U.S. LARP MAGNET PROGRAM*

Peter Wanderer[#], Brookhaven National Laboratory, Upton, NY, U.S.A.

Abstract

Progress and plans for the U.S. LARP R&D work are summarized. Results to date for work on materials and model magnets are presented in more detail.

INTRODUCTION

The primary goal of the LARP R&D effort is to demonstrate a “long, strong” superconducting quadrupole made with Nb3Sn by the end of 2009. Up to the present time, the focus has been on the development of the essential “building blocks” for Nb_3Sn magnets: materials, model magnets, supporting R&D, and IR design studies. The goal of the work on materials has been to establish a production method for Nb_3Sn that yields a superconductor that has high current density and stability against flux jumps. The goal of the work on model magnets has been to test 1 m versions of quadrupoles that reach 200 T/m using two different support structures. The supporting R&D has led to the early test of long (3.6 m) racetrack coils in one of the support structures, as a test for possible effects of magnet length on performance. It has also covered insulation and quench protection. The IR design studies have covered radiation studies, cryogenics, heat transfer issues, and magnet designs for several possible versions of IR optics (e.g., dipole first), as well as quadrupole designs for larger aperture and higher gradient.

Plans for R&D to reach the 2009 goal include the following: Construction and test of one to three 3.6 m, 90 mm quadrupoles, called LQ, with at least one test of both support structures. The plans for LQ R&D in general, and the support structures in particular, were reviewed by an external committee at the end of November. The LQ work has the highest priority in the LARP magnet R&D. The materials work is now directed toward increasing the diameter of the strand, additional studies of instability, and measurements of the strain sensitivity of the strand and the cable. Work toward a design which could test both high gradient and large aperture magnets is now concentrated on the large aperture (130 mm) version, with the possibility that the design might be close to the design needed for magnets that would be installed during the Phase I upgrade. A new task force, called JIRS (Joint IR Studies), has been established to pull together both magnet and accelerator physics work toward a Phase I upgrade.

This talk presents details of the LARP work on materials and model magnets. Other aspects of current LARP magnet work are presented in [1,2,3].

MATERIALS

Starting several years ago, R&D has led to the development of Nb_3Sn strand that has been used in recent LARP model 90 mm quadrupoles that reached 200 T/m. This material, manufactured by Oxford Superconducting Technology, is designated RRP (rod restack process) [4]. Development has been supported by the U.S. DOE Conductor Development Program and by purchases by the “base” programs of the DOE labs. Design studies for larger aperture quadrupoles indicate that a larger diameter strand is desirable. Allowing the filament diameter to increase with the strand diameter is undesirable for stability, so studies of strand with an increased number of filaments are underway. The present strand, designated 54/61, has 54 filaments, with a copper core having the area of seven filaments. The strand has been drawn to a diameter of 0.7 mm for use in the LARP magnets made thus far. The 108/127 configuration has been selected for use in larger-diameter (0.8 mm – 1.0 mm) strand.

The work of the materials group has also included considerable effort on standardizing strand testing at the three labs. Consistency has been achieved at the level of ±5%. The materials group works with a month-by-month plan showing materials purchase and use. So far it has achieved its goal that cable be available when needed for use in magnets.

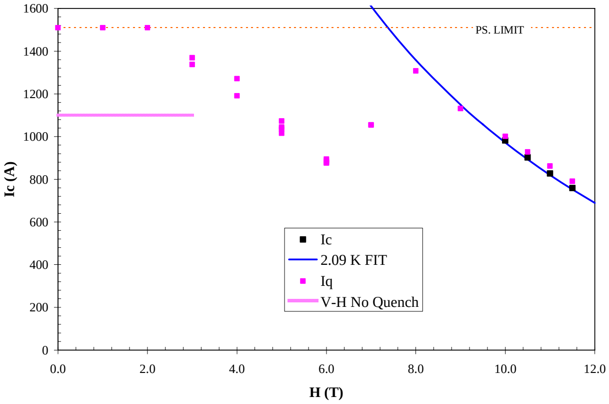

Fig. 1. Short-sample tests of 0.7-mm diameter RRP Nb_3Sn strand at 2.09 K.

The strand I_c measurements shown in Fig. 1 indicate the focus of stability studies now underway. At high field ($H_0 > 9$T), the strand I_c falls with increasing H_0 in the expected manner. At low field ($H_0 < 3$ T), the strand I_c is more than a factor of two greater than the current in individual strands in the magnets, indicating that the conductor will be stable in the low-field regions of the coils. However, at medium field, I_c drops to a value much less that its value at low field. This behavior is now under study. It may be the cause of quenching in the model

---

*Work supported by the U.S. Department of Energy
[#] wanderer@bnl.gov

magnets (see below). However, even the minimum I_c, at 6 T, is still a factor of two greater than the strand current in these magnets.

MODEL QUADRUPOLE PROGRAM

Several model quadrupoles, called Technology Quadrupoles (TQ), have been made and tested. These models are approximately 1 m long and have a coil aperture of 90 mm. The coils have been made jointly at Fermilab and LBNL. The coils have been assembled using one of two support structures, denoted collar (TQC) and shell (TQS). A cross section of a collared magnet is shown in Fig. 2 [5]. The azimuthal preload is applied primarily during the assembly process via the collars and (through the yoke) the stainless steel shell. The end preload is modest – sufficient to keep the coil in contact with the end support. A cross section of a magnet assembled with the shell support structure is shown in Fig. 3 [6]. In this case, some of the azimuthal preload is applied via bladders (made of thin stainless steel) which are inflated during assembly. When the desired room temperature preload has been achieved, keys are inserted between the yoke and the iron pads and the bladders removed. An aluminum shell surrounds the yoke and provides the remainder of the preload during cooldown. High axial preload is achieved via rods which run the length of the magnet (Fig. 4).

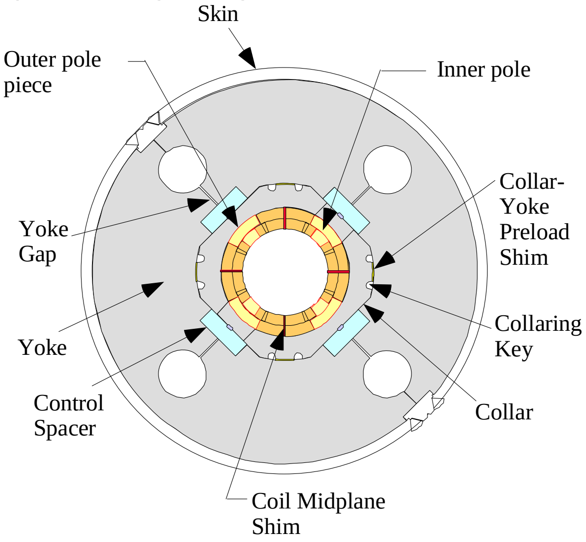

Fig. 2. Cross section of a TQC quadrupole cold mass

The most direct comparison of the collar and shell support structures was made by testing the same set of coils in both structures. The coils were made using 54/61 RRP strand. The coils were initially tested in a shell support structure (TQS02a). Starting from an initial quench gradient of 180 T/m, the magnet trained to ~90% of the expected conductor limit (220 T/m) at 4.4 K (Fig. 5). The magnet did not train to a higher gradient when further tested at 1.9 K. This behavior is not yet understood.

The coils were then reassembled in a collar support structure (TQC02E, where E stands for "exchange"). TQC02E also trained to ~90% of the expected conductor limit (200 T/m), from an initial quench gradient of ~ 165 T/m at 4.5 K (Fig. 6). Its quench performance at 1.9 K was slightly below that at 4.4 K, similar to the 1.9 K performance of TQS02a. (At the same fraction of the short-sample limit the two magnets have different gradients because of different yoke dimensions.)

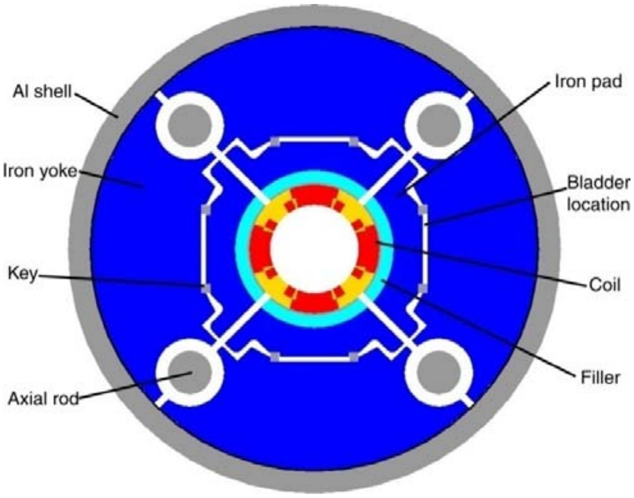

Fig. 3. Cross section of TQS quadrupole cold mass

Fig. 4. Photograph of a TQS quadrupole cold mass

Quench test data are also available from one additional magnet made with each of the support structures. In this case, the coils were made with MJR (modified jelly roll) Nb_3Sn, the predecessor of the RRP. Quadrupole TQS01 was tested in three versions (Fig. 7): TQS01a (standard assembly), TQS01b (reassembly with the limiting coil in version a replaced); and TQS01c (with reduced end preload). TQS01a quenched initially at ~ 180 T/m and advanced to ~ 195 T/m (~90% of the expected conductor limit) at 4.4 K. Its one quench at 3.2 K was higher than the quenches at 4.4 K. The 4.4 K training data of TQS01b lie below the training data of TQS01a, but the magnet did train to a higher gradient at 1.9 K.

TQC01 was tested in two versions. TQC01a, with a preload that was much lower than planned, and TQC01b, with satisfactory preload and two coils from TQS01. Given the low preload, it is not surprising that the initial quench was at a low gradient, 130 T/m, and that it trained only to 150 T/m at 4.5 K (Fig. 8). What is interesting is that, at 1.9 K, it trained to 200 T/m (~ 86% of the expected conductor limit). The performance of TQC01b at 4.5 K was better than that of TQC01a. At 1.9 K, it reached 200 T/m (~90% of the expected conductor limit).

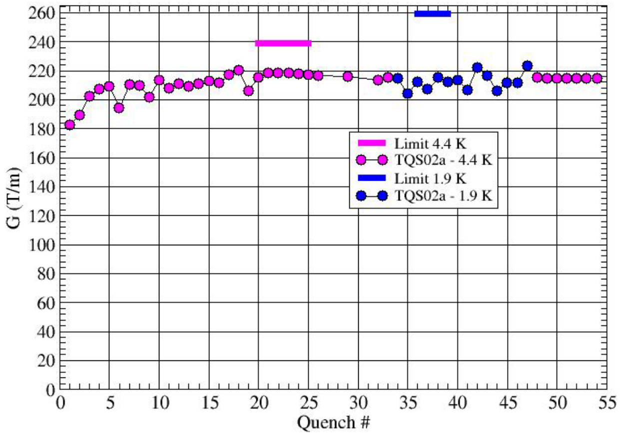

Fig. 5. Quench test data for TQS02a.

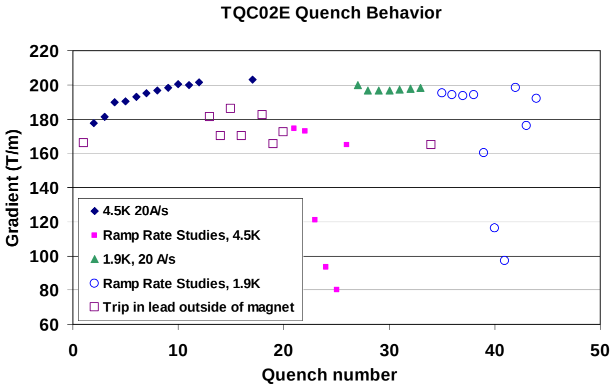

Fig. 6. Quench test data for TQC02E. (E denotes “exchange” – the coils were initially tested in the TQS support structure.)

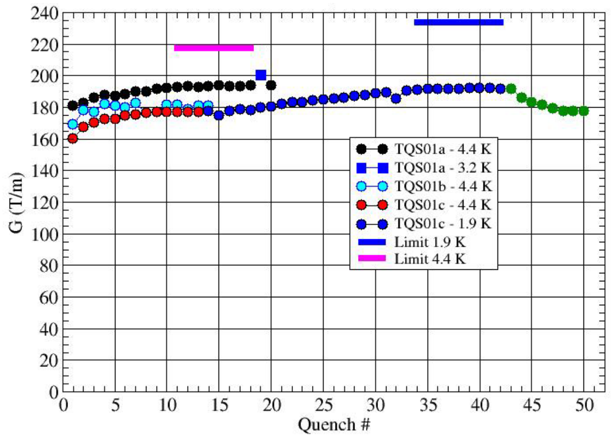

Fig. 7. Quench test data for the three versions of TQS01.

Overall, the 90 mm model quadrupoles reliably reach 200 T/m (~ 90% of the expected conductor limit) at 4.5 K. However, the factors affecting quench performance at 1.9 K are not yet fully understood.

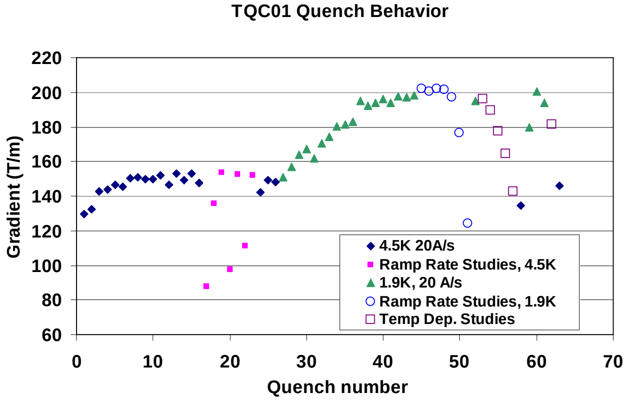

Fig. 8. Quench test data for TQC01.

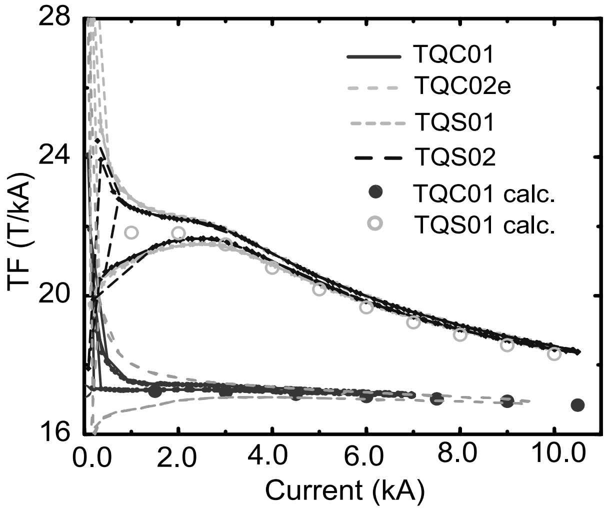

Fig. 9. Transfer function G/I calculations and measurements for the four TQs made thus far.

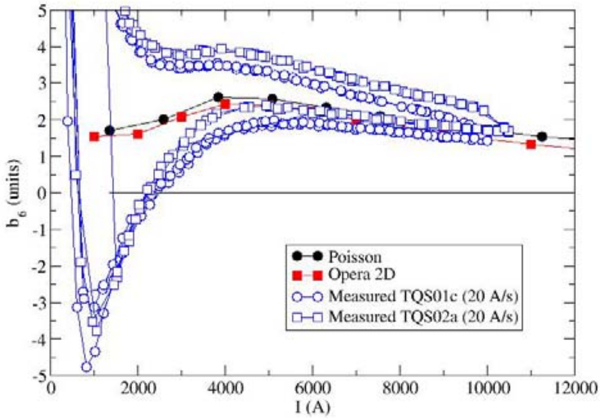

Fig. 10. Measurements and calculation of the first allowed harmonic for TQS01. The calculations do not include magnetization effects.

Field quality measurements of the TQs have been made [7]. Measurements of the transfer function (Fig. 9) are in agreement with the calculation for both the collar and shell structures (except for hysteresis at low current, which was not included in the calculation). The same is true of the measurements of the first allowed harmonic, b_6 (Fig. 10). Interestingly and surprisingly, measurements of this harmonic during a cycle which roughly simulates that of the LHC show no change with time during the ~ 1000 seconds when the current is held constant at the nominal value for injection (Fig. 11).

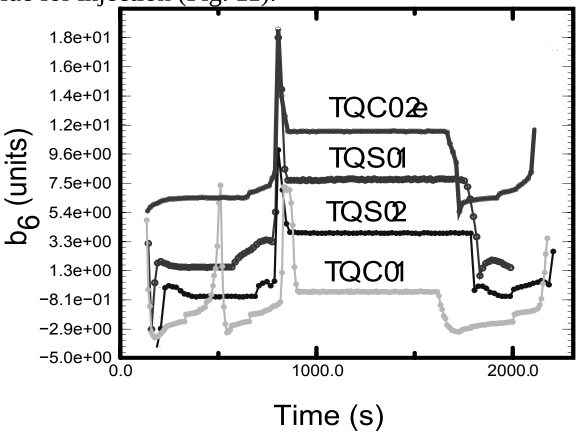

Fig. 11. Time dependence of the first allowed harmonic in the four TQs made thus far.

TECHNOLOGY SCALE UP

Another part of the LARP program focused on a test for length effects using a simple coil structure with a shell support structure, LRS01 (long racetrack shell). The goal was to make a (relatively) quick check for length effects. The 3.6 m coils, made from RRP conductor, were wired in the “common coil” mode (Fig. 12) [8]. The coils were preloaded using bladders and keys in the one direction with significant Lorentz force (Fig. 13). To maximize the Lorentz force, the coils were assembled with no gap between them. For this magnet, the coils were made at BNL, the support structure made at LBNL, and other components at Fermilab.

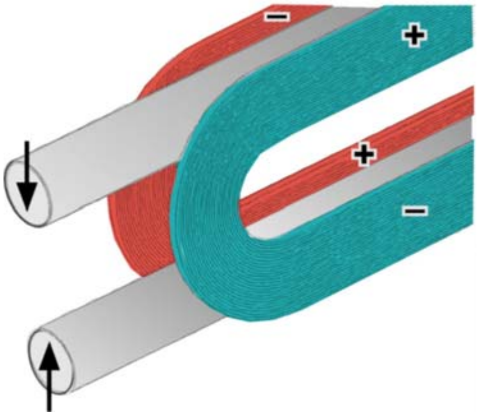

Fig. 12. Racetrack coils powered in the “common coil” mode for LRS01.

The magnet quenched initially at ~ 10 T and trained to 11 T at 4.5 K (~ 91% of the expected conductor limit, Fig. 14) [9]. The training performance was quite similar to that of a 0.3 m version of this magnet [10], although the short version, made with RRP, reached a slightly higher fraction of the conductor limit.

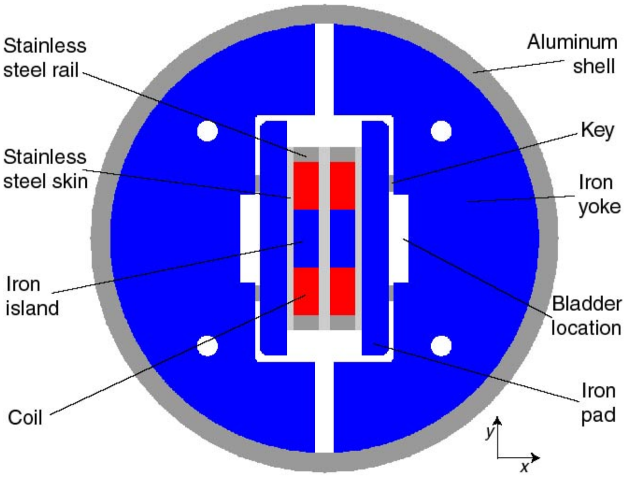

Fig. 13. Cross section of LRS01 coils and support structure.

To monitor the performance of shell support structure, strain gauges were mounted along the length of the shell. The gauges indicated that the assembly was as expected, as was the effect of cooling the support structure loaded with dummy coils (aluminum bars) to 77 K (Fig. 15) [11]. However, the gauges showed that the axial tension in the aluminum shell that arises during cooldown (because of the different thermal contraction coefficients of aluminum and iron) significantly relaxed when the coil was powered to 6 kA. After a thermal cycle, a similar slippage was observed during excitation to 3 kA. Given the good performance of the 1 m TQS quadrupoles, it was decided to segment the shell into 1 m sections. The reconfigured shell support will be tested with the same coils.

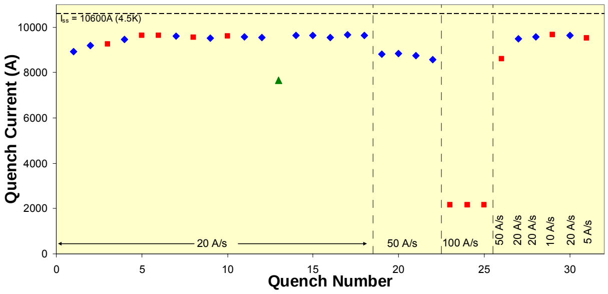

Fig. 14. Quench test data for the 3.6m common coil magnet LRS01.

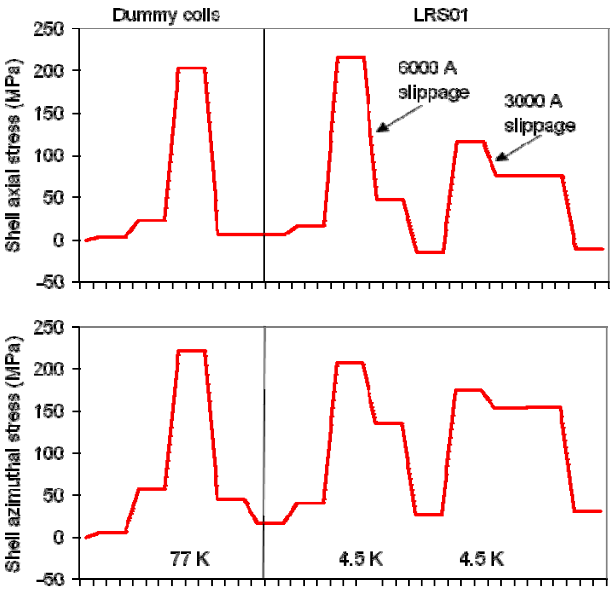

Fig. 15. Axial and azimuthal stress measurements made on the shell of LRS01 during cooldown and excitation.

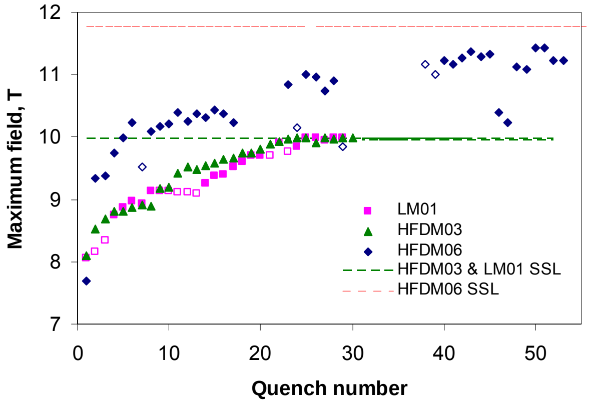

Fig. 16. Quench test data for 1m and 1m mirror dipoles.

Nb$_3$Sn mirror dipoles made under the Fermilab base program are also part of the data now available [12]. Models with length 1 m and 2 m (HFDM03 and LM01) made with PIT (power in tube) conductor had nearly identical quench performance, reaching the expected conductor limit at ~ 10 T (Fig. 16). A 1 m mirror dipole made with 108/127 RRP conductor reached 97% of its expected limit at 11 T. A 4 m long mirror model LM02 with 108/127 RRP strand has been fabricated and was tested in December reaching 10 T or ~90% of its expected conductor limit [13].

CONCLUSIONS

The “building blocks” – materials, model quadrupoles, 3.6 m racetrack coils and support structure – are in place. The LARP R&D program is ready to move to quadrupoles with longer length and greater aperture.

AKNOWLEDGEMENTS

I am grateful to my LARP colleagues for assistance in gathering the data presented in this paper.

REFERENCES

[1] G. Sabbi, “High Field Nb$_3$Sn Magnets,” presented at this workshop (IR07, Frascati, November, 2007).
[2] G. Ambrosio, “Long Nb$_3$Sn Magnets,” presented at this workshop (IR07, Frascati, November, 2007.
[3] A. Zlobin, “LARP Joint IR Studies,” presented at this workshop (IR07, Frascati, November, 2007).
[4] Oxford Superconducting Technology Inc., Carteret New Jersey USA.
[5] R. C. Bossert et al., “Test of TQC02, LARP technological quadrupole magnet, “ accepted for publication in IEEE Trans. Applied Superconductivity.
[6] S. Caspi et al., “Test results of TQS02, a second Nb$_3$Sn quadrupole magnet model for LARP,” accepted for publication in IEEE Trans. Applied Superconductivity.
[7] G. V. Velev et al., “Field quality measurements and analysis of the LARP technological quadrupole models,” accepted for publication in IEEE Trans. Applied Superconductivity.
[8] R.C. Gupta, “A common coil design for high field 2-in-1 accelerator magnets,” Proc. 1997 Particle Accelerator Conference, Vancouver, Canada.
[9] P. J. Wanderer et al., “Construction and test of 3.6 m Nb$_3$Sn racetrack coils for LARP,” accepted for publication in IEEE Trans. Applied Superconductivity.
[10] P. Wanderer et al., “LARP long Nb$_3$Sn racetrack coil program,” IEEE Trans. Applied Superconductivity, Vol. 17, No. 2, pp. 1140-1143 (June 2007).
[11] P. Ferracin et al., “Assembly and test of a support structure for 3.6 m long Nb$_3$Sn racetrack coils,” accepted for publication in IEEE Trans. Applied Superconductivity.
[12] F. Nobrega et al., “Nb$_3$Sn magnet technology scale-up using cos-thera dipole coils,” accepted for publication in IEEE Trans. Applied Superconductivity.
[13] A. V. Zlobin, private communication.