MAGNET DIVISION NOTES

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Title: Magnetic Properties of Fermilab 50 mm Aperture Dipole for Superconducting Super Collider

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Magnetic properties of Fermilab 50 mm Aperture Dipole for Superconducting Super Collider

Ramesh Gupta

1. Introduction

This note presents the magnetic analysis of the coil and iron cross section for the SSC 50 mm aperture dipole magnet with vertically split iron being built at Fermilab. The BNL magnets would be based on horizontally split iron design. This makes a significant difference in the mechanical properties of the two magnets. However, the coil and iron cross section for the straight section of the Fermilab dipole, except for few minor differences, is based on BNL design; therefore, the magnetic properties of this dipole would be quite similar to the one being built at Brookhaven. The cross section of the BNL magnet is described in detail in SSC Technical Note No. 88 (SSCL-N-699) by Gupta, Kahn and Morgan. In this note we shall discuss those features where the difference between the two cross sections has an impact on the magnetic field properties.

1.1 Coil Cross section

The cross section of the coil in the inner layer of the Fermilab dipole is identical to that of Brookhaven magnet. However, a late change in the thickness of the conductor to be used in the outer layer was dealt slightly differently in the two designs. The cable thickness was changed by 0.4 mil and since there are 26 turns in the outer layer it makes a total change of 10.4 mil in the pole angle of the outer layer. In the outer layer of the BNL coil a 10 mil shim will be used to fill this space and thus maintaining everything else in the construction similar to what it was before this change in outer cable thickness. In FNAL magnet another approach will be used. The pole angle will be reduced by 5 mil, either by changing the collar dimensions or by using 5 mil shim, and the coil will be allowed to expend 5 mil. This brings the low field value of sextupole harmonics quite close to zero. However, these are really very small differences in the details of coil construction and for all practical purpose these two cross sections are practically the same.

It may be noted that the initial few magnets are not known to, and probably should not be expected to, have the harmonics as per their design value. This is because of the fact that for several reasons the individual turns do not take their theoretically designated location. A few mil error here and there makes a noticeable difference in the field harmonics. Once a coil manufacturing process is established and several magnets are built, a systematic offset can be removed by making small changes in the coil designs to cancel those undesired harmonics out.

Table 1.1: The values of *low field* harmonics in prime units. These harmonics are in the units of 10^{-4}

b_2'	b_4'	b_6'	b_8'	b_{10}'	b_{12}'
0.164	0.071	-0.021	0.043	0.015	-0.001

In Fig. 1.1 the coil cross section of Fermilab magnet and values of several other parameters are given. The design values of low field harmonics in prime units is given in Table 1.1.

1.2 Iron Yoke Design

The basic design of the Fermilab iron yoke cross section is the same as that of the Brookhaven yoke. A few differences between the two designs arise mainly due to the vertically split iron v/s horizontally split iron configuration in the two designs. These differences and their influence on the iron saturation characteristic, particularly in the sextupole harmonic, is discussed below:

(a) In FNAL dipole the notch at the inner radius of the yoke for collar-yoke alignment is at the midplane whereas in the BNL yoke it is at the pole. The midplane notch helps in reducing b_2 saturation peak, whereas the pole notch makes it worse. The difference in b_2 peak in the two cases is about 0.25 prime unit.

(b) The FNAL yoke has an additional pinhole in each quadrant which is located below the space reserved for the bus work. It causes an extra pole saturation. The increase in b_2 peak due to this additional hole is 0.2 prime unit. The effect of this hole will become even more serious if it is brought further down. However, if the pins are solid and are made of low carbon magnet steel, they will not be a part of magnetic design. The transfer function would be up by 0.3% and the b_2 peak will be down by 0.12 prime unit if all pins (two in each quadrant) are made of solid low carbon steel.

(c) In FNAL dipole the notch or cutout at the outer radius of the yoke for welding purpose is at the pole whereas in the BNL yoke, it is at the midplane. The pole location produces no saturation effect, whereas the midplane location reduces the b_2 peak by an small amount.

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file = $2$DUA3:[GUPTA.INFMU]W6733E.D07;1        Run   6-SEP-90 12:41:22
 CHISQ=    0.2155 dB/Ellipse=    0.2180 Peak Enhanc=    0.000  0.000
TRANSFER FUNCTION=  10.47073  POLE ANGLE=  74.60458 Rfe= 6.781 Rref= 1.000
```

PARAMETERS	ORIGINAL	FINAL	DIFFERENCE	Face Angles	
1	6.	6.	0.	-0.33	-10.66
2	1.19215	1.19215	0.00000		
3	7.	7.	0.	9.59	-2.50
4	4.48867	4.48867	0.00000		
5	3.	3.	0.	2.51	-2.51
6	4.48867	4.48867	0.00000		
7	3.	3.	0.	2.51	-2.51
8	11.	11.	0.	-0.24	-8.39
9	1.05279	1.05279	0.00000		
10	15.	15.	0.	1.47	-9.73
11	-4.40000	-4.40000	0.00000		
12	0.00000	0.00000	0.00000		
13	0.00000	0.00000	0.00000		
14	4.73540	4.73540	0.00000		

Allowed primed Harmonics

n	bn-cal	bn-des	n	bn-cal	bn-des
0	10000.000	0.000	10	0.015	0.000
2	0.164	-0.280	12	-0.001	0.000
4	0.071	0.010	14	0.000	0.000
6	-0.021	0.000	16	0.000	0.000
8	0.043	0.000	18	0.000	0.000

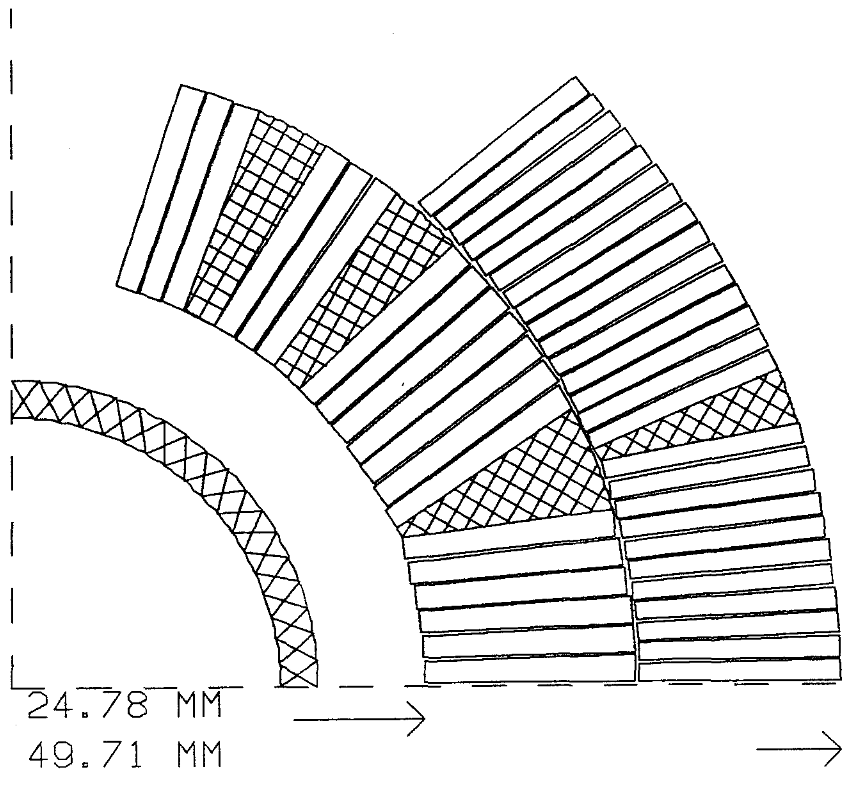

Figure 1.1: Modified Coil Cross section W6733 for Fermilab Dipole.

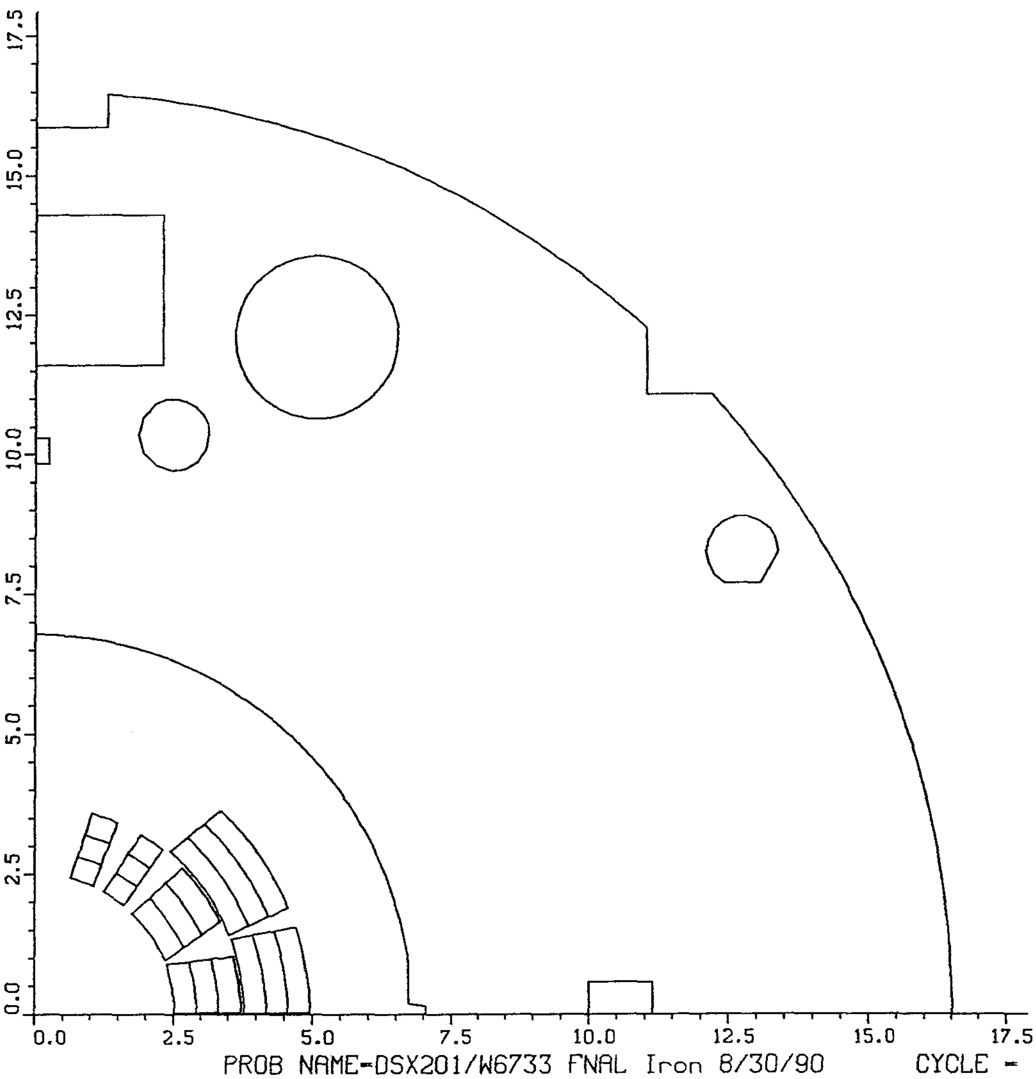

Figure 1.2: POISSON model for Fermilab DSX201/W6733.

(d) The location of the He bypass hole and Bus channel is slightly different in the two yokes. However, the difference is too small to produce any significant effect on the iron saturation.

(e) The size of the yoke-yoke alignment key in the FNAL dipole is $\frac{3}{16}'' \times \frac{3}{16}''$ and is located at the pole. The size of the yoke-yoke alignment key in the BNL dipole is $\frac{1}{2}'' \times \frac{1}{2}''$ and is located at the midplane. The FNAL alignment key at the pole has a negligible effect on increasing the pole saturation (0.01 prime unit of b_2) due to its smaller size. However, in the BNL yoke this key is a major part of the magnetic design. It is deliberately made of non-magnetic material (Stainless Steel) and reduces the b_2 peak due to iron saturation by about $\frac{3}{4}$ prime unit. A similar reduction in FNAL design yoke is obtained by incorporating a cutout at the midplane. The size of the midplane cutout in the present cross section is 11.5 mm $\times$ 11.5 mm and it begins at 100 mm from the center of the magnet. It reduces b_2 peak by about 0.6 unit. If the BNL size cutout for key is used in the FNAL yoke and if the cutout is made at the same location where it is in BNL yoke, the b_2 peak will be further reduced by 0.2 unit.

It may be pointed out that the peak value of the sextupole harmonics can be controlled in both designs by changing the size and/or location of the midplane cutout in the iron lamination. This will be a useful tool to emperically obtain a desired value of the b_2 peak (in b_2 v/s I curve) after obtaining a sufficient and reliable statistics. The difference between the calculations presented in this note and the measurements in the real magnets may, for example, be due to the following reasons:

(a) The coil distortion, and hence change in b_2, due to Lorentz Forces

(b) The magnetic properties of Iron being different then what is assumed in the calculations

(c) The limitation of computer calculations and of computer modelling.

The computer model of the Fermilab dipole is shown in Fig. 1.2. In Table 1.2 the results of field calculations for various values of current in each turn is given. The maximum change in the sextupole harmonic, b_2', due to iron saturation is 0.56 prime unit and in b_4' is 0.01 unit. There is practically no change in higher harmonics. The variation of field harmonics as a function of central field is plotted in Fig. 1.3. An iron packing factor of 97.5% is used in these calculations. The field lines at 6500 Amps are shown in Fig. 1.4.

Table 1.2: POISSON results - DSX201/W6733 FNAL Cross section.

I kAmp	B_o Tesla	T.F. T/kA	b_2' 10^{-4}	b_4' 10^{-4}	b_6' 10^{-4}	b_8' 10^{-4}	b_{10}' 10^{-4}	b_{12}' 10^{-4}
$\infty\mu$	$\infty\mu$	1.04525	-0.181	-0.039	0.000	0.047	0.015	-0.001
2.000	2.0902	1.04509	-0.175	-0.039	0.001	0.047	0.015	-0.001
3.000	3.1351	1.04504	-0.180	-0.039	0.001	0.047	0.015	-0.001
4.000	4.1781	1.04454	-0.178	-0.040	0.001	0.047	0.015	-0.001
4.500	4.6947	1.04326	-0.192	-0.041	0.001	0.047	0.015	-0.001
4.750	4.9491	1.04191	-0.178	-0.043	0.001	0.047	0.015	-0.001
5.000	5.2008	1.04016	-0.129	-0.044	0.001	0.047	0.015	-0.001
5.250	5.4473	1.03758	-0.005	-0.047	0.000	0.047	0.015	-0.001
5.500	5.6891	1.03438	0.141	-0.048	0.000	0.048	0.015	-0.001
5.750	5.9261	1.03063	0.271	-0.049	0.000	0.048	0.015	-0.001
6.000	6.1579	1.02632	0.349	-0.050	0.000	0.048	0.015	-0.001
6.250	6.3848	1.02157	0.375	-0.049	0.000	0.048	0.015	-0.001
6.500	6.6073	1.01650	0.348	-0.049	0.000	0.048	0.015	-0.001
6.750	6.8251	1.01112	0.266	-0.049	0.000	0.049	0.015	-0.001
7.000	7.0413	1.00590	0.171	-0.048	0.000	0.049	0.015	-0.001
7.250	7.2540	1.00055	0.039	-0.047	0.000	0.049	0.015	-0.001

1.3 Lorentz Force Calculations

The approximate value of Lorentz force on each turn at 6.5 kAmps (6.6 Tesla) is obtained from the components of the magnetic field (B_x, B_y) at the center of each turn. The magnitude of the radial and azimuthal components of the lorentz force, namely F_r and F_θ, on each turn is shown in Fig. 1.5. In this figure turn number 1 to 19, starting from the midplane, are in the inner layer and turn number 20 to 45 are in the outer. The lorentz force acts on the coil such that the azimuthal component compresses the coil on the midplane and the radial component expends it outward. Though the radial force on the turns in the outer layer is very small but the force on the turns in the inner layer must be transmitted through the outer layer to the structure of the magnet.

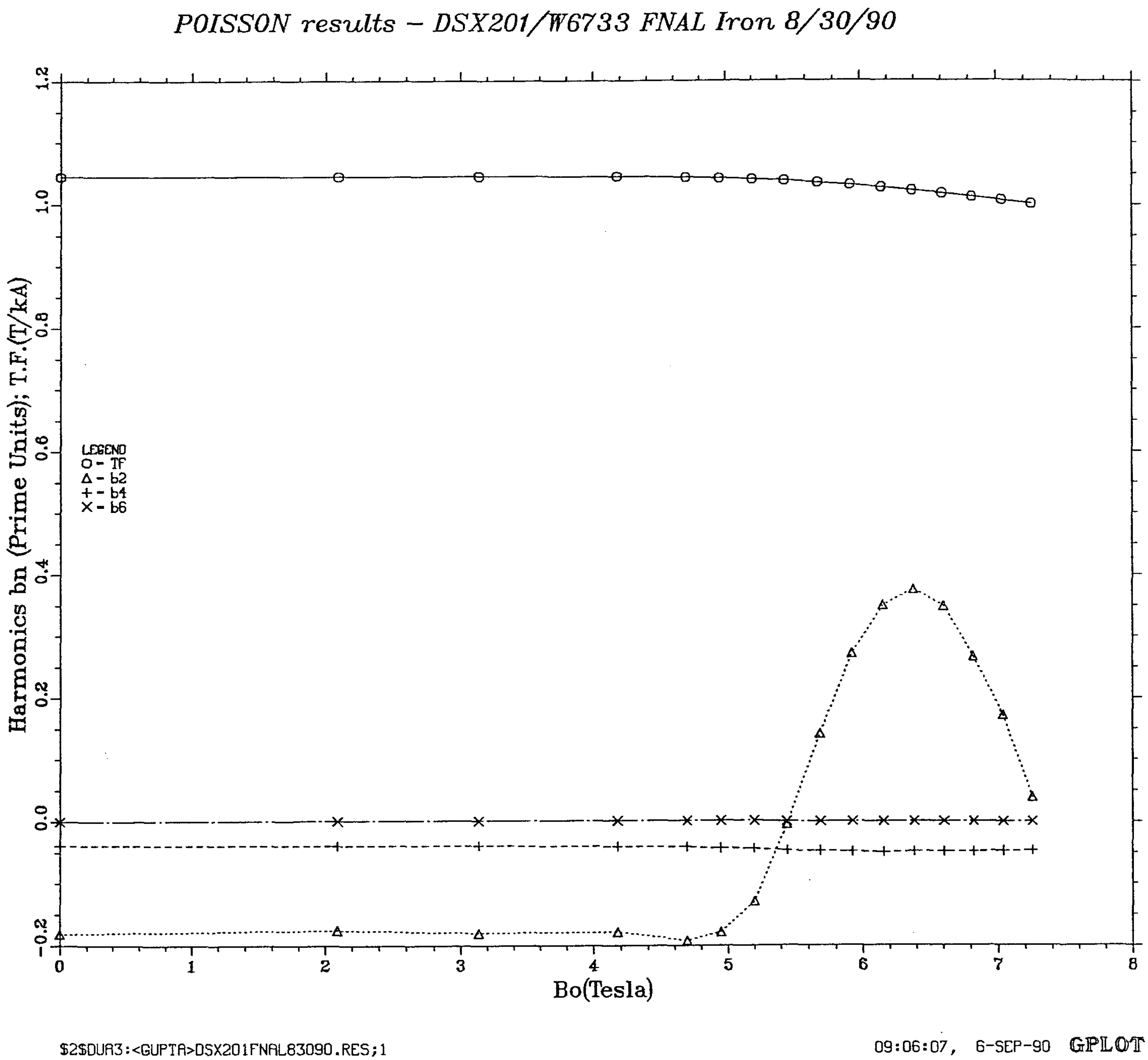

Figure 1.3: Variation in Field Harmonics as a function of B_o for Fermilab Vertically Split Iron lamination design as computed by POISSON.

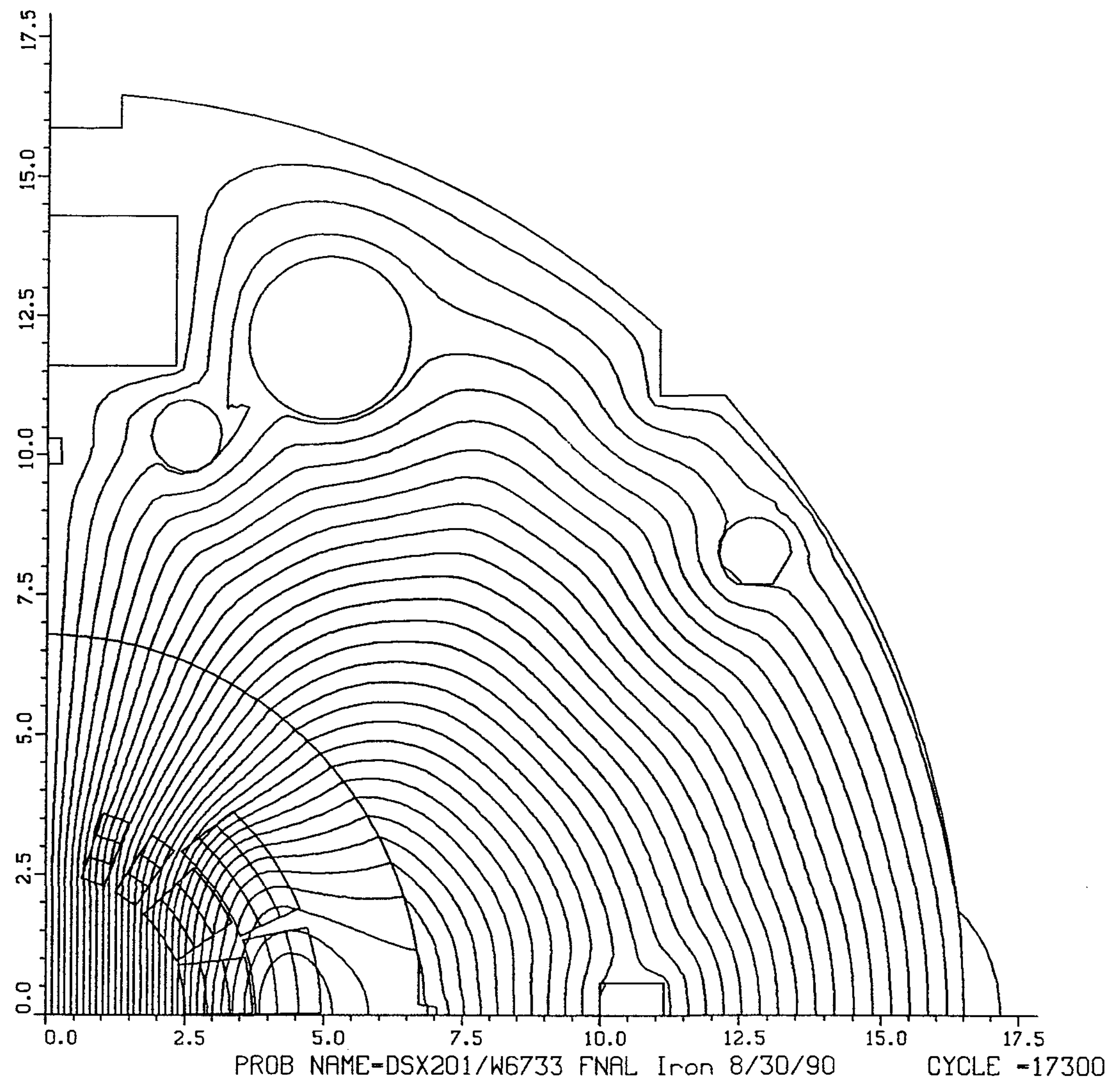

Figure 1.4: Field lines in Fermilab DSX201/W6733 at 6500 Amps.

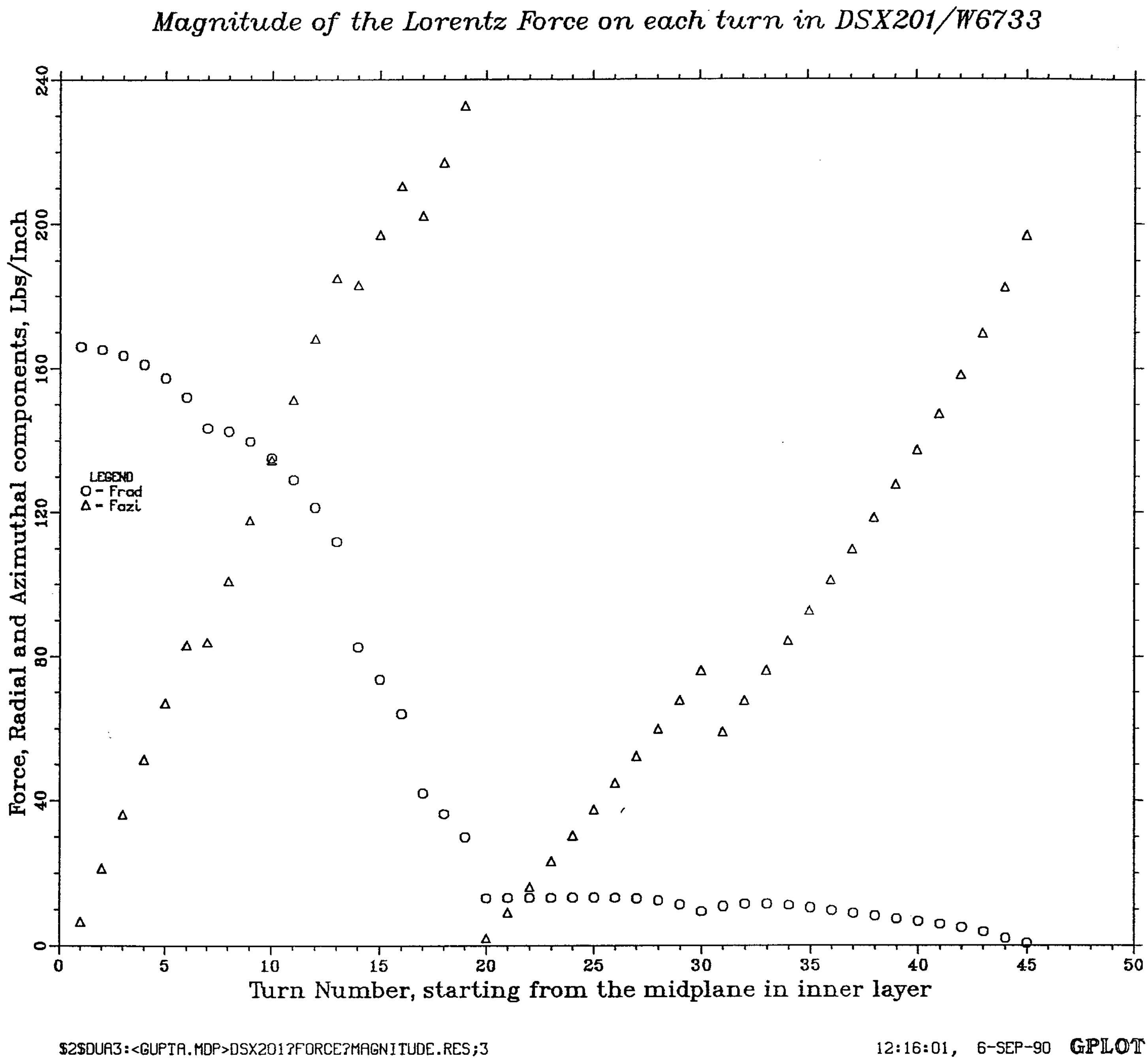

Figure 1.5: Magnitude of the Lorentz Force on each turn.