TEST RESULTS FOR A HIGH FIELD (13T) Nb3Sn DIPOLE

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Abstract

A Nb_3Sn dipole magnet (D20) has been designed, constructed, and tested at LBNL. Previously, we had reported [1] test results from a hybrid design dipole which contained a similar inner Nb_3Sn and outer NbTi winding. This paper presents the final assembly characteristics and parameters which will be compared with those of the original magnet design [2]. The actual winding size was determined and a secondary calibration of the assembly pre-load was done by pressure sensitive film. The actual azimuthal and radial D20 pre-loading was accomplished by a very controllable novel stretched wire technique. D20 reached 12.8T(4.4K) and 13.5T(1.8K) the highest dipole magnetic fields obtained to date in the world.

I. INTRODUCTION

The LBNL "Advancement of Accelerator Magnet Technology" program has concentrated on development of magnet construction techniques applicable to brittle superconductors. Nb_3Sn was chosen as the typical brittle superconductor due to its more extensive data base, and because presently it is the only superconductor with practical current density(J_c) in the field range of 11T to 16T. This paper will compare important design parameters previously published [2] with those achieved so far by a development Nb_3Sn dipole "D20". The dipole testing has produced several surprises which summarized were a) excellent ramp rate quench performance, b) excellent thermal stability (>20 watts;12T), and c) the magnet trained up to much higher fields in contrast with earlier Nb_3Sn dipole test histories [3, 4, 5]. The dipole had good high field performance 12.8T(4.4K) and 13.5T(1.8K), but at 1.8K was clearly not limited by it's critical current performance. The previous high field dipole record by Twente University group was 11.03T reached by an LHC model "MSUT" magnet [4]. The highly interdependent coil fabrication steps of Nb_3Sn require a more integrated approach to cabling, insulating, stepped multi-phased heat treatment, similar expansion and contraction materials, protection heaters, epoxy impregnation, assembly, and pre-loading due to the larger temperature range that the winding must operate compared to NbTi. There is a large body of Nb_3Sn data that indicates a substantial J_c loss with increasing perpendicular strain, which up to fields of 13.5T did not appear to be the limit in the present configuration of D20.

II. DESIGN

D20 is a four layer graded cable cosine Θ winding distribution 50mm bore dipole. The inner two layers (1&2) used one size cable (37-0.75mm dia strands) with a 1.57mm (1.65mm-meas.) thickness and a 14.66mm (14.66mm-meas.) width under a load of 34.5 MPa. These cable strands were made by two different manufacturers- Teledyne Wah Chang and Intermagnetics General. The outer two layers (3&4) use another size cable (47-0.48mm dia strands) with a 1.12mm (1.30mm-meas.) thickness and a 11.89mm (11.91mm-meas.) width under a load of 34.5MPa. These cable strands were manufactured by Teledyne Wah Chang. All of the cabling was done at the LBNL cabling facility. The coil design numbers as well as the maximum values attained to date are given in Table I and II.

D20 Design@4.35K	Central Field (T)	I. Layer Field (T)	O. Layer Field (T)
6400 A	13	13.3	10.45
7000 A Short Sample (SS)	14.	14.4	11.2
6925 A @ 4.5 K SS-11% (Degrad 140 MPa) = 6525 A	13.2	13.5	10.6
D20 @ 4.5 K Reached 6300 A	12.8	13.1	10.29
@1.8 K Reached 6712 A	13.5	13.8	10.75

Table I Magnetic Field versus I_c or I_q

D20 @ 13T 6400 A	Inner Cable IGC		Outer Cable TWCA	
	Design	Reached	Design	Reached
J_{cu} (A/mm^2)	1302	1367	1462	1535.1
$J_{non\ cu}$ (A/mm^2)	559	587	1550	1627.5
$J_{overall}$ (A/mm^2)	276	290	479	503

Table II Current Densities

Cable insulation is composed of single glass sleeve 0.12mm thick in the straight sections and then wrapped with extra glass tape 0.28mm thick around the ends to prevent shorts. The original fiberglass sizing is evaporated off the fabric before being replaced with the special palmitic acid and ethanol sizing and then drawn over the unreacted cable in preparation for winding. Wedges, pole pieces and end pieces are coated with alumina (0.13mm thick) for extra insulation. The training results indicate the pole surfaces are a problem. Due to the locations and sequence of the first quench set we conclude that an excellent insulation with a weak shear strength is needed(i.e. mica) between conductor and pole. There is a layer of fiberglass tape between the mandrel and the inner coil heater/ voltage tap kapton/stainless steel (ss) composite plane. There is a second layer of glass tape between coil layers 1 and 2, then the coil layer 2 heater/voltage tap kapton / ss composite plane outside

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layer 2. The final layer of the double winding package is a layer of fiber glass cloth. During the heat treatment, the heater/voltage tap composite space is occupied by an ss shim. The special sizing is evaporated before the start of the bronze/Nb_3Sn formation heat treatment sequence. The process was repeated for each of the double winding packages. Each of these reacted double winding packages had both Nb_3Sn/NbTi splices fabricated in the reaction fixture prior to voltage tap connection and the transfer to the potting fixture. The various electrical splices were monitored during the performance testing and the results are given in Table III.

Location	Type of Joint	R(nano·ohms)
Top/Mid	NbTi/NbTi	1.0
Mid Magnet	NbTi/NbTi	0.5
Bottom/Mid	NbTi/NbTi	1.0
T-4	NbTi/Nb_3Sn	0.7
B-3	NbTi/Nb_3Sn	0.8
T-3	NbTi/Nb_3Sn	0.9
T-2	NbTi/Nb_3Sn	0.5
T-1	NbTi/Nb_3Sn	0.7
B-4	NbTi/Nb_3Sn	0.8

Table III Joint Resistances

After potting, the four double winding packages were placed back into the potting fixture with a pressure sensitive film replacing one or more insulation layers on the appropriate loading surfaces. These fixtures were then loaded to moderate levels(few MPa) to determine the surface profiles as well as the size of the packages. This sizing information along with design numbers and component measurements were used to make an assembly of the entire magnet exclusive of the yokes and structure located radially outside them. In this assembly once again a pressure sensitive film replaced insulation layers on appropriate surfaces to check for the appropriate fit and to allow an independent check of the maximum load applied. All of the pole strain gauges were monitored and the bronze collared coil structure was wrapped with ss wire at the calculated tension up to about half the desired preload. The final wrap was 304 stainless steel 3mm x 1mm round edge wire 14 kilometers long in 18 layers(actual space for 25 layers) at a tension of 850N. These results then lead to the loading numbers of the final assembly within the yokes. See figure 1 for the final preload for D20. End plates held the magnet winding in axial compression up to 30% of the total Lorentz force (820 kN). Ten end loading bolts had strain gauges on them which were pre-calibrated and eight were monitored throughout the assembly and during testing.

III. EXPERIMENTAL RESULTS

The principal goals of the four layer Nb3Sn dipole were: a) explore the 12T-14T range, b) validate the technology required at these field levels, and c) provide a test facility to test insertion coils made with higher current density conductor or newer conductors and winding geometries in this field range. D20 was protected by heaters with a photo-etched geometry so that coil voltages would be minimum, and temperature increases be as uniform as possible. After the magnet reached LHe temperatures a series of protection heater tests were performed to measure their effectiveness similar to those reported earlier [6] except each layer was checked independently at 3.5T. The time delay after firing the heaters and the onset of resistance was 20 to 30 ms at 3.5T and <10 ms above 12.0T. The peak adiabatic heater temperature was 285K(layer 1) and 170K for the others with a peak surface power of 75 w/cm^2 and 26.5w/cm^2 respectively. The highest average winding temperatures after quench were in the outer layers(between 182K-203K). When the quench originated in an outer turn the highest hot spot estimate was 264K. By comparison, the inner two layers averaged 120K - 132K and if the quench originated there the highest temperature estimate was 168K. The maximum number of Miits(Million-ampere squared - seconds) absorbed during a quench during the test was 7.6. This maximum however did not occur at the highest field but was 12T - 13T. After nominal heater parameters were established, the actual spontaneous quench testing started. Figure 2 shows the quench history of D20.

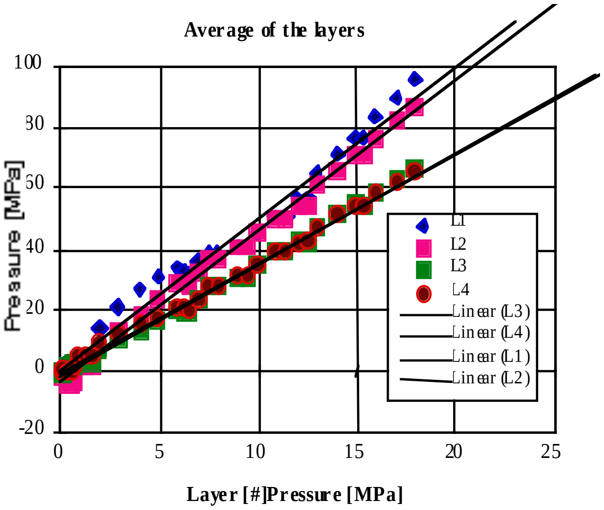

Figure 1 Winding layer Load versus stretched wire layer #

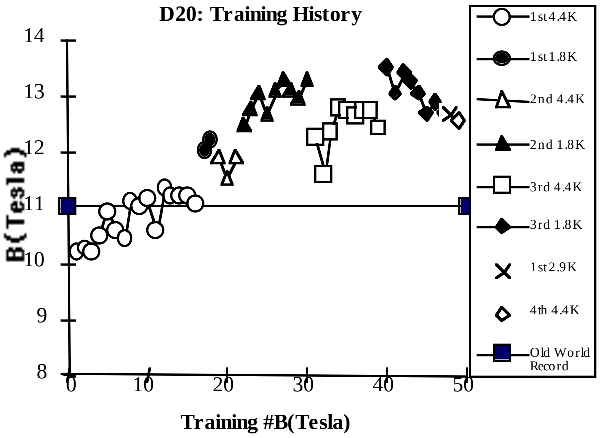

Figure 2. D20 Quench History

Unlike previous Nb_3Sn dipoles (3,4,5) D20 has trained to date 25% higher than the initial quench. The rate at which D20 trained was temperature dependent. The present training at 1.8K is in a length of conductor going to an outer layer lead splice in a low field region. Usually when warmed up (>4K) after low temperature (1.8K) training the coil's 4K performance has increased substantially. A full warm up/cool down cycle has yet to be completed to room temperature. D20 displayed reasonable heat input tolerance for a completely impregnated structure. When using the inner protection heater as a source it required more than 20 watts to quench the magnet at 12T(2K). D20 appears to be presently operating near its short sample at 4.5K, and it is quenching in the ramp between the pole turns of the inner coil pair. The ramp rate dependence of the quench current at 4.4K was excellent and is shown in Figure 3, compared with existing or proposed accelerators.

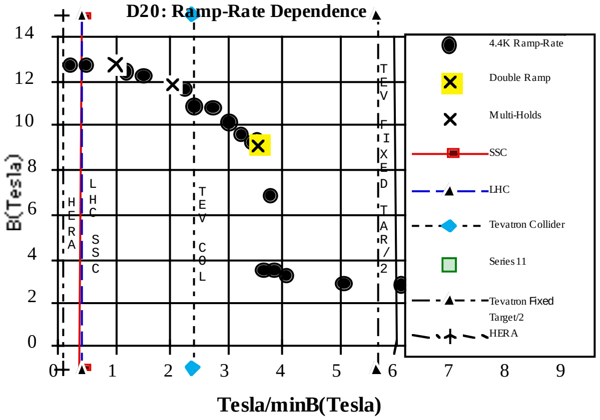

Figure 3. Ramp Rate Quench Current Values at 4.4K

The thermal margin of D20 was determined by ramping to a field level, holding, then rapidly ramping at (Eddy Current heating) 100 to 200 A/sec(12T~24T/min) and ploting the current change. The intercept of the zero current increase indicates that at least a few(0.4→0.8T) tenths of a tesla margin remains in the thermally quenched areas. However, within a millisecond most of a given layer turns are quenching together during these tests. The plot is shown in figure 4.

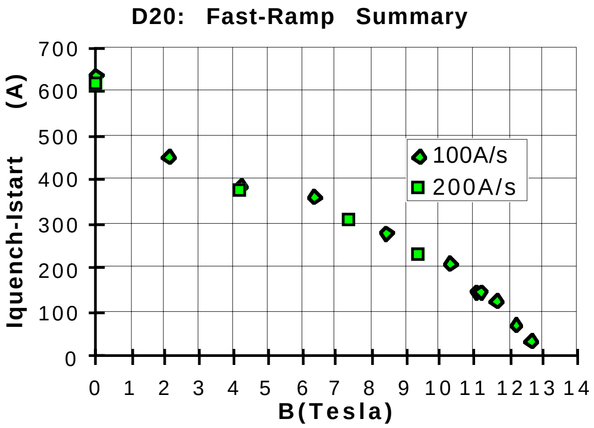

Figure 4. Thermal margin in Amperes as a function of Magnetic field (6400 amps ~ 13T)

Therefore, either the cable is damaged or the pole turn is separating from the post along the 1st layer to 2nd layer transition and the coil will have to be trained further. Afterwards, D20 should transition at the high field point. The reasons for the superfluid low field lead quench may be related to the change in geometry of that particular lead. Due to a splice box misalignment, the distance of the copper splice block and the straight section had to be made shorter. This shortening causes the splice block to end right at the edge of the end shoe. This produces a radial plane in that area such that the cable is not rigidly supported across that boundary with the metal filler pieces as is the normal case.

IV. CONCLUSIONS

The operation of D20 up to fields of 13.5 T certainly indicates that the strain limitations of the Nb_3Sn conductor up to this point have not been a limiting factor. Apparently the mechanical structure is adequate for this field range. There is still reasonable doubt that there was enough prestress once the magnet was cold. The excellent ramp rate behavior of the magnet has put added pressure to measure field quality, harmonics as function of time, as well as quantity which is planned in the next operational period. The D20 cryostat is presently being modified for extra current leads for sample coils. There is also a re-entrant cryostat (warm bore tube) being fabricated for the harmonic analysis equipment. Certainly it appears that fields up to 13.5 T and above are within reach. So far most of the ramp rate problems with the previous dipoles are not present in D20. This means strand to strand coupling is low. The application of high field Nb_3Sn dipole looks very promising.

V. ACKNOWLEDGMENTS

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