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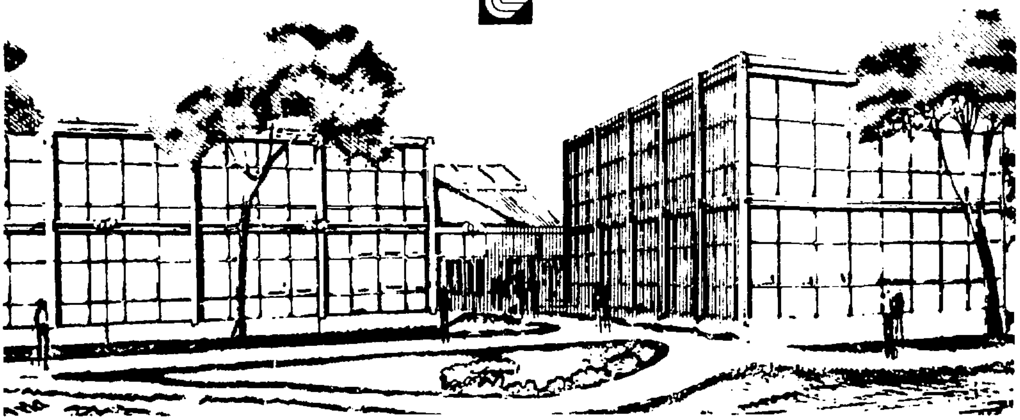

SUPERCONDUCTING MAGNETS FOR MIRROR MACHINES

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Abstract

The simple mirror configuration, consisting of a long solenoid with increased field strength at the ends (magnetic mirrors), proved to be an unstable plasma container and was replaced by the minimum |B| mirror configuration. The Yin-Yang minimum |B| coil was chosen for the Mirror Fusion Test Facility (MFTF) experiment and recent conceptual designs of standard mirror reactors. For the multicell field-reversed mirror reactor concept we returned to the long solenoid configuration, augmented by normal copper mirror coils and Ioffe bars placed at the first wall radius to provide a shallow magnetic well for each field-reversed plasma layer. The central cell of the tandem mirror is also a long solenoid while the end plug cells require a minimum |B| configuration.

The MFTF magnet is designed for a maximum magnetic field strength slightly under 8 T and is being constructed of niobium-titanium superconductor. An encouraging development for higher field superconductor was the demonstration in 1977 that multifilamentary niobium-tin superconductor at 12 T can tolerate cyclic strain to 0.6% without degradation of its current carrying capacity. The High Field Test Facility being built at Livermore will test 40 cm bore niobium-tin solenoids at 12 T. Also a 12 T minimum |B| -shaped demonstration coil has been proposed.

In general, because of the high plasma energies involved, mirror reactors benefit from high magnetic field strengths. For example, a 17 T maximum field strength was chosen for the plugs of the tandem mirror fusion reactor, and 12 T is proposed for the nearer term two component tandem mirror hybrid. We believe that mirror reactor magnets of these field strengths and even higher are possible. The 12 T goal of the present niobium-tin program is not an upper limit. Niobium-tin conductor has a useful current density capability at considerably higher field strengths, and advanced superconductors such as niobium-aluminum-germanium may reach to the 20 T range. Heat transfer to ensure magnet stability and magnetic force restraint become increasingly difficult at higher fields, but within limits such problems are amenable to engineering design solutions.

Introduction

There is considerable variation in the shape, size, and magnetic field strength of the superconducting magnet systems proposed for the several mirror reactor concepts. In some cases the reactor magnets are within the limits of presently developed technology; in other cases considerable development is required. In this paper I will review the superconducting magnet requirements of the various mirror reactors, discuss some of the magnet design considerations, and indicate the present status of magnet development for mirror machines.

Magnet Shape

Figure 1 shows the evolution of mirror machine concepts. The simple mirror configuration, consisting of a long solenoid with increased field strength at the ends (magnetic mirrors), proved to be an unstable plasma container and was replaced by the minimum |B|, or standard mirror configuration. From the center of a minimum |B| configuration, as produced by a pair of solenoids and Ioffe bars, a Baseball coil (shown in Fig. 1), or a Yin-Yang coil, the magnetic field strength increases in all directions and ensures MHD stability for the plasma.

By standard mirror confinement we mean confinement of the fusion plasma in the minimum |B| magnetic well of a single mirror cell. It is now clear that end losses from a standard mirror will severely limit the plasma Q (fusion power divided by trapped injected power) of such a device. The search for enhanced Q mirror machines has led to work on two new concepts: the tandem mirror and the field-reversed mirror.

By tandem mirror confinement (see Fig. 1) we mean three cells on a common axis wherein confinement in the central cell is enhanced by means of electrostatic stoppering provided by the plasma potential of the end plugs. The end plugs are standard, minimum |B| mirror machines; the central cell is a long solenoid.

By field-reversed mirror (FRM) confinement (see Fig. 1) we mean the confinement of plasma in a toroidal region of closed magnetic field lines generated by diamagnetic plasma currents in a nearly uniform background field. The individual field-reversed plasma layers are predicted to be small and low power (~20 MW fusion power); so we have proposed a multicell reactor concept. The background field for a multicell field-reversed mirror can be provided by a long solenoid. A shallow, minimum |B| magnetic well is provided for each plasma layer by normal copper mirror coils and Ioffe bars placed at the first wall radius. Figure 2 shows one cell of a multicell field-reversed mirror.

The minimum |B| configuration of most standard mirror and tandem mirror end plug designs is provided by either a Baseball coil or a Yin-Yang. The end plugs of the TMX experiment are Baseball coils. The MFTF experiment will have a Yin-Yang coil. Yin-Yang coils have been proposed for standard mirror reactors, including the large standard mirror fusion-fission hybrid. Our preliminary conceptual design for the tandem mirror reactor (TMR) used a Yin-Yang plug coil inserted within a solenoidal pair.

The magnetic field configuration is similar for Baseball and Yin-Yang coils. Figure 3 shows magnetic field lines and constant-B contours for a Yin-Yang coil. The particular design shown has a central field strength of 2.47 T and an axial mirror ratio of about 2. Note the large region of closed constant-B contours which identify the minimum $|B|$ well. The radial well depth at the midplane is 3/2.47 = 1.2. A rough rule of thumb for standard mirror confinement is that plasma can be stably confined on all field lines which intersect a closed contour at the midplane. The bundle of such field lines is a double-ended fan with a 90^0 twist at the midplane. Note that these field lines pass quite close to the conductors as they exit at the ends of the the machine. This limits the minimum coil size in reactor applications where neutron shielding must be placed between the plasma and the superconducting coil. We define a magnetic field utilization efficiency as the ratio of the on-axis mirror field divided by the maximum magnetic field inside the conductor. For the design shown the efficiency is 0.61. It could be readily increased to a value of about 0.75 by spreading the conductor bundle in the minor arc of the Yin-Yang. High utilization efficiency becomes increasingly important as higher field strength coils are considered.

Magnet Size

We will characterize magnet size by inside diameter for solenoidal coils and by the mirror-to-mirror distance for minimum $|B|$ coils. (Minimum $|B|$ coils of the Baseball or Yin-Yang type are roughly spherical and the mirror-to-mirror distance is approximately the mean diameter.) Table I gives the characteristic dimension for a variety of mirror machines. In general, the coil sizes for proposed mirror reactors are considerably greater than for the present experiments.

Magnetic Field Strength

High fusion power density is the motivation for high magnetic field strength in a fusion reactor. For a given plasma β and mean energy, the central plasma density in a mirror machine is proportional to B_0^2, where B_o is the vacuum magnetic field at the center of the machine. Since fusion power density is proportional to the square of the plasma density, the power density is proportional to B_o^4. The fusion power density is also proportional to β^2 and inversely proportional to the square of the mean plasma energy. Although β in a mirror reactor is about an order of magnitude higher than for a tokamak reactor, the mean plasma energy is also about an order of magnitude higher. Therefore, the fusion power densities for the two types of reactors are approximately equal for equal values of B_o.

Mirror machines, by definition, involve magnetic field strengths greater than the central magnetic field B_o. We call the maximum magnetic field on the axis of a mirror machine the mirror field, B_m. For a standard mirror the ratio of B_m to B_o is the axial mirror ratio. The confinement parameter $n\tau$ and plasma Q in a standard mirror are proportional to the logarithm of the mirror ratio. One of the tradeoffs in standard mirror reactor design is that for a fixed value of B_m, high Q favors a low B_o (high mirror ratio) while high power density favors a high B_o. In the tandem mirror reactor there is a similar but more complicated tradeoff. In the tandem mirror there are two different B_o's, one for the plugs and one for the central cell (B_{op} and B_{oc}). The fusion power density is proportional to B_{oc}^4 and $n\tau$ in the plug is proportional to the logarithm of B_m/B_{op}. In addition, $n\tau$ in the central cell is given by

$$n\tau_c \propto (B_{op}^2 / B_{oc}^2)^{T_e / T_i} \ln (B_{op}^2 / B_{oc}^2) \quad ,$$

where T_e/T_i is the ratio of electron to central cell ion temperatures. In the field-reversed mirror reactor, we believe that the field reversed plasma layers can be stably confined in very shallow magnetic wells ($B_m/B_c \simeq 1.001$ to 1.0001); so this reactor does not have a similar Q vs power density tradeoff.

Because of the geometry of mirror machines, the maximum magnetic field in the conductor usually exceeds B_m by a considerable amount. The maximum magnetic field usually occurs at or near the surface of a conductor, and we denote it as B_c. As mentioned before, we define a magnetic field utilization efficiency as the ratio B_m/B_c. For a given value of B_c, a high magnetic efficiency can help both the confinement and power density in a mirror machine.

Table II lists the three important magnetic field strengths for a variety of mirror machines. Long solenoidal coils (such as for multicell FRM reactor) have magnetic efficiencies near unity. Standard mirror coils with large axial mirror ratio ($B_m/B_o \simeq 2$) have magnetic efficiencies considerably less than unity.

It should be noted that not all of the coils for the mirror machines listed in Table II are superconducting. The coils for 2XIIB and TMX are normal copper. MFTF has superconducting niobium-titanium coils, as would the standard mirror hybrid, the multicell FRM reactor, and the central cell of the TMR. The plug solenoids for the preliminary design of the TMR were niobium-tin superconductor, but the Yin-Yang insert coils were normal, cryogenic aluminum.

Magnetic Design Considerations

A primary design consideration for superconducting magnets is that the current density in the superconductor be kept below the critical value at which the conductor goes normal. For each type of superconductor there is a surface in temperature-magnetic field - current density space above which the conductor goes normal. A sketch of this critical surface is shown in Fig. 4. In most cases the temperature is taken to be the saturation temperature of liquid helium at one atmophere, 4.2 K. At this fixed temperature the critical superconducting surface becomes a curve of superconductor current density j_{sc} vs magnetic field B. Figure 5 shows such curves for several superconductors.[1] The curve crosses the B axis at the critical magnetic field for the superconductor, at which it is superconducting only if the current density is zero. As the magnetic field is reduced below the critical field value, the allowable current density j_{sc} increases. Table III lists the critical magnetic field (at 4.2 K) for several superconductors.

The allowable current density in a practical superconductor is often less than that given in Fig. 5 because of non-superconducting materials resulting from the fabrication process. For example, a practical multifilamentary niobium-tin superconductor has been developed which exhibits a critical superconductor current density j_{sc} between 1.2 and 2.2 x 10^4 A/cm^2 at 12 T,[3] more than an order of magnitude below the curve of Fig. 5.

The bulk current density j in the conductor bundle of a superconducting magnet is defined as the total current divided by the cross sectional area of the bundle (excluding the external coil case and any external restraining structure). The bulk current density j is always less than j_{sc} because of interlayer insulation, helium coolant passages, copper stabilizer, and (possibly) internal structure. The cryostatic stability criterion requires that at any point along the conductor the surface heat transfer rate to the helium coolant must be sufficient to remove the joule dissipation power resulting from having the current locally flow in the copper stabilizer rather than in the superconductor. This will ensure that a local normalization will not cause a temperature rise and thus propagate through the coil. The problem of conductor design for cryostatic stability was formulated and solved in Reference 4 for the niobium-tin superconducting solenoids of the TMR plug coils. At high magnetic field strengths where j_{sc} is low, the required copper-to-superconductor ratio is the lowest, and j approaches j_{sc}. At low magnetic field strengths where j_{sc} is high, more copper is needed to ensure stability and j is much less than j_{sc}. As a consequence of this scaling, j is a much weaker function of magnetic field strength than is j_{sc}. Table IV gives data calculated for the TMR niobium-tin superconductor as a function of magnetic field strength.[4]

If a coil is to be designed for a high magnetic field strength, the conductor design can in principle be varied throughout the coil so that the current density is everywhere equal to the maximum allowable value at the local value of field strength. This will minimize the total amount of superconductor and copper stabilizer required. For practical reasons, the variation of conductor design can be done only in several discrete steps through the coil. Even so, iterative design calculations are required because the allowable j is a function of B, while the spatial variation of B must be calculated for a specific j distribution by magnetic field codes such as EFFI.[5] Such calculations were done for the solenoids of the TMR plug coils, where four different conductor designs were considered.

For most mirror machine magnet designs to date, the magnetic body forces are transmitted layer-to-layer through the conductor bundle and reacted by an external structure. For a thin solenoid of infinite length, the maximum conductor stress is equal to the "magnetic pressure," $B^2/2\mu_0$, and reaches 10,000 psi (a typical yield stress for fully annealed copper) for B = 13 T. For a typical Yin-Yang coil (such as MFTF), the maximum conductor stress exceeds the "magnetic pressure" by 50%, thus reaching 10,000 psi for B = 11 T. At higher magnetic field strengths an internal structure may be required to limit the stress in the conductor. In the solenoids of the TMR plug coils this internal structure took the form of periodic bands of stainless steel which reacted the magnetic forces by simple hoop stress. For the aluminum Yin-Yang insert coil for the TMR plug it was necessary to include a strut and plate structure in the conductor bundle cross section to transmit the magnetic forces to the outside of the coil. [4] Another possible solution to the problem would be to use a work-hardened copper or copper alloy with higher yield stress, but these materials also have a higher electrical resistivity which would increase the fractional amount needed for superconductor stabilization.

Present Status of Magnet Development for Mirror Machines

An early concern about niobium-tin superconductor was that the inherent brittleness of the material might limit its practical application. An encouraging development was the demonstration in 1977 that multifilamentary niobium-tin superconductor at 12 T can tolerate cyclic strain to 0.6% or higher without degradation of its current carrying capacity. [3] This work was done at Lawrence Livermore Laboratory with a special tensile tester capable of applying simultaneously loads up to 50,000 pounds, currents to 12 kA, and magnetic field strengths to 12 T at 4 K. A summary of conductor performance with strain is shown in Fig. 6. As tension is applied to the conductor, its critical current increases, reaching a maximum at about 0.3% strain. The critical current then falls as the load is increased, reaching its initial value at about 0.6% strain. This behavior is believed to be due to pre-compression of the niobium-tin by differential contraction as the conductor is cooled from the reaction temperature of 700° C, at which the Nb_3Sn is formed, to the operating temperature of 4 K. Figure 6 shows recovery of one of the samples from a strain of 0.9%, but permanent damage for the other sample. No effect of cyclic strains, 0.6% in amplitude, could be detected up to 500 cycles. These results indicate that this conductor can be safely used in practical coils designs.

The High Field Test Facility being built at Livermore (completion date 1980) will test 40 cm bore niobium-tin solenoids at 12 T. As another step in the development of high field coils for mirror machines, a 12 T minimum |B| -shaped demonstration coil has been proposed. Design of this coil will begin in 1979 and if funded, construction could begin in 1980 or 1981.

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Table I Coil Size

Mirror Machine	Characteristic Dimension
2XIIB experiment (Yin-Yang)	1.5 m
TMX experiment: plug (Baseball)	1.1 m
central cell (solenoid)	1.8
MFTF experiment (Yin-Yang)	3.4 m
Standard mirror hybrid (Yin-Yang)	13 m
FRM reactor (solenoid)	5.7 m
TMR: plug (Yin-Yang)*	2.8 m
central cell (solenoid)	8.4 m

*In the TMR design the plug Yin-Yang is inserted within a solenoidal pair with inside diameter = 5.75 m.

Table II
Magnetic Field Strengths for Mirror Machines

Mirror Machine	B_o	B_m	B_c	B_m/B_o	B_m/B_c
2XIIB	.9 T	1.8 T	4. T	2	.45
TMX Plug	1.0 T	2.0 T	2.7 T	2	.74
Central Cell	.2 T	2.0 T		10	
MFTF	2.0 T	4.0 T	7.7 T	2.0	.52
Standard Mirror Hybrid	2.6 T	6.0 T	8.5 T	2.3	0.70
FRM reactor	4.1 T	≃4.1 T	≃4.1 T	1.0001 to 1.001	≃1.0
TMR Plug	16.5 T	17.6 T	17.3 T	1.07	(1.02*)
Central Cell	2.4 T	17.6 T		7.3	

* The value of B_c given for the TMR is the maximum field seen by the conductor of the plug solenoid which surrounds the Yin-Yang insert coil. Since the field component due to the Yin-Yang is subtractive at the solenoid conductor, the value of B_m/B_c is greater than unity.

Table III
Critical Magnetic Field at 4.2 K

Superconductor	Critical B
Niobium-Titanium (NbTi)	12.0 T
Vanadium-Gallium* (V_3Ga)	23.6 T
Niobium-Tin* (Nb_3Sn)	26.0 T
Niobium-Aluminum-Germanium* ($Nb_3\ Al_{0.7}\ Ge_{0.3}$)	41.0 T

*Taken from Reference 2.

Table IV
Data for TMR Superconductor

B(T)	j_{sc} (A/cm^2)	Copper-to Superconductor ratio	j (A/cm^2)
19	2.9×10^3	0.76	1.6×10^3
14	7.0×10^3	1.9	2.4×10^3
9.5	1.5×10^4	3.4	3.4×10^3
4.3	3.3×10^4	6.4	4.5×10^3

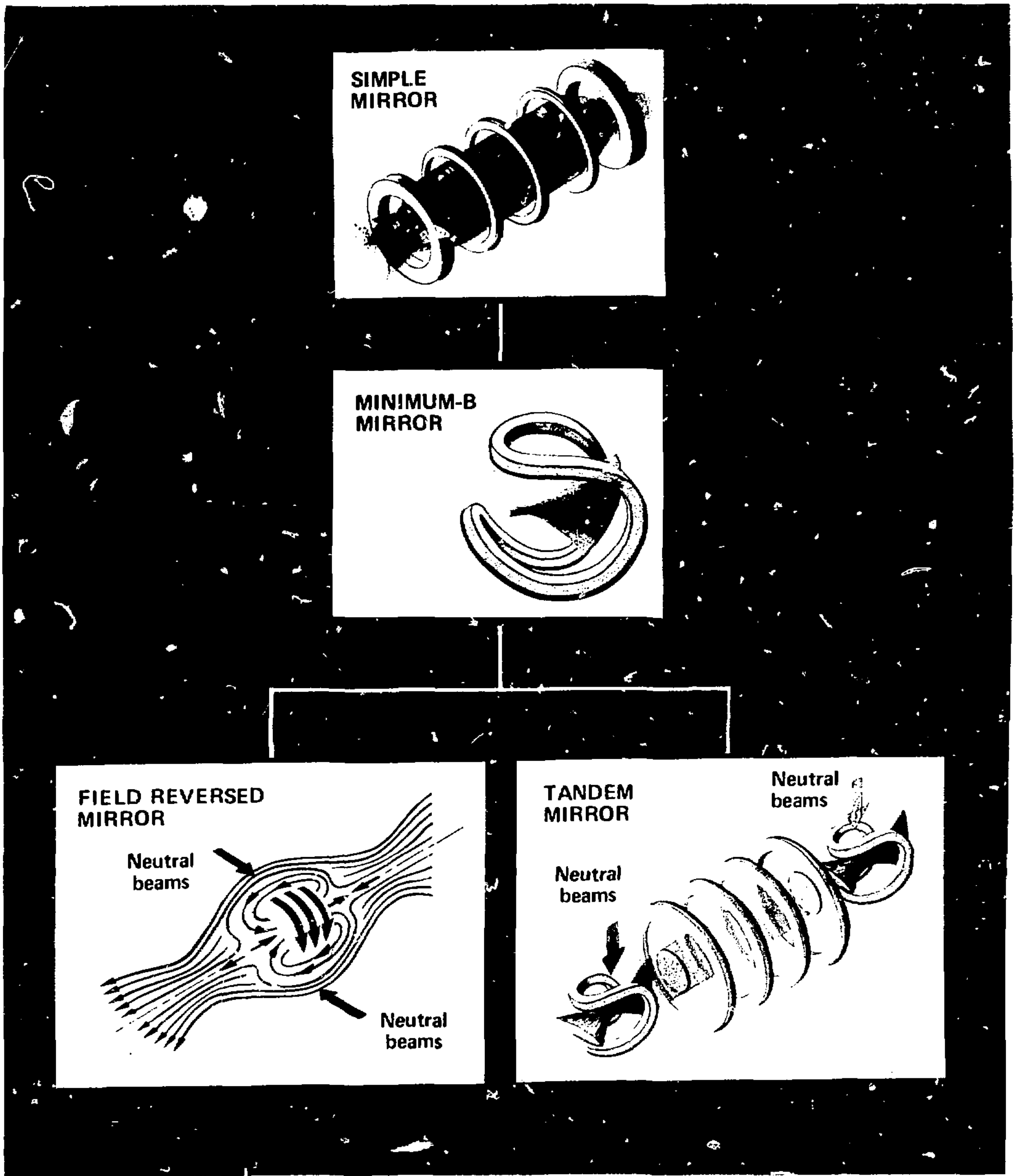

Figure 1

Evolution of mirror machine concepts.

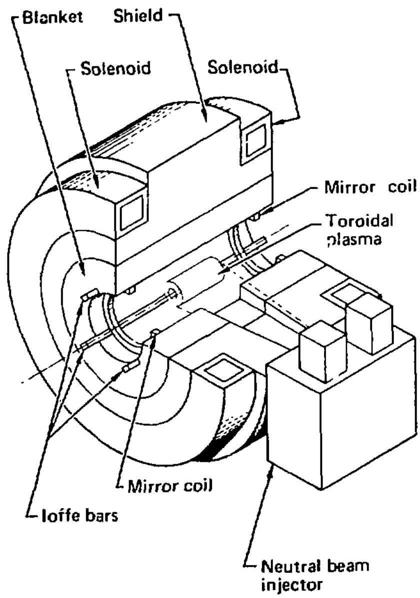

Figure 2

Single cell of a field-reversed mirror reactor.

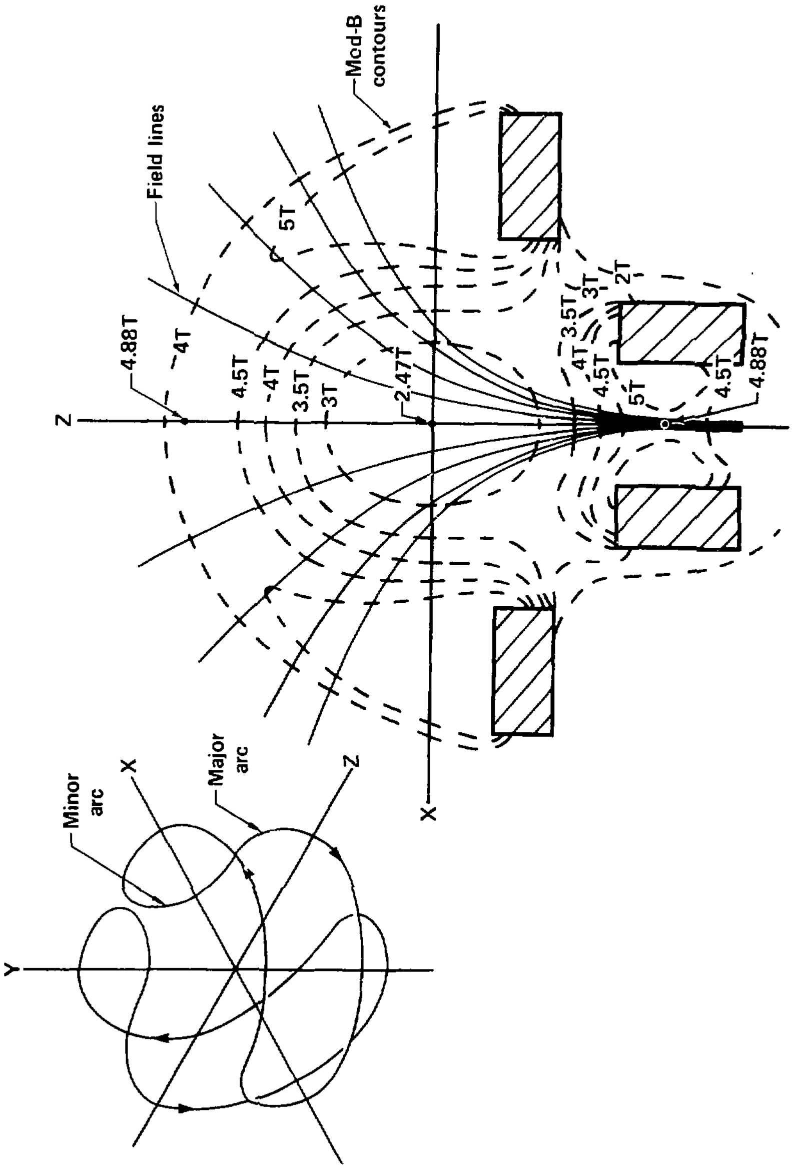

Figure 3
Magnetic field configuration for a Yin-Yang coil.

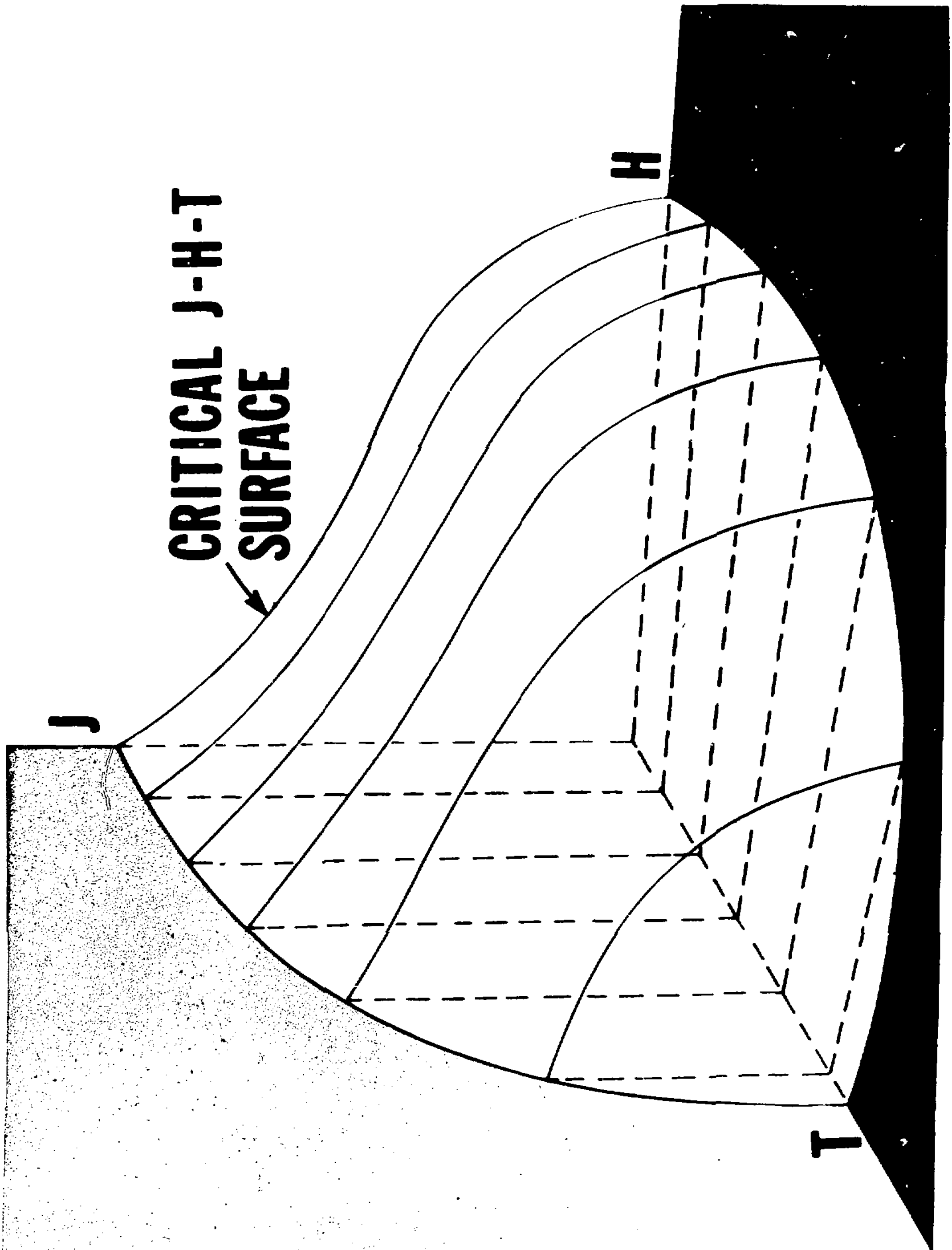

Figure 4

Typical superconducting boundary in temperature-magnetic field-current density space.

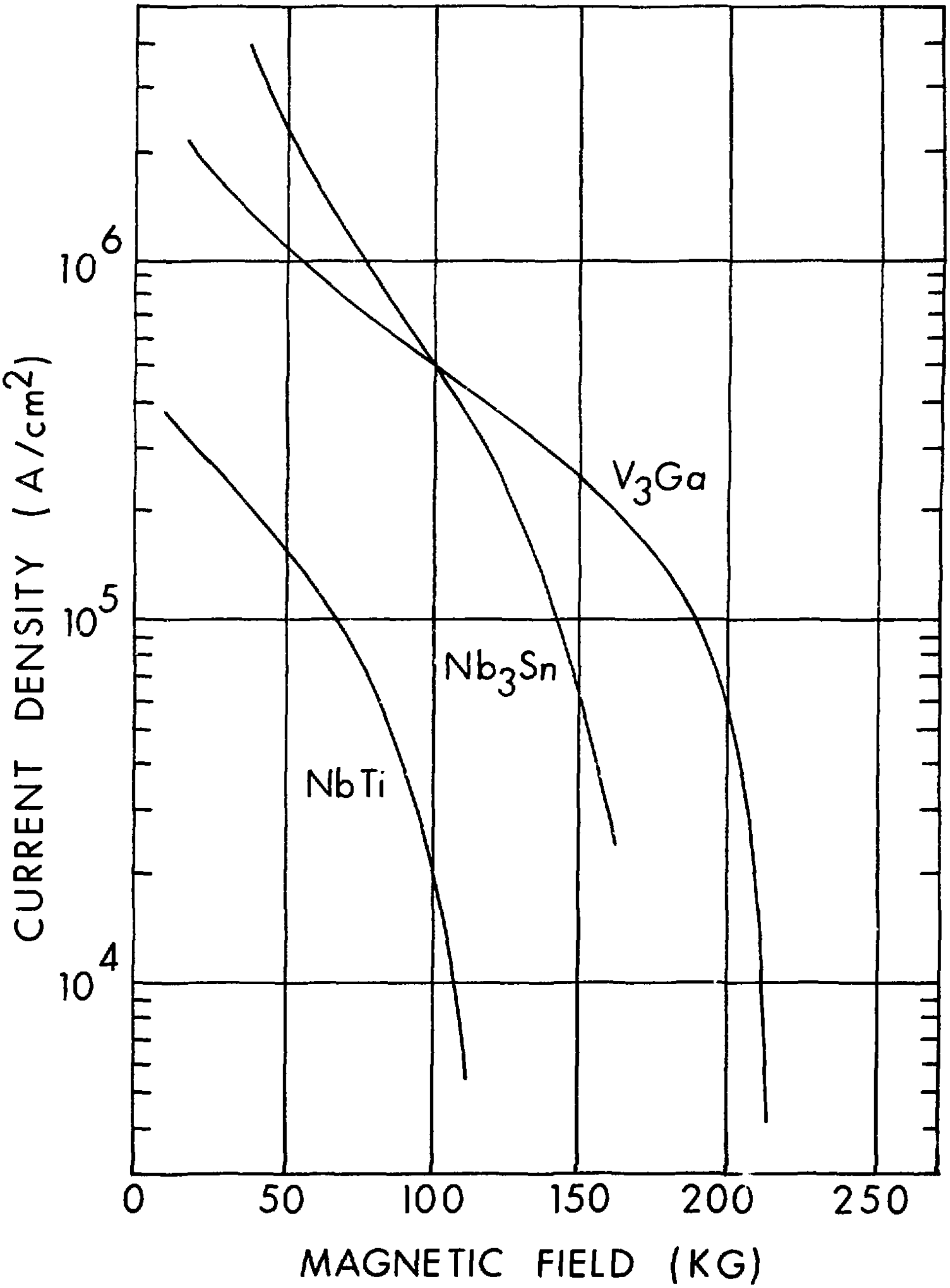

Figure 5

Superconductor current density vs magnetic field strength at 4.2 K.

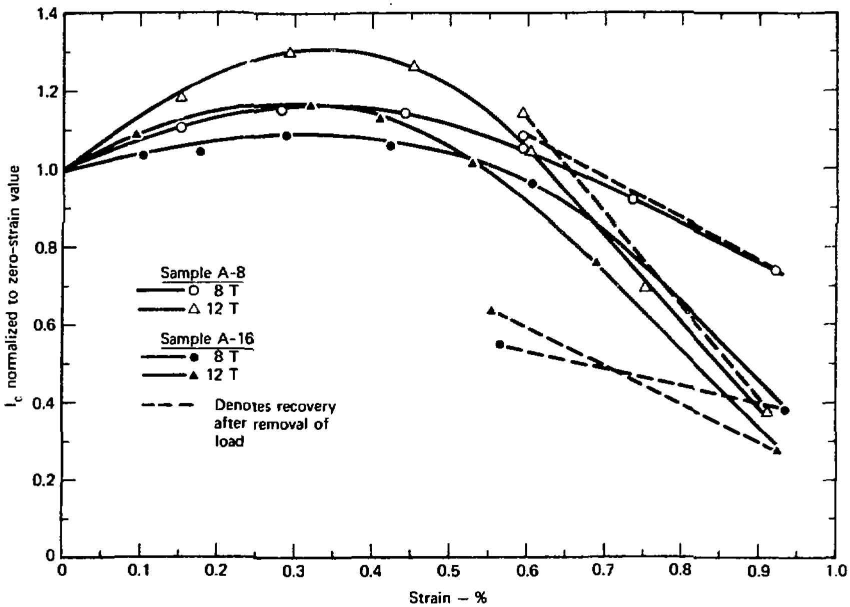

Figure 6

Dependence of critical current on strain and magnetic field for samples A-8 and A-16, including recovery data from maximum strain.