Synchrotron Light Source Magnets

CLS DESIGN NOTE – 5.2.31.2 Rev.0
(formerly 2.1.8.I)

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REVISION HISTORY

Revision	Date	Description	Author
B	May 18, 1999	Original Draft	L.O. Dallin
C	October 1, 1999	Update lattice to 500 Mhz	L.O. Dallin
D	October 18, 1999	Move first S1 sextupole 85 mm	L.O. Dallin
0	February 11, 2001	2.9 Gev operation Change File number Change effective length of quadrupoles and sextupoles Correct Figs. 11,13,14	L.O. Dallin

1. Introduction

The preliminary design of the synchrotron radiation source (SR1) magnets has been completed. The dipole, quadrupole and sextupole magnets comprising the main elements of the storage ring are illustrated in Figure 1 which shows one full cell. The magnetic properties of these elements have been modeled using POISSON (see Appendix I). For all the magnets AISI 1010 steel was used. (see Appendix I for B-H curve.) From these analyses the power requirements were determined.

Note regarding Rev.0:

In the revision of February 11, 2001 (Rev.0) the effective lengths of the quadrupole magnets were reduced. This is based on a request of the Machine Advisory Committee who suggested that the effective length will be closer to the physical length when the optimum chamfer in added to the pole ends. A 3D model of the CLS quadrupole indicated that the optimum chamfer would result in a effective length that is 17 mm longer than the physical length. The same model indicated the field gradient was 4% lower than the POISSON model presented in this report. Consequently, the magnetic lengths in this report were calculated by using:

Magnetic length (mm) = 0.96 * [Physical length (mm) + 17 mm] (with some round-off).

The nominal field gradients for the quadrupoles were recalculated by incorporating the new effective lengths into the DIMAD model of the storage ring lattice.

The effective lengths of the sextupole magnets are also reduced in Rev.0. For these magnets the effective length is now taken to be the physical length. The required nominal field gradients using the new effective lengths were recalculated with DIMAD.

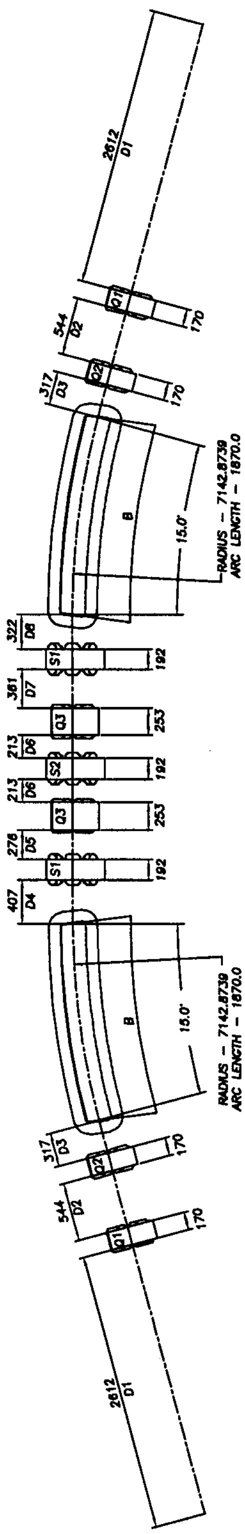

Figure 1 Full cell of the DBA achromat.

2. Dipole Magnets

The dipole magnets are gradient magnets with a bend angle of 15^{o}. At 2.9 GeV, a field strength of 1.3543 T and a field gradient of 3.867 T/m are required. Each magnet is built in a "C" configuration to allow the radiated photons to leave the magnet unimpeded by iron. A cross sectional view of the magnet is shown in Figure 2.

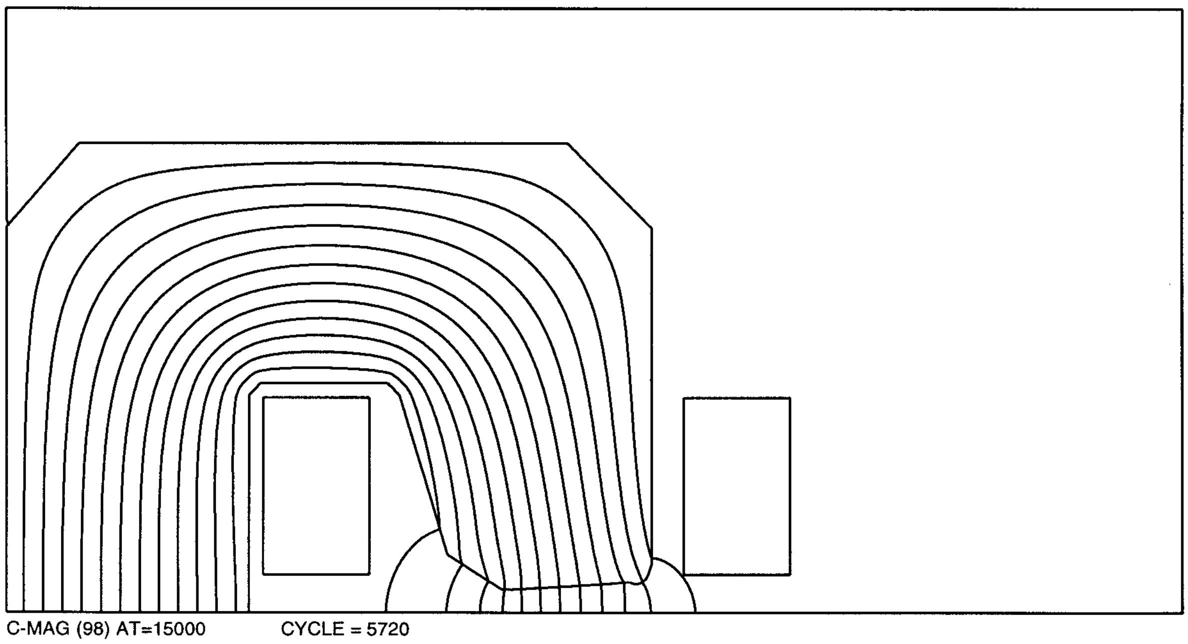

Figure 2 Cross section of the dipole magnet.

The magnet design was developed using POISSON. Because of the limited mesh size available in the program, the calculated field lines to the right of the dipole (see Figure 2) are valid to only a few percent. However POISSON can be used to calculate the variations in field strength and field gradient over a range of excitation currents to determine if the magnet design is robust. The results of these calculations are given in Table 1. The energy independent field gradient is given by

$$k1 = \frac{0.3B'}{E}$$

where B' is the field gradient in T/m and E is the beam energy in GeV. The design value is $k1 = -0.400\ m^{-2}$.

Table 1 Dipole Excitation.

I Ampere-turns	B T	k1 m^{-2}	E GeV
15000	0.8283	- 0.399	1.774
20000	1.1002	- 0.399	2.356
25000	1.3563	- 0.399	2.904
28500	1.4911	- 0.399	3.193

For these calculations the magnet iron permeability of AISI 1010 steel was used. At the field strengths where the magnets will be operating, saturation effects cause the field strength to be slightly non-linear with excitation current. The efficiency at 2.9 GeV is 97.3%

The magnet field strengths were calculated at the centre of the magnet pole. The field gradients were calculated by fitting a polynomial to the field profile over a region extending about ±25 mm from the centre. Over this "good field region" the higher order field gradients, B'', B''', etc., were less than 0.05%.

The coil dimensions are 146 mm by 89 mm. Allowing for a 17.5 mm by 17.5 mm conductor, there can be 8 by 5 windings or 40 windings per coil. To allow for insulation and packing, the actual conductors will be 16.26 mm (0.64 in.) square and they will have a 8.13 mm diameter cooling channel. From Table 1, the ampere-turns is 25000 at 2.904 GeV, so a current of 625 A must be supplied. From the magnet dimensions the electrical requirements can be calculated. A summary of the dipole parameters are given in Table 2.

Table 2 Dipole Magnet Parameters at 2.9 GeV

Number of magnets	24	
Bend angle	15	degrees
Field strength	1.354	T
Gradient, k1	- 0.400	m^{-2}
Gradient	- 3.87	T/m
Magnet arc length	1.87	m
Radius of curvature	7.14	m
Magnet gap on orbit	45	mm
Good field width	50	mm
Number of coils	2	
Ampere-turns	25000	
Number of windings per coil	40	
Current	625	A
Conductor area (less cooling channel)	183	mm^2
Conductor length per coil	179	m
Conductor length per magnet	358	m
Resistance per magnet (copper)*	0.035	Ω
Voltage drop per magnet	21.9	V
Power per magnet	13.7	kW

*resistivity = 1.79 E-8 Ω m

The quality of the good field region of the gradient dipole magnet is shown in Figure 3. The figure shows ΔB/B, on the horizontal (X) axis, with respect to the magnet center. ΔB is given by

$$\Delta B = B(x) - B - B' x$$

where B(x) is the field value calculated by POISSON on the transverse horizontal axis, and B and B′ are the dipole field and quadrupole fields derived from Table 1.

The four curves represent the four excitations shown in the table. For all excitations, the remnant field (ΔB) is less than 0.1% over a region of ±25 mm, defining a total good field region of 50 mm. At lower excitations the good field region is over 60 mm.

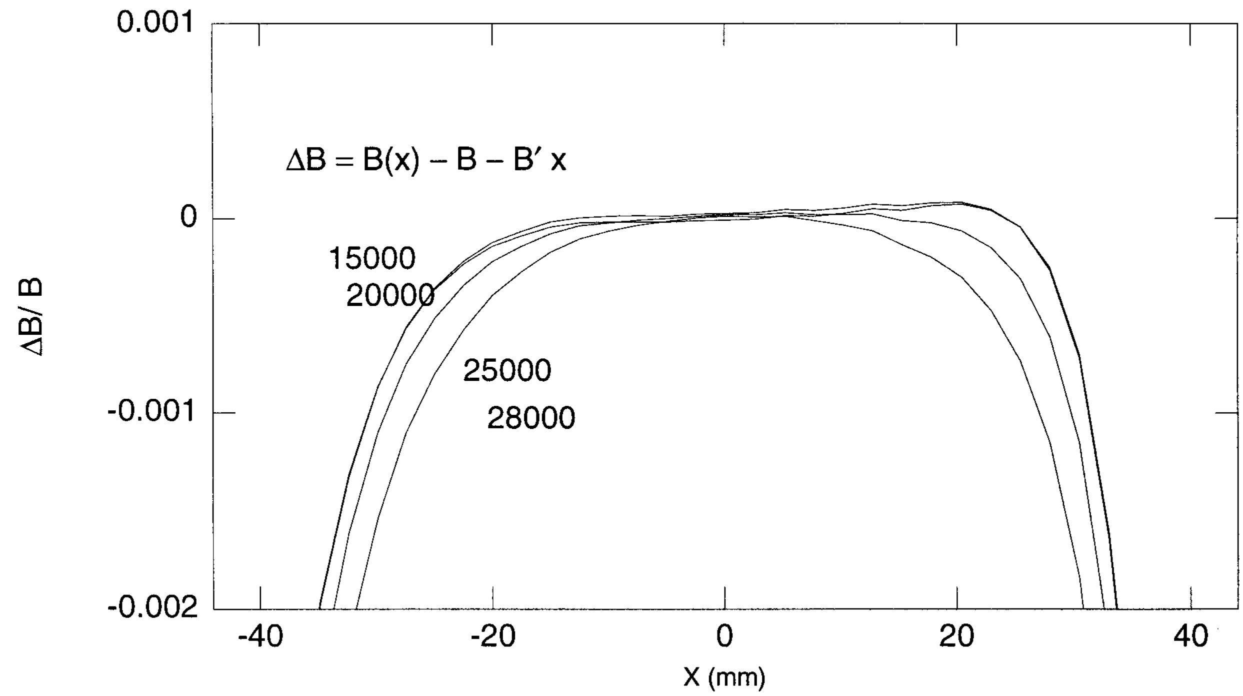

Figure 3 Remnant fields for the gradient dipole a different excitations.

3. Quadrupole Magnets

The SR1 lattice has three families of quadrupoles. Two (physical) lengths of quadrupoles are used. They are Q1: 0.170 m, Q2: 0.170 m, and Q3: 0.253 m. All quadrupoles have the same cross section as shown in Figure 4. An open sided configuration is used to allow synchrotron radiation an easy exit from the magnet.

A harmonic analysis, at a radius of 30 mm from the quadrupole centre, shows that the higher order field gradients are small, with less than 0.02% sextupole or octupole contamination. Details are given in Table 3.

Table 3 Quadrupole Excitation

Ampere-turns	B T	B' T/m	B'' T/m^2	B''' T/m^3	B'''' T/m^4	B''''' T/m^5
8000	- 0.189E-4	18.76	0.04	- 2.76	50.04	7.02E3
9150	- 0.198E-4	21.42	0.04	- 2.33	32.48	7.31E3
9500	- 0.209E-4	22.22	0.04	- 2.48	47.81	7.27E3

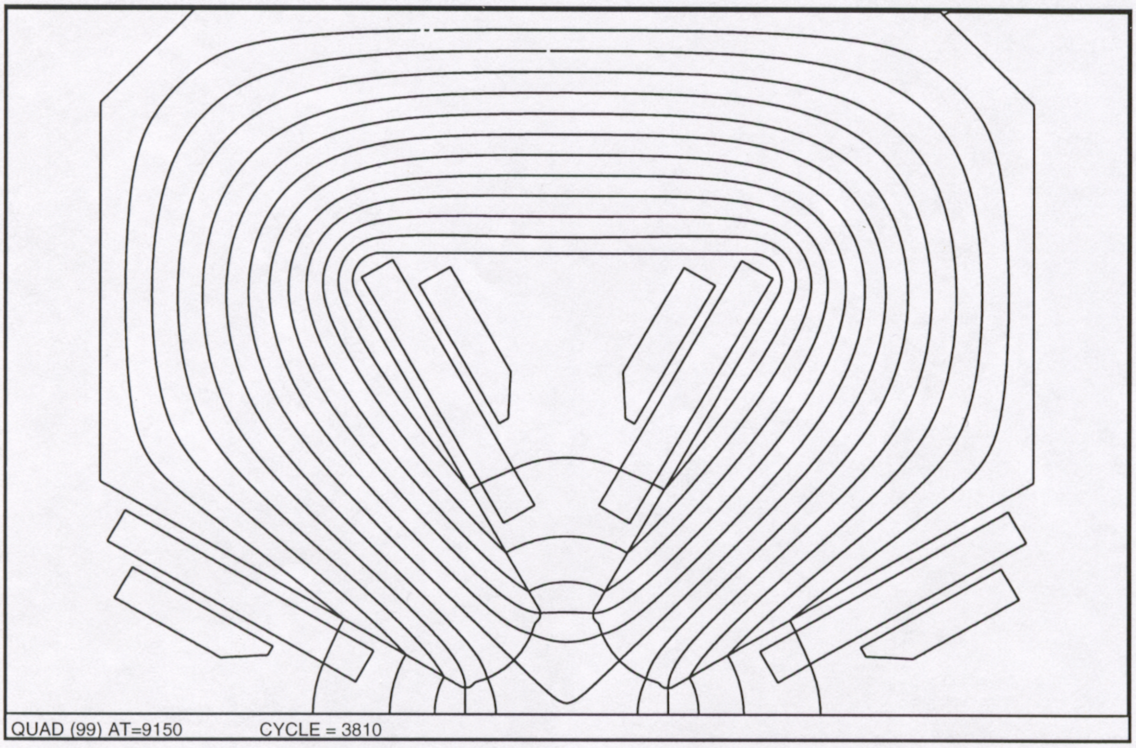

Figure 4 Quadrupole cross section

The magnet coils are in two parts as shown in Figure 4. Using 4.76 mm square hollow conductor, with a 3.19 mm diameter cooling channel, allows a total of 104 windings. Exciting a quadrupole to a maximum field gradient of 22.22 T/m requires about 9500 ampere-turns or 93.1 A.

A summary of the quadrupole parameters is given in Table 4. Ampere-turns have been linearly scaled from the data for 9500 ampere-turns. Maximum values represent upper limits required for tunability.

Table 4 Quadrupole Magnet Parameters at 2.9 GeV and at Maximum Excitation

	Q1	Q2	Q3	
Number of magnets	24	24	24	
Magnet length (physical)	0.170	0.170	0.253	m
Magnetic length	0.180	0.180	0.260	m
Magnet aperture radius	32.5	32.5	32.5	mm
Gradient, k1	1.806	1.670	2.083	m^{-2}
Gradient, $k1_{max}$	2.30	2.30	2.30	m^{-2}
Field gradient (nominal)	17.46	16.14	20.14	T/m
Field gradient (maximum)	22.22	22.22	22.22	T/m
Good field radius	30	30	30	mm
Number of coils (2 parts each)	4	4	4	
Ampere-turns (nominal)	7465	6900	8611	
Ampere-turns (maximum)	9500	9500	9500	
Number of windings per coil	104	104	104	
Current (nominal)	71.8	66.4	82.8	A
Current (maximum)	91.3	91.3	91.3	A
Conductor Area	14.7	14.7	14.7	m
Conductor length per magnet	288	288	356	m
Resistance per magnet (copper)*	0.35	0.35	0.44	Ω
Maximum voltage drop per magnet	32.0	32.0	40.2	V
Maximum power per magnet	2.92	2.92	3.67	kW

*resistivity = 1.79 E-8 Ω m

The good field regions for the quadrupole magnets are shown in Figure 5. $\Delta B/(B' x)$ is plotted, where

$$\Delta B = B(x) - B - B' x - B'' x^2.$$

The small dipole filed, B, has been subtracted since it can be compensated for using the ring orbit correctors. The effect of the sextupole component, B'', has been subtracted from the remnant field since it can be compensated for by adjusting the sextupole magnets in the ring.

Curves are derived from the information shown in Table 3. The good field region is about ±30 mm. The variations in the curves arise from the numerical accuracy of the POISSON calculations.

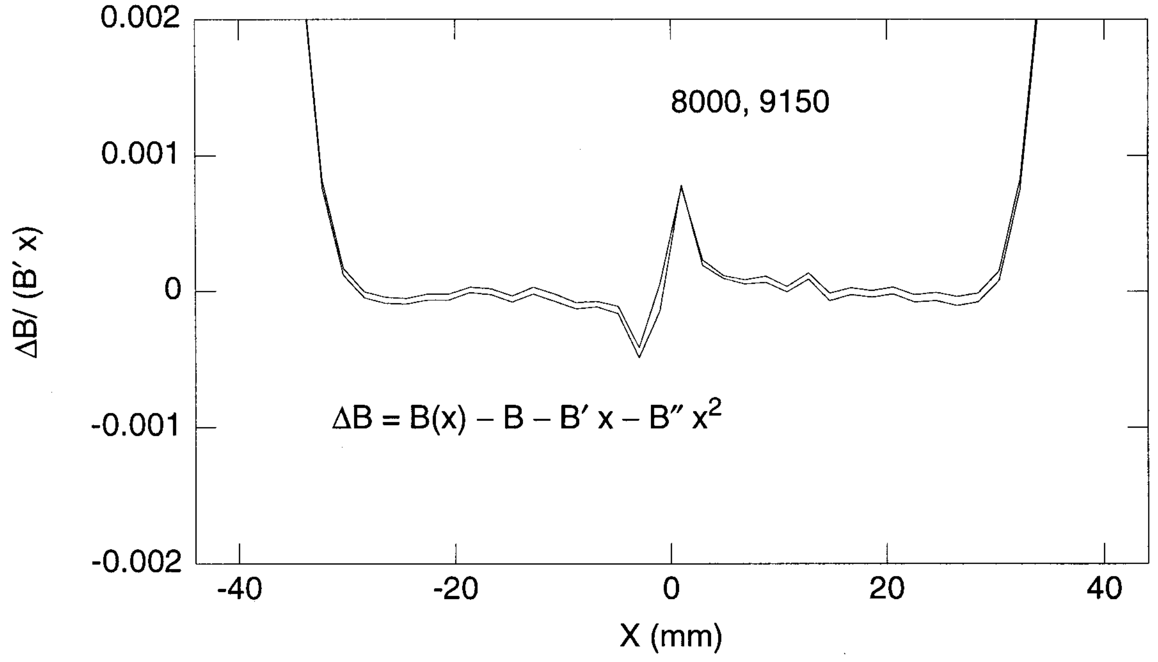

Figure 5 Remnant fields for the quadrupoles.

4. Sextupole Magnets

The SR1 lattice has two families of sextupoles, S1 and S2. The sextupoles all have the same cross section, as shown in Figure 6, and they are constructed using a "C" configuration.

The S1 sextupole magnets also serve as steering magnets (correctors) and have separate coil windings for each function. Both the S1 and S2 sextupoles have separate skew quadrupole windings. The harmonic content over the good field radius for each mode is given in Table 5. The different magnet modes are shown in Figures 6 to 9.

Table 5 Sextupole Excitation

Mode	Ampere-turns	B T	B′ T/m	B′′ T/m^2	B′′′ T/m^3	B′′′′ T/m^4
Sextupole (B_y)	3600 / 3600 / 3650 **3600 / 3600 / 3600** * 3600 / 3600 / 3600	- 1.21E-3 - 1.65E-3 0.07E-3	- 0.004 - 0.036 0.001	224.16 223.15 224.25	- 2.3 - 20.0 0.9	- 336 - 473 63
X-corrector (B_y)	1332 / 2664 / 1332	0.0745	- 0.013	- 0.31	- 5.1	2.3E4
Y-corrector (B_x)	2664	0.0867	- 0.000	0.02	1.27	- 2.7E4
Skew quad (B_x)	720	- 1.E-6	0.551	0.148	- 308	- 1.6

* right side return yoke included

The coils for exciting the sextupole field are shown in Figure 6. Using 4.76 mm square hollow conductor with a 3.19 mm diameter cooling channel allows 36 windings per coil. To reduce the quadrupole and octupole content of the sextupole mode, extra excitation of the outer poles was considered. In the above table the excitations using the extra Ampere-turns is denoted as 3600/ 3600/3650. This ratio could be accomplished with current shunts but is not necessarily required. Exciting the sextupole to a maximum pole tip field gradient of 268 T/m^2 requires 120 A.

The X-corrector coils are shown in Figure 7. Using the same conductor, described above, allows for 12 and 24 windings in the small and large coils respectively. The X-corrector is slightly affected by the magnet asymmetry.

The Y-corrector coils are shown in Figure 8. With the same conductor size there are 24 windings. The Y-corrector is not adversely affected by the magnet asymmetry.

The skew-quadrupole coils on the S1 sextupoles are shown in Figure 9. For these windings 2.04 mm diameter solid conductor is used. This allows for 48 windings. On the S2 sextupoles a winding similar to the center winding shown in Figure 7 is used to excite the skew quadrupole. This has 24 windings.

Exciting the maximum X-kick or Y-kick requires 111 A. The S1 skew quadrupole requires 15 A and the S2 skew quadrupole requires 30

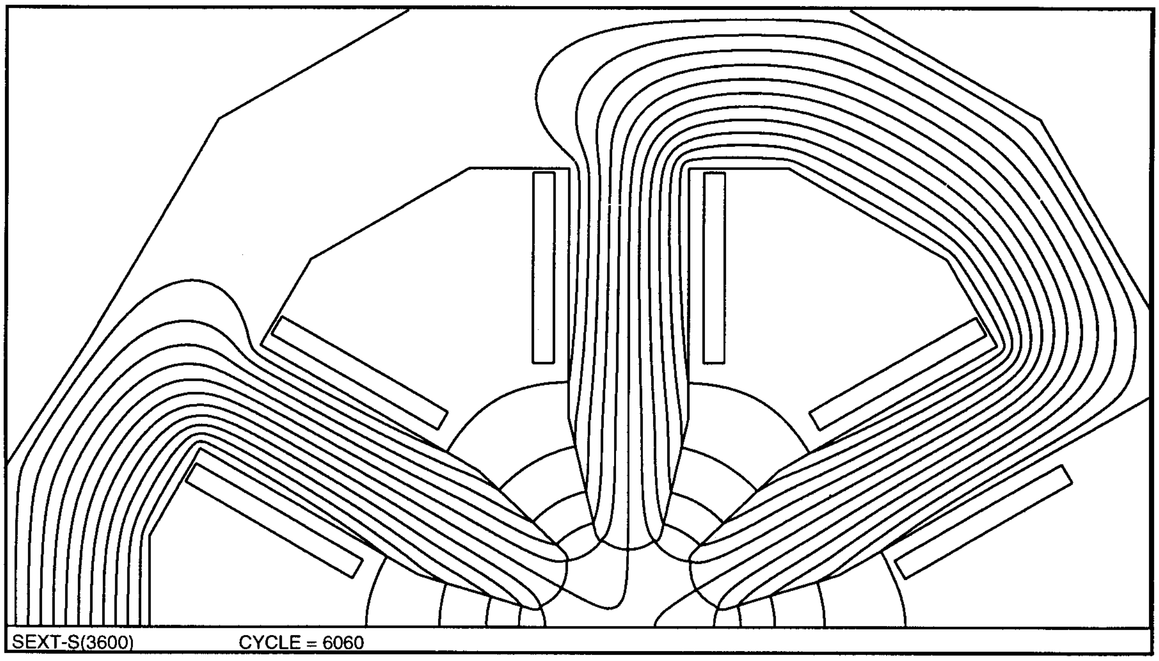

Figure 6 Sextupole cross section, sextupole mode.

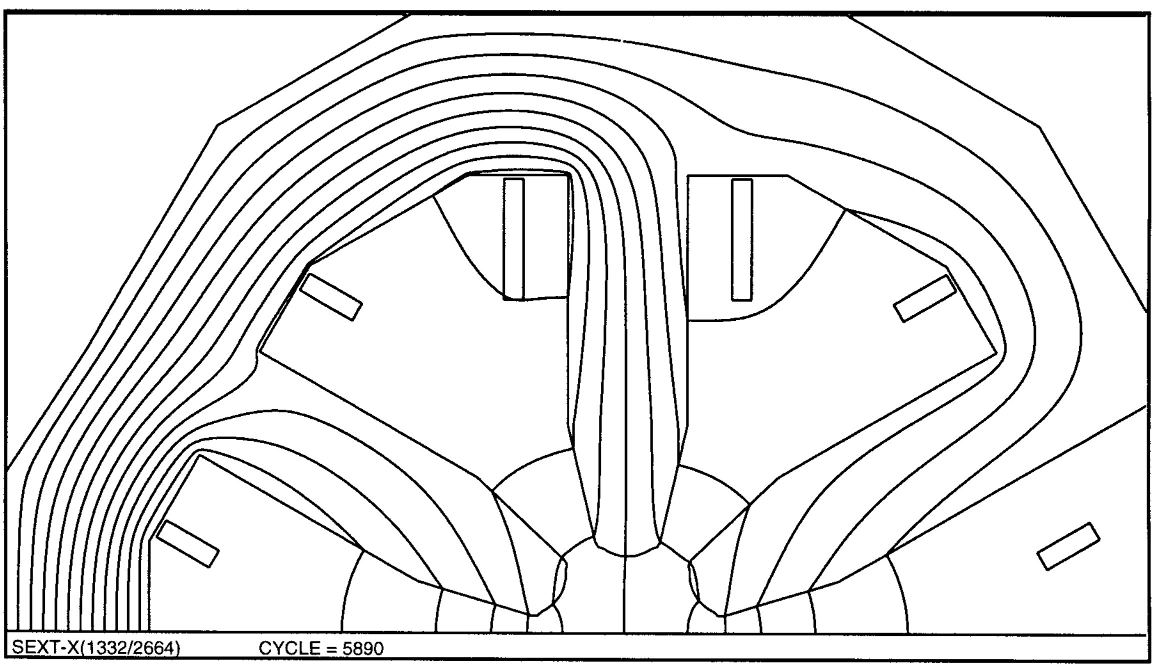

Figure 7 Sextupole, X corrector mode.

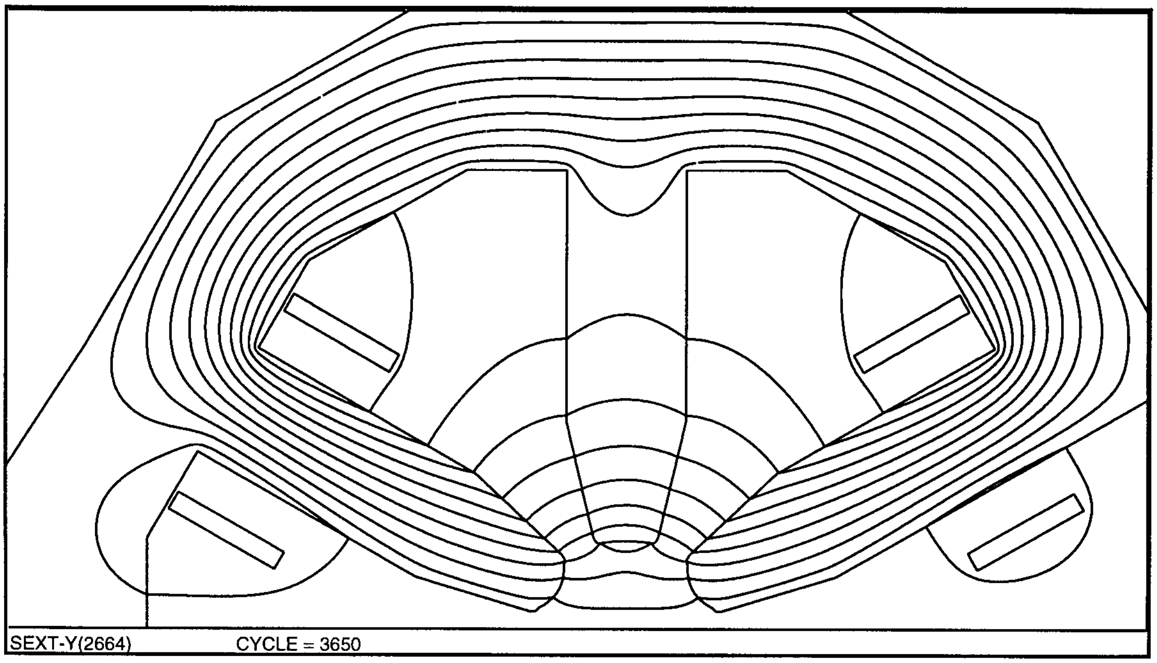

Figure 8 Sextupole, Y corrector mode.

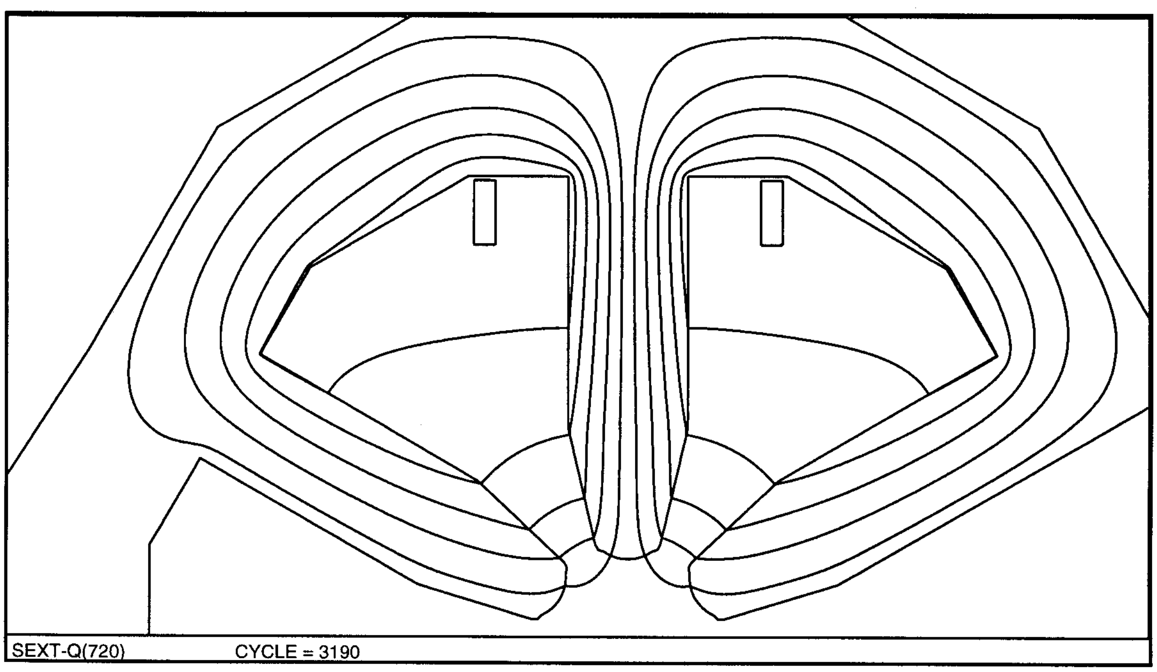

Figure 9 Sextupole, skew quadrupole mode.

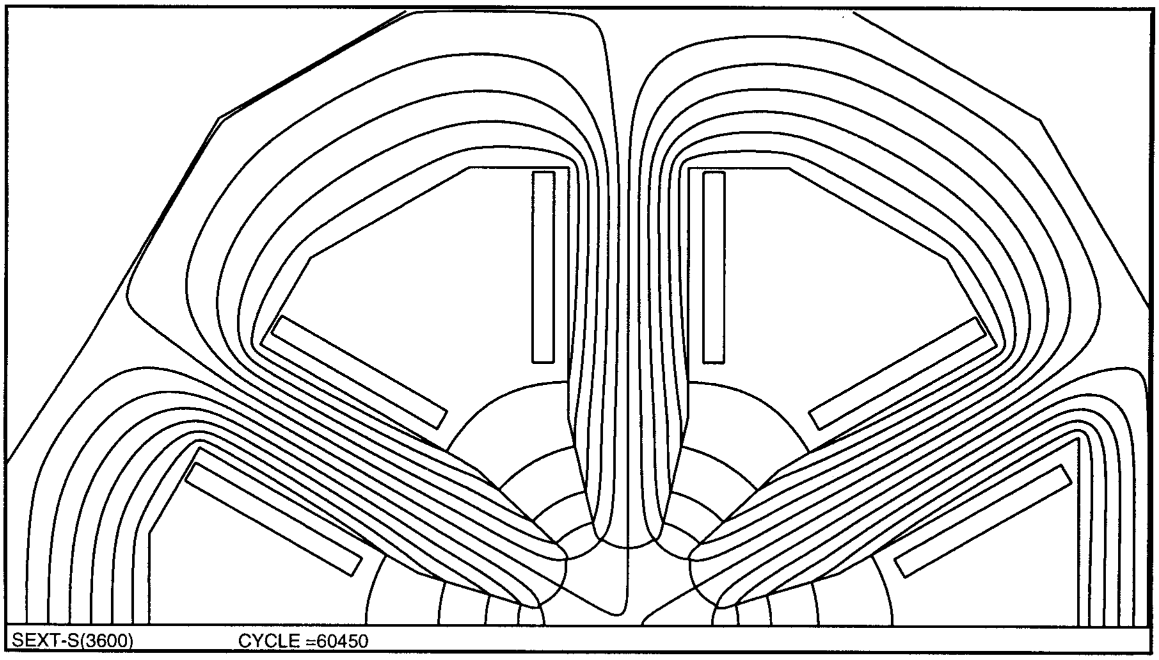

Figure 10 Sextupole with outside yoke simulated.

Table 6 Sextupole Magnet Parameters at 2.9 GeV and at Maximum Excitation

Number of magnets		36	
Magnet length (physical)		0.192	m
Magnetic length (sextupole mode)		0.192	m
Magnet aperture radius		39	mm
Maximum gradient		267.8	T/m^2
Gradient, $k2_{max}$		55.4	m^{-3}
Nominal gradient, k2 0 chromaticity	S1 S2	- 27.68 43.46	m^{-3}
Nominal gradient, k2 +2 chromaticity	S1 S2	- 31.23 49.39	m^{-3}
Good field radius		30	mm
Number of sextupole coils		6	
Number of windings per coil		36	
Maximum ampere-turns		4320	
Maximum current in coils		120	A
Conductor area		14.7	mm^2
Conductor length per coil		21.5	m
Resistance per coil (copper)*		0.026	Ω
Voltage drop per magnet		18.7	V
Power per magnet		2.25	kW
S1 sextupoles:			
Maximum horizontal field		0.074	T
Maximum horizontal kick		1.46	mrad
Maximum vertical field		0.086	T
Maximum vertical kick		1.70	mrad
S1 and S2 sextupoles:			
Maximum skew quadrupole gradient		0.54	T/m

*resistivity = 1.79 E-8 Ω m

The sextupole parameters are shown in Table 6. Maximum values represent upper limits required for tunability. The sextupole energy independent field gradient is given by

$$k2 = \frac{0.6B''}{E}$$

where B'' is the sextupole gradient in T/m^2 and E is the beam energy in GeV.

The good field region for the sextupole excitation is shown in Figure 11. $\Delta B/(B'' x^2)$ is plotted, where $\Delta B = B(x) - B - B' x - B'' x^2$. The effect of the dipole and quadrupole components have been subtracted from the remnant field since they can be compensated for by adjusting the orbit correctors and the quadrupole magnets in the ring. The thin curve is for the sextupole excited with all poles excited equally. The thick dark curve is the remnant field with the extra Ampere-turns on the outer poles. The gray curve is the remnant field with a outer return yoke (see below). In all cases, variations remain less than 0.5% over a region of ±30 mm.

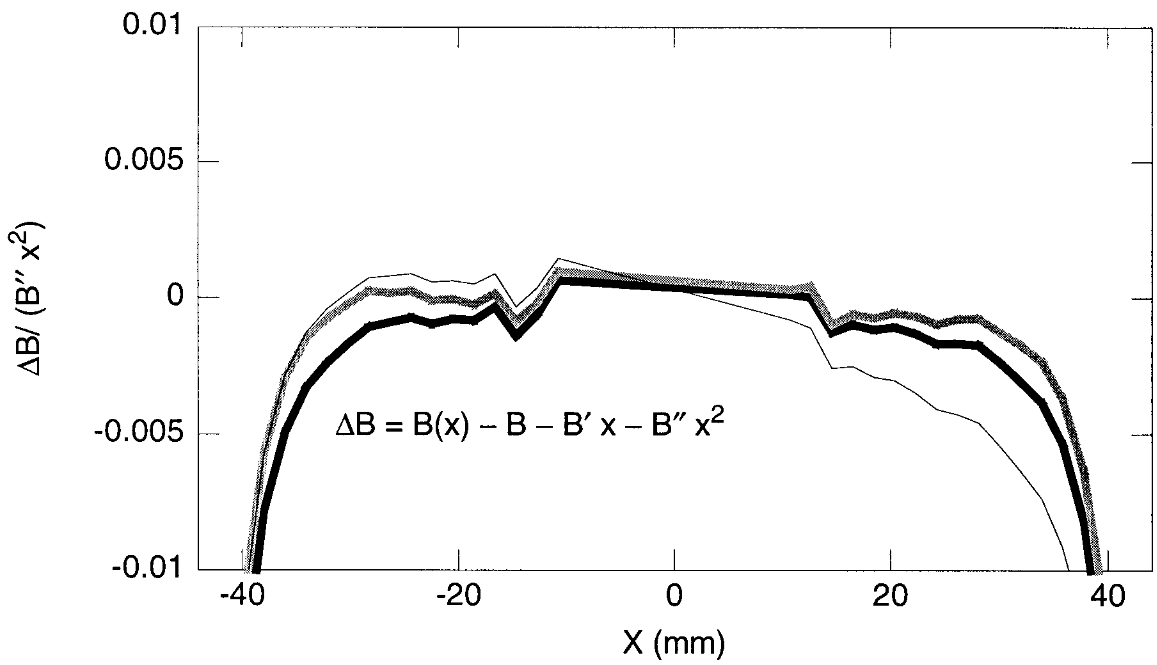

Figure 11 Remnant fields for the sextupole of Table 5.

The asymmetry of the sextupole design is evident in the distribution of the remnant field when the pole excitations are equal. The field quality can be improved by including a return yoke on the outside of the sextupole magnet rather than adding extra Ampere-turns on the outer coil. Such a yoke would have to extend around the anti-chamber of the vacuum system. This type of yoke was approximately simulated as shown in Figure 10. The field properties of the sextupole mode for this configuration are given in Table 5. The improvement in the sextupole field quality is shown in Figure 11 (gray line) where the remnant field now has the best good field region.

The good field region for the X-corrector mode is shown in Figure 12. For this plot ΔB is given by $\Delta B = B_y(x) - B_y(0)$. The good field region approaches ± 20 mm with 4% error.

The good field region for the vertical corrector is shown in Figure 13. For this plot ΔB is given by $\Delta B = B_x(x) - B_x(0)$. The good field region is similar to the X-corrector but with no asymmetry.

The good field region for the skew quadrupole is shown in Figure 14. For this plot ΔB is given by $\Delta B = B_x(x) - B_x'x$. The field quality is poor, about 6% error at ± 10 mm. However, such fields have been used successfully at ALS and are planned for SPEAR3. No advantage is gained by using a return yoke.

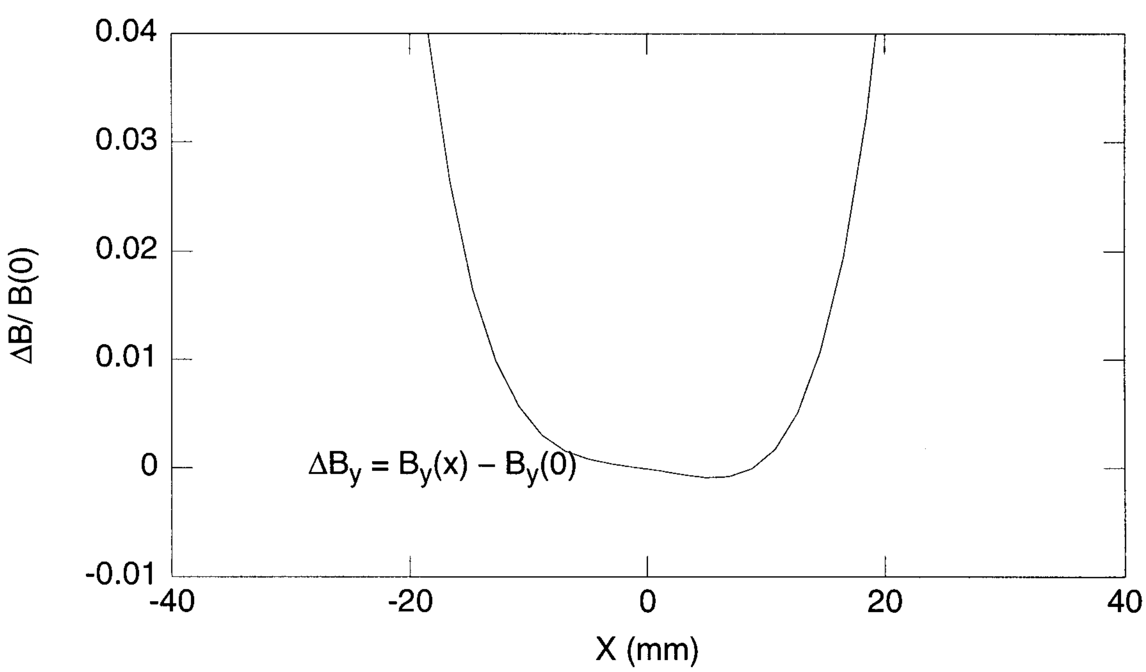

Figure 12 Remnant fields for the X-corrector of Table 5.

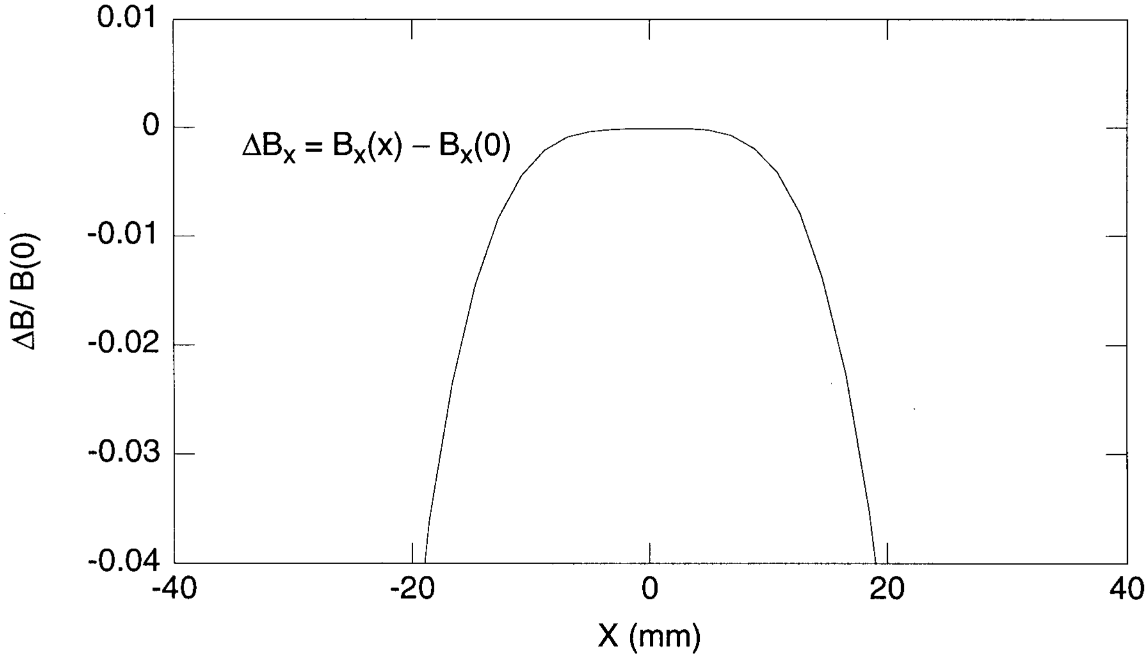

Figure 13 Remnant fields for the Y-corrector of Table 5.

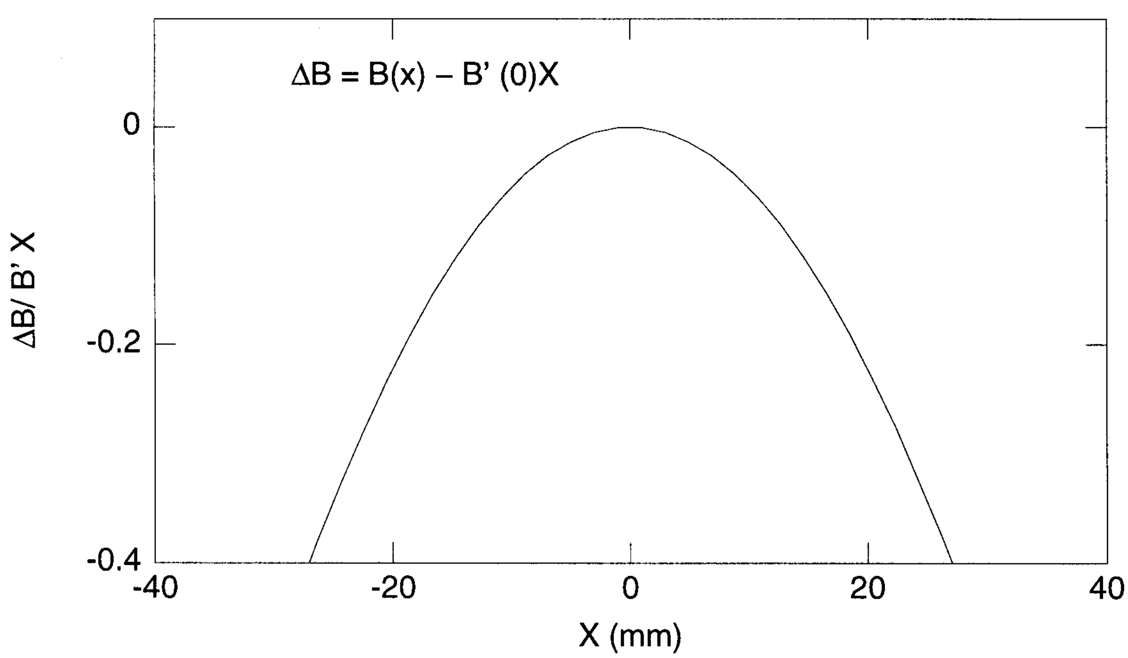

Figure 14 Remnant fields for the skew quadrupole of Table 5.

5. Appendix I

5.1 POISSON (Automesh) input for the gradient dipole

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5.2 POISSON (Automesh) input for quadrupoles

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$PO X= 1.2422  , Y= 4.0658  $
$PO X= 1.3627  , Y= 3.9371 $
$PO X= 1.4433 , Y= 3.7024 $
$PO X= 1.5287 , Y= 3.4547 $
$PO X= 1.6453 , Y= 3.2099 $
$PO X= 1.7848 , Y= 2.9590 $
$PO X= 1.9484 , Y= 2.7106 $
$PO X= 2.1378 , Y= 2.4704 $
$PO X= 2.29810 , Y= 2.29810 $
$PO Y= 2.1378 , X= 2.4704 $
$PO Y= 1.9484 , X= 2.7106 $
```

```
$PO Y= 1.7848 , X= 2.9590 $
$PO Y= 1.6453 , X= 3.2099 $
$PO Y= 1.5287 , X= 3.4547 $
$PO Y= 1.4433 , X= 3.7024 $
$PO Y= 1.3627  , X= 3.9371 $
$PO Y= 1.2422  , X= 4.0658  $
$PO Y= 1.1384  , X= 4.2040  $
$PO Y= 1.1384  , X= 4.4785  $
$PO X= 20., Y= 10.099742 $
$PO Y= 18.2, X= 9.060512$
$REG MAT= 3 , CUR= 00. , NPOINT= 24 $
$PO Y= 18.2, X= -9.060512$
$PO X= -1.1384  , Y= 4.4785  $
$PO X= -1.1384  , Y= 4.2040  $
$PO X= -1.2422  , Y= 4.0658  $
$PO X= -1.3627  , Y= 3.9371 $
$PO X= -1.4433 , Y= 3.7024 $
$PO X= -1.5287 , Y= 3.4560 $
$PO X= -1.6453 , Y= 3.2086 $
$PO X= -1.7848 , Y= 2.9592 $
$PO X= -1.9484 , Y= 2.7110 $
$PO X= -2.1378 , Y= 2.4707 $
$PO X= -2.29810 , Y= 2.29810 $
$PO Y= 2.1378 , X= -2.4707 $
$PO Y= 1.9484 , X= -2.7110 $
$PO Y= 1.7848 , X= -2.9592 $
$PO Y= 1.6453 , X= -3.2086 $
$PO Y= 1.5287 , X= -3.4560 $
$PO Y= 1.4433 , X= -3.7024 $
$PO Y= 1.3627  , X= -3.9371 $
$PO Y= 1.2422  , X= -4.0658  $
$PO Y= 1.1384  , X= -4.2040  $
$PO Y= 1.1384  , X= -4.4785  $
$PO X= -20., Y= 10.099742 $
$PO Y= 18.2, X= -9.060512$
$REG MAT= 3 , CUR= 00. , NPOINT= 8 $
$PO X= 8.021281 , Y= 20.0 $
$PO NT=2, X0=8.021281, Y0=18.8, R=1.2, THETA=-30. $
$PO X= 20., Y= 10.099742 $
$PO X= 20. , Y= 26.5 $
$PO X= 16. , Y= 30.5 $
$PO X= 0. , Y= 30.5 $
$PO X= .0 , Y= 20.0 $
$PO X= 8.021281 , Y= 20.0 $
$REG MAT= 3 , CUR= 00. , NPOINT= 8 $
$PO X= -8.021281 , Y= 20.0 $
$PO NT=2, X0=-8.021281, Y0=18.8, R=1.2, THETA=210. $
$PO X= -20., Y= 10.099742 $
$PO X= -20. , Y= 26.5 $
$PO X= -16. , Y= 30.5 $
$PO X= 0. , Y= 30.5 $
$PO X= .0 , Y= 20.0 $
$PO X= -8.021281 , Y= 20.0 $
$REG MAT= 1 , CUR= 5308. , NPOINT= 5 $  COIL1
$PO X= 8.3093 , Y=2.715  $
$PO X= 9.0806 , Y= 1.3791 $
$PO X= 19.6923 , Y= 7.5058 $
$PO X= 18.921, Y= 8.8417 $
$PO X= 8.3093 , Y=2.715  $
$REG MAT= 1 , CUR= 2692. , NPOINT= 6 $  COIL1X
$PO X= 12.6276 , Y=2.9074  $
$PO X= 12.8505 , Y= 2.5214 $
$PO X= 14.8649 , Y= 2.4178 $
$PO X= 19.3896 , Y= 5.0302 $
$PO X= 18.6183, Y= 6.3661 $
$PO X= 12.6276 , Y=2.9074  $
$REG MAT= 1 , CUR= -5308. , NPOINT= 5 $  COIL1B
$PO Y= 8.3093 , X=2.715  $
$PO Y= 9.0806 , X= 1.3791 $
$PO Y= 19.6923 , X= 7.5058 $
$PO Y= 18.921, X= 8.8417 $
$PO Y= 8.3093 , X=2.715  $
```

```
$REG MAT= 1 , CUR= -2692. , NPOINT= 6 $  COIL1BX
$PO Y= 12.6276 , X=2.9074  $
$PO Y= 12.8505 , X= 2.5214 $
$PO Y= 14.8649 , X= 2.4178 $
$PO Y= 19.3896 , X= 5.0302 $
$PO Y= 18.6183, X= 6.3661 $
$PO Y= 12.6276 , X=2.9074  $
$REG MAT= 1 , CUR= 5308. , NPOINT= 5 $  COIL2
$PO X= -8.3093 , Y=2.715  $
$PO X= -9.0806 , Y= 1.3791 $
$PO X= -19.6923 , Y= 7.5058 $
$PO X= -18.921, Y= 8.8417 $
$PO X= -8.3093 , Y=2.715  $
$REG MAT= 1 , CUR= 2692. , NPOINT= 6 $  COIL2X
$PO X= -12.6276 , Y=2.9074  $
$PO X= -12.8505 , Y= 2.5214 $
$PO X= -14.8649 , Y= 2.4178 $
$PO X= -19.3896 , Y= 5.0302 $
$PO X= -18.6183, Y= 6.3661 $
$PO X= -12.6276 , Y=2.9074  $
$REG MAT= 1 , CUR= -5308. , NPOINT= 5 $  COIL2B
$PO Y= 8.3093 , X=-2.715  $
$PO Y= 9.0806 , X= -1.3791 $
$PO Y= 19.6923 , X= -7.5058 $
$PO Y= 18.921, X= -8.8417 $
$PO Y= 8.3093 , X=-2.715  $
$REG MAT= 1 , CUR= -2692. , NPOINT= 6 $  COIL2BX
$PO Y= 12.6276 , X=-2.9074  $
$PO Y= 12.8505 , X= -2.5214 $
$PO Y= 14.8649 , X= -2.4178 $
$PO Y= 19.3896 , X= -5.0302 $
$PO Y= 18.6183, X= -6.3661 $
$PO Y= 12.6276 , X=-2.9074  $
```

5.3 POISSON (Automesh) input for sextupoles- sextupole mode

```
 SEXT-S(3600)
$REG NREG=22,DX=.194,XMIN=-31.,XMAX=26.,YMIN=0.,YMAX=31.
$REG NPOINT=16,KMAX=285,LMAX=155,YREG1=5.,MAT=1$
$PO X=0.,Y=31. $
$PO X=-10.909,Y=31. $
$PO X=-31.,Y=31 $
$PO X=-31.,Y=13.68442 $
$PO X=-31.,Y=11.5466 $
$PO X=-31.,Y=0. $
$PO X=-.3,Y=0. $
$PO X=-.1,Y=0. $
$PO X=.1,Y=0. $
$PO X=.3,Y=0. $
$PO X=26.,Y=0. $
$PO X=26.,Y=10.9693 $
$PO X=26.,Y=15.4165 $
$PO X=26.,Y=31. $
$PO X=10.909,Y=31. $
$PO X=0.,Y=31. $
$REG MAT=2,CUR=0.,NPOINT=16 $
$PO X=0.,Y=3.9 $
$PO X=.1888,Y=3.9091 $
$PO X=.3733,Y=3.9357 $
$PO X=.5501,Y=3.9776 $
$PO X=.7961,Y=4.0624 $
$PO X=1.0171,Y=4.1649 $
$PO X=1.1940,Y=4.2849 $
$PO X=1.4801,Y=4.3637 $
$PO X=1.6318,Y=4.6263 $
$PO X=3,Y=10.441 $
```

```
$PO X=3.,Y=22. $
$PO X=4.5,Y=22. $
$PO X=8.,Y=22. $
$PO X=10.909,Y=31. $
$PO X=0.,Y=31. $
$PO X=0.,Y=3.9 $
$REG MAT=2,CUR=0.,NPOINT=5 $
$PO X=8.,Y=22. $
$PO X=10.909,Y=31. $
$PO X=20.5266,Y=25.4473 $
$PO X=15.0529,Y=17.928 $
$PO X=8.,Y=22. $
$REG MAT=2,CUR=0.,NPOINT=10 $
$PO X=20.5266,Y=25.4473 $
$PO X=15.0529,Y=17.928 $
$PO X=16.0629,Y=16.1959 $
$PO X=16.8079,Y=14.8969 $
$PO X=17.5529,Y=13.5979 $
$PO X=20.5529,Y=8.40175 $
$PO X=22.,Y=9.2372 $
$PO X=26.,Y=11.5466 $
$PO X=26.,Y=15.9671 $
$PO X=20.5266,Y=25.4473 $
$REG MAT=2,CUR=0.,NPOINT=22 $
$PO X=20.5529,Y=8.40175 $
$PO X=10.542,Y=2.623 $
$PO X=4.8224,Y=.90 $
$PO X=4.5191,Y=.90 $
$PO X=4.3078,Y=1.1084 $
$PO X=4.1155,Y=1.2016 $
$PO X=3.9162,Y=1.3418 $
$PO X=3.7197,Y=1.5124 $
$PO X=3.5951,Y=1.6446 $
$PO X=3.4798,Y=1.7911 $
$PO X=3.3775,Y=1.9500 $
$PO X=3.2910,Y=2.1181 $
$PO X=3.2218,Y=2.2911 $
$PO X=3.1697,Y=2.4652 $
$PO X=3.1201,Y=2.7206 $
$PO X=3.0984,Y=2.9633 $
$PO X=3.1138,Y=3.1765 $
$PO X=3.0495,Y=3.4133 $
$PO X=3.1449,Y=3.6833 $
$PO X=7.542,Y=7.819 $
$PO X=17.5529,Y=13.5979 $
$PO X=20.5529,Y=8.40175 $
$REG MAT=2,CUR=0.,NPOINT=16 $
$PO X=0.,Y=3.9 $
$PO X=-.1888,Y=3.9091 $
$PO X=-.3733,Y=3.9357 $
$PO X=-.5501,Y=3.9776 $
$PO X=-.7961,Y=4.0624 $
$PO X=-1.0171,Y=4.1649 $
$PO X=-1.1940,Y=4.2849 $
$PO X=-1.4801,Y=4.3637 $
$PO X=-1.6318,Y=4.6263 $
$PO X=-3,Y=10.441 $
$PO X=-3.,Y=22. $
$PO X=-4.5,Y=22. $
$PO X=-8.,Y=22. $
$PO X=-10.909,Y=31. $
$PO X=0.,Y=31. $
$PO X=0.,Y=3.9 $
$REG MAT=2,CUR=0.,NPOINT=5 $
```

$PO X=-8.,Y=22. $
$PO X=-10.909,Y=31. $
$PO X=-20.5266,Y=25.4473 $
$PO X=-15.0529,Y=17.928 $
$PO X=-8.,Y=22. $
$REG MAT=2,CUR=0.,NPOINT=10 $
$PO X=-20.5266,Y=25.4473 $
$PO X=-15.0529,Y=17.928 $
$PO X=-16.8079,Y=14.8969 $
$PO X=-17.5529,Y=13.5979 $
$PO X=-20.5529,Y=8.40175 $
$PO X=-27.,Y=9.2372 $
$PO X=-27.,Y=11.5466 $
$PO X=-27.,Y=13.68442 $
$PO X=-27.,Y=14.2350 $
$PO X=-20.5266,Y=25.4473 $
$REG MAT=2,CUR=0.,NPOINT=22 $
$PO X=-20.5529,Y=8.40175 $
$PO X=-10.542,Y=2.623 $
$PO X=-4.8224,Y=.90 $
$PO X=-4.5191,Y=.90 $
$PO X=-4.3078,Y=1.1084 $
$PO X=-4.1155,Y=1.2016 $
$PO X=-3.9162,Y=1.3418 $
$PO X=-3.7197,Y=1.5124 $
$PO X=-3.5951,Y=1.6446 $
$PO X=-3.4798,Y=1.7911 $
$PO X=-3.3775,Y=1.9500 $
$PO X=-3.2910,Y=2.1181 $
$PO X=-3.2218,Y=2.2911 $
$PO X=-3.1697,Y=2.4652 $
$PO X=-3.1201,Y=2.7206 $
$PO X=-3.0984,Y=2.9633 $
$PO X=-3.1138,Y=3.1765 $
$PO X=-3.0495,Y=3.4133 $
$PO X=-3.1449,Y=3.6833 $
$PO X=-7.542,Y=7.819 $
$PO X=-17.5529,Y=13.5979 $
$PO X=-20.5529,Y=8.40175 $
$REG MAT=2,CUR=0.,NPOINT=7 $
$PO X=-23.1029,Y=0. $
$PO X=-27.,Y=0 $
$PO X=-27.,Y=11.5466 $
$PO X=-20.5529,Y=8.40175 $
$PO X=-21.3029,Y=7.10271 $
$PO X=-23.1029,Y=4.0716 $
$PO X=-23.1029,Y=0. $
$REG MAT=1,CUR=0.,NPOINT=9 $
$PO X=3.,Y=22. $
$PO X=3.,Y=23. $
$PO X=8.,Y=23. $
$PO X=15.9188,Y=18.4280 $
$PO X=18.4189,Y=14.0979 $
$PO X=17.5529,Y=13.5979 $
$PO X=15.0529,Y=17.928 $
$PO X=8.,Y=22. $
$PO X=3.,Y=22. $
$REG MAT=1,CUR=0.,NPOINT=9 $
$PO X=-3.,Y=22. $
$PO X=-3.,Y=23. $
$PO X=-8.,Y=23. $
$PO X=-15.9188,Y=18.4280 $
$PO X=-18.4189,Y=14.0979 $
$PO X=-17.5529,Y=13.5979 $

```
$PO X=-15.0529,Y=17.928 $
$PO X=-8.,Y=22. $
$PO X=-3.,Y=22. $
$REG MAT=2,CUR=0.,NPOINT=6 $
$PO X=-27.,Y=13.68442 $
$PO X=-27.,Y=0. $
$PO X=-31.,Y=0. $
$PO X=-31.,Y=8.03889 $
$PO X=-27.,Y=14.2350 $
$PO X=-27.,Y=13.68442 $
$REG MAT=1,CUR=0.,NPOINT=6 $
$PO X=-20.5529,Y=8.40175 $
$PO X=-21.4189,Y=8.9018 $
$PO X=-23.9189,Y=4.5717 $
$PO X=-23.9189,Y=0. $
$PO X=-20.5529,Y=0. $
$PO X=-20.5529,Y=8.40175 $
$REG MAT=1,CUR=3600.,NPOINT=5 $ SEX1
$PO X=13.320,Y=3.360 $
$PO X=13.845,Y=2.451 $
$PO X=22.145,Y=7.243 $
$PO X=21.620,Y=8.152 $
$PO X=13.320,Y=3.360 $
$REG MAT=1,CUR=-3600.,NPOINT=5 $ SEX2
$PO X=9.569,Y=9.855 $
$PO X=9.055,Y=10.746 $
$PO X=17.356,Y=15.538 $
$PO X=17.870,Y=14.648 $
$PO X=9.569,Y=9.855 $
$REG MAT=1,CUR=-3600.,NPOINT=5 $ SEX3
$PO X=3.750,Y=13.215 $
$PO X=4.8,Y=13.215 $
$PO X=4.8,Y=22.8 $
$PO X=3.75,Y=22.8 $
$PO X=3.750,Y=13.215 $
$REG MAT=1,CUR=3600.,NPOINT=5 $ SEX4
$PO X=-3.750,Y=13.215 $
$PO X=-4.8,Y=13.215 $
$PO X=-4.8,Y=22.8 $
$PO X=-3.75,Y=22.8 $
$PO X=-3.750,Y=13.215 $
$REG MAT=1,CUR=3600.,NPOINT=5 $ SEX5
$PO X=-9.569,Y=9.855 $
$PO X=-9.055,Y=10.746 $
$PO X=-17.356,Y=15.538 $
$PO X=-17.870,Y=14.648 $
$PO X=-9.569,Y=9.855 $
$REG MAT=1,CUR=-3600.,NPOINT=5 $ SEX6
$PO X=-13.320,Y=3.360 $
$PO X=-13.845,Y=2.451 $
$PO X=-22.145,Y=7.243 $
$PO X=-21.620,Y=8.152 $
$PO X=-13.320,Y=3.360 $
$REG MAT=1,CUR=00.,NPOINT=5 $ SEX1T
$PO X=12.789,Y=3.111 $
$PO X=13.114,Y=2.648 $
$PO X=13.575,Y=2.914 $
$PO X=13.320,Y=3.360 $
$PO X=12.789,Y=3.111 $
$REG MAT=1,CUR=-00.,NPOINT=5 $ SEX2T
$PO X=9.089,Y=9.52 $
$PO X=8.85,Y=10.033 $
$PO X=9.312,Y=10.3 $
$PO X=9.569,Y=9.855 $
```

```
$PO X=9.089,Y=9.52 $
```

5.4 POISSON (Automesh) input for sextupoles- X corrector mode (coils only)

```
$REG MAT=1,CUR=1332.,NPOINT=5 $ X1
$PO X=20.452,Y=4.124 $
$PO X=20.941,Y=3.278 $
$PO X=23.561,Y=4.791 $
$PO X=23.073,Y=5.637 $
$PO X=20.452,Y=4.124 $
$REG MAT=1,CUR=-1332.,NPOINT=5 $ X2
$PO X=13.797,Y=15.650 $
$PO X=13.309,Y=16.496 $
$PO X=15.930,Y=18.009 $
$PO X=16.418,Y=17.163 $
$PO X=13.797,Y=15.650 $
$REG MAT=1,CUR=2664.,NPOINT=5 $ X3
$PO X=5.228,Y=16.728 $
$PO X=6.205,Y=16.728 $
$PO X=6.205,Y=22.800 $
$PO X=5.228,Y=22.800 $
$PO X=5.228,Y=16.728 $
$REG MAT=1,CUR=-2664.,NPOINT=5 $ X4
$PO X=-5.228,Y=16.728 $
$PO X=-6.205,Y=16.728 $
$PO X=-6.205,Y=22.800 $
$PO X=-5.228,Y=22.800 $
$PO X=-5.228,Y=16.728 $
$REG MAT=1,CUR=1332.,NPOINT=5 $ X5
$PO X=-13.797,Y=15.650 $
$PO X=-13.309,Y=16.496 $
$PO X=-15.930,Y=18.009 $
$PO X=-16.418,Y=17.163 $
$PO X=-13.797,Y=15.650 $
$REG MAT=1,CUR=-1332.,NPOINT=5 $ X6
$PO X=-20.452,Y=4.124 $
$PO X=-20.941,Y=3.278 $
$PO X=-23.561,Y=4.791 $
$PO X=-23.073,Y=5.637 $
$PO X=-20.452,Y=4.124 $
```

5.5 POISSON (Automesh) input for sextupoles- Y corrector mode (coils only)

```
$REG MAT=1,CUR=2664.,NPOINT=5 $ Y1
$PO X=17.101 ,Y=3.836 $
$PO X=17.589 ,Y=2.990 $
$PO X=22.848 ,Y=6.026 $
$PO X=22.359 ,Y=6.872 $
$PO X=17.101 ,Y=3.836 $
$REG MAT=1,CUR=-2664.,NPOINT=5 $ Y2
$PO X=11.873,Y=12.892 $
$PO X=11.385,Y=13.738 $
$PO X=16.643,Y=16.774 $
$PO X=17.131,Y=15.928 $
$PO X=11.873,Y=12.892 $
$REG MAT=1,CUR=-2664.,NPOINT=5 $ Y3
$PO X=-11.873,Y=12.892 $
$PO X=-11.385,Y=13.738 $
$PO X=-16.643,Y=16.774 $
$PO X=-17.131,Y=15.928 $
$PO X=-11.873,Y=12.892 $
$REG MAT=1,CUR=2664.,NPOINT=5 $ Y4
$PO X=-17.101 ,Y=3.836 $
$PO X=-17.589 ,Y=2.990 $
$PO X=-22.848 ,Y=6.026 $
$PO X=-22.359 ,Y=6.872 $
$PO X=-17.101 ,Y=3.836 $
```

5.6 POISSON (Automesh) input for sextupoles- skew quadrupole mode (coils only)

```
$REG MAT=1,CUR=720.,NPOINT=5 $ Q1
$PO X=6.654,Y=19.576$
$PO X=6.654,Y=22.8 $
$PO X=7.73,Y=22.8 $
$PO X=7.73,Y=19.576 $
$PO X=6.654,Y=19.576 $
$REG MAT=1,CUR=-720.,NPOINT=5 $ Q2
$PO X=-6.654,Y=19.576 $
$PO X=-6.654,Y=22.8 $
$PO X=-7.73,Y=22.8 $
$PO X=-7.73,Y=19.576 $
$PO X=-6.654,Y=19.576 $
```

5.7 B-H curve for AISI 1010 steel)

B (Gauss)	H (Oersted)
5000.	1.13097
10000.	3.39292
11000.	3.99925
12000.	4.83177
13000.	6.02557
13875.	7.64739
14500.	9.49314
15450.	14.9402
15750.	17.6922
16275.	26.1041
16738.	39.1807
17023.	49.881
17275.	60.8677
17583.	76.4199
18088.	107.833
18500.	139.059
19025.	188.32
20500.	414.728
21500.	743.967
22262.	1171.37
22700.	1493.89
23338.	2055.36
24075.	2774.53
26000.	4699.45
30000.	8699.45