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SUPERCONDUCTING MAGNETS*

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During the past month a string of about 120 superconducting dipoles and quadrupoles more than 700m long representing about 1/8 of the Tevatron (a 1000 GeV proton synchrotron at Fermilab) was successfully tested. This is by far the largest pulsed superconducting magnet system ever operated. The dipoles are about 6m long and the quadrupoles are about 1.7m long. After some difficulties in pumping out and cooling down, once the magnet string is cold the pulsing was very stable and trouble free. Although large fully stabilized d.c. superconducting magnets are now in wide use, pulsed magnets using not fully stabilized (substabilized) cables have never been operated in this number and in a dynamic (pumped) cryogenic system of this magnitude. This in many respects signifies the coming to maturity of the technology. Figure 1 is a photograph of the Tevatron ring installed in the same tunnel and underneath the conventional magnet Main Ring.

In this paper, we will therefore, present and discuss superconducting magnets as a mature technology. Instead of describing individual exemplary magnets designed and constructed in various laboratories we will discuss first, the properties of Type II superconductor; second, the designs of dipoles and quadrupoles, the principal types of magnets required for storage rings and beam transfer lines; and finally, the life time of these magnets operating in the high radiation environment next to a fusion reactor.

Superconductors and Cables

The characteristics of a Type II superconductor are usually represented by the triple diagram of Fig. 2 where

J_c = critical current density

T_c = critical temperature

B_{c2} = upper critical field

For a Type II superconductor at some fixed low values of J and T starting at high externally applied field B, the conductor is normal. As B decreases the resistivity starts to deviate from (fall below) the normal value at B_{c2} and goes to zero at the lower critical field B_c. For Type I superconductors such as pure Pb, $B_c = B_{c2}$ and the resisitivity vanishes suddenly at B_c. T_c and B_{c2} are properties of the material. Simple theories[1] relate T_c and B_{c2} through normal-state property values and show that the B vs T curve at J = 0 is a parabola. Table 1 give T_c and B_{c2} for most of the known high-field superconductors.

Table 1 Critical temperatures and upper critical fields for high-field superconductors

Superconductors	T_c(K)	B_{c2}(T)
bcc Alloy		
V(40 atomic %) Ti	7.0	11
Nb(56 atomic %) Ti	9.0	14.1
Nb(25 atomic %) Zr	10.8	9.2
A-15 Compound		
V_3Ga	14.8	25
V_3Si	16.9	24
Nb_3Sn	18.0	28
$Nb_3A\ell$	18.7	33
Nb_3Ga	20.2	34
Nb_3Ge	22.5	38
$Nb_3(A\ell_{0.7}Ge_{0.3})$	20.7	43.5
Ternary Sulfide		
$PbMo_{5.1}S_6$	14.4	60

NbGe has the highest T_c of ∿23K and $PbMo_{5.1}S_6$ has the highest B_{c2} of ∿60 T. J_c and the J vs B curve depend on the geometry of the conductor and on the lattice defects in the material. Lattice defects such as dislocations, impurities or precipitates of a second phase act to "pin" the flux lines and prevent them from moving under the Lorentz force J x B. Hence the middle part of the J vs B curve at fixed T is roughtly given by JB = constant. The value of the constant depends crucially on the cold working and annealing of the material. The third set of curves, namely J vs T at fixed B is roughtly linear. Figure 3 shows the dependence of the critical "Lorentz force", J_cB, of a Nb-Ti alloy on annealing. For magnet design 6×10^9 T A/m^2 is a practical value for Nb-Ti at 4.2 K.

In practical application multi-filament conductors with Nb-Ti filaments set in Cu matrix are used. The filaments are twisted to reduce the effects of flux jump. The cold Cu provides a low resistivity parallel current path so that if the superconductor locally goes normal the current is shunted across in the Cu, thereby prevented from damaging the superconductor. If the Cu to superconductor ratio is high, say >10 to 1 the heating of the Cu by the shunted current is small and can be carried away by the coolant (liquid He). The temperature of the cable will remain low and the superconductor can recover. Such a cable is called fully stabilized. The average current density in a coil wound with fully stabilized conductor is necessarily low and can only be ∿ 1/30 of that in the superconductor. The minimum Cu to superconductor ratio needed to prevent damage is ∿ 1.5 to 1. For such a cable the shunted current heats up the Cu so much that it cannot be carried away sufficiently fast by the coolant. The heating and the normal region will propagate and the whole magnet will quench. Nevertheless no damage will come to the coil. After the power is turned off the coil can be cooled down again and re-energized in a matter of minutes. The average current density in such a substabilized (sub-fully stabilized) coil could be as high as 1/3 of that in the superconductor.

For d.c. application the filament could be quite thick, up to 50 μm, and a wire carrying a maximum current of 150-200 A is appropriate. For pulsed application the filament diameter should be smaller than ∿ 10 μm and many strands of the 200 A wire, say 20 to 30, must be made into a cable in which the strands are transposed, say every 5 cm, along the length to reduce the eddy current effects. A magnet wound with such a high current (∿5000 A) cable will have reasonably small number of turns and hence, reasonably low inductance for pulsing.

The J_cB values for A-15 compounds are generally higher, being ∿ 6 x 10^{10} TA/m^2 for Nb_3Sn at 4.2 K. Unfortunately all A-15 compounds are very brittle. Chemically sprayed Nb_3Sn on Cu tape or wire with a very large number (∿5 x 10^4) of very fine (<5μm dia.) Nb_3Sn filaments set in a Cu matrix are available for winding coils provided the bending curvature is not excessive.

Dipoles and Quadrupoles

In an infinitely long solenoid one can get arbitrarily large field with any available current density by simply piling layers after layers of coil windings on the outside. This is not true for multipole magnets. The maximum field or its spatial derivatives are limited by the attainable current density. For coils with uniform current density over their cross-sections to produce dipole and quadrupole fields the proper cross-sectional shapes are given by intersections of ellipses as shown in Fig. 4 where $r \equiv \frac{a}{b}$ is the ratio of the semi-major to semi-minor axes and where the aperture is adjusted to be roughly circular with radius $\approx b$. Fig. 4 shows that for a dipole $r \sim \frac{3}{2}$ is reasonable and that for a quadrupole r can be ~ 2. In practice, the crescent shaped areas are approximated by some arrangement of turns of the conductor that is easy to wind. In the Tevatron dipole whose cross-section is shown in Fig. 5 the crescent area is approximated by two circular shells of windings.

For the intersecting-ellipses coils with uniform current density J the dipole field B and the quadrupole field gradient G are given by

$$B = \mu_o J \left(\frac{r-1}{r+1}\right) 2b \qquad r \equiv \frac{a}{b} \qquad (1)$$
$$G = \mu_o J \left(\frac{r-1}{r+1}\right)$$

The highest fields on the coils are $B_{coil} \sim B$ for dipole and $B_{coil} \sim Gb$ for quadrupole. Therefore, if the limiting parameter is the Lorentz force JB we can rewrite Eqs. (1) as

$$B^2 = \mu_o (JB) \left(\frac{r-1}{r+1}\right) 2b \qquad (2)$$
$$G^2 = \mu_o (JB) \left(\frac{r-1}{r+1}\right) \frac{1}{b}$$

For a fully stabilized Nb-Ti coil at 4.2K with $(JB)_{max} = (1/30) \times 6 \times 10^9$ TA/m^2, $b = 0.1$m and $\mu_o = 4\pi \times 10^{-7}$ Vsec/Am we get

$$B_{max} = 3.2 \text{ T} \qquad (r = \tfrac{3}{2})$$
$$G_{max} = 29 \text{ T/m} \qquad (r = 2) \qquad (3)$$

Going to substabilized Nb_3Sn conductor we can gain a factor 100 in $(JB)_{max}$ and hence a factor 10 in B_{max} and G_{max}. As mentioned before these high fields are available only with high current densities. With the JB limit of Nb-Ti assumed above even if we go to $r = \infty$ (namely $a = \infty$) we get only an increase of a factor $\sqrt{5}$ in B and a factor $\sqrt{3}$ in G from those given in Eqs. (3).

At these high fields the magnetic forces on the coil are very large, generally many tons per cm of length of magnet. These forces must be confined by some mechanical structure. Also, since one generally does not like the magnetic field to extend far away from the magnet all coils should be magnetically shielded by an iron yoke. There are, then, two ways of providing the mechanical confinement.

1. Cold-iron structure

One could use the iron yoke to confine the forces on the coil. The yoke must then be in contact with the coil and be at the coil temperature. The cryostat must then enclose the entire coil and yoke. The mass to be cooled is very large. The cool-down time will be long. The iron next to the coil will be driven into magnetic saturation by the very strong field thereby distorting the field shape. The advantage, on the other hand, is that the iron yoke does provide a very simple and strong confinement structure.

2. Warm-iron structure

One could use a non-magnetic (say,stainless steel) collar to confine the forces on the coil, enclose only the coil and the collar in a smaller cryostat, and place the cryostat inside a room-temperature iron yoke or shield. The advantage is that the cool-down time is greatly reduced and that if the iron is far enough removed from the coil it will not be magnetically saturated and will not distort the field shape. The disadvantages are (a) the collar generally does not provide as strong a confinement structure as the heavy iron yoke, (b) the smaller cryostat generally results in greater heat leak, and (c) supporting the cryostat from the warm iron yoke is mechanically and thermally tricky. The Tevatron magnets as shown in Fig. 5 uses the warm-iron design.

Any movement of the coil conductor will create friction heating, thereby causing the conductor to go normal. Nearly all design difficulties are related to the requirements of strength and rigidity of the confinement structure and of thermal insulation of the cryostat. There is no problem with the superconducting behaviors of the conductors. Design concerns related to the coil conductor are generally simple mundane considerations such as avoiding large eddy current loops, avoiding breakage of the delicate superconducting filaments, providing good contact between conductor and coolant etc. As long as these fairly obvious requirements are satisfied the magnet will work reliably to the short sample limit. The mechanical and thermal requirements, although obvious, are, however, extremely demanding. It is likely that the ultimate performance of superconducting magnets will be limited by strength of material and mechanical engineering rather than superconducting properties of material.

Radiation Damage

Most intense radiation is received by the last focusing quadrupoles in the transport line just outside the beam entrance port on the reactor vessel. The radiation damage properties of all materials used in the construction of superconducting magnets have been extensively investigated[2] and are well known. Furthermore, engineering studies of this problem have been made for the HIBALL design and the results are discussed in the Design Report. Nevertheless, it is still worthwhile to make an independent first principle evaluation of the radiation damage effects. Such an evaluation is less accurate but gives a deeper and clearer understanding.

The neutron fluences were computed using a standard computer program and were given in the HIBALL Report. These are summarized in Table 2.

Table 2 Neutron yield for each 400-MJ d-t shot in the HIBALL reactor.

Total (14 MeV) neutron yield		1.4×10^{20}n
On blanket of reactor vessel		0.5×10^{14}n/cm^2
	Q7	Q8
On shield	0.7×10^{12}n/cm^2	1.6×10^{12}n/cm^2
On coil	0.6×10^{8}n/cm^2	0.8×10^{8}n/cm^2
On penetration plug (through beam pipe past Q7 and Q8)		1.1×10^{13}n/cm^2

Here, Q7 and Q8 are the two final transport quadrupoles with Q8 located right next to the beam port on the reactor vessel. Because of the high neutron flux the apertures of the quadrupoles are made almost twice the beam size and the extra space is filled with a shielding material. As shown in Table 2 the shielding reduces the neutron flux on the magnet coil by some 4 orders of magnitude. We will not attempt to modify this design, but will merely examine its performance and its effectiveness. The various radiation effects and tolerances are discussed item by item below.

A. Magnet quenching by neutron heating

The higher average current density in the coil using sub-stabilized conductor is desirable. On the other hand, during the sub-millisecond time of a shot the cooling by the coolant is ineffective and at liquid He temperature the heat capacity of the conductor is very small, less than 1 mJ/g/K. Depending on how close to the quench limit it is operating the magnet may quench with very little heating from the neutrons. Fig. 6 shows the results of some experiments carried out at Fermilab and the comparison with limits estimated from measured heat capacities. The agreement is good.

For neutrons (0.1 - 1 MeV) striking the conductor the energy deposition is given approximately by

$$10^9 n/cm^2 \quad \text{deposits} \quad 1 \text{ rad} \equiv 10^{-2} \text{ mJ/g}$$

Thus, the fluence of $\sim 10^8$ n/cm^2 on the magnet coil from a single shot is quite tolerable. However, without shielding the fluence of $\sim 10^{12}$n/cm^2 (value on shield) depositing $\sim$ 10 mJ/g will definitely cause the quadrupoles to quench.

B. Radiation Damage of Insulators

The radiation tolerances of some insulating materials are given in Table 3.

Table 3 Radiation tolerances of some insulating materials

Teflon	5×10^5 rad
PVC, Formvar	1.5×10^8 rad
Mylar (superinsulation)	5×10^8 rad
Fiberglass-epoxy (G10) Mineral filled epoxy	$\sim 5 \times 10^9$ rad
Kapton	6×10^9 rad
Ceramic (metal oxide)	$> 5 \times 10^{10}$ rad

One can avoid using Teflon, Formvar, PVC etc. but it is difficult to avoid using superinsulation in the cyrostat. Assuming a tolerance of 5×10^8 rad and a neutron fluence of 10^8n/cm^2 depositing 0.1 rad per shot we obtain a life-time for the quadrupoles of

$$5 \times 10^9 \text{ shots} \quad \text{or} \quad 10^9 \text{ sec} = 32 \text{ years}$$

at 5 shots/sec. Although, this is acceptable it is still worthwhile to find ways to replace mylar superinsulation by more radiation resistant material.

C. Resistivity of copper

The Cu matrix of the conductor can serve as stabilizer only because at liquid He temperature the electrical resistivity of Cu is very low. Irradiation of the Cu creates lattice displacements, dislocations and other defects which act as scattering centers for conduction electrons, hence increase the resistivity. The resistivity increase $\Delta\rho$ is given in terms of the neutron fluence ϕ by[2]

$$\Delta\rho = (4 \times 10^{-7}\Omega\ \mathrm{cm}) \left[1-e^{-(10^{-19}\mathrm{cm}^2)\phi}\right] \qquad (4)$$

As an example, the Cu used in Fermilab Tevatron magnets has a resistivity of $\sim 4 \times 10^{-8}\ \Omega$ cm at 4.5 K. Thus, $\Delta\rho$ should not be greater than, say, half this value or $2 \times 10^{-8}\ \Omega$ cm. Eq. (4) then gives a fluence limit of $\phi < 5 \times 10^{17}$n/cm^2. At 10^8n/cm^2 per shot and 5 shots/sec this corresponds, again, to a life-time of

5×10^9 shots or 10^9 sec = 32 years.

This is quite acceptable, especially since this degradation is recoverable by annealing at room temperature.

D. Degradation of superconductor

This has been investigated [3] extensively during the past 10 years. Roughly stated the findings are:

1. There is no noticeable degradation below a neutron fluence of $\sim 10^{18}$n/cm^2.
2. Both J_c and T_c are sharply reduced at a fluence of between $\sim 10^{18}$n/cm^2 and $\sim 10^{19}$n/cm^2.
3. Above $\sim 10^{19}$n/cm^2 J_c and T_c bottom out at some low values which then persist to very high fluences.
4. This degradation of critcal values is partially ($\sim$50-70%) recoverable by annealing at room or slightly higher temperature.

Taking 10^{18}n/cm^2 as the tolerance we get a life-time of

10^{10} shots or 2×10^9 sec = 64 years

which is, again, of the same order of magnitude as the other life-times.

All these studies indicate that a neutron fluence of 10^8-10^9 n/cm^2 per shot at 5 shots/sec or, equivalently, a neutron flux of 5×10^8-5×10^9 n/cm^2/sec is the upper limit for an acceptable life-time of the superconducting magnets. Shielding which reduces radiation to below this level is essential.

References

1. See e.g. D. Dew-Hughes, "Introduction to Superconducting Materials", Treatise on Mat. Sci. and Tech., Vol 14, p. 1 (1979 Academic Press)

2. See e.g. B. Brown, J. of Nucl. Mat. 97, p. 1 (1981)

3. See e.g. A.R. Sweedler, C.L. Snead, Jr., and D.E. Cox, "Irradiation Effects in Superconducting Materials", Treatise on Mat. Sci. and Tech., Vol 14, p. 349 (1979 Academic Press).

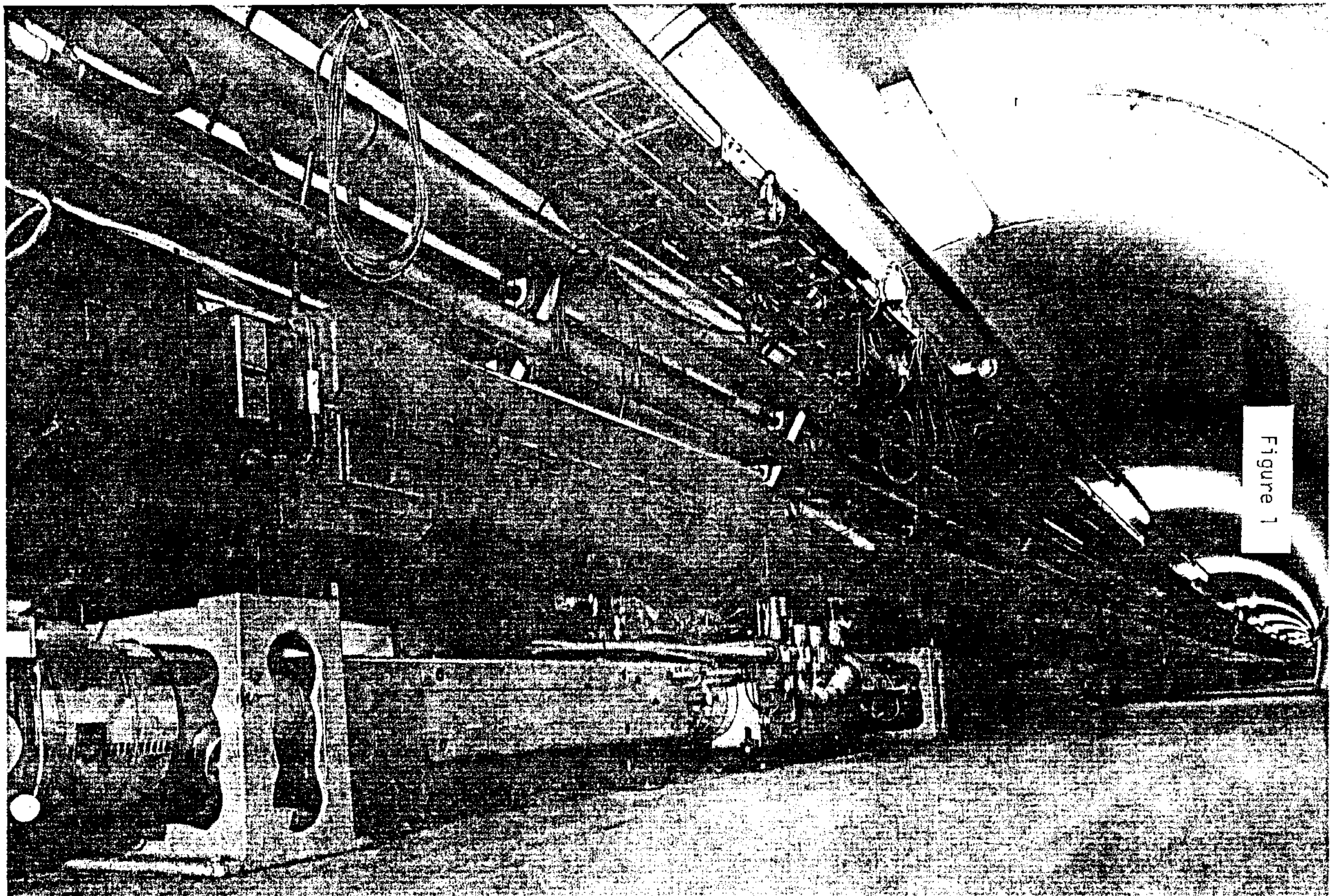

Figure 1. Photograph of the Tevatron at Fermilab. The upper ring is the 400 GeV Main Accelerator and is composed of conventional magnets. The lower ring is the 1000 GeV Tevatron and is composed of superconducting magnets.

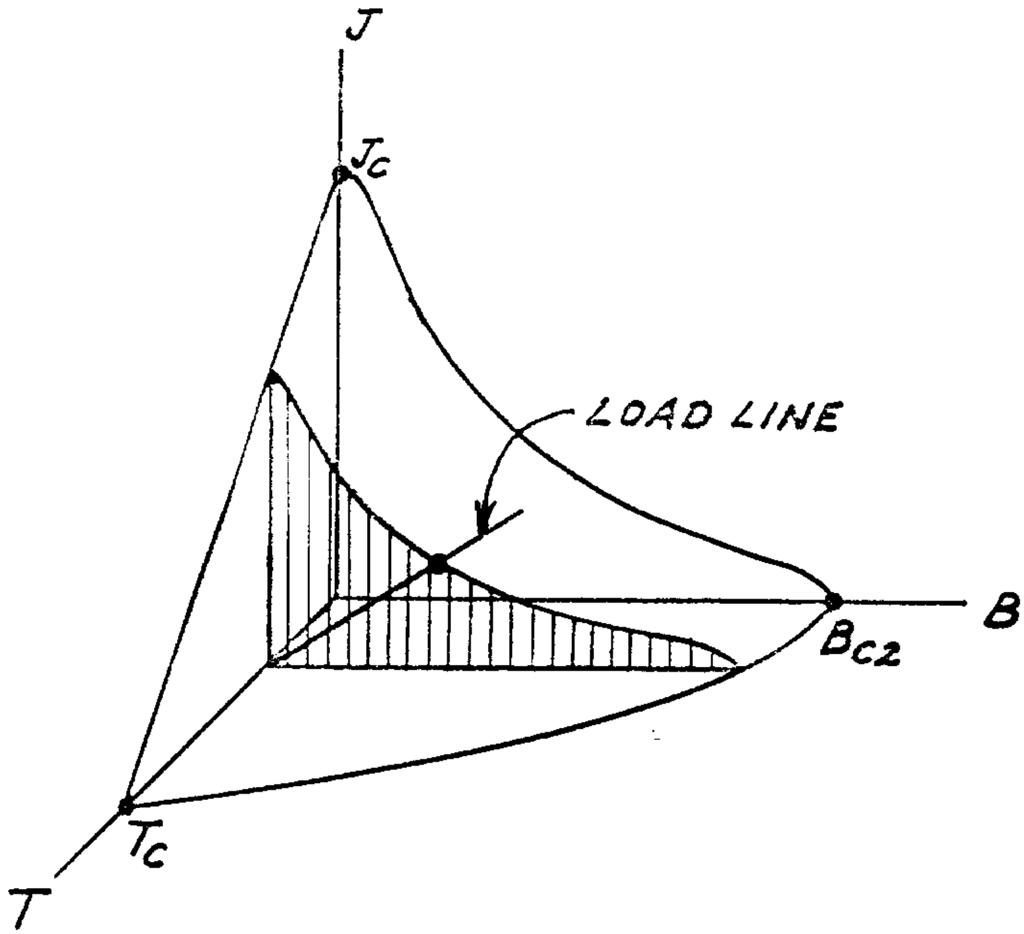

Figure 2. Diagram giving the superconducting region of a Type II superconductor in the space of temperature (T), current density (J) and magnetic field (B).

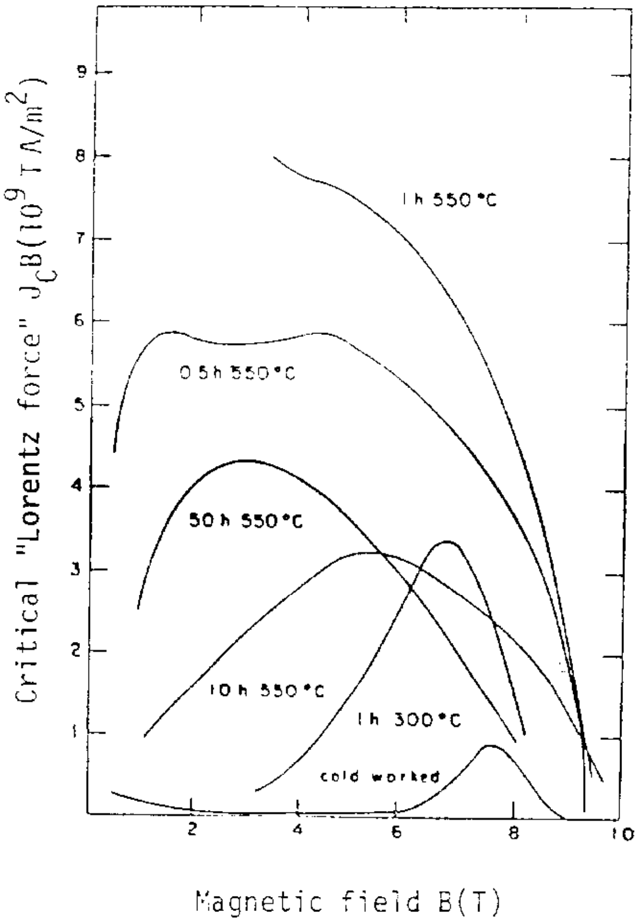

Figure 3. Critical "Lorentz force" J_cB versus field B for an Nb(65 atomic %) Ti alloy at 4.2 K after various annealing treatments.

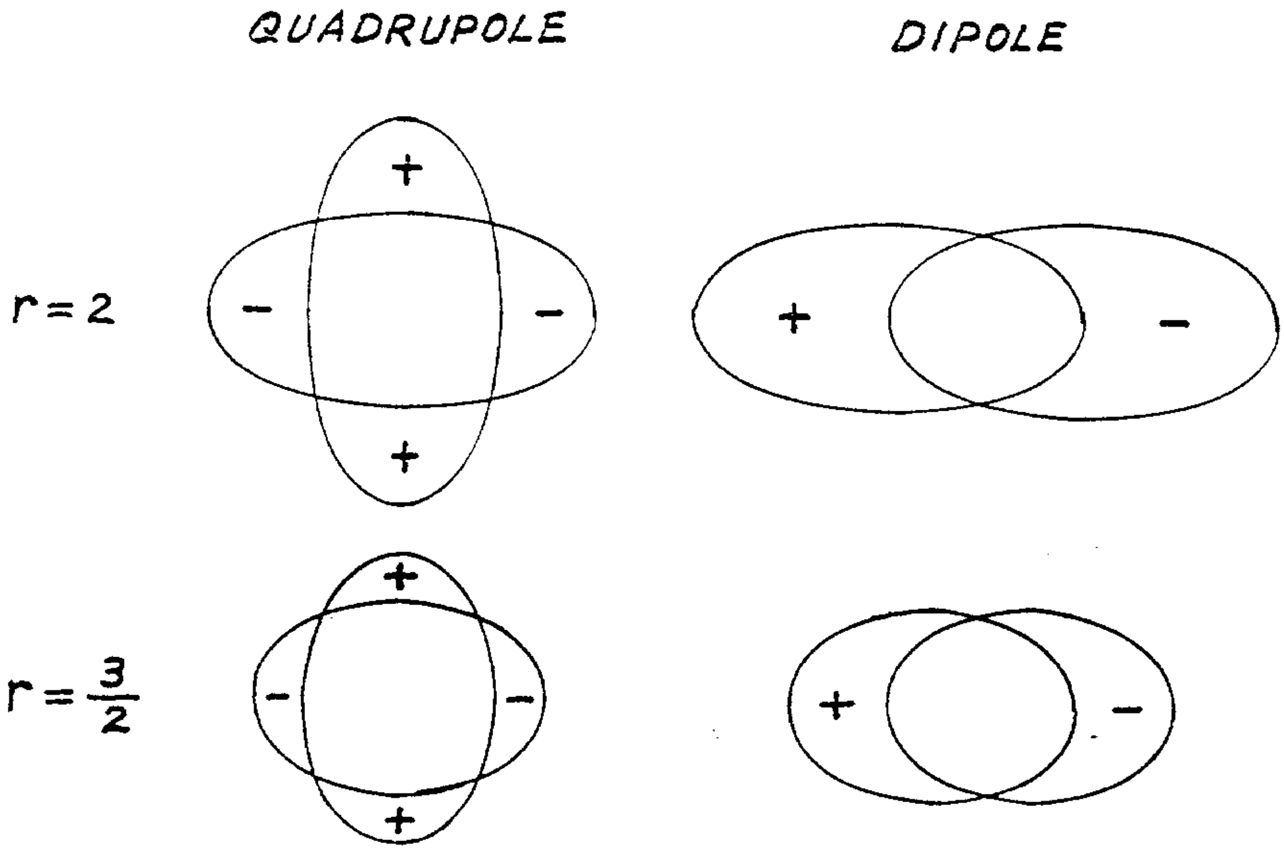

Figure 4. Proper cross-sectional shapes of coils with uniform current densities for dipoles and quadrupoles. The crescent shapes of coils are given by intersections of ellipses.

Figure 5

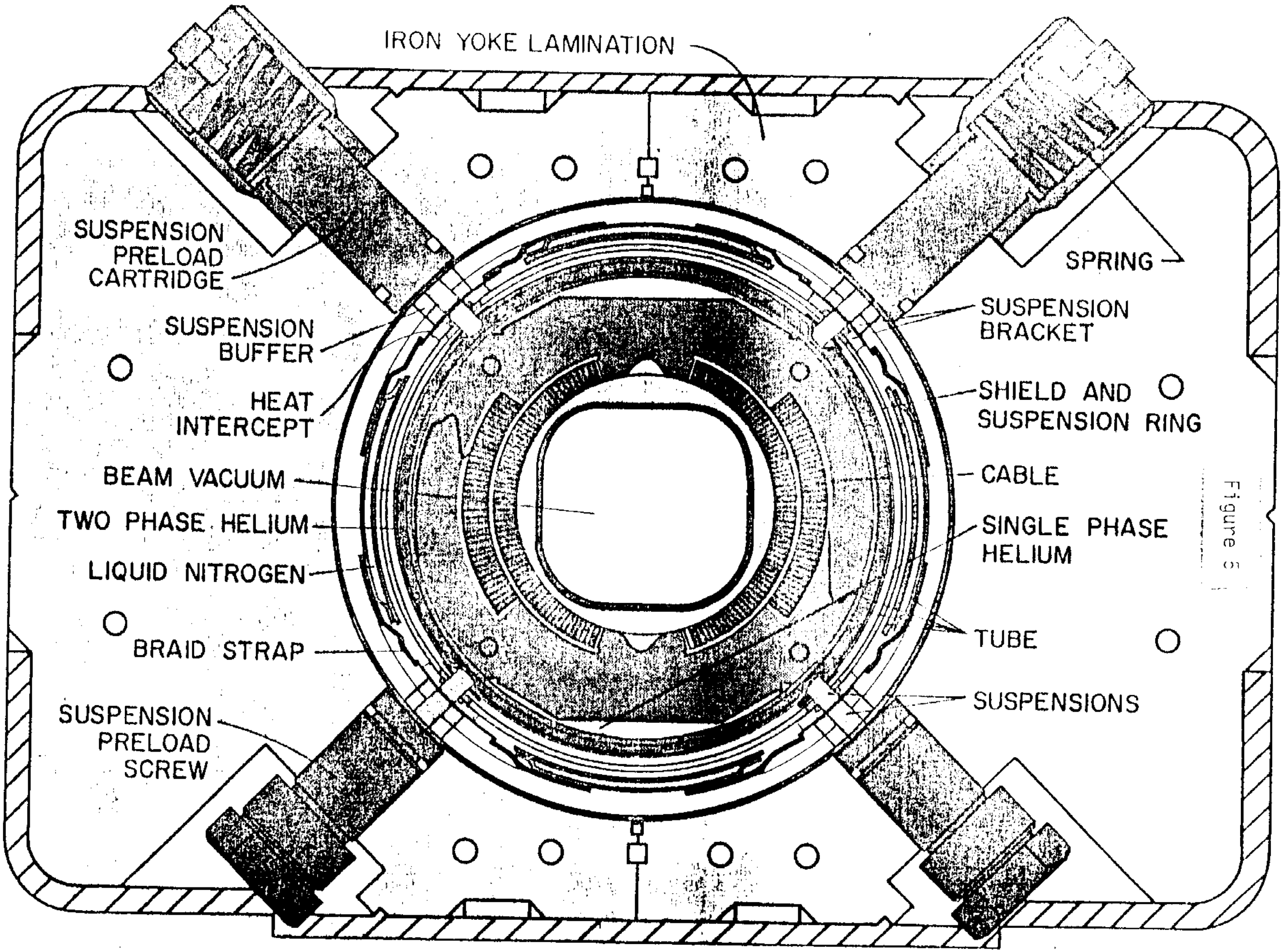

Figure 5. Cross-sectional drawing of the superconducting dipole magnet for the Fermilab Tevatron.

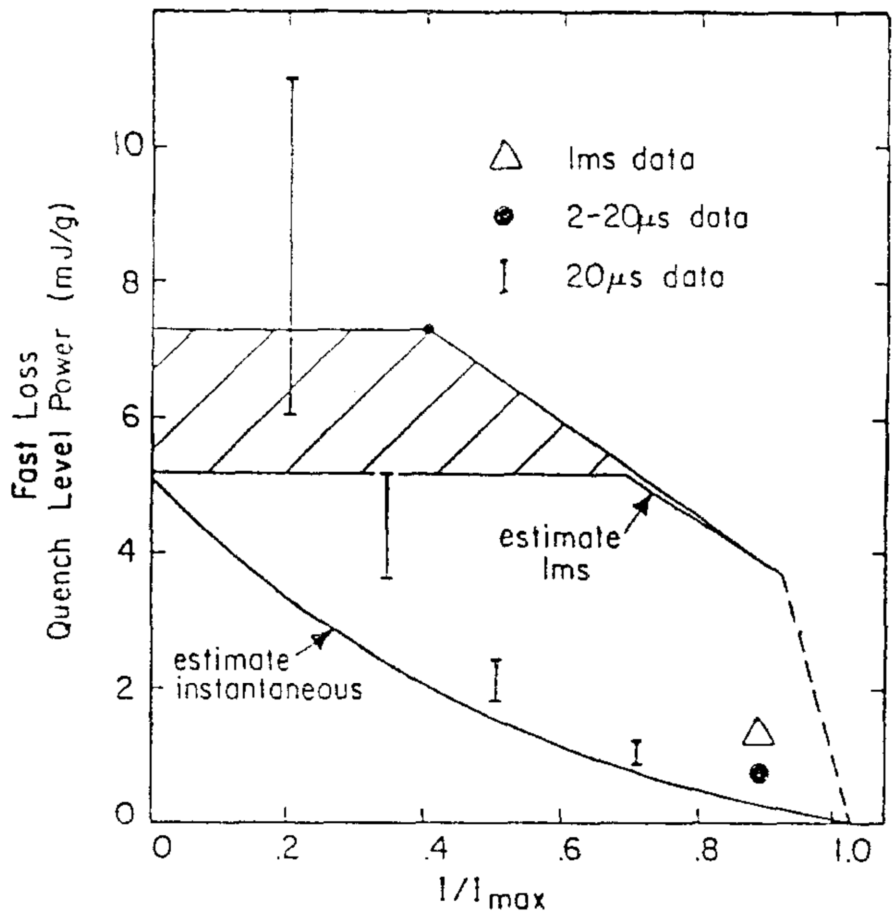

Figure 6. Measurements of quenching of superconducting magnets due to fast heating by particle beams.