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Review

# New horizons for extreme light physics with mega-science project XCELS

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**Abstract.** A short review of the Russian mega-science project XCELS and scientific problems to be solved are presented. We discuss the origin of multi-beam design to attain the highest field magnitude at optimal focusing. Then, we formulate particular physical problems of fundamental interest that can be solved within this project.

## 1 Introduction

Several projects have been started world-wide or are to be started soon to conquer the 10 Petawatt peak power level in a single laser pulse of 10–30 fs duration, which seems to be technologically justified and achievable in the next 5 years. Among them, Vulcan 10 PW in UK, Apollon 10 in France, ELI-Beams in Czech Republic, and ELI-NP in Romania are on the European research infrastructure roadmaps. The next intriguing step in this ascent to the highest power level is to find a way for coherent combining several multipetawatt laser beams providing extreme time-space energy concentration. The point is that for many interesting and even critical experiments in modern physics, the intensity of light is more important than its power. The intensity of about $10^{26}$ W/cm$^2$ announced in the Russian XCELS project [1] at combining 12 beams of 15 PW power can open up unprecedented possibilities for exciting new exotic processes. This intensity level surpasses the current intensity records by 4 orders of magnitude, and by 2 orders magnitude the result planned in the above mentioned European mega-project.

The XCELS laser facility will open up unique opportunities for studying new phenomena at the interface of high-field and high-energy physics. Once optimal focusing regimes are defined, a number of interesting problems regarding the ultrarelativistic particle dynamics and hard photon generation arise. First of all, not only electrons but also protons become relativistic under these optical field intensities resulting in

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unusual laser-plasma interaction regimes. Then, one can expect that the ponderomotive force of converging laser radiation provides a pressure pushing all of the electrons to the focal point and resulting in huge particle concentrations. Furthermore, the electrons experience strong radiation losses as the amount of energy converted to gamma rays per optical period is of the same order as the quiver energy. Gamma quanta, in their turn, initiate electron-positron pair production. As a result, a new state of matter emerges, a sort of boiler containing strongly interacting particles, optical fields, and gamma radiation with the energy density exceeding that at the center of the Sun by many orders of magnitude. This is a completely new physical object, and study of its fundamental properties and application prospects is a compelling task. In this paper we will discuss, specifically, how new regimes of ultrarelativistic interactions can be used to produce extra-brilliant directed gamma ray bursts and to create attosecond light probes for studying nonlinear properties of vacuum.

## 2 Optimal focusing of multi-beam laser

Splitting a single laser pulse into two identical counter-propagating pulses and using the same focusing optics for each gives an enhancement in field strength by a factor of $\sqrt{2}$. One can try to extend this idea using all possible directions in space. For monochromatic radiation with a wavelength $\lambda$ we can define focusing efficiency as a dimensionless factor in the expression relating the peak strength of the electric field $E_{max}$ and the total cycle-averaged peak power $P$: $E_{max} = f_e\sqrt{P/\lambda^2 c}$. The upper bound can be reached by the so-called $e$-dipole pulse geometry [2] corresponding to energy concentration into a volume of just $0.04\lambda^3$ (for a single cycle) and provides $f_e = 8\pi/\sqrt{3}$. The $e$-dipole pulse implies pulse convergence in the form of reversed emission of a dipole antenna and corresponds to an incoming intensity $\sim \sin^2\theta$, where $\theta$ is the polar angle.

Mimicking the $e$-dipole pulse using several laser beams is an optimal design for multi-channel facilities aimed at reaching the highest possible electric field strength. The first option called the *belt* concept corresponds to an array of laser pulses incident along the polar plane ($\theta = \pi/2$) equally separated in the azimuth angle. A small number of beams implies unrealistic values of the $f$-number required for each beam focusing, whereas a large number of beams leads to covering only a small part of the possible directions ($\theta \ll 1$), and a low focusing efficiency. In order to cover a larger number of directions with a greater number of beams we propose a *double-belt* geometry. This concept implies two similar arrays of laser pulses placed one under the other so that the directions of the beams are located in staggered order across the polar plane. For comparing both geometries, in Fig. 1 we plot the effective intensity ($I_{\mathit{eff}} = (c/8\pi)\, E_{max}^2$) as a function of the number of channels, assuming the total power to be equal to 200 PW and the wavelength to be 810 nm. The ideal case of an $e$-dipole pulse is shown by the solid line, whereas the dashed line is used to show the intensity when a single beam is focused by means of optics with an f-number equal to 1.2. As the use of 3 beams in a belt geometry requires an unrealistic value of the f-number we can conclude that 10 or 12 beams configured in the double-belt geometry give us the best result that turns out to be rather close to the theoretical maximum.

## 3 Amazing properties of ultrarelativistic electrons: Anomalous radiative trapping

At intensities of $10^{23}$ W/cm$^2$ or higher, dynamics of a single electron in the laser pulse acquires qualitatively new features. This is due to the increase of radiation

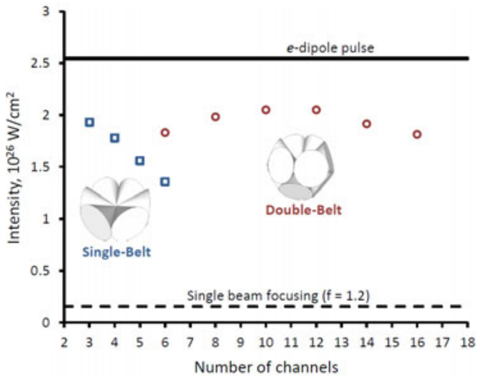


**Fig. 1.** Comparison of belt and double-belt focusing configurations for a different number of laser channels having a total peak power of 200 PW.

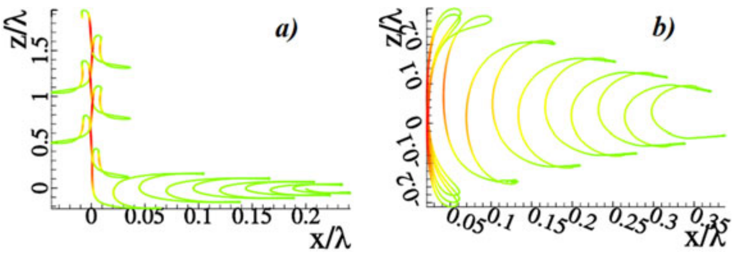


**Fig. 2.** Characteristic trajectory of the electron born near the magnetic field maximum in the field of a plane-polarized standing wave a) and in the field of a dipole wave b). The color palette from green to red (from light grey to dark grey) shows the increase of the particle gamma factor.

losses of the electron due to emission of hard X-ray (gamma) photons. The work of the radiation reaction (RR) force (or radiative friction) on the period of the field becomes comparable to the oscillation energy of the particle acquired in the laser wave. For the light intensity level expected in XCELS, electron dynamics become strongly dissipative, and the electron becomes an efficient converter of energy from the optical to the X-ray (gamma) range. Under these conditions, the particle trajectories take on quite an unusual shape, and the study of their dynamics is one of the most fundamental problems in the physics of superstrong fields. The effect of the RR force results in the compression of the phase space of an ultrarelativistic particle moving in the field of a plane standing wave [3]. For sufficiently large amplitudes of the laser fields ($a > 100$) phase attractors appear, i.e. particles are captured on specific trajectories and their properties become similar [4]. It was recently demonstrated [5] that the strong effect of radiation losses causes phenomena of normal and anomalous radiative trapping. In the amplitude range $600 < a < 4000$ electron trajectories are trapped in the area close to the nodes of the electric field (normal radiative trapping, or NRT). However, at higher intensities $a > 4000$, all the trajectories are localized in the antinodes of the electric field (anomalous radiative trapping, or ART) which seems somewhat counterintuitive. A typical example of such a trajectory is shown in Fig. 2a for $a = 4000$. An electron born near the node of the electric field drifts to the antinode (with its oscillatory energy growing proportionally to $a$) and is trapped on an attractor that is characterized by the maximum energy conversion efficiency from optical to hard energy photons with a narrow radiation pattern (Fig. 3a). Thus, ART looks very promising for creating high power directional sources of gamma radiation.

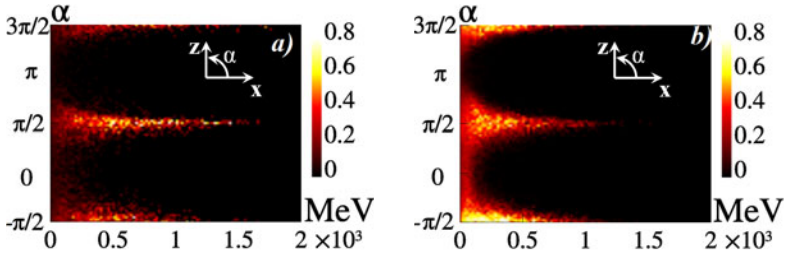


**Fig. 3.** Characteristic photon energy spectrum distribution over angle $\alpha$ for trajectories in a plane-polarized standing wave a) and in the field of a dipole wave b).

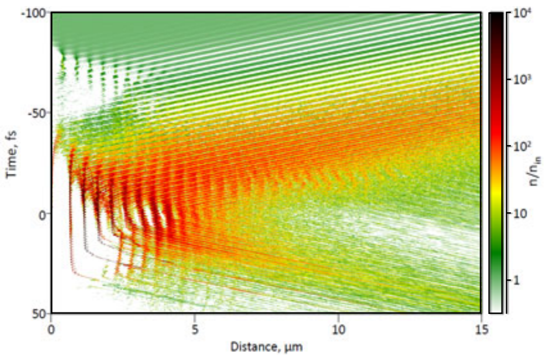


**Fig. 4.** The ratio of electron concentration to the initial concentration of uniformly arranged electrons as a function of distance to the focus and time during interaction with convergent dipole wave having power 200 PW and duration 30 fs.

Similar effects are observed in the optical field of the dipole configuration [5,6], which will be implemented in the full-scale project XCELS. The shape of the attractor for the electron trajectories depends on the position of the antinodes of the field with respect to the focus of the dipole wave. For the main peak, this trajectory resembles a figure eight (Fig. 2b) and the radiation pattern of hard photons is concentrated in a narrow angle along the dipole axis (Fig. 3b).

Increasing the number of electrons in the focal region of the dipole wave to boost the power of a gamma emitter is another interesting problem in the physics of extreme light fields. It turns out that during the conversion of the dipole wave, the ponderomotive force captures the majority of particles from a wide area and carries them to the center. As an example, Fig. 4 presents results of numerical modeling for the interaction of the dipole wave of power 200 PW and duration 30 fs with an initially homogeneously distributed electrons. A large number of the particles are moved to the center and trapped in areas of the antinodes of the electric field at distances 0 $\mu$m, 0.67 $\mu$m, 1.17 $\mu$m, 1.67 $\mu$m from the focus, respectively. The motion of the particles on the attractors is synchronized by the radiative friction.

## 4 Directed brilliant *boldsymbol*$\gamma$-ray sources

Efficient conversion of the laser pulse energy to the energy of high brightness gamma rays in an optical field interaction with electrons can be achieved if the following conditions are fulfilled. It is necessary 1) to achieve large enough self-consistent optical fields in plasma, 2) to provide a high density of electrons in a large field, and 3) to synchronize the motion of these electrons.

As was noted in Sect. 3, a single electron moving in an ultra-intense field may become an effective emitter of directional gamma radiation. However, ultimately creating a high-power $\gamma$-ray source requires not only proper single particle dynamics but also optimization of the overall structure of the self-consistent laser field and plasma distributions. In fact, it turns out that the radiation reaction effects coming into play may strongly modify the conventional electrodynamics of relativistic, laser-plasma interactions [7].

A very instructive example is a case of a homogeneous plasma in which, considering the laser field in the form of a traveling wave, we can obtain a standard nonlinear dispersion relation with the following expression for the dielectric permittivity [8,9]

$$\varepsilon = 1 - \frac{n}{\gamma(1+\delta^2\gamma^6)}(1+i\delta\gamma^3), \tag{1}$$

which contains real and imaginary parts. Here $n$ is the electron density normalized to the critical value $m\omega^2/4\pi e^2$ for the given laser frequency $\omega$, $\gamma$ is relativistic factor, and the parameter $\delta = 2e^2\omega/3mc^3$ is due to the RR effects. In the limit $\delta \to 0$, as is expected, the imaginary part vanishes to zero, whereas the real one reduces to the conventional relativistic dielectric permittivity $\varepsilon = 1 - n_0/\gamma$ [10]. The qualitative contribution of the RR effects is the appearance of the imaginary part, i.e. a plasma conductivity due to laser energy absorption caused by the RR effects. The imaginary part is comparable with the plasma contribution to the real part $(Im(\varepsilon) \sim Re(\varepsilon) - 1)$ at $\gamma \sim \delta^{-1/3}$, i.e., at $a \sim 500$. By optimizing the plasma-field structures arising in the interaction of laser fields with plasma it is possible to create a more efficient converter to gamma radiation.

Here we pay particular attention to circularly polarized lasers due to the peculiarity that the ponderomotive force steadily pushes the electrons and thus provides a high plasma compression regime. Penetration of circularly polarized radiation into a thick plasma layer is impeded by the fact that the electrons form structures reflecting nearly all incident radiation. A possible way to reduce the reflection is to make use of thin plasma targets with thickness $d < \lambda$, where $\lambda$ is the laser radiation wavelength. In particular, the problem of symmetric two-sided irradiation of a thin foil by laser pulses may be considered. Ponderomotive force from external field side may strongly compress the electrons producing an electron layer with a thickness tens and even hundreds times less than the wavelength, thus permitting the strong field to penetrate inside the layer and synchronously rotate the electrons with the field frequency. As an ultrarelativistic electron emits photons with a momentum in the direction of its motion, the radiation directionality pattern in time is a ray in the electron layer plane rotating at the laser frequency. Figure 5 illustrates a schematic of the intended experiment in which the efficiency of laser energy conversion to gamma quanta with energies of tens of MeV was calculated to amount to 50% [9].

## 5 Probing nonperturbative QED

Achieving extreme intensities in the XCELS project will provide an optical field magnitude in excess of $10^{16}$ V/m, which is a few percent of the Sauter-Schwinger limit. In these conditions we can expect the appearance of a direct field-induced ionization of vacuum leading to the production of electron-positron pairs in the geometry of the dipole focusing [11]. However, in an experiment, the presence of stray particles due to imperfect vacuum can result in an avalanche of pair production which is (perturbatively) triggered when particles (photons) are dragged (emitted) into regions of high field strength. The resulting beam depletion [12], or beam scattering from an

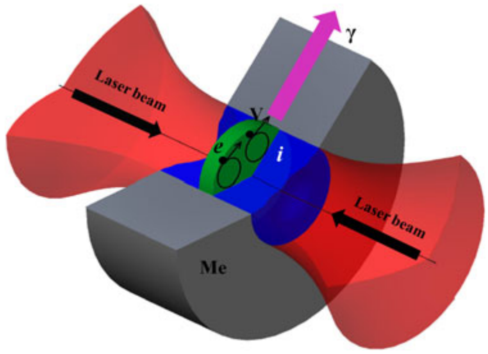


**Fig. 5.** Schematic of laser energy converter into $\gamma$ radiation.

**Table 1.** The number of pairs produced in one cycle as a function of wavelength and power.

| | $\lambda = 1\,\mu$m | $\lambda = 0.8\,\mu$m | $\lambda = 0.4\,\mu$m |
|---|---|---|---|
| 1660 PW | 1 | $10^3$ | $10^{10}$ |
| 1120 PW | $10^{-4}$ | 1 | $10^8$ |
| 320 PW | $10^{-23}$ | $10^{-14}$ | 1 |

emerging electron-positron plasma, then reduces the beam intensity. Even when the effect on the laser radiation is small, the generated particles can hinder observation of nonperturbative effects by producing a background which swamps the signals of interest. Hence, it is important to understand the conditions leading to cascades, and what backgrounds they produce. Indeed, if we could guarantee that within the focal volume there would be no high energy electrons and photons initiating perturbative processes (or rather, that such events would have a low probability), then we could focus beams to the intensities required to trigger nonperturbative pair creation, without first initiating cascades. Study performed in [11] indicates that in order to fulfill this requirement one needs to carry out experiments having the quality of vacuum as good as $10^5$ particles per cm$^{-3}$ (or pressure $10^{-12}$ mbar), which is in reach of current technologies.

Results of computations of the total number of pairs generated in the focal region of a convergent dipole wave with the listed power and carrier wavelength were obtained in [11] and are presented in Table 1. It is clear that a relatively strong dependence on the above parameters is observed. Only $10^{-14}$ particles per optical period may be generated at the wavelength of 0.8 $\mu$m and power of 320 PW close to that planned in the XCELS project, which is far from being sufficient conditions for reliable recording of the effect. However, by transitioning to the second harmonic, i.e. to a wavelength of 0.4 $\mu$m, it makes implementation of this experiment quite realistic. The recent computations of efficient conversion of high-power laser radiation to the second harmonic [13] also enables an implementation within the XCELS project.

Achieving field magnitudes by the direct focusing of laser beams sufficient for field-induced pair production is a formidable task as we can see from Table 1. However, the XCELS radiation can be used for a specific laser-plasma interaction resulting in the production of attosecond pulses with an intensity higher than that of the optimized double-belt configuration. This interaction regime, called the Relativistic Electronic Spring (RES), has been studied in our former paper [14]. The theory of RES predicts that electrons at the surface are pushed by the incident radiation so that they form a thin dense layer whose ultrarelativistic dynamics is defined by the parameters of the interaction. The most remarkable prediction of the RES is generation of a giant

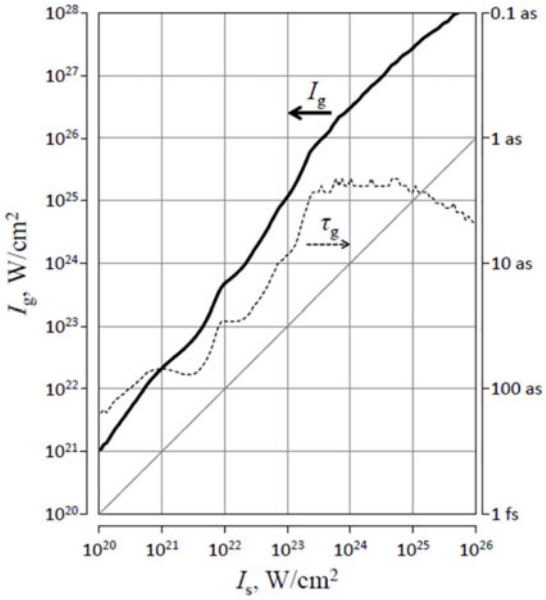


**Fig. 6.** Peak intensity (solid line) and duration (dashed line) of the giant attosecond pulse generated in the case of optimal parameters as a function of the incident wave intensity.

attosecond pulse for the case of an optimal incidence angle $\theta = 60°$ and optimal relation: $S = n/a \approx 0.4$, where plasma density $n$ and amplitude of incident radiation $a$ are given in the units or critical density and relativistic units, respectively. In Fig. 6 we plot peak intensity of the generated pulse $I_g$ and its duration $\tau_g$ (FWHM of amplitude) as a function of the intensity of the incident radiation $I_s$ for the case of optimal parameters. The results were obtained using PIC simulations with radiation losses included via an event generator according to the rate equation obtained in quantum electrodynamics, which makes the results valid up to the level of intensity that causes electron-positron pair production. One can see that generation of pulses with just a few attoseconds duration and $10^{26}$ W/cm$^2$ peak intensity can be achieved with laser radiation of the order of $10^{24}$ W/cm$^2$ intensity that corresponds (according to $S = n/a$) to the typical plasma density originating from deep ionization of the solid matter used as a target. According to the RES theory, the shape of the generated attosecond pulse can be slightly modified in a controllable way by varying parameters of the interaction. Thus, giant attosecond pulses generated at the next generation of laser facilities can be used for fundamental studies of intra-atomic structures on the timescales of merely several attoseconds. At the same time, focusing of giant attosecond pulses in space with the concept of a groove-shaped target [14] (see Fig. 7) can provide a way to reach intensities up to $10^{28}$ W/cm$^2$ and trigger experimental studies of highly nonlinear vacuum properties predicted by quantum electrodynamics.

## 6 Conclusion

To conclude, we have provided a short review of the Russian mega-science project XCELS and some of the early scientific problems to which it may be applied. First, we discussed the origin of the multi-beam design to attain the highest field magnitude with optimal focusing of the given laser setup. And then, we formulated particular physical problems of fundamental interest that can be solved within this project. They

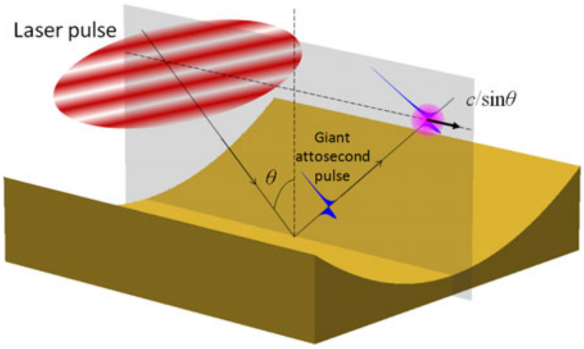


**Fig. 7.** Schematic representation of the concept of groove-shaped target.

include new regimes of single particle motions mostly due to the RR effects when efficient gamma ray generation occurs, new regimes of nonlinear electrodynamics, as well as QED resulting in highly efficient plasma converter for gamma rays, and probing nonperturbative QED with dipole or superluminal attosecond pulses.

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