THE TECHNOLOGY OF PULSED HIGH FIELD MAGNETS

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Different methods for generating strong pulsed magnetic fields are discussed with a view to applications in experimental physics:
wire-wound coils (< 70 T, 10 ms - 1 s), solid and polyhelix coils (< 100 T, ≈ 1 ms), destructive single turn coils (≈ 300 T, ≈ 2 μs), magnetic flux compression techniques (< 1000 T, ≈ 1 μs) and laser-generated hot electrons (≈ 10^4 T, ≈ 1 ns). For nondestructive coils, the peak field depends essentially on the strength of the conductor material. Megagauss systems are characterized by a typical speed of the order of several km/s which is directly related to the field and determines the longest possible pulse duration. Experiments must be designed to meet these conditions.

Introduction

The methods for generating very strong pulsed magnetic fields have been extensively discussed in recent reviews [1], in particular at MT-9 [2]. Therefore, the present paper will be restricted to a brief overview and a discussion of some recent developments.

In recent years, much engineering effort has been invested in the development of d.c. laboratory electromagnets which now can generate fields up to 35 T. It is technically feasible to generate higher d.c. fields but the cost increases so steeply that this becomes almost prohibitive, both for the facilities and for their operation [3,4]. Even now, some of the large magnet laboratories are operating on a reduced schedule because of the cost and the availability of the required electrical power. Superconducting magnets can be operated at reasonable cost. For some experiments, water-cooled magnets are still preferred because of the faster sweep rate. In the long run, the use of high-power magnets may only make sense for fields higher than 20 T.

Pulsed magnets are more economical by orders of magnitude and can provide fields up into the multimegagauss range, at the expense of less convenient experimentation in small volumes and at rapid field variation.

Wire-wound Coils

Magnetic fields with long pulse duration (≈ 10 ms - 1 s) are generated by means of compact wire-wound coils. The pulse duration scales with $\int B^2 dt \propto W$ where B is the magnetic induction and W the energy available from the pulsed power supply. This energy is absorbed adiabatically by the heat capacity of the coil. The mass of the coil is therefore proportional to the energy; approximately 1 kg of copper is needed per 100 kJ if the coil is precooled by liquid nitrogen. Typical data for the pulse duration are 15 ms (half period of a damped sine wave) for 100 kJ at 40 T in a bore of less than 20 mm. Increased energy results in a longer pulse duration as well as in a larger bore.

The big problem is the containment of the magnetic stress. All ordinary construction materials fail in the range between 30 T and 50 T. This is somewhat dependent on the specific coil design and external reinforcement, but essentially the mechan[illegible] strength must reside in the wire itself. The maximum field is approximately related to the yield strength σ of the coil material by the relation

$$B_{max} = \sqrt{2\mu_0\sigma}\ \sqrt{2}\ (1-1/\alpha)$$

where α is the ratio of the outer and inner radius (this equation is exact for a long coil without radial transmission of stress). For a coil with α=3.4, 50 T correspond to a stress of 1 GPa (copper-beryllium, strong steel). The achievement of higher fields is therefore mainly a matter of materials research, both for the conductor and for the insulating material.
A big step in this direction has recently been taken by Foner with the development of a copper wire containing extremely fine filaments of niobium. These subdivide the copper matrix into equally fine filaments such that these make an additional contribution to the strength. Surprisingly, this wire bends more easily than expected and can be wound into coils with 12 mm inner diameter. The new wire combines unusual strength with good conductivity and has made it possible to generate fields up to 70 T with 6 ms pulse duration in the first series of experiments [5]. It is likely that the combination of newly developed materials will bring further improvement. In these days, exceptionally strong insulating materials are under development, such as glass fibre and Kevlar composites and pre-stretched polyethylene, with claims for the ultimate yield strength going beyond 3 GPa. In practice, it has turned out that these values cannot be easily achieved in actual composites. When different materials are combined, it is not only the yield strength that counts but the ratio of Young's modulus which governs the distribution of stress between the materials. High performance pulsed field coils are driven into the regime of partial plastic deformation which proceeds from the inner to the outer radius and further complicates the analysis [6]. This is illustrated by Jones et al [7] with the example of a 50 T coil made from a newly developed copper wire with a steel mantle which can be manufactured at low cost. With insulating high strength composites it becomes possible to design an optimized layer by layer reinforcement of the coil.
A coil design for generating 60 T with 1 s pulse duration is proposed by Gersdorf et al [8].

Capacitor banks with thyristor switching are convenient power supplies. In single shot operation, thyristors can be used at their surge rating, presently this is of the order of 4 kV, 30 kA. The connection of many thyristors in parallel and series is now standard technology and leaves much leeway for the design. If each capacitor is individually switched by means of a rectifying element, this solves the safety problem of the entire capacitor bank discharging into a faulty capacitor. Otherwise, fuses must be installed; this presents some difficulty. Triggering by means of optical fibres is now quite feasible and reduces electrical interference.

For larger energies, flywheel-driven generators are used. Energy could be stored inductively at similar storage density, but suitable switching techniques are still under development which advances slowly. Under favourable circumstances, power can be directly obtained from a utility network. Pulse shaping by thyristor-controlled rectification then allows much

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variation in the shape of the field pulse [9].

Kido and Nakagawa [10] have obtained 50 T by the sequential discharge of two capacitor banks into two concentric coils, superimposing a 2 ms, 40 T pulse on a 10 ms, 10 T pulse. The short pulse was applied to the inner coil made of copper-beryllium, to avoid excessive damping due to the higher resistivity of the high strength material.

Solid Helix Coils

For some time, the highest fields were obtained with coils machined from a single rod of copper-beryllium or maraging steel, or by polyhelices consisting of several such coils. The small number of turns results in low inductance and thus in a short pulse duration of less than a millisecond for a typical capacitor discharge. The short pulse duration is also dictated by the high resistivity of the coil material. The recent advances with wire-wound coils may render these techniques obsolete. As was shown by Bobrov et al [11], the effect of the electrical skin depth results in excessive local heating in these thick-walled coils; it is estimated that it will be very hard to go beyond 80 T for this reason. In addition, the skin effect may result in a local accumulation of stress. In coils with massive conductors, a "saw effect" has been observed: it looks as if the magnetic stress were "sawing" slits into the conductor from the inside surface. The explanation goes as follows: Once a tiny crack develops at the inside where the strain is largest, the current is forced to go around it in a sharp bend; this results in increased local stress and arcing which tends to open up the gap.

Using three concentric helices powered by separate capacitor banks, Surma obtained 92 T in a 6 mm bore with a total energy of 60 kJ [12].

Megagauss Fields

Fields in excess of 100 T inevitably destroy the conductor material. The mechanical destruction proceeds at the speed of a shock wave in the material, this is of the order km/s (mm/μs) and determines the time scale in the microsecond range. Typical speeds are 2 km/s at 500 T and 5 km/s at 1000 T. In addition, ohmic heating results in melting and vaporization of the conductor material. The combination of these effects determines a typical speed which is directly related to the magnetic field squared and to the properties of the material. The inner surface of the coil will recede from the field at this speed. The analysis of a number of flux compression experiments has shown that this speed is closely approximated by the particle speed in a shock wave driven by magnetic stress [13].

In practical terms, the method best suited for experimentation in the laboratory is the discharge of a very fast capacitor bank into a small single turn coil [14]. Although the coil explodes most violently, the sample volume is protected by the magnetic field which pushes the bulk of the coil material away. Peak fields up to 300 T have been obtained so far, and there is speculation that this may eventually be extended to 500 T.

Flux compression by implosion can yield much higher fields but destruction of the sample always occurs shortly after peak field, because the implosion continues past peak field and may break up in instabilities. Such instabilities have been theoretically predicted but so far there has not been much direct experimental evidence for this. With standard explosive techniques, metal cylinders can be imploded at speeds up to 5 km/s. This results in a peak field of 1000 T. Fields up to 600 T in a "bore" of 5-10 mm can be obtained with fairly simple and compact devices containing about 1 kg of high explosive and requiring a capacitor bank of the order 200 kJ for the initial flux. Electromagnetically driven implosions can theoretically attain higher speeds, but in practice this is difficult. So far, fields up to 300 T have been obtained in the course of the development with energies up to 4 MJ [15]. This energy corresponds to 1 kg of high explosive. While electromagnetic implosion is certainly better suited for laboratory use, it ought to be mentioned that high explosives are quite reproducible and less difficult to handle than is generally believed, including safety hazards as compared to high voltage.

For generating the highest possible fields, the problem is in the limited speed of energy transfer through inductive-capacitive circuits. This is the reason why flux compression gives higher fields as the electromagnetic energy is generated in the device itself. The fastest transport of electromagnetic energy is provided by a laser beam. In recent years, a promising technique was discovered that directly converts the energy of a laser beam into electrical current [16]. If a high power laser is focused on a metal plate with an irradiance of more than 10^{14} W/cm^2, hot electrons with temperatures over 10 keV are generated by resonance absorption and are emitted from the target. The electrons can be collected on a second plate and passed through a small coil directly attached to the plates. The rise time of this very strong current pulse is of the order of a nanosecond, thus it appears feasible to obtain fields of the order 10^4 T as soon as enough energy becomes available in a laser pulse. To fill a volume of 1 mm^3 with electromagnetic energy at 10^4 T, 40 kJ are needed.

Practical Considerations

So far, pulsed magnets have mostly been built by the scientists using them. Now it appears that magnet designers are finally getting interested. Engineers building d.c. laboratory magnets are used to large installations, and this way of thinking appears to carry over to plans for setting up pulsed magnets. At this point, a note of caution ought to be added. Pulsed magnets are most practical when they are not too big. A capacitor bank with an energy of 100-200 kJ is an elegant, compact laboratory instrument. With a bank of this size, 50 T can be obtained with a half period of 10 ms in a bore of 2 cm. A very fast bank of similar size at about 50 kV can generate 150 T in 1 cm diameter or (hopefully) 300 T in 5 mm diameter with a rise time of 2 μs. It does not make sense to use much more energy for the megagauss field, as it would mainly increase the destructive effects which become difficult to handle; the pulse duration is anyhow limited by the material properties. For the nondestructive coils, increasing the energy to 10 MJ or more would extend the pulse duration to a second. Since this requires a very massive coil and large installation, it is a good question whether this pulse duration is really needed for a given experiment. Experience has shown that many experiments can be well done with a pulse duration of 10-20 ms; this is about the limit below which annoying effects become strong. These are mainly caused by eddy current heating and the associated movement of the sample (helium boiling!), and by voltages induced in the probe assembly. Both effects can be minimized by just making the samples small; for the eddy current heating the sample dimension perpendicular to the field must be smaller than the skin depth. This should be no problem with modern microfabrication techniques; so far these have not yet been applied in pulsed field experiments. It is easily estimated that this will allow an extension of some critical experiments into the megagauss/microsecond range. Of course, it goes without saying that for some critical experiments a longer pulse duration is indeed required, and that it does make sense to set up facilities for pulsed fields with a pulse duration of about one second at dedicated laboratories.

Experiments with a sinusoidal field pulse give an immediate double-check as the physical phenomenon under investigation is measured twice: once with increasing and once with decreasing field. In particular, this will reveal effects due to sample heating by eddy currents. In addition, it is always advisable to do some experiments in a d.c. field for comparison in the lower field range. This is a good reason for setting up one or more compact pulsed field generators at the national magnet laboratories, where the conditions for general experimentation are most favourable. As a bonus, researchers queuing up for the hybrid magnets could then be referred to pulsed magnets if the experiment can be adapted to pulsed field conditions; this is more often possible than it is now generally believed. This would not only open up the field range but also result in substantial economies, thus giving a good example of "ephemeralization" as promoted by Buckminster Fuller [17]: DO MORE WITH LESS!

References

[1] N. Miura and F. Herlach, "Pulsed and Ultrastrong Magnetic Fields", in Strong and Ultrastrong Magnetic Fields and Their Applications, Topics in Applied Physics Vol. 57, ed. F. Herlach, Springer-Verlag Berlin Heidelberg 1985, pp. 247-350

[2] F. Herlach and N. Miura, "Pulsed magnetic fields for experiments in physics", in Proceedings of the 9th International Conference on Magnet Technology, eds. C. Marinucci and P. Weymuth, SIN Villigen 1985, pp. 191-198

[3] D. B. Montgomery, "The generation of continuous fields: future prospects", in Solids and Plasmas in High Magnetic Fields, eds. R.L. Aggarwal, A.J. Freeman and B.B. Schwartz, North-Holland Amsterdam 1979, pp.293-299

[4] H.-J. Schneider-Muntau, "The generation of high d.c. magnetic fields", in these proceedings (BM-1)

[5] S. Foner, "68.4-T-long pulse magnet: Test of high strength microcomposite Cu/Nb conductor", Appl. Phys. Lett., vol. 49, pp. 982-983, October 1986 (in these proceedings: paper BM-5)

[6] F. Herlach, G. De Vos and J. Witters, "Stresses in coils for strong pulsed magnetic fields", in Proc. 8th International Conference on Magnet Technology, Journal de Physique, vol. 45 supplément au nr. 1, Colloque C1, pp. 915-921, January 1984

[7] H. Jones, F. Herlach, J.A. Lee, H.M. Whitworth, A.G. Day, D.J. Jeffrey, D. Dew-Hughes and G. Sherratt, "50 Tesla pulsed magnets using a copper conductor externally reinforced with stainless steel", in these proceedings (BM-4)

[8] R. Gersdorf, L.W. Roeland and W.C.M. Mattens, "A semi-continuous magnet coil for 60 T?", in these proceedings (BM-3)

[9] L.W. Roeland, R. Gersdorf and W.C.M. Mattens, "Computer-controlled 40 T magnetic field regulation", in these proceedings (AR-9)

[10] G. Kido and Y. Nakagawa, "Dual multi-turn solenoids for the accurate magnetization measurements", in these proceedings (AR-12)

[11] E.S. Bobrov, J.E.C. Williams and P.J. Raboin, "Development of a short-pulse high-field magnet system at FBNML", Proc. 4th Int. Conf. on Megagauss Magnetic Field Generation and related Topics, ed. C.M. Fowler, to be published in 1987

[12] M. Surma, "Pulsed magnetic field hybrid system at the A. Mickiewicz University", in Proc. 8th International Conference on Magnet Technology, Journal de Physique, vol. 45 supplément au nr. 1, Colloque C1, pp. 45-48, January 1984

[13] F. Herlach and J.E. Kennedy, "The dynamics of imploding liners in magnetic flux compression experiments", J. Phys. D: Appl. Phys, Vol. 6, pp. 661-677, (1973)

[14] K. Nakao, F. Herlach, T. Goto, S. Takeyama, T. Sakakibara and N. Miura, "A laboratory instrument for generating magnetic fields over 200 T with single turn coils", J. Phys. E: Sci. Instrum., Vol. 18, pp. 1018-1026, (1985)

[15] N. Miura, T. Goto, K. Nakao, S. Takeyama, T. Sakakibara and F. Herlach, "Megagauss magnetic fields - generation and application to magnetism", J. Magn. & Magn. Mater., Vol. 54-57, pp. 1409-1414, January 1986

[16] H. Daido, F. Miki, K. Mima, M. Fujita, K. Sawai, H. Fujita, Y. Kitagawa, S. Nakai and C. Yamanaka, Phys. Rev. Lett., Vol. 56, pp. 846-849, February 1986

[17] R. Buckminster Fuller, "Critical Path", St. Martins Press New York 1981