Title

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***Abstract*— Amongst the magnet development program of a large-aperture Nb_3Sn superconducting quadrupole for the Large Hadron Collider luminosity upgrade, six quadrupole magnets were built and tested using a shell based key and bladder technology (TQS). The 1 m long 90 mm aperture magnets are part of the US LHC Accelerator Research Program (LARP) aimed at demonstrating Nb_3Sn technology by the year 2009, of a 3.6 m long magnet capable of achieving 200 T/m. In support of the LARP program the TQS magnets were tested at three different laboratories, LBNL, FNAL and CERN and while at CERN a technology-transfer and a four days magnet disassembly and reassembly were included. This paper summarizes the fabrication, assembly, cool-down and test results of the six magnets and compares measurements with design expectations.**

***Index Terms*—Quadrupole, Nb_3Sn, LARP, Superconducting magnet**

I. INTRODUCTION

THREE US laboratories (BNL, FNAL, and LBNL) have collaborated in a development program towards the fabrication of a full scale Interaction Region (IR) quadrupole magnet made of Nb_3Sn conductor. The TQ–series magnets are the first R&D step towards an upgrade of the LHC IR region and are part of LARP [1],[2]. Using virtually identical coils in two different structures LBNL (Technology Quadrupole Shell–TQS) and FNAL (Technology Quadrupole Collar–TQC, [3]) built and tested a total of ten 1-meter long magnets. The LBNL TQS design is a shell based structure using "key and bladder" technology, successfully tested in a number of different Nb_3Sn magnets [4]-[9], while the FNAL TQC design is a collar based structure [10],[11]. The shell-based structure approach uses bladders for precise, room temperature pre-stress control, with negligible stress "overshoot" during magnet assembly. Interference keys are inserted to retain the pre-stress and allow bladder removal. A tensioned aluminum shell compresses internal iron and coil components, and applies a substantial fraction of the operational pre-stress during cool-down. Accordingly, the final coil pre-stress is monotonically approached from below, without overstressing the fragile conductor. An exploded view and assembly are shown in Figures 1 and 2. In section II, the structural design is outlined followed by test results in section III. In sections IV test results and conclusions are discussed.

Fig. 1. View of TQS magnet.

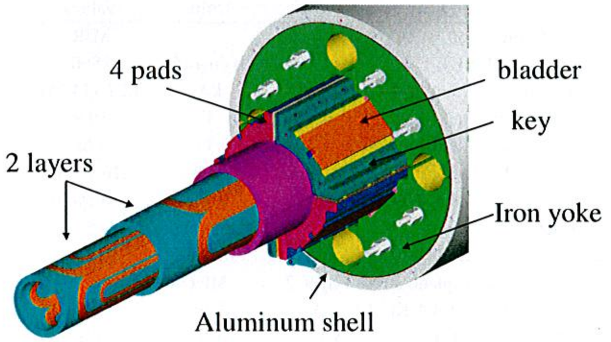

Fig. 2. Exploded view of TQS coils and supporting structure.

II. MAGNET DESIGN

A. *TQS01 and TQS02*

The main differences between the TQS01 and TQS02 are the conductor types and the coil island materials. TQS01 had MJR conductor and Aluminum Bronze islands and TQS02

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TABLE I

TQS MAGNET TESTS

MAGNET	COND	*COILS**	ISLAND	TEMP	TEST
TQS01a	MJR	**5, 6, 7, 8**	bronze	4.4 K	APR. 2006 LBNL
TQS01b	MJR	**14, 15**, 7, 8	bronze	4.4 K	NOV, 2006 LBNL
TQS01c	MJR	5, 15, 7, 8	bronze	4.4 K	MAR. 2007
				1.9 K	FNAL
TQS02a	RRP	**20,21,22,23**	titanium	4.4 K	JUNE 2007
				1.9 K	FNAL
TQS02b	RRP	22,23,**28,29**	titanium	4.4 K	MAR. 2008
				1.9 K	CERN
TQS02c	RRP	22,23,28,20	titanium	4.4 K	JUNE 2008
				1.9 K	CERN

* Bold numbers are for virgin coils.

TABLE II

TQS MAGNET PARAMETERS

	Units	Value
STRAND		
Diameter	mm	0.7
Cu/Sc		0.89
CABLE		
N strands		27
Mid-thickness bare	mm	1.26 ± 0.02
Width bare	mm	10.06 ± 0.05
Keystone angle	Degree	1.05 ± 0.1
Insulation thickness	mm	0.125
COIL		
Turns per block	inner layer	6/12
Turns per block	outer layer	16
Mandrel diameter	mm	90
STRUCTURE		
Shell thickness	mm	22
Shell outer diameter	mm	500

TABLE III

TQS01 PARAMETERS

	Units	Values
Type of conductor		MJR
J_c at (12 T, 4.2 K)	A/mm^2	1860
Short sample current at 4.4 K (1.9 K)	kA	12.1 (13.25)
Peak conductor field Layer 1 at 4.4 K	T	10.9
Peak conductor field Layer 2 at 4.4 K	T	9.68
Short sample gradient at 4.4 K (1.9 K)	T/m	216 (234)
Stored energy at 4.4 K (1.9 K)	kJ/m	370 (443)
Inductance	mH/m	5
Coil Lorentz mid-plane stress Layer 1	MPa	123
Coil Lorentz mid-plane stress Layer 2	MPa	83
Fx per quadrant at 4.4 K(12.1 kA)	MN/m	2.8
Axial end force at 4.4 K (12.1 kA)	kN	331
Applied axial force by 4 rods	kN	800

TABLE IV

TQS02 PARAMETERS

	Units	Values
Conductor type		RRP
J_c at (12 T, 4.2 K)	A/mm^2	2800
Short sample current at 4.4 K (1.9 K)	kA	13.8 (15.3)
Peak conductor field at 4.4 K (1.9 K)	T	12.5 (13.7)
Short sample gradient at 4.4 K (1.9 K)	T/m	243 (267)
Stored energy at 4.4 K (1.9 K)	kJ/m	480 (590)
Applied axial force by 4 rods	kN	550

had RRP conductor and Titanium alloy islands. Replacing the conductor was in line with using the best conductor available, and replacing the island material a result of quench onsets measured during the TQS01 tests. Gaps in between segmented pole islands in TQS01 (combined thickness of ≈ 2 mm) were introduced to prevent excessive strain on the conductor during reaction. Based on TQS01 quench-origins and additional ANSYS analysis [12],[13], the bronze islands were replaced with titanium alloy (Ti6Al4V) islands in TQS02. This eliminated the need for any gaps during reaction and axially compressed the pole-island while cold the conductor near the gaps is therefore under reduced axial tension. TQS02 coils showed no pole-segment gaps after reaction, and the coil ends remained attached to end spacers and shoes. Other than that, TQS01 and TQS02 had the same cross–section and used the same cable size, number of strands and structure. In all cases azimuthal pre–stress was set to the expect 1.9 K short-sample stress level of about 150 MPa corresponding to "no pole separation". Similarly an axial force was applied to prevent separation at the magnet "ends".

There were more magnet tests than available virgin coils. Out of 12 virgin coils available for TQS (each coil is one quadrant), a total of 6 tests were carried out by replacing "low" performing coils with a mix of virgin and "good" coils (Table I). The increase in the number of magnet tested was a result of the non–destructive nature of the magnet assembly and disassembly, the applied pre–stress and the continuous use of the same magnet structure. Testing magnets at FNAL and CERN also provided the opportunity for testing at 1.9 K. At CERN we had the opportunity to completely disassemble magnet TQS02b, replace one of its coils, reassemble, pre-stress and get it ready for testing in four days (magnet TQS02c).

B. Conceptual Design and Parameters

The magnet design and analysis were fully integrated between analytical, CAD and FEA programs (Roxie, ProE (CAD),TOSCA (magnetic analysis), and ANSYS (structural analysis). The results provided 1) the target room-temperature azimuthal and axial assembly pre-stress 2) predicted the cool-down impact on pre-stress and 3) provided axial and azimuthal response during excitation. Based on extensive ANSYS studies the applied axial force to TQS01 and TQS02 went beyond the axial Lorentz force in order to ensure coil-island contact in the end. This was accomplished by four aluminum tie-rods pulling end plates against coils "end–shoes". In the TQS01 series, 30% of that force was actually applied during assembly, the rest was a build–up during cool-down by the contracting axial aluminum tie rods. Design parameters, calculated pre-stress and strain gauge measurements are shown in Tables II–IV.

The TQS magnets were instrumented with strain-gauges mounted to the shell, rods and inner layer islands. While gauges on the shell and rods were fully temperature compensated, gauges on the inner layer islands were compensated computationally against gauges mounted on stress-free island material. More details on the instrumentation are available in [14].

C. *Assembly and Cool–down*

The magnet was assembled from two subassemblies [7]: a coil pack of four coils held together by four adjustable load pads to ensure uniformity, and a structure pack of four iron yokes separated temporarily by azimuthal gap-keys and held by an outer aluminum shell. During final assembly the gap-keys were removed and replaced by radial interference keys inserted between pads and yokes using pressurized bladders. The coils were pre-stressed azimuthally and axially using keys and bladders but the final operational pre-stress was reached only after cool–down (Table V). Differences in the thermal contraction properties between aluminum, iron, coils and islands increased the coil pre-stress (a build–up of azimuthal stress of more than 120 MPa during cool–down) partially confirming and refining ANSYS expectations with regard to property variations and friction factors.

III. TEST RESULTS

A. *Quench Performance*

The training curves of TQS01 and TQS02 are shown in Figures 3, 4 respectively at ramp rates of 20 A/s [15],[16],[17]. The 200 T/m target was exceeded in TQS02 by 10%. At 4.4 K the magnets started training between 74% and 89% of their respected short–sample limits and reached a plateau between 80% and 90% within 10–15 quenches, Fig. 5. The performance remained stable and had little or no fall–backs. TQS01 exhibited 1.9 K training to a stable plateau, and had no impact on subequent 4.4 K performance. TQS02's 1.9 K performance was erratic (192-224 T/m) and usually lower than its 4.4 K plateau performance. It has been recently shown that, due to the self field instability [18],[19] the current capability of high-J_c RRP strands can be lower at 1.9 K than at 4.2 K. Furthermore, at 1.9 K between 7 T and 12 T quench currents can be even lower than the critical current at 12 T and 4.2 K.

The origins of almost all quenches were not in the magnet–ends. Whereas in TQS01 quench onsets concentrated near island–gaps along the straight section, in TQS02 they were near the straight–section ends. While the majority of the quenches started around the first turn around the pole in the inner layer, a large number of outer layer quenches as well as multi-layer quenches (turn 2 and beyond) were also observed. Quenches were associated with both motion and flux jumps (low and high field). Measured quench propagation velocities varied between 15-50 m/s. Magnetic measurements were performed on the TQ magnets and results reported in [20], [21].

B. *Discussion*

We suggest the following arguments as a rebuttal to stability based solely on conductor suggesting mechanical and strain issues as an important additional contribution to stability

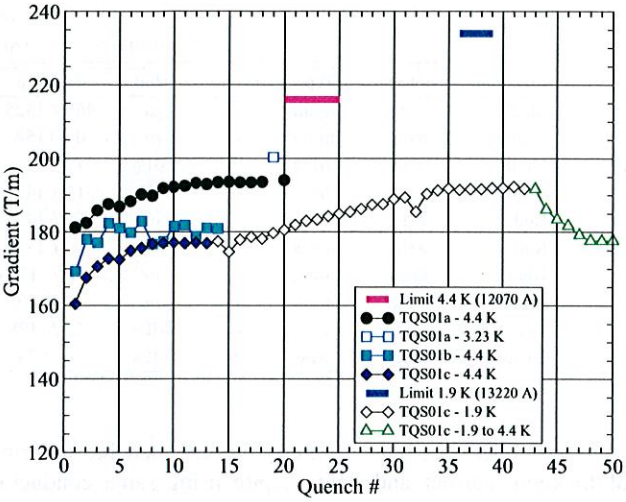

Fig. 3. Training of TQS01 magnet series.

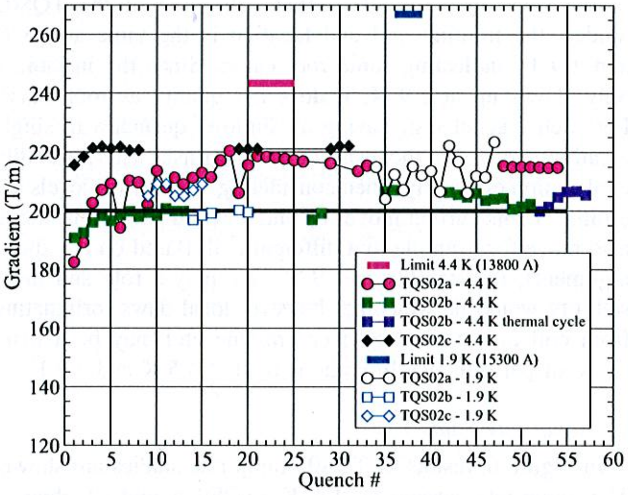

Fig. 4. Training of TQS02 magnet series.

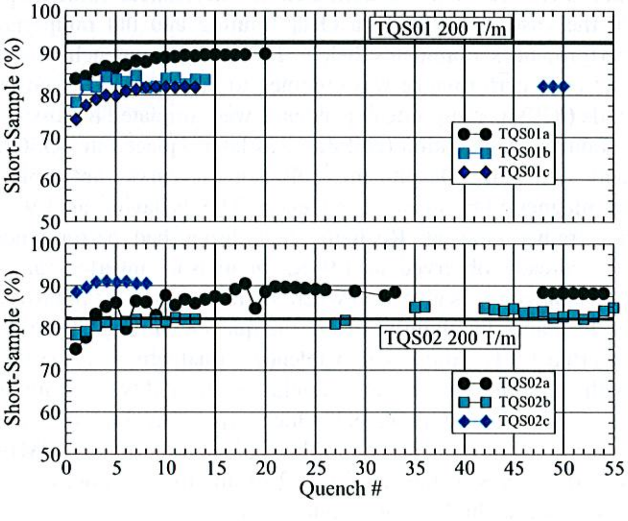

Fig. 5. 4.4K training of TQS01 & TQS02, normalized to their measured short-sample strand performances.

TABLE V

MEASURED STRAIN AND STRESS AT 300 K AND 4.4 K

Location	Direction	Type	Symbol	Unit	TQS01a	TQS01b	TQS01c	TQS02a	TQS02b	TQS02c
Shell	azim.	strain	ϵ_θ	$\mu\epsilon$	465 / 1325	620 / 1456	360 / 1275	335 / 1379	526 / 1600	600 / 1715
Shell	axial	strain	ϵ_z	$\mu\epsilon$	0 / 1154	0 / 1073	-25 / 1110	-58 / 1108	-37 / 1113	160 / 1110
Shell	azim	stress	σ_θ	MPa	42 / 153	55 / 163	31 / 148	28 / 157	40 / 176	55 / 185
Shell	axial	stress	σ_z	MPa	14 / 143	19 / 140	9 / 138	5 / 141	11 / 148	20 / 152
Rod	axial	strain	ϵ_z	$\mu\epsilon$	555 / 1435	550 / 1475	600 / 1400	150 / 1118	231 / 1255	260 / 1600
Rod	axial	stress	σ_z	MPa	44 / 113	44 / 117	47 / 110	12 / 88	16 / 99	20 / 125
Island	azim.	strain	ϵ_θ	$\mu\epsilon$	-150 / -1733	-172 / -1771	+15 / -1450	-174 / -918	Na	Na
Island	axial	strain	ϵ_z	$\mu\epsilon$	-63 / 776	-178 / 792	-150 / 730	-12 / -347	Na	Na
Island	azim	stress	σ_θ	MPa	-22 / -198	-30 / -202	-4 / -162	-25 / -146	Na	Na
Island	axial	stress	σ_z	MPa	-14 / 34	-30 / 34	-27 / 39	-9 / -89	Na	Na

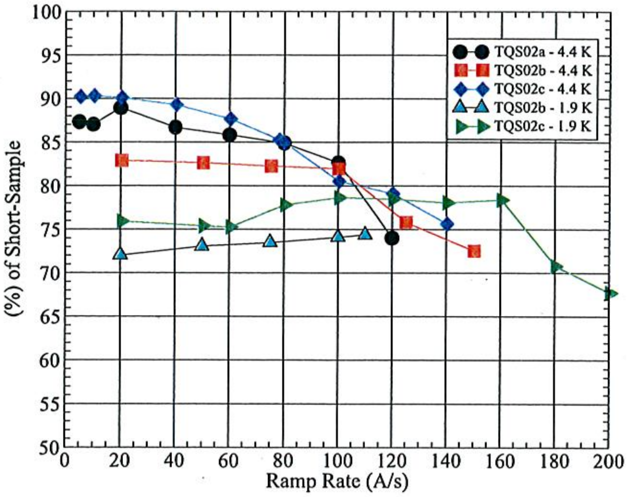

Fig. 6. TQS02's ramp-rate dependencies.

concerns. TQS02a-c have different limiting quenches in terms of location, current and field despite using same conductor and mostly identical coils. If this was an intrinsic strand problem (as measured in virgin strands) it should show up in the same way for all magnets. In some of the TQS02 models the limiting coil and location is the same at 4.5 K and 1.9 K, indicating same root cause. Since the instability only shows up at 1.9 K, it does not qualify as root cause. For each magnet test, having all limiting quenches in single location and coil is inconsistent with intrinsic wire instability explanation especially when considering that quench levels are erratic. As the current moves up and down, the location should also move for example to a different coil. Based on the above arguments, the stability at 1.9 K may play a role and more stability would be welcome however local flaws (originating from coil manufacturing, over-stressing etc) may be a main cause of performance limitations both at 4.5 K and 1.9 K.

C. Ramp-rate Study

In Figure 6, results of TQS02 ramp rate studies are shown. The ramp-rate curves at 4.4 K (TQS02a and c) show a more typical short-sample performance at low ramp-rates and therefore is more attributed to mechanical limitations. In the case of TQS02b, a clear limiting and flat ramp–rate performances dominates below 100 A/s. As quench onsets and poor performance was confined to one of TQS02b virgin coils (#29) its ramp-rate dependence was correlated to possible conductor degradation (coil #29 was later replaced in TQS02c with coil #20). Despite this behavior the curves are typical of magnet ramp-rates dependence. The behavior at 1.9 K was rather unusual. Realizing that diminished performance was already observed at 1.9 K, an unusual inverted ramp-rate behavior was also seen where higher ramp–rates improved performance by slightly raising the quench currents. TQS02's inverted 1.9 K ramp-rate dependence is qualitatively consistent with a thermal-mechanical conductor instability. We are in need of evidence to reveal which type. The fact that this behavior was not observed in the TQS01 tests (made of MJR strands) seems to link the TQS02 results to a conductor type issue such as high J_c and high strain.

IV. CONCLUSIONS

The design and test of six TQS magnets are presented. The TQS01 series reached a 4.4 K short-sample plateau of 80%–90%. The final test (TQS02c) showed that reassembled Nb_3Sn coils can start 4.4 K training at 88% and plateau within 3 quenches above 90%. The missing 10% in the short–sample performance and the 1.9 K behavior are issues that will require further investigation. The general absence quench-origins in or near the coil-ends support the design-intent for adequate coil-end support. Replacing the bronze pole-islands with titanium, eliminated pole-island gaps, significantly improved the appearance of reacted-coils , and eliminated quench-origins that correlated with pole-island gaps. Based on the knowledge gained with TQS, the LARP program built and tested a 3.6 m long sub-scale common coil magnet [22] and the assembly of a 3.6 m long extended TQS structure (called LQS) is now underway [23].

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