MEGAGAUSS FIELDS

Magnetic intensities thousands of times as great as one usually achieves with magnets are made by explosively compressing field lines. The fields can be applied to superconductivity, thin-film research and attempts at nuclear fusion

by Jiři G. Linhart

MEGAGAUSS MAGNETIC FIELDS are intimately connected with such entities as megaämperes, megajoules and megabars. Density of stored magnetic energy corresponding to megagauss fields is higher than that of high explosives, and it follows, therefore, that coils producing such fields will disintegrate under the enormous pressures and energy dissipations required. These and other relations between megagauss fields and explosives have caused the subject to fall for many years under the shadow of military classification.

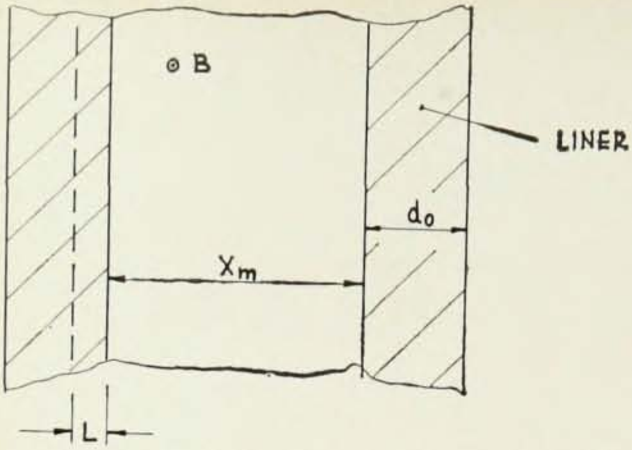
But megagauss fields have recently come into the open, particularly at a conference held last fall. It was organized by the EURATOM-CNEN association at the Laboratorio Gas Ionizzati at Frascati, near Rome. The purposes of the conference were two: first to describe experiments and theory related to the various methods of generating megagauss fields and second to discuss applications of these very intense fields.

The author, who was born in Prague, Czechoslovakia, reached London as an olympic swimmer and remained there to complete his education. By way of CERN, he reached the Laboratorio Gas Ionizzati at Frascati, near Rome, where he now works on fields and fusion. He is the author of a book titled *Plasma Physics* and is a black belt of Judo.

GENERATION OF MEGAGAUSS FIELDS

If one takes 100 000 atmospheres as the limit for pressures that can be generated in a static fashion, it follows that only fields $B<1.58$ megagauss can be produced and held by material structures. More intense fields can be produced dynamically by either rapid discharge of a capacitor battery into a coil or compression of a tube of magnetic flux by convergence of conducting material.

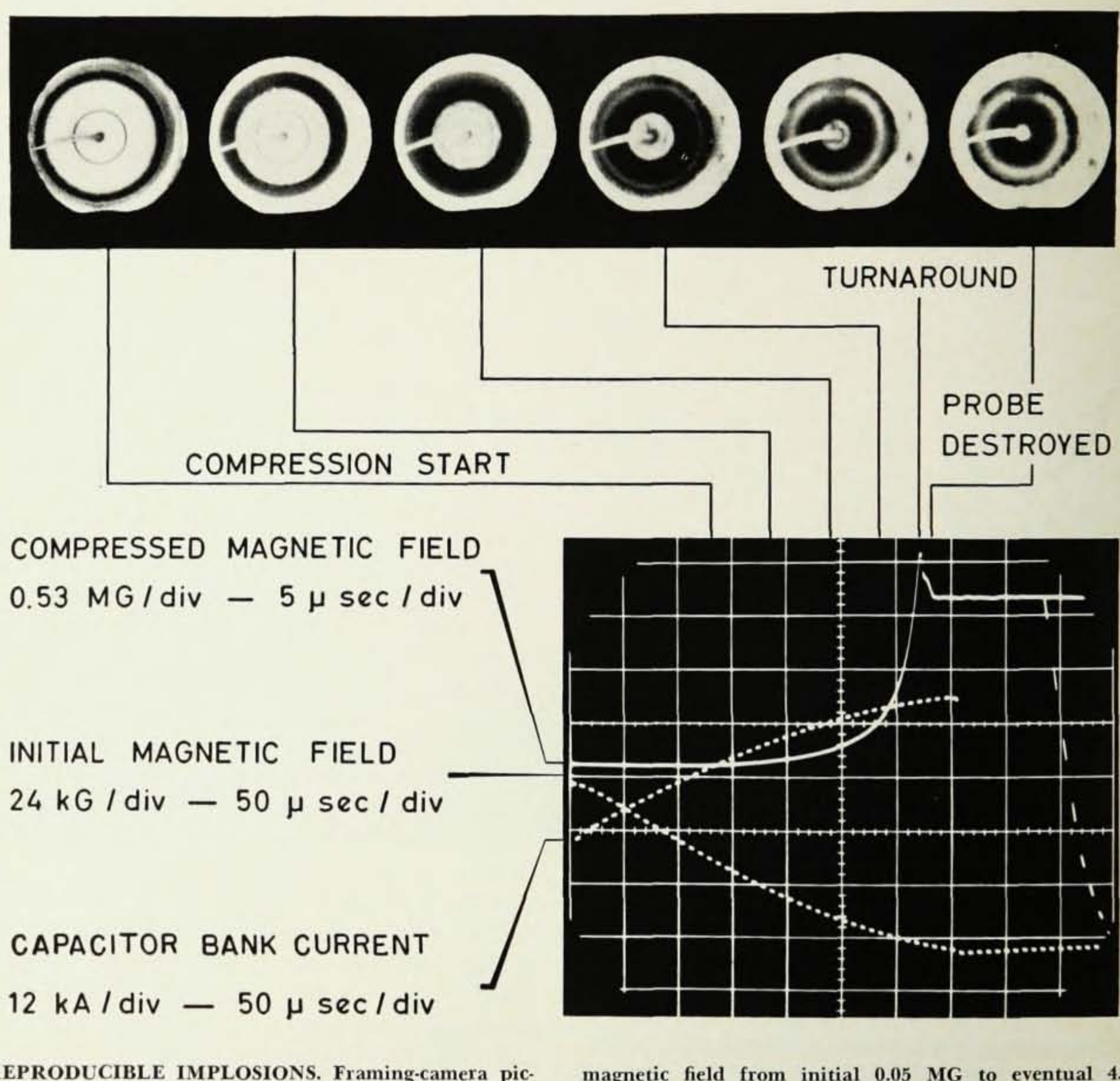
The magnetic energy density in a field of 5 MG is equal to 100 kJ/cm^3 whereas the pressure is 10^6 atm. The energy density in conventional fast capacitors is of the order of 1/100–1/10 J/cm^3, and it is evident, therefore, that it will be extremely difficult to empty a reservior having such a low energy density into a receptacle requiring a high energy density. This difficulty is reflected in the impedance matching of a large capacitor bank to a small coil—usually a single-turn one. At the Frascati conference R. W. Waniek and Harold P. Furth showed that this difficulty can be somewhat alleviated by a current transformer. With it magnetic fields up to



INTENSE FIELDS BY IMPLOSION. With perfectly conducting plane liner all kinetic energy could be converted into magnetic energy, but because sound velocity is finite, only that in L is converted. —FIG. 1

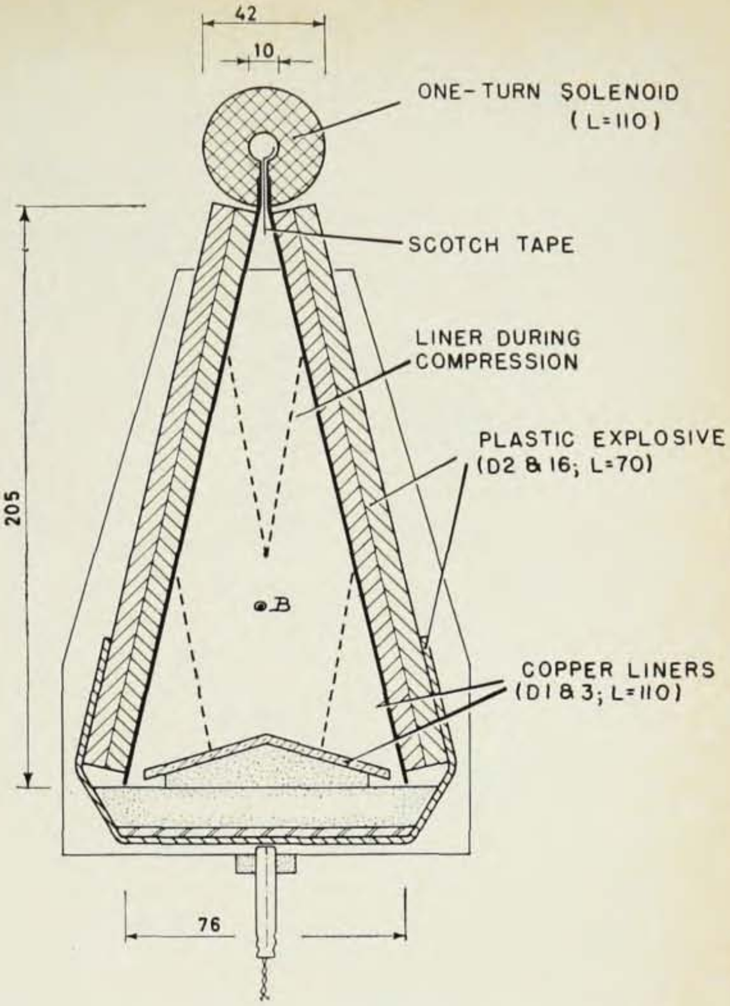
a megagauss can be obtained in a volume of a few cubic centimeters. The fields last for the order of several microseconds. It does not appear to be convenient to generate fields more intense than 2 MG with the capacitor bank as an energy reservoir even when current transformers can be used. This limit is due to two facts: first the coil generating the field will disintegrate in an explosive manner; second the volume of the capacitor bank becomes considerable. It is advisable, therefore, to use energy sources that have higher energy densities than capacitor banks and that nevertheless can be emptied within a time of the order of microseconds.

One of the most convenient devices belonging to this category is an electrically conducting liner propelled by a detonated high explosive. The explo-



REPRODUCIBLE IMPLOSIONS. Framing-camera pictures at top taken at intervals slightly greater than 5 microsec show that magnetic field is gradually compressed to a maximum and then after "turnaround" expands again. Solid trace in graph records increase of magnetic field from initial 0.05 MG to eventual 4.5 MG. Slightly after turnaround at maximum intensity measuring probe is destroyed by implosion as indicated by discontinuity in solid trace. These results were achieved by author's group at Frascati. —FIG. 2

MAGNETIC BELLOWS produces a planar compression. At end of compression most of flux has been squeezed into one-turn solenoid. Dimensions are in millimeters. —FIG. 3



sive liner accelerates the conducting liner (usually a sheet of metal) giving thus a kinetic energy density $\rho v^2/2$. The liner compresses a trapped magnetic flux and in doing so converts a portion of the kinetic energy into the stored magnetic energy of the compressed flux. Assuming a perfectly conducting, incompressible liner in a plane geometry (figure 1) it is clear that all the kinetic energy can be converted into magnetic field energy. At the moment of such a perfect conversion, one has

$$X_m B_{max}^2/8\pi = \rho v_0^2 d_0$$

where X_m is the minimum thickness of the squeezed flux and d_0 and v_0 are thickness and initial speed of the liner. In such a case the thicker the liner, the higher will be the maximum field. Since the speed of sound c is finite and in many cases of the same order of magnitude as v_0, only a layer of limited thickness L can convert its energy into the energy of the compressed field. If the characteristic time of compression is $t_c = 2X_m/v_0$ one has

$$L < c\, t_c \approx 2X_m\, c/v_0$$

Therefore using liners of thickness $d > L$ will not enable us to reach magnetic fields greater than

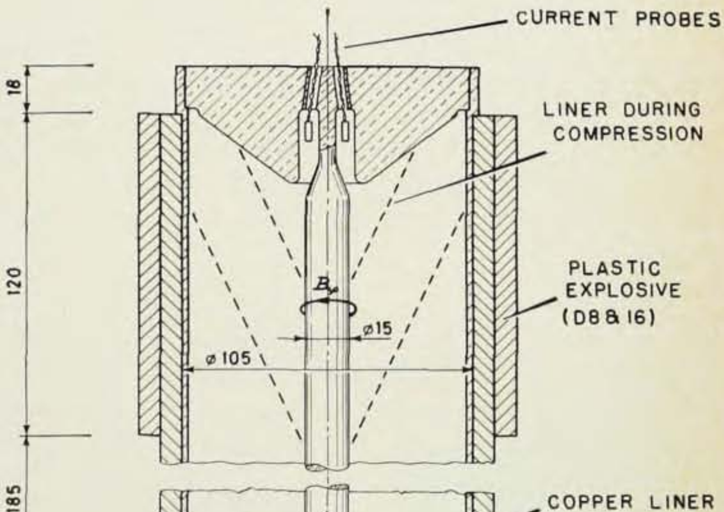
$$B_{max} \leq (8\pi\, v_0\, c\rho)^{\frac{1}{2}}$$

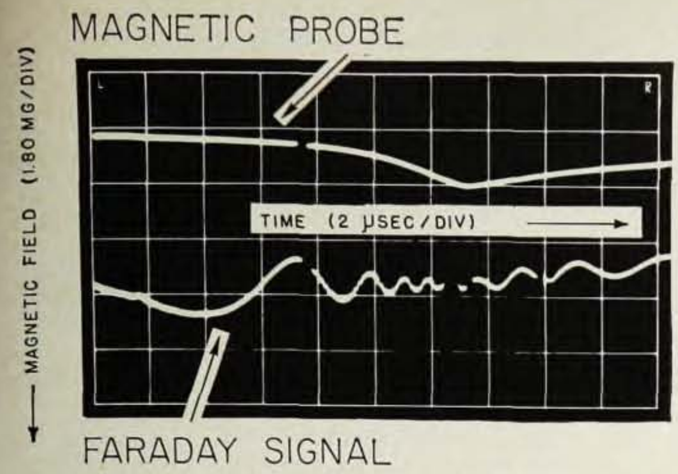
More intense fields can be reached only by increasing the initial kinetic energy of the liner.

Cylindrical and slab geometries

When flux compression is effected in a cylindrical geometry, greater fields can be reached because of convergence of the flow in the liner. Although the liner cannot be unduly thick (otherwise most of its kinetic energy is converted into the internal energy of the liner and not into the magnetic energy of the compressed flux), J. P. Somen demonstrated that even in ideal situations magnetic fields greater than 20 MG are difficult to obtain with explosive propul-

COAXIAL BELLOWS. This simplified design is electrically a short-circuited length of coäxial cable fed from a capacitor bank. When the current in the system reaches a maximum, the detonators (bottom of figure) are fired. Detonation wave—propagates in the explosive on outer surface of cable (the liner) propelling it radially inward. This motion is responsible first for crow-barring of capacitor bank and later for compression of magnetic flux into coäxial chamber where amplified field is measured by magnetic probes. Dimensions are in millimeters. —FIG. 4





FIELD MEASUREMENTS are made with magnetic probes (upper trace) or Faraday effect. Each minimum in lower curve corresponds to 180-deg rotation. —FIG. 5

sion of liners. The maximum attainable field is also limited by diffusion of the field into the liner, that is, by the flux loss. However, G. Lehner has shown that this limitation is not as serious as the dynamic one.

Several well documented experiments on flux compression in cylindrical geometry were described at Frascati. Regular and reproducible implosions have been achieved by the Frascati group, maximum fields obtained being around 4.5 MG (figure 2), the initial fields being about 50 kG. Similar results were described by M. Fowler (Los Alamos), the father of the flux-compression experiments. The French group (A. Brin and colleagues) reported measuring in one case 9.8 MG, several other measurements being clustered around 6 MG. These fields have been measured by small, shielded magnetic probes on the axis of the compressed flux tube.

One would expect that after the moment of maximum compression the liner is repulsed and the flux tube will begin to expand. Such behavior is termed a "turnaround." Although such behavior has been qualitatively observed in some experiments (Herlach, Knoepfel, figure 2) the curve $B(t)$ does not agree with theoretical expectations near the turnaround and better measurements are required before a satisfactory knowledge of processes near this point can be reached.

Flux compression can be achieved in geometries other than cylindrical. An essentially plane compression has been achieved in devices known as magnetic bellows or current generators (figure 3, Los Alamos, Frascati). Coaxial current generators have also been used (figure 4). In these the explosive can be situated inside the central conductor, and such placement makes the task of initial detonation extremely easy. At present, final fields in excess of 2 MG in a volume of the order of 10 cm^3 can be generated. The fields can persist effectively for 10 μsec. A variant of the coäxial current generator is the helix (or spiral) bellows in which the flux generated by many turns is gradually compressed into the last turn of the helix (D. B. Cumming, M. J. Morley). These fields have been measured also by both the Faraday effect (Frascati, figure 5) and the Zeeman effect (Los Alamos).

The reproducibility of these devices was demonstrated to conference participants during a visit to the experimental facility of the Frascati group; a compression device produced a well documented 2.3 MG, in nearly 10 cm^3.

Apart from the theoretical criteria already mentioned, the maximal attainable (and usable) fields are limited by jet formation on the inner surfaces of the liner as well as instabilities. The question of instabilities has not yet been studied exhaustively though attempts have been made by E. Harris, J. G. Linhart, J. E. Besancon and others to find solutions in simple cases. It appears probable that stability and jet formation will furnish more serious criteria than field diffusion and liner dynamics.

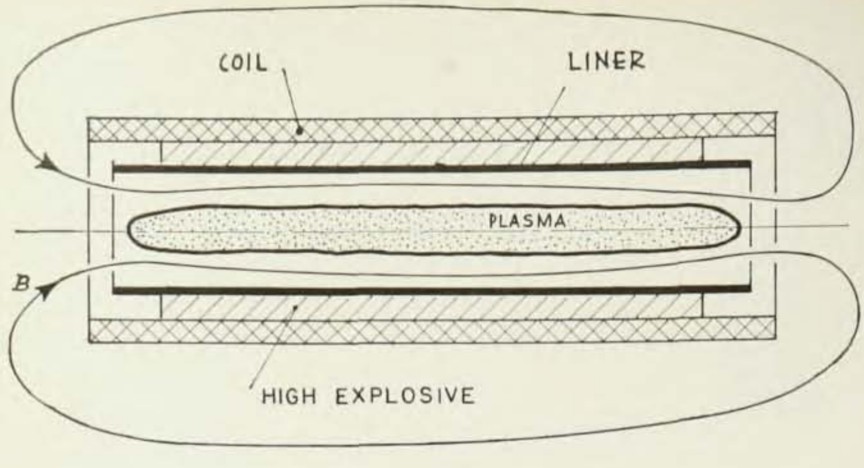
No promising plans for the generation of fields above 20 MG were presented at the Frascati conference, and it seems that new ideas will be required to reach such fields.

APPLICATIONS OF MEGAGAUSS FIELDS

Some applications of megagauss fields to solid-state physics were discussed during the meeting by J. L. Olsen. It appears that it may be interesting to investigate the effect of very strong fields on conductivity of metals. When the Larmor radius of electrons in a thin metal film becomes smaller than the thickness δ of the film, the electron reflection of the metal boundary will be substantially modified. This will occur for fields $B > 10^{-5}/\delta$ MG. Thus for $\delta =$ 0.1 micron and $B > 1$ MG the transparency and electrical resistance will be affected. There is also reason to believe that for megagauss fields superconductivity may reappear after having been destroyed when the critical field for the material has been exceeded.

An interesting subject of study is optical properties and radiation emission in strong fields. Already the Faraday effect and the Zeeman effect have been mentioned as means of measuring such fields. Observing the nonlinear processes of these effects may lead to a confirmation of or a correction to the theoretical models used according to D. Palumbo.

Another fascinating application of megagauss fields is adiabatic production of pressures in the



PLASMA-COMPRESSION DEVICE might produce densities of 10^{20} ions/cm^3 and temperatures of 10^8 °K. Confinement for only a few microseconds may eliminate disastrous role of instabilities. —FIG. 6

megaätmosphere range. Pressures in this range are usually produced by impact of fast, dense liners generating shock waves in the target material. The medium behind the front of the shock wave is heated by the wave, and consequently the large pressures are not always connected with pronounced compressions of the medium. A megagauss field can serve as a pressure cushion that does not readily transmit the sharp shock fronts and can, therefore, eliminate shock heating. There may be some very interesting applications to phase transitions in solids, transitions that may not be reversible and in which new types of solids can be created. The other advantage of magnetic cushions is the optical separation between piston and the studied specimen.

Plasma physics

Among the applications of very intense fields to plasma physics, the most interesting ones (discussed at the Frascati conference by the author) are related to controlled nuclear fusion. A deuterium-tritium plasma compressed and confined by megagauss fields can reach a density of 10^{20} ions/cm^3 at a temperature of the order of 10^8°K. For such a plasma to produce more fusion energy than the energy required to generate the plasma, confinement times of only a few microseconds will be required. It is likely that such short times will eliminate the disastrous role that instabilities play in all other approaches to nuclear fusion. An example of the form of devices that can be contemplated at present is shown in figure 6. Preliminary calculations show that this type of device, at a level corresponding to economic generation of fusion energy, should contain about one ton of explosive and produce fusion energy equivalent to between 10 and 100 tons of high explosive per shot. These are explosions that can be contained in an underground cavity, and pulsed boilers based on such principles are technically conceivable.

Another connection between plasmas and megagauss fields, discussed at Frascati by R. E. Kidder, is exemplified by the state of the inner face of the liner. The intense field diffuses into the metal, heating it, and were it not for the high pressure to which this layer is submitted, the layer would certainly explode and peel off as do the surfaces of exploding wires. Owing to the high pressure, the medium cannot expand very much, and it remains in the state of a degenerate plasma. The transport coefficients, especially the electrical conductivity, in such a medium have been studied by G. Lehner and such studies can be continued in the future.

Other application can be expected in connection with hypervelocity projectiles according to R. L. Chapman. It is not impossible that sharp gradients in megagauss fields can act as magnetic guns, driving projectiles that have suitable geometry and mass to velocities well in excess of a million centimeters per second.

FUTURE DEVELOPMENT

The Frascati conference clearly indicated the growth of interest in megagauss fields. A couple of facilities (bunkers, shooting ranges, etc.) exist now outside the classified establishments and some institutes consider having their own bunkers built. For future reference the proceedings of the conference should appear about when this article does. They will be published by EURATOM and distributed by Presses Académiques Européennes, Bruxelles.

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*Figures 2, 3, 4 and 5 were kindly transmitted to the author by F. Herlach and H. Knoepfel. Two of these figures have appeared in the Review of Scientific Instruments (***36***, 1088, 1965).*

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