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MAXIMUM FIELD CAPABILITY OF ENERGY SAVER SUPERCONDUCTING MAGNETS

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Introduction

At an energy of 1 TeV, the superconducting cable in the Energy Saver dipole magnets will be operating at ∿96% of its nominal short sample limit;[1] the corresponding number in the quadrupole magnets is 81%. All magnets for the Saver are individually tested for maximum current capability under two modes of operation; some 900 dipoles and 275 quadrupoles have now been measured. The dipole winding is composed of four individually wound coils. In general, the cable in the four coils comes from four different reels of cable. As part of magnet fabrication quality control, a short piece of cable from both ends of each reel has its critical current ($\rho = 1 \times 10^{-12}\Omega$-cm) measured at 5T and 4.3°K. We present below the statistical results of the maximum field tests on Saver magnets and explore the correlation with cable critical current.

Magnet Maximum Field Measurements

The first two measurements made on each production magnet at the Magnet Test Facility[2] are called "quench" and "cycle". In quench, a linear current ramp of slope 200a/s is applied to the magnet until a quench occurs. If the maximum current reached is greater than 4.5ka, the test is terminated. If it is less than 4.5ka, the test is repeated until subsequent runs differ by less than 50a. The cryogenic conditions are: (a) liquid He temperature (single phase out, vapor pressure thermometer read prior to the run) of 4.65 ± 0.04°K, (b) 1-2 psi of subcooling, (c) a mass flow of 20-25 g/s, and (d) the warm bore insert at 78°K. Very little "training" is observed, the average number of quenches being 2.6. In the second measurement, a repetitive waveform approximating the accelerator cycle is applied, a 20s flattop with 200a/s up and down ramps. Flattop current starts 300a below the quench result and on every second ramp is increased by 50a until a quench occurs on or near flattop. The maximum current distributions resulting from these two procedures (IQ for quench and IC for cycle) are given in Fig. 1 for 887 dipoles and 268 quadrupoles; of the latter, 209 are of the 66"-long variety. The distributions for the subsets of 774 dipoles and 216 quads presently installed in the completed Saver ring are essentially the same as for all magnets. Mean values and r.m.s. widths of the distributions are listed in Table I.

Table I

Mean Values and Widths of Maximum Currents (ka)

	Dipoles				Quadrupoles			
	Installed		All		Installed		All	
	Mean	σ						
IQ	4.50	0.18	4.48	0.20	4.75	0.20	4.71	0.23
IC	4.37	0.14	4.40	0.17	4.70	0.19	4.65	0.25
IC<4.44	51%		53%		6%		13%	

Magnetic field calculations[3] show that the maximum field at the conductor is 19% higher in dipoles

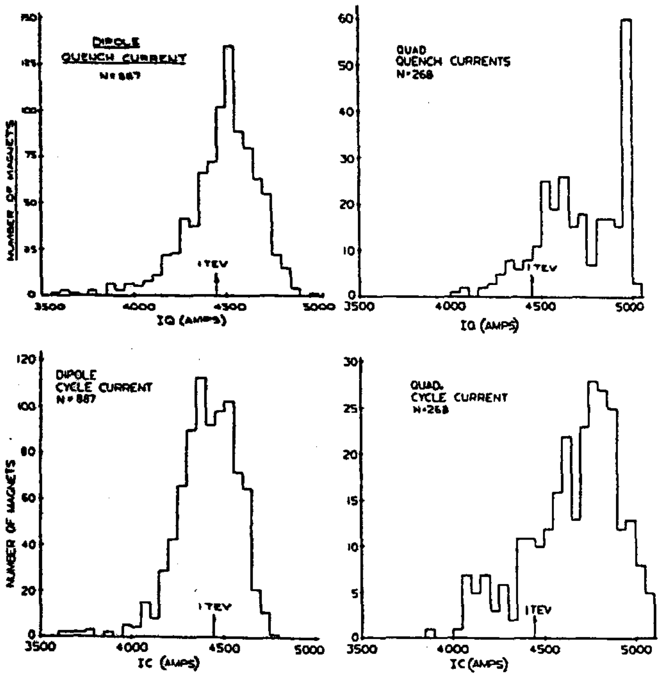

Fig. 1

compared to quadrupoles (at the same current). This is clearly evident in the IC distributions, the quads peak at 4.8ka, about 300a higher than the dipoles[4] (the IQ plot for the quads is truncated at the upper end due to the 5.0ka limit of the power supply used). The predominant difference between quench and cycle distributions is that cycle is shifted to lower values by ∿100a on average. The downward shift could be accounted for by a 0.12°K rise in temperature; during a cycle run, the temperature of the exiting single phase He is seen to rise ∿0.03°K.

Excitation to the 1 TeV level occurs at a current value of 4.44ka; in the dipole this yields a field of 4.43T in the gap and 4.85T at the high point in the coil. The last line of Table I gives the fraction of the magnets for which IC falls below the 1 TeV current; of the installed magnets, the fraction falling below 4.0ka is ∿1%. It is expected that the operating temperature in the ring will be about 0.05°K lower than the mean temperature prevailing in the MTF tests.

It has been observed that about 10% of the dipoles exhibit an anomolous behavior wherein the cycle current exceeds the quench current by 100-300a. Many of these magnets have a "non-quench" type of training; that is, the 200a/s quench current can be improved if the magnet is slowly raised to high currents. However, once a quench occurs, it reverts to the original lower value.

The repeatability of quench and cycle currents[5] was tested on a sample of 13 dipoles (magnets used in the B-12 test string). On average, the quench currents

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*Operated by the Universities Research Association, Inc. under contract with the U.S. Department of Energy repeated to within 100a, the cycle currents to within 30a. The latter is consistent with variations due to granularity of the method and MTF temperature variations.

Correlation with Cable Short Sample Data

As mentioned above, the two-shell dipole coil consists of four individual coils (two 35-turn inner coils and two 21-turn outer coils). A standard reel of cable, 4360 ft. long, can make three inner coils or five outer coils. A critical current measurement is done on a short (∿3" long) piece of cable taken from both ends of each reel. The test is done in liquid He at a pressure slightly above ambient atmospheric and with an external field of 5.0T transverse to the cable[6]. Since the maximum field in the outer coil of a dipole is only 73% of that in the inner coil, one is interested in the smaller of the two short sample limits (ISSMIN) of the two reels that are used in the inner coils of a given magnet. Fig. 2 shows the critical current distribution for the inner coils of 336 dipoles (shaded curve) along with the ISSMIN distribution (open curve) for the same magnets. The latter has a mean and width of 5.06 ± 0.22ka to be compared with 4.51 ± 0.20ka for the MTF quench tests on the same sample.

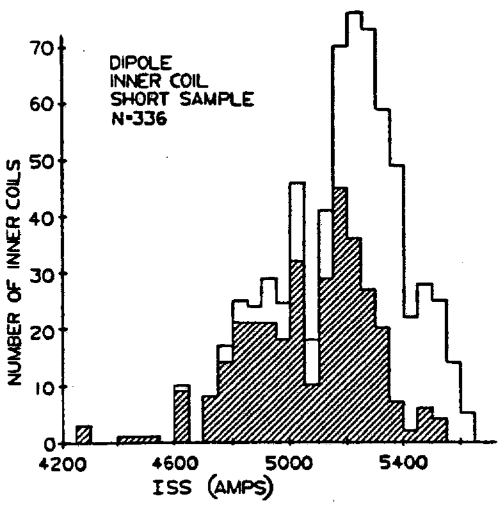

Fig. 2

In Fig. 3, we show a scatter plot of ISSMIN versus magnet quench current; no clear correlation is evident in the plot. There are many effects which tend to reduce any correlation, e.g., (a) magnet quench is caused by mechanisms other than cable superconducting limit; (b) variation of ISS along the cable in a given reel; (c) spread in temperature at which ISSMIN is measured (±0.03°K due to barometric pressure); (d) spread in temperature in MTF tests (±0.05°K, temperature recorded each test); (e) measurement uncertainties in ISSMIN and IQ. One can eliminate one of these and obtain a plot which is easier to interpret by using ISSMIN and the measured MTF temperature to predict IQ for each magnet. If I is the predicted quench current, then an approximate relation is

$$I^2 = \left(\frac{BSS \cdot ISS}{1 - \frac{TSS}{TB(SS)}}\right) \frac{1}{T} \left(1 - \frac{TMTF}{TB(MTF)}\right) \qquad (1)$$

where TSS is the temperature (taken to be 4.26°K) for the ISS run, TMTF is the measured temperature for the MTF test, and

$$TB(x) = 9.0 \sqrt{1 - \frac{B(x)}{12}} \quad {}^0K \qquad (2)$$

is the transition temperature for NbTi at magnetic field B(x) in Tesla. For the ISS measurement

$$B(SS)=BSS=5.0T + \text{cable self field at ISS} = 5.2T$$

and for the IQ measurement

$$B(MTF) = TI, \; T = 1.093 \text{ T/ka} \qquad (3)$$

where T is the magnet transfer constant for the high field point in the coil. Using eq. (1), we can predict a quench current for each magnet, given ISSMIN and TMTF. In Fig. 4, we show the scatter plot of cycle current versus predicted quench current. In this plot, the expected correlation line should have unit slope. With a little imagination, it is possible to see a unit slope boundary on the lower side of the cluster of points; but again, no strong linear correlation is apparent in the bulk of the data. A tail to the distribution in the IC dimension extending to lower current is not unexpected. In Fig. 5, the distribution of the ratio of cycle current to I is given; the r.m.s. width is 2.3% and 6% of the magnets fall in the tail of the distribution below a ratio of 0.92. It seems unlikely that this width arises from the cycle measurement since, as mentioned above, the measurement appears reproducible at the 0.7% level. If the width was a result of ISS varying along the reel of cable, we estimate that an equivalent r.m.s. variation of ISS of 6% is required. The measurements of ISS at both ends of each reel yield an r.m.s. of 102a, about 2 %. A recent study[7] of 15 reels of FNAL-type cable at BNL

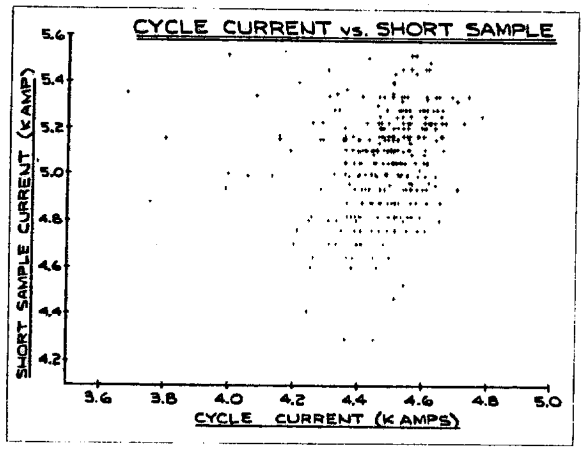

Fig. 3

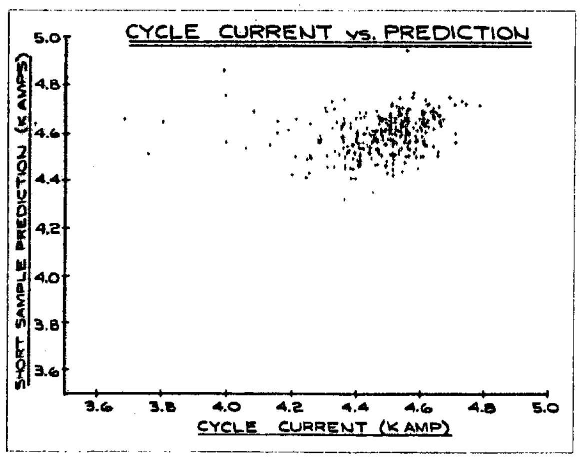

Fig. 4

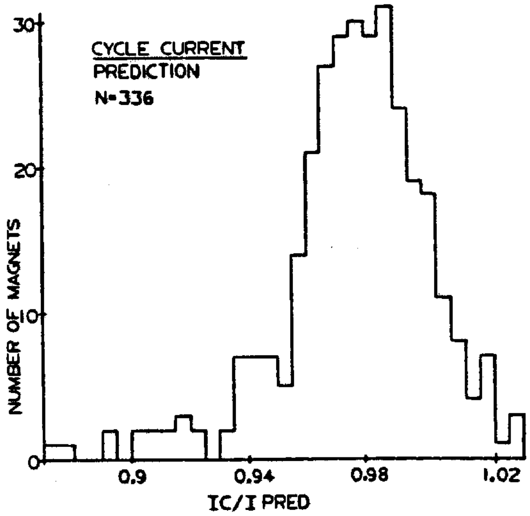

Fig. 5

indicates an average minimum to maximum ISS of 0.97. Additional information is obtained by examining the difference in cycle currents for pairs of magnets having ISSMIN originating from the same reel of cable (recall that 3 inner coils are wound from a given reel). In this sample of 336 dipoles, there are 103 cases where 2 or more magnets are "limited" by the same reel. The distribution of the differences for this subset of magnets has an r.m.s. width of 2.8%, comparable to that of the ratio shown in Fig. 5, naively one might expect it to be larger by a factor $\sqrt{2}$.

Conclusions

The individual measurement of the maximum current achievable in 887 dipoles and 268 quadrupoles for the Energy Saver allows the following conclusions:

1. When run in a cycling mode (~65s per cycle at a ramp rate of 200a/s), the dipoles have on average a 6% lower current capability than the quadrupoles.[4] Qualitatively, this is expected since the field at the conductor is 19% higher in the dipoles at the same current.

2. The average dipole will reach an equivalent energy of 0.99 TeV; 10% of the dipoles fall below 0.94 TeV and 7 of the installed dipoles lie below 0.90 TeV.

3. The average quadrupole achieves an energy of 1.05 TeV; 6% of the quads lie below 0.94 TeV.

A search for correlations between cable short sample critical current and magnet current on a subset of 336 dipoles indicates the following:

1. The cable critical current limits the magnet current for 94% of the magnets.

2. Sampling cable from both ends of a reel enables one to predict maximum magnet current to an r.m.s. accuracy of 2.3%.

3. The equivalent r.m.s. variation of critical current within a reel of cable may be as large as 6%, although some influence of coil fabrication is a possibility.

References

1. A. V. Tollestrup, "Care and Training of Superconducting Magnets", IEEE, Vol. MAG-17, No. 1, 863 (1981). Also see R. Yamada, M. Wake, and W. Fowler, "Maximum Quench Current of Energy Doubler Magnets", FNAL TM-969, 1620.00 (1980).

2. B. C. Brown, et al, "Report on the Production Magnet Measurement System for the Fermilab Energy Saver Superconducting Dipoles and Quadrupoles", Proceedings of this Conference.

3. S. C. Snowdon, Fermilab, private communication.

4. Cable is selected according to short sample current, higher current cable is used to wind dipole coils.

5. W. E. Cooper, et al, "Long Term Stability of Fermilab Energy Saver Magnets", Proceedings of this Conference.

6. W. B. Fowler, et al, "Summary Data from Large Scale Quality Control Tests on Superconducting Wire", IEEE, Vol. MAG-17, No. 1, 925 (1981).

7. M. J. Tannenbaum, et al, "Correlation of Superconducting Strand, Cable and Dipole Critical Currents in CBA Magnets", 1982 ASC Conference, Knoxville,TN.