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QUENCH PROPAGATION AND TRAINING IN SIMULATED SUPERCONDUCTING MAGNET WINDINGS*

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Summary

Training behavior similar to that which occurs in full scale superconducting accelerator magnets has been observed in small test windings. The test coils are formed from approximately 20 meters of conductor wound non-inductively, in Bifilar fashion. The resulting racetrack shaped coil is molded at elevated temperature to simulate the construction techniques used for the ISABELLE dipoles. The quench current of such windings has been measured as a function of applied field and the effect of parameters such as mechanical loading and porosity have been investigated. The velocity of propagation of the normal front has been measured both along and transverse to the direction of current flow for several test windings. The minimum energy required to produce a self propagating normal zone has also been determined in an attempt to quantify the relative stability of the coils.

Introduction

In order to achieve a better understanding of the details of quench initiation and the growth of normal zones in ISABELLE magnets, a series of simulated windings have been constructed and used to measure properties which are difficult or impossible to measure in full scale magnets. The two quantities of greatest interest are the velocity of propagation of the normal front and the minimum energy required to initiate a quench.

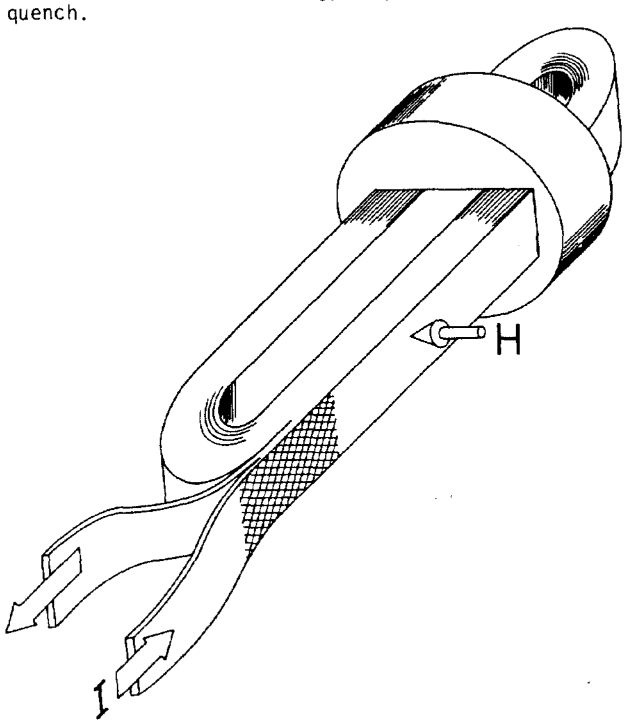

Fig. 1. Schematic of the simulated windings. The magnetic field is produced by a dipole magnet (not shown).

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Since the details of the windings can be easily varied in the simulated coils, they can be used to test new concepts before incorporating them into actual magnets. The amount of conductor in a test coil (~20m) is sufficiently large that it represents a more meaningful conductor test than the usual "short sample". This report summarizes the measurements made to date in these coil simulation experiments.

Construction Details

As mentioned above the windings are made in a "bifilar" fashion so that the magnetic field produced by the transport current will be small compared to the applied field. This configuration is shown schematically in Fig. 1. The two lengths of conductor are connected by a soldered joint on the inner turn. Standard epoxy impregnated fiberglass is used for turn to turn insulation and the turns are bonded by the same high pressure molding technique used in magnet fabrication.[1] Resistive heaters are imbedded in the coil at a number of locations and voltage taps are distributed along each length of conductor. Epoxy fiberglass bands are used to support the windings and center them in the test magnet. The background field is supplied by a 6T dipole magnet approximately one meter long.[2]

Training Studies

Initial training of each test winding is normally performed at 4T. The coils are energized by an automatic circuit which raises the current at approximately 100A/sec. until quench current is reached. The power supply is shut off by a quench detector when the voltage across the test winding reaches a preset value. This shut off circuit has a built in variable time delay so that the current can be held constant for a

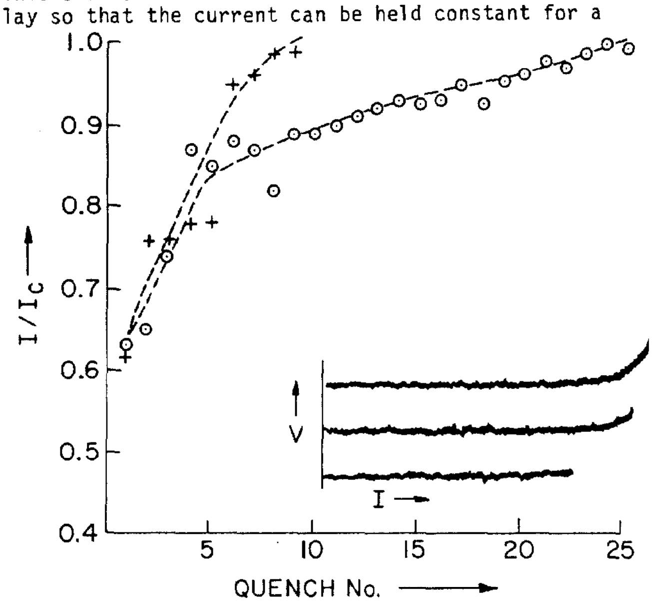

Fig. 2. The training curves for two test windings. The quench current has been normalized by scaling it to the critical current.

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short time after the quench to allow the measurement of quench velocities. When a winding has been fully trained at 4T, the field is increased to 5T and the procedure repeated. In general, very little further training is observed since the conductors are subjected to an almost constant maximum electromechanical force due to the reduced critical current at higher fields. The training curves for two windings are shown in Fig. 2. The coil represented by the circular points is typical of windings of low porosity and its performance is very similar to that observed in full scale magnets of the same construction. The other winding, which trains more rapidly, is of somewhat higher porosity. In order to normalize the effect of applied field the ratio of quench current to critical current is plotted against quench number. The critical current is defined as the current at which the effective resistivity of the conductor is 10^{-12} ohm-cm. When fully trained most test windings will operate in the resistive region (i.e., a finite, stable voltage can be maintained across the coil at constant current). This is illustrated schematically in the inset in Fig. 2. In the first few quenches when the current may be as low as 60-70% of critical current, the transition to the normal state is sudden and irreversible but as the test winding approaches critical current, the dc resistive voltage increases gradually until it is no longer thermally stable. Monitoring of the voltage taps verifies that this is happening uniformly along the conductor and that it is truly reaching critical current.

Test windings which have been mechanically preloaded by differential expansion[3] have shown the minimum training, reaching critical current in less than five quenches. A systematic study is now being conducted on the factors which influence training in these windings. Just how closely improvements in the behavior of test coils will be paralleled in full scale magnets remains to be seen.

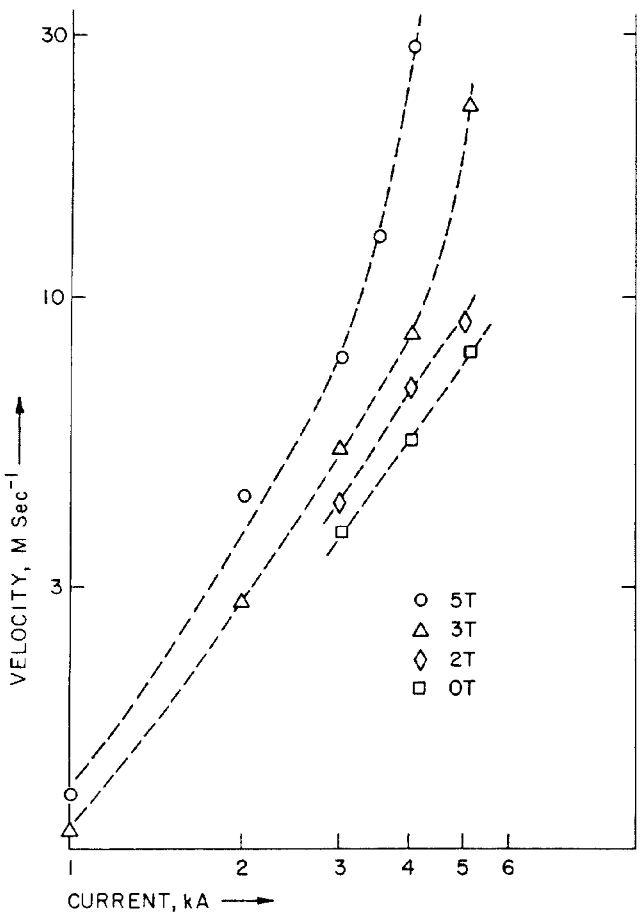

Fig. 3. The longitudinal quench velocity of a low porosity winding as a function of current.

Quench Velocities

The longitudinal propagation velocity can be determined in two ways; by initiating a normal zone and timing its passage at several points or by observing the growth of resistive voltage between two points and deducing the velocity from the normal state resistivity per unit length. In Fig. 3 the velocity of propagation along the conductor is given as a function of current for a low porosity winding. A more complete discussion of the method of velocity determination is given elsewhere.[4]

The transverse velocity is measured by simply timing the arrival of the normal front at the conductors adjacent to the one containing the heater.

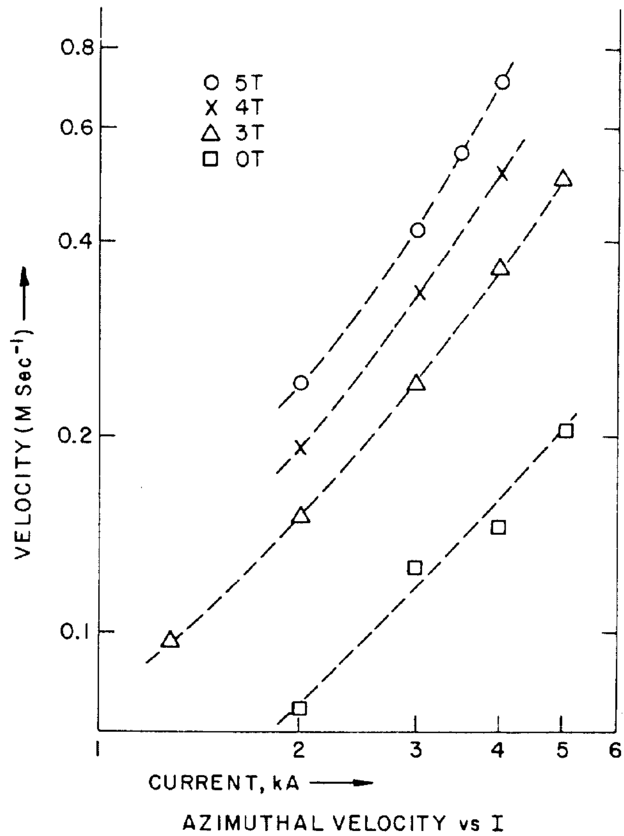

Fig. 4. The transverse (azimuthal) quench velocity of a low porosity winding plotted against current.

The uniformity of the velocity can be verified by observing conductors progressively further away from the initiating point. This transverse velocity is equivalent to an azimuthal velocity in the curved windings of a complete magnet. Fig. 4 gives the transverse velocities measured for the same winding as Fig. 3. The ratio of longitudinal to transverse velocity is approximately fifty.

Porosity

The volume of liquid helium contained in the windings of a superconducting coil can play an important part in determining the ability of the windings to tolerate sudden localized energy releases. Due to its high heat capacity, this trapped helium represents a significant fraction of the enthalpy reserve of the coil. For windings of the ISABELLE type, the porosity is largely determined by the spacing of the insulation wrapping and the epoxy content since the helium resides in the small channels formed by the insulation. This porosity can vary from virtually zero for epoxy-rich, butt-wrapped windings to approximately 5% of the volume for 80% insulation coverage and minimum epoxy fill. While a direct measurement of porosity is difficult, a simple test has been developed for estimating the relative porosity of both test windings and full scale magnets. A metal nozzle is pressed against a section of winding and the pressure drop required to force gaseous helium thru the turns is observed. The area examined amounts to about two square centimeters and the uniformity can be tested by making numerous measurements over the surface of a winding. Results for a number of test coils are shown in Fig. 5. TW1,

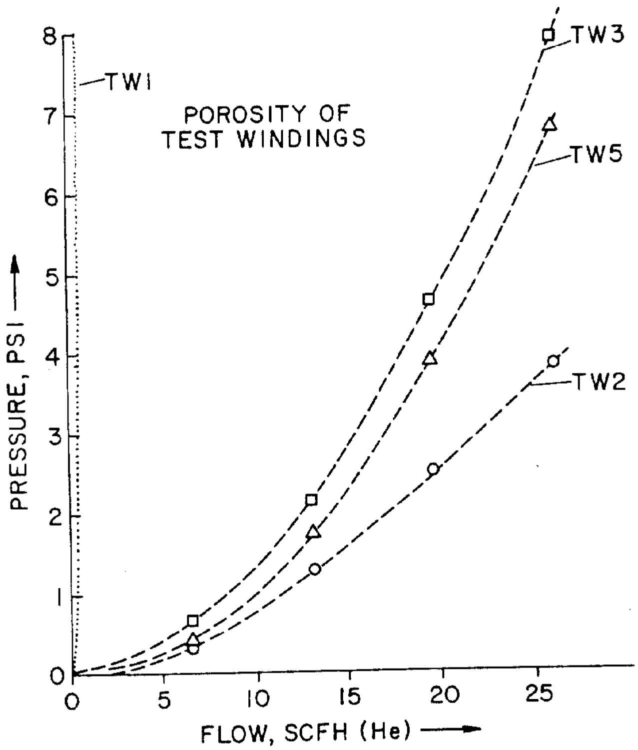

Fig. 5. Pressure vs. flow curves for a number of test windings.

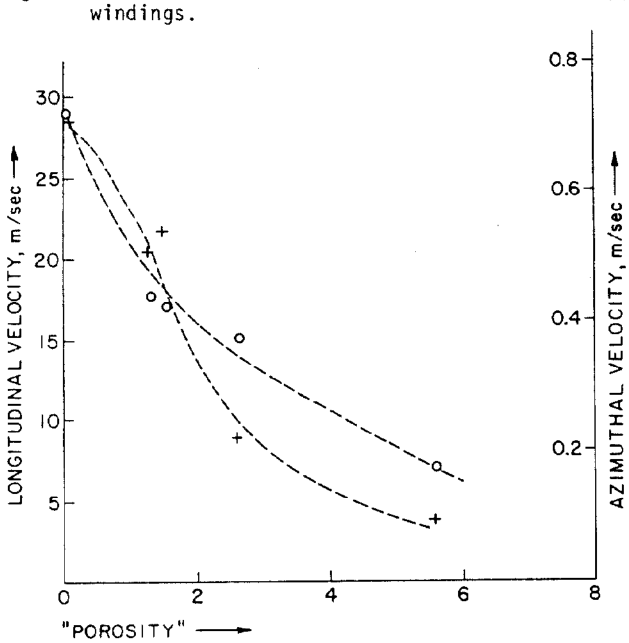

Fig. 6. The effect of porosity on the quench velocity at 5T and 4kA.

a winding with tightly wrapped, heavy epoxy insulation, is almost impervious to gas flow. The other windings are attempts to improve the effective porosity by varying the insulation characteristics. TW3 and TW5 were made from similar conductor and the difference in their porosity is representative of the reproducibility from winding to winding. A convenient unit of "porosity" has been formed by dividing ten by the pressure drop (in psi) required to force 25 SCFH of helium thru the turns of the coil.

One of the consequences of having liquid helium in the windings is shown in Fig. 6 where the longitudinal and transverse velocity are plotted against "porosity". The effect of trapped helium on the training behavior was compromised somewhat by structural problems in the high porosity windings but the trend was for fewer quenches in the more porous coils.

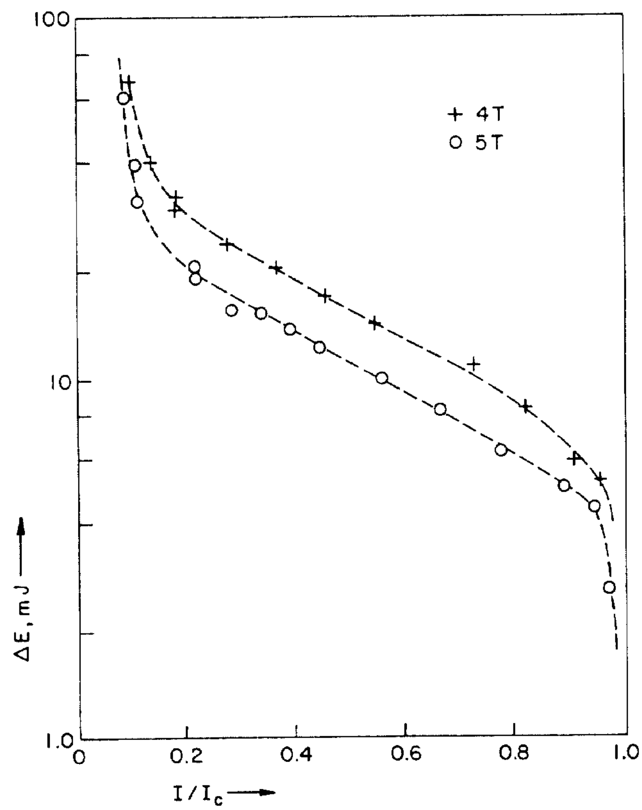

Fig. 7. The minimum energy required to initiate at quench plotted against reduced current.

Quench Energy

A study was made of the minimum energy required to cause a self propagating normal zone. This was done by pulsing one of the heaters with progressively higher currents until a quench occurred. Typical pulses were 3m5 in duration and several amps in magnitude. The minimum energy is plotted against reduced current in Fig. 7. The fraction of heater input energy which is actually deposited in the superconductor is difficult to determine and hence the absolute scale. Work is now in progress aimed at calibrating this energy so that a direct comparison of the relative stability of the different types of windings can be made.

References

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