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EXPERIMENTAL SIMULATION OF PULSED FIELD LOSSES

IN TOKAMAK TOROIDAL FIELD COILS*

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ABSTRACT

Experiments have been carried out to measure loss in a twisted multifilamentary composite superconductor when exposed to a transient longitudinal field. We investigate the variation of losses both as a function of transverse applied field and of sample transport current. Losses are probed mainly by measurement of the dynamic resistivity of the sample during the longitudinal pulse. Experimental results are compared with theories^{1,2,5,6,8} for the zero transport current case. The extension of theory to include transport current is also discussed, and the impact on tokamak toroidal field coil design is considered.

LIST OF SYMBOLS

	M.K.S. unit
B_1	Background dc field in perpendicular direction to the conductor
$\dot{B}_H$	Parallel field change rate
B_H	Parallel field
L	Half length of conductor
λJ_c	Average current density over composite
k_p	Twist pitch
r_o	Equivalent radius of composite
x_o	Twist parameter = $\frac{2\pi L_0}{L_p} \leq \frac{2}{5}$
w	Gap between filaments
d	Filament diameter
ρ_c	Transverse matrix resistivity ^{3,7}
$\dot{B}_o, \dot{B}_o$	Critical amplitude and change rate of parallel field that causes outer layer of filament saturation
$\dot{B}_c, \dot{B}_c$	Critical amplitude and change rate of parallel field that causes all filaments saturation
I_T	Transport current
I_c	Critical current
α	I_T/I_c
P_o	Calculated saturated hysteresis loss per unit volume
V_o	Loss voltage
V_M	Measured sample voltage

SUMMARY OF THEORY

It has been shown that the twisted filamentary conductor can exhibit a coupling effect in a time-varying longitudinal external field. Both Carr² and Turck⁶ have pointed out that the time constant associated with such coupling effect plays a very important role in determining the degree of coupling. Here, we will give a summary of the results of these calculations. It is interesting to note that from different approaches (circuit model, field model), the same results of $\dot{B}_o$ and $\dot{B}_c$ are obtained.^{1,2,3,4,5,6,8}

$$\text{For partial saturation: } \dot{B}_o = \frac{\lambda J_c \ell \rho_c w}{\pi r_o L^2} \quad (1)$$

$$\dot{B}_c = \frac{\mu_o \lambda J_c (d+w) \ell}{2\pi L} \quad (2)$$

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$$\text{For complete saturation: } \dot{B}_c = \frac{\lambda J_c \ell \rho_c}{2\pi L^2} \frac{w}{d+w} \quad (3)$$

$$\dot{B}_c = \frac{\mu_o \lambda J_c \ell P}{4\pi} \quad (4)$$

For practical conductors (either fine-strand cable or high-current monolithic) (1) and (3) generally give values $\ll 10^{-2}$ T/s, and $\dot{B}_o \ll \dot{B}_c$. It should be noted that the above results are for the case in which no transport current is present.

For a fully saturated conductor (by $\dot{B}_H$ only), both Shen¹ and Jünger⁵ have calculated the coupled hysteresis loss per unit volume to be

$$P_o \approx 1/8 \lambda J_c \dot{B}_H x_o r_o \text{ for } x_o \ll 1. \quad (1)$$

With the presence of the transport current, total losses supplied by both power supply and B field are approximately given as

$$P = P_o (1 + \alpha^2). \quad (2)$$

In our experiment the changes of P between $I_T = 0$ and $I_T = I_c$ are measured: i.e.,

$$\Delta P = P_o \alpha^2. \quad (3)$$

For a fully saturated condition, measured ΔP should agree with (3). If the conductor is only partially saturated by $\dot{B}_H$, then the measured ΔP should be higher than that given by (3) for $\alpha < 1$. Comparison between measured results of ΔP and Eq. (3) will be given in detail for three different samples.

1. EXPERIMENTAL TECHNIQUE

Experiments were carried out with the goal of simulating as closely as possible the electromagnetic environment expected for the toroidal field winding of a tokamak. Specifically it was desired to expose a current carrying conductor to a high transverse magnetic field component while simultaneously pulsing the component of field parallel to the conductor axis. These conditions were achieved by winding the test conductor into a small solenoid and then winding a torus for providing the pulsed field through the center of the solenoid and back around the outside. Background field transverse to the sample current was applied by suspending the apparatus in a dewar in the bore of a water cooled copper solenoid. A more detailed description is given in Ref. 1.

The most useful probe of the effect of the pulsed fields in the present experiment has been the sample voltage. Voltage V_M is measured along the length of the sample during a longitudinal field pulse because of the induced emf in the individual filaments linking the flux. The measured voltage thus reflects the induced emf's in the individual filaments reduced by the coupling losses in the filaments. When transport current flows in the sample V_M gives a direct measurement of the dynamic resistance in the composite.

Voltage leads were attached to each end of the sample with one lead being co-wound with the sample conductor to cancel spurious pickup and to compensate for the inductive voltage resulting from sample configuration.

Local change in longitudinal flux density $\dot{B}$ was measured via a pickup coil wound directly around the

sample conductor. The applied longitudinal field $H_{||}$ and rate of change $\dot{H}_{||}$ were obtained by monitoring the current to the toroidal windings surrounding the sample. All signals were recorded simultaneously using a Biomation 1015 Transient Recorder. Isolation of the individual signal channels was obtained by preamplification with identical dc instrumentation amplifiers (Neff model 124A).

II. RESULTS AND DISCUSSION

Experiments were performed using three quite different composite superconductors — different at least with respect to the characteristics that affect losses. Cross sections of the conductors tested are shown in Fig. 1 with relevant parameters listed in Table I. Each of these conductors was subjected to pulsed longitudinal fields of varying amplitude and ramp rate. Depending on the conductor, peak longitudinal fields ranged from 0.1 to 1.3 T with ramp rates from 0.3 to 2.6 T/s. During a pulse of the longitudinal field the transverse field $H_{\perp}$ was held constant at some value between 0 and 7.5 T, and transport current I_T was held constant at some value between 0 and I_c ($H_{\perp}$).

TABLE I.
Test Conductor Relevant Parameters

Conductor Identification	Outside diam. (mm)	Effective radius (r_e) (mm)	Pitch length (ℓ_p) (mm)	Pitch parameter (ℓ_p/r_e)	Effective filament diameter (d_f) (mm)	Effective filament spacing (s_f) (mm)	Overall superconductor fraction (f)	Sample length (ℓ_s) (mm)	Sample volume (V) (mm ³)	Critical current at applied field ¹ ($I_c, H_{\perp}$) (A)
74-9-C	0.508 ϕ	0.254 ²	8.15 (18)	0.251	16	26	0.345	4.54	920	60, 3 39, 4 45, 5 29, 6 18, 7
75-10-I	2.79x1.40	0.930 ³	19.3 (18)	0.373 ⁴	79	44	0.291	1.30	5090	2350, 3 1870, 4 1500, 5 1200, 6 942, 7
75-13-I	2.54x2.32	0.803 ³	33.8 (18)	0.203 ⁴	32	16	0.418	1.30	4300	2980, 3 1300, 4 1970, 5 1550, 6 1230, 7

¹ From short sample data with onset of resistance defined as 10^{-12} ohm effective resistivity in the superconductor fraction.

² Approximated as half the outside diameter.

³ $r_e = \sqrt{A/\pi}$, where A and T are the outside dimensions of the area containing all the filaments.

⁴ $\ell_p = 2(u/v)$, u and v defined as above.

Fig. 1. Cross section of conductors tested:

- (a) 74-9-C,
- (b) 75-10-M, and
- (c) 75-13-I.

As has been discussed, the measured sample voltage can be related to losses in the conductor resulting from exposure to transient longitudinal fields. First, consider the case of a conductor carrying no transport current. If certain conditions are met, a relatively simple relation can be made between measured voltage and loss using the model discussed previously. These conditions are that the conductor be round with uniformly distributed filaments and that $B_{||}$ and $\dot{B}_{||}$ be sufficiently large so that during the pulse the current in the filaments saturates at the critical current density J_c . In this case it can be shown that the measured voltage should be

$$V_M = \frac{3P_0}{I_c}$$

Note that since $P_0 \propto I_c$, V_M should be independent of I_c and thus of $H_{\perp}$ below the upper critical field. Since P_0 and thus V_M are in the simplest case proportional to $\dot{B}_{||}$, data for a wide range of $B_{||}$ is included on Figs. 2, 3, and 4 by plotting $V_M/\dot{B}_{||}$. The solid line in each figure represents $3P_0/\dot{B}_{||} I_c$ as calculated directly from the conductor parameters of Table I. Approach of the data to this line is indicative of the applicability of the simple model in explaining the losses in each particular conductor. Note that agreement is very good for the round wire with uniformly distributed filaments, and less good for the two rectangular conductors. The first inclination might be to attribute this discrepancy to the non-circular shape or possibly, in the case of conductor 75-10-M, to the absence of filaments in the central copper core. These effects may in fact be partially responsible, but a better explanation may be extracted by again appealing to the simple model. In order that the filaments fully saturate at J_c , $B_{||}$ and $\dot{B}_{||}$ must exceed the values of B_{c1} and $\dot{B}_{c1}$ respectively. Partial saturation occurs when $B_{||}$ and $\dot{B}_{||}$ exceed B_0 and $\dot{B}_0$ respectively. Examination of the calculated values for these critical parameters as listed in Table II shows that conductor 74-9-C is easily saturated, and probably all data compiled here represents the saturated case. Conductor 75-10-M was probably fully saturated only over part of the typical pulse. Conductor 75-13-I, on the other hand, was probably never fully saturated at the usual operating fields because the required magnitude of parallel field is outside the range of our apparatus.

TABLE II.

$B_{\perp}$ (T)	length (m)	74-9-C	75-10-M	75-13-I
		4.54	1.302	1.297
3	$\dot{B}_c$ (T/sec)	3.0×10^{-5}	9.7×10^{-4}	3.0×10^{-4}
	B_0 (T)	1.0×10^{-3}	0.18	0.19
	B_c (T)	0.14	1.0	2.71
4	$\dot{B}_c$		8.7×10^{-4}	2.4×10^{-4}
	B_0		0.16	0.15
	B_c		0.93	2.16
5	$\dot{B}_c$		6.9×10^{-4}	1.94×10^{-4}
	B_0		0.13	0.12
	B_c		0.74	1.75
7	$\dot{B}_c$		4.3×10^{-4}	1.24×10^{-4}
	B_0		0.08	0.08
	B_c		0.46	1.12

Fig. 2. Reduced loss voltage vs background field for sample 74-9-C.

Fig. 3. Reduced loss voltage vs background field for sample 75-10-M.

Measured dynamic resistance effects for each conductor are plotted in Fig. 5, 6, and 7. As indicated in Table II, sample 74-9-C should be fully saturated, which is consistent with the good agreement between measurement and Eq. (3) as demonstrated in Fig. 5. Figures 6 and 7 show the results for sample 75-10-M and 75-13-1 respectively. Note that the measured change in power with transport current is generally larger than predicted by Eq. (3). As discussed earlier, the unsaturated conductor has smaller loss than P_0 when it carries no current. However, as I_T approaches I_c the total loss will reach that value predicted for the saturated case.

CONCLUSION

We have verified that for a large conductor the longitudinal coupling loss without transport current may not be as large as expected due to incomplete saturation of the composite.

However, in most practical applications, where conductor carries transport current not far from its critical value, the total loss may still be approximated by the calculated value for conditions that give complete saturation.

Fig. 4. Reduced loss voltage vs background field, for sample 75-13-1.

Fig. 5. Measured change in loss vs normalized transport current for sample 74-9-C.

Fig. 6. Measured change in loss vs normalized transport current for sample 75-10-M.

Fig. 7. Measured change in loss vs normalized transport current for sample 75-13-1.

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