25.02 (1) E=216J
			
Converter d=1.7mm bottom Au~ 150 μg/cm² No foam!	Converter d=1.7mm bottom Au~150 μg/cm² Foam: CHO 0.01g/cc; 300 μm ρx=300μg/cm²	Converter d=1.7mm bottom Au~ 150? μg/cm² Foam:CHO 0.1g/cc; 90 μm ρx=900μg/cm²	Converter d=1.7mm bottom Au~ 160 μg/cm² Foam: CHO 0.1g/cc; 45 μm ρx=450μg/cm²

results N. Suslov, VNIEF, Sarov

Has foam been heated to a plasma state?

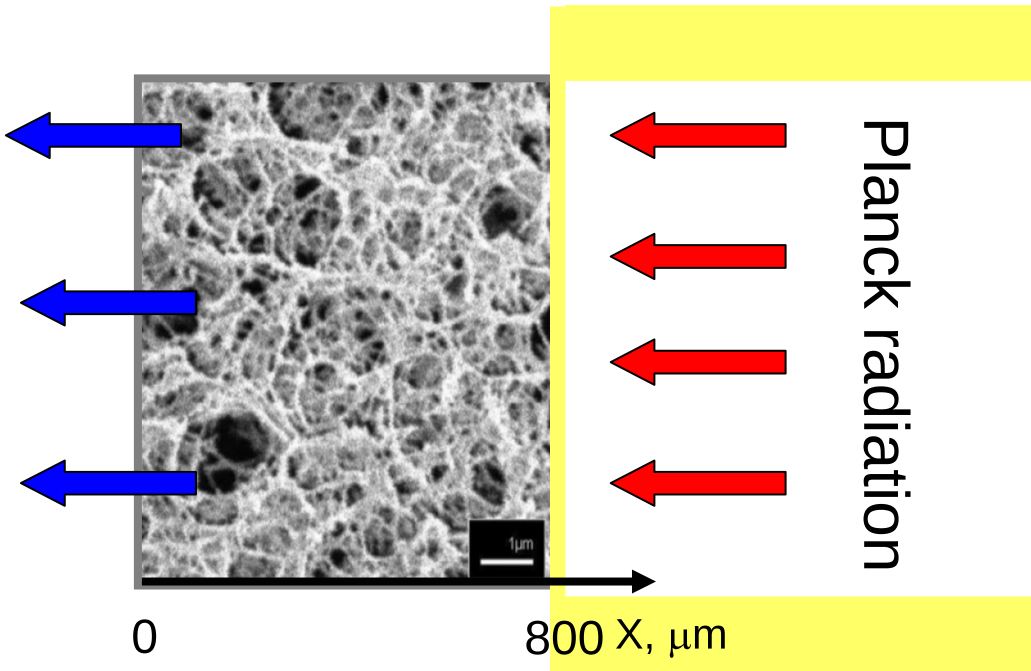
Hydrodynamics of CHO-foam heated by the external X-ray source: Planck, T_{rad}=20-40eV, $t_{x\text{-}rays}$ = 5ns

Code RADIAN: two-temperature hydrodynamics with radiative transfer equation using TAC-foam opacities calculated by N. Orlov, JIHT

transmitted radiation
(to TGS -spectrometers)

TAC-foam 0.002g/cc
800μm thick
ρx=160 μg/cm²

3-D network,
1 μm pore-size
0.1 μm solid wall



We would like to know: Te (x, time)=?, ρ (x, time)=?

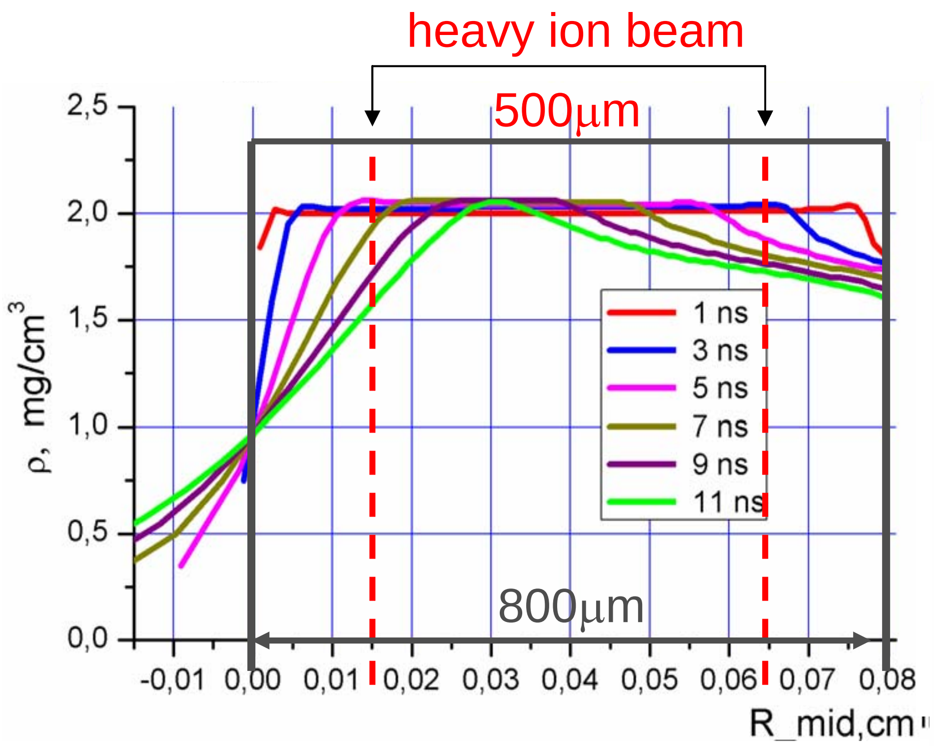
G. Vergunova, LPI, Moscow

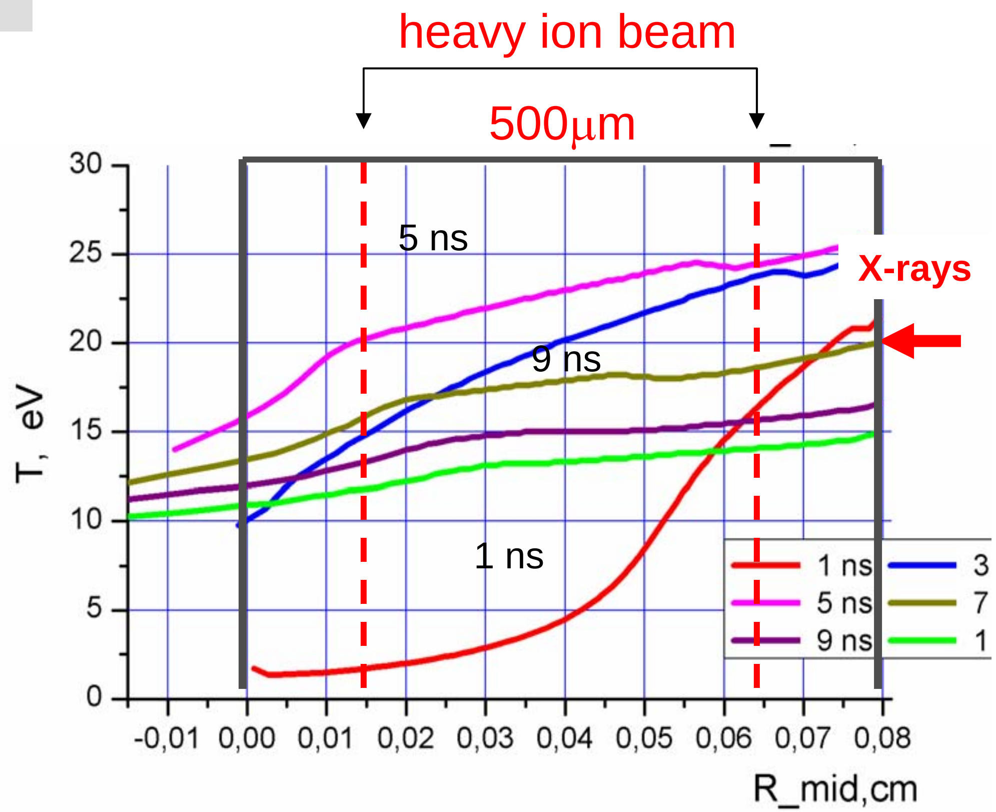
Hydrodynamics of CHO-foam heated by the external X-ray source

Planck T_{rad}=40eV; $t_{x\text{-}rays}$= 5ns; TAC 2 mg/cc, 800μm

Density :
slow 1-D expansion starts at 3-5ns.
Only 15% density fluctuations
in the interaction region of 500μm

Temperature:
time =3-9ns Te=15-25eV





G. Vergunova, Run 170

Has foam been heated to a plasma state?

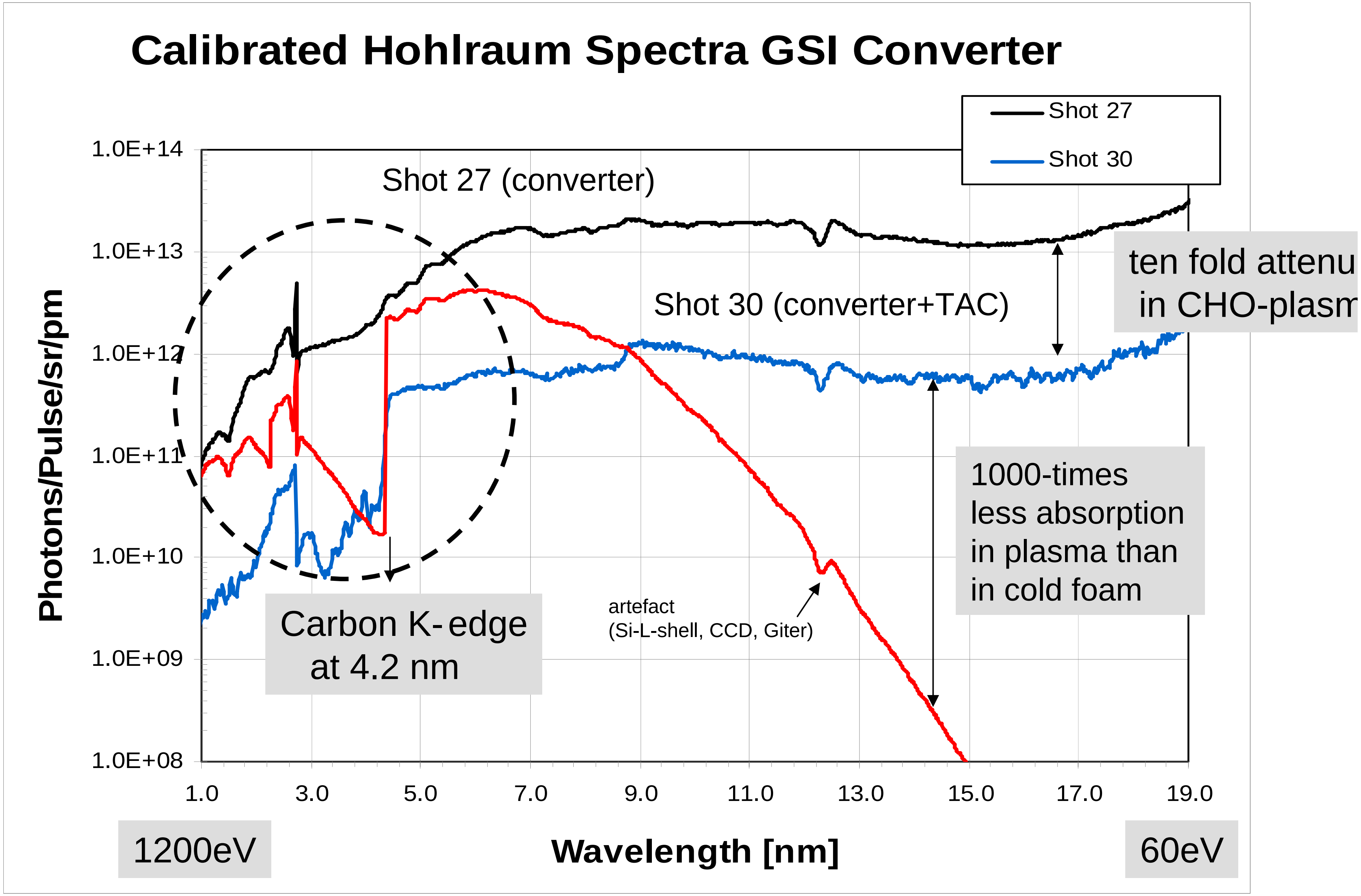
Diagnostic of plasma absorption properties

Experimental results show:
Deformation of the “cold” Carbon K-edge structure and increased transmission in plasma at photon energy close to the binding energies of Carbon L-shell electons

Method:
Analyses of the hohlraum radiation spectra transmitted through the foam target near Carbon K-edge (3.5-4.2nm or 280-350eV)

 o.rosmej@gsi.de

Absorption properties of heated to plasma foams



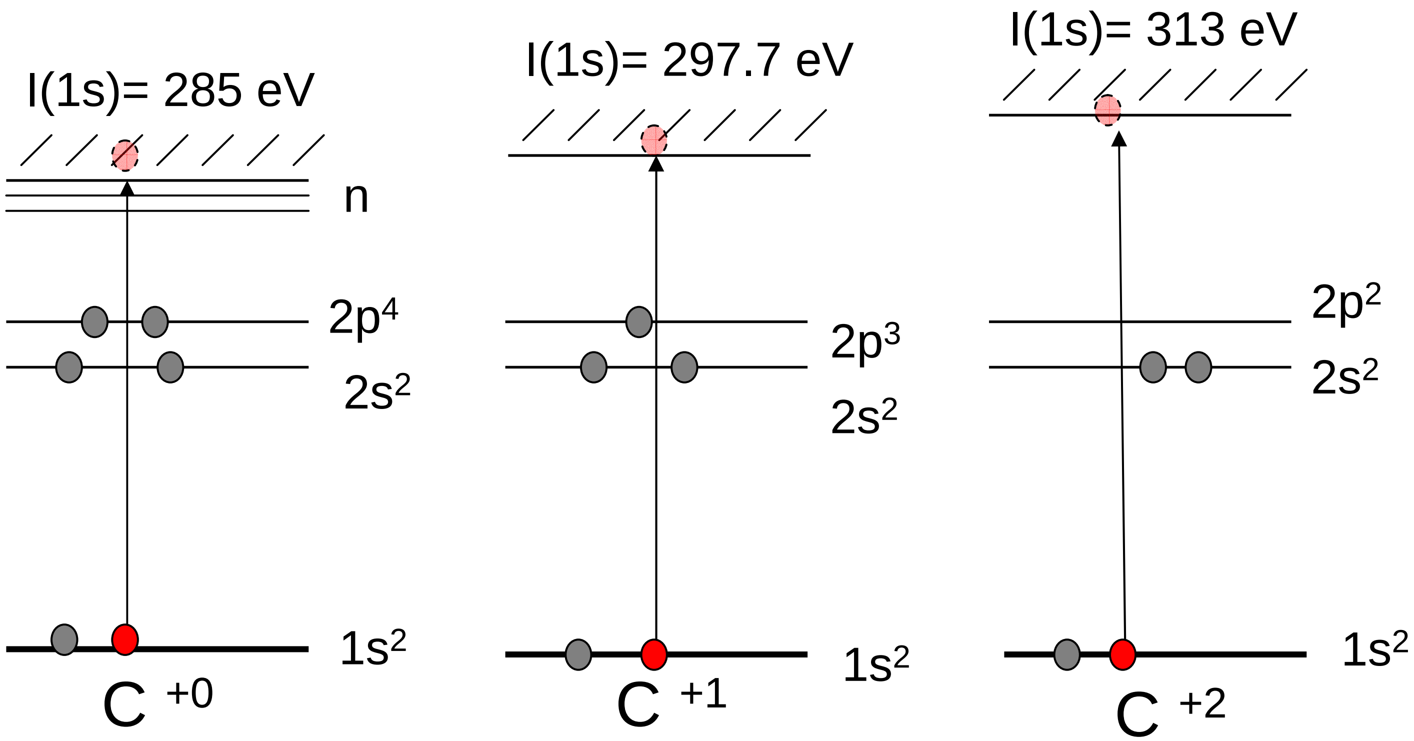
D. Schäfer, Th. Nisius, Th. Wilhein, Remagen

K-edge position depends on the ion charge

Isolated ion case

C^{+0} – 285eV, C^{+1} – 297.7 eV, C^{+2}- 313, 39 eV, C^{+3} -346.17 eV, C^{+4} – 380.51 eV

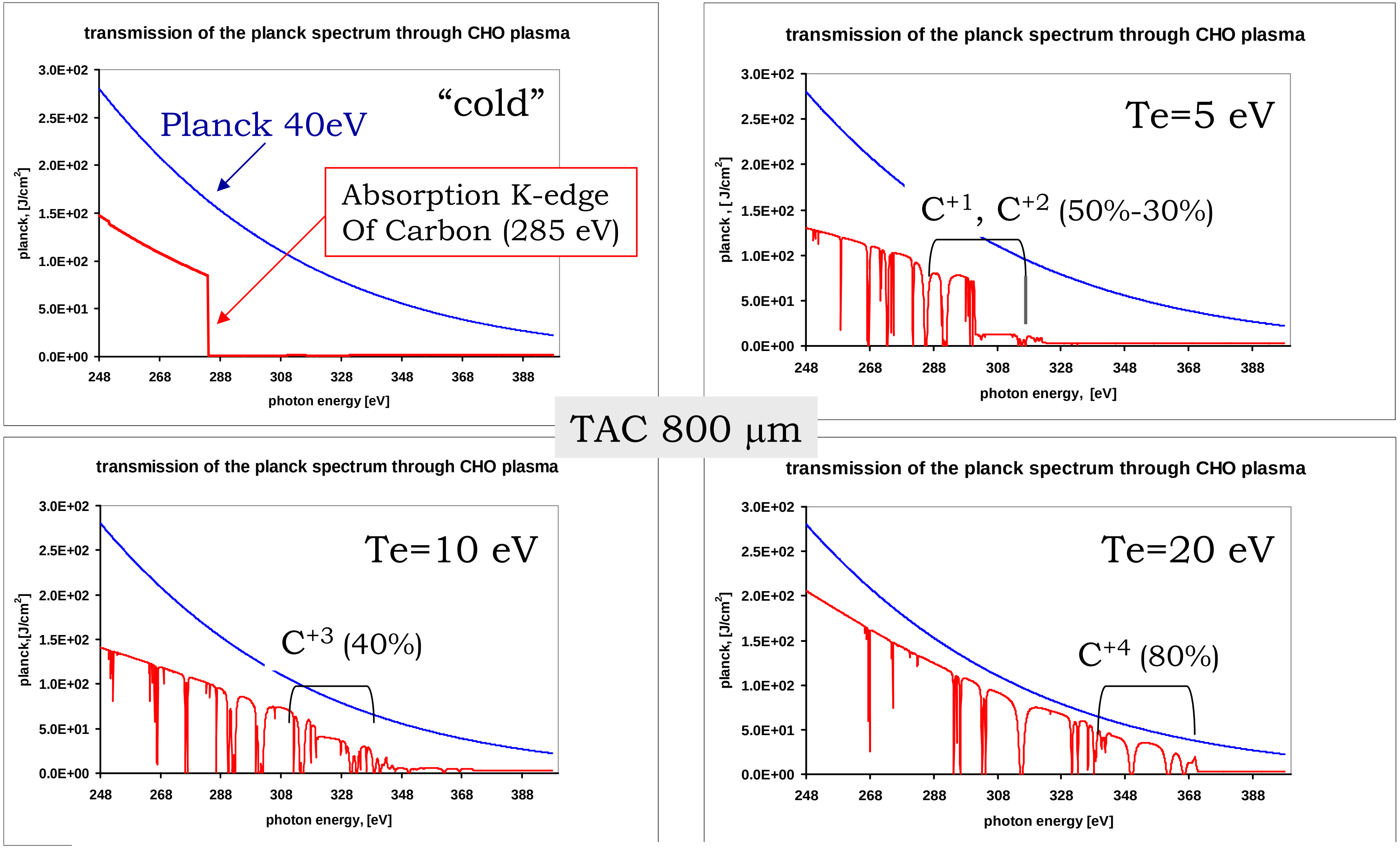
(G. Zschornack et al, Dirac-Fock-Slatter calculations, Rosendorf, 1986)



Absorption properties of CHO-Plasma

Nikolay Orlov, JIHT, Moscow

Dependence on plasma temperature/ionization degree

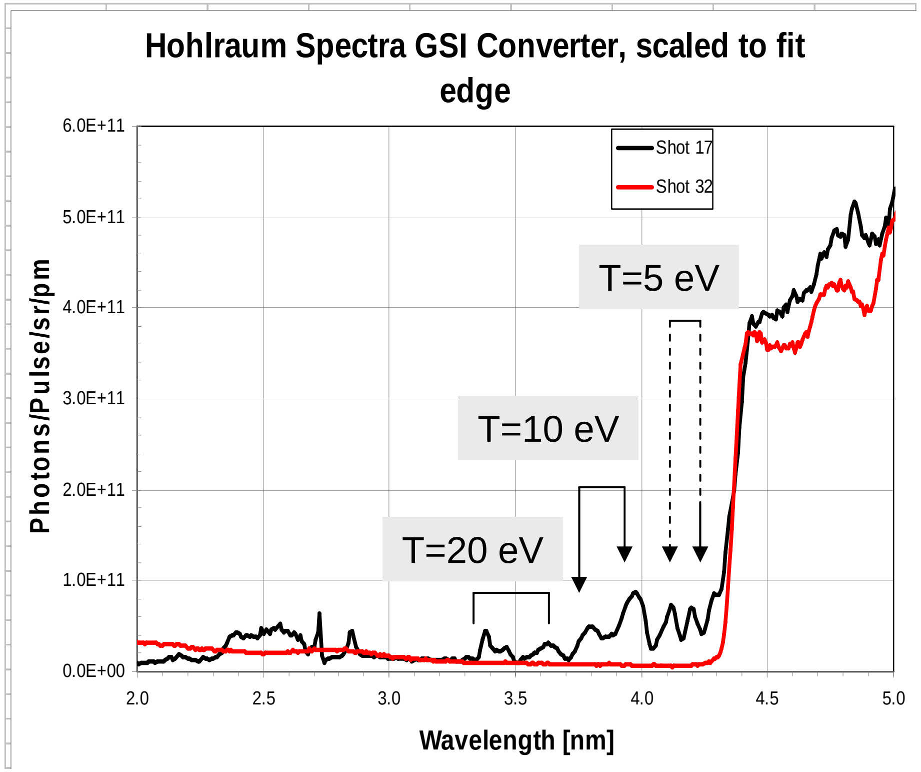


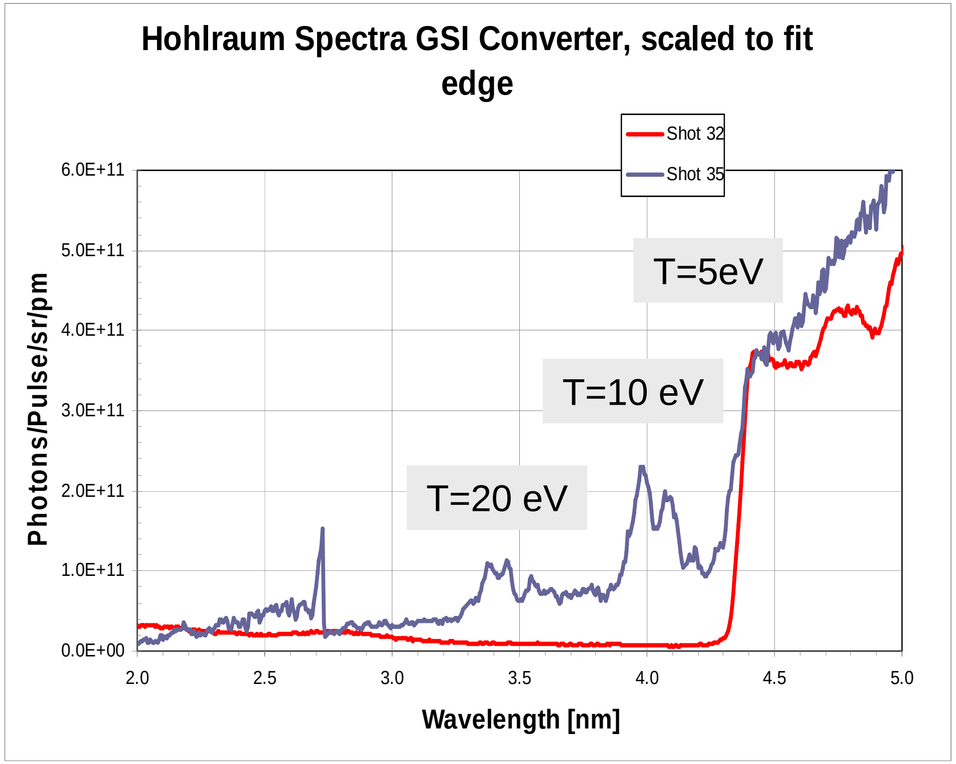
Calculated for homogeneous temperature distribution over the foam thickness

Simulation of experimental time - integrated spectra

demands knowledge on the history of foam heating (HD) and the plasma opacities in dependence on plasma temperature and density.

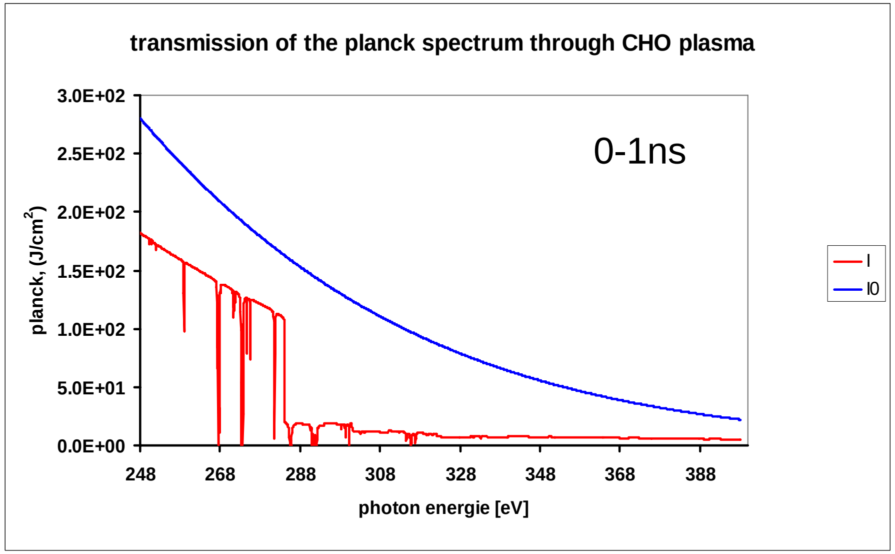
Laser: 160J *Target:* Converter + TAC-foam 800 μm	*Laser*: 240J *Target*: Converter + TAC-foam 1000 μm

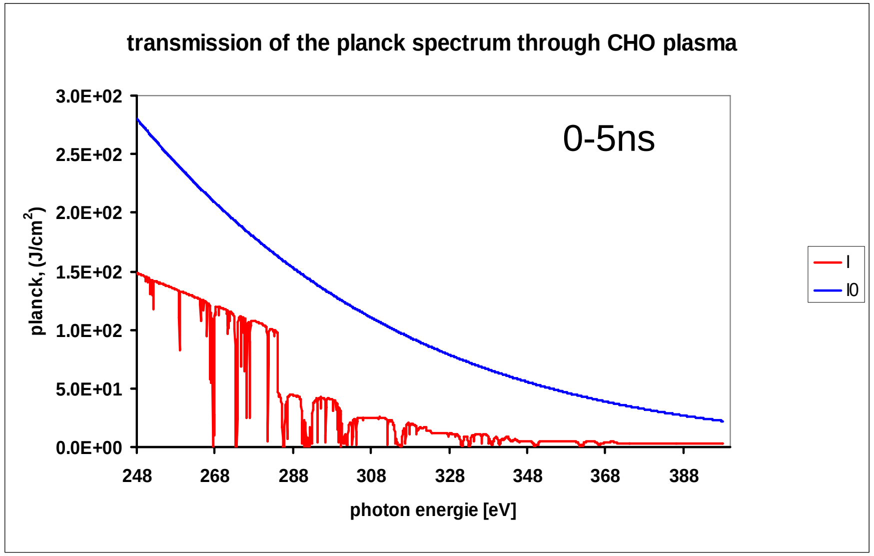


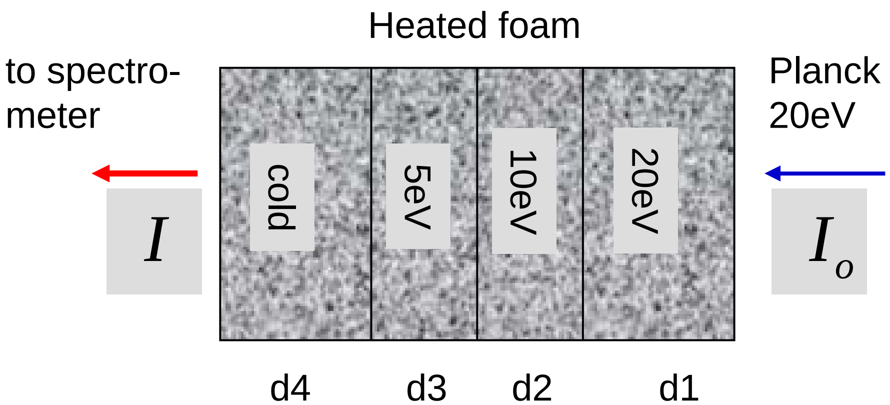


D. Schäfer, Th. Nisius, Uni-Remagen

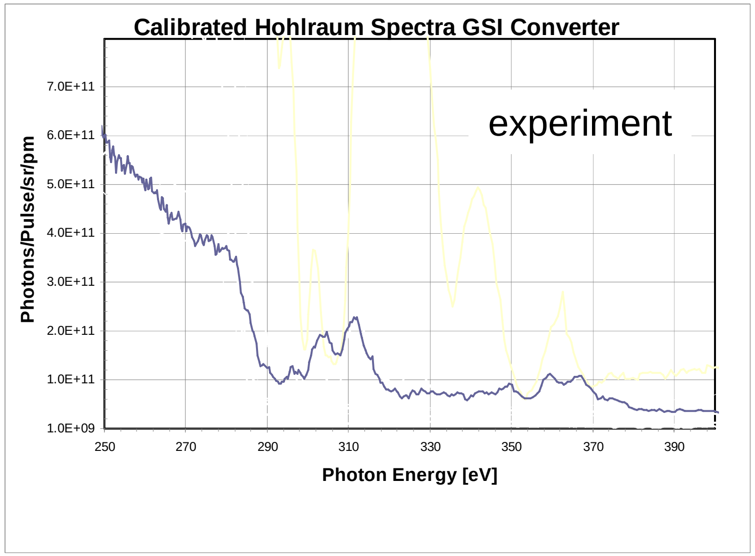
Simulation of experimental time - integrated spectra







$$I = I_o \cdot e^{-\rho(k_1 \cdot d_1 + k_2 \cdot d_2 + k_3 \cdot d_3 + k_4 \cdot d_4)}$$



B. Aurand, O. Rosmej

Indirect heating of low density CHO- foams

Summary:

Numerical simulations demonstrate the possibility of homogeneous heating of 1 mm thick low density foam layer by means of soft X-rays.

Absorption coefficients for TAC chemical composition have been calculated and used for simulations of the radiation transport in CHO-plasma

Experimental results:

- Effective conversion of the laser energy in to soft X-rays with near Planckian spectral distribution at **T_{rad}= 30-40 eV; 40J in soft X-rays**
- 1mm thick TAC foam layer of 2 mg/cc density **absorbs up to 90%** of hohlraum radiation in the photon range 50-1000 eV
- deformation of the K-absorption edges in heated by X-rays foams is used as a temperature diagnostics; estimated **Te~ 10-15 eV.**
- Rich experimental data on the **opacities** of CHO plasma with a coupling parameter

$$\Gamma \sim 0.3-0.5 \;;\; at \;\; z=2-4; \;\; n_i = 10^{20} - 10^{21} cm^{-3}$$

Outlook

- Repeat experiments using a full energy 2ω option PHELIX-laser
- Combined experiments with heavy ion beams are planed
- On the 8th and 9th of November Plasma Physics Advisory Committee will evaluate our experimental proposals for 2011

Publications to the topic

1. *Rosmej, O.N., Zhidkov, N., Vatulin, V., Sulov, N., Kunin, A., Nisius, T., Zhao Y., Wilhein, T., Stöhlker, T*. (2009). Experiments on heating of low Z targets by means of hohlraum radiation. **GSI Scientific Report 2009, 387**

2. *Rosmej, O.N., Orlov, N., Schäfer, D., Nisius, T., Wilhein, T., Suslov, N., Zhidkov, N., Zhao, Y.* (2009). Diagnostics of temperature and ionization degree of low Z foams in experiments on the ion stopping in plasma. **GSI Scientific Report 2009, 391**

3. *Vergunova, G.A., Gus´kov, S.Yu., Rozanov, V.B., Rosmej, O.N. (2010).* Formation of plane layer of plasma under irradiation by a soft X-ray source. **Journal of Russian Laser Research, 31, N5, 505-513**

4. *N. Orlov, O.N. Rosmej, D. Schäfer, Th. Nisius, Th Wilhein, N. Zhidkov, A. Kunin, N. Suslov, A. Pinegin, V. Vatulin, Y. Zhao,* Theoretical and experimental studies of material radiative properties and their applications to laser and heavy ion inertial fusion. **Submitted to LPB**

5. *O.N. Rosmej, A. Blazevic, V. Bagnoud, U. Eisenbarth, V. Vatulin, N. Zhidkov, N. Suslov, A. Kunin, A. Pinegin, D. Schäfer, Th. Nisiusc, Th. Wilhein, T. Rienecker, J. Wiechula, Y. Zhao, G. Vergunova, N. Borisenko, N. Orlov* Heating of low density CHO-foam layers by means of soft X-rays **to be published in NIMA**

6. Experimental and theoretical investigations of indirectly heated low density polymer layers. **to be published in PRE**

EMMI Physics Days

Indirectly heated plasma targets for combined PHELIX laser - heavy ion beam experiments

Great thanks to:

A. Blazevic, V. Bagnoud, Th. Hessling, U. Eisenbarth, B. Aurand, N. Zhidkov,

V. Vatulin, N. Suslov, A. Kunin, A. Pinegin, D. Schäfer, Th. Nisius, Y. Zhao,

J. Wiechula, T. Rienecker, N. Orlov, N. Borisenko, G. Vergunova, S. Gus´kov,

V. Rosanov, Th. Wilhein,Th. Stoehlker, V. Fortov