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Academician Basov, high-power lasers and the antimissile defence problem

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***Abstract*. A review of the extensive programme of the pioneering research and development of high-power lasers and laser radar undertaken in the USSR during the years 1964 – 1978 under the scientific supervision of N.G. Basov is presented. In the course of this program, many high-energy lasers with unique properties were created, new big research and design teams were formed, and the laser production and testing facilities were extended and developed. The programme was fulfilled at many leading research institutions and design bureaus of the USSR Academy of Sciences and defence industry.**

Keywords: *high-power lasers, laser radars, antimissile defence.*

1. Antimissile defence and lasers. Basic aspects of interest in the problem

In the early 1960s, when the idea of a laser generating a narrow high-power coherent light beam began to be implemented in the 'hardware' of engineering solutions, it became actually possible to create quantum optical generators with a high output power and a high radiation energy (the English acronym LASER was not yet accepted in the USSR at that time). Radio-frequency quantum generators (masers), the immediate predecessors of lasers, were created in the mid-1950s almost simultaneously and independently by the American and Soviet scientists (Ch. Townes, J. Gordon and H. Zeiger in the USA and N.G. Basov and A.M. Prokhorov in the USSR). Charles Townes, Aleksandr Prokhorov and Nikolai Basov were awarded the Nobel Prize in physics in 1964 for their fundamental studies in the field of quantum electronics and masers. The idea of generation of radiation in the optical range, based on the experimental and theoretical works on masers, was proposed in 1958 by Ch. Townes and A. Shawlow (USA) and A.M. Prokhorov and N.G. Basov (USSR). Since the early 1960s, specialists were flooded with reports concerning advances in laser research. Each issue of the leading scientific and technical journals reported new ideas on the design and construction of lasers, proposals, calculations, and experimental results. In this connection, it would be appropriate to recall the words of M.V. Lomonosov: 'Science is all the more astonishing because of its subtlety in spite of simplicity, and a small number of reasons can lead to countless manners of properties, changes and phenomena' [1]. This profound thought is aptly illustrated by the 'burst' in laser research in the first half of 1960s. Thousands of scientists in the biggest laboratories of the USA, the USSR, Europe, Japan and China embarked on the projects aimed at creating lasers. The temptation offered by the basic idea of amplifying the stimulated emission of a large number of particles, atoms and molecules in an optical resonator turned out to be profound. The Lebedev Physics Institute of the USSR Academy of Sciences (FIAN) became the leading research centre in the USSR for pioneering studies on quantum oscillators, including lasers. Scientists at the FIAN, especially those working under the supervision of A.M. Prokhorov and N.G. Basov, directed their efforts in the early 1960s at increasing the energy and power of laser radiation, and also at the quest for new types of lasers. An atmosphere of optimism and confidence about the possibility of attaining high energy characteristics of lasers prevailed at the institute.

After the creation of the first laser by Maiman at the Hughes laboratory on 15 May 1960, many scientists and military officers in the USA (and shortly afterwards in the USSR) started considering the possibility of creating weapons capable of destroying targets by 'incinerating' laser rays. Naturally, the first laboratory lasers were not so powerful and did not possess sufficient radiation energy to meet such demands. The understanding of many scientific and technical problems associated with the production of such a weapon came later. However, it was not long (just a few years) before the researchers obtained outstanding results on improvement of lasers and enhancement of their output power, which opened new avenues for using them to produce weapons that were soon termed as 'laser weapons'. Many developed countries, especially the USA and the USSR, embarked upon a race whose winner was anticipated to come first into possession of a powerful weapon of enormous force and long range, capable of destroying remote targets almost instantaneously.

For the USA and USSR, the antimissile defence (AMD) was (and still remains) a problem of great importance. In 1960s, the creation of AMD systems was treated as a national strategy problem in both the USA and the USSR, and this set the tone for the atmosphere in which the idea of using lasers in AMD systems emerged. In 1963, A.A. Grechko, the Deputy Defence Minister (subsequently, the Defence Minister) of the USSR, wrote to M.V. Keldysh,

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the President of the USSR Academy of Sciences, requesting him to evaluate the possibilities of using lasers for military purposes. In turn, Academician M.V. Keldysh asked the opinion of leading laser scientists at the FIAN, including N.G. Basov. The reply sent by the USSR Academy of Sciences stressed the enormous potentialities of lasers both for scientific and defence applications, and new trends were proposed for improving the energy parameters of the lasers available and for creating new types of lasers.

Researchers in the field of AMD at the Vympel design bureau (G.V. Kisun'ko was the Chief Designer and the inspiration behind the activities during those years) realised and evaluated the need to solve a number of fundamental design research problems associated with the prospects of creating AMD systems with necessary parameters [2]. The foremost among these problems was the accurate measurement of the coordinates of the ballistic missile warheads (BMWs) so that antimissiles with a splinter-type charge instead of a nuclear charge could be directed at these heads with a minimum miss. The absence of a nuclear charge in antimissiles alleviated the working conditions for the AMD system because it eliminated the problems associated with the action of a nuclear explosion in the warheads of antimissiles on own radars, not to mention the possible impact of such explosions over native territory, on land-based objects and the population of the region [2]. By using laser radars, one could expect to attain a high degree of precision in aiming the antimissiles for applying small diameters of the optical antennas (a few meters or smaller). The use of laser radiation instead of radiowaves employed in radars opened up the new possibilities for

(i) improving the precision of AMD radar systems;

(ii) selecting (recognition) BMWs among thousands of false targets (decoys) and missile fragments; and

(iii) solving the problem of lack of time during a 'short-range' interception of a BMW in the brief span of time after its entry into the dense atmospheric layers, when light decoys disappear due to deceleration, heating and burning, and their signals no longer appear on the AMD radars.

The interest of AMD specialists in high-power lasers was aroused owing to the speed at which the laser energy can reach the target, this speed being five orders of magnitude higher than the velocity of the antimissile. This saves precious seconds which the designers of the systems need so badly at the terminal interception stage when decoys burn out upon entry into the atmosphere on the one hand, thus making it easier to detect a BMW, while only a few seconds remain before the 'arrival' of the warhead on the other hand.

In those days, the AMD system was mainly treated as a land-based weapon system capable of destroying BMWs at the terminal stage of their flight upon entry into the dense layers of the atmosphere. The space-based AMD systems intended for the destruction of missiles at the initial (launching) stage, or at the intermediate part of their trajectory, were developed (though not executed yet) much later, in 1980's, when the drawbacks and limitations of the land-based terminal-stage interception AMD systems became more obvious.

It should be mentioned that even at that time, it occurred to many researchers that the implementation of an AMD system for protecting large territories or the country as a whole against a massive nuclear-missile attack was a practically insurmountable problem (technically and economically), at least at the prevailing level of technological advancement. However, it was hard to admit this, and there was no firm evidence to support such a conclusion, while an error of judgement in this case could be catastrophic for the country. There were apprehensions at all times that some new scientific discovery would allow a potential adversary to achieve a breakthrough and solve this problem. In this case, the country would remain practically unprotected from a nuclear missile attack while the enemy would enjoy such a protection. Hence, any new idea directed at a solution of the AMD problem was given due attention both by the military authorities and the leaders of the defence establishment of the USSR. Twenty years later, a large-scale programme called the strategic defence initiative (SDI) and aimed at creating a global AMD system for protecting the territory of the USA against a massive ballistic missile attack was initiated and supported by many (though not all) leading American scientists (the name of E. Teller is mentioned frequently in this connection) and the leadership of the country (President Ronald Reagan). In an article published in 1983, E. Teller, the initiator of the SDI programme wrote [3]: 'For quite a number of years... there has been interest in creating laser systems capable of destroying ballistic missiles. This idea has always had a great deal of appeal because of the almost instantaneous transit time of a light pulse from its source to the target.'

As early as 1962, specialists from Vympel, the leading organisation in the USSR engaged in AMD systems, began to consider the possibility of developing a laser radar for performing certain functions in the AMD system, in particular, high-precision determination of target coordinates. There were several obstacles in the path of this quest, associated with the construction of lasers, systems for forming and directing laser beams, optical detectors, as well as with the development of the theory and methods for processing laser ranging signals. Moreover, there were limitations imposed by the propagation of laser signals in the atmosphere.

A little later, the possibility of destroying BMWs by laser radiation was studied by N.G. Basov and his close associate O.N. Krokhin. Estimates showed that this requires creation of lasers with extremely high output energy (several orders of magnitude higher than that required for a laser radar), since a BMW is a rugged device capable of withstanding large mechanical and thermal stresses. The solution of the problem concerning the AMD required lasers for laser ranging with pulse energy several hundred times higher than that attainable in 1963–64, while the destruction of a BMW required an energy tens of millions (!) times higher. The exact value of the laser beam energy required for destroying a BMW was not clear. From the very beginning, it was clear to the collective led by N.G. Basov that a BMW is unlikely to be destroyed by thermal effects due to heating by laser radiation. O.N. Krokhin proposed to use for this purpose the mechanical recoil pulse appearing due to rapid evaporation of the outer layer of the thermal-insulating shell of the BMW caused by a high-intensity laser beam. This mechanism required a meticulous theoretical and experimental research, however, the very possibility of using such a system in principle for damaging targets did not arouse any doubts in those years.

The progress of any task, especially at the initial stage, is determined by the enthusiasts. It is often said that, in the first place, enthusiasts are people who believe in an idea in spite of the 'rational' arguments of the sceptics. Second, enthusiasts are people whose 'rational' arguments are in any case not accepted by the sceptics. It turned out that such enthusiasts existed among the designers of AMD systems, as well as among scientists. Of course, N.G. Basov was the main enthusiast and the driving force behind the project of using high-power lasers. In 1964–1965, he was able to convince the military establishment of the country, and especially the Defence Minister D.F. Ustinov, as well as a number of other state and military leaders, that this problem can be solved in principle. It must be mentioned here that being an engineer by education, D.F. Ustinov clearly understood the decisive role of science in developing the military potential of the country. He was accessible to leading scientists and designers, and wholeheartedly supported new projects that promised advancement of the armaments technology. He enjoyed a great reputation in matters of defence technologies, science and industry, and his opinion almost always proved decisive.

2. Beginning of the development of laser systems for AMD (1964–1968)

The first state programme of research in the prevailing trends of laser science and engineering was approved in the USSR in 1962. It was not directly linked to possible military applications of lasers and envisaged the development of different types of lasers (crystal lasers, glass lasers, gas lasers, and semiconductor lasers). Work was also undertaken on lasers that were found to be impracticable after careful studies, e.g., the hydrogen laser (it was proposed to create a laser based on ortho-para transitions in hydrogen). Apart from the FIAN, the leading institute of the USSR Academy of Sciences (the Institute was headed by D.V. Skobel'tsyn at that time, and the laser activity was supervised by A.M. Prokhorov and N.G. Basov), the collectives of many other research institutes, design bureaus and educational institutions also embarked on the laser research work. The foremost among these were the S.I. Vavilov State Optical Institute (GOI) in Leningrad (divisions headed by M.P. Vanyukov and A.M. Bonch-Bruevich), the Defence Research Institute of Applied Physics (headed by L.N. Kurbatov) in Moscow, the M.V. Lomonosov Moscow State University (Departments of Physics, R.V. Khokhlov and S.A. Akhmanov), and Research Institutes of Nuclear and Electronic Industry. An avalanche-like growth was observed in the number of research institutes and industrial plants, as well as higher education institutes engaged in the research and development of lasers, and probably a hundred of such organisations in the USSR were involved by the mid-1960s. As is the case of any new branch of engineering and technology, the military evinced a keen interest in the defence applications of lasers, supported and financed a considerable part of the research activity from the defence budget.

Starting from 1964, the research activity on AMD laser systems was carried out in two directions: laser radar (including the selection of targets) and destruction of BMWs by laser beams.

2.1 Development of an LE-1 laser radar

The giant pulse mode (later called the *Q*-switching mode), a new tool for generating short and very high-power laser pulses proposed in the USA and France for the first time, was found to be specially interesting for laser ranging. The fabrication of *Q*-switched lasers capable of generating nanosecond pulses led to endeavours aimed at exploring the possibilities of using them in pulsed high-precision AMD laser radars. In 1962, young theorists (V.G. Repin, A.A. Kuriksha, P.A. Bakut, *et al.*) from the division headed by N.A. Livshits at Vympel under the supervision of G.P. Tartakovskii began to analyse laser radar systems and studied the potentialities and peculiarities of laser radiation. Almost simultaneously, experimental work on lasers was started in division no. 56 at Vympel under the supervision of an energetic engineer O.A. Ushakov. A group of young engineers (V.F. Morskov, V.N. Lomakin, N.P. Kuksenko, Yu.P. Shilokhvost, *et al.*) working in this division eventually formed the core of designers of AMD laser systems. The laser laboratory of the division was headed by N.D. Ustinov (son of D.F. Ustinov, the effective head of the military establishment of the USSR). He was not a great scientist himself, but was rather an influential person whose participation in the project objectively facilitated the development of laser activity at Vympel. This activity was mainly stimulated by scientific advances achieved at the FIAN, and in particular, in the group headed by N.G. Basov. The studies on laser applications were performed at Vympel in a permanent contact with N.G. Basov and his colleagues, and were largely initiated by them. This cooperation dates back to even earlier times, when masers were used as low-noise amplifiers of signals in the receiver channels of the AMD radars.

The investigations performed at Vympel, which were based on the research and forecasts by Basov's group as regards lasers themselves, led to the submission of a project concerning the creation of an experimental AMD laser radar (tentatively called LE-1) to the military-industrial commission (MIC, the organ exercising state control of the defence industry establishment of the USSR) in the beginning of 1963 [4]. The project was based on the research carried out at the FIAN on the creation of ruby lasers. Initially, it was proposed to construct a radar using a ruby laser with an average output power of 1 kW and a peak pulse power of tens of megawatt in the giant pulse mode. It should be emphasised that N.G. Basov as well as many other Soviet scientists and designers, were highly optimistic while formulating the anticipated laser parameters, especially at the initial stages of the development of laser technology. Many optimistic predictions were not fully justified subsequently, but such an approach certainly facilitated a rapid and active development of laser studies and, of course, its financing by the state.

The decision to build the high-precision experimental LE-1 laser radar at the Balkhash antimissile proving ground for ranging BMWs at distances up to 400 km was affirmed in September 1963. A high degree of spatial and angular resolution of the radar (a few meters and a few angular seconds) was envisaged in order to 'discern' the individual parts of a complex target, e.g., a warhead surrounded by missile fragments and decoys. In the opinion of the designers, this should solve to a considerable extent the problem of selecting the actual warhead against the background of decoys. The scientific supervision of the project of building the laser radar was assigned to the FIAN (Basov's laboratory). A research programme aimed at studying the propagation of laser radiation in the atmosphere was also envisaged. This research was conducted at that time by the Institute of Physics of the Atmosphere, USSR Academy of Sciences, under the guidance of Academician A.M. Obukhov. The results of investigations carried out by many scientists from this institute were of fundamental importance and earned worldwide recognition. At the end of 1960s, when the LE-1 laser radar construction was started at the Balkhash proving ground, a special measuring complex was also built in the vicinity of the radar for monitoring and studying the state of the atmosphere and the propagation of laser radiation through it. Under the supervision of Academician V.E. Zuev, scientists from the Tomsk Institute of the Atmospheric Optics (IAO), Siberian Branch of the USSR Academy of Sciences, made a valuable contribution towards the realisation of this project.

In 1964 – 1965, the LE-1 project was developed and specified by the researchers at Vympel (G.E. Tikhomirov's laboratory in the division headed by O.A. Ushakov). The optical systems for the radar were developed at the State Optical Institute at P.P. Zakharov's laboratory, where the optical scheme of the radar was developed in collaboration with the researchers at Vympel. The radar was required to search for the targets in the 'error field' of radars designating the target to the laser radar, which required very high mean output power of the laser for those days. The design of the radar was dictated by the actual state of advancement in ruby lasers for which the practically attainable parameters turned out to be much lower than those anticipated in the beginning: instead of the expected value of 1000 W, the average output power of the laser was found to be only 10 W. Experiments carried out by P.G. Kryukov and his colleagues at Basov's laboratory at the FIAN showed that, contrary to the earlier expectations, the power build up by successive amplification of laser signal in a cascade of laser amplifiers is possible only to a certain extent. Radiation of very high power damaged the laser crystals themselves. Difficulties were also encountered due to thermo-optical distortion of laser radiation. For this reason, instead of one laser, 192 10-Hz lasers with pulse energy of 1 J were employed in turn in the radar. The total average output power of the multichannel laser transmitter in the radar was about 2 kW. This considerably complicated the design of the radar in which multiple-beam emission and detection of the signal were involved. High-precision and fast optical devices were required for forming, switching and directing 192 laser beams that determined the search field in the target space. An array of 192 specially designed photomultipliers was used in the receiver of the radar [4].

The problem was complicated by the errors associated with the large-size moving opto-mechanical telescope systems and opto-mechanical switches, as well as the distortions introduced by the atmosphere. Suffice it to say that the total length of the radar optical path was 70 m, and it consisted of several hundreds of optical elements, such as lenses, mirrors and plates, including moving elements whose mutual adjustments had to be preserved to the highest degree of precision.

Since the specialists at Vympel had no experience and technological facilities for optical instrumentation, the designing and production of lasers and other elements of the optical channel in the LE-1 were entrusted to the Geofizika central design bureau (Moscow), a prominent design bureau in optical industry under the supervision of D.M. Khorol, a talented scientist and designer. A special high-dynamic telescope TG-1 of diameter 1.2 m for forming and directing the laser beam was constructed in B.Ya. Gutnikov's development team at the Leningrad Optical and Mechanical Association (LOMO) in the department headed by the famous telescope designer B.K. Ioannessiani who was supervising at that time the development of the then world's largest astronomical BTA telescope with a mirror of diameter 6 m. By 1966, it became clear that the creation of the LE-1 required the efforts of not only scientists but also the industry, especially the optical and electronic industry. This necessitated the designing and batch production of many new devices, technologies and materials. These included high-quality ruby crystals, electro-optical crystals for switches to control the laser pulse shape, special flashlamps for laser pumping, highly sensitive photodetectors, etc. Because of all these factors, the laser radar was constructed and began to operate only in the mid-1970s.

After the establishment of the Luch (Ray) central design bureau and the transfer of relevant laser program to the ministry of defence industry, the work on the construction of the LE-1 was accelerated and acquired a firm footing. The capabilities of a number of organisations engaged in the field of optics were channelled in this direction. The designing of the laser radar was completed by 1970 – 1971. A TG-1 telescope with a unique set of parameters was constructed for the LE-1 jointly through the efforts of LOMO and the Leningrad Bolshevik plant (D.F. Ustinov was the Director of this plant briefly during the pre-war years). This telescope had a principal mirror of diameter 1.2 m and ensured high optical quality of the laser beam for velocities and accelerations several hundred times exceeding those in classical astronomical telescopes. Many new components of the laser radar were constructed, including high-speed precise scanning and switching systems for controlling the laser beam, photodetectors, electronic units for signal processing and synchronisation, as well as many other devices. The laser transmitter designed at Geofizika consisted of 192 then elaborated lasers, a cooling system, and an electric supply system. The production of high-quality ruby laser crystals, nonlinear KDP crystals, and many other elements was developed for the fabrication of the LE-1 radar.

The laser radar was controlled by computers which, however, were far from perfect. The radar was connected with the radar facilities of the proving ground through digital communication lines. Installation and adjustment procedures were started at the proving ground in 1973. Dozens, and at times even hundreds, of specialists from Luch, LOMO, Geofizika, fitting and adjustment units worked at the radar site in an endeavour to 'infuse life into' its systems and to make them work precisely and smoothly.

Work on the LE-1 was carried out under active support and continued attention of the leadership in the military establishment of the country. The radar site was frequently visited by 'top' guests from the military-industrial commission (MIC) and from the USSR Ministry of Defence. In May 1973, the top officers of the USSR Ministry of Defence headed by the Defence Minister A.A. Grechko visited the LE-1 radar as well as some other installations on the territory of the Balkhash proving ground. The group included nearly all the Deputy Defence Ministers of the USSR, commanders in chief of all services of armed forces, P.F. Batitskii, commander in chief of the USSR anti-aircraft defence, S.A. Zverev, Minister of Defence Industry of the

Figure 1. N.G. Basov, laser programme research supervisor, A.A. Grechko, Minister of Defence of the USSR, S.A. Zverev, Minister of Defence Industry of the USSR, military commanders, designers and testers at the LE-1 laser radar.

USSR, and L.I. Gorshkov, one of the leaders of the MIC. Also present were N.G. Basov, the scientific leader of the laser research and development AMD programme, and other scientists. Reports on the state of affairs concerning the radar were presented by N.D. Ustinov, as well as the designers and constructors of individual devices used in the radar. On the whole, Marshal A.A. Grechko did not evince a keen interest in the details of the project. He was more concerned about the potential applications and the efficiency of the radar. He exhorted the participants to hasten the test programme.

The adjustment and alignment work on the radar was completed in 1974, and its step-by-step testing was started with the participation of army specialists of the proving ground and engineers from all the designing organisations. First tests were carried out on measuring targets mounted on towers, which made it possible to monitor the characteristics of the radar radiation. Then, an aeroplane target with specially mounted optical sensors and light-reflectors was also subjected to radar tests. The pilots wore special goggles to protect their eyes from the possible harmful effect of laser radiation. The tests were accompanied by measurements of the atmospheric characteristics and of the errors associated with the functioning of the radar. These studies were performed by the scientists from the Institute of Atmospheric Optics.

Naturally, the LE-1 tests revealed a number of technical and organisational problems, which required modifications and even remaking of some devices used in the radar. Sometimes, quite 'peculiar' problems were encountered. For example, the cooling system of laser transmitter, which required about ten tons of high-purity ethanol – water mixture for filling, was a subject of discussions for several months. It was not a simple task to preserve this so-called 'port wine' and to prevent pilferage from the system.

In 1975, a more or less reliable tracking of aeroplanes at distances of about 100 km was achieved. The designers set out to test the radar on BMWs and artificial satellites. The target satellites were equipped with light 'beacons', laser signal measuring detectors, and optical reflectors. The tests provided reliable experimental data on all vital parameters of the LE-1 and confirmed on the whole its viability and attainment of most of the preset characteristics. However, the radar obviously could not work under cloudy conditions and was therefore unsuitable for use in the AMD system as such. Nevertheless, the LE-1 was found to be a reliable and quick tool for extratrajectorial measurements in several systems of defence application, including AMD. Following a decision by the Central Committee of the Communist Party of the Soviet Union and the USSR Council of Ministers in 1980, the LE-1 radar was accepted on the basis of test results as a means for precise trajectorial measurements at the Balkhash proving ground. Subsequently, the LE-1 was used for ranging and trajectorial measurements of the orbits of several Soviet and foreign satellites and spaceships. Preventive measures were taken to ensure that the signals (even of relatively low power) from the laser radar did not affect adversely the functioning of sensitive equipment mounted on spacecrafts. Despite the statements appearing in foreign press, surveillance of manned spaceships and space stations belonging to the USSR and the USA was extremely limited and practically forbidden.

The LE-1 radar provided valuable information on the reflecting characteristics (signatures) of space objects and made it possible to conduct experiments aimed at obtaining noncoordinate information about them. Active work on the LE-1 was continued until the mid-1980s [5]. During this period, its elements, including computers, electronic systems, photodetectors, and (partially) optical components were replaced and modernised several times. The LE-1 radar proved to be a valuable means of mastering laser technology and provided extremely valuable scientific and technical information on a number of problems. The technologies, elements and materials produced for the LE-1 were used extensively for fabricating many other laser devices and systems. Unfortunately, the LE-1 is now 'rusting' in the rocky steppes of Kazakhstan, many of its components have been dismantled and broken, and have aged both physically and morally. Attempts were made to try to 'revive' the radar jointly with Kazakh scientists, but this is a very expensive work and could not be continued, the more so because the LE-1 is now located on the territory of another sovereign state Kazakhstan. The possibility of using the radar in international programmes after restoration and modernisation cannot be ruled out.

2.2 Iodine photodissociation lasers for AMD

Since the main task of Vympel was to create complexes and weapon systems for the AMD, a fairly optimistic proposal put forth at the end of 1964 by N.G. Basov and O.N. Krokhin aroused considerable interest and was subsequently supported by many other scientists. This proposal concerns a direct attack (destruction or damage of the shell) on BMWs by high-power laser radiation. This proposal was born in the course of a quest for higher laser radiation power during the years 1962 – 1964, and was discussed at a number of meetings with M.V. Keldysh, president of the USSR Academy of Sciences. It was clear to the scientists at the very outset that a laser with a very high pulse radiation energy (initially, optically pumped ruby crystals, whose efficiency is quite low, were intended to be used) requires an exceptional pump source with an appropriate emission spectrum. In the first years of laser technology development, the attention of the scientists was pinned on high-power solid-state crystal lasers, and later on activated glass lasers using optical pump sources. The development of other types of powerful lasers was still in the conceptual stage in the first half of 1960s. Flashlamps could not ensure in principle the pump energy required for ultrahigh-power solid state lasers, and one had to look for other high-power pump sources.

O.N. Krokhin was the first to think about using the most powerful light source for pumping lasers, namely, the radiation generated during the explosion of an atomic charge in air. The power and radiation energy of such an exotic source were many orders of magnitude higher than for other sources [6]. In those years of the general 'laser enthusiasm', to which the highest military establishment of the country was drawn owing to the efforts of the scientists, the mechanisms and real potentialities of the destructive action of laser radiation were not quite clear. Hence, courageous and even risky projects were proposed sometimes.

One such project concerned the establishment of a research complex for carrying out experiments on land-based laser weapons for the AMD. By the way, it turned out later that the tendency to embark upon risky and not fully substantiated projects (not only on lasers) continued to be a weakness of scientists and military for a long time not only in the USSR (it is worthwhile to recall the programme of creating X-ray lasers pumped by the radiation from atomic explosions for use in the SDI in the USA in 1980s).

An analysis of the first schemes and ideas showed that the development of an ultrahigh-power laser weapon based on a flashlamp-pumped ruby laser was not possible because the flashlamps could not provide very strong total and specific radiation fluxes. The required number of ruby crystals was also far in excess of the production capacity of the industry. It was necessary to find a different laser with a more technological and cheaper active medium than ruby, as well as a real powerful pump source instead of the (imaginary) atomic explosion. In this respect, the creation of iodine photodissociation lasers (PDLs) played a special role in the development of laser technology for the AMD in the USSR. The physical idea underlying the PDL was put forth and published by S.G. Rautian and I.I. Sobel'man at the FIAN as early as 1961 [7]. They proved theoretically that excited atoms or molecules can be obtained by photodissociation of more complex molecules upon their irradiation by a powerful (non-laser) light flux. It was found later that the most efficient working medium for such lasers proved to be excited iodine atoms formed during photodissociation of various compounds, primarily the perfluoroalkyl iodides (e.g., CF_3I and C_3F_7I).

In 1964, the American scientists reported the generation of radiation with low energy and power from a laboratory PDL [8]. In 1966, the pulse radiation energy of such a laser was raised to 100 J in the USA. N.G. Basov and O.N. Krokhin proposed that precisely this kind of lasers should be used for attaining extremely high-energy parameters upon optical pumping by radiation from high-temperature explosive sources (such sources were not employed by the Americans). One of the main problems in designing the PDL concerned the creation of very high power non-lamp light sources with the spectrum required for pumping (photodissociation) of molecules of the active laser medium.

Perfluoroalkyl iodides have an intense UV absorption band, which can be used for pumping. The proper pump radiation is generated efficiently by a gas plasma at temperatures of the order of 25 000 K. Although the idea of using light radiation from nuclear explosion in air for this purpose was also considered, the original idea of scientists at the FIAN and the All-Union Research Institute of Experimental Physics (VNIIEF, also known as Arzamas-16, currently called the Russian Federation Nuclear Centre (RFNC) in Sarov) proved to be most significant for practical realisation of high-power PDLs. This idea was published openly only in the beginning of 1990s (see, for example, [9, 10]). N.G. Basov and O.N. Krokhin proposed to use powerful light radiation from a shock wave in a heavy gas, created by detonating an explosive charge (EC), for pumping. Other powerful light sources, e.g., electric charges or xenon flashlamps, were also considered. However, the intensity of flashlamp radiation was limited by the transmission coefficient of the quartz tube walls in the UV spectral region.

It is well known that the radiation intensity increases proportionally to the fourth power of the source temperature. Thus, a five-fold increase in the source temperature compared to the flashlamps increases the radiation intensity by a factor of 125. This circumstance was realised by scientists at the FIAN and led to a considerable increase in the pumping efficiency. In 1965, these scientists proposed to discard the quartz wall separating the heavy gas (e.g., xenon) of the explosive or electric pump source ('open discharge') from the active medium of the PDL. It was the use of the explosion of chemical ECs in the form of shock-wave front radiation for pumping PDLs that increased the energy and radiation power of PDLs by several million times over just 4 – 5 years and provided the radiation energy in 1970 that is still not accessible to most of the other lasers. The processes occurring in PDLs were studied in detail by V.S. Zuev [11].

The beginning of the experimental work on explosive iodine PDLs at the VNIIEF dates back to the initiative of N.G. Basov who in 1965 discussed with Yu.B. Khariton, the scientific supervisor of the VNIIEF, the problem of high-power pulsed light sources for pumping PDLs. Soon after, experiments with PDLs were started at Sarov by the team headed by S.B. Kormer together with physicists from the FIAN (mainly with V.S. Zuev and the members of his team).

In the course of the investigations carried out in 1965–1966 by the scientists from the FIAN, VNIIEF and Vympel (V.P. Arzhanov, B.L. Borovich, V.S. Zuev, V.M. Kazanskii, V.A. Katulin, G.A. Kirillov, S.B. Kormer, Yu.V. Kuratov, A.I. Kuryapin, O.Yu. Nosach, M.V. Sinitsyn, Yu.Yu. Stoilov, *et al.*) the possibility of obtaining high-power pulses at a wavelength of 1.315 μm from iodine photodissociation lasers was demonstrated. Already in the very first series of experiments, a high pulse power and radiation energy were achieved. Compounds of carbon, fluorine and iodine (trifluoroiodmethane CF_3I or hexafluoroiodpropane C_3F_7I) were used as the main components of the working medium of the laser. The creation of a PDL pumped by the UV radiation of the shock-wave front also required the rejection of a certain stereotype thinking: many regarded the very idea of an 'exploding' laser as wild. The scientists from the VNIIEF were in an advantageous position since the main subject of their activity (atomic and thermonuclear weapons) was always connected with the application and a profound study of explosions and complex processes occurring in matter under conditions of extremely high pressures, temperatures and power. To them, explosive devices were a common technology.

In 1965, N.G. Basov and O.N. Krokhin suggested the use of such lasers for destroying BMWs by a reactive mechanical pulse appearing upon rapid evaporation of the BMW surface irradiated by a high-power laser. N.G. Basov reported about this idea to D.V. Skobel'tsyn, the Director of the FIAN, and M.V. Keldysh, the President of the USSR Academy of Sciences. The latter invited Academicians Yu.B. Khariton, Ya.B. Zel'dovich, A.N. Shchukin, A.D. Sakharov, A.N. Tikhonov, A.M. Prokhorov, A.A. Samarskii, and G.V. Kisun'ko, Chief Designer of the AMD systems, to participate in the discussions of this proposal. At the meetings with M.V. Keldysh in 1963 and 1965, O.N. Krokhin put forth proposals to use high-power lasers for solving strategic defence problems [12]. It was proposed in 1963 to pump lasers by radiation from the shock-wave front resulting from a nuclear explosion, while in 1965 it was proposed to produce ultrahigh-power PDLs pumped by the shock-wave radiation produced in the explosion of a chemical EC or from other high-power UV radiation sources, including electric discharges.

In the autumn of 1965, N.G. Basov, Yu.B. Khariton, Scientific Supervisor of the VNIIEF, E.N. Tsarevskii, the Deputy Director on scientific research of the State Optical Institute, and G.V. Kisun'ko, Chief Designer of Vympel, sent a note to the Central Committee of the CPSU, in which they mentioned the basic possibility of destroying BMWs by laser radiation and proposed the initiation of the experimental programme. This proposal was accepted and the programme of developing a laser firing device for solving AMD problems, worked out jointly by Vympel, the FIAN and VNIIEF, was sanctioned by the Government in 1966. It was envisaged to develop high-power PDLs with an energy exceeding 1 MJ, and use them for setting up a scientific and experimental laser firing complex (SEC) at the Balkhash proving ground, where the ideas based on the use of laser technology for AMD systems would be verified under natural conditions. The programme was given the code name 'Terra-3'.

It became clear from the active research work of the experimenters and theorists as early as in 1966–1967 that the chosen approach could lead to laser pulse energies (the figure of 10 MJ was mentioned, which corresponds to an energy equivalent of 2 kg of a high-power EC) that sounded almost fantastic at that time. The scientists assumed that such a high energy and power could destroy the thermal insulation coating of the BMWs. These proposals were put forth under conditions when the lasers available in the laboratories had a pulse energy of about 1 J, i.e., about ten million times lower than the required value. Strenuous work by the enthusiasts from the FIAN, VNIIEF, GOI, Vympel, and groups from the State Institute of Applied Chemistry (SIAC) in Leningrad, where the technology for producing the necessary iodine and fluorine compounds was created and developed (V. S. Shpak was the Director of the SIAC at that time), Institute of Earth Physics (the sector headed by P.V. Kevlishvili), as well as a number of research and industrial organisations, made it possible to not only propose but also execute within a span of two years a whole range of original ideas and technical solutions in the fields of optics, high-intensity light sources, physics and engineering of explosions, chemistry of iodine-containing and other compounds, as well as the methods of their production and purification [11].

The first experiments with PDLs, carried out in 1965–1967, gave quite encouraging results and PDLs with output pulse energies of several hundred thousand joules (100 times higher than the energy of any laser known at that time) had been designed, constructed and tested by the end of 1969 at the VNIIEF with the active participation of scientists from the FIAN and GOI. Naturally, the iodine photodissociation lasers producing extremely high energies were not created overnight. Various versions of laser designs were tested. The decisive step towards the development of a reliable design suitable for attaining high radiation energies was made in 1966, when an analysis of the obtained experimental results revealed that the proposal made by the FIAN scientists in 1965 to remove the quartz wall separating the pump source from the active medium of the laser could be realised in practice. The overall design of the laser was considerably simplified and reduced to the form of a tube with a long EC inside it or on its outer surface, and the optical resonator mirrors at the end faces.

Such an approach made it possible to design and test lasers with a working cavity diameter of more than one metre and a length exceeding tens of metres. Such lasers were assembled from about 3 m-long standard sections. Later (in 1967), a group of gas-dynamic laser specialists (V.K. Orlov, K.I. Kozorezov, V.M. Kazanskii, A.V. Gorodulin, *et al.*), which was formed at Vympel and later transferred to Luch, joined the team involved in the research and construction of explosion-pumped PDLs. Dozens of problems were studied in the course of investigations, from the physics of the processes of propagation of shock waves and light waves in a laser medium to the technology and compatibility of materials, as well as the creation of special ways and means of measuring the parameters of powerful laser radiation. The problems associated with the explosion techniques were considered separately. The laser operation required an extremely smooth and rectilinear front of the shock wave. This problem was solved successfully. Explosive charges were designed, and methods were devised for their detonation so as to produce the required shock wave front. The creation of such PDLs made it possible to start experiments on studying the effect of high-intensity laser radiation on the materials and components of the targets.

As the work on explosive PDLs progressed, another problem arose: to many people, the idea of a laser capable of generating only one pulse and then inevitably destroying itself (at least partially) during its operation seemed absurd. It is worth mentioning here that the large-scale application of missile technology is almost completely based on missiles that are virtually annihilated during firing. Nonetheless, the idea of an exploding laser sounded quite unusual and was criticised, partly on account of the high cost of the first PDLs and their optical parts, which were destroyed in each experiment.

In this connection, research on the physics of reusable PDLs, in which other pump sources (especially, high-power electric discharges) were used, was started at the behest of Basov's laboratory at the FIAN and the group led by I.M. Belousova and I.V. Podmoshenskii at the GOI. Work on the experimental test-bench samples of such PDLs was carried out by a group of scientists at the VNIIEF under the leadership of A.I. Pavlovskii (with the participation of scientists from the GOI), and competed with the research on explosion PDLs at the VNIIEF which was headed by S.B. Kormer. Lasers demanded a very powerful and compact pulsed source of electric current. Magnetic explosion generators (MEGs), which had been developed at the VNIIEF for many years for other purposes, proved to be just the right kind of sources. MEGs (also known as cumulative magnetic generators) were destroyed during the explosion of an EC, but cost of an MEG was much lower than that of a laser. At the early of 1970s, the team led by A.I. Pavlovskii fabricated MEGs specially intended for pumping electric-discharge PDLs, and their production was started at the Elektrosila plant in Leningrad.

3. Laser programme and the development of optical industry

In the early 1960s, the production of any optical component or device of diameter more than 30 – 50 cm was considered as a unique problem in the USSR (and probably in other countries as well). About a dozen large-size mirrors and lenses were produced annually. Although the necessary technology and equipment for fabricating such optical devices in small numbers did exist at that time, the process of production depended to a considerable extent on skilled craftsmen and optical component makers. Years were spent on fabricating and finishing of large high-precision optics.

With the progress of the PDL research initiated by N.G. Basov, the demand for large optical elements (of diameter 0.4 – 1.5 m) increased manyfold. In each experiment, resonator mirrors in the PDL were destroyed, as well as many other optical elements required for measurements, radiation focusing, protection of sensors from fragments, etc. During the years 1965 – 1967, the optical industry was not prepared to fabricate several hundred large-scale optical elements per year. A significant role in the solution of this problem was played by the efforts of Yu.B Khariton and N.G. Basov, the resolute thrust of S.B. Kormer, the head of the PDL activity at the VNIIEF, as well as the enthusiasm and support of the bigwigs in the optical industry and, in the first place, S.A. Zverev, the Minister of Defence Industry, a specialist in optics by his profession and experience of work in the industry, who supported wholeheartedly the development of laser technology.

S.A. Zverev was an extraordinary person. His job as the head of a leading defence ministry in which optics only a part, which demanded of him universal knowledge and multifaceted qualities. All his activity was distinguished by far-reaching and courageous decisions, a statesmanlike approach to the problems, and an unmitigated enthusiasm and interest in new achievements in science and technology. He respected and valued the leading scientists, frequently visited the laboratories of N.G. Basov, A.M. Prokhorov, R.V. Khokhlov and scientists at the GOI, who sought help and support in developing laser technology, improving its financial and production base, and often found such a support from S.A. Zverev. Until the end of his life, S.A. Zverev remained the chairman of the special coordinating council on high-power lasers and systems based on them, provided strong support for the growth of laser technology, involved plants and engineers working there into the laser design and production activity. N.G. Basov and A.M. Prokhorov were permanent and active members of the council.

Owing to the efforts of N.G. Basov and Yu.B. Khariton and the key support of S.A. Zverev, new special workshops and departments were set up during 1967 – 1970 at a number of optical plants to produce laser optics components, dozens of large-scale lathes were designed and fabricated for finishing these components, and vacuum equipment for special optical coatings was purchased from abroad (the Soviet optical vacuum technology was traditionally backward). As a result of these efforts, the production and technological capabilities of the USSR were enhanced considerably to prepare all kinds of large-scale optical elements not only for lasers, but also for many other applications. Batch production of optical elements (plates, mirrors, lenses) of diameter up to 1.2 m was started for the first time in the world. The production of optical glass and optical crystals for laser technology was also increased.

4. Advancement of 'Terra-3' project and establishment of the Luch central design bureau

As the physicists and engineers strove towards perfecting the lasers, the draft of the SEC 'Terra-3' was developed at Vympel under the supervision of O.A. Ushakov (and, of course, with the participation of the scientists). N.N. Shakhonskii, a military engineer (later, major general) who was deputed to Vympel by the Ministry of Defence and who worked afterwards for many years at Luch (currently known as the Federal Research Centre, Astrofizika Research and Production Association), was the supervisor of the project. The project was developed under the conditions when the potentialities of the lasers being designed were not quite clear, nor were there any data concerning the vulnerability of BMWs or the resistance of the optical elements to laser radiation, and the ability of high-power and high-energy laser beams to pass through the atmosphere was also not known.

Several problems had to be solved, especially those concerning the formation of a collimated narrow laser beam and its rapid and precise aiming (a direct hit was required) at a BMW flying at a velocity of 3 – 4 km s^{-1}. At the initial stage, the work mainly involved an expansion of the list of unsolved problems that demanded immediate attention and action. It soon turned out that apart from the development of a high-power laser, the main problems facing the SEC were to meet the requirements on precise beam pointing (a few angular seconds), as well as the creation of optical elements capable of withstanding impact from high-power laser pulses without suffering any damage. During the execution of the first stage of the SEC project 'Terra-3' it was found that the resistance of optical elements to laser radiation was assumed by researchers at Vympel to be unrealistically high. When more powerful lasers were used in the experiments performed at the VNIIEF, it was found that the optical elements (optical glass and optical coatings) did not withstand the high-intensity laser radiation. Immediate action had to be taken to solve the problem. An extensive studies devoted to the fabrication of optical elements having a higher resistance to high-power laser radiation was carried out at the GOI, where the processes of their destruction and the factors determining their damage threshold were studied in detail (under the supervision of A.M. Bonch-Bruevich and G.T. Petrovskii). A new branch in optics, called high-power optics, was born. A programme was undertaken to produce optical equipment capable of withstanding high-intensity laser radiation fluxes.

Many research institutes and design bureaus and especially defence-related industrial organisations participated in the preparation of the draft of the SEC project. Various problems that were not related to lasers also had to be considered, e.g., the formation of high-precision drives for large mirrors, high-sensitivity photodetectors for the precision beam pointing systems, and protection of high-precision optical elements from shock waves generated upon detonation of several tons of EC in the lasers. Naturally, the creation of the SEC at the Balkhash proving ground would have been impossible without the direct participation of the military. The project was actively supported by colonel general G.F. Baidukov, the Head of the main directorate of the USSR Ministry of Defence and in charge of the AMD related problems. General Baidukov was a national hero and a member of the famous team that flew non-stop from Moscow to the USA through the North Pole for the first time in the history of aviation.

In 1967, the PDL pulse energies attained in the experiments were close to 1000 J. However, it was found that although these lasers could generate very high energies, they could not produce the expected narrow beam that was required for the operation. The optical inhomogeneities emerging in the laser led to the beam broadening. But laser energy can be transported over significant distances only in the form of a narrow beam. The beam divergence in the experiments was found to be about 100 times more than the anticipated value, thus rendering the creation of the system impossible. The idea of laser AMD was crashing!

Under the direct supervision of N.G. Basov and with active participation of scientists from the VNIIEF and GOI, investigations aimed at finding the reason behind such an unfavourable divergence of the radiation from explosion PDLs and the search for means to minimise it began at the FIAN. N.G. Basov and O.A. Ushakov were extremely worried over the prevailing situation. A way out of the dead-end had to be found as soon as possible. A 'brainstorming' was organised, resulting in a proposal by N.G. Basov and I.I. Sobel'man to use a two-cascade laser system, in which the radiation from many PDLs in the first cascade with a 'poor' divergence was directed to a laser-converter (Raman laser) in the second cascade with the help of a special optical system [13]. It was expected that the optical distortions in the active medium of such a laser would be insignificant because of its high efficiency and hence the output beam would have a low divergence. The Raman laser could be pumped simultaneously by several explosion lasers, hence it was also called the 'summator' [13]. The wavelength of the Raman laser was determined not only by the PDL pumping wavelength, but also by the material in which Raman scattering occurred. Later, the studies performed at the FIAN and VNIIEF showed that radiation from an iodine PDL-pumped liquid oxygen Raman laser was weakly absorbed in the atmosphere. This determined the choice of these lasers in spite of the considerable inconvenience of having to deal with large quantities of liquid oxygen, which is fire hazardous.

The Raman laser used in the second cascade was a cryostat with optical windows for coupling and outcoupling of radiation. When compressed gases were used, the laser was a thick-walled strong chamber capable of withstanding gas pressures of 50 – 100 atm. It also had optical windows for coupling and outcoupling of radiation and an optical resonator. The requirement was to create Raman lasers with the output energy that would be about million times higher than that obtained in the first lasers at the FIAN. The idea of the summator was accepted for realisation and was used at Vympel for refining the draft of the 'Terra-3' SEC project. A programme of comprehensive investigations was started and was followed a little later (in the early of 1970s) by the development of components of high-power experimental AZh4-T Raman lasers (a pulse energy of 10^4 J) and AZh5-T lasers (a pulse energy of 10^5 J), as well as of the methods and optimal optical systems for coupling and outcoupling of radiation. These works were performed at Luch at V.K. Orlov's subdivision under the supervision of E.M. Zemskov [14]. The radiation was transferred from the primary lasers to the summator with the help of an array of reflecting mirrors (up to several hundred mirrors) of area about 10 m^2.

In 1968, the draft project of the SEC 'Terra-3' was examined by a number of expert and scientific and technical councils. It is now clear that the project allowed too optimistic estimates on many questions, requiring further refinement and verification by large-scale experiments. However, these questions had not been studied comprehensively in those years. It turned out later that the most vulnerable part of the project concerned too optimistic estimates of the laser energy needed for damaging a BMW. Of course, there were other weak points also in the project. On the whole, the course of investigations and the SEC project were approved, although some leading scientists were sceptical about the prospects of lasers in AMD. But none of the critics could (or dared to) indicate specifically the basic drawbacks of the project and the criticism was restricted to specific remarks.

Of course, the adequately financed successful work on attaining extremely high parameters of the laser did attract a large number of scientists and administrators. The high reputation of the leaders of the project, especially N.G. Basov and Yu.B. Khariton, also played a significant role. The leaders of the military establishment (D.F. Ustinov, L.V. Smirnov, S.A. Zverev) apparently believed in the reality of the concept and increased the financing of the project. Even if they saw the risks involved, at least they did not restrict the financing. After all, the AMD programme was extremely important and the leaders did not want to 'miss' any aspect which could eventually lead to the creation of real weapon systems. On the other hand, it became clear gradually that the programme requires a fairly prolonged stage of research and large-scale experiments, creation of many new technologies, development of a special experimental test facility and new productions, which required a considerably long time.

In 1967 – 1968, it became clear to G.V. Kisun'ko and AMD system designers at Vympel that the laser weapon for the AMD would take a long time to materialise. However, the government was pressing them to come up with AMD systems in the nearest future [2], hence their interest in the laser project started abating. However, the teams of laser system designers had already been formed, the scales and financing of these projects continued to rise, leading research institutes were involved in the project, and relatively rapid and significant progress in creating high-power explosion iodine PDLs gave definite grounds for optimism in those years.

The understanding of the complexity of the problem also increased, and special organisational activity was called for. At the end of 1968, it was proposed to reorganise the activity and remove it from Vympel, which was mainly engaged in the development of missile systems for the AMD. O.A. Ushakov, the Head of laser research at Vympel, was an active initiator of such a reorganisation. He was interested not only in the progress in this field, but also realised that a specialised laser firm entrusted with the task of the AMD activity was envisaged and O.A. Ushakov had reasons to expect that he would be called upon to head this firm. The figure of N.D. Ustinov loomed somewhere in the background, but he did not play any active role in the reorganisation plans.

In order to complete the designing of the LE-1 radar, it was decided to create a new specialised design bureau called the Luch central design bureau with the team of laser designers from Vympel [specialised design bureau (SDB-56)] forming its core. S.A. Zverev, the USSR Minister of Defence Industry, emphasized that the new organisation was predominantly design-oriented, obviously assuming that the research problems facing it had already been solved or were being solved by the scientists of the USSR Academy of Sciences, the VNIIEF and GOI (this assumption proved to be erroneous and Luch was subsequently converted into Astrofizika central design bureau, also an applied research organisation).

With the involvement of the scientific programme supervisors from Vympel, the FIAN, VNIIEF and GOI, as well as the representatives from the USSR Ministry of Defence, the project of a resolution by the Central Committee of the CPSU and the USSR Council of Ministers was prepared within a few months, envisaging the deployment of a laser-firing research complex at the Balkhash proving ground, as well as some other organisational measures including the setting up of a special laser design company, to be named the Luch central design bureau (CDB), under the Ministry of Defence Industry. For this purpose, the Vympel design bureau, which was under the Ministry of Radio Industry, picked out the division headed by O.A. Ushakov (SDB-56) and a pilot plant. It was also envisaged to continue at Luch the work on the development of the LE-1 radar and to carry out the research programmes worked out by N.G. Basov at the institutes of the USSR Academy of Sciences and in the industry. After 'grinding' of the project at the MIC, it was approved in the autumn of 1969.

I.V. Ptitsyn, an experienced hand in the optical industry, who had acquitted himself creditably at his previous assignments and proved his capability to get things moving and to establish a sound material and technical base for his organisations, was appointed the director of the Luch central design bureau newly formed for realising the laser design programme. M.G. Vasin, an experienced missile specialist from one of the military design bureaus who had never worked with lasers or laser systems, was appointed quite unexpectedly the Chief Designer of Luch and the Head of the SEC 'Terra-3' project. His appointment indicated that the military establishment considered the scientific and technical problems of the laser-based AMD as already solved, and entrusted the newly created organisation with the task of coming up with a sensible design and technological implementation of the obtained solutions. This opinion, which was formed as a result of optimistic predictions and reports of many scientists and designers, later proved to be fundamentally erroneous.

Suddenly, O.A. Ushakov found himself in an unenviable position. Here was a person who had given many years of his life to the development and organisation of laser systems for AMD at Vympel, and was now relieved of the responsibility to supervise this activity. O.A. Ushakov was known to be a hard taskmaster and never felt shy of 'reprimanding' his associates for errors of omission. And he had N.D. Ustinov and many of his allies working under his leadership.

I.V. Ptitsyn, the Director of Luch was known to be an energetic and go-getting economic manager and director. He was able to launch quickly (of course, with a considerable support from the 'top brass') the construction of a building complex at the outskirts of Moscow for the newly created facility and solved many organisational problems associated with its administration. Unfortunately, I.V. Ptitsyn was not a very tactful person and could not find a common language with the scientists and designers, and he was forced to leave his post as director after a few years, but by that time the initial problems associated with coming into being had been solved successfully.

The heads of the main departments, V.F. Morskov (laser beam pointing system for the 'Terra-3' complex), N.D. Ustinov (laser radars, including LE-1), and V.K. Orlov (high-power lasers), became the Deputy Chief Designer of Luch. P.A. Bakut, a leading specialist on the processing of signals (including laser signals), became the head of the theoretical division of Luch.

At the behest of N.G. Basov and O.N. Krokhin, a prominent scientist and designer V.K. Orlov, winner of the Lenin prize, previously working at the atomic industry research centre, joined Vympel in 1969. In a short time, he was able to assemble a team of physicists and engineers who had solved in following years the problem of developing a whole range of high-power lasers, including PDLs. This team included leading specialists from Vympel (E.M. Zemskov, V.M. Kazanskii, I.S. Marshak, *et al.*), and also from other organisations. During 1970 and 1971, leading specialists and doctors of science G.G. Dolgov-Savel'ev (from the Institute of Nuclear Physics, Siberian Branch, the USSR Academy of Sciences), L.A. Vasil'ev (from a space-oriented research institute), and A.K. Piskunov (from the L.Ya. Karpov Physicochemical Research Institute) were invited to join Luch along with younger Ph.D.'s Yu.I. Kruzhilin, N.V. Cheburkin (a disciple of Academician R.V. Khokhlov) and others, who became later heads of not only sectors, but also organisations.

Researchers at Luch continued the activity started at Vympel in collaboration with the scientists from the FIAN, VNIIEF, GOI, and several other research institutes, on the topics that had existed before the inception of Luch, as well as on a number of new trends in lasers whose development was initiated, as a rule, by N.G. Basov. At the end of 1969, a scientific and technical council (STC) headed by N.G. Basov became the brain centre of the entire programme. The STC worked quite efficiently and vigorously for about ten years, and discussed regularly not only the state of affairs and the results of ongoing investigations, but also the new emerging proposals. The soul of the council was its chairman N.G. Basov. Apart from the above-mentioned leaders of individual programmes and sectors (Yu.B. Khariton, S.B. Kormer, A.I. Pavlovskii and M.G. Vasin), the council also included representatives from other research and design organisations, including V.S. Shpak, the Director of the State Institute of Applied Chemistry, A.M. Bonch-Bruevich and A.A. Mak, Heads of laser divisions at the GOI, A.M. Obukhov, the Director of the Institute of Physics of the Atmosphere, USSR Academy of Sciences, V.L. Tal'roze, the Head of laser research at the Institute of Chemical Physics (ICP), USSR Academy of Sciences, P.V. Kevlishvili, the Chairman of the special sector of the Institute of Earth Physics, USSR Academy of Sciences, as well as representatives of the Ministry of Defence and the Ministry of Defence Industry. Sometimes, other leading scientists also took part in the meetings of the council. In addition to these meetings of the STC, weekly scientific and technical consultations were conducted by N.G. Basov, where new ideas and projects were preliminarily discussed and ways of solving the continuously arising scientific and engineering problems were sought. Along with the development of laser science and engineering in USSR as well as in other countries, an extensive research programme was started by the STC on new types of lasers (electron-beam-controlled lasers, pulsed and cw chemical lasers, and Raman lasers), processes associated with the effect of laser radiation on materials and on military hardware, the propagation of laser radiation in the atmosphere, linear and nonlinear laser optics and laser-resistant optical materials. At least until the mid-1970s, the attention of the scientists was drawn by N.G. Basov primarily towards an increase in the energy characteristics of lasers, while efforts to improve the axial brightness of radiation (i. e., the attainment of high radiation energy, as well as an extremely low beam divergence) were started only at a later stage. The idea of using phase conjugation for this purpose was considered by STC immediately after the publication of the first pioneering works in this direction by the scientists at the FIAN (true, the term 'dynamic holograms' was used instead of 'phase conjugation').

In addition to the solution of a number of practical problems associated with the establishment and construction of the Luch CDB, the work on the creation of the SEC also began in right earnest. The technical project of the complex, which was headed by M.G. Vasin (at least formally, since many organisations and specialists participated in developing the complex) envisaged that the 'Terra-3' SEC to be constructed at the Balkhash proving ground will consist of explosion iodine PDLs, a liquid oxygen Raman laser (summator), a beam pointing system, and the equipment for controlling the complex.

The main buildings of the SEC were made of reinforced concrete and extremely rugged structures to withstand the impact of shock waves and, possibly, fragments resulting from a simultaneous explosion of many PDLs. It was estimated that the overall mass of a EC in lasers may be as large as 30 tons. The building housing the system for pointing the laser beams at the targets was situated at a distance of about 1 km from the explosion laser area and the Raman laser bunker so that the shock wave would reach the building containing the precision optics elements of the beam pointing system only after the radiation pulse had been sent towards the target, and the beam pointing system was also protected from laser fragments. The Raman laser radiation was to be sent to the beam pointing system through an underground channel connecting the two buildings. In the early 1970s, the military engineers started erecting all the SEC structures. Luckily for the designers, the construction activity was quite slow, which allowed the layout of the SEC to be changed many times following a clearer understanding of the problems arising in the course of the experiments.

The beam pointing system was designed and prepared with the participation of researchers from the GOI under the supervision of P.P. Zakharov and a team of researchers from the LOMO headed by R.M. Kashershininov and B.Ya. Gutnikov. The high-precision support-rotating device of original design was constructed at the Bolshevik plant. An 'optical vernier' system based on rotating mirror wedges was used to point precisely a high-power laser beam at the target (with an error of the order of a few angular seconds). High precision drives and reduction gears without play for the support-rotating devices were designed at the Central Automation and Hydraulics Research Institute with the participation of scientists from the N.E. Bauman State Technical University in Moscow. The optical track for the high-power radiation was made of mirrors and did not contain 'transparent' optical elements that could be destroyed by such radiation.

The radiation resistance of the optical elements was one of the most important problems and necessitated the introduction of several changes in the SEC programme. The first SEC project formulated in 1968 was based on the data on optical stability of materials to laser radiation obtained in laboratory experiments with low-power lasers, when the laser spot on the optical components was small (of the order of a few millimetres). The explosive PDLs were used to conduct experiments on much larger optical elements. The results of the tests were quite unpleasant for the designers: the optical elements of a large diameter and optical coatings were destroyed under actual conditions more frequently and at much lower radiation fluxes than in the first laboratory experiments. The reason behind this had to be found and new materials and technologies with a higher radiation resistance, as well as special equipment for processing of optical elements and deposition of stable coatings had to be produced.

The optical elements at the exit of the Raman laser had to withstand the highest laser radiation fluxes. The very first experiments with the high-power AZh5-T Raman lasers carried out by the group led by E.M. Zemskov at Luch revealed that these optical elements were damaged by high-intensity laser radiation. The optical glass had to be replaced by specially processed extra-strong optical fused quartz (more expensive and hard to produce) which was in contact with liquid oxygen inside the laser cell. Under the supervision of G.T. Petrovskii, a technology was developed at the GOI for fabricating 1-m diameter high-purity fused quartz disks for the Raman laser.

5. Development of high-power PDLs in 1970 – 1976

Experimental and design work on high-power PDLs was continued at Luch under the supervision of V.K. Orlov, E.M. Zemskov and V.M. Kazanskii with active participation of physicists from the FIAN (V.S. Zuev *et al.*), and at the VNIIEF under the supervision of S.B. Kormer and G.A. Kirillov (explosion lasers), and A.I. Pavlovskii (electric-discharge-pumped lasers) with the FIAN exercising the scientific supervision [10]. After the successful testing of the experimental explosion lasers with the output energy up to 1 MJ, it became necessary to fabricate industrial lasers whose design had to conform to the conditions of batch production at the plants. Projects of such lasers were worked out at Luch (FO-21 laser, etc.) [15], as well as at the VNIIEF (F-1200 laser). Subsequently, the FO-21 laser was modernised and it became possible to make its design extremely simple, thus reducing its cost by almost an order of magnitude. It was wittingly termed 'the pauper'. A large-size optical mirror of diameter 1.2 metres was constructed at LOMO. This diameter was chosen since it matched the standard diameters of pipes manufactured by the metallurgical industry for gas pipelines. Designing and batch production of the FO-32 PDLs with a lower output energy (pulse energy of a few tens of kilojoules), which were used widely in experiments, was also started.

The continued development of electric-discharge-pumped PDLs at the VNIIEF under the supervision of A.I. Pavlovskii led in 1974 to the fabrication of an experimental test-bench laser with a pulse radiation energy of about 90 kJ. The laser was housed in a strong reinforced concrete casemate and an MEG was installed next to it. The energy from the MEG was transferred to the casemate through a large number of special high-voltage cables through which a current of several hundreds thousand amperes could be supplied to the laser. Strong magnetic fields produced as a result of a powerful electric discharge in the laser volume necessitated a modernisation of its design. Such fields could cause malfunctioning of the laser due to the magnetic splitting and a shift of the spectral lines of active iodine particles. This undesired effects were eliminated due to the combined efforts of researchers from the VNIIEF and GOI. It was many years later, in the early 1980s, that MEG-pumped iodine PDLs were produced at the Los Alamos laboratory in the USA. It was reported that the pulse energy of such lasers did not exceed a few kilojoules.

In view of the progress reported in the building of test-bench reusable electric-discharge PDLs by a team under the supervision of A.I. Pavlovskii, the designers at Luch headed by V.K. Orlov proposed that the explosion PDLs should no longer be used in the SEC 'Terra-3', and should be replaced by electric-discharge PDLs. This rather unexpected proposal was accepted, and the SEC project had to undergo yet another revision. The building previously intended for the AZh7-T Raman laser was redesigned to house several electric-discharge PDLs. A platform for the MEG was to be erected near this building. A project for constructing the electric-discharge PDL (FO-13) with a pulse energy of 1 MJ was developed by the designers of the Perm Machine-building plant and Luch on the basis of the results of investigations carried out at the VNIIEF and GOI. However, this project was not realised for reasons which will be described below; the building for housing lasers was not finished and joined the ranks of so-called 'memorials'. This deserted building was shown to the group of American specialists visiting the complex at the end of 1980s. Only the beam-pointing system of the SEC 'Terra-3' was later developed to the stage of first trials which were also left unfinished.

6. Creation of the laser test centre

In the mid-1960s, when the lasers were 'firing' in the physics laboratories everywhere, it seemed that their path to the weapon systems was clear and simple, and all designers had to do was to just provide a technical 'appearance' to the research lasers, and pass them on to the military. However, these 'sweet' dreams were shattered quickly. Transformation of laboratory table lasers into high-power field lasers required a prolonged and complicated stage of activity on scaling them to the required values of the output energy, an improvement of almost all their parameters, the development of most reliable and simplest technical solutions from the operational point of view, and a quest for methods of their assembly and servicing under field conditions. Moreover, a transition from small to large lasers sometimes required radical changes in the laser design, because a simple variation in the geometrical size of devices is sometimes impossible for reasons connected with the physical processes occurring in the lasers. This kind of work requires a great deal of field experiments to work out the important details of the design and to study the propagation of high-power beams in the actual optical path. The existing proving grounds were insufficient for carrying out the bulk of such activity and it became obvious that a special testing and refining base must be constructed for high-power lasers, at par with the bases belonging to other branches of the defence industry, space and aeronautical industry, artillery, missile technology, etc.

The lack of ample proving grounds at the disposal of Luch retarded the development of PDLs and other high-energy lasers like CO_2 and CO lasers, chemical and solid state lasers that appeared in the early 1970s. It was almost impossible to create and test high-power lasers in the laboratories in Moscow. This was also realised by N.G. Basov soon. Hence, a search began under his leadership for an appropriate site for constructing the laser proving ground. An area covering tens of square kilometres somewhere in the central part of the country was sought. It should be in a secluded region, but must have good transportation and power communication facilities. After a search of several months and visits to various potential sites, the choice finally fell on a test-firing site for tanks some 20 km to the south-west of Vladimir abandoned by the military. The wooded marshland bogged by peat on all sides was practically virgin, unpopulated, had no roads (except forest roads) and no power lines. However, the territory was not far from the Moscow – Gor'kii highway and high-power transmission lines and a railway track (leading to old peat extraction sites) were quite close. The place was only 180 km from Moscow. The USSR Ministry of Defence readily agreed to release the unused exercise ground for the development of laser activity, and in the beginning of 1971, orders were issued by the USSR Government to create an interdepartmental research and test centre. Survey work began at the site of the construction.

The centre was given an undisguised name, the Raduga (Rainbow) DB. Major-general I.S. Kos'minov, who had earlier taken part in the development of missile technology and the creation of largest missile proving grounds in the country, was appointed the head of the centre [16, 17]. The story of development of Raduga deserves a separate narration [16]. It should be simply mentioned at this stage that the efforts of the Soviet military engineers led to the creation of an imposing testing and construction complex (and also a research and design complex since 1980s) in the heart of the marshy and impassable Vladimir forests in a comparatively short time, with isolated testing sites, necessary buildings, roads, measuring facilities, ample power, and all kinds of engineering installations. Moreover, a pilot plant for the production of high-power laser equipment was also constructed. A modern town Raduzhnyi was built near the testing centre with schools, kindergartens and medical facilities (at present, about 20000 people reside in this town). This is perhaps the only city in the world built solely in connection with the problems of creating high-power lasers and the need for testing and investigating these lasers. Several thousand people were working at Raduga by the mid-1980s, about a thousand of them being researchers and investigators. Testing of various types of lasers, e.g., solid state lasers, CO_2 lasers, CO lasers and metal vapour lasers, was carried out at the centre.

A little later, experimental laser radar test-benches were created at Raduga in the mid-1970s, including those with synthesized aperture. However, these radars were not ready in time to be used in the Terra-3 programme. N.G. Basov frequently visited the laser proving grounds at Raduga, where results of investigations on high-power lasers were studied and discussed, and meetings of the STC were held with the participation of all leading laser specialists in the country, sometimes with the participation of A.P. Aleksandrov and G.I. Marchuk, Presidents of the USSR Academy of Sciences. The progress in the work being carried out at Raduga was demonstrated from time to time to the leaders of the USSR Government, Ministers and military commanders.

7. Research and design of powerful lasers

At the initiative of N.G. Basov, the activity connected with the creation of the SEC, photodissociation lasers and laser summators for this complex was supplemented in 1970s by a whole range of programmes of research and development of other types of high-power laser technologies. Let us briefly consider the main aspects of this activity, which were pioneering, although in some cases they simply reproduced on the enlarged energy scale the results obtained in the laser laboratories of the USSR and abroad. The programmes of this activity, especially in the early 1970s, were frequently supplemented and refined following the emergence of new scientific ideas in the USSR and abroad. We are not in a position to describe here the details of these studies, which resulted in the publication of hundreds of papers and scientific reports.

Research on pulsed chemical lasers (PCLs) was started as an alternative to PDLs. Scientists hoped that the use of the energy of chemical reactions in the active medium of a laser could lead to a considerable increase in its efficiency and to a corresponding alleviation of the requirements imposed on the pump source (a decrease in the quantity of the EC or a complete rejection of the EC in the chemical reaction initiation system), as well as to the development of reusable lasers. Together with the researchers from the FIAN (A.N. Oraevsky's group), scientists' teams from the VNIIEF (S.B. Kormer and M.V. Sinitsyn's group), the Institute of Chemical Physics (the group led by V.L. Tal'roze) and the SIAC (under the supervision of V.S. Shpak) and several other institutes also participated in this work.

In the first place, the chemical laser based on the reaction of fluorine and hydrogen (or deuterium), whose energy parameters were found to be the highest, was studied. The interest in this laser was spurred by the hope that it should be possible to initiate a chemical chain reaction in it, which would considerably ease the constraints on the device initiating the triggering of a chemical reaction. Together with the scientists from the SIAC, the group from the VNIIEF worked on PCLs in which the chemical reaction was triggered by the so-called explosion lamp, i.e., a radiation source based on shock waves generated as a result of a moderate explosion, with a hope to create subsequently a laser that would remain undamaged after such an explosion. Investigations and experiments led to the creation of several models of (non-recoverable) explosion PCLs with a pulse energy of up to tens of kilojoules. However, the amount of EC required for initiating a chemical reaction still remained significant, although a bit lower than that required for a PDL of the same scale, and the lasers were destroyed in the experiments. In addition to the fundamental investigations of the chemical and physical processes occurring in PCLs, experiments were also carried out at the Institute of Chemical Physics with chemical lasers of different scales, in which nonexplosive sources were employed for initiating a chemical reaction. In the Chernogolovka branch of the Institute (near Moscow), the first model of a laser with the volume of the chamber equal to 300 L was fabricated. A little later, after the construction of a special test facility, the volume of the laser was increased to several cubic metres. However, the power of the source (pulsed flashlamps) used for initiating the chemical reaction was not sufficient and hence the characteristics of these lasers were not very high.

Investigations of PCLs led to several physical results, but did not lead to the development of lasers whose radiation power parameters could compete with PDLs. In the mid-1970s, work on the creation of pulsed and repetitively-pulsed chemical lasers with electron-beam triggering of the chemical reaction was also carried out at the VNIIEF and SIAC. However, the energy of these lasers also could not be scaled to the level of PDLs. Research on cw chemical lasers, on which the Americans had been pinning their hopes for a long time, was also undertaken.

The cw chemical laser investigations were envisaged under the 'Terra-3' programme, although they were not directly linked with the creation of the SEC. They were initiated by N.G. Basov and were jointly performed by researchers at the FIAN (A.N. Oraevsky), Luch (V.K. Orlov, A.K. Piskunov), Power Machine Building Design Bureau (PMDB, the Chief Designer V.P. Radovskii and scientific supervisor B.I. Katorgin, currently the head of the design bureau), SIAC (V.S. Shpak, M.A. Rotinyan), Institute of Chemical Physics (V.L. Tal'roze), and several other organisations. Research, development and testing of several models of chemical lasers with output powers up to a hundred kilowatts were carried out in the mid-1970s. The building of test bench samples of chemical lasers and the development of the complex technology of operation with them were considerably accelerated owing to the participation of PMDB with its specialisation in the development of missile engines, which have a lot in common (as regards design) with the cw chemical laser. The use of a highly toxic material like fluorine in such lasers called for the construction of special test facilities, vacuum pumping systems, and methods of utilisation of the exhausted materials. It must be mentioned that the work on cw chemical lasers within the framework of the 'Terra-3' project was carried out on a much more modest scale compared to the scale of programmes being carried out in the USA. Later, N.G. Basov started work on cw iodine – oxygen lasers, which was continued in the Kuibyshev (currently, Samara) branch of the FIAN.

In the early 1970s, following reports in the USSR and abroad on the creation of CO_2 lasers using electron beams for ensuring a stable electric discharge in the laser (e-beam laser) under a high (atmospheric) pressure of the active medium, work began in the USSR on the creation of high-energy lasers of this type called electro-ionisation lasers in the 'Terra-3' programme, although this term was not used by everybody.

Almost simultaneously, essentially the same type of lasers were developed for other purposes in scientific and design cooperation between the scientific teams led by Academicians A.M. Prokhorov, E.P. Velikhov, and B.V. Bunkin.

The first investigations on electro-ionisation lasers at the laboratory of N.G. Basov (in the group led by V.A. Danilychev) led to the optimistic predictions concerning the possibility of attaining high energy parameters (the efficiency and the energy output per unit volume) and a good optical quality of radiation. As always, these predictions were later justified only partially. At the initiative of N.G. Basov, design proposals for constructing an electro-ionisation laser with an average radiation power of 1 MW were prepared in collaboration with one of the aviation companies in Kuibyshev, led by I.A. Berezhnoi, and Luch. In 1973, it was decided to set up an experimental test-bench CO_2 laser of power 1 MW, which was tentatively called 3D-01. The work at Luch was carried out under the direct supervision of G.G. Dolgov-Savel'ev, while the FIAN side of the activity was led by V.A. Danilychev.

Once again, it was decided to increase the energy by a factor of 1000 over the value attained at that time. The choice of the laser design at the initial stage was quite complicated. The idea of a closed-circuit laser was used, in which the working substance (gaseous mixture) was pumped by a powerful fan through an electric-discharge optical cavity. The radiation was generated in this cavity. The heated gas was then passed through a cooling unit and then reused for operation. The gas-dynamic circuit of such a laser was similar to wind tunnels that had been used extensively for gas-dynamic aviation and space activity since long. A number of model systems with energy parameters inferior to those of the 3D-01 laser were constructed for carrying out scientific and engineering studies and for verifying certain technical solutions and the attainable parameters of electro-ionisation lasers.

The 3D-01 laser was developed and perfected until the end of 1970s, and a mean output power of several hundred kilowatts was attained. Almost at the same time, work on CO_2 lasers with electron preionisation was also carried out in other institutes under the supervision of A.M. Prokhorov and E.P. Velikhov. A significant contribution to the development of these lasers was made by V.D. Pis'mennyi, who moved from the Moscow State University to work at the Troitsk Division of the Institute of Atomic Energy near Moscow headed in those years by E.P. Velikhov. In contrast to the electro-ionisation lasers of N.G. Basov, these lasers were known as fast-flowing electric-discharge lasers. The lasers developed under the supervision of A.M. Prokhorov and E.P. Velikhov in collaboration with the researchers at the Almaz Research and Production Association (led by B.V. Bunkin) were constructed according to the open cycle design, when the spent gas was released into the atmosphere. Such lasers were found to be more suitable for applications involving short working cycles (a few seconds).

The 3D-01 laser became operative in 1976. It was only after some time that the parameters of its complicated systems, including specially designed high-power electron guns for organising a discharge in the powerful jet of a mixture of CO_2 and other gases, attained a level corresponding to the rated values. However, like PDLs, the angular divergence of the radiation from this laser was also found to be unsatisfactory in the beginning. Subsequently, the 3D-01 laser was replaced (but not under the 'Terra-3' project) by another more perfect electro-ionisation laser developed under the supervision of N.V. Cheburkin. The required level of divergence was attained only after several years, and necessary changes were made in the laser design.

8. Completion of the 'Terra-3' programme and further work on high-power lasers

In 1975, the construction of the building for the guidance system in the SEC 'Terra-3' was continued and the installation of the equipment was started. On the whole, the construction activity at the testing range was quite slow and, as a rule, its actual progress lagged behind the directive planning by several years. However, this did not harm the programme in any significant way since it enabled the designers, at least in certain cases, to modify (and at times radically alter) the SEC devices and systems as the need for such alterations arose incessantly.

By then, the leadership of Luch had been changed. N.D. Ustinov was appointed the chief designer of Luch and the SEC 'Terra-3'. B.E. L'vov, a quiet, prudent and pragmatic engineer of considerable experience was appointed the director of the enterprise. Not only the governing body, but even the name of the firm was changed: it was now called the Astrofizika Central Design Bureau.

The construction of the SEC could not remain unnoticed by the Americans who had apparently been following the construction activity at the Balkhash proving ground with the help of their national satellite surveillance system. It was reported in the American press in the end of 1970s that the Russians were building a laser device for the AMD at the Sary-Shagan proving ground on the banks of the lake Balkhash. Subsequently, the American military and civilian enthusiasts of the SDI exaggerated and vigorously played up this information which, true, was based on facts. In a book entitled ‘Beam Defence as an Alternative to Nuclear Destruction’, which was published in the USA in 1983, it was stated that the Russians had recently tested an advanced iodine laser which had been used to destroy a ballistic missile, thus demonstrating their capability to use lasers as a strategic weapon. Intelligence sources of the USA reported that the area around the proving ground was littered with the heads of destroyed missiles, thus proving that the Russians can successfully hit ballistic missile targets [18]. Pictures of the buildings of the SEC ‘Terra-3’, based on space photo surveillance data were also shown in publications of the defence and State departments of the USA (see, for example, [19]), as well as in a number of similar publications. The reports on the ‘achievements’ of the Soviet Union in the field of laser AMD were somewhat exaggerated, to put it mildly. The fragments of the broken-down building equipment scattered around SEC were rather a reflection on the working style of the builders and not a testimonial to the success of laser technologists.

Much later, in 1989, when the disarmament process had been set into motion, a large group of American politicians, specialists and journalists visited the Balkhash proving ground at the personal permission of M.S. Gorbachev. The ‘remnants’ of the SEC ‘Terra-3’ including the laser beam-pointing system and the unfinished building that was supposed to house the electric discharge PDL were shown to them.

But let us return to the period 1976 – 1977 when clouds started gathering around the ‘Terra-3’ project. After 10 years of strenuous activity, it became obvious (to the leadership also) that the laser weapon for the destruction of BMWs at the terminal stage of their trajectory could not be realised for the time being. I believe that the leading scientists, including N.G. Basov, the head of the scientific part of the project, had arrived at this conclusion even earlier. It was clear that the energy parameters of lasers and the engineering solutions used in the SEC ‘Terra-3’ obviously could not provide the transport of the laser energy to the target for destroying the BMW. The problems encountered upon the propagation of such powerful beams through the atmosphere also became quite obvious. Serious problems were also involved in designing and preparing the beam directing system, which was subjected, like many other parts of the ‘Terra-3’ complex, to extremely stringent constraints on the dynamics and precision of beam-direction, radiation resistance of the optical equipment, and several other parameters.

In the second half of 1970s, the creators of the complex were still not in possession of a laser beam of sufficient power to destroy BMWs. Moreover, the ways of attaining the required energy characteristics were also not clear. The designers at Astrofizika found themselves at a technical dead end: the design parameters of the complex being developed did not raise any hopes of destroying BMWs. Although the energy parameters of the lasers of other types being developed simultaneously at the initiative of N.G. Basov were considerably improved, the results (as in the case of explosion PDLs) gave no hope of destroying a BMW by laser radiation in the near future by incurring reasonable expenditures. It should be mentioned that after getting intelligence reports about the explosion PDL work in the USSR in the early 1980s, the Americans also produced such

Figure 2. Nikolai Gennadievich Basov (early 1980s).

lasers with energy in the kilojoule range at the Los Alamos laboratory [20] and began to study the effect of the radiation from these lasers on materials and objects.

The tests of the beam pointing system started in the second half of 1970s were far from completion and encountered serious problems, both technical and organisational. Instead of the high-power laser, a relatively low-power neodymium glass laser was used in the trials. The overall progress of the work was extremely slow and far from the stage of firing on real BMW (as was reported in the American press). By 1977, the ‘Terra-3’ programme, in spite of its formal existence, was divested of its inert dynamics and thrust which characterised it in the initial phase of its development. New ideas in the fields of laser physics and engineering put forth by the scientists from the FIAN, VNIIEF and GOI were original and moved things forward, but still did not solve the problems facing ‘Terra-3’.

On the whole, considerable progress was made in the laser research activity carried out in the USSR under the supervision of N.G. Basov not just within the framework of the ‘Terra-3’ system. Different types of lasers with outstanding energy characteristics were built. A new effect in the field of nonlinear optics of lasers, called phase conjugation, was discovered at the FIAN. This important discovery led to an entirely new and quite successful approach towards the problems of physics and engineering of high-power lasers, especially the problem of formation and pointing of extremely narrow beams at the targets. It was under the ‘Terra-3’project that the scientists from the VNIIEF and FIAN suggested the use of phase conjugation for transporting the energy of laser radiation to the target.

All these achievements were not (and could not be) envisaged in the SEC ‘Terra-3’ in the form in which it was conceived and developed in the middle of 1970s, although they also could not provide the solution of the main problem of destroying BMWs by laser beams. In many cases, the application of these achievements would have required a complete redesigning of the complex and appropriate modifications of its equipment. As early as in 1976–1977, when tests of the beam-pointing system were started, it became clear that the engineering solutions used in its design were outdated. Science moved forward at a faster pace than the designers and constructors of the 'Terra-3'complex. Hence, new and more advanced and 'promising' proposals kept on popping up in the course of the work, but an analysis revealed that all these proposals required many years of research and development and did not fit into the time frame set for the tests at the SEC 'Terra-3'. The proposal put forth by the teams of the FIAN and VNIIEF [21] was based on the application of the above-mentioned idea of phase conjugation to explosion PDLs. It was suggested that the target should be 'illuminated' first by an auxiliary PDL, and the radiation scattered back from the target should be amplified millions of times by a more powerful PDL and the beam returned precisely to the target using the phase-conjugation devices. This proposal, which is very interesting from the scientific and engineering points of view, was supported by Yu.B. Khariton, the scientific supervisor at the VNIIEF, but it called for a serious amendment of the ongoing experimental and theoretical investigations on the one hand, and a complete redesigning of the SEC 'Terra-3' on the other hand.

Thus, the 'Terra-3' programme was in crisis, although it continued to exist and was financed properly, a special design bureau (Luch) was set up under it, and production facilities were developed where dozens of plants were involved. The flywheel was in motion and could not be stopped all of a sudden. For a long time, neither the scientists and designers, nor the military customers of the project would admit openly that the existing level of technical advancement was not enough for solving the problem. But the project had been underway for over ten years and the creation of the laser AMD system seemed to move farther and farther from the goal. The dead-end situation (as regards the creation of the AMD weapon) was gradually catching up not only with the designers, but also became obvious to the 'leadership'. Besides, considerable progress had been made in the country towards the creation of missile systems for the AMD, the first AMD system for Moscow was already in operation, and the importance of the laser system decreased considerably.

Was the termination of the programme a defeat for the scientists and designers? The knowledge and understanding of the problems of laser physics and engineering, acquired by the scientists in the course of the project, raised little optimism as regards the main problem of the AMD – the destruction of BMWs. However, the military establishment of the country was convinced that the potential adversary also cannot solve the AMD problem by using lasers to strike the BMW at the final stage of the trajectory. In a later conversation in 1994, N.G. Basov, the head of the laser research programme, insisted that 'a negative result is also a result; but we did advance the lasers tremendously.'

The 'Terra-3' programme resulted in a considerable progress in the field of high-power laser physics and technology in the USSR, gave an impetus towards the creation of basically new techniques, especially in nonlinear optics. The programme raised the physics and technology of high-power lasers (primarily, pulsed and frequency-pulsed lasers) to levels higher than those attained by other countries in those years. The theoretical and experimental research carried out under the laser programme led by N.G. Basov provided a better understanding of the physics of the processes occurring in high-energy lasers and made it possible to solve important design and engineering problems. These achievements serve as the foundation for the development of high-power laser technology in Russia even today. First class results were also obtained in several interdisciplinary fields (propagation of laser beams in the atmosphere, pulsed light sources, interaction of radiation with matter, chemistry and technology of producing active media and laser components, etc.). Many scientific and technical achievements were used in subsequent research, including inertial thermonuclear fusion, that is being continued even to this date. N.G. Basov, O.N. Krokhin and their closest associates were the pioneers and initiators of controlled nuclear fusion research in which high-energy pulsed laser radiation was used for compressing a deuterium–tritium target. This, however, forms the subject of a separate publication.

After a systematic study of the reports of the scientists on the progress of the work, the military-industrial establishment of the country and, in the first place, the minister of defence industry S.A. Zverev, percieved in the second half of 1970s that the problem of the laser AMD had not been solved yet. The decision to close the programme to all intent and purpose was worked out and taken by the 'cabinet'. The Ministry of defence industry and the military establishment prepared a government project in the beginning of 1978, according to which the research activity was 'switched' from the unsolved problem to some other strategic problem for the country's defence. The major portion of the technical advancements made in the field of high-power lasers during work on the 'Terra-3' project (which were indeed significant) under the overall leadership of N.G. Basov was to be retained for some other activity. The execution of this decision facilitated the initiation of work in other branches of defence and civilian applications of lasers at Luch already in the early 1970s. Some of these projects went off quite successfully. After a series of discussions concerning the state of affairs and meetings with the Minister of Defence Industry S.A. Zverev, it was decided to wind up the 'Terra-3' activity, and the project was closed in 1978 in agreement with the USSR Ministry of Defence.

In the long run, the programme gave a tremendous impetus to the scientific and technical level of high-energy laser research and designing in the USSR. The energy parameters attained between the end of 1960s and the mid-1970s remain unsurpassed even to this date. An advanced design and engineering, testing and production base required for large-scale laser research in the country had been created. New communities of scientists and engineers were formed and have since been working productively. Laser laboratories in leading research centres of the country in Moscow, Leningrad, Sarov, Novosibirsk, and many other places have been extended and enlarged. Together with the defence programmes, these teams have also carried out many other programmes connected with the ideas put forth by N.G. Basov, e.g., the creation of powerful lasers for carrying out nuclear fusion with inertial confinement of plasma, to which N.G. Basov attached great importance. The ideas of nonlinear optics, in particular, phase conjugation, were applied to high-power lasers for the first time in the course of these investigations. The intellectual strength, inexhaustible energy and the vision of Nikolai Gennadievich Basov was the driving force behind these programmes for many years. The scientific achievements of these works have been reflected in hundreds of research publications by N.G. Basov, and his co-workers, which cannot be enumerated within the scope of this paper.

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