# SUPERCONDUCTING MAGNETS FOR CONTROLLED THERMONUCLEAR RESEARCH[*]

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Some of the general considerations for magnetic fields used in controlled thermonuclear research (CTR) are outlined in this paper, along with a list of a few of the early superconducting coils which have been built for this purpose and a list of coil systems now planned or under construction. These comments are intended as a general orientation for persons unfamiliar with CTR but with some understanding of superconducting magnets.

Basic to this discussion are some fundamental requirements for a fusion reactor. Most plasma confinement schemes receiving serious consideration today require a magnetic field which, if strong enough, confines moving charged particles to a helical motion about magnetic field lines and limits plasma escape across field lines to that net motion produced by classical scattering effects or by small-scale turbulence. In an "open-ended machine," escape of plasma along field lines is limited by the "magnetic mirror"[1,2] effect to particular components of the plasma which, by scattering, acquire enough momentum along field lines. In a "closed-ended" machine,[3] particles remain on magnetic "surfaces" contained within the vacuum chamber and are lost by diffusion and instabilities, but are not subject to the severe end losses of open systems.

Some basic general requirements for a fusion reactor are:

1) Plasma pressure must be less than "pressure" of the confining magnetic field: $2nkT < B^2/8\pi$.

2) A simplified power balance[4] for an ideal deuterion-tritium (D-T) system — assuming a reactor which produces heat by fusion reactions and by radiation only, which recovers this heat with an efficiency of 1/3, and which consumes only enough additional energy to heat the fuel to reaction temperature — leads to the criterion that $n\tau > 10^{14}$ sec/cm$^3$ for a positive power balance. This neglects all other loss mechanisms and power requirements, and therefore to this extent represents an optimistic limit.

For an optimum temperature of 15 keV, the above two criteria can be combined[5] to give

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1. R.F. Post, Rev. Mod. Phys. 28, 338 (1956).

2. R.F. Post, in Progress in Nuclear Energy, Series XI, Plasma Physics and Thermonuclear Research (Pergamon Press, 1959), Vol. 1, p. 154.

3. W.P. Allis, Nuclear Fusion (D. Van Nostrand, 1960), Ch. IX, "Stellarators."

4. J.D. Lawson, Proc. Phys. Soc. (London) B70, 6 (1957).

5. L.A. Artsimovich, Controlled Thermonuclear Reactions (Gordon and Breach, 1965).

$$B^2\tau > 6 \times 10^7 \ G^2 \cdot \text{sec} \ ,$$

which relates B to average confinement time.

It can be seen that for $\tau \approx 1$ sec, $B > 8$ kG, and at first glance it would seem that relatively weak fields might suffice for a dc system or that a pulsed system operating at, say, 60 cps might require only 60 kG. (There are some schemes for pulsed reactors involving very high densities for much shorter pulses which will not be discussed here, since superconducting coils do not appear appropriate for very fast field pulses.) At the optimum temperature, $P = 7 \times 10^{-17} \ B^4 \ W/cm^3$ for the ideal D-T reactor[5] and, therefore, at say 10 kG, $P \approx 0.07 \ W/cm^3$, which requires very large apparatus for reasonable central-station-scale power levels. Cost considerations may require P to be much higher; for example, if $P = 10 \ W/cm^3$, $B \approx 20$ kG. Also, because of various stability limits[6] the ratio

$$\beta = \frac{2n \ kT}{B^2/8\pi}$$

may be required to be much smaller than one, and therefore stronger fields would be required. It can be concluded that for fusion reactors there may be an ultimate lower limit to B of about 8 kG, but because of various plasma loss mechanisms, and required economical minimum power density, this limit is more likely to be at least about 20 kG. Since $P \propto B^4$, it is unlikely that fields much above the minimum will be required. Therefore, fusion reactors will probably be operated at fields only slightly larger than the minimum required for positive power output, and will probably require very large plasma volumes, perhaps several meters in radius. Since the ratio of the confining field at the plasma to the maximum field at the conductor may be as high as 3:1 for complex coil shapes (such as baseball coils), the field at the conductors may be about 60 kG which is well within the limit for practical NbTi materials using today's technology.

The above comments apply only to a theoretical fusion reactor. Present CTR experiments are not miniature fusion reactors but are designed to explore confinement and stability. Therefore, the above power reactor conditions and scaling laws do not, in general, apply. Usually, the experimental apparatus must have dimensions larger than a minimum number of particle orbit radii so that true plasma conditions can be achieved. For protons this radius is about 1 cm for 5 keV at 10 kG (typical for Alice[6]). For a minimum of 20 orbit diameters within the plasma, a coil size of at least 1 m is necessary. Required field strength can usually be reduced by increasing apparatus size, the deciding factor becoming cost. Plasma generation techniques must also be scaled to larger plasma volumes and this requirement makes small-volume, high-field apparatus desirable for most research. Plasma energies much lower than required for a reactor are sufficient for studying confinement in open-ended systems. This allows consideration of weaker magnetic fields and/or smaller apparatus size. However, present technology for building neutral beam sources (a currently popular method for creating a plasma) limits energies to a minimum of a few keV. At lower energies practical beams may become so weak that the losses may become competitive with plasma generation rates. The point to be emphasized here is that the size and strength of any open-ended CTR magnet system is strongly dependent on the state of the art in plasma source and vacuum technology, and parameters such as size and field can be varied over a wide range. Therefore, the next "generation" of open-ended coil systems may not necessarily involve larger size coils or higher field strengths if plasma production techniques can be significantly improved.

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6. R.F. Post, Lawrence Radiation Laboratory, Livermore, UCRL-70681 (1967). (Presented at Intern. Conf. on Plasma Confined in Open-Ended Geometry, Gatlinburg, Tenn., 1967).

Three examples of open-ended coil systems are illustrated in Fig. 1. Figure 1a is the simple mirror system used in many early experiments. Note that two of these systems, Figs. 1b and 1c, are not simple axially symmetric solenoid systems but involve three-dimensional current patterns. Figure 1b shows the superposition of a multipole field and a pair of mirror coils. This class of open-ended system has been used in many laboratories with pulsed or dc copper coils, originally without the multipole component; more recently, most such systems have a multipole component, which was demonstrated by Ioffe[7] to result in much more stable confinement. The plasma, being diamagnetic, tends to move toward the minimum-B region which these coils produce. Another current distribution which produces a similar field — using a single coil — is the baseball (or tennis ball) coil shown in Fig. 1c.

Some early superconducting solenoids were designed[8,9] and built for plasma studies and single-particle containment studies. The first superconducting minimum-B system used in a plasma experiment was a baseball coil,[10] although it was too small and weak for really useful results. A similar coil was built by Bronca et al.[11] but was not used for plasma studies. The first large superconducting minimum-B systems are now under construction: the IMP machine at ORNL,[12] a high-field mirror/Ioffe-bar system at NASA-Lewis, and a superconducting version of the Alice experiment in Livermore.[13] Some parameters of these coils are described in Table I. A major complexity of these coils is due to the noncircular shape which requires a support structure capable of withstanding bending stresses as well as hoop stresses.

Another class of CTR experiments which have been more recently proposed involves closed-ended systems with floating or levitated superconducting rings. Toroidal experiments with external coils have been made for many years[3] and have usually required only pulsed fields of a few milliseconds duration; therefore, superconductors have not been considered. However, to satisfy present requirements for good confinement, external coil systems such as stellarators must have high shear fields which, in a practical sense, require complex windings placed around a toroidal vacuum tank with exacting mechanical tolerances. A simpler way to provide a strongly stabilizing toroidal container is to have one or more current-carrying conductors buried within the plasma; i.e., the flux surfaces on which plasma is distributed completely surround the conductors. This is a simpler way to provide high shear and/or "minimum average B," although more investigation is required to determine the relative importance of these two parameters.

7.  M.S. Ioffe and E.E. Yushmanov, Nucl. Fusion Suppl. 1, 177 (1962).

8.  L.J. Donadieu and D.J. Rose, in High Magnetic Fields (M.I.T. Press/John Wiley & Sons, Inc., 1962). (Proc. Intern. Conf. High Magnetic Fields, Cambridge, Mass., 1961.)

9.  J.C. Lawrence and W.D. Coles, in Advances in Cryogenic Engineering (Plenum Press, 1965), Vol. 11, p. 643.

10. C.E. Taylor and C. Laverick, in Proc. Intern. Symposium on Magnet Technology, Stanford, California, 1965, p. 594.

11. G. Bronca, J. Krikorian, J.P. Pouillange, and D. Rappanello, in Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967, p. 547.

14. D.L. Coffey and W.F. Gauster, these Proceedings, p. 929.

13. C.D. Henning, R.L. Nelson, M.O. Calderon, A.K. Cargin, and A.R. Harvey, to be published in Advances in Cryogenic Engineering (Plenum Press, 1968), Vol. 14.

TABLE I

Superconducting Coils now Under Construction for Controlled Fusion Research

Open-Ended Systems

| Laboratory | Type | Characteristic dimensions, cm | Central field, kG | Max. field at conductor, kG |
|---|---|---|---|---|
| Oak Ridge Natl. Lab. | Mirror and quadrupole | 35 diam, 70 long | 20 | 75 |
| NASA-Lewis | Mirror and multipole | 51 diam | 75 | 90 |
| LRL-Livermore | Baseball | 120 diam | 20 | 75 |

Closed Systems — Levitated Rings

| Laboratory | Type | Ring diameter, cm | Ring current, kA |
|---|---|---|---|
| Princeton Plasma Physics Lab. | 1 ring "Spherator" | 152 (major diam) | 375 |
| Princeton Plasma Physics Lab. | 2 ring | 101 | 460 |
| | FM | 202 | 325 |
| LRL-Livermore | 1 ring "Levitron" | 80 | 500 |
| Culham, UK[a] | 1 ring | 50 | 500 |

[a]Tentative.

Several such devices have been built utilizing a temporarily levitated, inductively energized central conductor,[14] or conductors suspended on support rods.[15]  In the inductively energized case, the time-varying ring currents are accompanied by large toroidal plasma currents because of close inductive coupling; these plasma currents lead to undesirable instabilities.  In the rod-supported cases, collisions between supports and plasma cause rapid losses. A group of experiments is now under construction utilizing superconducting, magnetically levitated conductors.  Princeton plans a two-ring "quadrupole" device, called FM (floating multipole).  LRL-Livermore is building a single-ring machine of somewhat smaller size.

Similar experiments have been proposed at the University of Wisconsin, the Culham Laboratory in England, and the Institute for Plasma Physics at Garching in West Germany.  The technological problems imposed by levitated coils are unique; for example,

14.  H.P. Furth, in Plasma Physics (Intern. Atomic Energy Agency, Vienna, 1965), p. 411.

15.  T. Okawa and D. Kast. Phys. Rev. Letters 1, 41 (1961).

such coils must be periodically recooled to remain below their transition temperature; therefore, there is reason to use Nb3Sn because of its higher critical temperature rather than because of its high field capability. Practically all present design experience has been with coils immersed in saturated liquid helium at 1 atm or lower, whereas these floating coils will be subject to periodic temperature cycling and may be immersed in a gaseous rather than liquid environment when energized. The Princeton coils will be Nb3Sn, will be energized through removable leads, and will be immersed in saturated liquid when energized; the LRL coil will have no external leads, will be inductively energized, and will be contained in a sealed toroidal container which is permanently pressurized with helium gas to provide heat capacity. The heat transfer and general cryogenic design problems of periodically recooling these rings are, of course, unique. The ring position must be magnetically controlled by a system which maintains stability, because all such systems of current interest are inherently unstable.[16] Stability can be accomplished in a straightforward manner by a system of position-correcting coils and position sensors connected in an appropriate servo system. However, another possible way to stabilize such rings is to use superconducting surfaces located outside the plasma. If these surfaces were cooled below their critical temperature while the ring was mechanically held in its equilibrium position, then subsequent ring motion would be resisted by inductively generated eddy currents in the superconducting surfaces. Design of such surfaces is theoretically possible; this would represent a novel application for superconducting materials.

## CONCLUSIONS

Because of many parameters which can be varied in fusion experiments, it is difficult to generalize about specific requirements for magnets. Most research requirements can be satisfied by a range of coil shapes, sizes, and field strengths. The deciding factor usually is cost.

Superconducting magnets will be used for many nonpulsed controlled fusion experiments in the near future, mainly because of their lower cost compared to conventional systems for these inherently large size experiments.

The dc levitated coils for closed systems must be superconducting. Here the determining factor is not cost but rather the fact that no other practical method appears to be available.

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16. J. File, G.D. Martin, R.G. Mills, and J.L. Upham, J. Appl. Phys. 39, 2623 (1968).

(a) FIELD COILS

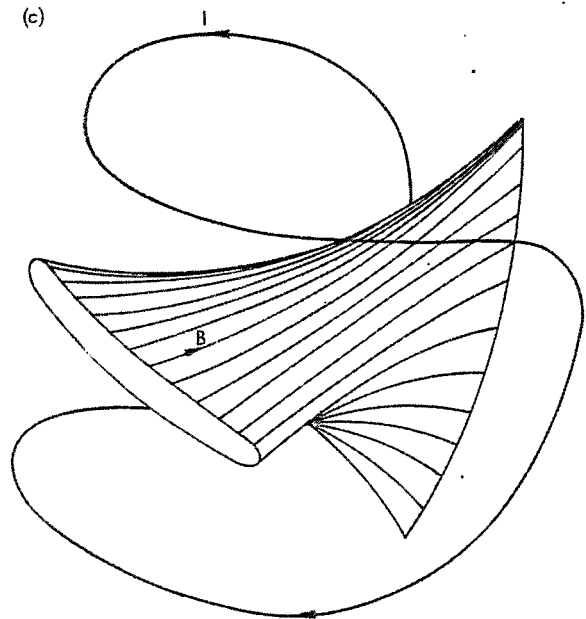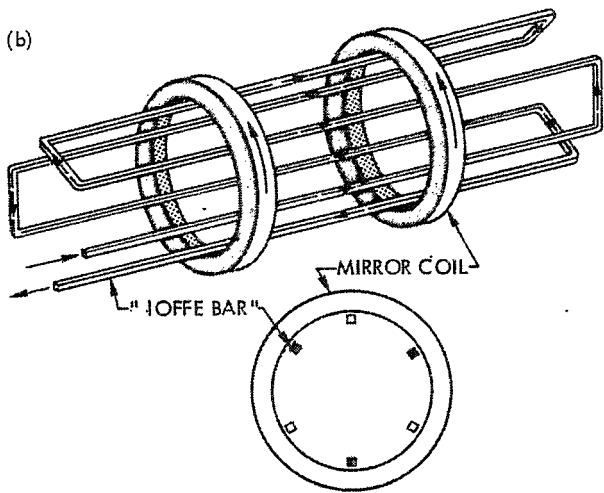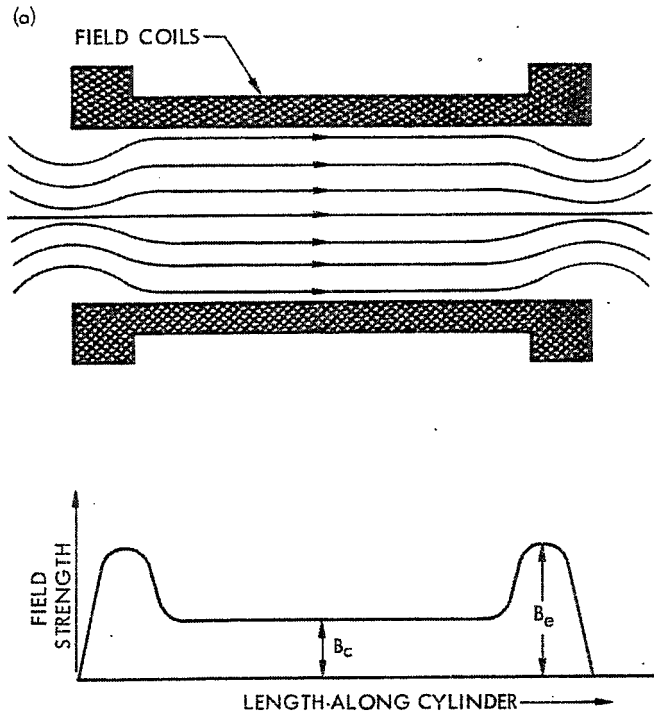FIELD STRENGTH

$B_c$

$B_e$

LENGTH·ALONG CYLINDER

(b)

MIRROR COIL

"IOFFE BAR"

(c)

I

B

Fig. 1.   Some open-ended coil systems.