SUPERCONDUCTORS FOR TOKAMAK POLOIDAL FIELD COILS

R. F. Schwall, S. S. Shen, L. Dresner, J. W. Lee,
L. R. Miller, and H. F. Yeh

Oak Ridge National Laboratory, Oak Ridge, TN 37830

MASTER

ABSTRACT

The a.c. losses and stability of a number of model conductors for tokamak poloidal field coils have been evaluated. The conductors employ mixed matrix NbTi superconductor cabled with copper stabilizer and were tested with insulated strands, bare strands and solder filled.

We present data for total loss per cycle as a function of maximum field and of field sweep rate. These losses are separated into filament hysteresis loss, filament coupling loss, stabilizing strand eddy loss and interstrand coupling loss. The data are compared with the predictions of a new theory which models the conductor as a LR circuit closely coupled to the magnet.

Data are also presented for the velocity of propagation or recovery of a normal zone, the full recovery current and the minimum propagating current. The dependence of stability on the degree of coupling between the strands and on the amount of helium present in the cable is also discussed.

Preliminary Summary Manuscript

INTRODUCTION

The poloidal field (PF) system in a tokamak fusion device provides a time varying flux which is used initially to break down the plasma and build up the plasma current and subsequently to compensate for plasma losses in sustaining the burn. Although the coil parameters vary somewhat from device to device, maximum fields up to 7 T and field sweep rates up to 7 T/sec are common. This combination of maximum field and field sweep rate is somewhat beyond the state of the art and, when

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combined with the large size of the magnets (approximately 10^{10} joules), presents a rather demanding design problem. In this paper we concentrate on the superconducting cable that is required.

A successful PF coil conductor must possess a rather unique set of attributes. High stability is required because of the large physical size of the device and the requirement of high reliability. Losses under time varying fields must be kept low to insure reliable economical operation. The conductor must be structurally sound to prevent conductor motion and finally it must be economical to fabricate.

MODEL CONDUCTORS

Although the final conductors for a PF coil will likely operate at currents of some tens of kiloamps the initial experiments are much more tractable at lower levels. We have therefore constructed a series of model conductors which operate at 2000 A and may be regarded as sub-elements of the final cable. A typical model conductor is illustrated in Fig. 1. The superconducting strands employ a rigid matrix for low coupling loss and moderately small (14 ϕ) filaments to minimize hysteresis loss. Three 0.04 cm strands are cabled with four copper strands of the same dimension to form a subcable. Seventeen of these are then cabled and compacted into a 0.7 cm x 1.0 cm rectangular cable. The filling factor is $\sim 60\%$.

One of the primary questions to be addressed is the degree of interstrand coupling which can be tolerated. Insulated strands with low coupling minimize losses but can result in inadequate current sharing and reduced stability. At the other extreme a solder-filled cable insures good complete current sharing and optimum structural rigidity but gives the largest losses. Since interstrand contact resistances are in general not amenable to calculation we have measured the stability and loss of a number of cables which are identical except for the interstrand insulation. Samples include bare copper stabilizer, insulated copper, solders-filled cables and conductors cabled around a reinforcing core.

LOSS MEASUREMENTS

We have measured the losses in the conductors using a magnetization technique. The sample configuration is shown in Fig. 2 and the

instrumentation in Fig. 3. This simple configuration was previously used by Fietz et al.¹ and the instrumentation is an adaptation of that used for measuring losses in pulsed coils.²

Two different field sweep techniques were employed in making the measurements. In the first the field was increased linearly to a maximum value and then decreased linearly to zero. Field sweep rates varied from zero to 1.5 T/sec . For measurements at higher values of dB/dt , the field is increased to some value and then the background field coil is allowed to discharge through a resistor. This allows measurements with dB/dt up to 1 T/sec . By varying the sweep rate one can separate hysteresis loss from the other components and by measuring the superconducting strands alone as well as fully insulated cables one can separate filament coupling losses from interstrand coupling. (At present the data has not been completely analyzed and rather than present incomplete and perhaps misleading results all experimental results will be deferred until the final manuscript is submitted.)

THEORY OF LOSSES

A transformer model is devised for pulsed magnet systems based on the fact that each loss mechanism is caused by a certain amount of flux linkages due to the time-varying transport current. Therefore, each loss is considered as a secondary circuit of a transformer whose primary is the self inductance of the magnet excited by the transport current (see Fig. 4).

Depending on the magnet design e.g., normal metal property, matrix resistivity, twist pitch, etc., each lossy secondary has a different time constant and hence a different response to the primary current. Transient analyses are performed for different modes of exciting current. Losses per cycle are presented as functions of secondary time constant.

It is found that such time constant of the secondary circuits shows the same effect on its losses as the impedance matching of a power transformer on its efficiency. Implication of this loading effect is discussed in comparison with the conventional field theory, and experimental ac loss data are evaluated in terms of this model.

STABILITY MEASUREMENTS

In these experiments we have attempted to measure the stability of an isolated conductor exposed to varying amounts of liquid helium.

Inter-turn heating occurs in the $\frac{1}{2}$ inch diameter wires of the cable in restricted cross-sections and is not uniform.

The experiment is shown schematically in Fig. 6. The sample is wound in a spiral groove cut in a rotating speed and placed in a background field coil. At some fixed values of field and sample current the heaters are used to drive part of the sample normal and the extent of this normal zone is monitored by voltage taps along the sample. In general, negative propagation velocities (corresponding to recovery) are measured by driving an extended portion of the sample normal with a heat pulse several seconds long and then observing the decreasing voltage across the sample after the heater is removed. Positive propagation velocities are measured by applying a short heat pulse to a localized heater and observing the increase in sample voltage. We have placed heaters on the whole cable and on individual subcables and have measured voltages on the entire cable, on the heated subcable, and on different strands. As in the case of the loss measurements, data and analysis will be presented in the final manuscript.

REFERENCES

1. W. A. Fletz, M. R. Bessley, J. Silcox, and W. M. Bob, Phys. Rev., **136**, A335 (1964).
2. S. S. Shen and H. J. Ye, "Pulse Loss and Voltage Measurements on Superconducting Coils," presented at the Applied Superconductivity Conference, Stanford, CA (August 1976); also published as BNL-DM-5635.

FIGURE CAPTIONS

- Fig. 1 Model poloidal field coil conductor. Strands are 0.04 cm diameter and superconducting strands contain 136 14 μ m diameter filaments.
- Fig. 2 Sample configuration for short sample magnetization measurements. The sample may be measured either open circuit or carrying a transport current.
- Fig. 3 Schematic of magnetization apparatus instrumentation. The digitized voltage signal is routed to a small computer which computes the magnetization and the loss.
- Fig. 4 Transformer model of loss in a cable. Each resistor (which can be current dependent) represents the loss due to a different mechanism.
- Fig. 5 Sample configuration for stability measurements. Heaters may be localized on one strand or distributed over the cable diameter.

FIGURE 1

FIGURE 2

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FIGURE 3

FIGURE 1

FIG. 5

FIGURE 5