



**Fermi National Accelerator Laboratory**

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## **The Magnetic Properties of the SLC Intersection Region Superconducting Quadrupole Triplets**

**A. D. McInturff, J. A. Carson, and 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

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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  $66.498 \pm 0.305$ cm and of  $Q_2$  is  $121.106 \pm 0.61$ cm. 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  $120.85 \pm .1$  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<sup>1</sup> 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.<sup>2</sup> 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

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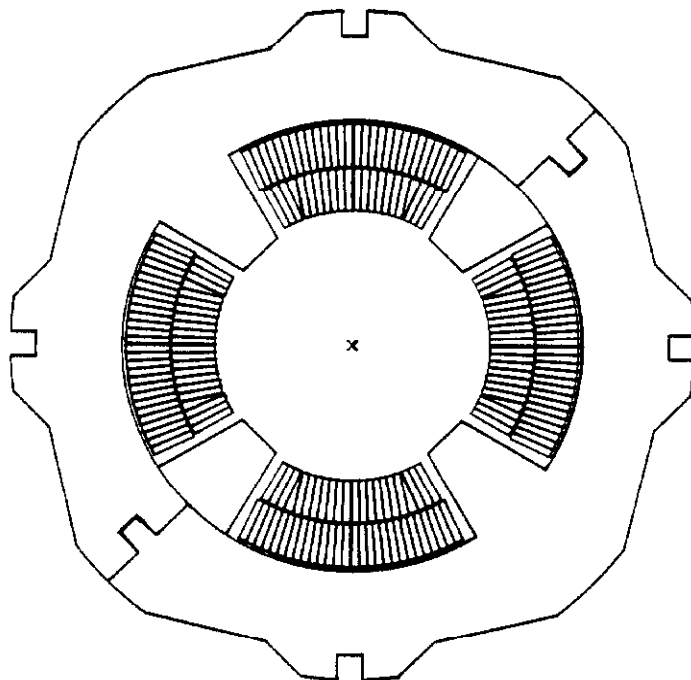


FIGURE 1 THIS IS A DRAWING OF THE CROSS-SECTION OF THE SLC COLLARED COIL ASSEMBLY.

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 into a geometrically stable shape in the transition area prior to coil winding. Extra

insulation was also added at the transition. The result of this "fix" was the virtual elimination of layer to layer electrical shorts occurring 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 ( $\mu$ m)                                                                                        | 17       | 19   |
| Critical Current Density at 6T and 4.2K of NbTi at an effective resistivity of $10^{-12}$ $\Omega$ -cm ( $A/mm^2$ ) | 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                | 7100 $\pm$ 300 Amps |
| ( $\rho_{eff} = 2 \times 10^{-12}$ $\Omega$ -cm, 5.85T, 4.25K) |                     |

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

The individual pole coil sizes in SLQ<sub>1</sub> 2602, 2603, 2604, 2605, and SLQ<sub>2</sub> 4804 matched to  $\pm 0.069$ mm 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.

### QUENCH HISTORY

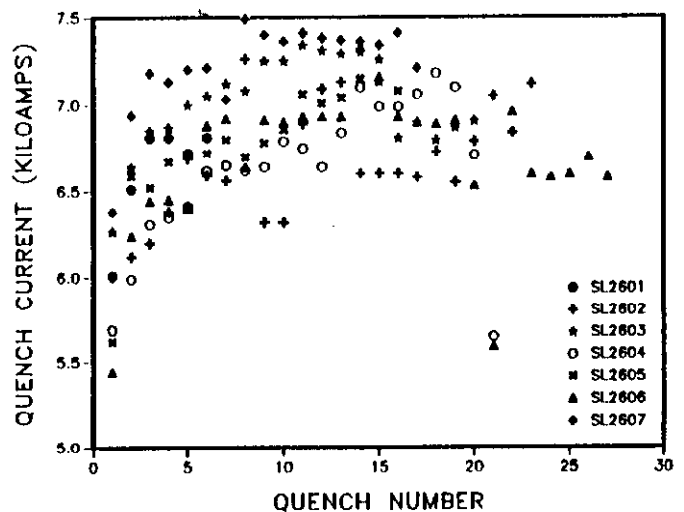


Figure 2A

### QUENCH HISTORY

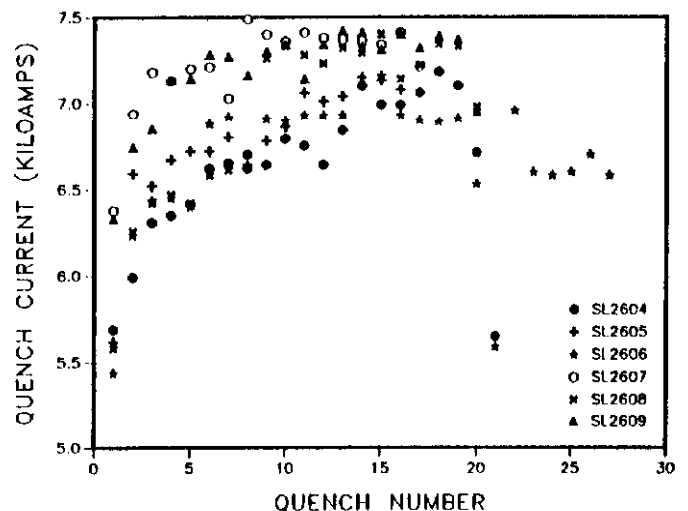


Figure 2B

### QUENCH HISTORY

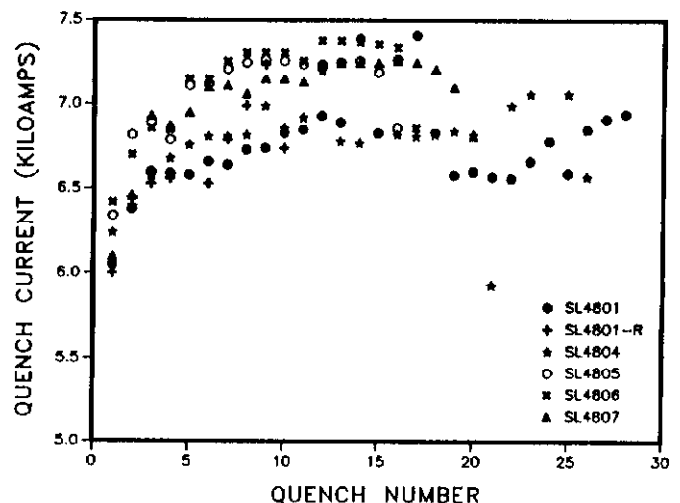


Figure 2C

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.

#### RAMP RATE DEPENDENCE OF QUENCH CURRENT

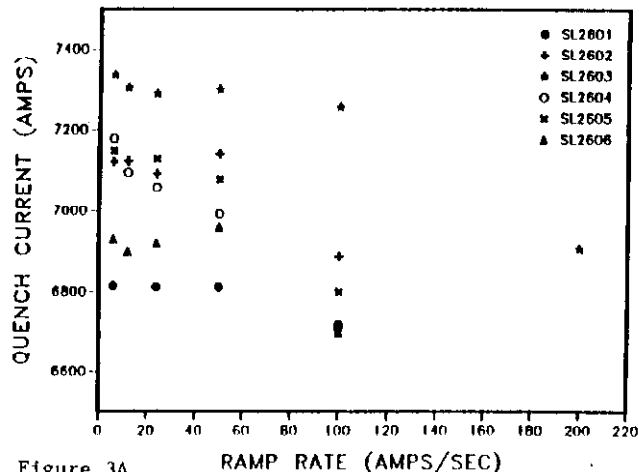


Figure 3A

#### RAMP RATE DEPENDENCE OF QUENCH CURRENT

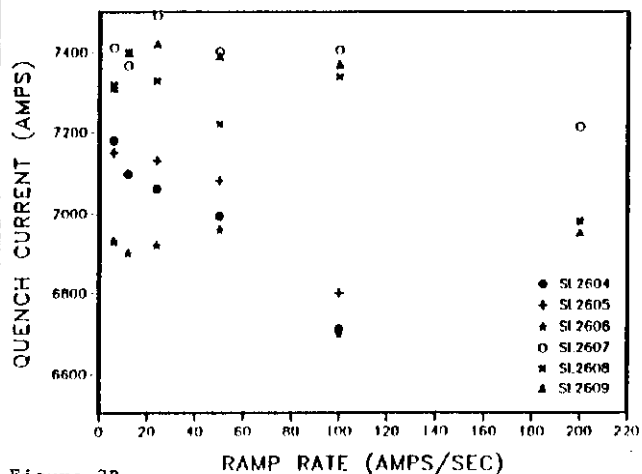


Figure 3B

#### RAMP RATE DEPENDENCE OF QUENCH CURRENT

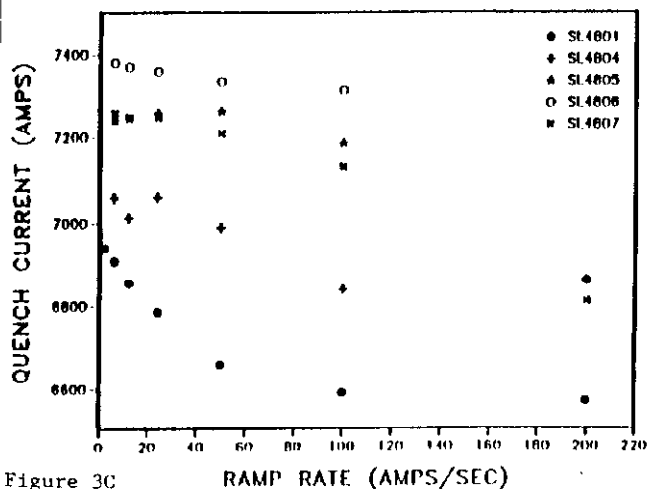


Figure 3C

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

| MAGNET              | ENERGY LOSS (JOULES) |       |       |       |       |       |
|---------------------|----------------------|-------|-------|-------|-------|-------|
|                     | CYCLE                |       |       |       |       |       |
|                     | 50 - 5000 AMPS       |       |       |       |       |       |
|                     | 6                    | 12    | 24    | 50    | 100   | 200   |
| Q <sub>1</sub> 2601 | 53.3                 | 58.9  | 60.7  | 62.7  | 65.6  | 68.4  |
| Q <sub>1</sub> 2602 | 32.6                 | 45.0  | 69.3  | 107.8 | 130.1 | 147.1 |
| Q <sub>1</sub> 2603 | 33.1                 | 46.4  | 74.0  | 113.2 | 131.6 | 150.0 |
| Q <sub>1</sub> 2604 | 34.2                 | 41.4  | 56.9  | 89.8  | 108.8 | 128.8 |
| Q <sub>1</sub> 2605 | 44.9                 | 79.5  | 102.3 | 120.0 | 135.0 | 152.0 |
| Q <sub>1</sub> 2606 | 27.3                 | 53.2  | 89.8  | 116.1 | 134.1 | 148.4 |
| Q <sub>1</sub> 2607 | 44.0                 | 86.5  |       | 148.1 | 147.5 | 160.8 |
| Q <sub>1</sub> 2608 | 34.2                 | 60.6  | 106.4 | 130.7 | 146.6 | 160.2 |
| Q <sub>1</sub> 2609 | 42.4                 | 59.6  | 99.8  | 127.2 | 149.0 | 157.1 |
| Q <sub>2</sub> 4801 | 42.2                 | 68.0  | 85.9  | 95.5  | 102.5 | 108.4 |
| Q <sub>2</sub> 4804 | 54.6                 | 85.5  | 121.9 | 146.5 | 166.1 |       |
| Q <sub>2</sub> 4805 | 64.0                 | 136.4 | 172.9 | 193.5 | 211.8 | 234.0 |
| Q <sub>2</sub> 4806 |                      | 137.2 | 165.8 | 189.9 | 210.0 | 240.0 |
| Q <sub>2</sub> 4807 | 93.9                 | 150.4 | 183.9 | 205.2 | 218.5 | 241.0 |

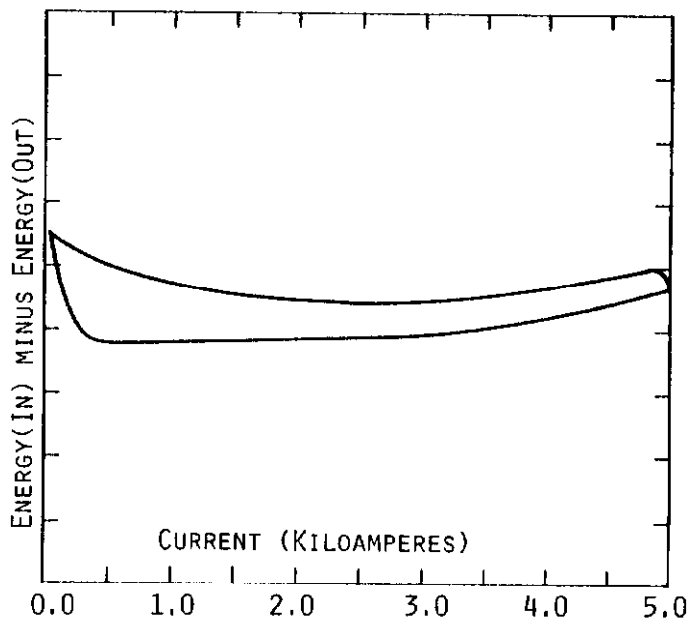


FIGURE 4 THE ENERGY(IN)-ENERGY(OUT) CURVE FOR SLQ<sub>2</sub> 4804. NOTE THE CURVATURE OF THE DATA INDICATING A CHANGE IN THE INDUCTANCE AT DEFLECTION OF THE COIL.

## 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" coil. The room temperature relative strengths are given in Table IV using the strength of SLQ<sub>2</sub> #4801 = 1. The actual measured ratio was 1.815 ± .006 (Spec. was 1.821).

Table IV

|            | INTEGRAL RELATIVE STRENGTH<br>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±.0029 |
| 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 | 0.9988±.0024 | 0.9972±.0024 | 0.9990±.0024 |

SLQ<sub>2</sub> 4801 - INTEGRAL STRENGTH (20 AMPS) PER AMP = 0.034 ± .00007  $\frac{\text{GAUSS}}{\text{CM AMP}}$

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

\* 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:

$$\frac{B_2(I_1, \frac{\text{Gauss}}{\text{cm}^2 \text{cm}})}{B_1(I_1, \frac{\text{Gauss}}{\text{cm}})} = B(\text{Norm}_2) (I_1, 1/\text{cm})$$

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

## PROBE 3 12 POLE SL2603.

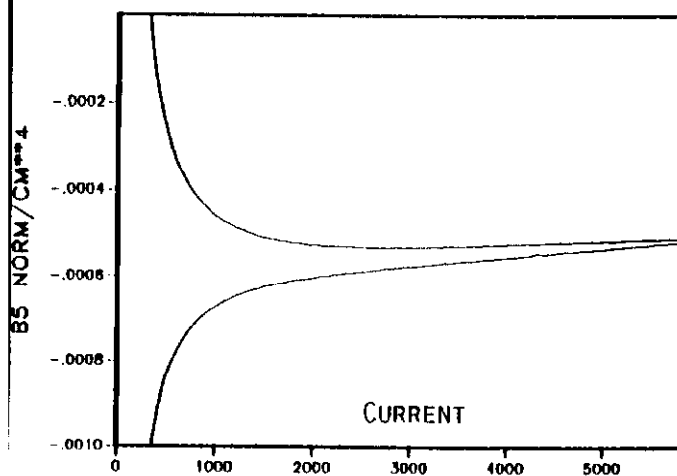


FIGURE 5 THE DUODECAPOLE (NORMALIZED) IS SHOWN AS A FUNCTION OF CURRENT FOR SLQ 2603 FOR A 5000 AMP TRIANGULAR CURRENT PULSE AS 6 AMPS/SEC

Table V

|      | INTEGRAL STRENGTH ( $\frac{\text{TESLA}}{\text{CM}}$ , 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 |              |              |
|------|--------------------------|--------------|--------------|
|      | 2000 AMPS                | 4000 AMPS    | 4750 AMPS    |
| 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

Table VII

| Normalized Integral Harmonics |        |       |       |       |       |       |       |       |       |
|-------------------------------|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| $\times 10^4$                 |        |       |       |       |       |       |       |       |       |
| 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  | -0.44 | 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 |       |       |       |       |       |       |       |       |  |
|-----|-------|-------|-------|-------|-------|-------|-------|-------|--|
| 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 | -0.47 | -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

 $\times 10^4$ 

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 |      |

## Normalized Harmonics Straight Section

 $\times 10^4$ 

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

 $\times 10^4$ 

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 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.

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 current of 4000 Amps.

# APPENDIX 1

Table A

| QUENCH HISTORY |                       |      |     |                       |      |     |                       |      |     |                       |      |     |
|----------------|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|
| Quench No      | SLQ <sub>2</sub> 2601 |      |     | SLQ <sub>2</sub> 2602 |      |     | SLQ <sub>2</sub> 2603 |      |     | SLQ <sub>2</sub> 2604 |      |     |
|                | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S |
| 1              | 4.2                   | 5.01 | 100 | 4.2                   | 6.00 | 100 | 4.2                   | 5.27 | 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                   | 5.31 | 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                   | 5.31 | 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                   | 6.60 | 50  |
| 13             |                       |      |     | 4.2                   | 7.13 | 12  | 4.2                   | 7.29 | 24  | 4.2                   | 6.80 | 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                   | 6.90 | 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                   | 6.90 | 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 A

| QUENCH HISTORY |                       |      |     |                       |      |     |                       |      |     |                       |      |     |                       |      |     |
|----------------|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|
| Quench No      | SLQ <sub>2</sub> 2605 |      |     | SLQ <sub>2</sub> 2606 |      |     | SLQ <sub>2</sub> 2607 |      |     | SLQ <sub>2</sub> 2608 |      |     | SLQ <sub>2</sub> 2609 |      |     |
|                | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S | 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 = AI<sup>2</sup> A(SLQ<sub>2</sub> 2606) = 11.0 x 10<sup>-8</sup> [Volts/kiloAmps<sup>2</sup>]  
A(SLQ<sub>2</sub> 2607) = 11.0 x 10<sup>-8</sup> [Volts/kiloAmps<sup>2</sup>]  
A(SLQ<sub>2</sub> 2608) = 5.0 x 10<sup>-8</sup> [Volts/kiloAmps<sup>2</sup>]  
A(SLQ<sub>2</sub> 2609) = 5.0 x 10<sup>-8</sup> [Volts/kiloAmps<sup>2</sup>]

Table C

| QUENCH HISTORY |                       |      |     |                       |      |     |                       |      |     |                         |      |     |
|----------------|-----------------------|------|-----|-----------------------|------|-----|-----------------------|------|-----|-------------------------|------|-----|
| Quench No.     | SLQ <sub>2</sub> 4801 |      |     | SLQ <sub>2</sub> 4803 |      |     | SLQ <sub>2</sub> 4802 |      |     | SLQ <sub>2</sub> 4801-R |      |     |
|                | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S | K                       | kA   | A/S |
| 1              | 4.2                   | 6.05 | 100 |                       |      |     |                       |      |     |                         |      |     |
| 2              | 4.2                   | 6.38 | 100 | 4.2                   | 4.32 | 100 | 4.2                   | 3.50 | 100 | 4.2                     | 6.00 | 50  |
| 3              | 4.2                   | 6.60 | 100 | 4.2                   | 4.27 | 100 | 4.2                   | 0.97 | 100 | 4.2                     | 6.45 | 50  |
| 4              | 4.2                   | 6.59 | 100 | 4.2                   | 4.14 | 100 | 4.2                   | 0.67 | 24  | 4.13                    | 6.53 | 24  |
| 5              | 4.2                   | 6.58 | 100 | 4.2                   | 4.55 | 6   | 4.2                   | 0.67 | 24  | 4.19                    | 6.56 | 24  |
| 6              | 4.2                   | 6.66 | 50  | 4.2                   | 3.76 | 200 |                       |      |     | 4.19                    | 6.58 | 12  |
| 7              | 4.2                   | 6.64 | 50  |                       |      |     |                       |      |     | 4.19                    | 6.53 | 12  |
| 8              | 4.2                   | 6.73 | 24  |                       |      |     |                       |      |     | 3.3                     | 6.79 | 50  |
| 9              | 4.2                   | 6.74 | 24  |                       |      |     |                       |      |     | 3.21                    | 6.99 | 50  |
| 10             | 4.2                   | 6.83 | 12  |                       |      |     |                       |      |     | 3.21                    | 7.24 | 50  |
| 11             | 4.2                   | 6.85 | 12  |                       |      |     |                       |      |     | 3.73                    | 6.74 | 50  |
| 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 <sub>2</sub> 4804 |      |     | SLQ <sub>2</sub> 4805 |      |     | SLQ <sub>2</sub> 4806 |      |     | SLQ <sub>2</sub> 4807 |      |     |
|                | K                     | kA   | A/S | K                     | kA   | A/S | K                     | kA   | A/S | 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 |                       |      |     |                       |      |     |                       |      |     |

Table E

| INTEGRAL HARMONICS |           |           |           |           |           |           |           |
|--------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\times 10^4$      |           |           |           |           |           |           |           |
| 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 |           |           |           |           |           |           |           |
|----------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\times 10^4$              |           |           |           |           |           |           |           |
| 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±.05 | -1.04±.44 | -0.31±.01 | -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 |           |           |           |           |
|--------------------|-----------|-----------|-----------|-----------|
| $\times 10^4$      |           |           |           |           |
| 4750 AMPS          |           |           |           |           |
|                    | 4804      | 4805      | 4806      | 4807      |
| A2                 | 3.86±.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 |           |           |            |           |
|----------------------------|-----------|-----------|------------|-----------|
| $\times 10^4$              |           |           |            |           |
| 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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