TEST RESULTS OF NB3SN QUADRUPOLE MAGNETS USING A SHELL-BASED SUPPORT STRUCTURE

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Abstract

In support of the development of a 90 mm aperture Nb_3Sn superconducting quadrupole for the US LHC Accelerator Research Program (LARP), test results of five quadrupole magnets are compared. All five assemblies used key and bladder technology to compress and support the coils within an iron yoke and an aluminium shell. The first three models (TQS01a, b, c) used Nb_3Sn MJR conductor and segmented bronze poles. The last two models (TQS02a, b) used Nb_3Sn RRP conductor, and segmented titanium alloy (TiAl6V4) poles, with no axial gaps during reaction. This presentation summarizes the magnets performance during assembly, cool-down and excitation and compares measurements with design expectations.

MAGNET DESIGN

Conceptual design and parameters

The magnet technology development effort of the U.S.-LHC Accelerator Research Program (LARP) is a partnership between magnet physicists and engineers from BNL, FNAL and LBNL [1]. The program's long term goal is to demonstrate that Nb_3Sn magnets are a viable choice for an LHC IR upgrade [2], by the year 2009. A successful test requires a gradient above 200 T/m, in a 3.6 m long magnet, having a 90 mm bore. Within the past three years a Technology Quadrupole (TQ, see Fig. 1) program investigated 1 m long cos-theta coils in two different structures: 1) TQC - a collar based structure and 2) TQS a shell based structure that utilizes bladder & key technology [5] to pre-stress the coils inside an iron yoke and tensioned aluminium shell (see Fig. 2). Test results of the TQS tests are presented here.

Fig. 1: A ready-for-testing TQS magnet shows the outer aluminum shell, its strain diagnostics, and the yoke. The four large axial rods axially compress the coil-ends, via a thick stainless-steel end-plate.

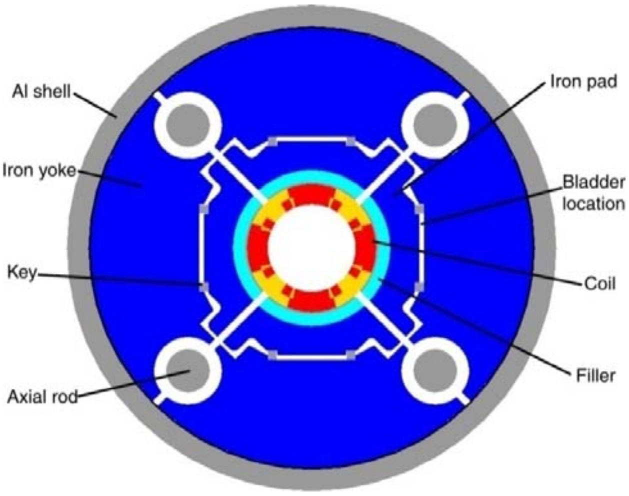

Fig. 2: TQS magnet cross-section showing coils, fillers, pads, keys, yokes, shell and axial supporting rods.

The shell-based structure uses bladders and keys for precise magnet assembly pre-stress control, with negligible stress "overshoot". Interference keys are inserted to retain the 300 K 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, during which the final coil pre-stress is monotonically approached from below, without overstressing the fragile conductor [2-6]. Plotted in Figure 3 is some of the reasoning why high field magnets need to move from collared structures to shell based structures.

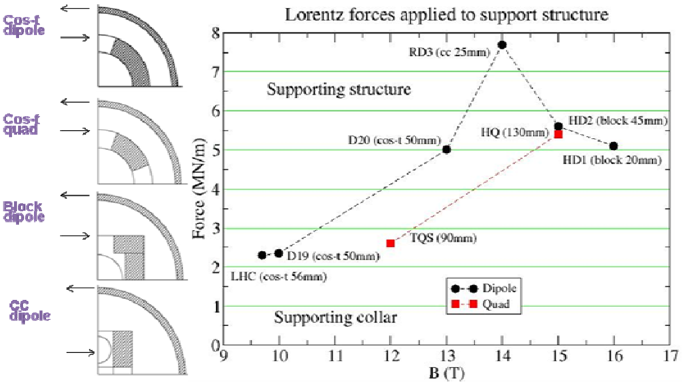

Fig. 3: Lorentz forces as applied to different structure.

TQS01 and TQS02 test results

The three TQS01 tests (a, b, c) used coils with segmented bronze islands and MJR conductor. Except TQS01a, which used virgin coils, tests b and c combined virgin and previously tested coils, see Table I. Small adjustments to pre-stress and friction coefficients were made with minimal impact on the magnet performance. During all three tests quench-origins clustered around the first pole-turn near the gaps in the segmented pole-islands. These gaps (combined thickness of ~2 mm) were introduced to prevent excessive strain on the conductor during reaction, and maintained during impregnation. Based on TQS01 quench-origins and additional ANSYS analysis, the bronze islands were replaced with titanium alloy (Ti6Al4V) islands for TQS02. This eliminated the need for any gaps during reaction and axially compressed the pole-island while cold (the conductor is therefore under axial tension).

TQS02 coils showed no pole-segment gaps after the reaction, and the coil ends remained attached to the end spacers and shoes. This resulted in the “best looking” coils yet produced in the TQ-program. The coil conductor was RRP with an SC current density of 2740 A/mm^2 at 12 T, 4.2 K (extracted strand, with no self field correction), a measured RRR of ~200, and a Cu to non-Cu ratio of 0.87.

Table I. TQS magnet tests

Magnet	Cond.	Coils	Island	T (K)	Test date
TQS01a	MJR	**5,6,7,8**	Bronze	4.4	Apr. 2006 LBNL
TQS01b	MJR	**14**,**15**,7,8	Bronze	4.4	Nov. 2006 LBNL
TQS01c	MJR	5,15,7,8	Bronze	4.4, 1.9	Mar. 2007 FNAL
TQS02a	RRP	**20,21,22,23**	Ti	4.4, 1.9	Jun. 2007 FNAL
TQS02b	RRP	22,23,**28,29**	Ti	4.4, 1.9	Mar. 2008 CERN
TQS02c	RRP	22,23,28,20	Ti	4.4, 1.9	Jun. 2008 CERN

TEST RESULTS

Training

The training curves of 5 tests are shown in Fig. 4 and 5. At 4.4 K the TQS01a reached its plateau value in less than a dozen quenches with a plateau current of 10625 A or 193 T/m and a maximum gradient of 199 T/m at 3.23 K. TQS02a trained slower, but achieved a plateau of 12000A or 215 T/m at 4.4 K, a onetime maximum of 12270 A or 219 T/m at 4.4 K, (90% short sample limit without self field correction). At 1.9 K, TQS01c gained ~1000 A (as expected), but after many quenches. However, TQS02a was erratic, with no net increase after 14 attempts. Its onetime maximum current and gradient were 12460 A and 222 T/m at 2.17 K. This anomalous 1.9 K training remains unexplained. Conductor limits are given in Table II. Plots with the measured stresses in the coil and in the structure are given in Fig. 6-8.

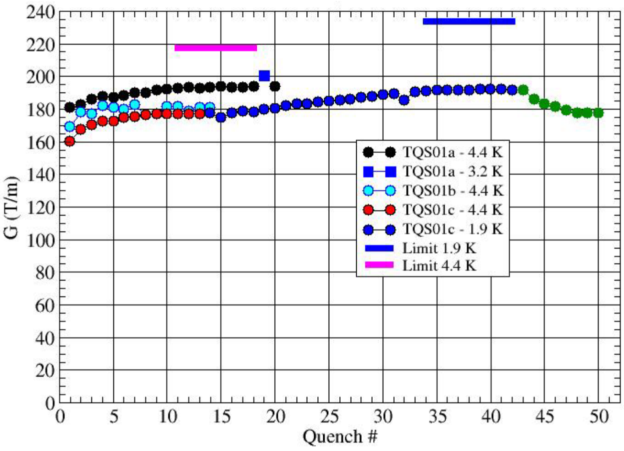

Fig. 4: Training curves of three TQS01 tests.

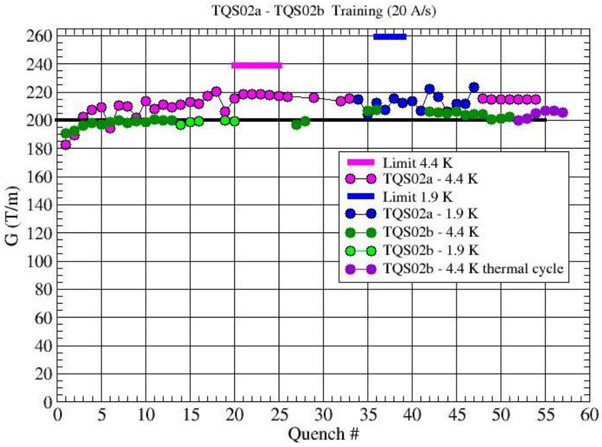

Fig. 5: Training curves of two TQS02 tests.

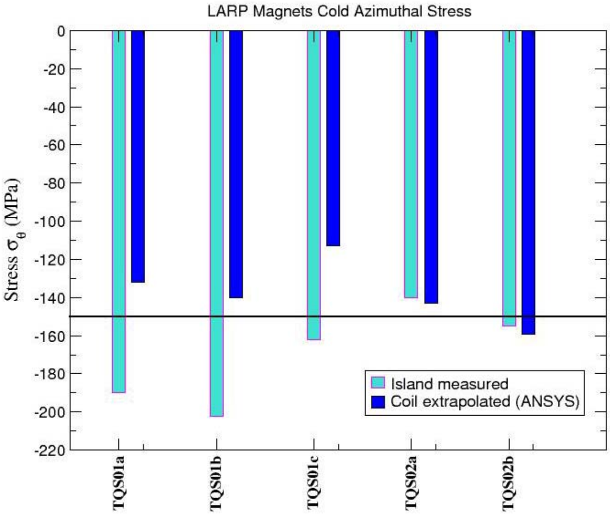

Fig. 6: Measured azimuthal stress in the island and in the corresponding coil next to it.

Table II. TQS conductor limits.

Magnet	**TQS01**	**TQS02**
Conductor	MJR	RRP
Iss 4.4 K	12100	13600
Gss 4.4 K	216	239
Iss 1.9 K	13200	14800
Gss 1.9 K	234	259

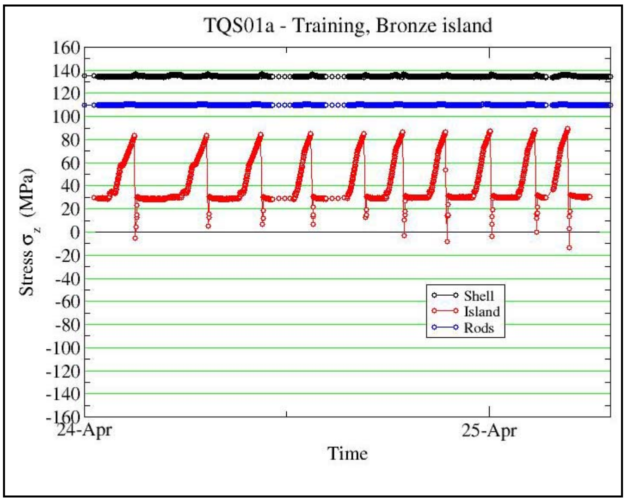

Fig. 7 Measured stress in TQS01a islands shell and rods (bronze islands).

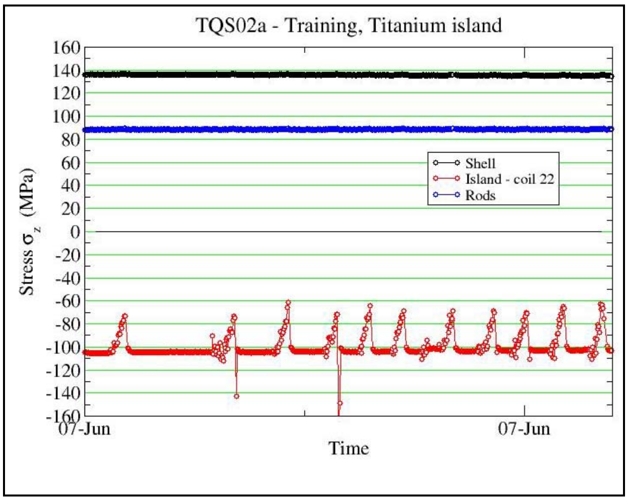

Fig. 8 Measured stress in TQS02a islands shell and rods (titanium islands).

CONCLUSIONS

The shell based magnets were tested using keys and bladder assembly. Measurements of strain in coils and structure followed expectations analyzed with the program ANSYS. So far we had 6 assemblies and 5 tests. The TQS magnets met the 200 T/m goal:

- Maximum gradients at 4.4 K: 180-222 T/m; plateau reached after 4-20 quenches with 80-90% of short-sample.
- Maximum gradients at 1.9-3.2 K: 192-225 T/m; plateau reached after 20 quenches with 77-84% of short-sample.
- In TQS02, bronze islands were replaced by titanium islands
- Quench location: TQS01 quenches were in the inner layer straight section (near island gaps), whereas TQS02a was dominated by outer layer quenches.
- A technology transfer of the bladder and key assembly structure to CERN has been successfully carried out for TQS02b,c.

Issues regarding the slow or no training at 1.9 K as well as the cause for outer layer quenches will require further studies.

ACKNOWEDGEMENT

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