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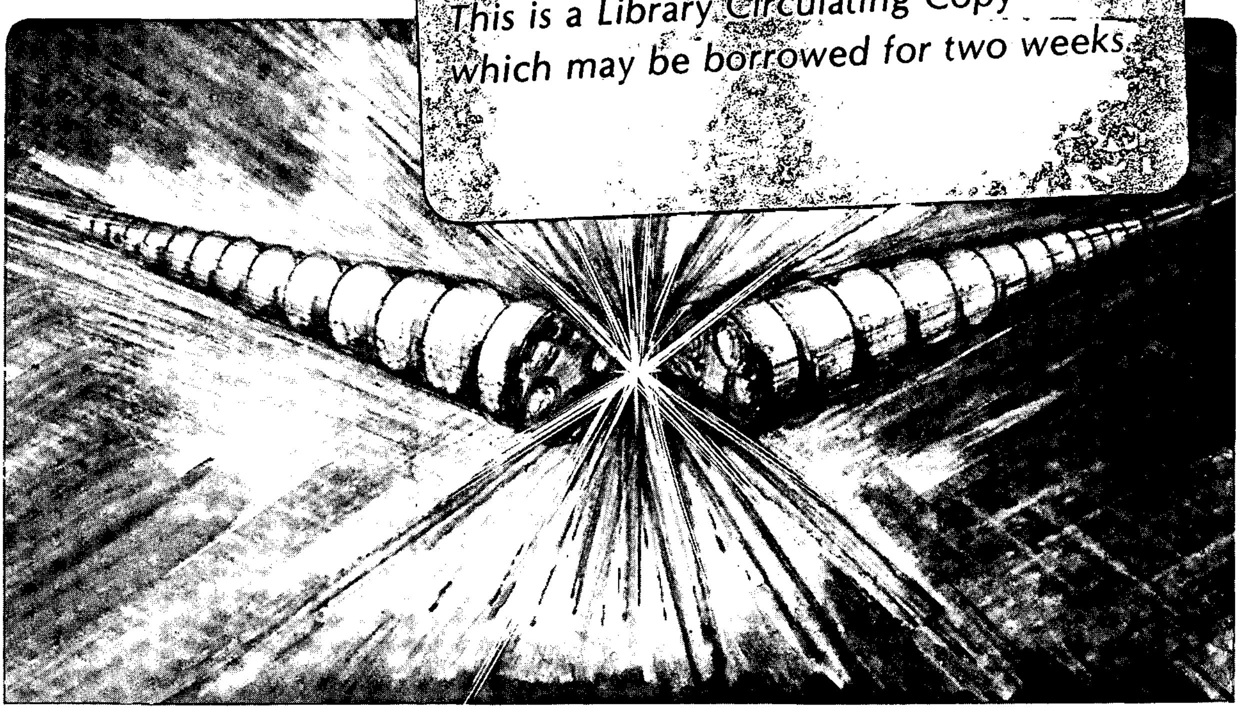

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DISCLAIMER

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ABSTRACT

A design is presented for a dipole magnet suitable for the proposed SSC facility. Test results are given for model magnets of this design 1 m long and 4.5 m long. Flattened wedge-shaped cables ("keystoned") are used in a graded, two-layer "cos θ" configuration with three wedges to provide sufficient field uniformity and mechanical rigidity. Stainless steel collars 15 mm in radial depth, fastened with rectangular keys, provide structural support, and there is a "cold" iron flux return. The outer-layer cable has 30 strands of 0.648 mm diameter NbTi multifilamentary wire with Cu/S.C. = 1.8, and the inner has 23 strands of 0.808 mm diameter wire with Cu/S.C. = 1.3. Performance data is given including training behavior, winding stresses, collar deformation, and field uniformity.

INTRODUCTION

The U.S. high energy physics community has begun preparation of a conceptual design and proposal for a 20 TeV colliding beam facility called the SSC (Superconducting Super Collider). R&D on the main dipole magnets has been initiated, and several models of promising magnet styles have been designed and tested. One of these designs, with a central field of approximately 6.4 T, a winding I.D. of 40 mm, collars for

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structural support, and a "cold" iron flux return yoke is designated "Design D" and is being developed by collaborating groups at BNL, Fermilab, and LBL. A cross section of this design is shown in Fig. 1. This paper describes the magnet portion of the system (windings, structure, iron) which has been developed mainly at LBL and BNL. Another paper in these proceedings describes the cryostat system that has been developed mainly by Fermilab.[1]

Because of the large number of dipole magnets required (approximately 8,000), an effort is made to minimize the cost and to anticipate the use of mass production techniques. The main design features are described below, and test results are presented on model magnets constructed at LBL and BNL.

COILS AND CABLE

To minimize the amount of superconductor and iron, we have chosen the very small inner diameter of 40 mm (the Tevatron at Fermilab has a bore diameter of 76 mm), used a minimum amount of copper in the cable, and have placed great emphasis on obtaining maximum current density in the NbTi superconductor. The cable is a flattened "Rutherford" cable arranged in two layers as shown in Fig. 1. Each layer consists of an upper and lower winding with the four windings connected in series; the outer cable contains less superconductor than the inner winding because it is in a lower magnetic field. The inner cable has 23 strands of 0.808 mm diameter wire with a copper-to-superconductor ratio of 1.3; the outer cable has 30 strands of 0.0648 mm diameter wire with a copper-to-superconductor ratio of 1.8. The copper-to-superconductor ratio is chosen to give the inner and outer layers approximately equal quench protection behavior. The strands do not need to be insulated from one another because the rate

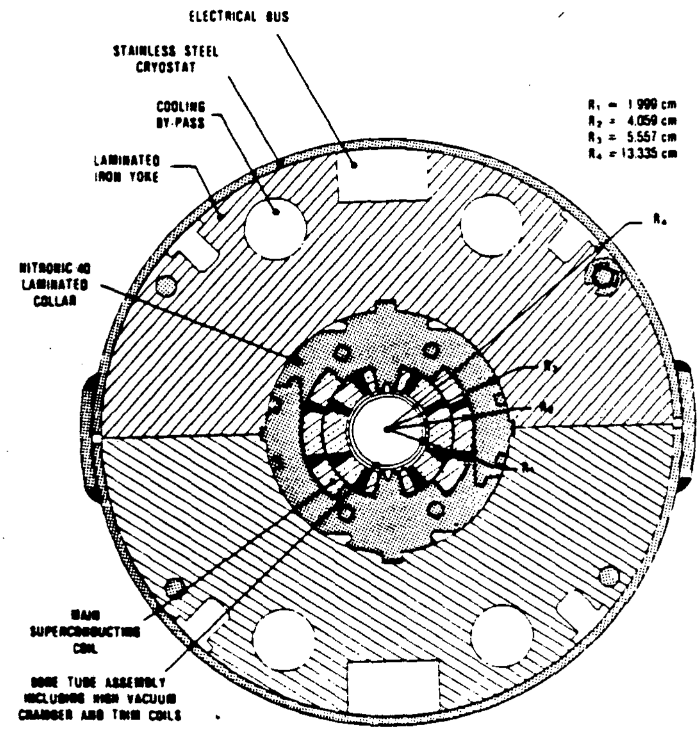

Fig. 1. Cross section of collared coil assembly surrounded by a circular split yoke of laminated steel.

of field increase during acceleration in the SSC is very low (approximately 15 minutes to accelerate from 1 to 20 TeV). The cable is compacted to an average of about 90% of its maximum density. One edge is thinner than the other to maximize the number of turns. Wedges, inserted in each layer, are located to maximize the uniformity of the field, and are also designed to provide for mechanical stability of the winding under the high circumferential compressive stress that is applied when the collars are squeezed into place. The winding is not supported on its inner diameter.

Because of the considerable benefits from maximizing current density (J_c) in SSC magnets, an R&D program was pursued to utilize, on a commercial scale, increased NbTi homogeneity and new methods of multiple heat treatments that are known to improve J_c. The results of this program, and the development of the Design D cable, are described by Scanlan.[2] The cable used in models built to date has strand J_c of about 2500 A/mm^2 (4.2 K,5 T, 10^{-12}ohm-cm) for the inner cable and up to 2700 A/mm^2 for the outer cable. These early models reach a central field of at least 6.6 T at 4.5 K. We expect that further improvements of the commercial material will be achieved soon, and that a critical field of about 6.8 T will be obtained. Tentatively, we have assumed an operating field of about 6.4 T, allowing for a safe operating margin.

COLLARS

Interlocking collars shown in Fig. 1, similar to those used in the Tevatron dipoles, provide structural support; however, instead of assembly by welding as in the Tevatron, rectangular keys are used to lock collars together. The collars provide precompression of the windings and complete support of the Lorentz forces. The collared coil assembly is suspended in the iron yoke by the four tabs, with enough clearance to allow for collar deformation under load; therefore, the split iron yoke does not need to resist the Lorentz forces. To minimize the radial collar thickness, a high-strength stainless steel, Nitronic 40* was selected for initial models, which allows a 15 mm thickness.

An estimate of the minimum circumferential precompression pressure required in the windings can be made as follows: at B_o = 6.5 T, the circumferential pressure in the windings at the coil mid-plane, generated by the accumulated Lorentz forces on each turn, is 38 MPa in the inner layer and 30 MPa in the outer layer, assuming rigid cable and no friction. If the collars are assumed to be rigid, the precompression in each layer must be greater than about 2/3 of this value to prevent the turn adjacent to the pole from separating from the pole under load; this is taken as a desired design requirement. For steel collars, the room temperature preload must exceed this value by approximately 10 MPa precompression during cooldown because the winding shrinks more than the collars. Target values for circumferential precompression at assembly are 34 MPa for the inner layer and 29 MPa for the outer layer.

One meter model magnets were made at LBL using both 15 mm Nitronic 40 collars, and 25 mm aluminum alloy collars. Collar deformation due to assembly, cooldown, and magnet operation is measured on these models.[3] Typical deformation of the steel collars in the 1-m models, in terms of change in diameter at assembly, is + 0.15 mm horizontal and + 0.30 mm vertical; these values include the effects of clearances and tolerances

*Armco, Inc.; approximately 410 MPa min. tensile yield strength at room temperature.

for the keys and pins. When energized to 6 T, the dimensions change by about + 0.08 mm horizontal and -0.05 mm vertical.

Pressure measurements are made at the pole on both inner and outer windings using a strain-gage system illustrated in Fig. 2.[3] Fig. 3 shows the pressure history during cooldown in a magnet with 25 mm aluminum collars. Note the net increase in prestress during cooldown of about 14 MPa because of the thermal contraction of aluminum being greater than the windings; this is in contrast to a decrease with stainless steel. Thus, about 28 MPa lower prestress is required at assembly for aluminum than for steel which is an advantage of aluminum collars. However, the approximately 1 cm greater thickness required of aluminum collars results in a decrease in magnetic field contributed by the iron yoke and, therefore, steel was selected for most of the models.

Figure 4 shows the pressure at the pole in an aluminum collared magnet as the winding is energized. These measured values differ significantly from the prediction of the simple friction-free, rigid collar model. During the first few cycles of the magnet to full field, a distinct hysteresis is seen, perhaps due to friction between layers and between cable and collars. After several cycles, the pressure at the pole decreased by about 24 MPa in both layers, the hysteresis disappeared, and measured pressure became reversible; similar behavior was seen in the magnets with steel collars.

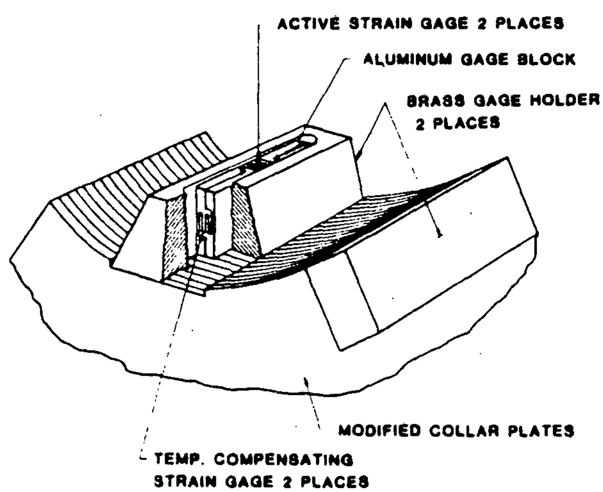

Fig. 2. Location of strain gages used to measure circumferential pressure between cable and collars.

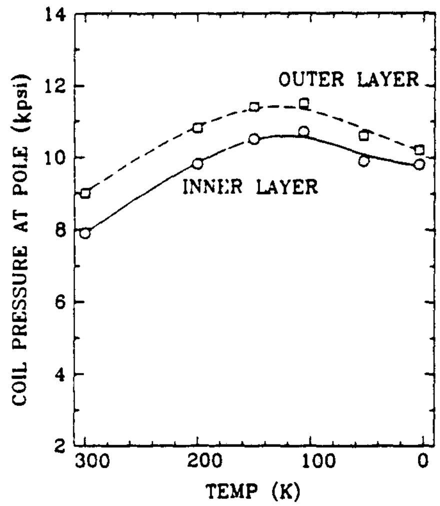

Fig. 3. Pressure vs. temperature during initial cooldown of magnet.

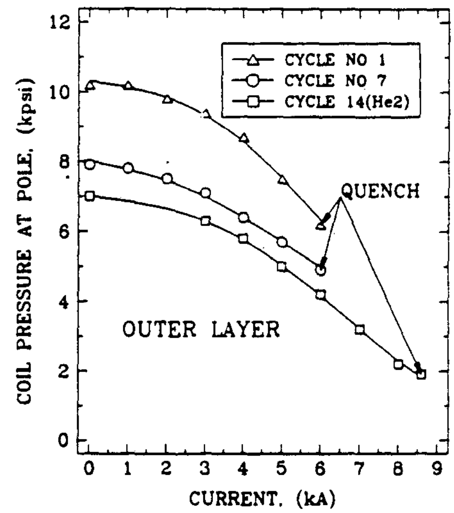

Fig. 4. Pressure vs. current for outer layer showing decrease as coil is cycled. (6 kA = 6 T)

MAGNETIZATION EFFECTS

Current induced in the superconducting filaments produces a diamagnetic effect as field increases and a paramagnetic effect as field decreases. Figure 5 shows a field line plot and Fig. 6 shows field lines due to magnetization alone for field increasing up to 0.28 T.[4] The resulting systematic distortion of the central field must be corrected by auxiliary windings. Such windings are generally relatively small and are

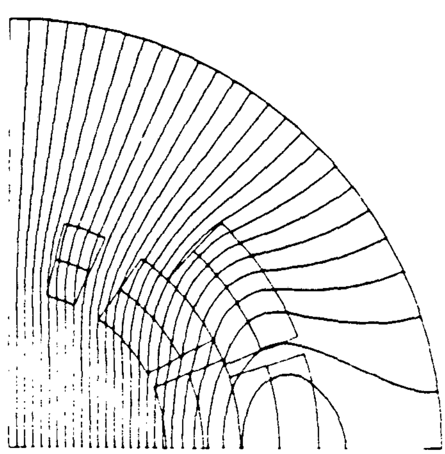

Fig. 5. Field line plot; includes transport current plus magnetization effects.

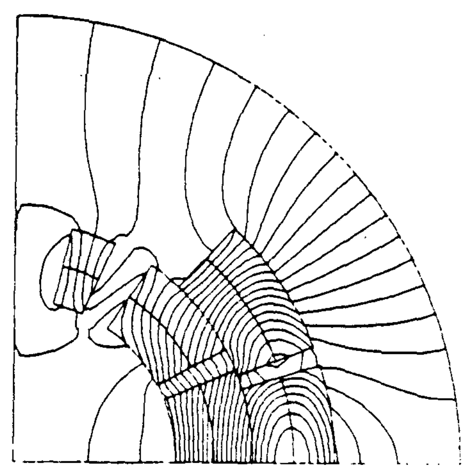

Fig. 6. Field line plot for magnetization only at B_0 = 0.28 T.

located near the focussing magnets (about every 100 m in the SSC). However, if the distortion exceeds a relatively small value of 2-3 x 10^{-4} of the dipole field, it must be corrected more frequently along the accelerator, perhaps continuously along the length of each magnet. The cable used in the Design D models has filament sizes of 23 μm and 19 μm on the inner and outer windings respectively, which produces a sextupole distortion of about 30 x 10^{-4}. Figure 7 shows the measured sextupole field in an LBL model, along with a predicted curve based on magnetization measurement of cable samples. It can be seen that the observed effect is closely predicted, and that, at the SSC injection field of about 0.32 T, the magnitude is 30 x 10^{-4}, which must be corrected locally. This can easily be done with a sextupole winding on the bore tube. The model magnets have such a winding, wound with a single layer of 0.51 mm diameter superconducting wire, and the ability to correct this effect has been demonstrated. Passive self-energized correction-coil schemes which do not require external power supplies, are being developed.[5,6] However, the magnitude of the field distortion is nearly directly proportional to filament size;[7] and for the SSC, 3 μm filaments will probably eliminate the need for distributed correction coils; 8 μm, filaments as used in the Tevatron, are easily produced. Recent progress indicates that 3 μm filaments with very high current density can be economically produced[8,9] using a variety of techniques. We can, therefore, eliminate or reduce the required correction field.

MAGNET CONSTRUCTION

The LBL model magnets differ in several minor details from the longer BNL models; The LBL cable insulation is two Kapton wraps; a 0.025 mm butt-wrap (not overlapped) is overlaid with a 0.05 mm butt-wrap; the outer Kapton has a thin epoxy adhesive layer to hold the turns together after molding. The BNL insulation is identical to that used on the Tevatron and CBA (Colliding Beam Accelerator at Brookhaven); it has an overlapped wrap of 0.025 mm Kapton covered by a butt-wrap of fiberglass tape impregnated with B-stage epoxy. Both schemes include molding of each of the four windings at about 69 to 117 MPa in a precision fixture at about 130°C to ensure reproducible coil dimensions and to glue the turns together, which will facilitate assembly of the coils.

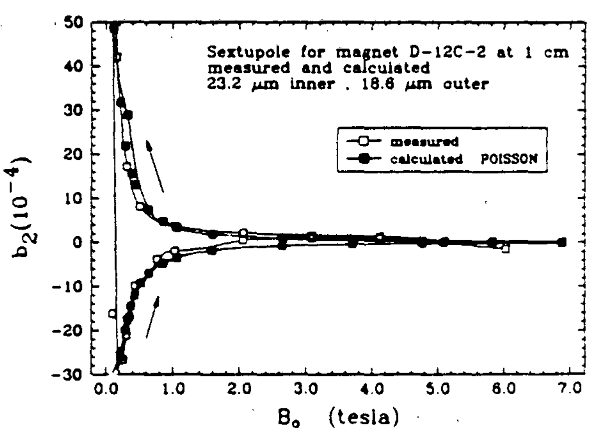

Fig. 7. Measured sextupole harmonic vs. B_o for LBL model D12C-2 compared with calculated values.

The ends of the BNL coils have large-radius bends designed to accommodate prereacted Nb_3Sn cable. This feature is not necessary for NbTi and will be eliminated. LBL ends have only a very slight bulge to allow easy winding of the inner cable around the small bore.[3] Even this small bulge can probably be eliminated, if necessary, with careful winding techniques.

Several layers of preshaped 0.13 mm in Kapton are placed between layers and over the outside of the assembled windings for electrical insulation. Collar halves are assembled into units about six inches long and fastened around the coils in increments as coils are moved through a collaring press. The winding is squeezed to a pressure about 2.5 times greater than the desired final prestress to permit easy insertion of the keys; cable prestress decreases as the load is transferred from press to collars because of keyway clearances and collar deformation.

Figure 9 shows a completed 1-m model in its rectangular iron yoke. Figure 10 shows a 4.5 m model ready for testing; it has a 267 mm diameter laminated iron yoke as illustrated in Fig. 1.

FIELD UNIFORMITY

Field uniformity in accelerator magnets is usually expressed in terms of a harmonic analysis of the variation from a perfect dipole field.

$$B_x + B_y = B_o \sum_{n=o} c_n z^n \quad \text{where} \quad c_n = a_n + i\, b_n,$$

defined at a reference radius, in this paper, of 1 cm; $z = x + iy$.

The coefficients b_2, b_4, b_6, etc., are the "allowed" multipole (sextupole, 10 pole, 14 pole, etc.) field components. In a perfectly symmetrical winding, all a_n's and odd b_n's are zero, and b_2, b_4, etc.,

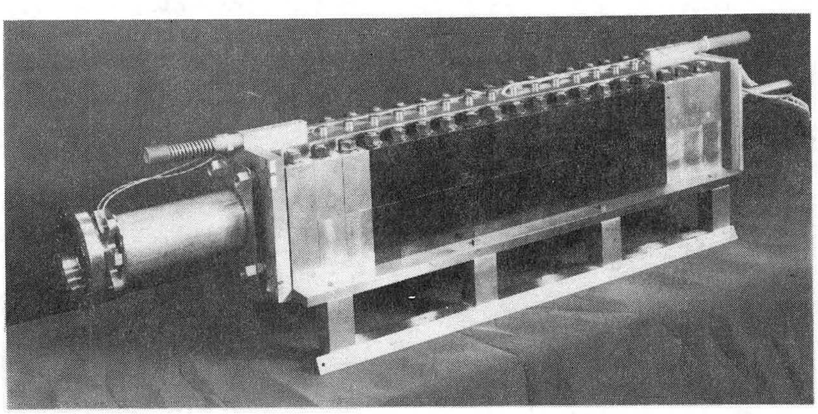

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Fig. 8. 1-m LBL model with a rectangular iron yoke ready for testing in a horizontal cryostat.

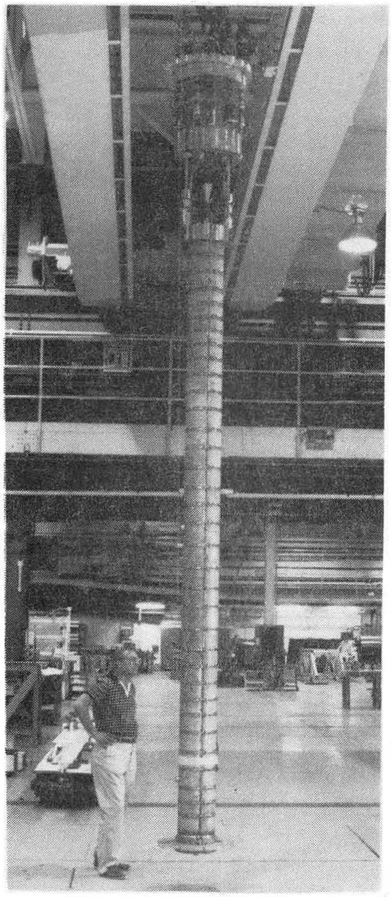

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Fig. 9. 4.5 m BNL model with a circular laminated iron yoke ready for testing in a vertical cryostat.

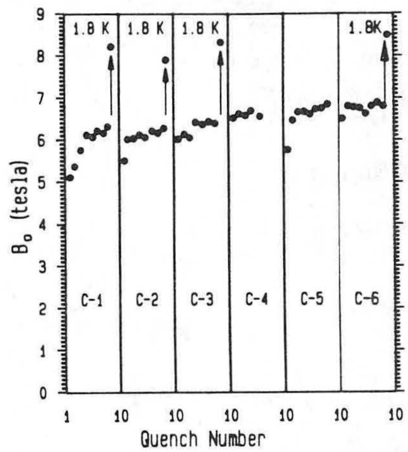

Fig. 10. Training behavior of the first six 1-m LBL SSC dipole models at 4.4 K. C-1,3 have 25 mm Al collars; C-2 has 15 mm machined collars, C-4,5,6 have 15 mm stamped collars and improved cable. Critical field achieved at 1.8 K is shown.

are controled and minimized by placing turns in the proper location. Field correction magnets are usually used to compensate for small systematic sextupole distortions.

Table 1. shows the mean value and standard deviation for all non-allowed multipoles in five LBL models.* The allowed terms, b_2, b_4, and b_6 are large because these models each have deliberate variations in

*Model C-1 has a different distribution of turns and wedges in the cross section, and is not included.

the cross section to adjust precompression stress on the cable. The table shows that the non-allowed terms are very small, implying a high degree of symmetry in the magnet cross section and implying that the desired magnet-to-magnet consistency can be expected using these construction methods and cable designs. It is expected that, after more models are constructed, a small dimensional adjustment of the three wedges can be incorporated into the design to bring the allowed multipoles into close agreement with the predicted values. Table 2. shows measurements on the BNL models, all constructed with identical cross sections; agreement with prediction is good.

MODEL MAGNET PERFORMANCE

Figure 10 shows the training behavior for six 1-m LBL models; magnets C-1 and C-3 have 25-mm aluminum collars; magnets C-4, C-5, and C-6 have improved cable with higher critical current and 15 mm stainless steel collars identical to those in the BNL models. Among these last three models only one quench below 6.4 T was experienced and the critical field was 6.6 T or higher. Figure 11 shows similar good training behavior for four 4.5 m BNL models.

Table 1. Measurements on LBL SSC Dipoles at r = 1 cm, B_o = 3 T, in units of 10^{-4} x Dipole.

		Magnet Designation					C-2 thru C-6		Expected
		C-2	C-3	C-4	C-5	C-6	Mean	σ	σ*
"Allowed" Harmonics	b_2	6.33	12.01	16.54	9.85	-6.06	7.73-	8.55	2.15
	b_4	1.00	1.24	-0.03	-0.50	0.54	0.77	0.77	0.59
	b_6	0.36	0.38	0.13	0.14	-0.68	0.07	0.43	0.08
	b_8	0.84	0.78	0.62	0.66	0.64	0.71	0.10	0.02
"Forbidden" Harmonics	b_1	-1.51	2.96	0.30	-0.79	-1.58	-0.12	1.88	1.8
	b_3	0.05	-0.24	0.28	0.41	0.13	0.13	0.25	0.35
	b_5	-0.08	-0.09	0.03	0.06	-0.17	-0.05	0.09	0.059
	b_7	-0.27	0.10	-0.04	0.02	0.27	0.02	0.20	0.016
	a_1	-0.55	0.25	0.09	-0.51	-1.42	-0.43	0.658	·3.3
	a_2	0.54	0.92	0.09	0.26	1.01	0.56	0.40	0.63
	a_3	0.12	0.25	-0.02	-0.08	-0.06	0.05	0.14	0.69
	a_4	0.22	0.20	-0.02	-0.02	-0.03	0.12	0.16	0.14
	a_5	-0.04	0.04	0.04	-0.02	0.00	0.00	0.04	0.16
	a_6	0.06	0.03	0.02	0.01	0.02	0.03	0.02	0.034
	a_7	-0.16	0.20	0.01	-0.01	-0.01	0.00	0.13	0.030
	a_8	0.12	0.08	0.06	0.07	0.00	0.07	0.04	0.006

Calculated "allowed" terms for the theorectical cross-section are b_2 = .4, b_4 = 0, b_6 = .2, b_8 = .8

Table 2. Measurements on BNL SSC Dipoles at r = 1 cm, B_0 = 2 T, in units of 10^{-4} x Dipole.

		Magnet Designation SLN-8	SLN-9	SNL-10	SLN-11	SLN-8 THRU SLN-11 Mean	σ	Expected σ*
"Allowed"	b_2	-2.03	-2.82	-5.62	-5.09	-3.89	-1.74	2.0
Harmonics	b_4	0.10	-0.21	-1.07	-0.78	-0.49	0.53	0.59
	b_6	0.02	0.01	-0.12	0.02	-0.02	0.07	0.08
	b_8	0.93	0.91	0.92	0.92	0.92	0.01	0.02
"Forbidden"	b_1	0.59	-0.39	1.01	-0.16	0.26	0.65	1.8
Harmonics	b_3	-0.06	-0.05	0.25	-0.25	-0.03	0.21	0.35
	b_5	-0.01	0.03	-0.03	-0.01	-0.01	0.03	0.059
	b_7	0.09	0.05	0.00	0.26	0.10	0.11	0.016
	b_9	-0.01	-0.01	-0.01	0.00	-0.01	0.00	
	a_1	-1.23	-2.51	-2.47	1.96	-1.06	2.10	3.3
	a_2	0.32	0.24	0.32	0.24	0.28	0.05	0.63
	a_3	-0.43	-0.40	-0.96	-0.37	-0.54	0.28	0.69
	a_4	-0.05	0.05	-0.20	0.22	-0.01	0.18	0.14
	a_5	-0.19	-0.03	0.12	0.13	0.01	0.15	0.16
	a_6	0.02	0.04	-0.05	0.07	0.02	0.05	0.034
	a_7	-0.01	0.00	0.01	0.01	0.00	0.01	0.030
	a_8	0.09	0.15	0.09	0.15	0.12	0.03	0.006
	a_9	-0.02	-0.00	-0.02	-0.02	-0.02	0.01	

*predicted by extrapolation from Tevatron and CBA dipole magnet measurement.[10]

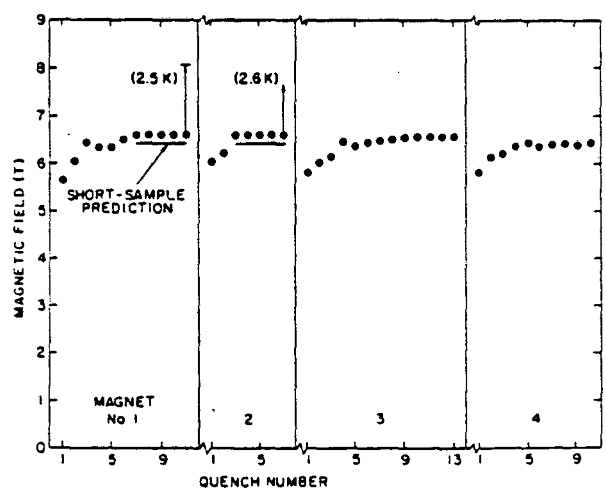

Fig. 11. Magnetic field at quench of four 4.5 m BNL SSC dipole models at 4.5 K.

CONCLUSION

This magnet design promises to meet the requirements for an SSC. Both the 1-m models and the 4.5-m models show minimal training behavior and good field uniformity. Several new design features appear to be practical for long magnet production including keyed collar assembly and multiple wedge-shaped spacers to control field uniformity. Also, it appears that high-current-density strands can be produced in large quantities, fabricated into 30 strand cable, and wound using conventional techniques.

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