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Test Results of a Nb_3Sn Wind/React "Stress-Managed" Block Dipole

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***Abstract*—A second phase of a high field dipole technology development has been tested. A Nb_3Sn block-coil model dipole was fabricated, using magnetic mirror geometry and wind/react coil technology. The primary objective of this phase was to make a first experimental test of the stress-management strategy pioneered at Texas A&M. In this strategy a high-strength support matrix is integrated with the windings to intercept Lorentz stress from the inner winding so that it does not accumulate in the outer winding. The magnet attained a field that was consistent with short sample limit on the first quench; there was no training. The decoupling of Lorentz stress between inner and outer windings was validated. In ramp rate studies the magnet exhibited a remarkable robustness in rapid ramping operation. It reached 85% of short sample(ss) current even while ramping 2-3 T/s. This robustness is attributed to the orientation of the Rutherford cables parallel to the field in the windings, instead of the transverse orientation that characterizes common dipole designs. Test results are presented and the next development phase plans are discussed.**

***Index Terms*—superconducting accelerator magnets, Nb_3Sn, stress control, wind/react**

I. INTRODUCTION

THE Accelerator Research Lab at Texas A&M University has been developing a new approach to superconducting dipole technology which removes or mitigates several of the difficulties encountered in fabrication of high-field Nb_3Sn magnet windings. The key components in the approach are: a) stress management structure within the winding package; b) preload of the stress management structure using pressurized metal-filled bladders; c) orientation of the cables parallel to magnetic field to minimize magnetization eddy current losses and their associated harmonic effects; and d) a flux plate closely coupled to the beam tube region to compensate the persistent current harmonics at injection field. This paper presents and discusses data obtained from the testing and operation of TAMU2. The construction details were presented in previous papers [1, 2]. The main objective in building and testing TAMU2 was to validate the stress management strategy [3] in which a support matrix is integrated with the windings and pressurized metal filled bladders [4] are used to preload the external structure and to transmit stress to the flux return yoke and ultimately to the aluminum retaining cylinder. An additional goal was to validate and iterate all of the fabrication tooling, materials, fixtures, and procedures for the wind/react Nb_3Sn coil construction. Fig. 1 shows a partial cross section of TAMU2 in which the key structural elements are indicated. Table I gives the main parameters of the dipole. The stress management strategy includes an arrangement of piers and beams that enclose the windings, laminar springs that provide the soft-modulus head-room to enforce *stress decoupling*, and mica paper lining each winding to release shear stress. The coil assembly is surrounded by an arrangement of thin 304L stainless steel bladders. After the coil assembly is positioned inside the flux return, the magnet assembly is heated (80 °C), the bladders are filled with molten Cerrolow 147 [5], a low-melt alloy similar to Wood's metal. The liquid molten metal is pressurized to a pressure somewhat greater than the maximum Lorentz load that is delivered to the windings at full field, and the magnet is cooled to solidify the bladder filling.

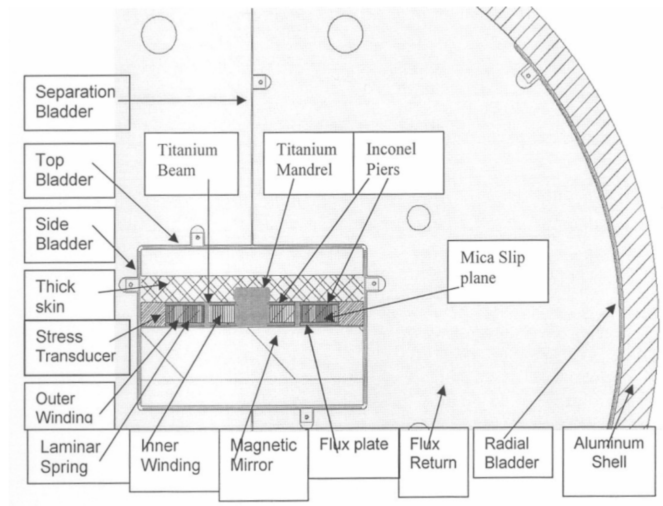

Fig. 1. Cross section of TAMU2. showing elements of stress management.

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TABLE I

Max field in coil (strand short sample)	6.88	T
Operating current	9,384	A
Stored energy	0.048	MJ/m
Max Lorentz force	0.73	MN/m
Superconducting cable:		
# strands	30	
Strand diameter	0.808	mm
J_{sc} (10 T, 4.5 K)	953	A/mm^2
J_{Cu} during quench	1,040	A/mm^2
Windings:		
inner	11	turns
outer	16	turns

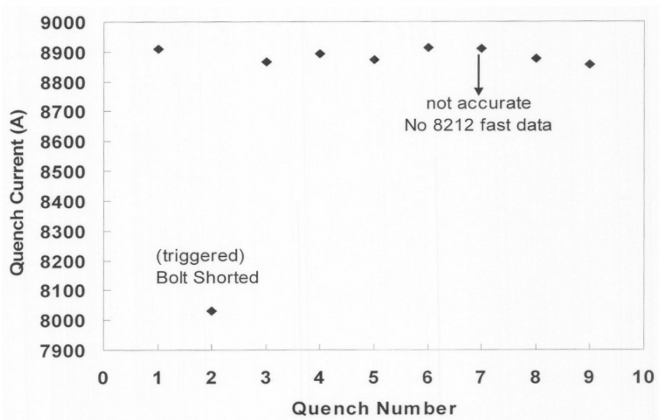

Fig. 2. Spontaneous Quench History of TAMU2.

This bladder thereafter acts as a smart shim creating and distributing the preload uniformly and accurately. The outer curved bladders preload the flux return within the super-alloy aluminum stress tube. The side bladders provide uniform stress transfer of horizontal Lorentz stress from the coil to the flux return. The top/bottom bladders friction-lock the beam elements of the stress management structure at the ends of the winding so that axial Lorentz force is transferred directly to the flux return [1, 2].

The bladders deliver preload to the stress management structure, but not to the windings themselves. The actual preload stress applied to the windings is controlled by the modulus of the laminar spring. The spring was designed to deliver ~5 MPa when half-compressed, and the windings were shimmed to approximately that degree of compression. After testing was complete the winding package was sectioned and precisely measured, and the actual spring preload was determined to have been ~2 MPa. It is important to note that this feature of stress management is quite unique among high-field dipole designs. A further test goal of TAMU2 was to test whether the very modest winding preload would result in premature quenching and/or training.

II. Testing Procedure

The TAMU2 tests took place at E. O. Lawrence Berkeley National Laboratory in January 2006 in the AFRD Supercon Test Station. Several special requirements for size and instrumentation had to be accommodated. The capacitor transducer's 10 kHz power and signal wiring harness and its' egress from and path in the cryostat were problematic. A procedure and scheme was worked out to prevent cross-talk between the transducers and the other signals leaving the magnet for the data acquisition (DAQ) and quench detection (QDC) circuits.

TABLE II

Quench #	Ramp Steps	Requested Ramp Rate (A/s)	Quench Current (A)	Comments:
1		10	8911	
2		10	8030	bolt shorted bus at 8030
3		10	8865	
4	20A/s-8kA	10	8894	
5	" "	10	8874	
6		20	8914	
7		20	8910	no 8212 fast data for accuracy
8	" "	5	8875	
9	" "	5	8856	
				Then ramp sequence started

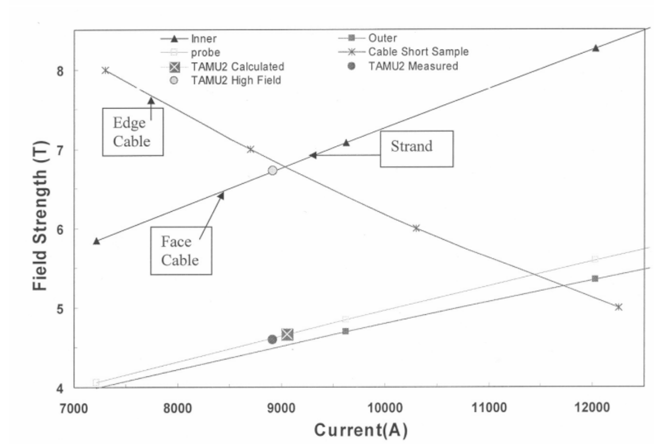

Fig. 3. TAMU2 load lines and Cable/field orientation Quench Current curves with additional operating points intersections shown.

A. *Spontaneous Quench behavior of TAMU2.*

The spontaneous training history is given in Table II and is plotted in Fig. 2. TAMU2 started and finished the testing at >98% of the cable short sample current that was measured by Dietderich [6] in the orientation of cable parallel to magnetic field (the orientation in this dipole) as shown in Fig. 3. There was no evidence of training. Quench #2 was caused by a bolt being magnetically levitated across the copper lead bus, creating a short and causing the protection heaters to activate. Fig. 4 shows the voltage traces of the typical spontaneous quench, except #2. All the rest originate at the same location within a millimeter or two; located on the innermost turn at the return post as shown in Fig. 5. The time delay between taps indicates an average quench velocity of 19.6 m/s. The quench origin location next to the post corresponds to the windings' peak magnetic field region. Therefore, there is no evidence for any conductor degradation anywhere in the windings, or of any quench initiation due to movement and/or of any friction release. This conclusion's significance is that there is no

TABLE III

Requested Ramp rate A/s	%Short Sample parallel cable	%Short Sample Strand	Average dI/dt A/s	DAQ8212 peak dI/dt A/s	Maximum Field Rate T/s	Quench Current A
5			2.8			8875
5			2.9			8846
5			2.8			8856
10			5.7			8911
10	logical circuit tripped when bolt shorted buss					8030
10			5.7			8865
10			5.7			8895
10			5.6			8875
20	99	86	11.6			8914
20	99	86	11.5			8875
100	99	86	128			8856
200	99	86	201			8856
400	98	85	339			8768
800	90	79	661			8322
1000	92	81	876			8351
1200	86	75	1127	1800	1.4	7808
1400	86	75	1231			7760
1600	84	73	1335	3300	2.3	7595
2000	84	73	2060	4200	3	7556

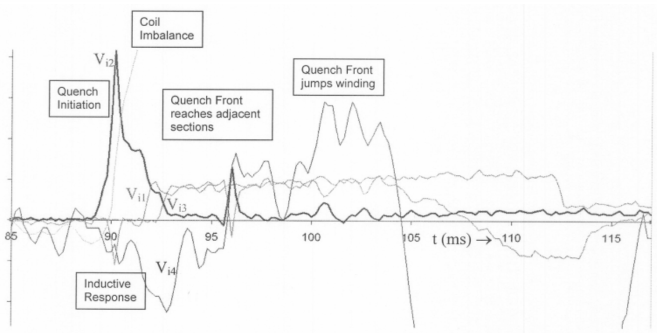

Fig. 4. One of similar copies of "The Spontaneous Quenches" except Q#2.

penalty associated with a small winding preload. This is the first major validation of the stress management strategy. The next step needed is verification at higher fields (>12 T).

B. *Quench Current as a Function of Ramp Rate*

Ramp rate studies were performed, in which coil current was ramped successively at faster rates and the quench current was measured. Table III presents the quench current *vs*. ramp rate; the data is plotted in Fig. 6. It was anticipated that coupling currents would be suppressed by the orientation of the cable parallel to the coil field. The coil cable conductor was Cr-plated internal-tin strand that had been made for the ITER project, and the Chrome plating aided as well in the further suppression of coupling currents. Nevertheless, the extreme robustness of TAMU2 for fast ramp rates was surprising. *It is the lowest ramp rate dependence ever observed at the LBNL test station*. The only limitation that was encountered, was the power supply's inability to regulate with the low inductance of TAMU2 at very high ramp rates. This performance data would indicate the magnet would be suitable for cycling at a few T/s in the 6 T field range, a region of current interest for future accelerator plans.

C. *Stress-Management*

All high-field superconductors (A15 compounds and oxide superconductors) are brittle. The ability to control the stresses in the windings of a high-field magnet made from these brittle conductors is key to their usefulness. TAMU2 is a first full embodiment of our stress management strategy, "by-pass/not add" and it's operational data should be valid at higher stress levels provided adequate spring deflection is still available.

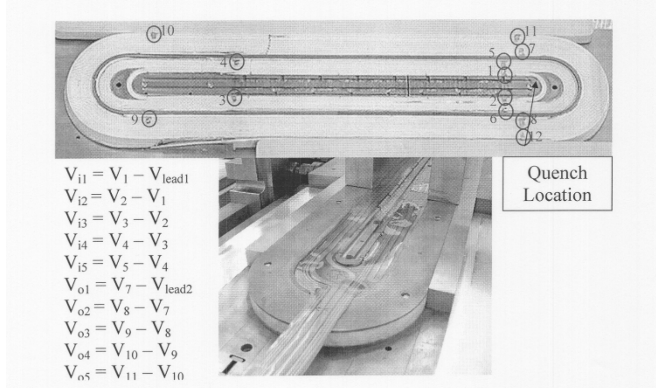

Fig. 5. Windings' Location of voltage taps, protection heater, and high-field.

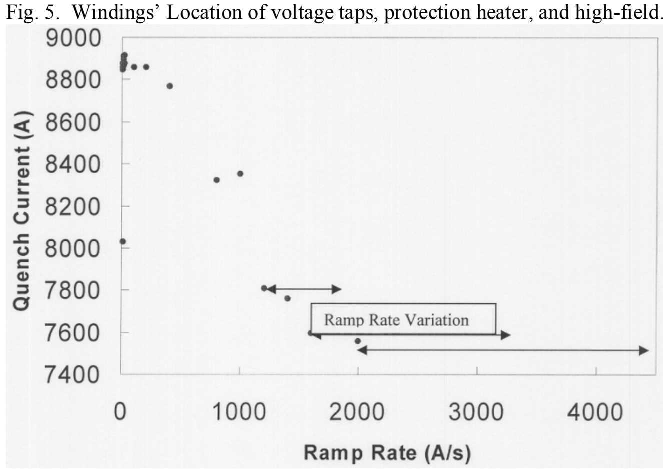

Fig. 6. Quench Current versus Ramp Rate & variation shown for TAMU2.

The outer winding of TAMU2 was instrumented with capacitive strain transducers on the outer bounding surfaces, along both sides and around one end of the winding. The calibrated response of a typical transducer is shown in Fig. 7. The complication encountered was the conditioning of the capacitance transducers was lost during the impregnation-curing cycle. This changed state of the transducers necessitated an autopsy of the coils after the testing was completed. The autopsy determined the initial state of the laminar springs, recalibrated windings' transducers (10 layer cable stack plus transducer), and enabled correlation with the previously obtained test data. During this process, the cross sections and position of the components were determined to ±25 microns. Therefore knowing the initial loading from the compression of the springs and the history of the loading cycles, a reasonably accurate loading history could be constructed. These conditioning cycles were affected most at the lower stress levels (<10 MPa) by the impregnation cycles' temperatures, but were more stable at the higher levels. There were a few more surprises found during the measurement of the cross sections. The most being that the straight sections were not symmetrically loaded (a side was actually completely unloaded). Other autopsy findings were as follows: a) the

TABLE IV
Measured capacitance (pF) increase

Transducer location	Serial Number										
Quench Number		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Left side (7-layer)	#3	60	70	70	70	70	70	70	70	70	70
Right side (5-layer)	#4	147	153	157	162	162	164	166	168	168	168
End Shoe (7-layer)	#5	1	3	9	7	4	3	4	4	4	4

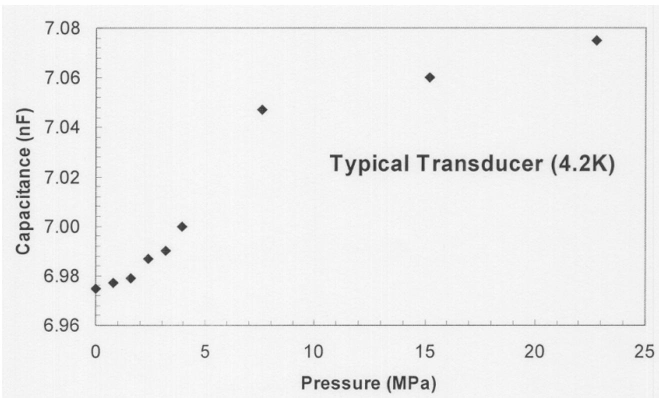

Fig. 7. Capacitor strain gage data after the impregnation cycle; 1st load cycle.

lead end spring was totally compressed, b) no voids were detected in the windings, and c) no epoxy was found inside the laminar springs' envelopes either straight or curved. Table IV gives the raw change of capacitance data (pF). Table V gives the derived stress for the standard quench training cycle to 8 kA after cycle #6, as obtained from the initial conditions (which were determined by the autopsy) and cycle capacitance change of the transducers. It can be concluded that the *Lorentz force from the inner winding was not transferred to the outer windings, but bypassed with a modest amount still locked in friction at the piers' interior surfaces*. Therefore the stress-managed structure performed as designed to this stress level and there was additional spring deflection available everywhere but at the non-quenching lead end.

III. Discussion of Data Analysis

The excellent ramp rate performance would make a winding similar to TAMU2 a possibility for the magnets for the GSI high-energy ring or for several of the fast cycling options for LHC injector chain to increase the integrated luminosity.

IV. Conclusion

The first full cycle of the *Stress-Management* approach for a Nb_3Sn wind/react coil fabrication magnet obtained the following results: a) The magnet did not exhibit any training quenches to within 95% current level of the weighted strand short sample (99% cable). b) The actual forces measured on the retaining piers were slightly more than three quarters of those generated by the outer winding alone. c) The internal loads on the end transducer (Ti beams) was at the level of the

TABLE V

Transducer location	Serial Number	Calculated Stress (MPa)		Gauge constant point of interest	measured value	error
		inner winding	outer winding	(pF/MPa)	(MPa)	(MPa)
Left side	#3	23.5	15.7	5.82	12.0	2.2
Right side	#4	23.5	15.7	13.4	12.2	3.8
End Shoe	#5	0.6	0.9	4.22	1.0	0.6

axial loads but the load transmitted to the end bolts was $\leq$ 10%. d) The peak field for the mirror coil geometry was ~6.8 T. e). The ramp rate dependence of the coil was exceptional. At a ramp to quench power cycle with an average ramp rate of 2.1 kA/s, and a peak rate of 4.2 kA/s, the quench current was 85% of the plateau value or 81% of the weighted strand short sample.

V. Third Phase

The third phase of the development is to construct two coil modules similar to TAMU2 except using high performance conductor (>2500 A/mm^2 at 12 T, and 4.2 K) and different thickness cables in the inner and outer windings in an assembly capable of reaching a 12 T to 13 T peak field.

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