In the midst of a cold Russian winter, these Russian and American experimentalists attempted to produce a plasma that was one hundred times hotter than the surface of the sun.

Lab-to-Lab

Scientific Collaborations Between Los Alamos and Arzamas-16 Using Explosive-Driven Flux Compression Generators

Stephen Younger, Irvin Lindemuth, Robert Reinovsky, C. Maxwell Fowler, James Goforth, and Carl Ekdahl

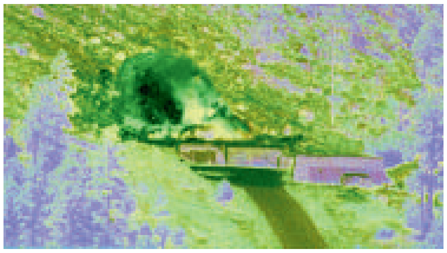
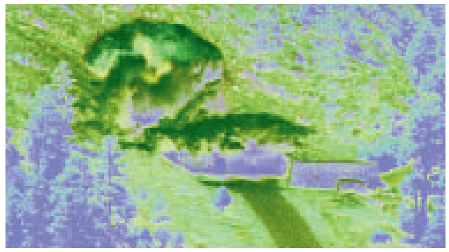
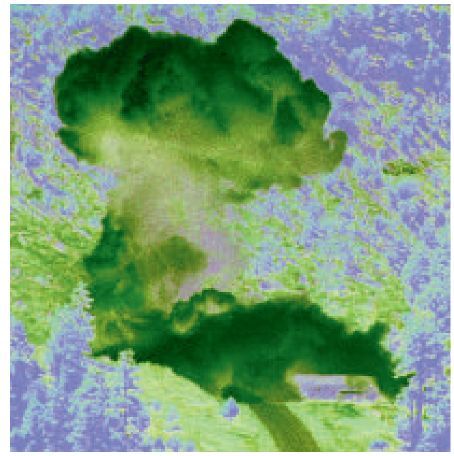
The first international conference on Megagauss Magnetic Field Generation and Related Topics was held in 1965 in Frascati, Italy. By then, Max Fowler, Wray Garn, and Bob Caird had already spent the better part of eight years producing megagauss magnetic fields. The small group of Los Alamos scientists had pioneered a technique called magnetic-flux compression, which takes the energy stored in the chemical bonds of high explosives and converts it to magnetic field energy. The energy is then delivered to an experiment as a pulse of either extremely strong magnetic field or extremely large electrical current. Although the Los Alamos magnetic-flux compression effort was relatively modest, Fowler and his team had achieved considerable success at building flux compression generators and had already produced magnetic fields above 10 megagauss (mega = 10^6). By comparison, the Earth's magnetic field is about 0.5 gauss, and that of an ordinary refrigerator magnet about 10 gauss.

A smiling Steve Younger congratulates Russian delegation leader Alexander Bykov after the success of the first, collaborative, nonweapons-related scientific experiment to be carried out on U.S. soil. The experiment, performed by Russian nuclear-weapon scientists and their Los Alamos counterparts, occurred in December 1993. On the left is Russian translator Elena Gerdova.

One of Fowler's motivations for building these devices was to use the enormous field to contain or compress a plasma. This compression could be a means of achieving thermonuclear fusion (the process by which the sun produces energy), which might make available to the world an unlimited energy source. Even without that exceptionally practical goal, Fowler and his team recognized that ultrahigh magnetic fields and intense electrical currents could find application in the study of phenomena ranging from material properties to x-ray generation.

While thumbing through the abstracts submitted to that 1965 conference, Fowler, to his surprise, noticed that some were from the Soviet Union. Nineteen scientists were represented in eight abstracts, and the Soviets were going to discuss the generation of megagauss fields by the technique of magnetic-flux compression.

"That was the first time I had seen anything of their work." said Fowler. "We had certainly never met any of

A time sequence of an explosive-driven, magnetic-flux compression experiment performed at the Ancho Canyon site in Los Alamos. The time elapsed between the first and last photos is on the order of fifty milliseconds.

them. It was strange, because their work seemed to be of the same scope as ours, and they were alluding to the same problems and the same solutions."

But the papers referenced by those abstracts were never submitted to the conference. No Soviet scientists attended, and the international community was left with only a tantalizing glimpse of the Soviet research program.

The Russian Magnetic-Flux Compression Program

We now know that the Soviet work had begun as early as 1951 when Andrei Sakharov, one of the premier scientists of the Soviet nuclear weapons program and winner of the 1975 Nobel Prize for peace, had sketched out an idea for compressing magnetic flux and generating high fields or currents. Like Fowler, Sakharov was seeking a means to achieve thermonuclear fusion, and he helped identify several schemes in which high magnetic fields could potentially help the fusion process. Some of the schemes were purely for research purposes, whereas others could potentially be used for weapons work.

Sakharov's ideas initiated a program involving some of the best Soviet weapons scientists, and an intense effort was devoted to the development of the high-field and high-current generators required to implement those ideas. The work was performed at Arzamas-16, the secret city that harbored the All-Russian (formerly the All-Union) Scientific Research Institute of Experimental Physics (VNIIEF), the Soviet Union's first nuclear weapons laboratory. Initially, much of the experimental flux compression work was carried out by Robert Lyudaev, who in 1952 succeeded in producing a magnetic pulse of approximately 1.5 megagauss. (In these explosive-driven flux compression schemes, the entire experiment is over in less than a millisecond. The field or current pulse rises "slowly," then quickly reaches peak value in the few microseconds before the generator is destroyed. In general, this research is referred to as high-explosive, pulsed-power research.)

Lyudaev's work was extended and advanced by scores of skilled Russian scientists, including Alexander Ivanovich Pavlovskii and Vladimir Konstantinovich Chernyshev, scientists who more than three decades later would play pivotal roles in establishing scientific collaborations between the Russian Federation and the United States. Pavlovskii eventually refined a generator, called the MC-1, to the point that it could reliably and predictably produce magnetic fields in excess of 10 megagauss. This was about the same field magnitude produced by Fowler's generators, but it was established in a larger and therefore more useful volume. Chernyshev's team developed a flux compression generator, called the DEMG, that could produce currents exceeding 200 megamperes. The Russian investigation into magnetic-flux compression continues to this day.

The Russian-American Pulsed-Power Collaborations

The independent development of the Los Alamos and Soviet pulsed-power programs represented something of an anomaly within the framework of modern science. Basic research is difficult and success often elusive, and the free exchange of ideas is vital. Yet here were two groups that were unable to communicate, much less exchange ideas. Despite the fact that flux compression generators were primarily used for pure scientific research, these devices could potentially aid in weapons development.† In the suspicion-charged atmosphere of the cold war, potential threats to national security superseded the desire for scientific exchange.

But times and situations change, and when the second Megagauss conference was held in Washington, D.C. in 1979, some fourteen years after the first conference, Soviet research papers were actually presented. However, neither Pavlovskii nor Chernyshev nor their team members were allowed to attend. Instead, a close colleague of theirs read

†A ten-megagauss magnetic field can exert an enormous pressure on a conducting material, one that is exceeded only by the pressures achieved in a nuclear explosion. The generators can therefore be used to study weapons materials and evaluate diagnostics without detonating a nuclear device.

a number of papers that were of interest the non-Soviet scientists in attendance.

Communication and interactions between the Los Alamos and Arzamas-16 pulsed-power groups gradually increased during informal meetings at subsequent conferences. Fowler first met Pavlovskii in 1982 at the third Megagauss conference in Novosibirsk, U.S.S.R. The two scientists had been indirectly influencing each other's work for more than a decade, but now a personal relationship developed between the two men. With Fowler's assistance, Pavlovskii visited both the United States and Los Alamos for the first time in 1989.

Megagauss-V was held later in 1989 in Novosibirsk. Pavlovskii, who was not in attendance due to health problems, had a letter delivered to Fowler that raised the issue of a joint research program for producing fields in the 20 to 30 megagauss range. The suggestion, though informal, was a recognition of the obvious. Faster progress would be achieved by both groups through a collaborative effort, and both groups would benefit.

Megagauss-V was also where Bob Reinovsky and Irv Lindemuth of Los Alamos met Vladimir Chernyshev for the first time. The Los Alamos and Soviet teams were by then well acquainted with each other's publications, and the meeting led to several speculative discussions about the possibility of future collaborations. The talk became more serious at the 1991 International Pulsed Power Conference, held in San Diego, and culminated in September of that same year when Chernyshev and Vladislav N. Mokhov met with Lindemuth in Moscow and presented a written proposal for a formal collaboration on thermonuclear fusion research using flux compression generators.

The Soviet proposal called for a generator to create a large magnetic field that would be used to implode a liner, which is a hollow metal cylinder. The liner would surround a dense, hot, plasma that would be created in a second magnetic field. This method of preparing a "magnetized" plasma was not akin to any method then being pursued in the United States. Imploding the liner would potentially compress the plasma to the very high densities and temperatures needed to initiate thermonuclear fusion. This speculative fusion scheme is known as MAGO in the Soviet Union. The collaboration proposal was signed by VNIIEF Director Vladimir Belugin and, evidently, had the support of Yuli Khariton—the "Soviet Oppenheimer"—as well as high-ranking officials from the Soviet Ministry of Atomic Energy. However, although the Soviets were willing to share with the Americans the results of their pulsed-power program, including their MAGO thermonuclear fusion research, the global political climate was changing so abruptly in the latter part of 1991 that the formal proposal went unanswered by the United States government.

In fact, the political climate turned severe with the collapse of the Soviet Union in December of 1991 and the Russian Federation's subsequent rapid decline towards economic chaos. Within the nuclear cities, the formerly elite nuclear weapons scientists were suddenly facing food-distribution problems and shortages of medical supplies. It was perceived by many in the West that the situation was becoming unstable and could potentially result in breakdowns in the security that safeguarded nuclear weapons and materials. Many feared that weapons of mass destruction or fissile materials could be stolen or sold to rogue nations or terrorists. President Bush himself was deeply concerned about the possibility of the so-called "brain drain," wherein nuclear weapons scientists would migrate to and work for other countries.

Los Alamos Laboratory Director Sig Hecker, aware of the various overtures extended to Los Alamos scientists by the Arzamas-16 scientists, pointed out to then Secretary of Energy Admiral Watkins that perhaps the Russian laboratory leaders themselves knew the best way to keep their scientists at home. That simple acknowledgment, and Watkins quick approval, led directly to the Laboratory Directors' exchange visits in February of 1992.

The Directors' exchanges would form the beginnings of the "lab-to-lab" collaborations between the United States and Russian nuclear laboratories. Scientifically, this program was for the purpose of conducting pure research, and was not directed towards the development of any weapon, fusion or otherwise. The Americans, and presumably the Russians, came to recognize that the technical advances that could emerge from the research would have a minimal and remote risk of being applied to weapons that posed a threat to either country.

Instead, the collaborations would have the positive effect of infusing a small amount of money into the Russian complex. This would help stabilize the financial situation and help keep the Russians scientists working. The United States would also reap the benefits of scientific exchange with world-class research institutions. It is interesting to note, however, that although the Directors' exchange formally cut the ribbon, the bridge that spanned the East-West political gulf had been built by scientists reaching out to one other. A friendly handshake between Max Fowler and Alexander Pavlovskii was transformed into a tangible link between Russian and American scientists.

Irv Lindemuth, Bob Reinovsky, Max Fowler, and Stephen Younger visited Arzamas-16 in June of 1992. During that visit, Younger, then the Program Director for Above-Ground Experiments, suddenly found himself elevated to the role of negotiations point man. Younger succeeded in forging an agreement that laid out the rules for the lab-to-lab program. The Russians would provide manpower, expertise, and equipment for joint experiments. Los Alamos would finance part of the experiments and would complement the Arzamas-16 devices with its significant expertise in fast diagnostics, recording instrumentation, and supercomputer modeling.

It was agreed that two experimental campaigns would initially be conducted, the first to take place at Arzamas-16. That experiment would test Chernyshev's DEMG high-current flux compression generator. The Russian scientists would then come to Los Alamos and help conduct an experimental series in superconductivity using Pavlovskii's MC-1 generators that had been purchased by Los Alamos. The contract establishing the lab-to-lab collaborations was signed at Los Alamos in November 1992.

That initial contract and the diverse collaborations that developed from it (including an on-going exploration of the MAGO fusion scheme) signified a manifest thawing of Cold War relations and a true shift in the respective roles of the labs. But another, more personal thawing took place as well. After more than forty years of mutual distrust and enmity, Russian and American weapon scientists were going to work together as collaborators and "side-by-side as equals."

The remainder of this article describes some of the experiments that were performed between 1993 and 1995. All of those experiments needed megagauss magnetic fields or megampere electrical currents to achieve their objectives. There will be a brief overview of the principle of magnetic-flux compression that is the basis for ultrahigh magnetic field or current generation, followed by a cursory description of several types of flux compression generators. The article will then proceed to describe five different series of experiments that used those generators.

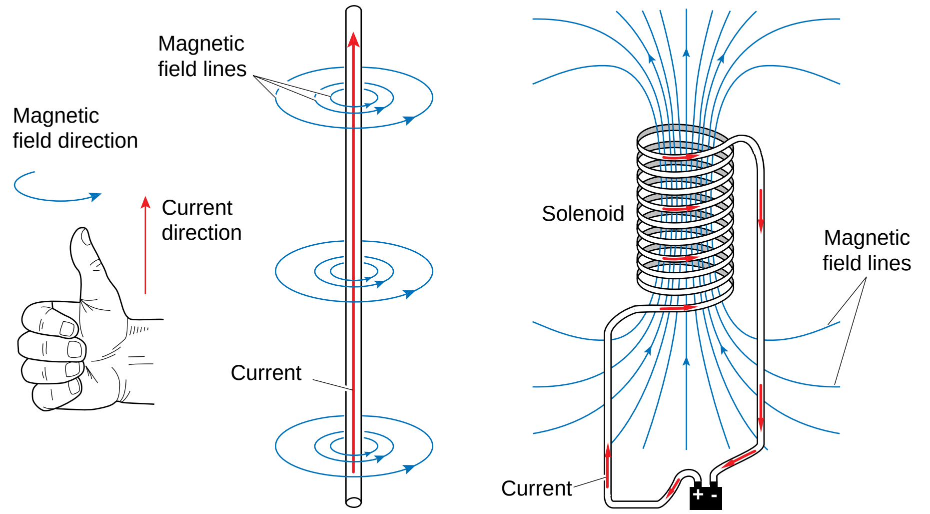


Figure 1. Magnetic Fields and Electrical Currents
Current (red) flowing through a straight wire creates circular magnetic field lines (blue). The field lines are drawn such that the field strength is indicated by the density of the lines (number of lines per unit area). Thus, the magnetic field strength decreases with distance from the wire. The direction of the magnetic field can be found by the "right hand rule." If the thumb of your right hand points in the direction of current flow, the magnetic field lines will point in the direction that your fingers curl. The magnetic field created by a current-carrying solenoid exits from one end of the coil and circles around to enter the other end. The field on the inside of the solenoid is relatively strong and uniform (equally spaced, dense field lines), whereas the field decreases in strength and is nonuniform outside of the coil.

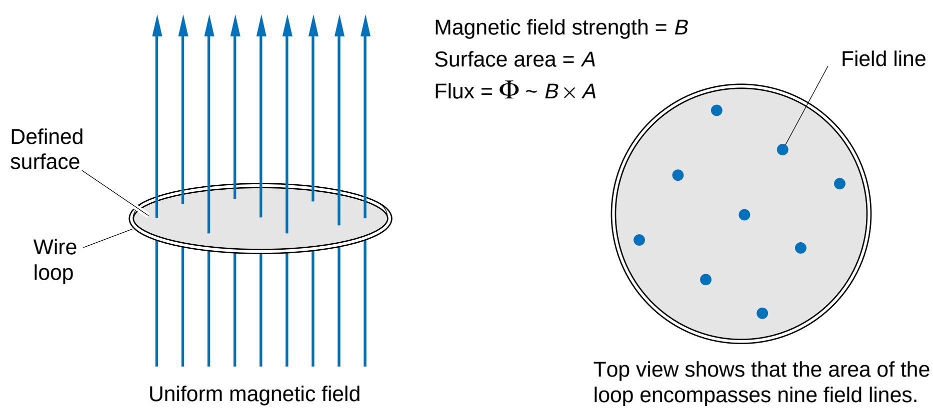


Figure 2. Magnetic Flux
In general, magnetic flux is calculated by integrating the perpendicular component of a magnetic field passing through a surface over the area of that surface. For the uniform magnetic field shown in the figure, the calculation is greatly simplified. The surface is the inside of the circular loop of wire, and the flux is simply the field strength times the area of the loop. Because the field strength is represented by the density of magnetic field lines, the flux is represented by the number of field lines. (Flux = number of lines per unit area × area = number of lines.)

The Principles of Magnetic-Flux Compression

Early in the nineteenth century, through the work of Oersted, Ampere, and others, it was recognized that an electrical current always generated a magnetic field. The size of the current determined the field strength, and the field always pointed in a direction that was at right angles to the direction of current flow (Figure 1).

Although many physicists during the 1820s were aware that currents were the source of magnetic fields, it wasn't until 1831 that Michael Faraday showed the converse to be true; a *changing* magnetic field generates an electric field that

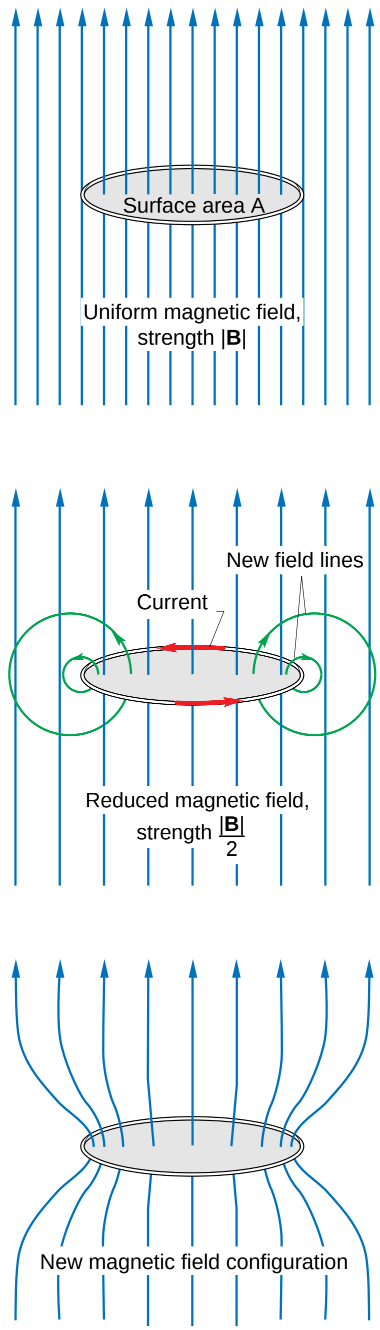


Figure 3. Faraday's Law and Flux Conservation

An external magnetic field (blue lines) threads a closed, perfectly conducting loop. Nine field lines, which represent the flux, thread the loop.

The external magnetic field is reduced to half its value, such that only five external field lines pass through the loop and contribute to the flux. This change in flux induces a current in the loop, which generates a new magnetic field (green lines). The current flows in such a direction that the induced magnetic field adds to the external field. The induced field negates the flux change, and the total flux through the loop is maintained (four green field lines plus five blue equals nine field lines).

Summing the external field and the induced field gives the final field configuration. The distribution of the magnetic field through the loop has changed, but the total amount of flux is conserved.

causes a current to circulate in a conductor. Faraday summarized his observations by stating that a change in the "magnetic flux" that threaded a loop of wire would generate an electromotive force, that is, a voltage, which would induce current to flow.

Figure 2 illustrates the concept of magnetic flux. Although the flux can be defined and calculated for any arbitrary configuration of field and conductors, a simple case is shown in the figure. There, a uniform magnetic field passes straight through a circular loop of wire. The flux in this case is simply the field strength times the area of the loop.

As described at the start of this section, a current is the source of a magnetic field, so that if the flux that threads a loop changes, and the change induces a current to flow in the wire, a new magnetic field is also induced. Faraday demonstrated that the direction of that new field counteracts the change in the flux (a phenomenon that had been described, but not quantified, by Lenz's law). In other words, attempts to change the flux through a conducting loop are counteracted by the induction of currents and fields. The induced field points in a direction that negates the flux change.

Suppose our loop is made from a perfectly conducting material, meaning that currents can circulate around that loop without losing energy. For a perfectly conducting loop, a change in the flux will induce a current that will be of sufficient strength to exactly counteract the change. As illustrated in Figure 3, the flux before and after will be the same, and the flux is said to be conserved.

Most materials are not perfect conductors but have some resistance. Current flowing through a copper or aluminum wire loses energy, which is dissipated as heat. An induced current will continuously decay at some characteristic rate (which depends on both the resistivity of the material and the "inductance" of the loop), and therefore, the induced magnetic field also decays. It becomes unable to counteract the flux change. A loop made of one-millimeter thick copper wire at room temperature and a few centimeters in diameter will maintain a constant flux for less than a millisecond. On the time scale of an explosion, however, which may last only a few microseconds, that loop maintains flux quite well. Thus, on short time scales, shorter than the characteristic decay time, even normal materials approximate perfect conductors, and flux is approximately conserved.

Suppose that instead of changing the magnetic field through the loop, the loop itself is changed and shrinks in size. The flux, which is proportional to both the field and the area, should decrease, but again, currents are generated in the conducting loop that create a new magnetic field. The induced field points in the same direction as the original field to counter the flux change, and the total strength of the field threading the loop increases.

This is the way ultrahigh fields and

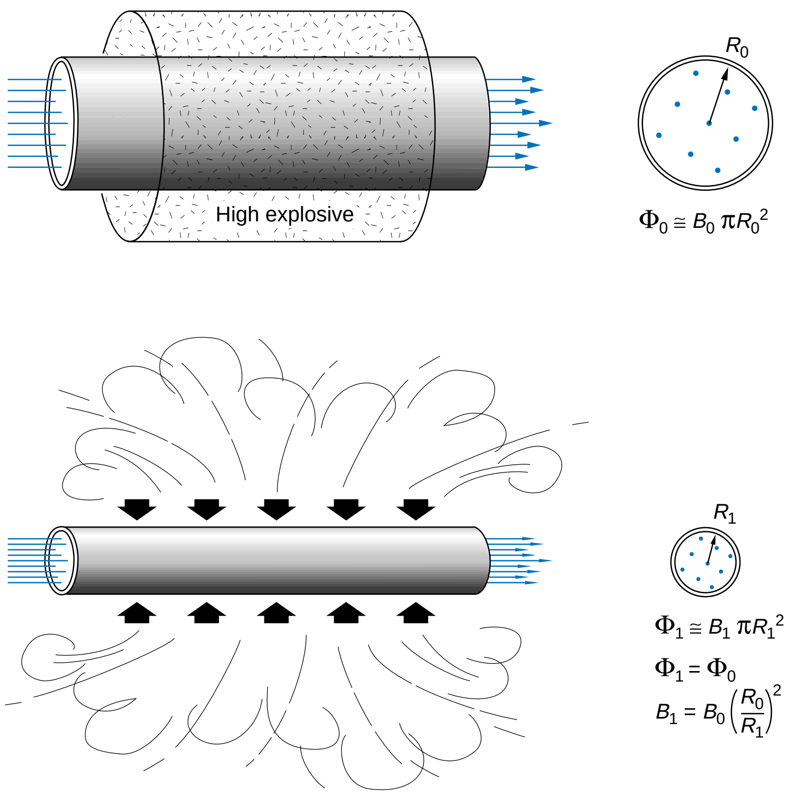


Figure 4. Explosive-Driven Flux Compression

A magnetic field is established within the interior of a metal pipe. The boundary for the flux is the pipe wall, and the surface that defines the flux is the cross-sectional area of the pipe. On short time scales, magnetic flux is conserved so that rapidly imploding the pipe and reducing the interior area compresses the flux (the density of field lines increases). Thus, although (ideally) the flux stays the same, the total magnetic field strength increases.

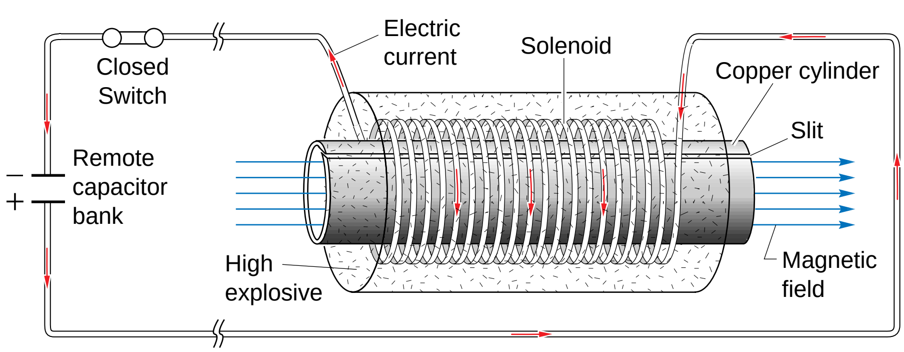


Figure 5. An Early Flux Compression Generator

The central copper cylinder is cut by a long slit, so that it is not initially a closed conducting surface and currents cannot circulate around its circumference. Flux cannot be conserved. When the remote capacitor bank is discharged and current runs through the solenoid, an initial magnetic field is easily established inside of the cylinder. Detonating the high explosives compresses the cylinder, and the slit closes. It is now a closed surface that conserves the flux. As described in the text, the magnitude of magnetic field inside the cylinder increases rapidly.

ultrahigh currents are created. A flux compression generator may use a hollow metal pipe instead of a loop, and a portion of an external field will go down the center of the pipe. High explosives, arranged symmetrically around the pipe, are detonated, and the pipe is rapidly compressed by the pressure of the explosion. The pipe wall collapses towards the axis. On the short time scale of the explosion, the flux is approximately conserved and remains relatively constant as the pipe cross section shrinks (Figure 4). The flux is "compressed" because the same amount of flux now occupies a significantly smaller area. To maintain the total flux, the magnetic field strength gets greatly enhanced, and that increasing magnetic field, in turn, generates a large current in the collapsing wall.

The high explosive plays a dual role in this scheme. First, it collapses the conductor so quickly that flux conservation is approximately true. Second, it is a source of energy. Energy is stored in a magnetic field and the amount of energy is proportional to the square of the field magnitude (B^2). Because the field magnitude increases, the energy content must also grow. That energy comes from the chemical energy stored in the molecular bonds that make up the explosive material. When the explosives are detonated, energy is released and does work on the conducting surface, so that it collapses. The conductor, in turn, does work on the field by compressing the flux, and the ultimate repository for the released chemical energy is the magnetic field itself.

Regions of high energy density want to expand and equilibrate with regions of lower energy density. A magnetic field of high energy density will, therefore, exert a physical pressure against any barrier that is trying to contain or exclude that field. The magnetic pressure also scales as B^2, and for the huge fields created by these flux compression generators, that pressure is enormous. A 1-megagauss field exerts a pressure of about 40,000 bar (a bar is about

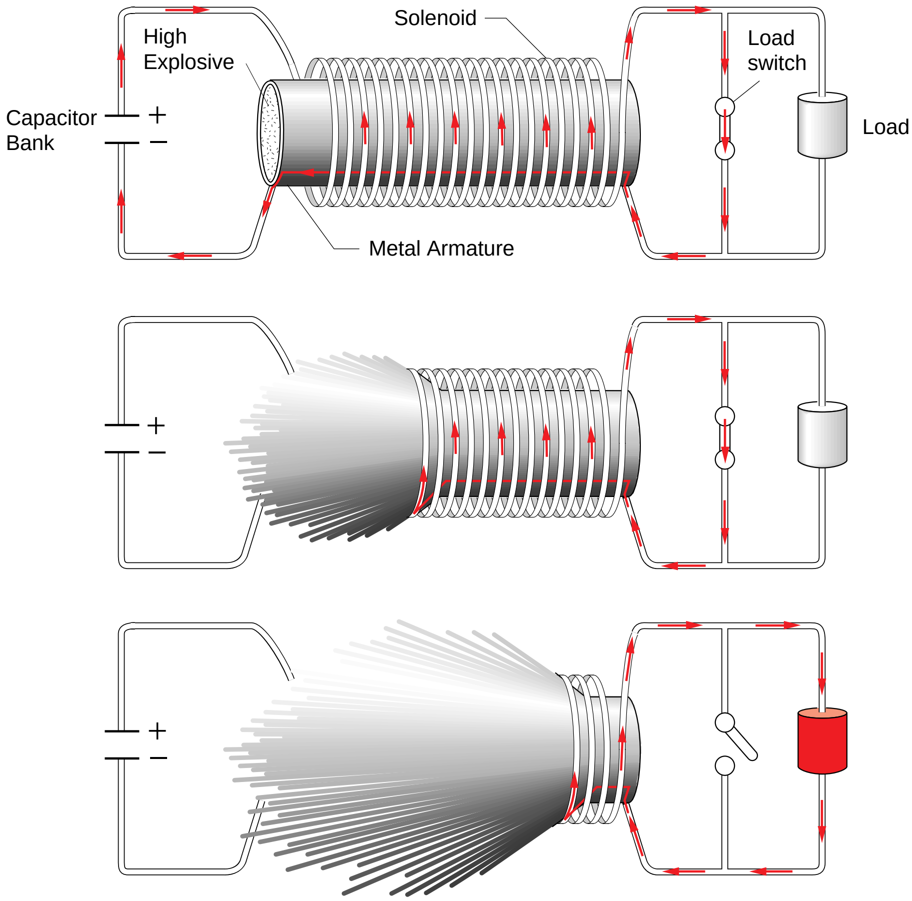


Figure 6. Helical generator

A helical generator has a long metal armature that is packed with high explosive and placed within a solenoid. As the capacitor bank discharges, the current generates a magnetic field in the space between the solenoid and the armature. The load switch is initially in the closed position, preventing the current from flowing through the load.

The explosive is detonated at one end, and the armature expands—like inflating a long balloon. The volume between the solenoid and the armature decreases in both the radial and longitudinal directions. This causes the magnetic flux to be compressed. Flux conservation results in an enhanced magnetic field, which induces a large current in the remaining loops of the solenoid.

At peak flux compression, the load switch is opened, and a greatly enhanced current is delivered to the load.

14.7 pounds per square inch), which will easily cause metals to buckle and deform. Between 1 and 2 megagauss, the pressure will cause the surface of a conductor to liquefy and vaporize. Above 2 megagauss, the vaporization occurs so rapidly and violently that the surface of a conductor is blasted off and shock waves penetrate into the material. A 10-megagauss magnetic field exerts on a conducting surface a pressure of 4 megabars, or 60 million pounds per square inch! This is larger than the pressure values existing in the center of the Earth (3.7 megabars).

Figure 5 shows the type of flux compression generator built by Robert Lyudaev. This device is very similar to a design published by Fowler and his Los Alamos team in the proceedings of a 1961 conference on high magnetic fields (see Further Readings, page 66, third reference). The device used a solenoid to establish an initial magnetic field inside a copper cylinder, and the cylinder was then imploded. The flux was compressed inside the metal cylinder, and the initial field was amplified by a factor of 10 or more. The peak value of the resulting transient magnetic field was estimated to be about 1.5 megagauss.

Fowler's and Lyudaev's early generators, as well as Pavlovskii's MC-1 generator, were intended to use the high magnetic field directly on an experiment that was placed within the central cylinder of the device. But as previously mentioned, the high magnetic field induces a large current in the collapsing conductor, and that current can be the intended output of the generator. In general, the design of a generator will differ depending on whether it is to deliver a high magnetic field or high current to the experiment. A helical generator, shown in Figure 6, is designed to deliver high current to a load located outside of the explosive region of the device. Often, helical generators are used as the first stage in a multistage flux compression scheme. The high output current is used to establish a new, very high initial magnetic field in a second generator.

Before leaving this section to discuss the various experiments, there is one final point to be made. These experiments are true one-shots deals. The generators work because high explosives are detonated, and therefore, the entire experiment must be completed in substantially less than a millisecond, after which time the generator and most of the experimental apparatus is completely destroyed. This places stringent conditions not only on the type of phenomena that can be investigated, but also on the reliability and predictability of the generator and experiment diagnostics. One does not have a second chance.

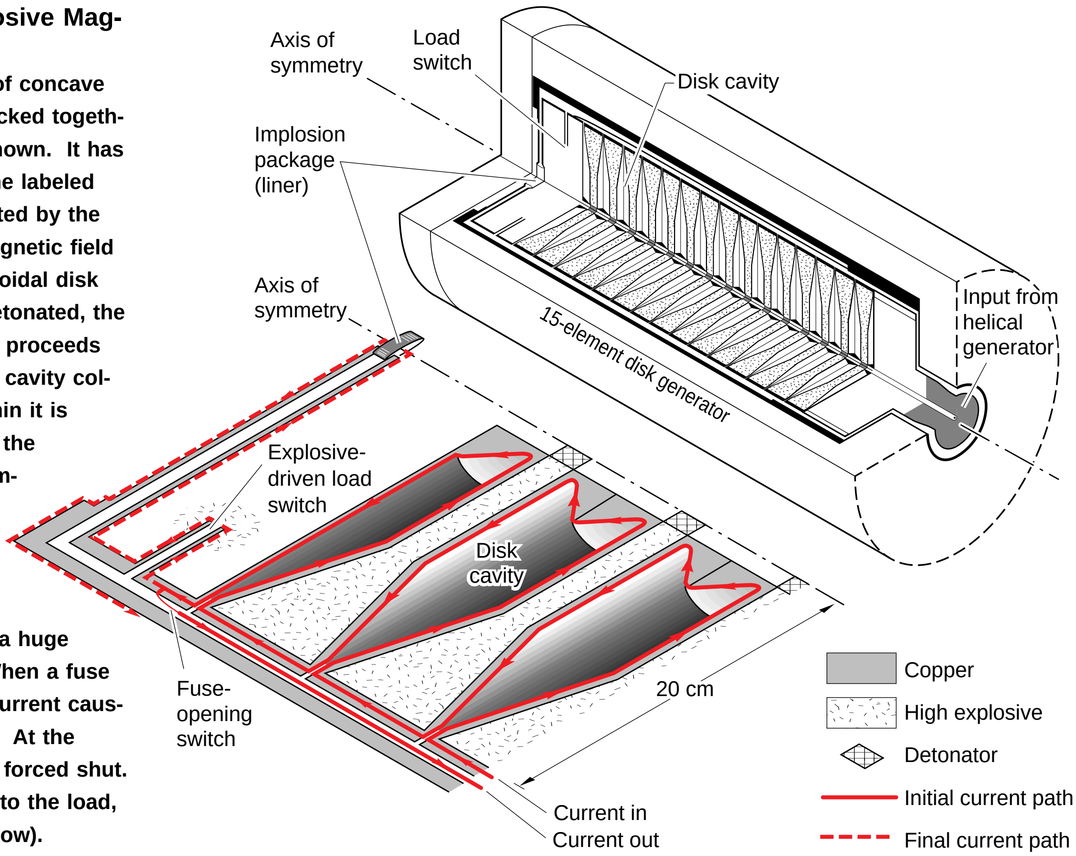


Figure 7. The Disk Explosive Magnetic Generator (DEMG)

The DEMG consists of pairs of concave conducting disks that are stacked together. A device of 15 disks is shown. It has cylindrical symmetry about the labeled axis. Current flows as indicated by the red line, and an azimuthal magnetic field is established within each toroidal disk cavity. When the DEMG is detonated, the explosion begins on axis and proceeds radially outward. As the disk cavity collapses, the magnetic flux within it is compressed and pushed into the thin region at the outer circumference of the device. That region is bounded by conducting surfaces, so when the flux density within that space rapidly increases, a huge current is induced to flow. When a fuse opening switch is used, the current causes the fuse to melt and open. At the same time, the load switch is forced shut. The current is then delivered to the load, which is often a liner (see below).

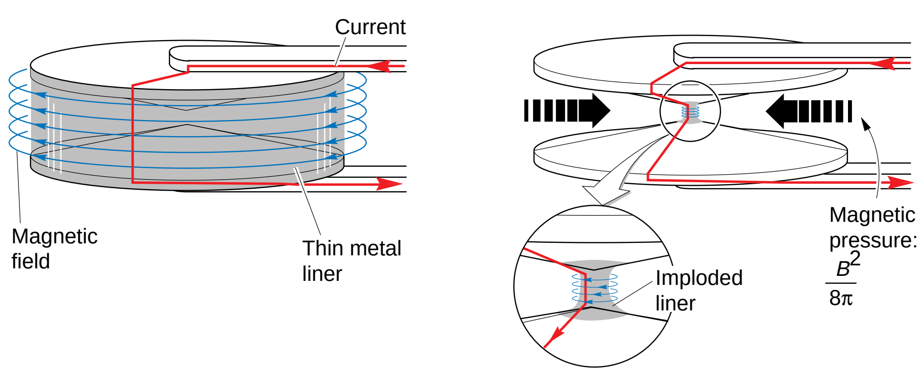


Figure 8. Implosion of a Liner

A liner is a hollow cylinder made of metal. Initially, there is no magnetic flux inside the cylinder. When an intense current pulse from a generator (represented by the single red line) passes down the walls of the liner, a large magnetic field is created. The inside of the liner remains at zero field due to flux conservation and field exists only on the outside. The magnetic pressure drives the liner inward.

The DEMG

The first scientific experiment conducted jointly by the nuclear-weapons laboratories of the United States and the Russian Federation occurred at a high-explosive facility at Arzamas-16 on September 22, 1993—the day after President Yeltsin sent tanks to surround the Russian White House. (The Los Alamos contingent, consisting of all the authors except Max Fowler, plus Lynn Veeser, Pat Rodriguez, and Jim King, tried to ignore the growing political crisis as they completed the final preparations for the experiment.) The objective of the experiment was to verify the performance of the unique high-current generator, the Disk-Explosive Magnetic Generator (DEMG) developed by Chernyshev, that could potentially be used for the MAGO plasma compression experiments, as well as other high-energy-density physics experiments.

The DEMG has no counterpart in the United States, and its properties and operation were unknown. Although small models of the DEMG had been briefly described at the Megagauss-III conference (1983), it was not until Megagauss-V (1989) that the full power of the DEMG was revealed.

The device, shown in Figure 7, has cylindrical symmetry and consists of a series of concave conducting disks that are stacked together in pairs, like opposing pie pans. Magnetic flux is trapped in the space between two disks. Detonating the DEMG collapses the disks, and the magnetic flux is compressed into a thin region bounded by a conducting cylinder. The enormously compressed magnetic flux generates a huge current in that conducting surface, and this current can be delivered directly to the experiment or "stored" for subsequent, rapid delivery to the experiment using a fast-opening switch.

For the 1993 DEMG test, a capacitor bank provided the initial current to create a magnetic field in a helical generator. The helical generator amplified the capacitor's output current of approximately 20 kiloamperes to the 6-megampere current required to power the main DEMG. That device had fifteen disks of 0.2 meter radius. It was to generate some 60 megamperes and deliver as much as 35 megamperes to a cylindrical aluminum liner, 2 centimeters long and 6 centimeters in diameter.

A high current pulse sent down the liner creates a large magnetic field that, for a short time only, exists on the outside of the liner wall (Figure 8). The large magnetic pressure drives the liner inward at huge velocities (up to hundreds of kilometers per second for very light liners). Diagnostics placed inside the liner at different azimuthal angles or different axial positions can detect the liner's arrival, and hence, measure the symmetry of the implosion. The liner can be in a solid, liquid, or plasma state as it implodes, depending on the amount of heat generated by the current and field. Shock wave phenomena, hydrodynamics, and material properties can all be studied with this type of electrical load. For this experiment, the liner was simply a well-understood and convenient diagnostic.

To improve the timing of the current delivery, a thin metal fuse was added that initially allowed the DEMG output current to be diverted away from the liner. When the current reached a critical value, the fuse melted. The high current was then delivered to the liner in less than 1 microsecond.

The rate of change of the current and pulse shape were measured at various points along the DEMG using VNIIEF-built probes (mostly tiny pick-up coils called B-dots, which measure the rate of change of the magnetic flux produced by the current). Los Alamos fielded two current probes (Faraday rotation probes, described in the following section) that allowed a more precise measurement of the DEMG's performance than had been previously achieved. The result of the experiment, shown in Figure 9, agrees with model predictions calculated using Los Alamos codes and parameters provided by the Russian scientists. But a probe located near the liner indicated that there was a partial failure in a transmission line, so that only 20 megamperes of the DEMG output was delivered to the load.

Still, the disk generator worked as the Russians had described in the literature, and this first collaborative experiment helped allay many lingering suspicions that existed within both camps. What remained was an atmosphere of enthusiasm, for it was clear that after years of parallel but separate research, scientists with similar backgrounds, interests, and goals were working together.

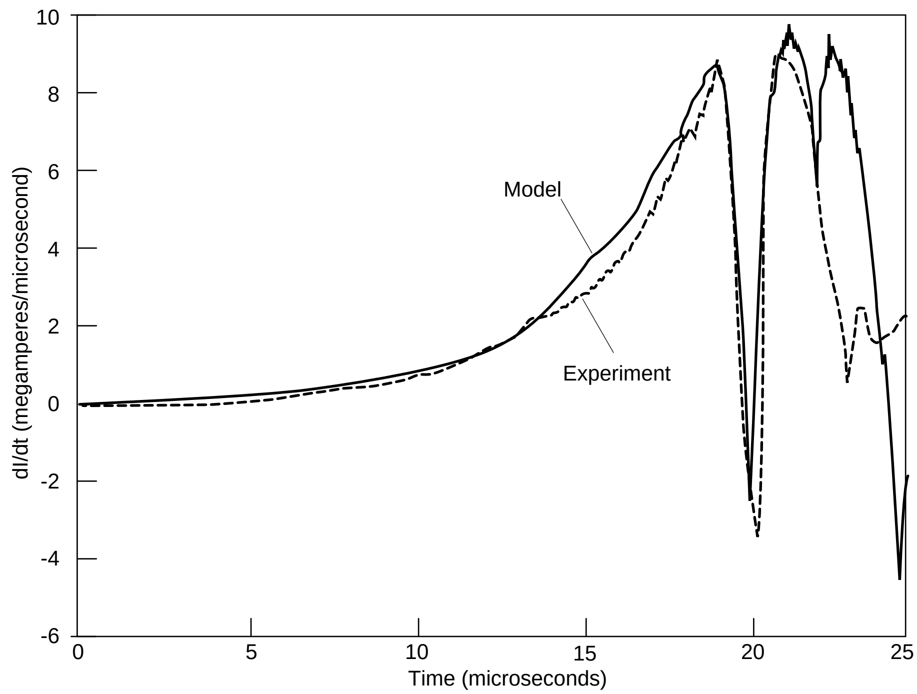


Figure 9. Output from the DEMG

The rate of change of current was measured by a probe that was located near the transmission line that led to the load. Although there are some discrepancies in the late time behavior, clearly the DEMG worked as predicted. The theoretical curve is from a Los Alamos computer model developed by Bob Reinovsky, which was run using input parameters provided by the Russian pulsed-power group.

Measurement of the Critical Field of YBCO Superconductor

At the end of 1993 and two months after the DEMG experiment was performed at Arzamas-16, a group of eight Russians came to Los Alamos, bringing with them five MC-1 generators that had been purchased by Los Alamos as part of the November 1992 agreement. The MC-1s (Figure 10) were used in a series of experiments to measure a key parameter of high-temperature superconductors. Unfortunately, the principal developer of the MC-1, Alexander Pavlovskii, had died in February of 1993 and did not live to see come to fruition the collaboration for which he had worked so hard.

A superconductor is a material that

when cooled below a certain critical temperature, T_c, experiences a sudden drop in its electrical resistance to immeasurably low values, and a direct current moving through a superconductor flows with no energy dissipation. How and why superconductivity occurs was described by Bardeen, Cooper, and Schrieffer in 1957 when they published a detailed microscopic theory of superconductivity.

The cornerstone of the BCS theory is that, below T_c, electrons with equal but opposite momentum and opposite spin form what is called a Cooper pair. By forming a pair, the two electrons lower the sum of their total energy, and thus, pair formation is energetically favorable.

Below T_c, a macroscopic number of electrons condense into paired states with total spin zero. This means that the pairs obey Bose statistics, and the entire ensemble of Cooper pairs can occupy the same quantum state and exhibit collective behavior. It is the collective behavior of the Cooper pairs that leads to resistanceless current flow, often called supercurrent flow.

To understand the supercurrent, first consider the normal current flow due to unpaired electrons moving through a material's crystal lattice. The electrons will scatter from atomic defects in the lattice and lose energy. An analogy is to consider the defects as bumps in an otherwise smooth road, and to consider the free electrons that make up the normal current as cars driving down the road. Each time a car encounters a bump, it slows down or changes direction. The cars encounter "resistance" to their movement.

In the collective state, the cars are all jammed together, front-to-back and side-to-side, forming a pack. Within the pack, cars are linked together as "Cooper pairs" (although the cars forming the pairs are not necessarily right next to each other). The entire pack speeds down the road, each car moving with the exact same velocity as all the others. Small bumps cannot affect the momentum of this single, collective "state," and the cars move down the road without resistance.

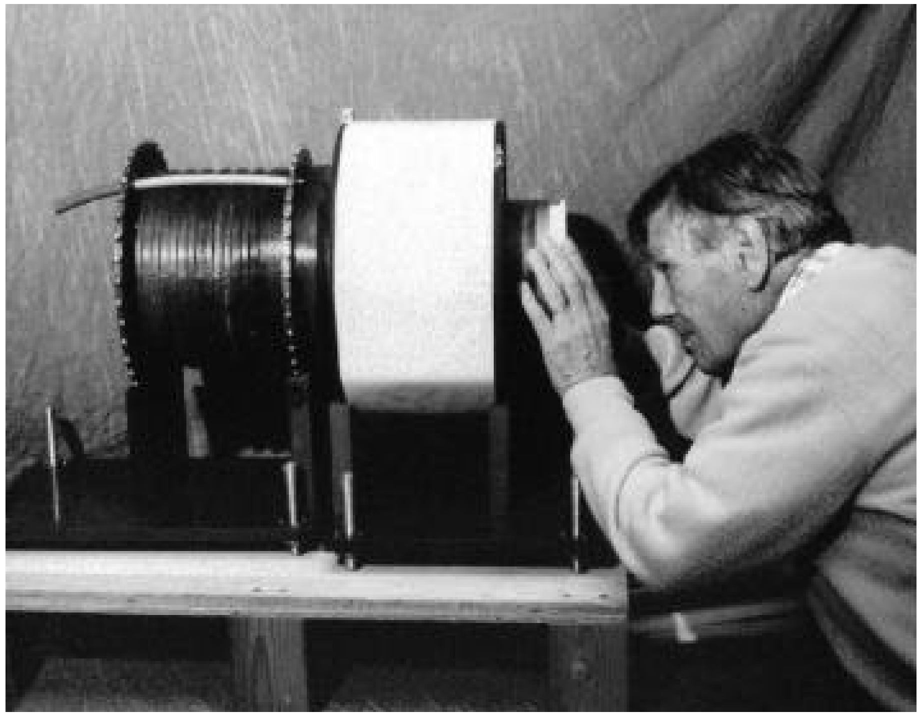


Figure 10. The MC-1 Flux Compression Generator
Max Fowler peers into the central region of an MC-1. The white ring is a mock-up of the high explosive that surrounds the central solenoid. Current is carried to and from the solenoid along numerous cables, although only a single cable is shown.

Analogies not withstanding, the collective state can be broken. The attractive interaction binding Cooper pairs together is very weak, and above the temperature of absolute zero, thermal energy is often sufficient to cause pairs to break. As the temperature of the material rises, the number of Cooper pairs decreases, until above T_c, all Cooper pairs are broken and a normal current flows through a resistive material.

A magnetic field can also destroy the superconducting state. Above a few hundred gauss, magnetic fields will penetrate most superconductors in the form of quantized vortices, which are circular tubes of circulating supercurrent. At the core of the vortex, superconductivity is suppressed over a radius termed the "coherence length," which is roughly equal to the size of the Cooper pair. As the applied magnetic field increases, the density of vortices increases proportionally.

At an external field value referred to as H_{c_2}, the cores overlap and the superconducting state is destroyed throughout the entire sample. Thus, H_{c_2} establishes the highest field in which a superconducting device can be operated without reverting to the "normal" resistive state. From an engineering standpoint, establishing the magnetic field dependence of a superconductor is extremely important. From a research standpoint, H_{c2} is related to the size of the vortex core or the coherence length, and knowing its value and temperature dependence, $H_{c_2}(T)$, is of great theoretical interest.

Prior to 1986, all of the conventional superconductors had to be operated at or near liquid helium temperature (4.2 kelvins), and that required expensive refrigeration technology. The highest T_c that had been observed in any superconductor was 23 kelvins for the compound Nb_3Ge, which has an H_{c_2} of 0.4 megagauss.

In 1986, a new class of superconductors, the "cuprates," was discovered that were based on a layered structure

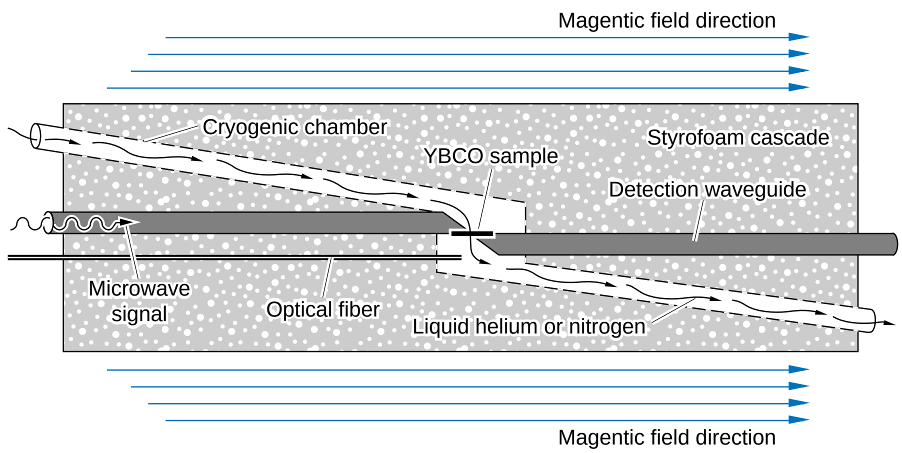


Figure 11. Schematic of the Critical-Field Experimental Setup
A styrofoam cylinder, placed within the center of the MC-1, held the entire experiment. A channel cut into the styrofoam formed a conduit for the delivery of cryogenic fluids that cooled the sample. The temperature was adjusted by changing the particular cryogen. The plastic waveguides directed a millimeter-wave signal to the YBCO sample for the detection of the superconducting to normal phase transition. The field was measured by both optical (Faraday rotation) and inductive (B-dot) probes.

of copper-oxide sheets separated by non-superconducting layers. The cuprates exhibit T_c's extending far above liquid nitrogen temperature (77 kelvins), a much easier temperature to maintain. The present record T_c of 135 kelvins is held by a mercury-cuprate compound. The potential for application of these high temperature superconductors in motors, generators, and high-field solenoids that can operate more economically at liquid nitrogen temperature is enormous.

Naturally, there is a great interest in measuring the critical field for these new cuprate superconductors. However, for compounds with critical temperatures above 90 kelvins, critical magnetic fields have been observed to exceed 0.3 megagauss at temperatures near 70 kelvins. That magnetic field is approximately at the limit of presently available direct current magnet technology. Since H_{c_2} only increases as the temperature plunges towards absolute zero, a measurement of the critical field at lower temperature values has not been possible.

Thus, the value of $H_{c_2}(T)$ was more than just idle curiosity. The model outlined above for how a magnetic field destroys superconductivity is quite general and has been experimentally verified in detail for the conventional superconductors and, in many respects, for the new cuprates. However, there is yet no established theory for the microscopic mechanism of superconductivity in the cuprates, and there is growing evidence to support the idea that there are fundamental differences with low temperature superconductivity. Recent experiments indicate, for instance, that Cooper pairs in the cuprates may have nonzero orbital angular momentum, in contrast to the BCS model and to the established behavior of conventional compounds. This difference could affect the detailed functional form of $H_{c_2}(T)$ at high fields. In addition, there have been predictions of novel magnetic structures developing at high fields that differ from the usual vortex lattice structure. It is clear that a determination of $H_{c_2}(T)$ over the range from T_c to low temperatures and in fields of several megagauss will be important in answering these questions.

The Los Alamos-Arzamas-16 collaboration was interested in directly measuring $H_{c_2}(T)$ for a YBCO (Yttrium-Barium-Copper-Oxygen) high-temperature superconductor as a function of temperature, data that previously could not be measured because of the high critical field value. A sample of the YBCO material was placed along the axis of the MC-1 generator. A flow-through cryogenic system maintained the sample at a predetermined temperature between 4 and 80 kelvins. For a given fixed temperature, the state of the material would be monitored while the magnetic field strength was continuously measured as it increased. At the critical field, the superconducting sample went normal.

The transition to a normal state was heralded by the appearance of a millimeter-wave signal at a receiver. When superconducting, the ceramic YBCO sample reflects electromagnetic radiation at millimeter wavelengths, but the radiation passes straight through the material when it is normal. As seen in Figure 11, the sample was sandwiched between two plastic dielectric waveguides. The probe waveguide brought a 4-millimeter wavelength (75 GHz) signal to the 0.15-micron thick YBCO sample. When the sample went normal, the radiation passed through the material, entered the detection waveguide, and was detected by a receiver.

Magnetic field values were measured with both B-dot pickup coils and with optical probes. An optical probe makes use of the Faraday effect, in which the plane of polarization of polarized light is rotated as it passes through an optical element situated in a magnetic field. The amount of rotation is proportional to the field strength. A polarized laser beam was transported to and from a cylinder of flint glass (the optical element) by fiber optic cables, and a comparison of the plane of polarization between the outgoing and the incoming laser beams measured the magnetic field.

To complement the high field, low temperature measurements, two additional experiments were performed at higher temperatures using low field generators built by Los Alamos. Figure 12 shows the four data points that were generated. At the lowest temperature, about 4 kelvins, the criti-

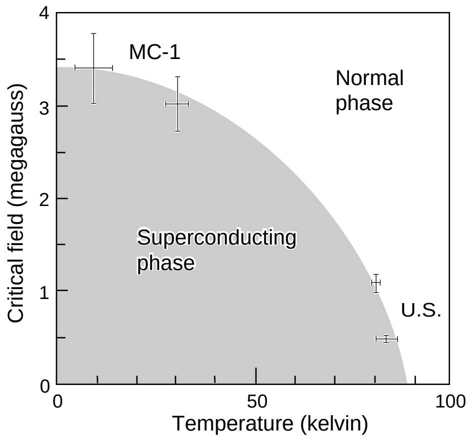


Figure 12. Critical Field of the YBCO Superconductor
The critical field, H_{c_2}, for the YBCO superconductor is plotted versus temperature. The critical temperature, T_c, for this material is about 90 kelvins. The border of the shaded region was drawn by hand to help guide the eye and is not a fit to the data. The temperature dependence roughly follows that of metallic, low temperature superconductors: $H_{c_2}(T) = H_{c_2}(0)[1-(T/T_c)^2]$, where $H_{c_2}(0)$ is the critical field at absolute zero.

cal field was over three megagauss, more than six times the peak field achievable in prior laboratory experiments. The seven collaborative experiments mapped out the curve of the critical field over the full temperature range. The data provides valuable information for theorists and experimentalists studying this material.

Fowler and Bruce Freeman of Los Alamos led the American team of more than two dozen scientists in these challenging experiments. This effort was the first time that Russians—let alone Russians from a nuclear weapons institute—had worked "behind the fence" at Los Alamos. Although most of the generators were Russian (Pavlovskii's MC-1 generator), the high explosives that powered them were American, and Los Alamos explosives engineers had to learn how to load the special "Russian initiator blocks" that served to detonate uniformly the exterior of the main explosive charge.

Hot Magnetized Plasmas

The third series of experiments, which were initiated at Arzamas-16 in April 1994, was the start of our collaboration on the MAGO thermonuclear fusion scheme. This was the topic that was originally proposed by Chernyshev and Mokhov in September of 1991. The goal of this series was to investigate the first step of the MAGO scheme, that is, the production of a hot, magnetized plasma that could potentially be imploded to thermonuclear fusion ignition conditions.

Fusion is the process by which two light atomic nuclei combine to form a heavier nucleus. But fusion does not normally occur under the conditions found here on Earth. All nuclei are positively charged, and as the familiar maxim states, like charges repel. Each nucleus is surrounded by a Coulomb barrier that normally prevents the nuclei from coming too close to each other.

But in the same way that a speedy bullet can pass right through a thick wall, nuclei moving at extreme speeds have sufficient energy to penetrate through the Coulomb barrier. A collision between intensely energetic nuclei will bring them so close that they feel the strong attractive nuclear force. The two nuclei will come together, fuse, and form a heavier composite nucleus.

As illustrated in Figure 13, a deuterium (D) nucleus and a tritium nucleus (T), two of the lightest nuclei available, will fuse to form an isotope of helium (^{5}He). That composite nucleus quickly decays into a neutron and an alpha particle (a ^{4}He nucleus). There is a large net energy release from the reaction, and both the alpha particle and the neutron fly off with a considerable amount of kinetic energy.

Because energy is released, scientists have long recognized the potential of fusion to be the basis for a commercial energy source. But realizing that potential has proven to be remarkably difficult. For decades, scientists have been frustrated in their attempts to advance beyond even the first critical step in energy production, which is achieving a self-sustaining, thermonuclear fusion reaction.

In thermonuclear fusion, the "fuel" for the reaction is a plasma (a state of matter consisting almost entirely of ions and electrons) that is heated to millions of degrees. That plasma temperature is a measure of the average kinetic energy of the ions and electrons. Because the particle energies are distributed according to a Maxwell-Boltzman distribution, a tiny fraction of the ions have energies that are much higher than the average energy. For all present day thermonuclear fusion schemes, the initial plasma temperature is such that only those few nuclei at the extreme high energy tail of the thermal distribution are sufficiently energetic to overcome the Coulomb barrier and fuse.

Energy is released by those early fusion events in the form of fast moving particles. If those particles are captured

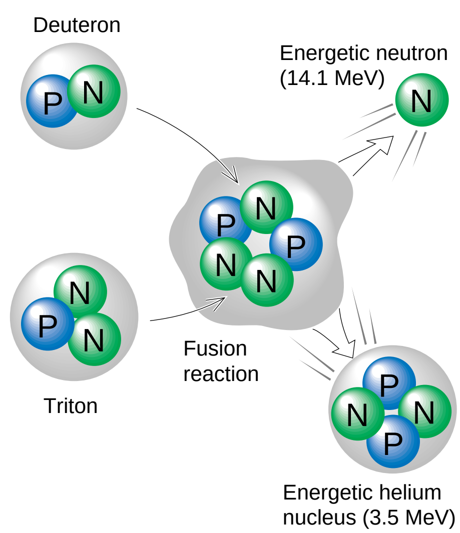


Figure 13. Thermonuclear Fusion
Einstein's famous equation, $E = mc^2$, relates mass to energy. The sum of the deuteron and triton rest masses at the start of the fusion reaction is actually more than the sum of the alpha particle and neutron rest masses after the reaction has finished. As a result of fusion, some mass is converted into energy, and that energy is imparted to the reaction products. Both the alpha particle and the neutron emerge from the fusion event with a significant amount of kinetic energy.

The magnetic force on a charged particle is directed at right angles to both the magnetic field and the particle's velocity.

A charged particle with a velocity that is entirely in the plane perpendicular to a uniform magnetic field moves in a circle.

A particle with a velocity component that is parallel to a uniform magnetic field spirals along the field line, which acts as a guiding center for the particle motion.

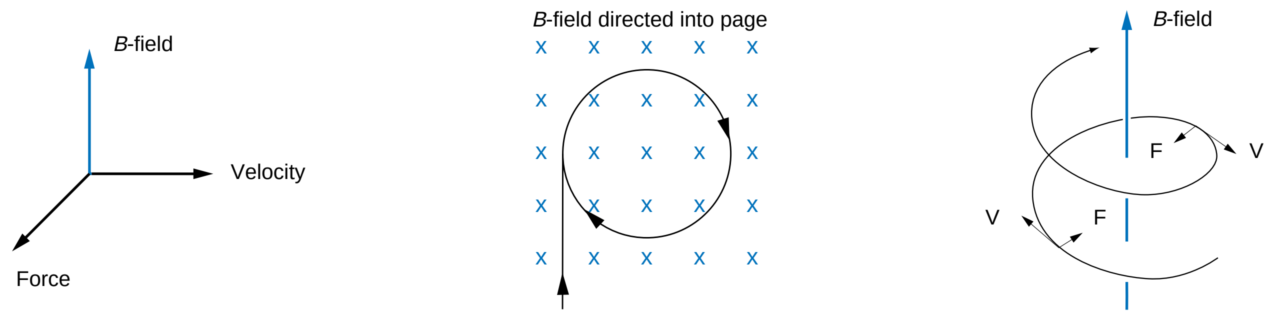


Figure 14. Motion of a Charged Particle in a Magnetic Field

When a plasma consisting of bare atomic nuclei and electrons is subjected to a magnetic field, the individual particles will spiral about the field lines. Stronger fields exert more force and the motion is a tighter spiral. Because the particles follow the field lines, magnetic fields can be used to contain a plasma and increase the particle confinement time.

and become part of the plasma, the energy released by early fusion events will go into increasing the plasma temperature. The number of energetic nuclei will increase, and the probability that two nuclei fuse will go up. The fusion reaction can become self-sustaining.

Unfortunately, there are always energy losses that cool the plasma and kill the fusion reaction. Plasma particles are in constant motion, and each time an electron scatters and gets accelerated by an ion, energy is radiated away (as continuum radiation, also known as bremsstrahlung). The plasma cools. To maintain the temperature, enough energy must be pumped into the plasma, either by initial fusion events or externally, to counteract those losses.

Because the energy gained by fusion and the energy lost through bremsstrahlung both have a temperature dependence, equating the two allows calculation of an “ignition” temperature, above which the plasma temperature is maintained and the fusion reaction becomes self-sustaining. For the DT reaction, the ignition temperature is about 4000 electron volts, or about 45 million degrees (one electron volt corresponds to about 11,600 kelvins).

Other loss mechanisms cool the plasma, but they are more amenable to experimental control. One is the loss of ions or electrons from the hot plasma. These carry energy away and the plasma cools. A second loss mechanism involves contaminants of “heavy” impurity ions, such as aluminum or iron, that increase the rate of bremsstrahlung, and again the plasma cools. If enough impurities are present, one can never win in the energy balance equation, and ignition can never be reached. Because impurities are nearly always present due to the outgassing of walls and insulator materials that comprise the plasma chamber, minimizing impurities has been a major challenge to all fusion schemes.

Even in this simplified picture of thermonuclear fusion, it is clear that constructing a system that is designed for getting useful power from fusion is a difficult undertaking. One wants a system that sustains a high particle collision rate for a long a period of time. But in any real system, these are often conflicting demands. For any given temperature, the collision rate can be increased by increasing the plasma density. But a high-temperature, high-density plasma exerts an outward pressure, and the higher the density, the more difficult it is to keep the plasma confined.

By making general assumptions about how much energy will be produced by a plasma and how much energy will be lost by that plasma, one can arrive at minimum conditions for achieving useful power. The product of the density, n, and the plasma confinement time, τ, that is, $n\tau$, is the relevant parameter, and the Lawson criterion states that a minimum value for $n\tau$ be approximately 10^{14} sec-cm^{-3}. There is little hope of achieving power from fusion unless the criterion is satisfied.

In the United States, fusion research has proceeded mostly along two paths. The first approach involves using a toroidal, or donut-shaped, reaction vessel, called a tokamak, to confine a low density ($n \sim 10^{14}$ cm^{-3}) plasma. High currents are sustained within the plasma that heat it to ignition temperatures. As shown in Figure 14, a charged particle will spiral around a magnetic field line. Within the tokamak, magnetic fields are created that twist around the interior of the torus. The field lines form closed surfaces, which the plasma particles are constrained to follow. In principle, the plasma is confined forever. Dynamical instabilities actually limit the confinement time τ to 0.1 to 1 second, but this is sufficiently long to balance the low particle density and bring $n\tau$ to within the range of the Lawson criterion. Generally, the tokamak is considered to be the most promising method for achieving fusion, and worldwide, billions of

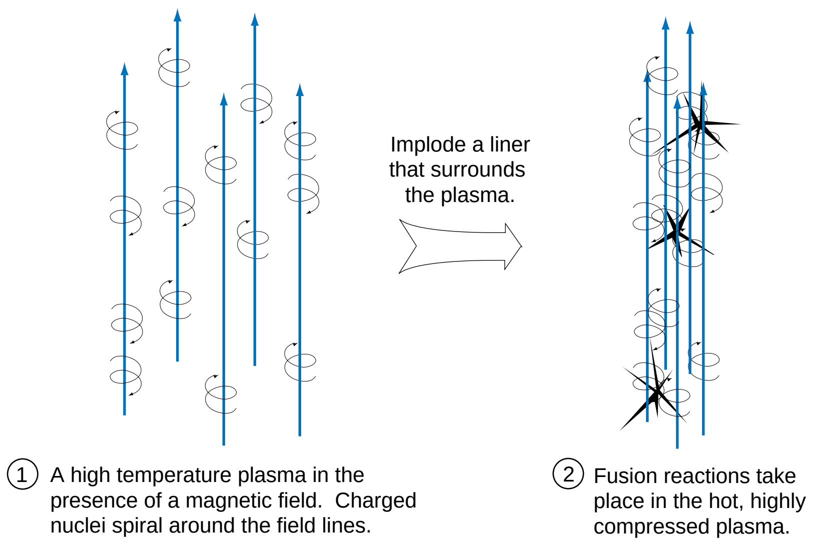


Figure 15. The MAGO Two Step Process

In the first step of MAGO, a DT gas inside of a thin liner is heated and ionized to a plasma in the presence of a magnetic field. The plasma particles are constrained to follow the magnetic field lines. In the second step, the liner surrounding this "magnetized" plasma is imploded, and the plasma gets compressed. The higher particle density results in an increased collision rate, which leads to more fusion events. The magnetic field reduces thermal energy losses and potentially helps capture the 3-MeV alpha particles that are released from D-T fusion events. If other thermal losses can be minimized, the plasma temperature may increase and reach ignition.

dollars have been invested in building, understanding, and developing these large and highly complex reactors.

The other mainline approach to thermonuclear fusion, vigorously pursued in the United States, is inertial confinement fusion (ICF). In an ICF scheme, a sphere of solid deuterium and tritium is subjected on all sides to an imploding force that drives the DT fuel inward. The severe compression creates a hot, high-density plasma and results in fusion reactions. However, there is no way to confine the plasma once it is created, and the heat of the initial fusion events tend to expand the sphere and cool the plasma before ignition temperature is reached. It is only because the implosion occurs so quickly (in billionths of a second) that the inertia of the inwardly moving fuel is able to hold the sphere together and maintain the temperature. The confinement time, τ, is on the order of only 10^{-11} seconds, which is balanced by the very high particle density ($n \sim 10^{24}$ to 10^{25} cm^{-3}).

So far, the most successful imploding force has been created by using laser pulses generated by the huge NOVA laser located at Lawrence Livermore Laboratory, or by the OMEGA laser located at the University of Rochester. However, an even more powerful implosion is needed to bring the plasma to ignition. It is hoped that the next-generation laser, to be built at the National Ignition Facility, will produce the required power.

An alternative approach to thermonuclear fusion, one that used elements of both the tokamak and the ICF approaches, was proposed by Andrei Sakharov (who incidentally helped elucidate the principles of the tokamak). He considered creating a high-temperature, DT plasma in a strong magnetic field so that the charged ions and electrons were "stuck" to magnetic field lines, as in a tokamak. The field would prevent energetic electrons from leaving the plasma and thus help reduce themal losses.

The hot, "magnetized" plasma would then be imploded by an external force as in an ICF scheme (Figure 15). The implosion would heat and compress the relatively dense plasma, and the strong field would help capture the energetic alpha particles produced during the fusion events. The approach could potentially simplify the apparatus required to bring about ignition.

The Russian scientists call this fusion concept MAGnitnoye Obzhatiye, or magnetic compression (MAGO), whereas the U.S. researchers refer to it as Magnetized Target Fusion (MTF). To implement the scheme, VNIIEF invented a novel, two-section chamber that produced a hot magnetized plasma by means of hypersonic flow (Figure 16). A gas mixture of DT is introduced into both sections of the chamber. Two current pulses sent through the chamber cause a portion of the DT gas in one section to become ionized and then propelled through a nozzle so that it enters the second section at a very high velocity. The effect of the abrupt collision between this plasma, moving at hypersonic speeds, and the relatively static gas in front of it is to raise the temperature of the gas rapidly to several thousand electron volts. This newly formed, extremely hot plasma quickly equilibrates to a temperature of several hundred electron volts, at which point it is a large volume, relatively dense, hot plasma, referred to as the target plasma in Figure 16.

In a full MAGO fusion scheme, the target plasma would be surrounded by a thin liner. Another current pulse, sent down the walls of the liner, would create a magnetic field that implodes the liner. This action would compress the plasma and potentially bring it to ignition conditions. (Figure 16 shows the chamber that was used for the plasma formation tests. In compression experiments, the chamber would be modified by replacing the thick, stationary outer wall with a thin liner.)

Producing the target plasma is the

intriguing aspect of the MAGO scheme, and the Arzamas-16 scientists presented some neutron data as evidence that the plasma had been created. The initial plasma temperature of several thousand electron volts is sufficient to initiate a burst of thermonuclear reactions, so that even without further compression, a small fraction of the plasma produced on the order of 10^{13} neutrons. Although those neutrons were simply a by-product of the plasma formation method, ironically, this neutron production was comparable to the highest ever achieved in the United States in pulsed-power or ICF experiments.

The objective of the first MAGO experiment, held in April of 1994, was to produce and diagnose the hot, magnetized plasma. The Chernyshev team provided a unique two-pulse helical generator to power the plasma chamber, and Los Alamos brought to Arzamas-16 more than a ton of advanced diagnostics equipment, which included spectrometers, plasma interferometers, and precision current probes. Excellent data were obtained with the U.S. instruments, and the experiment greatly improved our understanding of plasma flow through the nozzle as well as the final temperature and density distribution of the hot, dense plasma.

Still, the effectiveness of a magnetic field in reducing electron losses could not be deduced from that initial experiment. Thus, four more experiments were done by a team of Russian and American scientists at Los Alamos in October 1994. VNIIEF sent two of their two-pulse helical generators and two test armatures to Los Alamos. The first two experiments tested the performance of American explosives in driving the armature of the complex Russian generator. The third was a full MAGO plasma formation shot using the same Russian generator, but pure deuterium was used in the chamber instead of a deuterium-tritium mix. The purpose of that shot was to confirm the electrical performance of the device using Los Alamos explosives and our capacitor bank. The experiment served also to verify the operation of new diagnostics that would be used on the fourth shot.

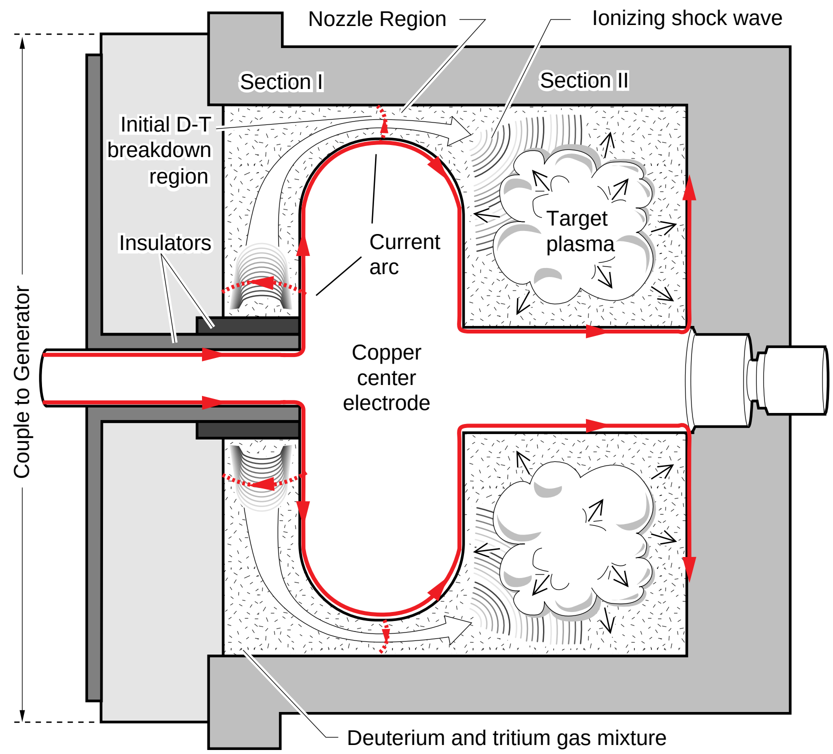


Figure 16. MAGO Two-Section Chamber and Target Plasma Formation
A cross section of the cylindrically symmetric, two-section MAGO chamber. The two sections are joined by a narrow opening that acts as a nozzle. Initially, a DT gas fills both sections. A current pulse of about 2 megamperes sent through the electrode creates a complex magnetic field pattern throughout the entire chamber. A second current pulse, reaching 6 to 8 megamperes, arcs through both section I and the nozzle region and creates a weak plasma. Due to the Lorentz force, this plasma is propelled through the nozzle. When the high-velocity plasma collides with the relatively static gas filling section II, shock waves are produced. These shock waves ionize the bulk of the gas and create a large volume, relatively dense plasma at a temperature of 100 to 300 electron volts. Such a plasma could possibly be compressed to thermonuclear ignition conditions in future experiments. (Figure courtesy of N. Shea, Defense Science)

Fourteen VNIIEF scientists and more than fifty Americans participated in the final experiment. Chernyshev and Mokhov led the Russians, and Reinovsky and Goforth were the Los Alamos shot coordinators. The experiment again used a Russian helical generator along with as complete an array of diagnostics as Los Alamos could provide. Two major neutron diagnostics were fielded. One, based on measurements of the time of flight of the neutrons to the detectors, attempted to obtain an indication of the plasma temperature. The second, based on neutron imaging, attempted to define the precise region from which the neutrons were produced. An array of optical and x-ray spectrometers were designed to provide critical information on the time dependence of plasma temperature as well as the presence of heavy ion impurities in the plasma.

The results of the experiment were very encouraging. The data analysis suggested that a hot, dense plasma had indeed been produced. Significantly, there were also indications that impurities generated in the first plasma chamber were delayed by several microseconds before arriving in the second chamber. This meant that the DT plasma in the second chamber would remain relatively free of harmful impurities and was likely to remain sufficiently hot for the 5 to 10 microseconds required to compress it to ignition conditions.

Another series of experiments at Arzamas-16 are planned to test MAGO/MTF concept. Ultimately, once a plasma has been judged suitable in terms of temperature, density ($n \sim 10^{18}$ cm^{-3}), and purity, the experiments will attempt an implosion using the same type of plasma formation chamber as before and a DEMG to provide the roughly 65 megajoules of energy estimated to bring about ignition. A joint experiment at Arzamas-16, planned for the summer of 1996, will be the first developmental test of the "high-energy" liner that will implode the hot plasma.

Isentropic Compression

The behavior of matter under extreme compression is of interest in terms of understanding phenomena as diverse as the atmospheres of gaseous planets and the structural mechanics of rock deep within the Earth. For example, the properties of materials under extreme pressures is important to geophysicists studying the origin and dynamics of earthquakes. Because many earthquakes occur deep beneath the surface, knowing the shear strength of rock at conditions found there could be important for developing predictive models of earthquakes.

One of the most successful techniques for compressing materials to high pressures is to use a diamond anvil press, which can currently achieve pressures up to about 2 megabars. Above that, a standard technique is to use high explosives to drive shock waves directly through the material. Although ultrahigh densities can be achieved via this technique, the shock waves abruptly jar the material and generate heat as they propagate. Strong gradients and transient effects often complicate the interpretation of data obtained by this method.

An alternative technique for achieving pressures above 2 megabars is to use magnetic pressure to implode a conducting surface that surrounds the sample of interest. The implosion can subject the sample to even higher pressures than are possible with shock wave methods. Because a flux compression generator produces a magnetic field that builds slowly and reaches its peak value after a few microseconds, the pressure increases in a relatively smooth and steady fashion. Thus, shock wave production and sample heating are minimized, and materials can be compressed with a minimum change of entropy (isentropic compression). This simplifies not only the data interpretation, it also opens up the possibility of studying the low-temperature behavior of materials.

Our Russian colleagues at Arzamas-16 had employed isentropic compression to study many different materials at pressures of many megabars. Hydrogen was of particular interest in the early Russian work. At very high pressures, this gaseous element was predicted to undergo a transition to an atomic, metallic phase. It proved to be very difficult to identify unambiguously the atomic phase, because under extreme pressure, hydrogen can form many different molecular phases that tend to obscure the interpretation of the data.

In 1994, we began discussions with the Russians to perform an isentropic compression experiment. Eventually, it was decided that we would attempt to measure the electrical conductivity of solid argon as it was compressed under a peak pressure of over 6 megabars.

Argon solidifies at liquid nitrogen temperatures. Because it is a closed-shell atom, argon is insulating under normal conditions, and even when solidified, the atoms of the crystal retain their monatomic character. Under extreme pressure, however, the atomic orbitals of adjacent atoms are predicted to overlap, which would allow electrons greater mobility, effectively increasing the electrical conductivity. The solid argon is predicted to undergo a transition to a conducting state at about 5 megabars. Any change in the electrical properties of the sample could be attributed to quasi-molecular or many-body behavior.

A preliminary attempt to measure electrical conductivity of the sample failed, however, due to the premature destruction of the current probes. A second experiment, conducted in August 1995, used a simpler current-probe design and very clearly demonstrated a conducting state for argon at pressures between 5 and 6 megabars.

This experiment was the first demonstration of the transition of argon from an insulator to a conductor at high pressure, and it held some surprises. The conductivity was remarkably low, indicating that rather than creating a conduction band of current carrying free electrons, the electrons were tending to "hop" from one atomic site to another. This behavior was unexpected, and thus the experiment has generated some theoretical interest. Future experiments will attempt to achieve even higher pressures, so that the crossover to the metallic phase should be more apparent.

Soft X Rays

Another topic of mutual interest to Arzamas-16 and Los Alamos is the creation of a soft x-ray source. Most pulsed-power sources of x rays are based on the fast implosion of a cylindrical liner. As described earlier, a very light liner driven inward by magnetic pressures can reach fantastic speeds of hundreds of kilometers per second. The interaction with the magnetic field heats the imploding liner and turns it into a moving wall of plasma. When this cylindrical wall of plasma reaches the implosion axis, it collides with itself, stops moving, and converts its kinetic energy into internal heat energy. That hot, stagnated plasma radiates x rays as it cools.

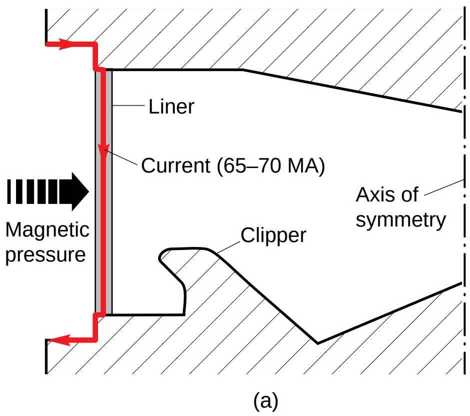
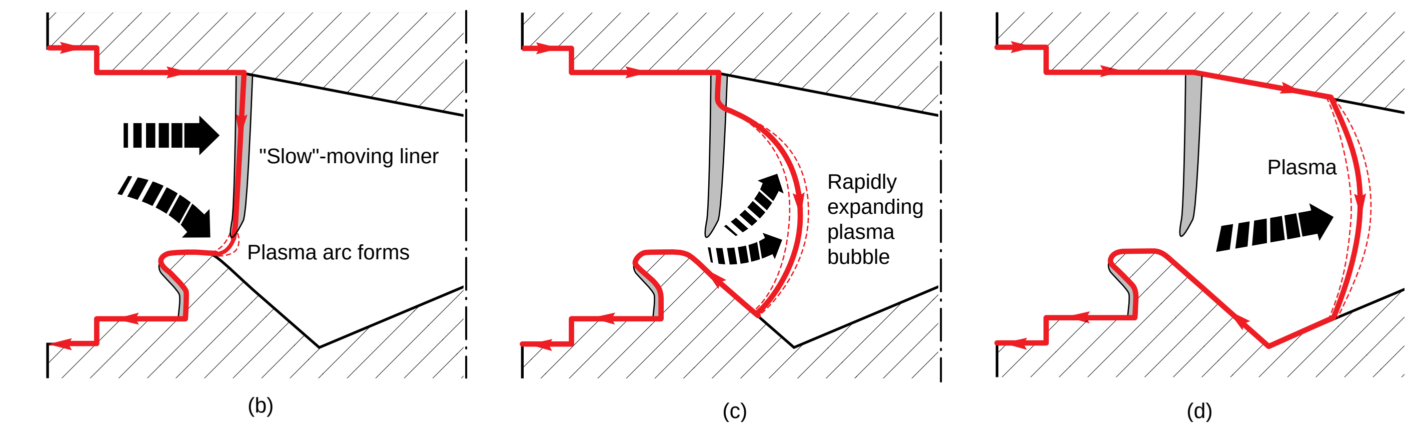


Figure 17. Generation of a Plasma Bubble

The figure shows one half of a cross section through a cylindrically symmetric chamber. a) Current begins to run through the thick aluminum liner. The current generates a magnetic field and the magnetic pressure accelerates the liner inward toward the clipper. b) At peak current, the liner moves past the clipper. The break in electrical continuity causes a "spark," or an arc of plasma, to form between the liner and the wall. c) The magnetic pressure expands the plasma arc into a "bubble." Due to its low mass, the bubble rapidly accelerates towards the implosion axis (the axis of symmetry). d) The remainder of the slow-moving heavy liner stays behind while the bubble races inward. Upon reaching the implosion axis, the plasma collides with plasma coming from other sides of the chamber, stagnates, and emits x rays as it cools.



For the above concept to work, the liner must reach a very high velocity. Otherwise, the total energy in the system is below what is necessary to create an intense thermal x-ray source. In addition, the implosion must proceed with a high degree of symmetry. If some section of the liner is moving faster than the rest, it will prematurely arrive at the implosion axis. Stagnation will occur somewhere off-axis, and the hot plasma will be distributed over a broad, indeterminate region.

Although many ideas have been tried, almost all of them have fallen short of the two criteria mentioned above. More often than not, the limiting factor is the growth of dynamical instabilities that cause the liner to break apart prematurely, so that the implosion is severely asymmetric. But obtaining a very rapidly rising current pulse is also problematic. The current source must deliver all of its energy in the tenths of microseconds before the rapidly moving plasma shell reaches the implosion axis. Designing a fast switch represents a significant challenge for any pulsed-power system.

The Chernyshev-Mokhov team conceived a novel approach to solve these problems. Rather than accelerating a low-mass liner, a magnetic field implodes a large-radius (19 centimeters), "heavy" (0.5-millimeter thick) aluminum liner. The acceleration occurs during the several tens of microseconds that the generator is powering up. When the generator has reached peak current, the liner, now in a liquid state, is cut by a knife-like protrusion called a "clipper." In a manner similar to running a wire through a film of soapy water, the break in the liquid liner causes a "bubble" to form between the clipper and the remaining liner, as shown in the Figure 17.

The bubble is really a section of the liner that is "thinned" to the point that the magnetic forces can ionize it and turn it into a plasma. The magnetic field that was driving the heavy liner now rapidly accelerates this plasma bubble so that it converges upon the axis of the device. The hot plasma stagnates and produces x rays.

The advantage of this scheme is that while the generator is powering up, the heavy aluminum liner is moving relatively slowly, so the opportunity for the growth of instabilities is greatly reduced. After the bubble is formed, its low mass can be accelerated rapidly by the peak field. There are no switches involved. In addition, the surface density of the bubble is much lower than that of the liner, which also helps in the suppression of hydrodynamic instabilities.

After a detailed analysis of the Russian's two-dimensional calculations, we defined a set of Los Alamos diagnostics that would test the key elements of the concept. A microwave interferometer was designed to measure the initial motion of the heavy liner. A set of fiber-optic and magnetic probes measured the progress of the plasma bubble during the fast phase of the implosion. A

DEMG was used to provide the current to drive the heavy liner. This ambitious experiment was conducted in February 1995 at the same firing point where the previous DEMG and magnetized plasma experiments had been conducted.

The results of the experiment were mixed. Los Alamos and VNIIEF analyses suggest that a bubble was indeed formed, although some significant asymmetries appear to have occurred during its implosion. The implosion axis was shifted approximately one centimeter off-center of the DEMG symmetry axis, probably because of a significant azimuthal asymmetry in the density of the plasma bubble that formed. The reason for the density asymmetry is not clear. One possible explanation is that the heavy liner may have had a nonuniform electrical connection to the current source, resulting in nonuniform acceleration. In any case, unless the unpredictable shift can be controlled, the scheme in its present configuration is unusable as an x-ray source because the x rays would be generated from an unknown location.

This experiment highlights the difficult nature of explosive-driven pulsed power research. The results of months of effort culminated in one irreproducible experiment that lasted but a few microseconds. The outcome was not all that had been hoped for, although analyses showed that the imploding plasma may well have had more implosion kinetic energy than presently available in any other concept. Ways of improving the technique and removing the asymmetries may therefore be explored in the future.

The Future

The unprecedented collaboration between the nuclear weapons laboratories at Arzamas-16 and Los Alamos reflects the changes that have occurred in the post-Cold War period. Scientists who were previously intense competitors in the design of weapons of mass destruction are now working together to apply their skills to problems of general scientific interest. In just over two years, Los Alamos and VNIIEF have performed experiments on ultrahigh current generation, the properties of high-temperature superconductors, the properties of magnetized plasmas, the compression of materials under megabar pressures, and the creation of a soft x-ray source. These experiments were conducted at the very sites previously used for weapons development.

Both sides are enthusiastic about continuing and expanding the collaboration. There is much to be learned about the promising MAGO/MTF fusion scheme first suggested by Andrei Sakharov. In forthcoming experiments, we hope to compress helium to the same conditions found in the gas-giant planets and thereby gain a better understanding of these remarkable bodies. A Los Alamos proposal that involves flying an explosive generator on a high-altitude balloon to stimulate lightning artificially has been accepted by the Russians. Several experiments to explore quantum field effects at high magnetic fields using the MC-1 generator have already been performed at Los Alamos (see "The Dirac Series—A New International Pulsed-Power Collaboration" on page 68). A DEMG experiment to drive the most energetic solid liner ever will be conducted this summer. In short, there seems to be no end to the possibilities for collaborations on scientific endeavors. ■

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Carl Ekdahl earned his Ph.D. in Physics at the University of California, San Diego, in 1971. He first joined the Laboratory in 1975 to carry out experiments in controlled thermonuclear fusion, then again in 1982 to lead experiments to heat a high-density plasma with electron beams and to launch a high-power microwave-source development program. In 1983, he joined Sandia National Laboratories to continue with beam-propagation experiments and became Supervisor of the High-Energy Beam Physics Division. He rejoined the Laboratory in 1986 to design, execute, and analyze experiments using the radiation from underground nuclear-weapon tests. As leader of a nuclear-test diagnostics group, he directed their transition into above-ground experimental activities, including the first lab-to-lab experiments with VNIIEF. He is currently Program Manager for high-energy-density physics in the Nuclear Weapon Technology Directorate. Prior to joining the laboratory, Ekdahl held positions with Scripps Institute of Oceanography, the Laboratory of Plasma Physics at Cornell University, and Mission Research Corporation.

C. M. (Max) Fowler joined the Laboratory permanently in 1957 with the responsibility of assembling a team to develop and apply explosive-driven magnetic-flux-compression devices. The early work of this team influenced subsequent megagauss solid state research, liner implosion of plasmas, and was instrumental in starting the "Megagauss" Conferences. Through his career, Max and his colleagues have used the explosive-driven magnetic-flux-compression technique to generate energy sources to power a number of plasma-producing devices, lasers, imploding foils, electron-beam accelerators, and railguns. This energy source was also used to power high-magnetic-field generators to study materials in megagauss fields, including high-temperature superconductors. Fowler received his B.S. in chemical engineering from the University of Illinois and his Ph.D. in physics from the University of Michigan. He was recently awarded an Honorary Doctorate from Novosibirsk State University for his work in high-energy-density physics and for furthering scientific relations between the United Sates and Russia. Fowler is active as a Los Alamos Laboratory Fellow and a Fellow of the American Physical Society.

James H. Goforth received his M.S. in physics from New Mexico State University in 1973. During a tour of duty at the Air Force Weapons Laboratories in Kirkland, NM, he directed the operation of a state of the art, 250-kilojoule capacitor bank for driving plasma z-pinch experiments. Also at the Air Force Weapons Laboratories, he participated in z-pinch and fuse opening switch experiments powered by flux compression generators at Los Alamos National Laboratory. He joined the Laboratory in August, 1976, as head of the detonator exploratory development unit. In 1981, he joined the Shock-Wave Physics Group, where he continues to do explosive pulsed-power research and development . His major contribution is the development of the explosively formed fuse opening switch that is in current use as the primary pulse compression stage of the Procyon explosive pulsed-power system. He has also played a substantial part in the development of all explosive pulsed power systems for the High Energy Density Physics Program. Goforth is currently project leader for the development of driver systems to be used for high-energy liner experiments.

Irvin R. Lindemuth received his B.S. in electrical engineering from Lehigh University in 1965, and his M.S. and Ph.D. in engineering-applied science in 1967 and 1971, respectively, from the University of California, Davis/Livermore. Prior to joining the Laboratory in 1978, Lindemuth was a technical staff member at the Lawrence Livermore National Laboratory. His areas of research include thermonuclear fusion, advanced numerical methods for computer simulation of fusion plasmas, and related pulsed power-technology. He currently is Project Leader for the International Collaboration in Pulsed Power Applications at LANL and has responsibility to provide technical leadership for the pulsed-power/magnetized-target fusion collaboration between Los Alamos and VNIIEF at Arzamas-16. Lindemuth is credited with establishing a Sister City relationship between the two nuclear cities and actively continues his participation and support of the program. In 1992, he was the recipient of a Distinguished Performance Award for his work in the formative stages of the LANL/VNIIEF collaboration.

Robert E. Reinovsky received his M.E. and Ph.D. degrees in physics from Rensselaer Polytechnic Institute in 1971 and 1973, respectively. From 1974 through 1986, he worked at the Air Force Weapons Laboratory (now Air Force Phillips Laboratory) in plasma and pulse-power physics. His principle interests were high-density plasma implosions, radiation processes, plasma diagnostics, and pulse-power physics. Reinovsky was responsible for developing and building four generations of the world-class SHIVA family of high-current, low-impedance pulse-power systems. Techniques in ultrahigh-current, high-explosive pulse power that were developed in Los Alamos in the1950s caught Reinovsky's interest. He joined the Laboratory in 1986 to continue work applying these techniques to ultrahigh-current plasma systems for applications to high-energy-density physics. Reinovsky led the explosive pulse group from 1990 to 1993 and later joined the program in high-energy-density physics as project leader for the Athena pulse-power project. He is currently Chief Scientist for that program.

Stephen M. Younger received his Ph.D. in theoretical physics from the University of Maryland in 1978. Prior to employment with the Laboratory, Younger worked at the National Bureau of Standards in Washington D. C., on related topics in theoretical atomic physics and was a member of the Nuclear Design Department at Lawrence Livermore Laboratory. His research at Livermore included advanced nuclear weapons designs and supervising design groups for the nuclear-driven x-ray laser and other nuclear-explosive concepts. He came to Los Alamos in 1989 and has directed programs in inertial-confinement fusion and above-ground experiments. In 1994, he was named Deputy Program Director for Nuclear Weapons Technology and was responsible for the physics associated with nuclear weapons. Younger currently is the Director of the Center for International Security Affairs at the Laboratory. His responsibilities include oversight for interactions involving Los Alamos and the Newly Independent States.

The Dirac Series

This April, scientists from seven laboratories under four flags gathered at Los Alamos to conduct a campaign of pioneering experiments using ultrahigh magnetic fields. This collaboration among Americans, Russians, Australians, and Japanese is without precedent. This series of experiments was named after the great physicist P.A.M. Dirac because his monumental contributions to quantum theory touch on all aspects of the physics and chemistry we intend to explore. We are sure Dirac would have appreciated the unification of world scientific efforts represented by this collaboration, as the world appreciated the unification he brought to science.

The International Group of Scientists and Technicians that Carried Out the Dirac Series. **More than seven universities and institutes, representing four countries, participated in the experiments that were conducted in Ancho Canyon at Los Alamos. The large white tubing seen in front was a vacuum line that was eventually connected to a cryostat located inside an explosive-driven flux compression generator.**

Some of the participants in this collaboration are Florida State University, the University of New South Wales, Louisiana State University, the University of Tokyo, the National Institute of Materials and Chemical Research (Tsukuba, Japan), Bechtel Nevada, and the All-Russian Institute of Experimental Physics (Arzamas-16). The Los Alamos contingent consists of program manager Johndale Solem, shot coordinator Jeff Goettee, and local staff members Max Fowler, Will Lewis, Dwight Rickel, Murry Sheppard, and Bill Zerwekh.

The Dirac series included four 1.5-megagauss experiments, using an explosive-driven generator designed at Los Alamos, and three 10-megagauss experiments, using the MC-1 explosive-driven generator designed at Arzamas-16. A brief outline of the goals of each experiment is given.

The Quantum Hall Effect at High Electron Density. The Hall effect describes the development of a transverse electric field in a current-carrying conductor placed in a magnetic field, and it was discovered nearly a century ago by Edwin Hall. The *quantum* Hall effect was discovered in 1980 by Klaus von Klitzing using the two-dimensional electron gas formed in a metal-oxide, silicon, field-effect transistor. At low temperatures, the degenerate electron ground state breaks up into energy levels called, "Landau levels." As von Klitzing adjusted the gate voltage to raise the Fermi energy level, he observed a quantized sequence of plateaus in the Hall conductivity at integral multiples of e^2/h, suggesting a fundamental unit of electrical conductivity. These plateaus were accompanied by near-vanishing resistivity in the electric-field direction. Von Klitzing won the Nobel Prize for his discovery of this "integer quantum Hall effect."

But the story was far from over. Using much higher fields and lower temperatures, researchers in 1982 reported a fractional quantum Hall effect; plateaus occurred in fractions of e^2/h. At first, only odd denominators were reported (1/3, 2/5, 3/5, 2/3, and so forth). These were quickly attributed to the interaction between electrons, that is, collective effects or quasiparticles. Sensible theories were propounded as to why the denominators were all odd, but in 1993 many re-

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searchers reported even denominators. At present, many theorists believe the fractional quantum Hall states are actually integral quantum Hall states of composite Fermions. For example, the 2/5 state has 5 flux quanta for every 2 electrons (that is, 2 filled Landau levels of composite electrons).

Although many experiments have been performed, precision experiments on the quantum Hall effect are often limited by imperfections in the sample. Fortunately, samples with higher electron densities are less sensitive to imperfections, and higher magnetic fields allow observation of the quantum Hall effect in samples with large electron densities. Ultrahigh magnetic fields are required to observe the effect. The object of this experiment is to explore integer and fractional quantum Hall effects in a high electron density, two-dimensional electron gas in a semiconductor heterostructure device. Clean data from this experiment will supply a stronger experimental basis for building a complete understanding of magneto-quantum electronic effects in solid state physics.

Waiting for Dirac. **Program manager Johndale Solem and Max Fowler (foreground) have done their jobs. On the day of the shot, responsibility for the experiment falls to the technicians and the shot coordinator, and to the individual researchers. In the background are Andy Maverick from Louisiana State University and Hiroyuki Yokoi from the National Institute of Materials and Chemical Research, Tsukuba, Japan.**

Quantum Hall Effect and Quantum Limit Phenomena in Two-Dimensional Organic Metals. Two-dimensional metals may be several orders of magnitude more conducting in the x and y directions than in the z direction. Their anisotropic conductivity suggests that these metals should behave somewhat like a composite of two-dimensional electron gases. The integer quantum Hall effect has been observed in preliminary laboratory experiments up to about 5 megagauss. At extremely high fields, the magnetic and Fermi energies are comparable, and we enter the realm called the quantum limit.

What happens to the two-dimensional metals in the quantum limit is simply unknown. If they retain their Fermi-liquid character, we expect something akin to the fractional quantum Hall effect, although we may see entirely new collective electronic configurations. On the other hand, the field may localize the conduction mechanisms and cause the material to behave more like a semiconductor or an insulator. The results will certainly lead to a deeper understanding of these very interesting materials as well as conduction mechanisms in general. Curiously, these two-dimensional metals have many aspects in common with biological materials, so the implications may transcend the domain of solid state physics.

Magnetic-Field Induced Superconductivity. Superconductivity derives from a net attractive interaction between electrons in the neighborhood of the Fermi surface. In conventional superconductors the interaction is the sum of a repulsion due to the Coulomb force and an attraction due to ionic overscreening.

As described in the main article, a magnetic field can break the superconducting state, although how it does so depends on the type of superconductor. Formally, there are two types of superconductors. Type I superconductors exhibit perfect diamagnetism: the magnetic field is abruptly expelled at the superconducting transition, and once above a critical magnetic field, the entire specimen reverts to the normal state. In a Type II superconductor, there is no flux penetration below a first critical field, but there is partial flux penetration in the form of evenly spaced thin filaments below a second critical field. In both Type I and

Type II superconductors, the critical field is a function of temperature.

Theoretical work at Los Alamos and elsewhere has suggested that in the quantum limit (the lowest Landau level), the temperature for a transition to the superconducting state can actually increase with field. The electron-electron repulsion is screened by the Debye length, and it can be shown that above some ultrahigh magnetic field values, the Debye length increases with field. The electron-electron repulsion can be reduced until attraction dominates.

This new kind of superconductivity has never been observed, and in principle, it can be observed only at ultrahigh fields. Besides leading to a deeper understanding of superconductivity, this research could result in a new kind of superconductor that thrives, rather than quenches, in a magnetic field.

Preparing for the experiment. **Mikhail Dolotenko of Arzamas-16 (kneeling), oversees the installation of his samples and diagnostics into the bore of the MC-1 flux compression generator (oriented vertically for this experiment). Lying down are Los Alamos technicians Tommy Herrera (facing) and Dave Torres.**

Zeeman-Driven Bond Breaking in $Re_2Cl_8^{--}$. Quadruply bonded metal complexes are a relatively new discovery in physical chemistry. Four bonds are formed between two metal atoms, and that two-atom core is free to interact with a variety of ligands. These complexes are of considerable interest, and they enjoy symmetry properties that make them simple to describe.

The lowest excited state of the rhenium-chloride complex consists of a singlet state (no spin) and triplet state (one unit of spin). The singlet is readily accessible by photoexcitation, and hence its energy level has been measured and is well-known. Little is known about the triplet other than it has an electron in an antibonding orbital. Thus, two rhenium atoms can form only three bonds when excited to the triplet state.

In this experiment, a new type of chemical manipulation will be attempted. The Zeeman effect, which is a shift of the energy level of an atomic or molecular state due to the presence of a magnetic field, will be used to reduce the energy level of one component of the triplet until it lies below the ground state. This level “crossing” will break the fourth bond, an event that will be visible in the material’s spectroscopy. The experiment is intended to give a measurement of the energy level of the triplet state, which has been heretofore inaccessible. This technique may usher in a new way of doing chemistry.

High-Field Exciton Spectrum of Mercury Iodide. Excitons are electron-hole pairs that act like loosely bound atoms within a solid host. Excitons in tetragonal crystals of mercury iodide have been studied by absorption and photoluminescence at low temperatures. In a direct-gap semiconductor, the hole and electron combine from the lowest energy state with the same crystal momentum. Direct-gap semiconductors produce light easily and are the basis of many of the light-emitting devices in use today. In an indirect-gap semiconductor, the hole and electron combine from the lowest energy state with a different crystal momentum and, consequently, produce light rather poorly.

Mercury iodide is somewhere in between. The crystal possesses a secondary local minimum in energy at different crystal momentum. A magnetic field breaks the symmetry and makes it possible to see which emissions in the near-band exciton photoemission spectrum are due to direct or indirect processes. Observing the spectrum at very high fields will enhance our understanding of these solid state devices.

Ultrahigh Magnetic-Field Calibration Standard. In some materials, a magnetic field along the direction of propagation will cause two circularly polarized components of an electromagnetic wave to propagate at different velocities. Thus, a linearly polarized wave will rotate as it travels through the material. This is called the "Faraday effect." The strength of the Faraday effect in a material is usually characterized by the "Verdet coefficient," which measures the rotation per unit field per unit length.

Materials were fabricated with either samarium or europium embedded in a plastic matrix. These rare-earth elements have ground states and excited states that are split by the spin-orbit interaction into numerous levels. Due to the Zeeman effect, an applied magnetic field will cause some excited states levels and ground state levels to interact and cross. After each crossing, the Verdet coefficient changes, and steps appear in a plot of the Faraday effect versus magnetic field. These steps are a function of only the interatomic state and are not influenced by the surrounding matrix. The specific magnetic-field value at which each crossing occurs can be calculated using well-defined atomic constants, and thus observation of the crossing can be used to calibrate the external field. In the sample with the europium impurity, the first crossing should be observed around 10 megagauss, the second around 12 megagauss, with periodic crossings up to 50 megagauss. In the sample with samarium impurity, the first crossing may be observed about 3 to 5 megagauss, with periodic crossings also up to 50 megagauss. These samples may prove to be the only probes capable of measuring magnetic fields up to 50 megagauss.

An International Exchange.
Members of the Russian delegation (from left to right: Elena Gerdova, Vadim Platonov, and chief scientist Olga Tatsenko) discuss physics with Noboru Miura from the University of Tokyo.

Faraday Rotation in $Cd_{1-x}Mn_xTe$. $Cd_{1-x}Mn_xTe$ is a member of a group of materials, called "diluted magnetic semiconductors," that contain magnetic ions (Mn^{++} in this case) that can undergo a spin-exchange interaction with band electrons. This spin-exchange produces an enormous spin splitting of the energy bands and, consequently, a giant Faraday effect. At low magnetic fields and room temperature, the Verdet coefficient is directly proportional to the field. At high fields, however, the Verdet coefficient is expected to reach a saturation level and even decrease slightly. At low temperature and high field, steps appear in the Verdet coefficient that are attributed to the coupling of pairs of the magnetic ions and more complex (3, 4, 5, and so forth) clusters of magnetic ions. In the linear regime, $Cd_{1-x}Mn_xTe$ is of great practical importance as an optical sensor of magnetic fields. Extension of the data for this material to ultrahigh fields will lead to a more complete understanding of the effect of magnetic clusters in diluted magnetic semiconductors.

Conclusion. The Dirac series of experiments will explore fundamental physics in the ultrahigh magnetic field regime of several different disciplines. These are extremely difficult experiments, and new measurement techniques are already being developed in the course of designing and performing these investigations. This international effort is a fitting extension to the Russian-American pulsed-power collaboration initiated under the lab-to-lab program. ■