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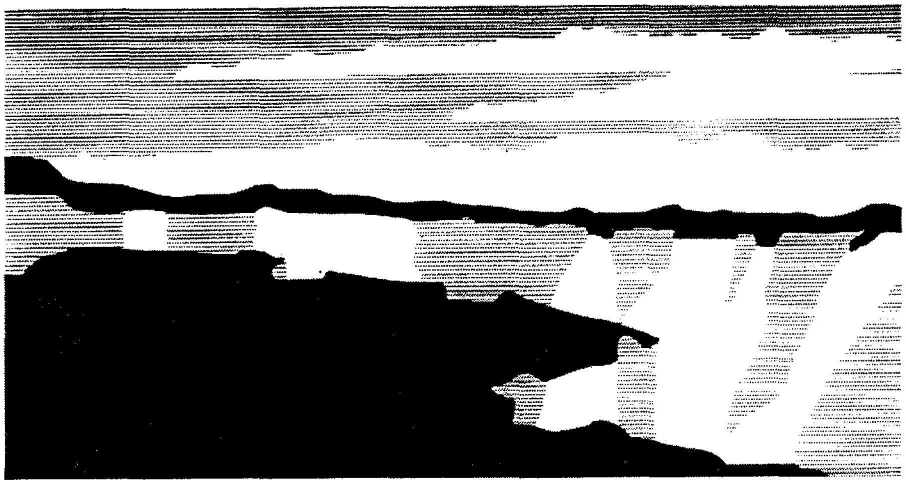

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Megagauss Technology and Pulsed Power Applications

Irvin R. Lindemuth*, Robert E. Reinovsky, and C. Maxwell Fowler

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Because of recent changes in Russia, there are opportunities to acquire and evaluate unique technologies for ultrahigh-magnetic-field flux compressors and ultrahigh-energy, ultrahigh-current pulsed-power generators that could provide inexpensive access to a variety of extreme matter conditions and high-energy-density physics regimes. Systems developed by the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) at Arzamas-16 (Sarova) have the potential to create entirely new thrusts in several areas of high-magnetic-field and high-energy-density R&D, including high-field and high-temperature superconductivity, the Faraday effect, cyclotron resonance, isentropic compression, magneto-optical properties, plasma physics, astrophysics, energy research, and related endeavors. Through a formal collaboration supported and encouraged by high-ranking DOE officials and senior laboratory management, we have gained access to unique Russian technology, which substantially exceeds US capabilities in several areas, at a small fraction of the cost which would be incurred in an intensive and lengthy US development program.

1. Background and Research Objectives

Magnetic flux compression techniques make it possible to produce ultrahigh magnetic fields and to generate ultrahigh-energy, pulsed electrical currents. Magnetic flux compression technology is of interest to Los Alamos National Laboratory as a means of accessing a variety of extreme matter conditions and high-energy-density physics regimes. Potential applications of magnetic flux compression technology include high-field and high-temperature superconductivity, the Faraday effect, cyclotron resonance, isentropic compression of solid materials, magneto-optical properties, plasma physics, astrophysics, energy research, and related endeavors.

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The principles of magnetic flux compression, pioneered at Los Alamos, are well known. In a purely electrical circuit, the electrical current and the stored magnetic energy can be increased by reducing the inductance of the circuit. In magnetic flux compression generators, pressures generated by the release of chemical energy are used to deform the electrical conductors, thereby reducing the circuit inductance and transforming chemical energy directly into electrical energy.

At the two most recent International Conferences on Megagauss Magnetic Field Generation and Related Topics (Megagauss-V, Novosibirsk, Russia, July, 1989; Megagauss-VI, Albuquerque, NM, November, 1992), scientists from the groups of A. I. Pavlovskii and V. K. Chernyshev at the All-Russian (formerly All-Union) Scientific Research Institute of Experimental Physics (VNIIEF) at Arzamas-16 (Sarov) reported remarkable advances in magnetic flux compression technology. Pavlovskii's group reported the development of the MC-1 magnetic flux compressor, which reliably produced magnetic fields greater than 10 MG in volumes of approximately 10 cubic centimeters. For comparison, the Los Alamos strip generator routinely produces approximately 3 MG. Since the magnetic energy is proportional to the square of the magnetic field strength, the energy density achieved by Pavlovskii is an order of magnitude higher than the strip generator. Pavlovskii has also reported initial designs for a 20 MG flux compressor.

Chernyshev's group and Pavlovskii's group both reported Disk Electromagnetic Generators (DEMG) which could produce 200 MJ or more of inductively stored electrical energies at current levels greater than 250 MA. For comparison, the Los Alamos CN-3 simultaneous coaxial generator, the performance standard for US generators, delivers approximately 20 MJ and 150 MA, so the energy capabilities of VNIIEF generators are an order of magnitude higher.

We now know that the magnetic flux compression program at VNIIEF is essentially "the legacy" of Nobel Peace Prize winner Andre D. Sakharov, who spent much of his scientific career at VNIIEF. It is estimated that a very intensive, expensive and lengthy development program would be required for the US to reach performance levels already demonstrated at VNIIEF. Fortunately, the political changes that have occurred in the former Soviet Union have made it possible for US scientists to work side-by-side with their Russian counterparts. Through this project, Los Alamos has established a formal collaboration with VNIIEF and the US is acquiring unique Russian magnetic flux compression technology at a cost well below that which would be incurred if the US were to attempt to develop such technology.

Almost concurrent with LANL's interest in acquiring VNIIEF technology, the Soviet Union disintegrated and the possibility of nuclear weapons proliferation by "brain drain," i.e., emigration or defection by Soviet nuclear weapons experts, became a major concern of US policy makers. Because they are at the top of the "nuclear pyramid," scientists from the still very secret VNIIEF, which was not even acknowledged to exist by the Soviet government as recently as five years ago, are a prime target of US "brain drain" prevention activities.

Collegial relationships established previously between LANL and VNIIEF scientists at the Megagauss conferences put LANL in a unique position to respond to national needs. Responding to policy established at the National Security Council level in late 1991, a formal scientific collaboration was established between these two premier nuclear weapons design laboratories. Now over three years old, this collaboration has received the support of high-ranking US Government officials and senior Laboratory management.

Eight joint LANL/VNIIEF experimental campaigns have now been conducted by the LANL/VNIIEF collaboration (September, 1993, at VNIIEF; December, 1993, at LANL; April, 1994, at VNIIEF; August, 1994, at VNIIEF; October, 1994, at LANL; February, 1995, at VNIIEF; August, 1995, at VNIIEF; September, 1995, at VNIIEF). These experiments include the first-ever scientific experiment performed jointly by nuclear weapons design laboratories of the US and the Russian Federation. In addition to the scientific benefits accruing to both nations, the collaboration serves as a symbol that the two nations are beginning to "beat swords into plowshares" and has received extensive favorable coverage in the Russian and US news media. Furthermore, the collaboration is playing an important role in “scientific conversion” as VNIIEF converts to a peacetime mode of operation.

2. Importance to LANL’s Science and Technology Base and National R&D Needs

The major mission for the DOE in the future will be reducing the nuclear danger, a mission that clearly requires interactions with the Russian nuclear design laboratories. Through the LANL/VNIIEF collaboration, LANL personnel have spent more time at VNIIEF than any other western group. The trust and respect that has been developed through this collaboration has provided LANL personnel with unprecedented access to VNIIEF administrators. Through our access, LANL has been able to provide timely information simply unavailable through any other channel to LANL, DOE, DoD, and State Department officials. Consequently the collaboration has played an irreplaceable role in the development of US policy towards Russia and has led to new funding for Russian-related activities. Furthermore, the partnership and recognition, as well as the funding, that collaboration provides serves as an incentive to VNIIEF scientists to remain at their institute and at the same time diverts some of their activity from mainline nuclear design.

In addition to a very important role in scientific conversion, this project represents a unique opportunity to acquire and evaluate technology that is simply unavailable anywhere else in the world. Acquisition of VNIIEF technology will give LANL a capability to produce higher magnetic fields and higher electrical energy/current pulsed sources than any other facility in the world except VNIIEF itself. Just as our present pulsed-power capabilities play a role in DOE and other national programs, the enhanced capabilities acquired in this project will put LANL in a unique position to apply high magnetic fields and ultrahigh-energy pulsed-power technology to a wide range of programs of national importance.

Many of the Laboratory's scientific activities in the future will involve the physics of matter under extreme conditions in high-energy-density regimes. There is a growing recognition that pulsed power will be the most viable means to access some of these regimes. The energy-rich technology that will be acquired in this project will enhance the Laboratory's ability in this area.

Imploding plasma liners have been pursued in the US for two decades as a means of generating soft x-rays for a variety of scientific applications. The traditional US approaches have been fraught with difficulties, e.g., the need to develop fast-opening switches and the need to overcome plasma instabilities. Soft x-ray yields of 1 MJ and greater have proven elusive. However, VNIIEF's unique technologies open up new possibilities.

Controlled thermonuclear fusion has been a part of the national and Laboratory R&D programs for more than four decades. As we have learned more about VNIIEF, we have concluded that controlled fusion has been the major motivation for VNIIEF's development of its unique technology. In fact, fusion has been described as "Sakharov's fondest dream." We now know that Sakharov, and those at VNIIEF who carry on the work initiated by Sakharov, have chosen an approach that in many physical parameters is intermediate between the more conventional magnetic fusion energy (MFE) and inertial confinement fusion (ICF). Through our collaboration, we are learning more about the VNIIEF approach, known in Russia as MAGO (MAGnitnoye Obzhatiye, or magnetic compression) and now known in the US as magnetized target fusion (MTF). MTF is essentially unexplored in the US and, based upon VNIIEF advances in this area, may warrant consideration in the US controlled fusion program.

3. Scientific Approach and Results

The LANL/VNIIEF collaboration uses unique VNIIEF technology to drive extreme condition physics experiments in implosion hydrodynamics, x-ray generation, basic science, and unconventional controlled fusion. Our basic approach is to join with VNIIEF scientists to perform joint scientific experiments of interest to both institutions. Each experimental campaign completed to date represents endeavors that neither institution has the capability of doing entirely by itself. In general, VNIIEF provides most of the system hardware and LANL provides sophisticated diagnostics not available at VNIIEF. LANL's advanced diagnostic capability and advanced computational capability complement VNIIEF's capabilities, which have been previously exercised on the VNIIEF systems and which simply are not available "off-the-shelf" in the US.

An underlying assumption in our approach is that US policy will evolve to the point where a long-term partnership between LANL and VNIIEF will be considered to be in the US's best interest. We are forming the foundation for such a partnership and we strive to identify topics suitable for a long-term relationship.

After a series of negotiations begun in June, 1992, the first joint experiments were conducted in 1993. The eight campaigns completed to date covered applications of VNIIEF high-current generator technology to imploding condensed matter and plasma liners, applications of VNIIEF high-magnetic field generator technology to high-temperature superconductors and isentropic compression of material samples to megabar pressure, and application of VNIIEF generator technology to formation of hot, magnetized hydrogenic plasma for fusion applications.

On September 22, 1993, the first experiment ever conducted jointly by scientists from nuclear weapons design laboratories of the two nations was conducted at VNIIEF. The experiment used a helical preamplifier, a DEMG, a fast-fuse opening switch, and an explosively operated closing switch to couple a 20 MA, 0.7 microsecond electrical pulse to a 6-cm-diameter, 2-cm-long imploding liner load. The current delivered to the load is shown in Figure 1. All LANL objectives for a first experiment were accomplished: we saw the system hardware for the first time; we witnessed the assembly and operation of the system; we demonstrated that we could field sophisticated pulsed power diagnostics in remote environments; we independently verified the performance of the DEMG; and we verified and improved our computational models of VNIIEF systems.

In 1994 LANL asked VNIIEF to perform a design study aimed at identifying a system capable of producing in excess of 2 MJ of soft ($T > 300$ eV) x-rays for a variety of potential scientific applications. That design study identified the Changing Mass Liner (CML) or "plasma bubble" approach, which represents an alternative to the imploding foil concept pursued in the US for more than a decade. Although the CML concept must be considered high risk, it may be the only concept yet available that is scalable to considerably higher energies. In February, 1995, at VNIIEF, the plasma formation stage of the CML concept was tested. Shown in Figure 2 is the electrical current waveform delivered to a slowly moving (< 5 mm/ms) liner that, at peak current, traveled beyond an electrode end and formed an imploding plasma arc or bubble. The ultimate viability of the concept depends on such things as the shape (symmetry), mass, and velocity of the imploding plasma. VNIIEF's analysis of the data was completed in September, 1995, and is currently being evaluated at LANL.

In December, 1993, a series of seven high-magnetic-field experiments were conducted at LANL, the first experiments ever conducted jointly in the US by scientists from the nuclear weapons design laboratories of the two nations. Five of the experiments used VNIIEF MC-1 generators which were mated with LANL high-explosives. The series verified the performance of the MC-1 using LANL explosives, determined the variation of performance with type of explosive, proved a new LANL microwave diagnostic for measuring high magnetic fields, measured for the first time the upper critical field of YBCO, a high-temperature superconductor, and obtained a body of data suitable for benchmarking LANL computer codes. The results of these experiments will be used to begin the joint design of a flux compressor capable of producing magnetic fields of 20 MG if an adequate funding source can be found.

In August, 1994, and August, 1995, at VNIIEF, the MC-1 high magnetic field generators were used in joint experiments at VNIIEF to isentropically compress liquid argon to high densities in order to study the transition to many-body behavior in strongly coupled matter. In an isentropic compression experiment, high explosives compress the magnetic field, which in turn presses on a central metal cylinder containing the sample. The experiments reached pressures of more than 6 Mbar, and, in August, 1995, the transition from insulator to conductor was observed for the first time. Figure 3 shows the oscilloscope waveform indicating the transition.

A Magnetized Target Fusion (MTF) system requires two elements: (a) a target implosion driver and (b) a means of preheating and magnetizing the thermonuclear fuel within the target prior to implosion. The energy-rich VNIIEF DEMG systems are prime candidates for a driver. In 1992, VNIIEF revealed major progress in plasma formation, an area that presented a major obstacle in previous US endeavors that would now be called MTF. In April, 1994, a team of LANL scientists traveled to VNIIEF to measure for the first time the performance of a VNIIEF MAGO system, a system for which many details remain unpublished. Because of the experience gained in September, 1993, considerably more LANL diagnostics were fielded on the April experiment. LANL successfully measured the fusion neutron yield of the experiment with both time-dependent and time-integrated techniques, used optical interferometry to gain insight into the electrical breakdown processes, and performed time-resolved visible and time-integrated near-uv spectroscopy to gain some insight into impurities within the plasma. Even more extensively diagnosed follow-up experiments were performed at LANL in October, 1994, and at VNIIEF in September, 1995. Each experiment has increased US knowledge of this system, and the diagnostics continue to suggest that the plasma may be suitable for subsequent implosion in an MTF context. Figures 4 and 5 show LANL measurements of the neutron and x-ray emission of the plasma.

Joint computer code bench-marking activities in the areas of pulsed power systems and the MAGO application are being conducted. VNIIEF's computed results for a series of test problems defined by LANL were delivered to LANL in September, 1994. The results of the MAGO plasma formation experiments are being used to normalize US and VNIIEF computer models; LANL's two-dimensional magnetohydrodynamic computations performed with the MHRDR (Magneto-, Hydro-, Radiative Dynamics Research) code are in good agreement with many of the observations, as shown in Figure 6.

Five additional MC-1 generators were purchased from VNIIEF in 1994 and will be used for a variety of high-magnetic field experiments in FY96. A series of joint conference presentations made in mid-1994 represent the first joint papers ever presented by nuclear weapons design laboratories of the two nations. In addition to numerous joint conference presentations, several formal papers have been published in refereed, archival journals and several additional papers are in preparation.

4. Summary and Prognosis

Through this project, US scientists have been exposed to previously inaccessible realms of high-energy-density physics, at substantial savings in developmental costs and time. Although LDRD funding for this three-year project has now been completed, the accomplishments of the project have attracted substantial programmatic funding and the LANL/VNIIEF collaboration begun under LDRD funding will continue. In FY96, the isentropic compression experiments will be continued. In addition, VNIIEF's largest DEMG, 1-m-diameter, will be used to deliver as much as 100 MJ of kinetic energy to an imploding liner load; successful execution of this experiment will represent a major step toward the development of a capability to generate ultrahigh pressure shocks and to implode a preheated, magnetized plasma in an MTF context. As with all previous joint campaigns, the future experiments are experiments which simply could not be performed with US "off-the-shelf" systems.

Based upon our evaluation of Russian accomplishments and potential, controlled thermonuclear fusion ignition via Magnetized Target Fusion (or MAGO, as known in Russia) appears extremely promising and we are actively seeking a US Government "champion" to elevate this approach to an appropriate level in the US controlled fusion program. A formal, joint US/Russian program in Magnetized Target Fusion has recently received supporting letters from leaders of the Russian scientific community, including Academician Yuli Khariton (the "Soviet Oppenheimer") and Academician Evgenni Velikov (head of the International Toroidal Experimental Reactor Council). In a recent letter to Secretary of Energy Hazel O'Leary, Russian Minister of Atomic Energy Victor Mikhailov wrote:

> "I believe that MAGO is an appropriate low-cost, technically feasible supplement to the controlled fusion research now being conducted in both of our countries. I would like to propose a US/Russian program to systematically evaluate MAGO in a timely and efficient manner."

As suggested by the list of references, the scientific benefit to the US and the Russian Federation that has been accomplished through this project is easy to document. More difficult to assess is the enduring impact of having established, for the first time, a US presence in the Russian nuclear weapons design laboratory at Arzamas-16. The success of the collaboration as viewed from the Russian side is summed up in an October, 1994, statement made by the leaders of the VNIIEF team (V. K. Chernyshev, Deputy Scientific Leader and Electrophysical Department Head, and V. N. Mokhov, Deputy Scientific Leader and Theoretical Division Head):

> "... the success of the two-year cooperation has exceeded our highest expectations. Both sides have learned much from each other and have found this relationship to be mutually beneficial. We complement each other in the way we approach scientific challenges... Today, when nuclear weapons stockpiles are being reduced at an unprecedented rate, highly qualified scientists have become available to use their considerable skills in peaceful applications of high energy density research. Their continued employment in this important area of science, which should prove to be a substantial benefit to mankind, deserves generous governmental and public support. There is no doubt that it will also lead to a more stable world and reduce the potential danger of nuclear proliferation. The current cooperation between the two laboratories is an example of such an effort and should facilitate scientific and technological progress in both countries."

Chernyshev has also stated that "this program has kept many young weapons experts from leaving Arzamas-16" and Mokhov has described the collaboration as "a little flame of hope for the future ... this is what our people need."

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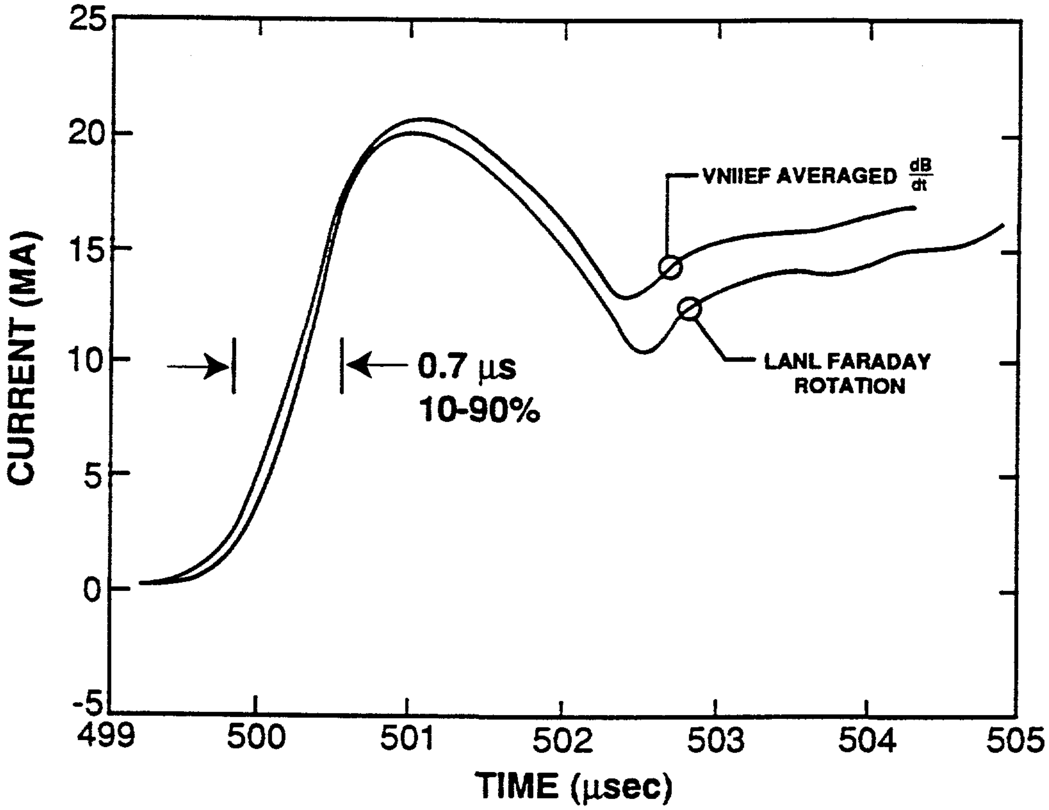

Figure 1. Current delivered to an imploding liner load by Russian DEMG/fuse combination. LANL Faraday rotation current measurements confirmed the DEMG performance. Even though a partial transmission line failure occurred, the current delivered exceeded existing US capabilities (US/Russian experiment at Arzamas-16, Russia, September, 1993).

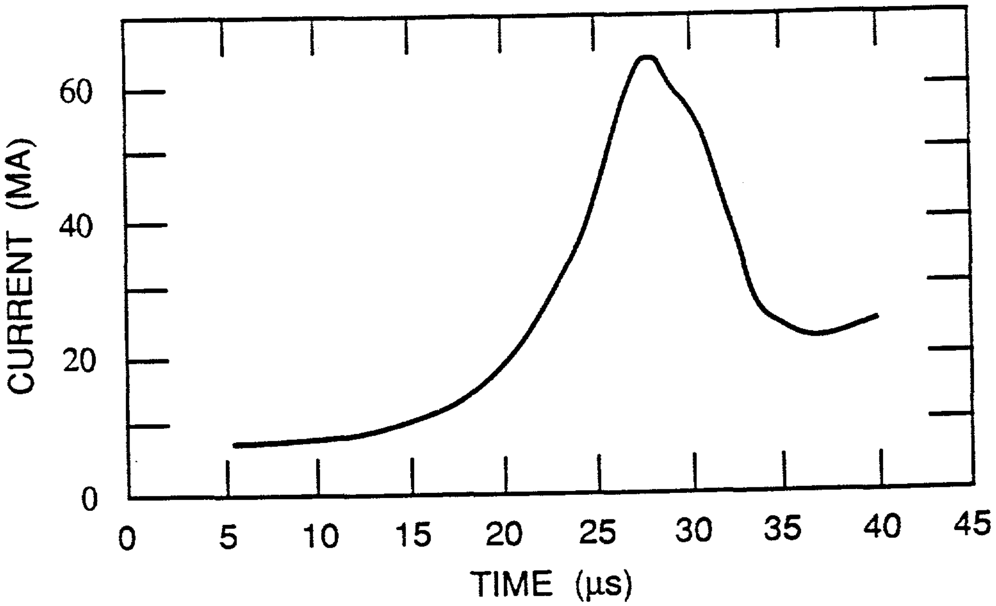

Figure 2. Current delivered to an imploding liner load by a Russian DEMG. The US does not have a comparable high-energy, high-current pulsed power source (US/Russian experiment at Arzamas-16, Russia, February, 1995).

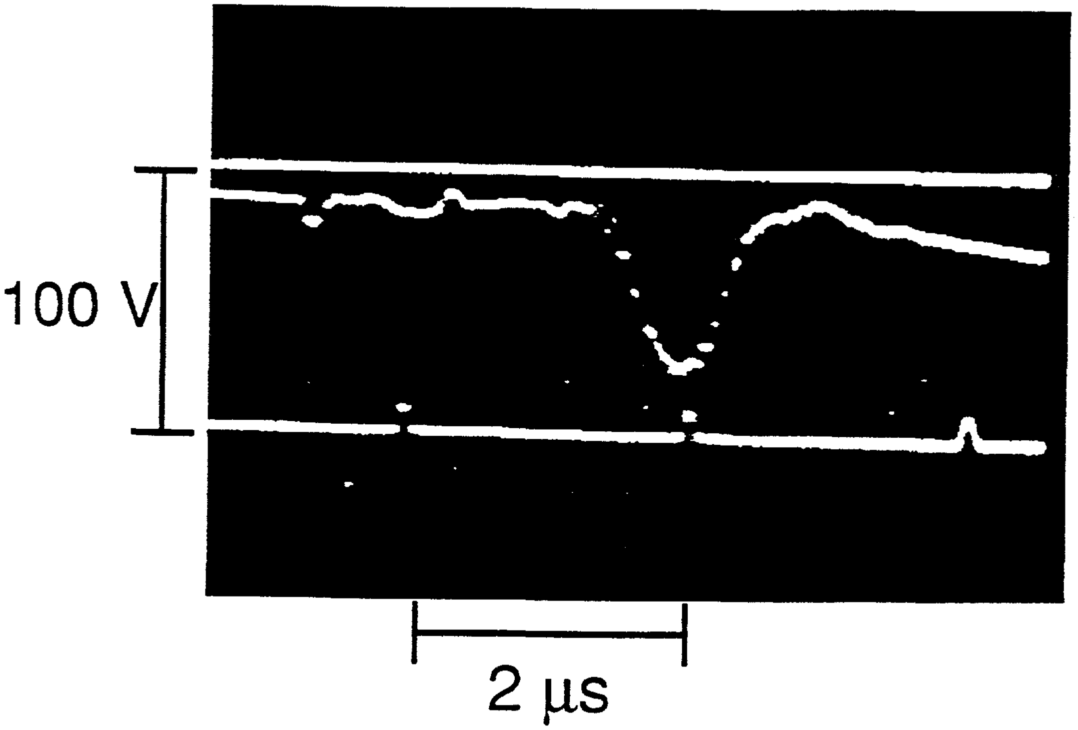

Figure 3. First evidence (the negative pulse) of the transition of isentropically compressed, liquid argon to quasi-molecular behavior under high pressure. Existing US generators do not create megagauss magnetic fields in a sufficiently large volume to do this (US/Russian experiment at Arzamas-16, Russia, August, 1995).

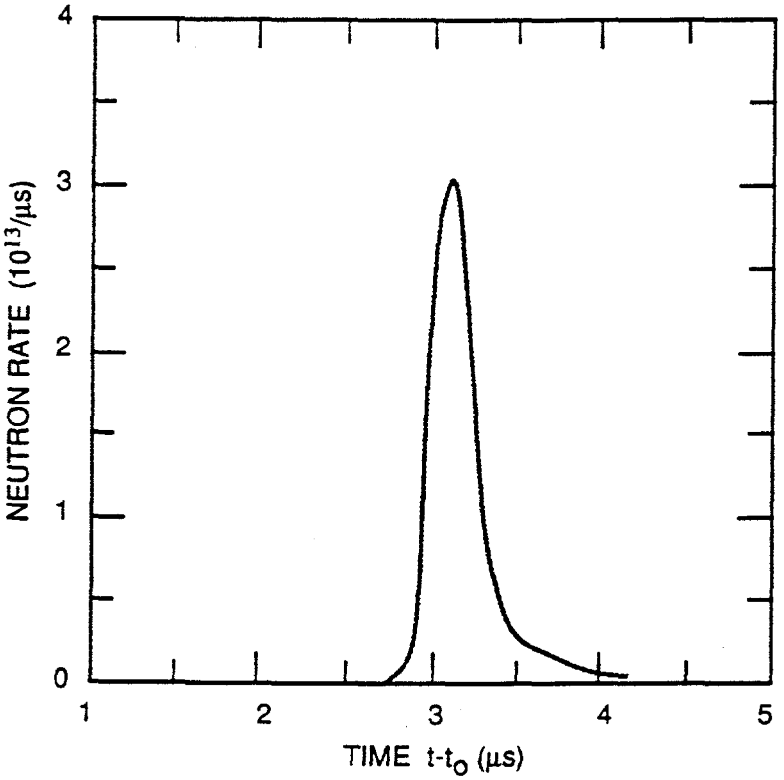

Figure 4. LANL measurement of the neutron yield of a Russian MAGO magnetized plasma formation system indicates that 10^{13} fusion neutrons were produced, the highest ever achieved at LANL (US/Russian experiment at Los Alamos, October, 1994).

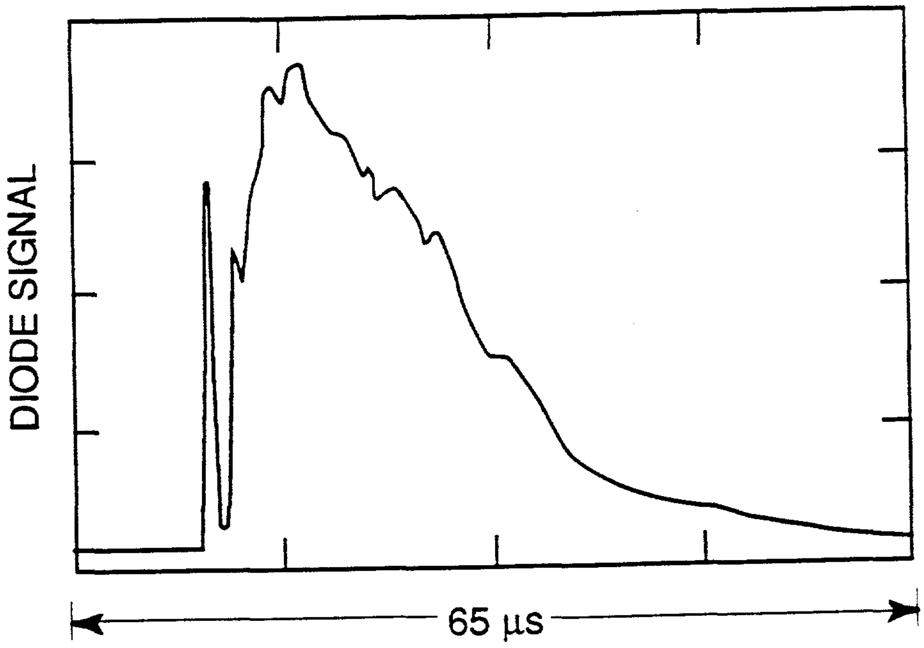

Figure 5. LANL filtered silicon diode measurement of x-ray emission above about 700 eV suggests that the hot plasma in the Russian MAGO magnetized plasma formation system has a lifetime of more than twenty microseconds (US/Russian experiment at Arzamas-16, Russia, September, 1995).

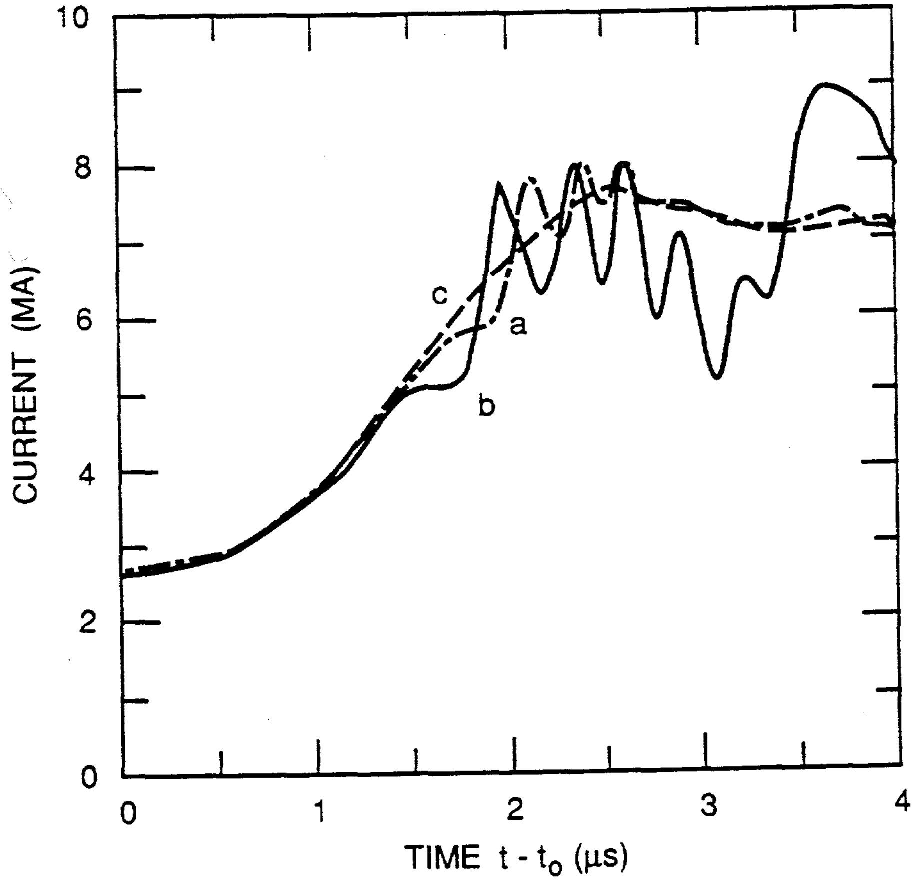

Figure 6. LANL two-dimensional magnetohydrodynamic (MHD) computations (curve a) are in good agreement with magnetic probe measurements (curve b) on the Russian MAGO magnetized plasma formation system. For reference, the plasma system driving current is also shown (curve c) (US/Russian experiment at Los Alamos, October, 1994).