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SCIENCE

CURRENT PROBLEMS IN RESEARCH

High Magnetic Field Research

Magnetic pressure can move mountains of metal or plasma for the engineer, and atoms for the physicist.

Harold P. Furth

The opposition encountered in bringing together two like magnetic poles is somewhat like the opposition of a gas to compression between two pistons. This item of common experience has its exact formulation in terms of Maxwell's electromagnetic field theory. Magnetic field is said to possess an energy density which is analogous to the thermal energy density of a gas. When a region of magnetic field is compressed or distorted, its energy content is raised. Accordingly, the action that generates the compression or distortion must be associated with the performance of work against a magnetic pressure, analogous to the thermal pressure of a gas.

To be more specific, the energy density associated with a magnetic field B, measured in gauss, is $B^2/8\pi$, measured in ergs. A magnetic field of 1 megagauss has an energy density of 40×10^9 ergs, or 1000 calories, per cubic centimeter, which is comparable to the chemical energy density of high explosives. The pressure that is exerted at the boundaries of a region of magnetic field B is also given by $B^2/8\pi$, measured in dynes. At 1 megagauss, the magnetic pressure is 40×10^9 dynes, or 560,000 pounds per square inch, which is comparable to the yield points of the toughest metals. For many purposes, what matters is not the maximum pressure that a given magnetic field is capable of exerting but the pressure differential associated with a small local increment or decrement ΔB. Simple algebra shows that the corresponding differential in pressure (and energy density) is given by $B\Delta B/4\pi$.

The author is on the staff of the University of California's Lawrence Radiation Laboratory, Livermore, Calif.

Applications of High Magnetic Fields

The achievement of very high magnetic fields has its obvious uses in pure and applied research. For instance, the confinement of a hot plasma in a "magnetic bottle" (the major problem in the development of fusion power) evidently requires a magnetic pressure at least equal to the pressure of the plasma confined. For reasons of stability, the main trend of fusion research is currently towards magnetic bottles where the plasma creates only a small perturbation ΔB in the magnetic field structure. To confine typically interesting plasma temperatures and densities of 10^9 degrees and 10^{14} particles per cubic centimeter, a magnetic field of 50 kilogauss or so will be needed, and the scaling laws are such that operation at still higher fields becomes increasingly attractive. If there were no problems and expenses involved in bottling the magnetic bottle itself in a system of conductors, the problem of bottling a thermonuclear plasma would be very greatly simplified.

It is instructive to contrast plasma containment in a magnetic bottle with particle containment in a high-energy accelerator. A stream of particles in orbit may be thought of as a loop of current producing a mean magnetic field perturbation ΔB. In a typical accelerator, with guide field B, the interaction energy density $B\Delta B/4\pi$ is infinitesimal compared with $B^2/8\pi$, and therefore the loss of the particle stream by plasma-type instabilities is out of the question. The main limitation is to be found precisely in the weakness of the magnetic interaction force. When conventional iron-core electromagnets are used, as has been the practice, the strength of the guide field is limited to 20 kilogauss, and the centrifugal tendency of the particles can be moderated only by resorting to physically large orbits. The 25-Bev proton accelerators being put into operation at CERN and at Brookhaven National Laboratory have diameters of about 100 meters. The attainment of substantially higher energies along the same technological route is thus limited by obvious financial and geological considerations. An alternative is to employ air-core magnets and begin to operate in the 100- to 500-kilogauss range, thereby reducing the physical scale by a factor of 5 to 25.

High magnetic field research can be divided more or less neatly into two categories. Some branches of research are concerned with high magnetic energy densities as such. An important example is the controlled-fusion project. There are technologically similar projects that concern themselves with the use of magnetic pressure for the propulsion of plasma streams or test projectiles to extreme velocities. The basic line of research in this category is, of course, the technology of high field generation itself, which is discussed in some detail below.

To the second category belong research applications based on the interaction energy density of a high magnetic field interacting not with itself but with infinitesimal perturbation fields. The example of the particle accelerator has been given. A much more general example is the use of high applied fields to interact with microscopic field regions inside matter. The high-field Zeeman effect, and the various galvanomagnetic, paramagnetic, diamagnetic, ferromagnetic, antiferromagnetic, and associated resonant effects, to mention a few, are all dependent on the transcendence of a magnetic interaction energy beyond the reach of some disturbing influence. The magnetic perturbation fields ΔB associated with atomic electron orbits, while confined to extremely small volumes, of 10^{-25} cubic centimeter or so, have large local amplitudes, easily falling into the 10^5 to 10^7 gauss range. The various electron orbits within an atom interact magnetically with each other. The application of an external B sufficiently strong to dwarf the individual ΔB's (and make the energy density $B\Delta B/4\pi$ locally transcend the energy densities $\Delta B^2/8\pi$) evidently calls for at least 1 megagauss. Since atomic volumes are so small, however, the total energy involved in the interaction of an atomic electron with a megagauss field corresponds to something rather less than mean thermal energy at room temperature. Moreover, the magnetic perturbations produced by different atoms tend to be random, and so the macroscopic reaction on the applied magnetic field is usually quite negligible. A familiar exception occurs in the case of ferromagnetic materials, where large conglomerates of atoms may act cooperatively to produce macroscopic fields of some tens of kilogauss. Even then the energy density involved amounts only to a fraction of a calorie per cubic centimeter.

Many magnetic properties of matter depend on the frequency of free electron gyration in an applied magnetic field relative to the frequency of electron collisions with various atomic obstacles. The gyration frequency is proportional to the strength of the applied magnetic field, while the rate of collision depends on the thermal velocity. The ratio of these two numbers determines whether electrons will gyrate in the magnetic field or follow randomly broken paths. For solid-state experiments that depend on the resonant acceleration of electrons in magnetic orbits, the collisional effect is about as disturbing as the presence of air inside a particle accelerator. When conventional field strengths of 20 kilogauss or less are used, such experiments must be conducted at very low temperatures, and a great many cannot be done at all. With megagauss fields, a new range of experimentation becomes accessible, some of it even at room temperature. Evidently, however, there are solid-state experiments that still cannot be done at all, and that await the further development of high-field technology.

The relative feebleness of available magnetic field strengths becomes especially noticeable in relation to the fields produced by the motion of charged particles in the nucleus. Over typical nuclear volumes of 10^{-37} cubic centimeter, there are magnetic fields in the 10^{15} gauss range. It appears unlikely that individual nucleons could be decoupled from each other and coupled to an external field. On the other hand, the total energy of interaction between a nucleus and an applied field of 1 megagauss corresponds to a thermal energy of only a few hundredths of a degree. Accordingly, experiments designed to align nuclei magnetically, in the face of disruptive thermal agitation, must be conducted either at extremely low temperature or in an extremely high applied field. These simple considerations illustrate how the strength of microscopic fields and their minuscule spatial extent provide separate incentives for the development of high-field techniques.

In high-energy physics, the most common use of magnetic fields is that already mentioned of guiding energetic particles along paths that are more or less strongly curved, depending on the field strength and the particle momentum. In many special cases, the use of conventionally weak fields has disadvantages that go beyond the practical inconvenience inherent in very large-scale installations. For example, if the magnetic analysis of secondary beams involving short-lived particles is not performed in as short a distance as possible, the desired beam component may disappear in the process of analysis.

Many high-energy experiments are carried out in media sensitive to the passage of particles, such as photographic emulsions, bubble chambers, or cloud chambers. The medium acts both as a target material and a detector of particle paths. A magnetic field is imposed whenever possible, for the purpose of momentum analysis; but if the medium is very dense and the applied field is conventionally weak, the random scattering of particle paths by collisions will mask their curvature in the magnetic field. Magnetic analysis has been used consistently in cloud chambers and low-density bubble chambers at 20 kilogauss or so but is only now coming into use with emulsion stacks and high-density bubble chambers, at applied fields of a few hundred kilogauss.

Magnetic Field as a "Two-Dimensional Gas"

In order to gain insight into the basic problems of high-field technology, it is often convenient to abandon familiar pictures of magnetic fields and forces produced by currents in wires and to think instead of the magnetic field as a sort of two-dimensional gas, with the flux lines taking the place of gas molecules. This analogy becomes exact for systems that are infinite and uniform along the direction of the field.

Consider, for example, an infinite tube of conductive material, containing an axial magnetic field. If the material has zero electrical resistivity, the field may be confined entirely to the tube bore (Fig. 1*a*), and there will exist an azimuthal surface current "generating" or "generated by" the magnetic field. The radial pressure exerted on the tube surface will be the same as the energy density of the magnetic field—namely, $B^2/8\pi$. By executing an imaginary radial displacement of the tube wall, it is easy to show that the algebraic identity of pressure and energy density is typical of a two-dimensional ideal gas.

If we now assign a finite resistivity to the tube material, the magnetic field will begin to "leak" radially outward, just like a gas confined in a porous vessel (Fig. 1*b*). The current associated with the magnetic field boundary will also spread to the volume of the tube, and like the magnetic field, it can do so only gradually. This is the basis of the "skin effect" familiar in high-frequency electrical engineering. As the magnetic field expands into the tube wall, it does work, and this corresponds to the appearance of Joule heat. The density of the work performed is, roughly speaking, equal to $B^2/8\pi$. Hence, we can calculate the temperature rise at the surface of the tube quite independently of the assumed resistivity, depending only on the heat capacity per unit volume, which for most solids is unity, at room temperature. When a megagauss field has leaked out, the tube surface temperature will have risen by some thousands of degrees.

We can now state a basic (approximate) scaling law relating to the generation of high fields in solid metal systems: The confinement of a magnetic energy density corresponding to 1 megagauss creates a surface temperature comparable to the melting points of metals, as well as a pressure comparable to their mechanical yield points. The theoretical expectations for soft metals with low melting points, like copper or aluminum, are of course much lower than those for hard metals with high melting points, like tungsten or certain copper alloys. It is only with the latter than one can hope to support megagauss fields without incurring damage.

Magnetic field leakage into a conductor is a diffusion process of the standard sort, with a diffusion constant which is just equal to the resistivity of the conductor. Thus we arrive at a second basic scaling law of high-field technology: The confinement time of a magnetic flux in a system of conductors is proportional to the conductivity and the cross-sectional area of the system. For copper systems of 10-centimeter diameter, the confinement time is roughly 0.1 second.

The diffusion of heat in metals follows the same scaling law as the diffusion of magnetic field, but with a different and usually much smaller diffusion constant. Thus, heat conduction ordinarily has little moderating effect on the high temperatures reached transiently during the leakage of a confined magnetic field out of a solid metal tube.

If we make a radial slit in our field-confining tube (Fig. 1*c*), a voltage can be applied, and additional magnetic flux can be introduced through the slit at a rate equal to the applied voltage. The voltage source may be thought of as the pump which supplies the magnetic "gas" to its tubular reservoir, from which it is continuously leaking. In steady-state operation, the rate of work done by the pump will be equal to the magnetic energy stored in the tube, divided by the leakage time. The power requirement on the pump does not depend on the area of the tube, since the area and the leakage time have the same dimensional dependence. The power required to maintain a 100-kilogauss field in copper at room temperature can thus be expressed simply as about 100 kilowatts per centimeter of length. The steady-state confinement of a 1-megagauss field (which no high-field experimenter thinks seriously of attempting at present) would impose the alarming requirement of 10 megawatts per centimeter.

Transient high-field generation has the great advantage that electrical energy can be accumulated at low mean power in a capacitor bank or a motor generator and then suddenly converted into magnetic energy, producing enormous instantaneous power. If the introduction of the desired magnetic flux into the tube is accomplished in a time that is short compared with the magnetic leakage time, the situation shown in Fig. 1*a* will be approximated. In that case, the energy per centimeter of tube length needed to produce a magnetic field B, is just $B^2/8\pi$ times the inside tube area. If the process of flux introduction consumes several leakage times, much more electrical energy is needed to reach the same peak magnetic field. Thus, it is easy to calculate that, for the sake of efficiency, copper systems of centimeter size must operate in the millisecond range, while systems that are smaller or made of less conductive metals, such as the harder alloys of copper, will do best with still shorter pulse times.

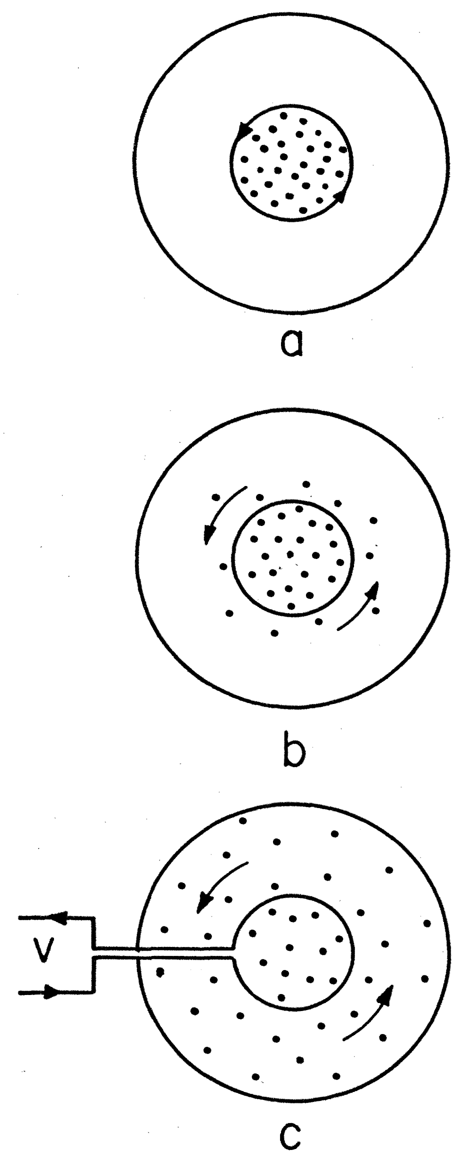

Fig. 1. Cross-section of an infinite flux-confining tube. Arrows represent the current, and dots represent the magnetic field. The magnetic return flux is not shown. (*a*) Initial state; (*b*) outward diffusion of magnetic field; (*c*) steady state.

The cost of producing rapidly deliverable energy is substantial and represents one of the prime limitations on the size and strength of pulsed high-field equipment. At 1 megagauss, the quantity $B^2/8\pi$ corresponds to 4000 joules per cubic centimeter, or at least $500 per cubic centimeter, if the energy comes from a capacitor installation. When the field volume is sufficiently great so that the flux-leakage time can be made to exceed 0.1 second, rotating electrical equipment becomes readily applicable, and the cost per cubic centimeter may drop by an order of magnitude.

In electrically efficient systems, where the situation of Fig. 1*a* is approximated, the rise in surface temperature is held to the theoretical minimum. Slower and less efficient systems imply higher temperatures in the conductor, and steady-state systems tend toward infinitely high temperature. The salvation of direct-current high-field magnets lies in honeycombing the conductor with coolant ducts. The low ratio of thermal to electrical conductivity is then offset by the shortness of the distance through which Joule heat must travel in order to be removed, relative to the distance through which the magnetic flux must leak in order to escape. The technical problems involved in this operation are such that the 100-kilogauss magnet built by Francis Bitter (*1*) in the 1930's still represents a record achievement. A 250-kilogauss direct-current installation (*2*), which was recently designed on the basis of improved rates of transfer of heat to coolant, may go into operation in the next few years.

With the honeycomb cooling technique and the moderate field strengths that are typical of direct-current high-field magnets, extreme low-temperature operation becomes somewhat attractive. At liquid helium temperature, the conductivity of certain pure metals improves by three orders of magnitude. The flux-leakage time is correspondingly greater, and the direct-power requirement and Joule-heating rate are correspondingly less. At such a low temperature, some materials have ratios of thermal to electrical diffusion constant greater than unity, and the heat-removal problem is thus further eased. On the basis of these ideas, various direct-current magnets with field strengths between 50 and 100 kilogauss have been operated with low-temperature coolants, including liquid hydrogen (*3*) and liquid air. The main drawbacks of this type of operation are the complexity and expense of the equipment and the magnitude of the indirect power requirement for producing the low-temperature coolant. Recent calculations by Post and Taylor (*4*) have shown that very large low-temperature systems are highly profitable, and so we may perhaps look forward to an era of refrigerated high-energy accelerators and fusion reactors.

Some Approaches to High-Field Technology

The design of actual high-field equipment is governed by basic considerations very similar to those developed for the infinite tube of Fig. 1. In systems of increased complexity, certain limitations can be removed. On the other hand, there arise vexatious practical requirements, such as the generation of the circulating current associated with the confined magnetic field. Roughly speaking, 1 gauss is associated with 1 ampere per centimeter of tube length. How to generate currents of some megamperes, as required for a megagauss field volume some centimeters in length, is by no means a trivial problem.

Five main technological avenues have been followed to produce high magnetic fields: (i) reduction of the input current requirement by means of a tubular coil wound of insulated wire; (ii) direct adoption of the solid tube design, with a straight or helical slit; (iii) use of motional effects in solid but nonrigid tubes; (iv) use of conductive fluid; (v) reduction of magnetic forces by means of force-free geometric designs. These techniques are briefly discussed in the following paragraphs.

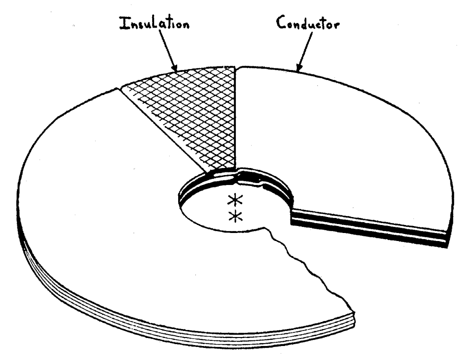

Fig. 2. Slightly modified form of the Bitter coil construction, as employed in a 300-kilogauss pulsed magnet (2.25-inch inside diameter) recently built by Birdsall and Furth at the Lawrence Radiation Laboratory.

Wire-wound coils. The foundations of high-field research were laid in the 1920's by the Russian scientist P. Kapitza (*5*), who was then working at Cambridge, England. His coils were wound of several layers of thick bronze wire, surrounding an experimental volume of several cubic centimeters. By short-circuiting a specially built motor generator, he was able to produce 320-kilogauss pulses in the millisecond range. To judge from Kapitza's large-scale conduct of solid-state experiments (*6*), this installation must have performed very satisfactorily.

For some 20 years after Kapitza's work there were no major innovations in technique. Capacitor banks or low-temperature cooling, or both, were used by some experimenters, but the size and strength of their magnets were modest as compared with Kapitza's.

High-field experimentation on the heroic scale was resumed only in 1954–55, behind the formerly closed doors of the controlled-fusion project "Sherwood." F. H. Coensgen (*7*) developed high-field coils made of copper windings embedded in a Fiberglas-base plastic and was able to reach 450 kilogauss over a a 100 cubic centimeter volume during millisecond times, by discharging a high-voltage capacitor bank. Coils of the same type, of 200-kilogauss strength with 10^3 cubic centimeter volumes, are still in daily use in "mirror machine" work (*8*), and a 70-kilogauss coil of 10^5 cubic centimeter volume is being put into operation.

On comparing the wire-wound coil with the solid tube of Fig. 1, one notes a number of important differences, aside from the obvious reduction in the input current requirement. When there are several concentric layers of windings, the same current must flow through all, and so even a very rapidly pulsed field will appear simultaneously throughout the body of the coil instead of appearing first inside the coil bore and gradually diffusing into the body. A multilayer coil in short-pulse operation is therefore more wasteful of stray magnetic energy than a solid tube. On the other hand, one can show that the enforced distribution of the coil current over the whole coil body makes it possible to reduce the rise in temperature to an arbitrary low if there is a sufficiently short pulse. The danger of melting can thus be removed in a wire-wound coil, but the danger of bursting is always very much aggravated, because of the relative fragility of the composite wire-insulator structure.

Solid metal coils. A practical coil resembling the flux-confining tube of Fig. 1 was first devised by Bitter (*1*) for his direct-current magnets. Bitter's coil is made of alternate copper and mica washers, each having a radial slit. These washers are stacked up artfully to form a solid tube with a helically winding slit (see Fig. 2). The Bitter coil is thus in effect a monolayer multiturn coil.

In 1954, R. W. Waniek and I began a high-field project at the Harvard Cyclotron Laboratory, aimed at providing accessory magnets for accelerator experiments (*9*). In view of the second-rate mechanical properties of wire-wound coil structures, our thinking turned to coils made of more or less solid metal. We began with an effort to exploit the high-field potentialities of Bitter's coil design in combination with Kapitza's pulse technique and the use of hard metals. To obtain the large currents required for coils with a small number of turns, we discharged low-voltage capacitors during 100-microsecond times directly into our coils, or during millisecond times, through a pulse transformer. With a rather modest technological investment, we were able to reach 600-kilogauss fields over 0.1 cubic centimeter volumes by the summer of 1955. Concurrently, we began to put our magnets to use in some simple semiconductor experiments (*10*).

Collaboration was established with the nearby Lincoln Laboratory, where B. Lax and his associates had become interested in applying our high-current, solid-metal technique in their own solid-state research. Various useful innovations were made at Lincoln, notably the machining of the helical slit directly into a solid tube instead of generation of the slit by an assembly process of the Bitter type. Fields as high as 750 kilogauss over 0.1 cubic centimeter volumes, during 100-microsecond pulse times, were soon reported by S. Foner and H. H. Kolm (*11*). A series of magnetic resonance experiments (*12*) was performed at the 100- to 300-kilogauss level.

In the fall of 1955 we began a fruitful collaboration with M. A. Levine of the Cambridge Air Force Research Center. By means of high-current techniques developed by Levine, we were able to draw multimegampere current pulses of 15-microsecond duration from a capacitor bank. The extremely high input current requirement of the solid, single-turn coil (Fig. 1) could thus be met for the first time. We proceeded to study the field-limiting phenomena peculiar to various metals and to evolve a systematic theory of high-field limitations in the flux-confining tube (*13*), somewhat as outlined in a previous section of this article.

Some of our single-turn coils of 0.1 cubic centimeter volume could be pulsed repeatedly at fields up to 900 kilogauss, with only minor surface damage. At still higher fields we began to find ourselves in a new domain, where inertia rather than tensile strength provided the main opposition to the magnetic pressure (see Fig. 3).

The maximum distance over which a flux-confining tube can expand in a given time can be estimated by equating the kinetic energy density reached by the tube material to the work done by the magnetic pressure in the process of expansion. A megagauss field in a solid copper system of centimeter dimensions can thus be estimated to last for times in the 10-microsecond range, even when the mechanical strength of the copper is neglected. (Since the tensile strength of copper is one-tenth the value of $B^2/8\pi$ at 1 megagauss, it may indeed be neglected.) In our experiments with 15-microsecond pulses, we found that peak fields as high as 1.6 megagauss could readily be reached. At the end of a typical pulse, the inside coil diameter would be distended to some five times its original value of about 0.3 centimeter.

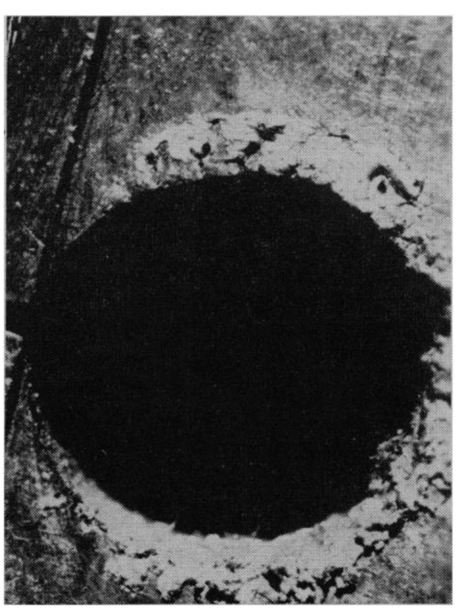

Fig. 3. End view of a single-turn coil made of beryllium copper, after pulsing at 1.2 megagauss. The coil expanded from 1/4 to 3/8 inch in inside diameter and suffered surface melting.

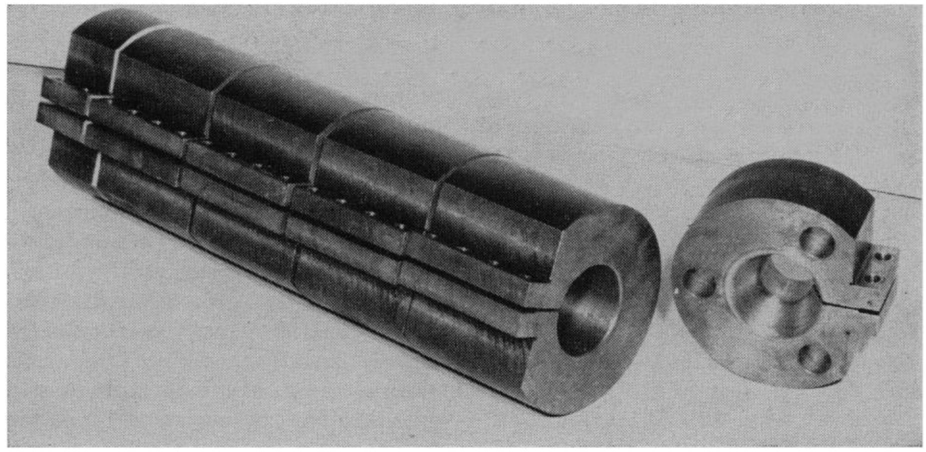

Fig. 4. Steel single-turn coil of 3-centimeter inside diameter, used for plasma compression at the Naval Research Laboratory. Inside the "magnetic mirror" end piece, field strength of 600 kilogauss has been reached.

During recent years, our rather primitive experiments with the solid flux-confining tube have been surpassed in many ways, both in technique and dimension. Figure 4 shows a single-turn coil used in "magnetic mirror" plasma experiments by A. Kolb (*14*) at the Naval Research Laboratory. In the mirror regions at each end, 600-kilogauss fields have been achieved nondestructively over a volume of many cubic centimeters, during 15-microsecond pulse times. Hardened steel is used as the coil material, and many megamperes of current are supplied from a low-inductance capacitor bank.

The highest fields to be obtained nondestructively thus far have been achieved at the Zenith Radio Research Corporation by W. W. Salisbury and L. C. Foster (*15*), and have not yet been reported in the literature. The method is based on the solid-metal single-turn coil principle, with the added feature that the input current is supplied by a wire winding, tightly surrounding the single turn. This transformer-like arrangement, which is sometimes called a "flux concentrator," has the merit of reducing the input current requirement, though usually at the expense of some electrical efficiency. Starting in 1956, on a program involving considerable metallurgical research, Salisbury and Foster found that, with certain high-conductivity bronzes and proper shaping of the inside coil surface, they were able to reach fields as high as 1.6 megagauss repeatedly in the same coil.

During the past year, some very sophisticated flux-concentrator designs that combine the virtue of high electrical efficiency with that of low input current requirement, have been developed at the Lincoln Laboratory.

On the basis of these various technological contributions, it appears that the use of reliable and convenient pulsed megagauss magnets may well become commonplace in physics and engineering during the next decade.

Coils with mobile walls. The highest magnetic fields ever generated in the laboratory were recently reported by C. M. Fowler, W. B. Garn, and R. S. Caird (*16*), at Los Alamos. A thin copper flux-confining tube was imploded by means of high explosives, and a large volume of initially weak magnetic field was compressed up to a strength of 14 megagauss in a volume of about 2 cubic centimeters. The attainment of such a prodigious magnetic field, and its duration near peak for about 2 microseconds, is ascribable to the inertia of the imploded system.

This technique of imploding tube walls that are designed to be mobile (Fig. 5*a*) is superior to the simple delayed-expansion technique (*13*) in a number of ways: first, the interval of maximum field is extended, because the inward motion must be arrested before expansion begins; second, the energy stored in the magnetic field is supplied principally from the chemical energy of the high explosive, rather than from expensive sources of fast electrical energy; and third, the input current requirement is small, since the current is amplified during the compression to the same extent as the magnetic field itself. These points are of considerable practical importance, since the energies and currents associated with the Los Alamos experiment are measured in megajoules and hundreds of megamperes, respectively.

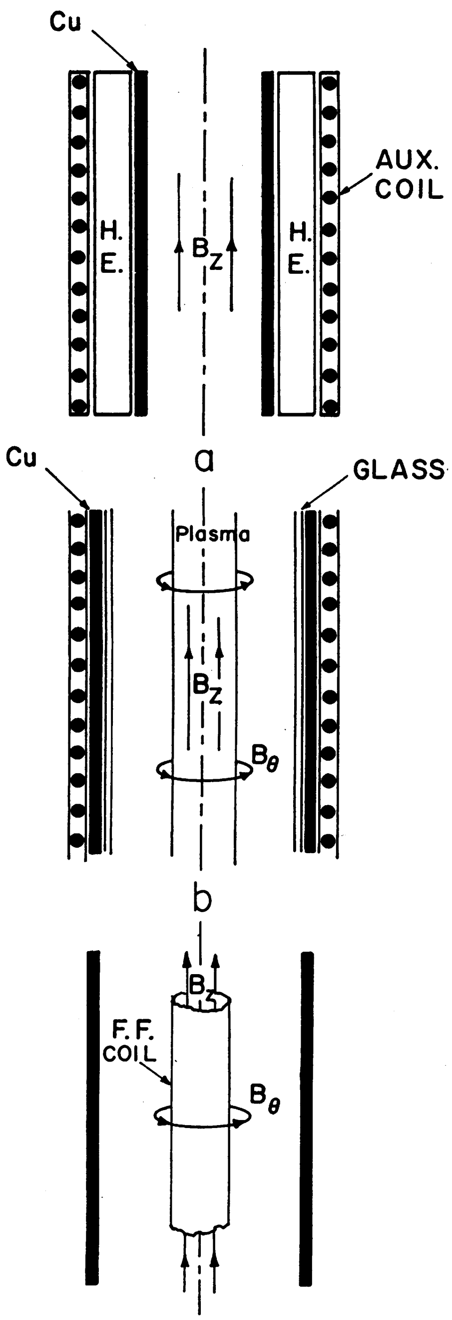

Fig. 5. (*a*) Implosion assembly. Initial magnetic field B_z is set up inside a copper tube by an auxiliary coil. The tube is then compressed by a high explosive. (*b*) "Stabilized pinch." The initial magnetic field is set up in gas by an auxiliary coil. Gas is then ionized to form plasma and compressed by pinch field B_θ. The copper shell is the return conductor for pinch current. (*c*) A force-free coil, made of helical wire windings separates regions of B_z and B_θ. The outer shell is the return conductor for coil current.

There exist quite a few "mobile-wall" experiments that are similar to the outstanding example that has been given. A common idea is, for instance, to generate large electrical energies and currents for outside use in an imploded tube with a slit and attached leads. The firing of a cannon ball through a high-field coil has been suggested for the same purpose, and conversely, the firing of a cannon ball *by* a high-field coil is a concept that dates back half a century.

Use of conductive fluid. From mobile "solid" conductors it is but a short step to the use of conductive fluid, such as plasma or liquid metal. The compression and heating of plasma by means of a fast-rising magnetic field is a common practice in controlled-fusion research. When a significant fusion power release has been achieved, the converse process—that of hot plasma expansion compressing the initial field—will increase magnetic energy in a manner analogous to the generation of magnetic from chemical energy in the Los Alamos implosion experiment. This is the basis of the statement that electrical energy can be generated directly by a fusion reactor.

In the "stabilized pinch" (*17*), illustrated in Fig. 5*b*, an axial magnetic field inside a plasma is compressed by the azimuthal pinch magnetic field. By this technique, fields in the 100-kilogauss range have been achieved for fractions of a microsecond. Construction of practical high-field magnets based on plasma does not seem very likely at present, because of the low electrical conductivities (0.001 that of standard copper) which have been achieved thus far. To obtain a conductivity comparable to that of copper (theoretically possible at 10 million degrees) appears to be about as difficult a problem as the control of fusion power itself. The main obstacle in both cases is that of instability phenomena.

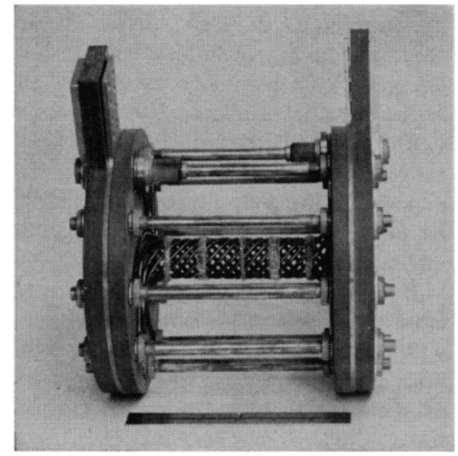

Fig. 6. A force-free coil built at Livermore Radiation Laboratory. The current flows along helical wires and returns through rigid outer rods (which are not force-free). Copper end plates (sandwiched between plastic) bear the main pressure caused by the pulsed field.

The use of a "flux-confining tube" consisting of radially inward-moving liquid metal has recently been suggested by H. H. Kolm as a means of generating strong, steady magnetic fields. With this ingenious technique (as indeed also with the Los Alamos implosion technique) one would again expect the ultimate limitations to come from instability phenomena.

Force-free coils. In order to avoid altogether the vicissitudes experienced in seeking to contain extreme magnetic field pressures, a fifth possible approach may be adopted (*14*). By winding coils three-dimensionally, instead of merely azimuthally, a three-dimensional magnetic field, instead of a purely poloidal one, can be produced. As has been found in plasma physics, a three-dimensional magnetic field and current structure can be made force-free, provided that exterior boundary conditions are met. These boundary conditions imply that a region of finite magnetic energy density corresponds to a finite total outward force at the boundary of the force-free system. The outward pressure can, however, be made arbitrarily small by placing the boundary at a sufficient distance. This is illustrated by the example of the "stabilized pinch," where the "pressures" of the axial and azimuthal fields are balanced against each other. If the plasma is kept cold by loss mechanisms, the magnetic field exerts no net pressure at all, except against the current-return-conductor encasing the pinch tube. As is well known, the strength of the azimuthal magnetic field set up by passage of a current along a cylinder drops off in proportion to the radial distance from the cylinder axis. By making the ratio of tube radius to pinch radius sufficiently large, the magnetic field strength at the wall can be made lower than that at the center of the pinch to the extent desired.

In seeking to produce force-free laboratory coils, it is natural to begin with structures approximating the "stabilized pinch" (Fig. 5*c*). A principal problem is how to terminate such structures in the axial direction. One possible approach is to imitate the toroidal "stabilized pinch," where there are no end effects. A number of equally simple solutions exist, resembling conventional coils more closely, and some of these have been built and tested at the Cambridge Air Force Research Center and at Livermore (Fig. 6).

Fragile elements have been used intentionally in coil construction, and structures readily deformable by hand have been found to withstand pulsed fields in the range of 100 to 200 kilogauss. The main mode of deterioration at present is again the same as in plasma high-field experiments—namely, the loss of the equilibrium configuration by an unstably growing geometric perturbation. The obvious remedy is to improve the accuracy with which laboratory models are made to meet theoretical designs, or to reinforce approximately force-free coils mechanically, thus preventing the initial growth of instabilities.

Properly made force-free coils will be wound in a great many layers, and, as in the case of ordinary multilayer coils, it will be possible to reduce the rise in temperature to an arbitrary low if the pulse is sufficiently rapid. Force-free coils are in principle exempt from both of the main high-field limitations —that due to melting and that due to mechanical deformation.

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Exobiology: Approaches to Life beyond the Earth

Joshua Lederberg

It is a privilege to discuss some basic problems in biology with an audience whose special concern is for the recent striking advances in the physics of the earth in the solar system. However, many of us are looking forward to the close investigation of the planets, and few inquisitive minds can fail to be intrigued by what these studies will tell of the cosmic distribution of life. To conform to the best of our contemporary science, much thoughtful insight, meticulous planning, and laboratory testing must still be invested in the experimental approaches to this problem. This may require international cooperation and also—perhaps more difficult—mutual understanding among scientific disciplines as isolated as biochemical genetics and planetary astronomy.

Many discussions of space exploration have assumed that exobiological studies might await the full development of the technology for manned space flight and for the return of planetary samples to the terrestrial laboratory. To be sure, these might be preceded by some casual experiments on some instrumented landings. One advantage of such a program is that time would allow exobiological experiments to be planned with composure and deliberation. Undoubtedly, this planning would be more rigorous insofar as it was based on improved knowledge, from closer approaches, of the chemistry and physics of planetary habitats. Unfortunately, this orderly and otherwise desirable program takes insufficient account of the capacity of living organisms to grow and spread throughout a new environment. This unique capacity of life which engages our deepest interest also generates our gravest concerns in the scientific management of missions beyond the earth. On account of these, as well as of the immense costs of interplanetary communication, we are obliged to weigh the most productive experiments that we can do by remote instrumentation in early flights, whether or not manned space flight eventually plays a role in scientific exploration.

The author is professor of genetics at Stanford University Medical Center, Palo Alto, Calif.

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Motivations for Exobiological Research

The demons which lurk beyond the Pillars of Hercules have colored the folklore and literature of ages past and present, not always to the benefit of fruitful exploration and dispassionate scientific analysis. Apart from such adventuresome amusements and the amateur delights of a cosmically en-