Prospects of PEARL 10 and XCELS Laser Facilities

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The goal of the XCELS project in Russia is establishing a large research infrastructure – the Exawatt Center for Extreme Light Studies. The core of the planned infrastructure will be a new unique source of light having the power of about 0.2 Exawatt. This source constitutes a 12 channel x 15 PW laser system based on technique of optical parametric chirped pulse amplification (OPCPA). The corresponding laser architecture was developed at the Institute of Applied Physics in Nizhny Novgorod where the first Petawatt-class OPCPA laser in the world, called PEARL, was launched in 2007 and a multi-Petawatt system is now under construction. The fundamental processes of laser-matter interaction at Exawatt power belong to an absolutely new branch of science that will be the principal research task of the infrastructure. There will open up opportunities for studying the space-time structure of vacuum, nonlinear QED phenomena and unknown processes at the interface of the high-energy physics and the high-field physics.

1. Main advantages of the PEARL setup architecture

OPCPA is a well established and promising technique to master subexawatt peak power level in the frame of current laser technologies. Existence of superbroadband synchronism, availability of large aperture nonlinear optical crystals, a huge gain per stage, and a relatively simple amplification architecture make this technique superior over the conventional amplification in laser media. A decade ago we found a “magic condition” of superbroadband synchronism for non-degenerate parametric amplification in a KD*P crystal, that is 1/527 nm = 1/910 nm + 1/1250 nm. It implies that radiation of Ti:Sapphire or Cr:Forsterite master oscillators with the pulse duration down to 15 fs can be efficiently amplified with OPCPA technique when pumping a corresponding crystal by the second harmonic of Nd:YLF or Nd:glass lasers. This approach has obvious advantages over the usage of degenerated synchronism in KDP because of 2.5 shorter pulse duration limit, less absorption losses, and more convenient beam separation. KD*P crystals can be available with 40 x 40 clear apertures that provides pump-to-signal conversion with a kJ pulse energy. 10^-10^ gain per stage has been demonstrated experimentally, boosting pulse energy from 1 nJ to 150 J in only three stages of OPCPA. These results have vigorously stimulated our program from PEARL to PEARL 10 to XCELS laser facilities.

PEARL was launched in 2007 with > 0.5 PW peak power, 24 J pulse energy, 43 fs pulse duration, and nearly diffraction limited beam quality. PEARL 10 has inherited the compact design of its predecessor and included advanced technical solutions to achieve the ultimate goal to boost the output peak power in an order of magnitude. Two new Nd:glass pump lasers with 0.5 kJ each will be used instead of one 0.3 kJ, and pulse duration will be shortened to 30 fs. 500 J channel of Nd:glass pump laser and the large aperture parametrical crystal unit are shown in Fig. 1.

Main parameters of PEARL and PEARL 10 setups are at table 1, first and second column correspondingly.

2. Basic parameters of the XCELS infrastructure

Main parameters of XCELS project are at third column of table 1.

A subexawatt laser facility significantly exceeding the level of radiation power in the most powerful systems, that are available, constructed or projected today, will be the core of the XCELS project. The complex will comprise 12 identical channels, each of which generating a pulse with the energy of 300-400 J, duration of 20-30 fs, maximum intensity at focusing more than 10^23 W/cm^2 (see Fig. 2 Schematic diagram of XCELS facilities). The channels are based on the proven OPCPA architecture with KD*P crystals having the aperture of 30 x 30 cm^2 in final cascades. It is supposed that optical puls-

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Fig. 1 (a) Compact 500 J Nd:glass pump laser; (b) Second harmonic convertor (to the right) and parametrical amplifier (in the center) of PEARL 10 facility.
es in laser modules of the subexawatt complex can be phased to an accuracy of hundredths fractions of a light wave period ($10^{-16}$ s). The first, prototyping phase of the project will be creation at the Institute of Applied Physics in Nizhny Novgorod by the end of 2016 of two such modules with the power of $10^{15}$ PW. (See Fig. 2 2-channel prototype of subexawatt laser). This will not only allow creating a reliable prototype of an XCELS module, but will also enable solving fundamental problems associated with phasing of channels, as well as completing diagnostic equipment for applications. In addition, final corrections will be made in the architecture and component base of the XCELS facility. Further work on creation of a subexawatt laser will be performed at the implementation phase. It includes construction of a new building and engineering infrastructure, assembling of the 12-channel laser system, an electron source with particle energies of 100 MeV, experimental laboratories, a computer and communication centers, supporting services. It supposed that the implementation phase will be finished in 2019.

The operational phase will start in 2020, and during two subsequent years all research laboratories around the XCELS source will come to the continuous operation mode. They include laboratories for experiments on the physics of strong fields, high-energy physics, laboratory astrophysics and cosmology, nuclear optics, neutron physics, laboratories for studying the properties of vacuum, attosecond and zeptosecond physics, and fundamental metrology. XCELS will also comprise a powerful center for data processing and computer modeling of the interactions of extreme light fields.

### 3. Approaching Exawatt level

12 laser amplification channels in the XCELS facility will enable achieving not only subexawatt power at collective action on a laser target but also a sharp increase of the optical field intensity near the focal point at coherent combining of the radiation of 12 pulses. For high accuracy phasing we use idea of interferometric compare of different beam phases. The optical length tuning realized with deformable mirror, which is driven by two feedback loops (fast and slow). Maximum field strength $E_{\text{max}} \approx 14.5 \frac{P^{1/2}}{\lambda}$ at focusing radiation with specified power $P$ and wavelength $\lambda$ can be attained in the converging dipole-wave geometry. However, it is hardly possible to obtain an optical field structure in the form of a converging dipole wave, even using all available up-to-date tools of adaptive optics. On the other hand, it is possible to approach the desired limit working with smooth wave fronts and focusing systems of F/1 class. A 12-channel system with focusing off-axis parabolas arranged in the form of a double circumferential layer (Fig. 3) will provide at the focal point only a 10% weaker field than $E_{\text{max}}$, which, with the total power of the channels of 200 PW, will produce an intensity over 1.3

| Item, PEARL | PEARL-10 | XCELS |
|-------------|----------|-------|
| Pump laser energy, fundamental harmonic, kJ | 0.31 kJ | 1 kJ | 12 kJ |
| Pump laser energy, second harmonic, J | 180 J (58%) | 2 ch @ 400 J (80%) | 12 ch @ 800 J (80%) |
| Chirped pulse energy (each channel), J | 38 J (21%) | 150 J (38%) | 300 J (38%) |
| Output energy, J | 24 J | 2 ch @ 120 J (80%) | 12 ch @ 225 J (80%) |
| Pulse duration, fs | 43 fs | 30 fs | 15 fs |
| Setup Power | 0.5 PW | 8 PW | 180 PW |
| Repetition rate, Ipulse at | 40 min | 5 min | 3 hour |
| Number of channels | 1 | 2 | 12 |

Using near flat top pulse shaping give us possibilities to increase pump-to-signal conversion efficiency at OPCPA final stage from 21% to 38%, and decrease synchronization requirements and influence desynchronization on output signal specter.
10^{26}$ W/cm$^2$. This intensity is equivalent to the intensity attained at focusing with $F/1$ of one radiation channel with a power of about 2 EW (!). The possibility of generating an order of magnitude higher intensities at optimal focusing of 12 coherently combined beams is a major challenging advantage of XCELS which will be the first infrastructure that will make it possible to carry out experiments on exawatt physics.

4. New particle and radiation physics with PEARL 10 and XCELS

Though the research program with PEARL 10 and XCELS is supposed to cover a broad range of phenomena such as laser-particle acceleration, photonuclear physics, laboratory astrophysics, etc, we will briefly consider several directions of the fundamental science that make this program specific in comparison with other upcoming multipetawatt laser facilities. This specificity stems from the capability to accelerate particles in the radiation dominated regime, to initiate nonlinear QED processes and to observe direct vacuum ionization by electromagnetic fields.

Starting from intensities of about $10^{23}$ W/cm$^2$ and higher, the interaction between laser radiation and matter develops in the radiative, near QED regime. In this regime the most of the laser energy is converted to the energy of gamma-quanta and the radiation reaction plays a key role. The laser to gamma-ray conversion efficiency grows as the laser intensity in power $3/2$ achieving ten percent at the level slightly above $10^{23}$ W/cm$^2$. In the radiative regime the laser-foil interaction became a very efficient mechanism for gamma-ray source. In the PEARL 10 relevant case of oblique incidence of a 3 PW, 10 fs laser pulse on a thin foil about $10^8$ photons/0.1% bandwidth are produced at the energy level of 1 MeV that significantly exceeds performance of the modern Compton gamma-ray sources. For configuration of counterpropagating circularly polarized laser pulses and a plane plasma target of nanometer thickness, the conversion efficiency from the optical to the gamma range can be significantly enhanced. At higher laser intensities numerous electron-positron pairs are produced, so that the electron-positron plasma dencity may exceed the foil density (see Fig. 4).

Even if we neglect collective processes and focus on a single particle moving in the fields of simplest configuration like a plane traveling or standing wave, the particle trajectories demonstrate astonishing features in the radiative, near QED regime. One of them is radiation trapping of emitting particles. This effect allows concentrating the emitting particles in space and synchronizing their motion in time, thus providing maximum efficiency and directivity of the $\gamma$-ray sources. Moreover, even single particle may initiate QED cascade in the strong laser field thereby resulting in avalanche-like production of hot and dense electron-positron and gamma-quanta plasmas.

At laser intensities higher than $10^{24}$ W/cm$^2$, QED cascading becomes one of the key processes accompanying laser-matter interaction. The scenario for QED cascading can be described as follows. The charged particle is accelerated in the laser field and emit high-energy photons, the photons by turn may decay in the laser field with electron-positron pair production. The arising electrons and positrons are accelerated in the laser field and create new generation of the photons and pairs. The number of the particles increases exponentially in time and

Fig. 3 12-channel system with focusing off-axis parabolas arranged in the form of a double circumferential layer to provide optical radiation geometry close to diverging dipole wave.

Fig. 4 The distribution of the ions, electrons, positrons and gamma-quanta calculated in 3D PIC simulation for the laser-foil interaction at laser intensity $10^{25}$ W/cm$^2$.

Fig. 5 The distribution of electron-positron pair density (a), the gamma-quanta density (b) and the laser intensity (c) at the XCELS focal spot because of QED cascade developing.
electron-positron pair plasma with gamma-quantas are produced. QED cascade stops when the total laser energy is converted to the cascade energy. The total number of the cascade particles can be estimated by balancing the laser energy and the energy of the cascade particles. The density of the self-generated electron-positron plasma is close to the relativistic critical density. The laser intensity of 12 XCELS laser pulse focused by dipole field configuration may reach $\sim 10^{26}$ W/cm$^2$.

The particle density and laser intensity distribution as a result of QED cascading in such field is shown in Fig. 5. About 15% laser energy is absorbed and ~11% the laser energy is converted into gamma-ray energy. The electron-positron plasma density may reach $\sim 10^{27}$ cm$^{-3}$.

Achieving extreme intensities in the XCELS project will provide optical field magnitude in excess of 1016 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 with production of electron-positron pairs in the geometry of the dipole focusing. However, this fundamental effect of the nonlinear QED can be hidden by development of cascades with the participation of high-energy photons emitted by the particles born. To investigate the spatio-temporal properties of the vacuum in the “pure” form, an approach based on a superluminal attosecond probe can be engaged. It involves a highly efficient conversion of femtosecond pulses of XCELS laser channels in attosecond pulses at a target with a groove-shape geometry, which provides energy concentration in a moving spot with dimensions of the order of 10 nm, i.e. an ideal probe to study nonlinear properties of vacuum.

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References

1) G. Freidman, N. Andreev, V. Ginzburg, E. Katin, E. Khazanov, V. Lozhkarev, O. Palashov, A. Sergeev, and I. Yakovlev: Proc. SPIE, 4630 (2002) 135.
2) V. Lozhkarev G. I. Freidman, V. N. Ginzburg, E. V. Katin, E. A. Khazanov, A. V. Kirsanov, G. A. Luchinin, A. N. Mal’shakov, M. A. Martyanov, O. V. Palashov, et al.: Laser Physics Letters 4 (2007) 421.
3) A. Gonoskov, I. Gonoskov, C. Harvey, A. Ilderton, A. Kim, M. Marklund, G. Mourou, and A. Sergeev: Phys. Rev. Lett. 111 (2013) 060404.
4) C. P. Rüdiger, C. S. Brady, R. Druclous, J. G. Kirk, K. Bennett, T. D. Arber, and A. R. Bell: Phys. Plasmas 20 (2013) 056701.
5) E. N. Nerush, I. Yu. Kostyukov, and L. Ji, A. Pukhov: Gamma-ray generation in ultrahigh-intensity laser-foil interactions, accepted for publication in Phys. Plasmas.
6) Ya. B. Zel’dovich: Sov. Phys. Usp. 18 (1975) 79.
7) A. V. Bashinov and A. V. Kim: Phys. Plasmas 20 (2013) 113111.
8) A. Gonoskov, A. Bashinov, I. Gonoskov, C. Harvey, A. Ilderton, A. Kim, M. Marklund, G. Mourou, and A. Sergeev: arXiv: 1306.5734 [plasm-ph].
9) A. R. Bell and J. G. Kirk: Phys. Rev. Lett. 101 (2008) 200403.
10) A. M. Fedotov, N. B. Narozhny, G. Mourou, and G. Korn: Phys. Rev. Lett. 105 (2010) 080402.
11) I. V. Sokolov, J. A. Nees, V. P. Yanovsky, N. M. Naumova, and G. A. Mourou: Phys. Rev. E 81 (2010) 036412.
12) S. S. Bulanov, T. Zh. Esirkepov, A. G. R. Thomas, J. K. Koga, and S. V. Bulanov: Phys. Rev. Lett. 105 (2010) 220407.
13) E. N. Nerush, I. Yu. Kostyukov, A. M. Fedotov, N. B. Narozhny, N. V. Elkina, and H. Ruhl: Phys. Rev. Lett. 106 (2011) 035001.
14) A. A. Gonoskov, A. V. Korzhimanov, A. V. Kim, M. Marklund, and A. M. Sergeev: Phys. Rev. E 84 (2011) 046403.
15) E. V. Baklanov, S. N. Bagayev, A. K. Dmitriev, A. V. Taichenachev, and V. I. Yudin: International Conference on Lasers, Applications and Technologies (ICONO/LAT 2013), Moscow, Russia, June 18-22, 2013.