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Formation of Compressed High-Energy Bunches of Charged Particles by Interfering Laser Pulses with Tilted Fronts and Their Application for Generation of γ-Rays

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Outline

- New concept of charged particles acceleration
- Application of acceleration scheme:
  - ✓ Electron acceleration and formation of compressed high-energy bunches
  - ✓ Electron-positron collision
  - ✓ Proton acceleration
  - ✓ Generation of γ-Rays

Charged Particles Dynamics in an Intense Laser Field

Charged particle driven by the Lorentz force of the laser field:

Relativistic Newton's equation for a charge particle:

$$\frac{d\mathbf{p}}{dt} = \mathbf{f}_{\mathrm{L}} \qquad \mathbf{f}_{\mathrm{L}} = q\mathbf{E} - \frac{e}{c}\left[\mathbf{vH}\right]$$

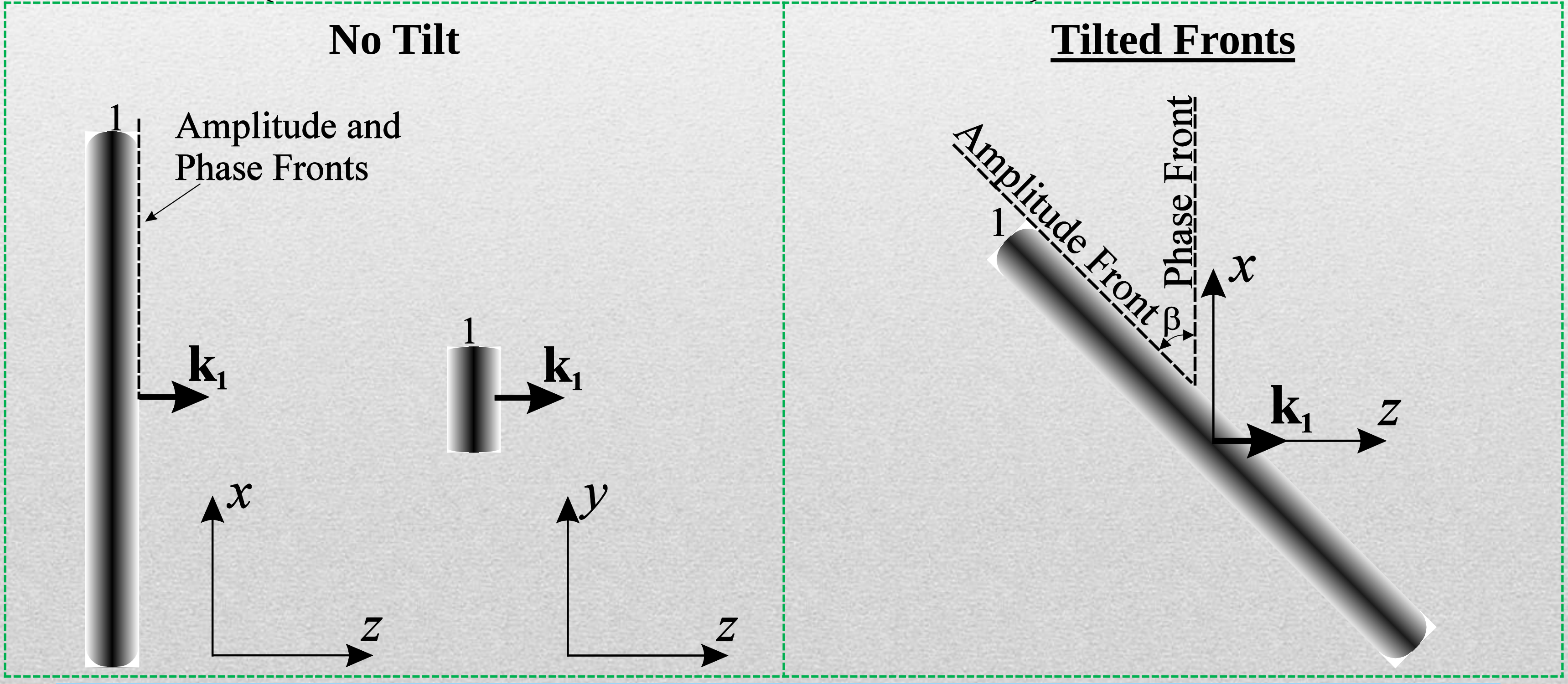
Relativistic laser intensity:

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

Expression for the Field of Laser Pulse with Tilted Amplitude Fronts

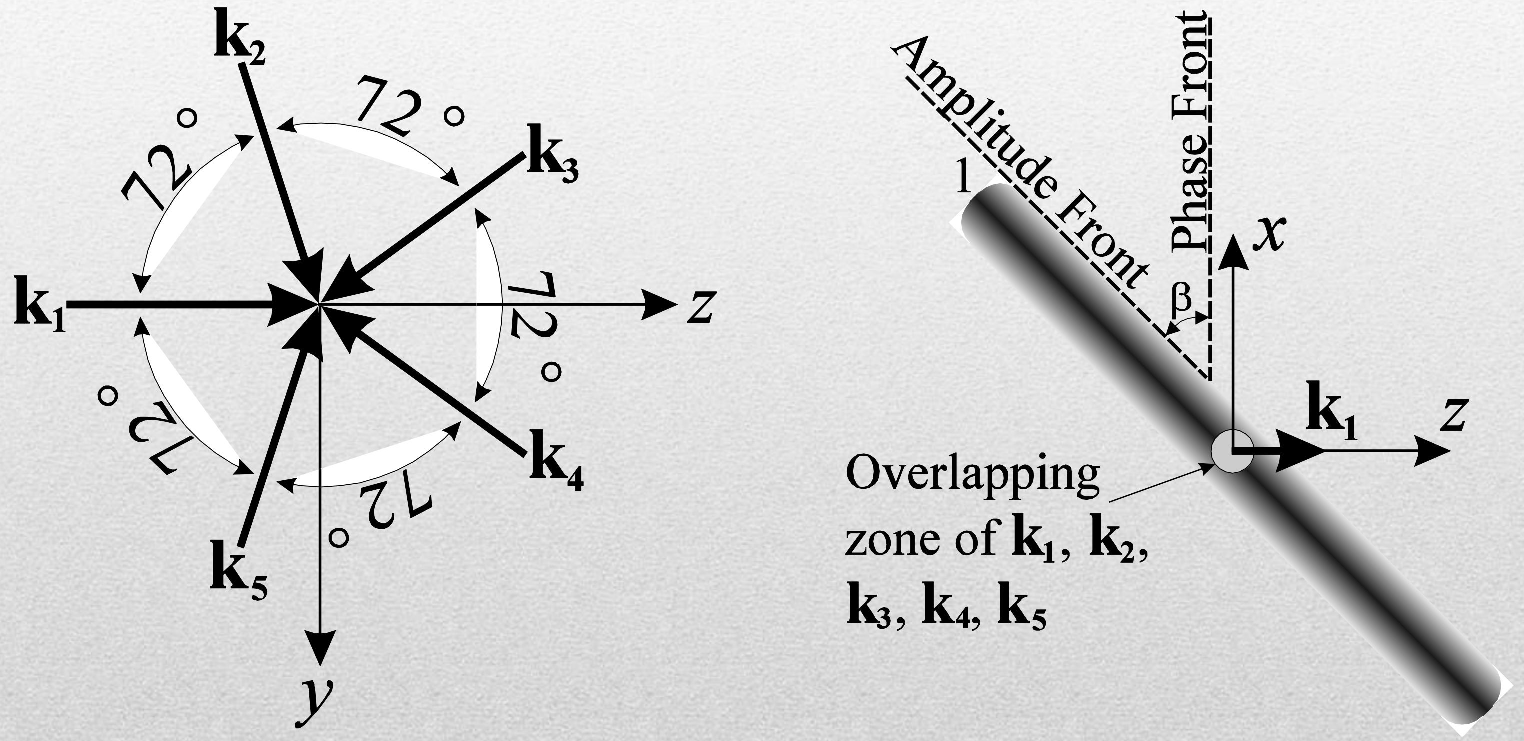
Relativistically intense laser pulse with a plane wave front, Gaussian transverse profile and different transverse sizes $\rho_{0x}, \rho_{0y}; \rho_{0x} >> \rho_{0y}$

$$E_x = E_0 \exp\left\{-\left[\left(\xi - z_d/c\right)/\tau\right]^s - \left(x/\rho_{0x}\right)^2 - \left(y/\rho_{0y}\right)^2\right\}\cos\varphi,\ \xi = t - (z + x\,tg\beta)/c$$



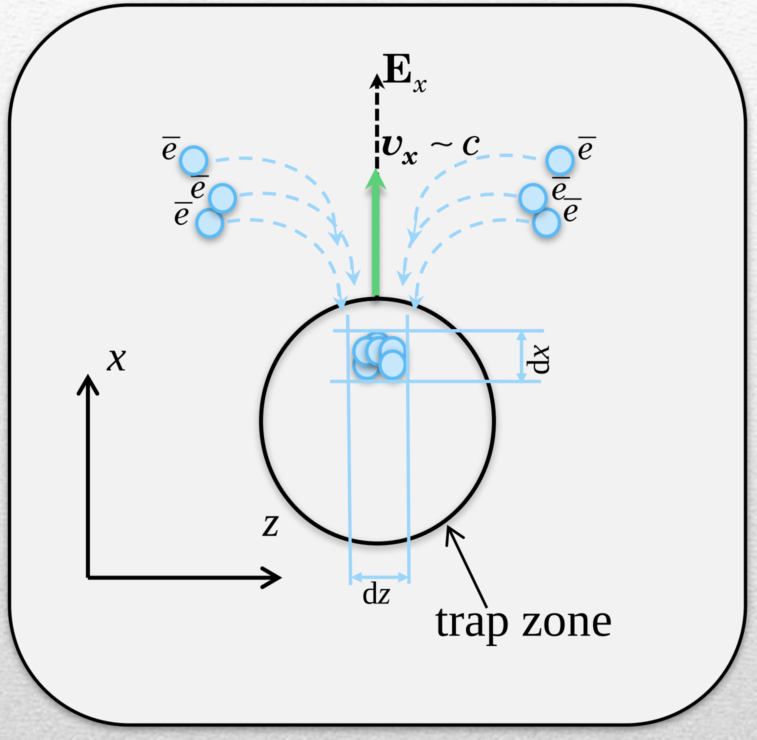
1 – laser pulse; **k₁** – wave vector shows the directions in which the beam propagate; β – angle between amplitude and phase fronts of laser pulse

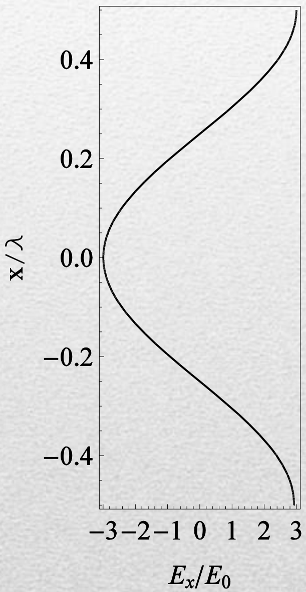
Scheme of Propagation of Laser Pulses

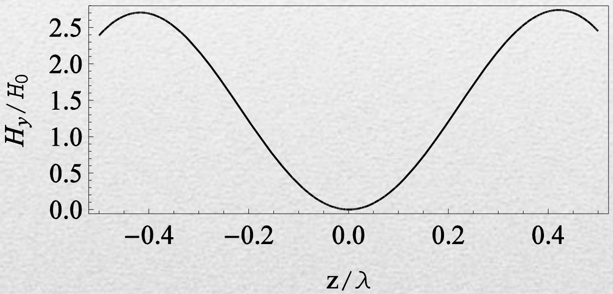


$\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$, $\mathbf{k}_4$ and $\mathbf{k}_5$ – wave vectors show the directions in which the beams propagate; 1 – laser pulse; β – angle between amplitude and phase fronts of laser pulse

Dynamics of Charged Particles in the Field of a Standing Wave Generated by Linearly Polarized Laser Pulses

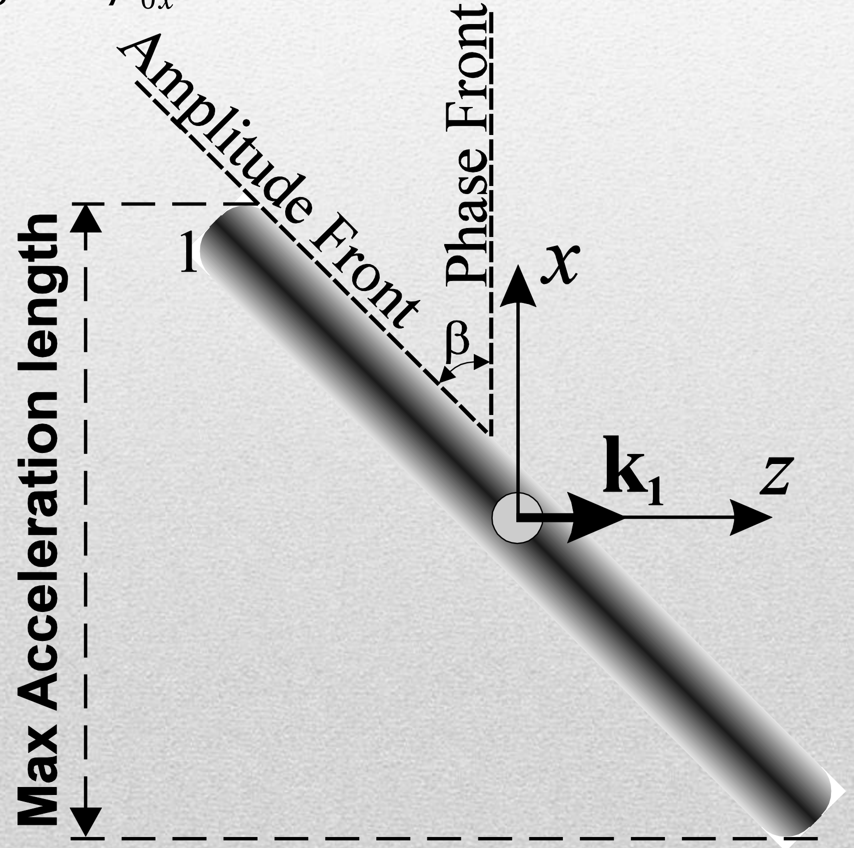






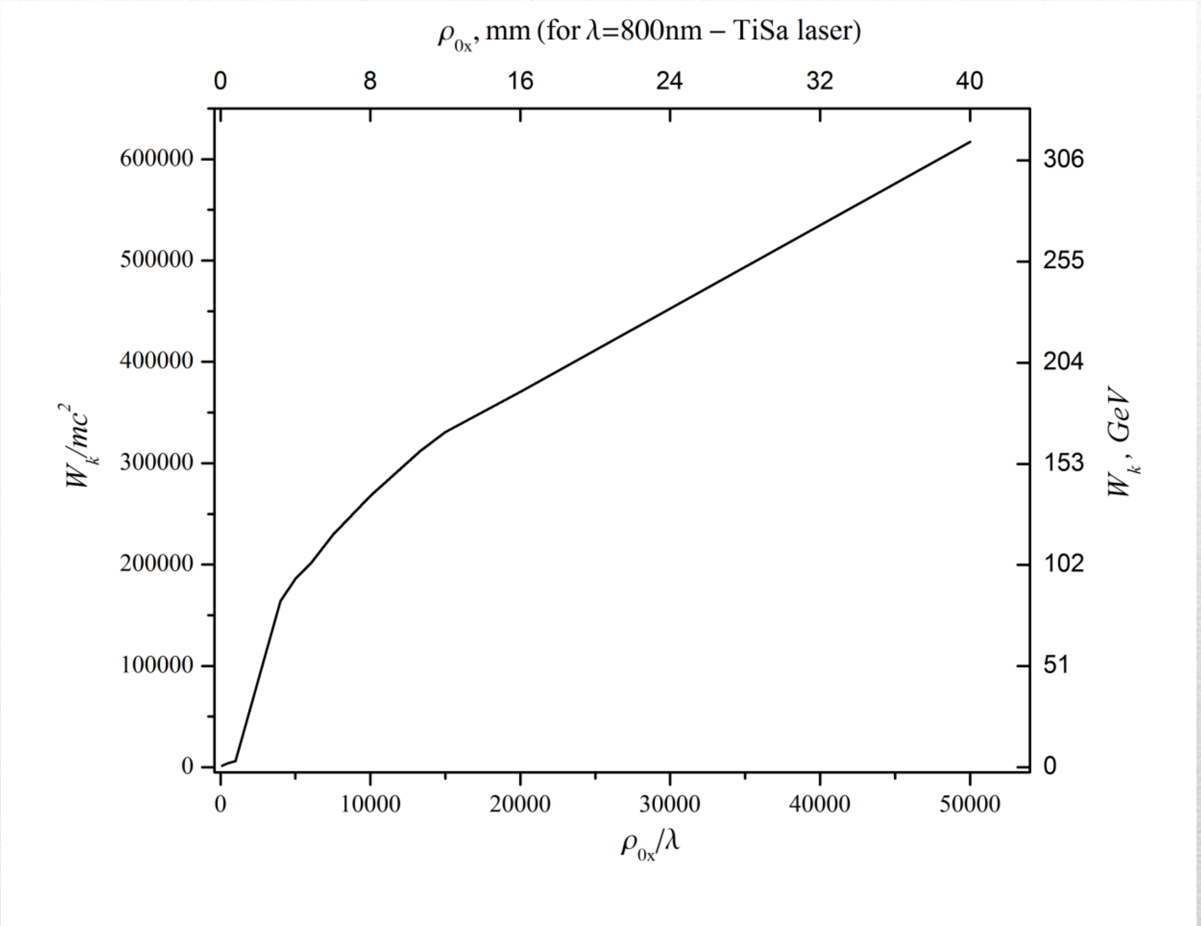
Dynamics of a Charged Particles in the Field of a Standing Wave Generated by Linearly Polarized Laser Pulses

For the certain <u>laser pulse energy</u> and <u>duration</u> acceleration length can be changed → change of ρ_{0x} :



$\mathbf{k}_1$ – wave vector shows the direction in which the beam propagates in the (x,z)-plane ; 1 – laser pulse; β – angle between amplitude and phase fronts of laser pulse.

Dynamics of an electron in the Field of a Standing Wave Generated by Linearly Polarized Laser Pulses



Laser pulses parameters:

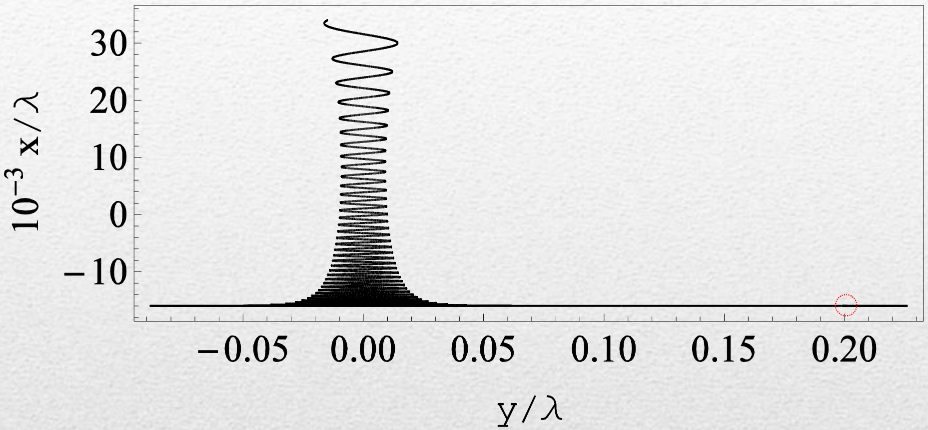
$$\rho_{0y}/\lambda = 2.5;$$

$$c\tau/\lambda = 2.5;$$

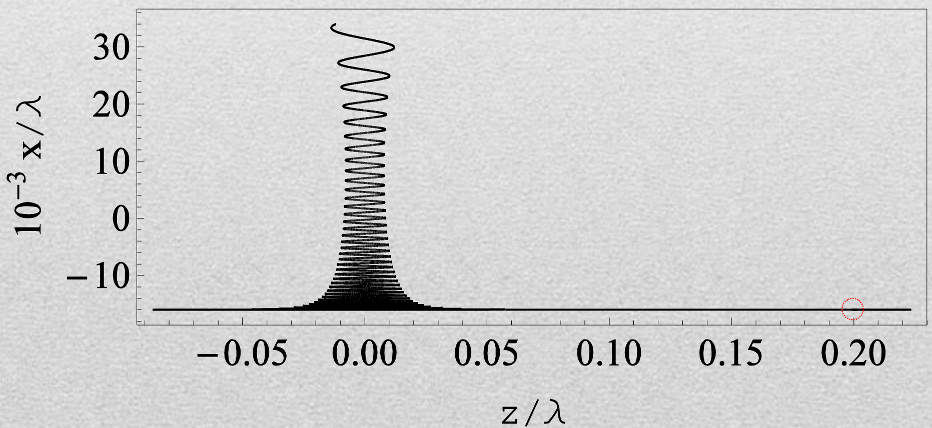
$$s = 4;\ \beta = 45^{o};$$

Dynamics of an electron in the Field of a Standing Wave Generated by Linearly Polarized Laser Pulses

(a)



(b)



Laser pulses parameters:

$\rho_{0x} / \lambda = 20000; \rho_{0y} / \lambda = 2.5;$

$c\tau / \lambda = 2.5; \quad I_m / I_r = 6;$

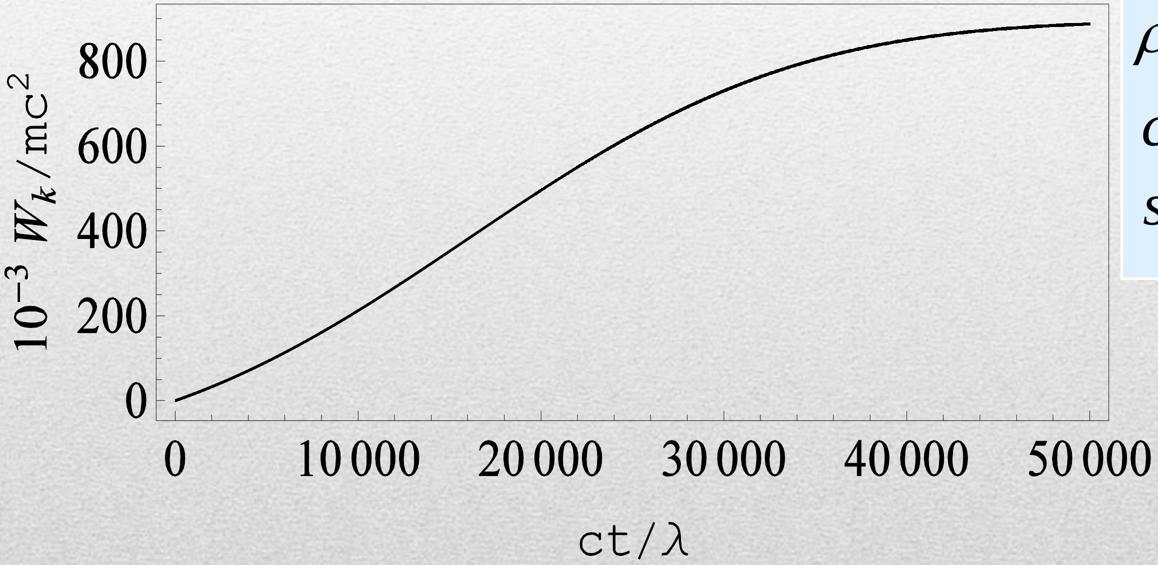
$s = 4; \quad \beta = 45^{\circ};$

$x_0 / \lambda = -16000;$

$y_0 / \lambda = 0.2;$

$z_0 / \lambda = -0.25;$

Dynamics of an electron in the Field of a Standing Wave Generated by Linearly Polarized Laser Pulses



Laser pulses parameters:

$\rho_{0x}/\lambda = 20000;\ \rho_{0y}/\lambda = 2.5;$

$c\tau/\lambda = 2.5;\quad I_m/I_r = 6;$

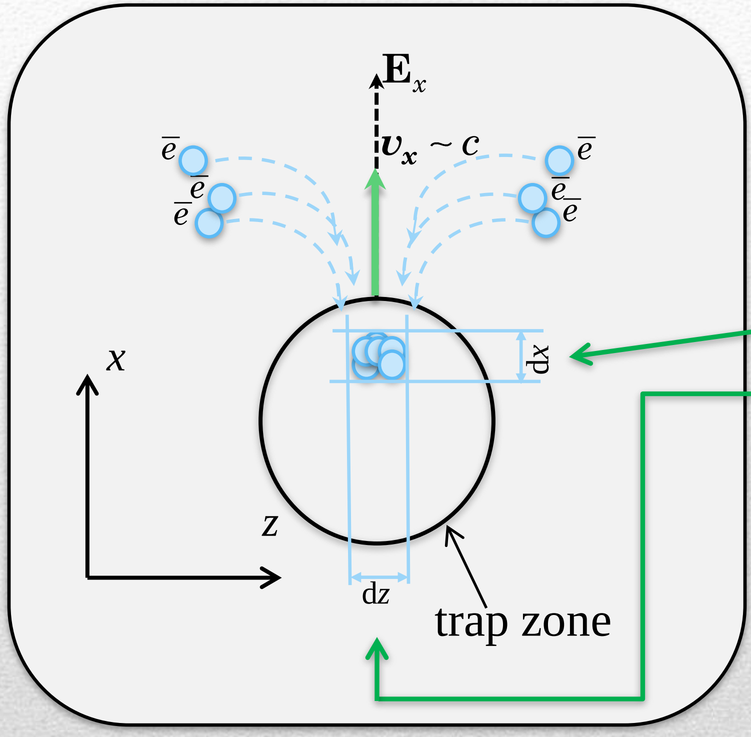
$s = 4;\quad \beta = 45^{\circ};$

$x_0/\lambda = -16000;$

$y_0/\lambda = 0.2;$

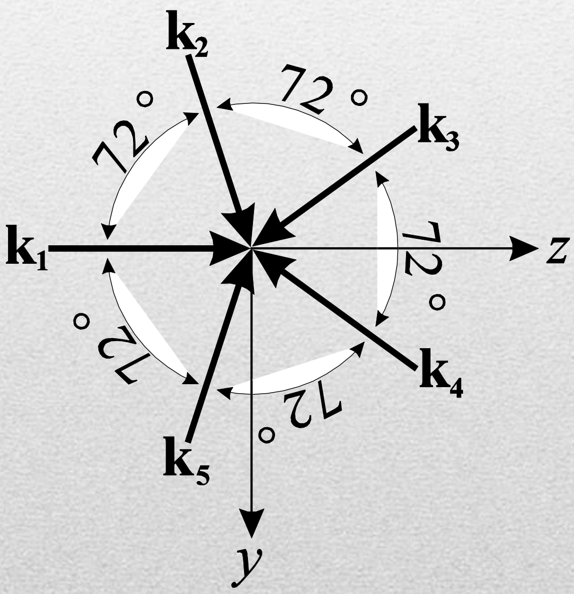
$z_0/\lambda = -0.25;$

Formation of Short Electron Bunches in the Field of a Standing Wave

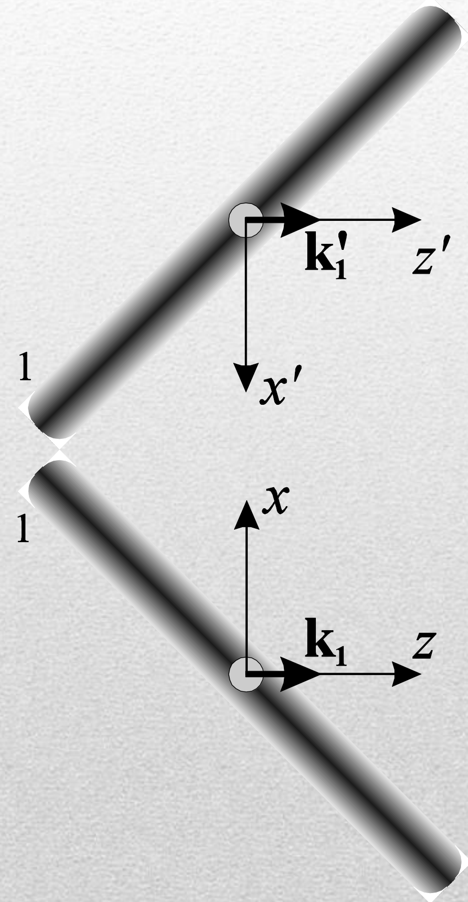


Longitudinal size (in x)	$\sim 10^{-3}\lambda$
Transverse sizes (in y and z)	$\sim 10^{-2}\lambda$
N of electrons in the bunch	$\sim 10^{5}$
Electron concentration	$\leq 10^{25}$ cm^{-3}
Acceleration length	$\sim 10^{4}\lambda$
Strength of the accelerating fields	18 TV/m
Laser pulse energy	9 J
Electron energy	500 GeV
Energy spread	~2%

Electron-Positron Collision Scheme

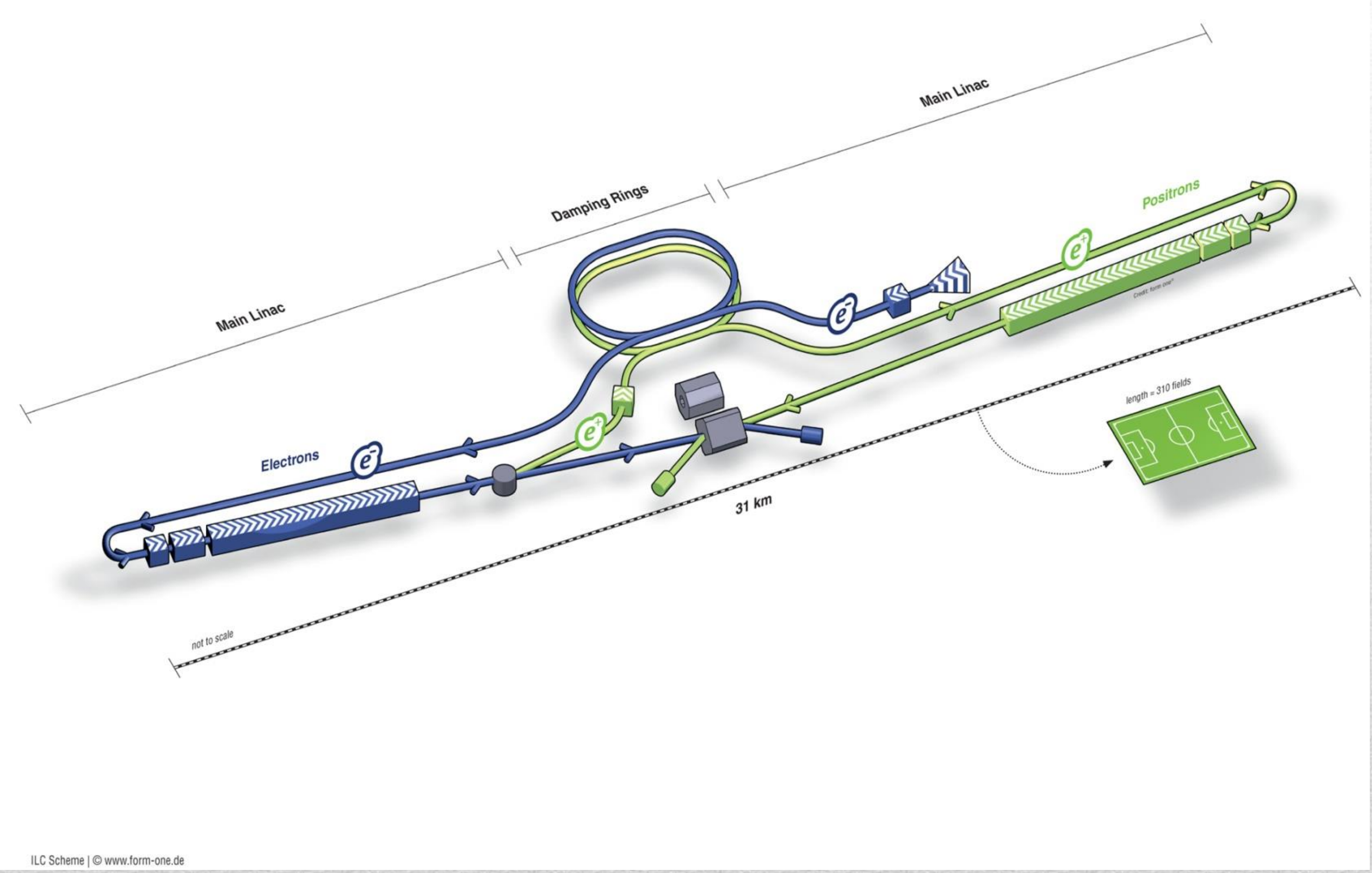


Positron acceleration



Electron acceleration

International Linear Collider



Collision energy 500 GeV (31 km long) or 1 TeV (50 km long). Accelerating gradient 31 MV/m.

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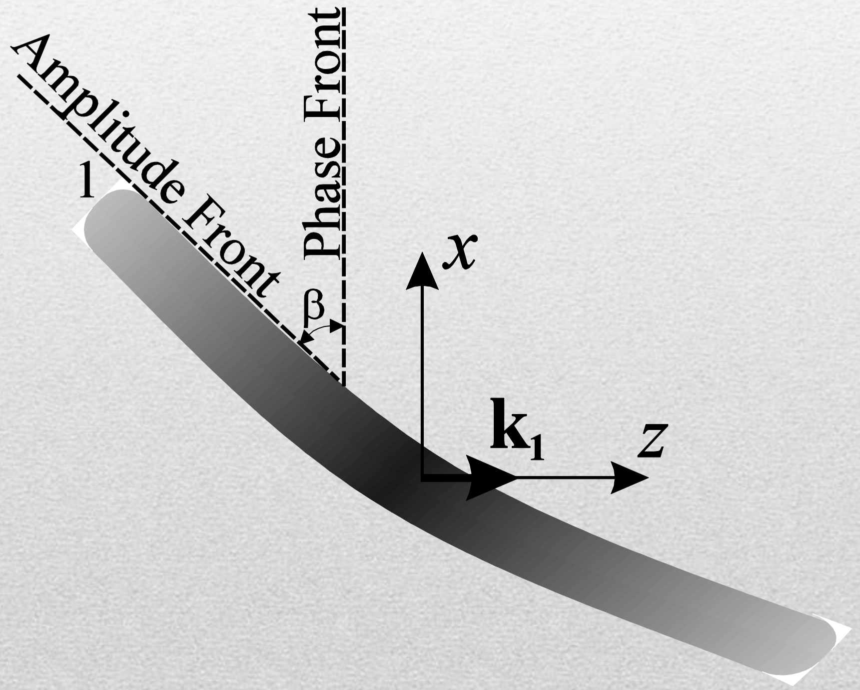
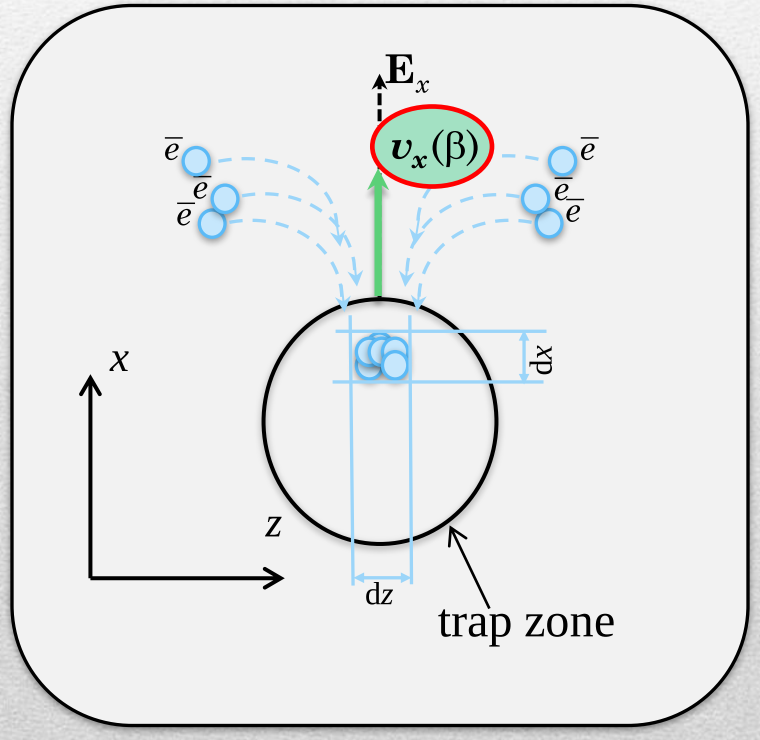
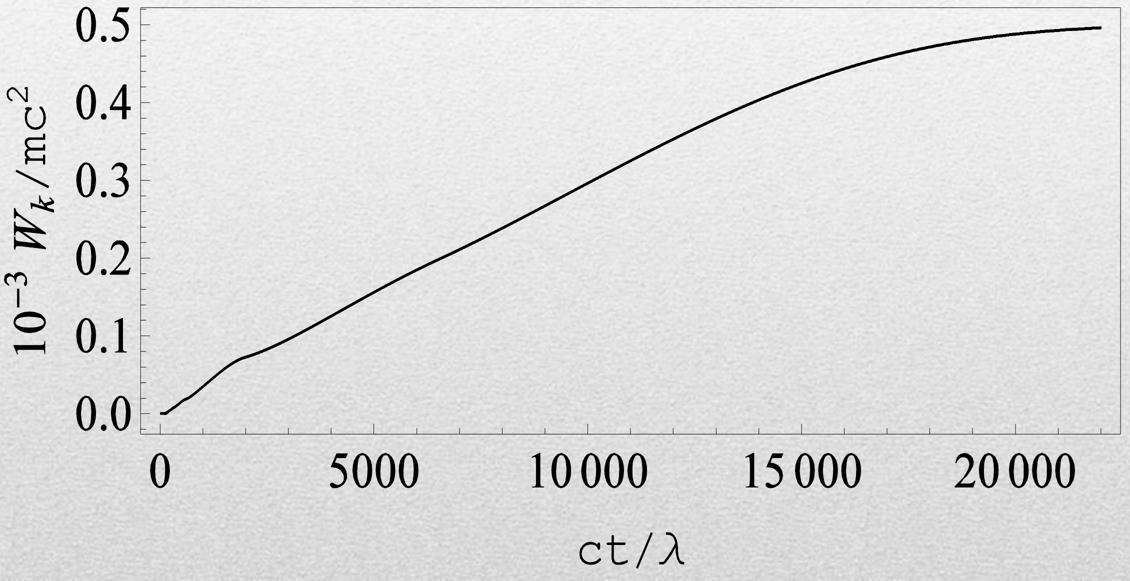
Modification of Acceleration Scheme

- β can be changed during acceleration
- Speed of trap zone propagation in x-direction can be changed





Proton Acceleration



Laser pulses parameters:

$\rho_{0x}/\lambda = 17\,000;\ \rho_{0y}/\lambda = 2.5;$
$c\tau/\lambda = 2.5;\ \ I_m/I_r = 50;$
$s = 4;$

$x_0/\lambda = 5;$
$y_0/\lambda = 0.0;$
$z_0/\lambda = 0.0;$

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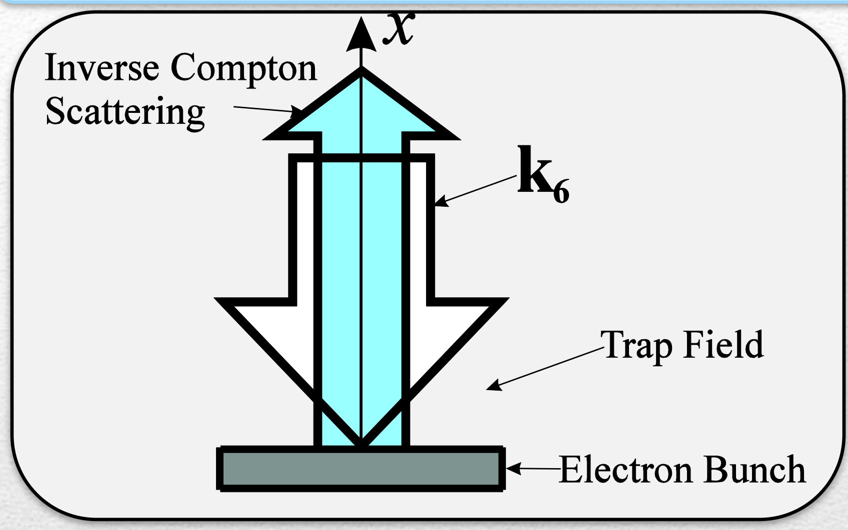
Inverse Compton Scattering



Compton scattering cross-section:

$$\sigma = (3/4)\cdot\sigma_T\cdot\mu^{-1}\cdot(ln\mu + 1/2)$$

$$\mu = (2hv/m_e c^2)\cdot\gamma\cdot(1-(\mathrm{v}/c)\cos\theta)$$

For ultrarelativistic electrons Compton scattering cross-section equals to Thomson cross-section:

$$\sigma_T = (8\pi/3)\cdot(e^2/m_e c^2) = 6.65\cdot 10^{-25}\,\mathrm{cm}^{-3}$$

Energy of γ-quanta: ⇨ Energy of γ-quanta in case of counterpropagation of laser pulse and electron bunch: ⇨ Energy of γ-quanta in case of ultrarelativistic electrons:

$$E_\gamma = E_{ph0}\frac{1-\frac{\mathrm{v}}{c}\cos\theta}{1-\frac{\mathrm{v}}{c}\cos(\theta-\vartheta)+\frac{E_{ph0}}{E_0}(1-\cos\vartheta)}$$

$$E_\gamma = E_{ph0}\frac{1+\frac{\mathrm{v}}{c}}{1-\frac{\mathrm{v}}{c}+\frac{2E_{ph0}}{E_0}}$$

$$E_\gamma \approx E_0$$

E_{ph0} – incident photon energy, E_0 – initial electron energy, v - laser's photon frequency, γ – Lorentz factor, v– speed of accelerated electrons, θ – angle of collision of laser pulse photons with electron bunch, ϑ – angle between directions of propagation of initial and scattered photons

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Inverse Compton Scattering

- ~99% of electrons accelerated to 500 GeV emit γ-quanta due to Inverse Compton Scattering in case of relativistic intensity of counterpropagating laser pulse
- γ-quanta energy close to electron energy
- Since longitudinal size of electron bunch compression to makes $10^{-3}\lambda$, time of interaction of electron bunch with counterpropagating laser pulse fits into attosecond (10^{-18}s) range. This leads to γ-quanta emission with the same phase. As a result generated γ-quanta are (partly) coherent.

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Conclusions

- Concept of charged particles acceleration is suggested. Proposed approach provides certain advantages compared to traditional accelerators.
- Charged particles are accelerated in the traps formed via the interference of several relativistically intense laser pulses with tilted amplitude fronts.
- Suggested scheme is applicable for extremely compressed high-energy electron bunches generation. Accelerated electrons gain energies on the order of several hundreds GeV.
- Resulting electron bunches, for the laser intensity on the order of 10^{18} W/cm^2, have the longitudinal sizes as short as $\sim 10^{-3}\lambda$ and the transverse sizes making $\sim 10^{-2}\lambda$.
- Modified scheme provides proton acceleration up to several hundreds GeV.
- γ-quanta generated in Inverse Compton Scattering are monochromatic, energy of these quanta is close to electron kinetic energy. In case of interaction of relativistically intense laser pulse with compressed electron bunch γ-quants are emitted with the same phase.

References

1. A.L. Galkin, V.V. Korobkin, M.Yu. Romanovskiy, V.A. Trofimov, and O.B. Shiryaev, "Acceleration of electrons to high energies in a standing wave generated by counterpropagating intense laser pulses with tilted amplitude fronts", Phys. Plasmas 19, p. 073102 (2012).

2. V.V. Korobkin, M.Yu. Romanovskiy, V.A. Trofimov, and O.B. Shiryaev, "Concept of generation of extremely compressed high-energy electron bunches in several interfering intense laser pulses with tilted amplitude fronts", Laser and Particle Beams 31, pp. 23-28 (2013).

3. A.L. Galkin, V.V. Korobkin, M.Yu. Romanovsky, O.B. Shiryaev and V.A. Trofimov, “Emission of ultrashot electromagnetic pulses from electron bunches formed and accelerated by laser beams with tilted amplitude fronts” Contrib. Plasma phys. 53, 109-115 (2013).

Electron Positron Collision Scheme

Thank you for your attention