

TESTING OF TAMU1: A SINGLE-APERTURE BLOCK-COIL DIPOLE*

C. Battle, R. Blackburn, N. Diaczenko, T. Elliott, R. Gaedke, W. Henchel, E. Hill[†], M. Johnson, H. Kautzky, A. McInturff^{††}, J. McIntyre, P. McIntyre, A. Sattarov, Texas A&M University, College Station, TX 77843 USA

R. Benjegerdes, P. Bish, D. Byford, R. Hannaford, and A. Lietzke, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

Abstract

The NbTi model dipole TAMU1 was successfully tested at Lawrence Berkeley Lab. The dipole reached 88% of short-sample current on the first quench, and trained rapidly to 98%. The incorporated quench heaters were capable of inducing a plateau quench in <10 msec. The splice resistance was measured to be 0.28 nΩ in the multi-kA range, indicating an excellent contact. AC loss properties were studied during ramp studies. Ramps to 1,000 A/s (0.9 T/s) operated at greater than 60% plateau current. The dipole is a success. It is significant that this high-field NbTi dipole operated successfully at short-sample current with minimal training, even though the coil was vacuum-impregnated with epoxy. We attribute this performance in part to the stress management that is integrated into the block-coil geometry.

1 INTRODUCTION

The superconducting magnet TAMU1 is a NbTi block-coil dipole, designed and built at Texas A&M University [1]. The magnet was built as a learning model, to evaluate construction techniques and materials that will be necessary for subsequent high-field Nb₃Sn dipoles. The coil was fabricated using the insulation materials (S-glass cloth, mica paper), vacuum impregnation, and provisions for stress management that are being developed for use in a 12 Tesla Nb₃Sn dipole [2].

Figure 1 shows the cross-section of the dipole windings and its flux return. The principal parameters are given in Table 1. The coil is asymmetric, built in the geometry that would be needed for a flux-coupled dual-bore dipole. The conductor used in all windings was the inner cable from the SSC dipole; its properties are given in Table 2.

2 CONSTRUCTION DETAILS

The coil is wound in three double-windings. Figure 3 summarizes the properties of each winding. Each double-winding is wound two-in-hand with an S-transition at the inner boundary. Successive double-windings are connected by a splice S_i. The windings were instrumented with voltage taps V_i, quench heaters Q_i, and spot heaters

H_i. Although all windings were instrumented, a number of the taps and heaters were damaged during impregnation and preloading. The surviving elements (indicated in Figure 3) were adequate to protect the magnet, to monitor the winding voltages, and to initiate a localized quench (spot heater H₄ located near the outer turn of winding 4).

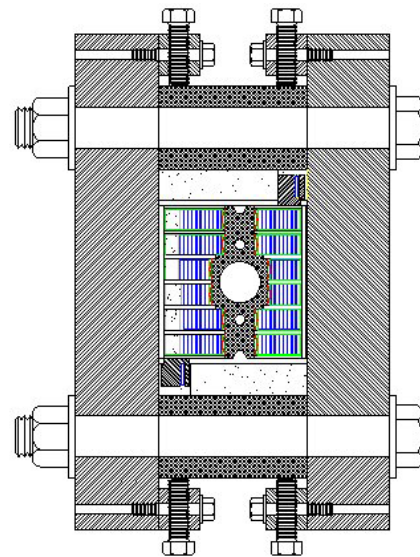


Figure 1. TAMU1 dipole cross section.

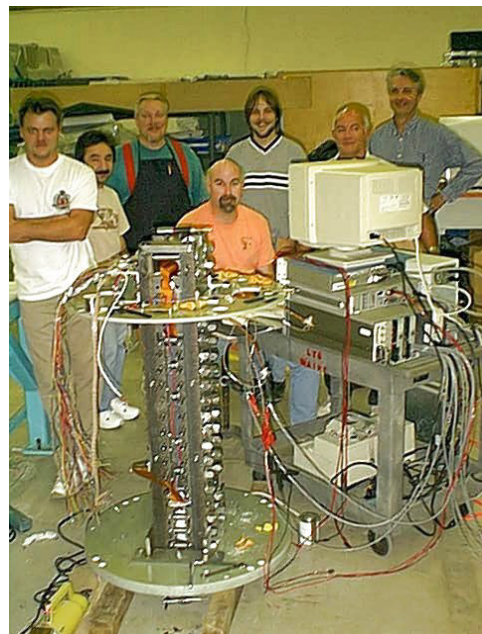


Figure 2. TAMU1 during final tests before cool-down.

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[†] Presently at FNAL, Batavia, IL 60510 USA.

^{††} mcinturff@phyacc.tamu.edu

On leave from LBNL, Berkeley, CA 94720 USA.

Table 1. Main parameters of the TAMU1 dipole.

Maximum field	6.5	Tesla
Maximum current	8.55	kA
Inductance	3.5	mH
Stored energy	70	kJ
Overall length	110	cm
Body length	50	cm
Beam tube diameter	2.5	cm

Table 2. Properties of SSC inner cable used in the coils.

Strand diameter	0.8	mm
j_{sc} @4.5 K, 5 T	2,850	A/mm ²
Cu/SC ratio	1.3	
# strands	30	
Cable width	12.7	mm
Cable thickness	1.50	mm

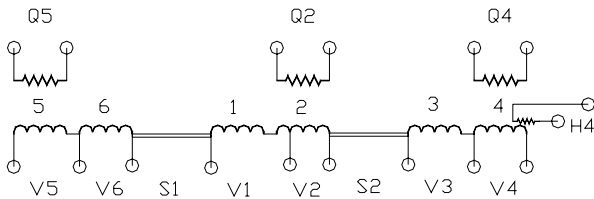


Figure 3. Schematic of voltage taps (V), splices (S), quench heaters (Q), and spot heater (H).

The coil was preloaded within its flux return by large bolts visible in Figure 1. Unfortunately the coil attained a horizontal bow of ~ 2 mm during vacuum impregnation. In order to provide uniform contact along the sides of the coil within the flux return, it was necessary to apply a “smart shim” of S-glass-reinforced epoxy. As a consequence it was not possible to close the rib/plate structure that was designed to provide stress management, so that the preload of the flux return was delivered directly to the coil. Several intermittent shorts (coil to case) were encountered in the preloading process. The coil was preloaded to 50 tons, $\sim 30\%$ of the maximum calculated Lorentz stress, without introducing any shorts. As the coil is excited to full field, the Lorentz load is expected to exceed the preload, and the retaining bolts should stretch elastically – the maximum bolt strain is calculated to be ~ 200 μm . We were concerned that the resulting coil motion might produce quenches at high field; it did not.

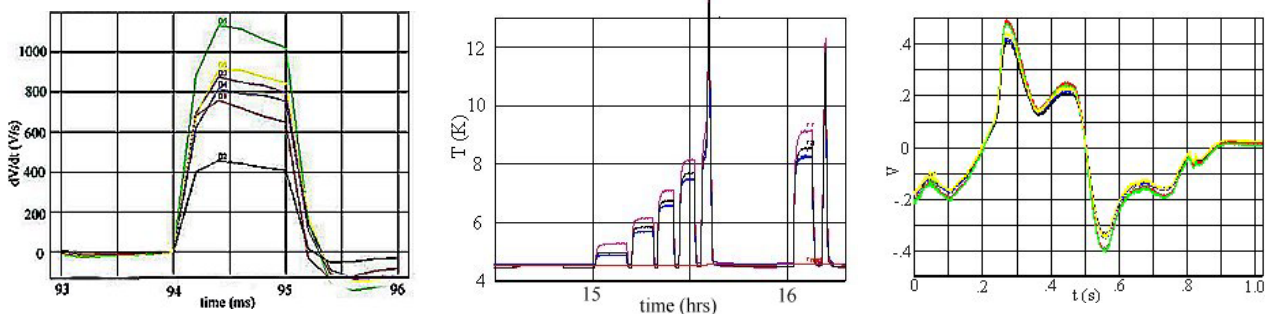


Figure 4. Detection and repair of turn-turn short: a) voltage response to triangular current ramp before ramp processing; b) temperature response in coil during current ramp sequence; c) voltage response to current ramp after processing.

2 TESTING

In preparation for testing, the resistances of all windings were measured to check for turn-to-turn shorts. An imbalance equivalent to two turns was observed between V_1 and V_2 , which was attributed to the placement of the voltage tap near the S-transition between coils 1 and 2.

2.1 Discovering and repairing a turn-turn short

The dipole was cooled to 4.5 K, and all windings were checked for turn-to-turn shorts by driving a triangular current waveform (20 A max) through the coil. The rate-of-rise was twice the rate-of-fall, so that the inductance of each winding could be checked independently at two frequencies. Figure 4a shows the voltage response. The voltages across coils 1 and 2 were observed to be mismatched by a ratio ~ 1.7 , much more than the resistive mismatch ratio of 1.22 from the locations of the voltage taps, indicating that there was a turn-to-turn short.

The short presumably had high enough resistance so that it did not perturb the resistance check at room temperature, but it provided a parallel current path in AC response. Such a short could pose a serious hazard in a high-current quench. A short removal scenario was attempted, in which the coil was exercised with a continuous sawtooth ramp to 300 A peak current, and the ramp rate was increased in a succession of steps until the coil quenched from AC heating. The rationale was that a substantial but limited amount of energy would be dumped through the short during the quench, sufficient to burn out the short without damaging the coil.

Figure 4b shows the temperatures measured at the locations T_1 , T_7 , and T_8 indicated in Figure 3. Each succeeding plateau corresponds to a continuous ramp to 300 A, at a series of increasing ramp rates: 50 A/s, 100 A/s, 200 A/s, 300 A/s, 400 A/s, 500 A/s, 600 A/s. At 600 A/s, the coil temperature reached the critical temperature $T_c = 9.3$ K, and the coil quenched. After recovery, the coil *did not quench again* during a repeated 600 A/s ramp sequence, but did with a 700 A/s ramp sequence. Something in the coil had changed to produce this change in behavior.

The voltages across the windings were then measured during a ramp to 300 A with 400 A/s up and 200 A/s down. Figure 4c shows the response. All winding inductances were consistent with their calculated values L_i , indicating that the short had been removed successfully.

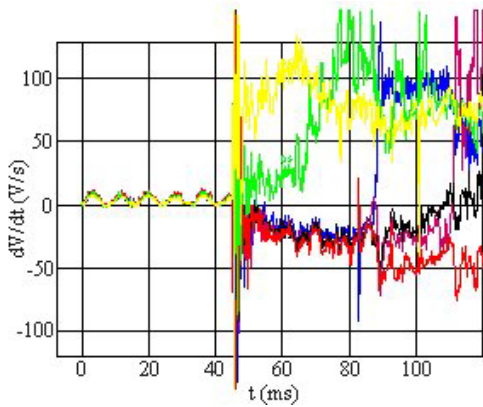
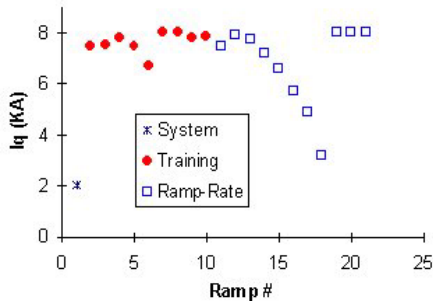

 Figure 5. dV/dt traces across the windings during quench.


Figure 6. Training history of TAMU1 dipole.

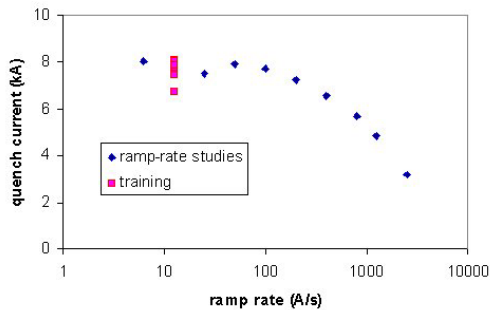


Figure 7. Ramp rate dependence of quench current.

2.2 Evaluation of quench heater operation

The coil current was next increased to 2,000 A with subsequent powering of each of the three quench heaters Q_i in order to evaluate their effectiveness in initiating quench in the coils that they contacted. Each heater has a room-temperature resistance of $\sim 1.5 \Omega$, and is situated next to the edge surfaces of all turns of a winding in the end region. Although two heaters were installed on each of the six windings, only three were operational by the time of testing. Fortunately the three operational heaters were on windings 2, 4, and 5, which enabled a quench to be initiated in at least one coil of each double-winding.

At 2,000 A, all three heaters were fired, each with a current pulse of 35-45 A for 26-16 ms, which corresponds to an adiabatic heater temperature of 125-150 K. The voltage response dV/dt across each winding is shown in Figure 5. A positive voltage corresponds to a resistive voltage, while a negative voltage corresponds to an inductive response as the coil current decreases. The three

windings with heaters were successfully quenched, while the other three windings remained superconducting for ~ 100 ms before quenching. This test validated that the quench heaters worked successfully and insured that all windings would remain below 200 K during quench.

3 HIGH-CURRENT TESTING

The current was ramped at 10 A/s to quench. The first quench occurred at a current of 7,200 A, 88% of short-sample current $I_c = 8,150$ A. Figure 6 shows the training history during a sequence of 9 quenches. The dipole attained a reproducible quench current of 8,050 A, $\sim 98\%$ of short-sample limit, on the sixth quench. The dipole field in the bore of the dipole was measured by a Hall probe to be 6.56 T at 8 kA coil current.

Some of the features of the quench behavior of the TAMU1 dipole are illustrated in Figure 5. Quench 2 appears to have been initiated by a major mechanical motion (the huge spike in all traces). Windings 5 and 6 quenched simultaneously. The other windings remained superconducting until the quench heaters were fired.

AC performance was characterized by measuring the quench current as a function of ramp rate. The results are presented in Figure 7. Quench current fell to 50% at a ramp rate of $\sim 1,500$ A/s.

The splice resistance $R = 0.28$ n Ω was inferred from the I/V dependence across each splice.

4 CONCLUSIONS

There has been a long-standing debate concerning quenches and the importance of helium access at the surfaces of strands within the cables of a NbTi coil in high-field dipoles. Many have considered such access to be critical for stability against microquenches and the absence of training [3]. TAMU1 is one of a very few high-field NbTi dipoles ever fabricated with vacuum-impregnated coils: there is *no* local access of helium to the strands of the cable. Yet TAMU1 exhibits very little training and operates reproducibly at or near the short-sample limit. We ascribe this attribute in part to the effective management of coil stress and the release of shear in the block-coil geometry.

6 REFERENCES

- [1] Blackburn *et al.*, 12 Tesla hybrid block-coil dipole for future hadron colliders, Proc. Appl. Superconductivity Conf., Virginia Beach, VA Sept. 17-22, 2000.
 - [2] C. Battle *et al.*, Optimized block-coil dipoles for future hadron colliders, Proc. Int'l. Conf. on Magnet Technology, Jacksonville, FL, Sept. 26-30, 1999.
 - [3] A. Tollestrup, Care and training of superconducting magnets, IEEE Trans. on Magnetics, **MAG-17**, #1, 863-872 (1981).
- G. Pasztor and C. Schmidt, J. Appl. Phys. **49**, 886 (1978).