# New prospects for studying fundumental properties of vacuum with ELI

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**Abstract:** It is shown that nonlinear vacuum effects, e.g., pair creation by a laser field, will be observable at Extreme Light Infrastructure facility in spite of the fact that the projected field strength is essentially less than the "critical" for QED value. Even a single pair initiates cascade of electrons, positrons and photons which results in electromagnetic burst of the laser field.

It is commonly accepted that nonlinear vacuum QED effects, e.g. pair creation or higher harmonic generation by a focused laser pulse in vacuum, could be observed when the field strength reaches the "critical" for QED value $E_S = m^2c^3/e\hbar = 1.32\cdot10^{16}$ V/cm. The corresponding laser intensity is equal to $I_S = cE_S^2/4\pi = 4.65\cdot10^{29}$ W/cm$^2$ and is much higher than intensity of any laser facility operating at this moment in time. However, the nowadays development of laser technologies promises very rapid growth of laser intensities. The realization of the Extreme Light Infrastructure (ELI) project [1] will make available a laser of about 1 Exawatt power and intensity $10^{26}$ W/cm$^2$, or even higher. We will show that in spite of the fact that the respective field strength is still essentially less than $E_S$ the nonlinear vacuum effects will be observable at ELI facility.

Let us explain the preceding statement by example of a constant electric field. The probability of vacuum to stay vacuum is given for this case by

$$C_V = \left|\langle 0|S(+\infty)|0\rangle\right|^2 = e^{-2VT\,\mathcal{I}m\mathcal{L}}, \qquad (1)$$

where $\mathcal{L}$ is Heisenberg-Euler correction to Lagrangian of the constant electromagnetic field [2]. At $E \sim E_S$

$$2VT\,\mathcal{I}m\mathcal{L} \sim \frac{VTc}{4\pi^3 l_C^4}, \qquad (2)$$

where $l_C = \frac{\hbar}{mc} = 3.86\cdot10^{-11}cm$ is the Compton length. Let V be of the order of the volume of a laser pulse near its focus $V \sim \pi\lambda^2 c\tau$ and $T \sim \tau$ with wavelength $\lambda = 1\mu$m and pulse duration $\tau = 10$ fs. Then, we obtain the following estimate for $C_V$

$$C_V = e^{-2VT\,\mathcal{I}m\mathcal{L}} \sim e^{-10^{25}}. \qquad (3)$$

This means that the probability of vacuum to vacuum transition is equal to 0 at $E \sim E_S$. If $E < E_S$, $C_V$ obtains an exponentially small factor $\exp(-\pi E_S/E)$. However, the pre-exponential factor (2) is so large that $C_V$ is appreciably less than 1 for $E \gtrsim 3\cdot10^{-2}E_S$. This means that pairs are created at field strengths less than the critical value.

The average number of pairs created by a single tightly focused laser pulse in vacuum was calculated [3,4]. The threshold value of intensity $I_{th}$, when only one pair per pulse is created, for the laser pulse with $\lambda = 1\mu$m, $\tau = 10$ fs and radius of the focal spot $R = \lambda$ is $I_{th} \sim 10^{28}$. Though this value is less than $I_S$, it is beyond ELI potentialities.

We argue that collision of four or more pulses essentially enhances the effect of pair production as compared with the case of a single or even two colliding pulses of the same total input energy. Due to the interference of the colliding waves the resultant field in the focal region acquires a "spotty" space-time structure. The total 4-volume of the resultant field decreases while the peak field goes up. The number of created pairs depends on the peak field exponentially while the effective laser pulse 4-volume decreases as a power. This explains the decrease of the threshold intensity for the case of a many-pulse collision.

We have considered [5] the configuration where up to 24 pulse are focused simultaneously to the same focal spot. The total electromagnetic energy is kept constant. In Fig. 1a we show how these pulses are focused. First eight pulses are focused in (yz) plane in colliding pairs along the y and z axis and along two lines which have angles $\pm\pi/4$ to y axis. Up to 24 pulses are added by introducing pairs of pulses along the lines which do not lie in (yz) plane and have an angle of $+\pi/4$ or $-\pi/4$ with one of the 4 lines in (yz) plane. These angles are measured in the plane that goes through the line in (yz) plane and x axis Fig. 1b.

The results of numerical calculation of number of pairs produced by the field of multiple pulses are presented in Table 1. Each of the pulses has a wavelength of $\lambda$=1μm, $\tau$= 10 fs and $R = \lambda/2$. The total energy

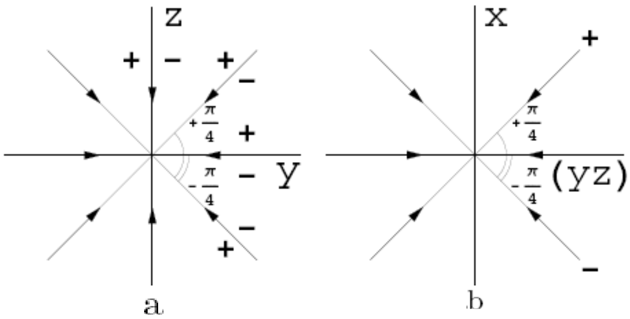


Fig. 1. Multiple colliding pulses focusing setup.

W of this multipulse configuration is 10 kJ. We also show the values of threshold energy $W_{th}$ for each pulse configuration.

Table 1. The number of 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 ($N_{e^+e^-} \sim 1$) |
|---|---|---|
| 2 | $9 \times 10^{-19}$ | 40 |
| 4 | $3 \times 10^{-9}$ | 20 |
| 8 | 4 | 10 |
| 24 | $1.6 \times 10^{6}$ | 5 |

So we see that the projected at ELI setup of 10 pulses with duration 10 fs and total energy 10 kJ [1] will make it possible to reach the threshold field. And for 24 pulses the resulting intensity is more than enough to produce a significant amount of $e^+e^-$ pairs.

The effect of pair creation initiates another process. The created particles being initially at rest are accelerated by the laser field and very fast gain a very high energy. Such particles will emit photons which in turn can create a pair. The particles of the pair are again accelerated by the laser field and hence an electromagnetic cascade of electrons, positrons and photons arises, see also [6]. Our estimate shows that cascades can arise at laser intensities higher than $10^{24}$ W/cm$^2$. We have estimated also the number of pairs in the cascade initiated by a single pair created in vacuum by two colliding 10fs laser pulses with $\lambda$=1μm [7]. Intensity of the colliding pulses was taken $I= 2.5\cdot10^{26}$ W/cm$^2$ (threshold intensity for this set of parameters and geometry of collision). The number of pairs appeared to be $10^{30}$. The total rest energy of this number of particles exceeds the energy of the colliding pulses. This means that we have exceeded the bounds of the external field approximation and have encountered the electromagnetic burst of the colliding laser pulses. This result brings us to doubt in attainability of the critical field strength $E_S$ with lasers.

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