BNL 28377

1980 Applied Superconductivity Conference, Santa Fe, N.M. Sept. 29–Oct. 2, 1980

QUENCH BEHAVIOR OF A SUPERCONDUCTING ACCELERATOR MAGNET

A.D. McInturff, W.B. Sampson, M. Garber and P.F. Dahl
Brookhaven National Laboratory
Upton, New York 11973

CONF-800980--9

Summary

Data are presented on the minimum energy required to cause quenches to propagate in an accelerator dipole magnet. The amount of stored energy dissipated into the magnet was measured as a function of dipole excitation current. This in turn determines the maximum coil temperature reached in a given magnet. Quench velocities in the longitudinal direction of the conductor were as high as 11m/sec. The azimuthal velocities or turn to turn velocities were found to be a function of the number of fiberglass layers of insulation that the quench had to cross and were on the order of a few tens of centimeters/sec. The field shape of a given magnet was found to be unchanged for more than 100 quenches. The coil to coil connection and inter-coil splice resistances were found to be less than a nano-ohm and therefore of little consequence in the cryogenic load considerations. No definitive answers were found on how to decrease the rate of training (130 Gauss/Quench average) required from 4.0T to 5.1T.

Introduction

In the development of magnets for the ISABELLE Storage Ring Accelerator [1], a series of magnets were constructed to ascertain the performance characteristics of the proposed ring magnet, i.e. dipoles, quadrupoles, and working line coils. These cosine θ designed magnets were designated ISA Mk I, II, through XVI. Then a final magnet ISA Mk XXI was constructed to check that the conclusions reached by the earlier magnet series were generally valid. Unfortunately, ISA Mk XXI is having a problem with the working line coil and the data from it are somewhat clouded as of the time of this conference. There were also a series of magnets produced as a preproduction run at the same production rate per winding fixture as is required by the ISABELLE construction schedule, designated 0001 through 0012. The bulk of the data in this paper are primarily obtained from ISA Mk XVI and XXI which yielded the greatest amount of data per QUENCH due to the complete instrumentation used in these coils. Data from earlier magnets, though lacking a great deal of detailed information in a given quench, can be compared to the latter coils by similarities in the voltage patterns that develop during quench.

Statement of Problems

In the present ISABELLE design the magnets are required to absorb their own stored energy by use of a voltage limiting diode across the input to the magnet. Therefore it is of utmost importance to understand the quenching behavior and limits of the coils. Computer studies utilizing a modified form of the Rutherford Lab "Quench" Code [2] to calculate the probable coil temperature rise were used as a guide. They predicted the temperature versus $\int I^2 dt$ for the ISABELLE conductor shown in Figure 1. They also predicted a peak temperature range for the transport current at a value of 3/4 the maximum with magnetoresistance effects of the copper taken into account. (In the actual case, inductive coupling at the higher values

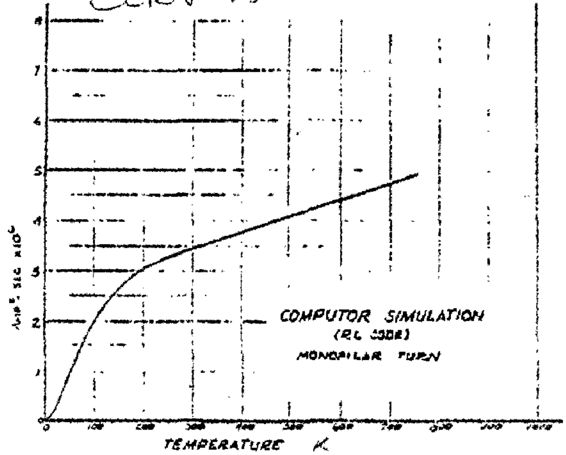

Figure 1. The temperature of a monofilar turn as a function of the total amount of energy it absorbs. This curve is a computer simulation with experimental verification at 100°, 230° and 530°K.

of $\dot{I}$ tends to accelerate the resistance buildup.) The other major worry in a magnet that is internally dissipating its own stored energy is the stability of the magnetic field shape. An operational problem is to measure the effective resistances and therefore the cryogenic loads they cause, of coil to coil connections, splices, end lead joints. The testing problem which is just beginning to be addressed is the very slow training rate of the magnets after reaching 4.0T. (i.e. typically 130 Gauss/quench).

Experimental Procedure

In a standard coil test the only normally monitored points in the dipoles are a) input leads b) each coil half, c) crossover or coil half to half interconnection. These measurements are accomplished utilizing a six terminal network. In the so called instrumented coil test up to seventy terminal networks were employed plus thermometry and heaters (to initiate quenches under known conditions). Strain gauges and piezo-electric microphones simultaneously measure coil parameters.

The quench is detected by observing the difference in voltage between the coil halves. In the standard testing set-up the data is taken in such a manner that any event can be reconstructed up to two seconds prior to the quench trigger. By analyzing the particular shape of the prequench voltages, it is possible to deduce from the early slope changes whether the quench originated in a multifilar turn, a turn next to a wedge, or in the middle of a block. When large voltage tap arrays are monitored, it is a simple matter of subtraction to determine the resistive section. The thermometers, carbon resistors and germanium thermistors, and linear bimetalic gauges are installed in such a manner as to isolate them from the liquid bath but keep them in good thermal contact with the coil conductor. The thermometers nominally tracked in less than 10msec. with the

*Work performed under the auspices of the U. S. Department of Energy voltage taps. The resistors and linear thermometers utilized four terminal outputs to increase their sensitivity and accuracy. Using the thermometry as an independent information source, it is possible to perform many cross checks on the validity of the data. By maintaining greater than three megohms to common mode ground it was possible to measure a tenth of a nano-ohm resistive effective dc voltage differences.

Data and Observations

1. Most of the quenches that occur before 4.6 to 4.7 T originate in the first block near the pole tip in the Cu-Ni inert turn magnets as well as in most of those using copper inert turns.

2. The azimuthal propagation time is directly proportional to the number of fiberglass layers of insulation that the quench must traverse.

3. The thin bakelite and epoxy wedges account for no more than one turn delay in quench propagation.

4. The onset of a quench is normally characterized by a linear voltage rise until a break occurs and that is followed by a linear rise with either two or three times the initial slope.

5. There are either fewer or at least statistically the same number of quenches occurring in ends versus those that occur in the straight section. Where voltage probes could determine the end precisely, none occurred.

6. The crossover connection has a typical resistance between 0.5 and 1×10^{-9} ohms.

7. The resistance of the leads and splices in the coil halves of the conductor is less than 0.1×10^{-9} ohms.

8. The longitudinal velocity of the quench at 3500 Amps and 4.5 Tesla is 11.5 m/sec. while the azimuthal velocity is 19.4 cm/sec. From the initiation stage to the final turn going normal, the average azimuthal quench velocity is 8.7 cm/sec. This is due to the large number of fiberglass layers in the monofilar region.

9. The longitudinal velocity of the quench at 3250 Amps and 4.3 Tesla is 7.11 m/sec.

10. The typical times required to cross a fiberglass turn to turn insulator were 22.4 ms/layer at 3250A, 12.5 ms/layer at 3500A, and 35 msec/layer at 3000A.

11. The difference in maximum temperature for Cu-clad material (e.g. ISA Mk XVI) vs the Cu-Ni clad material, e.g. ISA009, ISA Mk XXI, at 4 Tesla for a polar quench was about 120K. The resistance buildup was at the rate initially of 1.28 to 1 which is the copper ratio difference of the strands in the braid. Of these two series, the computer-simulated temperature of a turn, experimentally verified at several points, is shown in Figure 1. This figure indicates that for 4×10^6 to 4.5×10^6 A^2sec, the solder in a monofilar turn will melt. This was experimentally verified and measured in a test magnet. The maximum coil temperatures reached in the artifically induced quenches (minimum energy into heater) are shown in Figure 2. The rate at which the peak temperature falls off in the high current and field region is faster than that predicted by the computer model because the code does not take magnetic coupling (transformer effects) into account. The magnet ISA Mk XXI is essentially a compromise in design between the second set of preproduction dipoles 0007 through 0012 which used Cu-Ni jacketed superconducting wire and Cu-Ni inert turns and the more stable Cu jacketed wire used in ISA Mk XVI. If the totally stabilized Cu inert turns are used in the magnets of the large aperture size (13.09 cm ID) and high aspect ratio (length/width) then they are unable to switch fast enough at 2800 Amperes and will burn out due to excessive heating.

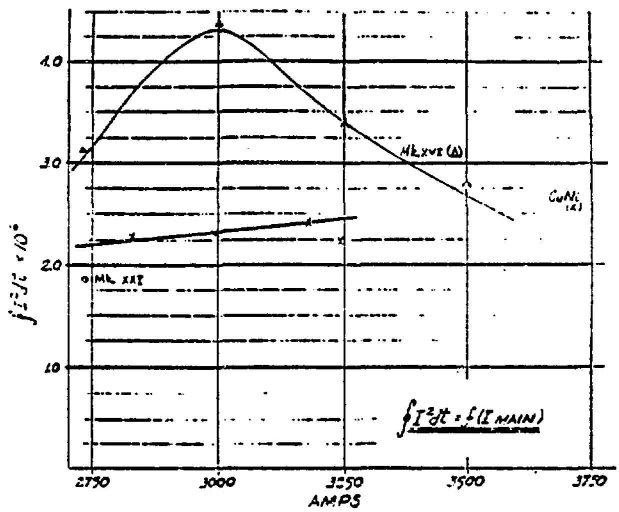

Figure 2. The maximum energy dissipated in monofilar turn as a function of transport current using a minimum energy input to initiate the quench.

Therefore ISA Mk XXI was a compromise using Cu in the postal region, trying to cryostabilize it from 3000 to 3500 Amps and therefore minimize the training. There were no postal quenches seen in ISA Mk XXI but, due to a shorted working line coil overheating, the magnet has not thus far operated past 2725 Amps. The thermistors in the postal block did see, after 2500 Amp, several 100 millidegree spikes in the 1st turn. A possible explanation would be the separation of the turn from the post.

12. The stability of the magnetic field, after the magnet absorbed its stored energy without destruction, seems to be excellent as shown in Table 1.

The data plotted in Figure 3 shows the minimum energy input into a heater built into the coil that will cause the magnet to quench at a given magnetic field. There is some question as to the exact numbers to put on the energy scale due to a short in the heater circuit to the coil winding. The order of magnitude is about 30 to 50 millijoules in the higher pulses.

The quench volumes in the naturally occurring quench (non heater induced) seemed to be about an order of magnitude larger than those of the heater induced variety. The heater occupies about a centimeter square, indicating that a natural quench evolved in at least ten times that volume.

FIELD QUALITY, ISA Mk XVI

As Designed

	B_o(Gauss)	$B_1\left(\frac{1}{10^5 cm}\right)$	$B_2\left(\frac{1}{10^6 cm^2}\right)$	$B\left(\frac{1}{10^7 cm^3}\right)$	$B_4\left(\frac{1}{10^8 cm^4}\right)$	$B_5\left(\frac{1}{10^9 cm^5}\right)$	
1000. Amps	13592	0	-206	0	113	0	
	0	0	0	0	0	0	$An\left(\frac{1}{cm^n}\right)$
As Computed from Mechanical Depth Measurements; Temperature and Compression accounted for							
1000. Amps	13551	2.5	-226	3	205	3	
		1.6	12	2	19	2	
D. C. Data Taken After 10 minute wait T(1/e)=4 minutes							
1000.8 Amps	13676	18	-255	22	127	-12	
		19	20	29	-20	-132	
A. C. Data		Ramp Rate		2 A/sec.			
999.6Amps	13664	19	-302	25	155	-15	Quench = 1
(1000)	(13669)	10	18	32	-7	-135	
999.6Amps	13630	19	-299	24	148	-7	Quench = 35
(1000)	(13677)	13	16	34	-5	-132	
1000 Amps	13854	17	-305	24	151	13	Quench = 105
		17	19	33	-7	-133	
1000.5Amps	13873	16	-312	25	152	-25	Quench = 106
		5	15	30	-6	-139	
988.1 Amps	13514	13	-302	25	-	-15	Quench = 107
(1000)	(13677)	10	14	33	-	-132	

Mechanical Tolerances, ISA Mk XVI
Block Placement Error in Inches } Coil #1 $\pm 4.1 \times 10^{-3}$
Coil #2 $\mp 3.3 \times 10^{-3}$

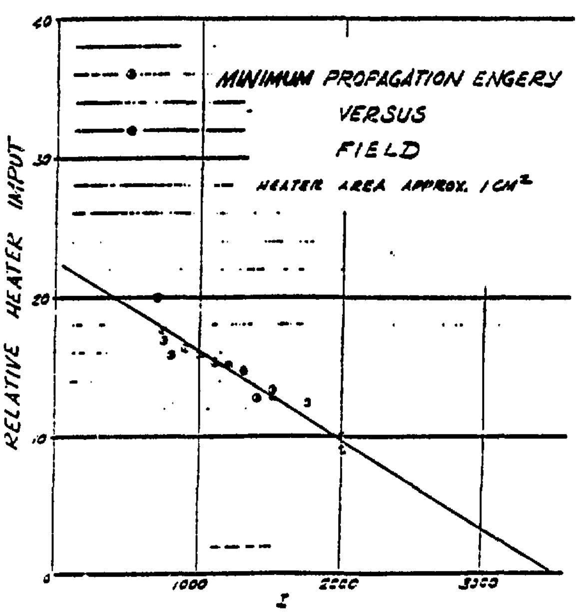

Figure 3. The minimum energy input into a 1 cm^2 heater that will initiate a quench at a given field and current.

Conclusion and Summary

The quench behavior of the later magnets in the ISA series and a majority of the standard magnets seems to be acceptable from the standpoint of internally initiated quenches up to the low 4T range.

The field stability with respect to internally dissipating the stored energy seems not to represent a problem with the Cu-Ni series up to fields in excess of 4.5T. The magnets seem to be out of tolerance from the paper design by a factor of two mechanically and three to four magnetically.

The thesis of cryostabilizing the polar turns or first block is as yet unresolved, but looks promising.

The ability of the magnets to absorb their own energy seems to be marginal if the copper ratio in the strands is increased but fine if the Cu-Ni jacketed strand material is used and the majority of the inert turns are Cu-Ni.

References

1. H. Hahn, "ISABELLE - A Status Report", these proceedings.

2. M.N. Wilson, Rutherford High Energy Laboratory Report RHEL/M 151 (1968)