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MEGAGAUSS MAGNETIC FIELDS. PHYSICS. TECHNIQUES. APPLICATIONS

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The Editorial Board and the authors believe that, in this issue, dedicated to the 40th anniversary of the Siberian Division of the USSR (Russian) Academy of Sciences, it is relevant to review the current status, problems, and prospects of ultrahigh magnetic field generation and the development of explosive generators of electromagnetic energy and their applications for some problems of experimental physics. The Institutes of the Siberian Division have made a substantial and, in many respects, decisive contribution to the development of this line of research and the promotion of international scientific cooperation. Our scientists advanced to a leading position in long-term scientific cooperation with the best foreign scientific teams and have continued in this role to the present day.

This review consists of two parts. The part presented in this issue deals with studies performed to date on the fast compression of a magnetic flux trapped in short-circuited conducting contours and the generation of ultrahigh magnetic fields and high-power current pulses. Prospects for future development are discussed, and the challenges facing researchers are outlined. These challenges now are, on the one hand, to improve the quality of the generated pulses by increasing their voltage and power and by controlling the pulse shape, and, on the other hand, to extend studies in the field of high energy densities and high energy fluxes to an increasingly wider class of objects. Since regular International Megagauss Conferences (MG) played a decisive role in the development of this research area, the history of these conferences and the evolution of their subject matter is described.

The second part of the survey, which describes in greater detail the most important scientific ideas and results, will be published in one of the forthcoming issues.

Introduction. The progress made in engineering is largely related to the production of new materials and the development of new sources of energy. In this way, many things are ultimately determined by attainable energy densities and available power flows. New sources of energy require, as a rule, overcoming higher activation energy levels in new energy processes. New materials are either rare elements in combinations impossible in nature or abundant elements in improbable states. In the first case, one should expend much energy to combine atoms. In the second case, high energy densities are most frequently required to overcome the activation barrier and transform the material to a previously unknown state. Studies of materials at extreme pressures, temperatures, and strain rates and under the action of strong fields and high-power radiation fluxes provide new knowledge leading to the production of new materials.

Often, advancements in science also depend on the energy scales of experiments and experimental setups. This is especially true for work in the field of controlled thermonuclear fusion and design of high-power laser systems, accelerators, and other research facilities. The largest experimental setups of such types consume power comparable with the output of a large power plant.

The above-mentioned circumstances have led to the formation of new research areas — high energy density physics and physical material science at extreme energy densities — and their active development over the last three decades. Progress in these areas is intimately related to the development of methods for increasing the energy density concentration in space and time. Such methods are called energy cumulation.

Interest in high magnetic fields is generated, on the one hand, by the possibility of using these fields to study properties of substances and materials and, on the other hand, by the possibility of accumulating high energy densities exceeding the energy density of the most energy-rich chemical compounds. The history

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of the problem of generation of high and ultrahigh magnetic fields covers several decades following the first brilliant studies of Kapitsa in the 1920s. The substantial progress in this field — the attainment of seemingly unattainable fields in excess of 10 MG — has been made possible by the formulation of new ideas and the development of appropriate techniques of utilizing high explosives (HE) and high-current electric discharges. The use of HE has allowed one to produce record-breaking magnetic fields for conducting experiments in various fields of physics and to design a new type of sources of electromagnetic energy — explosive-driven generators. These generators use the chemical energy of HE to generate a current pulse, and are at present sources of energy, current, and magnetic field of extremely high power.

Magnetic Cumulation. Cumulation has long been known. Energy cumulation in time is based on a well-known method: to accelerate a body for a long time interval and then to decelerate it rapidly, i.e., to generate a shock. Energy cumulation in space is a more complex phenomenon. It involves either acceleration of large masses with subsequent transfer of their energy to small masses or accumulation of energy in large volumes with subsequent transport of the energy together with part of the material to a small volume. The latter is possible in special flows and wave processes. One of the most impressive examples of energy cumulation in space is hydrodynamic cumulation under inertial compression of a cylindrical liquid shell. The cumulation limits are ultimately determined by the rigidity of the material, heat fluxes in it, and the flow stability. As a medium with high rigidity (speed of sound) and without heat losses, an electromagnetic field has no equal. Electromagnetic losses can occur only at the boundary between the field and the material in which the charges and currents producing the field are distributed. These losses are proportional to the volume–surface ratio, and, at sufficiently large dimensions, they can be relatively small. Furthermore, an important advantage of electromagnetic fields is the possibility of using the well-known electrotechnical methods of conversion of electromagnetic energy flows to manipulate the flows and concentrate them in a load.

Note one important aspect of the existing experience of energy cumulation. One should not expect energy compression higher than an order of magnitude in one cumulative cascade, and this is an indisputable empirical fact. This rule is especially true for systems intended for the production of extreme parameters. This means that one must start with primary energy sources having high specific characteristics. That is, for successive energy cumulation, one should use, as a primary source of energy, substances with maximum energy density and very high power of energy release. Among materials with such characteristics, condensed explosives are available, well studied, and widely used in industry and in civil and military engineering.

The method of magnetohydrodynamic conversion of the kinetic energy of moving conductors by fast compression of the magnetic flux in a short-circuited conducting cavity has turned out to be extremely fruitful in high energy density physics. This method is called magnetic cumulation (MC). The use of HE in MC schemes has made it possible to design pulsed sources of current with unique energy and power parameters and magnitude of magnetic field. With time, the range of research has been extended. The energy aspect has lost its absolute priority. At the same time, problems of quality of the generated pulses and studies of materials under extreme conditions have gained in importance. The laboratories engaged in magnetic cumulation research have increased in number. The regular International Megagauss Conferences have played a great role in the development of research in this field. To date, seven conferences have been held. The main features of these conferences are their steady and carefully selected topics, fairly permanent leading participants, and, what is more important, the leading positions of the chief persons at MG conferences in world science. The published proceedings and abstracts of the conferences [1–7] contain 683 scientific reports and are distributed from MG-I to MG-VII as follows: 30, 61, 65, 98, 100, 126, and 203. This is very rich material. It allows one to trace the development and evolution of scientific ideas that have inspired participants of unique scientific studies, to follow changes in the approaches and frame of mind of researchers, and to see the steady progress from year to year, from one MG conference to the next.

Scientists who were interested in other issues of high energy density physics united in other international communities formed around other scientific conferences. The widely known Pulsed Power Conferences, whose emphasis is on the development of pulsed sources of electromagnetic energy and methods of electrical-pulse formation, are most closely related ideologically and creatively to the Megagauss Conferences. The recently established scientific competition between the MG and Pulsed Power Conferences has turned out to be fruitful and useful for both conferences.

It is hardly possible to compile a full and, simultaneously, brief survey of all the papers presented at the MG conferences. Therefore, in this section of the paper, we shall only outline the main directions of research and the most important results of the leading laboratories in the USSR, U.S.A., Great Britain, France, Italy, and Japan without reviewing scientific ideas and details. Since the new is almost always the well-forgotten old, we believe that it is necessary to dwell in detail on the initial stage of studies in explosive magnetohydrodynamics. Looking back, we see that it is precisely at that time that the main ideas and principles were formulated. Lacking details, they were, as a rule, simple and clear. Sometimes, the initial formulations of projects were naive and full of optimism and airy self-assurance. Often the authors of ideas did not even guess how much patience and hard work were required to realize their brilliant and seemingly clear ideas. Nevertheless, today, many years later, we can see that the majority of the initial principles have turned out to be fruitful and correct. Only time and perseverance were required for success. Since the Institute of Hydrodynamics and some other institutes of the Siberian Division of the Academy of Sciences were among the pioneers in studies in the field of MC transformations and energy conversion, the research carried out there will be described in greater detail.

The First Stage of Magnetic Cumulation Research. The magnetocumulative method of producing ultrahigh fields and high levels of magnetic energy was proposed and realized in some magnetic cumulation generator (MCG) designs in the middle of the 1950s in the USSR by Sakharov, Pavlovskii, Lyudaev, Chernyshev et al. (All-Union Institute of Experimental Physics, formerly Arzamas-16, now Sarov) [8] and in the U.S.A. by Fowler, Caird, Garn, and Thompson (Los Alamos National Laboratory) [9], Shearer and co-workers (Lawrence Livermore National Laboratory) [10] and Cowan, Crawford, and Damerov (Sandia National Laboratories) [11, 12]. Since all these laboratories were primarily engaged in the development of nuclear weapons and their scientific activities were classified, the idea of the method by itself was first published by Terletskii [13]. But the experimental results on the generation of fields in excess of 10^7 G were published for the first time by Fowler et al. [9], who were among the founders of magnetic cumulation.

In succeeding years, magnetic cumulation research was originated in the USSR at the Institute of Hydrodynamics and the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences [14–17], in the Efremov Institute of Electrophysics Appliances [18], the Kurchatov Institute of Atomic Energy [19], the Kalinin Polytechnical Institute [20], the Shmidt Institute of Earth Physics [21], etc.

Work on magnetic cumulation was carried out at the Fulness Atomic Weapons Laboratory [22] in England and in the laboratories of the Atomic Center at Limeil [23] in France. In the U.S.A., besides the above-mentioned laboratories, many other scientific and technical organizations became involved in this field. Among these, the Illinois Institute of Technology [24] and the U.S. Naval Research Laboratory [25] should be noted for their marked contributions.

The group of Herlach, Knoepfel, and Linhart from the Laboratory of Ionized Gases (Frascati, Italy) played a great role in the development of magnetic cumulation. Beginning nonclassified research of magnetic compression as applied to problems of controlled thermonuclear fusion, this international team published, in a short time, a large number of both popular articles and serious papers concerned with limitations of the MC method for producing ultrahigh magnetic fields. The experimental results and their analysis were reported in detail by Herlach in his fundamental survey [26], which is possibly the best of all the papers published in the first stage of MC development. Lehner [27] compiled a very competent survey of theoretical results on the limits of the magnitude of magnetic fields. The survey by Somon [28] is concerned with detailed analysis of the liner stability, numerical calculations, and also numerical analysis of flux losses. And, finally, the book by Knoepfel [29], which contains an extensive bibliography and almost encyclopedic data on ultrahigh magnetic field generation problems from a number of fields of physics and technology, has been recognized by specialists and beginners.

Another important aspect of the activities of the Frascati group involved the organization of a number of scientific seminars and conferences. The First International Conference on Megagauss Field Generation and Related Topics was held at Frascati in 1965 [1]. The next was the summer workshop on high density physics at Varenna [30].

However, the Frascati group pursued extremely pragmatic objectives and included people of different scientific levels and depths who posed different problems. As a result, the group dissolved after seven years of existence. Its activities had the character of a campaign directed toward rapid applied results and can serve as an example of the "team" method of solution of scientific problems under present conditions where science is considered as a branch of industry.

Evaluating in general the results of the work of this group of researchers, one should recognize that their activities marked the termination of the first stage of magnetic cumulation research, which can be briefly characterized as the period of records, when fields in excess of 10^7 G, currents of the order of 10^8 A or higher, and magnetic energies at the level of tens of megajoules were attained very rapidly, even in the first experiments. However, no applications for all these records were found, and reproduction of the high parameters obtained turned out to be a difficult problem, which depended in many respects on the quality of the manufacture of MC systems, and, sometimes, simply on luck.

Research in the 1970s. During these years, magnetic cumulation research was carried out in several directions. MC generators were improved, and steady MC systems that ensured specified load current and energy parameters were designed. The first nonclassified papers were published by the outstanding team of brilliant researchers from Arzamas-16 (All-Union Institute of Experimental Physics) under the leadership of Pavlovskii, Lyudaev, and Chernyshev [31, 32]. Circuits with a pulsed transformer, pulsed transformers themselves [21, 33, 34], and also a circuit for energy accumulation in an inductance with subsequent commutation by means of opening switches [12, 35–39] were developed to couple MCG to loads. A project on the use of the latter circuit in plasma focus experiments in the megajoule range of energies was published by a group of French researchers [40].

Along with the classical explosive-driven magnetic cumulation technique, the magnetodynamic technique, in which a piston squeezing the field (liner) is accelerated by the pulsed magnetic field produced by a capacitor bank discharge, began to be developed [16, 18, 20, 41–43]. The design of MCG with a liner accelerated by a compressed gas [19] and generators with field compression by a shock-induced flow of ionized gases [44–49] was initiated.

In the field of applications of the ideas and methods of magnetic cumulation to plasma physics, considerable research activity was shown in numerical simulation and projects on the compression of a magnetic field together with a plasma. The focus here was on controlled fusion with so-called θ pinch [50], but the possibility of generation of a high field upon plasma compression also aroused considerable interest [51].

Ideas of using magnetic cumulation in solid-state physics evolved. The application of pulsed magnetic fields to the adiabatic compression of materials up to high pressures seemed attractive. Bitter [52] was perhaps the first who proposed using magnetic fields for material compression, and this idea was realized with different degrees of success by Bless [53], the Livermore group headed by Killer and Hawke [54], and by Pavlovskii's group [55]. While the application of magnetic fields to material compression opens up a new region of application of ultrahigh magnetic fields, the study of the electrical and optical properties of materials in megagauss fields extends the traditional and classical solid-state physics to the new range of fields. The beginning of extensive studies in this direction was reported by Fowler in his review [56], which aroused considerable interest at that time.

Two attempts were undertaken to use MCG in high-energy physics. At the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences, the group headed by Barkov designed an experimental complex for measuring the magnetic moment of hyperones and searching for a Dirac monopole in magnetic megagauss fields generated by MCG and developed a procedure for measuring such fields with an accuracy of 1% [57].

In the joint work of scientists from the Illinois Institute of Technology and Stanford Laboratory, an attempt was made to observe the interaction of a relativistic electron beam with a megagauss magnetic field and the associated phenomena such as bremsstrahlung radiation, radiation friction, creation of pairs and other nonlinear phenomena resulting from vacuum polarization [58]. The work was performed under the initiative of Erber, a specialist in quantum electrodynamics. Herlach was invited to perform the experiments. However, this scientific "team" suffered the fate of the Frascati group rather soon: after the first papers on the idea of experiments and the first tentative results, the group dissolved.

In the late 1970s, a rather strange situation arose in magnetic compression research. Despite the obvious advancements and attainment of record-breaking fields and currents, and also despite the scientific attractiveness of the method, the idea did not find any valuable application. Hopes for rapid success were not realized. The unstable operation of generators, the poor, or more precisely, intolerable reproducibility of results under conditions of expensive, laborious, complex, and dangerous explosive experiments cast doubt on the application of generators. Just at that time of crisis, it happened that six International Megagauss Conferences, MG-II–MG-VII were revived and held with increasing success. This ensured not only survival but also fruitful development of the new and prolific line of scientific investigations.

Megagauss Conferences. The Second Megagauss Conference was held from May 29 to June 1, 1979 in Washington, D.C. It summed up the results of the first two decades of work. The conference was organized by the Lawrence Livermore National Laboratory, the Los Alamos Laboratory, the Naval Research Laboratory, the Sandia National Laboratories, the Air Force Office of Scientific Research, the Office of Naval Research, and the Office of Fusion Energy and the Office of Inertial Fusion of the Department of Energy, the brilliant scientists of the U.S. military-industrial complex. Turchi from the Naval Research Laboratory supported by Fowler, Shearer, and Cowan, leading scientists from the Los Alamos, Livermore, and Sandia Laboratories, worked tremendously on the preparation of the conference. In the list of sponsoring MG-II organizations was the Institute of Hydrodynamics of the Siberian Division of the USSR Academy of Sciences, the only foreign institution, and Titov and Shvetsov were members of the Organizing Committee. There were only three participants from the USSR, and G. A. Shvetsov had to carry out a considerable task. Taking into account that the Organizing Committee decided that the proceedings of the conference should include only those papers that were submitted and discussed at the conference, he presented, apart from his own papers, 17 papers of his compatriots, who were not able to attend the conference. The papers of Soviet researchers were the enrichment of the MG-II [2] proceedings and made it a bestseller at the U.S. market of scientific publications in 1980.

At the Conference, scientists from Arzamas reported on their achievements in the design of ultrahigh magnetic field generators and power generators suitable for physical experiments and the development of improved recording methods, experimental sites, and reliable generators able to yield reproducible fields up to 10 MG. Great advancements had been attained in the creation of mathematical models of MC systems of both the electrotechnical and magnetohydrodynamic levels, in the development of methods of coupling MCG to a load, and in the study of losses and limitations of such power generators. Researchers from the United States reported on the results of extensive studies on compression of a plasma with a magnetic field.

The Third Megagauss Conference, held with great success from June 13 to 17, 1983 in Novosibirsk, was in many respects the key event for the further development of megagauss physics research. The conference was organized by the Institute of Hydrodynamics of the Siberian Division of the USSR Academy of Sciences. The Kurchatov Institute of Atomic Physics (Moscow) and the All-Union Institute of Experimental Physics (Arzamas-16) rendered considerable assistance to the host of the conference. The Chairman of the Organizing Committee Titov and the Scientific Secretary Shvetsov made substantial contributions to the preparation and work of MG-III. They also published the proceedings of the conference [3].

MG-III was a significant event, because for the first time it brought together leading researchers from all research laboratories of the world engaged in the generation of megagauss magnetic fields and related topics. Great progress in all research lines included in the program of the conference was demonstrated. The topics of the papers presented focused on the following research areas:

- Experimental techniques for ultrahigh magnetic field generation.
- Ultrahigh magnetic field generation.
- Applications of ultrahigh magnetic fields.
- Imploding liner systems for fusion.
- Modeling of magnetodynamic systems.
- Magnetic cumulation generators.

- Explosive MHD generators.
- Conductors and insulators at high energy densities.
- Switching and pulse-performing techniques.

The papers of A. I. Pavlovskii's group on the interaction of megagauss magnetic fields with liner material and development of cascade MCG of ultrahigh magnetic fields [59, 60] were the most outstanding event of MG-III. Similarly outstanding in the field of design of explosive generators of power was a series of papers of the same group and the papers of their brilliant colleagues headed by V. K. Chernyshev, their permanent rivals in long-term and creative competition. They presented the results of development and experimental tests on a wide range of magnetic cumulation generators of various designs operating over a wide range of output parameters [32, 39].

Great advancements were attained in the design of pulsed transformers for coupling MCG to loads and in the design of opening switches for managing currents in inductive storage. The Los Alamos group demonstrated a step-up mini-transformer of relatively simple design capable of operating with a flat MCG at a voltage of up to 1 MV [61]. Scientists from the Livermore Laboratory showed, among other achievements, an MCG using a gun projectile as a primary source of energy [62]. This generator did not live up to the hopes of the designers. It was complex, expensive, had large magnetic-flux losses, and confirmed the following well-known principle: the more complex the construction, the worse it operates. Miura and his collaborators from the Institute of Solid-State Physics of Tokyo University presented a thought-out project on equipping their laboratory with a set of sources of pulsed megagauss magnetic field, including solenoids powered directly by a capacitor bank and a compact magnetic cumulation setup with electrodynamic acceleration of the liner [63]. A new method of magnetic-field compression by a system of shock waves in a nonconducting material that becomes conducting under the action of high pressures and the results of successful experiments were reported by Bichenkov and co-workers from the Institute of Hydrodynamics of the Siberian Division of the USSR Academy of Sciences [64] and also, independently, by Nagayama from Kumamoto University (Japan) [65].

The fourth conference was held from July 14 to 17, 1986 in Santa Fe (U.S.A.) [4]. The conference was organized by the Los Alamos National Laboratory supported by the Lawrence Livermore National Laboratory, the Sandia National Laboratories, the U.S. Air Force Weapons Laboratory (the present Phillips Laboratory, the Kirtland Air Force Base). Fowler was Chairman of the Organizing Committee. The subject matter of the conference was close to that of the previous conference. The behavior of materials in ultrahigh magnetic fields and experimental techniques, equipment, and diagnostic facilities for ultrahigh magnetic field generation and design of explosive generators of electromagnetic energy received more attention than previously. The papers dealing with the design of switchers of high-power electromagnetic pulses had considerably increased in number. Almost a quarter of the papers presented at the conference were concerned with the compression of plasma systems and liners. Investigations of the electrodynamic acceleration of solid bodies had been considerably extended, and the number of papers on this topic had increased [66–70].

In the reproducible generation of extreme magnetic fields by explosive-driven systems, Pavlovskii and co-workers brought the level of record-breaking fields to 12 MG and began preparations to attempt 15 MG [71]. Furthermore, along with studies of the transformations of the electron structure of crystals in megagauss fields, they turned back to the problem of hydrogen metallization at a new level of both field generators and measurement accuracy of the magnetic fields, pressures, and geometry of the MC cavity [72, 73]. This group explored the shockless compression of solid hydrogen to 3.5 Mbar. They were able to compress hydrogen to 0.96 g/cm^3, and recorded the occurrence of electrical conductivity at a pressure of $\simeq$1 Mbar and density of 0.61 g/cm^3.

The advancements in the explosive-driven flux compression generation of ultrahigh reproducible fields of the 10-MG range stimulated designers of alternate systems, and 4 MG was achieved with discharges of fast batteries [74].

Pavlovskii, Miura and co-workers reported new data on the optical and resonance properties of crystals in megagauss magnetic fields.

The invited papers of scientists from the Bitter National Magnet Laboratory were a remarkable point of

MG-IV. Adherents of investigations in steady-state magnetic fields, they advocated the prospects of steady-state or almost steady-state solenoids (pulse duration $\simeq 10^{-2}$ sec) for 0.5–0.7 MG fabricated from modern composite materials.

As for power generation, the emphasis of the U.S. researchers was on the development of models and programs for the numerical simulation of the operation of MCG coupled to various loads and also on the development of more and more detailed and accurate calculation schemes for losses in such generators. Among possible applications, the focus was on the realization of implosion of a plasma liner and the associated production of a great output of soft x-ray radiation, the powering of high-power solid-state lasers by MCG, and also the possibility of placing a vacuum diode or another generator of a high-power electron beam at the outlet of MCG. Apart from circuit switches, pulsed transformers with extreme electric field, 0.98–1.97 MV/cm or higher, which could increase the coupling coefficient of such transformers to fantastic values (0.9 or higher) at a working voltage of $\simeq 1$ MV continued to generate interest among scientists. These projects reflected the hysteria of "star wars," which took hold of some people at that time. Against this background, the papers of our compatriots looked more moderate. They continued to develop new models and schemes for the calculation of losses in generators and more perfect methods for designing cascades, forming pulses, and coupling MCG to traditional loads.

The MG-V conference was held in Novosibirsk again (July 13–17, 1989). The range of problems considered was almost stabilized, moderate progress had been made in all research areas, and the range of physical studies of the behavior of materials in high magnetic fields had been extended. Replacing their leaders, younger scientists of well-known groups began to appear at the rostrum of the conference more often. As always, the Livermore scientists demonstrated an exceptionally high level of technological perfection. Chase and his collaborators reported on the details of the design of a helical MCG using expensive and perfect materials (copper with 10-μm grains, composite copper profiled windings of a magnetic coil, fiberglass wraps holding the coil), perfect technologies (electroplating of wires by a high-conductivity material, precision machining using numerically controlled machinery, the extrusion method of fabricating HE charges with 5-μm grains, and precise ignition of detonation), and very accurate measurements of the generator performance, within ten nanoseconds in time and about ten micrometers in space [75, 76]. These papers were an extension of the papers presented at the previous conference and contained a detailed description of the fabrication and test issues involved with a small helical MCG. These MCG were designed to study turn-to-turn electrical stresses, deformation of turns, and to evaluate the accuracy of the circuit analysis simulation program CIRC. Because of the accessibility of a wide range of various measurements, MCG seemed to be a suitable object to verify the agreement between numerical models and experiments.

The Sixth Conference was held in Albuquerque (U.S.A.) from November 8 to 12, 1992. It was organized by the Sandia National Laboratories and the Phillips Air Force Laboratory. Cowan was Chairman. Traditions were preserved. Pavlovskii and co-workers reported on the attainment of 15 MG. They planned to attain 20 MG in a cascade generator and perform experiments on the generation of fields of 100 MG with a nuclear explosion [77, 78]. Pavlovskii's group and Miura reported on new investigations of materials. Designers of power systems presented new larger-scale MCG, transformers, and switches. Analysts and designers reported on new calculation models for losses, gas dynamics, and plasma phenomena. Miura made the new statement that he approached 10 MG on his magnetodynamic setup [79].

The nation-wide project on the organization of a new magnet laboratory, presented by the U.S. Government, science, and industry aroused great interest. In this laboratory, it was planned to use all modern advanced techniques of high magnetic field generation. The Florida State University was chosen as the site for stationary and quasi-stationary machines, and the Los Alamos Laboratory for pulsed machines. Fowler [80] and a senior official of the U.S. Department of Energy presented papers on the scientific and organizational and financial aspects of this grand project. An impressive exhibition of new conducting, superconducting, and insulation materials, composites, and ceramics of interest for the design of high and ultrahigh magnetic field generators [81] was organized.

A peculiar supplement to the U.S. project was the paper of Herlach [82] on the outstanding advances of European scientists in the design of reusable warm solenoids with a quasi-steady-state field of $\simeq 1$ MG. The success was determined by the use of new composite and ceramic materials.

At the last session of the "Megagauss-VI" conference, Academician A. I. Pavlovskii invited the next seventh conference to Arzamas. MG-VII was held from August 5 to 10, 1996 at Sarov (formerly Arzamas-16) of the Nizhegorodskaya Region, but, unfortunately, without its recognized leader, because A. I. Pavlovskii died three months after the sixth conference. The Megagauss community suffered a heavy and irreplaceable loss. Another permanent member of the International Organizing Committee, V. F. Demichev from the Kurchatov Institute of Atomic Physics, also died at almost the same time. Previously, between the third and fourth conferences, the death of James Shearer from the Lawrence Livermore Laboratory had been a heavy loss for the megagauss community.

The "Megagauss-VII" Conference marks the transition of megagauss studies to a qualitatively new stage. After the sixth conference, the most important event was the organization and the beginning of regular activity of the new U.S. National Magnet Laboratory. Americans executed their project in a rational and straightforward manner. The changes in Russia were good fortune for them. Owing to these changes, U.S. scientists, without great effort, waste of time, and significant material expenses, acquired the thirty-year technological experience and know-how of the unique highest-level group of scientists gathered and trained in the Soviet atomic center in Arzamas. The beginning of large-scale work on the international MAGO and DIRAC projects was reported at MG-VII [83–85].

Eight laboratories from four countries participate in the DIRAC project on investigation of material properties in fields up to 10 MG. Western countries and Japan sponsor the studies and supply the equipment. The Arzamas scientists manufacture field generators, deliver technologies to Los Alamos, and perform experiments on their sites and in the United States. Project management and control over funds are executed exclusively by the U.S. side.

The object of the Russian–American MAGO project is to attain the initiation of a thermonuclear reaction in high magnetic field with powering of an experimental generator model by a system of higher-power explosive generators. Explosive generators producing electromagnetic energy of 400–1000 MJ in a unit module are being designed for this project by Chernyshev's group.

The second remarkable aspect of the last conference was the renewed interest in magnetic cumulation and explosive generators in Great Britain and France. In addition, united Germany joined these activities, and a research center of high magnetic fields was established in Berlin [86]. French scientists regenerated studies that were performed by Brin and Besanson and discontinued 20 years ago. To this end, a contract with the All-Union Institute of Experimental Physics was signed, and several young scientists were sent for training to the laboratories of Pavlovskii and Chernyshev.

The scientific content of the papers presented corresponded to the level and style of the MG conference. The invited papers aroused great interest. Among them, noteworthy are the paper in memory of Pavlovskii and his outstanding contribution to the development of the experimental base of the All-Union Institute of Experimental Physics [87] and also the survey of Trunin [88] on the outstanding investigation of condensed materials under extreme compression attained in underground nuclear explosion tests at collision rates of specimens up to 62 km/sec.

MG-VII in 1996 summed up forty years of studies in the generation and various applications of megagauss magnetic fields. At the concluding session of MG-VII, Deputy Director of the new National Magnet Laboratory Dr. Shneider-Muntau proposed his Laboratory as the organizer of the next Megagauss Conference and invited the participants of the Conference to Tallahassee, Florida in November 1998.

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