DYNAMICS OF AN ELECTRON DRIVEN BY RELATIVISTIC LASER RADIATION FOR NEW PRINCIPLES OF INTENSITY DIAGNOSTICS AND GENERATION OF ZEPTOSECOND ELECTROMAGNETIC PULSES

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ELECTRON DYNAMICS IN AN INTENSE LASER FIELD: BASIC ASSUMPTIONS

- Free electron driven by the Lorentz force of the laser field;
- Electromagnetic field envelope, tightly focused laser pulse;
- Relativistic laser intensity:

$$I \geq I_r = m^2 c^3 \omega^2 / 8\pi e^2 = 1.37 \cdot 10^{18} \cdot \left(1/\lambda\left[\mu m\right]\right)^2 \left[W / cm^2\right]$$

PROBLEM FORMULATION TO ELECTRON MOTION

- Relativistic Newton's equation for a free electron:

$$\frac{d\mathbf{p}}{dt} = -e\mathbf{E} - \frac{e}{c}[\mathbf{v}\mathbf{H}]$$

- Laser beam:

$$E_0(x,y,\xi) = E_m \frac{\rho_0}{\rho} \exp\left\{-\left[\frac{\xi - z_d/c}{\tau}\right]^s - \left[\frac{\sqrt{x^2+y^2}}{\rho}\right]^2\right\}$$

- Beam width

$$\rho(z) = \rho_0\sqrt{1 + z^2\lambda^2/4\pi^2\rho_0^4}$$

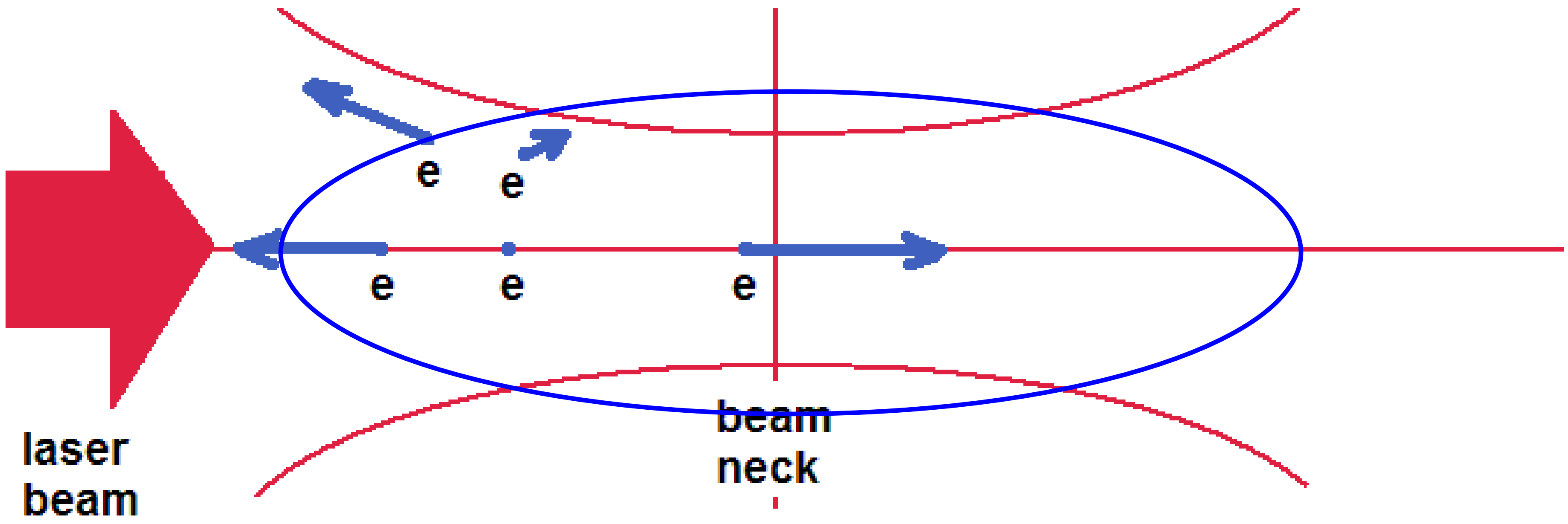
SOLUTION FOR FIELDS

$$\begin{cases} E_x = E_0\left(x,y,\xi\right)\sqrt{\left(1+\alpha\right)/2}\cos\varphi, \\ E_y = \mp E_0\left(x,y,\xi\right)\sqrt{\left(1-\alpha\right)/2}\sin\varphi, \\ E_z = -2E_0\left(x,y,\xi\right)\left(\varepsilon/\rho\right)\left(\sqrt{\left(1+\alpha\right)/2}\,x\sin\tilde{\varphi} \pm \sqrt{\left(1-\alpha\right)/2}\,y\cos\tilde{\varphi}\right), \\ H_x = -E_y, \\ H_y = E_x, \\ H_z = 2E_0\left(x,y,\xi\right)\left(\varepsilon/\rho\right)\left(-\sqrt{\left(1+\alpha\right)/2}\,y\sin\tilde{\varphi} \pm \sqrt{\left(1-\alpha\right)/2}\,x\cos\tilde{\varphi}\right). \end{cases}$$

- Linear polarization $\alpha = \pm 1$ Circular polarization $\alpha = 0$
- Upper sign corresponds to the left rotation, lower – to the right rotation.
- Small parameter $\varepsilon = \lambda/\left(2\pi\rho_0\right);$
- Phases $\varphi = 2\pi c\xi/\lambda + \arctan\left(z/z_R\right) - zr^2/z_R\rho^2 - \varphi_0$

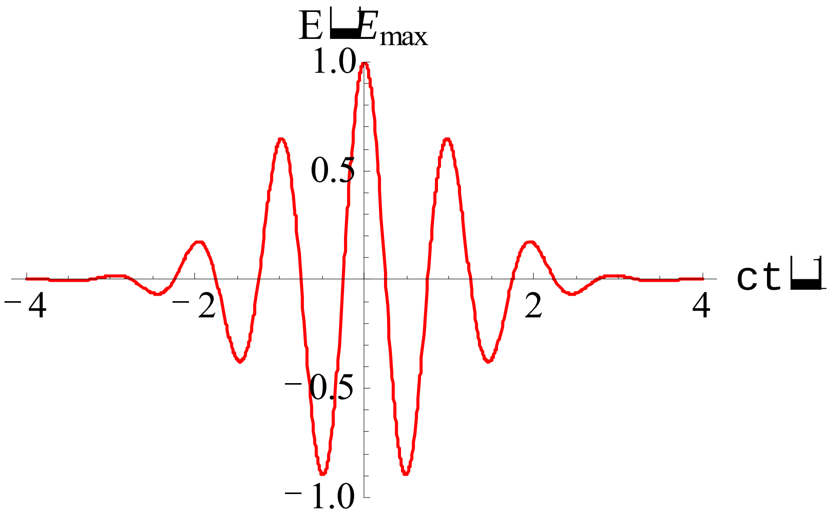
$$\tilde{\varphi} = \varphi + \arctan\left(z/z_R\right) \qquad z_R = \pi\rho_0^2/\lambda$$

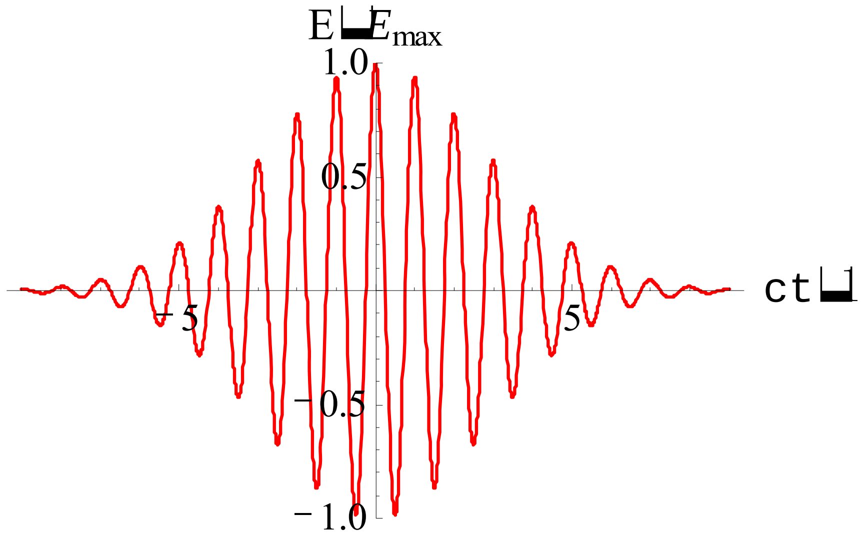
ELECTRON DYNAMICS



LASER PULSE PARAMETERS

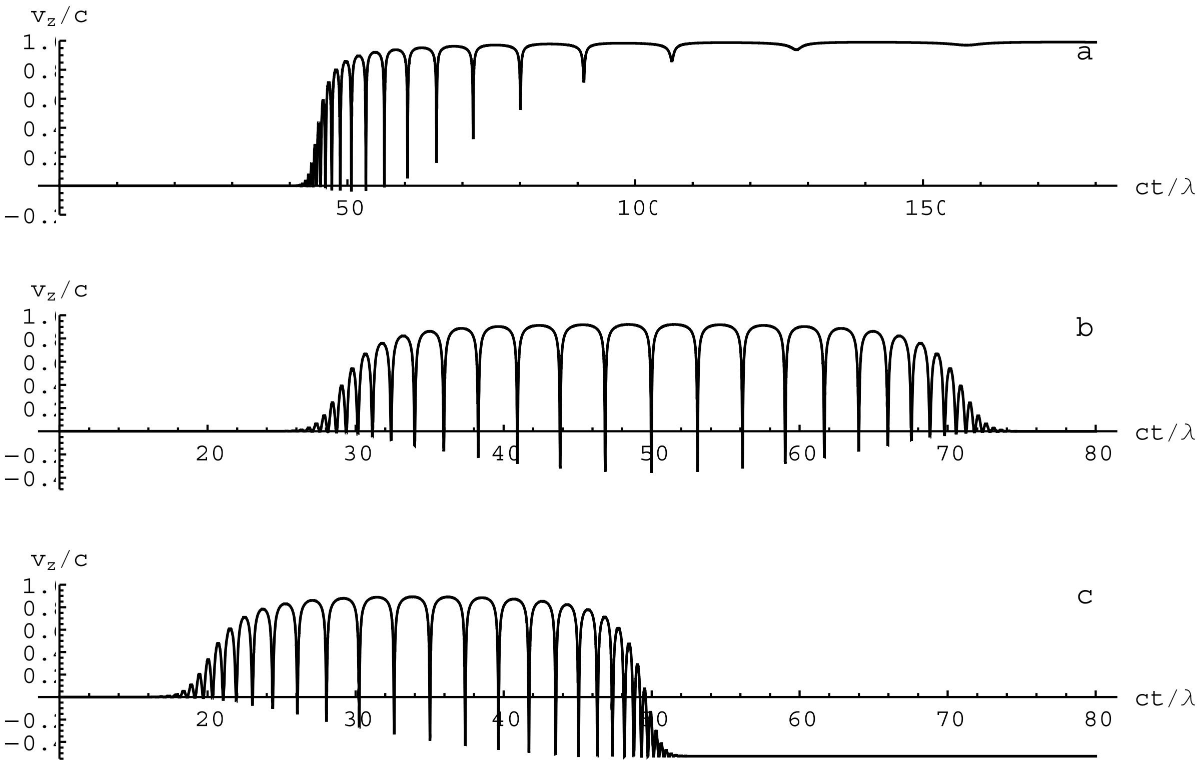
- Applicability criterion $\lambda / \rho_0 < 2\pi$ $\rho_0 / c < \tau$
- Basic parameters $I / I_r = 1000,\ 100 > c\tau / \lambda > 1.5$
- Plane phase front condition $L < z_R = \pi \rho_0^2 / \lambda$
- Basic Gaussian Laser Pulse Electric Field (s=2)





THE TEMPORAL PROFILES FOR THE ELECTRON VELOCITY 1

$$L > z_R, \rho_0 / \lambda = 3, c\tau / \lambda = 4$$



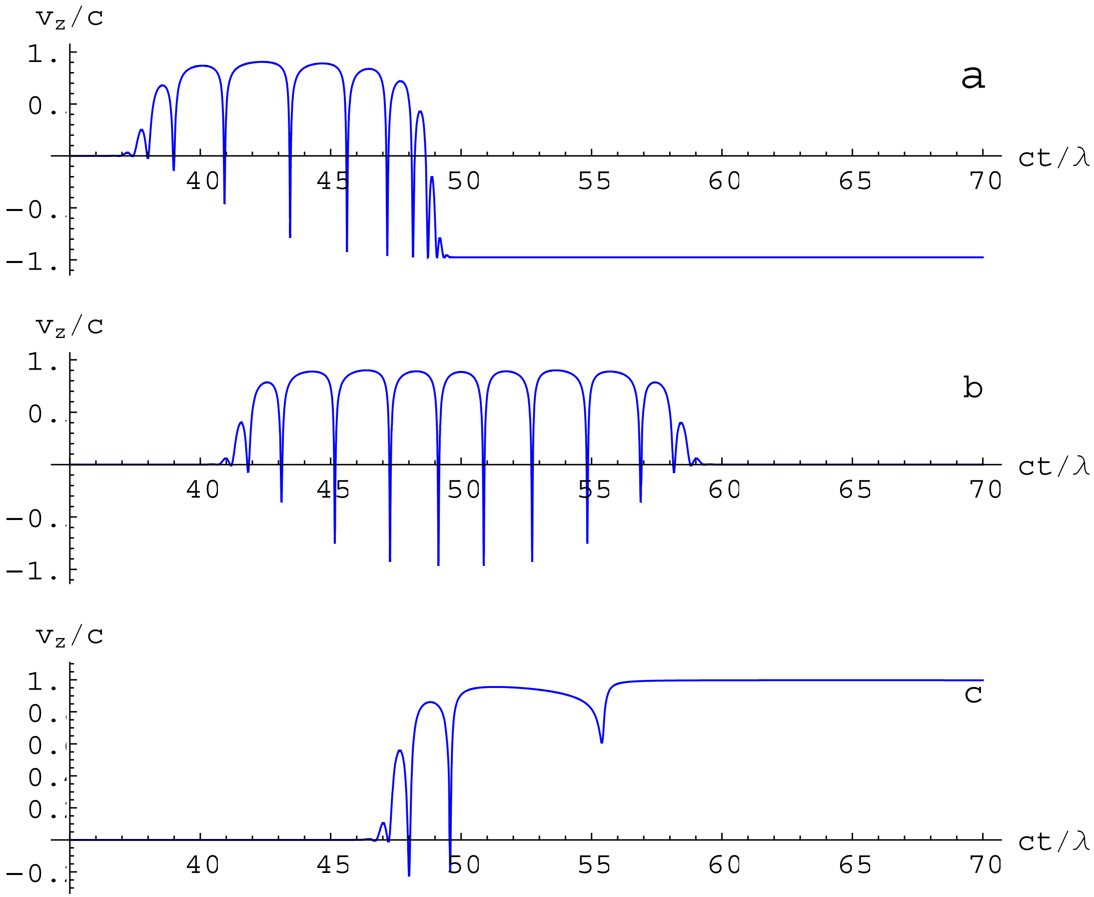
$$z_0/\lambda = 0$$

$$z_0/\lambda = -16$$

$$z_0/\lambda = -25$$

THE TEMPORAL PROFILES FOR THE ELECTRON VELOCITY 2

$$L > z_R, \rho_0 / \lambda = 1, c\tau / \lambda = 1,5$$

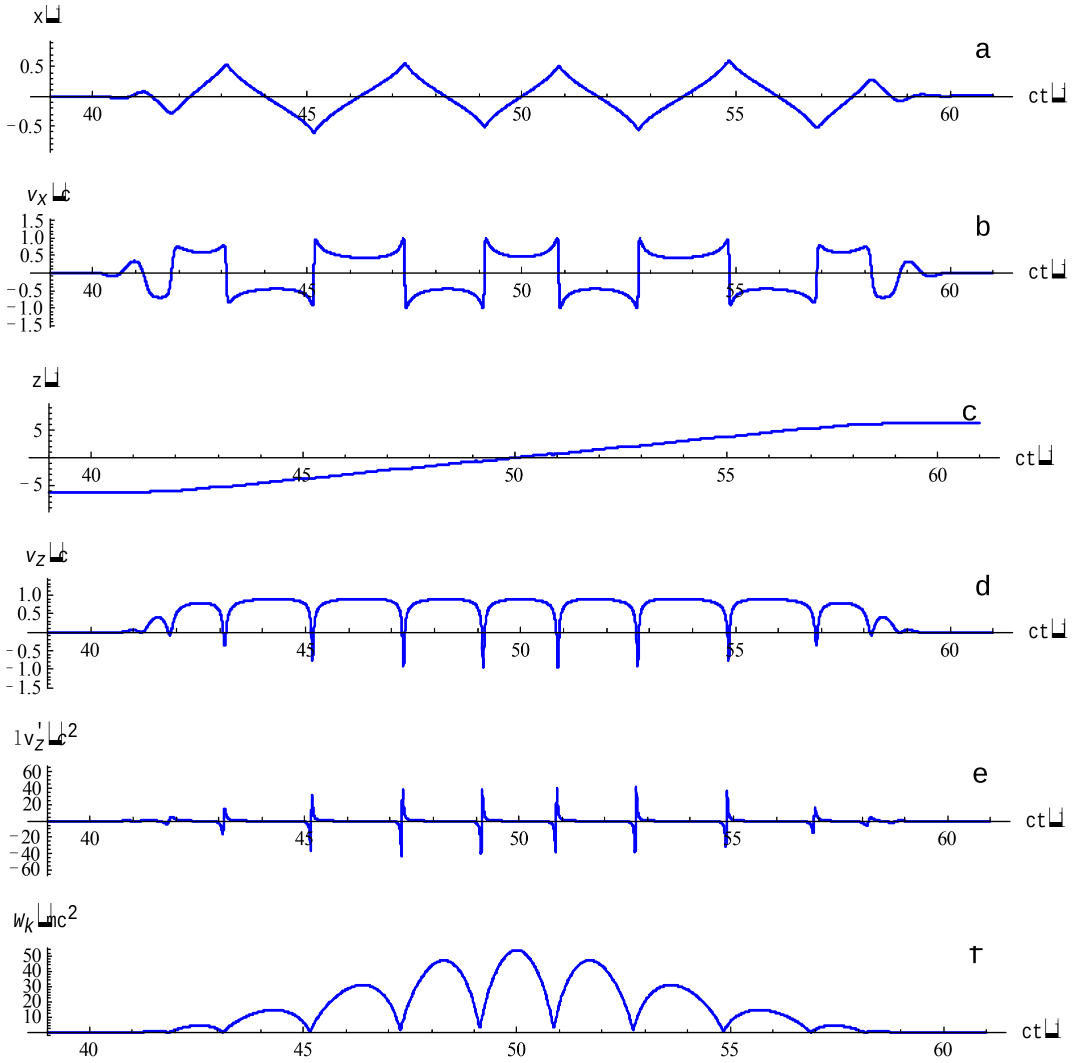


$z_0/\lambda = -10$

$z_0/\lambda = -6.2$

$z_0/\lambda = 0$

MOTION IN A LINEARLY POLARIZED FIELD



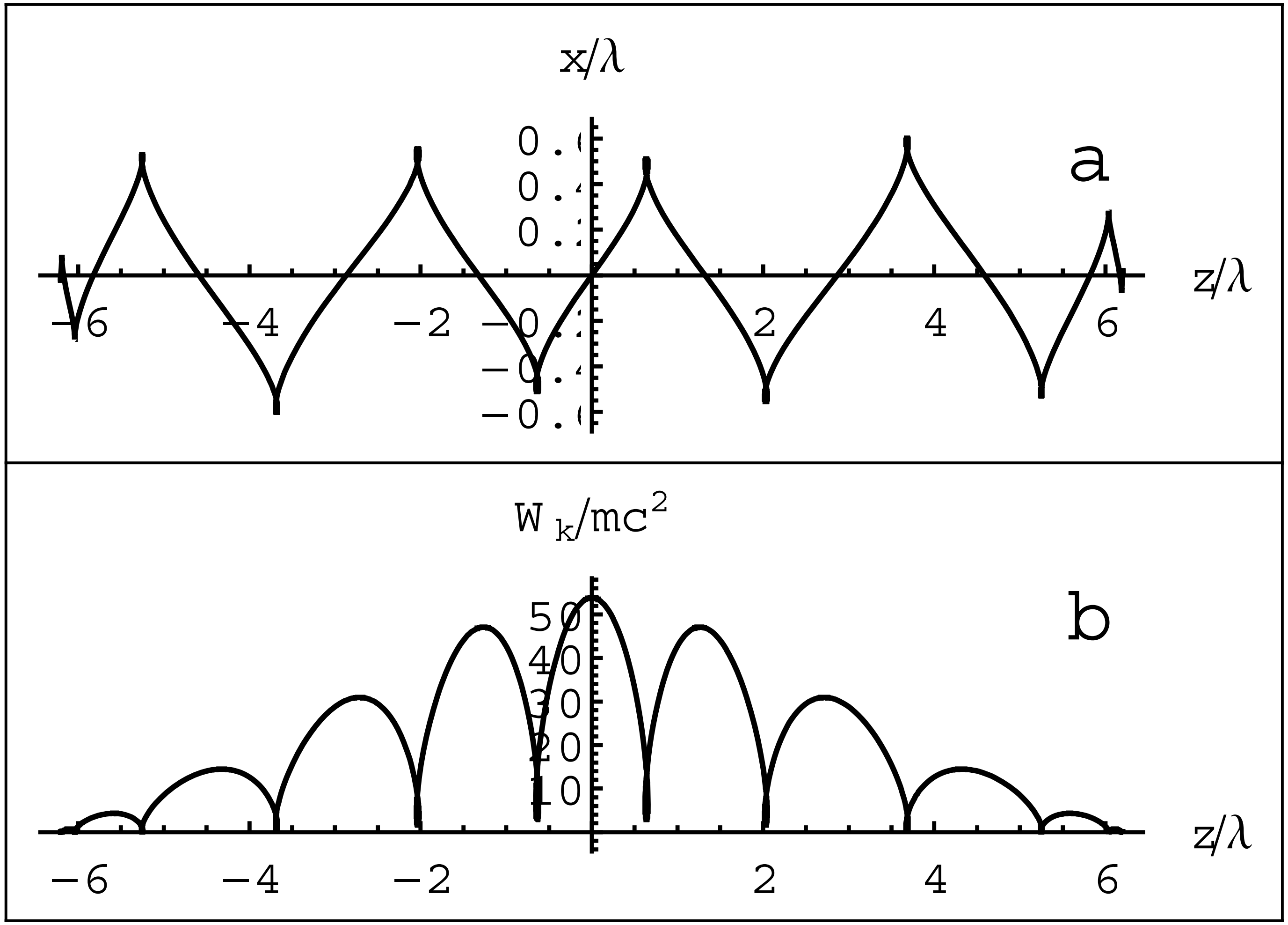
symmetrical case

$$c\tau/\lambda = 1.5$$

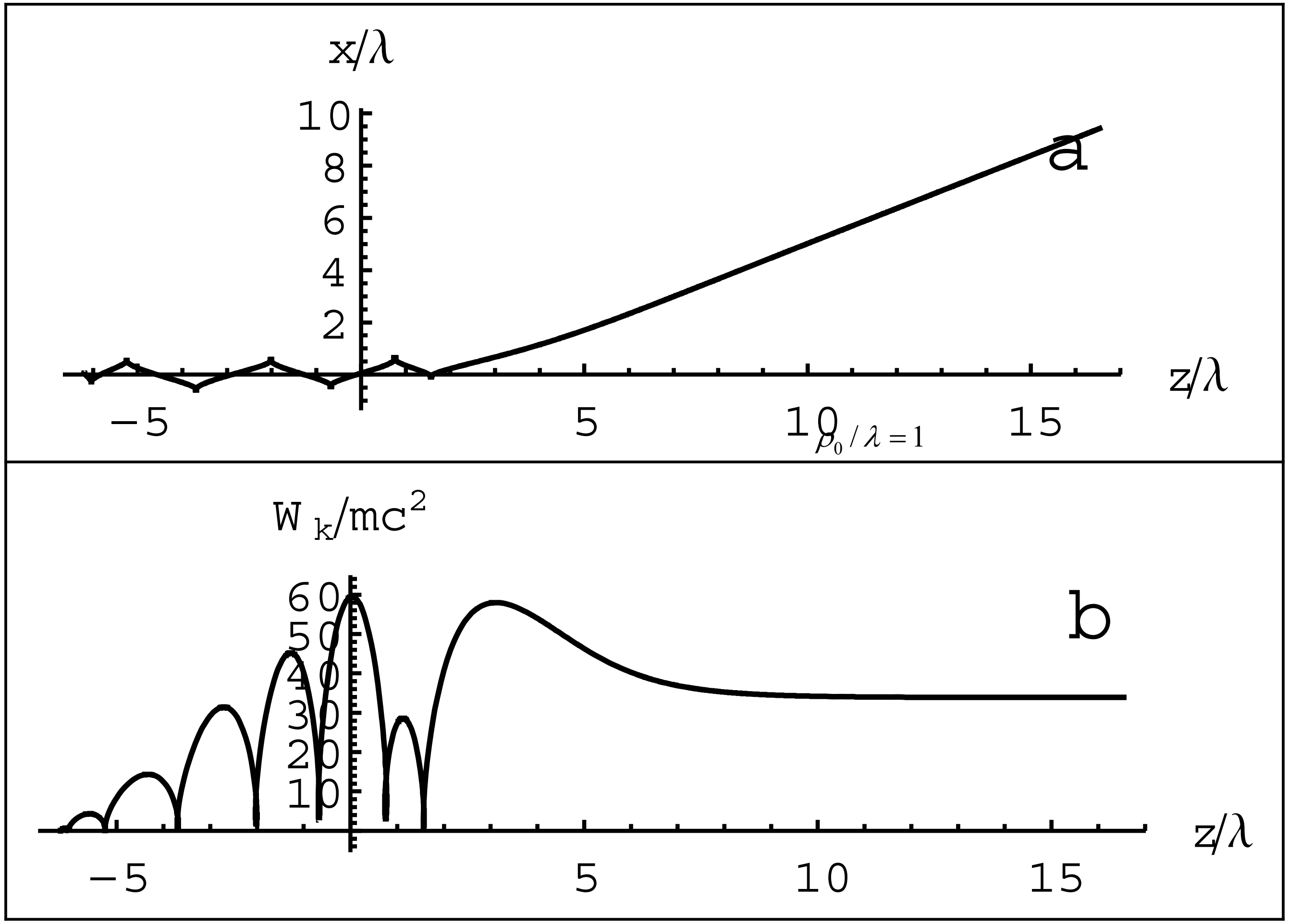
$$\rho_0/\lambda = 1$$

$$I_m/I_r = 1000$$

TRAJECTORY AND ENERGY



LINEAR POLARIZATION, INITIAL ELECTRON DISPLACEMENTS



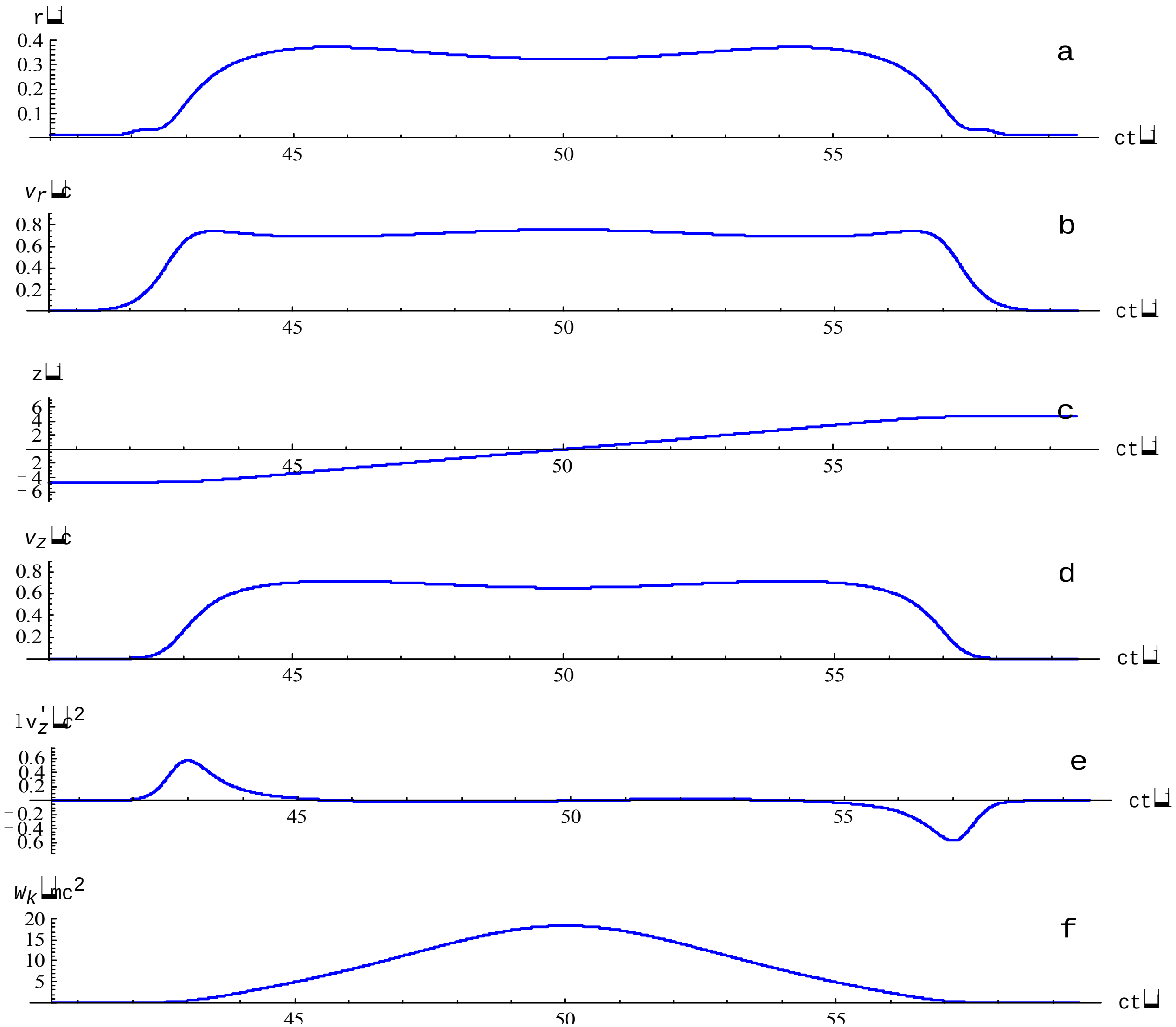
$\rho_0/\lambda = 1$

$c\tau/\lambda = 1.5$

$\Delta x/\lambda = 0.01$

$I_m/I_r = 1000$

MOTION IN A CIRCULARLY POLARIZED FIELD



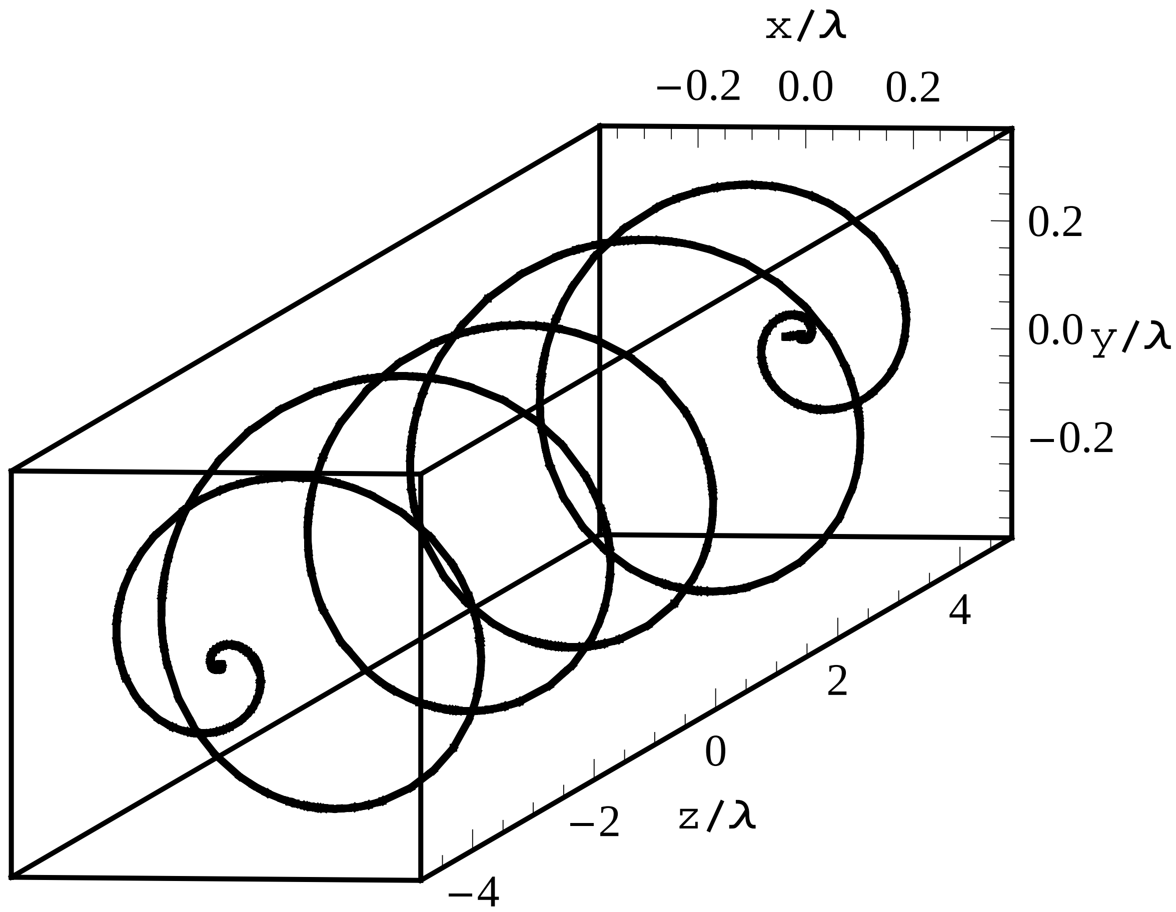
symmetrical case

$$\rho_0 / \lambda = 1$$

$$c\tau / \lambda = 1.5$$

$$I_m / I_r = 1000$$

SPATIAL PICTURE



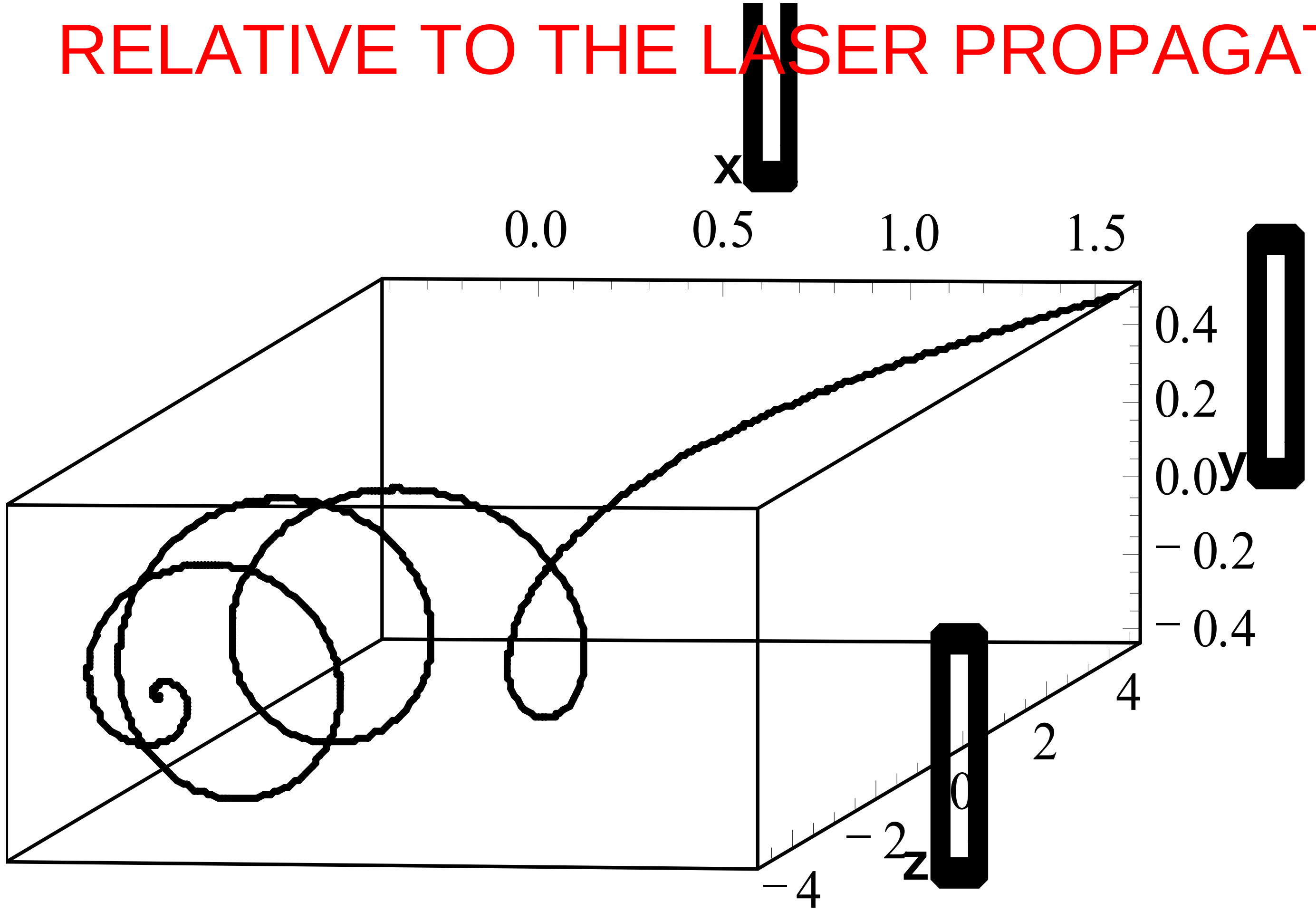
symmetrical case

$$\rho_0/\lambda = 1$$

$$c\tau/\lambda = 1.5$$

$$I_m/I_r = 1000$$

3D TRAJECTORY FOR CIRCULAR POLARIZATION
WITH AN INITIAL ELECTRON DISPLACEMENT RELATIVE TO THE LASER PROPAGATION AXIS

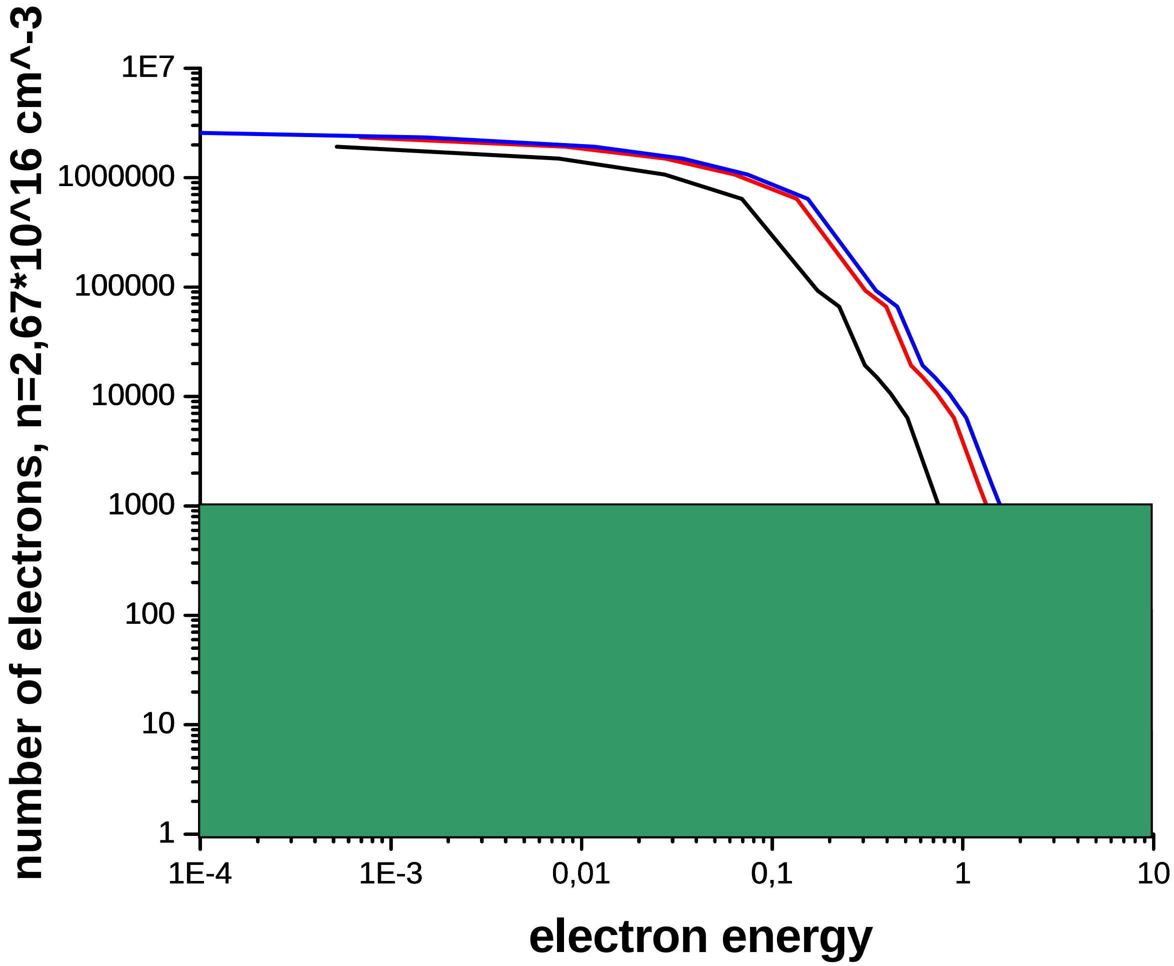


$$\rho_0 / \lambda = 1$$

$$c\tau / \lambda = 1.5$$

$$I_m / I_r = 1000$$

ELECTRONS ENERGY SPECTRA. SENSITIVITY OF DIAGNOSTICS



I = 10 I rel

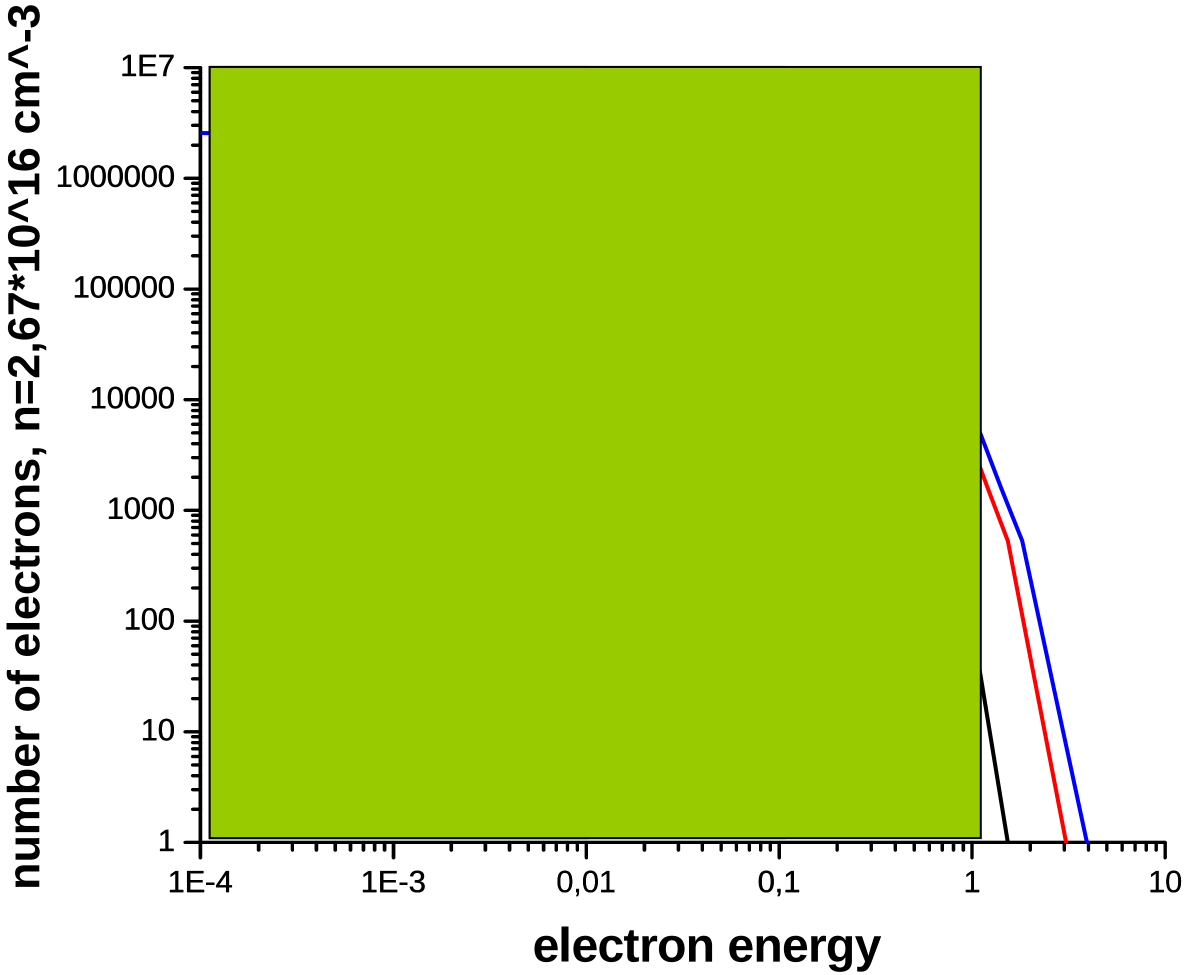
I = 50 I rel

I = 100 I rel

$\rho_0 / \lambda = 2.5$

$c\tau / \lambda = 15$

ELECTRONS ENERGY SPECTRA. FILTERING DIAGNOSTICS



I = 10 I rel

I = 50 I rel

I = 100 I rel

$$\rho_0 / \lambda = 2.5$$

$$c\tau / \lambda = 15$$

INTENSITY DIAGNOSTICS

- Electrons spectra permit to produce absolute measurements of the laser pulse intensity.

RADIATION OF AN ELECTRON DRIVEN BY THE RELATIVISTICALLY INTENSE LASER FIELD

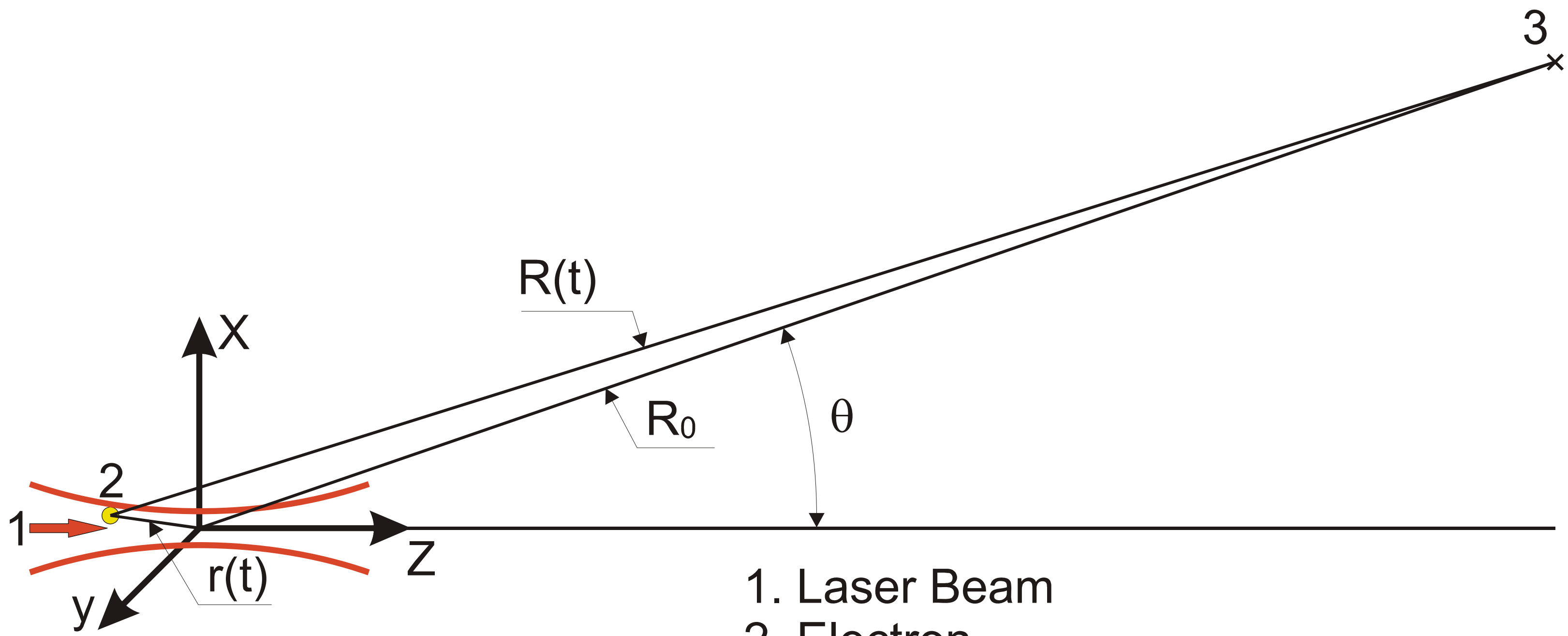
- The radiation of a moving electron (Lienard-Wiechert potential)

$$\mathbf{E}_{rad} = e\frac{1-v^2/c^2}{\left(R-\mathbf{R}\mathbf{v}/c\right)^3}\left(\mathbf{R}-\frac{\mathbf{v}}{c}R\right)+\frac{e}{c^2\left(R-\mathbf{R}\mathbf{v}/c\right)^3}\left[\mathbf{R}\left[\left(\mathbf{R}-\frac{\mathbf{v}}{c}R\right)\mathbf{v}'\right]\right]$$

$$t_r+\frac{R\left(t_r\right)}{c}=t \qquad \mathbf{r}(t)+\mathbf{R}(t)=\mathbf{R}_0 \qquad \mathbf{\Psi}=\mathbf{E}_{rad}/\left(e/\lambda^2\right)$$

OBSERVATION SCHEME

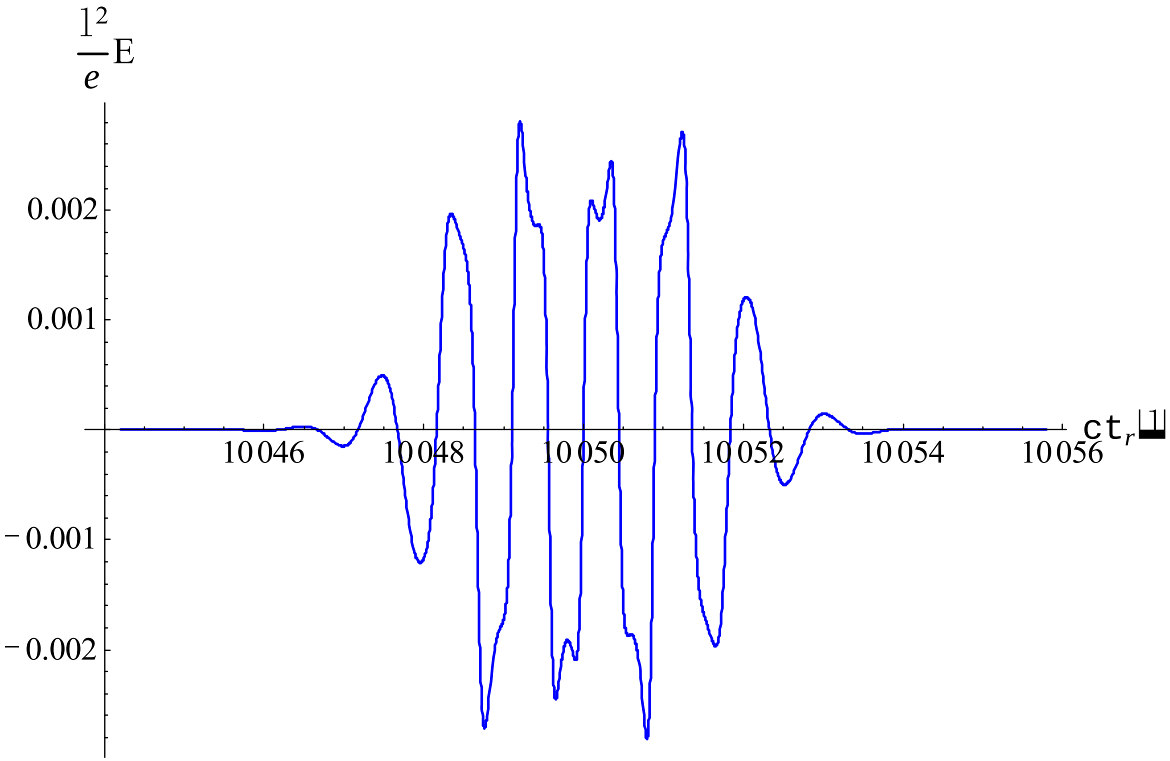
$$R_0/\lambda = 10000$$



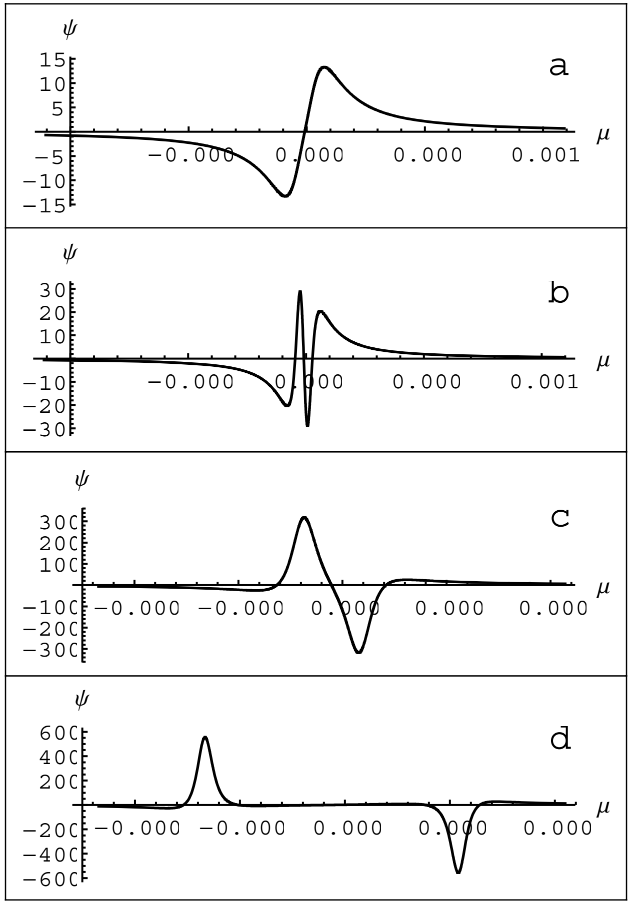
1. Laser Beam
2. Electron
3. Observation Point

ELECTRON FORWARD RADIATION CLOSE TO THE DRIVING FIELD

- Observation angle $\theta = 0^0$
- Linear polarization $I / I_r = 1000, c\tau / \lambda = 1.5, \rho_0 / \lambda = 1$



RADIATION OF A SEGMENT OF THE ELECTRON TRAJECTORY AT VARIOUS ANGLES



$\theta = 26.5^{\circ}$

$\theta = 27.2^{\circ}$

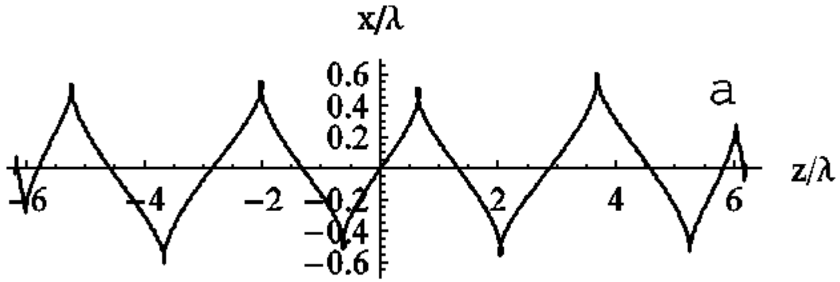
$\theta = 28.1^{\circ}$

$\theta = 29.5^{\circ}$

- Linear Polarization

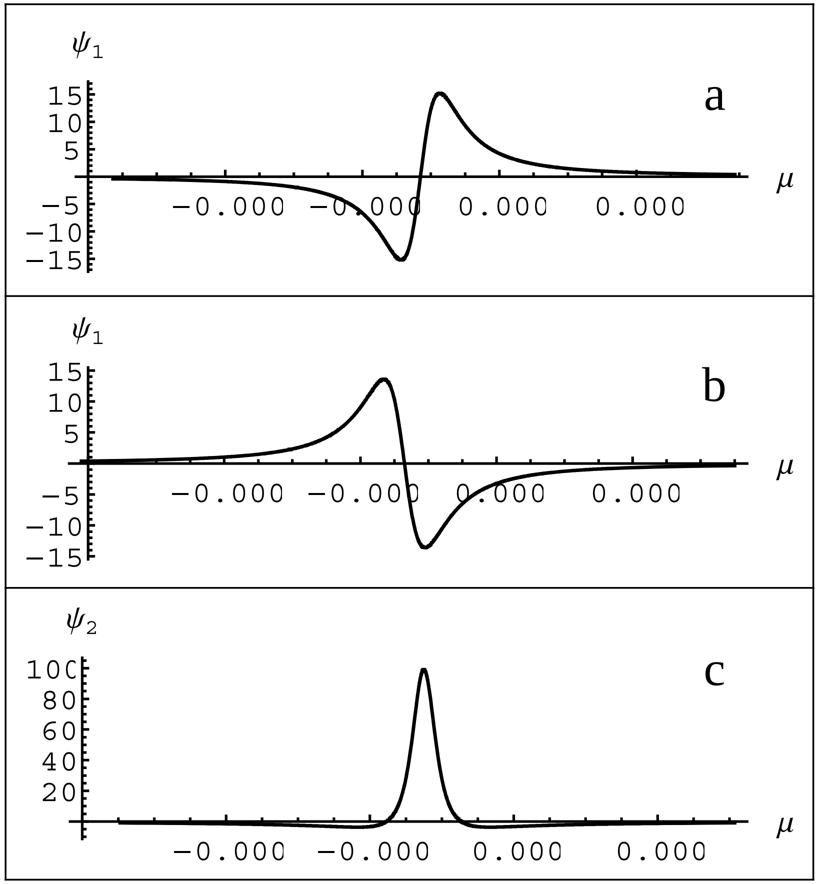
$$I / I_r = 1000; \quad c\tau / \lambda = 1.5; \quad \rho_0 / \lambda = 1$$

$$\mu = ct_r / \lambda - R_0 / \lambda - z_d / \lambda = ct_r / \lambda - 10050$$



- **Outburst duration: 0.04 attoseconds!**

RADIATION OF A SEGMENT OF THE ELECTRON TRAJECTORY AT VARIOUS ANGLES



$\theta = 47.5^o$

$\theta = 51^o$

$\theta = 49.25^o$

Circular polarization

$I / I_r = 1000; \quad c\tau / \lambda = 1.5; \quad \rho_0 / \lambda = 1$

$\mu = ct_r / \lambda - R_0 / \lambda - z_d / \lambda = ct_r / \lambda - 10050$

CONCLUSIONS

- An electron initially at rest obtains a considerable velocity as a result of the interaction with the field, its magnitude and sign depending on the electron's initial location versus the neck. This effect makes it possible to accelerate electrons to energies making a considerable fraction of its oscillation energy in the field.
- Electrons spectra permit to produce absolute measurements of the laser pulse intensity.
- The radiation emitted by an electron driven by a short relativistically intense laser pulse is a set of electromagnetic pulses with duration much shorter than the optical period.

- Galkin A.L., Korobkin V.V., Romanovsky Yu.M., and Shiryaev O.B. Physics of Plasmas. 15, 023104, (2008).