PIC simulations of laser interactions with solid targets

J. Limpouch, O. Klimo

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

S. Kawata

Utsunomiya University, Dept. of Electrical and Electronics Engineering, Yohtoh 7-1-2, Utsunomiya 321-8585, Japan

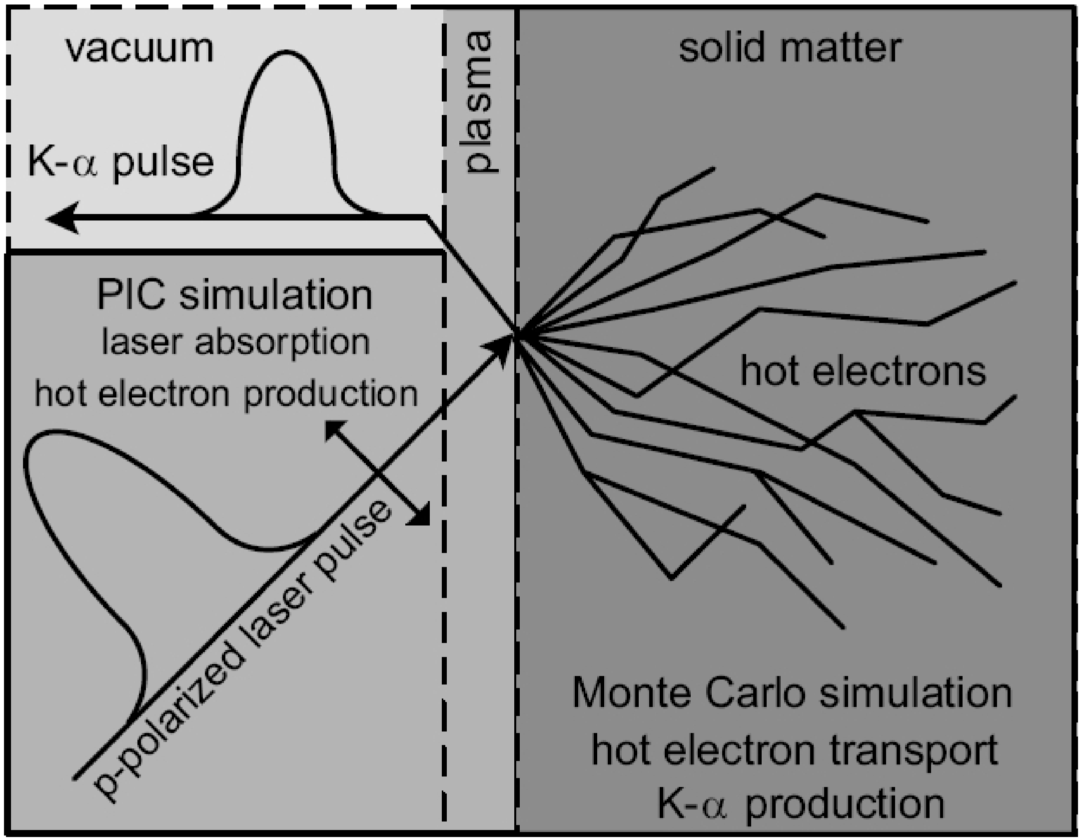
partially supported by

Czech Ministry Education, project LC528 „Laser Plasma Centre“
INTAS, project INTAS-01-0233
Czech Science Foundation project 202/03/H162
JSPS-AS CR Scientist Exchange Program

Outline

- Acceleration of electrons into solid targets
  - Generation of ultrashort x-ray pulses (K-α line)
  - Impact of prepulse and of ionization processes
  - Comparison of 1D and 2D PIC simulations
- Ponderomotive acceleration of quasineutral plasma blocks into target
- Acceleration of electrons in vacuum by laser beam with central intensity minimum

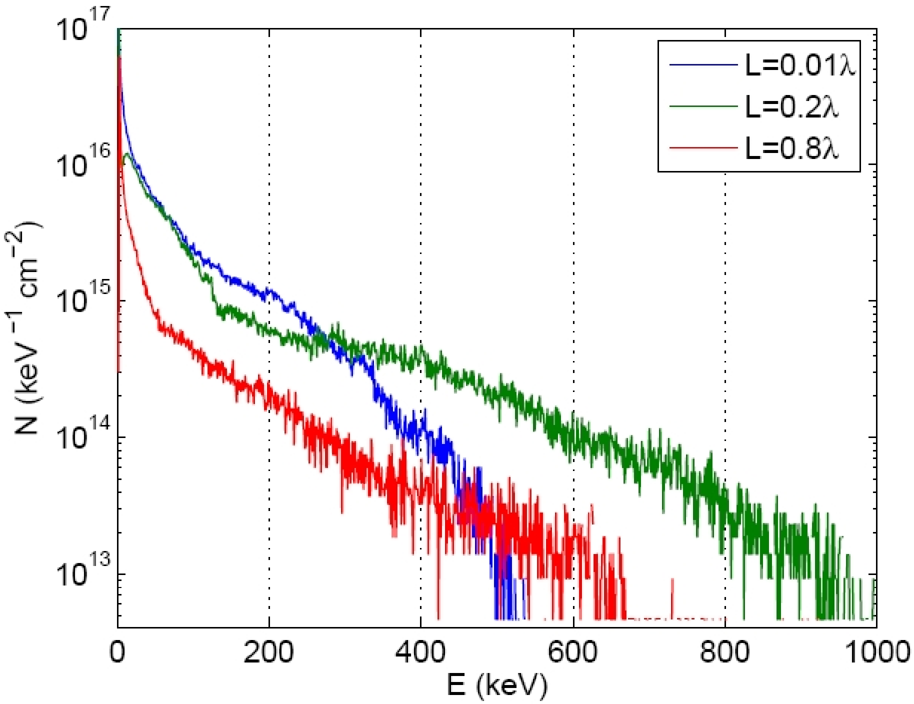
K-α emission – scheme of simulation

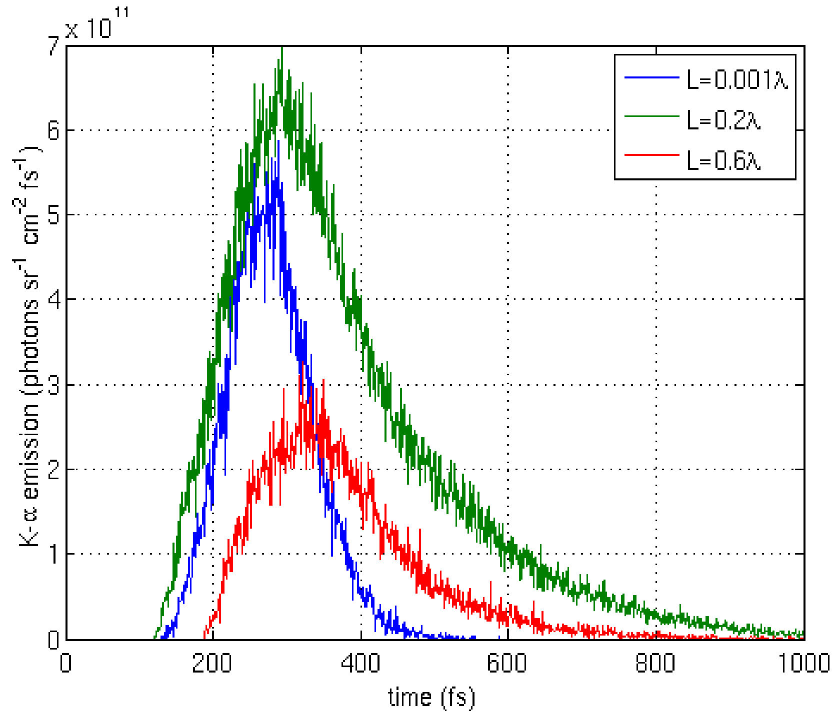


Times and velocity vectors of fast electrons crossing boundary are recorded and used as input for 3D time resolved Monte Carlo

- Plasma-vacuum interface modeled by PIC code
- Electrons reaching PIC boundary in target are substituted
- Longitudinal electric field may be included in Monte Carlo
- Detailed model of K-shell ionization process is included in MC code
- K-α (and K-β) emission and transport to vacuum

1D simulation results (Z constant)

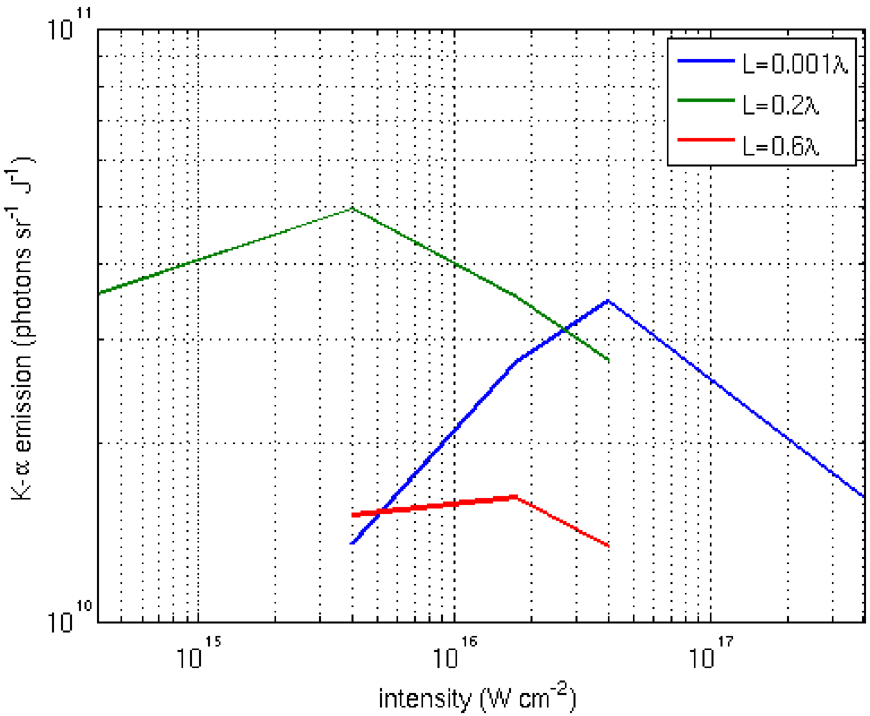


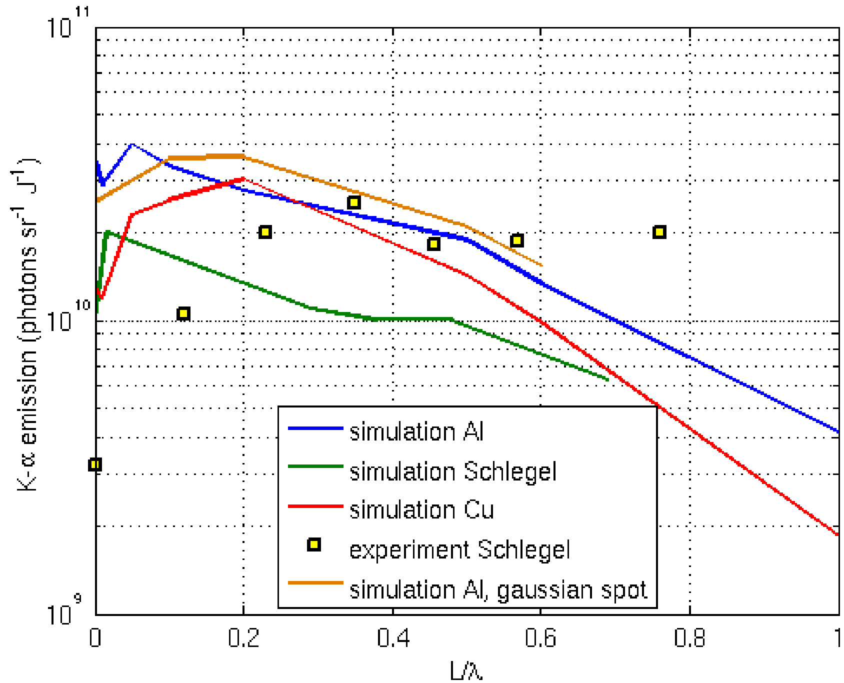


Spectra of fast electrons flying into Al target for 120 fs p-polarized pulse of I = 5x10^{17} W/cm^2, λ = 800 nm incident at 45°, Z=10, T_{e0} = 30 eV, exponential profile

K-α pulses emitted normally from surface of Cu target for 120 fs Ti:sapphire laser pul-se of intensity 4x10^{16} W/cm^2 and angle of incidence 45°

K-α emitted energy versus *I* and *L*

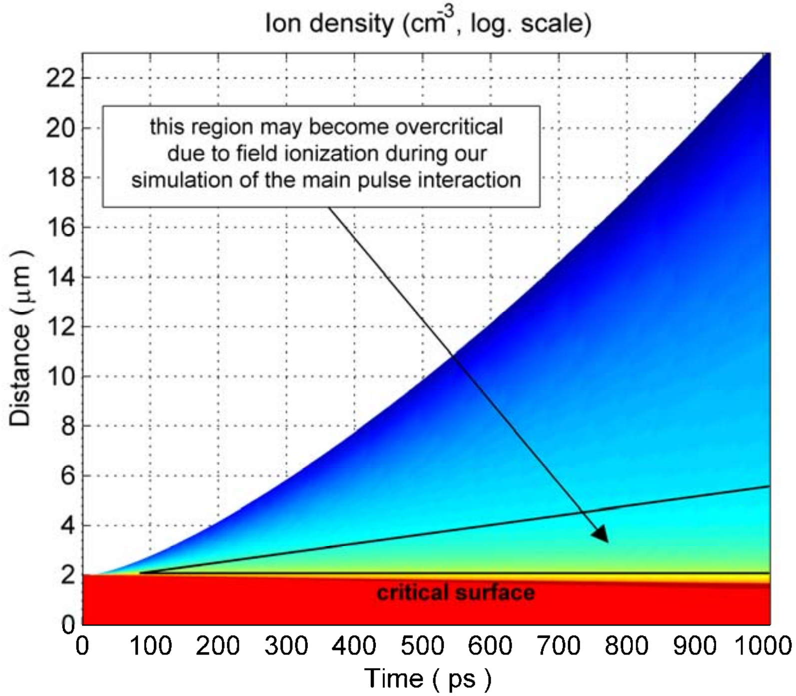


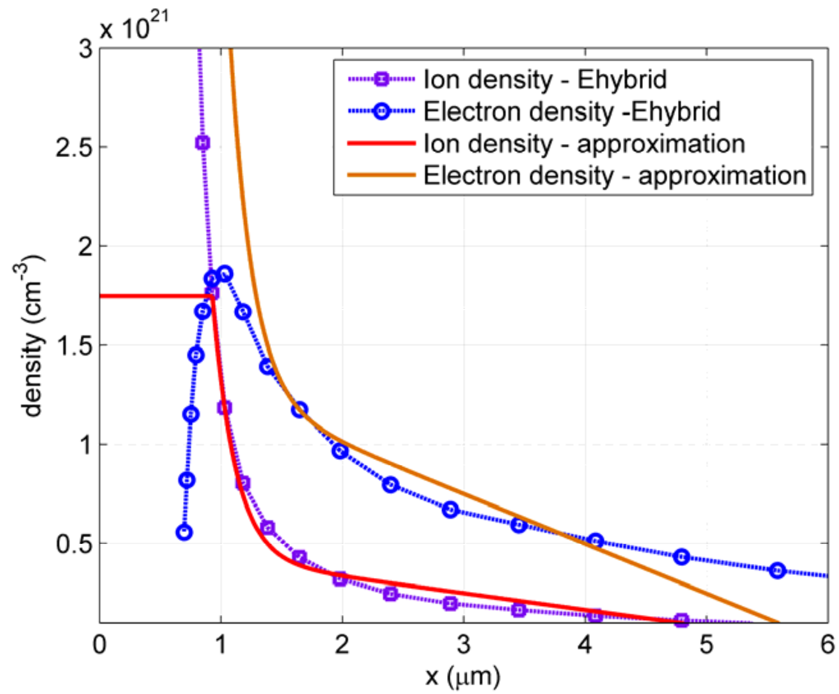


Optimum intensity for K-α emission of Al and incidence angle 45° for various scale lengths *L* of exponential density profile.
Optimum *I* >10^{18} W/cm^2 for Au ($K_{\alpha 1}$ = 68.2 keV) or U ($K_{\alpha 1}$ = 98.4 keV)

For small density lengths *L*, simulations predict much higher emitted energies then measured in experiments (J.Limpouch *et al*., Laser& Part. Beams 22 (2004), 147)

Impact of ASE and of ionization

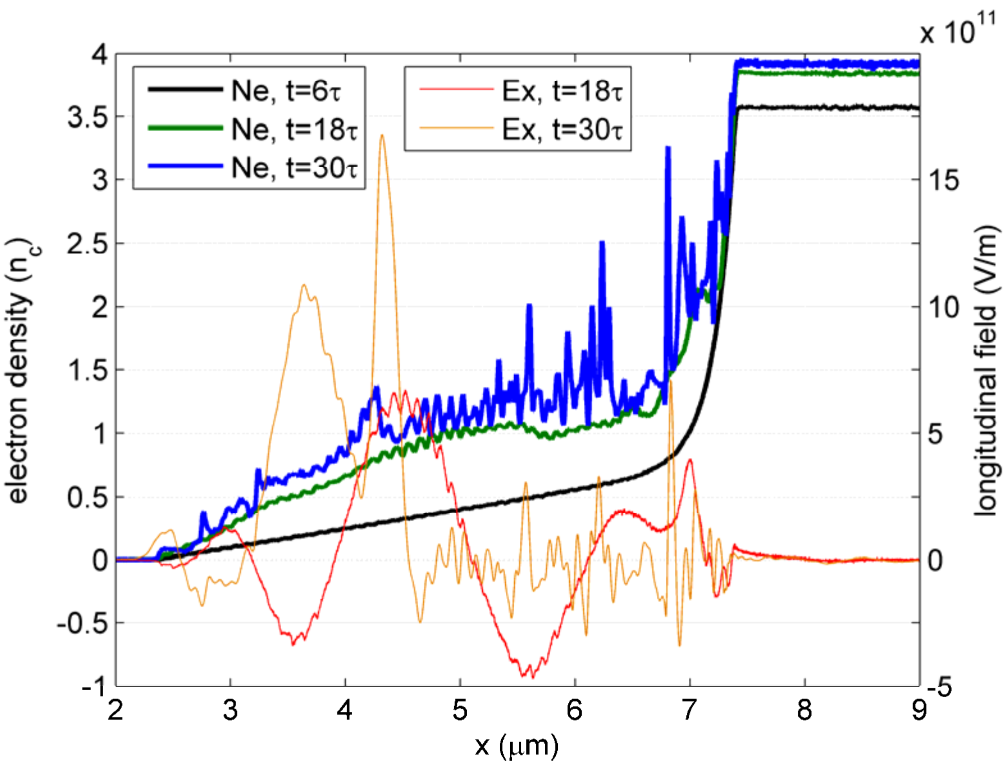


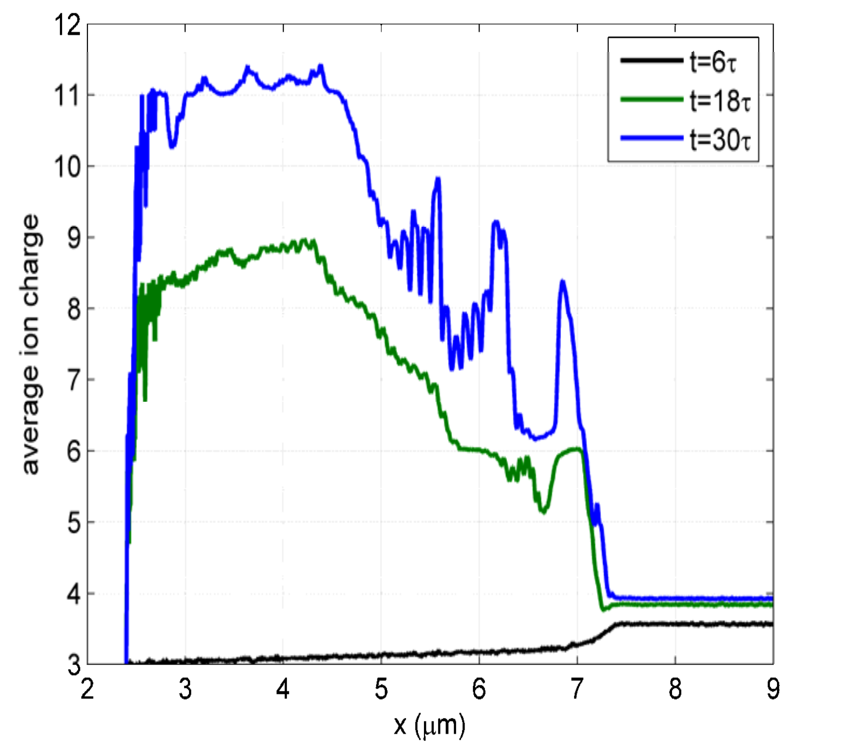


Optical field and collisional ionization added into PIC code
Initial profile for PIC taken from hydrocode Ehybrid simulation

Conditions for experiment in Max-Born (N. Zhavoronkov *et al*.)
Ti-sapphire 45 fs 5 mJ pulse, spot ∅ 6.7 μm, 10^{17} W/cm^2, Cu,
ASE contrast 10^7 at 1 ns (left ion density evolution, constant *I*)

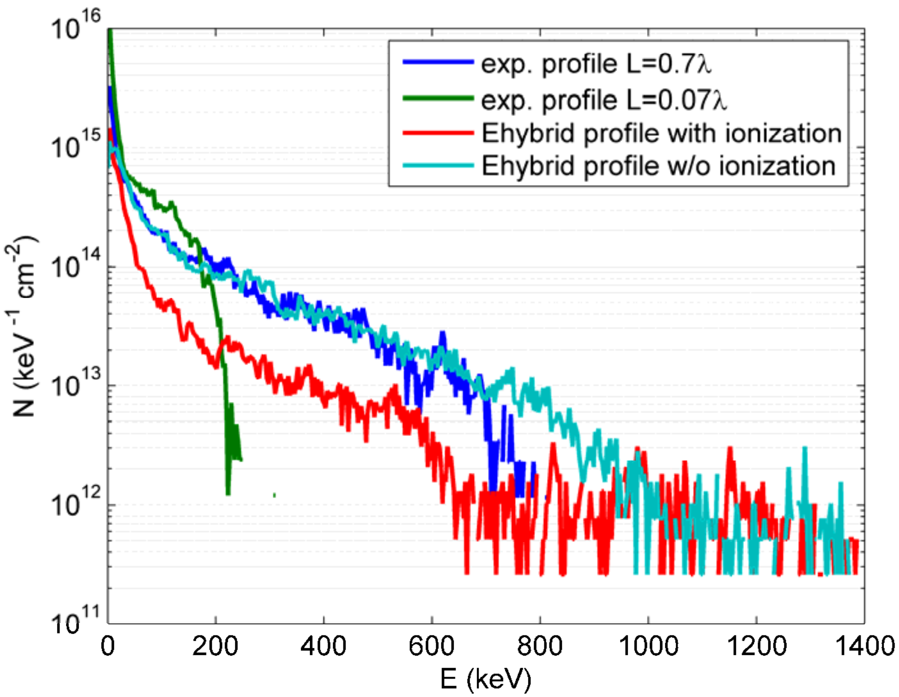
Profiles of electron density and Z in PIC

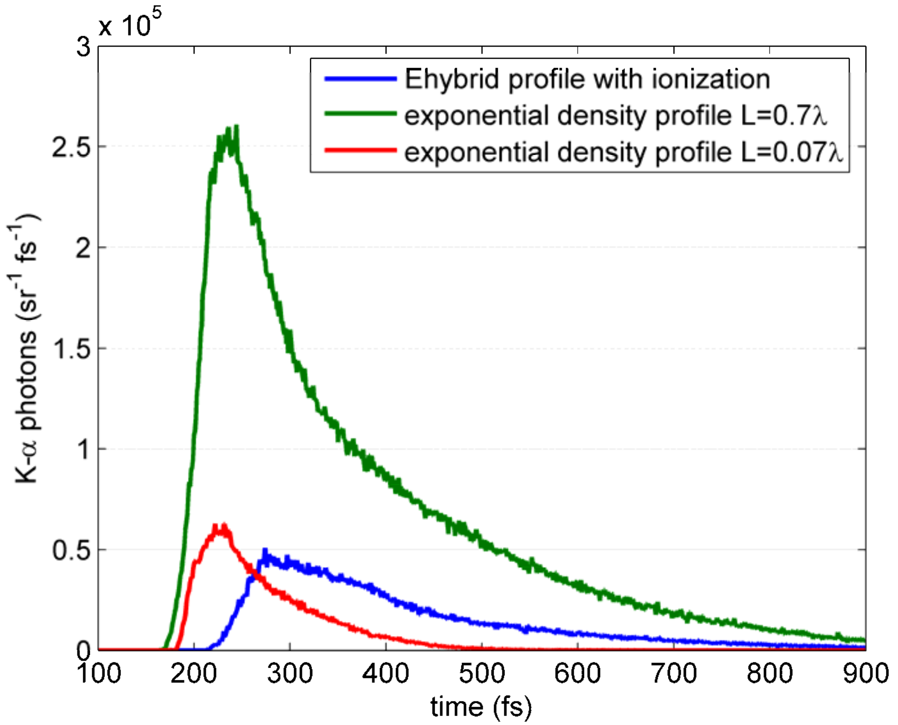




Profiles of electron density N_e and longitudinal electric field E_x (left) and of mean ion charge Z (right), Cu target. Maximum of $\sin^2$ laser pulse at t =27τ is in x=7, angle of incidence 25°. PIC starts from Ehydrid profile, T_{e0} = 50 eV, Z_0 = 3. (Z = 11 is Ar-like copper)

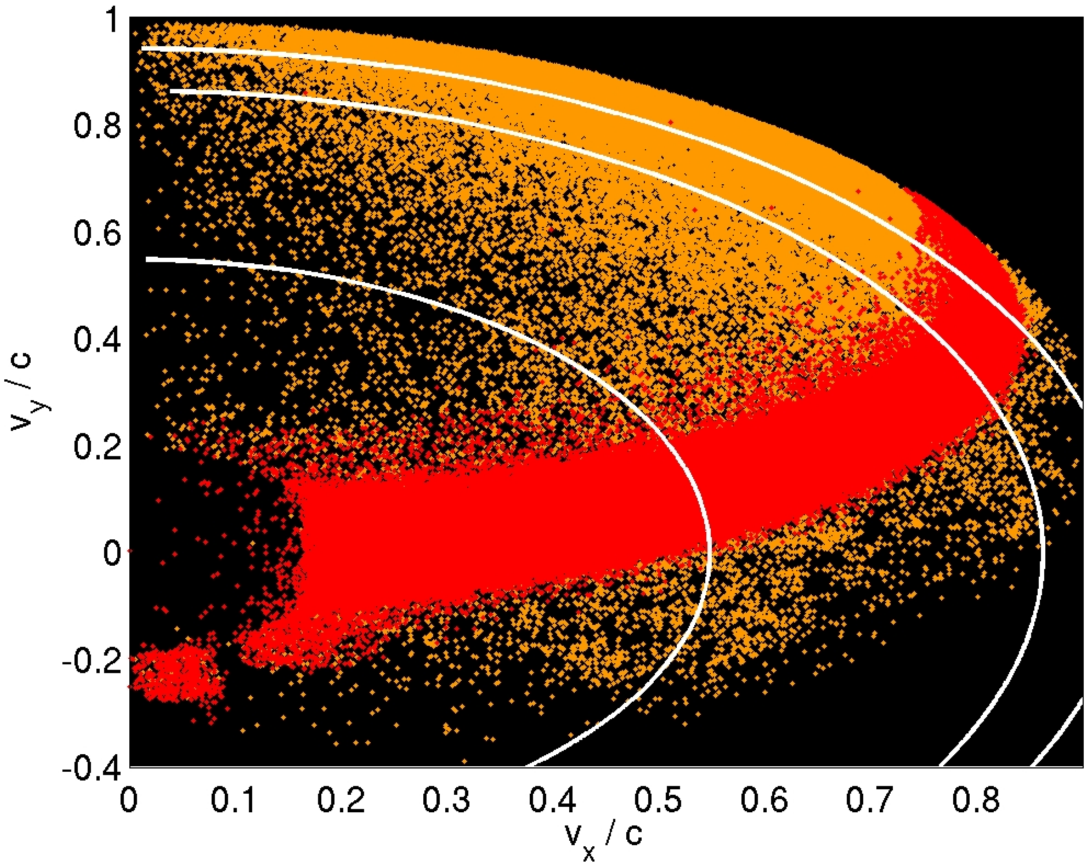
Fast electron spectrum and K-α emission





Sharp exponential profile (L=0.07 λ) leads to K-α emission near to experimental value, but emission does not maximize for angle 25°. Long profile (L=0.7 λ) leads to experimental value of optimum angle but it overestimates K-α emission, best Ehybrid profile with ionization

Fast electron angular distribution



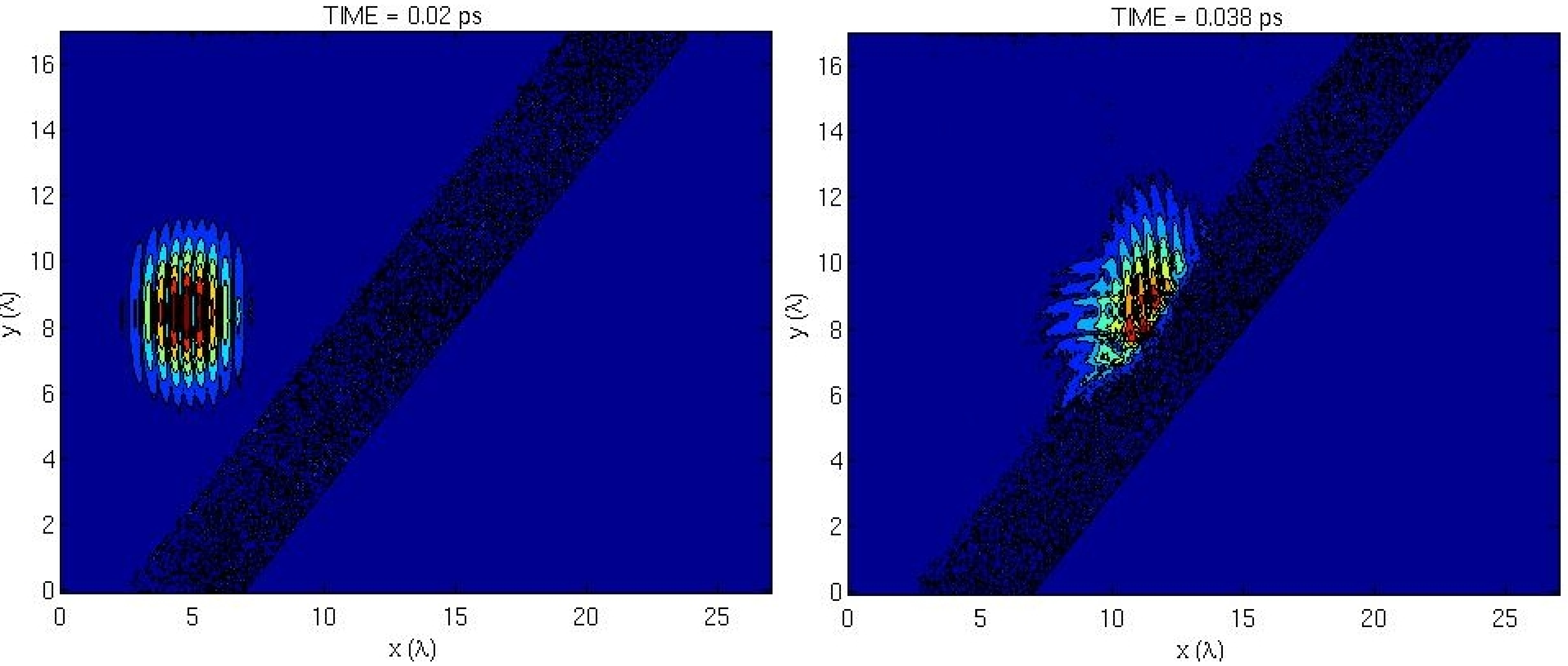
Orange electrons – from ionization of 2p shell, I_p > 780 eV, field ionization occurs near to laser pulse maximum

Red – all other electrons

Orange electrons have large angles to the target normal (red obey classic angle-energy law)

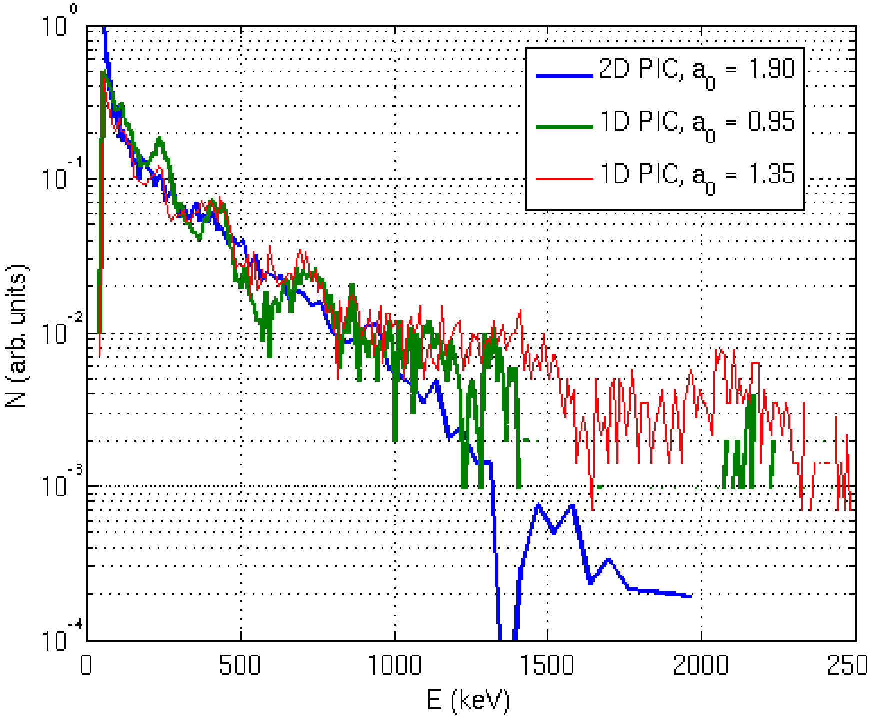
Angular distribution of fast electrons, Ti target, 65 fs laser pulse, $5x10^{18}$ W/cm^2 (a_0 = 1.52), angle of incidence 45°, Z_0 = 3, T_{e0} = 1 keV, L=0.3λ (with long pedestal L=7λ of n_e < ¼ n_c during whole simulation), white lines – 100, 500 and 1000 keV

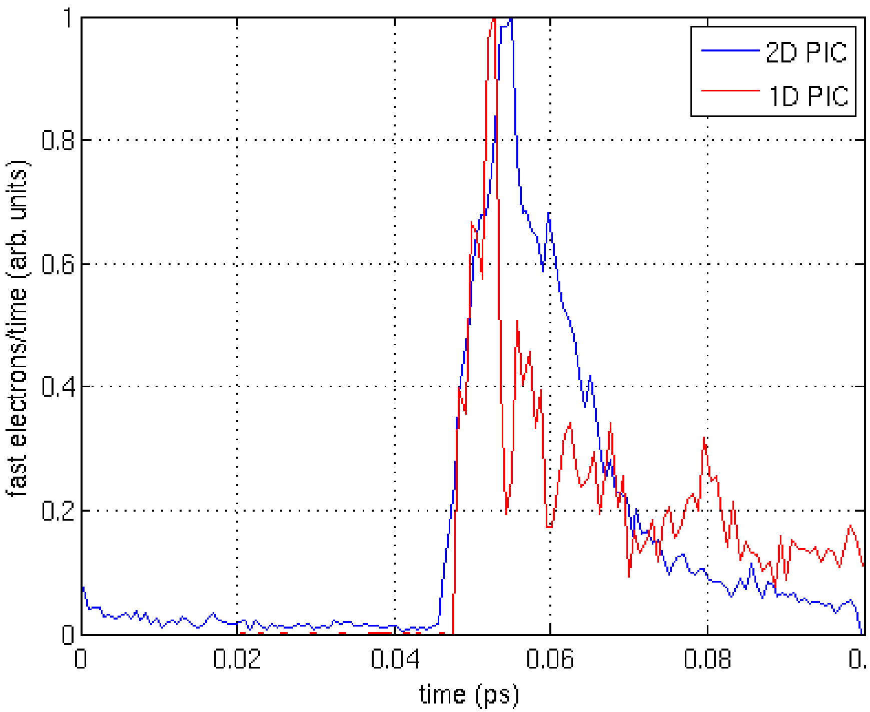
2D PIC simulations



Boundary condition – electrons are substituted at the rear side of slab by back moving thermal electrons, nothing is calculated behind the slab, plasma density – linear with $L = 0.24\lambda$ up to $n_{max} = 3\ n_c$, $T_{e0} = 10$ keV, $a_0 = 1.9$, $w_0 = 4\lambda$, $t_{FWHM} = 2.7\tau$ (=7.5fs)

Comparison of 1D and 2D PIC – fast electrons

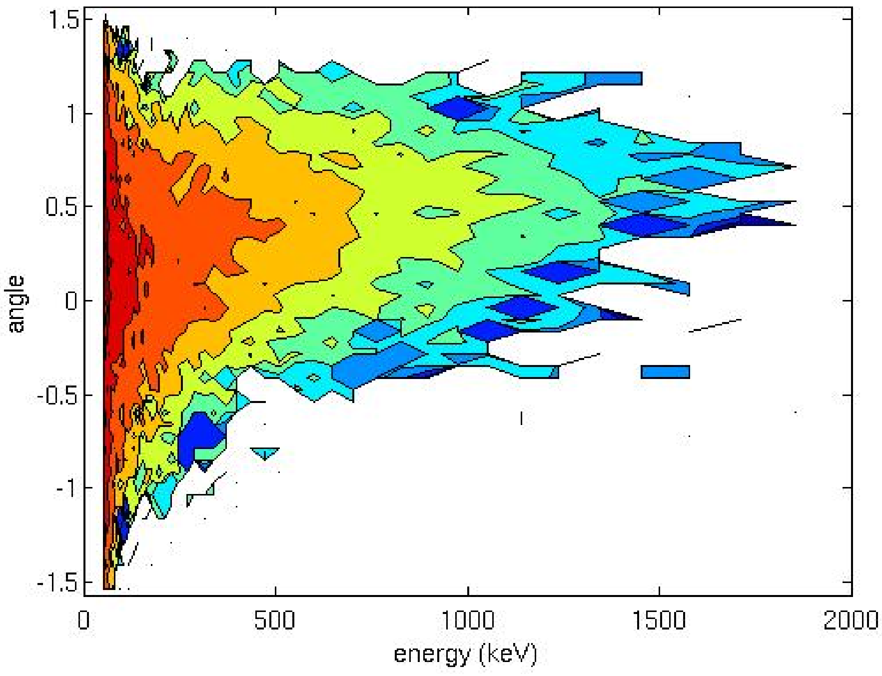


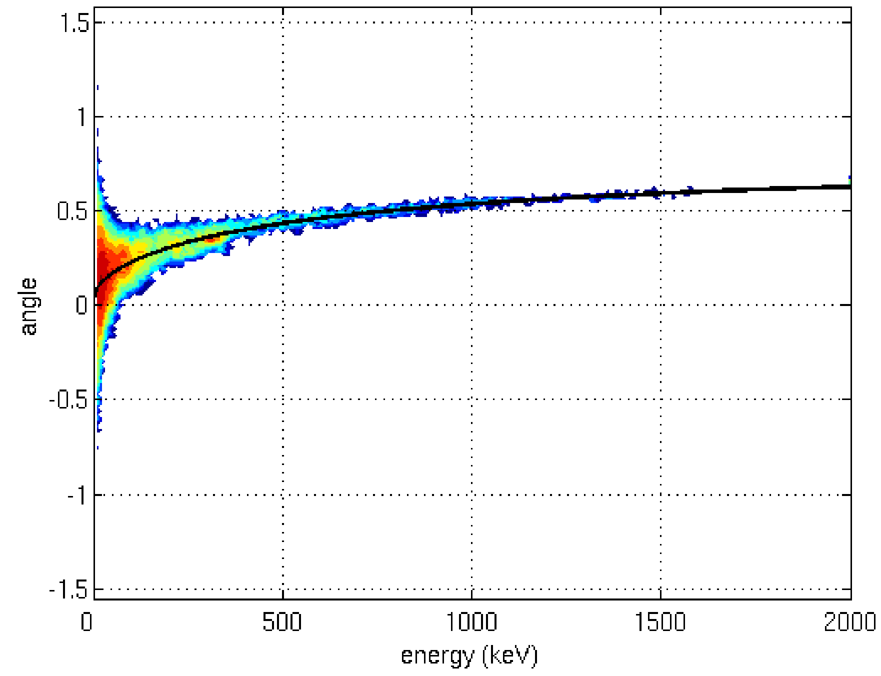


Energy spectrum of fast electrons from 2D PIC is similar to 1D PIC with $a_0/2$
2D has less very energetic electrons

Temporal profile of fast electron pulse on the rear boundary is slightly smoothed and broadened for 2D (due to angular spread?)

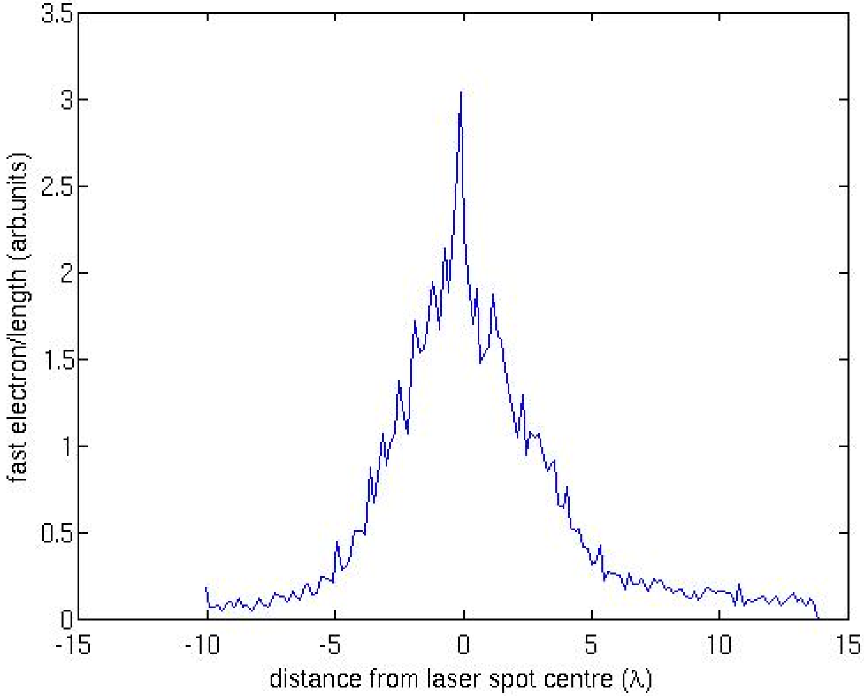
Angular distribution of fast electrons

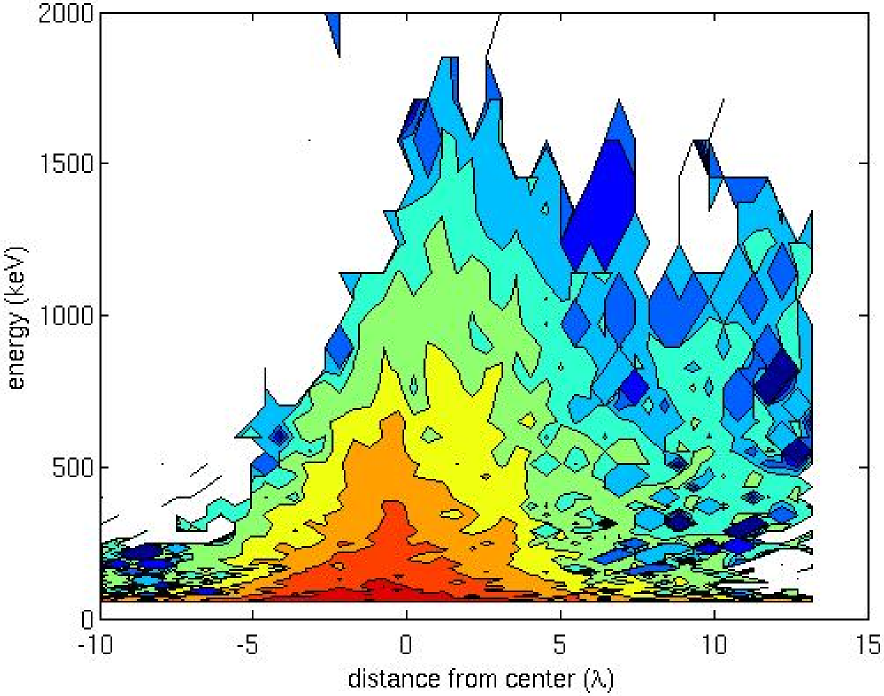




Angular distribution is much broader in 2D than in 1D, while the average angle dependence on electron energy obeys the classic law

Fast electron spot size

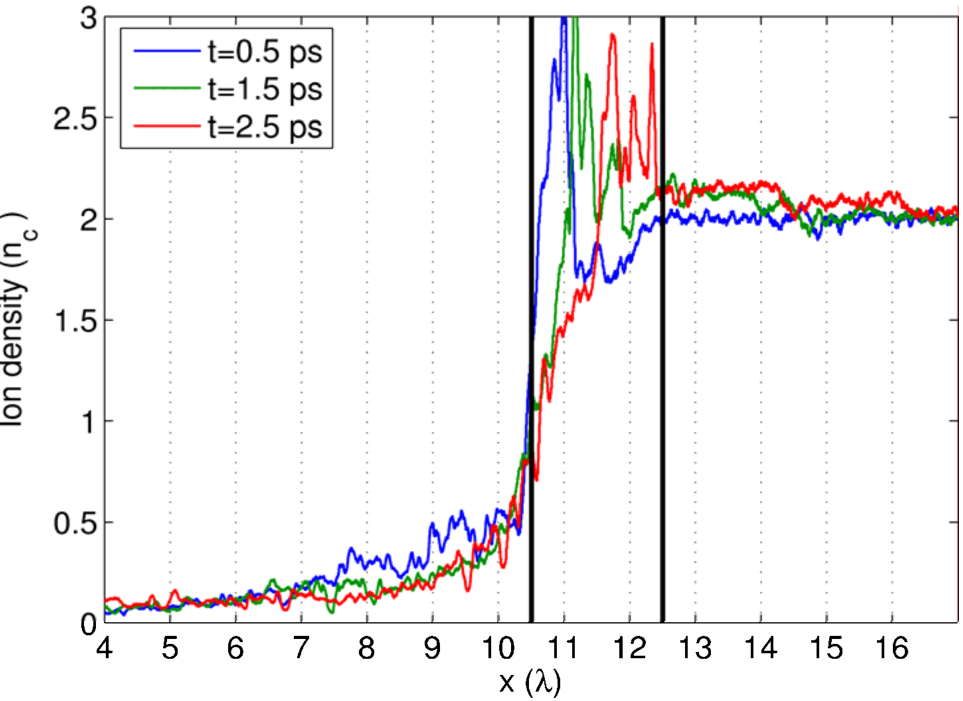


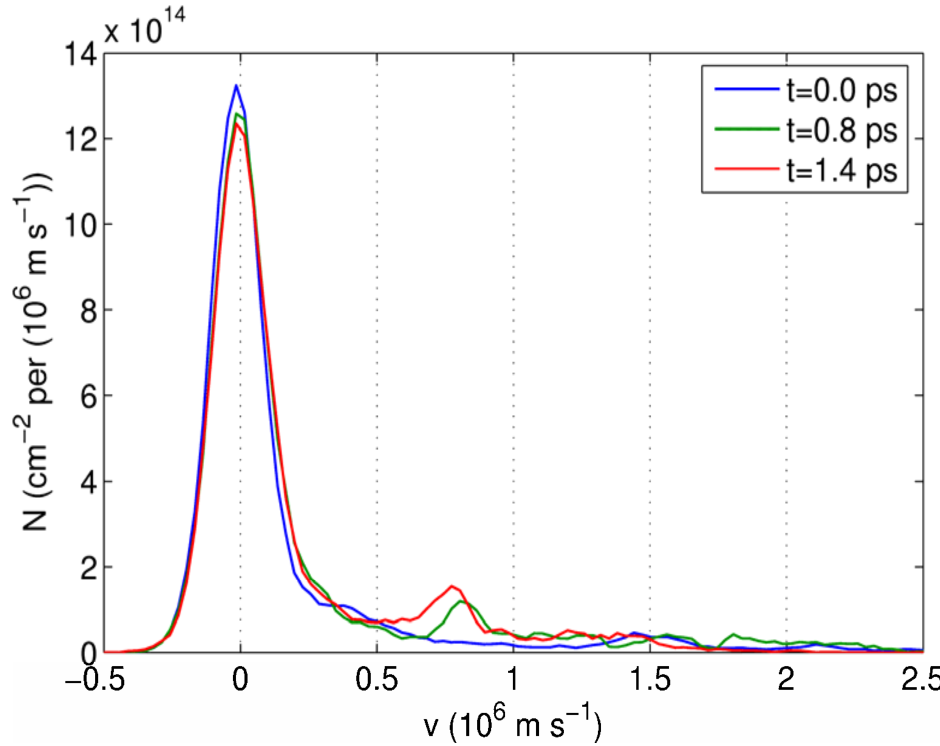


Distance is here along rear side of simulation zone from the point normal from the beam center at critical surface

Fast electron spot size is similar to laser spot, very small number of energetic electrons at greater distance

Ponderomotive acceleration of plasma blocks



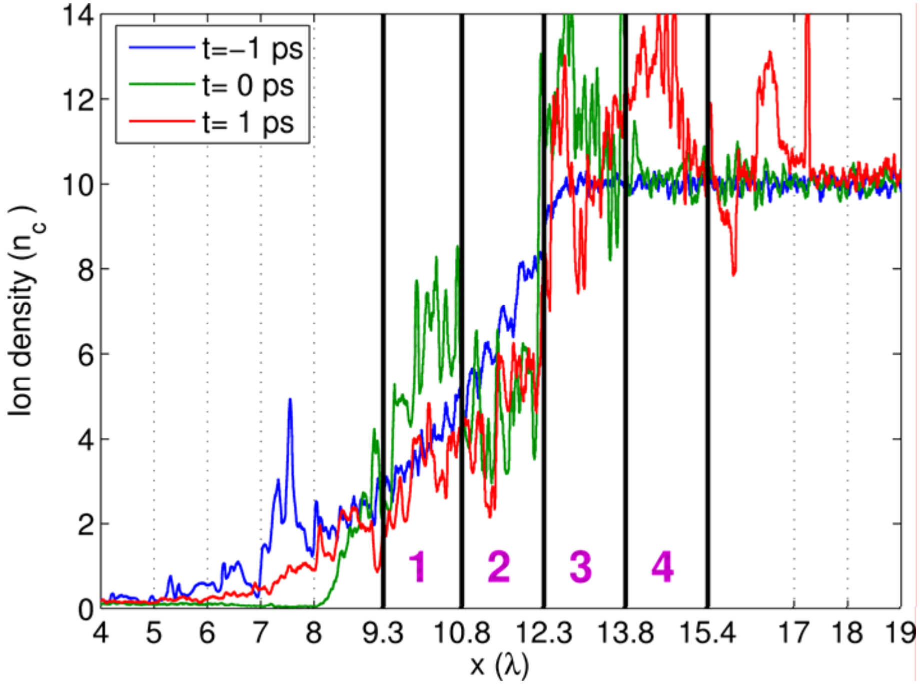


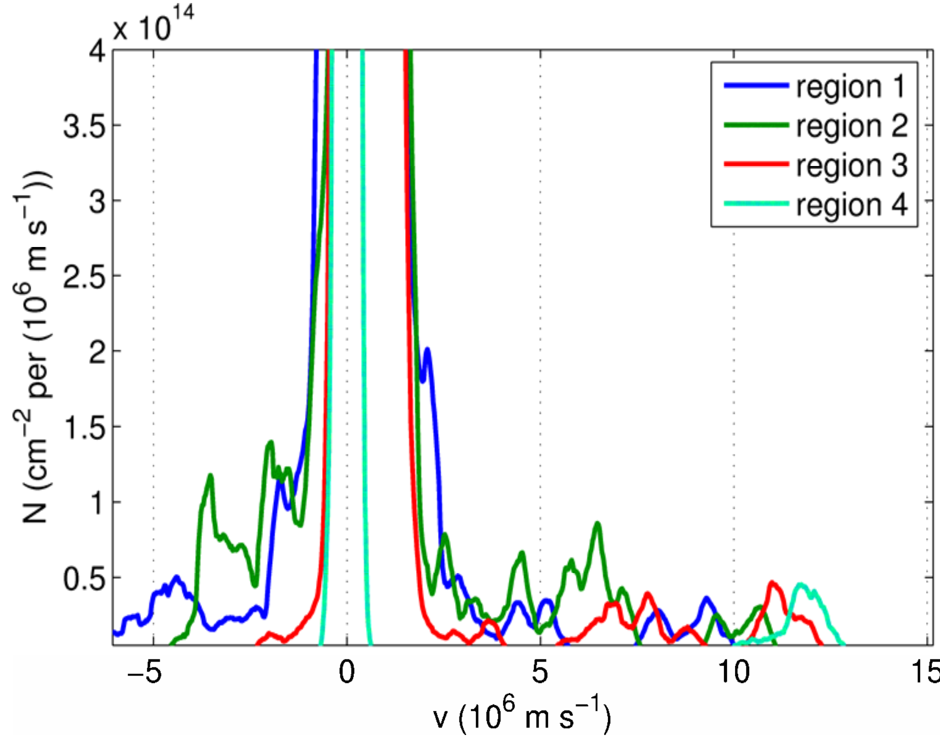
Idea of prof. Hora – 1D PIC capable to model longer pulses

1 ps pulse, λ = 1 μm, exponential profile L= 2.5λ, normal incidence, n_{max} = 2 n_c, t starts 0.9 after laser pulse maximum

Here I = 10^{17} W/cm^2, velocity spectrum average betw. 2 lines

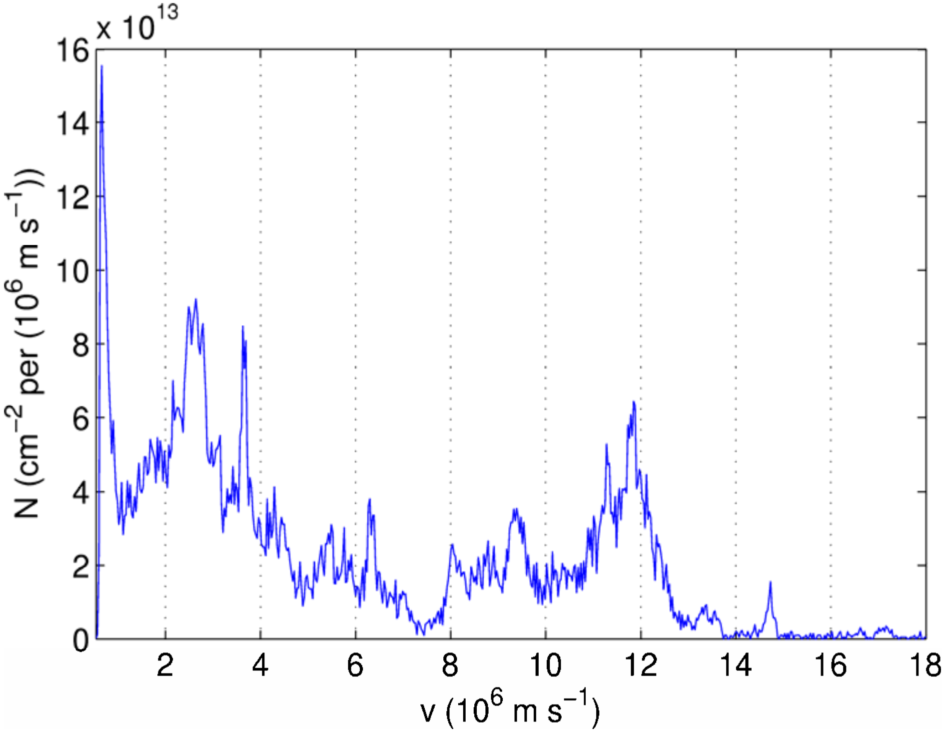
Relativistic intensity 10^{18} W/cm^2

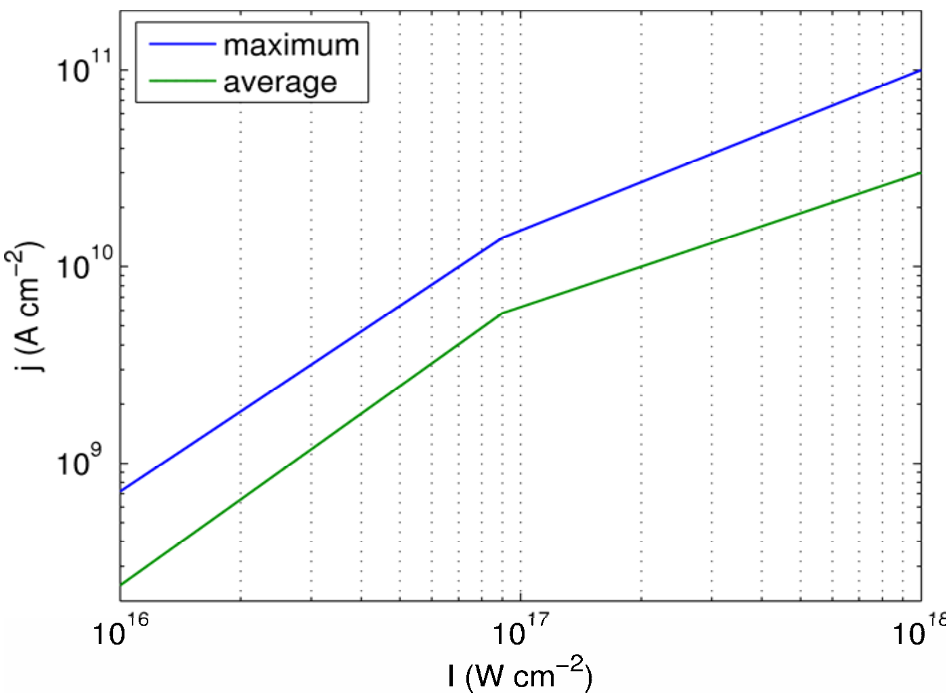




Density profile is significantly disturbed, more separate accelerated blocks are formed, the density snapshot cannot be used to estimate average velocity of accelerated ions, the distributions are taken in four separate regions, in the most right region well defined block is seen in distribution

Time-integrated ion distribution and ion current



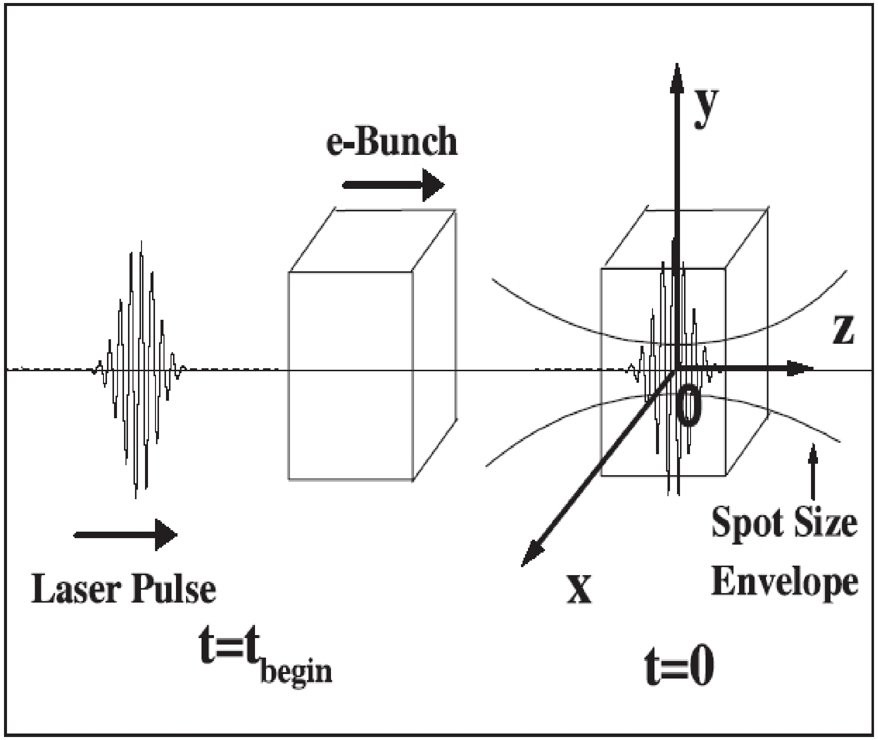


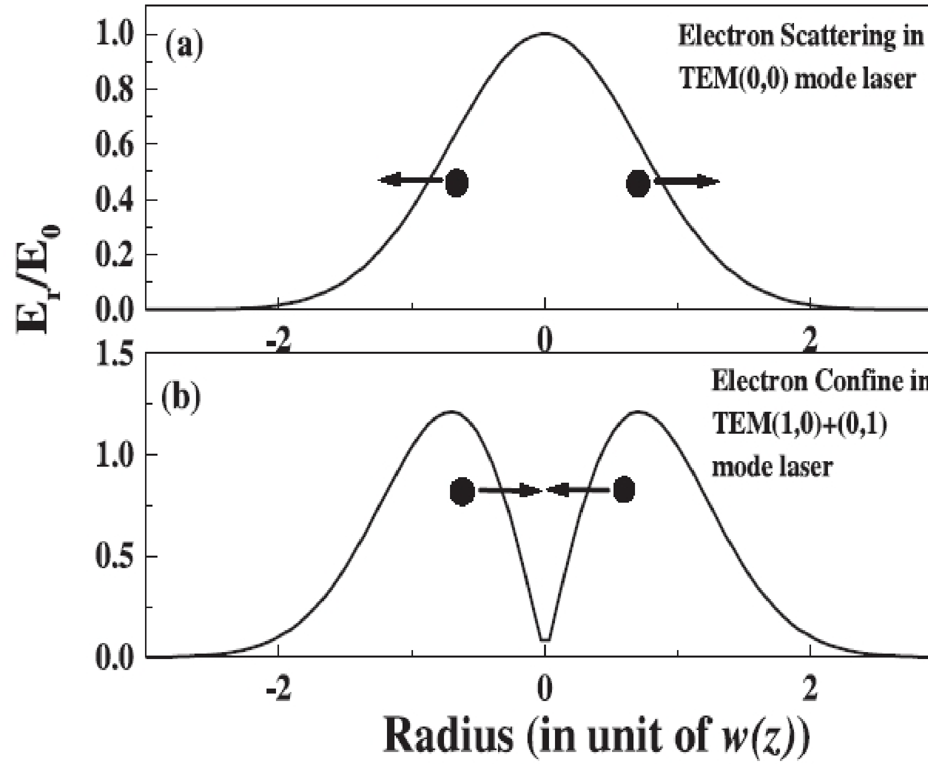
Time integrated spectrum of ions crossing the right side of region 4 (previous slide) for intensity $I = 10^{18}$ W/cm^2

Intensity dependence of average and maximum ion current calculated deeper inside plasma

The results basically agree with 2 fluid simulations

Electron acceleration in vacuum by laser beams with central intensity minimum

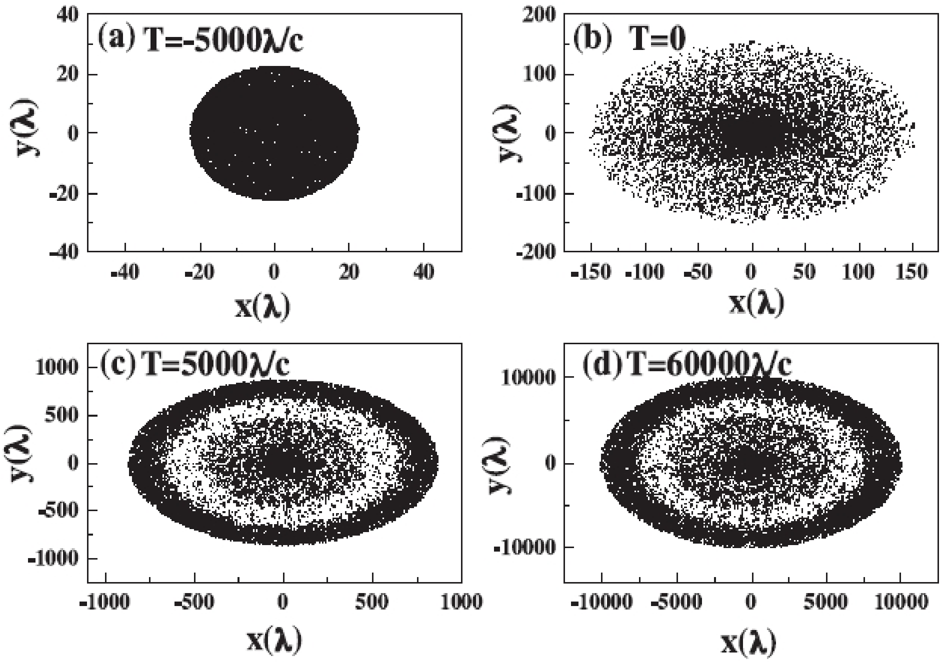


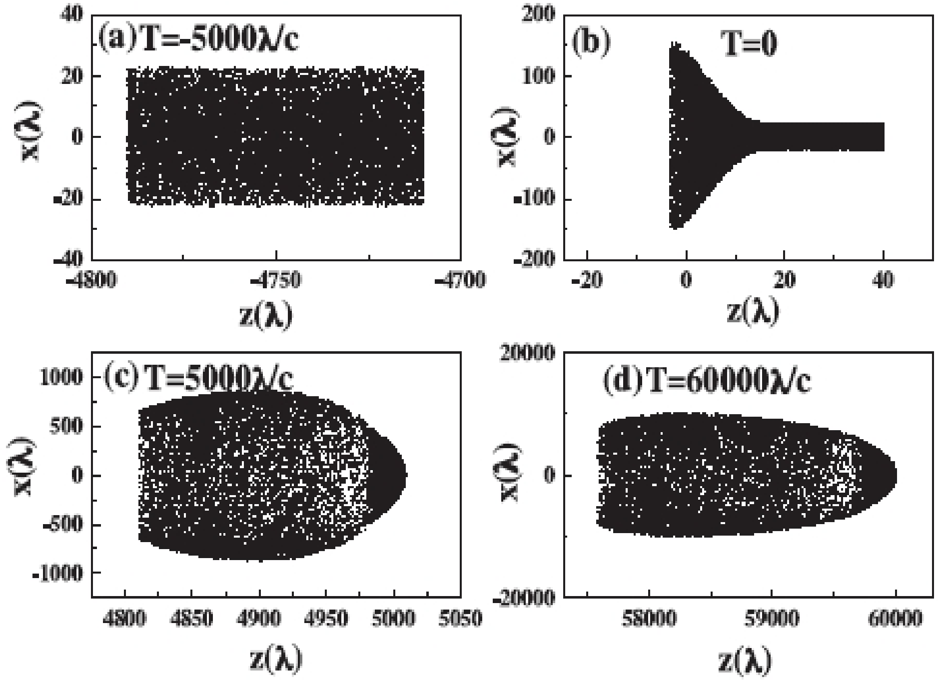


Laser pulse and electron bunch propagate in parallel and they coincide in best laser focus

Idea of prof. Kawata– for sum TEM(1,0)+TEM(0,1) modes ponderomotive confinement

Transverse and side-on profiles of electron beam



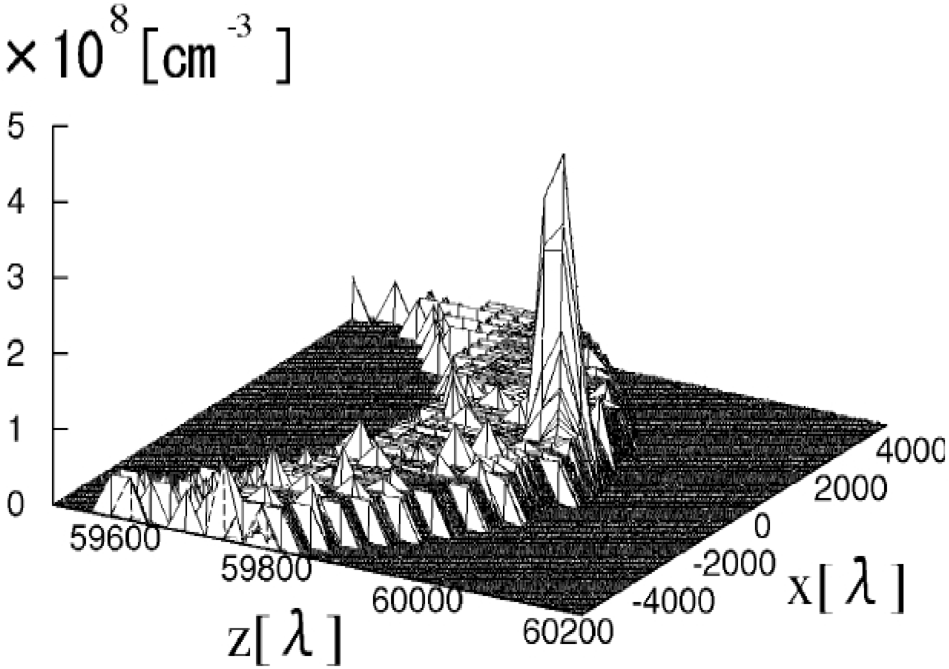


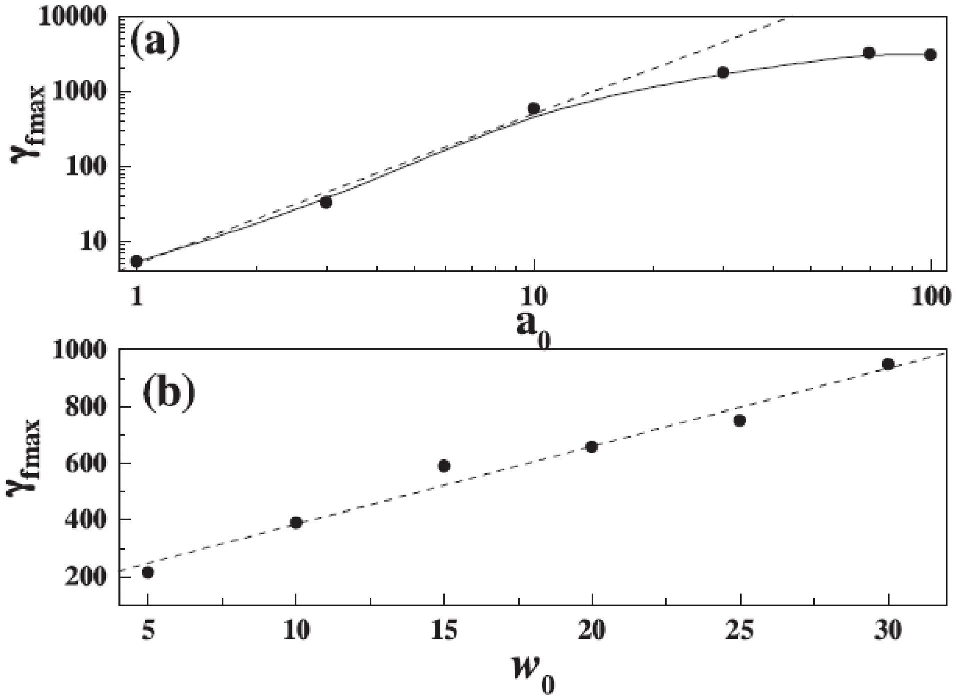
Electron beam transverse profile for $a_0 = 10$, waist $w_0 = 15\lambda$, laser pulse duration 10τ, electron bunch $\beta_z = 0.95$, $\beta_x = \beta_y = 0$, uniform bunch of radius 10λ and length 80λ

Acelerated part of electron bunch is confined in central forward position at rising part of laser pulse

Simulation of electron motion in vacuum fields

Acceleration by longitudinal PF





Electron density at the end of acceleration region, the high density at forward central part includes approx. 15% of all electrons

Electron energy is ~ a_0^2 up to a_0 = 10 and ~a_0 for high intensities

Electron energies ~ w_0 (laser waist)

Summary

- ASE and ionization has impact on fast electron spectrum and on K-α emission
- Electrons set free by optical field ionization near to laser pulse maximum are emitted at large angles and they do not obey classic angle-energy law
- 2D PIC simulations lead to broader fast electron angular spectrum
- Quasineutral plasma blocks may be accelerated into target by ponderomotive force in the vicinity of the criticsl surface (for ~ 1 ps laser pulses with $a_0 \approx 1$)
- Electrons may be accelerated in vacuum by short relativistic laser pulses with intensity minimum in the beam centre