Vacuum as a non-linear optical medium

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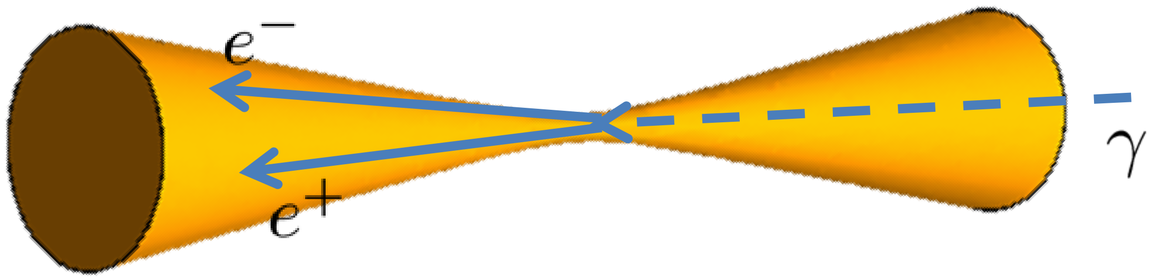
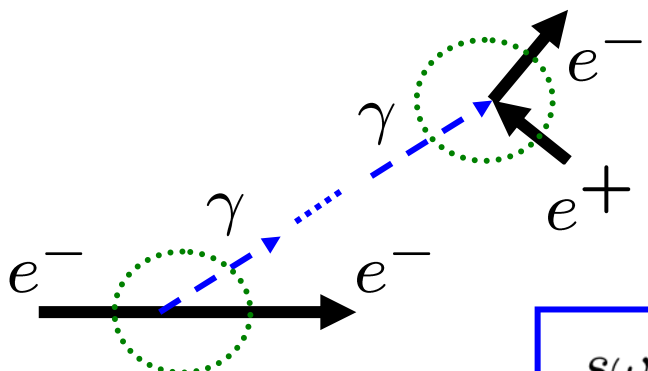
The only experiment on Vacuum polariztion by a laser field

SLAC, 1997





D.L.Burke, *et al.*, PRL, <u>79</u>, 1626 (1997)
C.Bamber, *et al.*, PRD, <u>60</u>, 092004(1999)

$$\boxed{s\omega + e^- \to e^- + \gamma \longrightarrow s\omega + \gamma \to e^- e^+}$$

Only theory of non-linear optics ih vacuum will be discussed!

The start of "Nonlinear Optics in Vacuum"

W. Heisenberg and H. Euler, Zeitschr. Phys. 98, 714 (1936)

Hans Heinrich Euler (1909–1941)

Werner Karl Heisenberg (1901-1976)

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2) + \frac{e^2}{hc}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot \frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

($\mathfrak{E}, \mathfrak{B}$ Kraft auf das Elektron.

$|\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{„137“}\frac{e}{(e^2/mc^2)^2}$ = „Kritische Feldstärke“.)

F. Sauter, ZS. f. Phys. 69, 742, 1931

“This polarization of the vacuum to be studied below will give rise to a distinction between the vectors $\mathfrak{B}, \mathfrak{E}$ on the one hand and $\mathfrak{D}, \mathfrak{H}$ on the other”

$$\left.\begin{aligned}\mathfrak{D} &= \mathfrak{E} + 4\pi\mathfrak{P},\\ \mathfrak{H} &= \mathfrak{B} - 4\pi\mathfrak{M},\end{aligned}\right\}$$

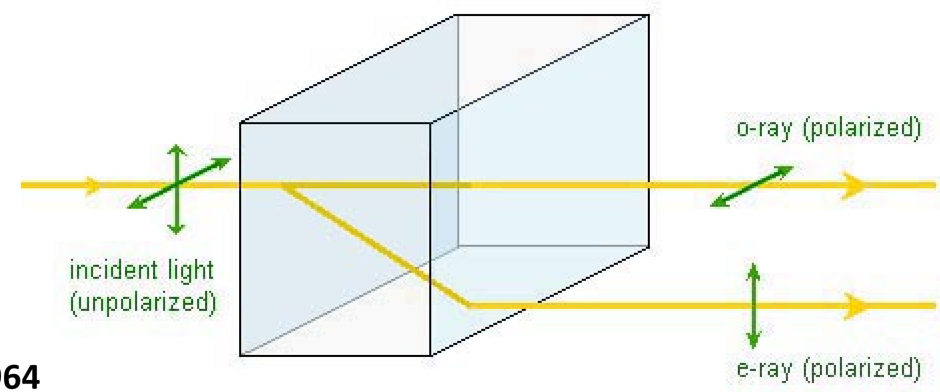
$$\mathfrak{D}_i = \frac{\partial\mathfrak{L}}{\partial\mathfrak{E}_i}, \quad \mathfrak{H}_i = -\frac{\partial\mathfrak{L}}{\partial\mathfrak{B}_i},$$

$$\mathfrak{D}_i = \varepsilon_{ik}\mathfrak{E}_k, \qquad \mathfrak{H}_i = \mu_{ik}\mathfrak{B}_k$$

permittivity of vacuum

permeability of vacuum

Vacuum birefringence



1. J.J. Klein and B.P. Nigam, Phys. Rev. 135, 1279, 1964

   constant electric field $E << E_S$

2. R. Baier, P. Breitenlohner, Acta Phys. Austr. 25, 212, 1967

   constant magnetic field $B << B_S$

$$\boxed{F_S = m^2c^3/e\hbar = 1.32 \cdot 10^{16}\mathrm{V/cm}}$$

3. N.B. Narozhnyi, Zh. Eksp. Teor. Fiz. 55, 714 (1968) [Sov. Phys. JETP 28, 371, 1969]

   constant crossed ($\vec{E} \perp \vec{H},\ E = H$) field of **arbitrary strength**

4. S.L. Adler, Ann. Phys. (NY) 67 212, 599 (1971)

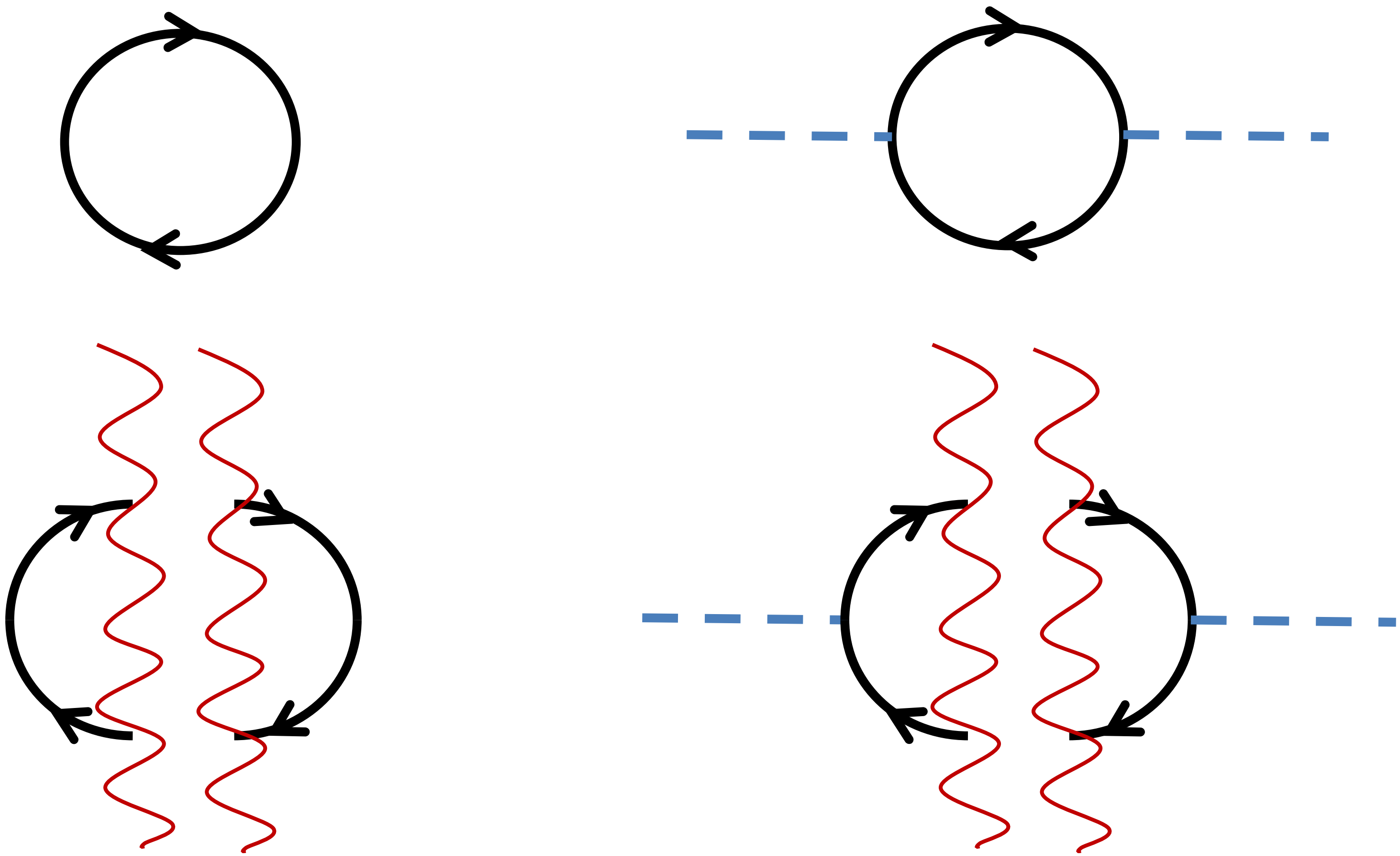
   constant magnetic field of **arbitrary strength**

5. I.A. Batalin, A.E. Shabad, Zh. Eksp. Teor. Fiz. 60, 894 (1971) [Sov. Phys. JETP 33, 483, 1971]

   constant electromagnetic field of **general configuration** and of **arbitrary strength**

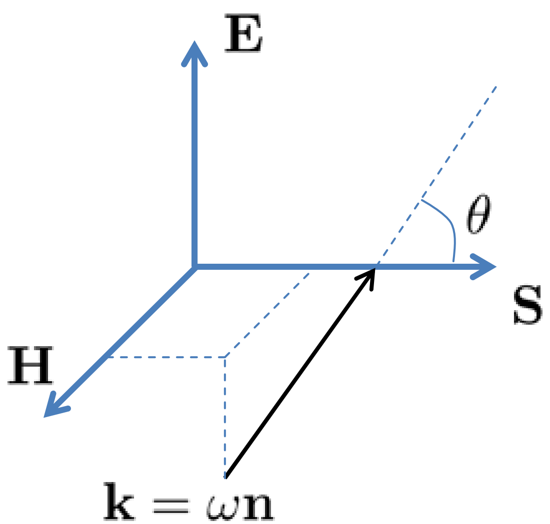
The PVLAS experiment to measure the effect of vacuum birefringence is under way (Ferrara University, Italy)

Vacuum polarization:



Crossed field: $\mathbf{E} \perp \mathbf{H}\,, \quad E = H = F$

$$\boxed{\hbar = c = 1}$$



$$\boxed{n_{1,2}(\omega, \mathbf{n}) = 1 - \frac{\alpha m^2}{2\omega^2} f_{1,2}(\kappa)}$$

$$\alpha = e^2 = 1/137 \qquad \kappa = \frac{F}{F_S}\frac{\omega}{m}(1-\cos\theta)$$

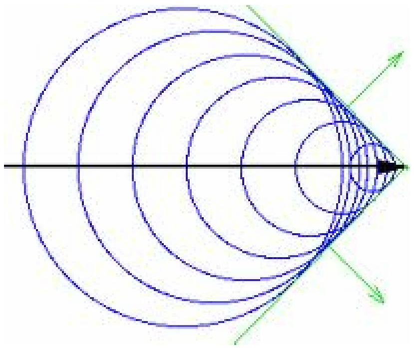
$$\kappa \ll 1, \quad n_1 \approx 1 + 2\frac{\alpha}{45\pi}\frac{m^2\kappa^2}{\omega^2}, \quad n_2 - 1 = \frac{7}{4}(n_1 - 1)$$

$$\kappa \gg 1, \quad n_1 \approx 1 - \frac{\alpha m^2}{14\pi^2\omega^2}(3\kappa)^{2/3}\sqrt{3}\Gamma^4\left(\frac{2}{3}\right)(1 - i\sqrt{3}), \quad n_2 - 1 = \frac{3}{2}(n_1 - 1)$$

Vacuum is a dispersive, absorptive and dichroic medium at

$$\kappa \sim \frac{F}{F_S}\frac{\omega}{m} \gtrsim 1$$

Cherenkov radiation



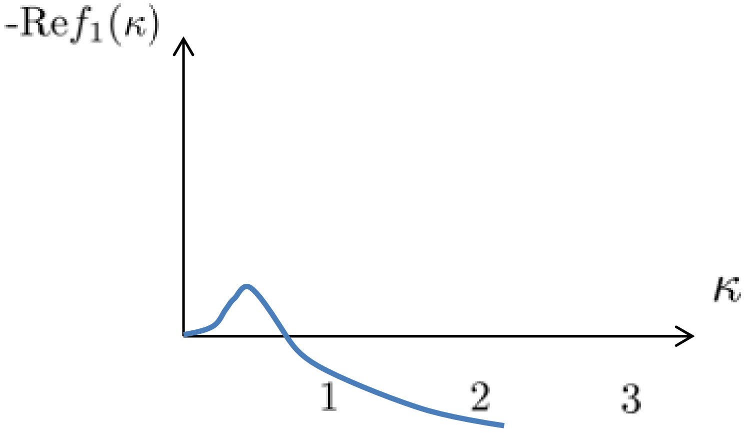
T. Erber, Rev. Mod. Phys. 38, 626, 1966
V.I. Ritus, Zh. Eksp. Teor. Fiz. 57, 2176 (1969) [Sov. Phys. JETP 30, 1181, (1970)]
I.M. Dremin, Pis'ma Zh. Eksp. Teor. Fiz. 76, 185 (2002) [JETP Lett. 76, 151, (2002)]

The emission angle: $\cos\theta = 1/\beta n\,, \quad \beta = v/c = \sqrt{1 - m^2c^4/\varepsilon^2} < 1$

The condition for ChR: $\beta n > 1\,, \quad \Delta n = n - 1 > 0\,, \quad \cos\theta_{max} = 1/n$

At: $\Delta n << 1\,, \quad mc^2/\varepsilon << 1$

$$\varepsilon \geq \varepsilon_{th} = \frac{mc^2}{\sqrt{2\Delta n}}\,, \qquad \theta_{max} \approx \sqrt{2\Delta n}$$



$\Delta n > 0$ at $\kappa < 1$

$$\Delta n \sim 4\frac{\alpha}{45\pi}\left(\frac{F}{F_S}\right)^2 , \quad \Delta\omega_{Ch} < mc^2\frac{F}{F_S}$$

$$\frac{F}{F_S} \sim 10^{-2} \Longrightarrow \Delta n \sim 2\cdot 10^{-8}$$

$$\varepsilon_{th} \sim 2.5\mathrm{GeV}\,, \quad \theta_{max} \sim 2\cdot 10^{-4}$$

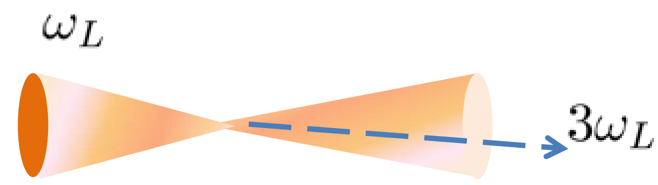
$$dN_{Ch}/d\omega dl = 2\alpha\Delta n$$

For $\lambda_L = 1\mu\mathrm{m}$ and $\frac{F}{F_S} \sim 10^{-2}$ focused to the diffraction limit $R \sim \lambda_L/2$

$$N_{Ch} \lesssim 2\alpha\Delta n\Delta\omega_{Ch}L_R \sim 10^{-1}$$

in the presence of the background due to Compton scattering

Harmonics generation

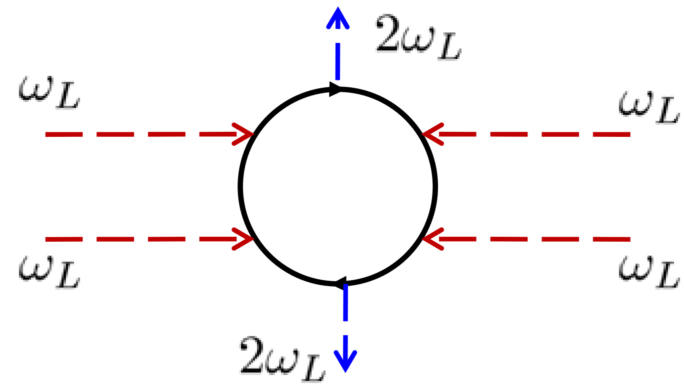


1. **A.E. Kaplan and Y.J. Ding, Phys. Rev. A <u>62</u>, 043805 (2000)**

Harmonics generation by a laser beam propagating in an external magnetic field

2. **A. Di Piazza, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Rev. D <u>72</u>, 085005 (2005)**

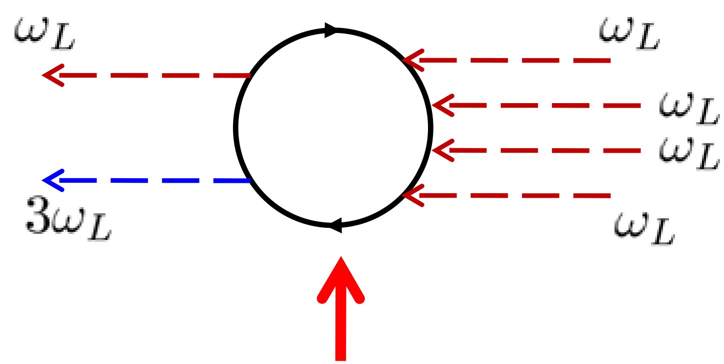
Harmonics generation by two colliding laser beams in vacuum



3. **A.M.Fedotov, N.B. Narozhny, Phys. Lett. A 362, 1 (2007)**

Harmonics generation by a **<u>focused</u>** laser beam in vacuum

The effect is detectable at $I \approx 10^{27} W/cm^2$!



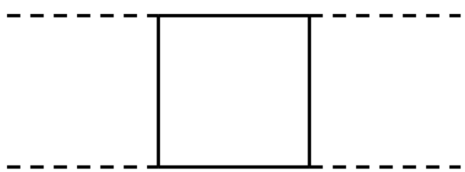
the effect of stimulated emission of a photon

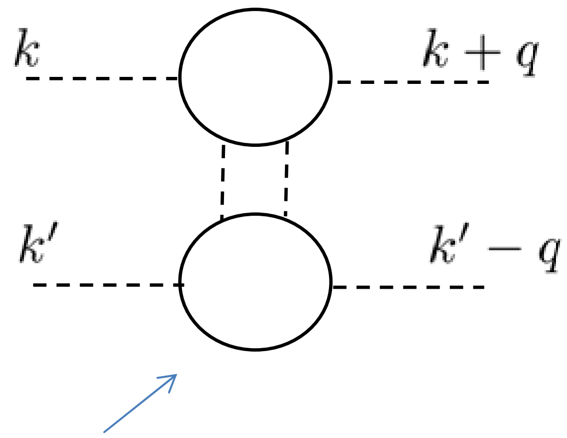
Self-focusing

1. **M. Soljacˇic´ and M. Segev, Phys. Rev A, 62, 043817 (2000)**

A superposition of two plane waves, modified by a slowly varying envelope is considered. It is shown that modified Maxwell equations in vacuum give rise to spatial solitons. The solitons exist because the diffraction, which tends to expand the pulse, is exactly balanced by the nonlinear effect of self-focusing that is trying to shrink the pulse. The peak intensity needed to support the soliton is about $10^{33}\,\mathrm{W/cm^2}$!

2. **D. Kharzeev and K. Tuchin, Phys. Rev A, 75, 043807 (2007)**





Attractive two-photon exchange

This diagram dominates at distances $r \gtrsim -\frac{\ln \alpha}{m} \approx 5 l_C$

Since the transverse size of a laser beam is $\gg 5 l_C$,

the self-focusing effect must exist!

The focusing angle θ_F

$$\boxed{\theta_F \sim \left(\frac{157}{16\pi^3}\right)^{1/2} \frac{\alpha^2}{180 m^4} \left(\frac{I}{\omega}\right)^{4/3}}$$

For a laser with $\lambda = 1\mu\mathrm{m}$: $I = 3 \cdot 10^{20} \mathrm{W/cm}^2 \quad \rightarrow \quad \theta_F \sim 10^{-10}$

$$I = 3 \cdot 10^{26} \mathrm{W/cm}^2 \quad \rightarrow \quad \theta_F \sim 10^{-2}$$

(though the estimates of θ_F does not look very reliable!)

The most promising nonlinear vacuum effect is

PAIR PRODUCTION BY LASER FIELD

$e^- e^+$ **pair creation by a laser field in vacuum becomes observable at intensities**

$$I \ll I_S$$

The probability for vacuum to stay vacuum in a constant electric field:

$$C_V = |<0|S(+\infty)|0>|^2 = |e^{iW}|^2$$

$$= e^{-2VT\,\mathcal{I}m\mathcal{L}}$$

$$\mathcal{I}m\{\Delta\mathcal{L}\} = \frac{c}{8\pi^3 l_C^4}\left(\frac{E}{E_S}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\pi\frac{E_S}{E}n}$$

$\Delta\mathcal{L}$ - the Heisenberg-Euler correction to em field Lagrangian

J. Schwinger, Phys.Rev., 82, 664 (1951)

Laser pulse:

$$VT \sim \pi R^2 \cdot c\tau \cdot \tau = \pi R^2 c\tau^2$$

R - focal spot radius

τ - pulse duration

$$\boxed{R \sim \lambda \sim 1\mu m\,, \tau \sim 10 fms\,, E \sim E_S}$$

$$2VT\mathcal{I}m\mathcal{L} \sim \frac{c^2\tau^2\lambda^2}{4\pi^2 l_C^4} e^{-\pi} \sim 10^{24}!!!$$

$$\boxed{C_V = e^{-2VT\mathcal{I}m\mathcal{L}} \sim e^{-10^{24}} = 0!!!}$$

$$\underline{E < E_S}$$

$$C_V \sim \exp\left\{-10^{25}\left(\frac{E}{E_S}\right)^2 e^{-\pi\frac{E_S}{E}}\right\}$$

$$\boxed{C_V \sim e^{-1} \sim 0.4}$$

at

$$\left(\frac{E}{E_S}\right)^2 e^{-\pi\frac{E_S}{E}} \sim 10^{-25}$$

$$\boxed{E \sim 6 \cdot 10^{-2} E_S}$$

The number of pairs created by an electromagnetic field

$$\boxed{N = \frac{e^2 E_S^2}{4\pi^2 \hbar^2 c} \int dV \int dt\, \epsilon(\vec{r},t)\eta(\vec{r},t) \coth \frac{\pi\eta(\vec{r},t)}{\epsilon(\vec{r},t)} \exp\left(-\frac{\pi}{\epsilon(\vec{r},t)}\right)}$$

N.B. Narozhny, S.S. Bulanov, V.S. Popov, V.D. Mur, PLA 330, 1 (2004)

$$\epsilon = \mathcal{E}/E_S,\ \eta = \mathcal{H}/E_S$$

$$\mathcal{E} = \sqrt{\left(\mathcal{F}^2 + \mathcal{G}^2\right)^{1/2} + \mathcal{F}}, \quad \mathcal{H} = \sqrt{\left(\mathcal{F}^2 + \mathcal{G}^2\right)^{1/2} - \mathcal{F}}$$

$$\mathcal{F} = (\vec{E}^2 - \vec{H}^2)/2\,, \quad \mathcal{G} = (\vec{E}\cdot\vec{H})$$

In the reference frame where $\vec{E} \,||\, \vec{H}\,,\ |\vec{E}| = \mathcal{E}\,, |\vec{H}| = \mathcal{H}$

Pair production by a single focused pulse

N.B. Narozhny, S.S. Bulanov, V.S. Popov, V.D. Mur, PLA 330, 1 (2004)
A.M. Fedotov, Las. Phys., 19, 214 (2009)

$I, W/cm^2$	E_0/E_S	N_e Δ=0.1	N_e Δ=0.05	N_h Δ=0.1
$4\cdot10^{27}$	0.16	$4.0\cdot10^{-11}$	$4.6\cdot10^{-42}$	$9.6\cdot10^{-23}$
$1\cdot10^{28}$	0.25	24 !!	$3.1\cdot10^{-19}$	$2.0\cdot10^{-7}$
$2\cdot10^{28}$	0.35	$3.0\cdot10^{7}$	$1.4\cdot10^{-7}$	16
$6\cdot10^{28}$	0.62	$8.4\cdot10^{13}$	$1.9\cdot10^{5}$	$3.4\cdot10^{9}$

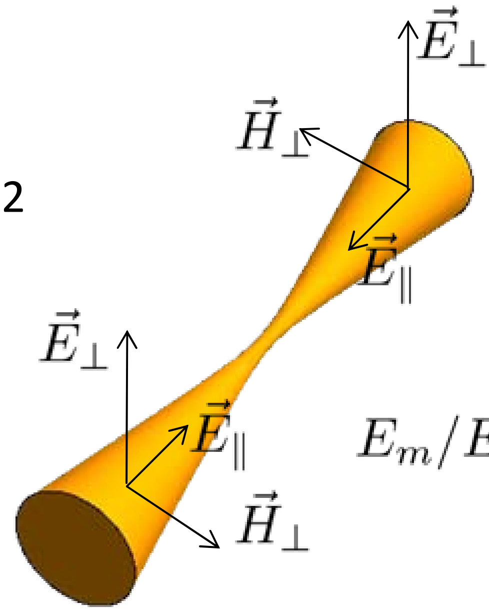
$\lambda \sim 1\mu m\,, \tau \sim 10fms$ $\Delta = \lambda/2\pi R$

The threshold can be lowered essentially at the expense of

MULTIPLE PULSES TECHNOLOGY

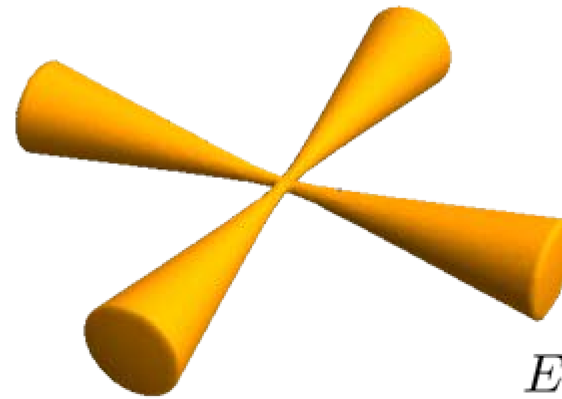
Collision geometry (linear polarization)

n=2

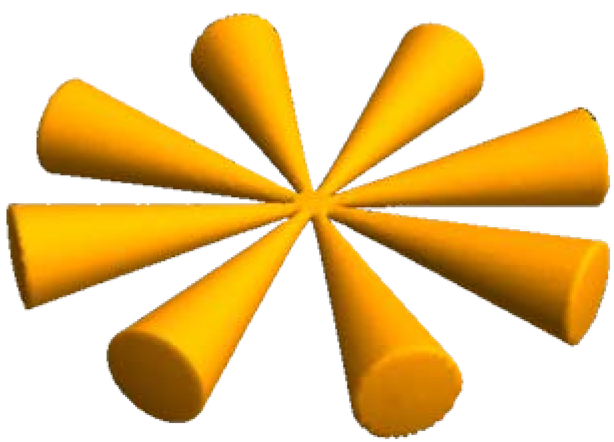


$E_m/E_0 \approx 1.4$

n=4

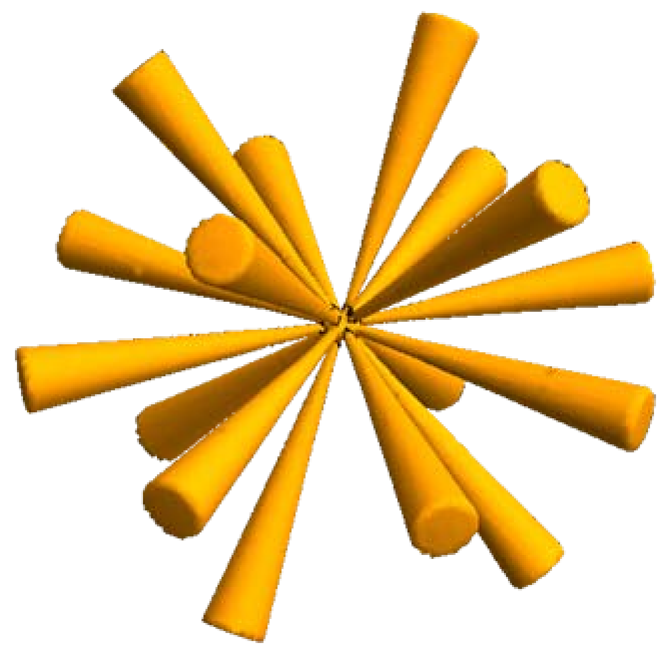


$E_m/E_0 = 2$



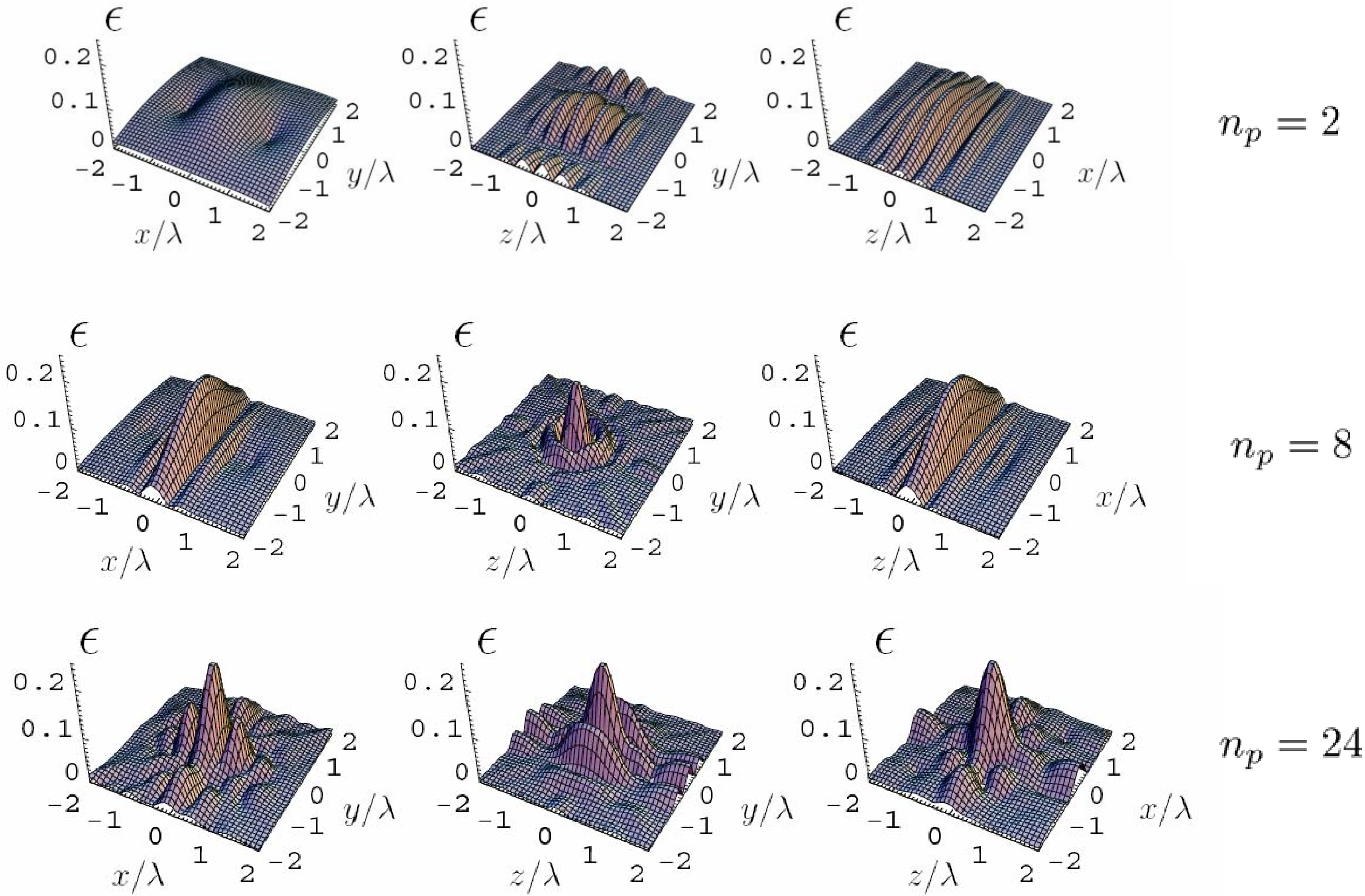
n=8

$E_m/E_0 \approx 2.8$



n=16

$E_m/E_0 \approx 3.4$



ϵ
0.2
0.1
0
x/λ
y/λ
z/λ
$n_p = 2$
$n_p = 8$
$n_p = 24$

The number of created pairs N_{e+e^-} and threshold energy W_{th} For different number n of colliding pulses

n	N_{e+e^-} at $W = 10$ kJ	W_{th}, kJ ($N_{e+e^-} = 1$)
2	9.0×10^{-19}	40
4	3.0×10^{-9}	20
8	4.0	10
16	1.8×10^{3}	8
24	4.2×10^{6}	5.1

$$\lambda = 1\mu\text{m}\,, \quad \tau = 10\text{fs}\,, \quad R = 0.5\lambda$$

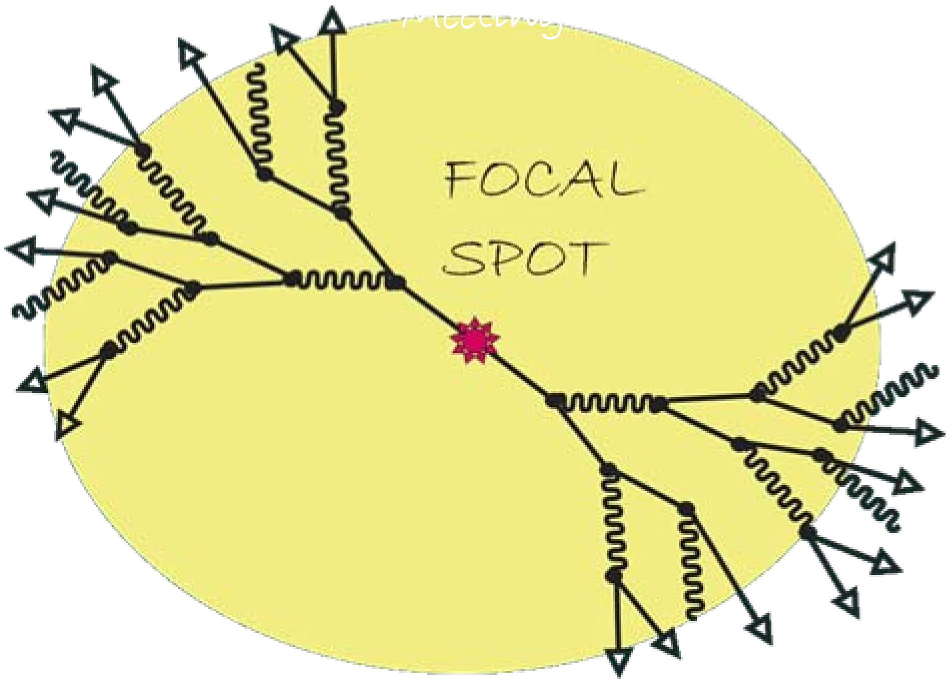
$$\boxed{I_{tot} \sim 5 \times 10^{25}\text{W}/\text{cm}^2}$$

S. S. Bulanov, V.D. Mur, N.B. Narozhny, *et al.*, PRL, 104, 220404 (2010)

Pair creation from vacuum may be observed with laser fields of the strength <u>2÷3 orders lower than the critical (Sauter) field</u> E_S.

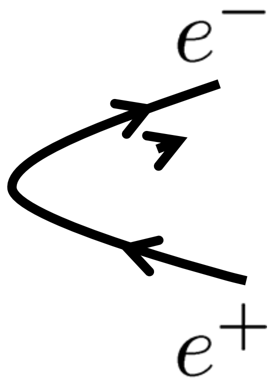
What will happen after creation of a single pair?

Particles are accelerated by the field and …

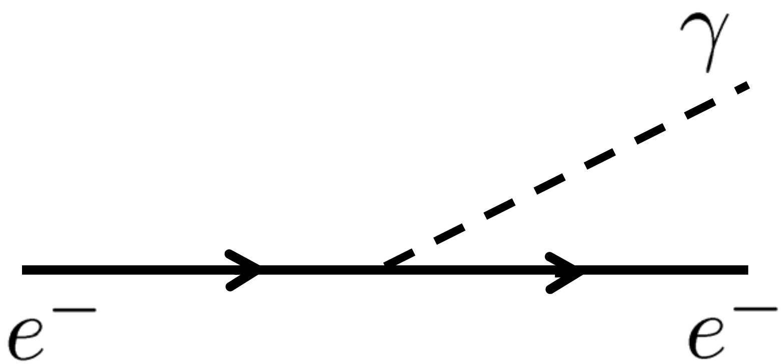


A. R. Bell and J. G. Kirk, Phys. Rev. Lett. 101, 200403 (2008).
A.M. Fedotov and N.B. Narozhny, in Extreme Light Infrastructure: Report on the GC Meeting, 27-28 April 2009, Paris, http://www.extreme-light-infrastructure.eu
A. M. Fedotov, N. B. Narozhny, G.Mourou and G. Korn, Phys. Rev. Lett. 105, 080402 (2010).

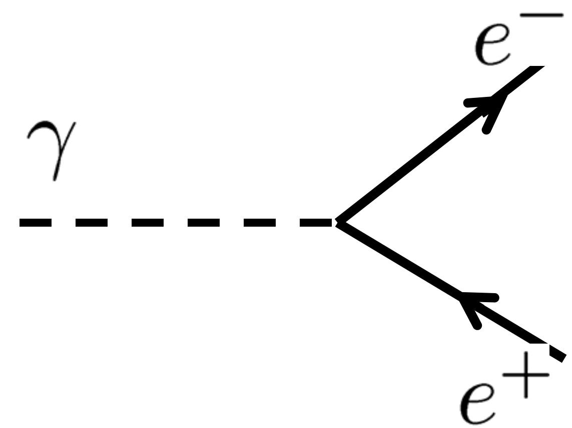
Elementary processes



- pair creation by the laser field from vacuum



- photon emission



- pair photoproduction

Dynamical quantum parameter

(Lorentz and gauge invariant)

$$\boxed{\chi = \frac{\sqrt{-e^2\hbar^2(p^\mu F_{\mu\nu})^2}}{m^3c^4}}$$

$\chi \ll 1$ - **classical limit**

$\chi \gtrsim 1$ - **the process is essentially quantum**

$$\boxed{\chi = \frac{e\hbar}{m^3c^4}\sqrt{\left(\frac{\varepsilon\vec{E}}{c} + \vec{p}\times\vec{H}\right)^2 - (\vec{p}\cdot\vec{E})^2}}$$

if $p^0 \sim mc^2 \quad \rightarrow \quad \chi \sim \frac{E_0}{E_S}$

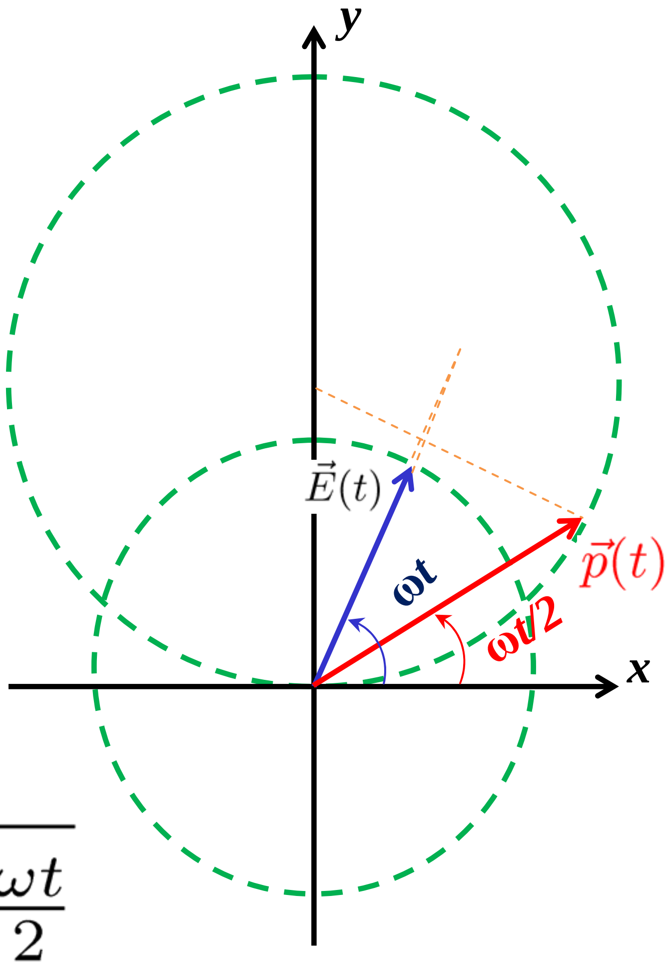
Mechanism of acceleration

Toy model:
uniformly rotating electric field

$$\frac{d\vec{p}}{dt} = e\vec{E}(t), \;\; \vec{p}(0) = 0$$

ω – rotation frequency

$$\chi(t) = \frac{E_0}{E_S}\sqrt{1 + 4a_0^2 \sin^4 \frac{\omega t}{2}}$$



$$\boxed{a_0 = \frac{eE}{m\omega c}}$$

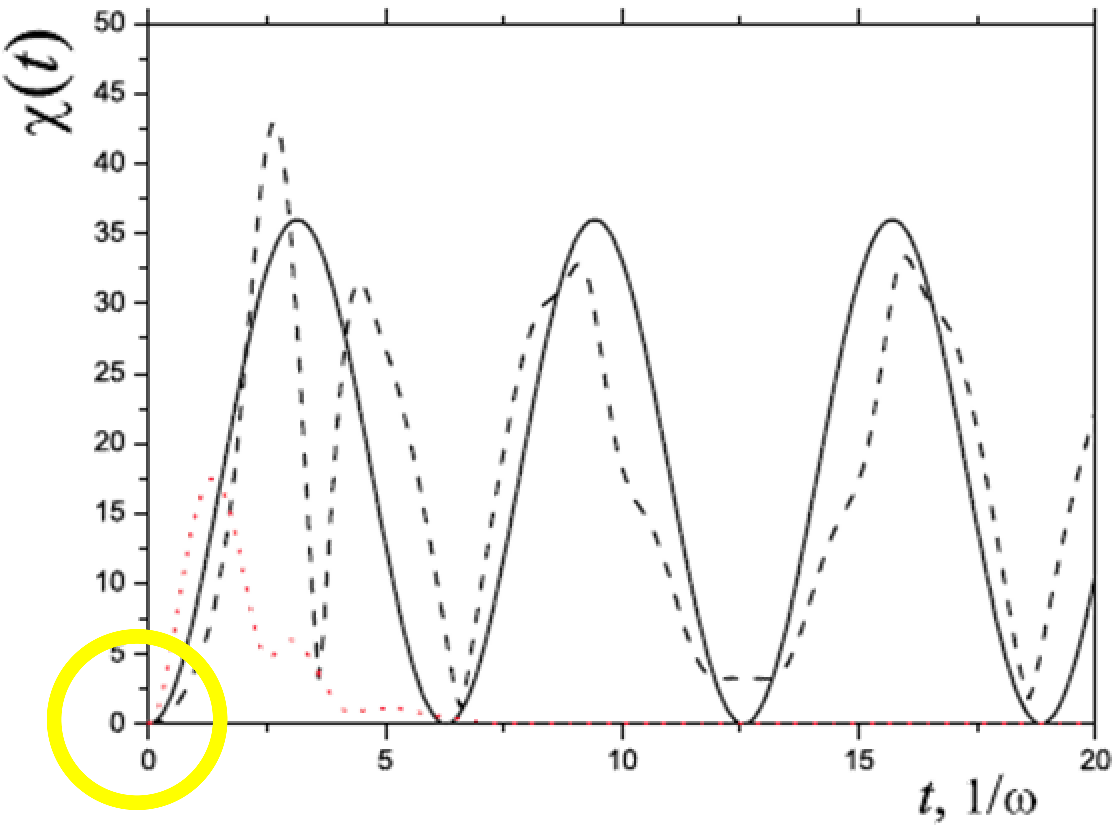


FIG. 1: Evolution of quantum dynamical parameter χ along the particle trajectory for $a_0 = 3 \cdot 10^3$, $\hbar\omega = 1$eV in three cases: head-on collision of two elliptically polarized plane waves (solid line); collision at 90^0 of two linearly polarized plane waves with orthogonal linear polarizations (dash line); single tightly focused e-polarized laser beam (dot line).

Acceleration time t_{acc}

$$\chi(t_{acc}) \sim 1$$

$$\boxed{t_{acc} \sim \frac{1}{\omega}\frac{E_S}{E_0}\sqrt{\frac{\hbar\omega}{mc^2}} \sim \frac{1}{\omega a_0}\sqrt{\frac{mc^2}{\hbar\omega}}}$$

$$E_0/E_S \gtrsim 10^{-2} \longrightarrow \omega t_{acc} \ll 1$$

These results are typical for field of different configurations

Probabilities of elementary processes

Under conditions

$$\boxed{\mathcal{E}, \mathcal{H} \ll 1, \chi \qquad a_0 \gg 1}$$

The particle feels any field as a constant crossed field

A.I.Nikishov, V.I.Ritus, ZhETF, 46, 776 (1964)

The electron (positron) radiation lifetime (mean free path/c)

$$t_e \sim 1/W_e \qquad W_e -$$ The probability of photon emission in a crossed field (A.I.Nikishov, V.I.Ritus)

$$\boxed{t_e \sim \frac{\hbar}{\alpha m c^2} \left(\frac{\alpha E_S}{E_0} \right)^{1/4} \sqrt{\frac{mc^2}{\hbar\omega}}}$$

The photon lifetime

$$\boxed{t_\gamma \sim t_e}$$

The escape time

$$\boxed{t_{esc} \sim \lambda/2c}$$

The following hierarchy of time scales

$$\boxed{t_{acc} \lesssim t_e\,, t_\gamma \ll t_{esc}}$$

should be respected for occurrence of electromagnetic cascade

(for optical frequencies)

$$\boxed{\mu = E_0/E_* \gtrsim 1}$$

$$\boxed{E_* = \alpha E_S \quad eE_* l_e = mc^2}$$

- determines a natural threshold for electromagnetic cascades.

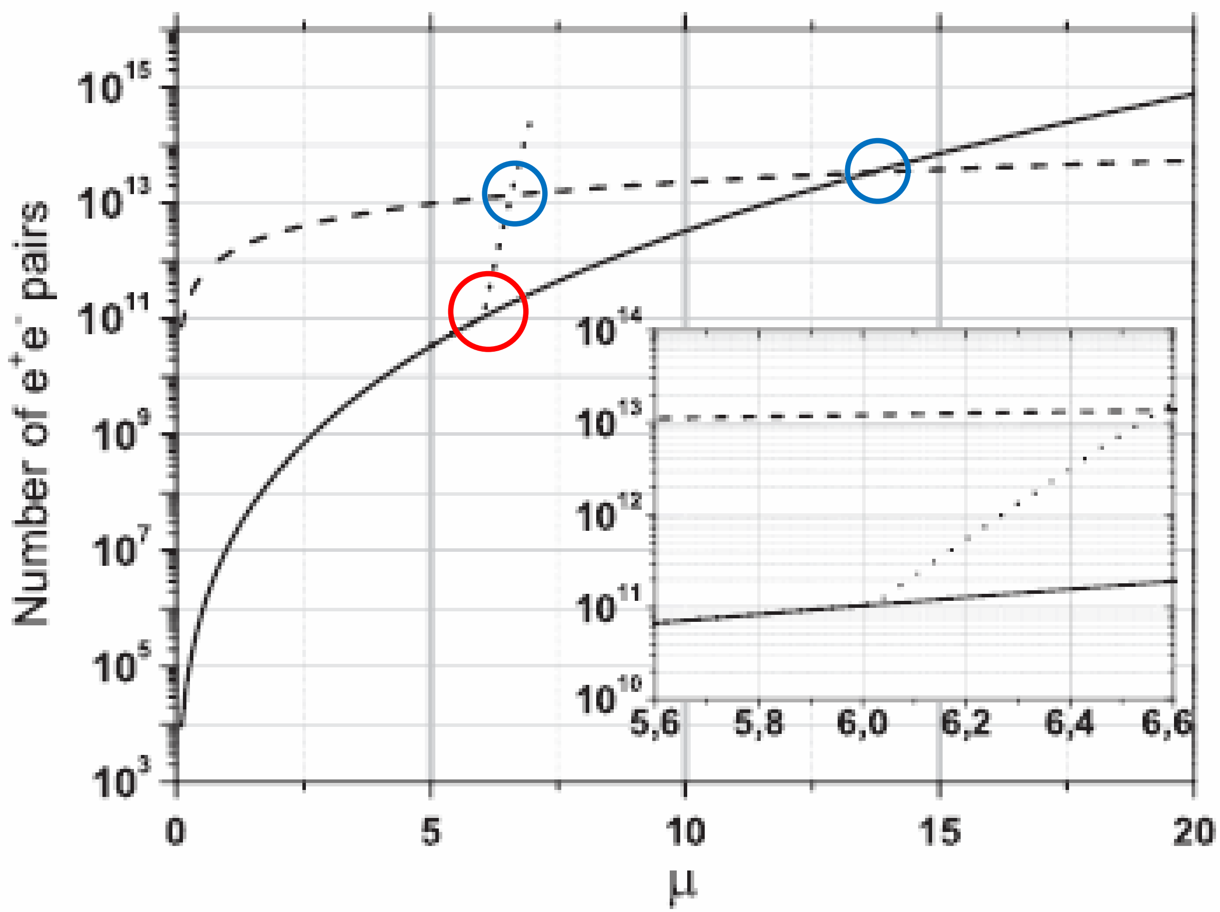
$$I_* = 2.5 \cdot 10^{25} \mathrm{W/cm}^2$$

The number of created pairs/shot

$$N_e \sim \exp\left(\frac{t_{esc}}{t_e}\right) \sim \exp\left[\pi\alpha\mu^{1/4}\sqrt{\frac{mc^2}{\hbar\omega}}\right]$$

The maximum number of created pairs limited by the energy of the laser pulse

$$N_{e,max} = \frac{W_L}{\epsilon_e} \sim \alpha\mu^{5/4}\left(\frac{mc^2}{\hbar\omega}\right)^{5/2}$$



Fedotov, A. M.; Narozhny, N. B.; Mourou, G.; Korn, G. PRL, 105, 080402 (2010)

FIG. 2. Pair production as a function of . The solid curve corresponds to the number Ne of pairs produced by a single cascade process. The dotted curve shows the number of pairs produced by multiple cascades generated by pairs created by two colliding circularly polarized 10 fs laser pulses. The branching point corresponds to the threshold value of where the spontaneous pair production begins. The dash line shows the limit for $N_{e^+e^-}$ determined by the energy of the laser pulse. The laser frequency $\hbar\omega = 1$ eV. The inset shows the magnified region of intersection of the curves.

Creation even of a single pair from vacuum must cause the QED cascades (avalanche production of hard photons and electron-positron pairs), which may result in depletion of the initiating laser pulses.

Monte-Carlo code for simulation of cascades in EM field has been developed

N. V. Elkina, A. M. Fedotov, I. Yu. Kostyukov, *et al*., arXiv:1010.4528E, *to be published in* PR ST AB

The results support qualitative estimations of A. M. Fedotov, et al., PRL 105, 080402 (2010).

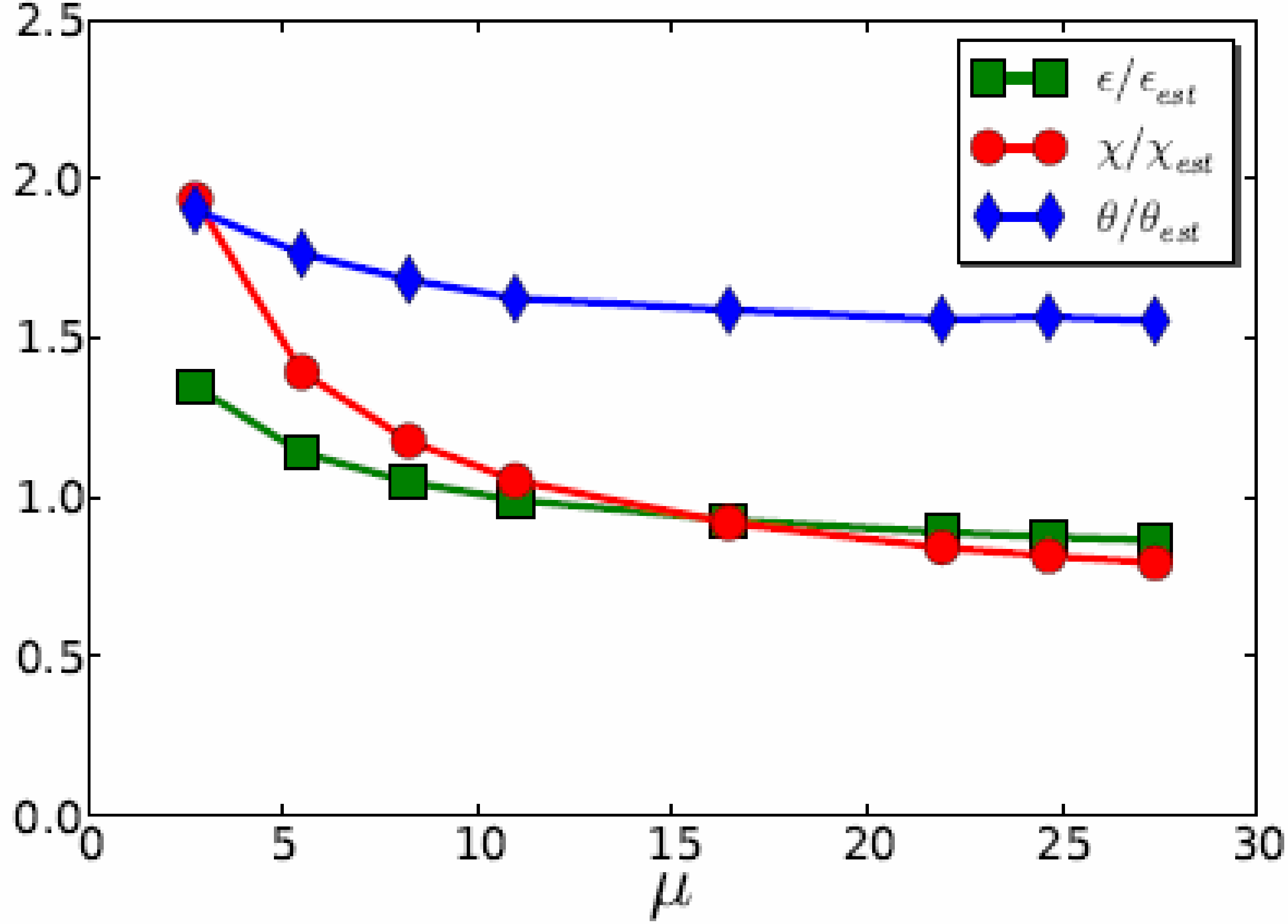
The cascade equations for a uniformly rotating homogeneous electric field

$$\frac{\partial f_{\pm}(\boldsymbol{p}_e,t)}{\partial t} \pm e\boldsymbol{E}(t)\cdot\frac{\partial f_{\pm}(\boldsymbol{p}_e,t)}{\partial \boldsymbol{p}_e} = \int w_{rad}(\boldsymbol{p}_e+\boldsymbol{p}_\gamma \to \boldsymbol{p}_\gamma) f_{\pm}(\boldsymbol{p}_e+\boldsymbol{p}_\gamma,t)\, d^3p_\gamma$$

$$- f_{\pm}(\boldsymbol{p}_e,t)\int w_{rad}(\boldsymbol{p}_e \to \boldsymbol{p}_\gamma)\, d^3p_\gamma + \int w_{cr}(\boldsymbol{p}_\gamma \to \boldsymbol{p}_e) f_\gamma(\boldsymbol{p}_\gamma,t)\, d^3p_\gamma,$$

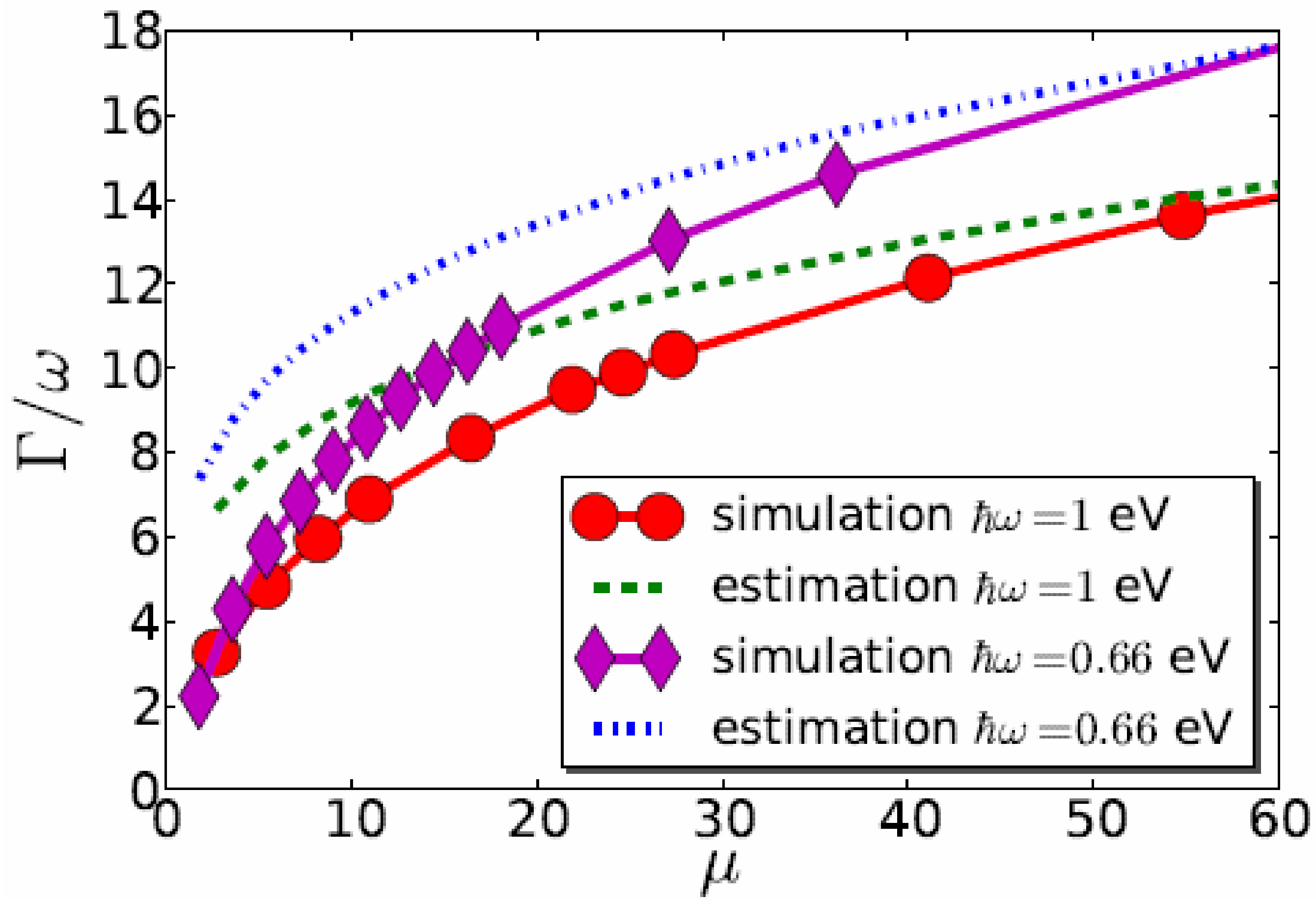
$$\frac{\partial f_\gamma(\boldsymbol{p}_\gamma,t)}{\partial t} = \int w_{rad}(\boldsymbol{p}_e \to \boldsymbol{p}_\gamma)[f_+(\boldsymbol{p}_e,t)+f_-(\boldsymbol{p}_e,t)]\, d^3p_e$$

$$- f_\gamma(\boldsymbol{p}_\gamma,t)\int w_{cr}(\boldsymbol{p}_\gamma \to \boldsymbol{p}_e)\, d^3p_e.$$



The μ dependence of the mean values of energy ϵ, dynamical quantum parameter χ, and the angle θ between the momentum of an electron and the field, over the estimated values. $\hbar\omega$ = *1eV*.

$$\boxed{N_{e^+e^-} \sim e^{\Gamma t}}$$



The increment Γ as a function of the dimensionless field strength μ for two rotation frequencies $\hbar\omega$ = 1 eV and ħω = 0:66 eV

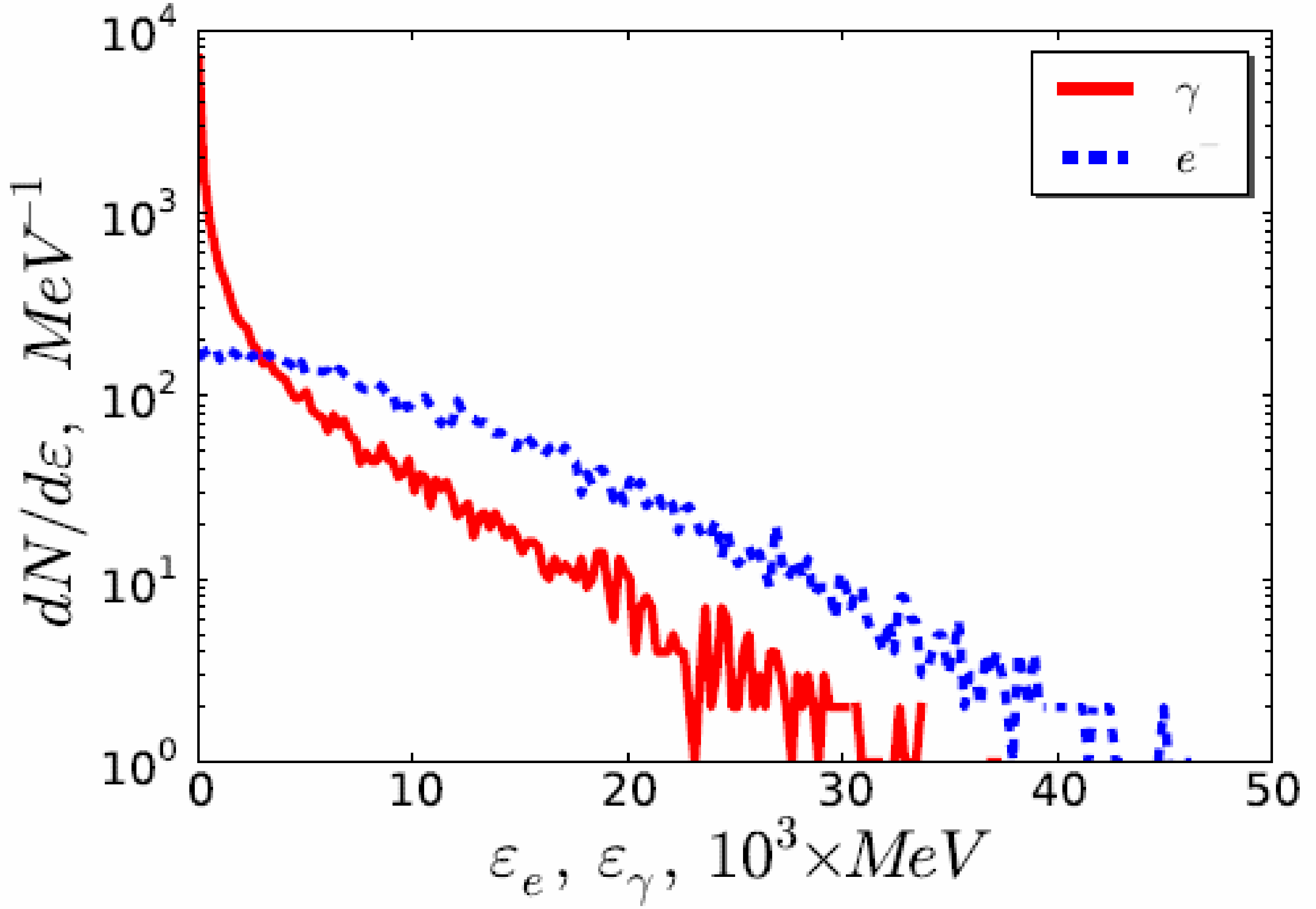


FIG. 6: The energy spectra for different components of the cascade at $t = 1.2\times\omega^{-1}$ for $a_0 = 5\times 10^4$ and $\hbar\omega = 1\,\mathrm{eV}$.

In preceding calculations (both, estimations and Monte-Carlo simulations):

1. The laser field was modeled by a uniformly rotating homogeneous electric field (toy model);
2. Back-reaction was neglected.

The next step:

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Laser Field Absorption in Self-Generated Electron-Positron Pair Plasma

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Recently, much attention has been attracted to the problem of limitations on the attainable intensity of high power lasers [A. M. Fedotov *et al.*, Phys. Rev. Lett. **105**, 080402 (2010)]. The laser energy can be absorbed by electron-positron pair plasma produced from a seed by a strong laser field via the development of the electromagnetic cascades. The numerical model for a self-consistent study of electron-positron pair plasma dynamics is developed. Strong absorption of the laser energy in self-generated overdense electron-positron pair plasma is demonstrated. It is shown that the absorption becomes important for a not extremely high laser intensity $I \sim 10^{24}$ W/cm^2 achievable in the near future.

DOI: 10.1103/PhysRevLett.106.035001 PACS numbers: 52.27.Ep, 12.20.Ds, 52.38.Dx, 52.65.Pp

A 2D numerical model to study production and dynamics of EPPP in the field of two colliding linearly polarized laser pulses is developed. The laser pulses have Gaussian envelopes and propagate along the x axis.

The components of the laser field at t = 0 are:

$$E_y, B_z = E_0 \exp\left(-y^2/{\sigma_r}^2\right)$$
$$\times \sin(kx - \phi)\left[e^{-(x+x_0)^2/\sigma_x^2} \pm e^{-(x-x_0)^2/\sigma_x^2}\right]$$

$2x_0$ **- the initial distance between the laser pulses**

k **- the wave number of the laser field**

ϕ **- phase shift**

Parameters of simulations:

$$\lambda = 0.8\mu\mathrm{m}\,,\, \tau = 100\,\mathrm{fs}$$

diameter of the focal spot $d = 10\mu\mathrm{m}$

$$I = 3 \times 10^{24}\mathrm{W/cm^2} \quad (E_0 \approx 3E_*)$$

The cascade is initiated by a single electron located at x = y = 0 with zero initial momentum for t = 0 (e.g., electron belongs to a pair created by a high-energy photon)

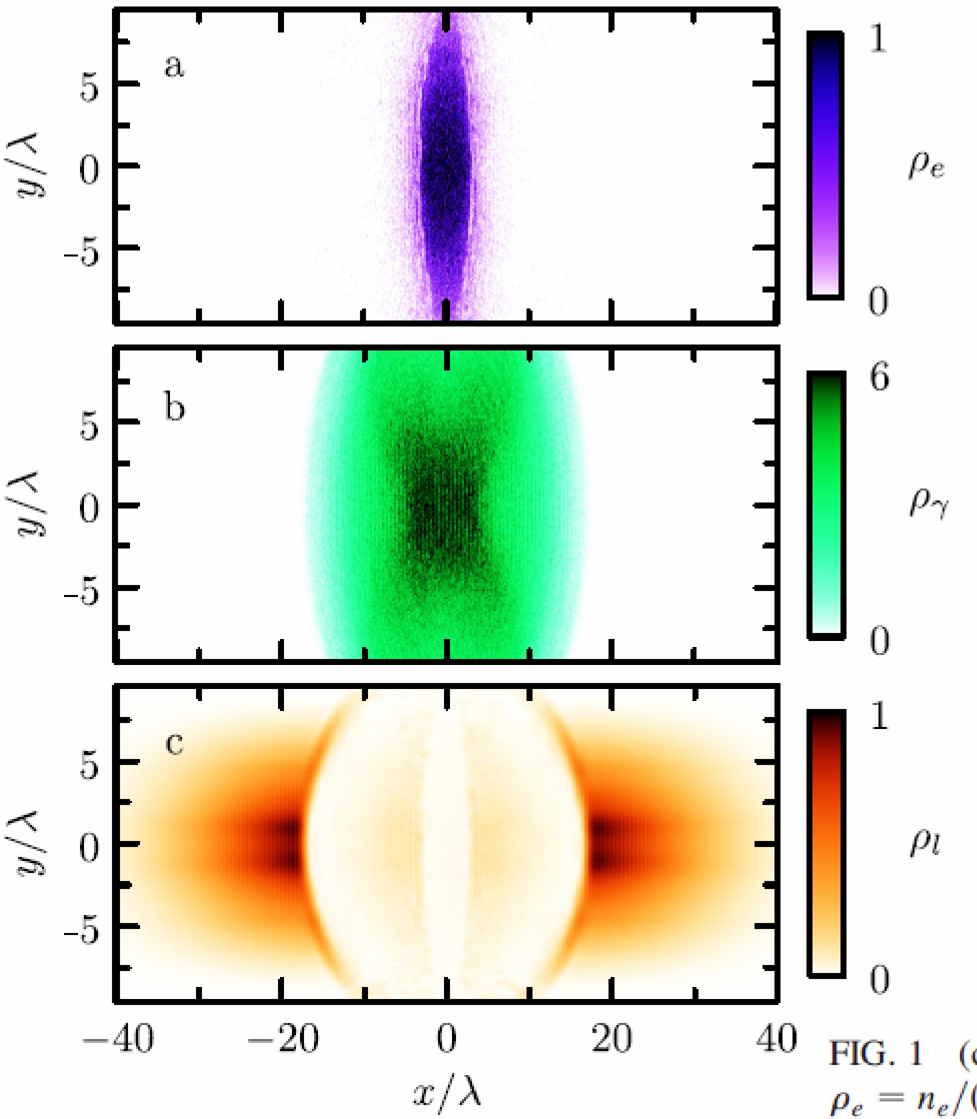

FIG. 1 (color online). The normalized electron density $\rho_e = n_e/(a_0 n_{\rm cr})$ (a), the normalized photon density $\rho_\gamma = n_\gamma/(a_0 n_{\rm cr})$ (b), and the laser intensity normalized to the maximum of the initial intensity ρ_l (c) during the collision of two linearly polarized laser pulses at $t = 25.5\lambda/c$. The density distribution of positrons is approximately the same as that of electrons.

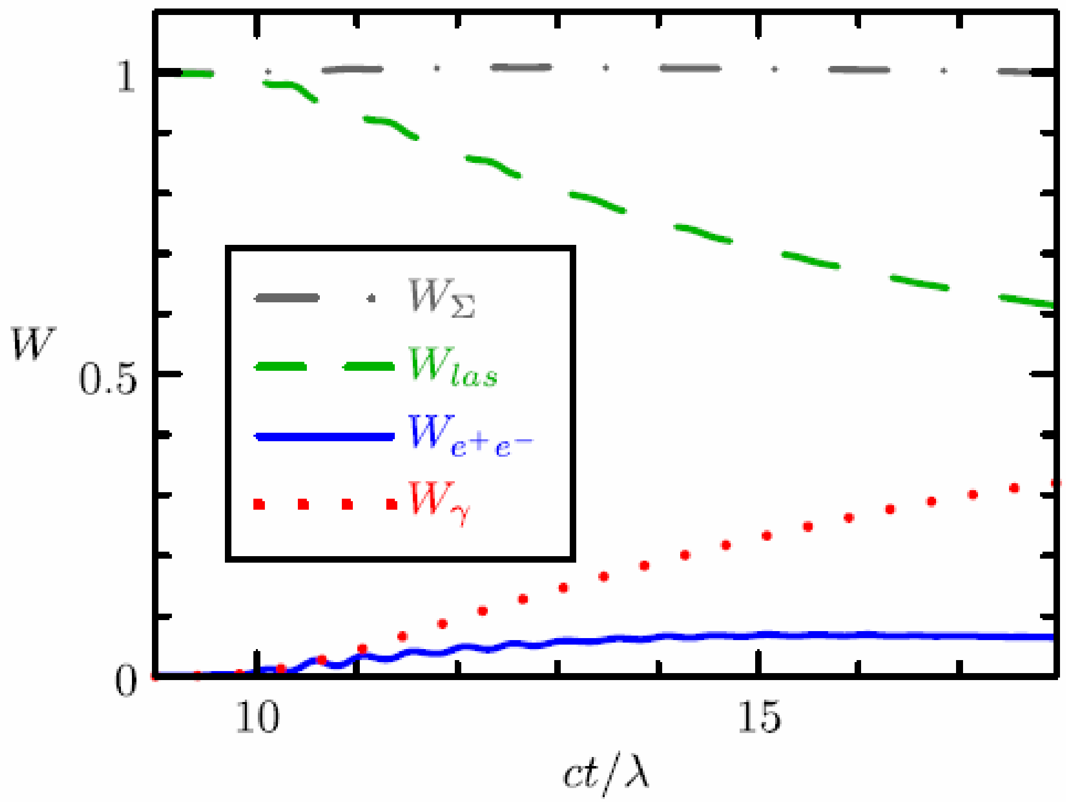

FIG. 2 (color online). The electron and positron energy (solid line), the photon energy (dotted line), the laser energy (dashed line), and the total energy of the system (dash-dotted line) as functions of time. All the energies are normalized to the initial energy of the system.

At the initial stage of the cascade development, the number of created particles is growing exponentially. Then the growth substantially slows down.

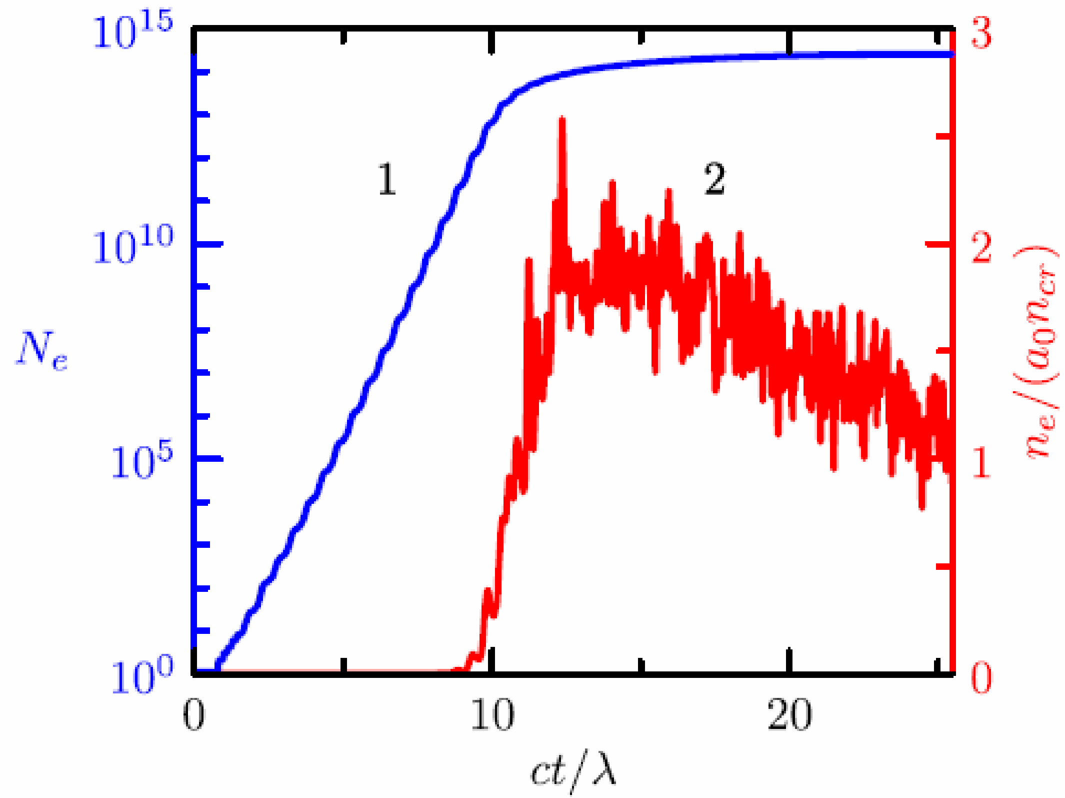

FIG. 3 (color online). The number of the electrons produced in the cascade (line 1) and the EPPP density normalized to the relativistic critical density (line 2) as functions of time.

Calculations confirm the N. Bohr's conjecture that the critical QED field strength E_S can be never attained for a pair creating electromagnetic field!

THANK YOU FOR ATTENTION!