7th EMMI Workshop on Plasma Physics with Intense Laser and Heavy Ion Beams WLIB

Moscow 9.- 10. December 2014

FAIR-relevant experiments at the PHELIX-laser facility

overview of the experimental program with Russian contribution

2010-2014

Olga Rosmej Plasma Physics Department
GSI+FAIR

Plasma Physics at FAIR

Challenge: fundamental properties of matter under extreme conditions

HIHEX

Heavy Ion Heating and Expansion

> 0.5 GeV/u >10^{10}part/100ns U-beam

demand on backlighter
$E_{ph.}$ > 100 keV

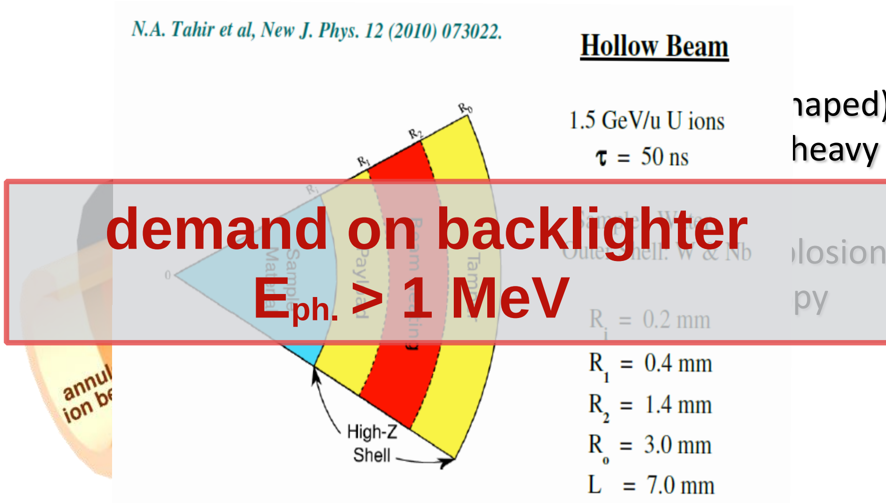
Pb up to 1g/cm^2 areal density

- Homogeneous heating in sub-µs (2kJ/g)
- Sample material reaches different physical states (depending on energy & density)

LAPLAS

Laboratory Planetary Science (SIS100)

1.5 GeV/u 5.10^{11}/100ns U-beam



demand on backlighter
$E_{ph.}$ > 1 MeV

- Reaches physical conditions like interior of giant planets (Jupiter, Saturn)
- Helps to understand the core structure

FAIR-relevant experiments at the PHELIX- facility

Continuation of the research program with high energy and high intensity laser beams in the period of accelerator shut-down is crucial advantage of PP-research.

Important requirement - combination of exciting physics with FAIR-relevance

- **Secondary laser sources for probing of HED-matter:**
  laser generated electron, proton, and neutron beams
  X-ray and Gamma-sources (characteristic, continuum)
- **Generation of Warm Dense Matter by laser accelerated electron/proton beams**
- **Ion stopping in non-ideal plasmas**
- **Opacities of non-ideal plasmas**
- **Shock generation for EOS**
- **Development of new diagnostic methods**
  Hard-X ray and Gamma detectors;
  transmission crystal spectrometers for monochromatic backlighting;
  electron spectrometers, etc.

Statistic 2010-2014

Experimental projects approved by PPAC: **10**
Laser beam-times (2010-2014): **14**
Russian participants: **30** (theory, simulations, diagnostics)

Russian institutions participated in PP-research program with laser:

1. Joint Institute for High Temperatures (*3D-PIC, HD-simulations, opacity, X-ray diagnostics*)
2. Lebedev Physical Institute (*HD-simulations, nano-targets manufacturing*)
3. Moscow State University (*nano-targets manufacturing and characterization*)
4. All Russian Scientific Research Institute of Experimental Physics, RFNC-VNIIEF, Sarov, Russia (*HD-simulations+ radiation transport, X-ray diagnostics*)
5. Keldish Institute for Applied Mathematics (*opacity simulations*)
6. National Research Nuclear University "MEPhI„ (*VISAR-diagnostic*)
7. Prokhorov General Physics Institute (*simulations of laser driven shock, post-diagnostics*)
8. Institute for Theoretical and Experimental Physics (*experimental support*)
9. Kurchatov Research Center - in future (*X-ray diagnostics)*

FAIR-relevant experiments at the PHELIX-facility

1. GSI - Laserlab Europe Projekt P017 (PHELIX- laser): *“ Characterisation of X-ray production by ultra-intense laser pulses in nanostructured targets*”, 2009

2. GSI - Projekt P014: *“Investigation of direct and indirect heated low- Z foams as plasma targets for PHELIX - heavy ion beam crossing experiments”,* 2010

3. GSI - Projekt U266: *Heavy ion stopping in X-ray heated dense plasma layers”*, March, Sept. 2011

4. GSI –Project P042 *Experiments on hot-electrons and Silver (21 keV) Ka-production,* 2012

5. DFG - Projekt U272: *“Investigation of heavy ion stopping in ionized matter: combined laser – heavy ion beam experiments”*, March, Aug.2012

6. GSI-Project P77 *Development of X-ray monochromatic radiography diagnostics at PHELIX facility for WDM experiments*, June 2013

7. GSI-Project P90 *Investigation of highly collimated mono-energetic target surface electron (TSE) beam for PHELIX-heavy-ion heated plasma joint experiments,* Jan. 2014

8, 9. GSI-Projecsts P078; P081; P089 *Investigation of equations of state of materials in shock and release waves with PHELIX,* Feb., Nov. 2014

10. GSI - Projekt U280: *“ Heavy Ion Stopping in non-ideal plasma: PHELIX-heavy ion beam combined experiments”,* May 2014

FAIR-relevant experiments at the PHELIX-facility

1. GSI - Laserlab Europe Projekt P017 (PHELIX- laser): *“ Characterisation of X-ray production by ultra-intense laser pulses in nanostructured targets”*, 2009

2. GSI - Projekt P014: *“Investigation of direct and indirect heated low- Z foams as plasma targets for PHELIX - heavy ion beam crossing experiments”,* 2010

3. GSI - Project U266: *“Heavy ion stopping in X-ray heated dense plasma layers”*, March, Sept. 2011

5. DFG - Projekt U272: *“Investigation of heavy ion stopping in ionized matter: combined laser – heavy ion beam experiments”*, March, Aug.2012

5. GSI –Project P042 *„Experiments on hot-electrons and Silver (21 keV) Ka-production”,* Feb. 2012 (JIHT, theory, diagn.)

6. GSI-Project P77 “*Development of X-ray monochromatic radiography diagnostics at PHELIX facility for WDM experiments”*, June 2013 (JIHT, X-ray diagn.)

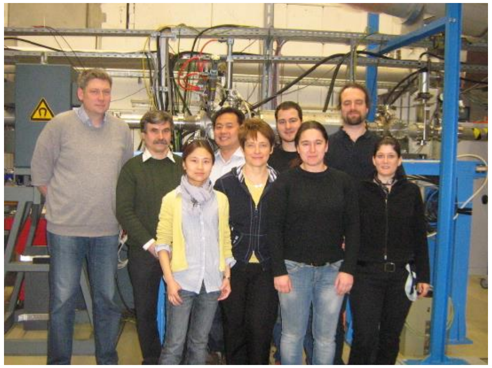
7. GSI-Project P90 “*Investigation of highly collimated mono-energetic target surface electron (TSE) beam for PHELIX-heavy-ion heated plasma joint experiments”,* Jan. 2014 (JIHT, theory)

8, 9. GSI-Projects P078; P081; P089 “*Investigation of equations of state of materials in shock and release waves with PHELIX”,* Feb. Nov. 2014 (GPI, ITEP, JIHT, theory, diagnostics, targets)

10. GSI - Project U280: *“ Heavy Ion Stopping in non-ideal plasma: PHELIX-heavy ion beam combined experiments”*, May 2014 (Sarov, LPI, MSU, theory, diagnostics, targets)

Experiment is a team work

GSI PHELIX-laser March 2011

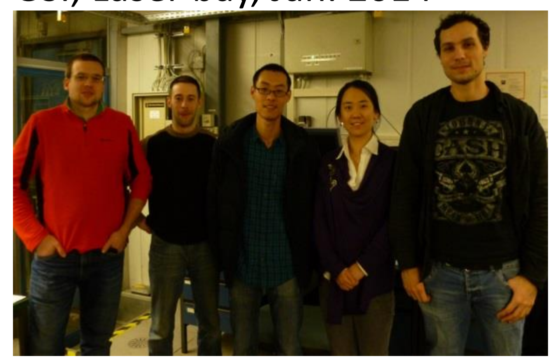


GSI November 2014

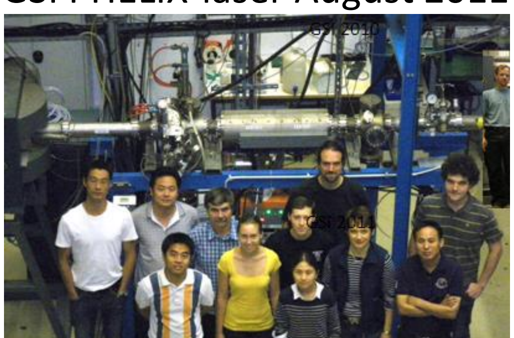
GSI PHELIX-laser bay, Feb. 2012

Paris LULI-laser April 2011

GSI, Laser bay, Jan. 2014



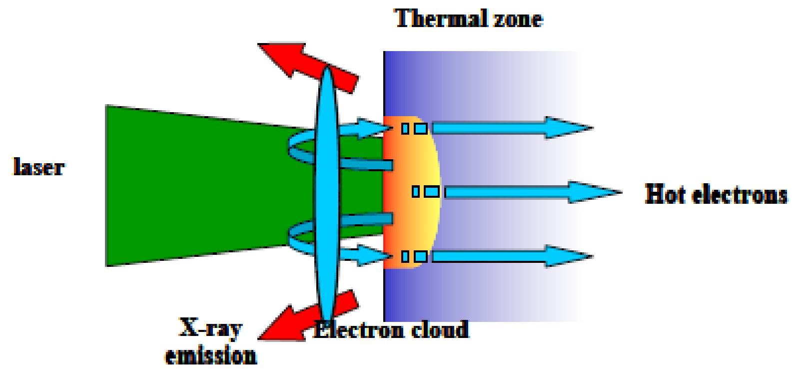
GSI PHELIX-laser August 2011



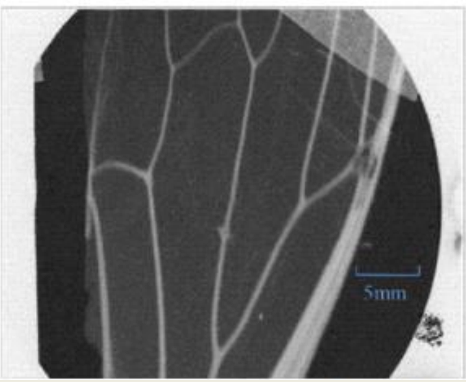
GSI PHELIX-laser August 2012

Laser driven electron and X-ray sources

X-rays and energetic electrons production in laser-target interaction



X-ray emission from plasmas heated by intense fs laser



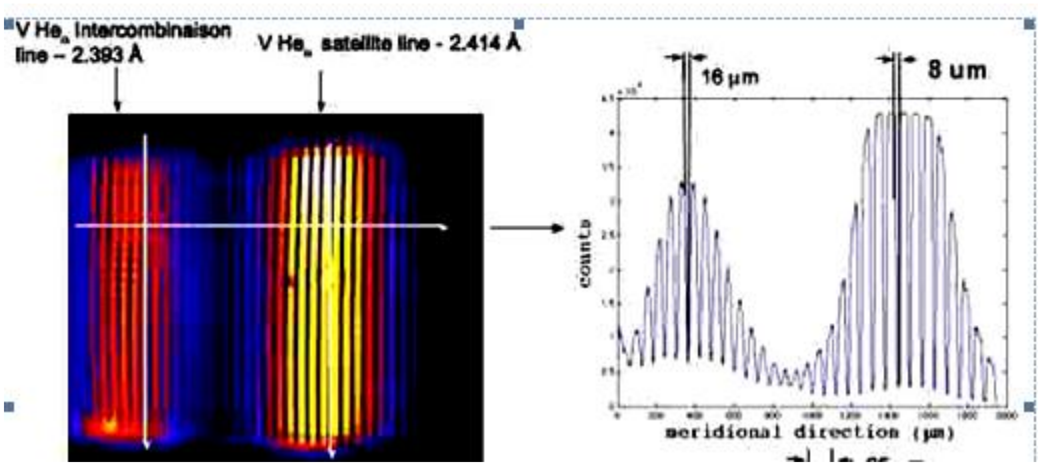
fly's wing X-ray image
at single laser shot

X-rays (characzteristic and Bremsstrahlung) are best candidates to backlight HED **objects. Attenuation and scattering of X-ray photons are used for diagnostic purposes.**

Advantage of such X-ray source:
short (fs-ps) bursts of X-rays provide a **time history** of dynamic processes in plasma

Experiments with relativistic fs PHELIX-pulse

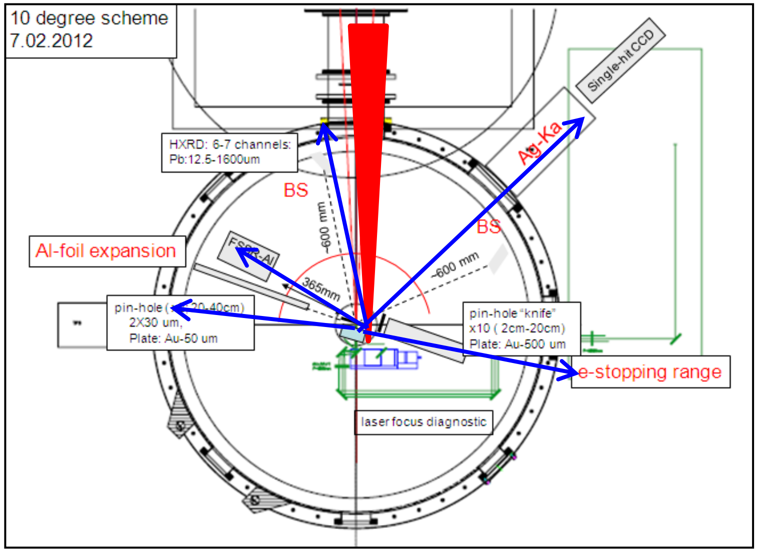
- **electron acceleration in relativistic laser-matter interaction**
- **interaction of laser accelerated electrons with matter (e_transport, radiation)**
- **high energy Ka monochromatic backlighter (quantitative measurements)**

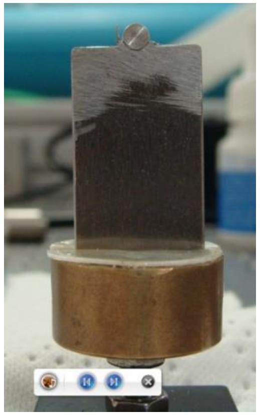


S. Pikuz et al

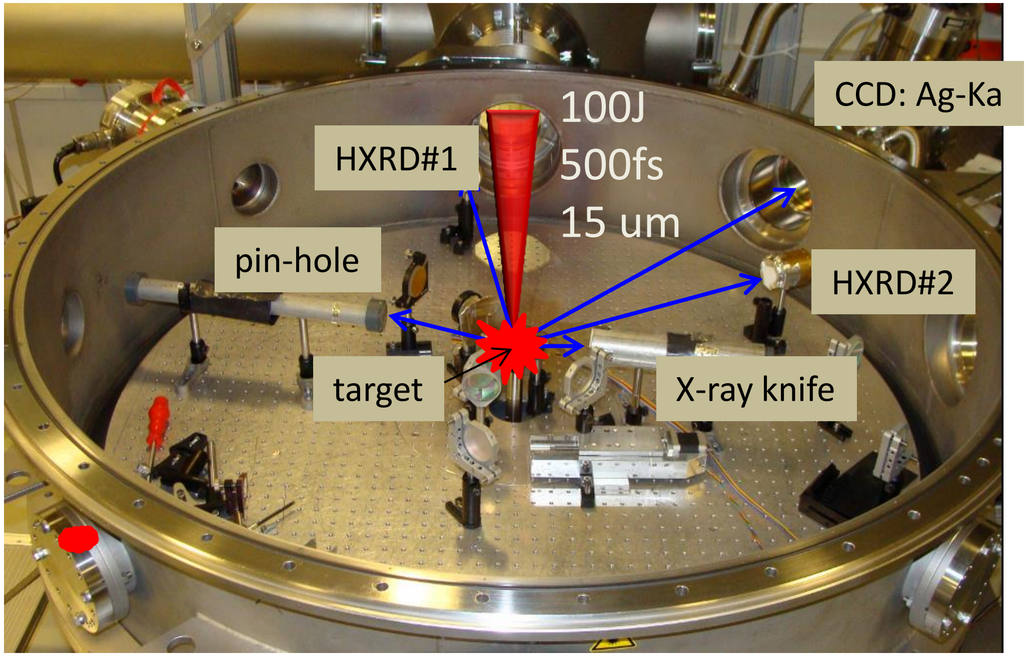
X-rays for backlighting at FAIR

Feb. 2012





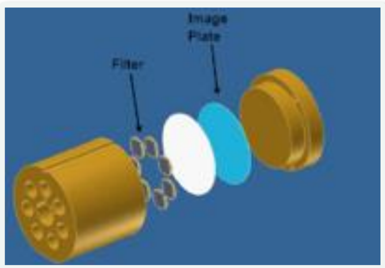
Silver target befor and aftershot



Experiment 9-15.02.2012

Measurements of bremsstrahlung spectra and Silver K-alpha (21 keV)

HXRD

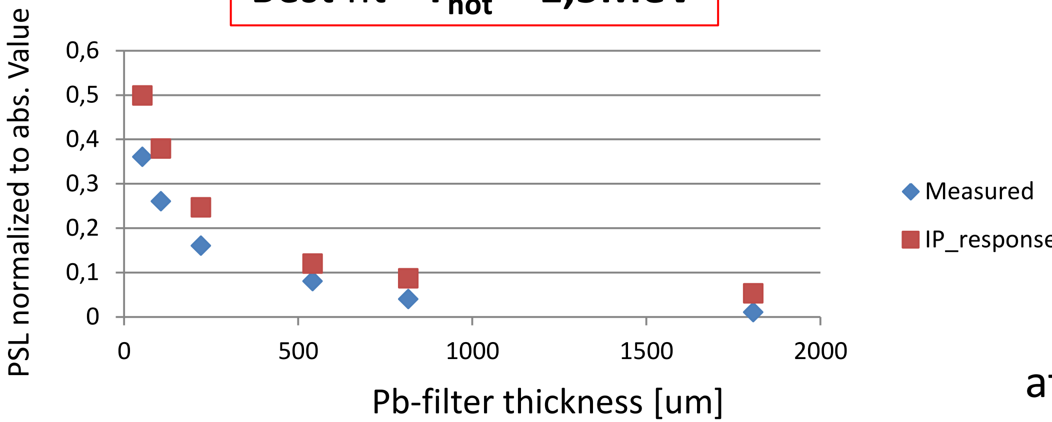


Shot 10:

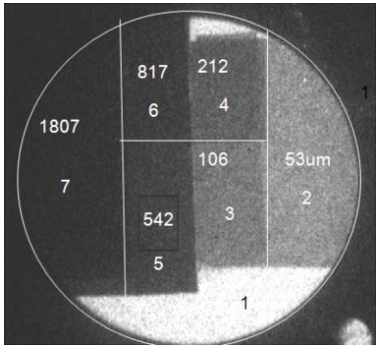
I= 1,8e+19 W/cm^2

K-alpha: 1.5 mJ

Best fit - $\mathbf{T_{hot}}$ **= 1,5MeV**



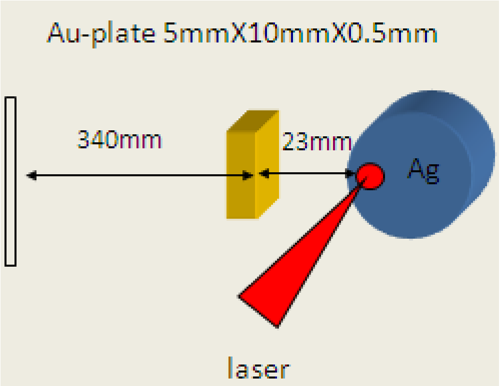
Beer Lambert law

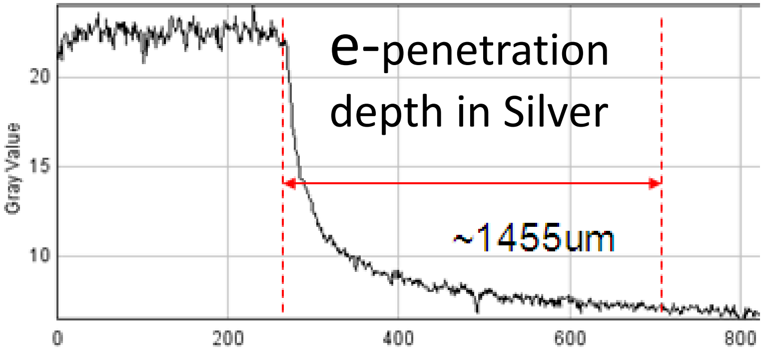


attenuation of BR in Pb-foils of 50-1800 um

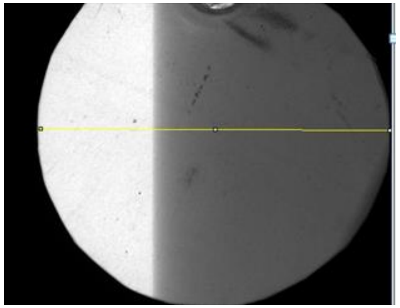
1.5 mm-stopping range of **2 MeV**-electrons in Ag

X-ray knife



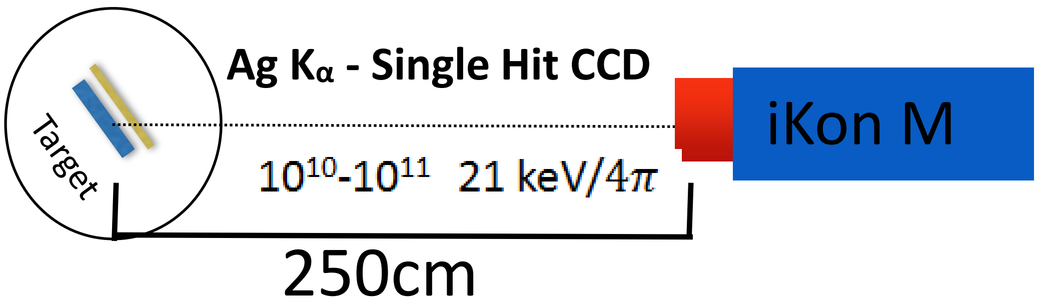


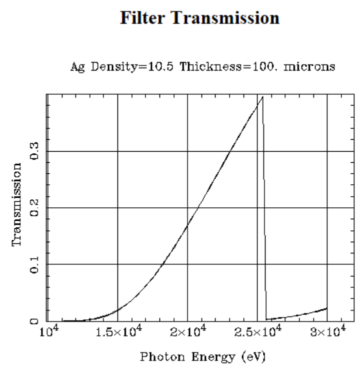
X-ray image



e-stopping range

Measurements of bremsstrahlung spectra and Silver K-alpha (21 keV)





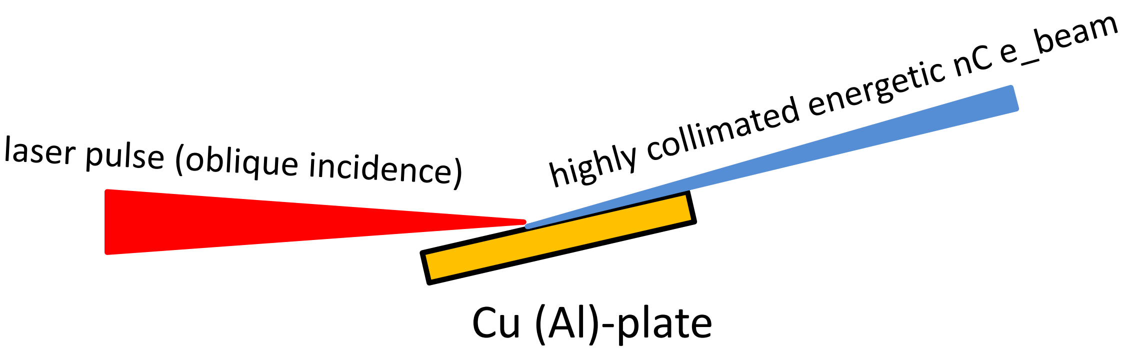
Target	absolute photon Energy [J]	$\eta_{conv.}$ [%]
Ag bulk	$1{,}52 \cdot 10^{-3}$	$1{,}57 \cdot 10^{-5}$
100µm Ag - Plexi	$6{,}08 \cdot 10^{-4}$	$6{,}49 \cdot 10^{-6}$
10µm Ag - Plexi	$2{,}15 \cdot 10^{-4}$	$2{,}13 \cdot 10^{-6}$

Is it sufficient for backlighting experiments?
Depends on background conditions in FAIR-target chamber

Optimisation for high laser intensitits using **hot electron refluxing effect** in thin foils.

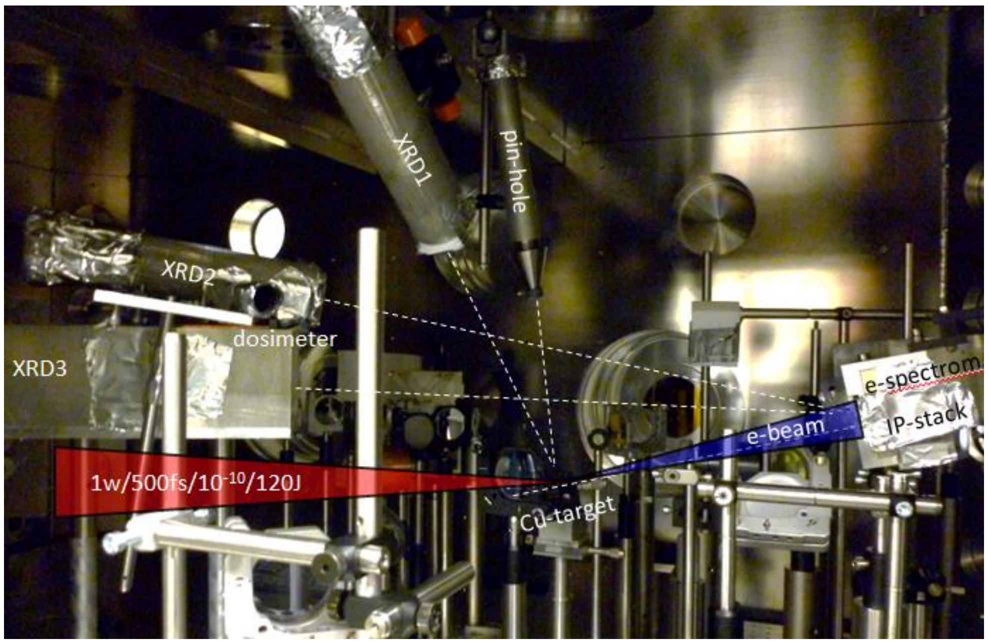
FAIR-relevant experiments at the PHELIX-laser

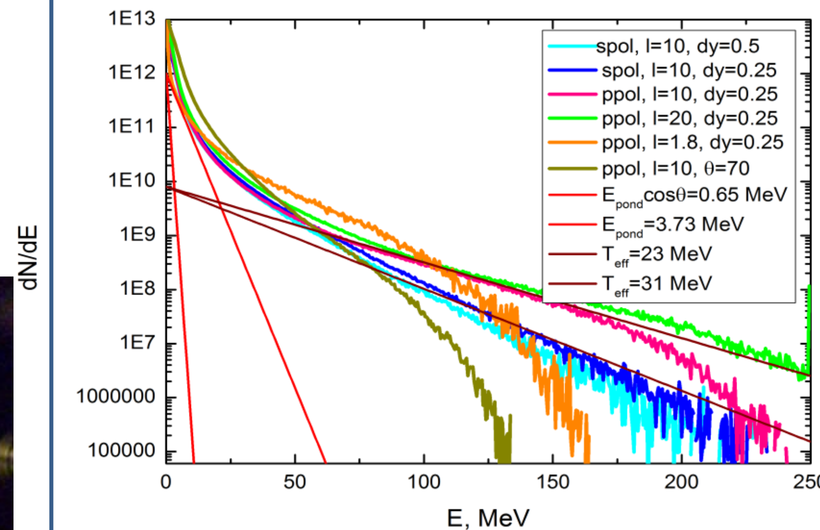
- **laser accelerated electron beams for radiographic applications mechanism of target surface (**guided**) e_acceleration (TSE)**



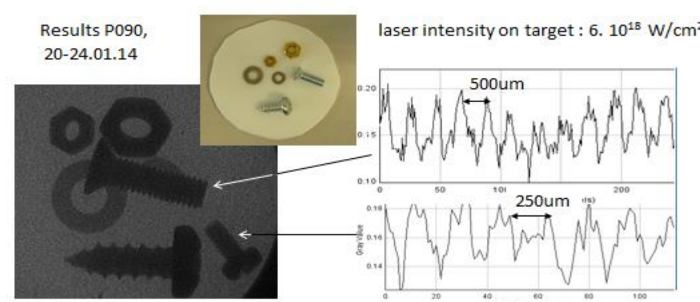
Laser driven electron acceleratio (TSE)

Generation of the highly collimated energetic Target Surface Electron beam with nC-charge in the ultra intense laser system.





3D-PIC predictions of the electron energy distrib. by N. Andreev and L. Pugachev, JIHT



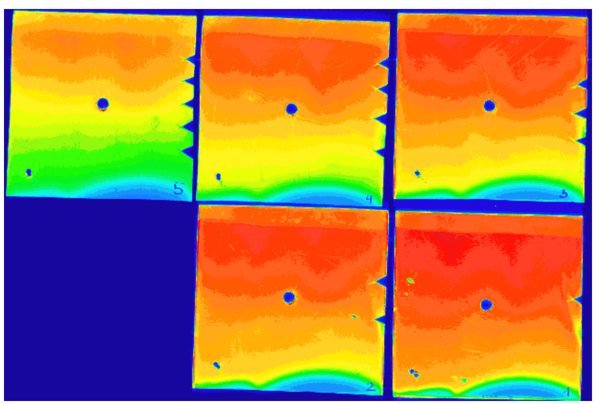
Radiographic image of high areal density object by hard x-rays caused by accelerated electrons

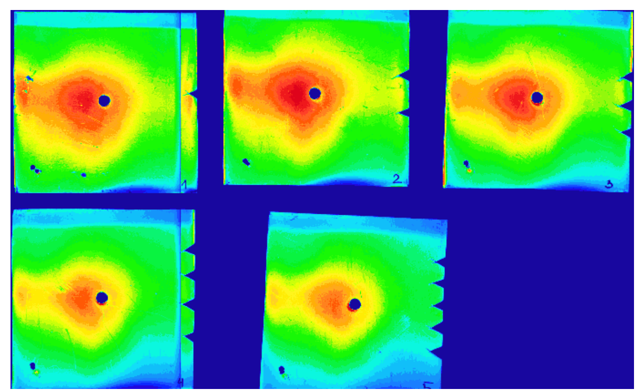
Laser driven electron acceleration (TSE)

By changing the prepulse intensity ratio and laser incident angle, the spatial distribution and energy spectrum of the TSE beams are studied and optimized

Laser condition: E=110-120 J, φ=20×25 μm, time=0.5 ps, ns contrast: 10^{-10}
Prepulse ratio: 5×10^{-6}, time delay: 2.8ns
Laser incident angle: 72^o - 80^o

Image Plate stacks: collimation of the e-beam





Experiment continuation- June 2015

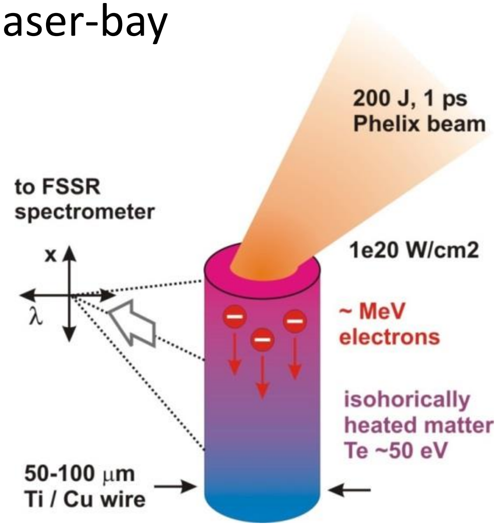
FAIR-relevant experiments at the PHELIX-laser

- **laser accelerated electrons for WDM generation**

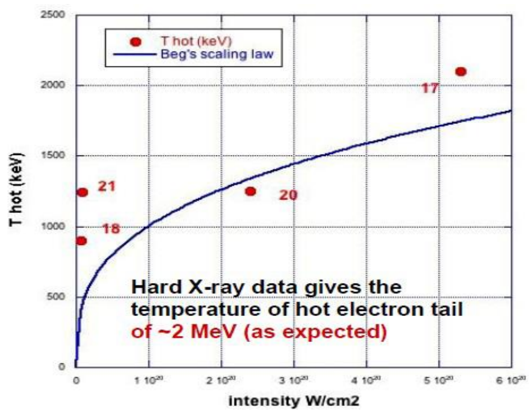
Laser accelerated electrons for WDM generation

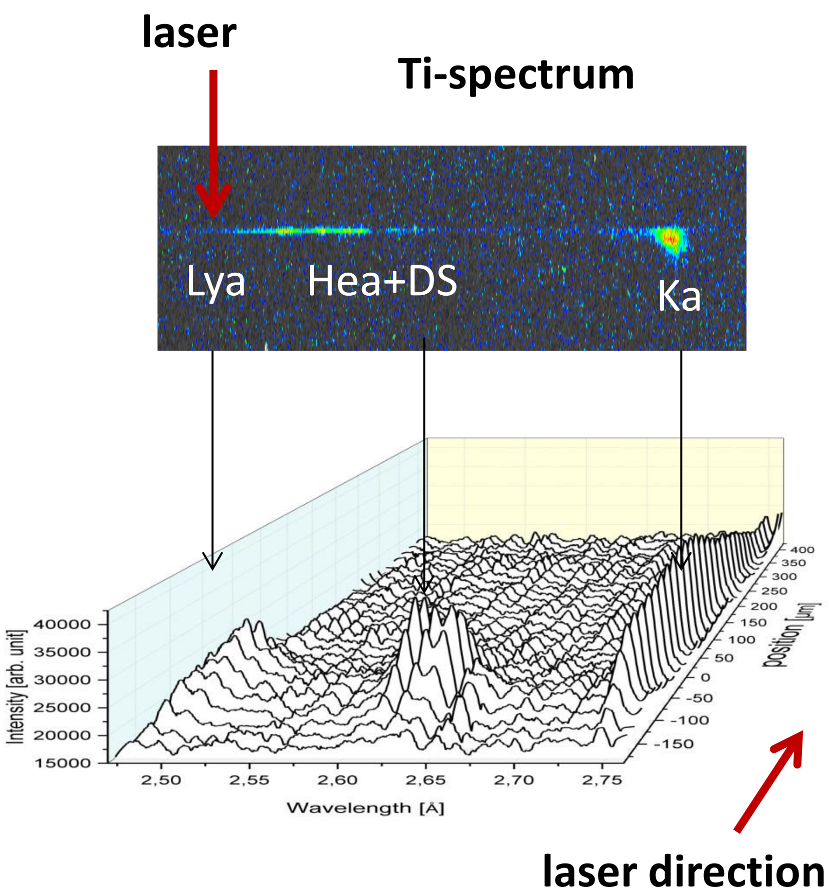
June 2013

Laser: 1ω (1.056 μm); 500fs ; 120 J foc. in 6 μm, I=10^{20} W/cm^2, ns-contrast 10^{-10}
Target: d=50 μm l=2mm Ti-wire
area: laser-bay



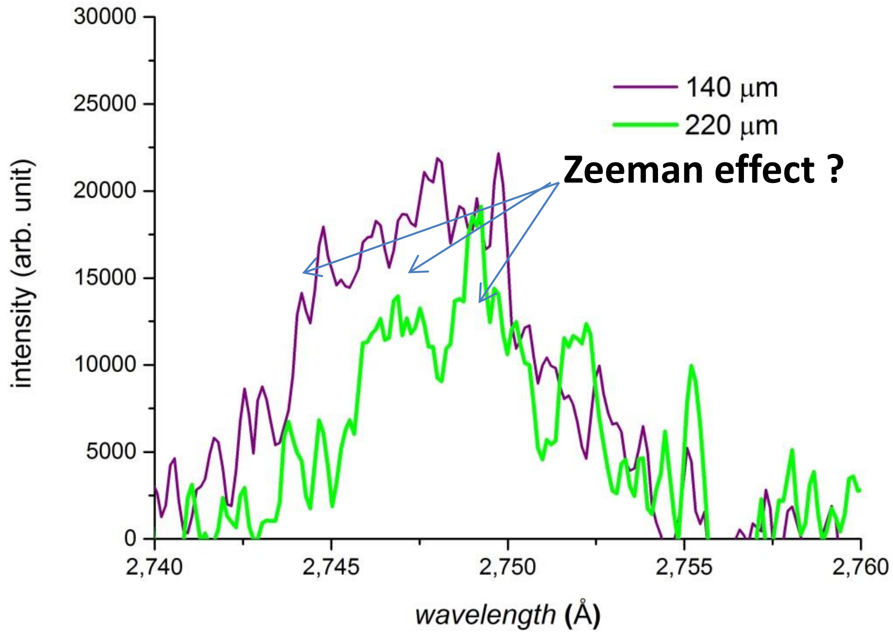
1- 2 Mev hot electron temperature

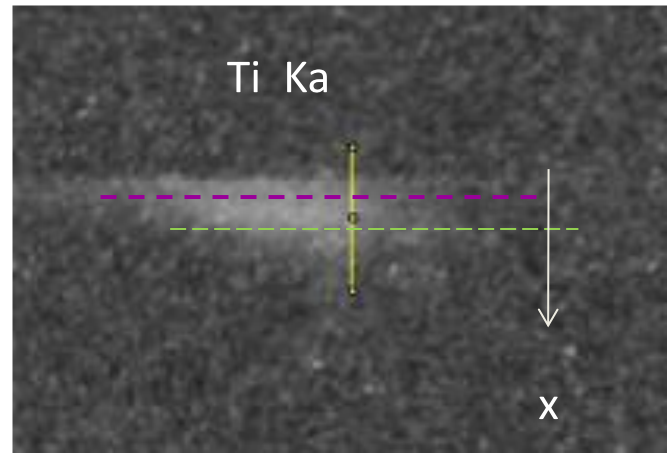


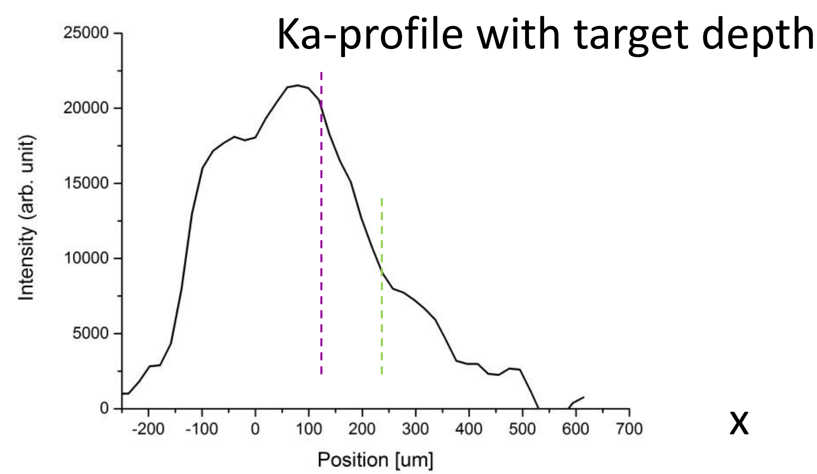


Laser accelerated electrons for WDM generation

- **K-alpha broadening helps to infer on temperature profile of the wire(up to 30 eV)**
- **Ka triplet-struchture indicates presence of high magnetic fields**







- **Penetration depth of electrons shorter then expected for cold target**
  - **Magnetic field (up to MGaus)**
  - **Ohmic barrier**
  - **Refluxing on target edge**

FAIR-relevant experiments at the PHELIX-laser

- **Ion stopping in non-ideal plasmas**

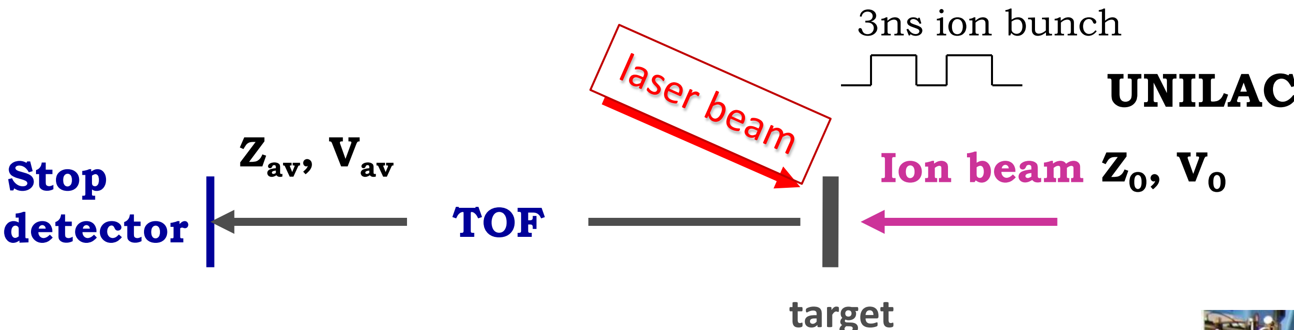
Heavy ion energy loss depends on target density (gas-solid effect) and target temperature (E-loss on plasma free electrons).

FAIR: during interaction Solid-Liquid-Gas-Plasma phase transitions

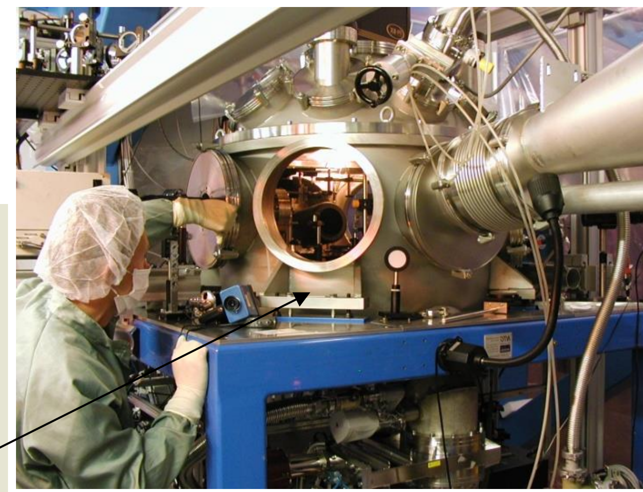
Laser – Heavy Ion Beam combined experiment

May 2014

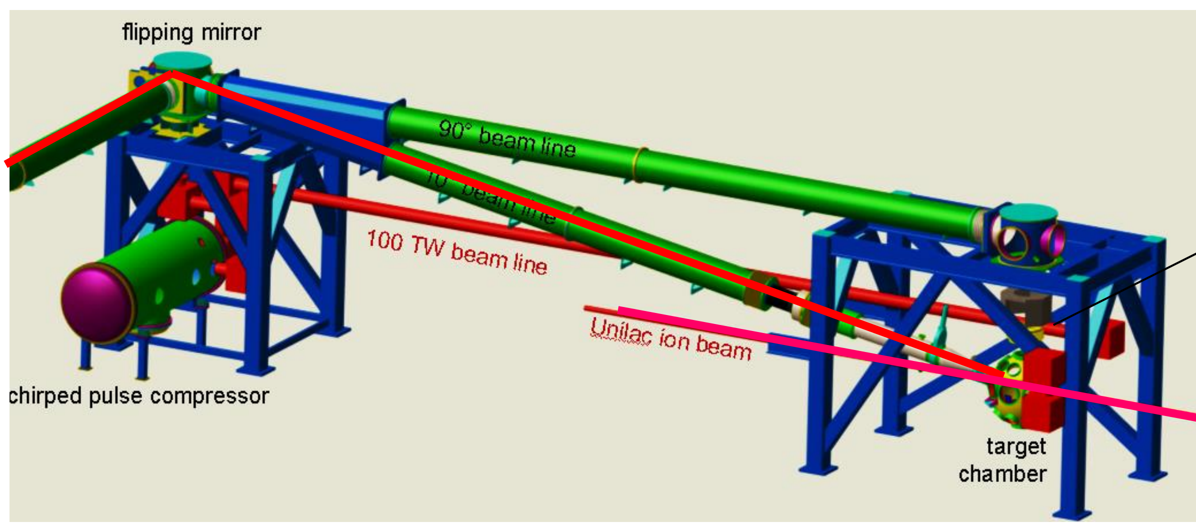
Interaction of heavy ions with ionized matter : **increased plasma stopping power**



Target chamber



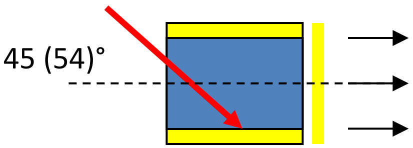
PHELIX-laser (Nd: glass) 1-10 ns, 0,532 um, 180J



Heavy ion beam:
1<Z<92, E=3–13 MeV/u,
RFQ: 108/36 MHz

Diagnostics of the converter radiation field

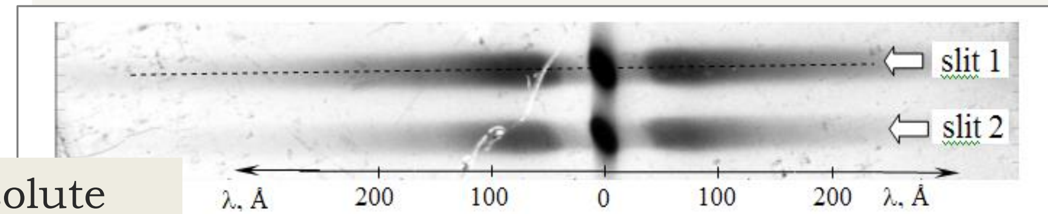
Laser
~250J, 1.4 ns



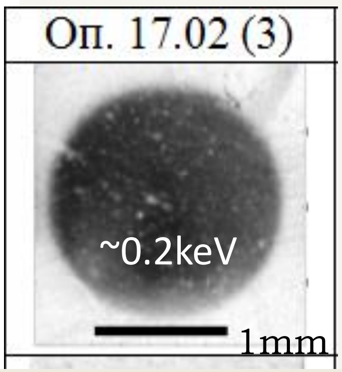
to TGS
X-ray diode
pin-hole

converter

Transmission Grating Spectrometer

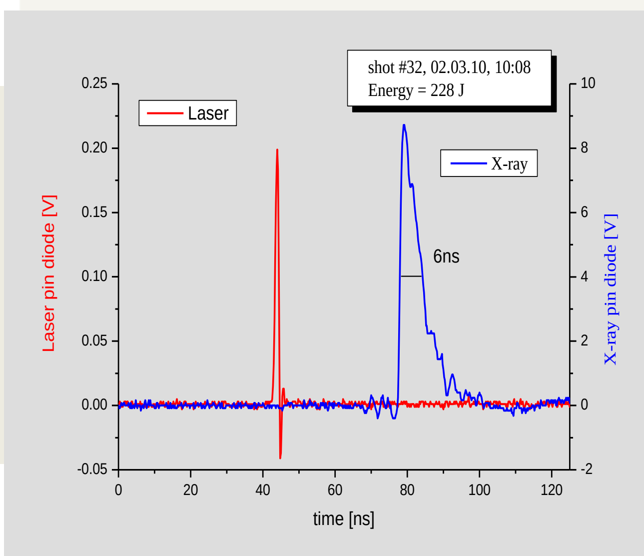


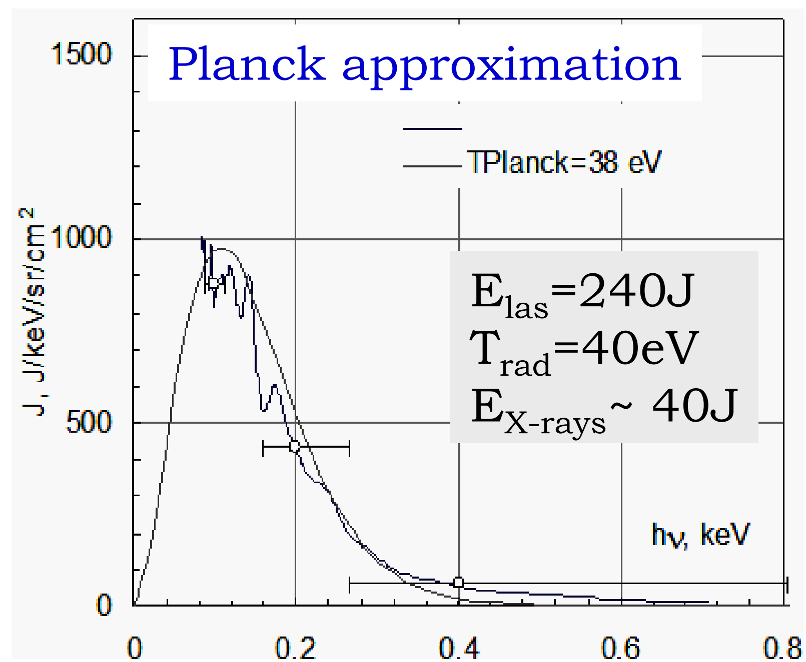
absolute calibrated UV-film



pin-hole image of the hohlraum in 0.2-0.28 keV

Soft X-ray signal ~ 6ns
(laser pulse-1.4ns)





Theoretical supprt on all stages of experiment

Theoretical support is crutial on all stages of experiment:
starting with project design up to avaluation of obtained results!

Galina Vergunova (LPI) : 1D HD with radiation transport in duffusion approximation (code RALEF)

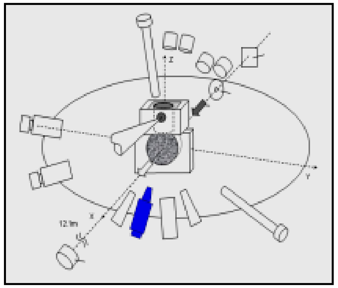
Nikolay Orlov (JIHT): opacitty in warm dense plasmas (ot available) for specific material composition ($C_{12}H_{16}O_8$)

M. Basko, V. Novikov, A. Grushin (**IMP, Keldish**): 2D HD with real radiation transport (code RALEF II)

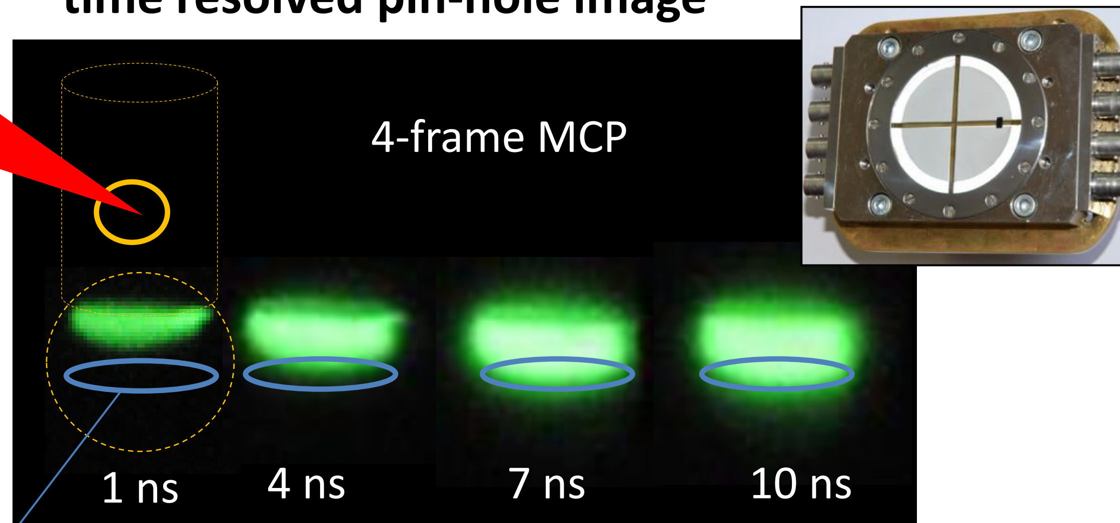
talk Orlov N. Yu. et al: Theoretical and experimental studies of radiative and gas dynamic properties of substances at high energy density in matter.

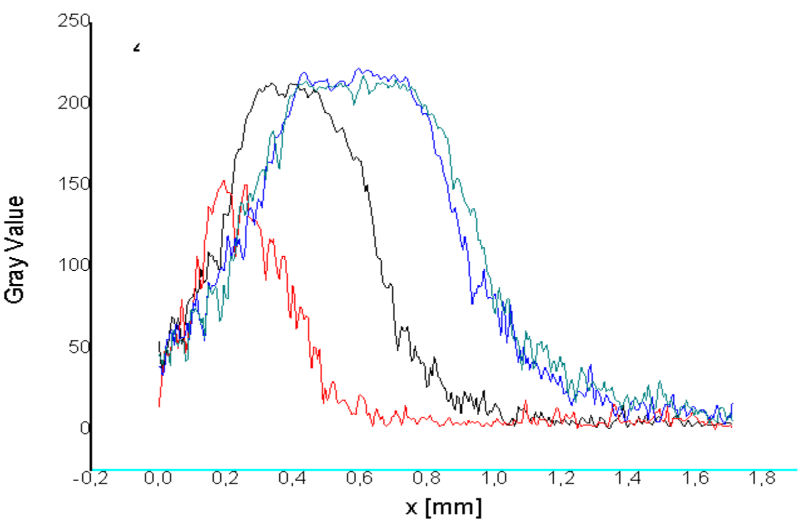
Supersonic radiation heat waves in plasma

time resolved pin-hole image



ion beam position



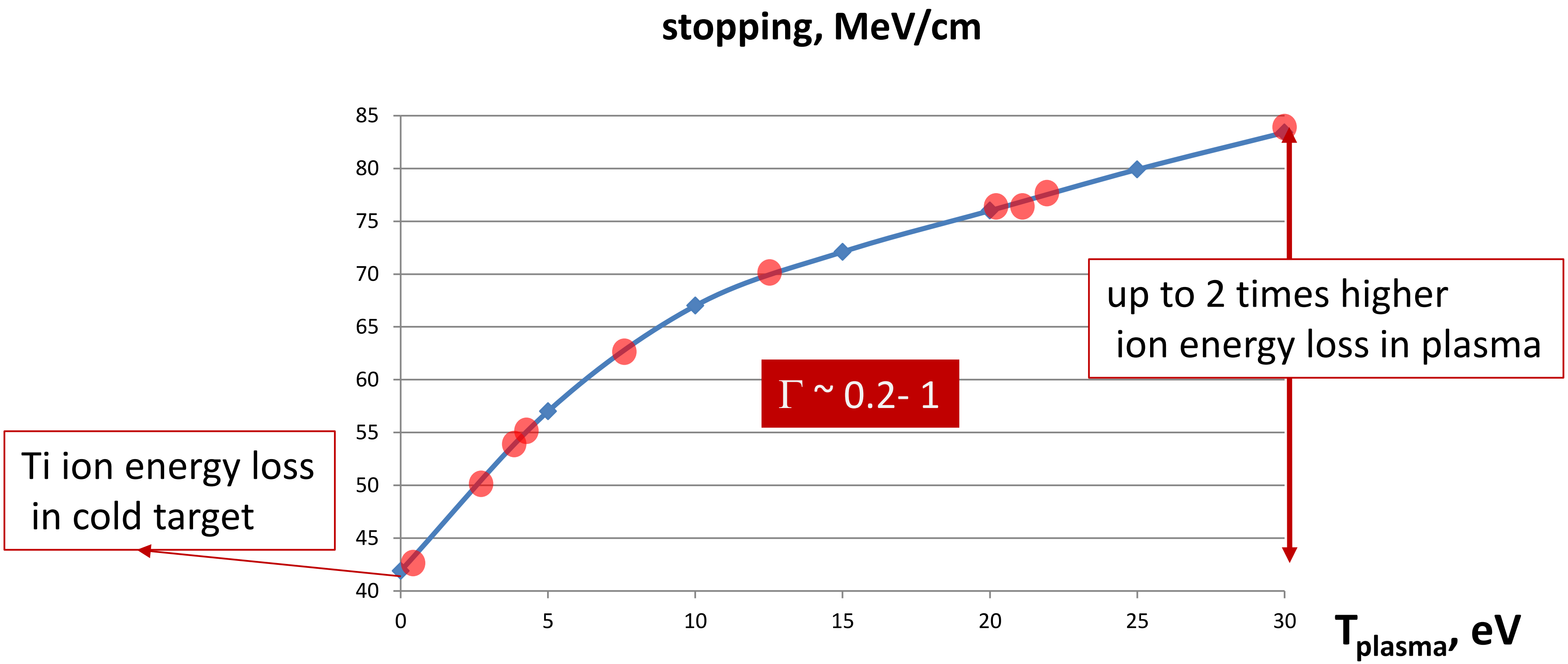


supersonic heat wave velocity $V \sim \frac{T^5}{\rho \sim const}$

$$V(1\,ns) = 1.2\;10^7 cm/s \rightarrow T \sim 25\;eV$$
$$V(4\,ns) = 8.3\;10^6\,cm/s \rightarrow T \sim 23\;eV$$
$$V(7\,ns) = 4.0\;10^6\,cm/s \rightarrow T \sim 20\;eV$$
$$V(10\,ns) = 1.4\;10^6\,cm/s \rightarrow T \sim 15\;eV$$

Ion stopping in dense plasmas

Energy loss of 240 MeV T-ion beam in C-plasma

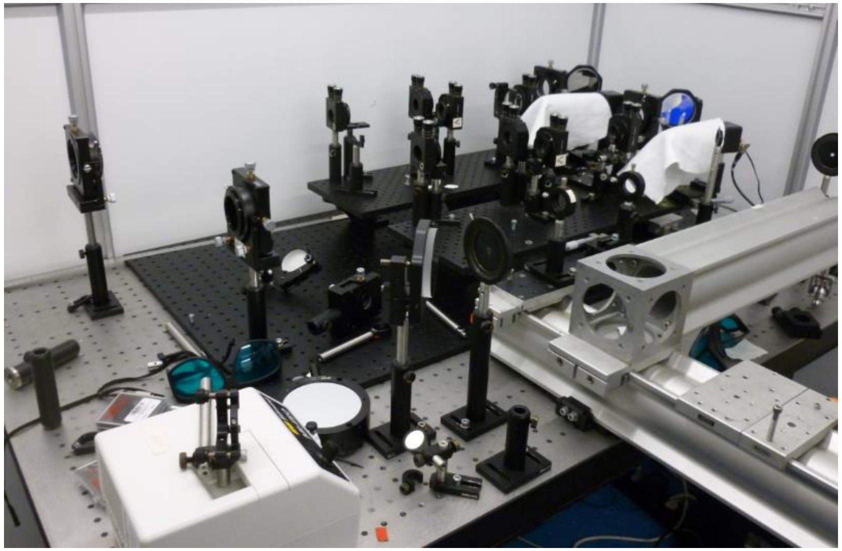


By varying the **delay between the laser and the ion pulse** we can probe **different plasma conditions**

simulations: T. Rienecker ; num. code M. Basko;
measurements: D. Msartsovenko, Sarov; R. Maeder, T. Rienecker, AP, Uni-Frankfurt

FAIR-relevant experiments at the PHELIX-laser

- **Laser generated shocks for EOS**



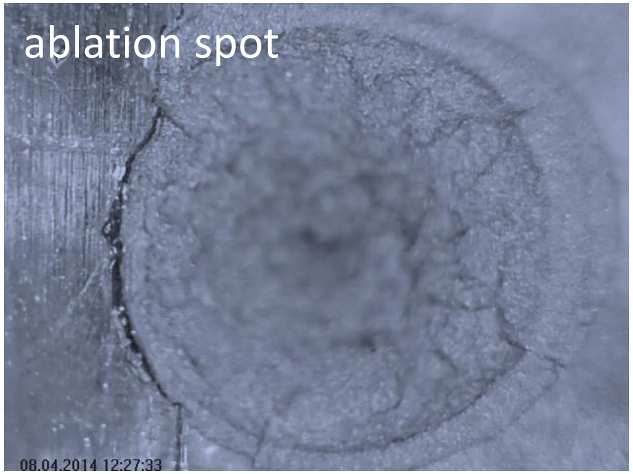
part of VISAR-system , GSI

Laser generated shocks for EOS

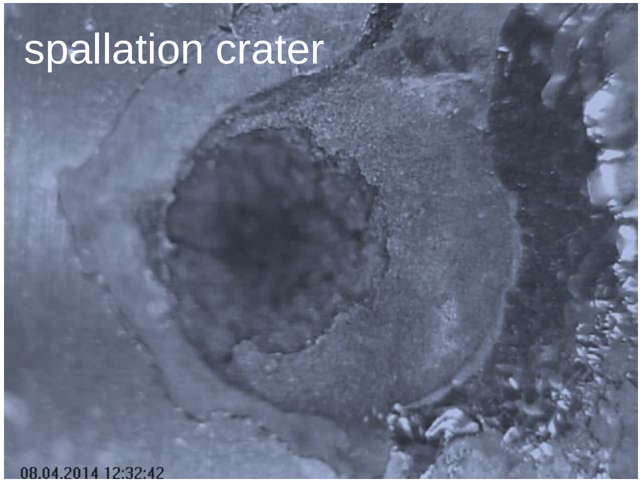
Laser: 2ω (0. 530 μm); 1.2 ns ; 120 J, 0.5-1mmm Phase plate, I<10^{14} W/cm^2
Target: 0.1-2 mm thick plates of Al (standart) and novel Carbon composites
area: Z6

for these laser parametres in Carbon expected
max. presure up to 4 MBar, shock velocitites - up to 23 km/s

Images of ablation spots and spallation craters, obtained with an optical microscope (2mm thick Al plate,GSI), post shot diagnostic.



The front side of the target, irradiated by ns-laser pulse

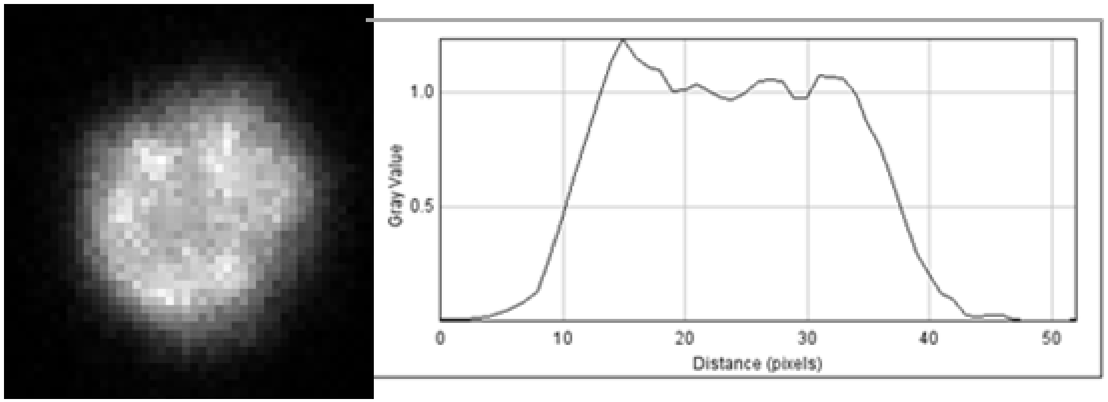


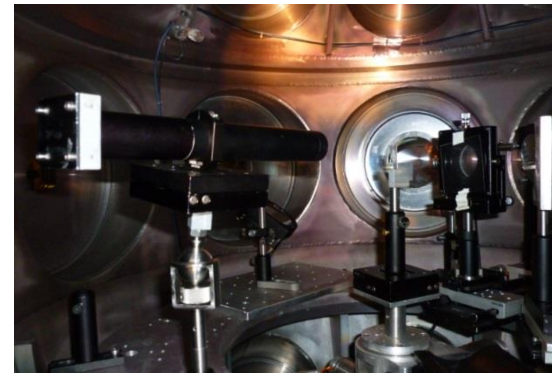
The rear side of the target: spallation crater.

talk: I. K. Krayuk et al, Study the dynamic tensile strength of graphite in stress produced by nanosecond and picosecond laser pulses

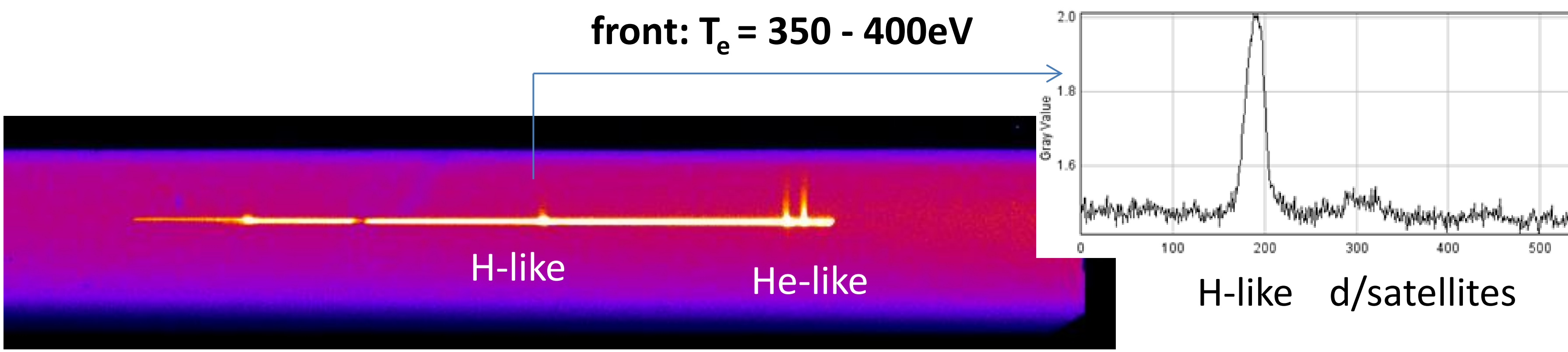
Front diagnostics in laser driven shock experiments

X-ray pin-hole image of the plasma radiation-reflects laser intensity distribution

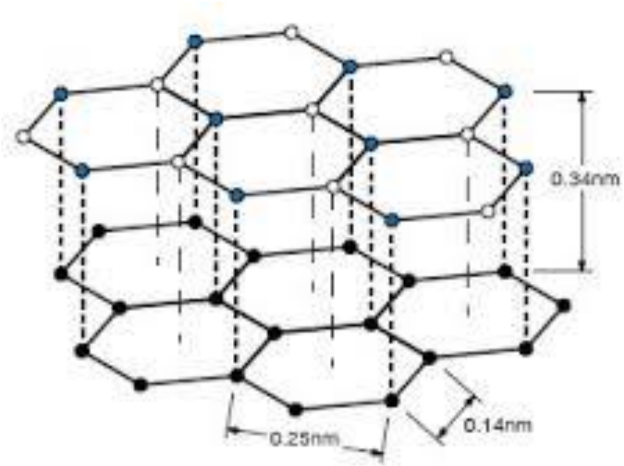




FSSR time intergated spatially resolved X-ray spectrum of H-anfd He-like Al

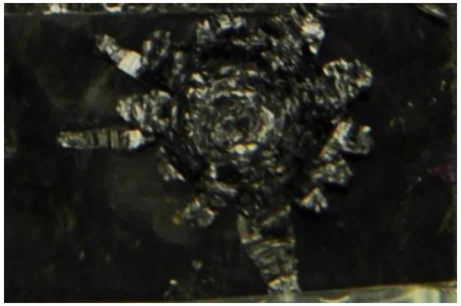


HOPG
Highly Oriented Pyrolitic Graphite

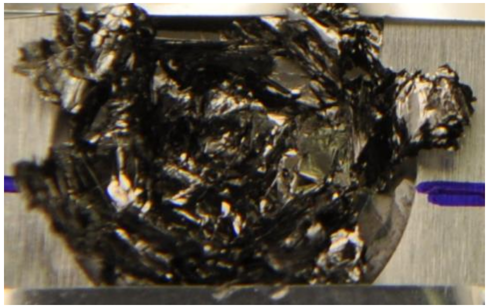


- Hexagonal crystalline structure
- Low Mosaicity
- density 2.27 g/cm^3

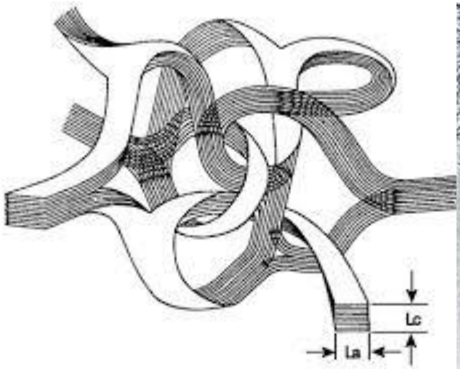
Front side crater

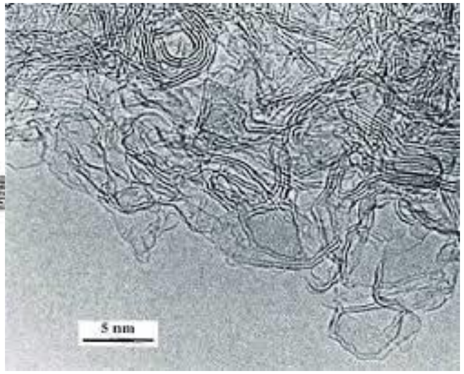


Back side crater



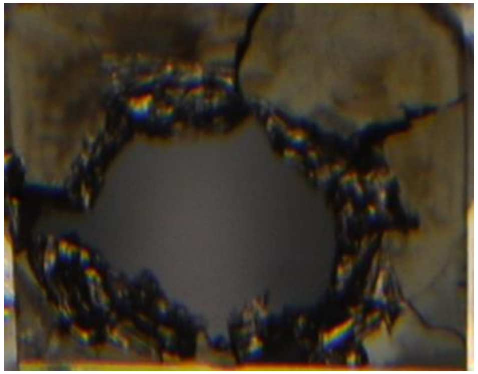
GC
Glassy Carbon



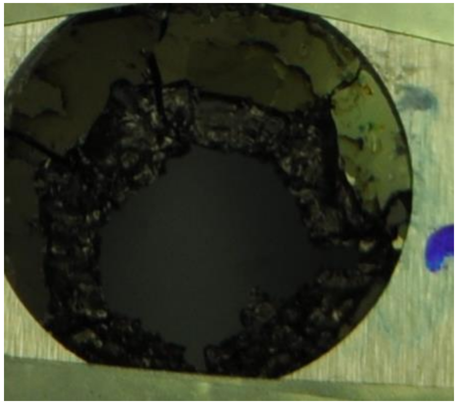


- a non-graphitizing carbon which combines glassy and ceramic properties with those of graphite
- - density 1.42 g/cm^3

Front side crater

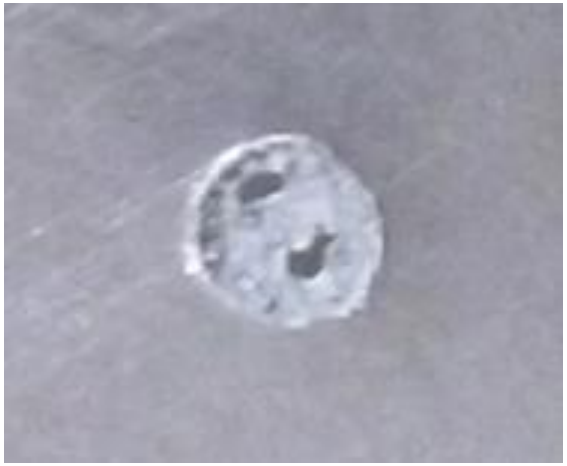


Back side crater



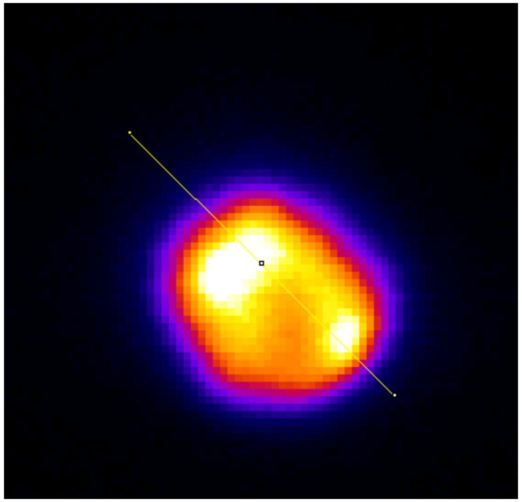
Importance of the lasere enegy distribution for planar shock generation

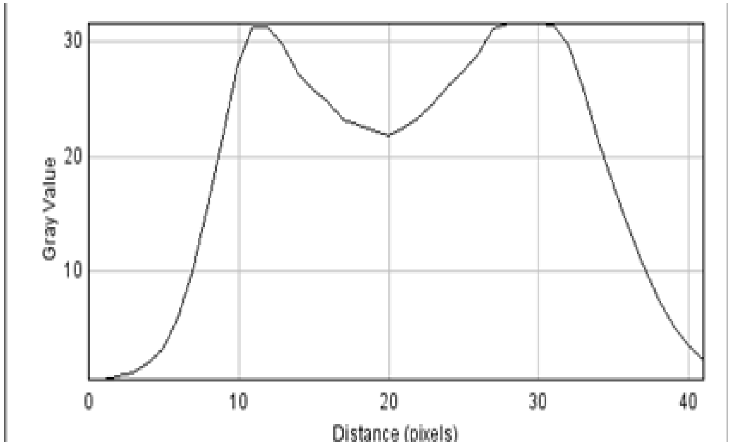
spallations on the rear side of 300um Al plate after 120J laser shot



shot 18, November 2014

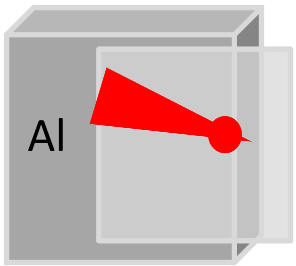
X-ray pin-hole image (>500eV) of the from plasma radiation and its profile

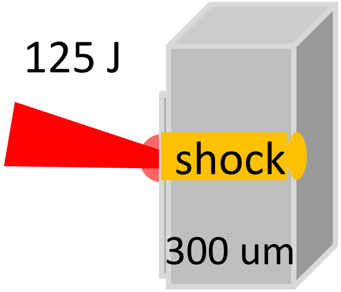




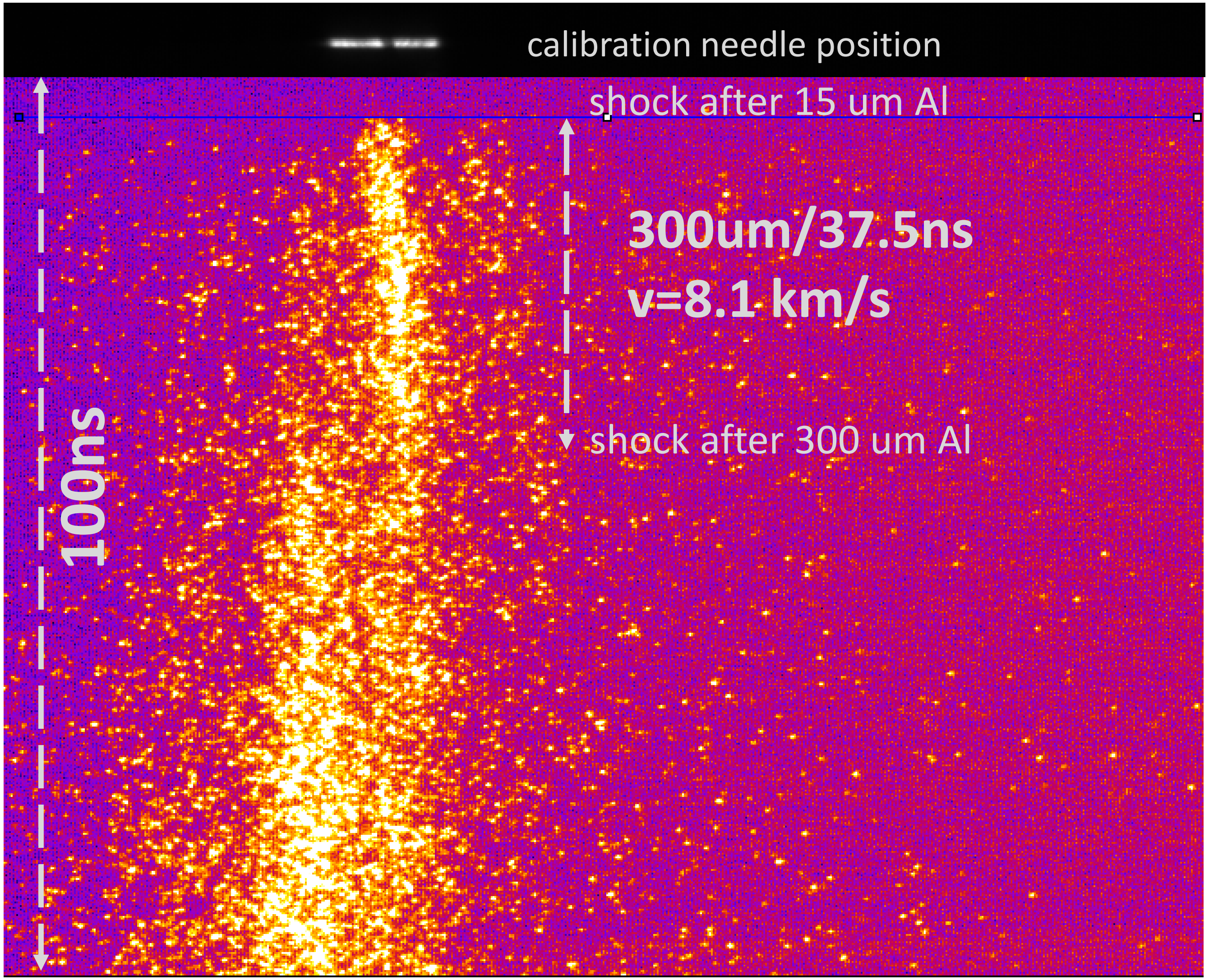
Laser driven shock waves in Al plate

results of Streak Optical Pyrometry (SOP), Feb. 2014





optical streak of the target rear side radiation with temp. of some eVs.



Laser driven shock waves

Important to continue this type of experiments with ns laser pulse:

1. EOS - physics
2. creation of WDM on the rear target side with interesting properties
3. working out of FAIR-relevant diagnostics (VISAR, SOP, etc.)

Working moments

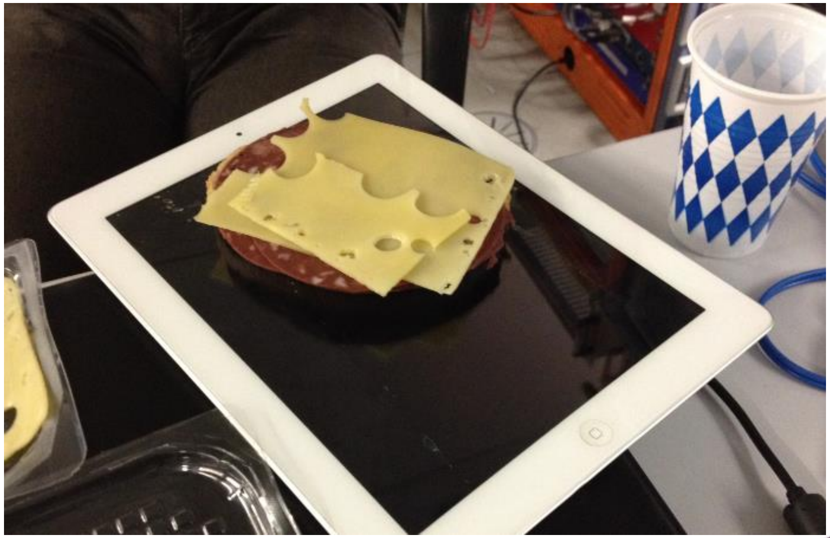
Preparation of the laser-shot

shot

ITEP and MIPhI young generation

Daily discussion of results and problems

Working moments and fun



You are welcome!

waiting for the perfect shot