SSCL-Preprint-48

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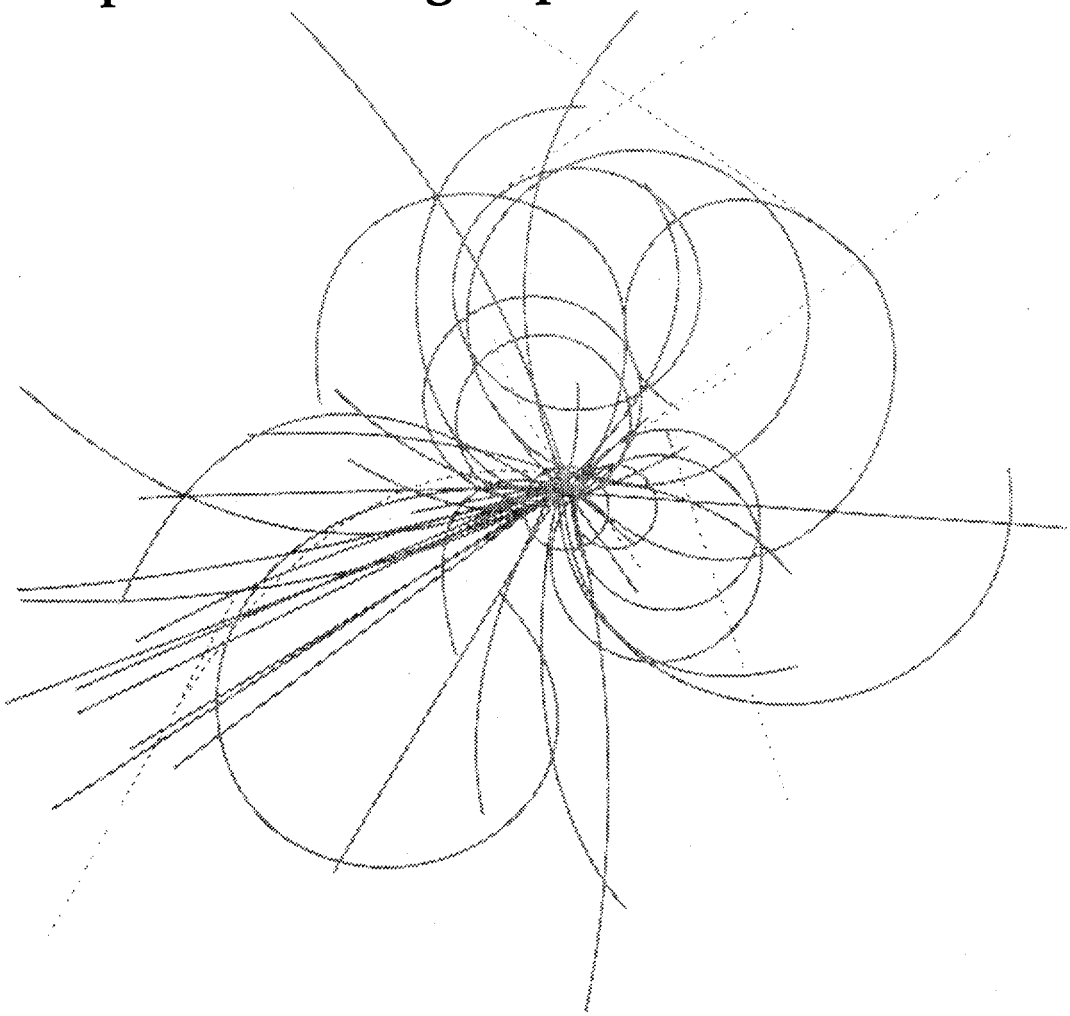
Superconducting Super Collider Laboratory



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SUMMARY OF PRODUCTION DEVELOPMENT, DETAILS, AND RESULTS FOR MODEL DIPOLES AT SSCL

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INTRODUCTION

DSA-101 and DSA-102 are the first two model dipole cold masses to be assembled at the Superconducting Super Collider Laboratory (SSCL) in Texas. They were "built-to-print" per the first Fermilab-designed 50-mm short dipole magnet. Because the magnets were designed in English units, all results are presented in English units. Both magnets were completed and tested in the fall of 1991.

The SSCL developed this model dipole magnet program in order to initiate magnet production capability in Texas. The approach used was to expand on the continuing progress of the national laboratories—Lawrence Berkeley Laboratory (LBL), Brookhaven National Laboratory (BNL), and Fermi National Accelerator Laboratory (FNAL)—and to develop internal tooling and processes to build model dipole magnets. By producing two 50-mm Collider Dipole Magnets, the SSCL was able to verify technology and provide an opportunity to develop in-house technical experience.

Both magnets performed well. DSA-101 exhibited very little quench training; DSA-102 had several non-plateau quenches. All quenches were well above the nominal SSC operating current of 6500 A.[1]

Construction details and the results of the first two model dipoles will be presented. Procedural considerations and assembly details, along with a discussion of lessons learned during the start-up phase of magnet construction, will also be presented.

DESCRIPTION OF MAGNETS AND INSTRUMENTATION

The two DSA magnets were built per the first Fermilab 50-mm model magnet design. They were identical to FNAL's DSA-321 and DSA-323. Features of the magnets included:

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Vertically split yoke

External ramp splice

Stainless steel end can and collet

1.3:1 Cu/Sc for inner, 1.8:1 Cu/Sc for outer.

Magnet instrumentation included one strain gauge collar pack, bullet-type end gauges, and voltage taps. Spot heaters and quench protection heaters were not installed.

COIL WINDING

The coil winding for DSA was performed on the Model Coil Winder and Tensioner, which were designed by SSCL based on concepts from FNAL and LBL. The mandrel was procured by the SSCL using the FNAL 50-mm dipole coil configurations. The mandrel was designed as solid tooling (vs. laminations or EDM blocks), and peripheral tooling was fabricated for mounting to the winder. Other design-specific tooling (key inserts, winding keys, and mold retainers) was received from the tooling designed and procured by FNAL.

All coil parts were duplications of the direct material used by FNAL. The cable and wedges were insulated by FNAL and shipped to the SSCL. The DSA end parts (G-10 end keys, end spacers, and saddles) were procured by SSCL, and the additional pieces were shipped to FNAL in support of their model program. Modifications were made to the tooling, coil parts, and processes during the practice coils, which were used as developmental tools.

The solid mandrel was fabricated with a slot on the top surface to provide clearance to a nut bar that was used to mount the winding keys. Inserts were made to fill the slot at the ends of the mandrel so that the end turns would be made over a continuous surface. Another tooling issue that arose involved the hold-down clamps at the coil ends. These clamps are designed to extend over the ends of the coils to provide alignment and rigidity of the end parts (see Figure 1).

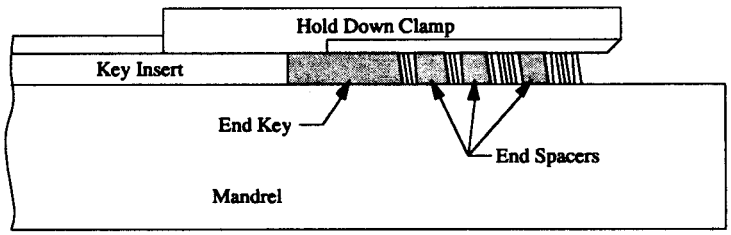

Figure 1. Inner Coil End.

The clamps provided an interference for the insertion of the end parts, which meant that there was also minimal clearance for the cable. No changes were made for DSA, with the intention that the problem will be resolved in later model magnet programs.

Slight modifications to the coil parts were made prior to the initial process development to facilitate the winding. The end pieces were designed to the dimension of a cured coil, which created an interference fit on the wound coil. Relief slots were cut into the pieces to ensure conformance of the ends prior to curing. Wedges were received in 12-ft sections, which provided an opportunity for development of proper wedge length. Based on the gaps between the wedges and end pieces on the practice coils, the wedges were cut to 0.06 in. over print length.

The process variable of primary concern during the initial development was the cable tension. Experiments were performed to find the proper average between the cable not

conforming (tension too low) and the cable collapsing (tension too high). The result was a tension of 70 lb for both inner and outer coils. Another large factor in the development of coil winding dealt with the experience of the technicians. A definite lesson learned is that the practice coils were invaluable for building technical expertise.

COIL CURING

The coil curing was performed in the Model Curing Press, which was procured as a turn-key press from an outside supplier. The press is similar in concept to the model curing presses at FNAL and LBL. The curing cavity and pusher bars were procured by the SSCL using the FNAL 50-mm dipole coil configurations. The curing cavity was also designed as solid tooling (vs. laminations), and peripheral tooling was fabricated to distribute the heating oil. The modifications made during curing of the practice coils primarily pertained to the processes rather than the tooling.

The initial development centered on the end loading, which was applied mechanically by torquing a screw jack. Several trials were performed in order to examine the effect of increasing end loads on the coil end compression. The final torque used was 110 ft lb, which translated to an estimated load of 3800–4950 lb. Even though coil lengths within 0.06 in. were achieved, the hydraulic end loading appears to have the most consistent results.

The next process variable that was examined was the temperature profile during the cure cycle. The specification for the epoxy system in the fiberglass prepreg presents a certain required profile to maximize curing results. The design of the curing cavity and mandrel incorporated thermocouples for routine monitoring of the cycle, but the proximity of the thermocouples suggested that there would be a temperature lag and delta for the coil. To verify the process, additional thermocouples were placed directly on the practice coils, and the cycle was derived from the monitored temperatures (see Figure 2).

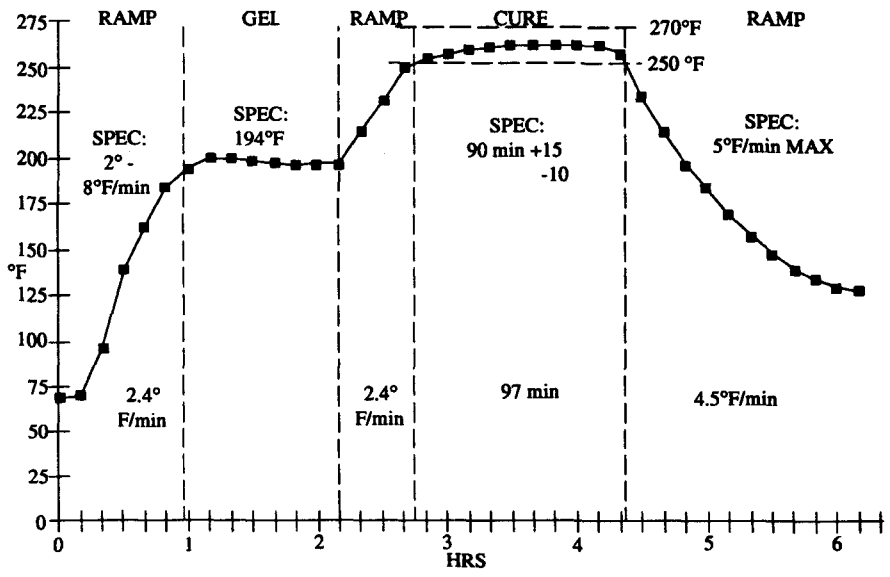

Figure 2. Temperature Profile.

The majority of the development effort during the practice curing focused on an adhesion problem that surfaced at the start of the program. Basically, there was a breakdown of mold release at the key inserts and mold retainers due to the high coil loads. This allowed

the epoxy to bond to the tooling and tear during the coil disassembly. Experimentation with mold releases was performed, and a Frekote Sealer and 44-NC mold release was found to be the best combination. The mold release solved the problem involving the key inserts, but the adhesion to the mold retainers still existed. It was concluded that there was still a breakdown of mold release due to the friction of coil sizing, concentrated at the large wedge (see Figure 3).

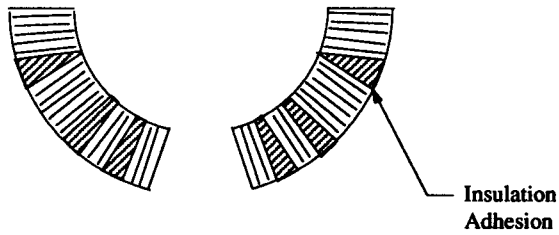

Figure 3. Inner Coil Configuration.

It was determined that the majority of the coil movement for sizing occurred during the initial loading, so the curing cycle was modified to minimize the friction without sacrificing proper cable positioning. Table 1 describes the final curing cycle.

Table 1. Final Curing Cycle.

Step	Description	Comments
1	Load azimuthally to 620 lb/in.	Closed press and provided majority of coil movement.
2	Load radially to 65 lb/in.	Positioned cable.
3	Load azimuthally to 2800 lb/in., radial load increased to approx. 300 lb/in.	Further positioning of cable and coil.
4	Release azimuthal and then radial load to line pressure.	Allowed clearance for end pre-loading.
5	Load radially to 35 lb/in.	Re-positioned cable.
6	Load azimuthally to 2300 lb/in., radial load increased to approximately 150 lb/in.	Pre-loaded coil in preparation for 1st heating ramp.
7	At gel temperature, release azimuthal load to 500 lb/in. and then radial load to 50 lb/in.	Allowed clearance for final end loading.
8	Load azimuthally to 13,670 lb/in., radial load maintained below 500 lb/in.	Final positioning and sizing of coil at a coil stress of approximately 13,400 psi.

With the lessons that were learned and the modifications that were made with the practice coils, the DSA coils were produced without any major complications.

COIL AZIMUTHAL SIZE

Coil size was measured in the usual "deviation-from-standard" manner. The average coil sizes for the coils used in the DSA magnets are shown in Table 2. Ideally, the magnet design calls for no pole shims to compensate for variations in coil azimuthal size. The Fermilab magnets, DSA-321 and DSA-323, were assembled without pole shims. Generally, the SSCL coils were smaller than the Fermilab coils, requiring that pole shims be used. DSA-101 and DSA-102 were assembled with pole shims in order to obtain coil prestresses within the target range.

COIL ASSEMBLY AND COLLARING

During the first attempt at collaring (practice collaring), no pole shim was used on the outer coils. However, outer coil prestresses were too high. The only alternative available was to remove one 5-mil layer of kapton ground plane insulation from the outer pole surface. (There are four such layers on the outer pole and three on the inner pole.) This resulted in a negative value for the outer pole shims. Inner coil G10 pole shims of 8 mil worked well for both magnets. As shown in Table 2, the average coil stress was on the high end of the target range. Average peak coil stress during collaring is also shown in Table 2. Springback losses were high, which is consistent with the square key method of collaring that was used on these magnets.

There were no electrical shorts detected in any of the coils at any time during the assembly of both magnets. There was a problem with excessive current leakage during routine hypot testing of DSA-102 at 5000 V. The path of the current leakage was found to be across the surface of the G10 pole piece on the lead end of the magnet. The G10 material had become contaminated with a glycerol-based liquid soldering flux that was used for voltage tap installation. The pole pieces were insulated with kapton tape and re-assembled into the magnet. There were no further problems with excessive current leakage.

Table 2. Comparison of collaring data for FNAL and SSCL DSA magnets.

	Azimuthal Size Average (mil)	Shim Size	Average Coil Stress (psi)	Peak Coil Stress (psi)
		SSCL Magnets		
DSA-101				
Inner Coils	–3.4	+8	12,570	18,319
Outer Coils	+3.2	–7	9,859	17,553
DSA-102				
Inner Coils	–3.7	+8	13,447*	20,423
Outer Coils	+2.1	–2	9,198*	16,521
SSCL Target Coil Prestresses:	Inner: 9,000–13,000 psi		Outer: 6,000–10,000 psi	
		FNAL Magnets[2,3]		
DSA-321				
Inner Coils	+9.8	0	8,975	14,442
Outer Coils	+6.5	0	13,217	22,165
DSA-323				
Inner Coils	+5.7	0	6,900	11,507
Outer Coils	+6.5	0	11,470	20,275

END COLLET ASSEMBLY

The stainless steel end cans were installed with Fermilab-designed tooling that hydraulically presses the end cans over the end collets. The design did not allow for added insulation between the coil ends and the collet pieces. Kapton could have been added to increase prestress in the coil ends; however, hydraulic pressures used to seat the end cans indicated that there was sufficient prestress in the coil ends when compared to previous magnets built at Fermilab (see Table 3). The hydraulic pressure used to seat the end cans, along with end can deflection data, are the only indicators available to determine whether

sufficient prestress exists in the coil ends. FNAL-built DSA-321 was used as a benchmark for this data, since it also used a stainless steel end can design. (Later designs used an aluminum end can.)

Table 3. Hydraulic Pressure Required to Seat End Cans (psi).

Magnet	Lead End	Return End
DSA-321	7000	5000
DSA-101	8500	9000
DSA-102	7500	6500

YOKE ASSEMBLY

The yoke assembly operation was performed on the shell welding press insertion table, which was procured by the SSCL using FNAL 50-mm dipole shell welding press drawings. A 10-ft section of the press was constructed in the SSCL's Magnet Evaluation Lab for DSA model dipole fabrication. The FNAL design-specific tooling, consisting of two types of laminated molds, was modified to account for the difference in length between the 15-m-long collider dipoles and the 1.8-m-long DSA model dipoles.

Along with the tooling, the cold mass components were obtained. The collared coil assemblies for both DSA magnets were manufactured at the SSCL as described previously. The yoke packs were fabricated at FNAL because SSCL did not possess yoke pack assembly tooling at the time of the magnet builds. The half shells and alignment bars were procured by the SSCL materials group.

Miscellaneous fixtures were designed by the SSCL to aid in yoke assembly. These fixtures included a yoke pack lifting device used to load yoke packs weighing as much as 350 lbs onto the assembly/insertion table, and a shell rounding fixture that clamped the upper shell around the yoke pack assembly before the cold mass assembly was installed in the shell welding press.

Several mechanical measurements were taken during the yoke assembly of the DSA magnets. The collared coil and yoke pack assembly lengths were compared, and the yoke pack length was modified by removing yoke laminations to allow enough clearance for the strain gauge wires of the collared coil to exit the cold mass assembly. Shell-to-alignment bar gap measurements were recorded, and the gaps were set at the average gap measurement to keep the cold mass from twisting prior to shell welding.

Once the cold mass assembly was completed, a series of electrical tests were performed to verify that the magnet was still functioning properly. These electrical tests included coil resistance, inductance, and "Q" measurements, a coil impulse test, and coil-to-ground hypot tests.

SHELL WELDING

Shell welding of the cold mass was performed after the cold mass assembly was hydraulically compressed in the shell welding press. The press hydraulic system, consisting of 60-ton hydraulic cylinders spaced at 12-in. centers on both sides of the press, lowered the upper mold tooling onto the upper shell of the cold mass assembly until a pressure of 5800 psi was exerted on the cold mass. Gas tungsten arc welding (GTAW) was used to manually apply tack welds between the upper half shell and alignment bar simultaneously down both sides of the cold mass. The lower half shell was tack welded to the alignment bar

in the same manner. One root pass and one filler pass were applied to each of the four gaps between the half shells and the alignment bars.

Two practice cold mass assemblies were welded prior to the DSA magnets so that weld samples could be analyzed for welder qualification and process certification. As a result of successful weld samples, the DSA magnets simulated welding consistent with ASME code, Section VIII requirements. This effort was made to prepare for welding to code requirements on future magnet builds.

During the practice welding, it was found that the shell ends were drawn inward by the combination of the thinner end yoke packs not supporting the shell against the press force at the ends of the cold mass, and of the welding itself. This shrinking of the shell openings prevented the end plates from being installed in the cold mass during practice final assembly. To resolve this problem, expanding mandrel fixtures were designed and fabricated at the SSCL. These mandrels were installed in the ends of the shell to support the shell ends against the inward force of the press during shell welding of the DSA magnets.

Throughout the shell welding of the two DSA magnets, the collar pack strain gauges were monitored to collect coil stress data using the SSCL strain gauge data acquisition system. A comparison of the post-collared and post-welded average coil stress of the DSA magnets is shown in Table 4 (inner coil) and Table 5 (outer coil). For both magnets, the average inner coil stress increased after shell welding, and the average outer coil stress decreased. These results are consistent with the coil stress data for the FNAL 50-mm model dipole magnets.

Table 4. Comparison of DSA average inner coil stress (psi).

DSA-101		DSA-102	
Post-collared	Post-welded	Post-collared	Post-welded
12,544	13,327	13,447	15,023

Table 5. Comparison of DSA average outer coil stress (psi).

DSA-101		DSA-102	
Post-collared	Post-welded	Post-collared	Post-welded
9,843	9,625	9,198	8,542

FINAL ASSEMBLY

Final assembly of the DSA magnets included cutting the cold mass shell to length; installing the pressure plate, temperature compensation gauges, and bullet gauges on the return end of the magnet; and installing and welding the end plates.

Shell cutting was performed using a split frame circular cutter. A fixture was designed at the SSCL to set the cut line of the shell at the return end. This dimension was critical in spacing the gap between the inner surface of the return end plate and the outer surface of the bullet gauge pressure plate. The DSA-102 bullet gauge wires and temperature compensation gauges were damaged because the shell was not cut properly at the return end, resulting in too small a gap between the end plate and pressure plate. The end plate was removed, the bullet and temperature compensation gauges were replaced, and spacers were installed and welded between the shell and return end plate to resolve the gap problem. Bullet gauge wire routing was also modified to keep the wires away from the tightest gap between the two plates.

After both end plates were installed, they were manually welded to the cold mass shell using GTAW. Electrical tests of the bullet and temperature compensation gauges were included in the process control specification before and after end plate welding to verify that the gauges functioned properly. The tests were incorporated before end plate welding because the temperature compensation gauges on DSA-101 were damaged during end plate assembly. (This discovery was made when they were tested after welding.) The decision was made to not replace these gauges for cold testing of the magnet.

TEST RESULTS

Quench histories of both magnets are shown in Figure 4.[1] DSA-101 exhibited very little training, while DSA-102 had several "non-plateau" quenches. All quenches for both magnets were significantly above the SSC operating current of 6500 A.

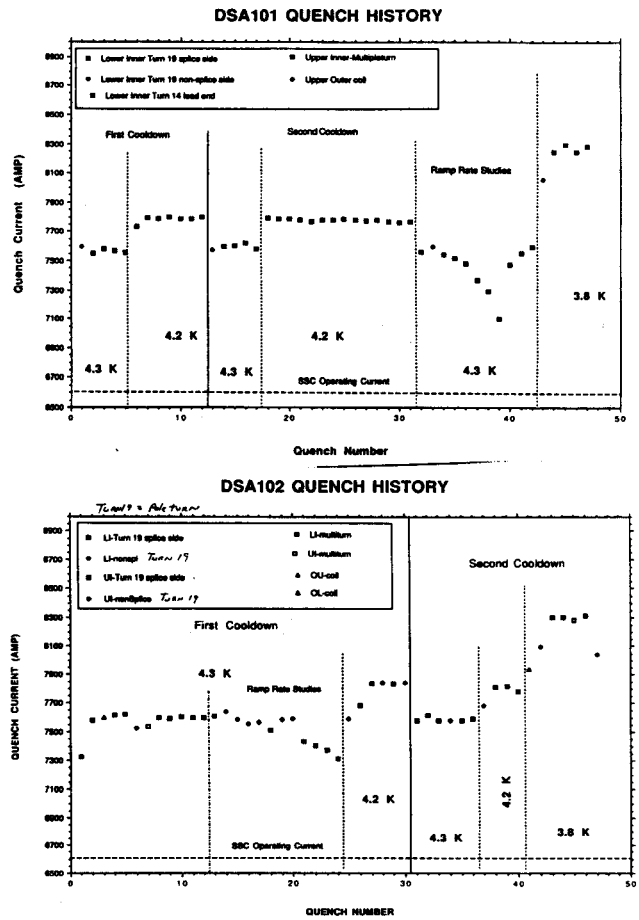

Figure 4. DSA Quench Histories.

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