Horké elektrony v laserovém plazmatu z pohledu rentgenové spektroskopie.

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Míry a váhy

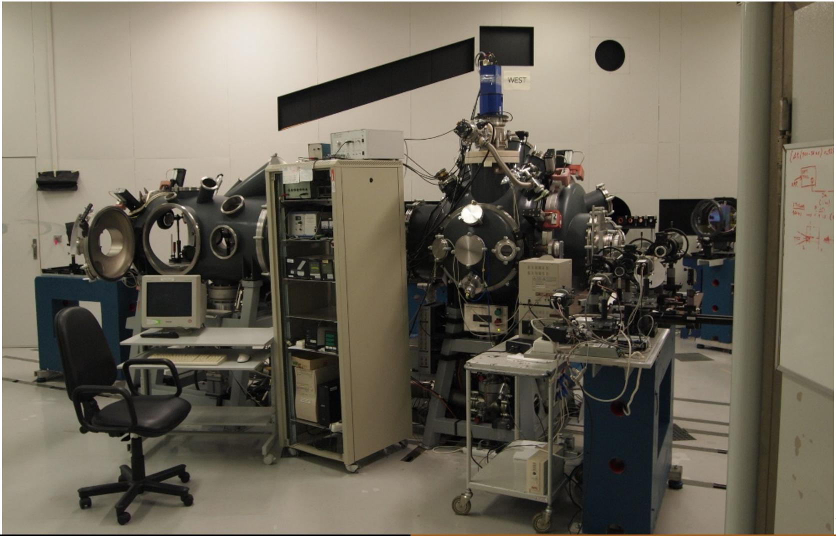
Plasma produced by an impact of strong laser radiation on solid targets.

- PALS laser: < 1 kJ, 438 or 1315 nm, 10^{16} W cm^{-2}
- Timescale – fs - ns
- Temperatures – keV
- Densities – $10^{17} \div 10^{22}$ cm^{-3}
- Velocities – up to 10^{8} cm s$^{-1} \approx 0.03\ c$

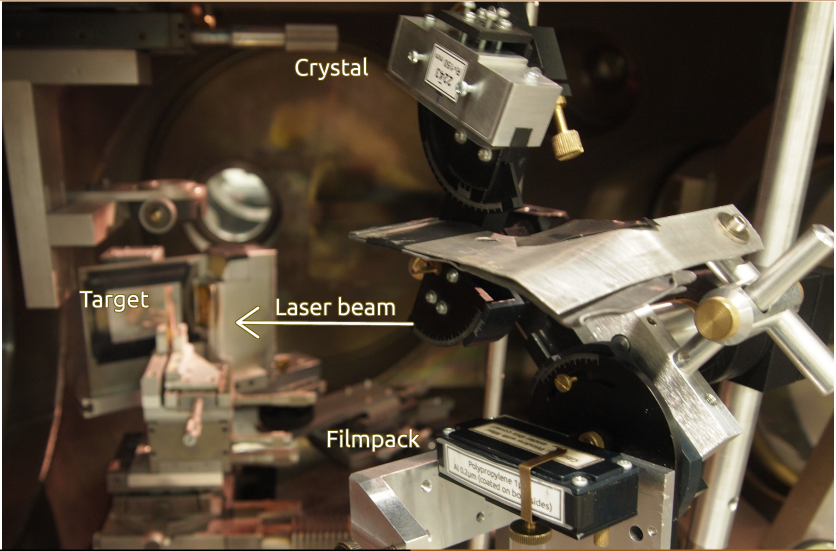
X-ray spectroscopy

- Using diffraction quartz or mica crystals.
- Observing mainly H– and He– like emission of mid–Z elements (Mg, Al, Si, Cu, ...)
- Range $1 \div 10$ Å $\approx 1 \div 10$ keV

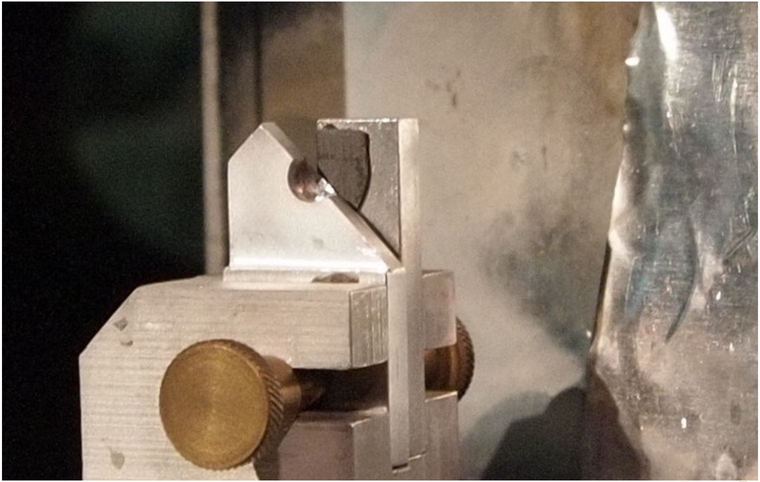
Experimentální hala



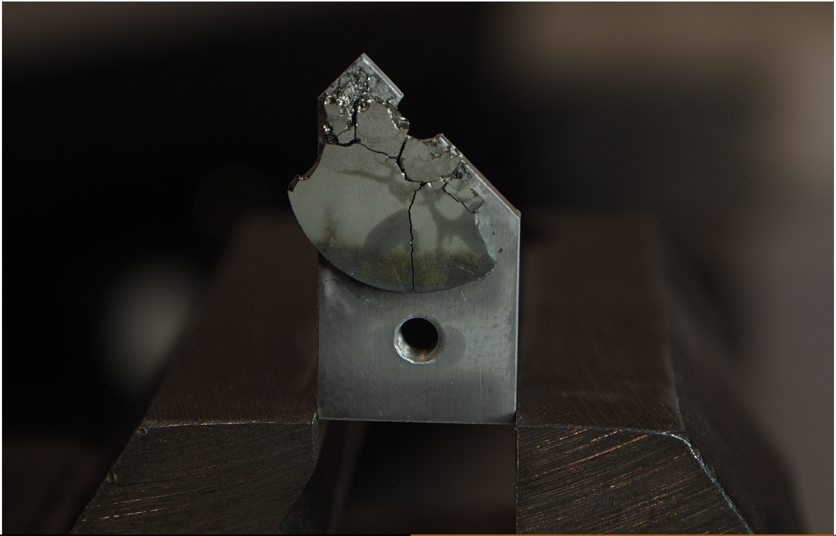
Vnitřek komory se spektrometrem



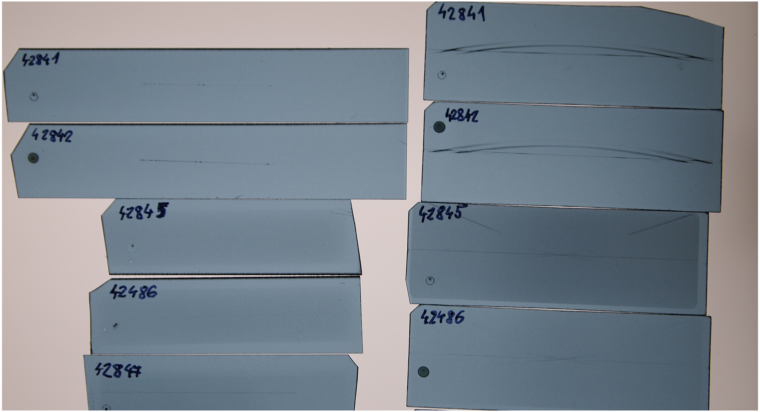
Terčík - komplikovanější varianta



Germaniový terčík



Hrubá naměřená data



Úvod do horkých elektronů

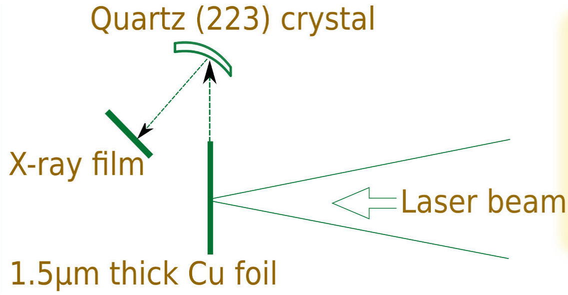
- Interaction of high power laser in subcritical plasma is accompanied by plasma **parametric instabilities**, i.e. Stimulated Raman or Brillouin scattering or two–plasmon decay.
- In these instabilities, the electrons are accelerated to **suprathermal** energies. Resulting non-Maxwellian electron spectrum is often approximated by two temperature distribution.
- The fraction of so called suprathermal electrons has much higher free path in plasma, thus penetrates further into the target and performs **K-shell ionization** in cold material.

Motivace

- Suprathermal electrons are intensively investigated in context with their role in applications related to the **inertial confinement fusion** and to the laser-based particle acceleration.
- Either *Fast Ignition* or *Shock Ignition* ICF schemes are crucially dependent on high quality understanding and modeling of hot electron creation, propagation and interaction.
- Studying of x-ray spectra motivates and verifies improvements of knowledge of detailed **atomic physics** and plasma models.

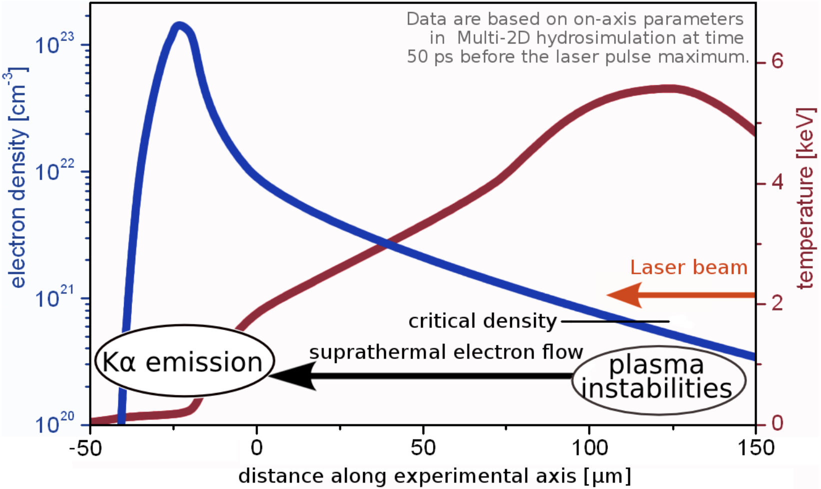
Experimental scheme

- Irradiation of thin Cu foil with high-power laser.
- Principal diagnostics: high-resolution x-ray spectroscopy.



PALS laser[1]
Wavelength:
438 or 1315 nm
Energy: 400 J
Focus: ∅ 70 µm
Intensitity:
4×10^{16} W/cm^2

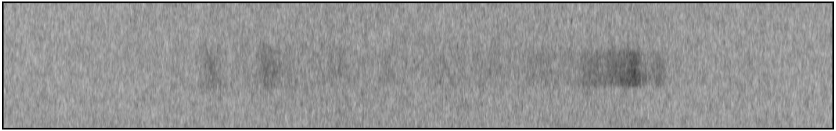
Experimental scenario



X-ray spectrometer

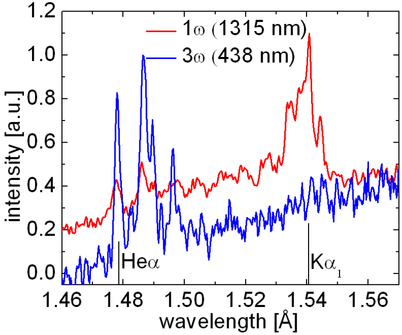
- Spherically bent quartz (223) crystal.
- Rowland circle scheme.
- Wavelength range: 1.46 - 1.57 Å (7900 - 8500 eV).
- Spectra recorded on an x–ray film.

raw film:

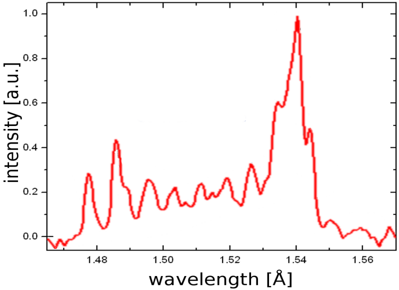


X-ray spectra

- Emission varied significantly with irradiation laser frequency.
- 1ω: dominated by K_α produced in cold material by the action of suprathermal electrons.
- 3ω: dominated by He_α induced by high bulk plasma temperature.

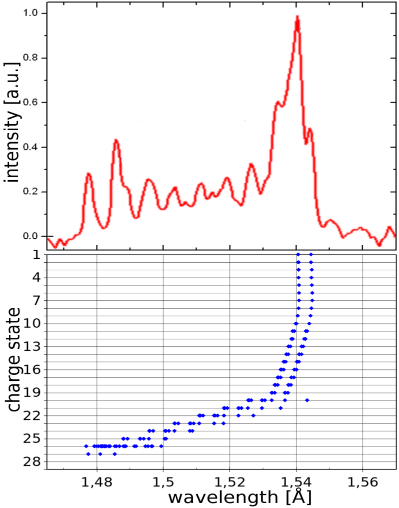


Theoretical spectral lines



Experimental (1ω) spectra, averaged over 6 shots to reduce noise.

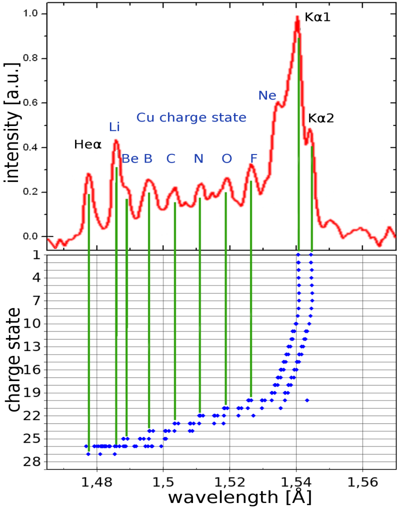
Theoretical spectral lines



Experimental (1ω) spectra, averaged over 6 shots to reduce noise.

Spectral lines included in the Flychk Collisional-radiative model according to their wavelength and the charge state they originate in. All lines represents the **1s – 2p** transition!

Theoretical spectral lines



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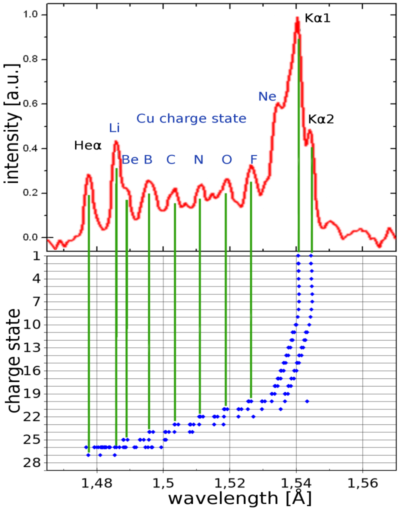
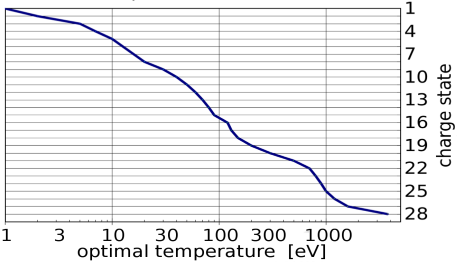
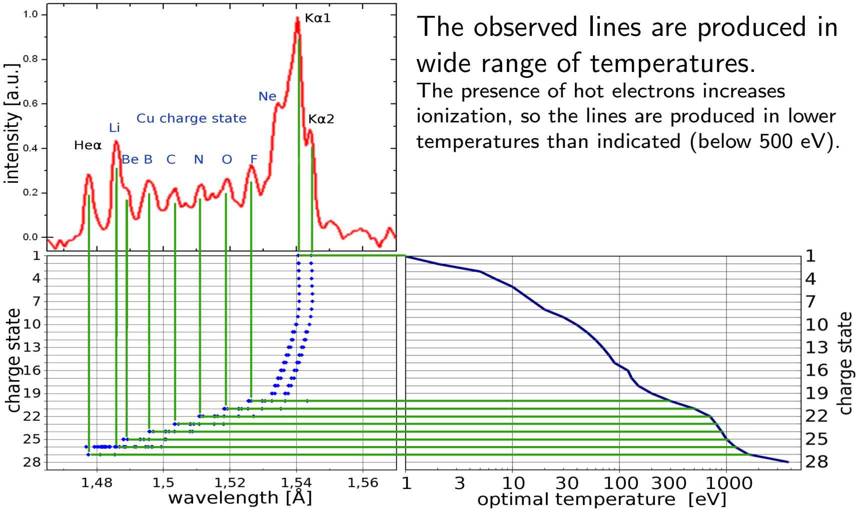
Theoretical spectral lines



Dominating charge state for given temperature. (Data obtained from PrismSpect for fixed ρ without hot electrons.)



Theoretical spectral lines



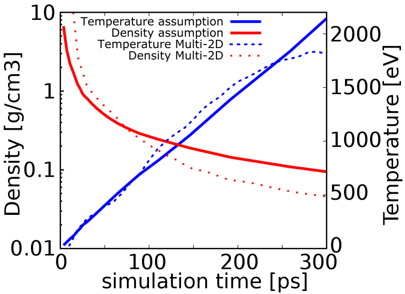
The observed lines are produced in wide range of temperatures.

The presence of hot electrons increases ionization, so the lines are produced in lower temperatures than indicated (below 500 eV).

Model assumptions

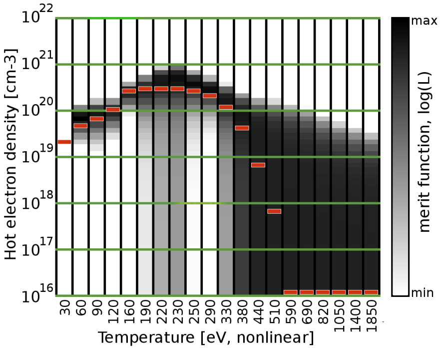
- Usual evaluation - comparing with single–parameter synthetic spectrum - is not possible.
- Attempt to make the most simple suitable model:

- Single-cell with **temporal** evolution.
- Temperature **linearly** increasing
- Density decrease according to an **isobaric expansion**.
- good agreement with Multi-2D hydrodynamics.
- $T_{\text{he}} = 100\text{keV}, p = 100\text{Mbar}$



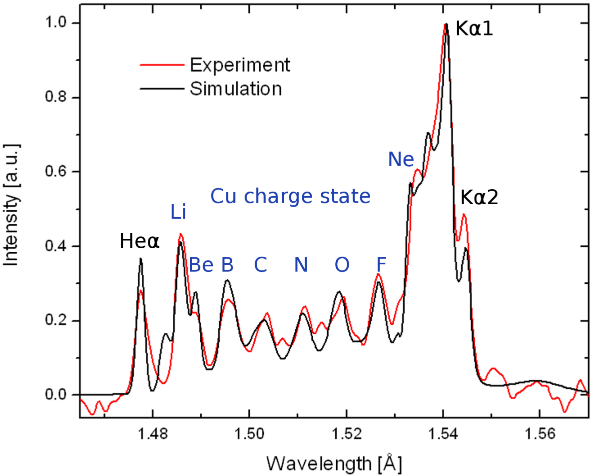
Fitting

- Time–evolution split into ≈ 20 *points*.
- For each point, set of spectra were calculated by *Flychk* for T and ρ given by the model, and n_{he} varied $10^{16} \div 10^{22}$ cm^{-3}.

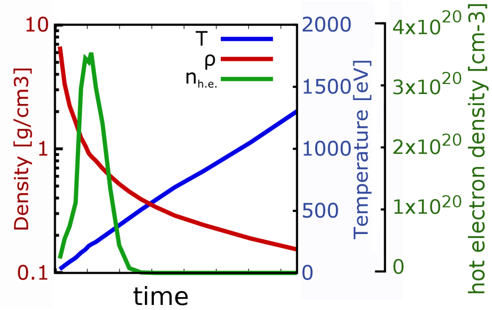


- Iterative fitting algorithm varies the n_{he} evolution and searches the best agreement between the experimental and theoretical spectra.

Fitted spectra (7900 ÷ 8460 eV)



Results and discussion



- The found peak value $n_{\mathrm{he}} = 3 \times 10^{20}$ cm^{-3} (corresponding to the hot electron fraction $f = 0.5$ at n_c) is rather high.

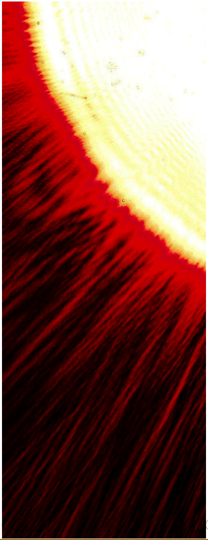
- This value is probably not realistic with respect to the expected location of hot electron creation in the subcritical region.
- The neglecting of the spatial evolution may be the main cause!

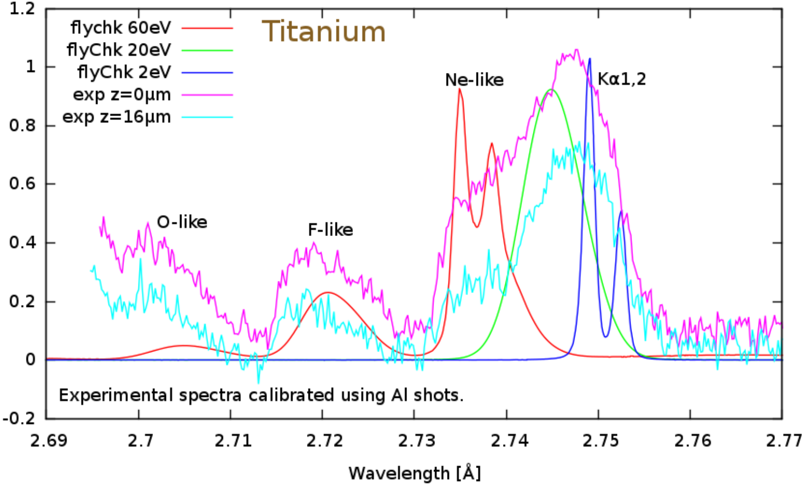
Spatial evolution

- Each observed line can be emitted only in a very narrow range of temperatures, which corresponds to a particular temporal interval in the presented model.
- The intensity of each line is proportional both to the n_{he} and the duration of the emission.
- Since the model assumes short emission times, it predicts too high n_{he}.
- In the experiment (as well as in hydro simulations) the temperatures below 500 eV are present for longer time — the region of their occurrence is moving in the direction of the laser propagation (i.e., into the cold target) during the heating process. Thus, each spectral line is emitted within a longer period, which would refer to lower estimates of n_{he}.

Conclusions

1. Well separated spectral lines of He-like till F-like Cu are **measured** and **clearly identified**.
2. Quantitative interpretation is significantly complicated by the spectra dependence on two spatially-separated effects: the **production** of hot electrons, and the presence of the colder target material (**diagnostics**).
3. An approach of hydrodynamic-model **independent** method for the evaluation of n_{he}has been demonstrated, leading to an **excellent agreement** between synthetic and experimental spectra.
4. This method results in **overestimated** values of n_{he}. To remedy this, the more rigorous description is needed, e.g., by using spatially evolving parameters from hydrodynamics, or by using thin, reduced-volume foils in experiments, whose expansion could be neglected.

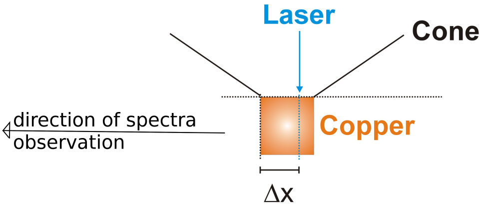




1–

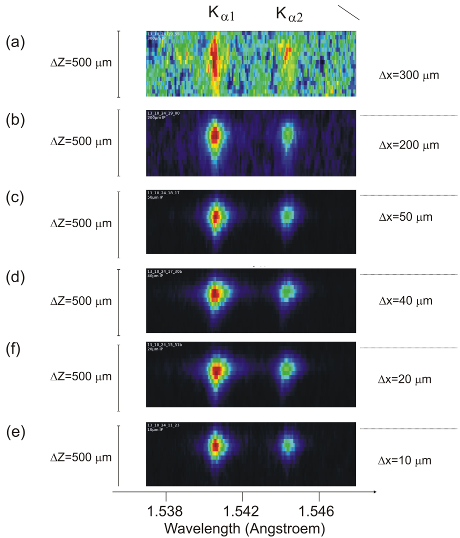
µm–thick Ti target irradiated by 400 J 1ω radiation, Vertical–geometry Johann spectrometer with cylindrically-bent quartz (400) crystal

ELFIE experiment

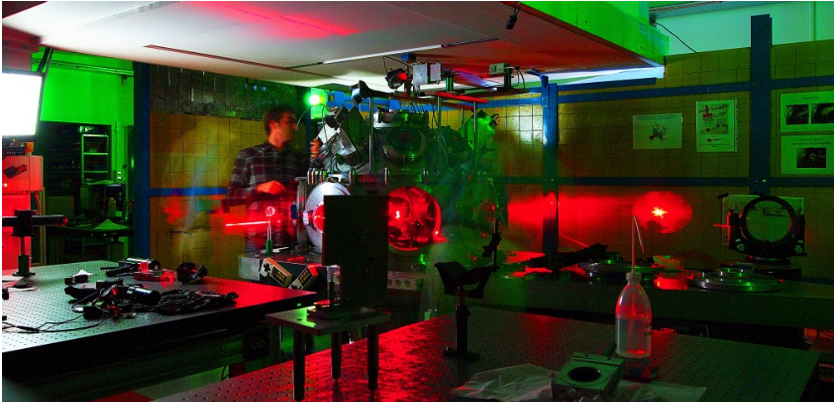


- ELFIE laser:
- E 8 J
- t = 250 fs

- Horké elektrony jsou produkovány poblíž ohniska, procházejí pevným materiálem až k okraji.
- Jehlan zabraňuje proudění h.e. podél povrchu.


$K_{\alpha 1}$
$K_{\alpha 2}$
(a)
ΔZ=500 μm
Δx=300 μm
(b)
ΔZ=500 μm
Δx=200 μm
(c)
ΔZ=500 μm
Δx=50 μm
(d)
ΔZ=500 μm
Δx=40 μm
(f)
ΔZ=500 μm
Δx=20 μm
(e)
ΔZ=500 μm
Δx=10 μm
1.538
1.542
1.546
Wavelength (Angstroem)

- Thank you for your attention.



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