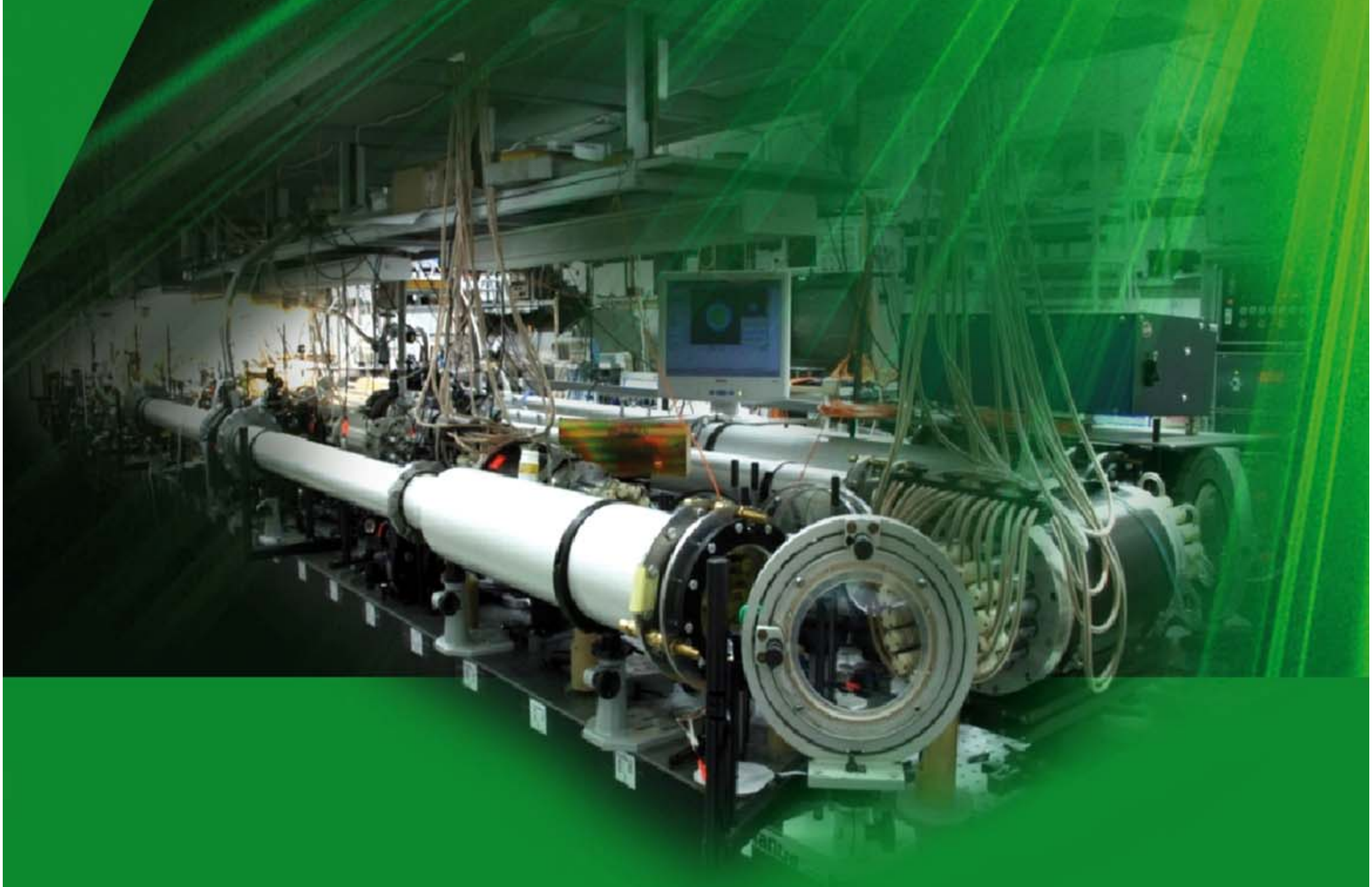
Exawatt Center for Extreme Light Studies (XCELS)



1. Project summary

The goal of the Project is establishing a large research infrastructure – the Exawatt Center for Extreme Light Studies (XCELS) using sources of laser radiation with giant (exawatt) peak power. The Project rests upon the considerable advance made in the recent years in Russia and worldwide on creating petawatt lasers (1 Petawatt = 10^{15} W) with intensity up to 10^{22} W/cm^2 and ultrashort pulse duration (< 100 femtoseconds = 10^{-13} s). The core of the planned infrastructure will be a new unique source of light having the power of about 200 Petawatt with a further prospect to increase it up to 1 Exawatt (1 Exawatt = 10^{18} W) and beyond. The fundamental processes of such laser-matter interaction 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 and unknown phenomena at the interface of the high-energy physics and the physics of high fields. The envisaged applications of results of these studies will include among others development of compact charged-particle accelerators with sizes hundreds times less that the available ones, creation of sources of ultrashort pulses of hard X-ray and gamma radiation for diagnosing materials with unprecedented spatial and temporal resolution, elaboration of new sources of radiation and particles for clinical applications, and others.

Priority areas of research

The research program providing priority of XCELS functioning will include the following key areas:

1. Creation of sources of ultrashort coherent and incoherent radiation with record high brightness in the X-ray and gamma ranges based on radiation of ultrarelativistic charged particles moving in ultraintense laser fields, use of these sources for diagnosing processes and structures with picometer spatial and subfemtosecond temporal resolution.

2. Development of multicascade compact laser electron accelerators with energies above 100 GeV, use of the laser-plasma acceleration principles for developing advanced accelerator complexes with particle energies of 1-10 TeV.

3. Elaboration of compact laser ion accelerators with energies of 0.1-10 GeV and development of their applications in radiography and medicine.

4. Production and investigation of extreme states of matter arising under the action of ultrarelativistic laser fields; modeling of astrophysical and early cosmological phenomena in laboratory conditions.

5. Creation of sources of electromagnetic waves of attosecond (10^{-18}s) and subattosecond duration based on the generation of high harmonics of laser radiation and supercontinuum in a hyperwide spectral range in the course of the nonlinear interaction of powerful femtosecond laser pulses with matter, development of methods for application of such sources in the fundamental metrology and diagnostics of fast processes in matter.

6. Creation of a source of electromagnetic radiation with peak power over 1 Exawatt (10^{18}W) on the basis of the interaction of multipetawatt laser pulses with plasma in ultrarelativistic regime.

7. Study of the space-time structure of vacuum probed by radiation with intensity exceeding 10^{25} W/cm^2, investigation of the phenomena of quantum electrodynamics in the presence of ultraintense laser fields, including producing of matter and antimatter by means of radiation.

8. Research into a new field of science – nuclear optics – based on the use of secondary sources of gamma radiation for excitation and diagnostics of intranuclear processes.

The above program of priority research points to XCELS multifunctionality. A considerable amount of research will be carried out at the junction with other areas of knowledge – high energy physics, nuclear physics, astrophysics, and biomedicine.

Interest in the Project in other countries

XCELS's radiation source characteristics will essentially surpass the level of the most powerful available or projected laser facilities in the world, including the most advanced ones within the framework of the European infrastructure mega-project ELI (Extreme Light Infrastructure). Therefore, XCELS will naturally attract a worldwide interest in the research community by providing opportunities for international collaboration in a wide range of modern sciences and applications.

To date, the interest in participating in the creation and exploitation of XCELS was expressed by the Ministry of Education and Science of France, the Commissariat of Atomic Energy of France, the Nuclear Energy Agency of Japan, the European Centre for Nuclear Research, Los Alamos National Laboratory (USA), Fermi National Accelerator Laboratory (USA), High Energy Accelerator Research Organization KEK (Japan), Rutherford Appleton Laboratory (UK), The John Adams Institute for Accelerator Science

(UK), Center for Antiproton and Ion Research FAIR (Germany), National Research Institute of Canada. It is supposed that the main contribution of foreign partners will be supply of high-tech research equipment for the laser complex and research laboratories, totaling about 15% of the Project cost.

Currently, the most important foreign contributions to the development of the XCELS Project are made by France. In 2009, Russia and France signed the international agreement on the development of research on extreme laser fields ELISA which stimulated development of the XCELS Project. In 2011, the Ministry of Education and Science of France organized the new international institute IZEST (International Institute for Zettawatt-Exawatt Science and Technology) to provide scientific and scientific-organizational support of projects aimed at developing exawatt power lasers and their applications. XCELS is regarded by this institute as a major research project that will play a decisive role in the development of the corresponding field of knowledge in the next decade. This initiative has been supported by the largest research laboratories wishing to collaborate with IZEST and XCELS.

The XCELS Project is also supported by the leading international organization on the creation and use of ultra intense lasers ICUIL (International Committee on Ultra Intense Lasers), which coordinates the activities of the major laser labs around the world.

Negotiations on cooperation under the XCELS Project are initiated with the heads of the European infrastructure project ELI and representatives of the European Commission. The ELI project, which aims at creating and using sources of extreme light fields has successfully completed the preparatory phase, in which 13 European states participated. By the results of the preparatory phase, the European Commission made a decision to build in 2011-2016 three new laser centers with sources having power of about 10 PW in Hungary, the Czech Republic and Romania with the cost of construction of each of about 280 million euros. The facility that will be built in Hungary is intended for research on the generation and use of attosecond pulses. The facility constructed in the Czech Republic will be used to develop laser-plasma accelerators and new sources of X-ray and gamma radiation. In Romania, the facility will be intended for conducting research in the field of photonuclear physics. XCELS will naturally be of interest for international cooperation with the ELI consortium on extreme laser fields, as it will have a laser source of the next generation and a research program using fields that are not available in other research centers.

Basic parameters of the XCELS infrastructure

The subexawatt laser significantly exceeding the level of radiation power inherent in the most powerful available, constructed or projected laser systems worldwide, will be based on the technique of optical parametric chirped pulse amplification (OPCPA) to the petawatt power developed at the Institute of Applied Physics RAS. The complex will comprise 12 identical channels, each of which will generate 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 (Fig. 1.1). The channels operate by the scheme of parametric amplification in KD*P crystals with the aperture of final cascades of 30×30 cm^2.

It is supposed that optical pulses in laser modules of the subexawatt complex will be phased to an accuracy of hundredths fractions of a light wave period (10^{-16}s). The first phase of the Project will be creation at IAP RAS of two such modules with the power of 15 PW each based on parametric amplification in KD*P crystals. 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, 12 channels of the main XCELS laser complex will be assembled by the proven technology in a newly constructed building of the international center.

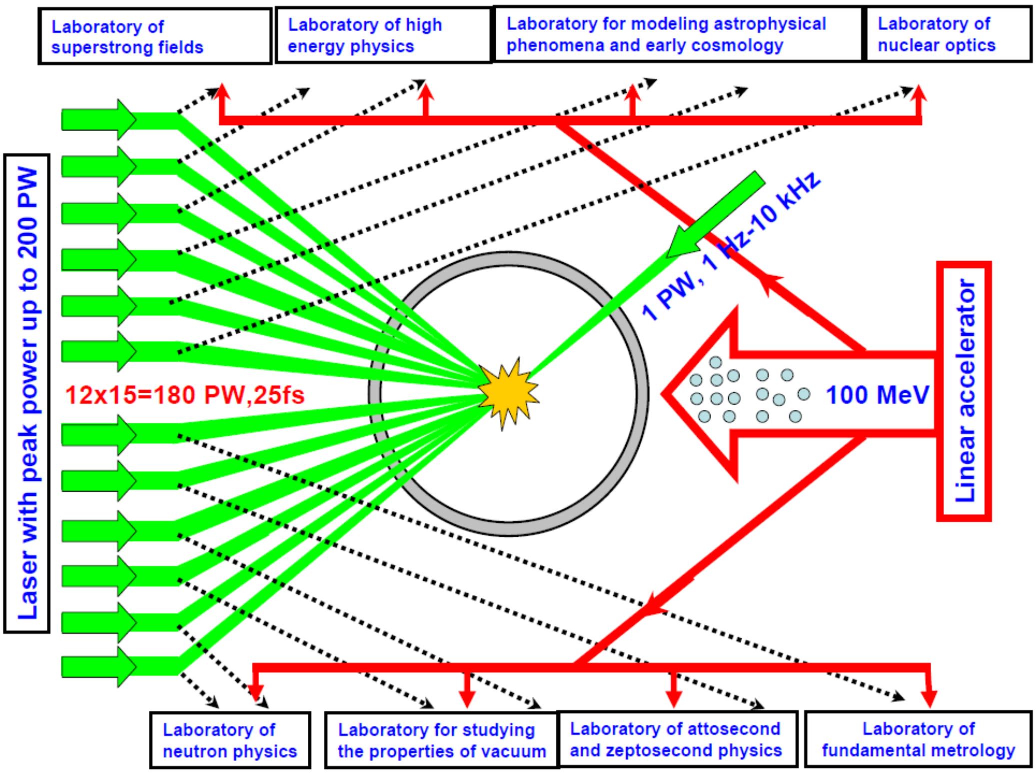


Fig. 1.1. General layout of subexawatt laser channels, the main target chamber, linear accelerator, and research laboratories

The resulting radiation at the output of the laser complex will have the following parameters: power 200 PW, pulse duration 25 fs, wavelength 910 nm, divergence not more than 3 diffraction limits.

Along with the subexawatt laser XCELS will house a 100 MeV linear accelerator of electrons and unique 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.

XCELS will be a unique research center of international level both in terms of the radiation source parameters and the planned research program. The period of superiority over the existing facilities and the ones constructed outside Russia intended for studies of extreme light fields will begin with the launch of the first laser prototype with the power level of 10 PW (2016) and will continue with the rise in the laser complex power (2019). The future superiority will be ensured by creation of a source of electromagnetic radiation with peak power exceeding 1 Exawatt on the basis of the interaction of multipetawatt laser pulses with plasma in the ultrarelativistic regime (2021). The superiority of the collective program of experimental studies will be maintained from the beginning of the first experiments on the two-channel prototype (2017) and far-reaching.

Fig. 1.2. Prospective view of XCELS

From the point of view of the proposed research program, level of technological requirements to the unique laser complex, required qualification of the scientific and technical personnel, the most appropriate base for XCELS in the Russian Federation is the Institute of Applied Physics of the Russian Academy of Sciences in Nizhny Novgorod. XCELS construction and exploitation will involve collaborative efforts of a large team of Russian research and educational centers, including the Institute of Applied Physics RAS (IAP RAS), Institute on Laser and Information Technologies RAS (ILIT RAS), Russian Research Center (RRC) "Kurchatov Institute", Joint Institute for Nuclear Research (JINR), P.N.Lebedev Physics Institute RAS (LPI RAS), General Physics Institute RAS (GPI RAS), Budker Institute of Nuclear Physics (BINP), Joint Institute for High Temperatures RAS (JIHT RAS), Institute of Laser Physics of the Siberian Branch of RAS (ILP SB RAS), Russian Federal Nuclear Center (RFNC-VNIIEF), Moscow State University (MSU), National Research Nuclear University MEPhI (MEPhI), University of Nizhny Novgorod (UNN), and others.

In addition to the main base, the XCELS complex will include satellite laboratories engaged in elaborating and finalizing different critical technologies of the subexawatt laser and in developing some applications of results of the basic research obtained in XCELS. These laboratories may be organized, in the first place, in ILIT RAS, RRC "Kurchatov Institute", and MEPhI.

The average number of XCELS employees is about 300 persons, including 100 full-time engineering and technical personnel and administrative staff, 100 full-time Russian scientists, and 100 visiting Russian and foreign specialists.

Total Project budget and schedule of its implementation

The preliminary cost of the center is estimated to be 40.3 billion rubles, including 32.2 billion rubles from the state budget, 6.1 billion rubles from foreign partners, and 2 billion rubles of extra-budgetary funds from domestic sources. With the start of the Project in 2014 the 200 PW laser facility will be built by 2019 with the subsequent program of experimental research intended up to 2023. The corresponding XCELS roadmap is available on page 22.

2. XCELS: Why in Russia and why in Nizhny Novgorod

Besides the essential budget investments, the feasibility of the XCELS Project in Russia is substantiated by the presence of world-renowned scientific schools and the availability of highly qualified researchers and engineers in the area of the Project.

Major Russian scientific schools in the area of XCELS

Russia has world-renowned scientific schools in the main areas of XCELS research, i.e. in the fields of laser physics, interactions of powerful electromagnetic radiation with matter, high-sensitivity optical measurements, and theoretical physics. These schools work in the major Russian academic institutions and universities.

Three scientific schools in the General Physics Institute are closely connected with the work of the prominent scientists, Nobel Prize winners Academicians A.M.Prokhorov and N.G. Basov. These are:

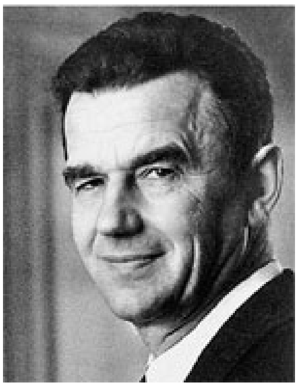
- «The physics of coherent laser-matter interaction, methods of controlling spatial, temporal and spectral characteristics of laser radiation" under the supervision of the Corresponding Member of RAS Pavel Pashinin.
- «The physics and technology of crystals and nanocrystalline materials for photonics," Supervisor – Academician Vyacheslav Osiko.
- «New effective optical materials and components for the near and middle infrared spectral ranges," Supervisor – Corresponding Member of RAS Ivan Shcherbakov.

Alexander M. Prokhorov

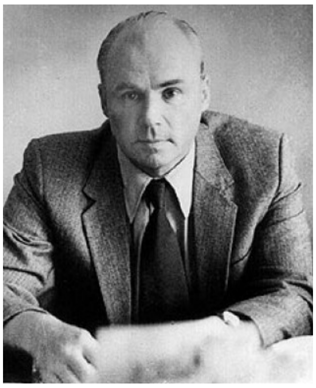
Nikolay G. Basov

At the P.N.Lebedev Physics Institute there are the scientific schools in theoretical physics headed by Academician Leonid Keldysh, in quantum radiophysics headed by Academician Oleg Krokhin, and in the theory of fundamental interactions supervised by the Corresponding Member of RAS Vladimir Ritus.

The school at the Moscow State University was formed by the outstanding Soviet scientists Academician Rem Khokhlov and Professor Sergey Akhmanov, founders of nonlinear optics. Currently, this school has the name “Femtosecond nonlinear and quantum optics” and is headed by Professor Vladimir A. Makarov.



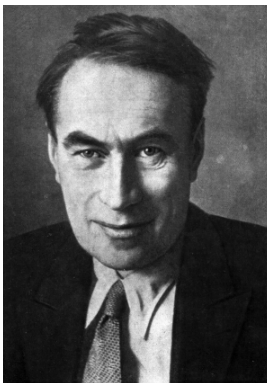
Rem V. Khokhlov



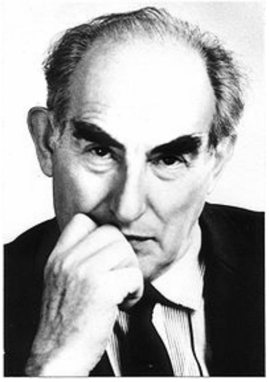
Sergey A. Akhmanov

The Institute of Applied Physics has three scientific schools, which owe their origin to the founders of the Nizhny Novgorod radio physics Academician Alexander Andronov, Nobel Prize winner Academician Vitaly Ginzburg and Academician Andrey Gaponov-Grekhov. These are:

- “The interaction of intense electromagnetic radiation with plasma” headed by Academician Alexander Litvak.
- “Femtosecond optics, nonlinear dynamics of optical systems and high-sensitivity optical measurements” supervised by the Corresponding Member of RAS Alexander Sergeev.
- “Ultraintense light fields and their interaction with matter, large aperture nonlinear optical crystals, lasers with high average and peak power, parametric conversion of laser radiation” founded by Prof. Victor Bespalov and Prof. Gennady Freidman.



Alexander A. Andronov



Vitaly L. Ginzburg

Andrey V. Gaponov-Grekhov

The Joint Institute for High Temperatures (JIHT) has the school “Investigation of the properties of condensed matter and plasma under extreme conditions at high energy densities” under the supervision of Academician Vladimir Fortov.

At the Institute of Laser Physics SB RAS there is a school in the area of XCELS that is called “Ultrahigh resolution laser spectroscopy and its applications” that is headed by Academician Sergey Bagaev.

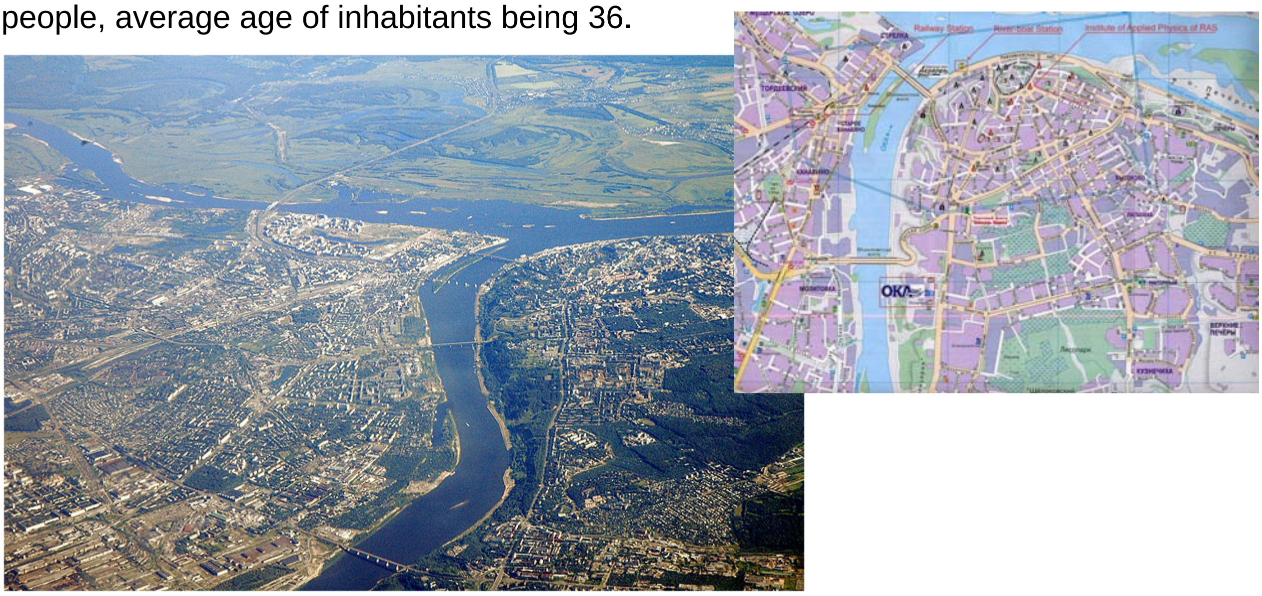
The National Nuclear Research University MEPhI has the school “Basic problems of the behavior of quantum systems in radiation fields” supervised by Prof. Nikolay Narozhny.

Nizhny Novgorod and the Nizhny Novgorod Region – overview

Why is Nizhny Novgorod a natural choice for the XCELS site?

Nizhny Novgorod is one of the biggest industrial, scientific, educational and cultural centers in Russia. It was founded in 1221 and recently regained its original name, having been renamed Gorky in 1932 in honor of the celebrated author Maxim Gorky, who was born in Nizhny Novgorod. Nizhny Novgorod is situated in the central European part of Russia, about 400 km east of Moscow, at the confluence of the Volga and the Oka rivers. The City has advantageous geographical location for economic and social development.

It covers an area of 41.1 thousands hectares, its population is 1370.2 thousand people, average age of inhabitants being 36.



Nizhny Novgorod is a beautiful historical and cultural center. The image of the city has preserved the multitude of historic and cultural layers that gave ground to UNESCO to include Nizhny Novgorod in the list of 100 cities constituting world historical and cultural value.

Brilliant examples of old Russian architecture are the Nizhny Novgorod Kremlin that has been preserved since the early 16-th century, the architectural ensemble of the Nizhny Novgorod Trade Fair that became a subcenter of the city in the 19th century, making the trade fair one of the biggest in Russia and Europe, and numerous churches and monasteries, more than 600 unique historic, architectural and cultural monuments.

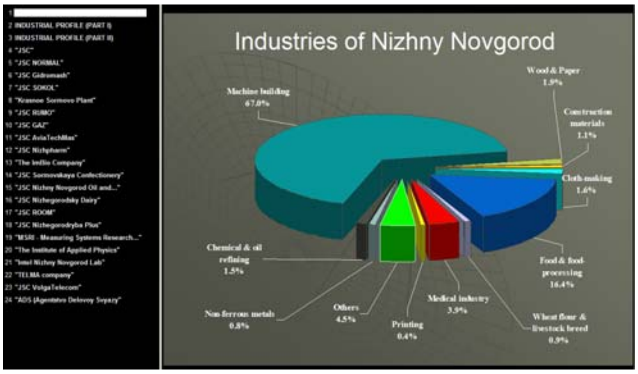
There are about 200 culture and art institutions in Nizhny Novgorod, including 8 theatres, 5 concert halls, 97 libraries, 17 cinema theaters, 25 institutions of children optional education, 16 museums, 7 beautiful parks. One of the biggest concert organizations in Russia is the Nizhny Novgorod State Academic Philharmonic Society established in 1937, now named after Mstislav Rostropovich.

The advantageous geographical location and a traditional role of Nizhny Novgorod as a trade center gave premises for creation of a comparatively high-developed transport infrastructure. Railways, motor roads, water- and airways conveniently connect Nizhny Novgorod with any Russian region, the CIS and foreign states.

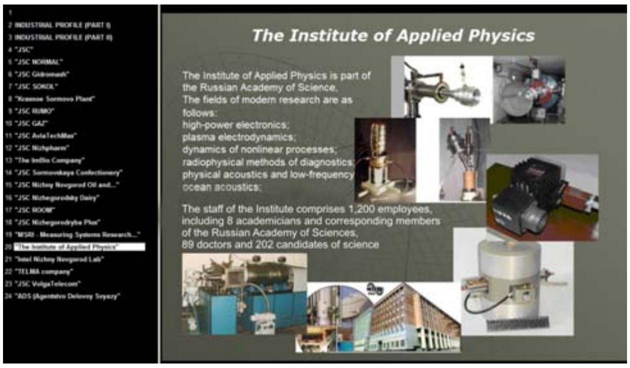
The Nizhny Novgorod transport junction, which includes the international airport "Nizhny Novgorod", the railway station, and a river port is one of the most visited in Russia. Rivers and channels connect Nizhny Novgorod with 5 seas and afterwards provide an exit into the ports of the Scandinavian countries, the Eastern Europe, Africa and Asia.

Nizhny Novgorod belongs to the five most populated and industrially developed cities of Russia, is a center of the Nizhny Novgorod region and a recognized capital of the Volga economic region. It is a big business and industrial center. Business rhythm and search for new technologies guarantee its economic success in the third millennium.

Industry occupies a significant place in the City's structure. The principal branches are motor car construction, radio electronics, ship-building, atomic energy industry, metal-working industry, ferrous and non-ferrous metallurgy, wood manufacturing, food and light, medical and printing industries. Many achievements of Nizhny Novgorod have worldwide fame: the world's first commercial fast-breeder reactor, radars of the fifth generation, the world leadership in designing hydrofoils and surface effect vehicles, and others.



Industries of Nizhny Novgorod



The Institute of Applied Physics

The Institute of Applied Physics is part of the Russian Academy of Science.
The fields of modern research are as follows:
high-power electronics;
plasma electrodynamics;
dynamics of nonlinear processes;
radiophysical methods of diagnostics;
physical acoustics and low-frequency ocean acoustics;

The staff of the Institute comprises 1,200 employees, including 8 academicians and corresponding members of the Russian Academy of Sciences, 89 doctors and 202 candidates of science

The advance in industries has become possible thanks to the well developed system of education.

The Nizhny Novgorod scientific-educational cluster

The Nizhny Novgorod region has all necessary conditions for effective development of scientific-educational complex and innovations.

The system of science and education comprises both fundamental and applied sciences. There are about 100 R&D facilities in the Nizhny Novgorod region, including 10 branches of federal ministries and agencies and institutes of the Russian Academy of Sciences, the Russian Federal Nuclear Center (Sarov), 18 specialized R&D institutes, 24 design, technological and survey companies, over 20 industrial companies. The number of researchers per 10 000 population in the Nizhny Novgorod region exceeds the Russian average by 4 times.

The developed defense complex, engineering industry, including aircraft manufacturing and ship-building), radio electronics, nuclear physics and power engineering, medicine, science of materials form the basis of the technological foundation of scientific and educational complex of the region.

The educational policy is based on the strategic goal to pursue innovative development and broad collaboration with national and international partners.

A strong educational system of Nizhny Novgorod provides education to 300,000 school students and 247,000 college and university students every year. Nizhny Novgorod universities are among leaders in Russia and get top positions in the rating of the Russian Ministry of Education and Science.

The number of higher educational institutions of the Nizhny Novgorod region (concentrated in Nizhny Novgorod), including branches of other universities exceeds fifty. They train tens of thousands of students, with about 5000 professors and teachers. Leading universities of the city are among the best universities of Russia. These are the Nizhny Novgorod State University, the Nizhny Novgorod State Medical Academy and the Nizhny Novgorod Linguistic University. Also worth mentioning are the State Technical University of Nizhny Novgorod and the State University Higher School of Economics.

International educational programs are continuously developing. These include the Russian-French, Russian-Italian and Russian-Danish public universities, the International Institute of Economics, Law and Management established as a result of collaborative effort of Nizhny Novgorod and European universities.

Fundamental studies are focused mainly at the academic institutes and at the Nizhny Novgorod State University. The first Radiophysics Department in the USSR was opened at UNN after World War II, and in the early 1960s the country's first department of computational mathematics and cybernetics. It is here that early research on the subject of the Project – quantum electronics, laser physics, plasma physics, mathematical modeling of physical processes, parallel computing was conducted.

Six institutes of the Russian Academy of Sciences work in Nizhny Novgorod. These include

- Institute of Applied Physics
- Institute for Physics of Microstructures
- Institute of Chemistry of High-Purity Substances
- Institute of Organometallic Chemistry
- Nizhny Novgorod Branch of Mechanical Engineering Institute
- Nizhny Novgorod Department of the Institute of Sociology

In 2009 the Nizhny Novgorod institutes of the Russian Academy of Sciences formed the Nizhny Novgorod Scientific Center (NNSC) that is headed by Academician Alexander Litvak.

Council of the Nizhny Novgorod Scientific Center at the general meeting in 2009

The Center was established to coordinate the work of the academic institutes in the Nizhny Novgorod region, especially in interdisciplinary research, and organization of their interaction with applied research industry, industrial enterprises and regional universities. The major task of the center is also solution of infrastructural and social problems of academic science in the region, including provision of the institutes with up-to-date information and supercomputer technologies. Among the goals of the Center is interaction with local authorities, particularly aiming at their assistance in implementation of Projects in the interests of the region.

The Institute of Applied Physics is acknowledged leader of the academic science in Nizhny Novgorod.

Building of the Institute of Applied Physics

Institute of Applied Physics, the host of the XCELS Project

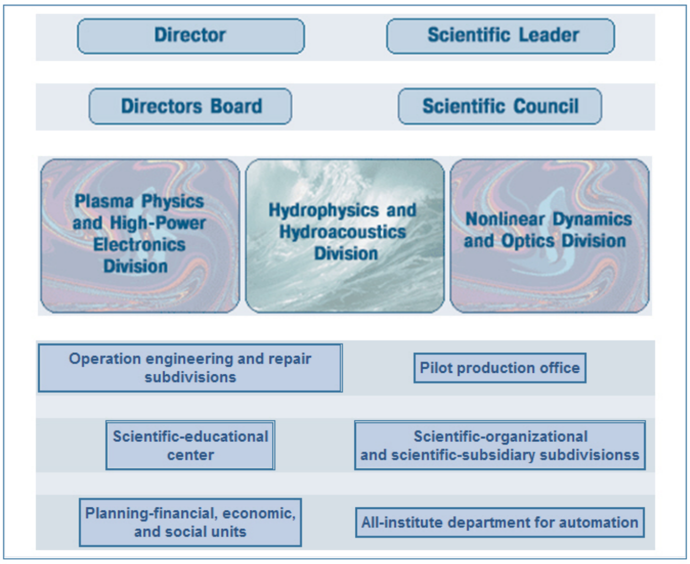
IAP RAS began independent activities in April 1977. The Institute was created on the basis of several divisions of the Radio Physical Research Institute of the Ministry of Higher Education of the Russian Federation. For a quarter of a century it was headed by Academician Andrey V. Gaponov-Grekhov. In 2003 Alexander G. Litvak was appointed director of the Institute and A.V. Gaponov-Grekhov became the research supervisor of IAP RAS.

IAP RAS is one of the largest and most successful institutions of the Russian Academy of Sciences. Scientific studies are provided by about 1,200 employees, about 490 of whom are scientists, including 8 academicians and corresponding members of RAS, 89 doctors and 202 candidates of science. About one third of the scientists are young people aging less than 35.

IAP RAS was conceived and created as a multipurpose institution combining fundamental and applied research in the field of plasma physics, high-power electronics, geophysics, and laser physics. The common oscillation-wave problems combining these research lines, the strong scientific foundation for applied studies, tight connections between science and the higher-education system, and high criteria for training young researchers are the main components in the model of a large academic institution implemented at IAP RAS.

Over thirty years this model proved its viability: it worked even in the nineties, which were hard times for Russian science, and its fundamental principles are, as previously, valid and important.

At present, research at IAP RAS is concentrated in three main scientific divisions: the Plasma Physics and High-Power Electronics Division, the Hydrophysics and Hydroacoustic Division, and the Nonlinear Dynamics and Optics Division.



IAP RAS structure

The main lines of IAP RAS research include:

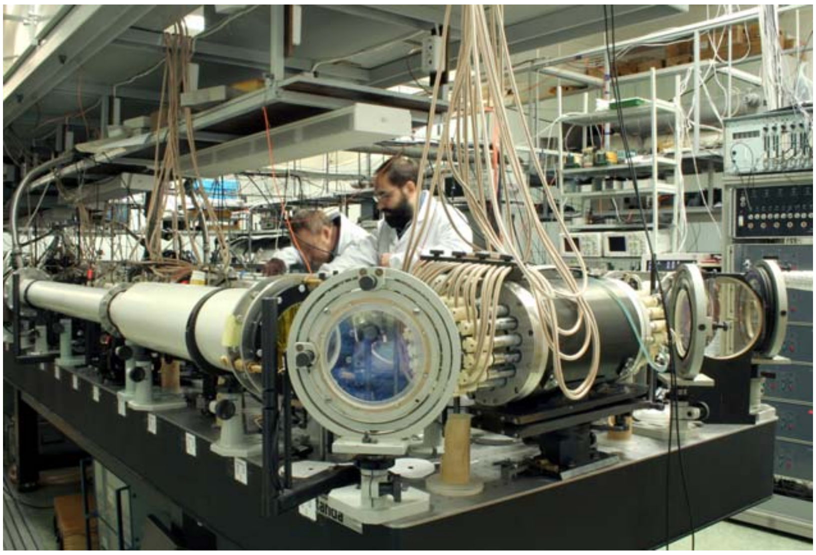
- **high power electronics** (gyrotrons and their applications, relativistic electronics, microwave processing of materials),
- **plasma electrodynamics** (powerful radiation interaction with plasma, plasma astrophysics, geophysical electrodynamics),
- **radiophysical methods of diagnostics** (plasma diagnostics, millimeter and submillimeter radioastronomy, remote diagnostics of natural media, coherent seismoacoustics, vibroacoustics and spectroscopy, nonlinear acoustics, optical tomography),
- **low-frequency ocean acoustics** (long-range sound propagation in the ocean, acoustic tomography of the ocean, low-frequency radiating complexes, hardware for underwater acoustics),
- **dynamics of nonlinear processes** (nonlinear waves, dynamic chaos and structures, internal and surface waves),
- **laser physics and nonlinear optics** (femtosecond lasers and superstrong fields, processes in phase conjugation systems, laser dynamics, water-soluble crystals, biophotonics).

IAP RAS carries out over 350 scientific researches along the main directions of IAP activities annually, takes an active part in implementation of federal special, academic, interdepartmental, international and other programs and Projects.

The most prominent recent achievements of IAP RAS:

- Creation of unique gyrotron complexes for processing and creation of materials with new properties and powerful gyrotrons of the next generation for the International Thermonuclear Reactor (ITER).
- Development of the unique technology of plasma chemical deposition of diamond films from gas phase, which allows significant increase of the growth rate of diamond discs of high optical and mechanical quality.
- Development of high-rate growth and precision processing of water-soluble crystals.
- Development of the technique of optical coherence tomography for imaging internal biotissue structures and designing the corresponding devices that opened up new opportunities for nanobiophotonics and medical diagnosis, including diagnosis of cancer.
- Creation of the petawatt parametric laser complex (PEARL) that is one of most powerful laser facilities in the world; its architecture based on the technique of optical

parametric amplification has been proved to be most promising for extension into the multipetawatt range.



– Creation of a multiterawatt Ti-sapphire laser complex and its use in experiments on acceleration of wake wave electrons, generation of coherent soft X-radiation, and atmospheric discharge initiation by femtosecond radiation in filamentation regime.

IAP RAS has its own pilot production equipped with modern facilities. The main task of the pilot production is timely and high-quality execution of the tasks set by the Institute's scientific divisions. The Institute possesses high-power experimental capability and modern diagnostic techniques.

A number of innovative enterprises have been established at IAP RAS. Their main task is bringing research results to operating models and prototypes and production of high-tech devices and equipment.

The IAP RAS researchers have numerous awards, including the Lenin Prize (1988) and fourteen State Prizes (1980, 1983, 1984, 1985, 1987, 1991, 1997, 1999, 2000, 2003), the Russian Federation State Prize for Young Scientists (2003), a number of RAS medals, the Medal of the European Geophysical Society, K.J.Button Medal, W. Lamb Medal, Prize of the International Thermonuclear Fusion Society, and others.

IAP RAS has wide international scientific relations. Its employees participate in major international scientific and technical programs and international projects under CRDF, NATO, ISTC, and others. Annually, about 150 employees go abroad for international scientific conferences, meetings, and sessions of different committees and societies, and approximately the same number of foreign scientists visit the Institute.

International contacts worldwide

In 2011, the institute carried out works under more than 25 international projects and grants, among which are the Projects under the international programs ITER, HiPER, LIGO, and in collaboration with big international labs like CERN, DESY, KEK and others.

Experience of the Institute of Applied Physics in the field of the Project

Confidence in the feasibility of the Project to create a subexawatt laser is based on high scientific and technological level of IAP and its collaborators. Currently, OPCPA is the only amplification technique provided by the available component base that allows IAP to be the world leader in the exploration and development of OPCPA. In 2007, this institute in collaboration with the Russian Federal Nuclear Center-VNIIEF launched the laser "PEARL" with a pulse power of 0.56 PW, pulse duration about 45 fs and energy 25 J, which is one of the most powerful lasers in the world. This laser uses parametric amplification in the KD*P crystal with the aperture of 10×10 cm^2 which was grown at IAP RAS by the original technology of oriented high-rate crystal growth.

Construction of the laser complex "PEARL-10" with a pulse power of more than 5 PW (Fig. 2.1) was started in 2009 and is advancing successfully. Clean room with untied recessed footing with an area of 200 m^2 and special means of radiation protection from damaging factors that accompany the interaction of high-power light with matter was prepared. Optical equipment is currently installed. The first phase of the XCELS Project – the creation of two modules with the power of 15 PW – will be a natural continuation of these works that are to be completed in 2016. Further work on creation of a subexawatt laser will be associated with replication of laser channels (12 channels) and assembly of a single complex in the XCELS building.

Fig. 2.1. "PEARL-10" laser complex under construction in IAP RAS:
pump laser for parametric amplifier (left)
front end and optical compressor 110 cm in diameter and 500 cm long (right)

Another important factor for Project success is availability at IAP RAS of the unique technology of high-rate growth of nonlinear optical KDP and KD*P crystals that are key elements of the superintense parametric light amplifiers. This technology is based on the method of high-rate growth of profiled monosector crystals. It was the result of scientific research carried out at IAP RAS for several decades. This technique allows producing optical elements with an aperture of 40×40 cm^2 and, which is important for a unique installation containing dozens of nonlinear optical crystals, reducing the growth time by almost an order of magnitude as compared to the classical method and minimizing the waste of the crystal during processing.

IAP RAS has production capacity necessary for production of nonlinear optical components of laser systems for the XCELS Project (Fig. 2.2). It has a crystal samples machining line, including unique diamond micromilling machines and devices for controlling monocrystal billets and roughness parameters of machined surfaces with nanometer precision.

Fig. 2.2. Installations for growing large-aperture nonlinear optical crystals in IAP RAS (left) and element for frequency conversion of superintense optical radiation

For creation in the XCELS complex of channels with peak power of 15 PW, Nd-glass laser pump systems with pulse energy exceeding 1 kJ and pulse duration of about 2 ns are required. RFNC-VNIIEF has a rich experience in creating and operating such systems. VNIIEF has the laser facility "LUCH" with 4 channels of pulse energy in each channel of more than 3 kJ and duration of about 3 ns. The "LUCH" facility was used in the joint Project of VNIIEF and IAP RAS to produce pulses with energies of about 100 J in the parametric amplifier "FEMTA". This result is a world record in the power of parametric amplification of femtosecond pulses and a demonstration of one of the technologies critical for implementation of the XCELS Project (Fig. 2.3).

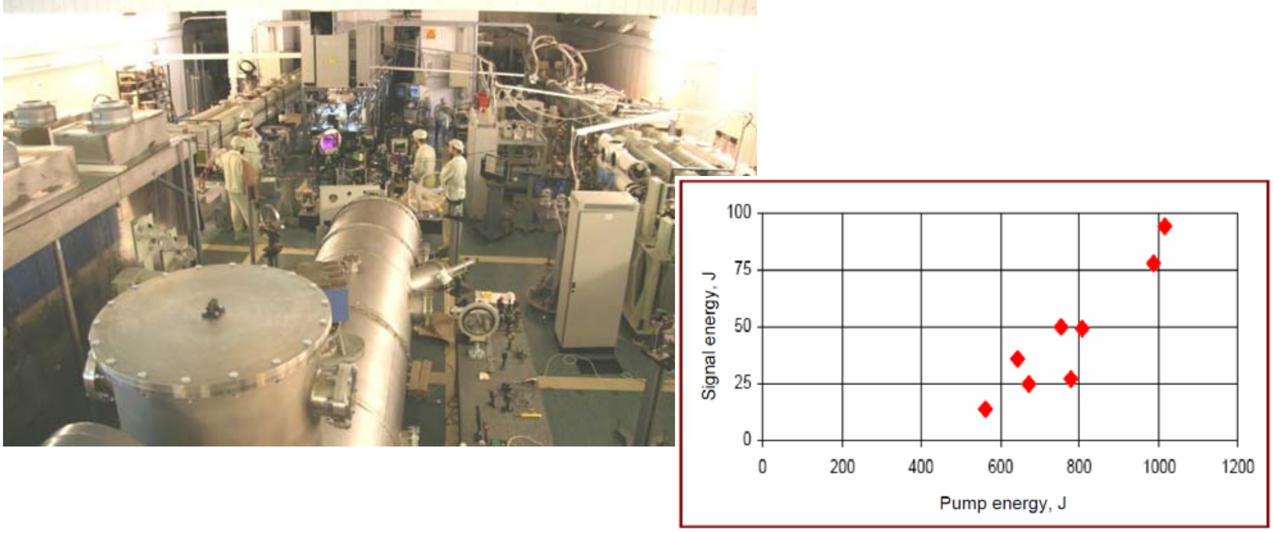


Fig. 2.3. "LUCH" facility with parametric amplifier "FEMTA" at VNIIEF (Sarov) and record characteristics of parametric amplification of femtosecond pulses

Experimental studies of fundamental scientific problems and new applications that will be implemented in XCELS are also based on solid scientific and technological reserve available to scientists in our country. For example, based on the petawatt laser "PEARL" an installation for studying laser-plasma acceleration of electrons in the interaction of powerful optical radiation with gas targets was elaborated in IAP RAS. Accelerating fields over 1 GeV/cm were produced and acceleration of electron bunches with energies up to 300 MeV, spectral width of about 10 MeV, charge of 200 pC, and angular spread of about 2 mrad was demonstrated, which is among the world's best results in laser-plasma acceleration of charged particles. These results were obtained using exclusively domestic experimental and diagnostic base (Fig. 2.4).

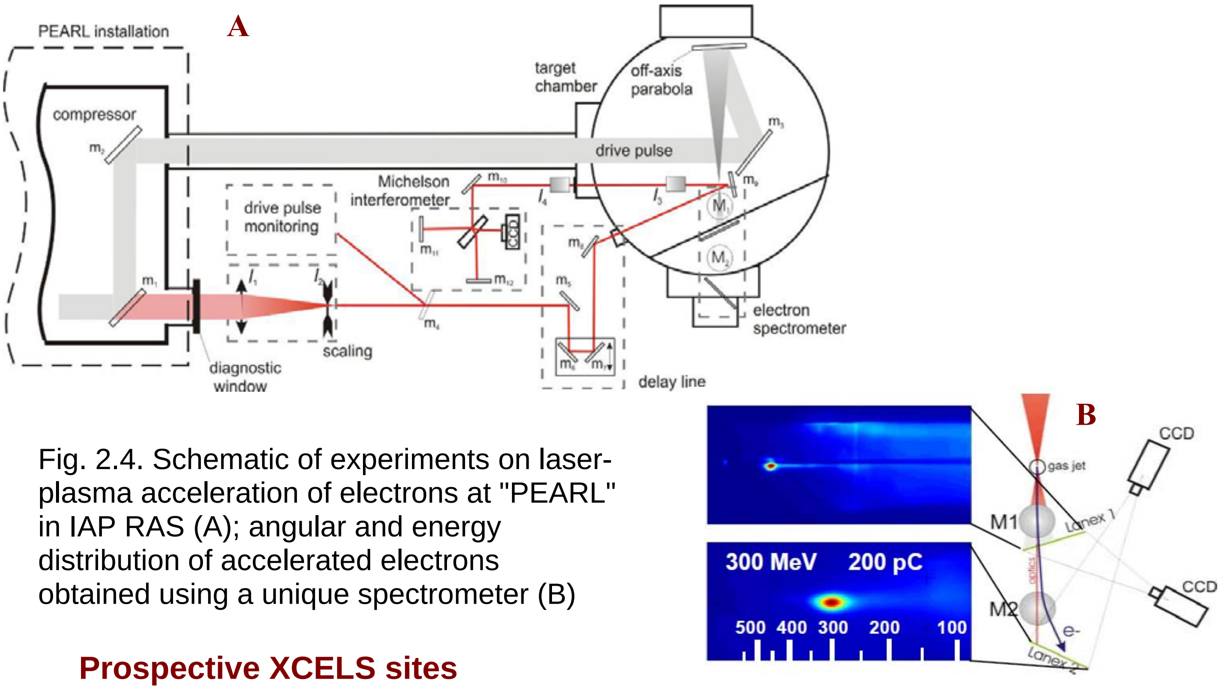


Fig. 2.4. Schematic of experiments on laser-plasma acceleration of electrons at "PEARL" in IAP RAS (A); angular and energy distribution of accelerated electrons obtained using a unique spectrometer (B)

Prospective XCELS sites

To accommodate XCELS, ground area of about 5 hectares, rather far from highways and industrial plants is required. The total area of the laboratory, administrative and ancillary facilities will be about 25 000 m^2, about 15 000 m^2 of which must have different degrees of radiation protection.

Offers of land were obtained from the Administration of Nizhny Novgorod, Nizhny Novgorod Scientific Center RAS, and Nizhny Novgorod State University. Three possible XCELS locations (plots 1-3) and plot 4 owned by IAP RAS for construction of the prototype of 200 PW laser are shown in Fig. 2.5. The site for XCELS will be selected on the basis of the international Project expertise.

The implementation of the XCELS project was approved by the Government Commission on High Technology and Innovation with Vladimir V. Putin as the Chairman on July 5, 2011 (http://www.xcels.iapras.ru/).

Prospective ground areas for XCELS construction

① A plot of land offered by the Administration of the Nizhny Novgorod Region (federal property)

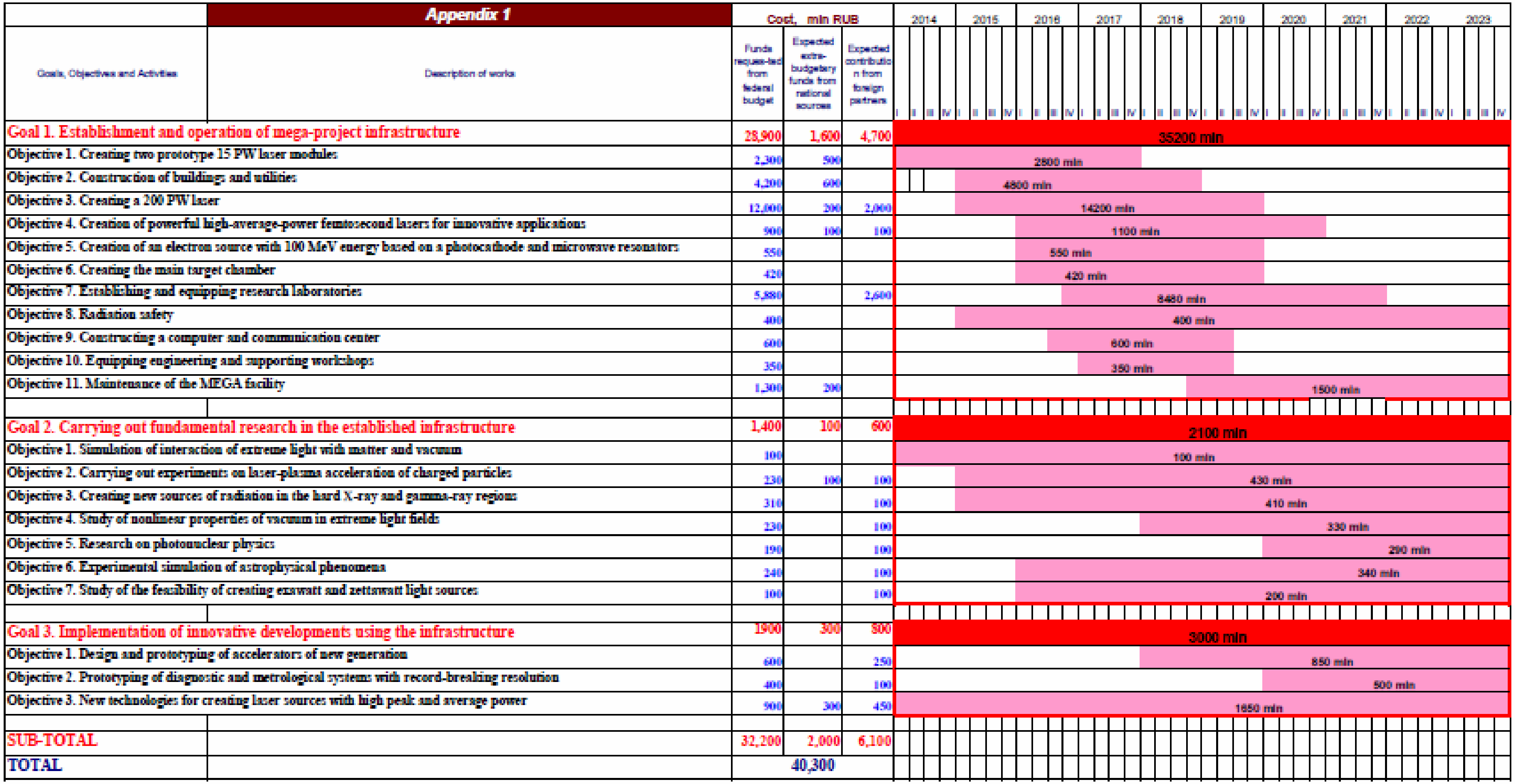
② A plot of land offered by the Nizhny Novgorod Scientific Center RAS (NNSC RAS), which is currently fixed in perpetuity of the Institute of Physics of Microstructures of the RAS (federal property)

③ A plot of land offered by the Nizhny Novgorod State University (federal property)

④ A plot of land to host the prototype offered by IAP RAS (federal property)

Fig. 2.5.

XCELS Roadmap



	Appendix 1	Cost, mln RUB			2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Goals, Objectives and Activities	Description of works	Funds reques-ted from federal budget	Expected extra-budgetary funds from national sources	Expected contribution from foreign partners	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV	I II III IV
Goal 1. Establishment and operation of mega-project infrastructure		28,900	1,600	4,700	35200 mln									
Objective 1. Creating two prototype 15 PW laser modules		2,300	500		2800 mln									
Objective 2. Construction of buildings and utilities		4,200	600			4800 mln								
Objective 3. Creating a 200 PW laser		12,000	200	2,000		14200 mln								
Objective 4. Creation of powerful high-average-power femtosecond lasers for innovative applications		900	100	100			1100 mln							
Objective 5. Creation of an electron source with 100 MeV energy based on a photocathode and microwave resonators		550					550 mln							
Objective 6. Creating the main target chamber		420					420 mln							
Objective 7. Establishing and equipping research laboratories		5,880		2,600			8480 mln							
Objective 8. Radiation safety		400				400 mln								
Objective 9. Constructing a computer and communication center		600					600 mln							
Objective 10. Equipping engineering and supporting workshops		350						350 mln						
Objective 11. Maintenance of the MEGA facility		1,300	200						1500 mln					
Goal 2. Carrying out fundamental research in the established infrastructure		1,400	100	600	2100 mln									
Objective 1. Simulation of interaction of extreme light with matter and vacuum		100			100 mln									
Objective 2. Carrying out experiments on laser-plasma acceleration of charged particles		230	100	100		430 mln								
Objective 3. Creating new sources of radiation in the hard X-ray and gamma-ray regions		310		100		410 mln								
Objective 4. Study of nonlinear properties of vacuum in extreme light fields		230		100					330 mln					
Objective 5. Research on photonuclear physics		190		100							290 mln			
Objective 6. Experimental simulation of astrophysical phenomena		240		100			340 mln							
Objective 7. Study of the feasibility of creating exawatt and zettawatt light sources		100		100			200 mln							
Goal 3. Implementation of innovative developments using the infrastructure		1900	300	800	3000 mln									
Objective 1. Design and prototyping of accelerators of new generation		600		250					850 mln					
Objective 2. Prototyping of diagnostic and metrological systems with record-breaking resolution		400		100							500 mln			
Objective 3. New technologies for creating laser sources with high peak and average power		900	300	450	1650 mln									
SUB-TOTAL		32,200	2,000	6,100										
TOTAL		40,300												