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ORPUS 1 - A PULSED SUPERCONDUCTING SOLENOID*

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R. E. Schwall†

ABSTRACT

A recent series of reference designs for Tokamak Experimental Power Reactors (EPR's) has indicated that superconducting poloidal field (PF) coils will be necessary for successful operation of these devices. It would also be desirable to use superconducting PF coils in earlier tokamak fusion devices if such coils could be developed quickly enough.

In this paper, the PF coil performance requirements are briefly reviewed and some implications for the coil design are developed.

A small coil (stored energy 14 kJ) has been built using construction techniques similar to those which could be employed for PF coils. The coil has been charged at rates up to 2 T/sec. Both maximum field and charging rate were limited by available power supplies. Loss measurements were carried out during pulsed operation and data for hysteretic and eddy current loss are presented. The loss measurement system used allows considerable insight into the effects of conductor motion and training.

I. TOKAMAK REQUIREMENTS

In 1975 a series of detailed reference designs were produced for the proposed tokamak EPR.¹⁻³ Perhaps the greatest effect of these designs on the superconducting magnet development effort was a somewhat clearer definition of the requirements that plasma physics - in its present state - places on the magnet system. The initial plasma breakdown and current buildup requires a flux change of approximately 130 Wb in ≈ 2 sec. Although the various coil systems developed divide this flux somewhat differently between the PF coils, the bulk must be produced by the central air core solenoid. The dimensions of this solenoid are set by the machine dimensions; in the ORNL design, the coil outside diameter (OD) is 3.8 m.

The requirements of flux change, coil OD, operating cycle, and, to a certain extent, series operating current form the basic constraints within the PF system must be designed.

At the present time there appear to be two basic operating cycles which will satisfy the EPR flux change requirements. The first is a symmetric cycle where the magnet is ramped from -65 Wb to $+60$ Wb in 2 sec, charged slowly to $+65$ Wb in ~ 100 sec, and then reversed again, to -65 Wb in an additional 100 sec. This cycle has the advantage of requiring the lowest maximum field in the PF coils and hence being the most conservative magnet design. The principal disadvantage is the large power supply (≈ 2000 MW instantaneous) required for the fast ramp. An asymmetric cycle where the magnet is charged to 120-130 Wb and then discharged into a dump to provide the flux charge would eliminate the power supply problem, but complicates the magnet design by requiring higher fields. The principal effort to date has been focused on the symmetric cycle; this effort is the basis of the remainder of this paper.

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II. POLOIDAL FIELD MAGNET DESIGN

A rather large number of pulsed superconducting magnets have been built in the past six to eight years and a considerable amount of information is available on coil performance and losses. The PF coils, however, pose a unique set of problems. The central solenoid must achieve a maximum field (B_0) of 7 T and a 14-T field change in 2 sec. Systems considerations also dictate that the coil be highly stable, i.e., have a low overall current density. The situation is distinct from the synchrotron dipoles (where both B_0 and $\dot{B}$ are lower) and from previously considered energy storage magnets (where the coil dimensions may be adjusted to obtain lower B_0). A calculation of the loss expected in a PF coil system indicates that an epoxy-impregnated coil will not operate without quenching - the heat transfer is simply too poor. Hence one is led to a force-cooled design utilizing a cable in a conduit or to a non-impregnated pool-boiling design. The first alternative is being pursued by MIT⁴ under contract to ORNL and the second is being evaluated at ORNL.

Since the requirements of $B_0 = 7$ T and $\dot{B} = 7$ T/sec are the determining factors in the coil, their origin is illustrated in Fig. 1. Here the overall current density, maximum field and average hoop stress are plotted vs the inside radius for a 65-Wb 1.9-m outside radius solenoid. By making the coil thicker (i.e., by making a_1 smaller) the overall current density (J) and the hoop stress (σ_H) are reduced but an increased B_0 is required. The compromise design published in Ref. 1 used $a_1 = 1.5$ m, which gives $B_{02} = 7$ T, $\sigma_H = 86.19$ MPa (12,500 psi), and $J = 1460$ A/cm². Although there is some latitude in making the choice of a_1 , these parameters are similar to those obtained in other studies.⁵

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Fig. 1. Design curves for 65-Wb control solenoid, 3.8 m OD, 12 m length.

III. ORPUS I

A. Design

One of the principal problems in any unpotted coil is conductor motion and the difficulty is especially acute when a cabled conductor is used. The release of heat which accompanies the sudden movement of a frictionally constrained conductor is commonly thought to cause "training" of such coils, and the degree to which the coil trains is usually taken as a measure of its performance. If a conductor is essentially unconstrained and the sudden breaking of a high modulus frictional bond is not present, one would expect the primary source of motional heating to be the thermo-mechanical hysteresis⁶ of the conductor itself. Since this heat appears uniformly over the operating cycle, it should not lead to excess degradation of a well-cooled coil.

The ORPUS (Oak Ridge Pulsed Solenoid) series of coils is being built to test various conductors and construction techniques for use in PF coils. The program involves testing the coils to the limits of their performance and making careful measurements of the power dissipated during pulsed operation. From this program we expect to produce a coil capable of the performance required of PF coils.

ORPUS-1 is a reinforced, highly ventilated solenoid wound from copper matrix, formvar-insulated, NbTi compacted cable. The coil parameters are given in Table I; a cross section is shown in Fig. 2. The design is such that there is no cumulative axial stress on the conductor. Each turn is supported by grooves machined in the G-10 spacers. The hoop stress is partially supported by the co-wound stainless steel reinforcement, and tensile tests on the conductor show that the stress-strain curve of the conductor is linear and reversible to over three times the maximum hoop stress.

TABLE I
Coil Design Parameters

a ₁ (inside radius)	4.01 cm
a ₂ (outside radius)	7.62 cm
b (half length)	12.7 cm
Inductance	5.78 mH
Stored energy	14 kJ
Series current at 4.2 T	2198 A
Overall current density at 4.2 T	9875 A/cm ²
Conductor current density at 4.2 T	32660 A/cm ²
Number of turns	412
Number of layers	12
Superconductor	NbTi
Copper: NbTi	1.9:1
Filament diameter	2.8 x 10 ⁻³ cm
Strand diameter	6.6 x 10 ⁻² cm
Number of filaments	276
Strand twist length	1.27 cm
Cable transposition length	5.08 cm
Number of strands	11
Insulation	formvar
Cable dimensions	0.43 x 0.15 cm
Maximum conductor hoop stress	78.6 MPa
Maximum reinforcement hoop stress	172. MPa

Fig. 2. Section of ORPUS-1 solenoid showing the construction details. Vertical helium channels are 1.5 mm wide, well above the "bubble breakaway" limit.

This design is intended to produce a situation where heating is largely due to movements of the cable itself as opposed to a potted coil construction in which cracking of the epoxy can cause significant heating.

B. Performance

Some difficulty was experienced in obtaining a repeatable resistive transition during short sample tests of the conductor. The best results were obtained by stripping the conductor of its insulation and soldering it to a heavy copper cylinder, but even this did not yield a totally reversible I-V curve. If we compare the coil performance to this benchmark, however, the quench current on the first charging was 70% of short sample and in four quenches the coil trained to 78%, the limit of our available power supplies. This corresponds to a current of 2260 A and a central field of 42,200 G. When larger power supplies are available, the coil will be tested at higher I and an attempt will be made to train to higher currents.

The power dissipated in the coil during charging and discharging was measured by an electrical method. The technique used is essentially an extension of one previously published by Wilson.⁷ The system is shown in Fig. 3 and a discussion of its calibration is given by Shen and Yeh.⁸ Basically, a signal proportional to dI/dt is subtracted from the magnet terminal voltage and the result is then digitally integrated to give an output proportional to Φ , the flux penetration in the conductor. When this is plotted against the magnet current a "hysteresis loop" for the coil as a whole results, the area of which is proportional to the loss. The hysteresis loop is a composite average of the magnetization of all the conductor in the coil and, while its interpretation is more complicated than a short sample magnetization curve, considerable information about the coil performance can be obtained.

In Fig. 4 the hysteretic loss in the coil for slow charging rates is presented. The results are quite similar to those seen in a short sample with $Q \approx H^3$ until the conductor is fully penetrated and $Q \approx H$ after penetration is achieved. The transition between the two regions is somewhat broadened by the field distribution in the coil. The two points above the rest of the data are cycles of a previously uncharged magnet and indicate the additional flux required to initially saturate the filaments.

Also of interest is the eddy current loss due to the flow of current between filaments during rapid charging. The energy dissipated due to this mechanism has the form

$$\Delta Q_E = K \frac{(\Delta B)^2}{\Delta t} \quad (1)$$

Fig. 3. A block diagram of the system used to measure losses. ϕ refers to the flux inside the conductor and ϕ_{ext} refers to that within the coil but external to the conductor.

Fig. 4. Hysteresis loss per cycle as a function of coil current. The left scale gives total energy dissipated in the coil and the right scale gives energy per unit volume of NbTi.

where K is a coil parameter which depends on the conductor diameter, twist pitch, critical current, matrix resistivity and filament diameter all suitably averaged over the coil, and ΔB is a change in magnetic field taking place in a time Δt . To evaluate the magnitude of the eddy current loss, the magnet was charged at different rates to approximately the same current. Since B is not constant during the charge and discharge, a suitable average must be taken in order to properly interpret the data. In the experiments described here, the coil current and voltage is digitized once every 17 msec. Using these points a piecewise linear approximation of the B vs t curve can be made and an average rise time τ calculated. This is given by

$$\frac{1}{\tau} = \frac{2 \cdot B_{max}^2}{\sum_{i=1}^N \Delta B_i^2} \Delta t$$

In this equation Δt is the time between measurements (17 msec) and ΔB is the change in magnetic field during that interval. The sum is taken over the entire current cycle. In Fig. 5 we have plotted the additional loss measured (after subtracting the hysteresis loss) vs $1/\tau$. Although there is considerable scatter in the data, Eq. (1) is seen to predict the additional loss reasonably well for rise times shorter than ≈ 1.7 sec. Data was not taken for rise times longer than this, but one would expect Q to vary more slowly than $1/\tau$ as B becomes smaller and interfilament coupling is reduced in parts of the coil. This is consistent with the data of Fig. 7 since Q_p extrapolates to zero at a finite value of $1/\tau$. Work is now in progress to develop an analytical method for predicting the eddy current loss which will account for the spatial variation of J_c , B , and the matrix resistivity through the coil.⁹

C. Conductor Motion

Figure 6 shows a typical set of data at moderate field ($B_{max} = 3.04 \text{ T}$). The coil had been previously cycled to a higher current and the hysteresis loop is a minor loop with an initial magnetization due to trapped flux. Note that the coil voltage is always positive for decreasing current.

In Fig. 7 a pulse taken at a higher field ($B_{max} = 3.94 \text{ T}$) is presented. The effects of conductor motion are obvious. The coil voltage, which is properly compensated at low current, begins to distort as the coil inductance changes; this gives a rising voltage prior to the current maximum and a negative voltage immediately after the maximum. The hysteresis loop is quite distorted. The coil had quenched on the pulse prior to this and the fact that the hysteresis loop does not close indicates that a portion of the conductor was no longer fully penetrated.

Conductor motion was consistently observed above $\approx 3 \text{ T}$ in the coil, but any additional loss due to the motion was too small to be resolved. This, plus the fact that there appeared to be no rate dependence of the quench current, indicates that the degradation from short sample performance and the training were not due to conductor motion alone but to some discontinuous slippage of the magnet structure. As the loss measurement methods are developed, we hope that it will be possible to provide more quantitative evaluations of the effects of motion and to incorporate these results into the design of future coils.

Fig. 5. Excess loss measured (above the hysteretic loss) as a function of an average pulse rise time.

Fig. 7. Output for a high field low speed pulse. The waveforms are discussed in the text.

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Fig. 6. Typical output from the loss measuring apparatus for a moderate-field (~ 2 T), low-speed pulse.