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STUDIES OF QUENCH PROPAGATION IN A SUPERCONDUCTING WINDOW FRAME MAGNET*

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ABSTRACT

During the testing of a meter long, superconducting window frame magnet, information from many spontaneously generated quenches have been recorded by an on-line computer system. Nearly every layer in an eleven layer dipole had a voltage tap and for some layers this subdivided into two halves. This allowed us to study development of the quenches in some detail. Knowledge of the resistances throughout the magnet also allowed the temperature distributions in the superconducting windings to be determined. A qualitative picture of the quench was developed and quantitative values of quench propagaton velocities were compared to heat transfer calculations.

INTRODUCTION

Superconducting dipole magnets for beam transport and accelerator applications are generally not cryostable because of the economic need for very high current density conductors. Therefore a reasonably good understanding of the quench propagation times is required to insure that no portion of the quenched superconductor becomes overheated while other portions of the conductor remain superconducting.

Seven years of operating experience and numerous beam radiation heating experiments with the window frame or rectangular current sheet dipole magnets in the fast extracted proton line at the AGS have demonstrated the practical survivability of dipoles of this design.[1,2,3] Improved instrumentation and experience while testing a 3 meter long eleven layer window frame magnet for the AGS slow extracted beam line have enabled us to make more quantitative measurements. Details of the construction of this magnet can be found in references 4 and 5. An on-line data acquisition system was able to sample magnet voltages at times small compared to the quench propagation times.

Conductor Configuration

The basic structure of the conductor package is shown in Fig. 1. The overall size of the dipole windings are 14.5 cm high by 3.2 cm wide. Layers of 42 turns of 1.25:1.00 Cu to SC monolithic superconductor coated with 5.4×10^{-3} cm thick Formvar insulation were interspersed with sheets of corrugated high purity aluminum (RRR=4000). The corrugations in the aluminum provided channels for liquid helium (at 4.5°K) over half the area, and the high diffusivity of the high purity aluminum ensures that it acted as a nearly isothermal layer between the conductors. The surface of the aluminum was anodized to provide further electrical insulation. The vertical channels in the aluminum were interconnected top and bottom with horizontal channels which allowed contact between the helium and the magnet iron.

The two outside conductor layers were "graded", that is, wound with conductor 60% of the cross sectional area of the main winding.

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Measurement Apparatus

The superconducting magnet was powered by a well-filtered 3600A Acme power supply for these quench measurements. A diagram of the test arrangement can be found in reference 5. For the quench measurements, usually 16 channels of voltage information were recorded. These included the current shunt, the "H coil" which produced a signal proportional to dI/dt, and one or more voltage taps on each layer of the superconductor.

The voltage taps each passed through resistive voltage dividers (typically 5%) and 20 msec filter networks into differential amplifiers capable of eliminating common mode voltages of up to 125 V. With this isolation, each layer voltage could be read directly providing extra precision and direct interpretation of the voltages. Next, each channel was digitized in sequence by a 12 bit A/D converter and transferred directly to the memory of a PDP-LSI-11 computer.[6] Typical data acquisition took 1 msec per channel (system capability of 0.4 msec per channel) so that each channel was recorded every 16 msec. With a 24,000 word memory in the LSI-11, 24 seconds of data could be recorded.

Since the quenches recorded were spontaneously generated, a special looping program was developed which retained ∿6 seconds of data prior to a manually operated trigger. This alleviated the need for the electronic trigger sensitive to the beginning of quench, and allowed us to follow the voltage patterns from the very beginning.

Measurements and Data Reduction

Measurements were made at two different current levels. One level was ∿900 A with the full complement of turns powered and another level of ∿1350A with only two-thirds of the turns powered. In both cases, the central magnetic field was ∿3.6 Tesla.

The internal resistance of the power supply is sufficiently low that only a few volts (< 5V) appear across the input terminals of the magnet. Therefore, the layer voltages are essentially only the sum of the resistive and inductive components of that layer. The inductive voltage can be determined from the inductance of each layer multiplied by the rate of change of current as measured by the external "H" coil or an unpowered layer in the case of the high current quenches. Knowledge of the resistance of the layer and measured resistance ratio for the conductor enable us to compute an average temperature for each layer.

Observations and Conclusions

In Fig. 3, there appear to be three distinct time intervals during the quench. First there is an initial time of 0.4 sec between the start of the quench in the initial layer and its appearance in the next layer. Then there is a time interval in which the velocity of quench propagation is approximately constant from layer to layer. Finally, there is an acceleration of the velocity at the end of the quench.

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Both the copper within the conductor and the high purity aluminum have a conductivity per unit area more than two orders of magnitude greater than that of the Formvar insulation, so that the only significant thermal barrier for heat propagation from one layer to the next is the insulation.[7] Because the high purity aluminum forms a nearly isothermal layer between one layer and the next, then the variations of temperatures within the layer are expected to be small. In Fig. 4, the time variation of the temperature is shown during a quench, and the average temperature between halves of layer 5 never exceeds 15°K. In quenches where the quench is initiated in another layer, this variation is considerably smaller.

Our interpretation of the initial delay prior to the period of uniform velocity is that the quench has started in a single turn in a relatively short interval of length due to some mechanical disturbance. Since the quench cannot propagate to the next layer until essentially all of the helium in between layers is vaporized, the propagation at this time is two dimensional. By analyzing in detail the initial time variation of the quench voltage shown in Fig 2a, we are able to calculate the longitudinal and turn to turn propagation velocities under the assumption that these velocities are constant. The result of this calculation indicates a longitudinal velocity of 6.3 m/sec and a turn to turn propagation time of 28 msec. This turn to turn time is in near agreement with the observed time of the onset of resistance in the second half of this layer, and about a factor of two larger than the expectation from the thermal conductivity of the Formvar insulation. Rough calculations of the longitudinal velocity indicate that this value is reasonable.

In the interval during which the layer to layer quench propagation time is almost constant, we calculate the heat flow from layer to the next in a one dimensional manner. The fact that a large portion of layer must be resistive before the quench propagates to the next layer can be seen in Fig. 3, where the top half of layer 1 becomes resistive just shortly before a signal is seen in layer 2. Due to the Formvar insulation, the temperature rise inside the quenched superconductor is very rapid compared to the layer to layer propagation time. Then in the absence of helium in the aluminum channels, the quench propagation time is determined by the heat flow through the insulation layers and the specific heat of the unquenched conductor. The time for the conductor to rise from 4.5 to 7°K is ∿6 m sec after the 900 A quench which is short compared to the observed time of 158 msec. Not surprisingly, the large thermal reserve of liquid helium is an important factor in the quench propagation time. If the heat of vaporization of the helium in the channels is included in the amount of heat which must flow out of one conductor, then the time of propagation is ∿100 msec. Uncertainties in the thermal conductivity of the Formvar, and the heat transfer at the Formvar-helium interface make this calculation uncertain to at least a factor of two. To summarize, this central interval of constant velocity can be calculated approximately as a one dimensional problem from the thermal conductivity of the Formvar insulation and the heat of vaporization of the liquid helium.

The final acceleration of the velocity of the quench can be ascribed to a combination of bulk flow of heated helium gas, the reduced heat of vaporization due to pressurization of the liquid helium, and the higher current density in the outer two "graded" layers.

Converting the observed resistance ratios in each layer to average layer temperatures, we can plot the temperature versus time distribution shown in Fig. 4 for the quench initiated at 1272 A. As expected, the layer in which the quench was initiated reaches the highest temperature, but nowhere for these currents does the temperature exceed 70°K.

Comparison of the quench propagation times at 924 A and 1272 A indicates that the layer to layer propagation velocity is at least linear in the current, but no more than quadratic. However, caution must be used in reaching any firm conclusions due to the different number of layers powered, and the difficulty in establishing the velocity in the high current case. It was also found that quenches initiated in the top half layer proceeded slower initially than those initiated in the bottom half layer, but the later portion of the quench proceeded more rapidly.

During the testing of our next series of 1.5 m window frame magnets, we plan to carry out a more systemated series of tests with heater induced quenches. Hopefully, this will allow us to place many of these ideas on a firmer quantitative basis.

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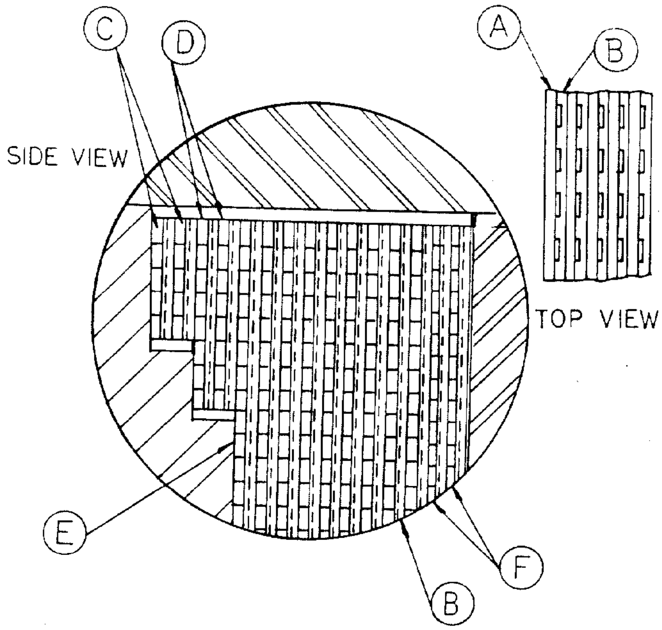

Fig. 1. Construction of superconducting coil package. A-Rectangular superconducting wire(3.4x1.7mm^2). B-high purity aluminum spacers with corrugations for helium channels (1.3mm thick). C and D-Helmholtz windings for sextupole bias correction. E-First layer of main dipole winding. F-Graded layer windings with 60% of cross sectional area.

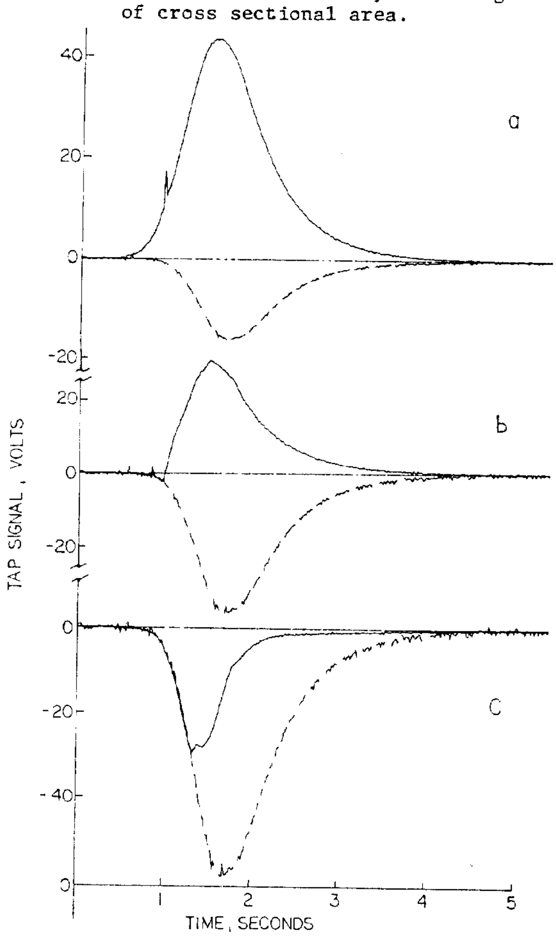

Fig. 2. Typical voltage tracings for a quench at 1272A. The solid curves are the entire layer voltage and the dashed curves are an unpowered layer scaled to the inductance of each individual layer. a,b and c are layers 5 (top half), 6 and 10 respectively. The quench was initiated in 5 (top half).

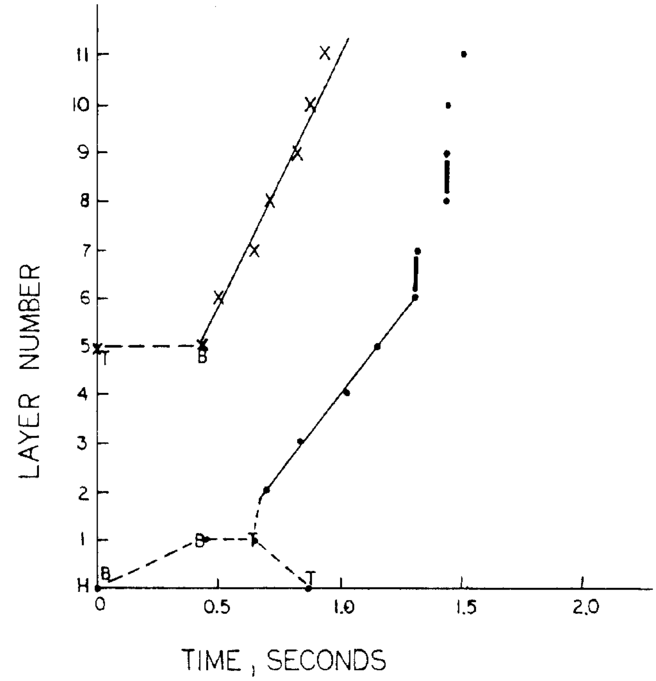

Fig. 3. Time of first resistance seen in each layer for (•) a quench at 924 A and (x) a quench at 1272 A. H refers to the Helmholtz windings and T and B refer to the top and bottom half windings. The light solid lines are least squares fit to the linear portion of the quench.

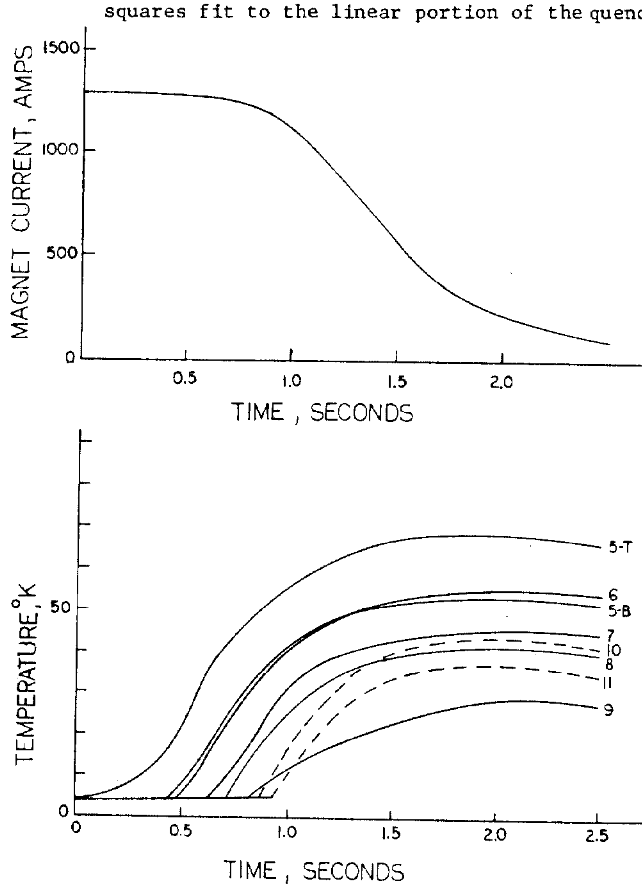

Fig. 4. The current and average temperature distributions per layer for a quench initiated at 1272.