Vacuum Acceleration in the Field of a Tightly Focused Laser

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In collaboration with

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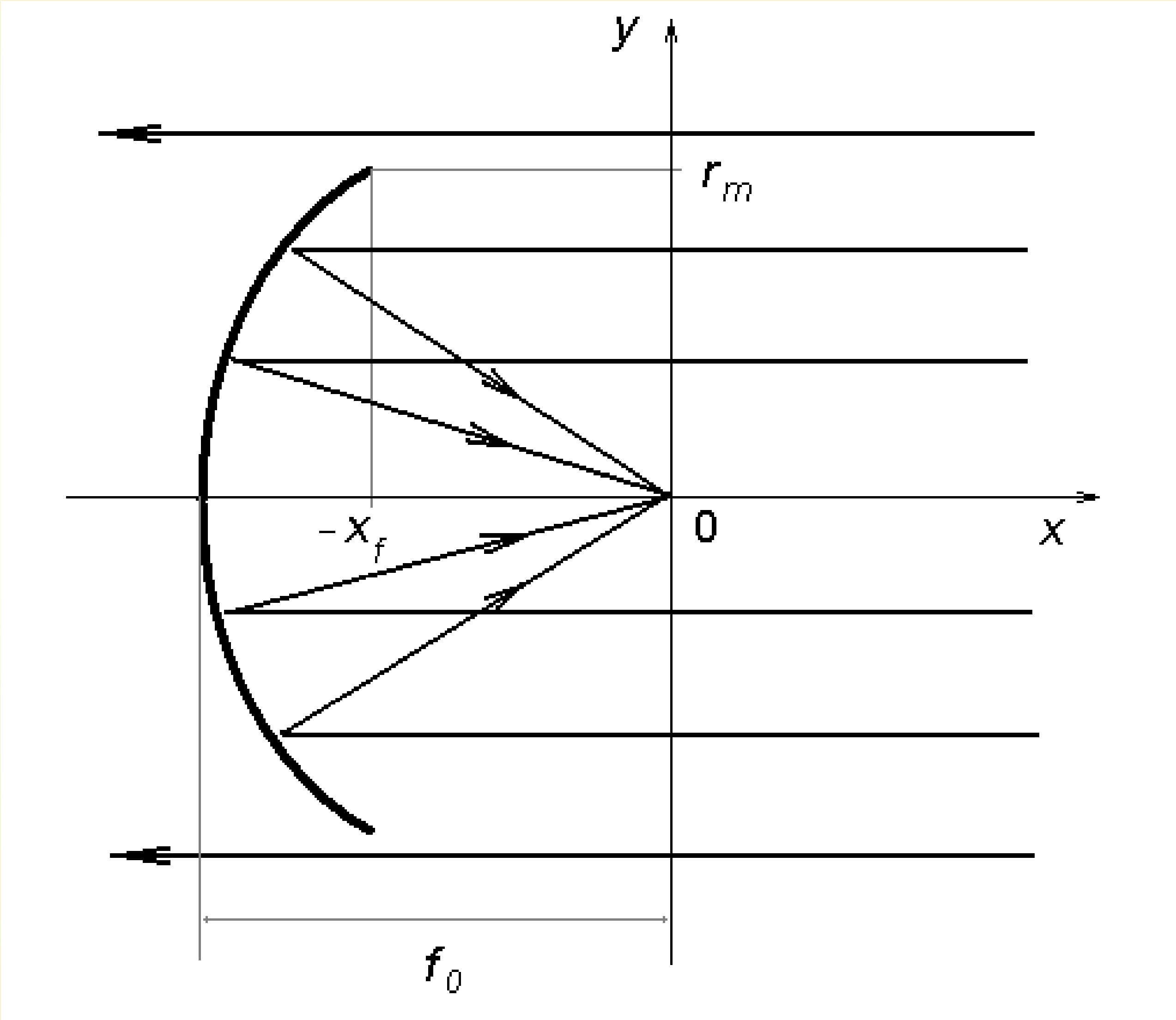
Introduction

- We consider the problem of direct acceleration of electrons by the laser in vacuum
- Tight focusing is used to acquire high laser intensities
- In this regime we cannot use the paraxial approximation

Methodology

- Correct field representation being a solution to the Maxwell equations is required
- Numerical solution for both fields and equations of motion needs to be employed
- Test particle approach is used for general understanding of the acceleration process
- Particle-in-cell (PIC) simulation is used for more realistic laser-plasma interaction

Focusing of the laser by a parabolic mirror



$$f_{\#} = \frac{2r_m}{f_0}$$

Typical laser parameters:

P ~ 100 TW, mirror $f_{\#}$ ~ 1, pulse length ~ 30 fs, max. intensity in focus ~ 10^{22} W/cm^2

Stratton-Chu integrals*

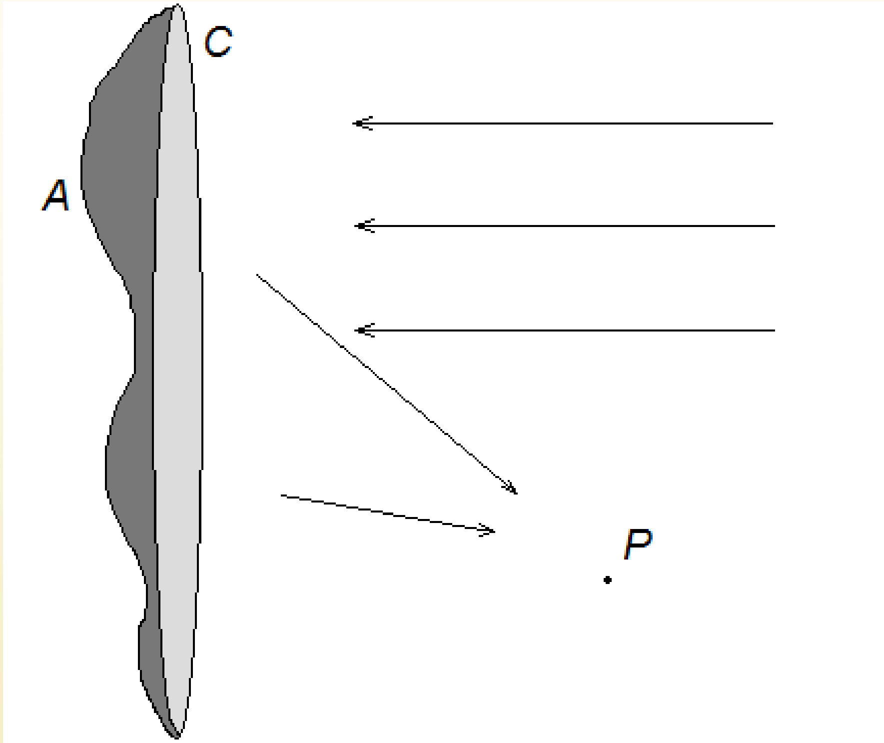
$$\vec{E}(P)=\frac{1}{4\pi}\iint_A\left[jk\left(\vec{n}\times\vec{H}\right)G+\left(\vec{n}\times\vec{E}\right)\times\nabla G+\left(\vec{n}\cdot\vec{E}\right)\nabla G\right]\mathrm{d}\,A,$$

$$\vec{H}(P)=\frac{1}{4\pi}\iint_A\left[jk\left(\vec{E}\times\vec{n}\right)G+\left(\vec{n}\times\vec{H}\right)\times\nabla G+\left(\vec{n}\cdot\vec{H}\right)\nabla G\right]\mathrm{d}\,A$$

$$G=\frac{\exp\left(jk\left|\vec{r}_A-\vec{r}_P\right|\right)}{\left|\vec{r}_A-\vec{r}_P\right|},$$

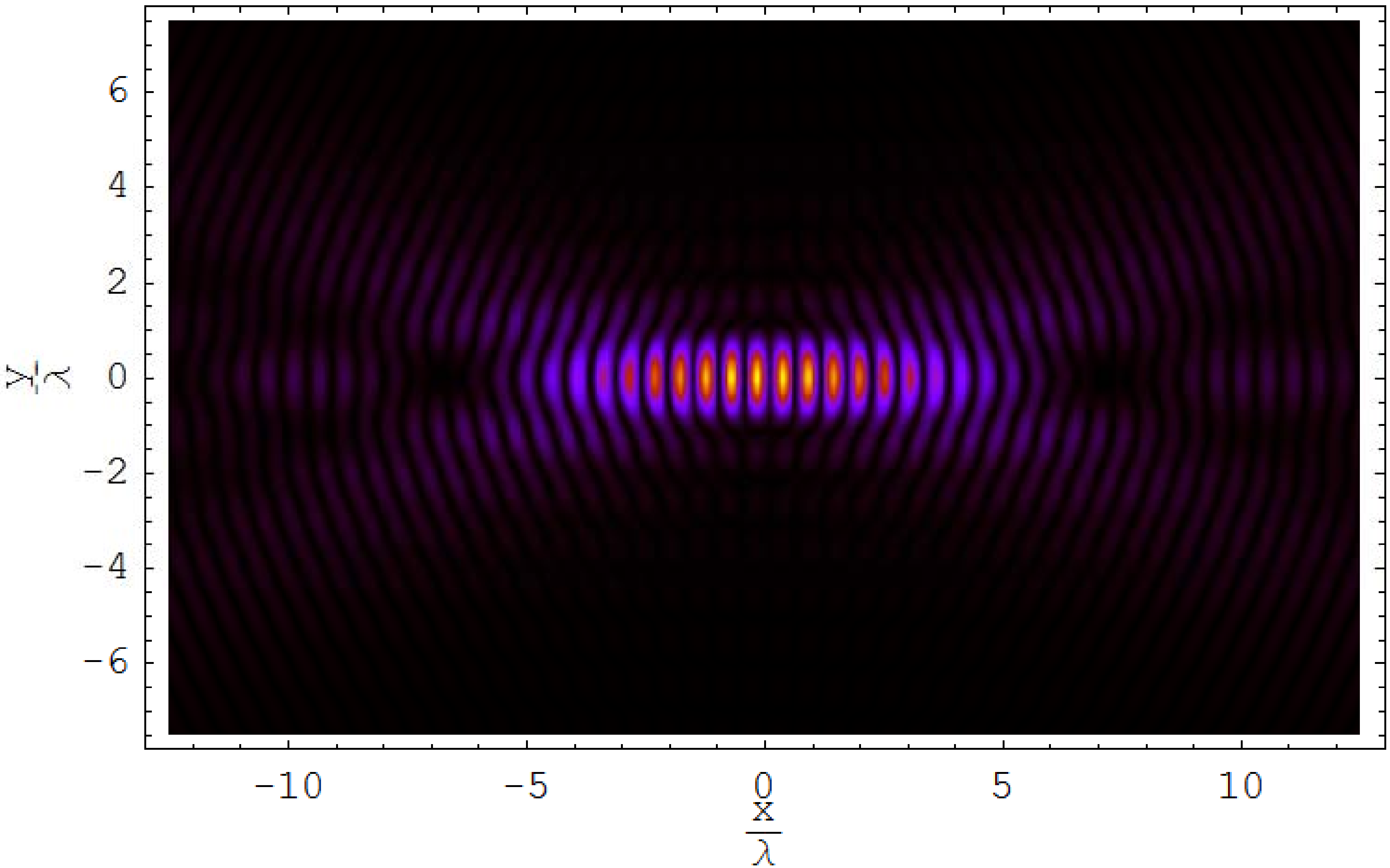
$$k=\frac{\omega_\lambda}{c},$$

$\vec{n}$ – inner normal to the surface



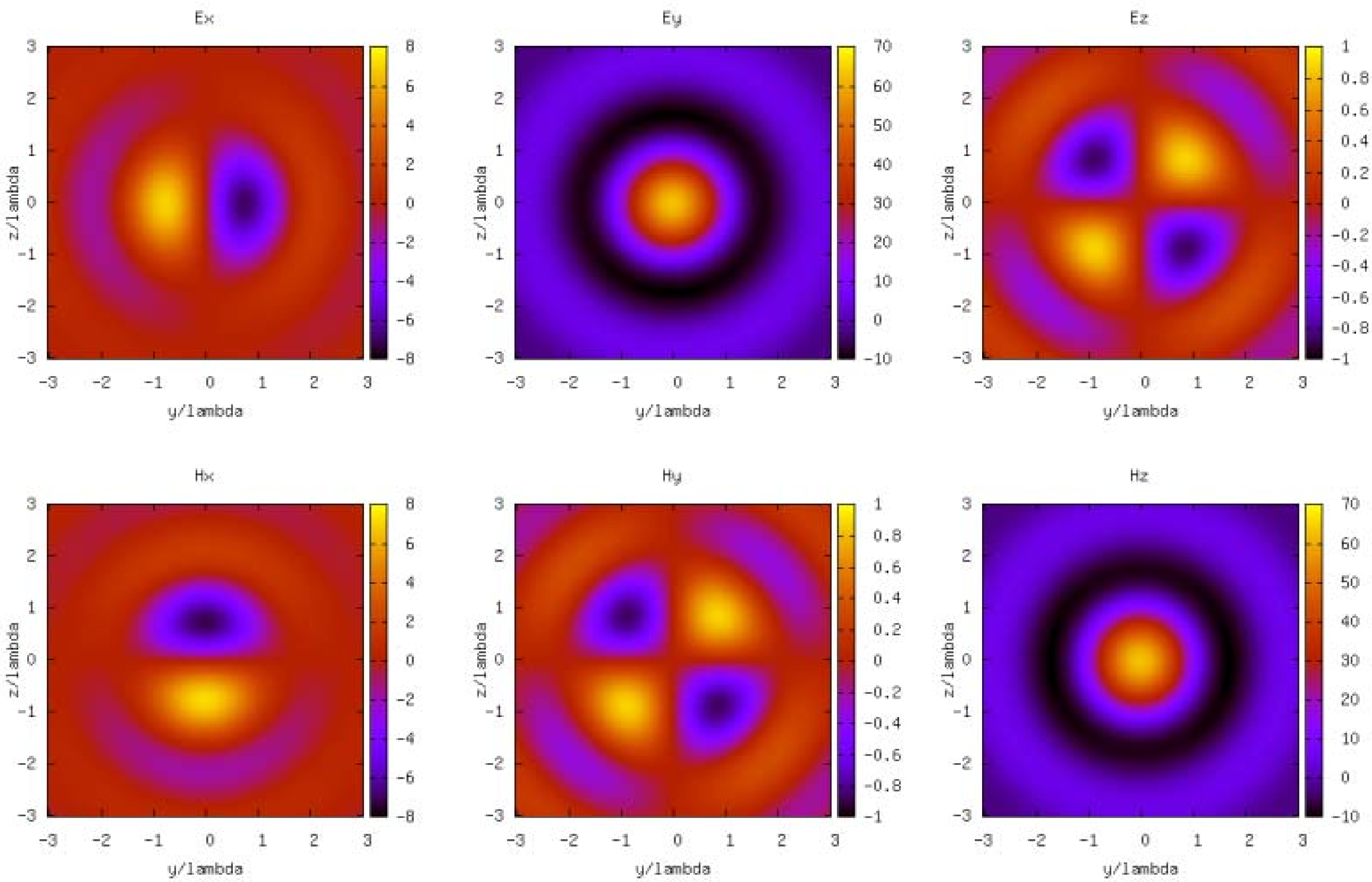
*J.Stratton, L.Chu. "Diffraction Theory of Electromagnetic Waves", Phys. Rev. **56** ,99 (1939)

Focused pulse structure



Poynting vector for $f_{\#}=1$

Electromagnetic field in the focus

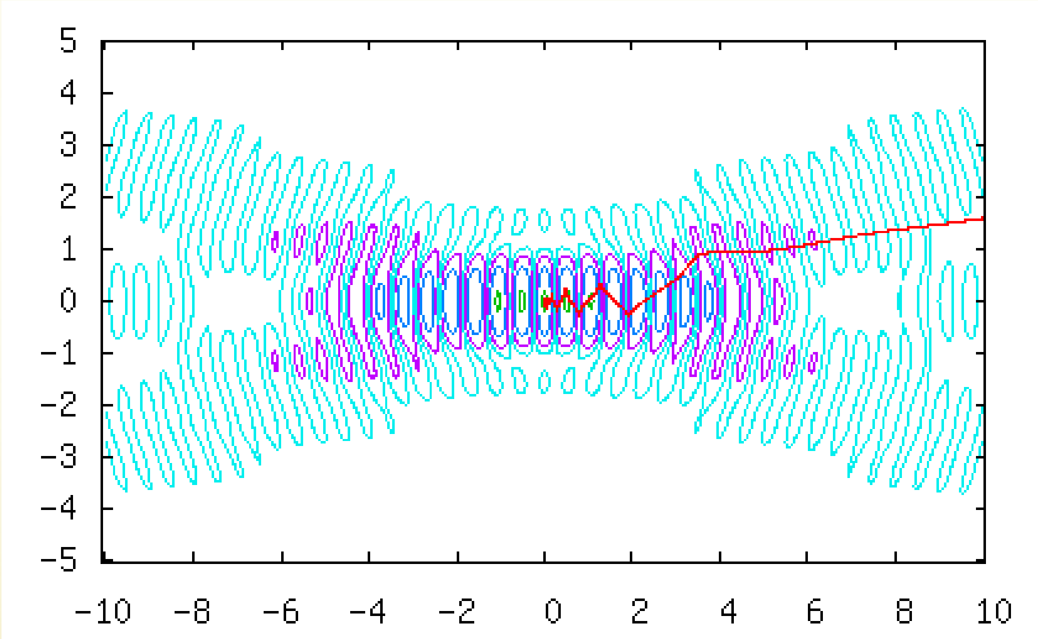


Test particle acceleration*

Motion of a single particle in the known electromagnetic field

$$\frac{\mathrm{d}(\gamma m \vec{\mathrm{v}})}{\mathrm{d}t} = q\left(\vec{E} + \vec{\mathrm{v}} \times \vec{B}\right)$$

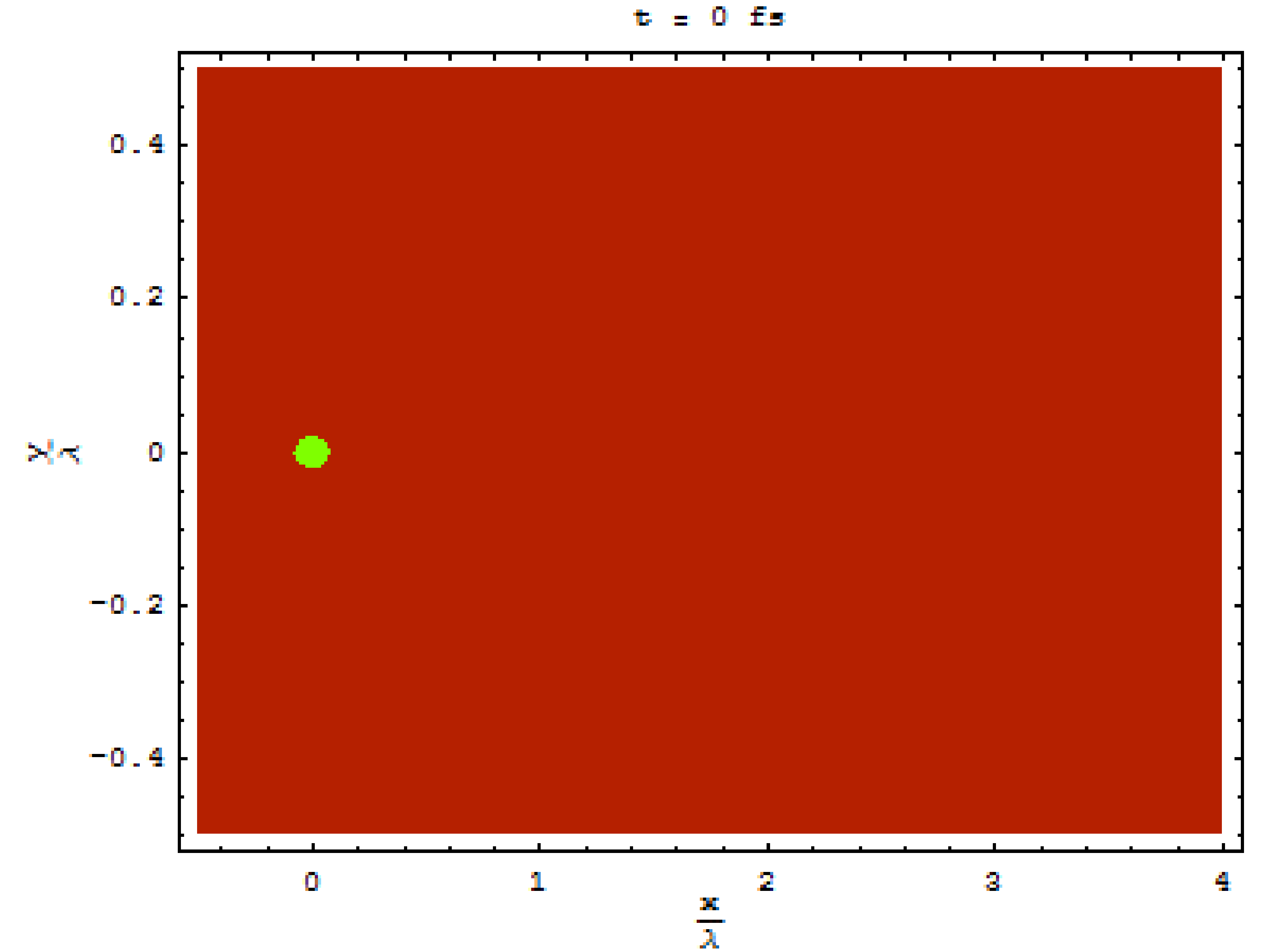
Trajectory of a particle started from the best focus:



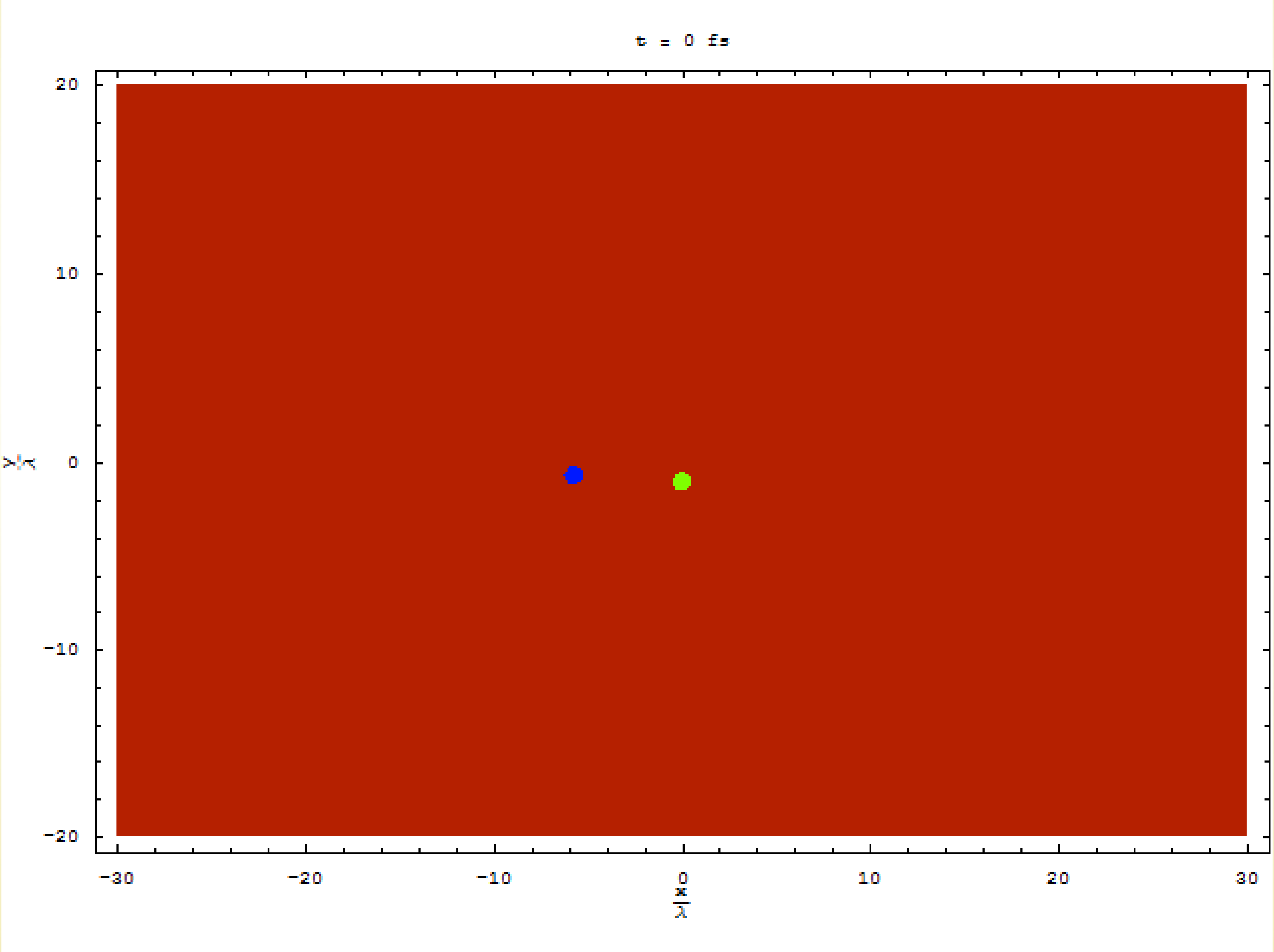
Particles are able to acquire non-zero energy in the acceleration process because of high field nonlinearities causing asymmetry between the initial and final states of the particle

*K.I.Popov et al, Phys.Plasmas **15**, 013108 (2008)

Plane Wave Launch

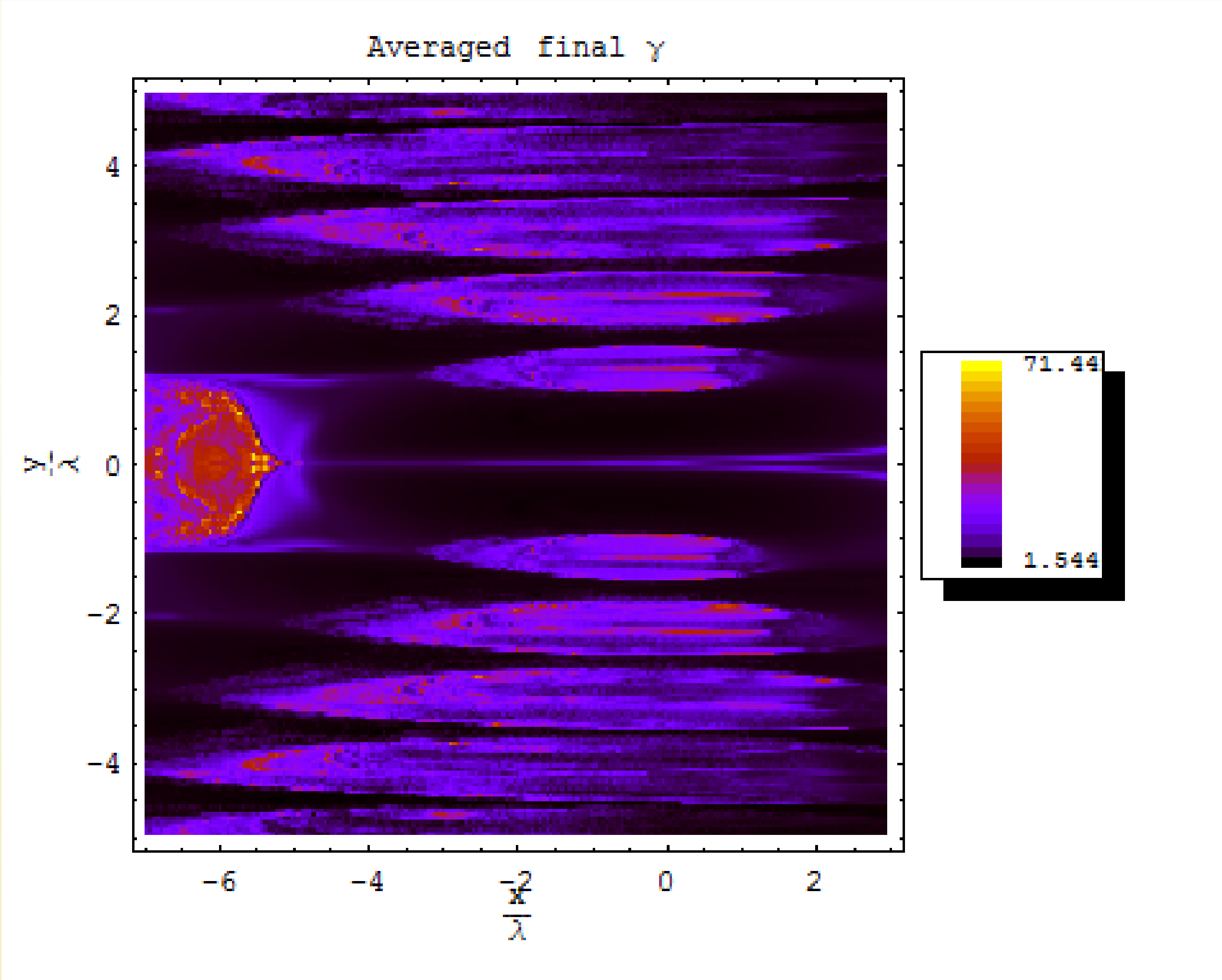


Tight Focus Case



Energy map

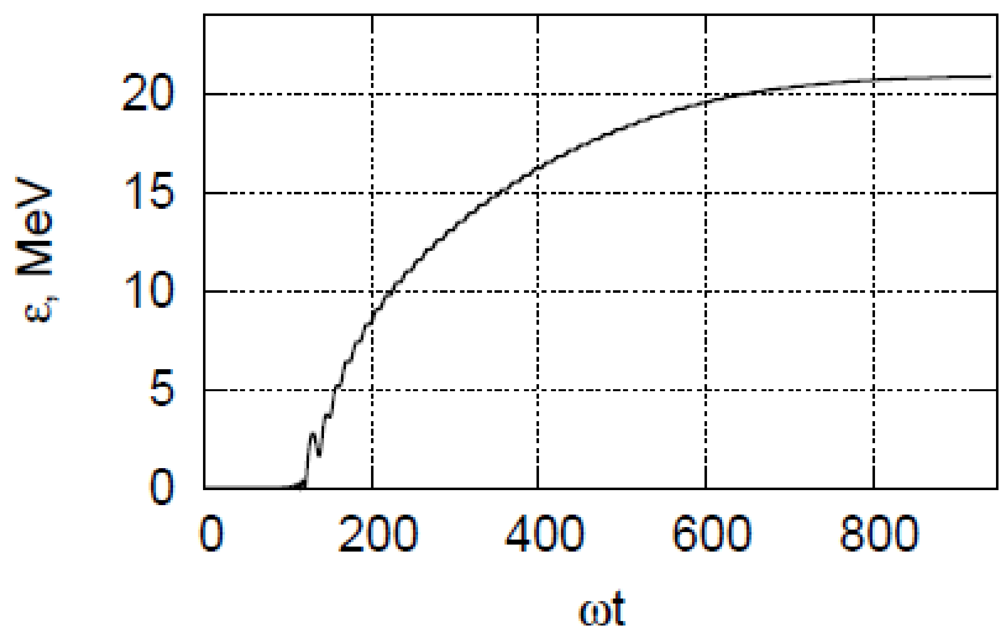
- The final energy depends on the particle initial position and phase.
- Final γ-factor averaged over the laser phase vs. initial position of the particle is the energy map



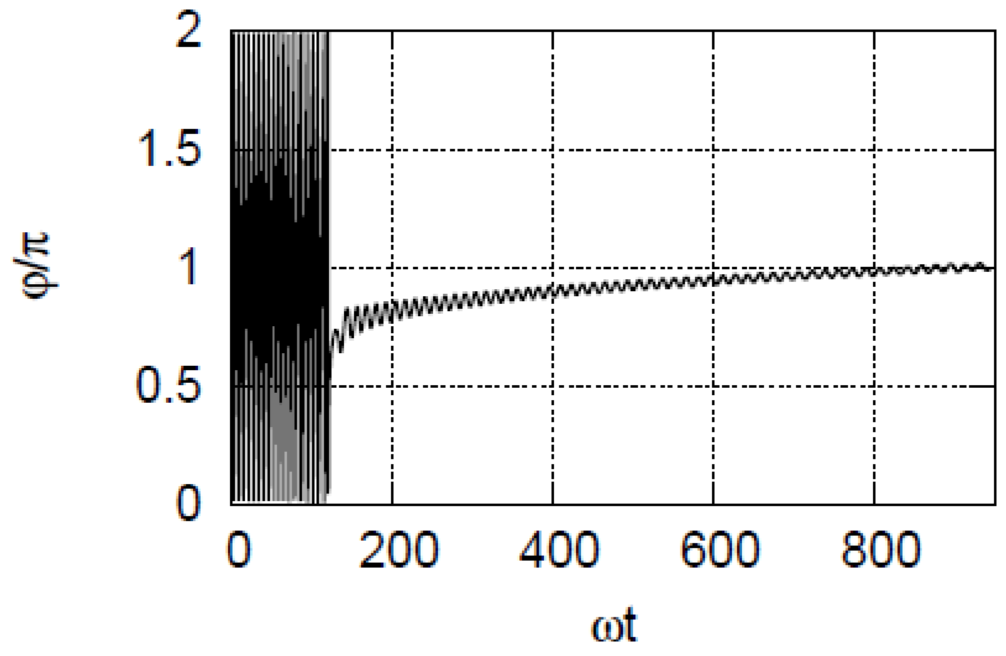
Acceleration mechanism

Typical acceleration scenario: particle pre-accelerates in a complicated process and then acquires a velocity close to the speed of light. When the velocity is close enough to the speed of light, the particle starts to co-propagate with the pulse. The main energy gain is acquired during the co-propagation with the pulse.

Particle energy:

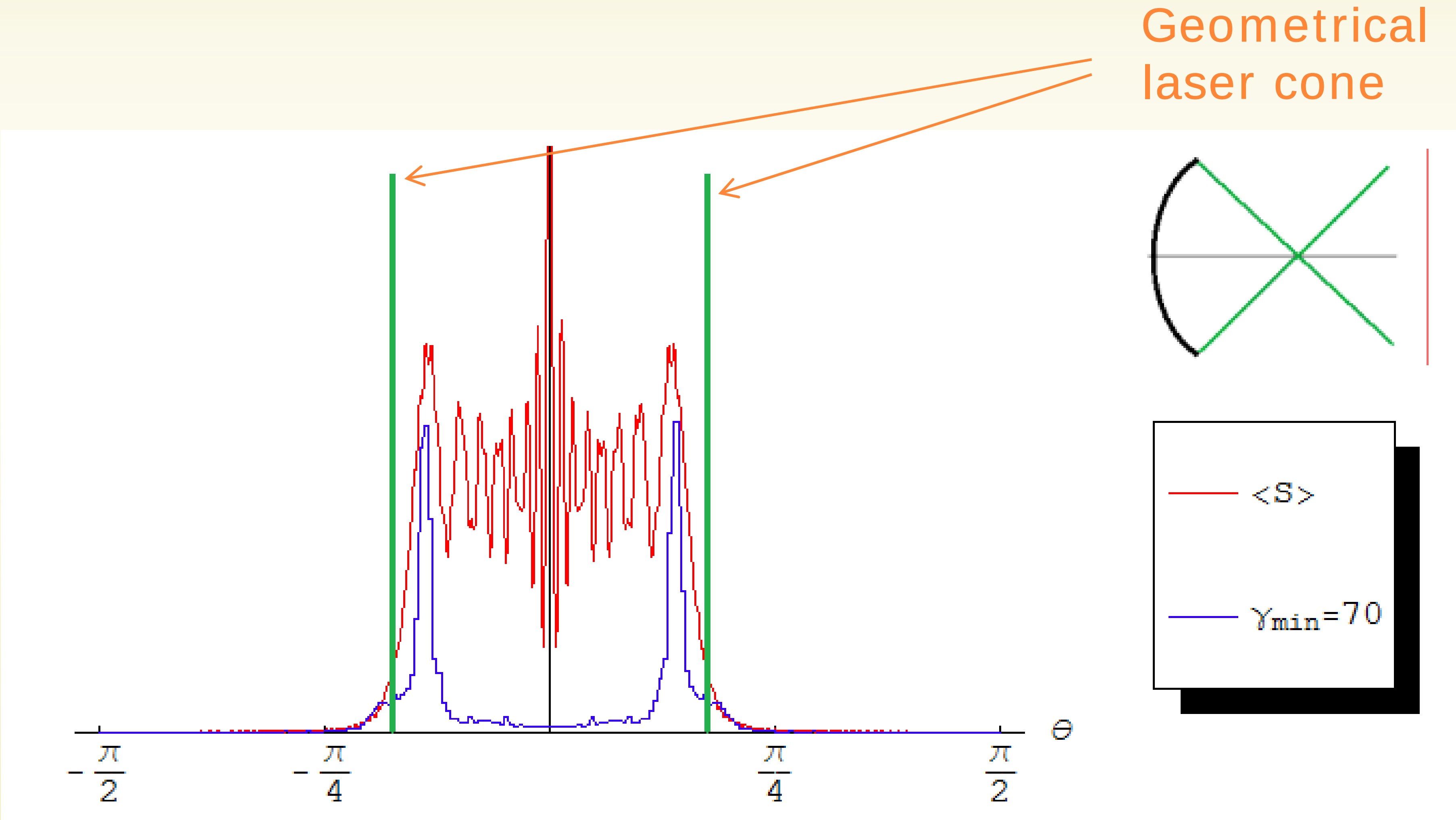


Local field phase:



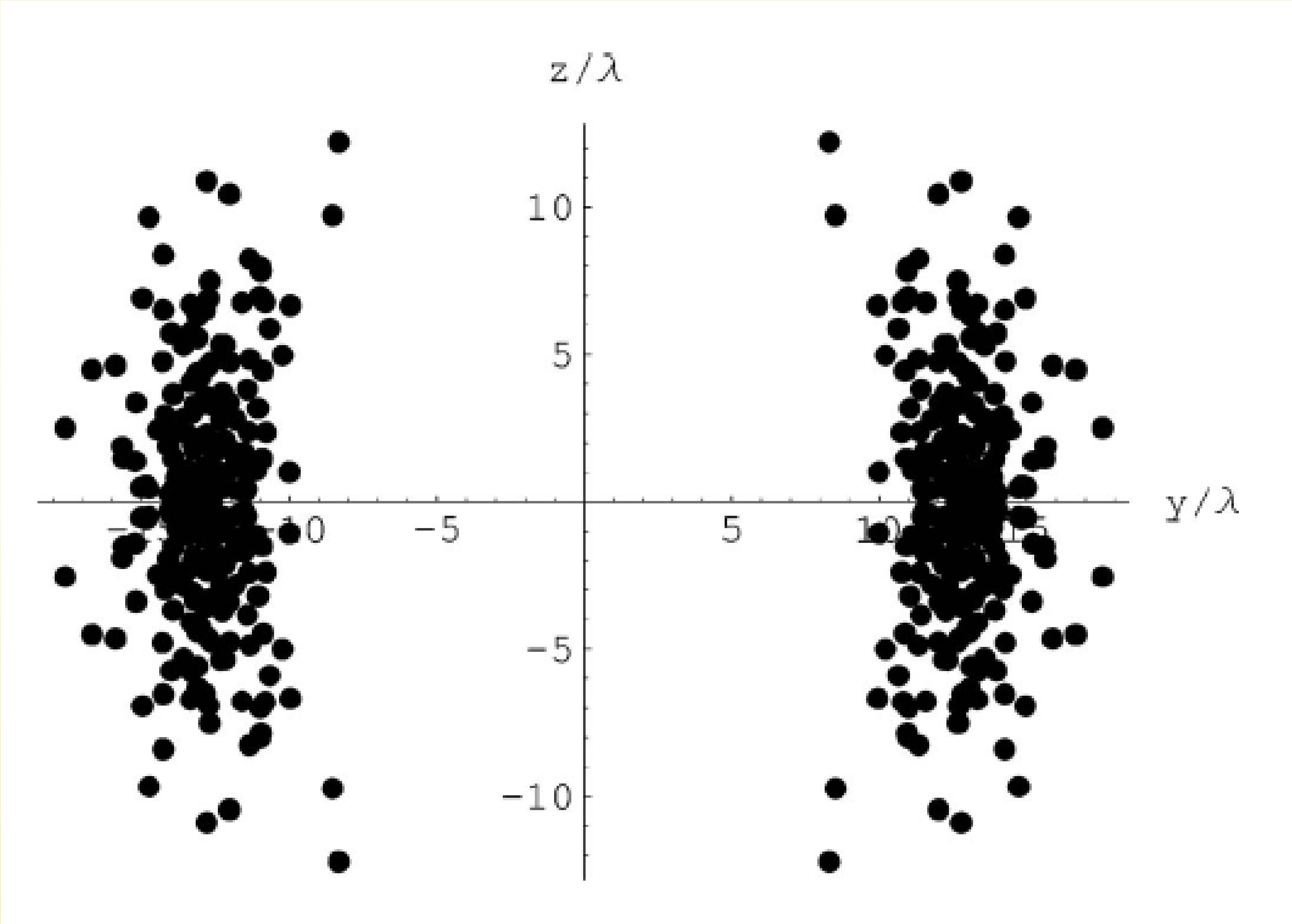
Jets formation

Vacuum acceleration process is characterized by formation of the jets along the laser focusing cone



Jets formation

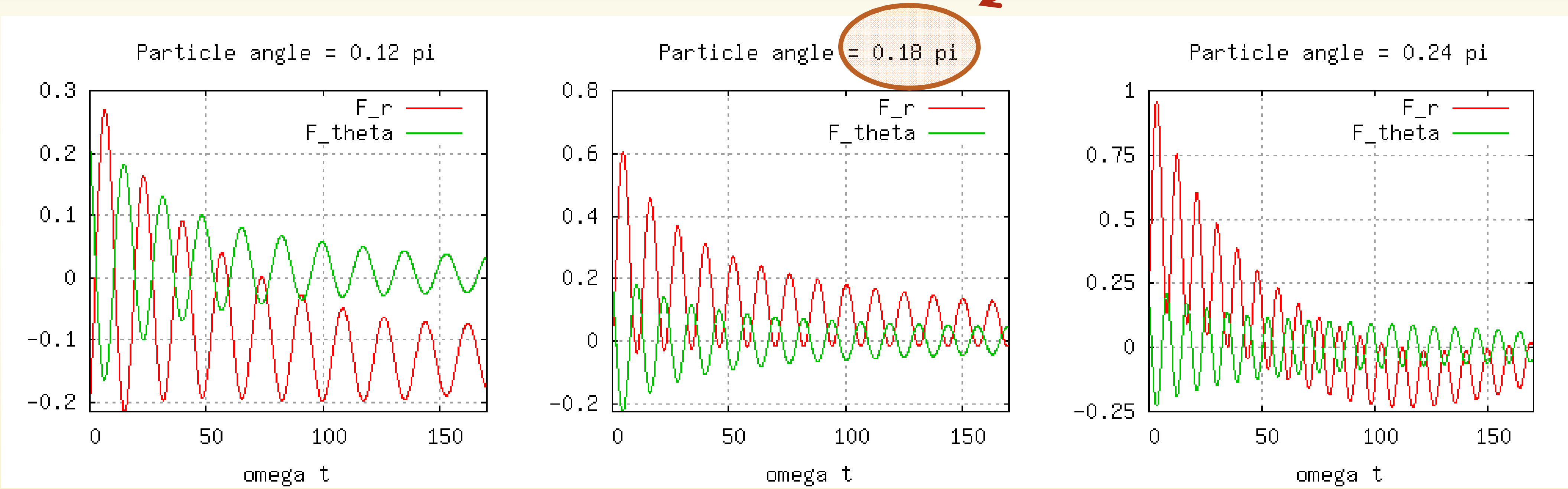
2 % of the most energetic particles from the test particle simulations as they would be detected on a screen behind the interaction area



The particles were initially uniformly distributed in the plane perpendicular to the laser propagation

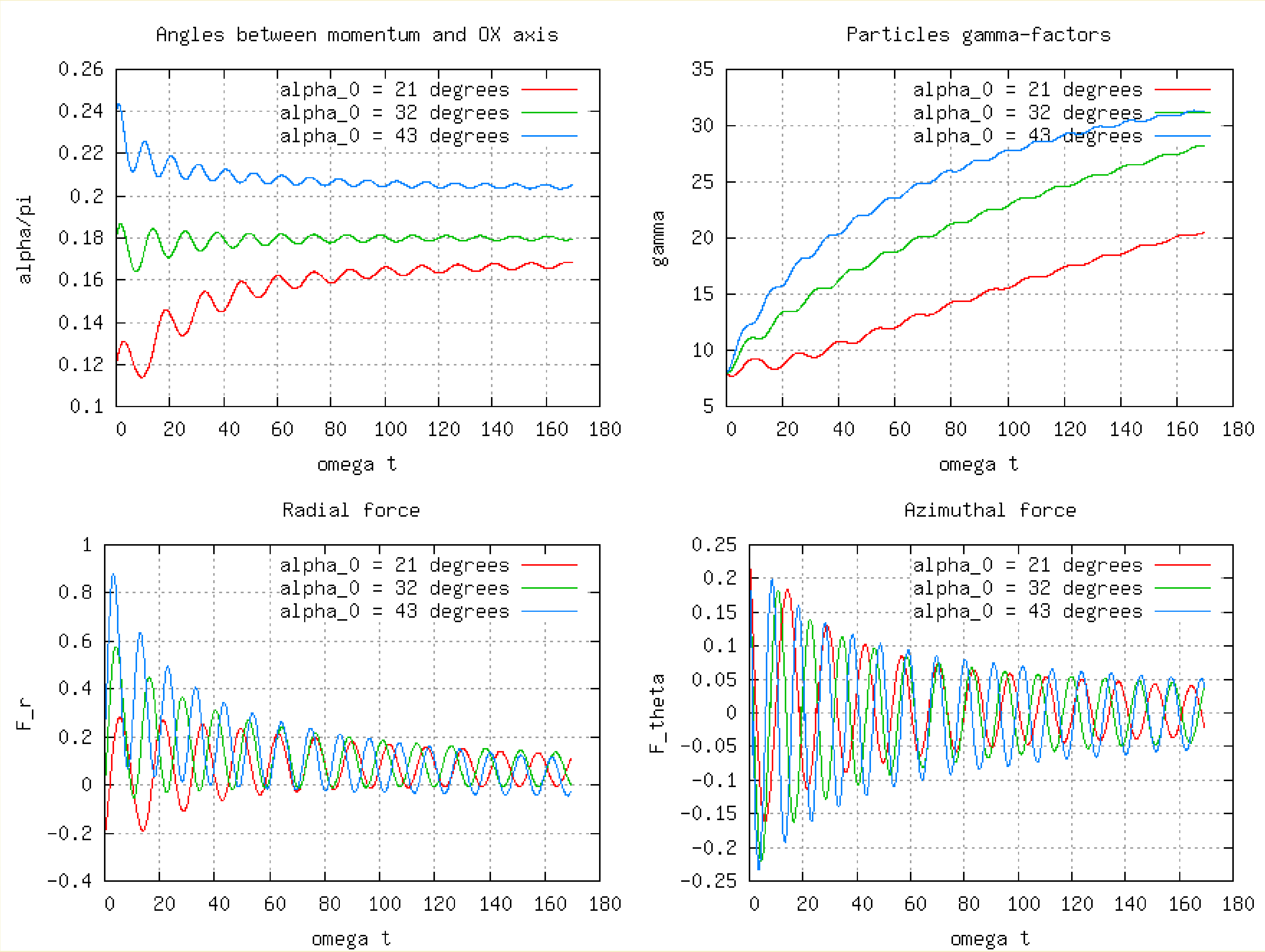
Jets formation

Preferred angle



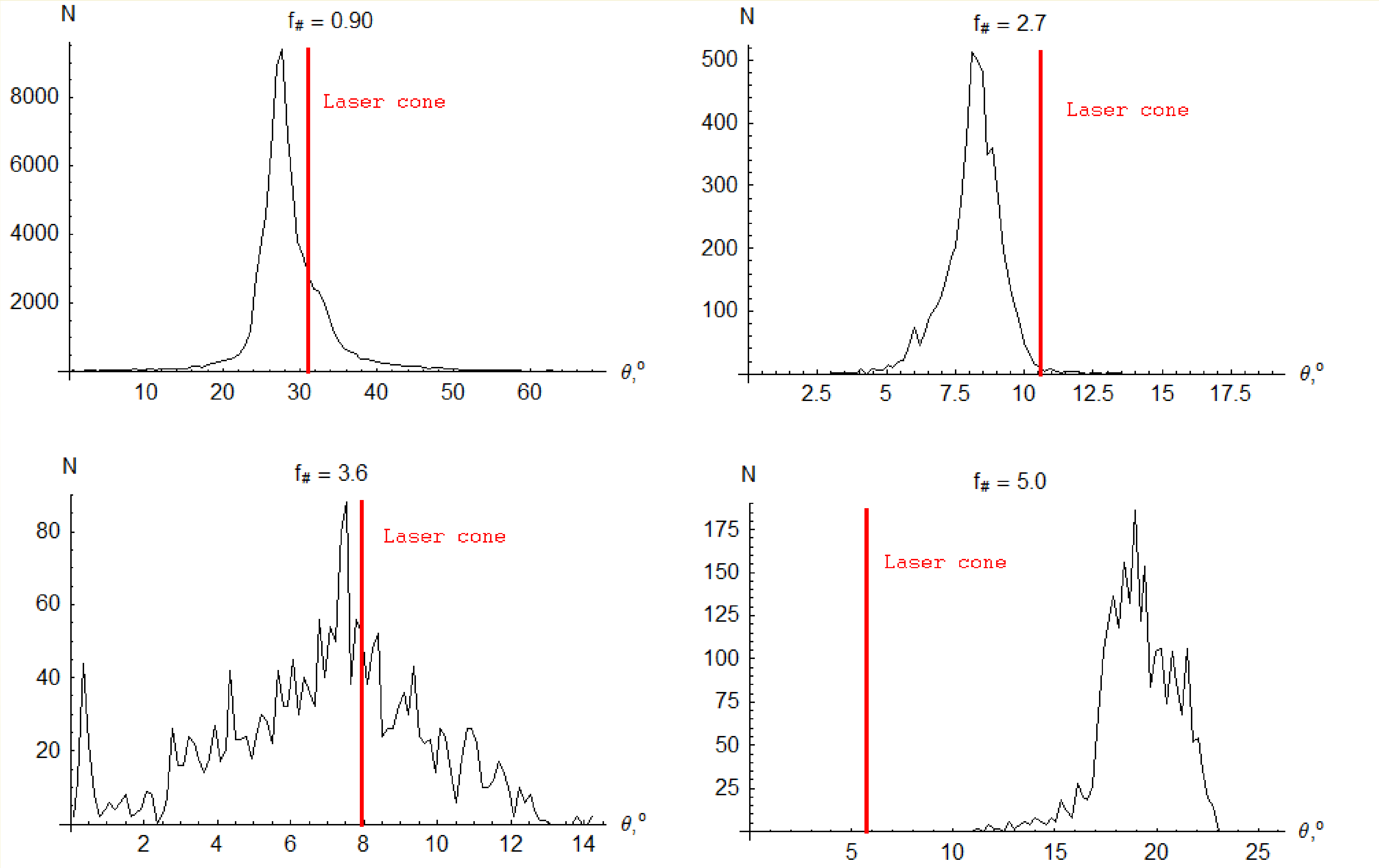
Forces acting onto a hypothetic particle moving with the specified angle to the OX axis with velocity 0.997c (γ = 12)

Jets formation



Particles injected into a certain point under different angles tend to bend towards the preferred direction

Jets formation and tightness of focusing



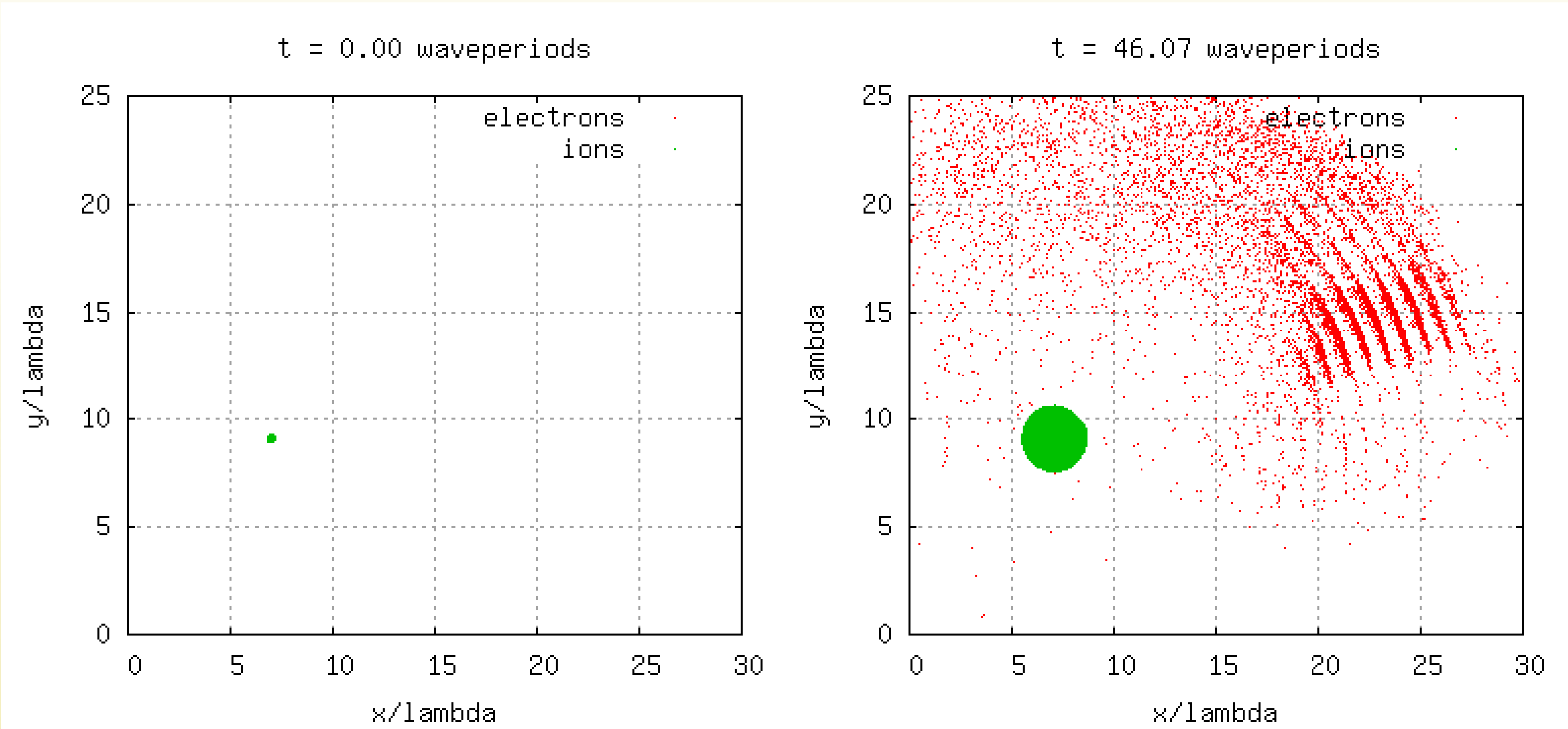
Angular distribution of 5% most energetic particles

PIC simulations

- The 3D Particle-In-Cell (PIC) code was used to simulate the interaction between the tightly focused pulse and a plasma configuration
- The fields calculated by Stratton-Chu integrals were used as boundary conditions for the finite-difference Maxwell solver of the PIC code
- Plasma is supposed to be pre-ionized

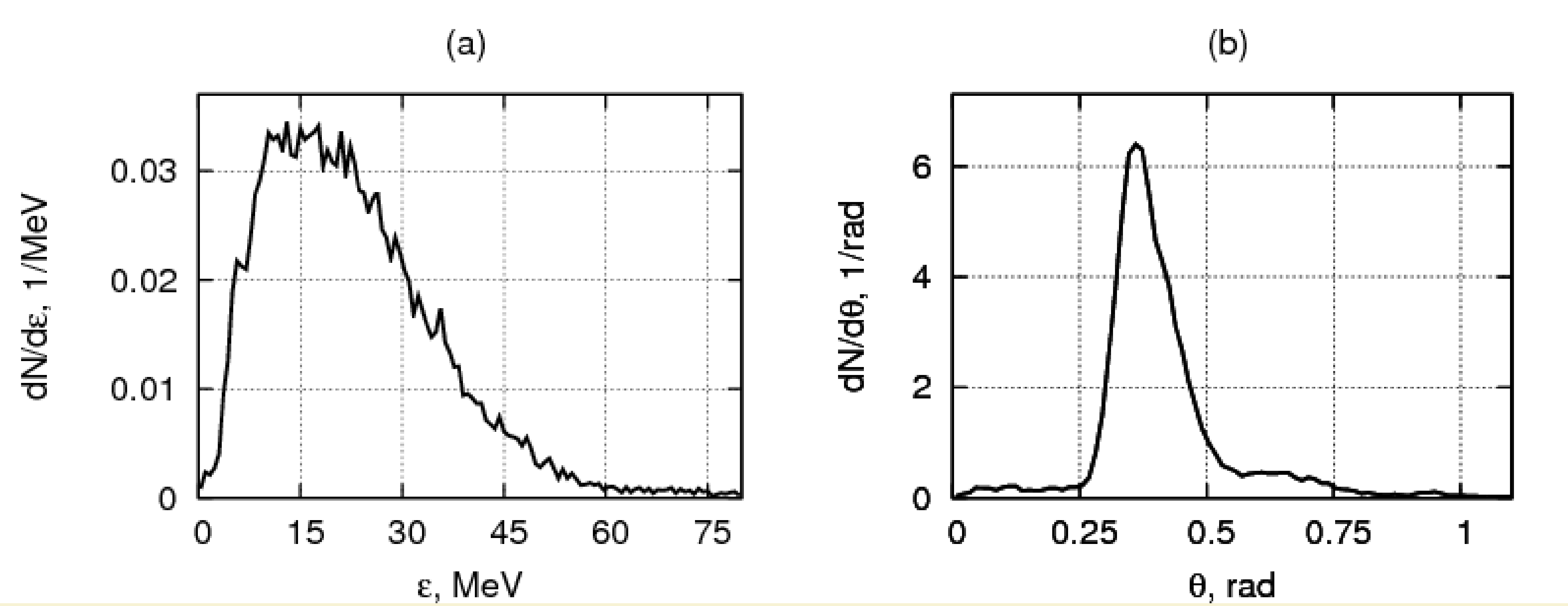
Interaction with a cluster

Cluster is a target close to the test particle.
Projections of the particles coordinates onto XY plane from the interaction of a **400 nm cluster of n = 25 n_{cr}** with a **30 fs** laser pulse focused by an **f-0.9 parabolic mirror**. Maximum laser intensity is **10^{22} W/cm^2**. The projection of the laser focus on the pictures is in the point (7λ; 7 λ). Simulations are 3D.



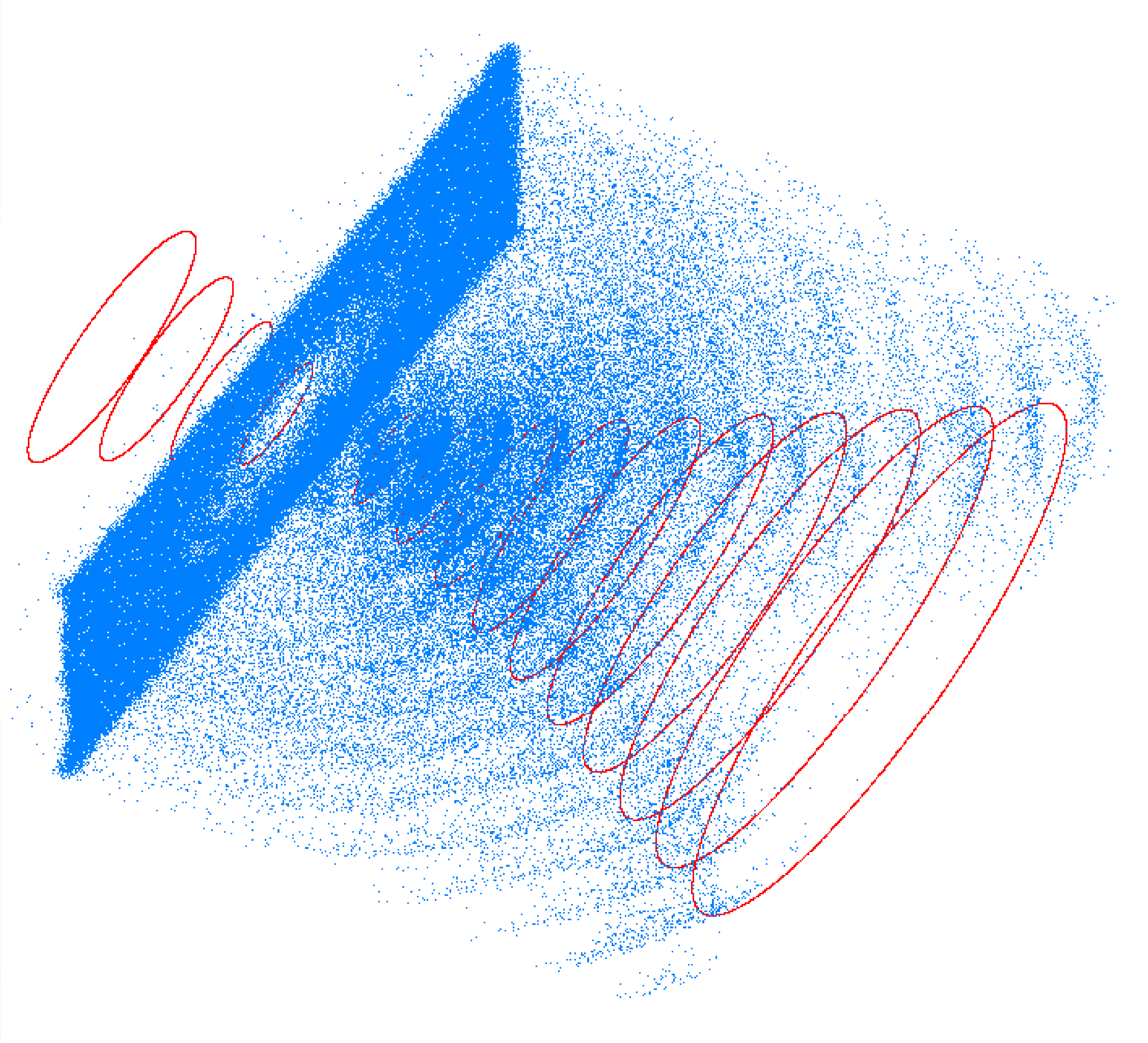
Interaction with a cluster

Energy spectrum and angular distribution of electrons from interaction between the tightly focused laser and a 400-nm spherical plasma



Estimated number of particles in the jet: up to 10^8

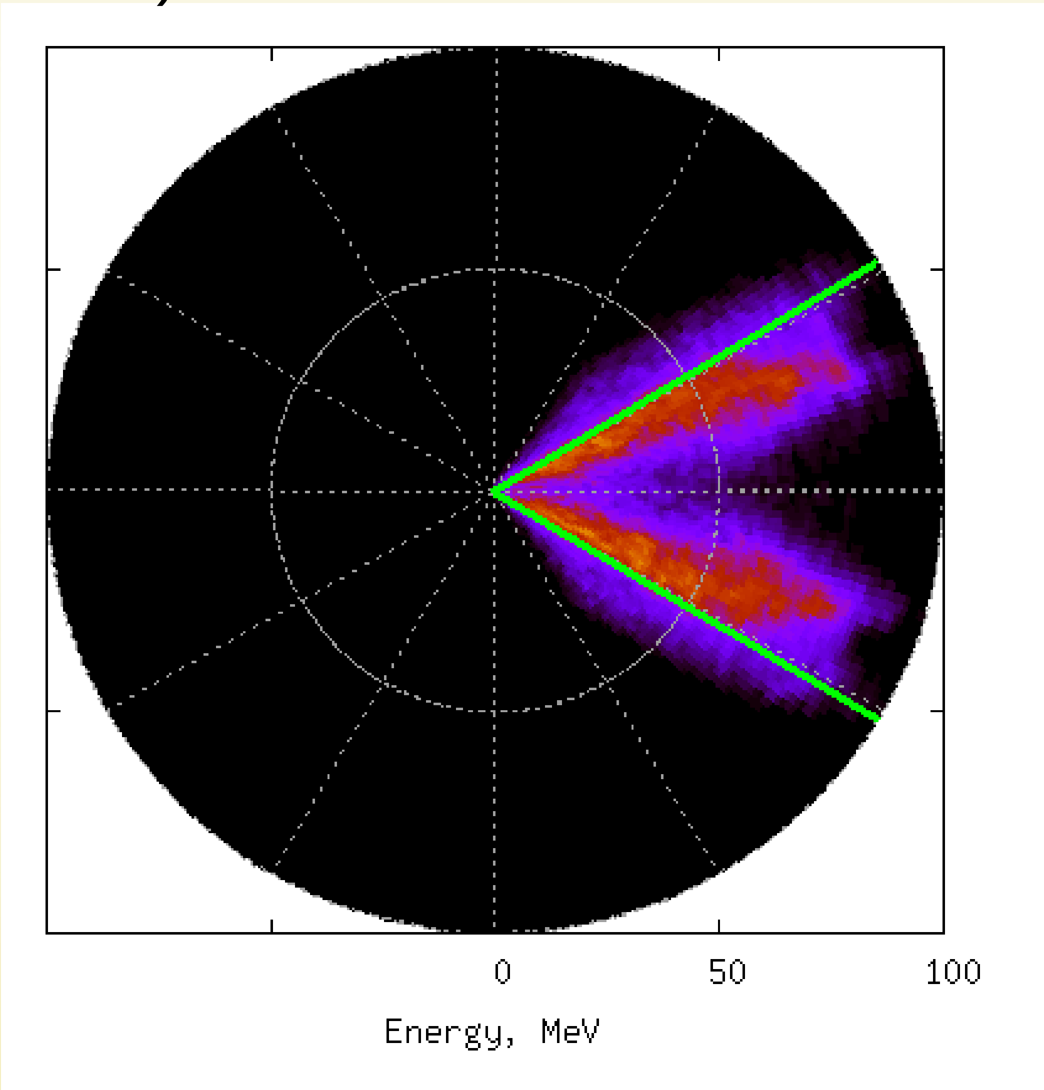
Interaction with an ultrathin foil



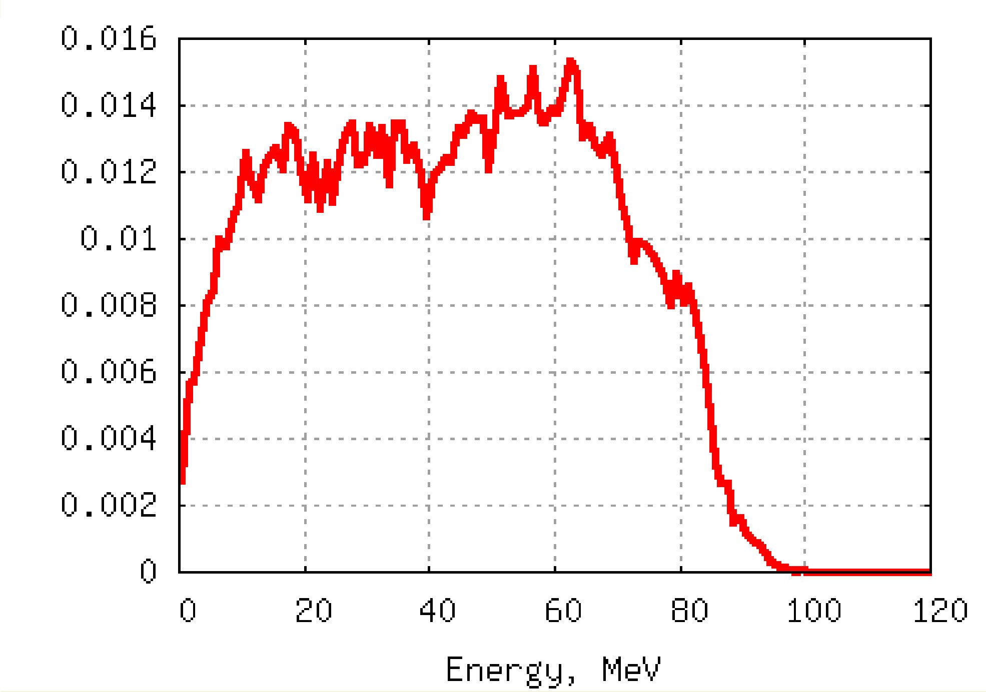
Typical foil parameters: $n = 50\ n_{cr}$, foil thickness $\delta \sim 80 - 120$ nm

Characteristics of the jets

Energy-angle diagram (green lines represent geometrical laser cone):

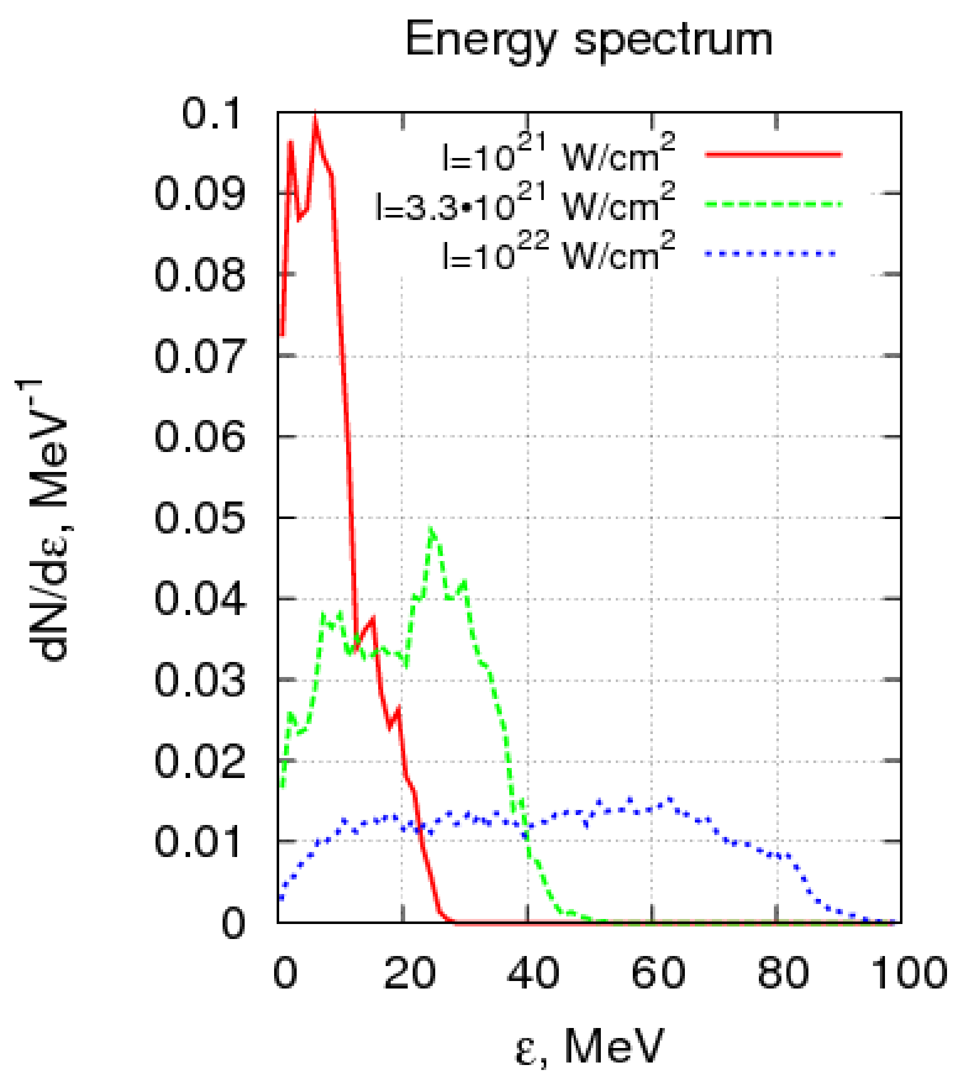


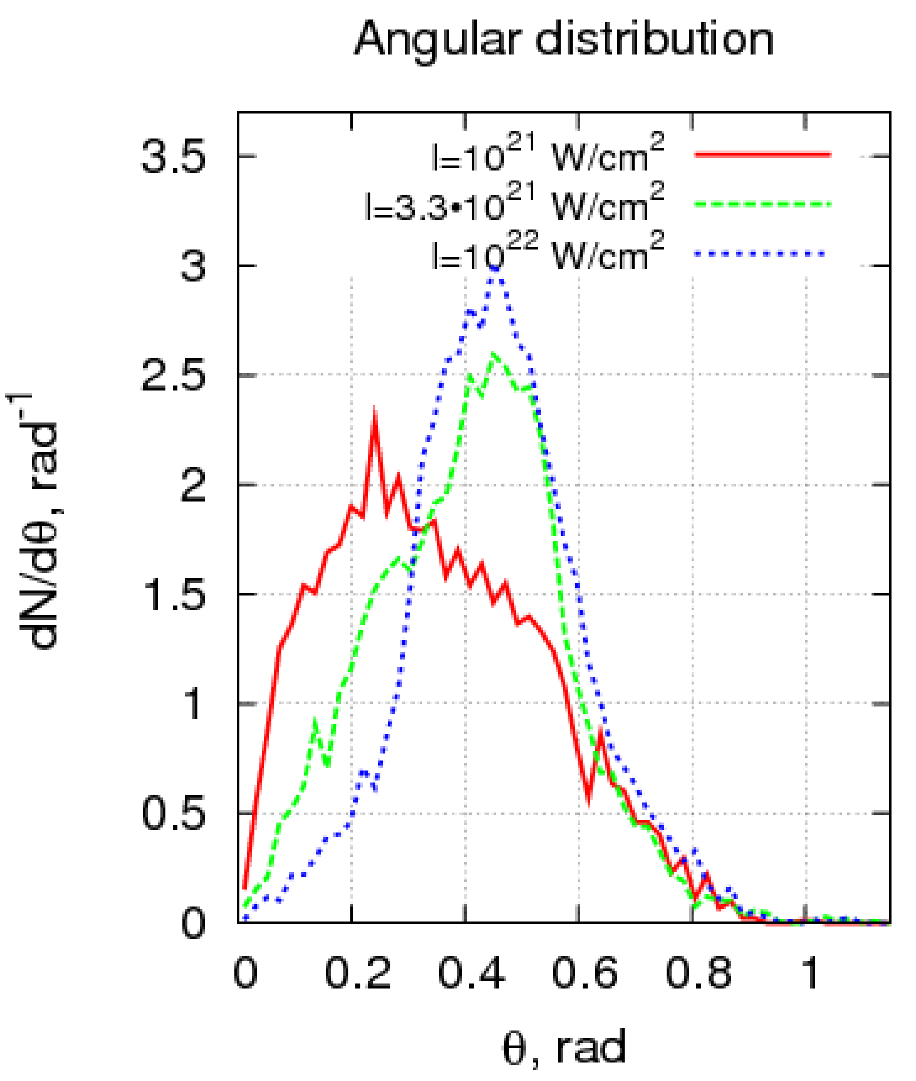
Spectrum of the particles within 10° of the maximum jet density:



Estimated number of electrons within 10° of the maximum jet density: **10^8** for ~ 10^{10} in the focal spot

Dependence of particles spectrum and angular distribution on laser intensity





Foil density 50 n_{cr}, foil thickness 80 nm

Conclusions

- Test particle and PIC simulations of electron acceleration in the field of a tightly focused laser being numerical solution to the Maxwell equation are performed

- Quasi-monoenergetic spectra of electrons are observed for interaction of the pulse with special nanotargets

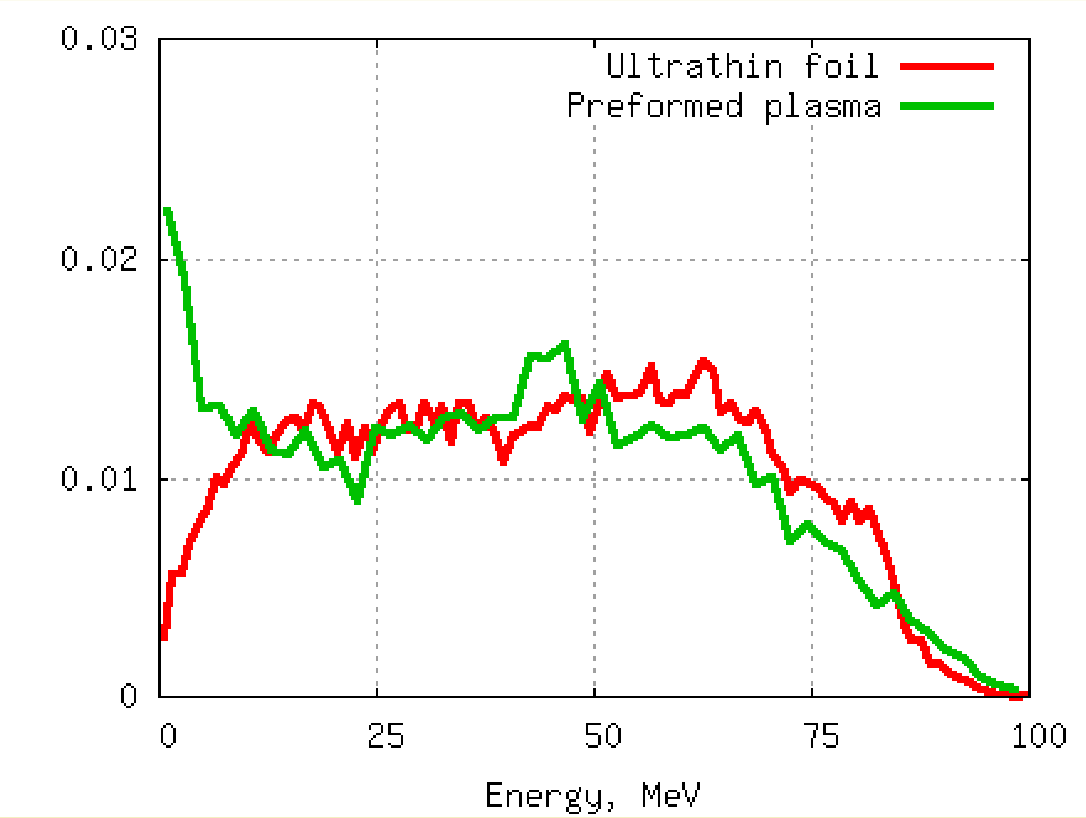
- Spreading out of plasma slightly worsen the resulting spectra

- Up to 10^8 electrons having energies between 10 and 80 MeV and moving within angle of 10° is possible with an f-0.9 mirror focused laser of maximal intensity 10^{22} W/cm^2 with a high contrast ratio

Preformed plasma

- The same charge, but spread out
- May be a consequence of the laser prepulse

$$n(x) = n_0 \exp\left[-\frac{(x-x_0)^2}{\Delta x^2}\right],$$ Δx ~ few microns, 1 μm below



$n_0 = 2.8\ n_{cr}$

The charge is equal to that of an ultrathin foil of $n = 50\ n_{cr}$ and thickness of 80 nm.