Laser Driven X-ray Radiography On Warm Dense Matter

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WDM: Definition

Warm **D**ense **M**atter = Dense **plasmas** at **temperatures** of **0.5 – 50 eV** (≈ 5.000 – 500.000 K) at **around solid density**

WDM→ **strongly correlated** $\langle E_{pot} \rangle \approx k_B T_e$

WDM → **partly degenerated** $k_B T_e \approx E_{Fermi}$

<u>Example:</u>

Titanium @ solid density, T = 10 eV:

Coupling parameter: $\Gamma := \frac{\langle E_{pot} \rangle}{k_B T_e} \approx 10$ (Γ << 1 for ideal plasma)

Degeneracy parameter: $\Theta := \frac{k_B T_e}{E_{Fermi}} \approx 2$ (Θ >> 1 for classical plasma)

Pressure: p = 5 MBar (!)

Part of HED: pressures > 1MBar, energy densities of > 100 J/mm³

WDM: Why Should We Care?

WDM can be found:

- in the center of giant planets or brown dwarfs
- whenever a solid is transformed into a plasma
- during the process of ICF

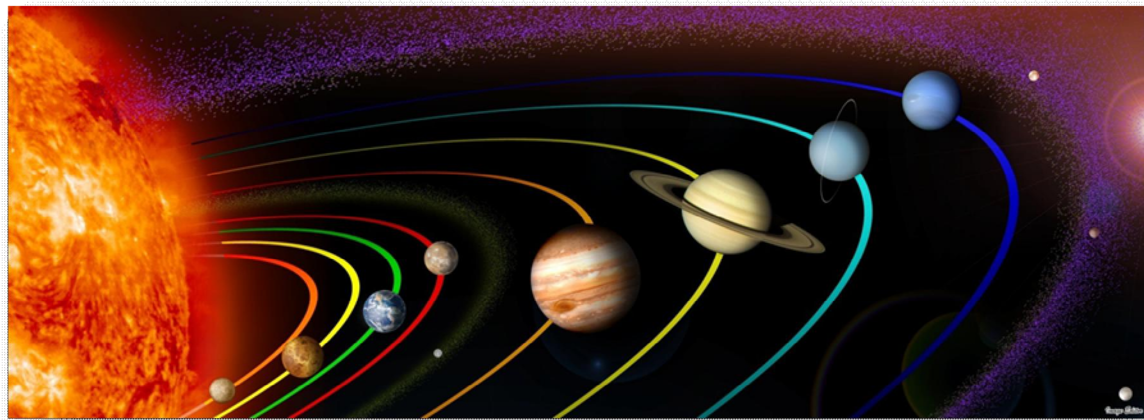


Image: Massachusetts Academy of Sciences

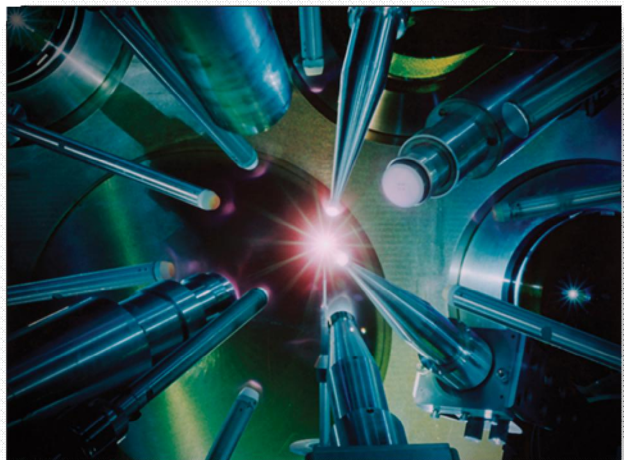


Image: Lawrence Livermore National Laboratory

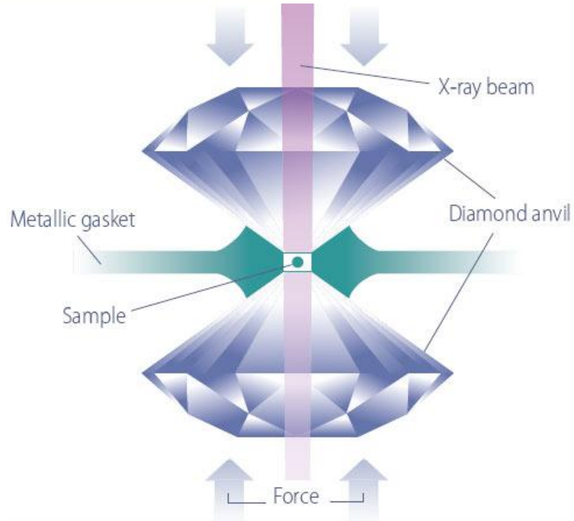
Moreover:

- Wanted: complete physical description
- Access to this regime only recently possible

HED: Generation in the Laboratory I

Static Pressure:

Isothermal pressure increase possible.
Maximum achieved pressure ≈ 3-4 Mbar



Shock:

Dynamically reach higher pressures
Maximum achievable compression in a single shock limited! (→ Hugoniot-curves)

Examples for shock compression methods:
Flyer plate impact (gas guns, z-machine)
Laser shock compression (typ. ns-long, high-energy laser pulses)

HED: Generation in the Laboratory II

Energy deposition inside target:
via charged particles (protons, ions):

$$\frac{dE}{dx} \propto -\frac{n_e Z^2}{\beta^2}[\ldots]$$

via x-rays:

$$\frac{dE}{dx} = -\mu_E(h\nu)$$

(Quasi-)Isochoric heating: heating process **faster than hydro**-expansion

<u>Examples for quasi-isochoric heating via particles:</u>
Heavy-ions at high ion beam intensities (HHT @ GSI, HIHEX and LAPLAS @ FAIR) (~ ns timescale)
Laser-generated protons or ions (~ ps timescale)
Laser-generated electrons (~ ps timescale)

Laser-generated Electrons I

Laser intensities about ≥ 1E18 W/cm² ($|\vec{E}_{\max}| \geq 2.7E12$ V/m)

→ Electron energies

$$\langle E_{kin} \rangle = \frac{m_e}{2} \langle v^2 \rangle = \ldots = \frac{1}{4} \frac{e^2 |\vec{E}_{\max}|^2}{m_e \omega^2} \approx 90 \sqrt{I_{18} \lambda_\mu^2} \quad \text{[keV]}$$

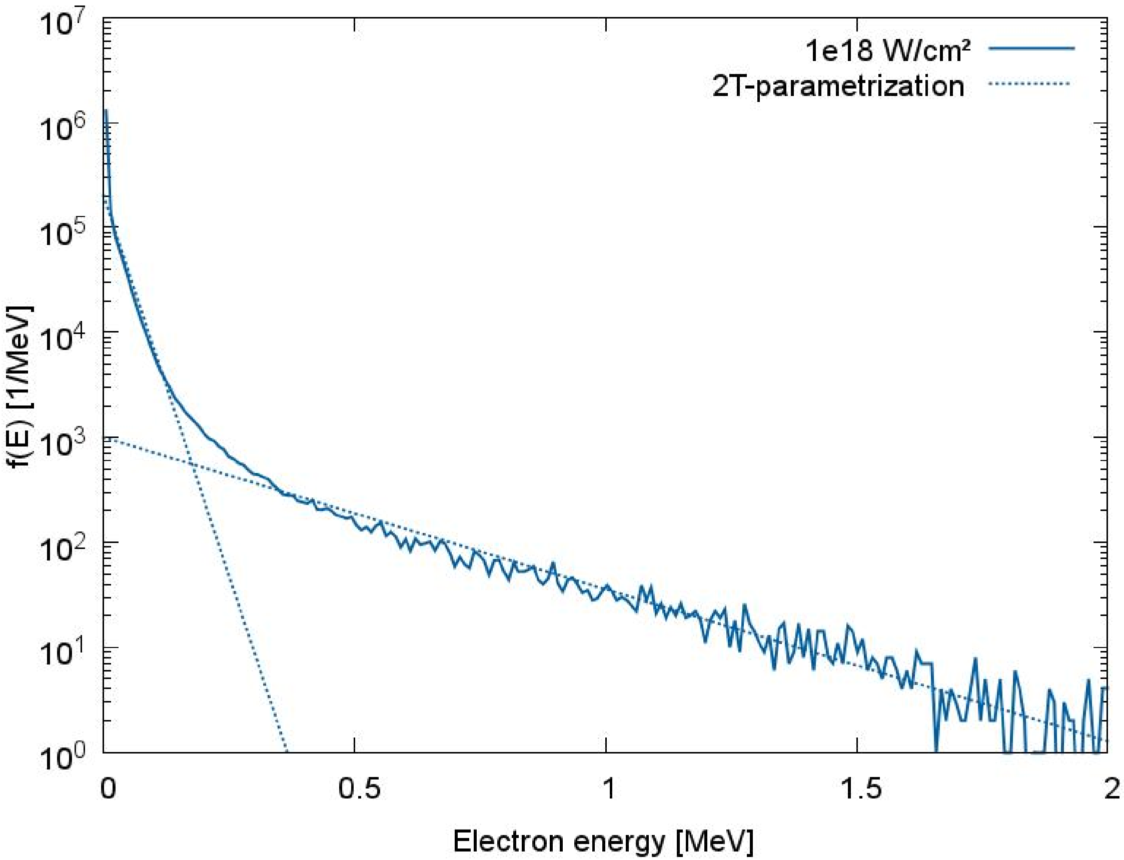
<u>Laser-plasma interaction:</u>

- inverse bremsstrahlung
- resonance absorption
- skin-layer heating
- Brunel-heating
- **J** x **B**-Heating
- Ponderomotive acceleration
- Anharmonic resonance
- ...

Dependent on plasma-gradients, intensity, polarization…

Laser-generated Electrons II

Simulation via **Particle-In-Cell (PIC)** codes.



$$f(E) \propto$$

$$\frac{\eta_1}{T_1} Exp[-E/T_1] + \frac{\eta_2}{T_2} Exp[-E/T_2]$$

Typical:
η ≈ 10%, T ≈ 100s – 1000s keV

$$T_{Wilks} = 511\left(\sqrt{1+\frac{I_{18}\lambda_{\mu}^{2}}{1.37}}-1\right)\ [\mathrm{keV}]$$

$$T_{Beg} = 100\cdot\left(10\cdot I_{18}\lambda_{\mu}^{2}\right)^{1/3}\ [\mathrm{keV}]$$

Calculations performed by A. Karmakar, P. Gibbon, FZ Jülich

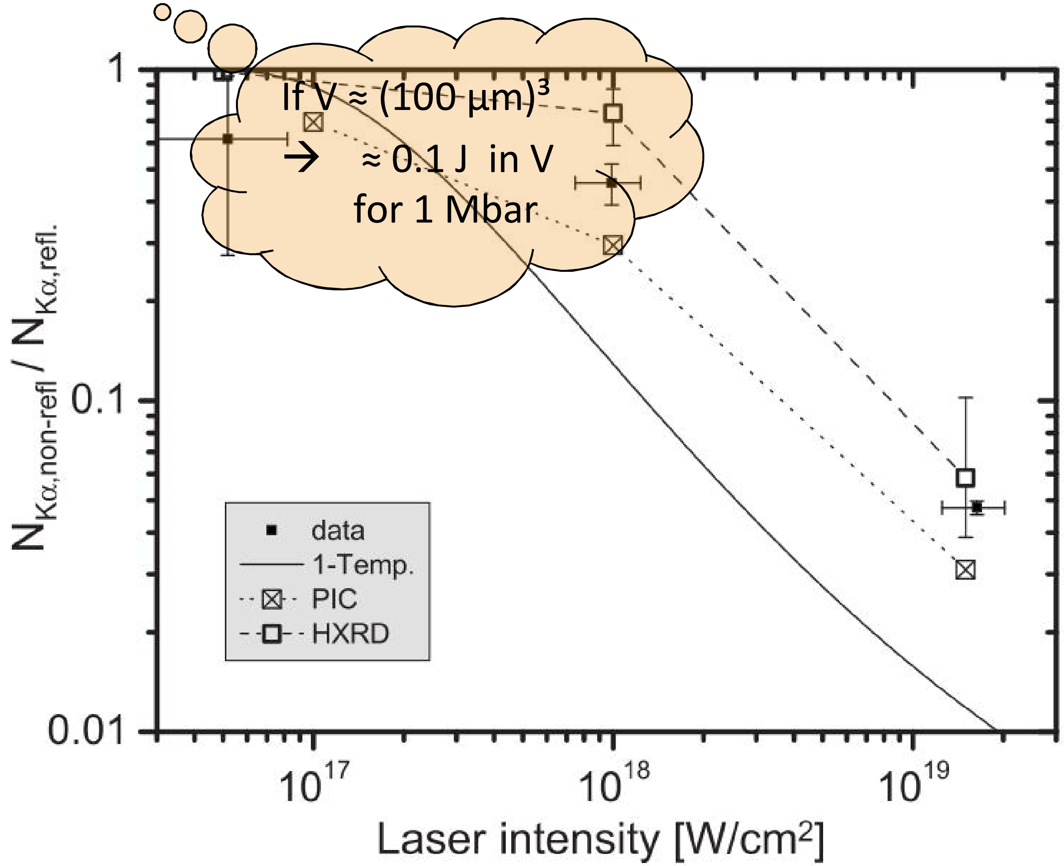
Electrons in a Cage

Typical electron energies: 100 keV – 10 MeV → **Range in solids ≈ mm to dm**

How can we deposit the energy in a small volume?

→ **Refluxing** of the hot electrons can be responsible for >95% of K_α and X-ray yield!

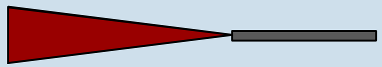
P. Neumayer et al., The role of hot electron refluxing in laser-generated K-alpha sources, Physics Of Plasmas 17, 103103 (2010).



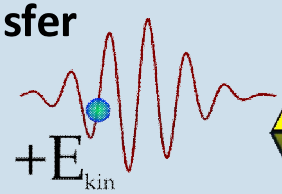
Recipe: HED Via Isochoric e^--Heating I

Prepare a small, free-standing target (foil, wire, droplet etc.)

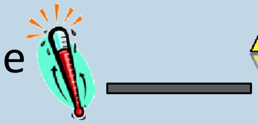
Focus a high-energy laser onto the target



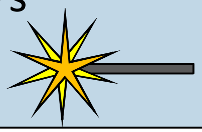
Energy transfer
Laser → e^-



Energy deposition
inside the target volume



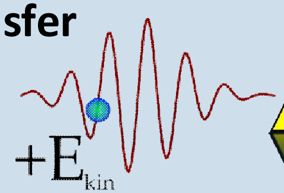
Expansion
($v \approx v_s \sim 30$ km/s
= 30 µm/ns)



Recipe: HED Via Isochoric e⁻-Heating II

Physics of… | Responsible for… | Measured by…

Laser absorption, hot electron generation → **Energy transfer** Laser → e^-



Electron transport, return currents etc. → **Energy deposition** inside the target volume

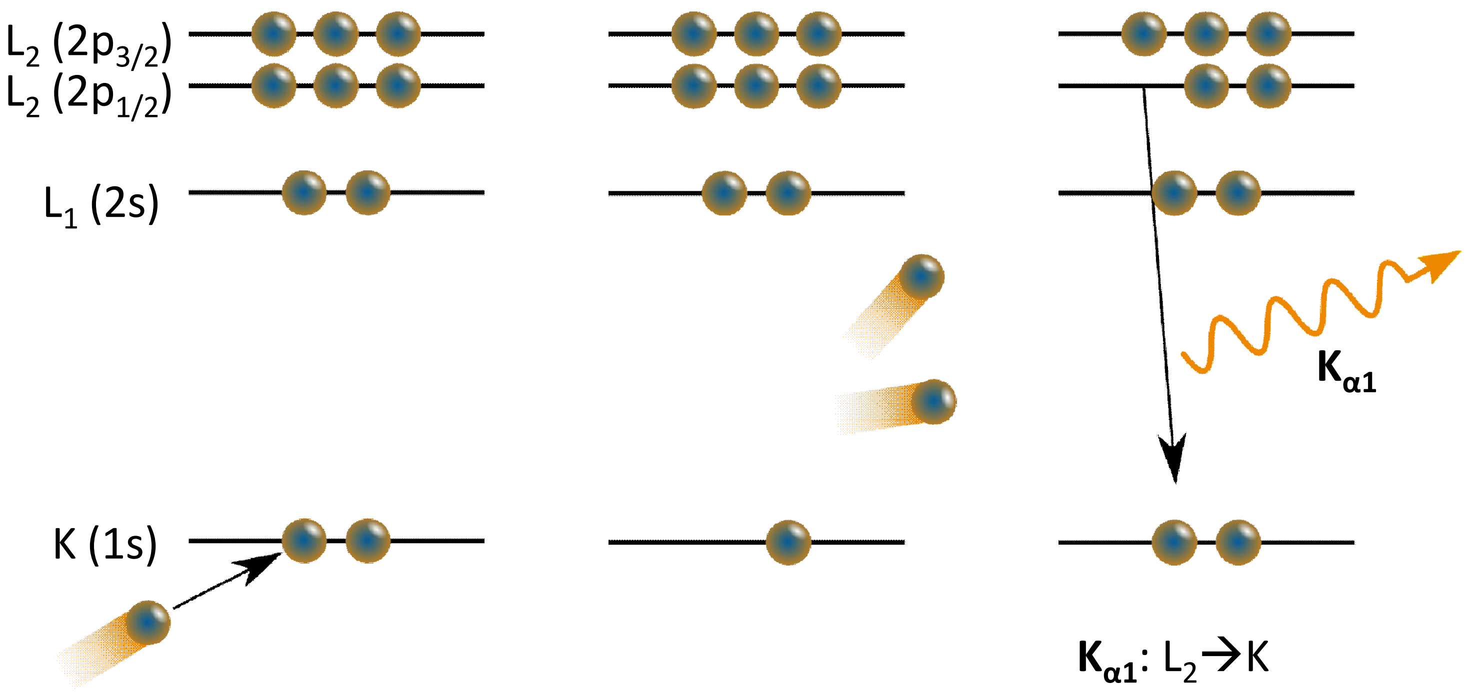
Measured by: Spatially resolved K_α-spectrometry

Fluid dynamics, EOS → **Expansion** ($v \approx v_s$ ~ 30 km/s = 30 µm/ns)

Measured by: X-ray radiography

Reminder: K_α-Radiation

Line emission characteristic for material, charge state and temperature

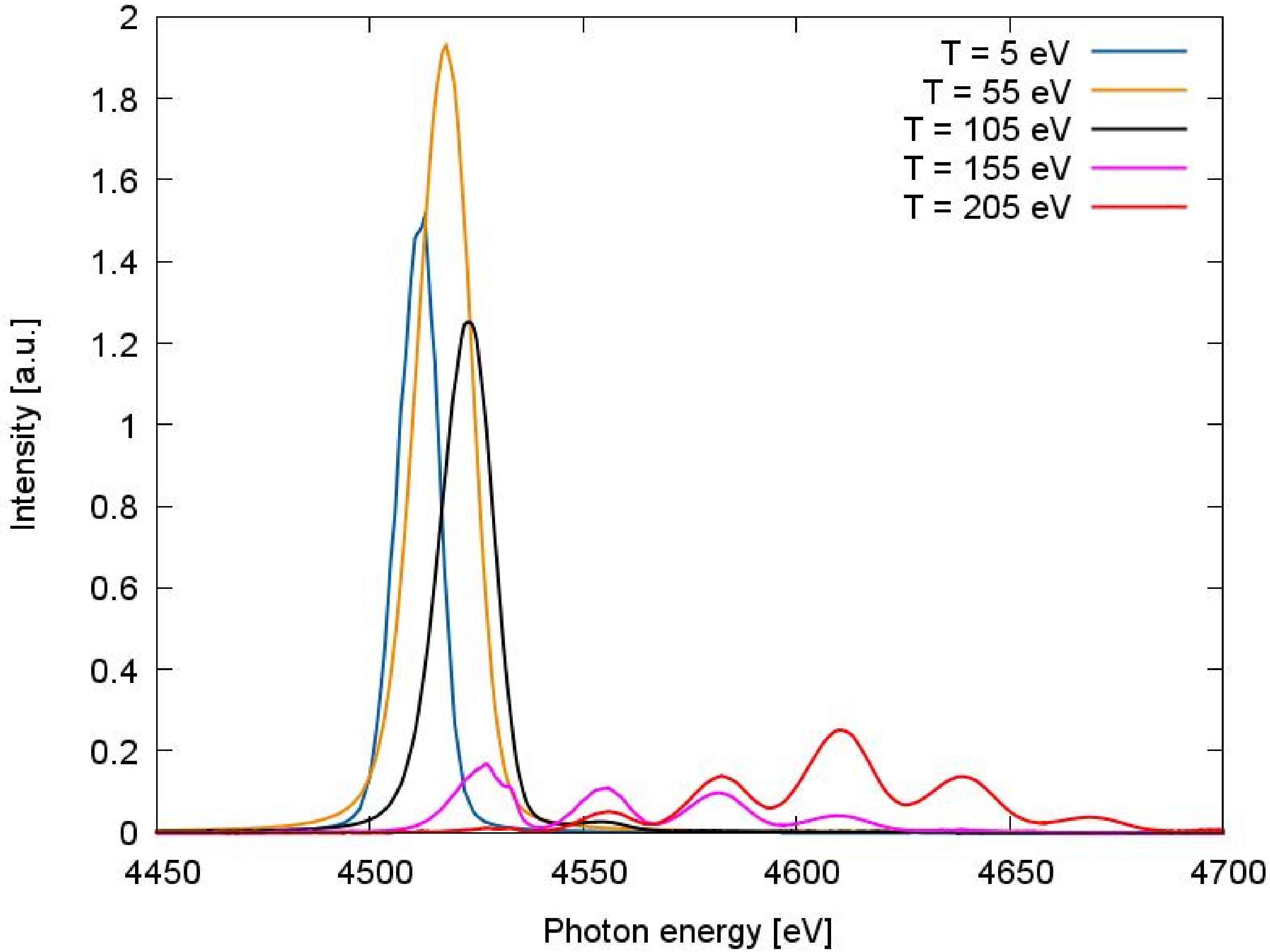


$K_{\alpha 1}$: $L_2 \rightarrow K$
$K_{\alpha 2}$: $L_3 \rightarrow K$

K_α -signal at X → electron ($E \geq E_{K\text{-ionization}}$) passed X

K_α-spectrometry

Atomic kinetics simulation (FLYCHK) for Ti @ solid density



Higher T
→ ionization

Different energy levels in different ion species
→ appearence of satellites

X-ray Radiography: Requirements

Radiography = taking photographs of the inside of a sample at different waiting times after start of expansion

Typical sample size L ≈ 10 – 100 µm →

- **spatial resolution** better than L
- **time resolution** better than ≈ L/v_s = 0.3 – 3 ns

$n_e < n_c(h\nu)$ and reasonable opaqueness →

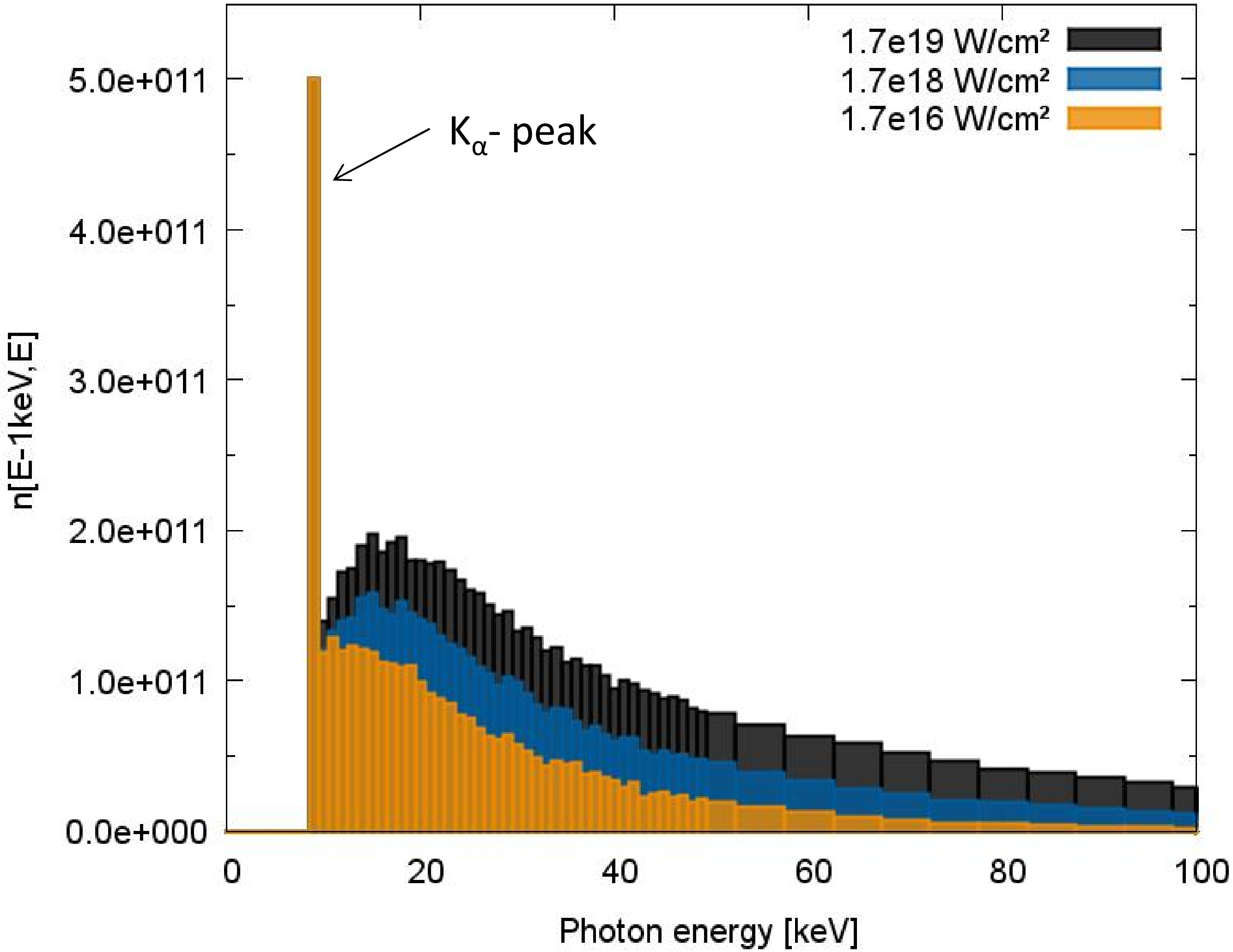
- **hν ≈ 1 – 10s of keV** (intermediate x-rays)

Photon number of „imager" ≥ self emission of target →

- **bright** backlighter

→ second high energy laser beam focussed onto a thin foil → Bremsstrahlung + line emission confined to foil

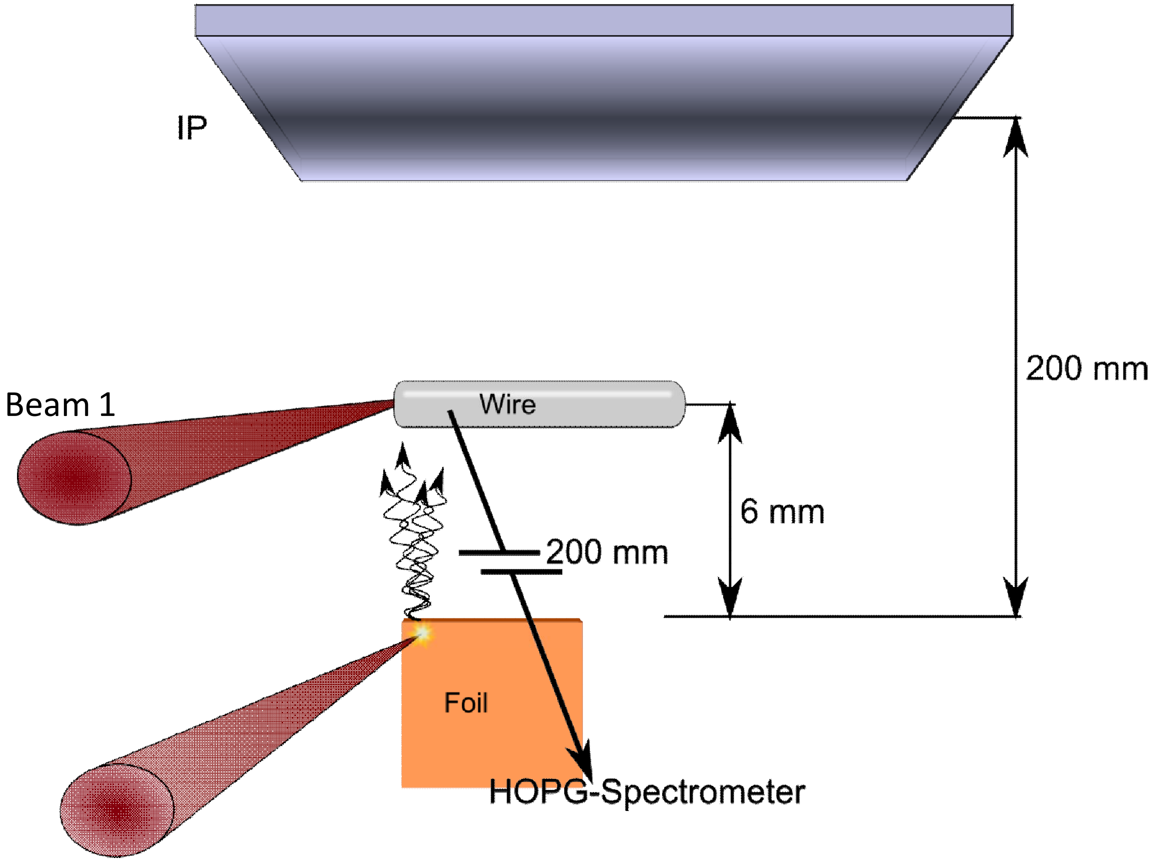
X-Ray Radiography: Imaging Spectrum

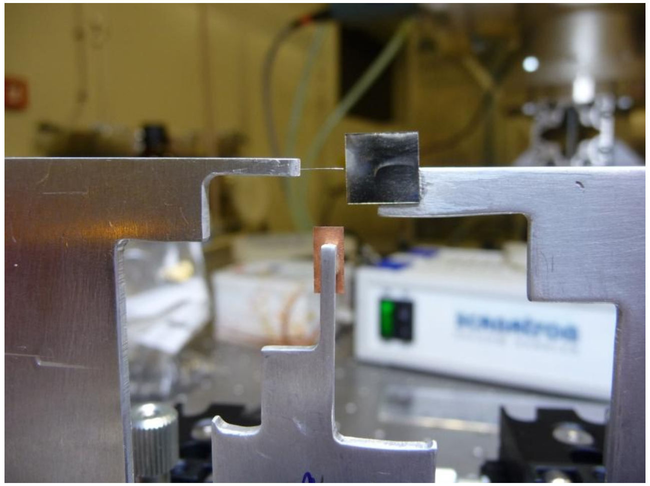


Spectrum must be known to extract densities from radiograph!

Experiment: Target Setup

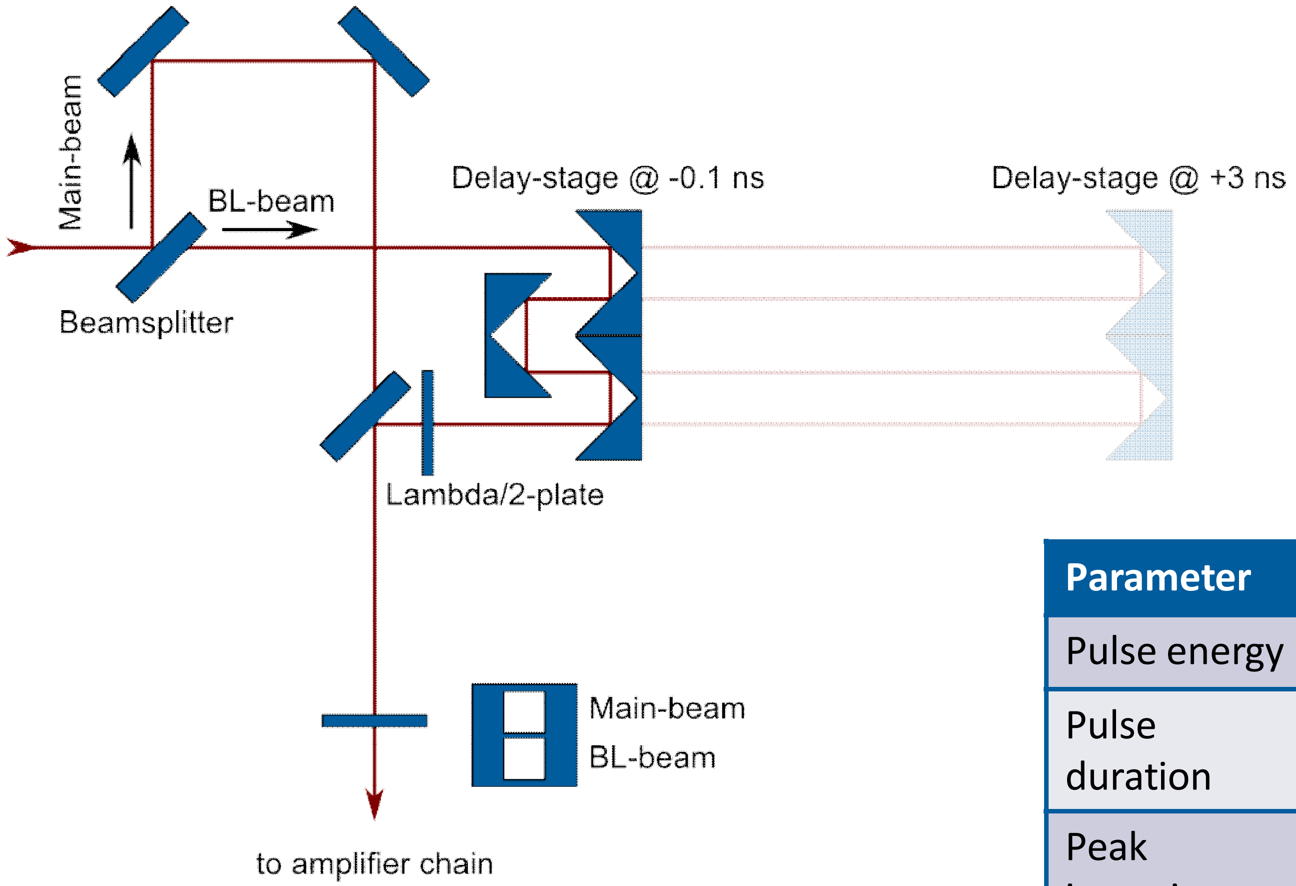
WDM-target: Ti – Wire (d = 50 & 80 µm, L = 5mm)
Backlighter-target: Cu – Foil (d = 3 & 7.5 µm)

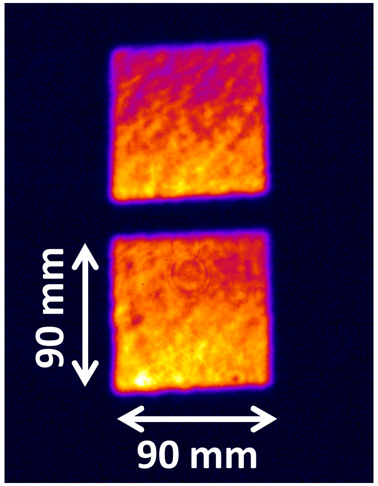




Experiment: Double-Beam

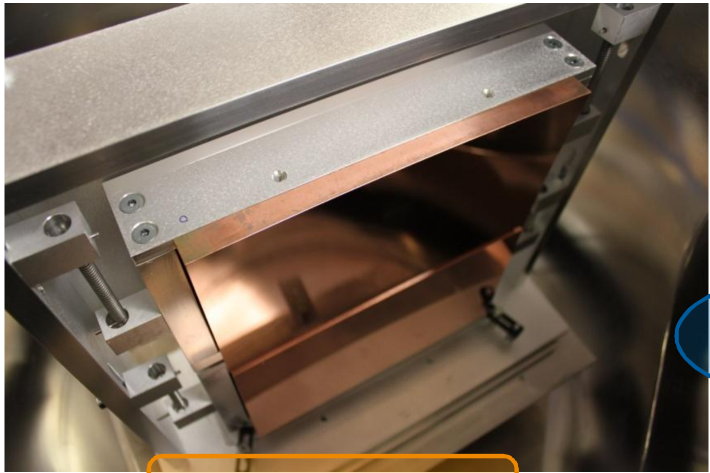
Schematic of the double-beam setup



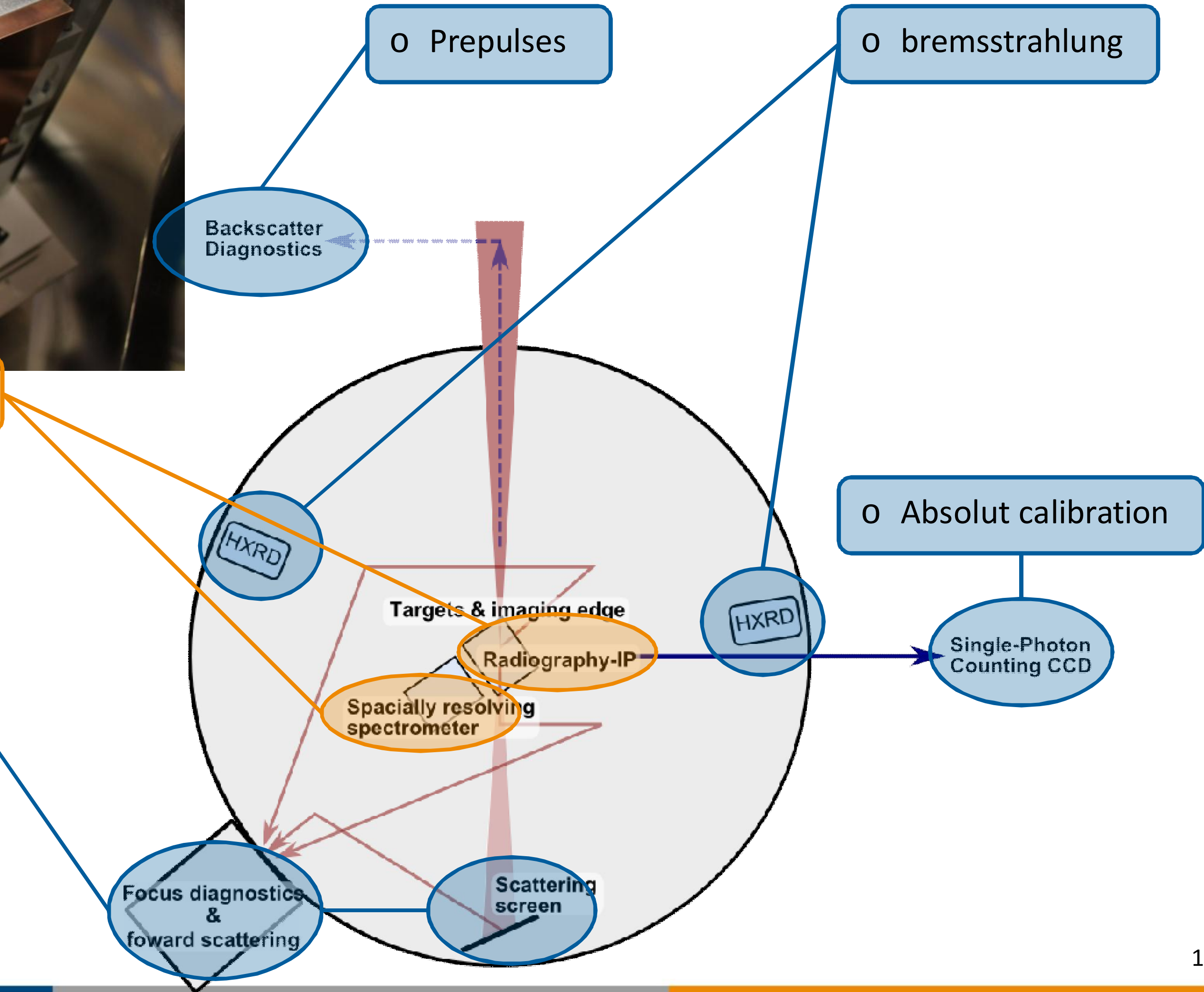


Parameter	Beam 1	Beam 2
Pulse energy	Up to 50 J	Up to 50 J
Pulse duration	500 fs to 8.5 ps	500 fs to 8.5 ps
Peak intensity	3E17 – 8E18 W/cm²	≤1.5E17 W/cm²

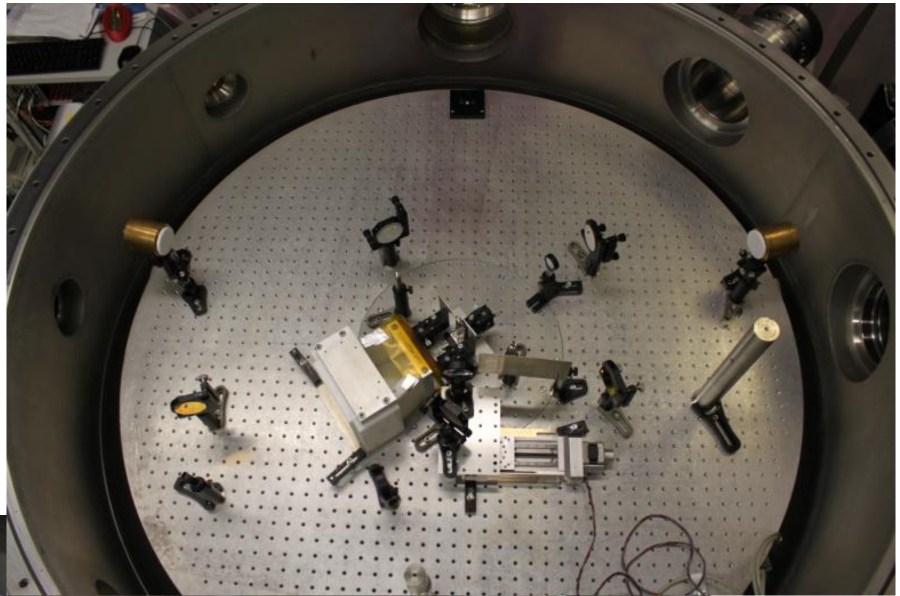
Experiment: Diagnostics

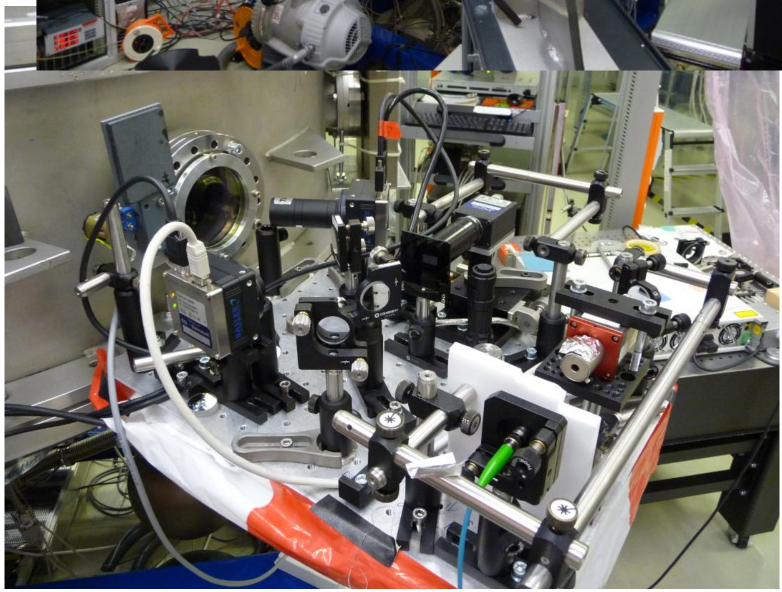


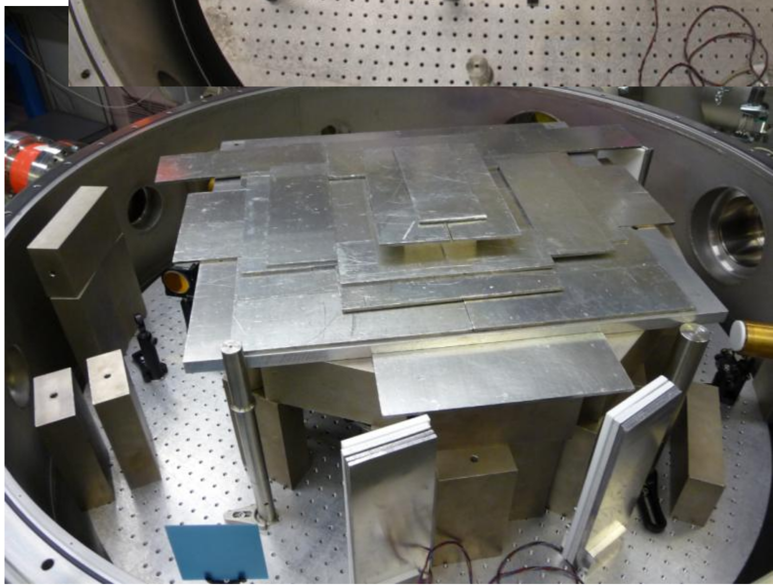
- Main Diagnostics



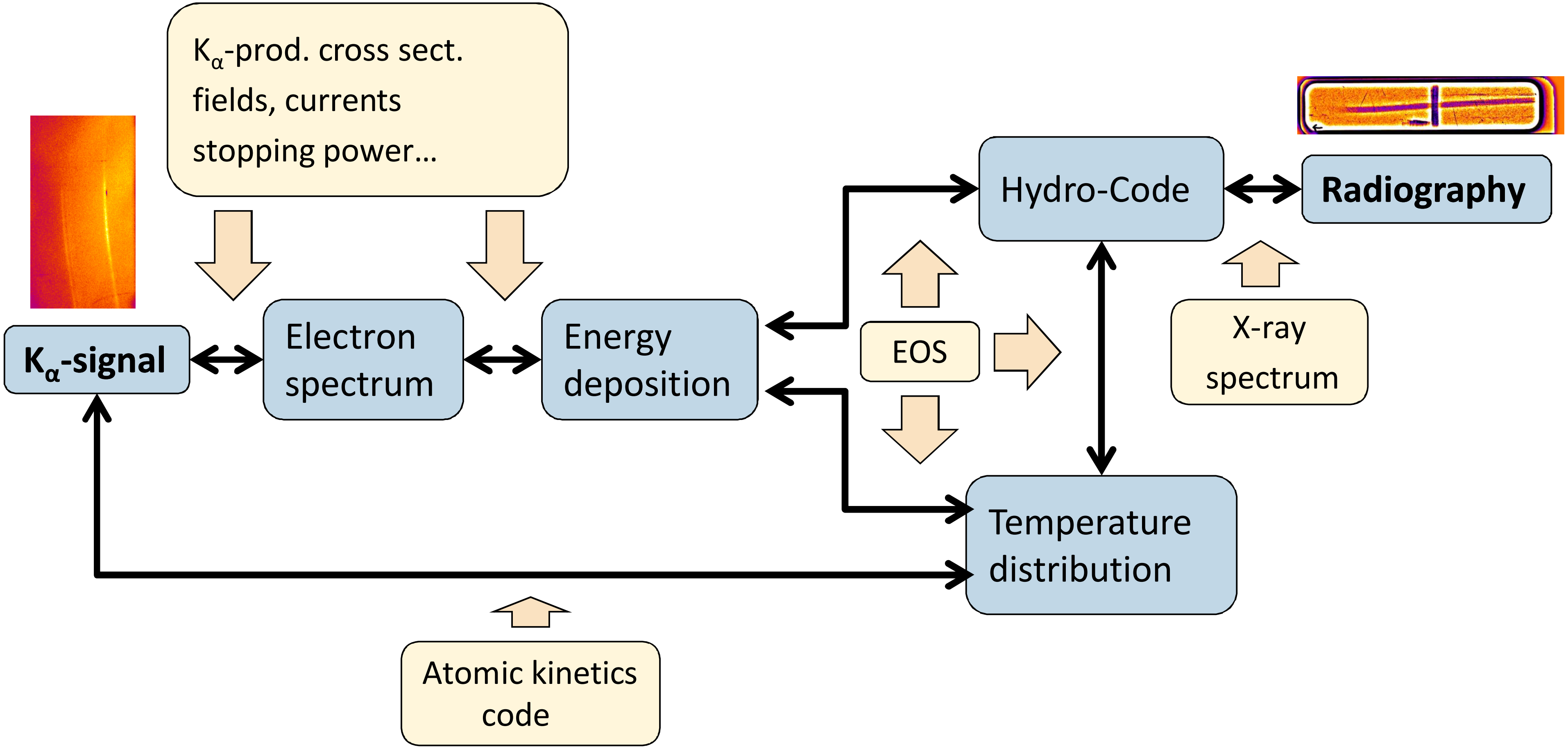
Experiment: Impressions







Analysis

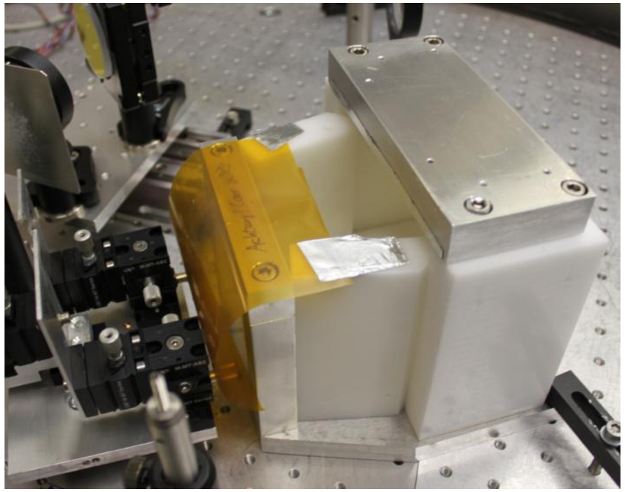


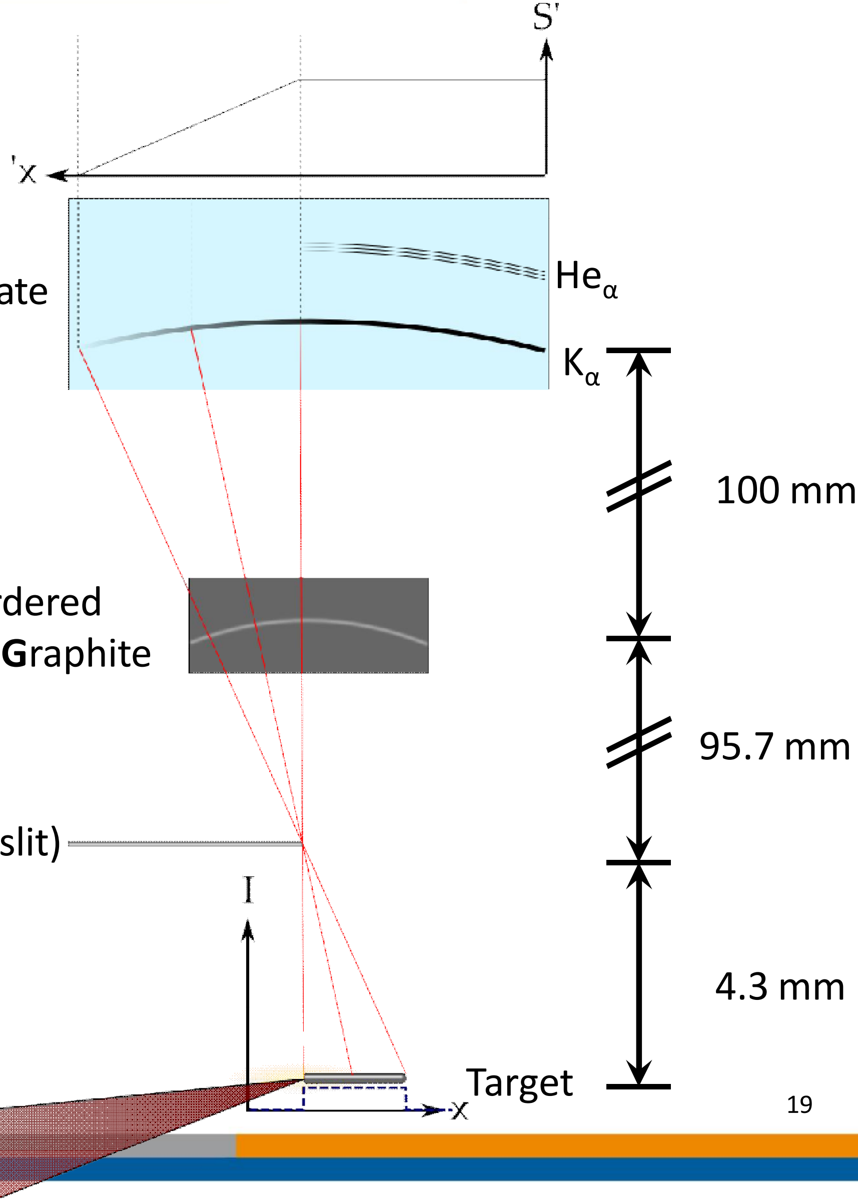
K_α-prod. cross sect.
fields, currents
stopping power…
K_α-signal
Electron spectrum
Energy deposition
EOS
Hydro-Code
Radiography
X-ray spectrum
Temperature distribution
Atomic kinetics code

Analysis: HOPG Spectrometer

- Resolution 25 µm
- Magnification ≈ 45
- Spectral coverage Ti-K_α up to Ti He_α

$$S'(x') = \int_{\infty}^{x_0(x')} dx S(x)$$





Analysis: Hot Electron Spectrum I

Parametrized according to $$f(E) \propto \frac{\eta_1}{T_1} Exp[-E/T_1] + \frac{\eta_2}{T_2} Exp[-E/T_2]$$

Self-developed collisional model (1D) including:

- relativistic K_α-production cross section
- ESTAR stopping power
- ohmic heating
- refluxing
- EOS for temperature (PROPACEOS)

not including:

- self-consistent electric and magnetic fields
- multi dimensional effects

Analysis: Hot Electron Spectrum II

Example: shot 34

Experiment:

$E_{laser, eff}$ = 36.7 J
d_{wire} = 50 µm
$\eta_{laser \rightarrow K\alpha}$ = 3.9E-4
$\#_{K\alpha\text{-photons}}$ = 2E13

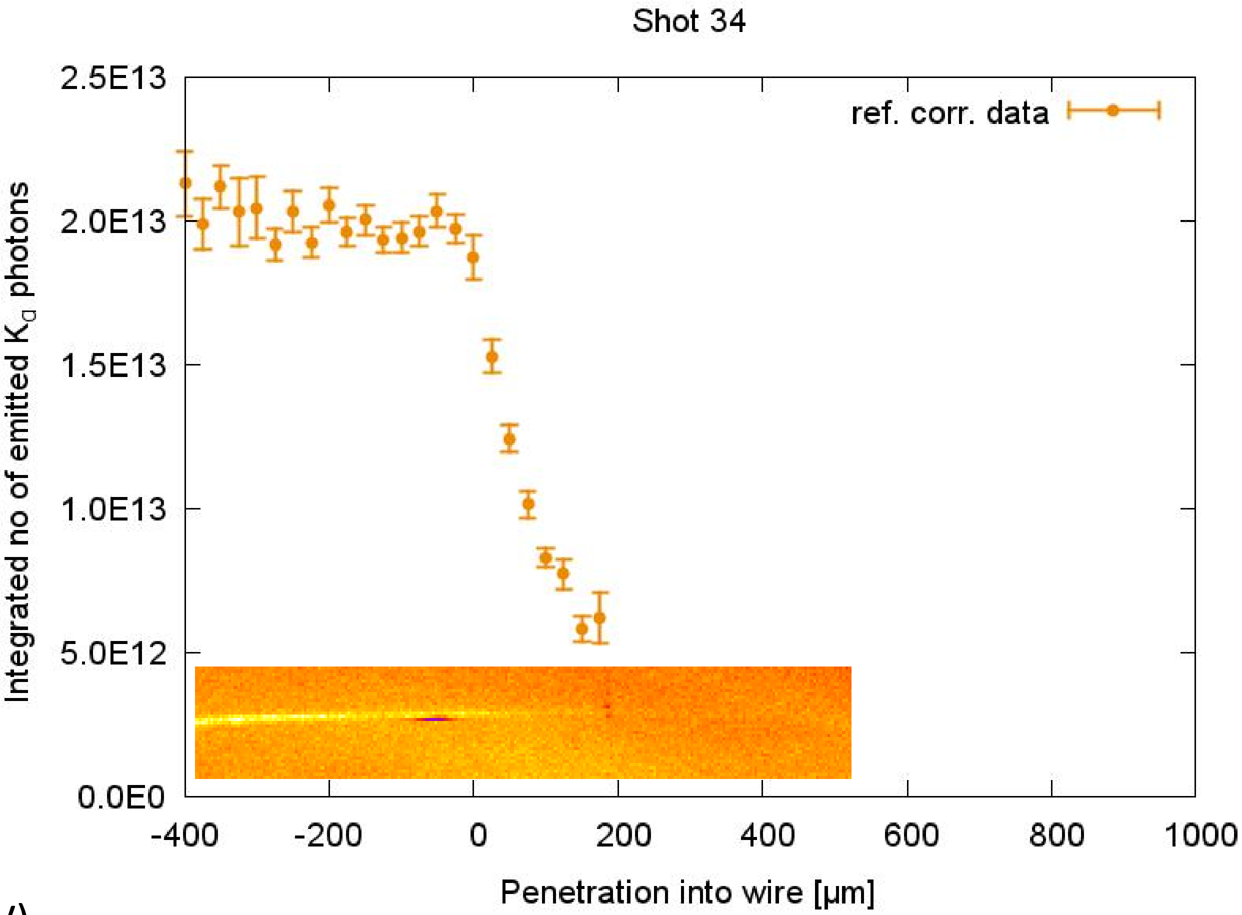
Best fit:

η_1 = 12.5 %
η_2 = 1.5 %

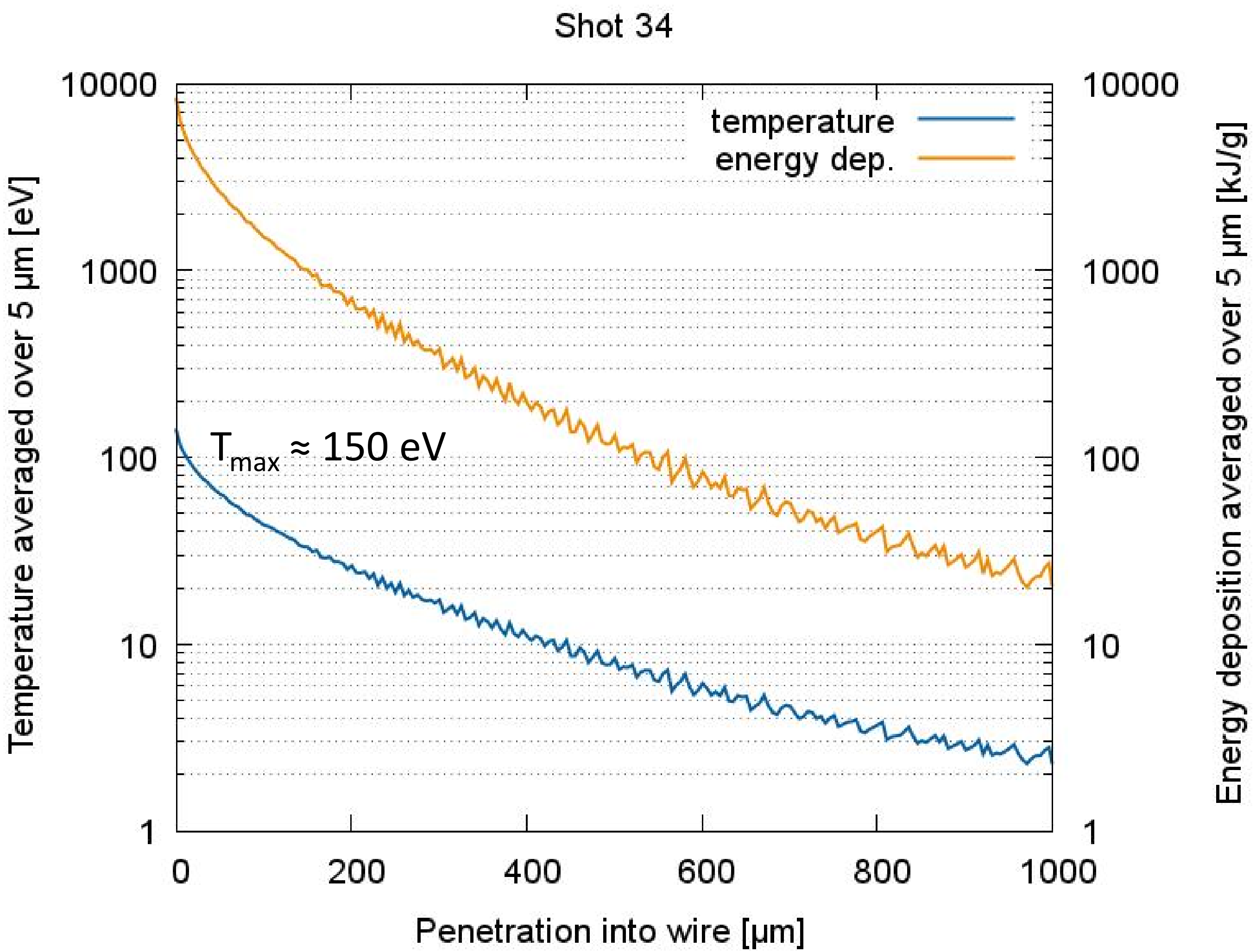
T_1 = 110 keV
T_2 = 400 keV

(Wilks: 105 keV, Beg: 184 keV)

max. current ≈ 200 kA



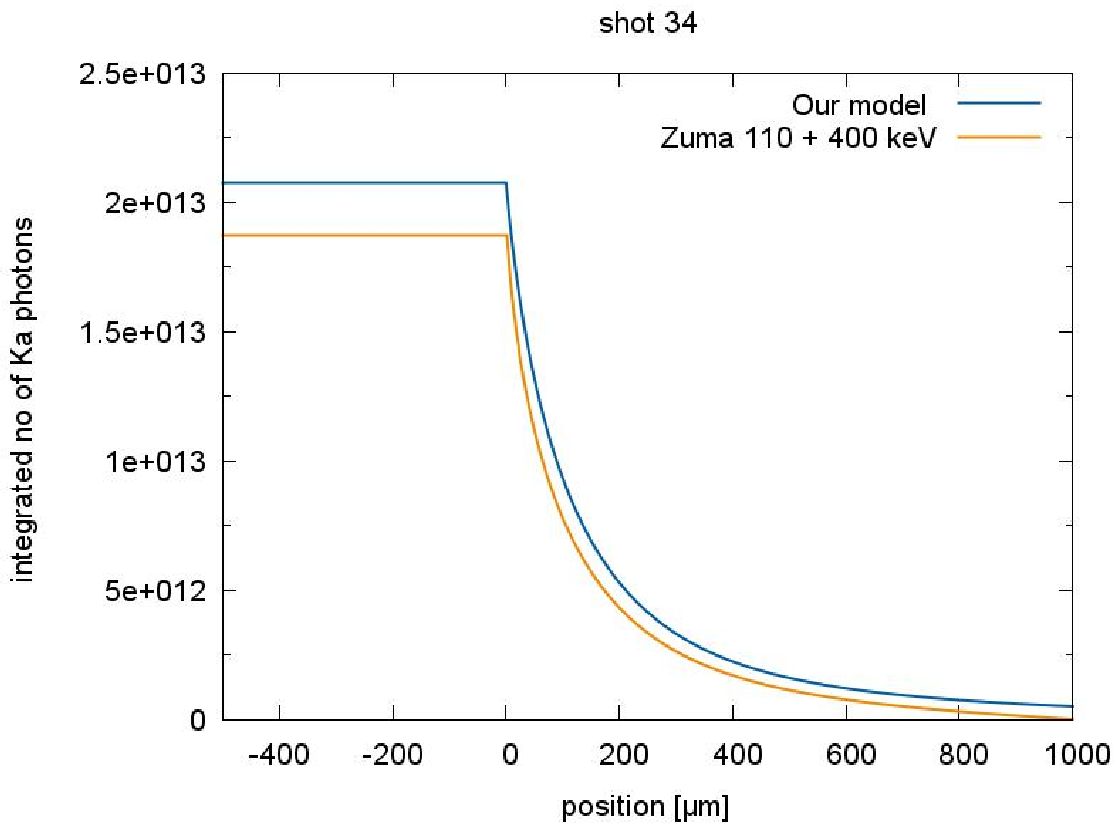
Analysis: Energy Deposition



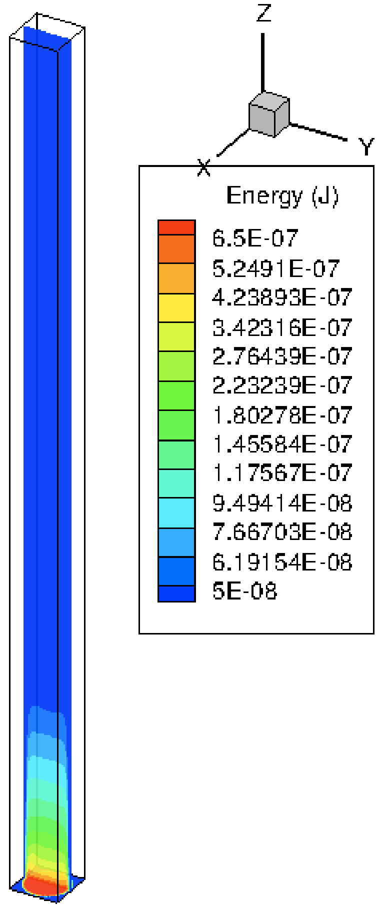
→ Relation
Temp. <-> Space
En. Dep. <-> Space

Comparison to 3D Hybrid PIC Code

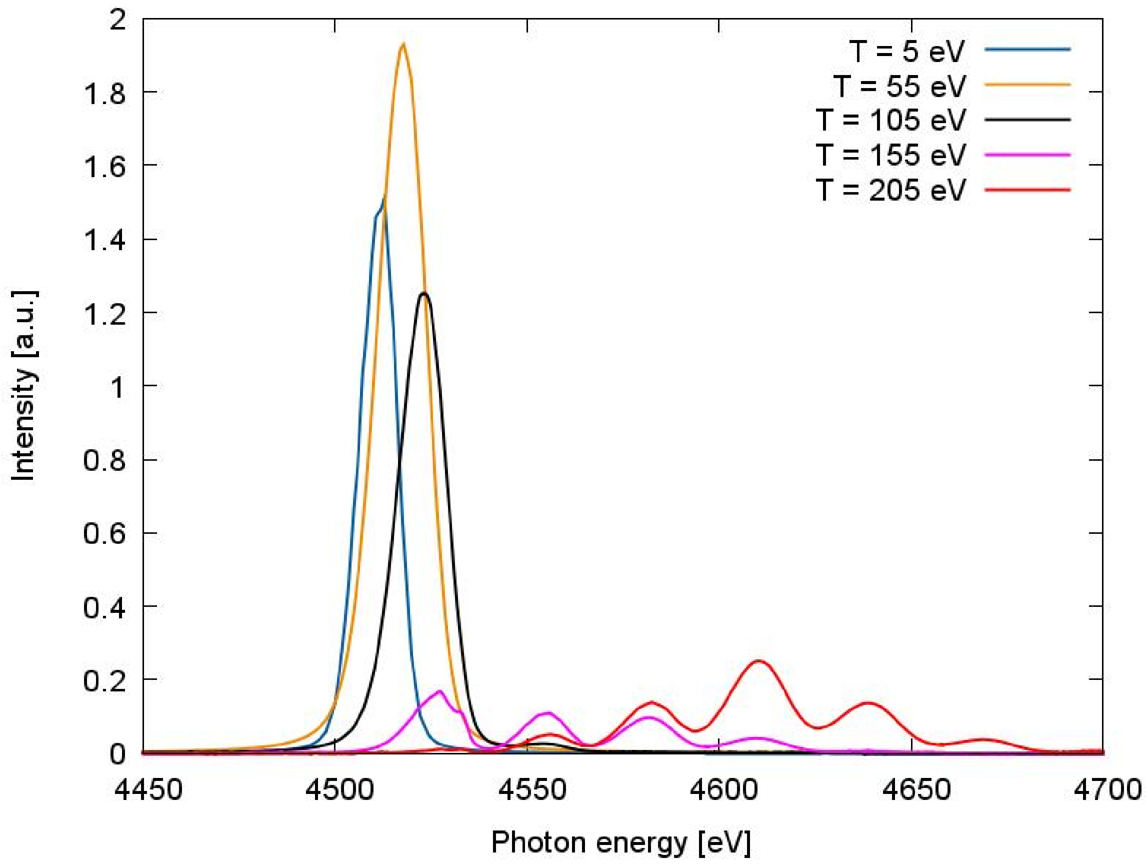
ZUMA: Modelling electron transport in 3D including fields, return currents etc.

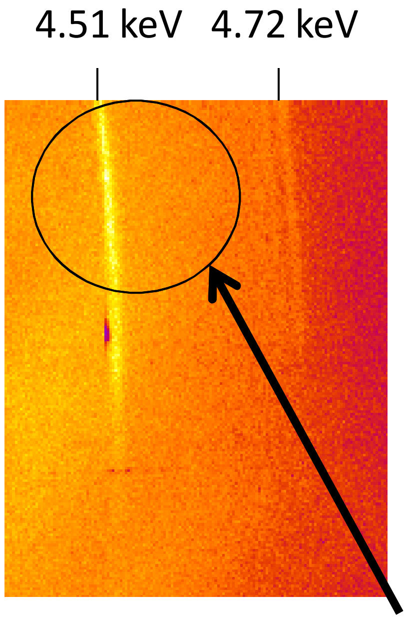


K_α production



Analysis: Spectral Properties of Ti- K_α



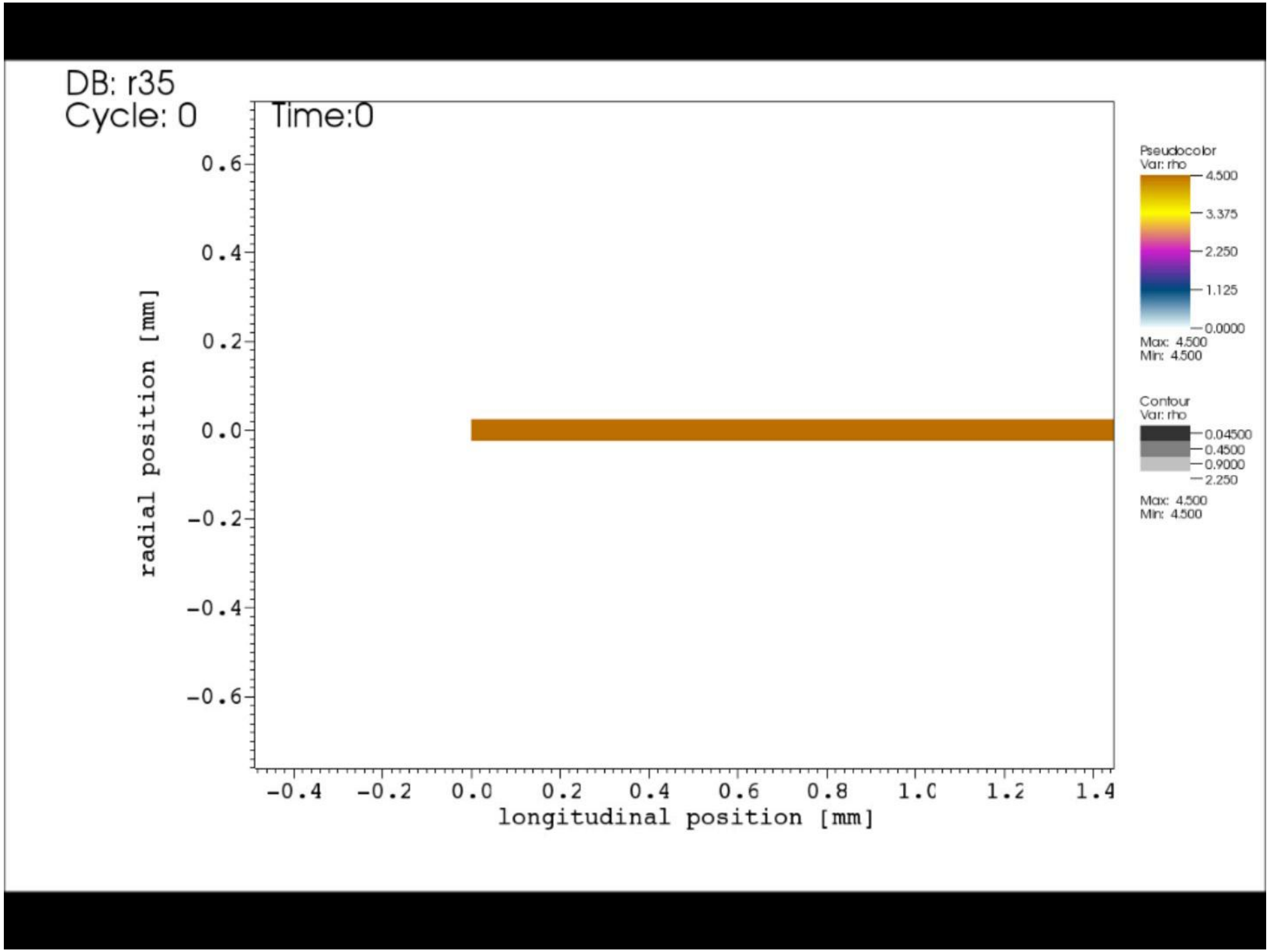


No sattelites!

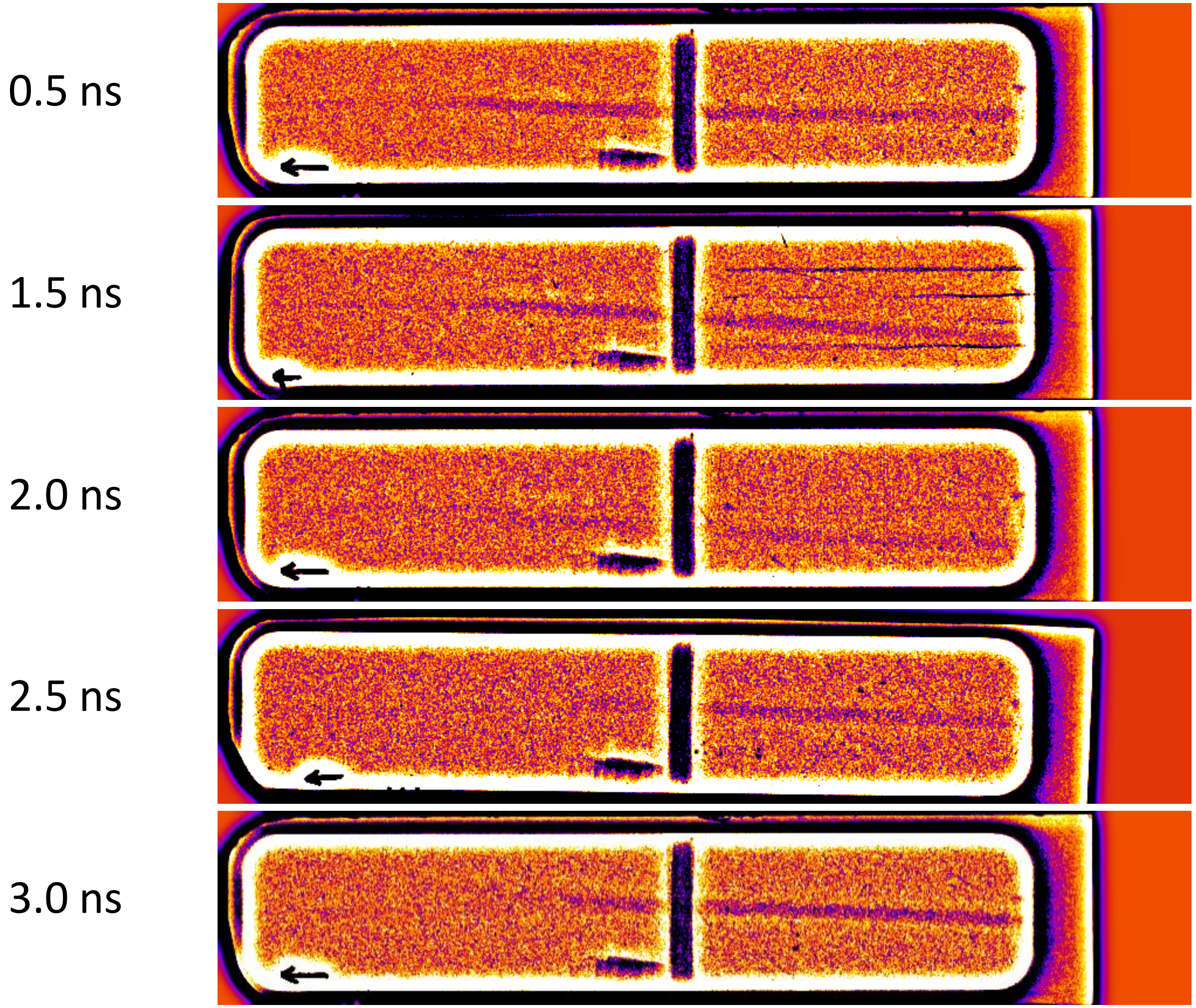
$T_{max} \approx 150$ eV ?

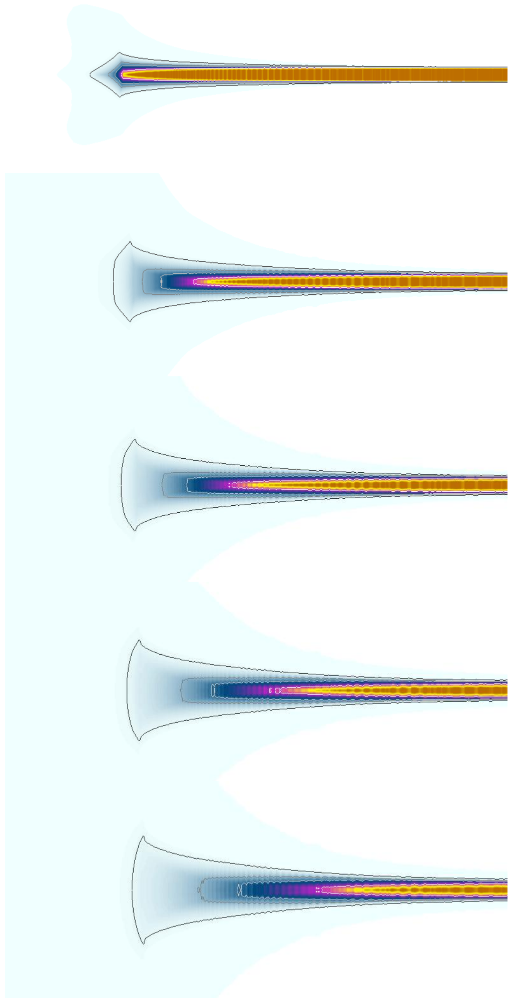
→ T < 300 eV

Hydrodynamics: RALEF-2D Simulation

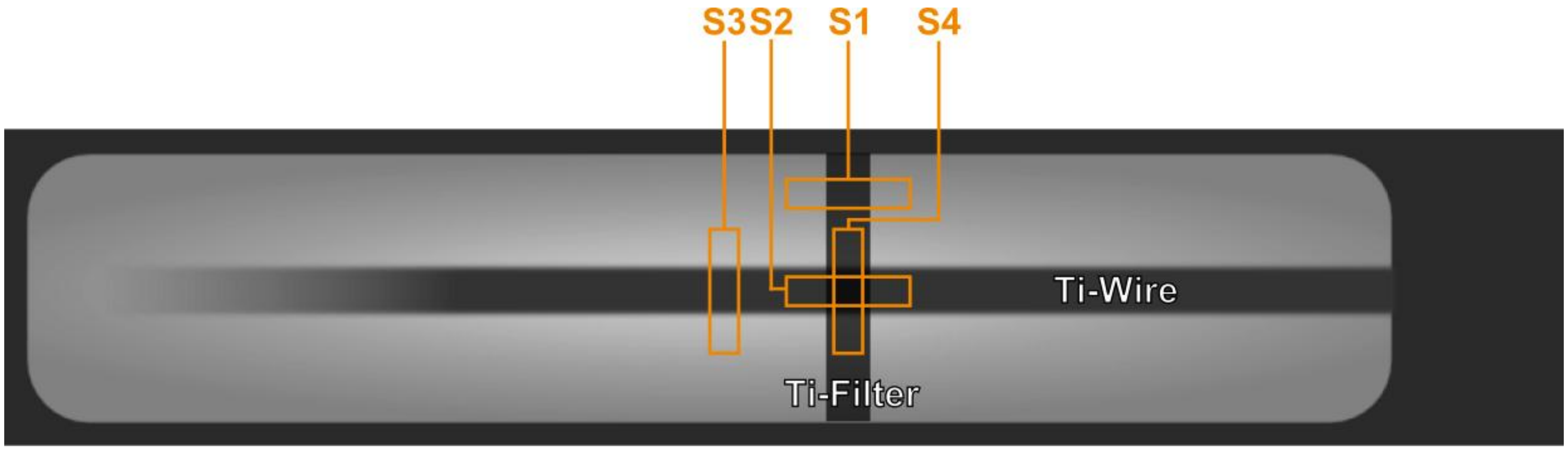


Hydrodynamics: Qualitatively





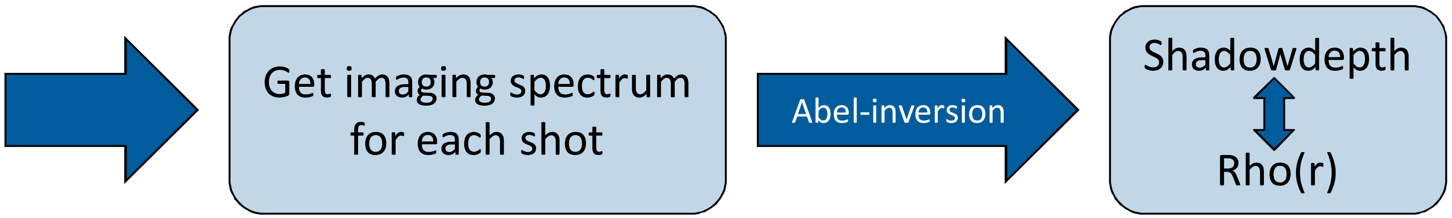
Hydrodynamics Quantitatively



- Testshots: Resolution: (19±2) µm (transversal) x (60±10) µm (longitudinal)

<u>Important: imaging Spectrum?</u>

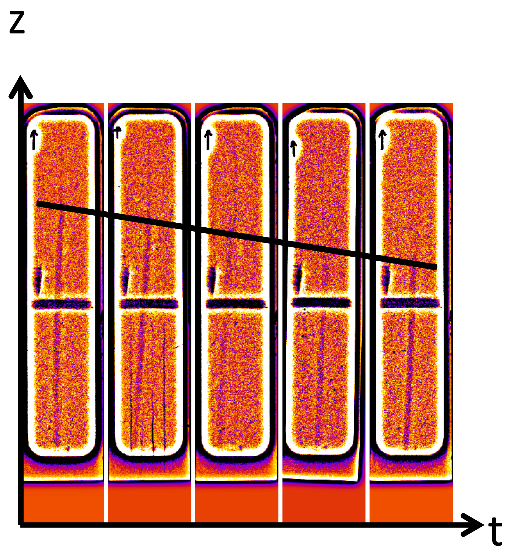
- Comparison of „shadowdepths“ for different lineout positions and directions
- Distinguish between imaging radiation and background

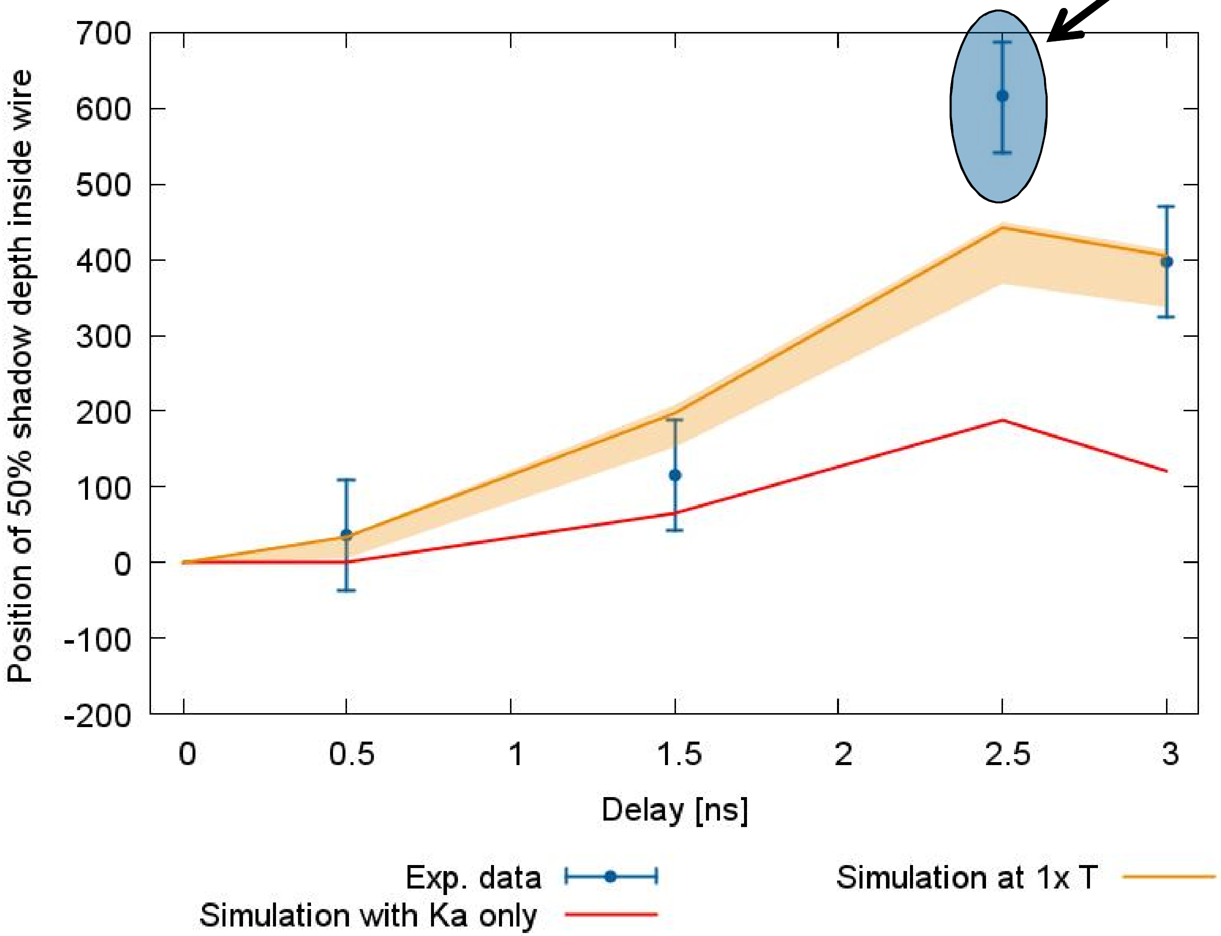


1D Hydrodynamics: „Burning"-Speed

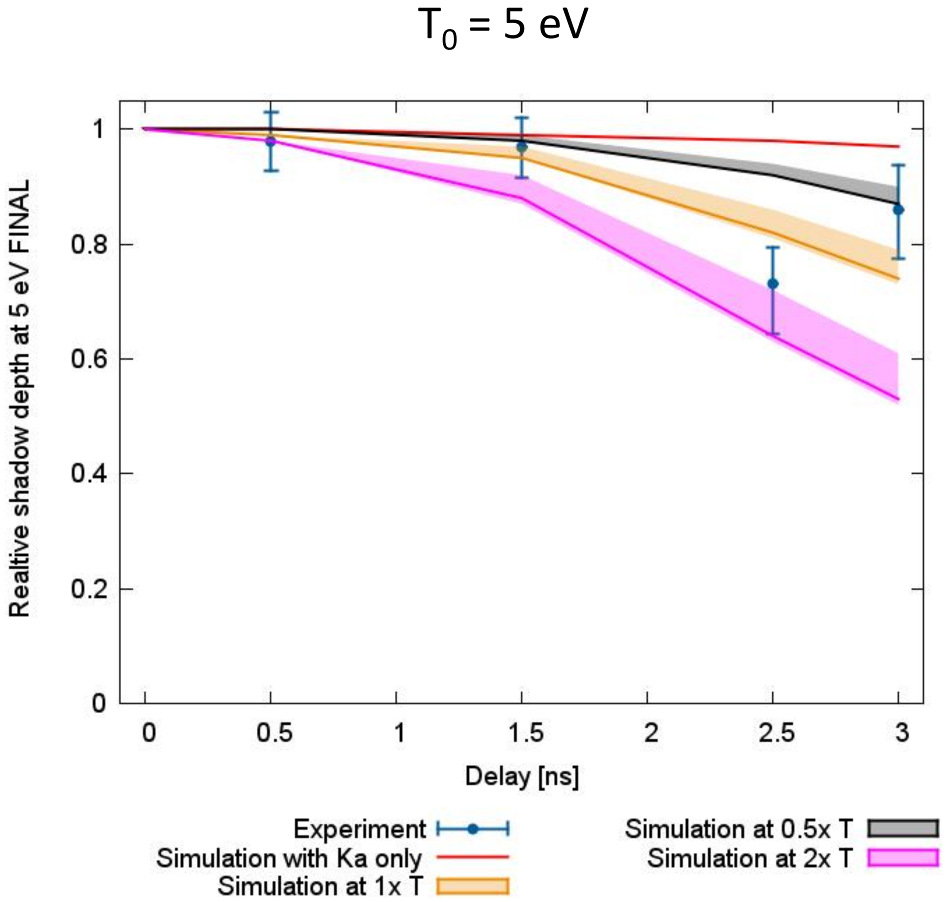
Results of <u>1D hydro</u> simulation using HELIOS code

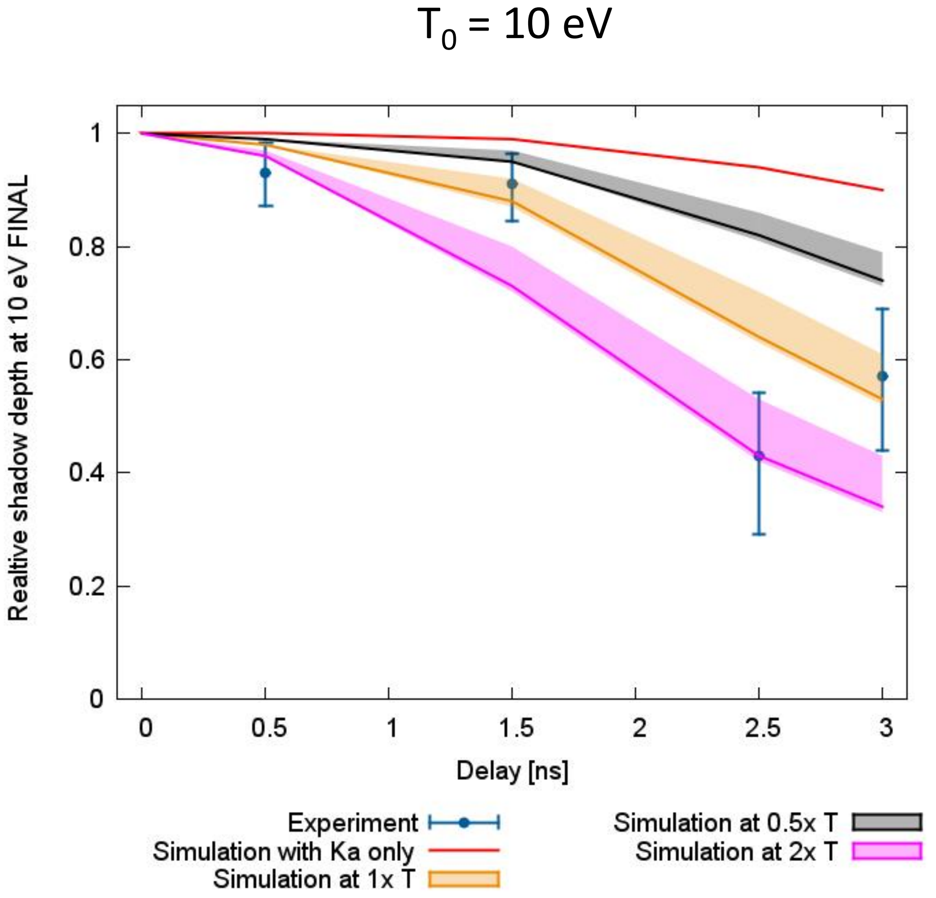
Larger prepulse





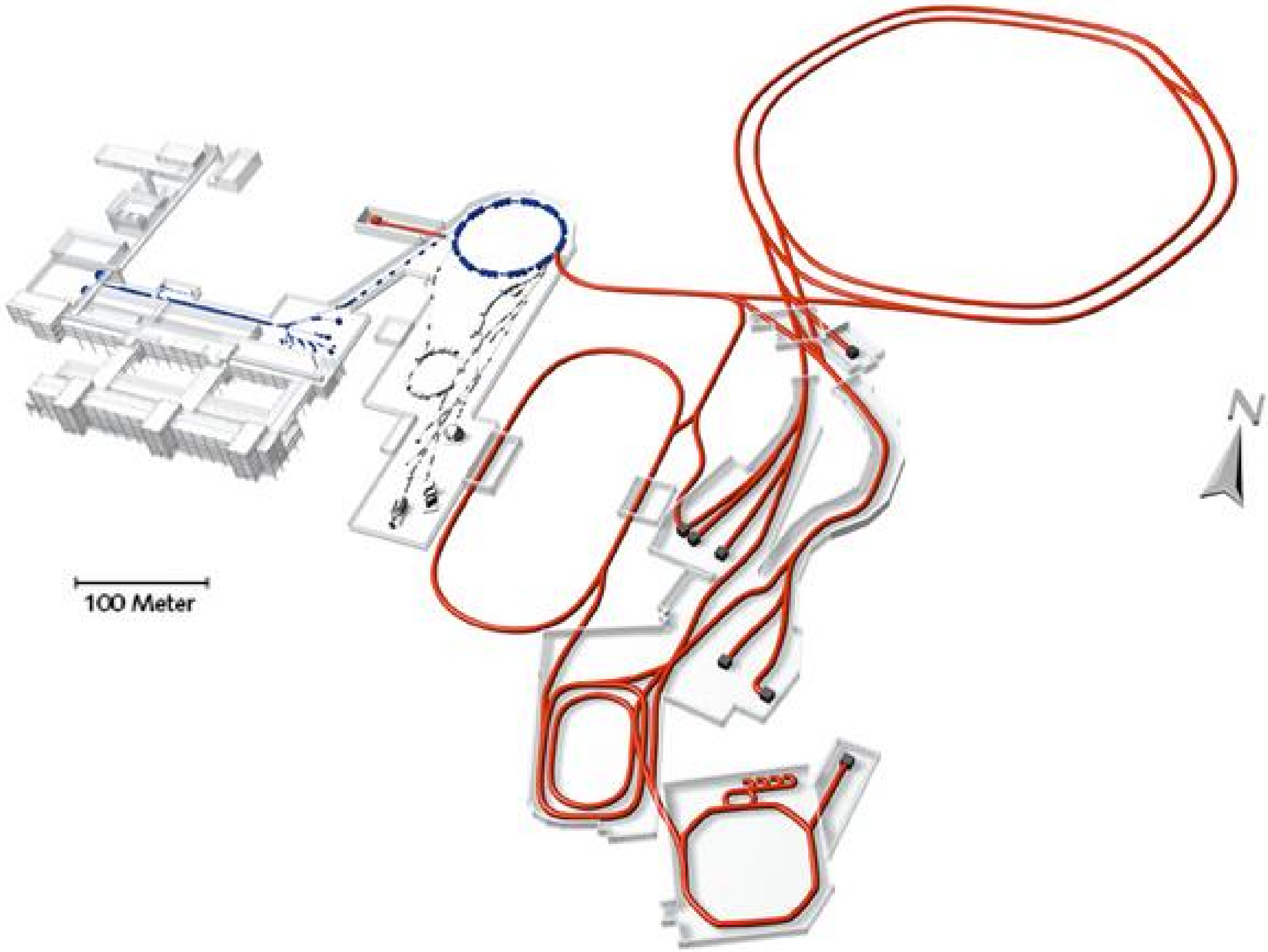
1D Hydrodynamics: Fixed Initial Temperature



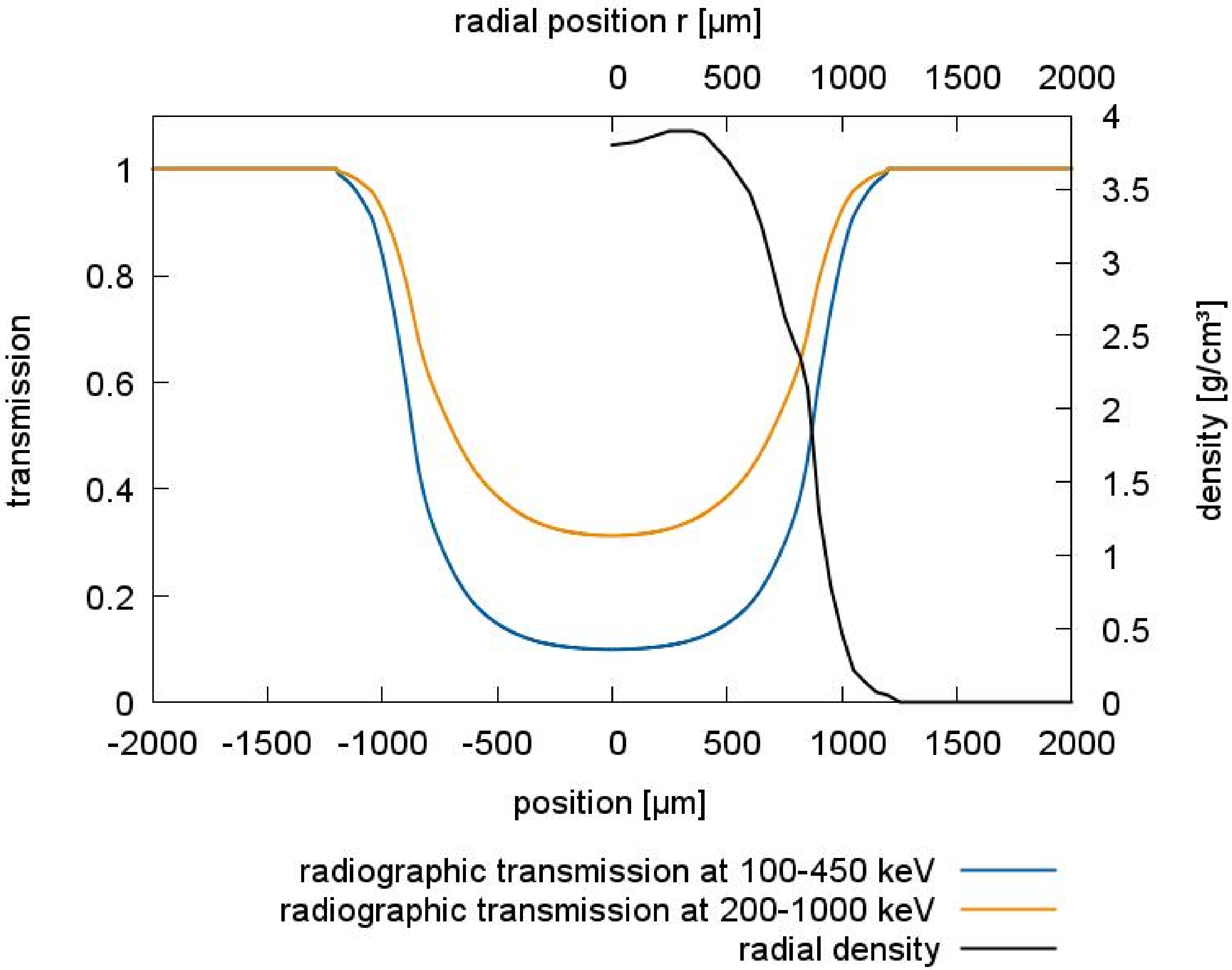


Problems occur at higher T_0 due to steepness of T-gradients & 2D effects

X-Ray Radiography @ FAIR



X-Ray Radiography @ FAIR



Snapshot:
Expansion of a solid lead cylinder r = 300 µm close to critical point

$I_{max} = 10^{19}$ W/cm², E > 50 J

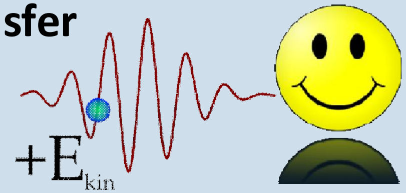
→ > 10^{12} bremsstrahlung-photons (4π sr) in relevant spectral range!

Density taken from N.A.Tahir et al., Phys. Rev. Lett. 95, 035001

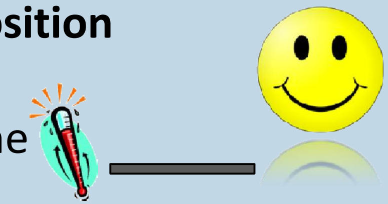
Summary

- ✓ First laser pump-probe experiment at PHELIX
- ✓ <u>Electron generation & transport:</u>
  Good agreement between simple model and full 3D hybrid PIC
  → 3D effects negligible
  → Collsional + ohmic heating main contributors
  → Full refluxing
- ✓ <u>Wire Hydrodynamics:</u>
  - o Agreement (1D) at moderate temperatures
  - o Good reproduction of „burning-speed“
  - o Not-so-good agreement at high temperatures
    → 2D effect
- ✓ Smaller exp. errorbar → test of EOS (Δ = 10-20 %)
- ✓ X-ray radiography: promising complementary method to probe dense, heavy ion produced plasmas

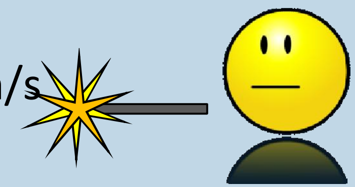
Energy transfer
Laser → e^-

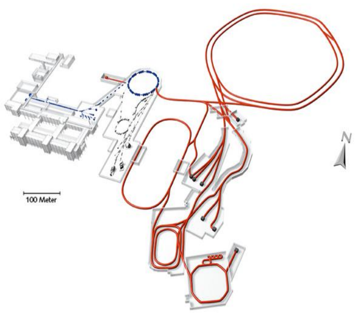


Energy deposition
inside the
target volume



Expansion
($v \approx v_s$ ~ 30 km/s
= 30 µm/ns)





Thanks are given to the collaborators…

B. Aurand[1,4], M. Basko[1,8], B. Ecker[4,6], T. Kühl[2,4], T. Ma[7],
F. Rosmej[5], B. Zielbauer[2,6], D. Zimmer[2] and P. Neumayer[1,3]

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[7]LLNL, Livermore, USA; [8]ITEP, Moscow, Russia

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Thank YOU for your attention.