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THE MAGNETIC PROPERTIES OF THE SLC INTERSECTION REGION SUPERCONDUCTING QUADRUPOLE TRIPLETS

A. D. McInturff, J. A. Carson, H. E. Fisk

Fermi National Accelerator Laboratory*
P. O. Box 500
Batavia, Illinois 60510

R. A. Erickson

Stanford Linear Accelerator Center†
P. O. Box 4349 Bin 21
Stanford, California 94305

Abstract: The measured magnetic field parameters of the quadrupoles which comprise the final triplet lens system for the the SLAC Linear Collider intersection region are presented here. The minimum design gradient specifications for these quadrupoles are 1.7T/cm at 4.6K and 1.6T/cm at 4.6K in a 0.6T external solenoidal field. These gradients are about three times larger than those available with the conventional iron/copper quadrupoles now used in the SLC. Superconducting quadrupoles of two lengths have been specified for the SLC triplets. The effective magnetic length of type Q_1 is 66.498 ± 0.305cm and of Q_2 is 121.106 ± 0.61cm. The superconducting performance characteristics of the quadrupoles that have been measured are: maximum critical current as a function of bath temperature, rate of change of magnetic field, and as a percentage of the "short sample". "Short sample" performance is defined as the current reached by the cable in a perpendicular magnetic field equal to the peak field in the winding at bath temperature. The maximum gradient achieved during testing was 2.09T/cm (4.25K) and 2.10T/cm (3.2K). This represented 95% of the strand critical current value. The magnetic length of the first Q_2 was measured to be 120.85 ± .1 cm. The Fourier harmonic coefficients of the magnetic field were measured as a function of current and are reported.

Introduction: A pair of superconducting triplets comprise the proposed superconducting final focus system. The operational gradient for the elements in the triplets is about 1.35T/cm at a beam energy of 55 GEV. This higher gradient should increase the luminosity by a factor of 1.6 to 3.2 compared[1] to the present conventional system. The triplet quadrupoles do not have iron shields due to their physical position inside the 0.6T solenoidal field of the detector.

Design and Construction

The design of the SLC triplet quadrupole is covered in an earlier paper.[2] The cross-section of the 96 turn winding and collar structure is shown in Figure 1. The inner winding diameter is five centimeters, and the clear aperture is 4.6cm. This aperture was dictated by the background radiation requirements of the experimental detector. A smaller aperture would result in unacceptably high rates of secondary scattered electrons. The design of these quadrupoles is basically similar to the Tevatron quadrupoles, except for the smaller aperture. The magnetic field was lowered in the ends of the coil by the addition of six spacers between the turns nearest

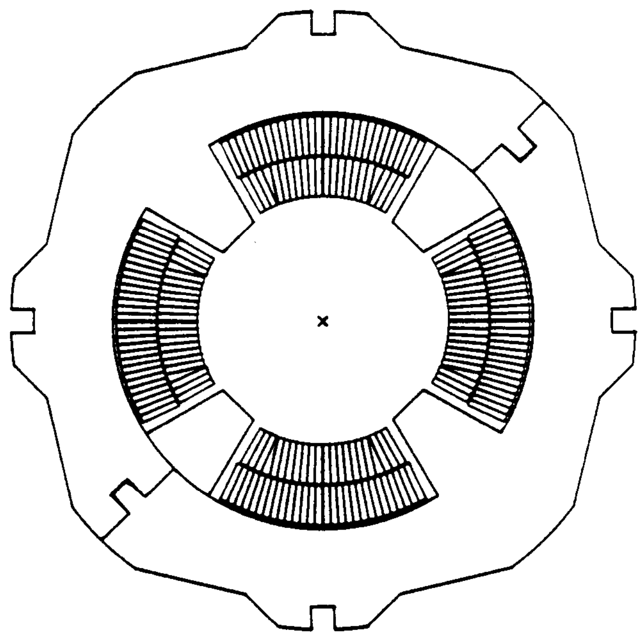

FIGURE 1 THIS IS A DRAWING OF THE CROSS-SECTION OF THE SLC COLLARED COIL ASSEMBLY.

the pole. There was no additional attempt to correct the harmonics in the ends of these quadrupoles. This smaller aperture, and the resulting sharp bends in the coils, led to turn-to-turn shorts. This problem was solved in the early stages of construction, as discussed below.

After construction began, a breakdown in insulation was encountered on the second 120cm quadrupole, #4802. The cable insulation was discovered to have failed at the transition area where the cable makes it's way from the inner coil to the outer coil. Cable damage was also evident. This same problem caused two additional 120cm quadrupoles (#4800 and #4803) which were in the production pipe line to fail. The coil pre-stress for Magnets #4801 and #4803 was also noticed to be excessive. All coil winding and assembly was halted at this time. The insulation damage in the transition area was determined to be caused by an unstable cable geometry resulting from the torturous path the cable has to follow in the transition area. This resulted in the cable moving from it's as-wound position causing interferences and excessive loading during the coil molding and curing processes. A fixture was developed that soldered the cable int geometrically stable shape in the transition area prior to coil winding. Extra

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insulation was also added at the transition. The result of this "fix" was the virtual elimination of layer to layer electrical shorts occuring in the windings, both before and after the assembly into a magnet. The small aperture had made the geometry of this transition much more sensitive to shape and rigidity than had previously been seen in Tevatron magnets.

The excessive coil pre-stress encountered in quadrupoles #4802, #4803, and #4800 was traced to an excessive overlap of the Kapton inner wrap insulation around the cable. This resulted in a build-up during the winding process, which in turn, resulted in high molding and collaring pressures. high molding pressures can lead to insulation creep and result in turn-to-turn shorts. The situation was remedied by increased quality control during the cable insulating process.

The characteristics of the strand used to fabricate the cable are given in Table I and the cable in Table II.

Table I

Strand Characteristics

Strand Diameter	0.6807mm	
Copper Vol/NbTi Vol	1.28/1	
	(a)	(b)
No fil of Nb-47.5 wt%Ti	709	570
Filament diameter (μm)	17	19
Critical Current Density at 6T and 4.2K of NbTi at an effective resistivity of 10^{-12} Ω-cm (A/mm²)	2081	2100
No of twists/cm	= 0.8	
Strand Coating = 97% Sn + 3% Ag		

a) Original Order
b) Subsequent Order

Table II

'Rutherford' Style Cable* Characteristics
Using Strand from Table I

No of Strand	23
Width of Cable	0.7798cm
Thin Edge Thickness	0.1168cm
Thick Edge Thickness	0.1372cm
Cable Length 120cm Q_2	280 meters
Cable Length 66cm Q_1	176 meters
Critical Current at High Field point in Winding (ρeff = 2 x 10^{-12} Ω-cm, 5.85T, 4.25K)	7100 ± 300 Amps

*Note: These are the same physical dimensions as the "Tevatron" cable.

The individual pole coil sizes in SLQ_1 2602, 2603, 2604, 2605, and SLQ_2 4804 matched to ≤ 0.069mm which resulted in a reduction of the Fourier coefficients of the magnetic fields produced.

Magnet Performance

The quadrupoles did show 'training'; 'training' being defined as premature superconducting to normal state resistive transitions occurring during early powering cycles. The various training scenarios could be summarized as follows: The first quench usually occurred at or above six kiloamperes (Grad = 1.68T/cm). For about five to ten quenches at slow ramp rates (2 to 6 amps/sec), the quadrupole would quench at around seven kiloamperes (Grad = 1.96T/cm) at 4.2K. Quench histories are shown in Figure 2. See Table A, B, C, and D for actual data.

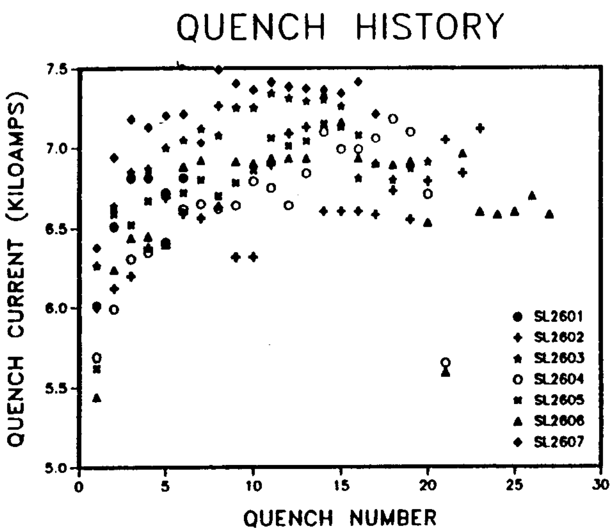

Figure 2A

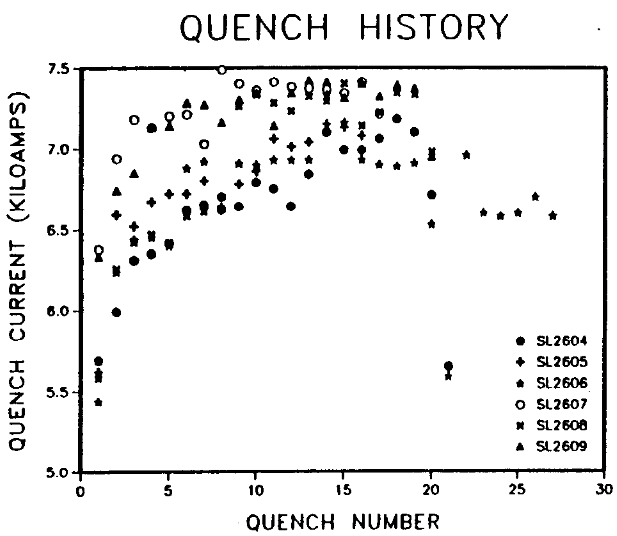

Figure 2B

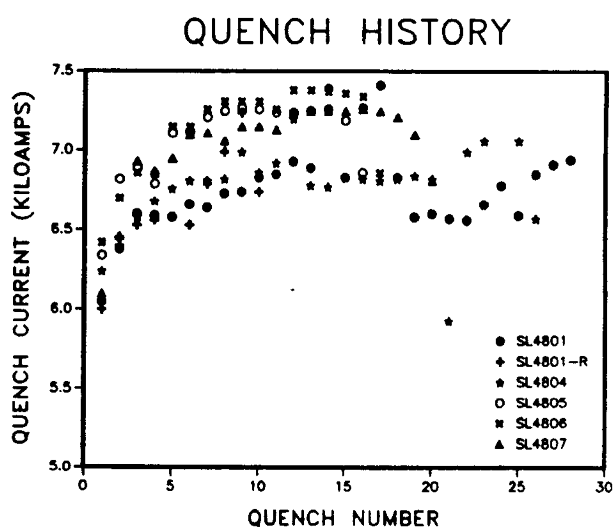

Figure 2C

The magnets made before the transition fixture was used showed a marked ramp rate dependence. Magnets fabricated with the fixture had a much less pronounced ramp rate dependence. This ramp rate dependence can be seen in Figure 3. It is of interest to note that the SLC triplets will operate DC at a gradient of about 1.4T/cm. There is a time dependence to the magnetization contribution of the harmonic content of the magnet field which will be given later.

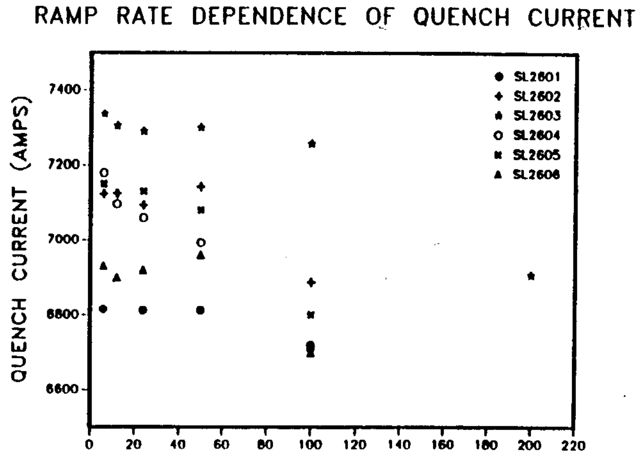

Figure 3A

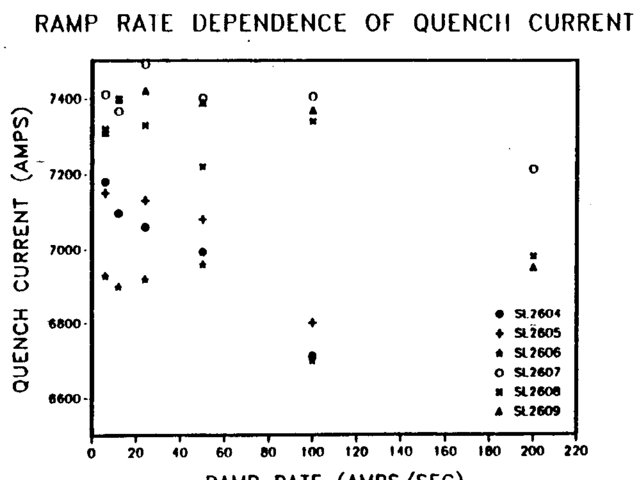

Figure 3B

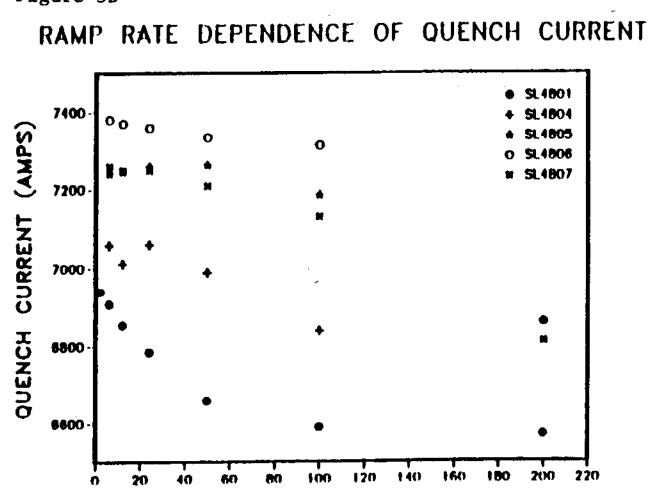

Figure 3C

The energy loss due to eddy currents while ramping the magnet (Joules/cycle) is given in Table III. Typical data is shown in Figure 4. The I^2 curvature of the hysteresis cycle is due to the change in inductance of the magnet due to deflection caused by the Lorentz forces. The magnets are protected by quench heaters during the testing. The characteristic 7 ohm heater inputs required to quench the magnets powered to one kiloamp were in the range of 460 Joules in 0.14 seconds to 280 Joules in 0.28 seconds.

Table III

ENERGY LOSS (JOULES)
CYCLE
50 - 5000 AMPS

MAGNET	RAMP RATE (AMPS/SEC)					
	6	12	24	50	100	200
Q_1 2601	53.3	58.9	60.7	62.7	65.6	68.4
Q_1 2602	32.6	45.0	69.3	107.8	130.1	147.1
Q_1 2603	33.1	46.4	74.0	113.2	131.6	150.0
Q_1 2604	34.2	41.4	56.9	89.8	108.8	128.8
Q_1 2605	44.9	79.5	102.3	120.0	135.0	152.0
Q_1 2606	27.3	53.2	89.8	116.1	134.1	148.4
Q_1 2607	44.0	86.5		148.1	147.5	160.8
Q_1 2608	34.2	60.6	106.4	130.7	146.6	160.2
Q_1 2609	42.4	59.6	99.8	127.2	149.0	157.1
Q_2 4801	42.2	68.0	85.9	95.5	102.5	108.4
Q_2 4804	54.6	85.5	121.9	146.5	166.1	
Q_2 4805	64.0	136.4	172.9	193.5	211.8	234.0
Q_2 4806		137.2	165.8	189.9	210.0	240.0
Q_2 4807	93.9	150.4	183.9	205.2	218.5	241.0

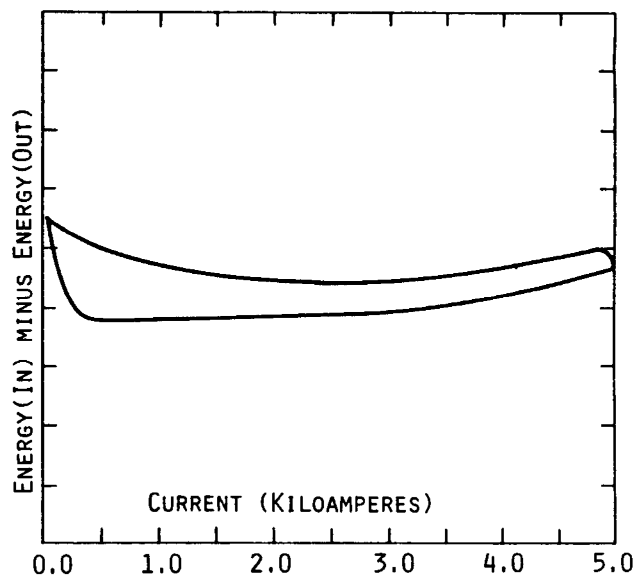

FIGURE 4 THE ENERGY(IN)-ENERGY(OUT) CURVE FOR SLQ_2 4804. NOTE THE CURVATURE OF THE DATA INDICATING A CHANGE IN THE INDUCTANCE AT DEFLECTION OF THE COIL.

Magnetic Characteristics

The integral strength and harmonics were first measured at room temperature by powering the quadrupoles with 5, 10, 15, and 20 amps, using a rotating 1.68m long "Morgan"[3] coil. The room temperature relative strengths are given in Table IV using the strength of SLQ_2 #4801 = 1. The actual measured ratio was 1.815 + .006 (Spec. was 1.821).

Table IV

INTEGRAL RELATIVE STRENGTH
ROOM TEMPERATURE

	5	10	15	20	AV
4801/2601	1.809±.009	1.813±.001	1.816±.005	1.812±.001	1.812±.003
4801/2602	1.809±.003	1.814±.003	1.811±.003	1.812±.003	1.811±.002
4801/2603	1.806±.003	1.808±.003	1.807±.003	1.807±.003	1.807±.002
4801/2604*	1.809±.004	1.816±.004	1.810±.004	1.809±.004	1.811±.004
4801/2605	1.805±.005	1.811±.003	1.807±.003	1.805±.004	1.807±.003
4801/2606	1.804±.006	1.811±.005	1.807±.005	1.803±.004	1.806±.003
4801/2607*	1.824±.008	1.822±.007	1.819±.006	1.816±.005	1.820±.007
4801/2608*	1.810±.005	1.816±.004	1.808±.004	1.810±.004	1.811±.004
4801/2609*	1.828±.009	1.818±.006	1.811±.007	1.810±.004	1.817±.007
4801/4801	1.0	1.0	1.0	1.0	1.0
4801/4802		0.9972±.01			
4801/4803		0.9965±.002			
4801/4804	0.9963±.0015	0.9975±.0015	0.9973±.0015	0.994±.0015	0.9963±.0015
4801/4805	1.0037±.0032	1.0022±.0034	0.9998±.0032	0.9974±.0025	1.0008±.0028
4801/4806	1.0003±.0024	1.0009±.0024	0.9992±.0024	0.9971±.0024	0.9994±.0024
4801/4807	0.9997±.0024	1.0004±.0024	0.9938±.0024	0.9972±.0024	0.9990±.0024

SLQ_2 4801 - INTEGRAL STRENGTH (20 AMPS) PER AMP = 0.034 ± .00007 $\frac{T}{CM}\frac{CM}{AMP}$

CALCULATED TRANSFER FUNCTION = 2.793 $\frac{GAUSS}{CM\ AMP}$

* ALL READINGS TO DATE

The 1.68m long rotating coil was also inserted in the aperture when the magnet was at liquid helium temperatures. The integral gradient and the integral Fourier components of the field were measured at 2000, 4000, and 4750 amperes DC. The ramped harmonic content of the magnet field was also measured. Figure 5 is a curve of duodecapole as a function of magnet current. The cold strengths of the various quadrupoles are given in Table V in terms of (Tesla/cm)(cm).

The integral normalized harmonics at 2kA and 4kA are given in Table VI. These harmonics are given at 1cm radius and are normalized by the gradient at that current, i.e., the sextupole term normalized at I_1, is given by:

$$\frac{B_2(I_1, \frac{\text{Gauss}}{\text{cm*cm}})}{B_1(I_1, \frac{\text{Gauss}}{\text{cm}})} = B(\text{Norm}_2)\ (I_1,\ 1/\text{cm})$$

The center of a quadrupole is defined by the condition A_0 and B_0 = 0, i.e., no dipole field.

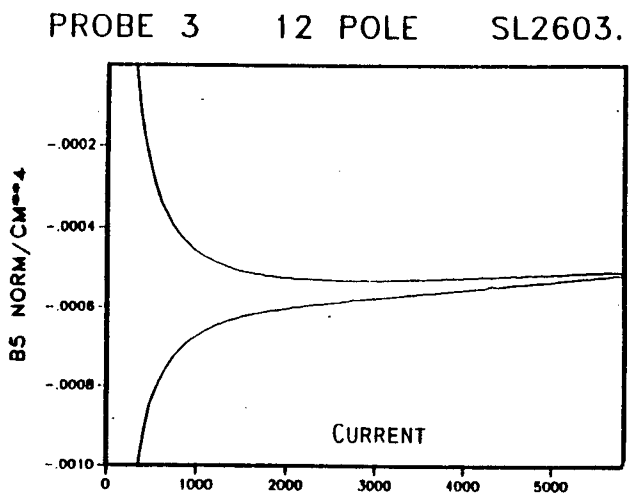

FIGURE 5 THE DUODECAPOLE (NORMALIZED) IS SHOWN AS A FUNCTION OF CURRENT FOR SLQ 2603 FOR A 6000 AMP TRIANGULAR CURRENT PULSE AS 6 AMPS/SEC

Table V

INTEGRAL STRENGTH ($\frac{TESLA}{CM}$. CM), 4.2K

	2000 AMPS	4000 AMPS	4750 AMPS
2601	37.38 ± .10	-	-
2602	37.47 ± .04	75.06 ± .13	-
2603	37.52 ± .03	75.07 ± .10	88.99 ± .11
2604	37.61 ± .05	75.08 ± .11	89.12 ± .12
2605	37.43 ± .07	74.93 ± .15	88.99 ± .18
2606	37.49 ± .13	75.06 ± .19	89.17 ± .23
2607	37.42 ± .04	74.96 ± .09	89.11 ± .12
2608	37.44 ± .08	75.06 ± .12	89.17 ± .23
2609	37.55 ± .06	75.21 ± .10	89.38 ± .12
4801	68.11 ± .15	136.21 ± .44	161.40 ± .50
4804	68.37 ±.10	136.71 ± .33	162.00 ± .38
4805	68.05 ± .15	136.21 ± .45	161.78 ± .44
4806	68.11 ± .27	136.30 ± .20	161.85 ± .29
4807	68.03 ± .14	136.18 ± .39	161.50 ± .29

GRADIENT (TESLA/CM) 4.2K

2601	0.5614 ± .004	-	-
2602	0.5617 ± .0013	1.120 ± .002	-
2603	0.5624 ± .0014	1.121 ± .004	1.331 ± .004
2604	0.5643 ± .0014	1.126 ± .003	1.335 ± .003
2605	0.5606 ± .0011	1.122 ± .002	1.332 ± .003
2606	0.5611 ± .0015	1.123 ± .002	1.333 ± .002
2607	0.5606 ± .0003	1.122 ± .001	1.333 ± .001
2608	0.5606 ± .0005	1.123 ± .001	1.333 ± .001
2609	0.5618 ± .0004	1.125 ± .001	1.336 ± .001
4801	0.5613 ± .0018	-	-
4804	0.5635 ± .0016	1.123 ± .003	1.333 ± .003
4805	0.5604 ± .0011	1.122 ± .002	1.333 ± .005
4806	0.5609 ± .0013	1.123 ± .002	1.334 ± .005
4807	0.56-9 ± .0011	1.122 ± .002	1.333 ± .004

Table VI

Normalized Integral Harmonics

x 10*

2kA

	2601*	2602	2603	2604	2605	2606	2607	2608	2609
A2	-10.09	-3.61	-0.05	-4.89	-9.14	4.85	1.53	3.25	0.03
B2	- 6.50	2.94	1.25	0.38	-4.21	5.25	-4.51	3.50	-8.44
A3	- 0.14	0.40	-0.55	1.88	0.78	-0.18	0.18	-0.64	-0.18
B3	- 1.58	0.68	4.52	0.76	0.79	0.29	-1.66	0.95	0.92
A4	- 3.24	0.18	-0.99	0.05	4.24	0.30	2.46	0.17	1.25
B4	- 1.39	-1.64	3.50	-.044	1.93	0.29	0.11	0.04	-0.25
A5	0.30	-0.19	-0.36	-0.32	-0.67	-0.53	-0.36	-0.35	-0.25
B5	6.35	6.37	6.03	5.26	7.27	5.36	5.35	5.40	5.47
A6	0.03	0.01	-0.03	0.02	0.09	0.02	0.00	0.02	0.01
B6	- 0.08	-0.02	-0.11	-0.02	-0.01	0.05	-0.01	0.04	-0.08
A8	6.53	-0.16	0.02	-0.09	-0.13	-0.03	-0.24	0.01	-0.12
B8	0.08	0.04	0.26	0.14	0.04	-0.01	-0.03	0.00	-0.02
A9	0.00			-0.00	0.01	-0.02	0.03	0.03	0.02
B9	0.00			-0.29	0.23	-0.28	-0.28	-0.27	-0.28

*Data taken at 1 kiloamp

4kA

	2601	2602	2603	2604	2605	2606	2607	2608	2609
A2		3.75	-0.05	-4.89	-9.44	5.27	1.71	3.65	-0.34
B2		3.21	1.25	0.67	-4.35	5.19	-4.55	3.57	-8.54
A3		0.29	-0.78	1.98	0.77	-0.18	0.16	-0.70	-0.26
B3		0.76	4.34	0.68	0.58	0.32	-1.61	0.86	0.99
A4		0.24	-1.34	0.13	1.70	0.13	2.30	0.24	1.13
B4		1.58	3.50	-0.45	1.70	0.29	0.05	0.03	-0.24
A5		-0.02	-0.84	-.047	-0.63	-0.53	-0.31	-0.32	-0.22
B5		5.97	5.43	4.73	4.75	5.00	5.14	5.03	5.10
A6		-0.01	-0.04	0.02	0.09	0.03	0.00	0.02	0.00
B6		-0.02	-0.11	-0.03	-0.03	0.05	-0.01	0.03	-0.07
A8		-0.16	0.06	-0.09	-0.13	-0.04	-0.23	0.00	-0.10
B8		0.04	-0.26	-0.14	0.05	-0.01	-0.03	0.01	-0.02
A9				0.00	0.01	-0.02	0.02	0.03	0.01
B9				-0.29	0.26	-0.28	-0.27	-0.27	-0.27

Normalized Integral Harmonics

x 10*

2kA

	4801	4804	4805	4806	4807
A2	-0.49	3.25	2.17	-4.63	0.29
B2	4.49	-3.25	2.56	-3.38	1.64
A3	1.42	-0.39	-0.43	-0.32	-0.66
B3	2.40	-1.05	0.05	0.48	-0.69
A4	-0.67	0.43	-0.09	2.14	2.20
B4	-2.96	-0.68	-0.16	-0.38	-0.24
A5	-0.26	0.73	-0.42	-0.11	-0.38
B5	5.61	2.71	5.18	5.27	5.42
A6	0.37	0.04	0.01	-0.04	-0.00
B6	0.38	0.01	-0.02	0.02	-0.00
A8	0.04	-0.01	-0.19	-0.19	-0.21
B8	0.48	-0.08	0.14	0.20	-0.04
A9	-0.18	-0.01	-0.02	-0.02	0.03
B9	-0.21	-0.29	-0.28	-0.28	-0.28

4kA

	4801	4804	4805	4806	4807
A2		3.67	2.42	-4.66	0.32
B2		-4.02	2.67	-3.31	1.70
A3		-0.39	-0.52	-0.31	-0.66
B3		-1.24	0.06	0.48	-0.63
A4		0.36	-0.13	2.00	2.10
B4		-0.75	-0.18	-0.35	-0.25
A5		-0.77	-0.42	-0.10	-0.38
B5		3.30	4.93	5.10	5.16
A6		-0.65	0.01	-0.05	-0.00
B6		-0.95	-0.02	0.01	-0.00
A8		-0.01	-0.19	-0.19	-0.29
B8		-0.08	0.15	0.20	0.23
A9		-0.01	-0.02	-0.02	-0.03
B9		-0.33	-0.28	-0.28	-0.28

The next set of data of interest are the straight section field strengths and harmonic content. The magnet design was originally done to minimize the various non quadrupole components of the field. In Table VII, the body field normalized Fourier components are given for 2kA and for 4kA.

Table VII

Normalized Harmonics Straight Section

x 10*

2kA

	2601	2602	2603	2604	2605	2606	2607	2608	2609
A2	-5.14	-0.69	-0.39	0.93	-4.71	-0.98	-1.83	1.63	-1.14
B2	-1.72	0.09	0.17	-2.34	-0.63	2.10	-2.26	-1.82	-2.02
A3	0.15	0.32	0.50	-0.98	-0.09	-0.03	0.19	0.33	0.16
B3	0.54	-1.10	1.48	-0.72	0.68	0.74	1.74	-0.46	-0.78
A4	0.65	0.49	0.64	-0.47	-0.17	-0.13	0.15	-0.01	-0.07
B4	1.07	0.59	2.63	1.29	1.02	0.71	-0.95	-2.30	0.94
A5	-0.60	0.09	0.00	0.05	-0.63	-0.33	-0.24	-0.22	-0.11
B5	5.87	6.51	6.01	4.32	0.82	5.22	5.44	5.37	5.27
A6	-0.16	0.02	-0.02	0.04	-0.09	0.00	0.03	0.00	0.04
B6	0.70	0.21	0.10	-0.02	0.03	-0.01	0.01	0.03	0.05
A8	5.11	0.10	-0.03	-0.03	0.07	0.10	-0.38	0.13	-0.05
B8	0.30	0.02	0.44	0.13	0.75	0.11	0.18	0.10	-0.07
A9	-0.02	0.00	-0.01	-0.12	0.25	0.00	0.12	0.27	-0.76
B9	-0.33	-0.34	-0.34	-0.23	-0.24	-0.31	-1.12	0.27	0.11
A13	0.00	0.00	0.00	0.01	-0.02	0.00			
B13	0.00	0.01	0.00	0.02	0.15	0.00			

4kA

	2601	2602	2603	2604	2605	2606	2607	2608	2609
A2		-0.46	-0.38	0.80	-4.95	-0.60	-1.73	1.70	-1.36
B2		0.17	0.12	-2.07	-0.98	2.39	-2.59	-2.06	-1.95
A3		0.43	0.55	-1.07	-0.07	-0.03	0.24	0.41	0.24
B3		-1.22	1.42	-0.69	0.71	0.69	1.72	-0.50	-0.78
A4		0.49	-0.64	-0.48	-0.07	-0.20	0.15	0.04	-0.05
B4		0.63	2.43	1.18	1.04	0.74	-0.86	-2.09	0.90
A5		0.08	0.01	0.00	-0.15	-0.31	-0.20	-0.19	-0.08
B5		6.08	5.55	4.86	0.08	4.81	5.09	5.05	4.85
A6		0.02	0.07	0.05	-0.09	-0.01	0.03	0.00	0.04
B6		0.03	0.03	-0.03	-0.09	-0.02	0.03	0.03	0.06
A8		-0.11	0.08	-0.14	0.16	0.10	-0.35	-0.04	-0.02
B8		0.02	-0.16	0.14	-0.02	0.12	0.30	-0.12	-0.08
A9		0.00	0.00	0.26	-0.43	0.02	-0.14	0.19	-0.72
B9		-0.34	-0.34	-0.58	-0.58	-0.32	-1.27	0.23	-0.04
A13					0.00	0.00			
B13					0.01	-0.00			

A13 = 0.0004 ±.002

B13 = -0.002 ± .001

Normalized Harmonics Straight Section

x 10*

2kA

	4801	4804	4805	4806	4807
A2	-5.30	-2.56	-0.29	-5.44	-0.58
B2	-1.80	1.19	2.25	-0.71	0.68
A3	-1.34	0.32	-0.57	0.86	-0.18
B3	-1.12	-1.25	-0.14	0.66	0.32
A4	-1.80	-1.29	0.31	2.42	-0.26
B4	-1.10	-0.42	0.71	-0.02	0.56
A5	-0.37	0.91	0.39	-0.12	-0.43
B5	0.32	2.08	5.48	5.59	5.75
A6	-0.36	-0.05	-0.01	-0.00	-0.01
B6	-0.39	0.03	0.02	0.07	0.03
A8	-0.31	-0.08	0.02	0.02	-0.05
B8	0.00	0.09	0.12	-0.12	0.00
A9	-0.15	0.29	0.02	0.01	0.09
B9	-0.20	-0.35	-0.32	-0.32	-0.29
A13	-0.88	0.31	0.00	0.00	0.00
B13	-0.11	0.07	-0.00	-0.00	0.00

4kA

	4801	4804	4805	4806	4807
A2		-2.83	-0.31	-5.48	-0.61
B2		1.44	2.36	-0.76	0.71
A3		0.30	-0.57	0.84	-0.19
B3		-1.30	-0.14	-0.67	0.29
A4		-1.04	0.27	2.38	-0.26
B4		-0.51	0.72	-0.01	0.53
A5		0.53	0.39	-0.11	-0.42
B5		0.87	5.19	5.30	5.48
A6		-0.03	0.01	0.01	-0.01
B6		-0.06	-0.02	0.07	0.03
A8		0.25	0.01	-0.02	-0.05
B8		-0.20	0.10	-0.16	0.00
A9		-0.98	0.01	0.01	0.06
B9		-0.30	-0.32	-0.32	-0.25
A13			0.00	0.00	0.00
B13			-0.00	-0.00	-0.03

A13 = 0.0004 ± .002

B13 = -0.002 ± .001

The integral and straight section harmonics at the operational field current of 4759 Amperes is given in Appendix 1, Table E and F.

There appeared to be a change in the normalized duodecapole term of about a half a unit (10^{-4}) in a time period of approximately 200 seconds at a magnet curent of 4000 Amps.

APPENDIX 1

Table A

QUENCH HISTORY

Quench No	SLQ$_1$ 2601 K	kA	A/S	SLQ$_1$ 2602 K	kA	A/S	SLQ$_1$ 2603 K	kA	A/S	SLQ$_1$ 2604 K	kA	A/S
1	4.2	6.01	100	4.2	6.00	100	4.2	6.27	100	4.2	5.69	200
2	4.2	6.51	50	4.2	6.12	50	4.2	6.64	100	4.16	5.99	100
3	4.2	6.31	24	4.2	6.20	50	4.2	6.85	100	4.16	6.31	100
4	4.2	6.81	12	4.2	6.38	50	4.2	6.87	100	4.2	6.35	100
5	4.2	6.72	100	4.2	6.69	50	4.2	7.00	100	4.21	6.41	100
6	4.2	6.81	6	4.2	6.59	50	4.2	7.05	100	4.21	6.62	50
7				3.2	6.56	50	4.2	7.12	100	4.18	6.65	50
8				3.2	7.26	50	4.2	7.08	100	4.22	6.62	50
9				4.1	6.32	200	4.2	7.25	100	4.22	6.64	50
10				4.2	6.32	200	4.2	7.25	100	4.22	6.79	50
11				4.2	6.89	100	4.2	7.34	6	4.2	6.75	50
12				4.2	7.09	24	4.2	7.31	12	4.2	6.64	50
13				4.2	7.13	12	4.2	7.29	24	4.2	6.84	50
14				4.2	6.60	6	4.2	7.30	50	3.1	7.10	50
15				4.2	6.60	6	4.2	7.26	100	4.2	6.99	50
16				4.2	6.60	6	4.2	6.81	200	4.2	6.99	50
17				4.2	6.58	6	4.2	6.90	200	4.2	7.06	24
18				4.2	6.73	6	4.2	6.80	200	4.2	7.18	6
19				4.2	6.55	50	4.2	6.87	200	4.2	7.10	12
20				4.2	6.79	50	4.2	6.91	200	4.2	6.71	100
21				4.2	7.05	50				4.2	5.65	200
22				4.2	6.84	6						
23				4.2	7.12	6						

Table B

QUENCH HISTORY

Quench No	SLQ$_1$ 2605 K	kA	A/S	SLQ$_1$ 2606 K	kA	A/S	SLQ$_1$ 2607 K	kA	A/S	SLQ$_1$ 2608 K	kA	A/S	SLQ$_1$ 2609 K	kA	A/S
1	4.2	5.62	100	4.2	5.44	100	4.2	6.38	100	4.2	5.58	100	4.2	6.33	100
2	4.2	6.59	100	4.2	6.24	100	4.2	6.94	100	4.2	6.26	100	4.2	6.74	100
3	4.2	6.52	100	4.2	6.44	100	4.2	7.18	100	4.2	6.42	100	4.2	6.85	100
4	4.2	6.67	100	4.2	6.45	100	4.2	7.13	100	4.19	6.47	100	4.2	7.13	100
5	4.2	6.72	100	4.2	6.40	100	4.2	7.20	12	4.19	6.42	100	4.2	7.14	100
6	4.2	6.72	100	4.2	6.88	24	4.2	7.21	12	4.19	6.58	100	4.2	7.28	6
7	4.23	6.80	100	4.2	6.92	24	4.2	7.03	12	4.19	6.61	100	4.2	7.27	6
8	4.2	6.70	100	4.2	6.64	100	4.2	7.49	24	4.2	6.70	100	4.2	7.16	6
9	4.2	6.78	100	4.2	6.91	24	4.2	7.40	50	4.25	7.26	24	4.2	7.30	12
10	4.2	6.86	100	4.2	6.90	24	4.2	7.36	6	4.23	7.33	24	4.2	7.34	12
11	4.19	7.06	24	4.2	6.93	6	4.2	7.41	6	4.24	7.28	24	4.2	7.14	12
12	4.2	7.01	6	4.2	6.93	6	4.2	7.38	6	4.24	7.23	6	4.2	7.34	24
13	4.2	7.04	6	4.2	6.93	6	4.2	7.37	12	4.23	7.32	6	4.2	7.42	24
14	4.19	7.15	6	3.2	7.33	6	4.2	7.36	24	4.23	7.29	6	4.2	7.41	24
15	4.19	7.13	24	3.8	7.16	6	4.2	7.34	50	4.23	7.40	12	4.2	7.31	6
16	4.21	7.08	48	4.2	6.93	6	4.2	7.40	100	4.2	7.14	50	4.2	7.40	12
17				4.2	6.90	12	4.2	7.21	200	4.2	7.22	50	4.2	7.32	24
18				4.2	6.89	24				4.2	7.34	100	4.2	7.39	50
19				4.2	6.91	50				4.22	7.33	100	4.2	7.37	100
20				4.2	6.53	100				4.21	6.98	200	4.2	6.95	200
21				4.2	5.59	200									
22				4.2	6.96	50									
23				4.2	6.60	100									
24				4.2	6.58	100									
25				4.2	6.60	100									
26				4.2	6.70	100									
27				4.2	6.58	100									

Interest - EinEout = AI²

A(SLQ$_1$ 2606) = 11.0 x 10^{-4} [Volts/kiloAmps²]

A(SLQ$_1$ 2607) = 11.0 x 10^{-4} [Volts/kiloAmps²]

A(SLQ$_1$ 2608) = 5.0 x 10^{-4} [Volts/kiloAmps²]

A(SLQ$_1$ 2609) = 5.0 x 10^{-4} [Volts/kiloAmps²]

Table C

QUENCH HISTORY

Quench No.	SLQ$_2$ 4801 K	kA	A/S	SLQ$_2$ 4803 K	kA	A/S	SLQ$_2$ 4802 K	kA	A/S	SLQ$_2$ 4801-R K	kA	A/S
1	4.2	6.05	100	4.2	4.32	100	4.2	3.50	100	4.2	6.00	50
2	4.2	6.38	100	4.2	4.27	100	4.2	0.97	100	4.2	6.45	50
3	4.2	6.60	100	4.2	4.14	100	4.2	0.67	24	4.13	6.53	24
4	4.2	6.59	100	4.2	4.55	6	4.2	0.67	24	4.19	6.56	24
5	4.2	6.58	100	4.2	3.76	200				4.19	6.58	12
6	4.2	6.66	50							4.19	6.53	12
7	4.2	6.64	50							3.3	6.79	50
8	4.2	6.73	24							3.21	6.99	50
9	4.2	6.74	24							3.21	7.24	50
10	4.2	6.83	12							3.73	6.74	50
11	4.2	6.85	12									
12	4.2	6.93	6									
13	4.2	6.89	6									
14	3.0	7.39	100									
15	3.0	6.83	50									
16	3.2	7.27	50									
17	3.2	7.41	50									
18	3.9	6.83	12									
19	4.2	6.58	100									
20	4.2	6.60	100									
21	4.2	6.57	200									
22	4.2	6.56	200									
23	4.2	6.66	50									
24	4.2	6.78	24									
25	4.2	6.59	100									
26	4.2	6.85	12									
27	4.2	6.91	6									
28	4.2	6.94	2									

Table D

QUENCH HISTORY

Quench No	SLQ$_2$ 4804 K	kA	A/S	SLQ$_2$ 4805 K	kA	A/S	SLQ$_2$ 4806 K	kA	A/S	SLQ$_2$ 4807 K	kA	A/S
1	4.2	6.24	100	4.2	6.34	100	4.2	6.42	100	4.2	6.10	100
2	4.2	6.40	100	4.16	6.82	100	4.2	6.70	100	4.2	6.46	100
3	4.2	6.58	100	4.16	6.89	100	4.18	6.86	100	4.12	6.93	100
4	4.2	6.68	100	4.16	6.79	100	4.16	6.85	100	4.25	6.87	100
5	4.2	6.76	100	4.16	7.11	100	4.15	7.15	100	4.14	6.95	100
6	4.2	6.81	100	4.16	7.12	100	4.16	7.15	100	4.12	7.10	100
7	4.2	6.81	100	4.16	7.21	100	4.16	7.26	100	4.12	7.11	100
8	4.2	6.82	100	4.16	7.25	50	4.15	7.31	100	4.18	7.06	100
9	4.2	6.99	6	4.16	7.27	50	4.16	7.31	100	4.13	7.15	12
10	4.2	6.86	6	4.16	7.26	50	4.16	7.31	100	4.23	7.15	12
11	4.2	6.92	6	4.15	7.24	6	4.2	7.26	6	4.2	7.13	100
12	3.1	7.20	50	4.16	7.24	6	4.2	7.38	6	4.11	7.24	6
13	4.32	6.78	100	4.15	7.25	12	4.2	7.38	6	4.19	7.25	6
14	4.16	6.77	100	4.16	7.26	24	4.2	7.37	12	4.12	7.25	12
15	4.14	6.83	100	4.15	7.19	100	4.2	7.36	24	4.12	7.25	12
16	4.15	6.82	100	4.15	6.86	200	4.2	7.34	50	4.12	7.26	6
17	4.15	6.82	100	4.16	7.19	100	4.2	6.86	200	4.12	7.25	24
18	4.15	6.81	100	4.19	7.19	100				4.14	7.21	50
19	4.16	6.82	100	4.18	7.12	100				4.12	7.10	100
20	4.14	6.84	100	4.14	7.15	100				4.12	6.81	200
21	4.15	6.82	100	3.15	7.76	24						
22	4.2	5.93	200	4.12	7.24	24						
23	4.2	6.99	50	4.2	7.09	100						
24	4.2	7.06	24	4.2	7.13	100						
25	4.2	7.81	12	4.2	7.12	100						
26	4.2	7.06	6									
27	4.2	6.57	100									

*Interest - EinEout = AI²

A(SLQ$_2$ 4804) = 19.5x10^{-4} [Volts/kiloAmps²]

A(SLQ$_2$ 4805) = 7.5x10^{-4} [Volts/kiloAmps²]

A(SLQ$_2$ 4806) = 7.5x10^{-4} [Volts/kiloAmps²]

A(SLQ$_2$ 4807) = 7.5x10^{-4} [Volts/kiloAmps²]

Table E

INTEGRAL HARMONICS

x 10^4

4750 AMPS

	2603	2604	2605	2606	2607	2608	2609
A2	-0.09±.03	-4.93±.02	-9.54±.01	5.39±.02	1.89±.06	3.64±.14	-0.25±.18
B2	-1.22±.01	0.77±.01	-4.54±.02	5.22±.03	-4.55±.10	3.70±.25	-8.47±.12
A3	-0.81±.08	2.01±.01	0.72±.01	-0.20±.01	-0.12±.01	-0.72±.03	-0.27±.01
B3	4.27±.02	0.64±.01	0.51±.01	0.33±.01	-1.60±.01	0.83±.03	1.00±.01
A4	1.22±.12	0.24±.04	1.86±.07	0.22±.02	2.34±.01	0.23±.08	1.06±.04
B4	-4.90±.04	-0.39±.04	1.61±.09	0.30±.01	0.01±.02	0.05±.04	-0.23±.05
A5	-0.63±.11	-0.46±.18	1.38±.28	-0.52±.00	-0.26±.02	-0.35±.10	-0.23±.04
B5	4.67±.02	4.14±.19	4.32±.35	4.86±.00	5.00±.04	4.88±.14	5.00±.03
A6	0.04±.00	0.02±.00	0.09±.00	0.03±.00	0.00±.00	0.02±.02	0.00±.01
B6	0.11±.00	-0.03±.00	-0.03±.00	0.05±.00	-0.02±.01	0.04±.02	-0.09±.01
A8	-0.06±.01	-0.10±.00	-0.13±00	-0.04±.00	-0.25±.00	0.01±.01	-0.11±.01
B8	0.26±.00	-0.14±.00	0.05±.00	-0.01±.00	-0.02±.00	0.01±.00	-0.02±.01
A9	0.00±.00	-0.01±.00	0.01±.00	-0.02±.00	0.02±.00	0.02±.00	0.01±.00
B9	0.00±.00	-0.29±.00	0.26±.00	-0.28±.00	-0.27±.00	-0.27±.00	-0.27±.00

STRAIGHT SECTION HARMONICS

x 10^4

	2603	2604	2605	2606	2607	2608	2609
A2	-0.38±.01	0.72±.01	-5.00±.00	-0.54±.00	-1.60±.01	1.83±.02	-1.47±.01
B2	0.10±.00	-1.97±.00	-1.11±.01	2.48±.01	-2.76±.01	-2.16±.01	-1.94±.01
A3	0.55±.01	-1.11±.00	-0.07±.01	-0.04±.01	0.28±.02	0.45±.01	0.26±.01
B3	1.39±.01	-0.67±.01	0.07±.01	0.70±.01	1.72±.01	-0.05±.01	-0.77±.01
A4	0.63±.00	-0.50±.02	-0.08±.03	-0.21±.00	0.16±.00	0.05±.01	-0.03±.01
B4	2.36±.01	0.91±.04	1.04±.01	0.74±.01	-0.80±.01	-2.11±.04	0.87±.01
A5	0.02±.00	-0.23±.15	-1.04±.44	-0.31±.00	-0.21±.01	-0.20±.01	-0.07±.01
B5	5.40±.00	3.33±.26	0.67±.41	4.67±.00	5.01±.00	4.94±.00	4.73±.01
A6	-0.04±.01	0.05±.00	-0.02±.01	-0.01±.00	0.03±.00	0.00±.00	0.05±.00
B6	0.08±.02	-0.03±.00	-0.04±.02	-0.02±.00	0.03±.00	0.03±.00	0.05±.00
A8	-2.02±.04	-1.20±.02	0.09±.01	0.10±.01	-1.33±.04	1.47±.08	0.49±.04
B8	1.34±.07	0.06±.03	-0.12±.02	0.12±.02	1.11±.07	1.38±.09	-0.47±.02
A9	0.00±.00		0.00±.00	0.00±.00	0.25±.18	0.30±.10	-0.67±.12
B9	0.00±.00		-0.01±.00	-0.00±.00	-4.76±.09	-3.36±.11	-3.94±.21
A13							
B13							

Table F

INTEGRAL HARMONICS

x 10^4

4750 AMPS

	4804	4805	4806	4807
A2	3.96±.02	2.24±.02	-4.66±.01	0.37±.01
B2	-4.16±.02	2.68±.02	-3.34±.01	1.71±.02
A3	-0.38±.01	-0.45±.01	-0.35±.01	-0.66±.01
B3	-1.29±.01	0.03±.02	0.50±.01	-0.62±.01
A4	0.20±.11	-0.13±.01	1.96±.01	2.09±.02
B4	-0.83±.08	-0.19±.01	-0.35±.01	-0.26±.01
A5	-0.83±.44	-0.42±.00	-0.10±.01	-0.38±.01
B5	3.93±.48	4.85±.01	4.95±.01	5.10±.01
A6	0.04±.00	0.01±.00	-0.05±.00	-0.00±.00
B6	0.02±.02	-0.02±.00	0.01±.00	-0.01±.00
A8	-0.01±.00	-0.19±.00	-0.19±.00	-0.29±.00
B8	-0.08±.00	0.15±.00	0.19±.00	0.23±.00
A9	-0.01±.00	-0.02±.00	-0.02±.00	-0.03±.00
B9	-0.33±.00	-0.28±.00	-0.28±.00	-0.28±.00

STRAIGHT SECTION HARMONICS

x 10^4

	4804	4805	4806	4807
A2	-2.03±.01	-0.33±.01	-5.50±.01	-0.64±.01
B2	3.98±.01	2.37±.00	-0.77±.01	0.72±.01
A3	-0.61±.01	-0.59±.00	0.82±.09	-0.18±.01
B3	1.81±.01	-0.15±01	0.68±.10	0.29±.00
A4	0.90±.09	0.27±.01	2.38±.01	-0.26±.00
B4	0.75±.05	0.75±.01	-0.02±.01	0.54±.01
A5	0.53±.26	0.38±.00	-0.11±.00	-0.42±.01
B5	0.79±.30	5.12±.00	5.23±.00	5.42±.00
A6	0.08±.00	0.01±.00	0.01±.00	-0.01±.00
B6	0.03±.00	-0.02±.00	0.07±.00	0.03±.00
A8	-2.55±.04	0.09±.01	-1.40±.02	-0.35±.01
B8	-1.65±.02	1.00±.02	1.63±.03	0.08±.01
A9	0.10±.00	0.01±.00	0.01±.00	
B9		-0.32±.00	-0.32±.00	-0.28±.02
A13		0.00±.00	0.006±.00	0.00±.00
B13		0.00±.00	-0.002±.00	0.00±.00

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References

[1] R. Erickson, T. Fieguth, and J.J. Murray, "Superconducting Quadrupoles for the SLC Final Focus," SLAC-PUB-4199, January, 1987.

[2] R.A. Lundy, B.C. Brown, J.A. Carson, H.E. Fisk, R.H. Hanft, P.M. Mantsch, A.D. McInturff, R.H. Remsbottom, and R. Erickson, "High Gradient Superconducting Quadrupoles," IEEE TRANS. on Nuclear Science, Vol. NS-32, No. 5, pp. 3707 - 3709, 1985.

[3] G.H. Morgan, "Stationary Coil For Measuring the Harmonics in Pulsed Transport Magnets," Proc. 4th International Conf. on Magnet Technology, Brookhaven, Sept. 19-22, 1972, USAEC CONF-720908, NTIS, Springfield, Va., (1973) pp. 787 - 790.