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On some scientific results obtained at institutes of the Physical Sciences Division of the Russian Academy of Sciences over the past 25 years

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Abstract. **This paper is based on my report at the Scientific Session held on May 27, 2024, as part of the General Meeting of the Physical Sciences Division of the Russian Academy of Sciences. The presented results concern such scientific areas as condensed matter physics and physical materials science, optics, laser physics and laser technologies, plasma physics, physical electronics, radiophysics, and acoustics. These areas have been actively developing in recent decades and retain their relevance today.**

Keywords: optics, laser physics, condensed matter physics, radiophysics, physical materials science, medical physics

At the turn of the 21st century, Russia faced the need to overcome the consequences of the destructive 1990s, and the need for change could hardly bypass the Academy of Sciences. This was preceded by setting up the Russian Academy of Sciences (RAS) in 1991 on the basis of the USSR Academy of Sciences [1], which was a consequence of the collapse of the USSR. This painful procedure was accompanied by a decline in the prestige of the Academy itself, as well as a decline in the prestige of scientists. In fact, the reforms of the RAS have been ongoing for the past 25 years. The reforms that began in 2002 were internal reforms of the Academy. They could not solve the main problem of catastrophic underfunding of science. The leadership of the Academy, quite rightly, in my opinion, adhered to the principle of 'do no harm.' There could be no noticeable benefit from such reforms, but 'no harm, however, either.' There was an understanding that hasty, ill-considered, unprepared decisions undiscussed with the scientific community and imposed 'from above' could bring no benefit.

How did the reforms, which were inherently cosmetic, affect the work of the Division of General Physics and Astronomy? It was merged with the Division of Nuclear Physics to form the Physical Sciences Division (PSD RAS) consisting accordingly of two sections.

During this turbulent time, the Academician-Secretaries of the Physical Sciences Division were Aleksandr Fedorovich Andreev, Viktor Anatol'evich Matveev, Ivan Aleksandrovich Shcherbakov (yours truly), and currently Vitalii Vladimirovich Kveder (Fig. 1).

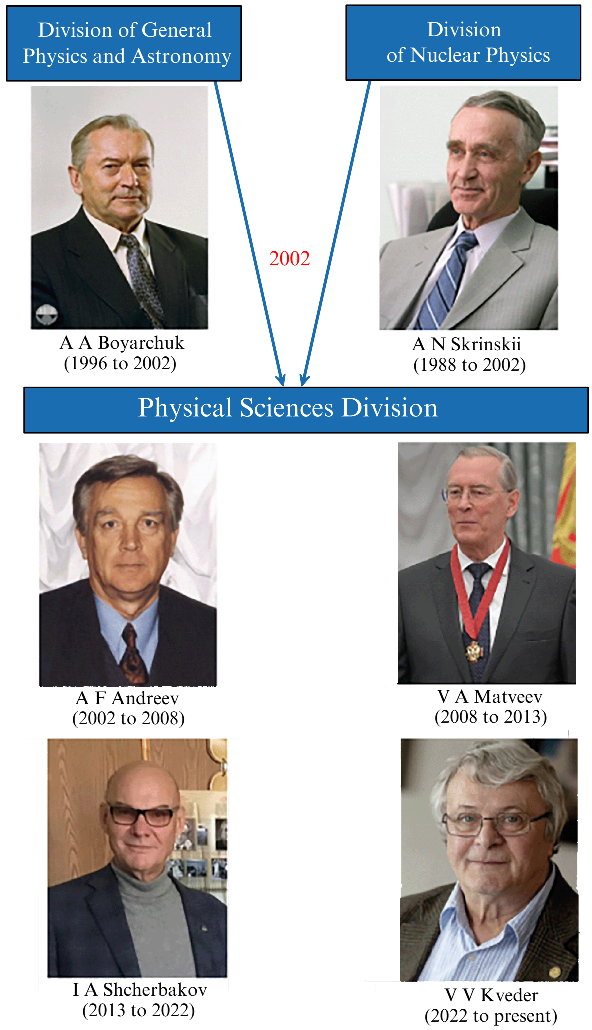

Figure 1. Internal reform of RAS in 2002. Academician-Secretaries of divisions (indicated are years as division heads).

Radical reforms were launched from above in 2013. There were changes in the management structures of the Russian Academy of Sciences, with the dominance of bureaucracy, the formalization of reporting, changes in the terms of remuneration of scientific workers, and the unification of scientific organizations, sometimes representing different fields of knowledge, on a purely territorial

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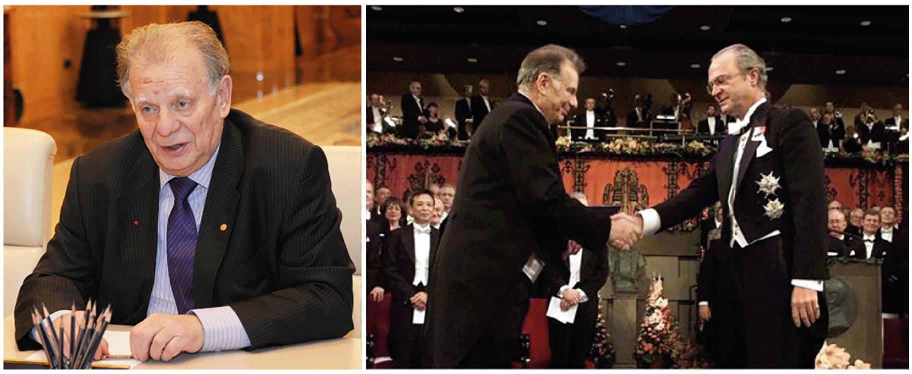

Figure 2. Left: Academician of RAS Zhores Ivanovich Alferov. Right: presentation of Nobel Prize to Zh I Alferov.

basis. None of the above contributed to the development of a creative atmosphere in the scientific institutes under the scientific and methodological guidance of the Physical Sciences Division. What the term 'scientific and methodological guidance' meant was not clearly stipulated anywhere, at least at that time. Despite this, scientists of the division obtained a number of world-class results that received international recognition.

To start with, it is necessary to recall the work awarded Nobel Prizes previously carried out in the institutes of the Division of General Physics and Astronomy.

The 2000 Nobel Prize in Physics was awarded to Zh I Alferov [2] and H Kroemer [3] "for developing semiconductor heterostructures used in high-speed and opto-electronics" and J Kilby [4] "for his part in the invention of the integrated circuit" (Fig. 2).

The 2003 Nobel Prize in Physics was awarded to A A Abrikosov [5], V L Ginzburg [6], and A Leggett [7] "for pioneering contributions to the theory of superconductors and superfluids" (Fig. 3).

The authors of this work unquestionably occupy a worthy place in the list of Nobel laureates.

In 2010, the Nobel Prize was awarded to A Geim [8] and K Novoselov [9] "for groundbreaking experiments regarding the two-dimensional material graphene."

In 2023, the Nobel Prize in Chemistry was awarded to M Bawendi, L Brus, and A Ekimov "for the discovery and synthesis of quantum dots."

The two areas of work have much in common. The first concerned the experimental study of two-dimensional structures and the second concerned one-dimensional. They are underlain by the previously known quantum-dimensional effect.

Both prizes are 'half ours,' since their Russian-speaking laureates belong to the Chernogolovka and Leningrad scientific schools, respectively, although they currently live outside our country.

There is no escape from mentioning another Nobel Prize: the 2017 Physics Prize received by R Weiss, B Barish, and K Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves," which is undoubtedly one of the most important discoveries of the 21st century.

Here, it is necessary to emphasize two circumstances.

The entire ideology of this remarkable experiment was set out in the paper by M E Gertsenshtein and V I Pustovoit "On the Question of Detecting Low-Frequency Gravitational Waves" [10]. The LIGO facility relied on the ideas of the optical method for detecting gravitational waves using an interferometer and a laser [11] expressed in this paper.

It is amazing that the idea of employing a laser was expressed in 1962, only two years after the advent of the laser itself.

However, Vladislav Ivanovich Pustovoit, who was alive at the time, was not included in the team that received the Nobel Prize, which, in my opinion, is a blatant injustice (Fig. 4).

The contribution of Russian scientists to the detection of gravitational waves is not limited to the work of M E Gertsenshtein and V I Pustovoit. The LIGO facility used unique optical Faraday isolators [12] developed at the Institute of Applied Physics (IAP RAS) with the parameters necessary for detecting gravitational waves (Fig. 5), as well as many years of

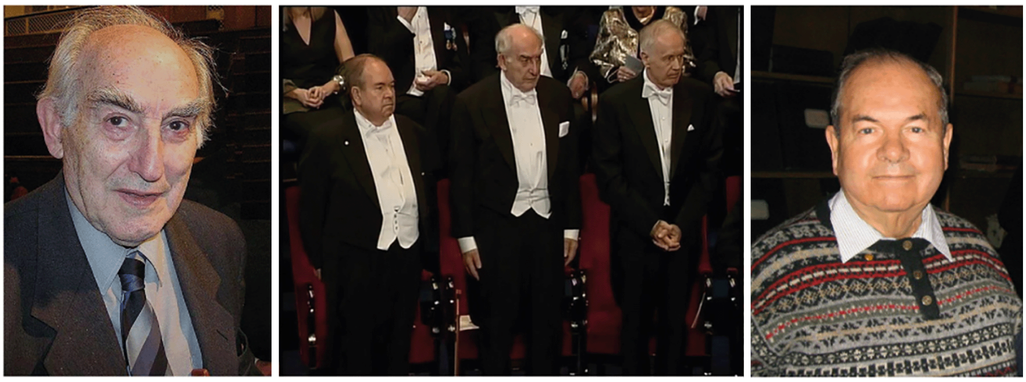

Figure 3. Left: Academician of RAS Vitaly Lazarevich Ginzburg. Center: 2003 Nobel Prize laureates A A Abrikosov, V L Ginzburg, Anthony Leggett. Right: Academician of Russian Academy of Sciences Aleksei Alekseevich Abrikosov.

Figure 4. Left: Academician of RAS Vladislav Ivanovich Pustovoit. Right: LIGO detector.

experience of scientists from Lomonosov Moscow State University (MSU), who worked in the field of searching for gravitational waves [13].

Justice was partly restored by the awarding of the 2018 State Prize in Science and Technology to V I Pustovoit, V P Mitrofanov, and E A Khazanov "for the development of fundamental principles and instrumental solutions to the problems of recording gravitational waves" (Fig. 6).

In total, 27 State Prizes have been received over the past 25 years with the participation of members of the PSD RAS or staff members of the institutes of the PSD RAS.

During the period under review, the achievements of the members of the PSD RAS were recognized five times with the highest RAS award, the Lomonosov Great Gold Medal of the

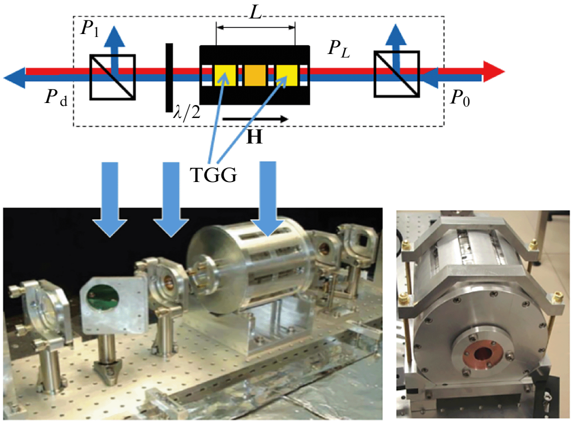

Figure 5. Faraday optical isolators.

RAS. In 2000, it was awarded to Academician A V Gaponov-Grekhov for his outstanding contribution to the development of the physics of oscillatory and wave processes; in 2005, the laureate was Academician Yu A Osip'yan for his fundamental contribution to the physics of dislocations in solids and the development of the photoplastic effect; in 2010, the medal was awarded to Academician S T Belyaev for his outstanding contribution to many important areas of modern physical science: plasma physics, the theory of quantum and relativistic systems of many particles, the theory of the atomic nucleus and nuclear reactions, and the physics of elementary particle accelerators; in 2015, this award was presented to Academician L V Keldysh for his outstanding contribution to the physics of tunneling phenomena, including the tunneling effect in semiconductors and its relation to electronic and vibrational crystal spectra, and the discovery of tunneling modification of optical absorption spectra, tunneling ionization of atoms, molecules, and condensed media by powerful optical laser fields; and, finally, in 2017, the laureate was Academician Yu Ts Oganesyan for basic research in the field of interaction of complex nuclei and experimental confirmation of the hypothesis of the existence of 'islands of stability' of superheavy elements.

After such a brief introduction, we proceed to a review of some specific results obtained by staff members of the institutes of the Physical Sciences Division of the Russian Academy of Sciences since its creation.

Considerable study was devoted to the technology and investigations of artificial diamonds.

The L F Vereshchagin High Pressure Physics Institute of the RAS (HPPI RAS) together with the Lebedev Physical Institute of the RAS (LPI RAS) have obtained a unique material: superconducting diamond. The study of its physical properties testifies to a classical phonon mechanism of superconductivity in the diamond. A sufficiently high superconducting transition temperature (> 6 K) and a high upper critical field (~ 15 T) allow us to consider superconducting diamond as a promising material for electronics.

Also developed at the HPPI RAS was a new class of superhard diamond composites. Comparative tests conducted at Baker Hughes have shown that the wear resistance of these composites when turning granite is more than twice as high as that of the best commercial analogues.

At the Prokhorov General Physics Institute of the RAS (GPI RAS) together with the National Research Center (NRC) Kurchatov Institute, single crystals of ultrapure diamond were synthesized. At room temperature, the result-

Figure 6. Laureates of 2018 State Prize in Science and Technology: (left to right) Valerii Pavlovich Mitrofanov, Vladislav Ivanovich Pustovoit, Efim Arkad'evich Khazanov.

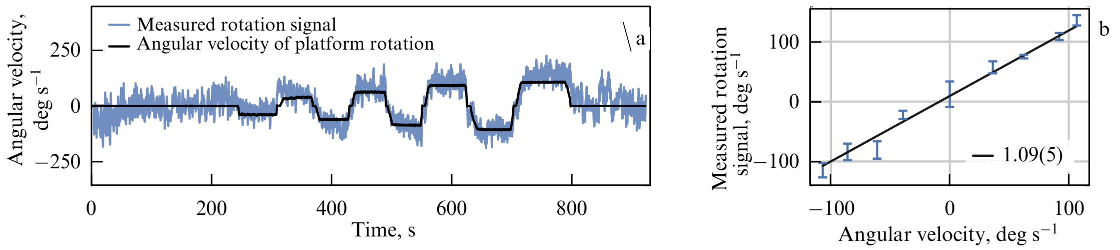

Figure 7. (a) Results of measuring angular velocity of platform rotation using nuclear spins of nitrogen-vacancy color centers. (b) Estimate of scale factor of setup.

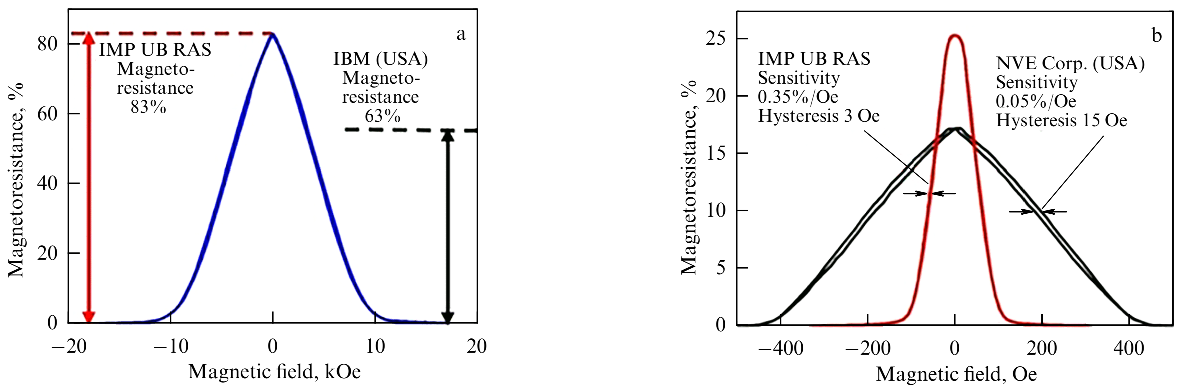

Figure 8. (a) CoFe/Cu superlattices with record magnetoresistance. (b) Highly sensitive NiFeCo/Cu superlattices with low hysteresis.

ing samples exhibited high thermal conductivity for synthetic diamond: 34 W m^{-1} K^{-1}.

At the LPI, an original method for measuring the angular rotation velocity of a laboratory setup was proposed and implemented using an ensemble of NV-centers associated with nuclear spins in diamond (Fig. 7).

The Mikheev Institute of Metal Physics of the Ural Branch of the RAS (IMP UB RAS) has developed magnetic metallic nanostructures with a giant magnetoresistance effect that are superior in functional characteristics to foreign counterparts (Fig. 8).

A nanolithography setup ($\lambda = 13.5$ nm) with a resolution of 30 nm was made at the IAP RAS. The emergence of technologies that allow the development and production of modern lithographic equipment in Russia was thereby demonstrated.

At the Lebedev Physical Institute, together with the Kotelnikov Institute of Radio Engineering and Electronics of the RAS (IRE RAS), a complex of technologies for large-size optical ceramics based on aluminum-yttrium garnet was developed. In terms of laser quality, the resulting ceramics are not inferior to foreign analogues. It is pertinent to note that, for a long time, Japan was a monopolist in the making of large-size laser ceramics. The importance of the result is that this material may eventually replace laser glasses, in particular, in laser thermonuclear fusion facilities.

The Ioffe Institute of the RAS has developed a technology for the growth of epitaxial multilayer large-area graphene that has no equivalent in Russia. Based on SiC graphene, a prototype of a solid-state gas sensor with a record sensitivity to the density of NO_2 molecules of no worse than 2 ppb (two parts per billion) has been manufactured.

The Institute of Solid State Physics of the RAS (ISSP RAS) has made a new group of heat-resistant alloys for use in the temperature range above 1200 °C. Structurally, the new materials are natural composites in which the role of the matrix is played by molybdenum-based solid solutions, while that of the strengthening phases, by refractory carbides. High-temperature mechanical tests of the new alloys have demonstrated the ability to withstand loads at temperatures of 1200 °C or higher for several thousand hours.

The world's most powerful parametric amplifier of laser pulses was made at the IAP RAS. The initially achieved peak power level was 560 TW for an energy of 24 J and a duration of no more than 45 fs, which allows an intensity of 10^{22} W cm^{-2} to be realized in the focusing of laser radiation. Further improvement of this setup made it possible to achieve a peak power of 1.5 PW for a pulse duration of 11 fs (Fig. 9).

A fivefold shortening of laser pulses after their phase self-modulation was implemented at the same institute. Experimentally demonstrated was the possibility of shortening laser pulses with an energy of 17 J from 70 fs to 14 fs, which made it

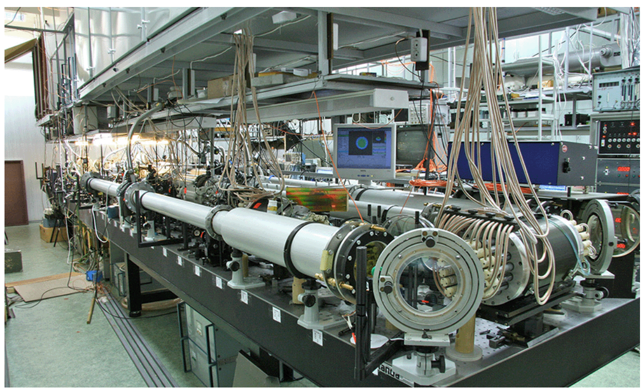

Figure 9. Parametric amplifier of laser pulses (PEARL facility).

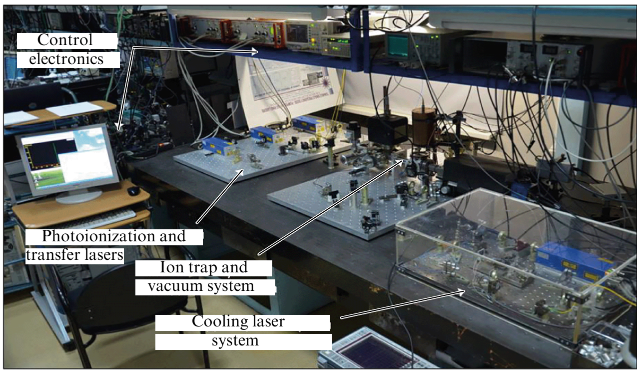

Figure 10. Optical frequency standard.

possible to eliminate the limitation on the pulse shortening coefficient of greater than two, which had previously been thought of as insurmountable.

An optical frequency standard based on the quadrupole transition of a single ytterbium-171 ion localized in space has been developed at the Institute of Laser Physics of the Siberian Branch of the RAS (ILP SB RAS). The optical standard demonstrates a long-term frequency instability of $\sim 10^{-17}$. In terms of the combination of its parameters, the frequency standard has no domestic equivalents and is at the level of the best world samples (Fig. 10).

High Current Electronics Institute of the Siberian Branch of the RAS (HCEI SB RAS) has made a THL-100 hybrid laser system, which has no counterparts in the world. A record peak power of 40 TW for the visible region (475 nm) has been achieved. The system comprises a Ti:Sa femtosecond complex and an XeF amplifier.

At the Ioffe Institute, high-power quantum cascade lasers for the spectral ranges of 4.5 and 8 μm were developed and investigated. The highest output power achieved was 13 W from one emitter in the 8-μm region, which is a record for the said spectral range. Efficient lasing near 8 μm persists up to above-room temperatures.

At the GPI RAS, together with the G G Devyatykh Institute of Chemistry of High-Purity Substances RAS (IChHPS RAS) and the Lebedev Physical Institute, rare-earth ion-activated laser chalcogenide glasses for volume and fiber sources of mid-IR radiation were developed. Using glass samples with Tb^{3+}, Pr^{3+}, Ce^{3+}, Na^{3+}, lasing in the spectral range of 4.5–6.0 μm was obtained. In experiments on cerium ions, the radiation wavelength was tuned in the 4.5–5.6 μm range. These results seem to be fundamentally important, since it was previously believed that obtaining lasing at wavelengths longer than 3 μm using crystalline and glass active elements is difficult, if not impossible, due to the efficient electron-phonon interaction in such matrices and, as a consequence, the low quantum yield of luminescence at transitions whose energies are comparable to the energy of the Debye phonon.

One of the most important recent results in the area of fiber optics is the making of bismuth optical fibers at the Scientific Center of Fiber Optics of the RAS (SCFO RAS) together with the IChHPS RAS. Transmission at a rate of 10.6 Gbit s^{-1} in the spectral region of 1441–1453 nm over an 80-km-long optical fiber was implemented with the use of a bismuth fiber amplifier.

The developed bismuth amplifier allows the spectral band of the signal to be broadened to 1300–1700 nm and the speed of information transfer in fiber-optic communication lines to be augmented several-fold.

The developed series of devices reliant on bismuth optical fibers have no analogues in the world.

A subpicosecond gas-filled fiber laser of the mid-IR range was made at the GPI RAS jointly with the Institute of Spectroscopy RAS (ISAN). A revolver optical fiber filled with deuterium was used as the active medium. An efficient two-stage Raman conversion of $1.03 \rightarrow 1.49 \rightarrow 2.68$ μm was implemented. Generation was obtained at a wavelength of 2.68 μm with a pulse energy of ~ 10 μJ, which is two orders of magnitude higher than any other subpicosecond fiber lasers in the mid-IR range. The duration of the output pulses is 920 fs, and the quantum conversion efficiency was as high as 28%.

A disk multichannel laser with phase synchronization of channel radiation was proposed and implemented at the GPI RAS. Synchronization is achieved by overlapping the 'tails' of the intensity distribution of the pump sources. Synchronization of radiation from ten pump sources was implemented. The total divergence angle corresponds to the radiation divergence of a single-mode laser with an aperture equal to the total aperture of all 10 laser channels, which is $\sim 1.27\lambda/D$.

At the IAP RAS, together with the A V Rzhanov Institute of Semiconductor Physics of the Siberian Branch of the RAS (ISP SB RAS), stimulated emission at a record-long wavelength of 19.5 μm was obtained in heterostructures with HgTe/CdHgTe quantum wells under optical pumping. Suppression of Auger recombination in quantum wells compared to bulk structures was demonstrated, and the ensuing possibility of extending lasing to the 20-50-μm wavelength range was demonstrated.

ISAN has developed spectroscopy of single quantum objects. An experimental complex was made for highly sensitive detection of single nanoparticles by scattering or fluorescence signals and determination of their sizes. The sensitivity of optical signal detection was achieved to allow detection of single nanoparticles down to 40 nm in size.

At the GPI RAS, a model of a generator of ultra-wideband pulsed electromagnetic radiation of subnanosecond duration was made based on a parabolic photocathode 200 cm in diameter excited by ultra-short laser pulses; the generator's scope of application comprises communications, probing, and electronic warfare (Fig. 11).

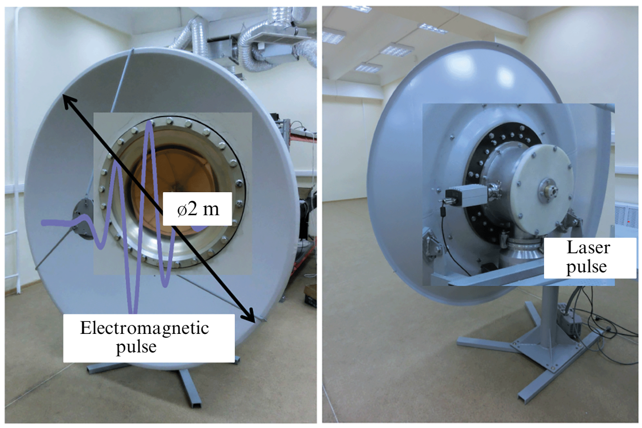

Figure 11. Model of generator of ultra-wideband pulsed electromagnetic radiation of subnanosecond duration reliant on wide-aperture parabolic photocathode 2 m in diameter excited by ultrashort laser pulses.

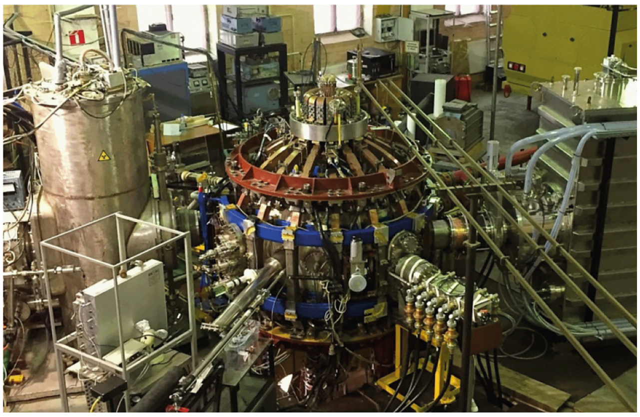

Figure 12. Globus-M2 spherical tokamak.

A solid-state ultrahigh-power pulsed system was developed at the Institute of Electrophysics, Ural Branch of the RAS (IEP UB RAS). Pulses with a duration of ~ 100 ps and an amplitude of 1.9 MV are formed in a coaxial line. Record high output voltage (26 MV ns^{-1}) and current (0.5 MA ns^{-1}) buildup rates were achieved. For solid-state pulse systems, record high values of peak power (77 GW) and its rise rate (1.6 TW ns^{-1}) were obtained.

The Russian spherical tokamak Globus-M2 with an increased magnetic field was put into operation at the Ioffe Institute. With an increase in the magnetic field from 0.4 to 0.7 T and the plasma current from 0.2 to 0.33 MA with an unchanged value of the additional heating power and stability margin, a significant increase (up to threefold) in the temperature and energy plasma store was recorded. A twofold increase in the plasma energy retention time was recorded. Further improvement in the facility made it possible to increase the magnetic field to 1 T and the current flowing through the plasma to 0.5 MA. In this case, the plasma temperature became as high as 45 million degrees, which is only half the temperature required to ignite the reaction of controlled thermonuclear fusion of hydrogen isotopes. The high-density plasma temperature achieved at Globus-M2 was demonstrated for the first time in domestic research on tokamak-type facilities. In world practice, comparable temperatures have been recorded in facilities of much larger dimensions, operating at a higher magnetic field, which demonstrates the great potential of spherical tokamaks as a basis for making compact thermonuclear devices for different purposes (Fig. 12).

A pulsed 3-mm relativistic gyrotron with a high level of output power was developed at the IAP RAS. The power obtained was higher than 5 MW in pulses with a duration of about 1 μs. The accelerating voltage was 240 kV, the beam current was 100 A, and the radiation frequency was 94.43 GHz with an efficiency of 23%.

A record narrow gyrotron radiation line at a frequency of 263 GHz with a radiation power of 100 W was experimentally realized. The line width was 1 Hz. This result opens up new possibilities for spectroscopic research and allows making master oscillators to ensure the coherence of a large number of gyrotrons.

Scientists from the Physical Sciences Division of the RAS, in cooperation with medical organizations, made a significant contribution to the development of medical instrumentation

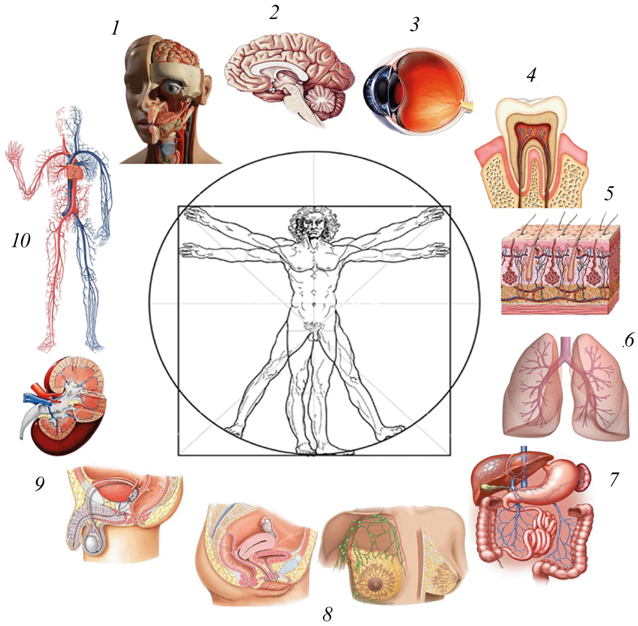

Figure 13. Objects of photodynamic therapy.

and the development of new medical technologies reliant on the instruments developed.

Specifically, at the IAP RAS, together with the Privolzhskii Research Medical University of the Ministry of Health of the Russian Federation (PRMU) and the Federal Research Center Crystallography and Photonics, a new method of biomedical diagnostics — compression optical coherent elastography — was developed and implemented in a prototype of a medical device. With the help of this method, it is possible to visualize local deformations of different natures and monitor the purity of the reaction boundary. The method has no counterparts in the world and opens up previously inaccessible prospects for solving a wide range of medical problems.

A number of institutes with physical, chemical, and medical profiles introduced a new line in medicine: photodynamic diagnostics and therapy, which has found wide application in many medical centers. Photodynamic therapy is used to diagnose, monitor, and treat oncological diseases of various human organs: head and neck (*1*), brain (*2*), eyes (*3*), skin (*5*), lungs (*6*), stomach, intestines, liver (*7*), female reproductive organs (*8*), and genitourinary organs (*9*). Photodynamic therapy is also used to treat non-oncological diseases, such as atherosclerosis (*10*), periodontitis (*4*), retinal degeneration (*3*), and psoriasis, arthrosis (*5*) (Fig. 13).

Developed at the GPI RAS was an ophthalmological femtosecond laser, Femto Visum, for intrastromal treatment of the cornea. The mechanism of action of radiation with a wavelength of 1.054 μm and a duration of 250-400 fs is the destruction of corneal tissue with multiphoton absorption.

The multiphoton absorption mechanism ensures the absence of thermal damage to adjacent tissue layers and the possibility of performing precision interventions inside the cornea without damaging its surface layers.

The developed ophthalmological device is used for layer-by-layer delamination of the cornea instead of a mechanical instrument, producing intrastromal canals and keratoplasty, and performing intrastromal precision interventions by making microscopic incisions inside the cornea (Fig. 14).

Figure 14. Femto Visum femtosecond laser for intrastromal corneal treatment.

The same institute developed the Lazurit laser surgical complex, which is a scalpel-coagulator, and a laser lithotripter. Laser lithotripters existed before, but Lazurit differs from them fundamentally and is a striking example of how basic results find important practical applications. In previously known laser lithotripters, the destruction of stones occurs due to a rather high light energy, which may be fraught with unwanted consequences for the patient. The principle of operation of Lazurit is based on the light-hydraulic effect discovered by G A Askar'yan, A M Prokhorov, and T P Shipulo back in the 1960s, which involves the generation of a shock wave when laser radiation interacts with liquid. In this case, the destruction of stones occurs not due to light energy but due to the energy of the shock wave. It is this circumstance that determines the advantages of Lazurit over other laser lithotripters, which include:

— safety of the action on the soft tissues surrounding the stone;

— efficiency of fragmentation of stones of any localization and any chemical composition;

— high fragmentation rate;

— absence of thermal heating and damage to fiber means of delivery.

With the help of Lazurit, surgical operations were successfully performed in the treatment of urolithiasis, which could not be performed in any other way (Fig. 15).

Figure 15. Lazurit laser surgical unit.

I consider it appropriate to include in the review of achievements two additional results obtained recently at the GPI RAS and not included in my report at the Scientific session of the General Meeting of the Physical Sciences Division. We are dealing with a gas-discharge fiber laser with microwave pumping and precision measurement of the group velocity of ultrasound in solid media.

The gas-discharge fiber laser developed on xenon atoms with a radiation wavelength of 2.027 μm has no world equivalent, combines the advantages of fiber and gas-discharge lasers, and is, in fact, a new type of laser radiation source. The developed scheme keeps open the possibility of further improving the design by scaling the discharge length in a hollow-core fiber and using different gases and their mixtures as active media in order to increase the output power and broaden the spectral range.

A method, also with no counterpart in the world, was developed for studying the spatial dependence of ultrasound velocity in metals for a millimeter-thick sample. The method relies on laser-ultrasonic structuroscopy, which makes it possible to achieve record-breaking accuracy in measuring the ultrasound velocity ($\sim 0.1\%$) due to the use of laser-driven broadband submicrosecond acoustic pulses. The development shows promise for monitoring stress states in the course of different technological operations.

In conclusion, it should be noted that, during the period under review, a large number of results were obtained that meet the highest requirements of modern science and were presented in the annual reports of academic secretaries at general meetings of the Physical Sciences Division of the RAS. Selecting only a small number of them for a publication of limited volume seemed to be an extremely difficult task. The main criterion was that the result reached or exceeded the international level. Nevertheless, it is impossible to rule out the subjective component of the selection. Therefore, I apologize to those who may disagree with my choices. It should also be mentioned that the analysis of results in the field of nuclear physics and astronomy was not part of my task: they will be considered in papers by other authors.

In conclusion, the author expresses his appreciation to E Yu Kilpio for assistance in selecting the material and formatting the work.

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