Frontiers in Intense Laser-Matter Interactions Theory

Max Planck Institute of Quantum Optics, Garching, Germany

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New Prospect for Studying Fundamental Properties of Vacuum with ELI

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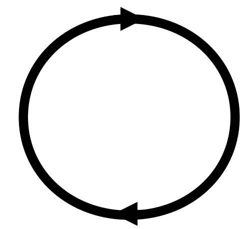
Nonlinear vacuum effects are determined by Heisenberg-Euler Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \Delta\mathcal{L}$$



$$\mathcal{L}_0 = \frac{\vec{E}^2 - \vec{H}^2}{2}$$

→ linear Maxwell equations

em fields (photons) do not interact

$\Delta\mathcal{L}$ → nonlinear correction to Maxwell equations

photons do interact!

It is believed that nonlinear vacuum effects

- Pair creation by laser pulse in vacuum
- Harmonic generation
- Vacuum birefringence
- Photon splitting
- ....

could be observed if

$$E_0 \sim E_S = \frac{m^2c^3}{e\hbar} = 1.32 \cdot 10^{16}\mathrm{V/cm}$$

or

$$I \sim I_S = \frac{c}{4\pi}E_S^2 \approx 0.5 \cdot 10^{30}\mathrm{W/cm}^2$$

Segueing from Relativistic to Ultra-relativistic Laser-matter Interaction!

PLANNED:

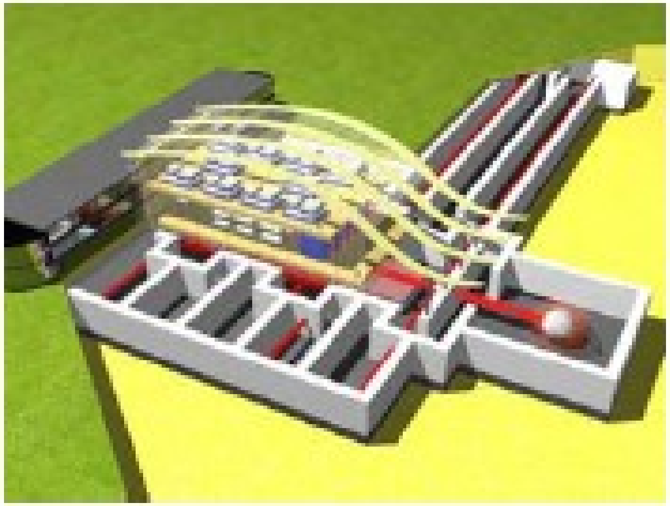
1. A single beam Ti:Sa laser chain delivering 10 - 15-fs pulses with an energy in the range of 700 J (50 to 70 PW)

2. Active phase control for the amplified beams in conjunction with large-aperture optics, will yield intensities as high as $10^{25}\mathrm{W/cm}^2$.

3. A combination of 10 single 50 – 70-PW beamlines could lead to peak power of 500 – 700 PW and corresponding intensities on target in the range of $10^{26}\mathrm{W/cm}^2$!

$$I \gtrsim I_L = 10^{23}\mathrm{W/cm}^2$$

$$\left(\eta_p = \frac{eE}{m_p \omega c} \gtrsim 1\right)$$



(Proposal for an European Extreme Light Infrastructure, www.extreme-light-infrastructure.eu)

$$I_{ELI} \ll I_S!$$

Is it possible to observe nonlinear <u>vacuum QED effects</u> in such fields?

The answer is YES !

The probability for vacuum to remain vacuum is

$$C_V = |<0S(+\infty)|0>|^2 = |e^{iW}|^2$$
$$= e^{-2VT\mathcal{I}m\mathcal{L}}$$

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

$l_C = \frac{\hbar}{mc} = 3.86 \cdot 10^{-11} cm$ - **Compton length**

J. Schwinger (1951)

For laser pulse:

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

R - radius of the focus spot

τ - duration of the laser pulse

at $R \sim \lambda \sim 1\mu m\,,\, \tau \sim 10\, fms\,,\, E \sim E_S$

$$2VT\mathcal{I}m\mathcal{L} \sim \frac{c^2\tau^2\lambda^2}{4\pi^2 l_C^4} \sim 10^{25}!!!$$

$$C_V = e^{-2VT\mathcal{I}m\mathcal{L}} \sim e^{-10^{25}} = 0!!!$$

$$E < E_S$$

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

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

at

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

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

Average number of created pairs

$$\frac{dN}{dtdV} = \frac{e^2 E_S^2}{4\pi^2 \hbar^2 c} \epsilon\eta \coth\frac{\pi\eta}{\epsilon} \exp\left(-\frac{\pi}{\epsilon}\right), \quad \epsilon > \eta$$

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

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

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

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

The formation length (coherence length) for pair production in a constant field

A.I.Nikishov, 1969

$$l_f = l_C \left(\frac{E_S}{E}\right)^{3/2}$$

formation length
and time

$$t_f = l_f / c$$

If the field is not static and uniform but

$$\Delta l \gg l_f \,, \quad \Delta t \gg t_f$$

Δl and Δt are space and time scale of variation of the field

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

$\epsilon(\vec{r},t), \ \eta(\vec{r},t)$ - local values of field invariants for the laser pulse

A plane monochromatic wave does not create pairs!

$$\mathcal{F} = (\vec{E}^2 - \vec{H}^2)/2 = 0\,, \qquad \mathcal{G} = (\vec{E}\cdot\vec{H}) = 0$$

A focused laser pulse creates pairs! $\mathcal{F}\,,\mathcal{G} \neq 0$

It is not a static and uniform field.

Space scale of variation of the laser pulse is wavelength λ

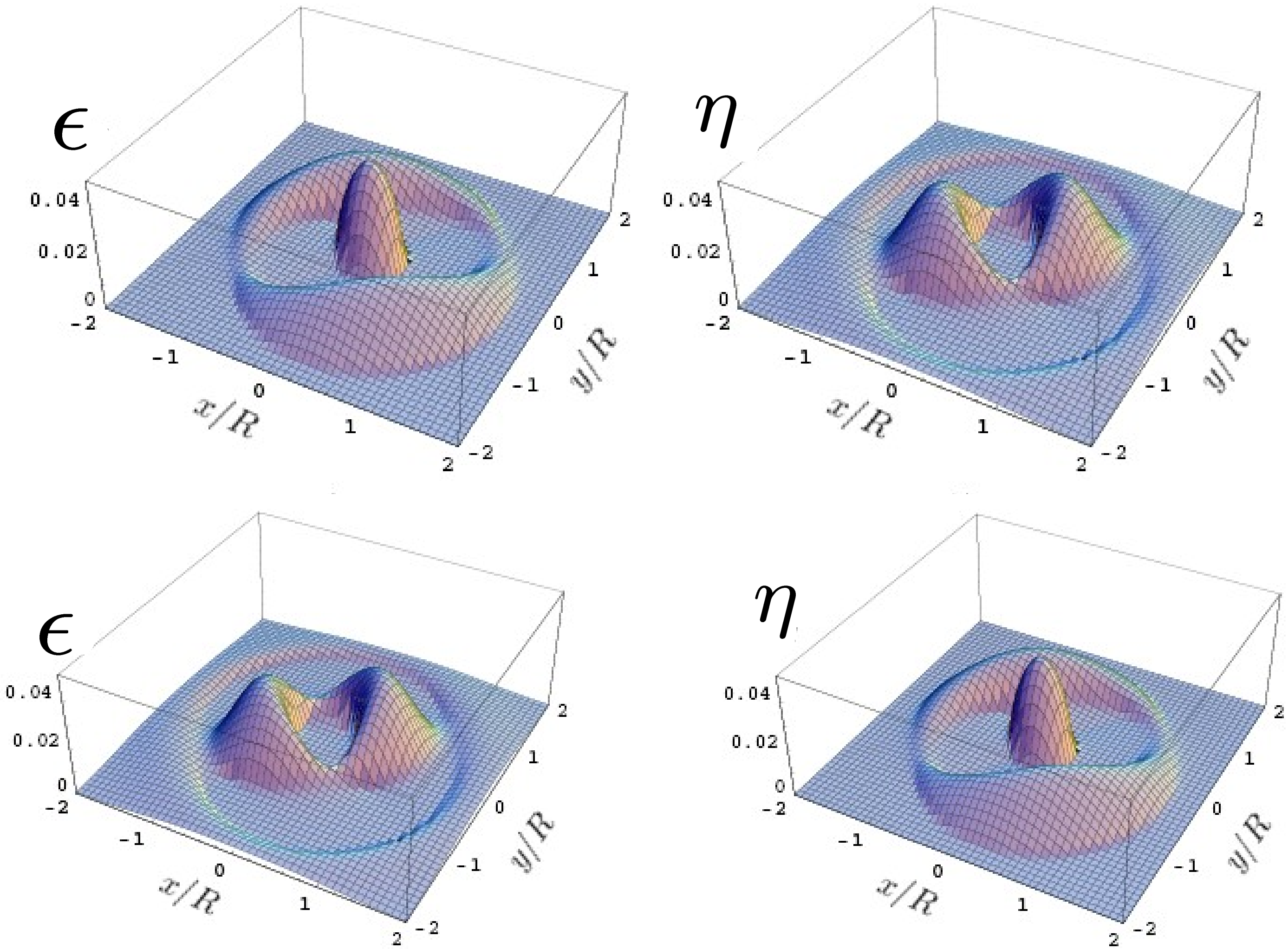
We can use the static field formula locally if

$$l_f \ll \lambda \;\Rightarrow\; E_0 \gg E_S \left(\frac{l_C}{\lambda}\right)^{2/3}$$

$\lambda = 1\mu m \;\; E_0 \gg 5.3 \cdot 10^{-5} E_S$, or $I \gg 1.3 \cdot 10^{21}\, W/cm^2$

A single focused laser pulse $(\epsilon \sim \Delta E_0)$

(focal plane, t=0)



e- pulse

h-pulse

An analytical model for a focused laser pulse was used

N.B.Narozhny, M.S.Fofanov, JETP, 90, 753 (2000)

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)

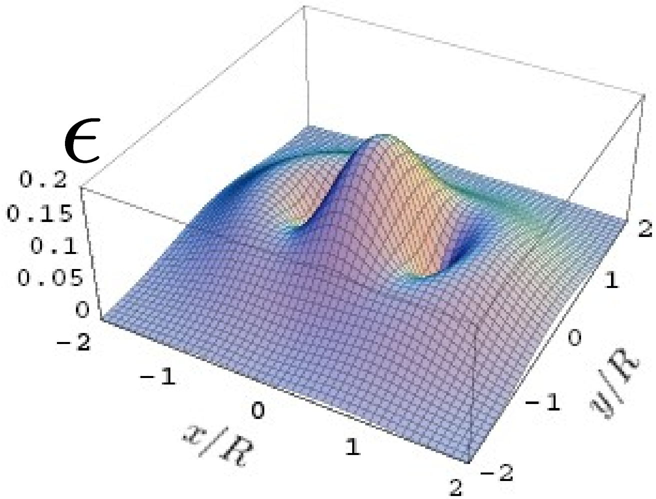
$I, W/cm^2$	E_0/E_S	N_e Δ=0.1	N_e Δ=0.05	N_h Δ=0.1
4·1027	0.16	4.0·10-11 !!	4.6·10-42	9.6·10-23
1·1028	0.25	24	3.1·10-19	2.0·10-7
2·1028	0.35	3.0·107	1.4·10-7	16
6·1028	0.62	8.4·1013	1.9·105	3.4·109

$\lambda \sim 1 \mu m \, , \tau \sim 10 fms$

$\Delta = \lambda / 2\pi R$

Two head-on colliding laser pulses

$(\epsilon \sim E_0)$



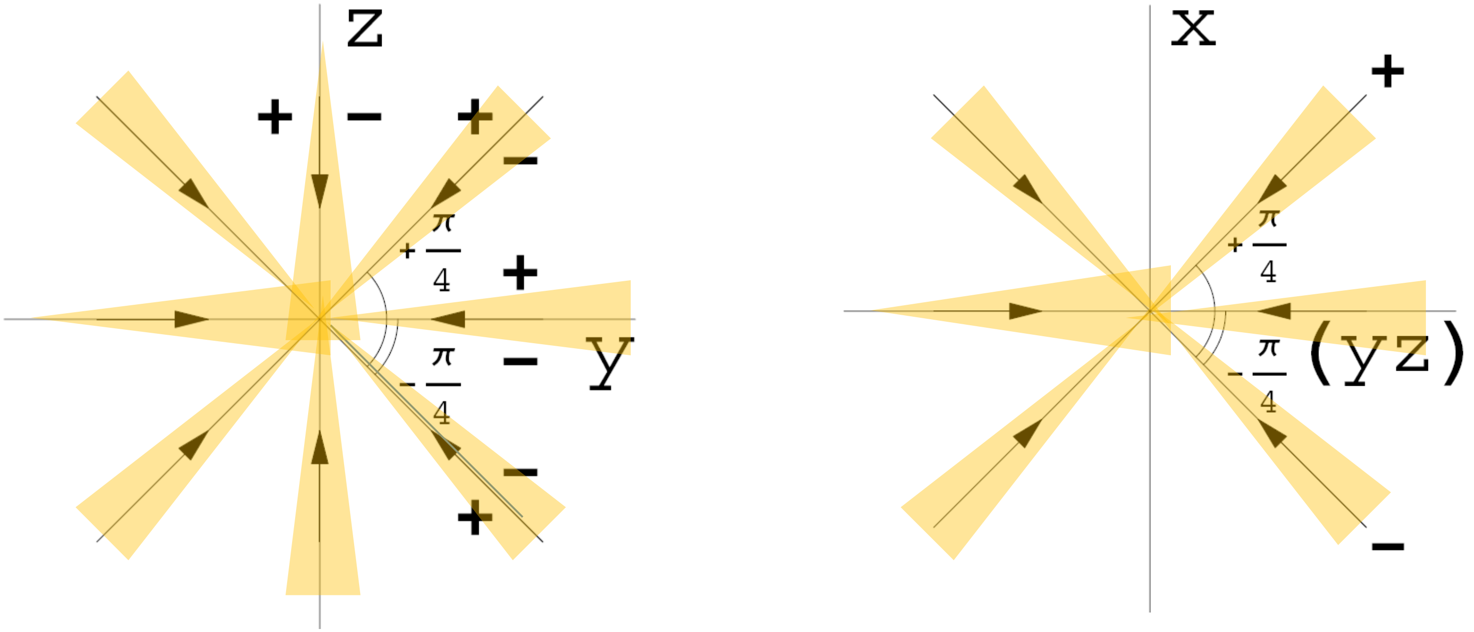
Pair production by two colliding pulses

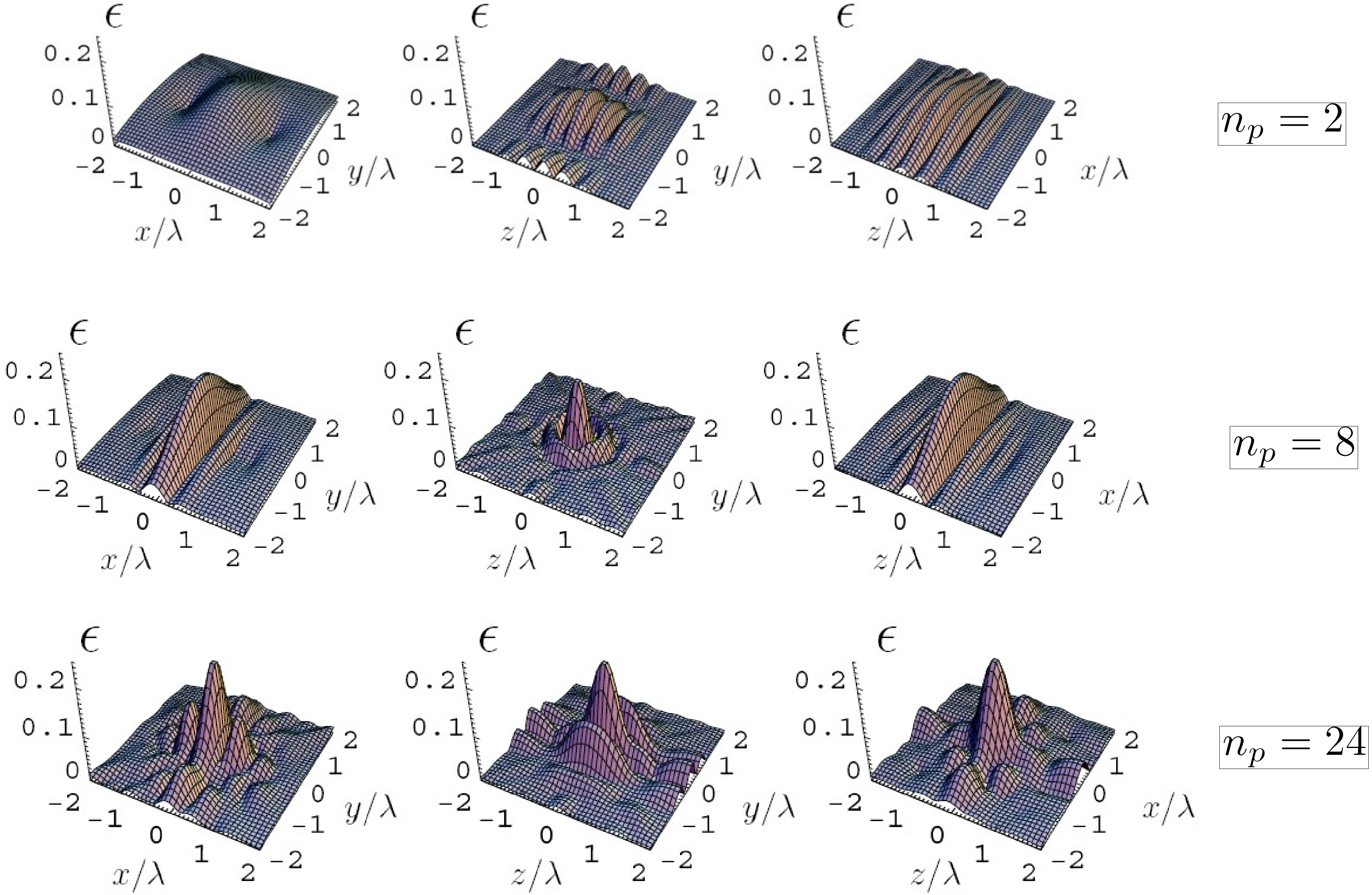
S.S. Bulanov, N.B. Narozhny, V.S. Popov, V.D. Mur, ZhETF 129, 14 (2006)

$I, W/cm^2$	E_0/E_S	N_e Δ=0.1	N_e Δ=0.05	N_h Δ=0.1
1.0·1026	2.5·10-2	4.5·10-12	6.0·10-9	7.1·10-13
2.0·1026	3.6·10-2	5.1·10-2	7.2	1.8·10-2
2.5·1026	4.0·10-2	14 !!	1.2·103	6.0
5.0·1026	5.7·10-2	2.6·107	5.5·108	1.8·107

1. The effect becomes observable at $I \approx 5 \cdot 10^{26} W/cm^2$
2. Small difference between e- and h-pulses

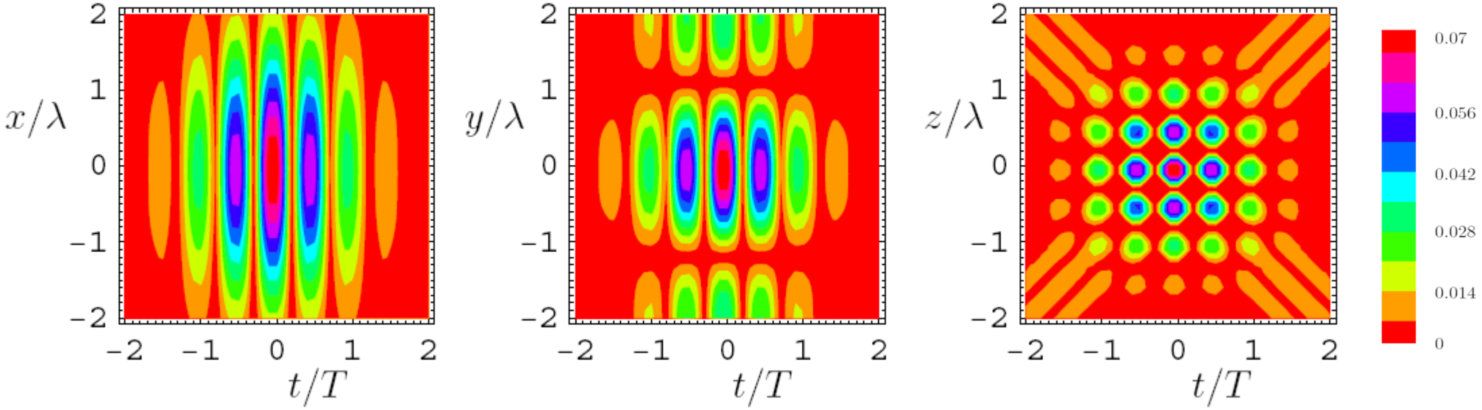
Multiple colliding laser pulses



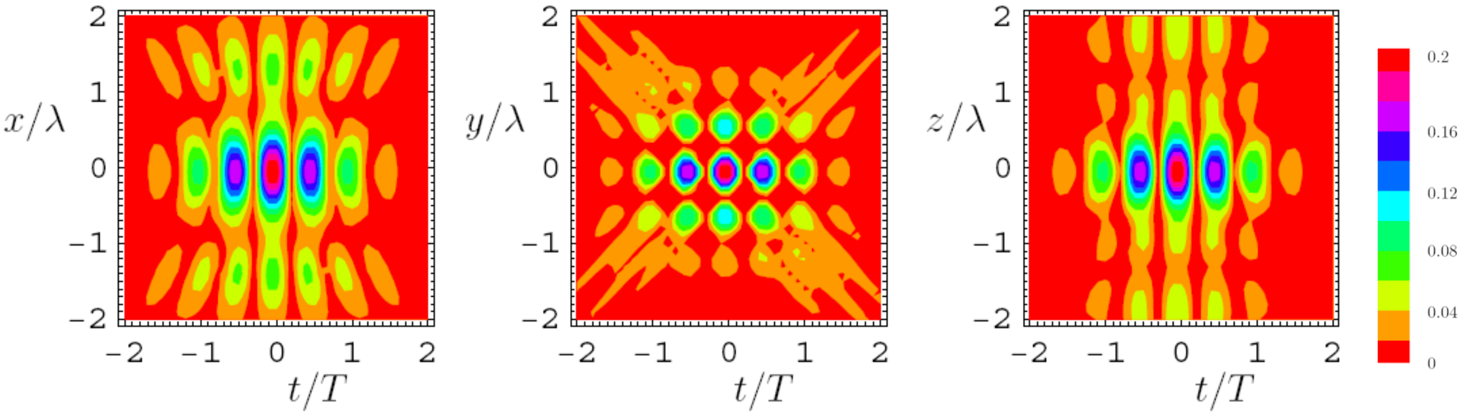


ϵ
x/λ
y/λ
z/λ
$n_p = 2$
$n_p = 8$
$n_p = 24$

2 pulses



24 pulses



The number of pairs Ne+e- and threshold energy Wth for different number n of colliding pulses.

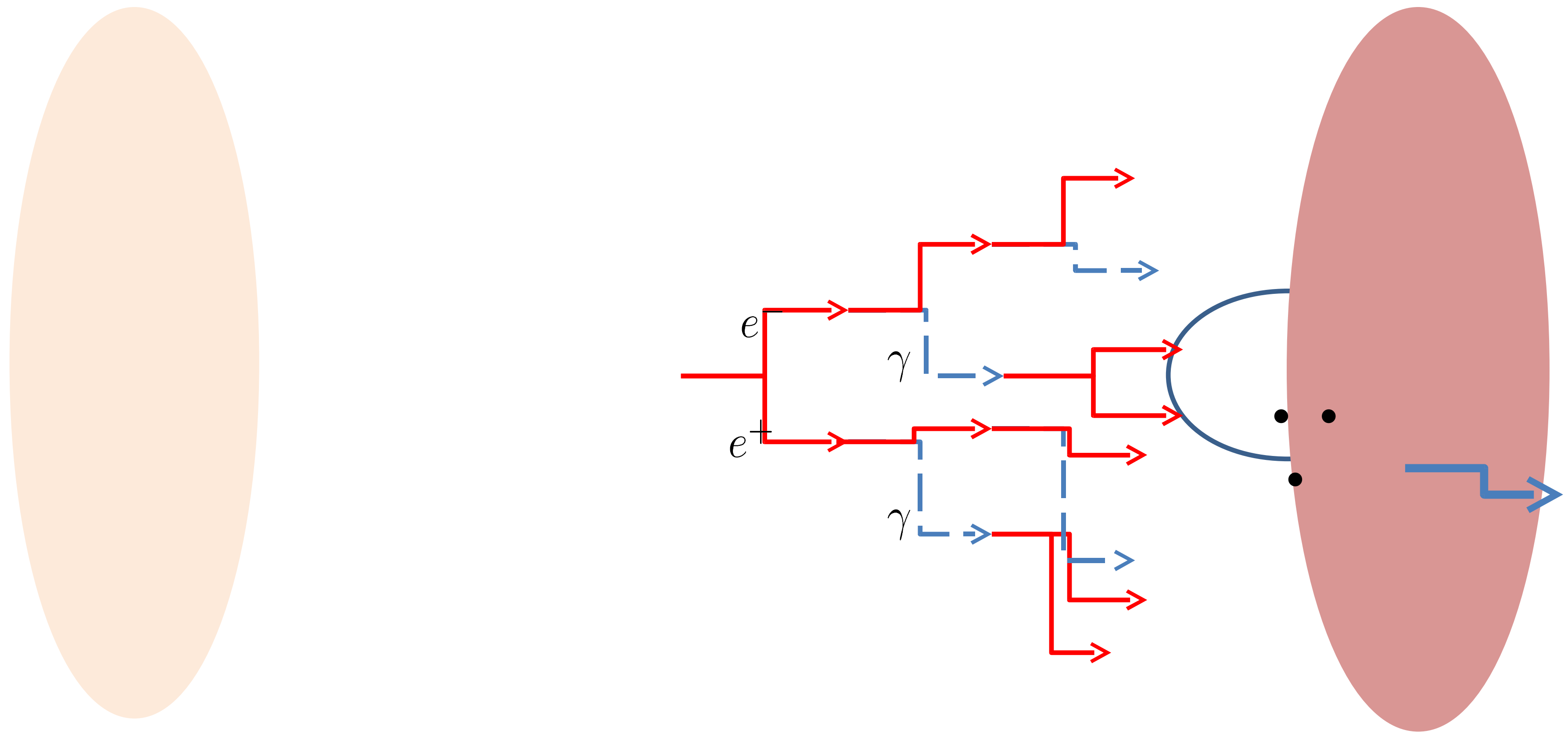
n	$N_{e^+e^-}$ at $W = 10$ kJ	W_{th}, kJ ($N_{e^+e^-} \sim 1$)
2	9×10^{-19}	40
4	3×10^{-9}	20
8	4	10
24	1.6×10^{6}	5

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

S. S. Bulanov, V.D. Mur, N.B. Narozhny, *et al.*, submitted to PRL

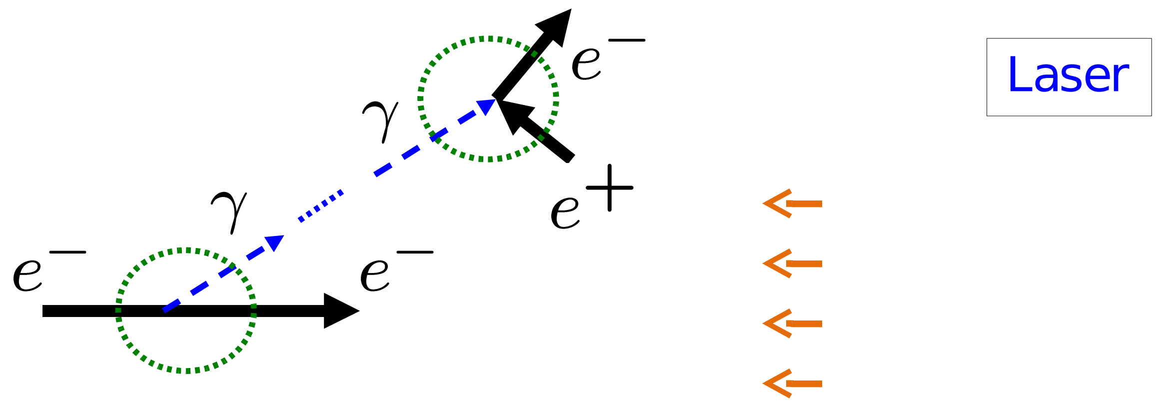
Electromagnetic cascades induced by a created pair

Pair creation can give start to an electromagnetic cascade



The effect was observed at SLAC experiment

D.L.Burke, et al., PRL, 79, 1626 (1997)



Laser:

$$\lambda = 0.527\mu\text{m (green)}\,,\ \tau_L = 1.6\text{ps}\,,\ I \approx 1.3\times 10^{18}\text{W/cm}^2\,,$$

$$a_0 = \frac{eE}{m\omega c} \approx 0.3$$

Energies of particles: $\varepsilon_e = 47\text{GeV}\,,\ \varepsilon_\gamma = 29.2\text{GeV}$

$$W_\gamma \sim \frac{\alpha}{m\gamma} a_0^2\,, \qquad \tau_e \sim 1/W_\gamma \sim 10^{-13} s$$

$$W_{e^-e^+} \sim \frac{\alpha}{\varepsilon_\gamma} a_0^{10}\,, \qquad \tau_\gamma \sim 1/W_{e^-e^+} \sim 6 \cdot 10^{-11} s$$

No of steps of the cascade / laser shot $\sim \dfrac{\tau_L}{\tau_\gamma} \sim 2 \cdot 10^{-2}$

Excellent agreement with experiment!

Pair production by two colliding pulses

For a laser: $\lambda = 1\mu\mathrm{m}\,,\ \tau_L = 10^{-14}\mathrm{s}$

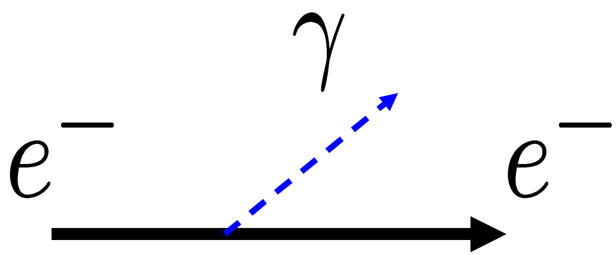
$I_{th} = 2.5 \cdot 10^{26}\mathrm{W/cm^2}$ ($\approx$ 1 pair/shot)

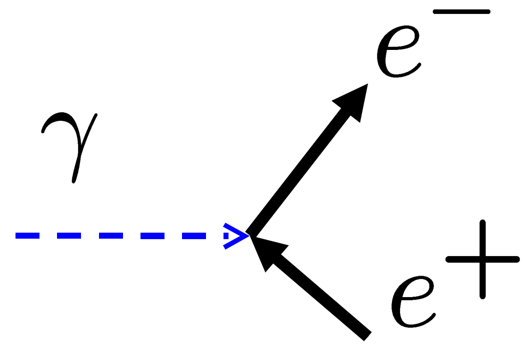
Dynamics is determined by $\chi = \frac{\sqrt{-e^2(p^\mu F_{\mu\nu})^2}}{m^3c^4}$

$a_0 \approx 10^4 \gg 1$

$\chi \gg E_0/E_S \approx 10^{-2}$

locally constant crossed field





$$W_\gamma \sim \frac{\alpha m}{\varepsilon_e} \quad \text{at} \quad (\chi_e \sim 1) \qquad\qquad W_{e^-e^+} \sim \frac{\alpha m}{\varepsilon_\gamma} \quad \text{at} \quad (\chi_\gamma \sim 1)$$

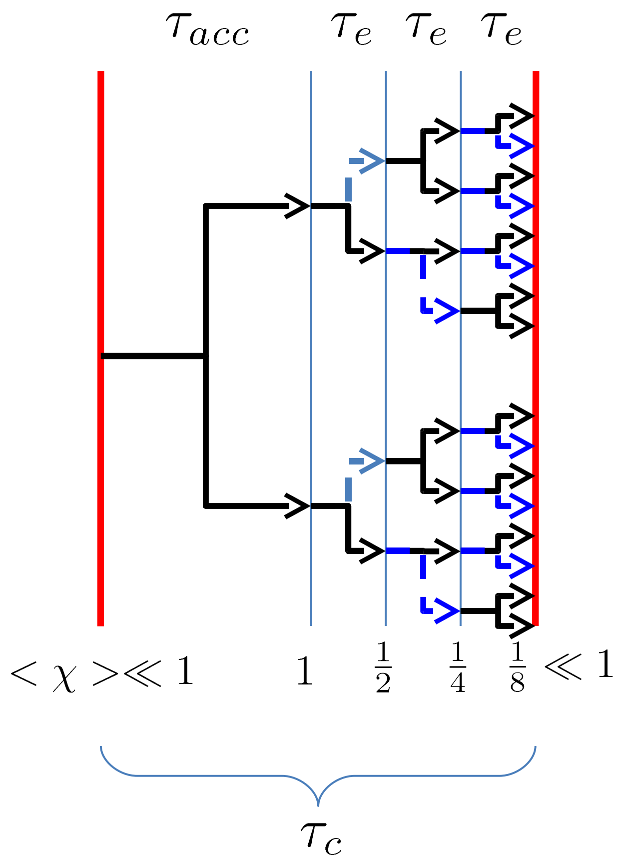
The first pair is created at rest with $\chi \sim 10^{-2}$

after

$$\tau_{acc} \approx \tau_C \sqrt{\frac{m}{\omega}\frac{E_S}{E_0}} \sim 0.7 \cdot 10^{-16}\mathrm{s}\,, \quad \chi_e \sim 1$$

e^- e^+ emit photons, χ of secondary particles ~ 1

$$\tau_e \sim \tau_\gamma \sim W_\gamma^{-1} \sim 10^{-17}\mathrm{s}$$



at $t = \tau_c\,,\;\; N_c = 10$

$$\tau_c = \tau_{acc} + 3\tau_e \approx 10^{16}$$

...

The charged particles are pushed out of the pulse due to ponderomotive effect

$$\tau_{out} \sim \lambda/c \sim 3 \cdot 10^{-15} < \tau_L$$

The total number of created particles

$$N \sim N_c^{\frac{\tau_{out}}{\tau_c}} \sim 10^{30}$$

BANG !!!

$$W_L \approx 400\mathrm{kJ} \approx 2.5 \cdot 10^{18}\mathrm{MeV}$$

$$W_{e^-e^+} > mc^2 N = 5 \cdot 10^{29}\mathrm{MeV}$$

$$W_{e^-e^+} \gg W_L!!!$$

The electromagnetic explosion destructs the laser pulse !

SUMMARY

- The effect of pair creation by electromagnetic field in vacuum can be observed at ELI facility with field strength 2-3 orders of magnitude lower E_S .
- Creation of a single pair leads to development of an electromagnetic cascade (a shower of electrons, positrons and photons) which destructs the laser field.

THANK YOU FOR ATTENTION