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Nb_3Sn Magnet Development for LHC Luminosity Upgrade

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Nb_3Sn MAGNET DEVELOPMENT FOR LHC LUMINOSITY UPGRADE*

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Abstract

This paper presents the main points of magnet R&D for a LHC Luminosity Upgrade carried on through the LHC Accelerator Research Program (LARP) work on magnets at Berkeley, Fermilab, and BNL. Work on materials and on racetrack magnets is described in some detail. The others areas of LARP work are only outlined here and discussed in detail in other talks at this meeting

INTRODUCTION

The main goals of LARP are to reach 200 T/m in a 90 mm, 3.6 m Nb_3Sn quadrupole by the end of 2009, to fully qualify Nb_3Sn magnets for use in the LHC, and to supply Nb_3Sn magnets for the LHC Phase 2 Luminosity Upgrade.

MATERIALS

The Nb_3Sn strand now in use for LARP magnets is the 54/61 RRP® internal tin strand made by Oxford Superconducting Technologies. The designation 54/61 refers to the number of subelements in use (54), compared to the number possible (61), as indicated in Fig. 1. The strand has a diameter of 0.7 mm, a Jc of at least 2400 A/mm^2 (12T, 4.2K), and a RRR greater than 100. The heat treatment of the strand was optimized to achieve a J_c consistent with 220 T/m and suppression of low-field instabilities.

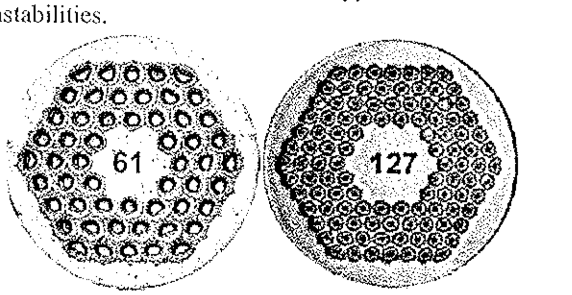

Fig. 1. Photographs of the cross sections of 0.7 mm diameter Nb_3Sn strand, 54/61 (left) and 108/127 (right).

Magnets with larger aperture, likely needed for LHC, will require a larger-diameter strand. The materials group is now studying recently produced RRP 108/127 as a strand that can be used in the range 0.8 – 1.0 mm with acceptable instability (Fig. 1).

Thus far, LARP has received from OST 688 kg of 54/61 at 0.7 mm. Recently, 180 kg of 108/127 with a larger spacing between the subelements was delivered with most of the strand at a diameter of 0.8 -1.0 mm. An order for 85 kg of 54/61 with increased copper spacing between the subelements has been placed. The increased spacing mitigates the deformation of the subelements during cabling. The 54/61 standard material is of high quality, as indicated by the good piece lengths achieved (92% greater than 1 km).

The strand R&D presently underway includes measurements of the effect of tensile strain on the critical current of the 54/61 strand, being carried out by NIST in Boulder, Colorado. Results are expected this coming summer. Studies of the 108/127 strand are focused on mapping the effect of different heat treatments on Jc and stability.

During the development of the heat treatment for the 54/61, tests were conducted only at 4.2 K. The heat treatment chosen, 72 h/200 °C + 48 h/400 °C + 48 h/640 °C, yielded strand that was stable at low fields (~ 3 T) up to currents at least twice the current in the magnet. Recent magnets at 1.9 K have not reached quench currents higher than those reached at 4.2 K, and with greater quench-to-quench variation in current (e.g., Fig. 2). This has been observed in several magnets. It appears highly likely that the magnets are limited by conductor instability, rather than construction. It is thought that the magnet performance is related to results of strand tests at 1.9 K and 4.2 K (Fig. 3). In this test, the strand stability is greater than 1000 A at low field at both temperatures, but has a lower stability threshold at medium fields (~ 6 T) at the lower temperature. This issue is under study at the strand level.

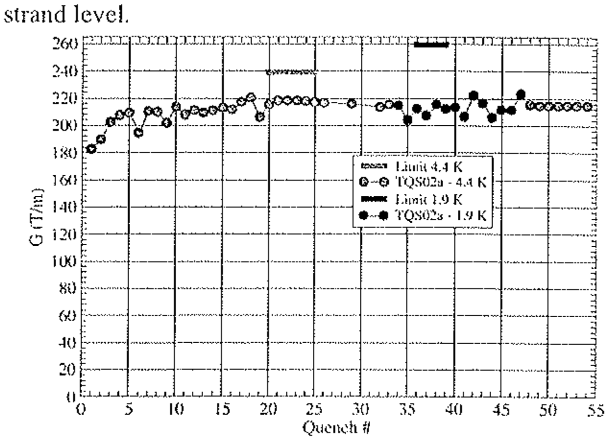

Fig. 2. Quench test results for the 1m-long, 90 m-aperture quadrupole TQS02.

In order to better understand this issue, LARP will test 1 m sections of cable during the coming months in the FRESCA facility at CERN, where tests can be carried out at both 4.2 K and 1.9 K. (Cable testing was not undertaken earlier due to budget limitations.) Cable tests are also planned for the National High Magnetic Field lab in Florida. At this facility, testing is at 4.2 K and the load on the cables can be varied at cryogenic temperatures.

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This allows for efficient measurements of cable critical current versus transverse compressive stress.

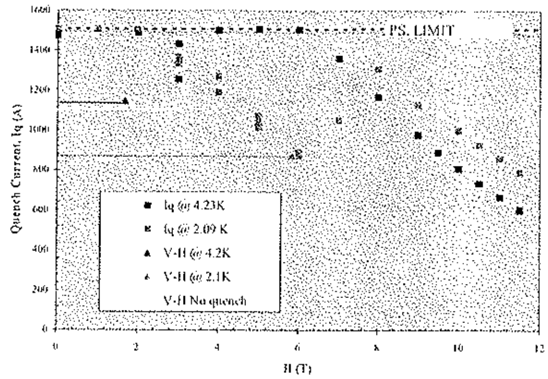

Fig. 3. Quench test results for 0.7 mm Nb_3Sn strand at 4.2 K and 2.09 K. The V-H data were taken with a constant magnet current and a ramped field.

DC magnetic field measurements of the quadrupoles have shown behavior of the transfer function G/I (Fig. 4) and the duodecapole (Fig. 5), the first allowed harmonic in agreement with calculation. Interestingly, the duodecapole during the "front porch" (the period of time when the current is held constant while the LHC is filled with protons) is constant (Fig. 6). This is qualitatively different than the behavior of this harmonic in NbTi magnets. The reason is not yet understood.

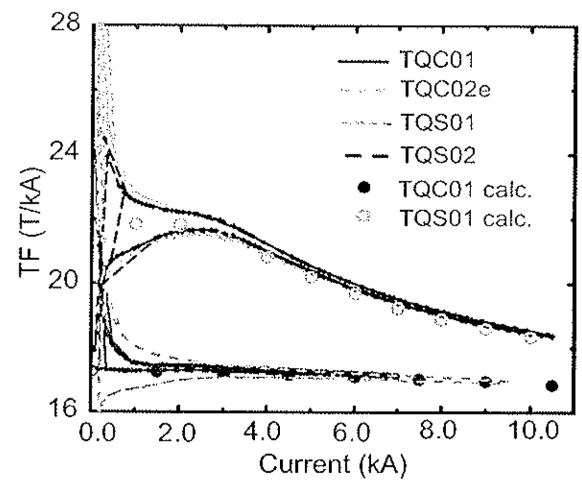

Fig. 4. Measured and calculated values of the transfer function of two quadrupoles. Differences in the saturation are due to differences between the collar (TQC) and shell (TQS) support structures.

The dynamic effects are quite significant (Fig. 7). At a ramp rate which roughly corresponds to the LHC ramp rate, 10 A/s, change in the transfer function due to ramping varies 1% between magnets. This effect is likely due to eddy currents which flow between the strands in the cable. The strands are sintered together during reaction which effectively makes the cross-over resistance very low. The eddy currents can be greatly reduced by making cable made with a 25 μm stainless steel strip ("core") between the top and bottom layers. NbTi cables have been made in this fashion. Time and budget permitting, this method of reducing eddy currents will be introduced to LARP magnets also.

RACETRACK MAGNETS

To provide an early test for possible length effects in coils, a pair of 3.6 m long racetrack coils was assembled using a "shell" support structure (LRS01). The support structure is relatively simple to build because the only significant Lorentz forces are perpendicular to the plane of the coils (Fig. 8). The forces are transmitted via keys (which control the preload) through the iron yoke to the aluminum shell. The initial quench test of the magnet (LRS01) yielded good results (Fig. 9).

During one of the ramps to quench, there was a sudden loss of axial strain in the shell (Fig. 10). The axial strain in the shell was built up during cooldown and was due to the difference between the thermal contraction of the shell (integral $\delta l/l \sim 4 \times 10^{-3}$ from room temperature to 4.5 K) and that of the yoke (integral $\delta l/l \sim 2 \times 10^{-3}$).

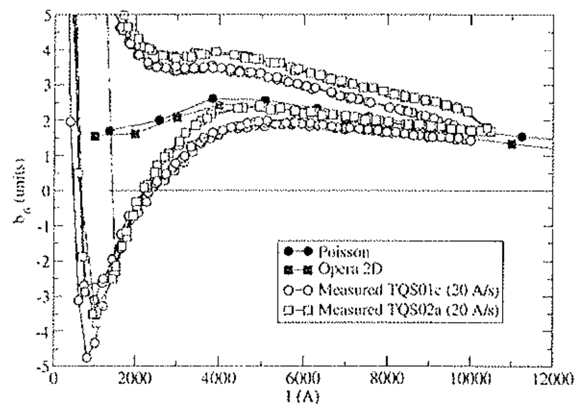

Fig. 5. Measured and calculated values of the first allowed harmonic for collared and shell quadrupoles. The calculation does not include the effects of the magnetization currents.

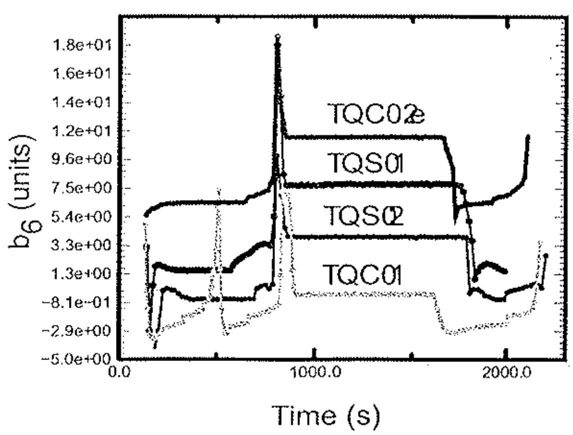

Fig. 6. Measured values of the first allowed harmonic for two collar and two shell quadrupoles, versus time, for a simulated LHC injection cycle.

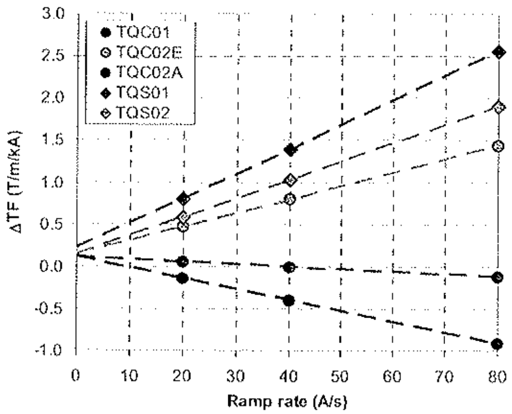

Fig. 7. Measurement of the eddy current effect on the transfer function at a gradient of 45 T/m.

This loss of axial strain in the shell did not affect the quench performance of the magnet. However, it was decided to reduce this stick-slip effect by segmenting the shell into four lengths of ~1 m [1]. The coils were reassembled into the segmented shell support structure and tested (LRS02). The change of axial strain was reduced by a factor of ~ 4, as expected (Fig. 11). The quench performance of the magnet improved, to ~ 96% of the estimated limit of the conductor (Fig. 9). The peak field on the conductor at the maximum quench current was ~ 11.5 T [2].

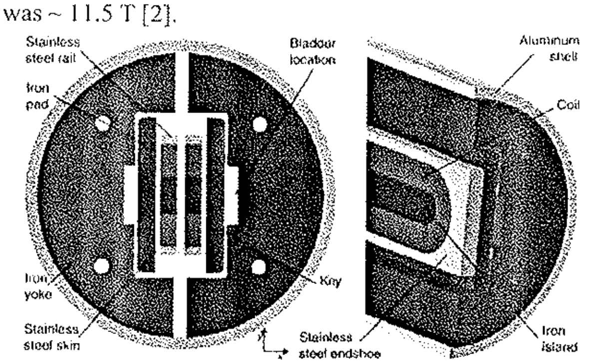

Fig. 8. Cross section and angle views of the 3.6 m long racetrack magnet, LRS.

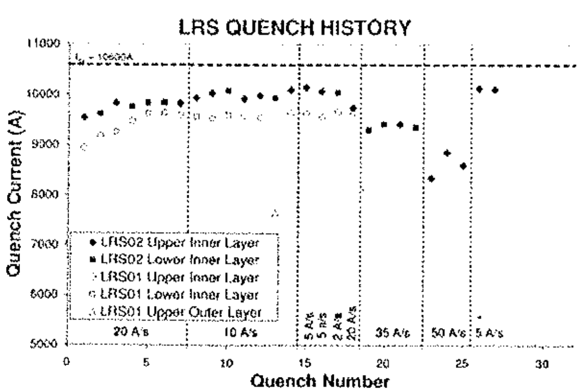

Fig. 9. Quench history of LRS01 (open symbols) and LRS02 (solid symbols).

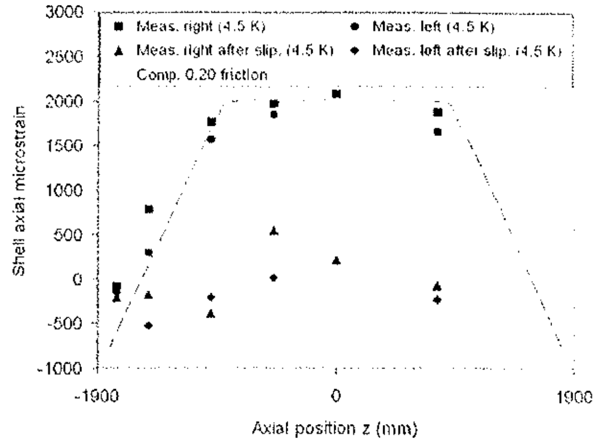

Fig. 10. Shell axial strain versus length for LRS01 at 4.5 K, before and after the loss of strain.

The good performance of LRS02 allowed the quench current to be measured as a function of ramp rate between 5 A/s and 35 A/s (Fig. 12). Although there is no well-established calculation for extrapolating to a ramp rate of zero, a linear or near-linear extrapolation yields a conductor quench limit that is consistent with the extracted strand data for the magnet. This suggested that the thermal margin expected for this conductor is available in the magnet.

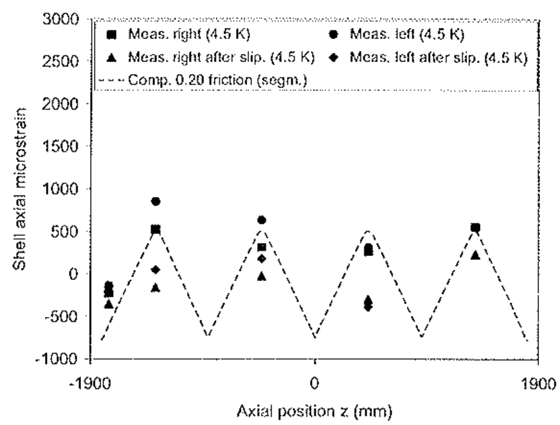

Fig. 11. Shell axial strain versus length for LRS02 at 4.5 K, before and after the loss of strain.

TECHNOLOGY QUADRUPOLES

The Technology Quadrupole (TQ) program for 1 m-long, 90 mm-aperture magnets is developing coil manufacturing methods and two different coil support structures, collar (TQC) and shell (TQS). The discussion in this note is limited to a brief comparison of the two support structures. Detailed presentations of the TQ program were made in other contributions to this workshop [3, 4].

Collar support structures (Fig. 13) are well known through their use in NbTi accelerator magnets. The coils are supported azimuthally by stainless steel collars and, for these magnets, also by the welding of the stainless steel skin around the iron yoke. Preload is controlled via shims at the midplanes of the coils and by shims between the collars and yoke. A significant portion of the azimuthal preload is created during assembly. The axial preload is modest – sufficient to keep the coil in contact with the end shoe under all conditions [4].

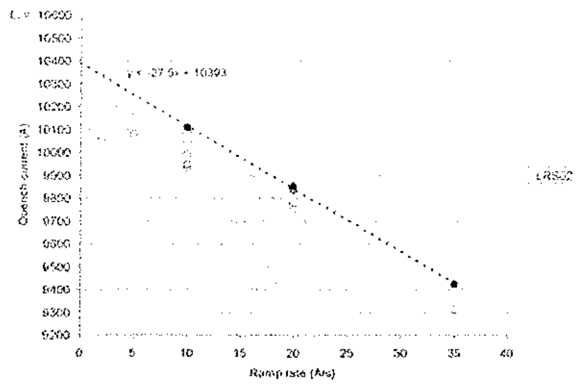

Fig. 12. Quench currents in LRS02. The fit is to the highest currents at each ramp rate (solid symbols).

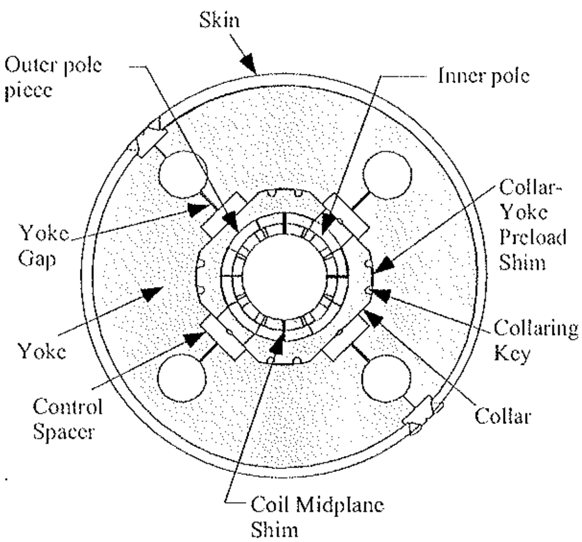

Fig. 13. Cross section of collar support structure (TQC).

Shell support structures (Fig. 14) make use of "bladder and key" technology to establish the room temperature preload [1]. The coils are assembled with a small azimuthal preload using iron pads. Separately, the yoke is assembled inside a thick aluminum shell. The coil and pad assembly is then installed into the yoke and shell. Stainless steel bladders, placed between the two assemblies, are inflated to obtain the desired azimuthal preload. Keys are installed to lock in the preload and the bladders removed. The largest part of the azimuthal preload is created by the aluminum shell during cooldown. The preload during assembly is modest. The axial preload is high, to limit the motion of the coil ends during excitation. It is implemented by full-length aluminum rods (Fig. 15).

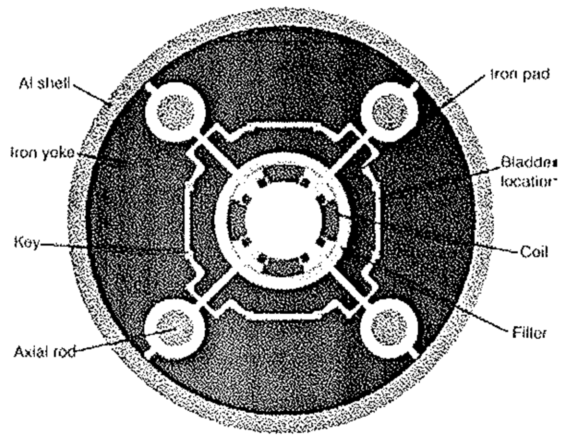

Fig. 14. Cross section of shell support structure (TQS).

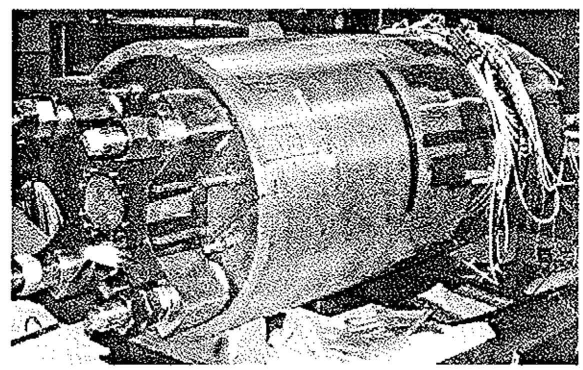

Fig. 15. Photo of a completed TQS quadrupole. The four thick rods provide the strong axial support.

Magnets made in the TQ program routinely reach, and sometimes exceed, 200 T/m [3, 4]. The test results also give baseline values for field quality, quench propagation, and quench protection. Looking ahead, the TQ support structures will be used to test needed developments in, e.g., the conductor and cable, in 1 m magnets before being implemented in 3.6 m magnets.

LONG QUADRUPOLES

The success of the long racetrack magnets indicates that there is no fundamental problem in extending the quadrupole length to 3.6 m. Work is underway to build and test 3.6 m-long, 90 mm-aperture quadrupoles in both collar (LQC) and shell (LQS) support structures. The goal is to reach a gradient of 200 T/m by the end of December, 2009 [5]. The collar support structure will be the same as the TQC, except longer. The shell support structure has evolved somewhat (Fig. 16), and now includes the use of pieces called "masters" that will facilitate assembly with the segmented yoke and shell [1].

A key feature of the LQ R&D plan is to use the same set of coils in both support structures. This minimizes the time and resources needed to test both structures, increasing the paths to the Dec. 2009 goal. The most efficient way to do this is to test the coils in the shell support structure first, because it is faster to remove the coils from a shell structure (using the bladders) than from a collar structure (which requires the skin to be cut off). In order to make coils faster, facilities for reacting and impregnating coils are being built at both BNL and Fermilab. All winding and curing will be at Fermilab.

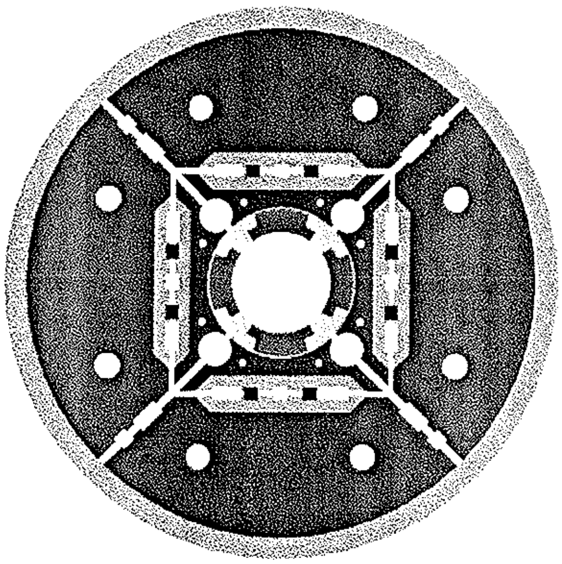

Fig. 16. Shell support structure for long quadrupoles. One each side, the masters (grey) are spaced by two keys (black). The keys determine the preload.

The fixtures used for curing, reaction, and impregnation LQ coils process one coil at a time. The same fixtures used to make TQ coils processed two coils at once. The change was made when left-right asymmetries were discovered in the TQ coils. Processing one coil at a time is expected to reduce the asymmetries. At the time of WAMSDO, practice coils from copper and Nb_3Sn had been wound and cured. Initial debugging of the reaction fixture (adding a flat plate to remove a bow that occurred during reaction of the first Nb3Sn coil, as shown in Fig. 17) has taken place.

The quench protection system is designed to keep the coil temperature below 380 K and the MIITS below 7.5, calculated for a 60 mΩ dump resistor and with the adiabatic approximation. In the calculation, a quench detection time of 5 ms and a heater delay time of 12 ms have been used. (These values are based on TQ experience.) To achieve this, the coils will be outfitted with quench protection heaters on both inner and outer layers. Because of the flux jumps (which decrease in amplitude as the current increases), it will be necessary to begin the ramp with a quench detection threshold of several volts. At high current, the threshold will be about ¼ volt.

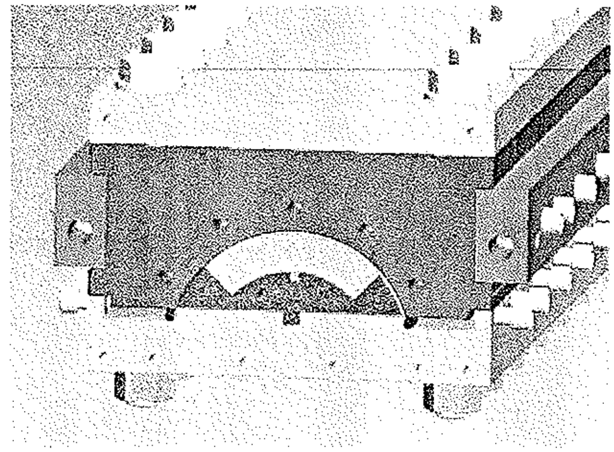

Fig. 17. View of the tooling that will be used to react and impregnate 3.6 m quadrupole coils.

LARGE APERTURE QUADRUPOLES

Design of a large aperture (~110 mm – 130 mm) 1 m-long quadrupole, HQ, is currently underway [6]. The aperture of this two-layer magnet will be close to that of the NbTi quad planned for the LHC Phase 1 Upgrade [7, 8]. It is felt that comparison of the design and performance of this magnet with that of the NbTi quad will permit easier evaluation of the features of Nb_3Sn important for its use in an accelerator.

The follow-on to HQ is a 3.6 m-long version, QA. The quadrupoles to be built for the Phase 2 Upgrade are called QB.

SUMMARY

The LARP Magnet R&D program has yielded 1 m-long, 90 mm-aperture quadrupoles that reliably reach 200 T/m. It has also produced a racetrack magnet with a shell support structure that reached 96% of the conductor limit. Practice coil for a 3.6 m-long quadrupole have been made, in line with the schedule which calls for a 3.6 m quadrupole to reach 200 T/m by the end of 2009. Design of a large aperture quadrupole is well underway.

ACKNOWLEDGEMENTS

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