LA-UR-02-6671

LA-UR-02-

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October 16, 2002

This is the text of an invited plenary paper to be published in the Proceedings of the Ninth International Conference on Megagauss Magnetic Field Generation and Related Topics, Moscow/St. Petersburg, Russia, July 7-14, 2002

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

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Abstract

Since 1992, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) and the Los Alamos National Laboratory (LANL), the institutes that designed the first nuclear weapons of the Soviet Union and the United States, respectively, have been working together in fundamental research related to pulsed power technology and high energy density science. Experimental and theoretical work has been performed at Sarov and Los Alamos in areas as diverse as imploding liner physics and applications, fusion plasma formation, isentropic compression of noble gases, and explosively driven high current generation technology, all traditional areas of the Megagauss series of conferences. Recent joint work has focused on the Atlas capacitor bank (23 MJ, 30 MA, 6 μs) now operational at LANL. Even before Atlas became operational, VNIIEF's DEMG capability was used to provide the US with the first available data at ATLAS' upper performance limit (31 MA, 4 μs, 12 km/s velocity for 50 g liner mass). VNIIEF has recently designed and fielded imploding liner experiments on Atlas, with the goal of studying material strength properties by observing unstable perturbation growth. This paper traces the origins of this collaboration and reviews the scientific accomplishments.

Introduction

In late 1993, the Russian Federal Nuclear Center-All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) and the Los Alamos National Laboratory (LANL) combined efforts to conduct two joint experimental campaigns. On September 22, 1993 (the day after Boris Yeltsin disbanded the Russian Parliament), the first joint experiment was performed at VNIIEF when a joint VNIIEF/LANL team assembled, executed, and diagnosed a complex generator/fuse/liner experiment based upon VNIIEF's unique pulsed power capability, the Disk Explosive Magnetic Generator (DEMG) [1]. In December of the same year, five VNIIEF MC-1 high-magnetic field generators were used at LANL in a series of joint experiments that included high-temperature superconductivity studies [2].

The 1993 experiments were unprecedented in the nuclear age. VNIIEF and LANL are the institutes that designed the first nuclear weapons for their respective nations. Each institute began in a "secret city" that did not appear on unclassified maps when the institutes were founded.

The participants of the 1993 joint experimental campaigns were people entrusted with some of their nations' most sacred secrets, the knowledge of nuclear weapons. Interactions by these people with foreigners was generally discouraged, and even prohibited. The LANL participants in the September experiment at VNIIEF (J. H. Goforth, C. A. Ekdahl, J. C. King, I. R. Lindemuth, R. E. Reinovsky, P. J. Rodriguez, L. R. Veeser, S. M. Younger) were the first Americans to work behind the security fences of VNIIEF. The VNIIEF participants at the December 1993 experiments at LANL (A. I. Bykov, M. I. Dolotenko, E. A. Gerdova, N. P. Kolokolchikov, Y. B. Kudasov, E. I. Panevkina, V. I. Platonov, V. G. Rogatchev, O. M. Tatsenko) were the first Russians to work behind the security fences at LANL. For the dozens of scientists, engineers, and technicians from the host institutions, these experiments presented logistical, safety, and security issues never previously encountered. The success of these experiments attests to the leadership of the "shot coordinators," A. A. Petrukhin of VNIIEF for the September experiment and C. M. Fowler and R. B. Freeman of LANL for the December experiments.

Although Presidents Bush and Yeltsin had previously agreed that scientific collaboration between the US and Russia would be expanded, agreement among government officials that the nuclear weapons design laboratories of the two nations should work together was not universal. The tensions of the Cold War were not easily forgotton.

The 1993 experiments were based upon VNIIEF magnetic flux compression technology that exceeded US "off-the-shelf" capability. Magnetic flux compression technology was pioneered at VNIIEF by a team originally lead by Nobel Peace Laureate Andre D. Sakharov and at LANL by a team lead by C. M. Fowler, a co-author of this paper. V. K. Chernyshev, a co-author of this paper, and the late A. I. Pavlovskii were early members of Sakharov's team. Motivated originally to evaluate possible defense applications of flux compression technology, the two teams worked independently for many years, essentially unaware of the others' accomplishments. However, an early US publication [3] announced the achievement of magnetic fields in the 10-15 MG range and stimulated Soviet work. The Soviets followed with a report of the achievement of 25 MG [4]. In an earlier document [5], the Fowler team stated its intention to apply high-magnetic field technology to controlled thermonuclear fusion, and the dream of fusion was to remain a strong motivation for both teams in the coming decades. In fact, VNIIEF scientists have described controlled fusion as "Sakharov's fondest dream."

The 1993 experiments were the first of the more than 30 joint experiments that have been completed by joint VNIIEF/LANL teams. In this paper, we review the origins of the VNIIEF/LANL collaboration and discuss its accomplishments.

The Role of the Megagauss Conferences

Throughout the nearly fifty years of the Cold War, the series of International Conferences on Megagauss Magnetic Field Generation and Related Topics has been the principle forum for scientific exchange of ideas and accomplishments in the area of magnetic flux compression technology. C. M. Fowler, a co-author of this paper, is the only scientist to attend all nine conferences. Because of collegial relationships and friendships established at the early Megagauss conferences, the Megagauss conferences were to become the foundation for one of the most remarkable scientific collaborations since the beginning of the Cold War. Megagauss conference participants have emerged as principles in the formal VNIIEF/LANL collaboration, the first scientific collaboration to be established between nuclear weapons design laboratories of the Russian Federation and the United States.

The Soviet team, lead by Sakharov, submitted eight abstracts to the first Megagauss conference, held in Frascatti, Italy, in 1965. Chernyshev and Pavlovskii had been encouraged by Sakharov to attend the conference, but permission was denied by the Soviet government at the last moment. Instead, the Soviet Union was represented by two scientists who were not working in the flux compression field, A. Naumov and S. Kapitza, son on Physics Nobel Laureate P. Kapitza. Hence, the eight papers were not presented at Megagauss-I. Nevertheless, the eight abstracts alerted Fowler and the US team about the well-developed Soviet flux compression effort. Although Sakharov was the leader of the Soviet team, it was not readily apparent from the author lists on the abstracts. In fact, Fowler thought for some time that the late R. Z. Lyudaev might well have been the team leader. Both Pavlovskii and Chernyshev, and other Russian scientists as well, have remarked that Lyudaev did, in fact, play a significant role in the Soviet program.

Nearly two decades would pass before Chernyshev, Fowler, and Pavlovskii would meet in person.

Fowler had hoped to meet Pavlovskii at the second Megagauss conference held in Alexandria, Virginia, in 1979, but the security regulations of the Soviet Union again prevented Pavlovskii from attending. Instead Pavlovskii's papers were read at Megagauss-II by Gennady A. Shvetsov of the Lavrentyev Institute of Hydrodynamics in Novosibirsk, Russia. The helical flux compression generator performance reported in the Pavlovskii papers at Megagauss-II stimulated additional helical generator work at Los Alamos. At Megagauss-II, Shvetsov, who would later, in 1992, play an important role as facilitator in the establishment of the VNIIEF/LANL collaboration, also announced that the Megagauss-III conference would be held in Novosibirsk, a significant step in continuing the Megagauss series and, as discussed below, in laying the foundation for the collaboration.

Pavlovskii and Fowler met for the first time in 1982 at a conference at the Lavrentyev Institute. Both have recalled the excitement they felt at their very first face-to-face contact. They met again at Megagauss-III in 1983 when Fowler lead a LANL delegation that included Dennis Erickson, a Megagauss Institute member who would later, in 1992, play an oversight role in the formative stages of the VNIIEF/LANL collaboration. By 1983, the US team recognized that Pavlovskii was leading the largest VNIIEF flux compression effort. However, Fowler observed that the Chernyshev team appeared particularly creative and that US scientists should closely monitor developments by this team.

Pavlovskii and Fowler would subsequently meet occasionally on Fowler's visits to Russia and on Pavlovskii's first visit to the US in 1988. In the decade following their first meeting, as each was educating a new generation of scientists, their friendship would continue to grow, although the political differences between their two nations would stand as a barrier to dialogue and scientific exchange. Nevertheless, each shared a dream that someday they could work together.

In a letter dated June 30, 1989, Pavlovskii wrote to Fowler expressing his regrets that Pavlovskii's health prevented him from participating in the Megagauss-V conference and expressing his opinion that "it seems that it is high time to think about a joint program of works on both super-high magnetic fields cumulation and experiments setting in such fields." On the subject of "joint works," Pavlovskii asked Fowler, "what is your opinion?" but Los Alamos security regulations prevented Fowler from responding.

At Megagauss-V, Pavlovskii's and Chernyshev's groups reported remarkable advances in high-current generation. I. Lindemuth and R. Reinovsky, understudies of Fowler, met Chernyshev for the first time at Megagauss-V. Those initial discussions would focus on Chernyshev's disk explosive magnetic generator (DEMG) and a fusion-related paper co-authored by Chernyshev [6]. As a parting comment, Chernyshev offered, prophetically, "maybe some day we can do an experiment in which you and your colleagues design the load and we provide the generator."

At the conclusion of the Megagauss-V conference, one of the conference organizers, G. A. Shvetsov, lead a post-conference tour to St. Petersburg and Moscow. Pavlovskii had recovered from his illness sufficiently that he met the tour group, which included Erickson, Fowler, Goforth, and Lindemuth, at the Kurchatov Institute in Moscow and showed to the American team for the first time the MC-1 generator.

In September, 1990, Fowler returned to Novosibirsk and again met Pavlovskii. At this meeting, Pavlovskii informed Fowler that, should LANL be interested, Pavlovskii could get the LANL Director, and possibly Fowler, into Pavlovskii's "explosives firing area." Telegrams were exchanged in the months following, but a visit to VNIIEF did not materialize.

The Role of Controlled Fusion

During the Cold War, US analysts were quick to review any open publications that appeared to give any information about the highly secretive Soviet nuclear weapons program. In 1979, V. N. Mokhov, Chernyshev, and their colleagues published a paper proposing a possible solution to the controlled thermonuclear fusion problem [6]. At the time, Chernyshev was known because of his role in the Megagauss conferences, but Mokhov was unknown. However, the paper had been submitted for publication by Academician Yuli B. Khariton, who was known to be the leader of the Soviet Nuclear weapons program, so it appeared that the publication represented important work being conducted in the Soviet program.

Although US analysts were quite surprised by the advanced computational capability displayed in the 1979 paper, most discounted the Soviet fusion concept because of the lack of details, because the required energy source seemed to be far beyond anything previously reported by the Soviets, and because the US was not exploring such an approach. However, a 1988 analysis of the paper by Lindemuth, R. C. Kirkpatrick, Reinovsky, and R. S. Thurston lead to a LANL speculation that the Soviets were pursuing an approach to fusion that had no analog in the US controlled fusion program.

There were a number of possible reasons why the Soviets (or LANL) might be pursuing fusion. First of all, because they must understand the feasibility, or lack thereof, of "pure fusion" weapons, nuclear weapons programs are chartered to understand as much as possible about the fusion process. Clearly, laboratory fusion experiments can offer insight into some aspects of fusion weapon physics. Fusion neutron sources potentially have applications in stockpile stewardship and certification. And, controlled fusion research can help to attract and maintain talent in an era without nuclear testing. But, perhaps most importantly, controlled fusion has always been a "holy grail" for fusion weapons scientists. In fusion, the skills developed in weapons research can be applied to a problem that, if solved, will benefit all mankind. The weapons programs are, of course, the only programs yet to achieve fusion beyond "breakeven," and at least the inertial confinement fusion program has its origins in the nuclear weapons programs of Russia and the US.

The 1988 LANL study concluded that the approach advocated by the Soviets was more than plausible if the fusion target imploded by magnetic fields contained magnetized thermonuclear fuel. LANL had previously performed a theoretical and computational study of such a possibility [7], although the approach had not been adopted by the US controlled fusion program.

Their natural interest in fusion, and the synergism of fusion with megagauss and megamp techniques, drew VNIIEF and LANL together. The DEMG performance that Chernyshev reported at Megagauss-VI in 1989 made the Soviet approach much more credible.

That VNIIEF was pursuing a magnetized target approach was confirmed when the Soviet government opened VNIIEF to American visitors for the very first time in October, 1990. A prospectus given to participants of the Joint Verification Experiments (JVE) program stated that the institute conduced "electrophysical investigations...we investigate...preheating methods of magnetized plasma, its subsequent implosion and inertial confinement ."

Pavlovskii and Chernyshev traveled to the United States in June, 1991, to participate in the Eighth IEEE International Pulsed Power Conference, which was held in San Diego, California. At this conference, the Soviet visitors initiated discussions on possible collaborative efforts. Among the participants in the collaborative discussions were Academician G. A. Mesyats, G. A. Shvetsov, J. Degnan and G. Kiuttu of Phillips Laboratory (now Air Force Research Laboratory), M. DiCapua of the Lawrence Livermore National Laboratory, and Lindemuth and Reinovsky.

At the San Diego conference, Chernyshev reported [8] VNIIEF's progress in technologies for controlled thermonuclear fusion and Reinovsky reported [9] LANL's initial studies of the utility of the DEMG, a study that had been prompted by VNIIEF's Megagauss-V publications. The Chernyshev paper reported to the international community for the first time that the Soviet fusion approach was known as MAGO ("magnitnoye obzhatiye," Russian for "magnetic compression"). Although the Chernyshev paper did not discuss the fusion physics in detail, the paper made it clear that both initially cold, unmagnetized and preheated (and, hence, magnetized) fuel had been considered in the MAGO context.

Following the IEEE Pulsed Power Conference, Pavlovskii, Chernyshev and Shvetsov visited Phillips Laboratory and were hosted at Los Alamos by Fowler. In the subsequent discussions, controlled thermonuclear fusion emerged as a subject of mutual interest because of the scientific "grand challenge" nature of the topic and the fact that it was an appropriate unclassified application of the skills developed in the nuclear weapons programs of both nations. In July 1991, LANL coined the name "Magnetized Target Fusion (MTF)" to distinguish the magnetized variant of MAGO, and related concepts [10], from the two more conventional and more well known approaches, magnetic confinement fusion and ICF.

Until September, 1991, all collaborative discussions had been at the "scientist-to-scientist" level, and US officials did not know how seriously to take the Soviet overtures. However, in September, as Lindemuth returned through Moscow from the Second International Youth School on Plasma Physics and Controlled Fusion held in Sochi, Russia, Chernyshev, Mokhov and several colleagues (N. P. Bidylo, S. F. Garanin, A. A. Petrukhin, E. I. Panevkina) traveled to Moscow to deliver a formal written proposal for collaboration "on the topic: achievement of combustion thresholds (scientific break even) using the MAGO pulsed thermonuclear system with collisions of magnetic targets under the influence of magnetic fields."

The VNIIEF proposal presented to Lindemuth had been signed by VNIIEF's director, V. Belugin, and had been discussed with high-ranking officials of the Soviet Ministry of Atomic Energy (MINATOM) and other Soviet government organizations. VNIIEF and Russia had clearly elevated the collaborative discussions to a higher level. Upon delivery of the proposal to LANL, Stephen M. Younger, then Program Director for Above Ground Experiments, was appointed LANL's administrative point-of-contact for Russian collaborative issues. Global events that quickly followed as the Soviet Union dissolved precluded Los Alamos from making a formal response to VNIIEF's proposal.

Although LANL did not formally respond to the VNIIEF proposal, Chernyshev invited Kirkpatrick, Lindemuth, Reinovsky, Thurston and Younger to participate in the Third Zababakhin Scientific Talks held in Kistym, Russia, January, 1992, and hosted by VNIIEF's sister laboratory, the All-Russian Scientific Institute of Technical Physics (VNIITF). At the Talks, Mokhov discussed preheated, magnetized targets in a MAGO context and reported results of experiments forming a preheated, magnetized plasma [11]. Subsequent US computations of the experiments [12] reported by Mokhov were presented at the Megagauss-IX conference later in the year and lead to the conclusion that the MAGO plasma formation system could, in fact, be the source of plasma that some US observers felt was a major obstacle to MTF. The VNIIEF data and the US computations rekindled a US interest in the fusion area now known as MAGO/MTF.

The Formation of the Collaboration

In addition to inviting LANL scientists to attend the Zababakhin Talks, Chernyshev also invited the Americans to visit VNIIEF in Sarov (then known as Arzamas-16) after the conference. Since only three groups of western visitors had been permitted to enter Sarov previously, such an invitation was rather remarkable. Because of concerns related to the rapidly changing world at the time, LANL management decided to send only Lindemuth and Reinovsky.

When the Soviet Union dissolved in late 1991, the fate of the Russian nuclear weapons complex became a national security concern for the United States. Ways to quickly contact scientists at the Russian nuclear weapons laboratories were sought from the US laboratories through communications originating at the US National Security Council. Fortunately, Chernyshev's invitation made it possible for LANL to quickly respond to the concerns of the US Government.

Prior to their departure from the US, LANL Director Sig Hecker asked Lindemuth and Reinovsky to extend on behalf of Hecker an invitation to the Directors of VNIITF and VNIIEF to travel to the United States for discussions on unclassified nuclear topics of mutual interest. Key guidance on how to deliver Hecker's important messages was provided to Lindemuth and Reinovsky by Younger and D. Erickson, who was then LANL Deputy Associate Director for Nuclear Weapons Technology.

Upon arrival at the Zababakhin Talks, Lindemuth and Reinovsky immediately sought to make contact with the VNIITF leadership. VNIITF Director V. Nechai and VNIITF Chief Scientist E. Avrorin met with the American visitors during the week of the Talks. The visitors also met with Pavlovskii and Chernyshev, who were also attending the Talks. Pavlovskii in turn contacted VNIIEF leadership so that when Lindemuth and Reinovsky arrived in Sarov on January 22, 1992, VNIIEF leadership was prepared to hear the invitation.

Pavlovskii accompanied the VNIIEF director to LANL in February, 1992. At LANL, Pavlovskii presented what Younger would later describe as the most fascinating scientific speech he had ever heard. During the February visit, LANL and VNIIEF were clearly finding much in common and many topics appropriate for collaboration were being identified.

Following a May, 1992, high-level "government-to-government" meeting in Moscow, in which Younger participated, Fowler, Lindemuth, Reinovsky, and Younger visited VNIIEF in June, 1992, where they were hosted by Pavlovskii and Chernyshev. G. A. Shvetsov accompanied the LANL team from Moscow and served as a facilitator in a week of intense discussions. Collaborative topics appropriate for initial "lab-to-lab" collaboration were delineated and action items for both institutions were agreed upon. Essentially all of the topics were topics that historically have fallen under the umbrella of the Megagauss conferences.

During the June visit, the LANL team witnessed an MC-1 high magnetic field experiment at Pavlovskii's firing point. Pavlovskii asked Fowler to push the button that set off the experiment, and Fowler was presented a bottle of vodka as payment for his services to VNIIEF. The mutual admiration and friendship between Pavlovskii and Fowler had finally lead to a collaborative relationship!

A large delegation of VNIIEF scientists participated in the Megagauss-VI conference held in Albuquerque in November, 1992. In his opening address, J. Pace VanDevender of Sandia National Laboratory noted that US/Russian collaboration in Megagauss conference areas appeared to be a real possibility and particularly emphasized that "Russian technologies can build a new discipline between magnetic and inertial fusion." VanDevender was, of course, referring to MAGO/MTF.

Following the Megagauss-VI conference, Pavlovskii and Chernyshev lead a VNIIEF delegation to LANL. The VNIIEF delegation included N. Bidylo, M. Dolotenko, L. Gerdova, L. Panevkina, A. Petrukhin, O. Tatsenko, and V. Rogatchev. Chernyshev, Pavlovskii, and Younger signed a Technical Memorandum of Agreement that defined mutually agreeable conditions that would lead to the first joint experimental activities.

The November 1992 meeting in Los Alamos would be the last time Chernyshev, Fowler, and Pavlovskii--the three pioneers whose work had provided the foundation for the VNIIEF/LANL collaboration—would be together (Fig. 1). The unfortunate death of Pavlovskii in February, 1993, provided a set-back to the fledgling collaboration, but Pavlovskii's VNIIEF and LANL colleagues were determined to carry out the work that Pavlovskii had been so instrumental in formulating.

Thus, the Megagauss conferences, combined with a common interest in controlled fusion, laid the foundation for the VNIIEF/LANL collaboration. The changes that have happened in the world political climate in the last decade are clearly reflected by VNIIEF's role in the Megagauss conferences. In the proceedings of Megagauss-V, and in the proceedings of the previous four conferences, VNIIEF authors' affiliation was listed as the Kurchatov Institute in Moscow, due to the very strict security regulations of the former Soviet Union. By the time of Megaguss-VI in Albuquerque in 1992, the Soviet Union had acknowledged VNIIEF's existence and Pavlovskii gave a very poignant review of Sakharov's contributions to magnetic flux compression. In addition, Pavlovskii announced that Megagauss-VII would be hosted by VNIIEF and that conference participants would have the opportunity to visit Sarov, the city that was off-limits to foreigners just a few years earlier and the city that Sakharov could only refer to as "the Installation" in his autobiography. At Megagauss-VII, VNIIEF scientists presented papers that were jointly authored with scientists from several laboratories in France and the US.

Although scientists from VNIIEF and many other Russian institutes have established many collaborations with foreign scientists in many nations, the VNIIEF/LANL collaboration remains one of the most scientifically productive. More than 10% of the papers presented at the Megagauss-VIII conference, and nearly that many at Megagauss-IX, reported accomplishments of the VNIIEF/LANL collaboration.

Accomplishments of the Collaboration

Scientific progress quickly followed the 1993 campaigns with a focus on experiments at both VNIIEF and LANL covering a broad range of topics. Following a "step-by-step" process, more than twenty additional joint experimental campaigns have been performed either at VNIIEF or at LANL. Key events of the collaboration are summarized in Table I. The results of the experimental campaigns have been well-documented in the scientific literature (see, e.g., these proceedings, the proceedings of the Megagauss-VII and VIII conferences, and [13]). In fact, the collaboration can point to more that 250 conference presentations and formal publications. Many of the papers have been plenary, invited, or review papers.

Two of the longest standing thrusts of the collaboration have been: (a) using the VNIIEF MC-1 generator to isentropically compress noble gases to 1-10 Mbar; and (b) characterizing the VNIIEF MAGO plasma formation system to determine whether or not the plasma so formed is suitable for subsequent liner-on-plasma compression in a MAGO/MTF context.

The isentropic compression element of the collaboration continues to progress. Insulator problems that plagued the measurement attempts have been overcome, with a conclusion that Teflon is better than sapphire and ceramics, in contrast to generally accepted beliefs. The approximate conductivities of argon and krypton have been determined, with Argon behaving like a semi-conductor and krypton behaving more like a liquid metal.

The MAGO-II experiment conducted at LANL in 1994 [14] set a LANL record for the number of deuterium-tritium fusion neutrons produced in a single experiment (10^{13}). Since that time, several different types of chambers have been designed, modeled, and/or tested. Of particular note is the improved two-dimensional magnetohydrodynamic (MHD) capability that has been developed at VNIIEF. VNIIEF and LANL publications have stimulated a fledgling worldwide interest in the MAGO/MTF approach to fusion.

The very successful 1993 high magnetic field experiments at LANL lead to a more ambitious set of experiments called "the Dirac series" [15]. In the Dirac series conducted at LANL in April 1996 and June 1997, scientists from ten laboratories in six nations (Australia, Belgium, Germany, Japan, Russia, and the United States) used VNIIEF MC-1 and LANL "strip" generators to create a high-magnetic-field environment for studies of phenomena that included the Quantum Hall effect at high electron density, the Quantum Hall effect and quantum limit in two-dimensional organiz materials, magnetic field induced superconductivity, Zeeman-driven bond-breaking, high-field exciton spectra, and Faraday rotation in diluted magnetic superconductors. These experiments spawned the "Kapitsa series" of experiments that have been conducted at VNIIEF with multi-national participation.

To complement LANL's programmatic thrust to use magnetically imploded liners as impactors for hydrodynamic studies [16], VNIIEF designed and fabricated five experiments that were fielded on the LANL Pegasus capacitor bank. The RUS1&2 experiments (December, 1997) explored growth of magnetically driven Rayleigh-Taylor instabilities in alloys with different strength and resistivity. The RUS3&4 experiments (February, 1999) investigated the MHD stability of colliding solid liners. Building on the excellent understanding of the magnetically driven Rayleigh-Taylor instability learned from the LANL Liner Stability (LS) series of experiments [17], the RUS-5 experiment (May, 1999) confirmed a VNIIEF prediction that LS-like perturbations oriented not in the m=0 mode but oblique to the magnetic field would not grow [18].

The VNIIEF DEMG provides an opportunity to study liners with more kinetic energy than can be obtained otherwise. In February 1995, the joint team conducted the XRAY-1 experiment intended to test the first phase of a unique VNIIEF concept [19] to generate several megajoules of soft x-radiation. Representatives of the Phillips Laboratory also participated in this experiment.

The High Energy Liner HEL-1 experiment [20] (August, 1996) used a 5-module, 100-cm-diameter DEMG to deliver a 100-MA current pulse to a liner that was accelerated to approximately 4 km/s and achieved a kinetic energy of greater than 20 MJ. As such, this was the highest current, highest energy liner experiment ever involving US scientists. A number of applications of the HEL-1 system can be envisioned. As one example, the system potentially makes more than 20 MJ of kinetic energy available for fusion fuel heating in a MAGO/MTF context. This value of energy is more than one-hundred times greater than the kinetic energy that will be available for heating the fuel of a conventional, unmagnetized target on the US National Ignition Facility (NIF).

With the advent of the Atlas capacitor bank at Los Alamos, much of the recent collaborative effort has focused on Atlas and its applications. Even before Atlas became operational, VNIIEF designed an Advanced Liner Technology (ALT) system to emulate Atlas. The ALT system [21] is based upon a 10-module, 40-cm-diameter DEMG coupled to a fuse opening switch. A key challenge in the design of the system was slowing the fuse opening process so that the current delivered to a "standard" Atlas load would approximate the expected Atlas waveform.

The ALT-1 and ALT-2 experiments (November, 1999; June, 2001) provided LANL with the first available data in Atlas' upper performance range. Shown in Fig. 2 are the measured waveforms compared with a predicted Atlas waveform. Considering the complexity of the HEMG/DEMG/fuse system, the reproducibility of the ALT system is remarkable, making the ALT system an excellent candidate for continuing Atlas physics experiments during the year or so that Atlas is being disassembled and reassembled at the Nevada Test Site.

One-dimensional computations accurately predict the liner flight determined by VISAR measurements in the ALT experiments. The VISAR and other diagnostics suggest a high-quality implosion. Unfortunately, attempts by the joint team to obtain radiographic images of the liner implosion process were unsuccessful, leaving a key gap in our understanding of liner stability [22].

VNIIEF has completed preliminary designs of a DEMG-based HEL system that could enable equation-of-state (EOS) measurements at 15 Mbar. LANL has incorporated VNIIEF EOS and resistivity models into LANL codes, leading to a better understanding of liner behavior. VNIIEF has begun an investigation of possible application of VNIIEF's multiframe x-ray imaging technique to US facilities such as Atlas. Using a high-explosive based, non-pulse-power technique, VNIIEF has obtained new data on the effect of thermal softening on Rayleigh-Taylor-like unstable perturbation growth in accelerated metal plates. As part of the effort to exploit the Atlas capability as quickly as possible, VNIIEF has designed and fabricated a innovative three-layer liner system that will be the first step in a new Atlas technique for studying material strength properties [23]. A number of additional joint endeavors are documented elsewhere.

Unexpected Benefits of the Collaboration

The scientific collaboration between VNIIEF and LANL is unique in many ways. The two teams work "side-by-side as equals" with frequent and extensive face-to-face contact and reciprocal access to facilities. The two teams have complementary capabilities that are being brought together to benefit both of their nations.

The uniqueness of the collaboration has not gone unnoticed. Media coverage of the collaboration has been frequent, extensive, and highly favorable. Articles on the collaboration have appeared in the New York Times, Washington Post and the Los Angeles Times. The collaboration was covered twice by CNN Science and Technology Week and was the cover story for International Newsweek (February 5, 1996). Most recently, the collaboration was featured in the Discovery Channel documentary "Stockpile," which first aired in October, 2001.

The benefit to the Russian Federation and the United States extends beyond the increase in scientific knowledge. Building upon the trust and understanding developed during the first experimental campaigns, and a few telephone conversations, VNIIEF and LANL leaders laid the foundation for the Materials Control, Protection, and Accountability (MPC&A) program that now assists Russia in securing its nuclear materials [24]. The collaboration served as a model for Working Group I (Computations, Experiments, Materials) of the June 1996 Moscow Protocol for Scientific and Technical Cooperation, an agreement signed by then-US Assistant Secretary of Energy for Defense Programs V. Reis and by Russia's First Deputy Minister of Atomic Energy L. Ryabev. It is anticipated that expanded fundamental, unclassified scientific collaboration as exemplified by the VNIIEF/LANL relationship will be an element of the "new strategic relationship" established by Presidents Putin and Bush.

As traveling scientists carried back to their homes stories of their early and unprecedented visits to their overseas counterpart, Sarov and Los Alamos citizens quickly recognized in each other similar histories and missions, common patriotic and family values, and a mutual prayer that the nuclear weapons designed and developed in their cities would never need to be used in warfare. First a few, and then literally thousands, of "pen-pals" letters carried by the traveling scientists lead to the two cities becoming "Sister Cities" [25].

Student/teacher, business, civic, art and medical exchanges have now been conducted between the two communities. In December 1993, Los Alamos students presented to the VNIIEF delegation in Los Alamos for the joint experiments a 200-page "Friendship/Peace" book for the Sarov community. In April 1994, a group of Sarov students traveled to Los Alamos for a High School Critical Issues Forum on Nuclear Dismantlement. The Sarov city administration so valued the relationship that in 1995 the administration presented a bell cast in the traditional Russian way to the Los Alamos County government. The ongoing medical exchange program has had a tremendous benefit not only to the two cities but also to the international medical community as joint clinical studies in diabetes and asthma have resulted in papers presented at international medical conferences [26].

Concluding Remarks

VNIIEF and LANL have now completed a decade of working together to bring scientific benefit to the Russian Federation and the United States. Unfortunately, the first decade ended with a minor setback. The first experiment using the VNIIEF 3-layer liner design [23] was attempted on Atlas in April, 2002. However, an electrical short occurred in the power flow hardware approximately 1 microsecond after Atlas was discharged. This short reduced the current delivered to the VNIIEF-designed-and-fabricated liner cassette to approximately 12 MA, slightly more than half of the design current of 22 MA. The short also destroyed the symmetry of current delivery to the liner. Although both teams were disappointed by the unfortunate outcome, all recognize the risk of such an occurrence on every experiment they attempt. This setback will make the joint LANL/VNIIEF team more determined than ever to continue the remarkable record of scientific accomplishment that has been the hallmark of the collaboration since its inception a decade ago.

The collaboration described in this paper would not have been possible without the support and encouragement of many officials of the governments of Russia and the United States and many administrators at VNIIEF and LANL. Most importantly, the collaboration would not have been possible without the technical expertise of our VNIIEF and LANL colleagues, all exceptional scientists, engineers, technicians or interpreters totally committed to the scientific excellence that collaboration makes possible.

While the number of our colleagues involved is unfortunately far too many to name all, we note that a special contribution has been made by those willing to leave their families and their culture for long periods of time and travel across ten time zones to make the endeavors described here a success. From VNIIEF, in addition to those mentioned previously, the travelers have included V. G. Baturin, A. A. Bazanov, O. M. Burenkov, A. M. Buyko, V. A. Demidov, A. N. Demin, U. N. Dolin, B. T. Egorychev, S. F. Garanin, Y. N. Gorbachev, B. E. Grinevich, V. A. Ivanov, V. P. Korchagin, A. I. Kuzaev, I. V. Morozov, S. V. Pak, the late A. I. Pischurov, V. D. Selemir, N. Y. Seleznev, A. N. Skobelev, V. V. Vakhrushev, G. I. Volkov, A. R. Volodko, V. B. Yakubov, and R. R. Zubayerova. From LANL, in addition to those mentioned previously, the travelers have included B. G. Anderson, W. L. Atchison, R. J. Bartlett, R. R. Bartsch, J. F. Benage, W. Broste, R. E. Chrien, D. A. Clark, R. J. Faehl, G. C. Idzorek, J. Kammerdiener, R. C. Kirkpatrick, J. S. Ladish, H. Oona, T. L. Petersen, G. Rodriguez, P. T. Sheehey, the late S. Schachowskoj, J. S. Shlachter, J. L. Stokes, L. J. Tabaka, D. T. Westley, and W. D. Zerwekh. The VNIIEF authors would also like to acknowledge the contributions of V. I. Mamyshev, N. N. Moskvichev and the late E. S. Pavlovskii. The LANL authors would like to express appreciation to Ms. Janet Neff-Shampine for her administrative support of this work and to J. C. Cochrane for his leadership role on the joint VNIIEF/LANL experiments conducted on the LANL Pegasus and Atlas capacitor banks.

Each participant in this unprecedented collaboration has accumulated a lengthy string of memories. For some, the collaboration has been the most significant accomplishment of their professional careers. For all, the personal experiences will be repeated over and over to their grandchildren and their grandchildren's children.

Perhaps equally or more significant than the scientific accomplishments is the fact that the VNIIEF/LANL collaboration has demonstrated that the nuclear weapons design laboratories of Russia and the United States can work effectively "side-by-side as equals" to bring demonstrable scientific benefit to both nations. Because VNIIEF and LANL developed the first nuclear weapons of their respective nations, it is perhaps symbolic of a future of reduced global tensions that VNIIEF and LANL have started their second half-century working together. The participants in the collaboration are continually cognizant of the comment made by former LANL Director Norris Bradbury: "the whole object of making nuclear weapons is not to kill people, but to find time for somebody to find other ways to solve these problems." The trust and respect developed through this collaboration have provided a foundation for broader interactions between the nuclear weapons laboratories of the two nations [24].

The Megagauss series of conferences has been the basis for these remarkable events.

Table I. Key events in the LANL/VNIIEF collaboration

6/92: defined topics (VNIIEF)
11/92: signed first contracts (LANL)
9/93: first joint experiment (VNIIEF)
12/93: 5 high-B experiments (LANL)
4/94: magnetized plasma experiment (VNIIEF)
8/94: isentropic compression experiment (VNIIEF)
10/94: 2 magnetized plasma experiments (LANL)
2/95: x-ray source experiment (VNIIEF)
8/95: isentropic compression experiment (VNIIEF)
9/95: magnetized plasma experiments (VNIIEF)
5/96: Dirac-I high-magnetic-field experiments (LANL)
5/96: High I generator test (VNIIEF)
8/96: high energy liner experiments (VNIIEF)
9/96: isentropic compression experiments (VNIIEF)
6/97: Dirac-II high-magnetic-field experiments (LANL)
10/97: isentropic compression experiments (VNIIEF)
12/97: 2 liner stability experiments (LANL)
7/98: isentropic compression experiments (VNIIEF)
8/98: magnetized plasma experiments (VNIIEF)
2/99: 2 liner stability experiments (LANL)
5/99: liner stability experiment (LANL)
10/99: advanced liner technology experiment (VNIIEF)
6/01: advanced liner technology experiment (VNIIEF)
4/02: 3-layer-liner material strength experiment (LANL)

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Fig. 1. Three pioneers in magnetic flux compression science and technology. From left to right, Vladimir K. Chernyshev (VNIIEF), C. Maxwell Fowler (LANL), Alexander I. Pavlovskii (VNIIEF). This photo was taken in Los Alamos in November 1992, and was the last time the three would be together.

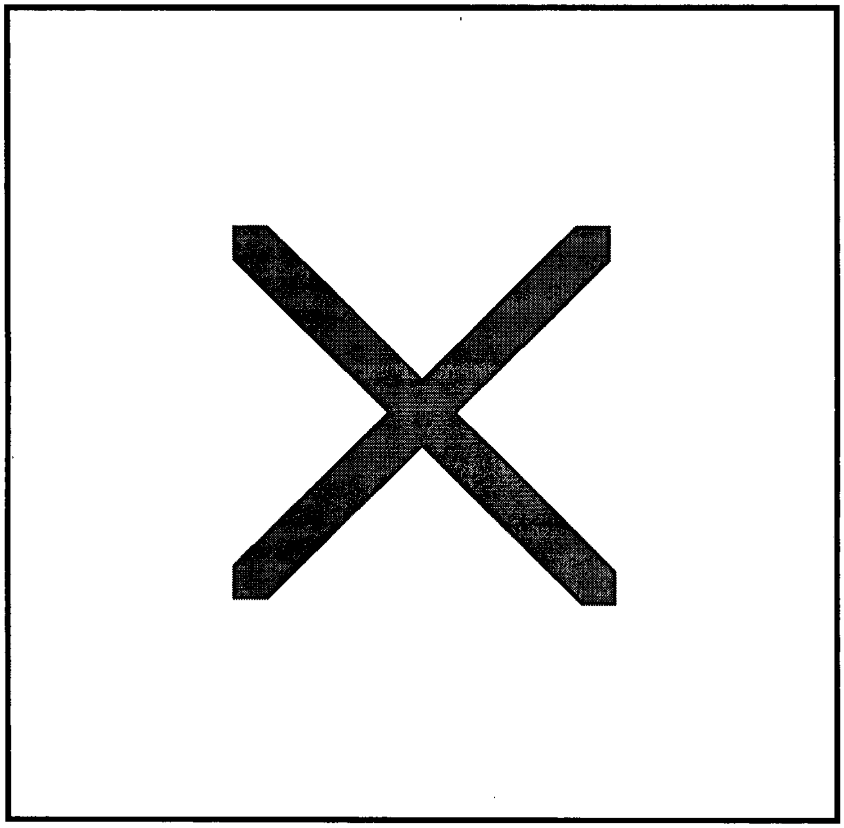
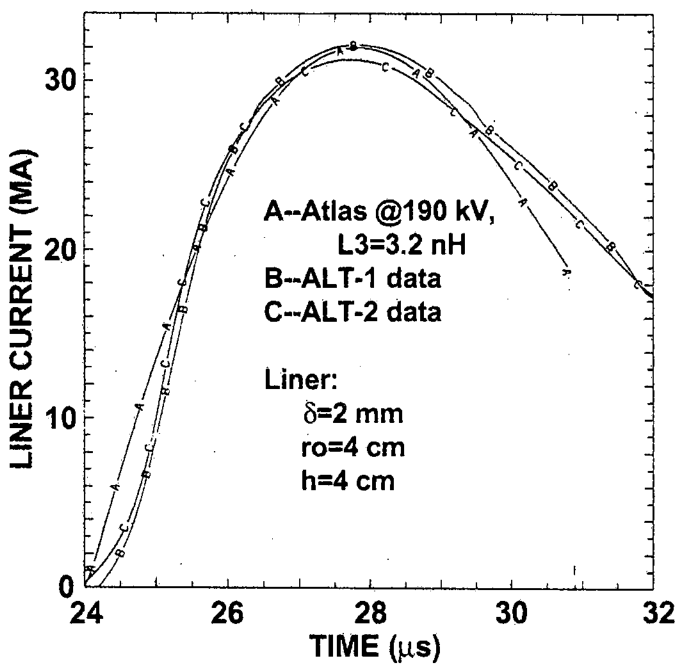


Fig. 2. A predicted current waveform for an Atlas low inductance configuration and the el
current measured on the Advanced Liner Technology ALT-1 and ALT-2 experiments.



LINER CURRENT (MA)
0
10
20
30
24
26
28
30
32
TIME (μs)
A--Atlas @190 kV,
L3=3.2 nH
B--ALT-1 data
C--ALT-2 data
Liner:
δ=2 mm
ro=4 cm
h=4 cm

FIG. 2