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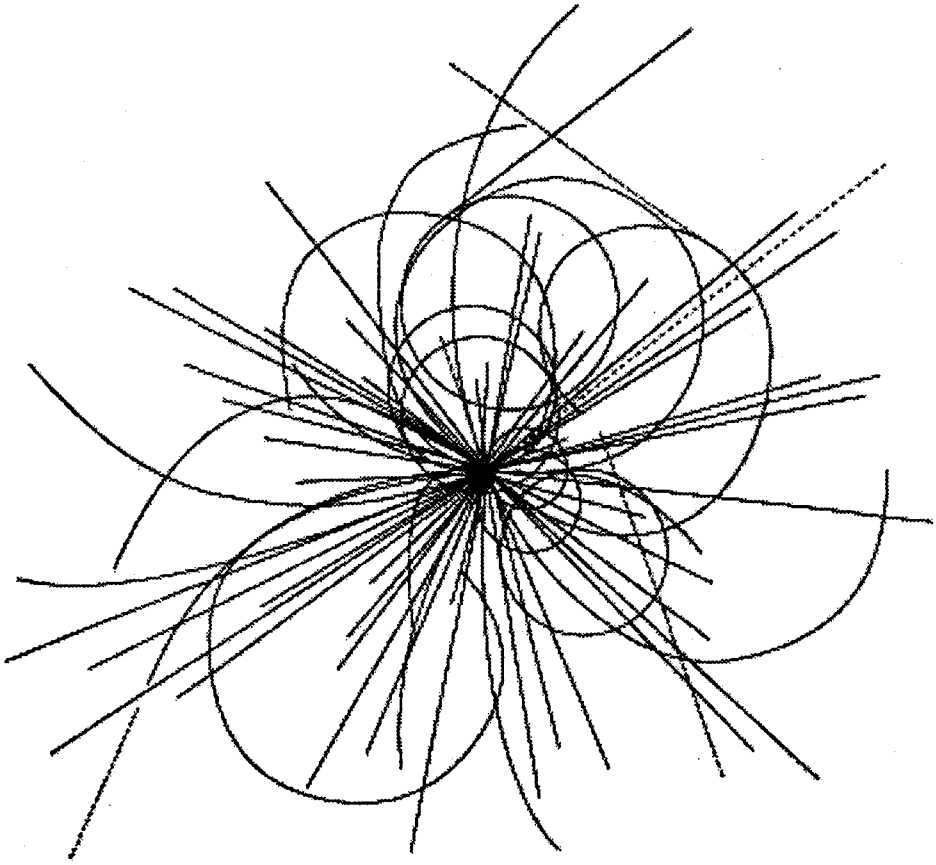

Superconducting Super Collider Laboratory

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Status of the SSC Superconducting Magnets

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ABSTRACT

Several 50-mm-aperture, 15-meter-long-dipole-magnet-prototypes and five 40-mm-aperture, 5-meter-quadrupole models have been built and tested for the SSC magnet development effort. Five of the dipoles and one quadrupole have been connected in a string representing a collider half cell, and tested cryogenically at the Superconducting Super Collider (SSC) site. The magnets were designed and produced by a consortium consisting of the Superconducting Super Collider Laboratory (SSCL), Fermi National Accelerator Laboratory (FNAL), Brookhaven National Laboratory (BNL), Lawrence Berkeley Laboratory (LBL), along with General Dynamics Corporation (GD), Babcock and Wilcox (B&W) and Westinghouse Electric Corporation (WEC). A description of the magnets, including properties of their superconductor, is presented. The test results from individual magnet tests and the string test are reviewed with respect to meeting collider requirements. The significant features of the baseline production magnets and the plans for prototype through production will be presented. In addition, the status and test results for special magnets built at the SSC Laboratory will be discussed.

1. FOREWORD

Thus far in the SSC collider magnet development program, 19 prototype collider dipoles and 5 quadrupoles have been built and tested. The dipoles have been primarily intended for the Accelerator Systems String Test (ASST) that is a major project milestone now completed at the SSC site. These magnets represent the culmination of a development program conducted by the SSCL at BNL, FNAL and LBL to achieve magnets capable of meeting the operating requirements for this 20-TeV-on-20-TeV proton accelerator. The further development of these magnets is now to be carried out in industry with General Dynamics (GD) and Westinghouse (WEC) as the Leader and Follower Subcontractors for the Collider Dipole Magnets and Babcock and Wilcox (B&W) as the Leader Subcontractor for the Collider Quadrupole Magnets. Some of the design features of the ASST magnets have been used in prototype designs of the industrial subcontractors. These are described along with the plans for production of prototypes through the initial production.

All the magnets have now been cryogenically tested and those designated as ASST have been delivered to the SSC site for use in the ASST and other testing programs. Quench performance studies and magnetic measurements have been extensively performed on the dipoles and to a lesser extent on the quadrupoles because of their later development in the program. In addition to meeting the goals of the ASST, these magnets represent collider prototypes that have been developed with the collider

requirements in mind. Thus, the test data is reviewed with respect to meeting accelerator requirements and looking at some issues which are being resolved to complete this final phase of the magnet R&D program.

Special magnets for the intersection regions of the collider are also being designed and built at the SSC Laboratory. This program has included fabrication and testing of two models for a 5-cm-aperture quadrupole which is described and test results presented.

2. MAGNET REQUIREMENTS

The SSC consists of a series of five accelerators, one linear accelerator (Linac) and four synchrotrons of increasing energy that ultimately attain two proton beams of 20 TeV. The last two accelerators are comprised of superconducting magnets. This paper addresses the magnets in the final ring, the Collider which is 87.12 km in circumference. The Collider consists of two rings of superconducting magnets, one on top of the other with a beam spacing of 90 cm as shown in Figure 1. The beams are focused together in two interaction or collision areas by a series of special insertion region magnets which are of somewhat different designs. The regular arcs are made up of half cells, each containing five dipoles, one quadrupole and one spool piece for providing power, cryogenic and correction magnet provisions. In total, there are 7632 15-m dipoles and 1564 quadrupoles in the collider rings. In addition, in 104 half cells in the regular arcs a 15-m dipole is replaced with one of 13-m length to accommodate some additional cryogenic equipment in the spool piece. The aperture requirement for the dipoles was increased from 40 mm to 50 mm in 1990 to provide the necessary amount of linear aperture for stable beam operation based on beam dynamics studies. For this purpose, it was not necessary to increase the aperture of the arc quadrupoles; thus it has remained at 40 mm. However, a special interaction quadrupole of 50-mm aperture, which is described below, has been developed at the SSCL. A list of the principal dipole and quadrupole parameters necessary for operation at 20 TeV is given in Table I.

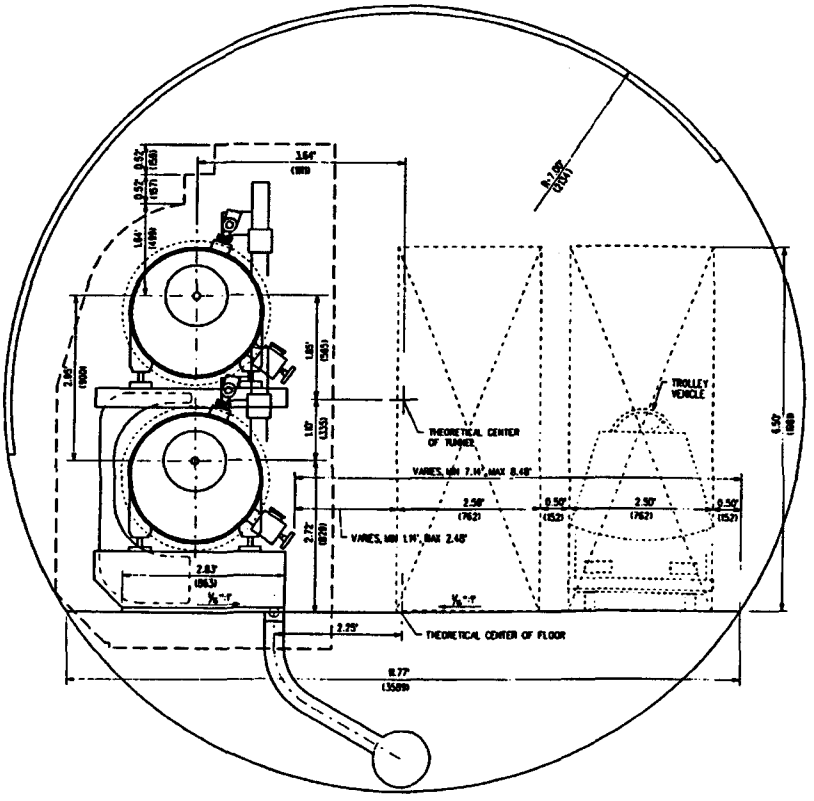


Figure 1. Super Collider – Tunnel Cross Section.

TABLE I. ASST DIPOLE AND QUADRUPOLE PARAMETERS.

PARAMETER	DIPOLE	QUADRUPOLE
Maximum Operating Temperature	4.35 K	4.35 K
Nominal Field or Gradient	6.6 T	211 T/m
Operating Current	6500 A	6500 A
Cold Mass Length	15.256 m	5.07 m
Ramp Rate	4 A/s	4 A/s
Inner Coil Aperture (mm)	50	40
Collar Outer Diameter (mm)	135.62	113.1
Yoke Outer Diameter (mm)	327.3	266.7
Shell Outer Diameter (mm)	340	276.1

3. STATUS OF THE COLLIDER DIPOLE MAGNETS

3.1 Design Features

The prototype dipoles described here have been built and tested both at FNAL and BNL. The designation and objectives for these magnets are listed in Table II. The assembly of the magnets at FNAL by a team from GD and also at BNL by a team from WEC was necessary to achieve the objective of the ASST, to test a string of industrially-assembled magnets. Both of these prototype magnets are designed to have almost identical magnetic performance and design for interconnect interface; however, the

TABLE II. SSC DEVELOPMENT AND ASST DIPOLES.

MAGNET	COLD MASS DESIGN	FABRICATION	OBJECTIVE
DCA311	FNAL	FNAL	Demonstration Dipole (ASST)
DCA312	FNAL	FNAL/GD	Tech. Transfer to GD (ASST)
DCA313	FNAL	GD	ASST
DCA314	FNAL	GD	ASST
DCA315	FNAL	GD	ASST
DCA316	FNAL	GD	ASST
DCA317	FNAL	GD	ASST
DCA318	FNAL	GD	ASST
DCA319	FNAL	GD	ASST
DCA320	FNAL	FNAL	Cable Insulation Studies.
DCA321	FNAL	FNAL	Cable Insulation Studies.
DCA322	FNAL	FNAL	Cable Insulation Studies.
DCA207	BNL	BNL	Demonstration Dipole (ASST)
DCA208	BNL	BNL/WEC	Tech. Transfer to WEC (ASST)
DCA209	BNL	WEC	ASST
DCA210	BNL	WEC	ASST
DCA211	BNL	WEC	ASST
DCA212	BNL	WEC	ASST
DCA213	BNL	WEC	ASST

mechanical design details for the cold masses of the FNAL and BNL prototypes differ somewhat and have been previously described.[1,2,3] A cross section of a completed magnet assembly with cryostat is shown in Figure 2. The superconducting cable for the 16 ASST magnets was obtained from three different sources. The description and superconductor parameters for these magnets are given in two tables. The properties that are common to the cables used in all the magnets are shown in Table IIIa. The variable properties for the cables used in individual magnets (with the vendor for the strand designated by a, b, or c) are listed in Table IIIb. The principal differences between the FNAL and BNL version of the cold mass for the ASST dipoles are given in Table IV.

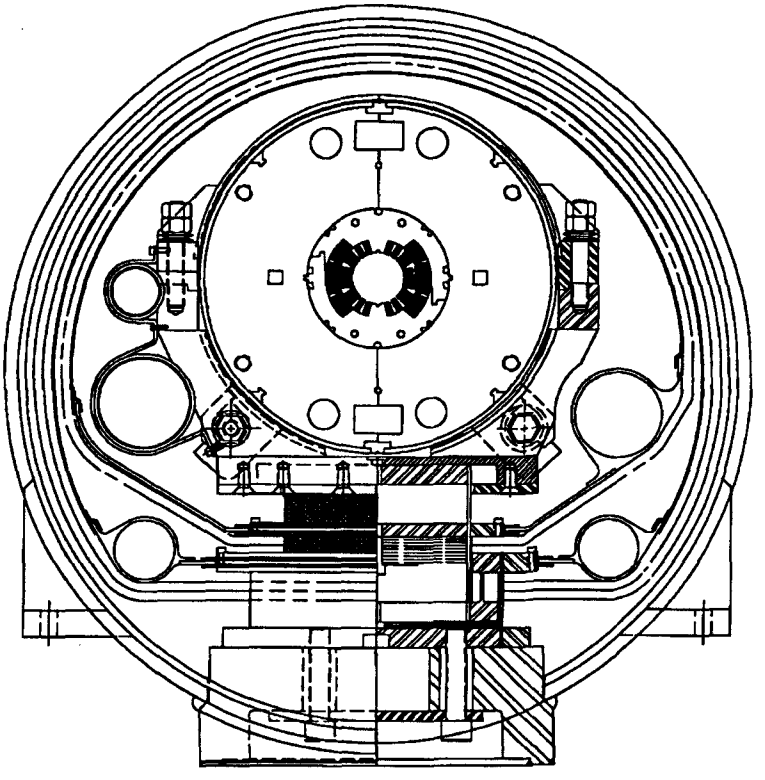


Figure 2. ASST 50-mm Dipole Magnet.

TABLE IIIA. COMMON SUPERCONDUCTOR PROPERTIES FOR ALL MAGNETS.

		INNER	OUTER
NbTi, Hi Homogeniety, %Ti		47.0	47.0
Strand Diameter	(mm)	0.808	0.648
Twist Pitch of Strand	(mm)	13 ± 1.5	13 ± 1.5
No. of Strands Per Cable		30	36
Width of Cable (Bare)	(mm)	12.34	11.68
Mid–Thickness of Cable (Bare)	(mm)	1.458	1.156
Cable Keystone Angle	(deg)	1.20	1.01
Lay Pitch of Strands in Cable	(mm)	86	94
Filament Diameter	(μ)	6	6
No. of Filaments		8000	4400

TABLE IIIB. VARIABLE PROPERTIES.

MAGNET	MANUFACTURER		RESIDUAL RESISTANCE, OHMS		COPPER: S.C.		CRITICAL CURRENT DENSITY IN STRAND NBTI, NbTi, A/sq.mm[b]		CRITICAL CURRENT IN CABLE, A[b]	
	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER
DCA207	a	a	38	38	1.54	1.75	1787	2397	10836	10339
DCA208	a	b	37	41	1.34	1.76	1732	2614	11371	11205
DCA209	b	b	38	41	1.50	1.80	1835	2629	11265	11158
DCA210	b	a	38	41	1.50	1.75	1814	2505	11224	10809
DCA211	b	a	38	39	1.48	1.72	1793	2575	10873	11105
DCA212	c	c	35	37	1.51	1.77	1661	2389	10308	10242
DCA213	c	c	36	37	1.50	1.78	1636	2372	10039	10106
DCA311	c	a	37	38	1.51	1.72	1647	2536	10079	10850
DCA312	a	a	40	39	1.53	1.77	1755	2516	10673	10772
DCA313	a	a	42	38	1.52	1.75	1722	2506	10512	10772
DCA314	a	a	39	38	1.52	1.75	1722	2478	10512	10681
DCA315	a	a	39	41	1.52	1.75	1784	2505	10869	10869
DCA316	b	b	39	39	1.51	1.77	1811	2518	10985	10780
DCA317	a	b	39	40	1.52	1.81	1722	2608	10512	11012
DCA318	b	b	40	37	1.54	1.79	1790	2500	10851	10645
DCA319	b	b	37	42	1.50	1.81	1802	2616	11038	11058

[a] Where upper and lower coils have different properties, the minimum value is shown.
[b] Measured at 4.2 K and 7 T for inner conductor and 4.2 K and 5.6 T for outer conductor.

TABLE IV. BNL-FNAL ASST DIPOLE MAGNET COMPARISON (WHERE DESIGN DIFFERENCES EXIST).

DESIGN FEATURE	BNL VERSION	FNAL VERSION
Direction of Yoke Lamination Split	Horizontal	Vertical
Radial Interference Fit of Collared Coil Assembly Relative To Yoke (mm): Horizontal Vertical	 0 to –0.025 0.15 to 0.25	 0.1 to 0.2 –0.25 to –0.35
Coil End Construction	Individually Determined with Insulators between Turns	Grouped Ends with Saddle Pieces
Method of Clamping Ends of Coils	Collars Similar to Those Used in Straight Section	Conical Collet Type Clamp
Location of Inner- Outer Coil Splice	Internal: Contained in Lead End of Collared Coil	External: At Lead End In Collet Clamp

3.2 Quench Performance

The requirements for the quench performance of the collider dipole magnets at 4.35 K are:

- No initial quenches below full field (6.65 T).
- No more than two quenches required to reach 5% above full field.
- After being warmed up (thermal cycle), the magnets should meet the preceding two requirements.

We will now examine the prototype magnets with respect to these requirements. Figure 3a is a plot of the 4.35 K initial quenches with a thermal cycle shown by the dotted vertical line for the ASST magnets assembled at FNAL. It is seen that there are initial quenches below operating current in five of these magnets. The origin of these quenches was the same in three cases (DCA313, DCA314 and DCA317) and was at the lead end of the magnet near where the transition occurs from the straight section to the collet end of the coil which contains the splices. After a thermal cycle, these quenches and that in DCA316 did not occur. It is also noted that the second quench in DCA319 was at 16 A/s and was a ramp rate effect. The same type of quench plot for the seven magnets assembled at BNL is shown in Figure 3b. In this case it is seen that there was one lower current initial quench at the operating field level. Thus, both series of magnets exhibited very little training and less re-training after the thermal cycle. Some of the magnets were also tested at 3.5 K to examine the mechanical stability of the design at higher forces. In

this case it was seen that these magnets are capable of operation above 8000 A, also with little or no training.

Thus, we have seen for the 16 magnets tested that the average plateau current at 4.35 K is ≥7300 A. This is a 10% margin relative to the operating current of ~6500 A. This plateau is sensitive to ramp rate, as low as the 1–4 A/sec level, as will be seen below.

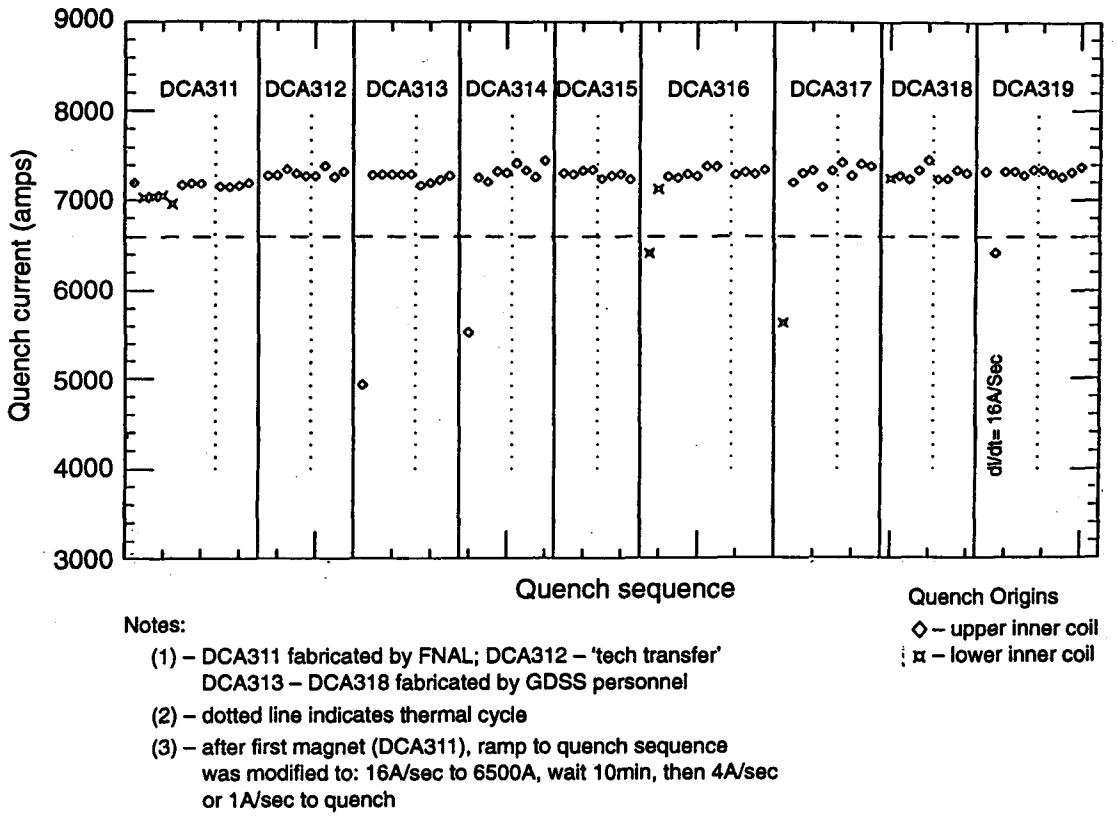
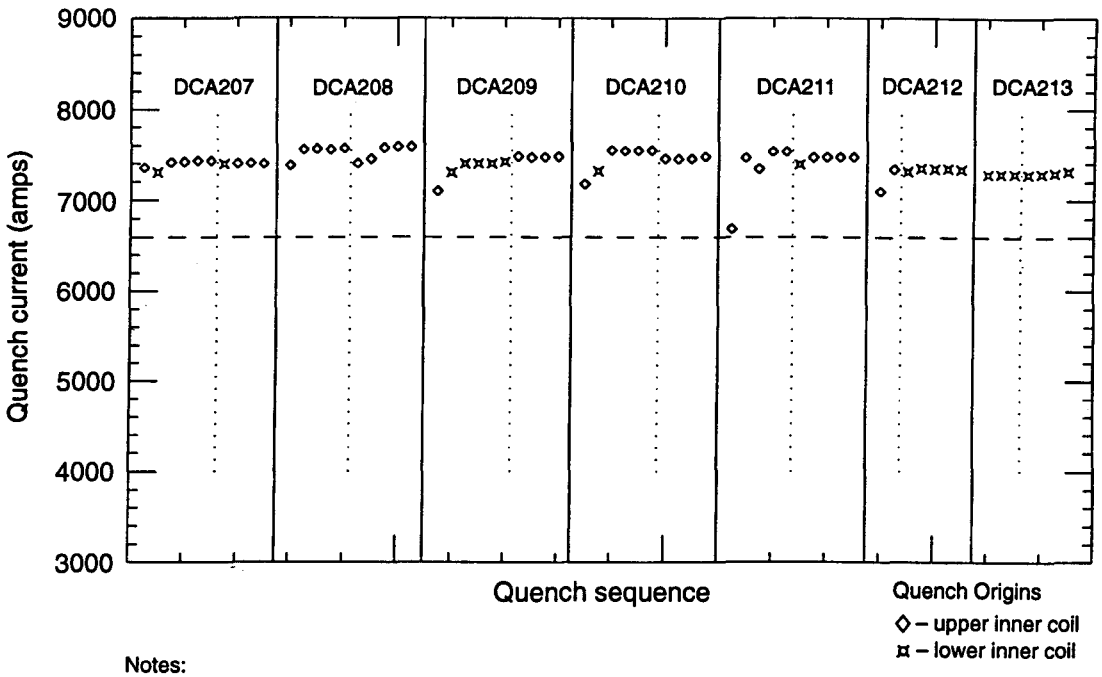


Figure 3a. 4.35 K Quench Performance. Full-length 50-mm Aperture SSC Dipoles – FNAL/GDSS.



Notes:

(1) – DCA207 fabricated by BNL; DCA208 – 'tech transfer', DCA209-211 fabricated by WEC; DCA212-on fabricated by BNL

(2) – dotted line indicates thermal cycle

(3) – after first magnet (DCA207), ramp to quench sequence was modified to: 16A/sec to 6500A, wait 10min, then 4A/sec or 1A/sec to quench

Figure 3b. 4.35 K Quench Performance. Full-length 50-mm Aperture SSC Dipoles – BNL/WEC.

3.3 Ramp Rate Sensitivity

The variation of quench current with ramp rate is expected as a result of the heating of the cable by induced eddy currents. However, the effect in these magnets was somewhat different than expected. Figure 4 is a plot of the quench current vs. ramp rate for 10 magnets assembled at FNAL. The designation a,b, or c after each magnet name and by line type for the chart indicates the vendor for the strand used for the inner cable in each magnet. It is noted that the shape of the curves varies with the source of the conductor and that there is an abrupt drop in quench current at rather low ramp rates for one of the cables, which, however, is less affected at high ramp rates. The present thinking is that these effects are due to variation of inter-strand resistance to a very low level in some of the cable causing an increase in eddy current heat. A program has been instituted to control the processing of the strand by the manufacturers to

permit a controlled copper oxide layer as one approach to achieve inter-strand resistance uniformity. Another approach that is being investigated is to evaluate a chemically-induced process for coating some of the strands with a resistive copper oxide layer. The eddy current effects are not considered to be an issue for the quench performance of the collider which operates at the low ramp of 4 A/sec. However, the High Energy Booster requires ramping at 60 A/sec and therefore increasing the cable inter-strand resistance is aimed mainly at that program.

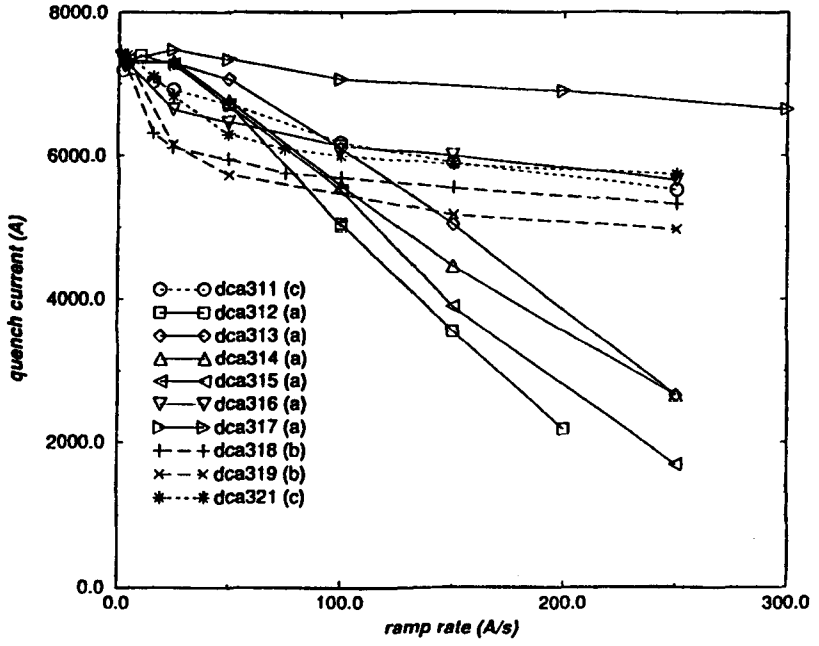


Figure 4. Ramp Rate Sensitivity for FNAL/GD Dipoles.

3.4 Multipole Measurements

The field quality[4] is important in both the steady state and transient mode (when the magnet is being ramped). Steady state measurements are made at a current of typically 2000 A, where superconductor magnetization effects are small and the yoke iron is not saturated. This measurement is made along the entire length of the magnet and the multipoles reported are the average of these measurements. In order to examine transient effects, multipoles are measured at fixed positions along the length to determine time decay of multipoles and also multipole behavior during continuous current ramp from injection to normal operating current. We will examine the characteristics of these magnets for these type of measurements.

For the steady state case, the measured multipole distribution for the FNAL ASST magnets is shown in Figure 5a. These measurements were taken cold at 2000 A for an up ramp of current. The acceptance limit for an individual magnet, ±3σ from the mean value of the ensemble of magnets, is indicated by the limit line for each harmonic. It is seen that the distribution of harmonics is rather tightly controlled within the acceptance band. The same type of plot for a fewer number of magnets assembled at BNL (with different tooling) is shown in Figure 5b. Except for the b2 harmonic, the multipole distribution is rather tightly controlled. Having looked at the distribution of measured multipoles in these magnets, we will now look at how closely their average or systematic values compare to the

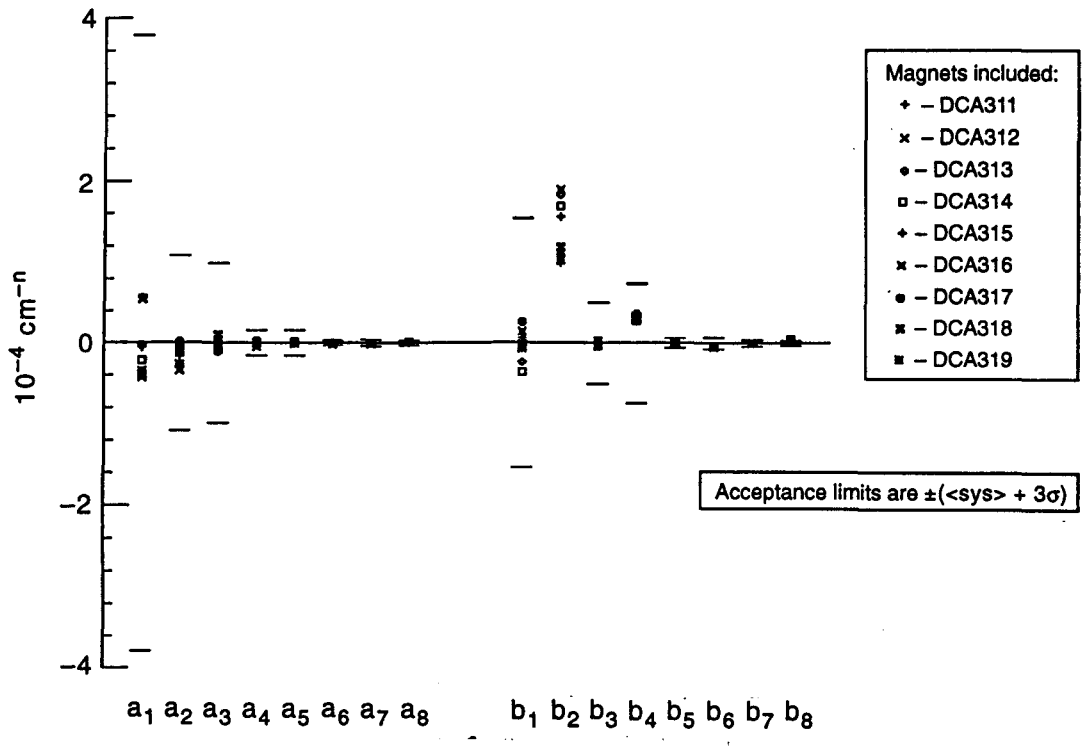


Figure 5a. Measured Values of Multipoles for FNAL/GD ASST Dipoles Showing Acceptance Limits.

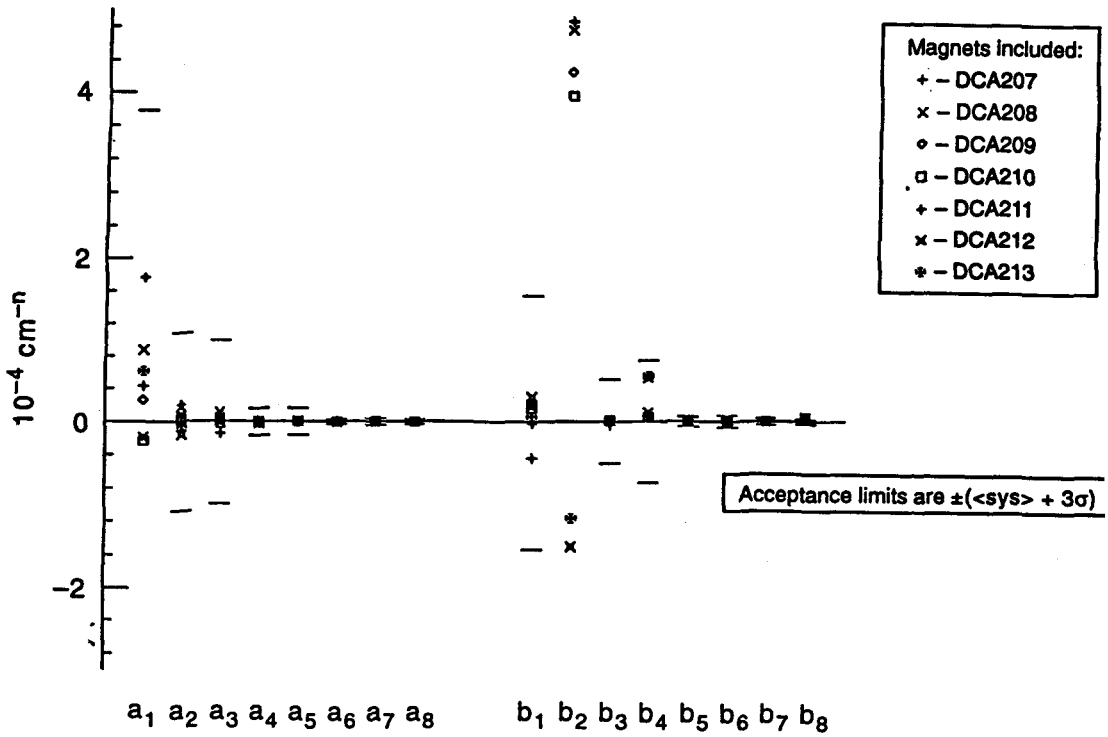


Figure 5b. Measured Values of Multipoles for BNL/WEC ASST Dipoles Showing Acceptance Limits.

allowable limits. Figure 6a shows the ratio of the average of each harmonic (with distribution widths) to the allowable value for the series of magnets assembled at FNAL. It is seen that a few of the multipoles are out of tolerance. This includes both allowed and unallowed harmonics.[4] In the same manner, the systematic multipoles for the magnets assembled at BNL are shown in Figure 6b. In this case we again see some allowed and unallowed harmonics out of tolerance. This situation is being addressed by GD who has iterated the magnetic design to correct these offsets for the allowed multipoles. This magnetic design embodying these corrections will be used in the GD prototype magnets. The unallowed multipole offset is dependent on variations of coil size and tooling design. The GD magnets will be fabricated on new tooling designed to produce more uniform coil sizing which will also be verified in their prototype magnets.

Eddy current contributions to multipoles have been noticed in some of the magnets (DCA312, DCA313, DCA314 and DCA315) that have been tested in this program. This is evidenced by the unexpected appearance of a1 and b1 harmonics when the current is ramped in these magnets. This is believed to be associated with a non-uniformity of the inter-strand resistance in some cables, as contrasted to the quench current degradation due to low inter-strand resistance as mentioned above. It has not been assessed at this time whether this is a problem that requires correction; however, it is expected that it will be corrected by controlling the surface oxide layer on the superconducting wire as mentioned above.

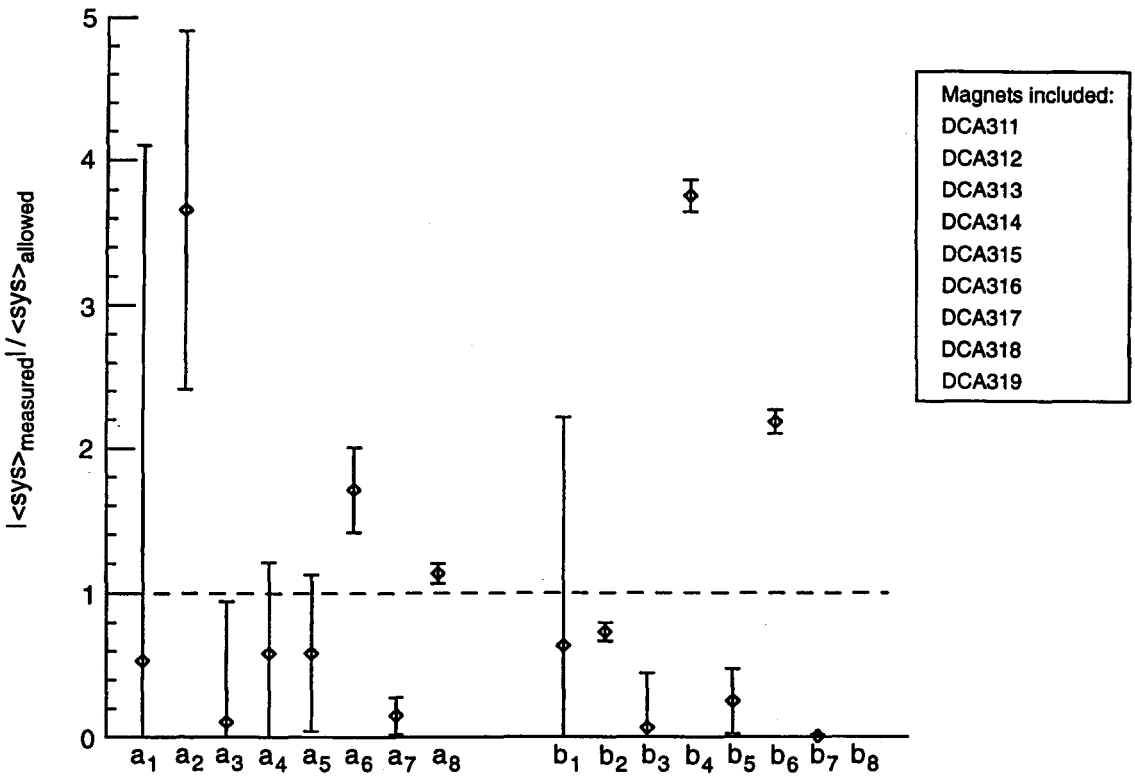


Figure 6a. Ratio of Measured Harmonics to Allowed Values for FNAL/GD ASST Dipoles.

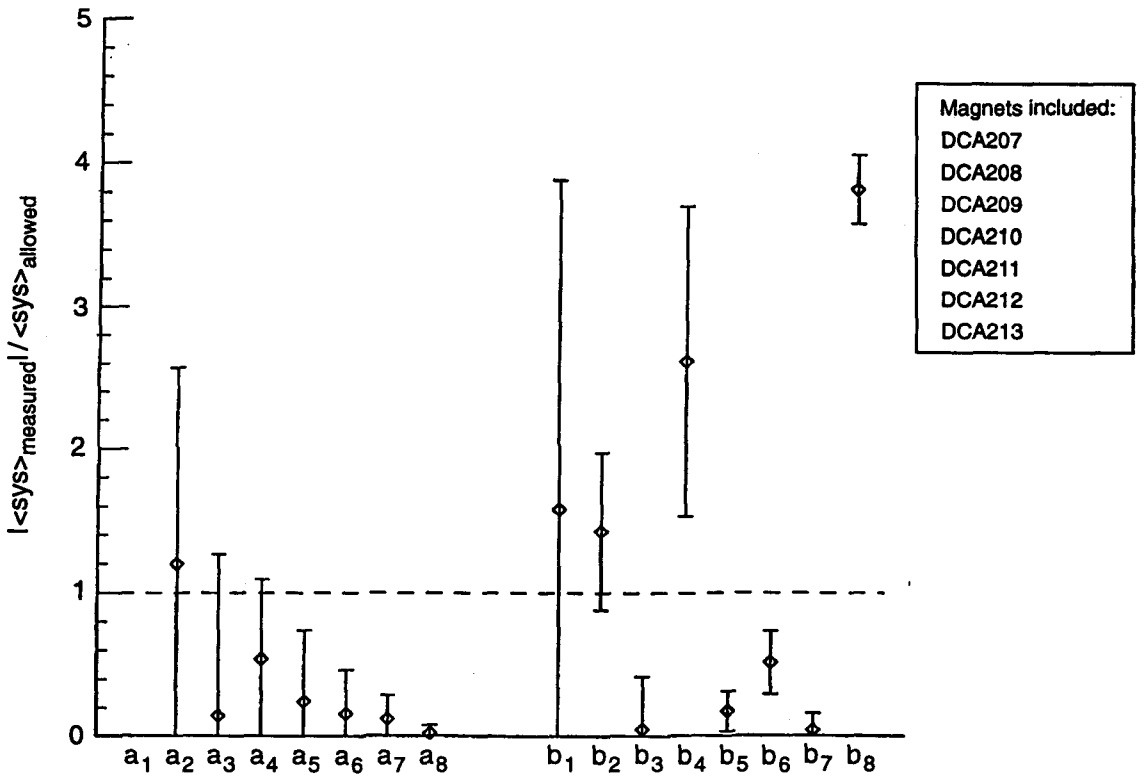


Figure 6b. Ratio of Measured Harmonics to Allowed Values for BNL/WEC ASST Dipoles.

3.5 Performance of Magnets in a Half Cell String Test

The string test consisted of five model dipoles (DCA313–DCA317) and one quadrupole magnet (QCC403) which were connected in a string with two spool pieces at the SSCL N15 site. The primary objective of the test was to demonstrate the capability to operate five industrially-assembled dipoles connected in a string at the collider operating conditions of 6500 A and 4.35 K. The spool pieces were required at each end of the string for cryogenic and electrical service connections. The quadrupole was added to simulate the operation of a complete half cell. The primary objective was attained when the current was ramped up to 6525 A and held there for a few minutes as shown in Figure 7. Future plans for the string include upgrading the refrigerator by the end of the year to permit extensive quench, heat load and system parameters testing.

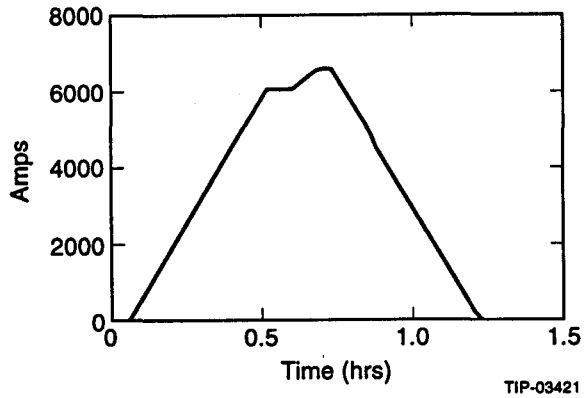


Figure 7. Current Ramp for ASST Milestone.

3.6 Manufacturing Experiences and Future Development

General Dynamics has developed a baseline design for the Collider Dipole Magnet based on the concepts employed in the ASST magnets described above. In addition, lessons learned at FNAL and BNL during the industrial assembly of these magnets have been folded into the design and manufacturing processes for the next phase of magnet production. Most of the features of the cold mass construction and cryostat have been taken from the FNAL design with some features from the cold mass of the BNL design. Table IV lists the main differences between the FNAL and BNL cold mass designs, and Table V lists the principal features of the GD dipole design.

The magnet development program will continue with the production of 12 prototype magnets of the GD baseline design at the Hammond, LA. plant of GD. This will be followed by the manufacture of 35 pre-production magnets and 251 Low Rate Initial Production (LRIP) magnets at each location according to the schedule in Figure 8 which also includes the quadrupoles by B&W. Each of the prototype and pre-production magnets will be cryogenically tested to verify quench performance and field quality and as many of the LRIP magnets as possible will be tested at the four cryogenic test stands at Hammond and at the three in Round Rock.

TABLE V. GD BASELINE DIPOLE DESIGN COLD MASS FEATURES.

DESIGN FEATURE	GD VERSION
Magnetic Design	Iteration of ASST Design To Correct Systematic Multipole Offsets.
Yoke Laminations	6.25 mm Thick, Fine Blanked with Semi-Perforations To Index Laminations Together, Horizontal Split.
Collar Laminations	2.5 mm Thick, Fine Blanked with Semi-Perforations To Couple Pairs of Laminations Together.
Coil End Construction	Grouped Ends between Saddle Pieces Clamped in End Collars.
Inner–Outer Coil Splice	Modified Internal Splice in Lead End.

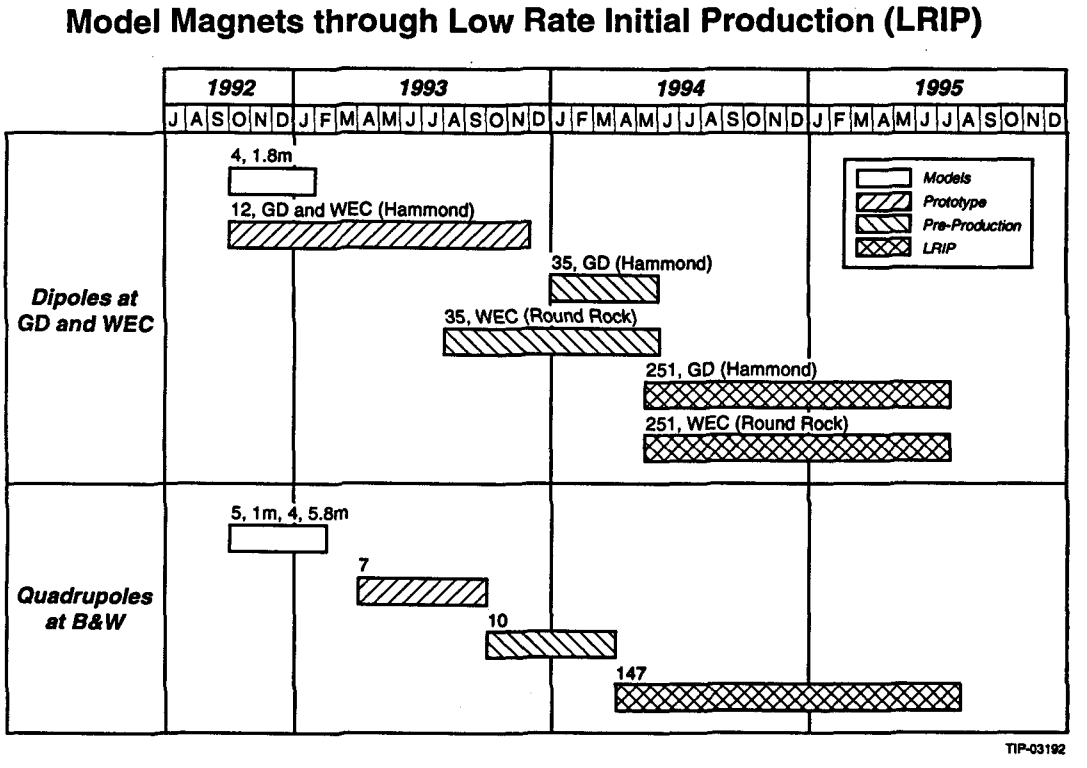


Figure 8. Collider Dipole and Quadrupole Program Schedule.

4. STATUS OF THE QUADRUPOLE MAGNETS

The initial development of the quadrupole magnets has been carried out at LBL over the past two years; thus, the program has not yet achieved the maturity of the dipole program. Several 1-m models and full-length 7-m magnets with cryostats have been built and tested.[5] LBL has been responsible for the design of the cold masses for the full-length models and the cryostats were designed and built at SSCL. A cross-section of the LBL quadrupole design is shown in Figure 9. The quench performance of five full-length prototype magnets is shown in Figure 10. The primary concern is the quench performance since significant training and re-training (after a thermal cycle) is evident. However, most training occurs well above operating current. The continued development of the Collider Quadrupole Magnet will be carried out by B&W according to the schedule in Figure 8. The magnetic cross-section will be the same as the LBL design; however, the cold mass mechanical design is somewhat different as shown in Table VI.

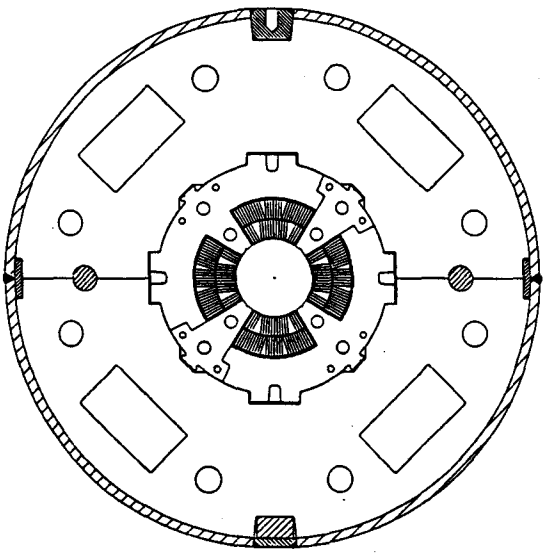
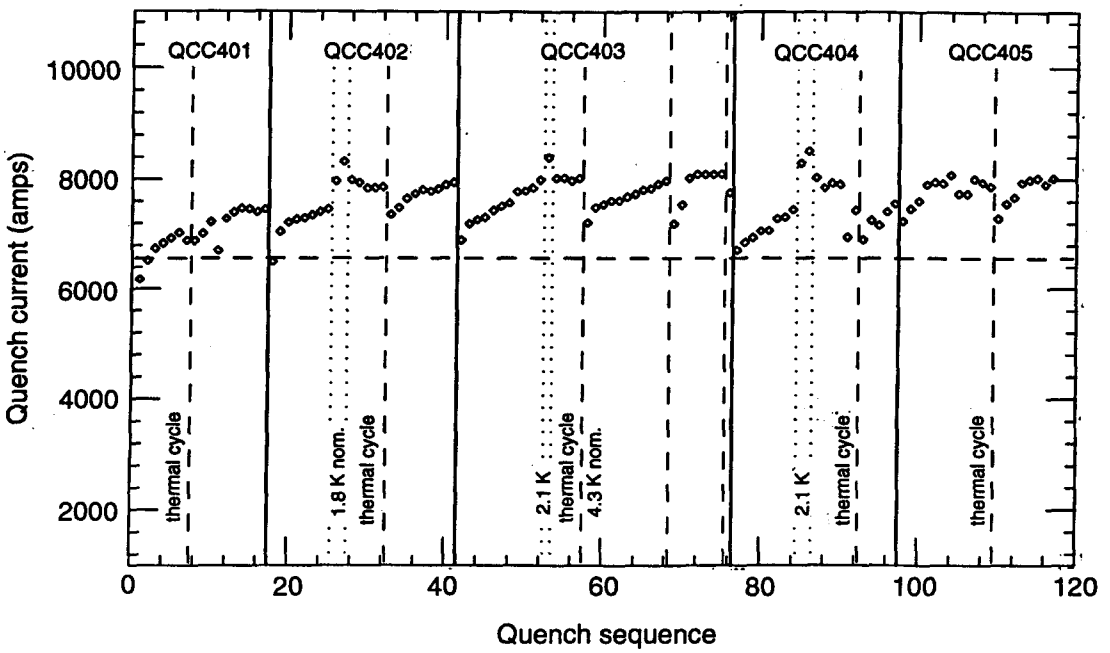


Figure 9. LBL Model Collider Quadrupole Cross Section.



Notes:

(1) –dashed lines indicate thermal cycles; magnet warmed to 300K and then re-cooled

(2) –temperatures other than nominal 4.35K are indicated on the plot

Figure 10. Quench Performance – Full Length Collider Quadrupoles. QCC-Series– LBL Design.

TABLE VI. B&W BASELINE DESIGN COLD MASS FEATURES COMPARED WITH LBL PROTOTYPE DESIGN.

DESIGN FEATURE	B&W VERSION
Magnetic Design	Same Magnetic Cross-section as LBL Version.
Collar Laminations	Two Piece Stainless Steel Collars Derived from HERA Quadrupole Design. (LBL Version Used Four Piece Aluminum or Stainless Steel Collars.)
Coil End Support	Unsupported with a Sliding Interface between Collars and Yoke. (Subject to Verification in Model Magnet Tests.)
Inner–Outer Coil Splice	No Splice Is Used. Outer Coil Is Wound and Cured over the Previously Cured Inner Coil. Requires a Spacer between Inner and Outer Coils.

5. SPECIAL MAGNETS FOR THE COLLIDER

In addition to the magnets in the regular arcs, special dipole and quadrupole magnets are required to focus the two proton beams in the interaction regions of the collider. These magnets are intended to be designed and fabricated at the SSCL. The first of the models for a 5-cm aperture, 14-m-long interaction region quadrupole has been designed, built and tested at the SSCL. This magnet is shown in cross section in Figure 11. The coils in this quadrupole design are assembled with collars that are similar to those used for the dipole magnets. Thus, collaring of the coils can be efficiently performed on the same press used for the dipole magnets. The quadrupole symmetry of the coils is obtained from the four laminated insets that form the poles as shown. This magnet achieves a gradient of 190 T/m at the operating current of the collider and utilizes two layers of the same cable that is used for the outer layer of the dipole. Two 1.8-m long models of this magnet have been built and tested. Figure 12 shows the quench performance of the most recently tested model, QSE102. There were three training quenches well above the operating current of the machine. Degradation of quench current with ramp rate is shown, but little effect is seen in the region of normal machine operation.

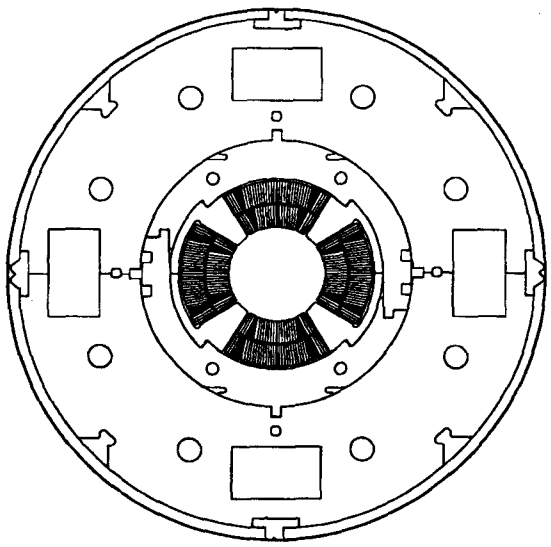


Figure 11. Cross Section of 50 mm Aperture Quadrupole for Collider Interaction Regions (QSE102).

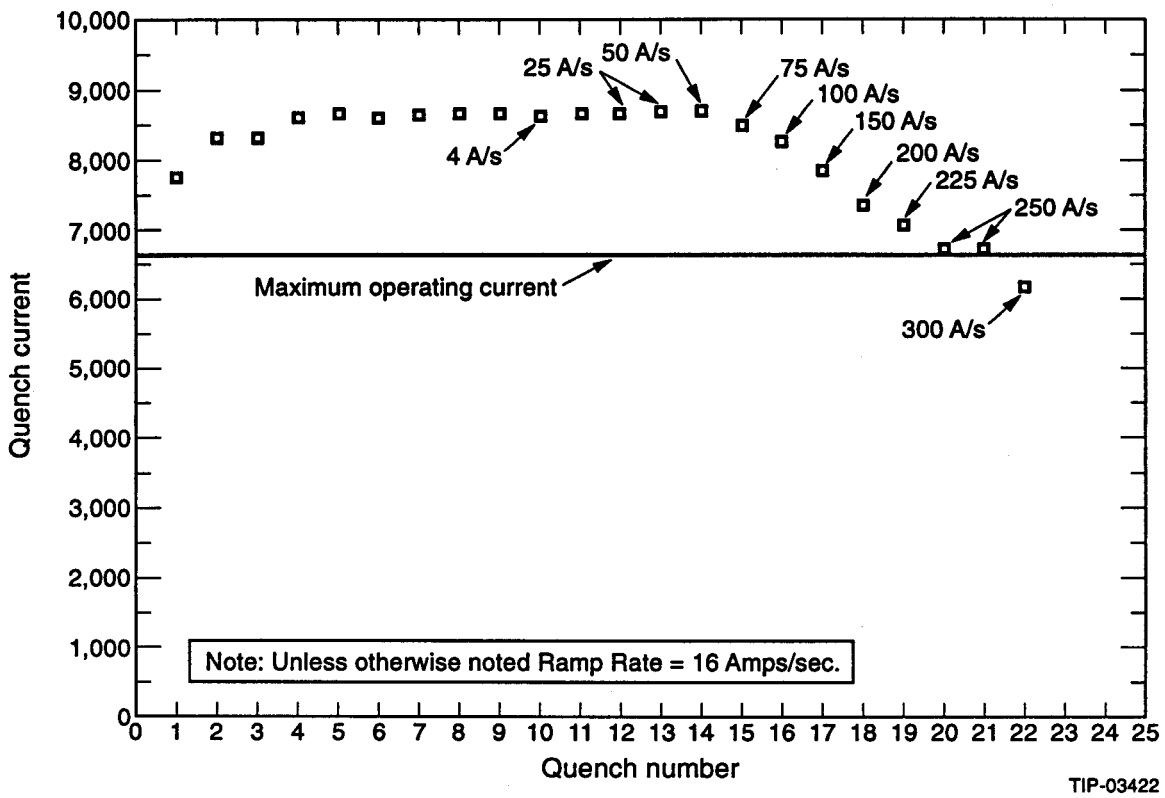


Figure 12. QSE 102 Quench Performance September 2, 1992.

6. CONCLUSIONS

1. Quench performance of individual dipoles shows little training and almost no re-training with 10% operating margin above collider requirements at 4.35 K.
2. Verification of half cell operation (string test) was successful by demonstrated capability of sustained operation at 6500 A.
3. Present concerns: Ramp rate dependent eddy current effect in dipoles. Quench performance of collider quadrupole models: new cold mass mechanical design by B&W is in the model stage at B&W.
4. Field quality random multipoles are well controlled in the dipoles. Systematic allowed multipoles need tuning; work underway at General Dynamics for prototype. Systematic unallowed multipoles dependent on new tooling being set up in Hammond plant: information forthcoming.
5. The program to design and build the first "in-house" magnets for the collider has been initiated. Two models for the insertion region quadrupoles have been built and successfully tested at the SSCL.

REFERENCES

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[2] Delchamps, S.W., *et al.*, "SSC Collider Dipole Magnet End Mechanical Design," ibid., p. 2185.

[3] Anerella, M., *et al.*, "Construction and Test Results from 50 mm Aperture SSC Collider Dipole Models," Presented at the International Industrial Symposium of the Supercollider, New Orleans, March 4–6, 1992. To be published in *Supercollider 4*.

[4] For the accelerator operation, a specified quality or purity of the dipole field is required. The magnetic aberrations to the dipole field can be quantified by the level of multipoles present as defined by a Fourier expansion of the measured central field in the magnets. Thus if a_n and b_n represent the amplitude of the harmonics having 2n+2 poles in the skew and normal directions that are present in the pure dipole field, then the quality of the field can be described by amplitude of these coefficients. Furthermore, certain of the harmonics are associated with symmetric conductor placement in the four quadrants of the two dimensional cross section of the coil. These are called the "allowed harmonics" of the dipole symmetry and are b_0, b_2, b_4, b_6, ... *etc*. Other harmonics, all the a_n and b_n where n is odd, can not occur with symmetrical placement of the conductors and are thus "unallowed." thus, the allowed harmonics can be tuned to an acceptable level by an adjustment of the conductor positions in the magnetic design. On the other hand, the unallowed harmonics can only be affected by the manufacturing process or content of magnetic material in the cold mass.

[5] Taylor, C.E., *et al.*, "Construction and Test Results on 40 mm Bore 5 m Long Quadrupole Magnets for the SSC," IEEE Transactions on Applied Superconductivity, for March 1993.