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TEST RESULTS OF Nb₃Sn RIBBONS FOR THE PRINCETON D COIL TEST PROGRAM

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ABSTRACT

A previously described D coil test program has been modified. Details of a smaller Nb₃Sn D coil test program are described. Cusp coil tests have been made with several Nb₃Sn-NbTi hybrid field coils. Measurements of both the quench and recovery currents as a function of magnetic field component perpendicular to the wide edge of the ribbon are presented.

I. INTRODUCTION

In recent months there has been a proliferation of projected plasma research devices and proposed fusion reactors recommending the use of a D or modified D coils. Some of the devices proposing such coils are: The Princeton Fusion Reactor Reference Design¹, the University of Wisconsin Fusion Reactor Reference Design², the Joint European Tokamak³, and others. It has been shown previously¹ that high fields up to 160 kG, may be extremely useful in fusion power reactors as well as advanced plasma physics experimental devices. The objective of this program is to develop reliable high field superconducting magnets for these toroidal devices.

The D shape is unique to a particular current filament in a toroidal field. The shape depends on its location in a bundle, and the magnetic field at that point. File et al⁴, previously have shown that this kind of coil, which partially accommodates the large forces generated by high magnetic fields, will be stable if it is in pure tension, and therefore not subject to any bending moments. It is interesting to note that not only does this result in a system of minimum stress, but also one of maximum stored energy⁵, a property that may be useful to those engaged in research in that field.

Later, it was pointed out by File and Sheffield⁶, that a torus of N coils, has T different shaped D's if each turn T is to be in pure tension. Further, the straight stem of the D must also be modified, for the reason described below.

A previously described D coil test program⁷ has been considerably modified and details of the smaller Nb₃Sn D coil test program are described. In addition test results on Nb₃Sn ribbons to be used in the manufacture of the hybrid superconducting background coils for the smaller D coil are presented in section III.

II. D COIL TEST FACILITY

We are examining the engineering compromise that must be made in order to take maximum advantage of constant tension coils in toroidal magnets. For example, we have found that winding techniques are greatly enhanced by adding a slight curvature to the straight stem of the D. The stem, instead of being straight, is an arc of constant curvature, tangent to the D and offset at the centerline of the D by about 1 or 2% of the

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horizontal diameter, see Fig. 1. The effects of this curvature and other engineering compromises on the constant tension configurations are being studied and will be reported later.

Fig. 1 "D" Coil Parameters

The previously described 100 kG test facility⁷ utilized six background coils and a D shaped test coil. We now plan to test a smaller D coil in a modified test stand consisting of two hybrid Nb₃Sn-NbTi coils previously called the auxiliary coils. The design specifications of these coils are shown in Fig. 2 and Table I. The Nb₃Sn portions of the coils are wound in pancake fashion using 1/2 cm wide 200 ampere tape. The NbTi coils are wound in an integral coil form with the Nb₃Sn windings. The NbTi coils are layer wound from multifilament composite conductor .254 x .342 cm in cross-section.

Fig. 2 Test Stand Coil Specifications

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TABLE I

	D Coil	Hybrid Nb ₃ Sn Section	Hybrid NbTi Section
Ampere Turns	300,000	400,000	400,000
Overall Current Density	7895 A/cm ²	6200 A/cm ²	6800 A/cm ²
Number of Turns	4300	2030	494
Winding Type	layer	Pancake	layer
Maximum Total Field	40.7kOe	35.4kOe	31.1kOe
Operating Current	80A	197A	809
Insulation	6.4x10 ⁻⁴ cm mylar	1.27x10 ⁻³ cm mylar	Slotted G-10 and mylar
Conductor Dimensions	.23cm wide, .015cm Thk, .005cm Stn Stl, .010cm cu.	area 1 .5cmx.053cm area 2 .5cmx.050cm area 3 .5cmx.045cm	.254cmx.343cm

In Fig. 3 we show a plot of the BR product of the smaller D coil in the present test stand. Shown for comparison is the BR product of twenty similar D coils arranged in a toroidal fashion.

Fig. 3 BR Product vs Position around "D" Coil

The proposed D coil is layer wound from old RCA SR2100 material in a manner similar to the coil used in the Princeton FM-1 machine⁸. The coil will contain 4300 turns of 0.23 cm wide copper clad Nb₃Sn ribbon which carries a current of 80 amperes. The coil is wound in a modified constant tension configuration with a major and minor diameter of 77.5 and 64 cm. The minor cross-section of the coil is 5 x 7.6 cm. When energized in the test stand a maximum total field of 35.7 kOe is reached in the test coil. The maximum radial field at the conductor is 10.1 kOe.

III. Nb₃SN RIBBON TESTS

Several Nb₃Sn composite ribbons, originally obtained for the construction of the 100kG Nb₃Sn-NbTi hybrid test stand, are to be used for the modified test stand described above. Ribbon dimensions and configuration, as well as the maximum magnetic field H₁ perpendicular to the broad face of the ribbon and its accompanying parallel field component H₁₁ are given in Table II.

TABLE II
Nb₃Sn Ribbon* Properties

Current Rating + (amps)	Copper Thickness (10 ⁻³ cm)	Stainless Steel Thickness (10 ⁻³ cm)	Total Thickness (10 ⁻³ cm)	Max. Perp. field, H ₁ (kOe)	Parallel field H ₁₁ (kOe)
200	25	19	51	43	65
220	20	21	48	25	75
200	15	21	43	20	78

*0.5cm wide Nb₃Sn composite ribbon supplied by Intermagnetics General Corp.

+Current at 100kOe parallel field

Since the Nb₃Sn ribbons are to be operated in a dynamically rather than cryogenically stabilized mode there was concern that the large magnetic field component H₁ might result in flux jumps which could drive the superconductor normal. To investigate this possibility, we performed cusp coil tests with two of these materials having the least and most stabilizing copper. The behavior of the other material can be easily approximated by interpolation. One would like to simulate the typical magnetic and thermal environment that the superconductor will encounter in the full size magnet. In the cusp coil tests the superconductor sees mainly a perpendicular component of the magnetic field whereas in the test stand the superconductor ribbon is immersed in a field that includes a large parallel component. The magnetic field at which flux jumps occur varies inversely with critical current density J_c of the diamagnetic shielding current in the superconductor. The collapse of this current and subsequent entry of magnetic field during a flux jump results in heating that can drive the superconductor normal. Since J_c decreases with increasing total magnetic field, the presence of an additional parallel magnetic field component raises the field at which flux jumps occur above that for the case of only a perpendicular magnetic field component present. If, during the cusp coil tests, no flux jumps that drive the superconductor normal occur at fields up to the design maximum perpendicular magnetic field, the material is considered to be flux jump stable in the full size magnet. If a flux jump does occur in this range, we must then consider the presence of the additional parallel field and examine the possibility that it will move the flux jump to a higher perpendicular field than is actually displayed.

Experimental Procedure

The experimental configuration is shown in Fig. 4. The cusp coil consists of two pancake wound coils, series connected in such a way that the self-magnetic field profile between them has the shape of a cusp. An external field coil provides the large magnetic field component perpendicular to the broad ribbon

surface. Each of the pancake coils is equipped with a nichrome wire heater, installed in the middle of the pancakes. The heater is used to remove remanent magnetization from the Nb_3Sn as well as to create a normal region during the recovery current tests which will be described later. In addition, each pancake has a thin wafer-type Hall probe (Aerospace Controls, Inc. type HA-12) mounted flush with the top of the ribbon. The Hall probe is used to indicate flux jumps as well as the absence of remanent magnetization. The latter is done to assure the virgin magnetization state for the quench tests.

Fig. 4 Cusp Coil Test Experimental Configuration

Three cusp coils were used for the tests (Table III). The coils have 50% of the surface area exposed to the helium bath. Helium is circulated through radial cooling channels. To investigate the effect of cooling channel configuration on cusp coil behavior, the G-10 epoxy-fiberglass cooling channel discs of coil 4 were replaced by discs with wider cooling channels. The coil was then relabeled 4A.

TABLE III
Cusp Coil Properties

Cusp Coil No.	Copper Thickness (10^{-3} cm)	Cooling grooves width (cm)	Cooling grooves depth (cm)	Insulation
3	15	0.64	0.079	0.0013cm mylar + GE7031 varnish
4	25	0.64	0.079	0.0013cm mylar
4A	25	0.87	0.079	0.0013cm mylar

The cusp coil is operated in two modes. The first is a constant voltage mode. For a given current the power supply output voltage is fixed by a $5.9\text{m}\Omega$ load resistor. This mode of operation simulates a low inductance, short time constant coil which can reduce its current rapidly following the creation of a normal region. The second mode of operation is a constant current mode with the compliance voltage of the power supply set at its maximum value of 10 volts. In this case, the power supply tries to maintain a constant current through the cusp coil by adjusting its compliance voltage. This simulates a high inductance, long time constant coil which can not reduce its current rapidly upon the creation of a normal region.

Measurements are made in the following two ways. In the first, the cusp coil current is fixed and the external magnetic field H_1 is raised at a constant rate (typically 0.03kOe/sec) and returned to zero. During the time that the field is ramping up, we monitor the cusp coil to see if a flux jump induced quench occurs. The method is similar to that of Noguchi¹⁰.

In the second measurement, both the cusp coil current and external magnetic field are set at some value and the heater current in one of the pancakes is brought up until a thermal runaway occurs in that pancake. Heater current is then decreased to zero. The highest cusp coil current for which complete recovery of superconductivity occurs is defined as the recovery current.

Experimental Results

Fig. 5 Flux jump induced quench current vs external magnetic field recovery current for heater induced thermal runaway in constant voltage mode.

Fig. 6 Flux jump induced quench current vs external magnetic field and recovery current for heater induced thermal runaway, both in constant voltage mode.

the constant voltage and constant current mode of operation a large flux jump occurs in one of the pancakes when the external magnetic field $H_{\perp}$ reaches a certain value (20kOe) for cusp coil 3 and 28 kOe for cusp coils 4 and 4A). The occurrence of this large flux jump creates a normal region from which the cusp coil can recover if the cusp coil current is low enough. In some cases one of the pancakes will flux jump and recover whereas the other pancake which transitions at a higher field will not recover. The field value for a first flux jump is the same for both modes of operation.

We compared our results for the flux jump magnetic field B_{fj} with those of Koyama and Lubell¹¹. They find agreement of theory and experiment at high external magnetic field sweep rates ($\dot{B} = 4.35$ kOe/sec) using a new theory of dynamic stabilization proposed by Koyama¹². At low values of $\dot{B}$ they find that agreement is not as good and $B_{fj}(\text{exp}) > B_{fj}(\text{theory})$. For the low $\dot{B}$ rates available with our apparatus (0.026-0.066 kOe/sec), the experimental value of B_{fj} was a factor of 2 higher than the calculated one and showed no noticeable dependence on $\dot{B}$.

Comparing the experimental results for cusp coils 3 and 4 shows that B_{fj} does scale roughly with the thickness of stabilizing copper.

2. Recovery Current The cusp coil behavior is quite different for each of the two modes of operation. In the constant voltage mode, a thermal runaway induced by either a flux jump or heater current immediately produces a fall in cusp coil current and

a transition of the pancake into a partially resistive state. (0.2 to 0.5 of normal state resistance). Below a threshold value of recovery current, the cusp coil recovers completely once the thermal disturbance is removed.

In the constant current mode, a thermal runaway does not cause the current to fall immediately since the power supply voltage increases to maintain the current. Power generation in the cusp coil is consequently greater for a given current in this mode. At current values comparable to those used during the constant voltage mode, the whole pancake goes normal. For cusp coil 3 no recovery after a heater induced thermal runaway is possible for a current as low as 100 amps. By comparison, the recovery current for the constant voltage mode is around 200 amps.

IV. CONCLUSION

The Nb₃Sn ribbon superconductors obtained for a Nb₃Sn-NbTi hybrid coil as part of the reduced D coil test stand can be run in a dynamically stabilized field state as long as the perpendicular magnetic field component is kept low enough to prevent large flux jumps from occurring. For the two ribbons with the least and most stabilizing copper these field values are 20 kOe and 28 kOe. One of the ribbons meets the original design criterion for the maximum perpendicular field given in Table II while the other does not. Since the background coils of the reduced D coil test stand will operate at a lower field level than the large test stand, ($H_{\perp} = 25.6$ kOe, $H_{\parallel} = 12.5$ kOe, the ribbons should be flux jump stable.

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