Simulations of femtosecond K-α emission from short-pulse interactions

J. Limpouch, O. Klimo, V. Bína

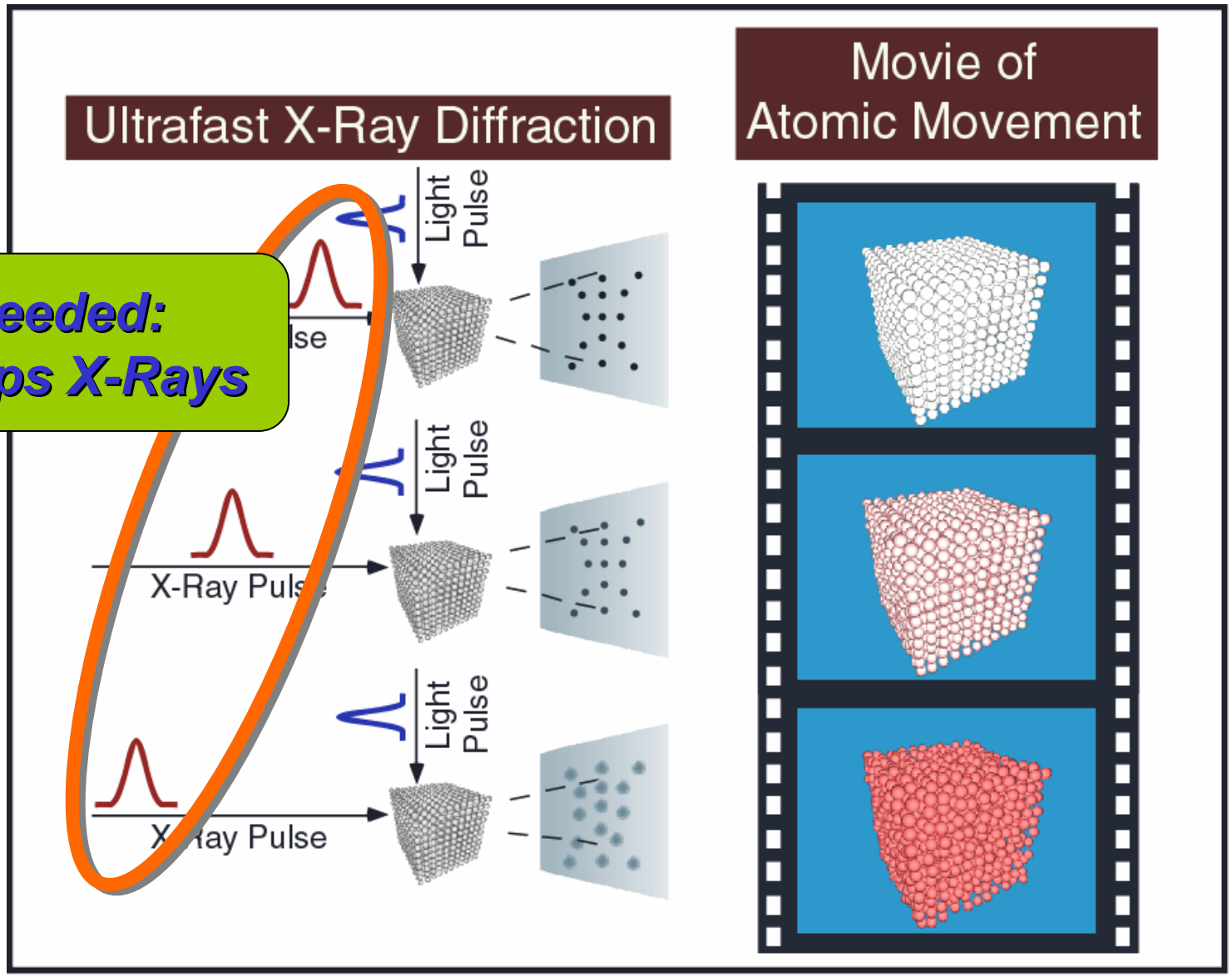
Czech Technical University in Prague,
Faculty of Nuclear Sciences and Physical Engineering,
Břehová 7, CZ-11519 Prague 1, Czech Republic

Syllabus:

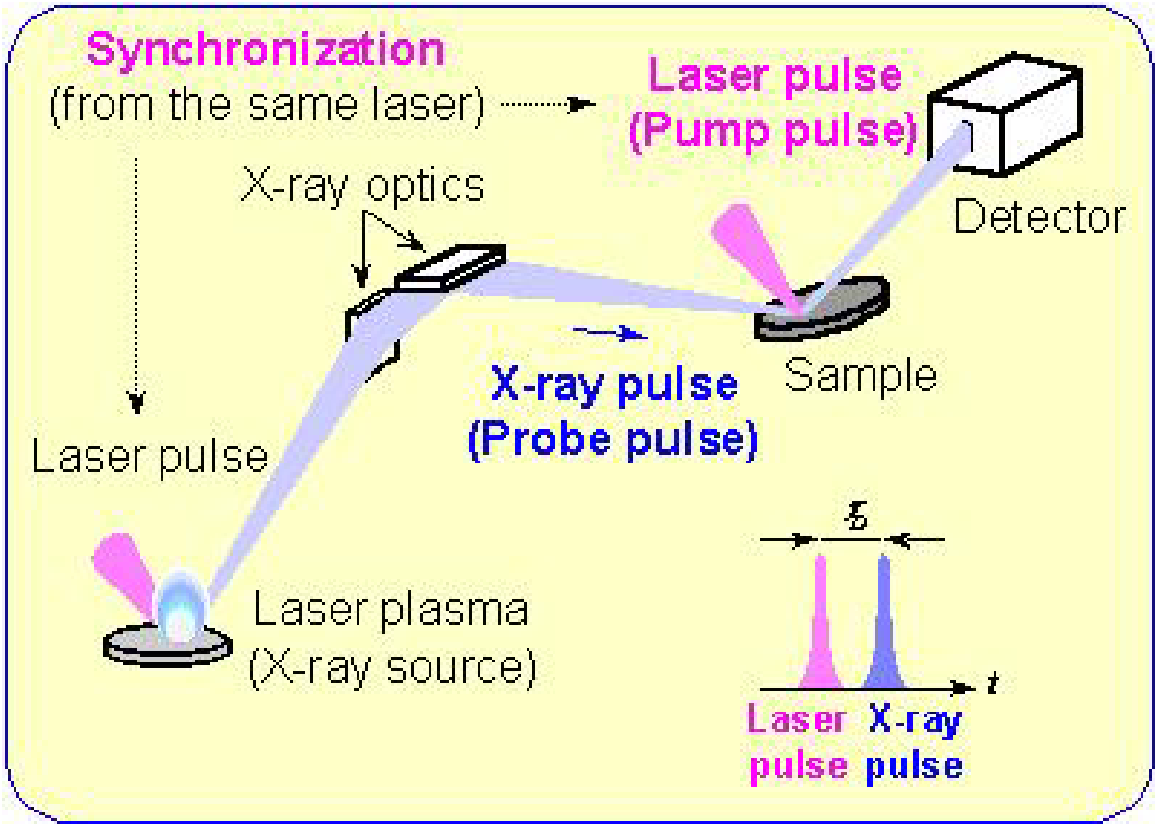
1. Time-resolved crystallography
2. Emission spectra from SP interactions
3. Simulation scheme and parameters
4. Our PIC code
5. Spectra of fast electrons flying into solid target
6. Angular distribution of fast electrons
7. Our Monte-Carlo code
8. Efficiency of K-α emission from Al, Cu and layered targets
9. Emitted K-α pulses from Al and Cu
10. Conclusions

Collaboration with A. A. Andreev, L. Drska, L. Kocbach, H. Nakano and S. Kawata is gratefully acknowledged

Time-resolved Crystallography



Scheme of x-ray pulse-probe measurement



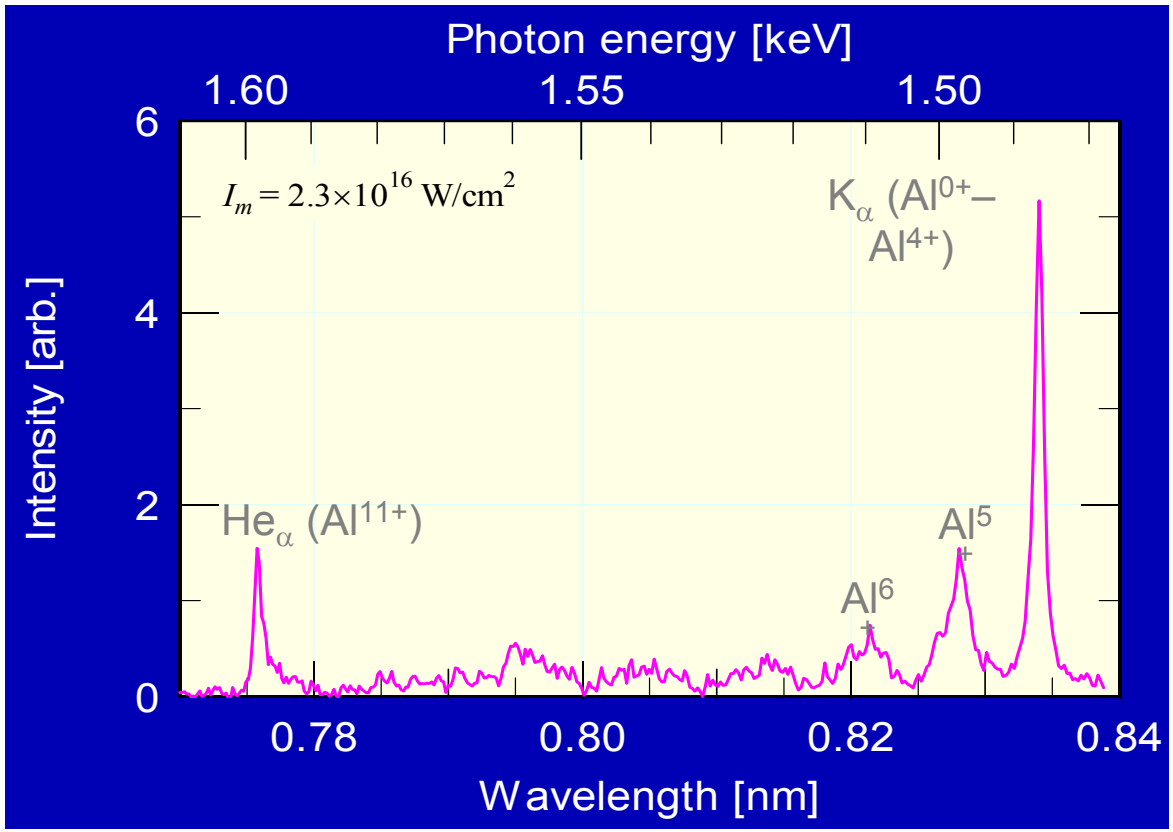
Weak laser pulse – sample excitation

Main laser pulse – generates X-ray pulse incident with variable delay on sample

K-α emission best – shortest pulse, high intensity, narrow spectrum

Moderate laser intensities – 10^{16} – 10^{17} W/cm^2 – preferable
higher intensities - fast electron fly longer distance, x-ray pulse longer and efficiency decreases due to photon reabsoption

Time integrated spectra from solid target

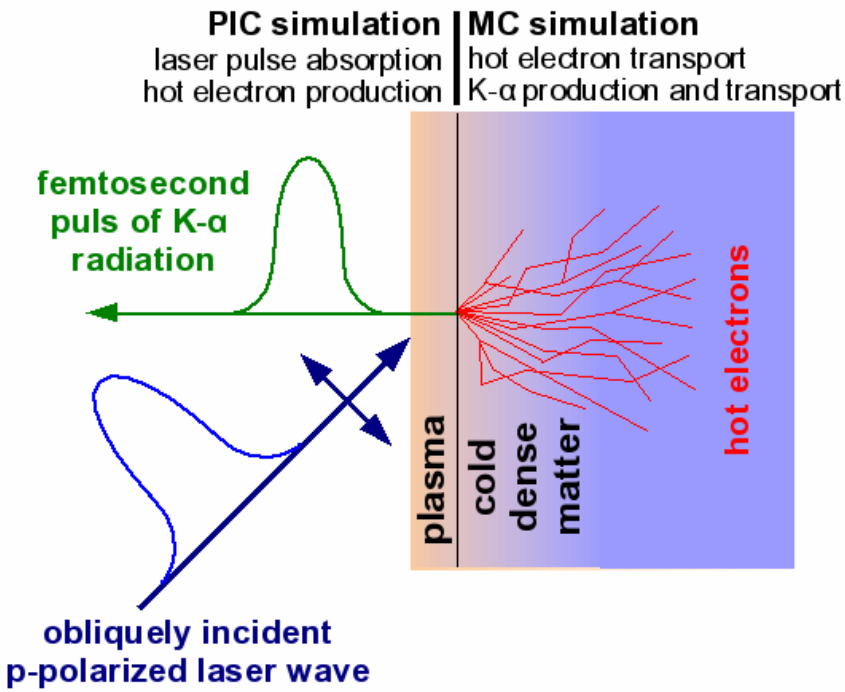


Nakano, NTT Japan
Solid Al target
Irradiated by 100 fs 30 mJ Ti:Sapphire laser λ = 790 nm
I_m = 2.3 x 10^{16} W/cm^2
p-polarization, pre-pulse, incidence 30^o

Resonance He-like line – 1598 eV – pulse lengths up to 30 ps -our simulation

K-α emission – when energetic electron penetrates into cold target it can knock out electron from K-shell, vacancy is filled quickly (<10 fs) either Auger electron or photon is emitted (1488 eV)

Simulation scheme and parameters



Simulation split into 2 regions

Interaction region – hydrodynamics code is used only to find density scale length, PIC code → hot electron velocities and times of boundary crossing recorded

Solid target region – Monte Carlo code for hot electron transport, it may include self-generated electrostatic fields

Transition layer – zero width assumed, potential jump can be applied

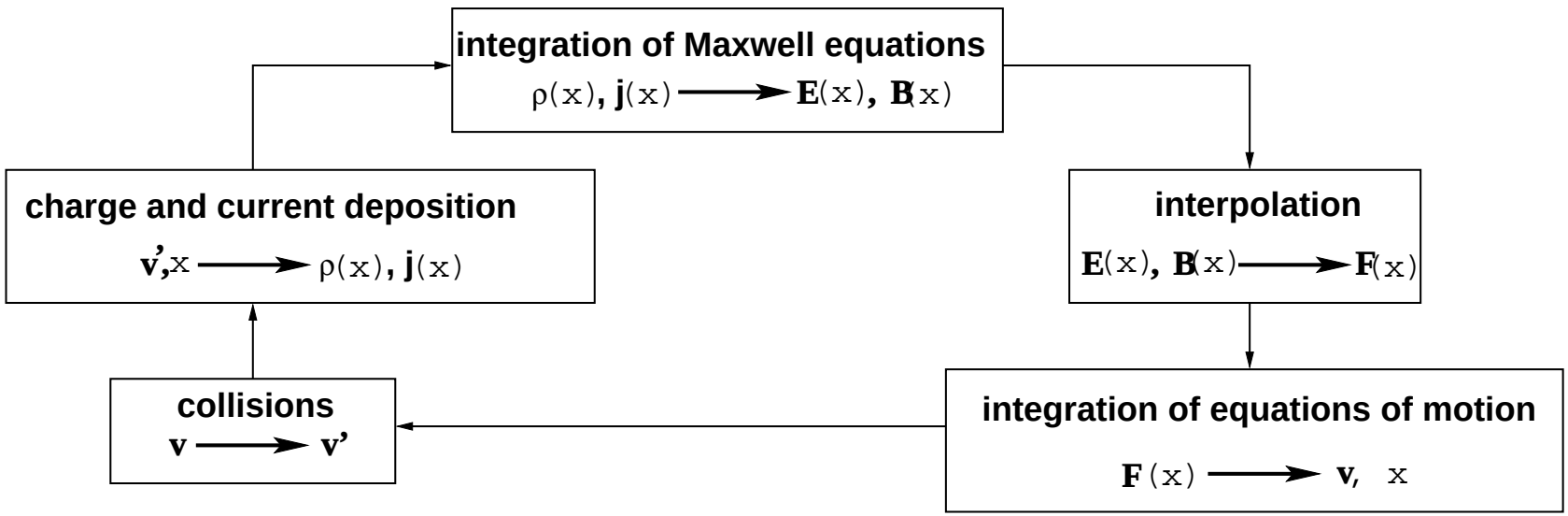
2 experiments studied a) LULI – T. Schlegel et al., Phys. Rev. E 60 (1999), 2209 and b) NTT Japan – H. Nakano et al., Appl. Phys. Lett. 79 (2001), 24

a) 120 fs, 800 nm, 45°, $I_{main} = 4 \times 10^{16}$ W/cm^2, $I_{prepulse} = 4 \times 10^{14}$ W/cm^2, SiO_2

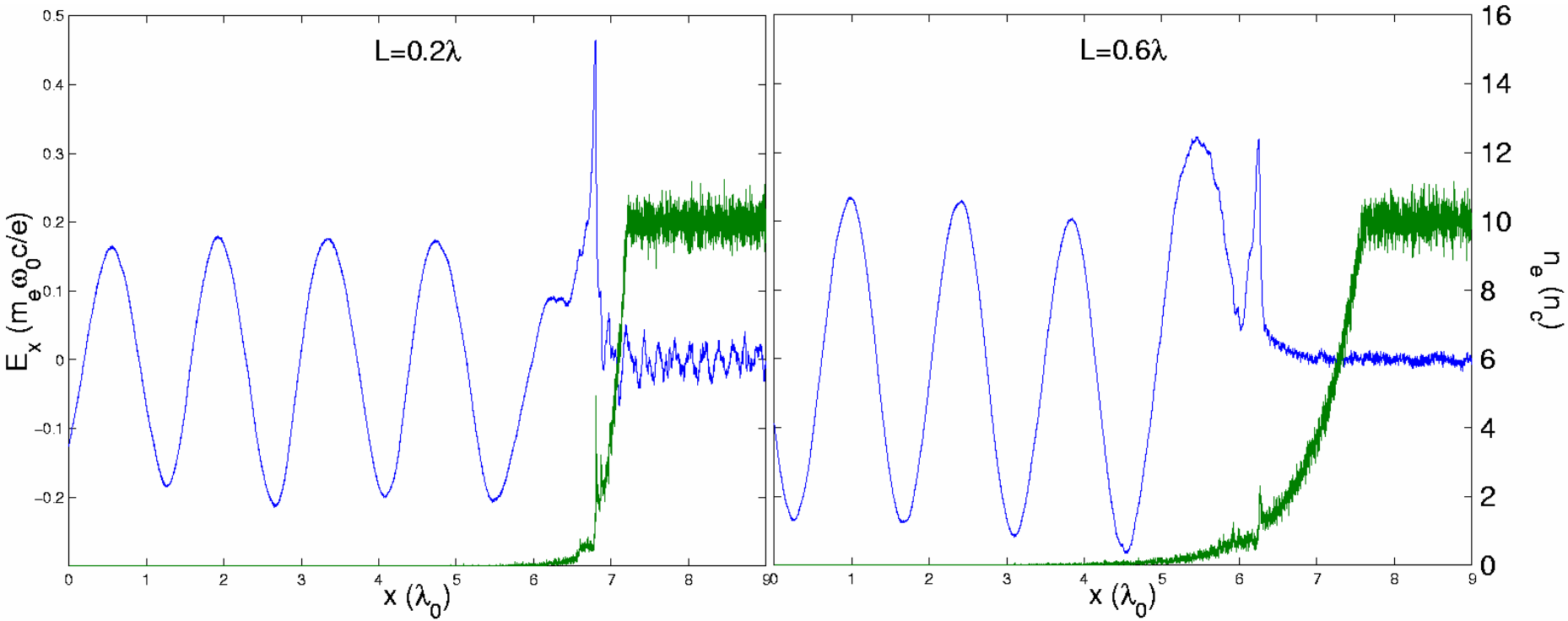
b) 100 fs, 790 nm, 30° , $I_{main} = 2.3 \times 10^{16}$ W/cm^2, $I_{prepulse} = 8.5 \times 10^{14}$ W/cm^2, Al

Our PIC code

- Evolved from LPIC++ code by Lichters, Pfund and Meyer-ter-Vehn
- 1D3V relativistic PIC code using boosted frame to treat obliquely incident laser
- Electrons leaving PIC simulation box to the dense target are substituted by flux of Maxwellian electrons with initial electron temperature T_{e0} in order to maintain neutrality (ions are reflected from both boundaries)
- Elastic short-range Coulomb collisions were incorporated using methodology proposed by Takizuka and Abbe

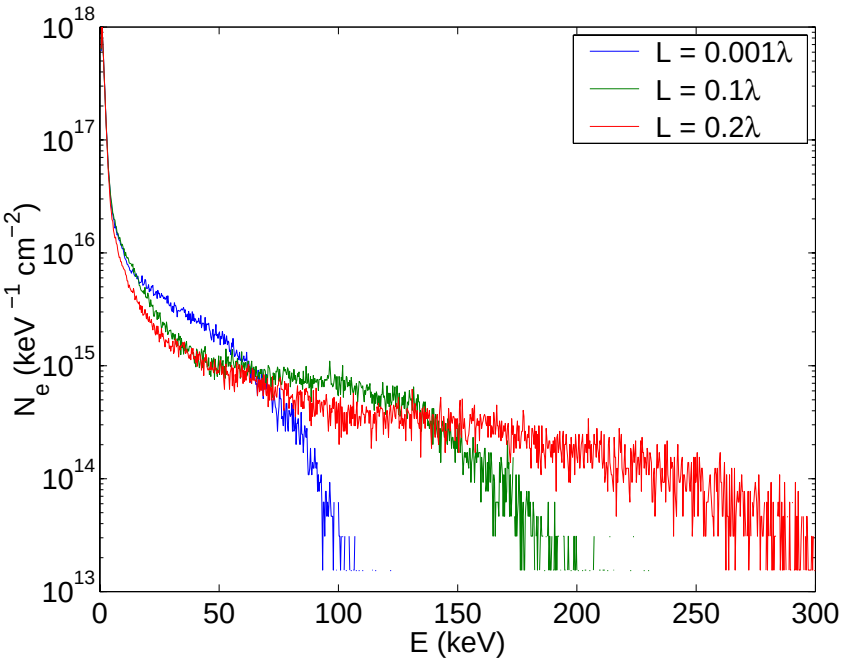


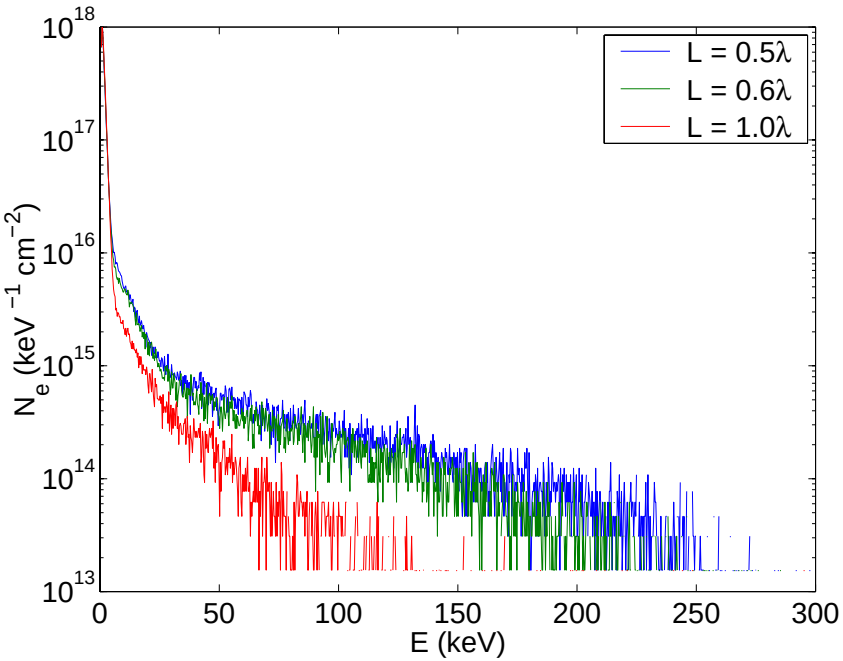
PIC simulation of laser-plasma interaction



Longitudinal electric field, incidence angle 45°, maximum of 120 fs pulse of max. intensity I =4 x 10^{16} W/cm^2, L = 0.2 λ - optimum scale length for resonance absorption, electron density modified by field, ion density nearly unperturbed (exponential + constant)

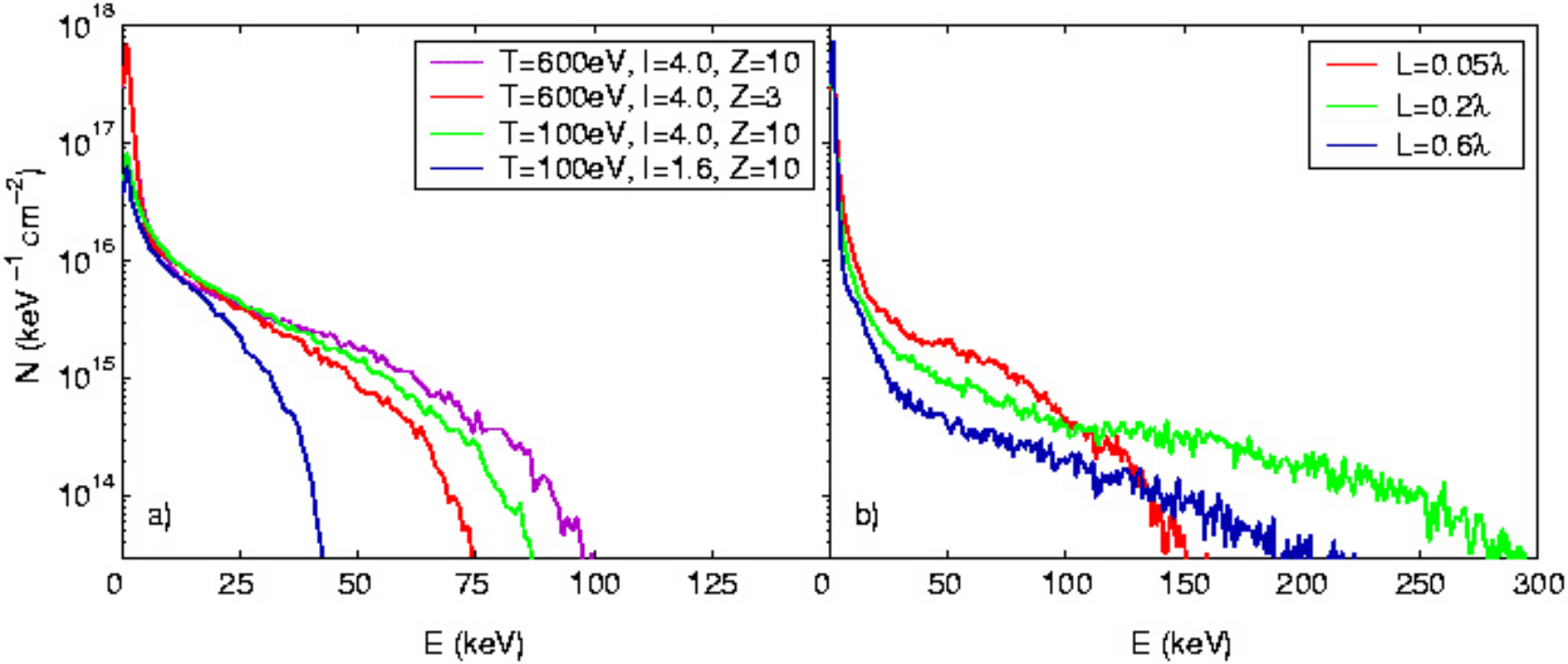
Time-integrated spectra of fast electrons leaving the PIC simulation box into the target





Gaussian 120 fs FWHM laser pulse, λ = 800 nm, I_{main} = 4 x 10^{16} W/cm^2, Al, mean ion charge Z = 11, initial temperature T_e = 600 eV, T_i = 100 eV

Electron temperature and intensity impact on fast electron spectra



Left – L = 0.001 λ, I in 10^{16} W/cm^2, Right – I = 4x10^{16} W/cm^2, T_{e0} = 600 eV, Z = 10

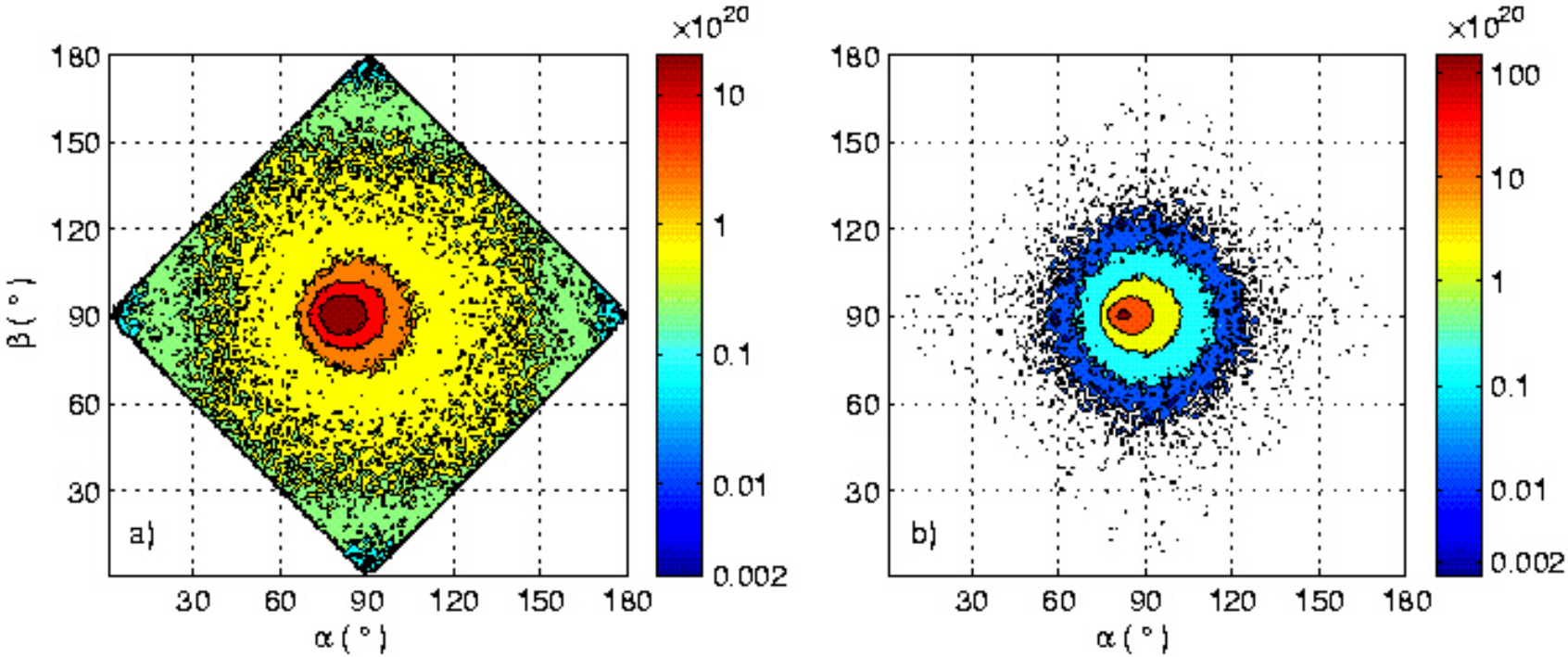
Initial electron temperature T_{e0} has small impact on electron spectra above 5 keV

For sharp boundary electrons are too slow at low intensities, while they can have optimum energy around 50 keV for optimum density scale length

Maximum plasma density in simulation box practically do not influence spectra

Very small impact of mean ion charge Z

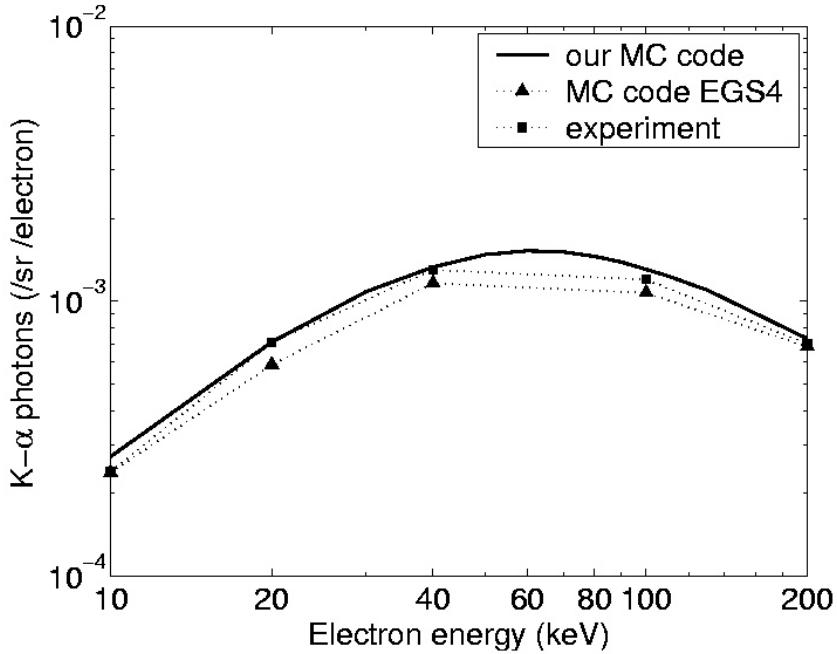
Angular dependence of energy flux in electrons with energy > 1.5 keV for T_{e0} = 600 eV, 100 eV



Angle (0,0) normal to the target, laser incidence α = 45°, β = 90° (electrons slightly shifted from normal into direction of laser propagation), for T_{e0} = 600 eV thermal electrons with E > 1.5 keV do exist, fast electrons are collimated

Our Monte Carlo code

- Our Monte Carlo code "HEIKE" takes times when electrons cross the boundary and their velocity vectors from PIC code, jump of electrostatic potential may be applied on boundary
- Monte Carlo code simulates electron trajectories with temporal resolution in detail, including all elastic and inelastic collisions (elastic and inelastic scattering, K-shell ionization), bremsstrahlung taken into account via continuous slowing down
- Self-generated electric field may be included via iteration algorithm
- X-ray absorption and secondary x-ray fluorescence were taken into account by simply assuming exponential attenuation inside the target (Beer's law)
- Materials – Al, Cu, plastic, Ti

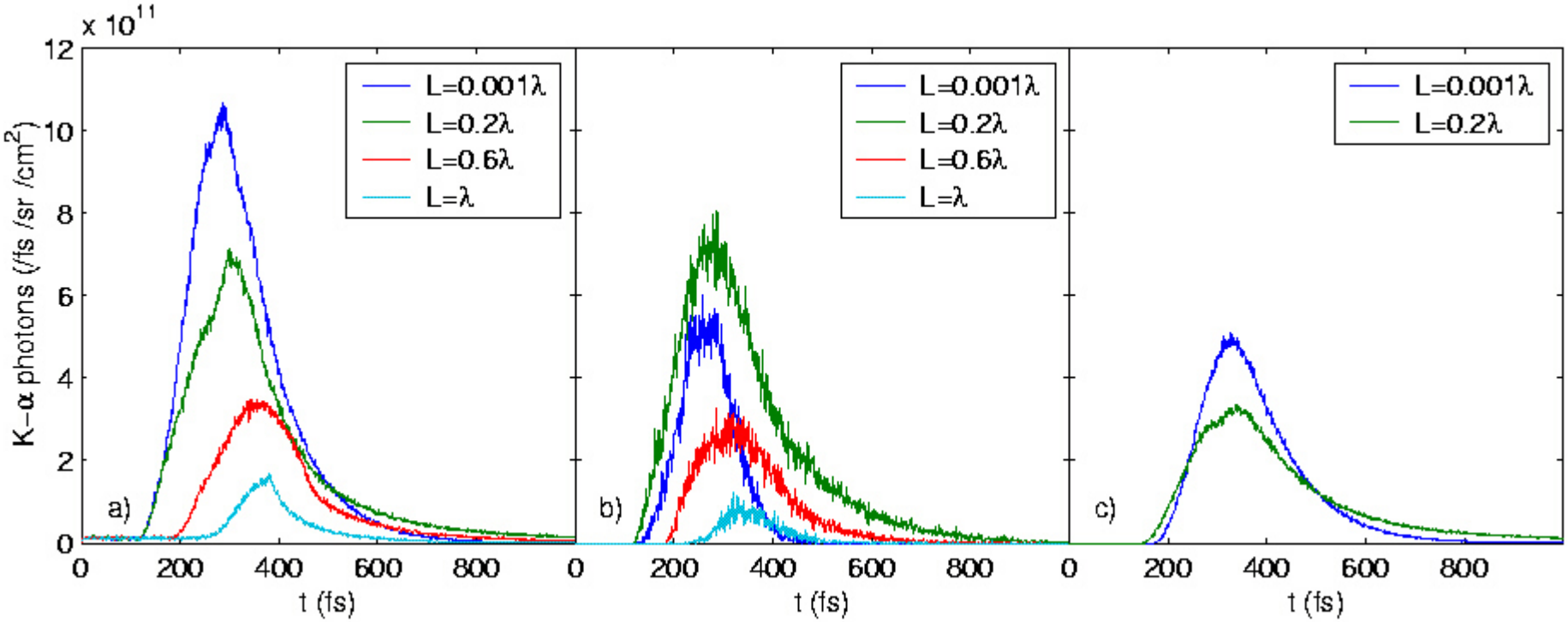


Number of K-α photons emitted normally from target front side per 1 electron in monoenergetic beam (comparison 40, 100 keV)

Optimum for Al $\approx$ 50 – 60 keV

Optimum for Cu $\approx$ 200 keV

K-α pulses emitted normally from the front surface of Al, Cu targets and Al target with 2 μm PE layer



Al – maximum K-α emission for short L below optimum for resonance absorption

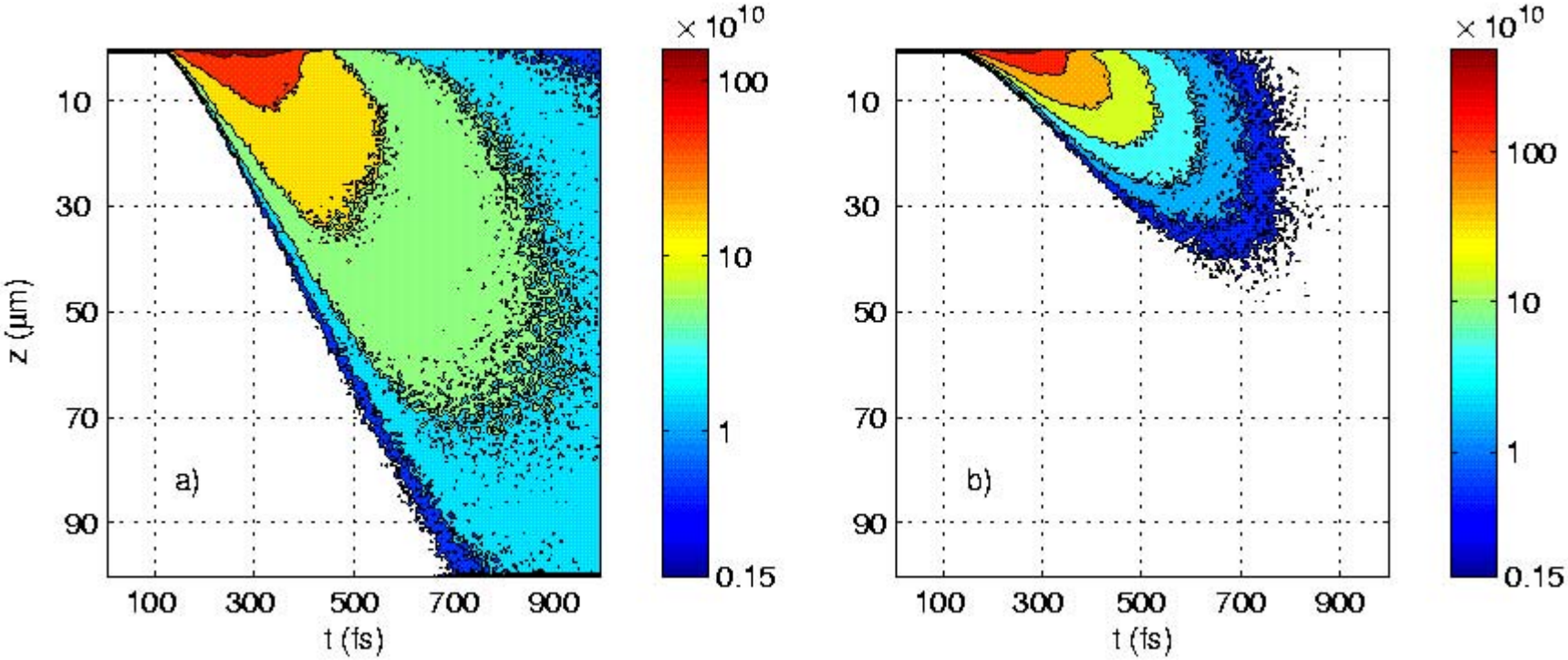
Cu – maximum K-α emission for optimum L

Pulse lengths - ~ 200 fs for Al, ~ 250 fs for Cu with longer trailing edge

Pulse starts later for larger L due to longer distance from critical surface

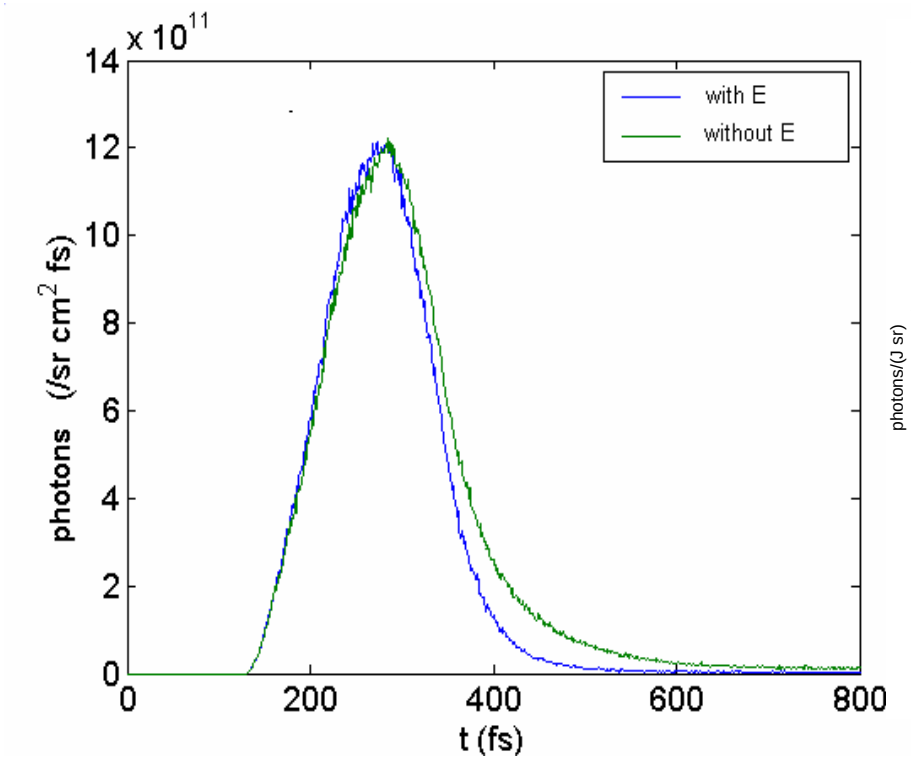
Thin plastic layer suppresses emission from the same highly ionized element

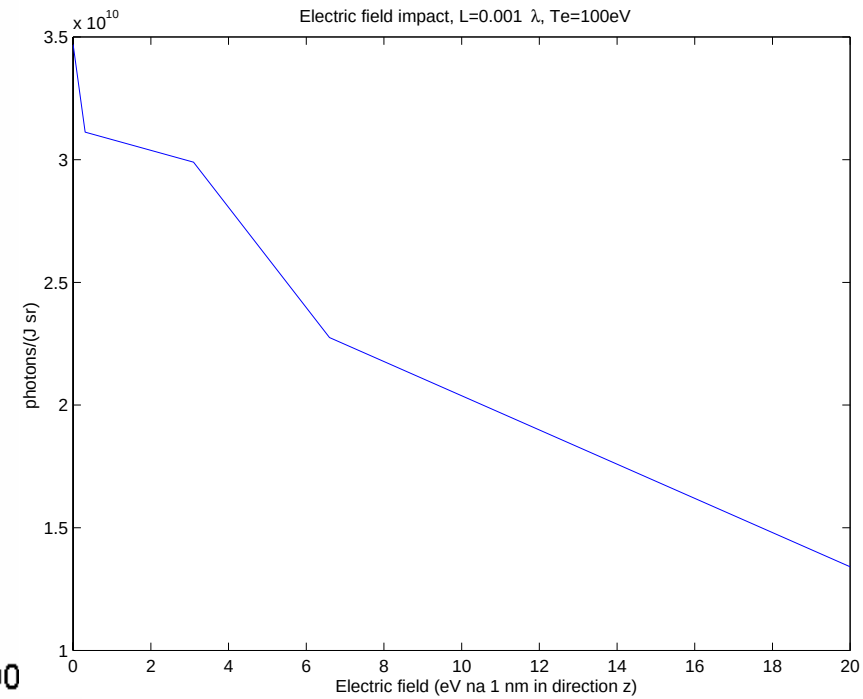
K-α emission versus time and depths



Time and depth of K-α photon emission for L = 0.2 λ and L = 0.001 λ for I_m = 4 x 10^{16} W/cm^2, λ = 800 nm (photon reabsorption is not included)

Influence of self-generated electric field (L=0.001)





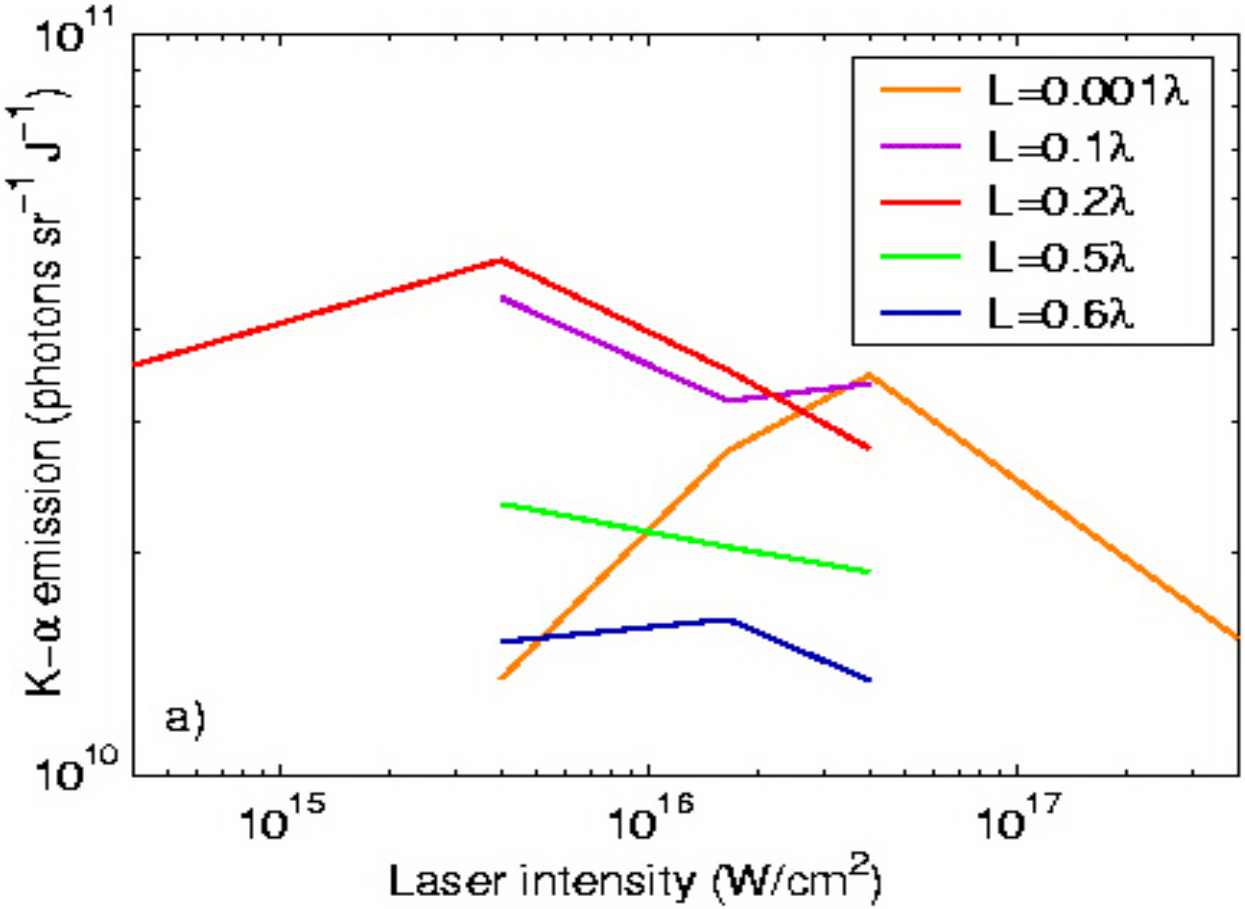
K-α emitted pulse for sharp boundary and I_{main} = 4 x 10^{16} W/cm^2

a) Electric conductivity equal to solid Al at 50 eV (minimum conductivity)

b) Dependence of emitted energy on constant electric field (in keV/μm)

In transition layer potential up to 10 keV may exist (FP heat flux simulations)

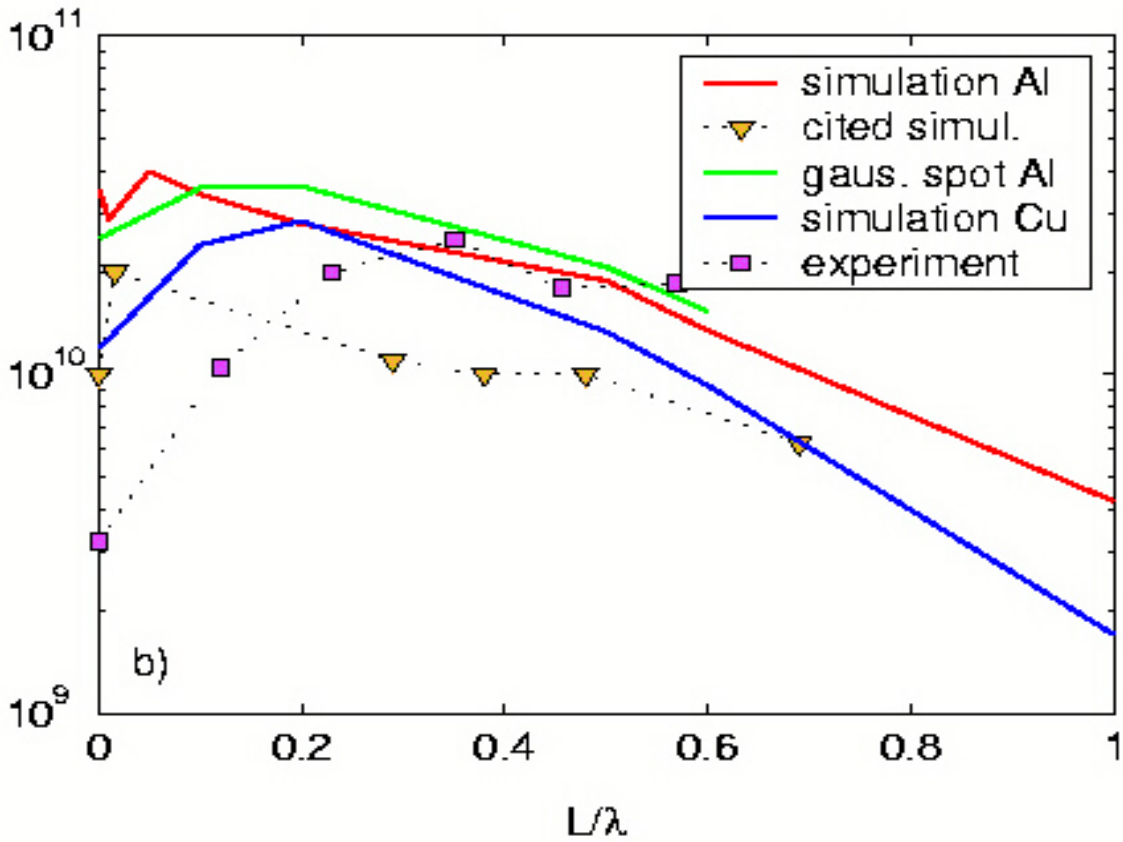
K-α dependence on laser intensity



Optimum laser intensity for K-α emission exists for each density scale length L.

The optimum intensity is minimal for L optimum for resonance absorption and this point seems to be absolute maximum of the conversion efficiency

K-α dependence on density scale length L and integration over focal spot



Simulation cannot reveal experimental decrease of K-α emission for small *L* (as in Schlegel et al.), for heavier element maximum at resonance ab. optimum

Integration over focal spot – the spot emitting K-α is wider for L optimum for resonance absorption than for small density scale lengths L

Conclusions

- Simulation of K-α emission were performed at moderate laser intensities for Al, Cu, and layered targets
- The impact of assumptions used in simulations was investigated
- K-α pulses as short as 200 fs may be emitted from the target front (experiments in Jena suggest pulses much shorter than 650 fs)
- Use of prepulse enhances K-α emitted energy particularly if laser intensity is relatively small for given emitting material
- For relatively high laser intensities K-α emission is maximum at density scale length L < optimum for resonance absorption, however the effective surface of focal spot may be broader for L optimal for resonance absorption
- Self-generated electromagnetic fields do not influence K-α emission substantially for the assumed laser intensities
- 1-2 μm thick plastic layer on target surface may make experiment more clear without substantial decrease of K-α emitted energy

Future plans

- Use 2D PIC code for hot electron spectra and to resolve the question of intermediate energy electrons at short density scale length (maybe vacuum sheath field is higher in 1D code then in 3D experiment)
- When fast electrons are spatially resolved, our Monte Carlo code can calculate the spatial distribution of K-a emission that can be measured experimentally
- Include atomic physics into our PIC or use another code with atomic physics included so that we can asses the impact of transient target ionization