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Megagauss Physics

The production, measurement, and applications of megagauss fields are surveyed.

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The capability of producing large magnetic fields has existed for more than a decade. Magnetic fields greater than 1 megagauss (MG) were produced with capacitor banks as the primary energy source as early as 1957 (*1, 2*); fields in excess of 10 MG, produced by explosive flux-compression techniques, were reported as early as 1960 (*3, 4*); and the first major conference dealing with megagauss fields was held in 1965 at Frascati, Italy (*5*). In this article I present a broad survey of megagauss physics which includes a discussion of recent developments in the field.

One megagauss serves as a natural boundary in high field production because fields greater than this result in the destruction of the magnetic field coil. The origin of this difficulty follows from the expression for the energy density U (in ergs per cubic centimeter) and pressure P (in dynes per square centimeter) associated with a magnetic field B:

$$U = P = B^2/8\pi \quad (1)$$

According to Eq. 1, a field of 5,000 gauss exerts a pressure of about 10^6 dyne/cm^2, approximately 1 atmosphere, whereas a field of 1 MG exerts a pressure of 40,000 atmospheres, or about 600,000 pounds per square inch. This pressure exceeds the elastic and structural limits for normal materials, which explains why fields in the megagauss range are transient and destructive. A consequence of electromagnetic theory is that good conductors tend to exclude magnetic fields. Physically, this is brought about in the following way: when an external field is impressed upon the conductor, eddy currents are induced within the conductor which produce fields with a sense opposite to that of the applied field, thus resulting in field cancellation within the conductor. Furth *et al.* (*1*) have shown that these currents increase the surface temperature of the conductor (in degrees Kelvin) by approximately 3000 B^2 (where B is in megagauss). Thus, most materials also show signs of melting when subjected to megagauss fields. A comprehensive discussion of high field production requires a knowledge of the high-pressure and high-temperature behavior of the conductor in both solid and liquid states. Allowance must be made for conductor vaporization at higher fields, and ultimately for the transition of part of the conductor to a plasma state (*6*).

Large fields occur naturally or inherently in some experiments. Current filaments give rise to external solenoidal magnetic fields whose magnitudes (in gauss) vary inversely with the distance r (in centimeters) from the filament according to Eq. 2

$$B = 0.2\ J/r \quad (2)$$

where J is the current (in amperes).

Fast capacitor banks can drive megampere currents through millimeter-sized conductors, and these currents produce megagauss fields near the conductor surface. For example, Mather reports (*7*) that, in some high-density plasma experiments, 2-megampere currents flow along plasma filaments with radii of the order of a millimeter. Transient fields of the order of 4 MG therefore exist at the surface of the filament.

As an extreme case I should mention the enormous extraterrestrial magnetic fields that may exist. The possibility that fields as large as 10^8 MG could be created in neutron stars was noted as early as 1964 (*8*). Somewhat later, an explanation of pulsar signals was based upon the existence of fields of the order of 10^6 MG in rotating neutron stars (*9*). The energy density of such fields is awesome. A field of 10^7 MG in a volume of 1 cubic centimeter has an energy of about 4×10^{24} ergs, the energy released by a 100-megaton weapon.

Production of Megagauss Fields

Axial fields have regions of spatial uniformity suitable for use in a wider range of experiments than solenoidal fields, which are variable over space, according to Eq. 2. Consequently, in this discussion I will consider only axial field production (*10*).

Figure 1 shows schematically the ways in which axial megagauss fields have been produced. Those shown in Fig. 1, a–c, rely upon inertial containment to sustain the fields. The simplest of the inertially contained systems, Fig. 1a, was pioneered by Forster and Martin (*11*). The energy source is a reasonably low-inductance capacitor bank, and the load coil is formed from a simple thin copper strap bent into the load shape required. The load coils are destroyed in each shot but are simply replaced. Massive load coils, Fig. 1b, powered by a capacitor bank were used by Furth *et al.* (*1*) and later by Shearer (*12*), who obtained fields of the order of 3 MG. Shearer's report contains some particularly dramatic pictures of the deformation damage sustained by the coil blocks. In the inertial confinement system of Fig. 1c, the

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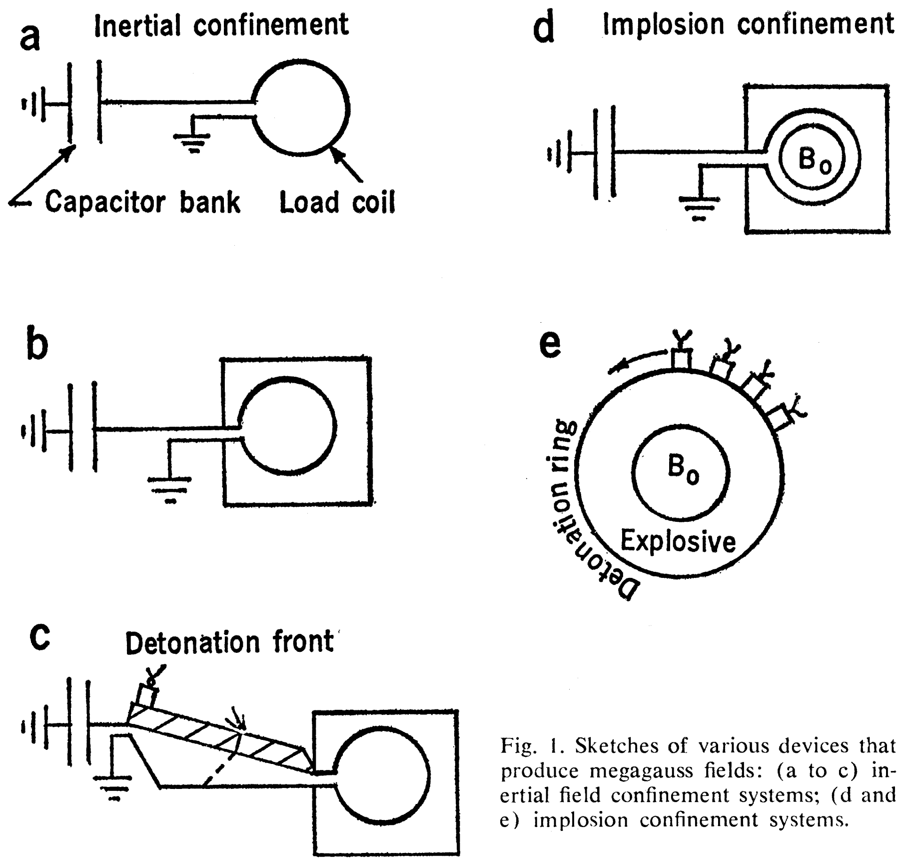


Fig. 1. Sketches of various devices that produce megagauss fields: (a to c) inertial field confinement systems; (d and e) implosion confinement systems.

initial flux is supplied at relatively low fields from a capacitor bank not only to the load coil but also to a larger cavity. This cavity is then compressed through the action of the explosive strip shown in Fig. 1c. As the detonation front moves along the strip, the top metal plate of the cavity is driven toward the load coil, thus increasing the flux density in the load coil. Various modifications of this technique have been used to produce fields in excess of 2 MG (*13, 14*). Megagauss fields produced with capacitor banks are generally restricted to small volumes, with diameters and lengths of a few millimeters. Much larger field volumes are available with explosive flux-compression systems. Diameters of 2 cm and lengths of 8 cm are typical.

External confinement systems are shown in Fig. 1, d and e. Both systems rely upon the cylindrical implosion of a conductor or "liner," as it is usually called. The liner, as it moves in radially, compresses an initial central magnetic field to much larger values. Figure 1d illustrates a system in which implosion of the liner is itself achieved by an external magnetic field produced by a capacitor discharge, as first done by Linhart (*15*). Cnare (*16*) first achieved megagauss fields with this method by careful matching of the liner to the drive field. Alikhanov *et al.* (*17*) have produced axial megagauss fields, but the coil and liner geometry were such that the implosion fields were tangential.

Figure 1e shows schematically how very large fields are produced with explosive compressions (*3, 4*). Initial fields B_0 are induced inside a conducting liner. Subsequent compression of the initial flux is achieved with explosives. To produce ultrahigh fields in a consistent manner, great care must be taken to assure symmetry of the implosion. Besancon (*18*) has made the most thorough study of systems which consistently produce fields in excess of 10 MG.

The possibility of producing 50-MG fields with explosives has been discussed by Bitter (*19*). However, the task will be enormous since the magnetic pressure of such a field is 100×10^6 atmospheres.

Measurement of Megagauss Fields

Most experimenters determine field strengths from the electric signals induced in small area coils placed in the field region. Field values obtained in this way are now thought to be accurate to within 1 percent or so, at least to 10 MG. However, as recently as the Frascati Conference (*5*) the accuracy of small coil or "probe" measurements was questioned, and values of the field quoted were classified as confirmed only if a subsidiary measurement of the field agreed with that obtained from the probe signal. At that time parallel measurements had been carried out to fields only as high as 2 MG, with Faraday rotation or Zeeman splitting measurements of well-known materials used for the companion measurement. Somewhat later Garn *et al.* (*20*) obtained a calibration at 5.1 MG, by measuring the Zeeman splitting of the sodium *D* lines.

In fields greater than 10 MG, eddy current heating of the probes can be serious, as discussed by Besancon (*18*). Another problem arises from possible distortion of the probes. Kilovolt potentials are developed, even in probes of very small area. Since the probes are normally connected to a resistance of 50 ohms, they carry significant currents and are therefore subjected to large radial forces in megagauss fields. Because the probe wires are normally of very small diameter, it is probable that they have undergone substantial radial motion, at least in some experiments reported in the past. This motion would result in probe areas smaller than the calibrated value with the result that calculated field values would be low.

Megagauss Fields as Pressure Sources

Megagauss fields were considered quite early (*21*) as pressure sources for powering θ-pinches, highly successful devices for producing high-temperature plasmas (*22*). When deuterium is used in these devices, thermonuclear fusion is achieved, as evidenced by the emission of neutrons of energy characteristic of deuteron-deuteron reactions. The linear θ-pinch device consists essentially of a ceramic cylinder containing a few hundredths of a torr of deuterium gas, placed in an axial field coil. Various methods are used to ionize and preheat the deuterium to such a condition that it becomes a good electrical conductor. Subsequent application of current in the surrounding coil, normally supplied by a fast capacitor bank, results in magnetic drive fields which compress the plasma.

Figure 2a shows schematically an end view of the pinch device. Under highly simplified conditions, the plasma compression process can be described by the ideal gas laws of Eq. 3. In the first of these two expressions, the ideal gas equation of state, the pressure P is expressed in terms of the magnetic field B, according to Eq. 1, while n is the density of particles per cubic centimeter and T is the absolute temperature. The factor 2 in this equation accounts for the electrons present in a fully ionized hydrogenous plasma. The second expression in Eq. 1 further relates the pressure and particle density of a hydrogenous plasma during isentropic compression. To these equations may be added the equation for the fusion reaction rate, R, of Eq. 4. Here, R is expressed in reactions per unit plasma volume in unit time and $\sigma(T)$ is the deuteron-deuteron plasma cross section. This function can be determined from the cross sections of the deuteron-deuteron reactions when the plasma velocity distribution is given, such as for the Maxwell-Boltzmann distribution (*23*).

$$P = B^2/8\pi = 2\ nk\ T;\ P\ n^{-5/3} = \text{constant} \tag{3}$$

$$R = \frac{n^2\ \sigma(T)}{2} \tag{4}$$

Once the initial conditions are known (which determine the constant), the expressions in Eq. 3 are sufficient to permit one to determine n and T as functions of B. Knowledge of these quantities, in turn, allows calculation of R from Eq. 4.

The graph in Fig. 2b gives two magnetic field curves. The dotted curve shows the usual continuation of fields produced by capacitor banks beyond the first peak such as occurs in laboratory θ-pinches. Peak field values are of the order of 100 kilogauss (kG). Typical reaction rates obtained are 10^7 cm^{-3} per microsecond, and total yields observed per shot are around 10^7 neutrons per centimeter of plasma column length.

The solid curve in Fig. 2b shows how the drive field would vary if the θ-pinch coil were sealed off at the peak field produced by the capacitor banks and subsequently imploded. Thomson *et al.* (*24*) have summarized the results of a number of experiments performed at Los Alamos in which this technique was employed. Implosion was achieved with the use of high explosives which were placed around the field coils. Figure 6 of (*24*) shows that deuteron-deuteron reaction rates of 10^{12} cm^{-3} per microsecond could be achieved in principle with drive fields of 1 MG. Similar considerations show that fields of 10 MG could produce rates as high as 10^{18} cm^{-3} per microsecond for deuterium-tritium mixtures. Linhart (*25*) has investigated conditions under which profitable fusion yields might be obtained. He concluded optimistically that an imploded θ-pinch powered by a ton of explosive would produce fusion energy equivalent to that of several tons of explosive.

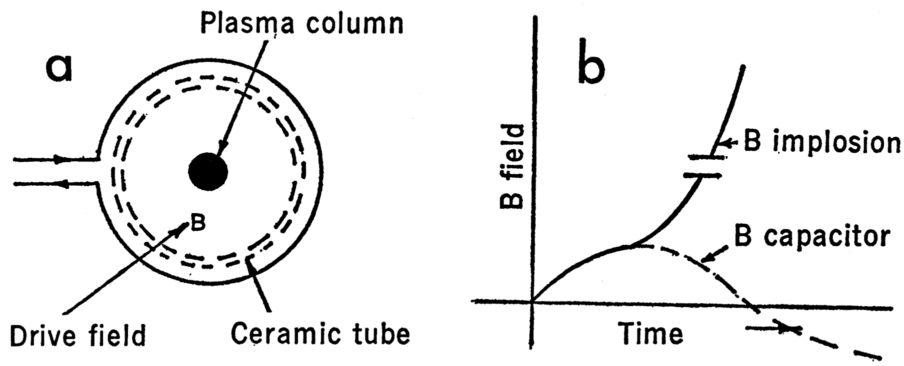


Fig. 2. (a) End view of a θ-pinch device that produces high-temperature plasmas. (b) Magnetic drive fields as produced by a capacitor bank and by implosion.

As Thomson *et al.* have pointed out (*24*), the yields actually obtained in the Los Alamos experiments were several orders of magnitude lower than predicted. Part of the reason for this is now understood. The buildup time to large fields, several microseconds, was too long to prevent the plasma from escaping out of the ends of the relatively short coils used. There still remains promise for this technique if suitable methods can be found to preheat the plasma properly in certain multimegagauss systems that were developed in the program.

Recently widespread interest has developed in the use of laser beams to heat material to fusion temperatures. It has been pointed out that megagauss fields (*26*) could be used to reduce the laser energy input for a given amount of fusion output.

The use of shock-wave techniques to obtain high-pressure equation of state data is now well known. An early summary of the techniques has been given by Rice *et al.* (*27*), and the subject has been updated by McQueen and his coworkers (*28*). The method consists of driving a shock wave through the material under investigation and, from suitable measurements, inferring the shock-wave velocity and the particle velocity of the material behind the shock front. These values, with the application of mass, momentum, and energy conservation equations across the shock front, together with information on the initial conditions of the material, would make it possible for one to calculate the pressure, density, and internal energy of the shocked material.

The locus of pressure and volume points for a material shocked to various pressures from the same initial condition is called the shock Hugoniot. The shock process is irreversible, a feature which manifests itself in two ways. The material gets increasingly stiffer as the pressure increases, tending asymptotically to a minimum volume, and at the same time heats up drastically at high pressures. On the other hand, isentropic compression to the same pressure can result in much greater compression and far less heating, particularly for softer materials (*29*). With the use of the shock-wave data and other information available for most materials, high-pressure equation of state data may be calculated for state points off the Hugoniot. These calculations can be particularly reliable when the state points are not too far away from the Hugoniot (*27, 28*).

Recently, several groups have begun to apply magnetic compression techniques to obtain high-pressure data not readily accessible by shock-wave techniques. The reason for this inaccessibility is that the magnetic pressures, unlike the pressures generated by shock waves, build up gradually and the compression process is nearly isentropic. Thus, for soft materials in particular, high-pressure points far off the shock Hugoniot can be reached. In the experimental arrangement used by the Los Alamos group (*14*) the sample under study is encased in a conducting sleeve which is placed within a high field coil of the type shown in Fig. 1c. As the magnetic field builds up, it compresses both sleeve and sample. The drive field

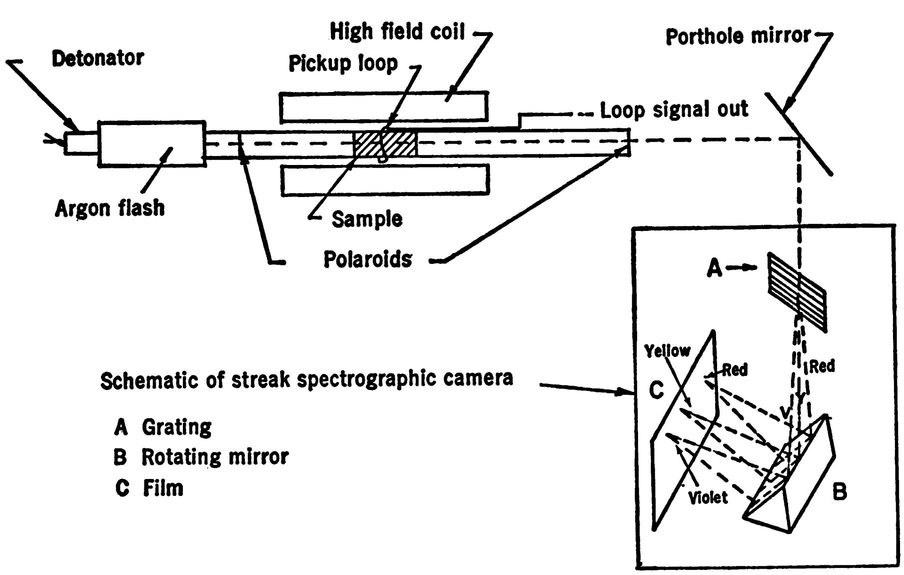


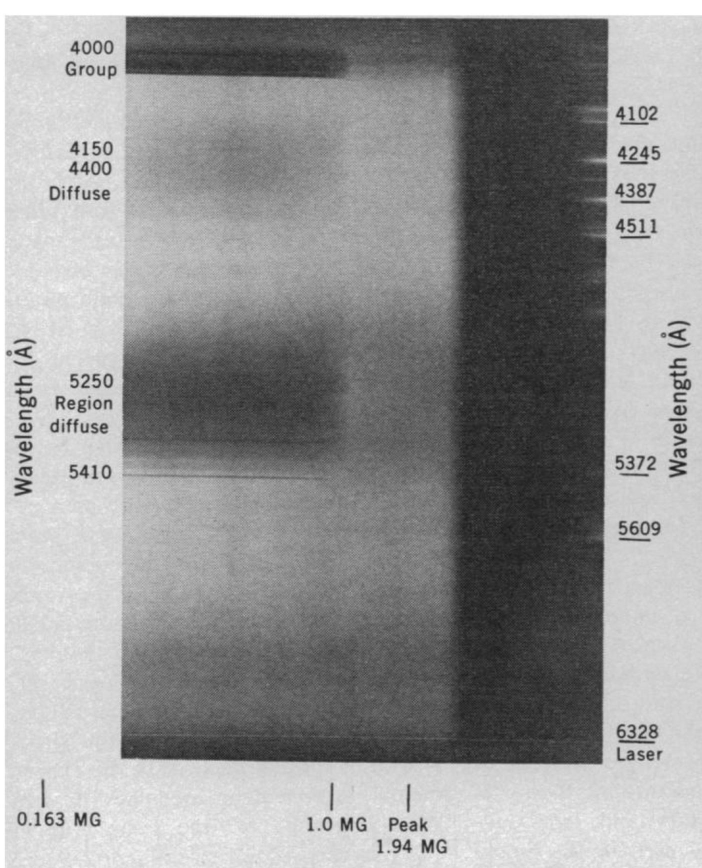
Fig. 3. Schematic drawing of the system used for megagauss field optical experiments. Light passing through the sample is directed to the spectrographic sweep camera which splits the light by wavelength and focuses it on the film at a position determined by the orientation of the rotating mirror.

outside the sleeve is monitored by a probe which allows calculation of the pressure, while a flash x-ray picture taken down the sleeve axis permits measurement of the sample volume at one instant during the magnetic field buildup. These experiments are designed to obtain data points for condensed hydrogenic materials in the range of 40 to 160 kilobars (drive fields of 1 or 2 MG). Hawke and his co-workers (*30*) have applied cylindrical implosion systems which generate drive fields of the order of 10 MG. They have obtained data for several materials up to 4 megabars. A major investigation at present is the search for metallic hydrogen, and they hope to measure its transformation pressure if it is found (*31*).

Finally, the work of Bless (*32*) may be cited as a use of megagauss fields for pressure generation. Samples under investigation were embedded in a hollow conducting cylinder and subjected to high pressures upon passage of large currents (from a capacitor discharge) through the cylinder. Investigation of the recovered samples showed that some of them had been exposed to pressures up to some hundreds of kilobars, thus implying solenoidal drive fields on the cylinder in the megagauss range.

Megagauss Fields and Particle Physics

Erber (*33*) has reviewed a number of the electromagnetic processes that could occur when high-energy particles interact with intense magnetic fields. The transition probabilities of the various processes generally increase with the



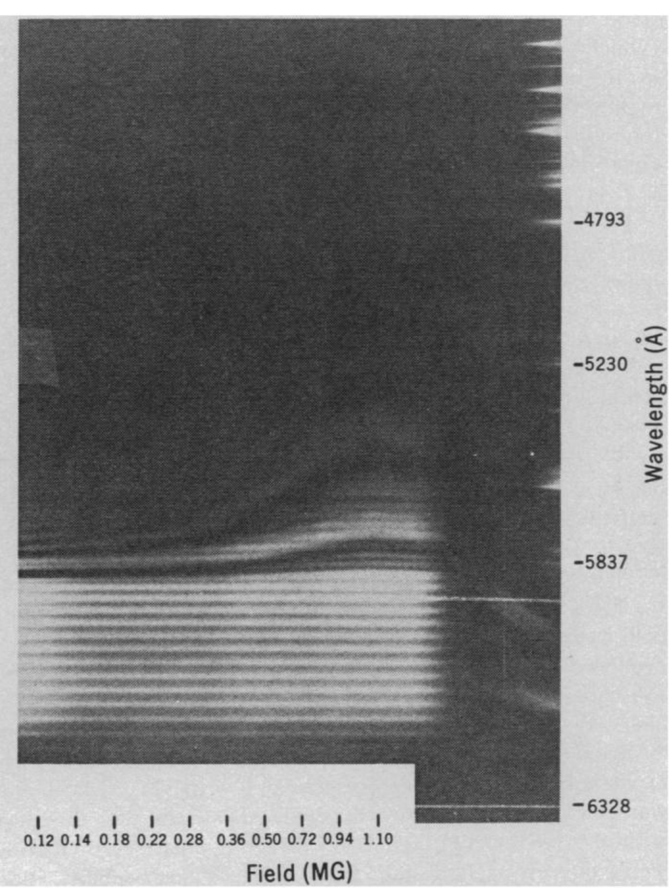


Fig. 4 (left). High field spectrum of MnF_2 at 7°K. Note the disappearance of much of the structure near 1 MG. Fig. 5 (right). High field transmission spectrum of GaSe at 7°K showing the field variation of several exciton levels. The vertical diffraction fringes at the right of the exciton bands arise because the GaSe crystal is optically thin and is of uniform thickness.

dimensionless parameter τ, given by the first expression of Eq. 5. In this equation, E is the energy of the particle, m is the electron rest mass, c is the velocity of light, and B is the magnetic field; B_c, a characteristic field, is given by the second expression in Eq. 5, where e is the electronic charge and h is Planck's constant.

$$\tau = (E/mc^2)\ (B/B_c);$$
$$B_c = m^2c^3/2\pi eh \doteq 4 \times 10^7 \text{ MG} \quad (5)$$

The processes become more favorable at higher particle energies and larger fields, although, even with use of the large energy machines under construction today and the multimegagauss fields now available, many of the processes are still marginally detectable or not detectable.

However, the observation of some interaction phenomena does appear feasible, and, in the case of magnetic bremsstrahlung (synchrotron radiation), experimental confirmation of some classical effects has already been achieved. Mashkour (*34*) has reported on the experimental bremsstrahlung results obtained from the interaction of 20-giga-electron-volt (Gev) electrons with magnetic fields up to about 1.5 MG. Excellent agreement was obtained between measured and calculated bremsstrahlung distributions. The experiments were carried out at the Stanford Linear Accelerator Center (SLAC). The program was directed by Erber, and the megagauss field facility was designed by Herlach [see (*35*)].

As Erber has noted, quantum effects not normally considered in synchrotron radiation theory should arise at sufficiently high particle energy and magnetic field strengths. These effects come into play when the photon radiation reaction competes favorably with the normally dominant Lorentz forces. This problem has been considered recently by Shen (*36*). Although the effect was marginal in the SLAC experiments, it probably could have been observed if higher fields had been used. Shen predicts that a similar experiment carried out in 5.0-MG fields, with a beam of 400-Gev electrons, would show a detectable beam deflection and change in bremsstrahlung intensity distribution arising from the radiation reaction.

Megagauss fields also are applicable in high-energy particle analysis. Kim *et al.* (*37*) have noted that better energy resolution could be obtained from the analysis of particle tracks in nuclear emulsions if the emulsions were situated in large magnetic fields. Measurement of the angular deviation of a track left by a particle in the emulsion allows calculation of the particle's radius of curvature, from which, with the known value of the field, its momentum may be calculated. Uncertainties arise, however, because the natural deflection of the particle by the field is altered as a result of the multiple scattering of the particle by the nuclei in the emulsion. Kim *et al.* have showed that these uncertainties could be reduced with the use of higher fields, which lead to greater field deflection but do not increase the probable scattering deflection. Utilizing fields of about 200 kG, they were able to reduce the scattering uncertainty to about 10 percent.

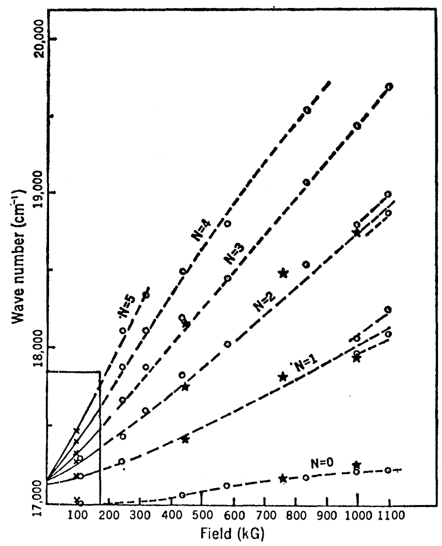


Fig. 6. Exciton energy levels of GaSe at high fields. The region set off by the rectangle to 175 kG contains data obtained by Aoyagi *et al.* (*46*) and the 100-kG data (X's) was obtained by Halpern (*47*).

Recently, Heckman and Herlach (*35*) have carried out similar experiments with the SLAC beam and the megagauss devices used for the bremsstrahlung measurements mentioned earlier. A stack of emulsion disks of small diameter was placed inside the magnetic field coil, and, as with the bremsstrahlung experiments, the accelerator beam was timed to pass through the coil at peak field. An analysis of the resultant emulsion tracks showed that the radii of curvatures could be measured to within an accuracy of the order of 3 percent.

Large electric fields accompany the generation of megagauss fields, and this has led to several suggestions for their use as particle accelerators. Terleskii (*38*) was the first to propose the use of implosion-produced fields, but no details of the acceleration mechanism were given. He stated that 100-Gev particles could be produced in systems achieving 10-MG fields.

Fowler and Garn (*14*) considered the use of several types of flux-compression devices as accelerators. One application called for accelerating large quantities of 100-volt deuterium ions, which can be produced from explosive jets (*39*), to energies in the 10-kilovolt range. In principle, this can be done by injecting the deuterons into a cylindrical implosion system, in which case the particle energy multiplication factor turns out to be the same as the field multiplication factor. In the example treated a low initial field of 500 gauss was required to adjust the initial orbit of the deuterons to the physical dimensions of the implosion system. Use of the same implosion system but with an initial field of 50 kG would allow injection of 1-million-electron-volt (Mev) deuterons. With a typical field multiplication of 100, the deuterons could be accelerated to 100 Mev.

The prize for concepts of this kind must go to Sakharov (*4*). He has discussed a betatron device capable of generating 1000-Gev particles, which requires a central field of 10 MG. The physical dimensions are such that the peak magnetic field energy is equivalent to that in a megaton bomb. He has stated, however, that bursts of 10^{18} protons would be produced in each shot, and that the experiment could be repeated 50 to 100 times for the cost required to build a permanent machine of this energy.

Solid-State Studies

Solid-state studies in megagauss fields are beset with a number of difficulties. Physical limitations arising from the transient nature of the fields exclude some otherwise interesting investigations (*40*). From the practical side there are other experimental disadvantages. The fact that at fields greater than 1 MG the magnetic field coil is destroyed is a serious limitation; the loss of the specimen under investigation, when it is subjected to implosion-produced fields, is intolerable in some cases; and extraneous electrical pickup can be a serious problem when electronic detection equipment is employed.

In spite of these difficulties, several investigations have been carried out in which electrical diagnostics were employed. Caird *et al.* (*41*) and Herlach

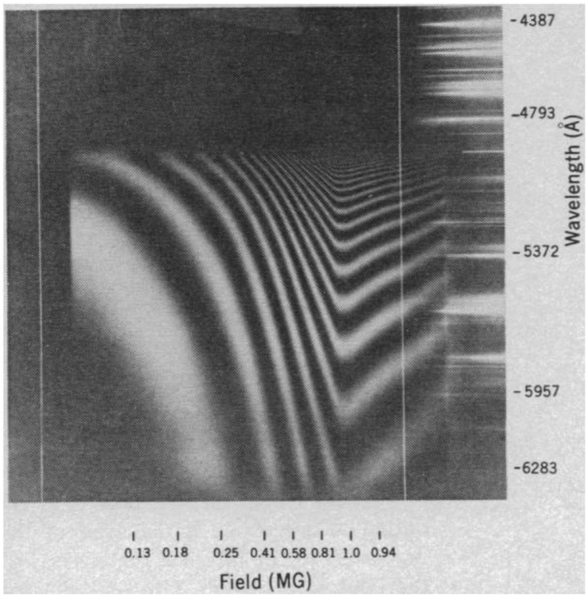


Fig. 7. High field Faraday rotation spectrum of CdS at 7°K. The rotation increases enormously for wavelengths near the absorption edge.

et al. (*42*) have reported on megagauss Faraday rotation in quartz and crown glass. Polaroids were placed on both sides of the sample, and single wavelength lines of light (the mercury blue and green lines) were transmitted through the samples. The variations of light intensity with magnetic field produced by the rotation of the light polarization planes were detected by photomultiplier tubes.

Recently, Davis and Herlach (*43*) have made reflection cyclotron resonance studies on InSb in megagauss fields. Intense light sources were obtained from both CO and CO_2 lasers, and the reflected light signals were monitored with GaAs detectors. Fields as high as 1.5 MG were employed, and new resonances were observed as high as 800 kG.

Magnetoresistance measurements have been made with thin bismuth wires (99.9 percent pure) in megagauss fields (*14*). An external power source was used to drive a current through the wire, and the voltage across the sample was monitored during the buildup of the magnetic field. It was found that at 300°K the transverse magnetoresistance increased linearly to a value of 22 times the zero field resistance at 250 kG. At larger fields, it began to show signs of saturation, reaching a value of 40 times the zero field resistance at 1 MG.

Lasers are now available which can furnish intense, coherent beams of light at many different wavelengths. If they are used, noise problems in the electronic detection of optical signals can be greatly reduced. However, such light sources furnish high field information at only a single wavelength or perhaps a few discrete wavelengths per experiment.

High Field Optical Experiments

I would like to devote the remainder of this article to a discussion of a few high field optical experiments carried out at Los Alamos, in which data have been obtained over the continuous visible wavelength spectrum for each experiment. The general experimental setup is shown in Fig. 3. The sample under investigation is placed in the high field coil. A source of intense white light, produced by shocking a tube of argon gas with a detonator, is directed through the sample and then to a high-speed spectrographic camera with a rotating mirror. Straight optical absorption of the light can be obtained, or, by placing Polaroids ahead of and behind the sample as indicated in Fig. 3, Faraday rotation experiments can be performed. More experimental details for room-temperature operation have been given by Garn *et al.* (*44*), and the extension of the technique to operation at cryogenic temperatures has been discussed by Caird and his co-workers (*45*).

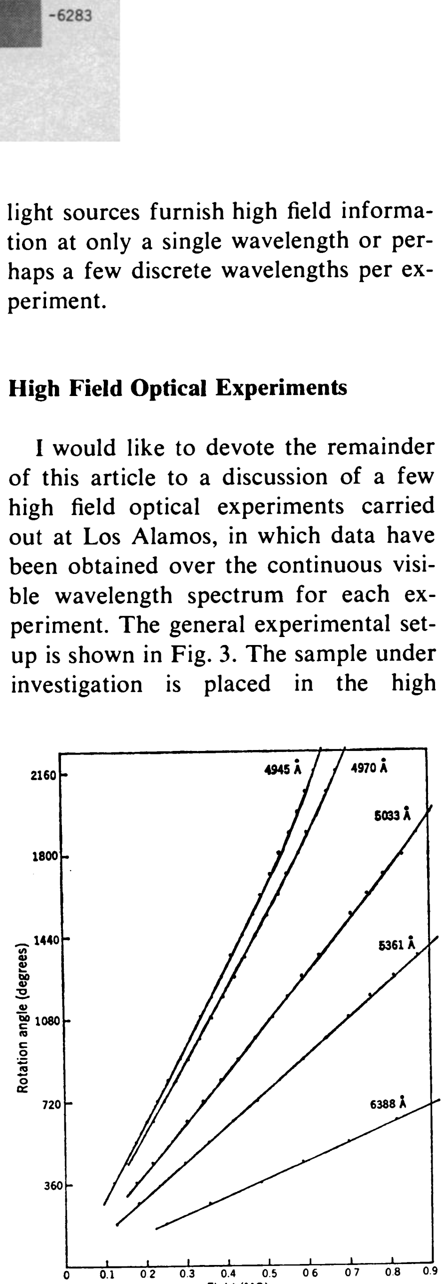


Fig. 8. Plot of the rotation angles of polarized light versus the field in CdS for selected wavelengths. For wavelengths near the absorption edge, the rotation is not linear with the field.

Caird *et al.* have presented results which confirm the prediction that the sublattice magnetic moments of low-temperature MnF_2 should become parallel at twice the exchange field, 1.1 MG. The complete disappearance of a number of absorption lines and bands at 1.02 MG is consistent with this theory. This work, which was done in a field system normally peaking at 1.1 MG, has been extended (*14*) with the use of MnF_2 crystals of other orientations, and 2-MG field systems. Figure 4 is a photograph of a record obtained at 2 MG. In this case also the abrupt disappearance of much of the structure occurs at about 1 MG. The line spectrum at the right in Fig. 4, obtained from an explosive bridge wire and the helium-neon laser line at 6328 angstroms which is superimposed on the record, serves as a wavelength calibration.

Figure 5 is a record of the absorption spectrum of a thin sample of GaSe. The samples used were thin single-crystal platelets, and the resulting interference fringes superimposed on the exciton absorption structure are quite apparent. The results obtained for this material are given in Fig. 6, where possible line splitting of some of the exciton lines at high fields is indicated. Records obtained recently at higher fields (*14*) show evidence of still more structure which is not understood.

Figure 7 shows a Faraday rotation record obtained for CdS. Clearly evident is an absorption cutoff region around 4900 Å. The explanation of the unusual character of Fig. 7 can best be obtained by following a particular wavelength of the white light spectrum across the photograph. The alternate light and dark regions then correspond to 90° rotations of the polarization plane of the light of that particular wavelength as the field increases. The sudden leftward deflection of the light and dark streaks occurs at peak field. Beyond this point the field begins to drop but at a slower rate than the rise near peak. Rotation angles are plotted as a function of field for several wavelengths in Fig. 8. For the longer wavelengths, the rotation up to 1 MG is linear with the magnetic field. For wavelengths near the absorption edge, the amount of rotation increases enormously and is no longer linear with the field. This experiment has been repeated at higher fields, and preliminary results indicate that deviations from rotation linearity with field begin to occur at longer wavelengths. This is an odd result, since, in an experiment performed without the use of Polaroids, the absorption edge was observed to move 63 Å toward the violet at 1.9 MG. Details of the experiments with CdS and several other materials are available in (*14*).

Summary

Fields greater than 10 MG can be produced by explosive flux compression and fields up to 3 MG with capacitor banks. Measurement of fields up to 10 MG is reliable, but difficulties may be expected at higher fields. Megagauss fields have been applied successfully as high-pressure sources, in high-energy particle physics, and in solid-state investigations. Other uses remain to be exploited: plasma compression by megagauss fields has been relatively unsuccessful but shows promise; their use as particle accelerators has been studied only theoretically; and much work remains to be done, both experimentally and theoretically, in connection with applications of megagauss fields in solid-state physics.

Note added in proof: Since this article was prepared, Grigor'ev *et al.* have carried out some experiments (*48*) in which they have compressed hydrogen up to a density of 1.95 grams per cubic centimeter with a calculated pressure of 8×10^6 atmospheres. They report five different pressure-density points and claim that their data can be explained by assuming that the transition to the metallic phase occurs at a pressure of 2.8×10^6 atmospheres, with a density change from 1.08 to 1.3 g/cm^3. Using the flux compression techniques described earlier in this article, Hawke *et al.* [see (*30, 31*)] have obtained a pressure-density point at 1.5×10^6 atmospheres and 1.0 g/cm^3, which is also not inconsistent with a predicted equation of state of metallic hydrogen (*49*). In view of the experimental uncertainties, none of the pressure-density data can yet be used conclusively to establish the transition's existence. Hawke and his co-workers are presently engaged in measurements of the electrical conductivity of the compressed hydrogen. Observation of a significant conductivity at the proposed transition pressure would be a more definitive test of a metallic transition. In addition, two lower pressure-density points have been obtained for deuterium by the Los Alamos group, by means of the flux compression methods described earlier in this article. One point agrees to within experimental error with a slight extrapolation of Stewart's data (*50*). The second point is at a pressure of $65 \pm 3 \times 10^3$ atmospheres with a density of 0.71 ± 0.10 g/cm^3. The data are tentative, and efforts are under way to obtain more data points at both higher and lower pressures.

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$$T \to T_0P/4P_0$$
$$V \to V_0/4$$
The ideal gas isentropic compression equations give as the volume and temperature for the compressed gas
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