

LS-12

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First Designs and Cost Estimates for the
Storage Ring Dipoles and Quadrupoles

Summary

The magnets described in this report are defined in reports LS-1 and LS-2. The required number considered here for each type of quadrupole resulted from the assumption that 16 insertion device straight sections were for undulators and 16 were for wigglers. A list of the major design criteria for the magnets is given and the results of the designs and the cost estimates obtained with the computer program MADEST are summarized. A total cost for the fabrication of these magnets is estimated to be \$6578.5 K. Also included are descriptions of the magnetic field calculations for the dipole magnet that were done using the computer programs TRIM, PE2D, and POISSON. These produced data on the vertical field shape in the radial direction for a flat pole dipole. These results permitted the magnitudes of the harmonic components in the radial field distribution and the track of an electron through a dipole to be estimated.

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MADEST CALCULATIONS

The dipole and quadrupole magnet designs for the storage ring have been designed with the computer program MADEST. The program was also used to calculate the costs of the resulting magnets. Since the costs of these magnets are a large part of the total cost of the entire complex, the costing methodology had to be checked.

These checks involved the design and cost estimating of the dipoles and some quadrupoles in other electron facilities, some of which have been built. The comparisons were done for the costs appearing in the corresponding proposals for PEP (Stanford, 1975), CESR (Cornell, 1975), CHEER (FNAL-Canada, 1980), and NCAM (Lawrence Berkeley, 1983).

Our cost calculations are presently based on data that has been developed through the GEM, Julich, and ASPUN projects in the last several years, and through many years of collective experience in the fabrication of many magnets for the ZGS, the IPNS RCS, and the FNAL electron cooling ring and of prototype sector magnets for GEM.

Using this data the costs for the PEP and CESR magnet were higher than those that were proposed in 1975. There was, however, agreement to within 10% for the later machines at NCAM and CHEER. We are, therefore, presently using our 1983 data for the SLS magnets which can be easily adjusted for inflation.

From here the designs for the storage ring magnets for the 6 GeV Synchrotron Light Source (SLS) were developed based on parameters specified in reports LS-1 and LS-2. We also tried to include in these designs many of the same criteria used for the magnet designs in the electron facilities covered in the proposals listed above and the European Synchrotron Light Source (ESRP). The gap parameters as specified in LS-1 and LS-2 are summarized below:

Storage Ring Magnets
Original Gap Parameters

<u>Magnet Type</u>	<u>Quantity</u>	<u>L (m)</u>	<u>B or B' (T) or (T/m)</u>	<u>Aperture (cm)</u>
M	64	2.95	0.6661	6.5H x 14W
QD1	32	0.7	-4.292	6.5 dia
QF2	32	1.0	18.385	6.5 dia
QD3	32	0.7	-17.649	6.5 dia
QD4	64	0.7	-7.499	6.5 dia
QF5	64	0.7	10.863	6.5 dia
QD6	32	0.7	-11.900	6.5 dia
QF7	32	1.0	8.880	6.5 dia

The quadrupole magnets form four groups, each covering a different strength range and, therefore, requiring different coils. The parameters for these combined cross-section designs are listed below:

Storage Ring Magnets
Combined Gap Parameters

<u>Magnet Type</u>	<u>B' (T/m)</u>	<u>Aperture (cm)</u>
QF2/QD3	19.0	6.5 dia
QF5/QD6	12.0	6.5 dia
QD4/QF7	9.0	6.5 dia
QD1	5.0	6.5 dia

Some of the other primary magnet characteristics are summarized below:

1. All magnets shall be compatible with the double-chamber design of the vacuum chamber as described in notes from the Vacuum Task Group since November 1-- major dimensions were defined about mid-November.
2. Magnet cores to be made from laminated steel 1.5mm thick. This will allow the cores to be magnetically matched by shuffling the laminations. Also it allows total freedom to specify the pole tip shapes including edge shims.
3. The back and top yoke thicknesses of the dipole C-core shall be thick enough to keep the gap height deflections at 6 GeV to less than about 0.025 mm - this was the PEP criteria and corresponds to a 0.04% change in gap height.

4. The magnets shall be parallel stacked with magnet steel end plates made from magnet steel and welded tie bars. The dipoles will be curved by pressing laminations against a curved bar at the appropriate radius before welding.
5. The quadrupole cores shall have only top and bottom yokes. This not only keeps the midplane clear for the vacuum chamber but also maintains the magnet symmetry. A C-core disrupts right-left symmetry and would greatly complicate the shim design. The upper and lower magnet halves can be supported by a stainless steel strong-back bolted to the inside radius faces.
6. The dipole supply currents shall be less than 1000A and the quadrupole currents respectively shall be less than 500A. This would require two and one, respectively, 535MCM cables for each interconnection run.
7. All coils shall have only one potted assembly per pole. The dipole coils must fit through the gap.
8. The dipole coils shall have current densities in the copper conductor of around $2.5A/mm^2$. Values like this are often quoted as being "optimum." The coils shall have a W/H ratio of around 2, and the vertical distance between the two coils shall be large enough to clear the vacuum chamber, anti-chamber. They shall also have at least two layers of conductor on each pole to prevent having electrical and cooling connections next to the core. Therefore, there will be only one water circuit per pole. This could allow us to have only three water hoses per magnet or maybe even one.
9. The quadrupole coils shall also have current densities in the copper conductors of around $2.5A/mm^2$. The coils shall be shaped to keep the area around the midplane clear for the vacuum chamber. The same conductor shall be used in all quadrupoles and the coolant hole shall be around 0.5 times the outside width to assure that the conductor can be made. There shall be no more than four cooling circuits per magnet keeping the number of hoses to a minimum.

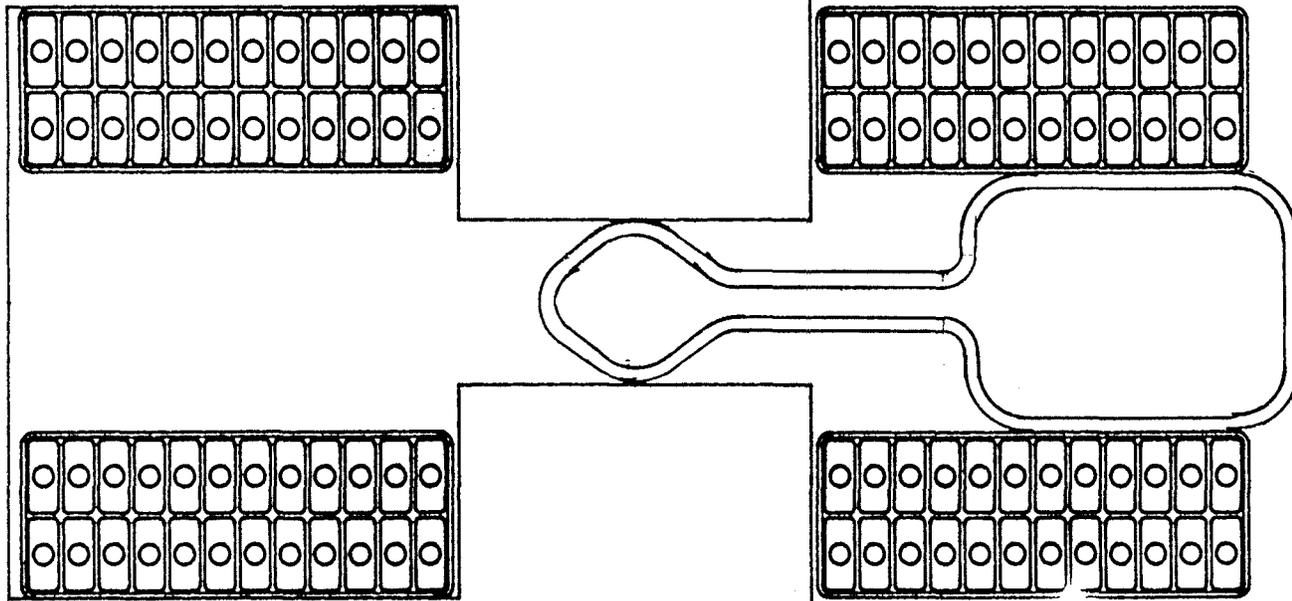
10. The coolant water system shall be capable of supplying a 100 psi pressure gradient across each magnet and a supply temperature of no larger than 38° C. These are typical values for the IPNS RCS accelerator. The temperature gradient across each magnet shall be less than about 17° F.

The dipole gap deflections were estimated by R. Wehrle for a case with a 21 cm wide pole and a 21 cm wide yoke. He found the deflections are less than .025 mm and were consistent with those he found using the same methodology for the PEP dipole. We, therefore, have generalized by keeping the yoke equal to the 14 cm pole width in the latest design.

The preliminary design for the dipole is summarized in Table I and the cost data is shown in Table II and a summary of the dipole costs is presented in Table III. A sketch of the dipole and vacuum chamber is shown in Figure 1.

A number of coils were designed for the QF5/QD6 quadrupole and it was noted that power losses could vary from about 4kW to less than 1kW per magnet depending on how many conductors were placed in the coil on each pole. It was decided that the coil should be made from only one, series connected conductor with enough copper to keep the power losses to about 2kW per magnet. This is a fairly low value and allows each quad to be cooled with only one circuit. This could possibly eliminate the water hoses on the quads making very durable magnets.

The design for the QF5/QD6 quad is summarized in the parameter list in Table IV. This is a representative example of the quad cases. The cost data for the quadrupoles is shown in Table V an example of the quadrupole cost tables is shown in Table VI for the QF5/QD6 magnet. A sketch of the cross section of the QF5/QD6 quad and the vacuum chamber is shown in Figure 2. A summary of some of the design results and the costs for the eight magnets for the storage ring is given in Table VII.



0 5 cm.

Figure 1 - Storage Ring Dipole and Vacuum Chamber

TABLE I
Storage Ring Dipole Design

1	<u>DESIGN PARAMETERS of MAGNET SYSTEM:</u>		
2			
3	Number of magnets	=	64
4	Type of magnet	=	Dipole HF
5	Type of excitation	=	Simple AC
6	Repetition frequency	(Hz)=	0
7	Dipole field strength	(G)=	6661
8			
9	<u>DESIGN and OPERATING PARAMETERS of a SINGLE MAGNET:</u>		
10			
11	<u>*Vacuum chamber*</u>		
12	Chamber type	=	None
13	<u>*Gap*</u>		
14	Gap axis shape	=	Curved
15	Effective length of field along gap axis	(cm)=	295
16	Total width of pole	(cm)=	14
17	Total gap height	(cm)=	<u>6.5</u>
18	<u>*Core*</u>		
19	Distance from-Field edge to-Core end	(cm)=	3.25
20	-Pole side	(cm)=	3.25
21	-Coil to-Pole face	(cm)=	<u>1.85</u>
22	-Pole side	(cm)=	.25
23	-Top yoke	(cm)=	0
24	-Side yoke	(cm)=	.5
25	-Endplate end	(cm)=	<u>.5</u>
26	Maximum average field density inside yoke	(G)=	<u>9753</u>
27	Ratio of side yoke thicknesses(L/R)	=	0
28	Overall core-Height	(cm)=	51.2
29	-Width	(cm)=	45.95
30	-Length	(cm)=	288.4
31	Total mass of magnetic core	(kg)=	4148
32	Lamination thickness	(cm)=	.15
33	Lamination stacking method	=	Parallel
34	Radius of curvature of gap axis	(cm)=	3000
35	End plate thickness	(cm)=	2.54
36	End plate material	=	Magnet st.
37	<u>*Coil*</u>		
38	Conductor material	=	Copper
39	Conductor-Height	(cm)=	<u>2.85</u>
40	-Width	(cm)=	1.2
41	-Hole diameter	(cm)=	.8
42	-Corner radius	(cm)=	.2
43	Number of coolant holes	=	1
44	Conductor min. bend radius(inside edge)-Width	(cm)=	5
45	Insulation-Tape-Thickness-Turn	(cm)=	.05
46	-Ground	(cm)=	.1
47	-Width-Turn	(cm)=	2.5
48	-Ground	(cm)=	2.5
49	Insulation total thickness-Turn	(cm)=	.1
50	-Ground	(cm)=	.2
51	Average turn length	(cm)=	654
52	Hydraulic bend factor	=	1.1
53	Magnetic efficiency	(%)=	<u>90.6</u>
54	Ampere-turns per pole	(Amperes)=	<u>19012</u>

TABLE I
(Continued)

55	Coil configuration definition	=	Manual
56	Number of layers of conductors per pole	=	2
57	Number of conductors per layer per pole	=	12
58	Effective number of turns per magnet	=	48
59	Number of turns per cooling circuit	=	24
60	Number parallel connected conductors per magnet	=	1
61	Coil-Height	(cm)=	6.5
62	-Width	(cm)=	17.2
63	*Electrical*		
64	Stored energy	(J)=	6940
65	Total inductance	(mH)=	22.1
66	Total coil resistance	(mOhms)=	20.84
67	Supply current	(Amperes)=	792
68	Voltage across magnet	(Volts)=	16.5
69	Overall magnet-Height	(cm)=	51.2
70	-Width	(cm)=	45.95
71	-Length	(cm)=	323.8
72	Min. length from gap center to magnet edge-Vert.	(cm)=	25.6
73	-Horiz.	(cm)=	24.95
74	Total mass of an assembled magnet	(kg)=	5044
75			
76	<u>OPERATING PARAMETERS of the MAGNET SYSTEM:</u>		
77			
78	*Cooling circuit*		
79	Coolant supply temperature	(C)=	38
80	Coolant temperature gradient	(C)=	19.49
81	Pressure gradient	(psi)=	100
82	Coolant flow	(gpm)=	164.4
83	*Power losses*		
84	Electrical losses in magnets	(W)=	837063
85	Electrical power to operate coolant pumps	(W)=	10217

TABLE II
Unit Cost and Effort for the Storage Ring Dipole

1	<u>MISCELLANEOUS ASSUMPTIONS AND FABRICATION PARAMETERS:</u>		
2			
3	Number of lamination parts	=	1
4	Number of stamping operations per lamination part	=	1
5	Number of core edges to machine	=	2
6	Number of coil pottings per pole	=	1
7	Core is potted	=	No
8	Mass of miscellaneous components	(kg)=	45.45
9	Average shipping distance	(km)=	1448
10	Shipping costs	(\$/kg)=	0
11	Effort efficiency for work calculated in mhrs	(%)=	80
12	Operating life	(yr)=	10
13	Duty factor during operation	(%)=	50
14	Contingency	(%)=	0
15			
16	<u>RAW MATERIAL COSTS:</u>		
17			
18	Magnetic steel sheet	(\$/kg)=	1.76
19	Low carbon steel	(\$/kg)=	1.1
20	Copper conductor	(\$/kg)=	4.4
21	Insulation tape-Turn	(\$/cm)=	.001969
22	-Ground	(\$/cm)=	.001969
23	Coil potting epoxy	(\$/kg)=	3.52
24	Electric power	(\$/kW-hr)=	.06
25			
26	<u>FABRICATED PARTS COSTS:</u>		
27			
28	Laminations	(\$/unit)=	.8
29	Low-carbon steel end plates	(\$/unit)=	500
30	Miscellaneous coil fittings	(\$)=	200
31	Miscellaneous assembly fittings	(\$)=	400
32			
33	<u>TOOLING FABRICATION COSTS:</u>		
34			
35	Lamination die	(\$)=	30000
36	Core stacking fixture	(\$)=	12000
37	Lamination edge machining fixture	(\$)=	4000
38	Vapor degreaser for laminations	(\$)=	6000
39	Coil-Winding fixture	(\$)=	6000
40	-Potting fixture	(\$)=	8000
41	Vacuum impregnation consumable hardware	(\$)=	100
42	Alignment fixtures	(\$)=	0
43			
44	<u>EXCESSES INCLUDED:</u>		
45			
46	Minimum number of spare magnets	(%)=	0
47	Low carbon steel	(%)=	0
48	Magnetic steel sheet	(%)=	1
49	Outer surface trim per machined side	(cm)=	1
50	Laminations	(%)=	.5
51	Coil end lengths	(cm)=	61
52	Copper conductor	(%)=	10
53			
54	<u>MISCELLANEOUS MATERIALS USAGE:</u>		
55			

TABLE II
(Continued)

56	Coil potting epoxy per insulation volume	(%)=	75
57			
58	<u>LABOR COSTS:</u>		
59			
60	Technical staff(TS)	(\$/mmo)=	0
61	Drafting(DR)	(\$/mmo)=	0
62	Machinists(MA)	(\$/mhr)=	35
63	Technician(TE)	(\$/mhr)=	35
64	Riggers(RG)	(\$/mhr)=	35
65			
66	<u>FABRICATION EFFORT PER PROJECT:</u>		
67			
68	Magnet design-TS	(mmo)=	1
69	-DR	(mmo)=	1.5
70	Procurement & QC-TS	(mmo)=	0
71	Core stacking fixture-Design-TS	(mmo)=	.2
72	-DR	(mmo)=	.5
73	-Assem. & align.-TS	(mmo)=	.2
74	-TE	(mhr)=	.5
75	Coil tooling design-TS	(mmo)=	.2
76	-DR	(mmo)=	.5
77	Core tooling design-TS	(mmo)=	.3
78	-DR	(mmo)=	.6
79	Project administration-TS	(%)=	0
80			
81	<u>FABRICATION EFFORT PER MAGNET:</u>		
82			
83	Core-Stacking-TE	(mhr/unit)=	.016
84	-Edge machining-MA	(mhr)=	12
85	-Welding-MA	(mhr)=	4
86	-Assembly-TE	(mhr)=	4
87	-Moving-RG	(mhr)=	2
88	-Supervision-TS	(mmo)=	.05
89	Coil-Application of turn insulation-TE	(mhr/wrap)=	.003
90	-Winding-TE	(mhr/bend)=	.25
91	-Brazing of cooling & elec. joints-TE	(mhr/joint)=	4
92	-Application of ground insulation-TE	(mhr/unit)=	1
93	-Potting-TE	(mhr/unit)=	16
94	-Tests-TE	(mhr/unit)=	2
95	-Supervision-TS	(mmo)=	.05
96	Magnet assembly-Coil installation-TE	(mhr)=	2
97	-Cooling & elec. connections-TE	(mhr)=	4
98	-Tests-TE	(mhr)=	8
99	-Moving-RG	(mhr)=	2
100	-Supervision-TS	(mmo)=	.05

TABLE III
Major Costs for Fabricating Storage Ring Dipoles

Cost estimates for 64 magnets.

COSTS FOR FABRICATING THE MAGNETS:

Purchased Materials and Parts	Quantity	Cost (K\$)
Magnetic steel	372448 kg	651.3
Laminations	121480	97.2
End plate fabrication	128	64.0
Copper conductor	57162 kg	251.5
Tape insulation	17922570 cm	35.3
Epoxy	2056 kg	7.2
Misc hardware	2909 kg	44.8
Shipping	434575 kg	0.0
	Subtotal	1151.3

Effort	TS	DR	MA	TE	RG	Cost (K\$)
		(man-months)				
Core-Machining			5.5			33.6
-Assembly			1.8	15.7	.9	112.0
Coil-Winding				22.6		137.2
-Insulating				.9		5.6
-Assembly				29.5		179.2
-Potting				14.7		89.6
-Testing				1.8		11.2
Magnet-Assembly			1.8	2.8		28.0
-Testing				3.7		22.4
Moving					.9	5.6
			9.1	91.7	1.8	Subtotal 624.4

COSTS DISTRIBUTED OVER ENTIRE PROJECT:

Design-Tooling	.7	1.6				
-Magnet	1.0	1.5				
Tooling-Fabrication						66.0
-Assembly	.2			.2		1.4
Supervision	9.6					
	11.5	3.1		.2		Subtotal 67.4

Administration
Contingency

Grand Total 1843.1 x 1.1 = 2027.5
(1985\$K)

Effort totals 11.5 3.1 9.1 91.9 1.8

To build and operate for 10 years at 4380 hours each is \$4070 K.

Costs to Engineer-Design-Inspect-Administrative are 0% of the costs to build.

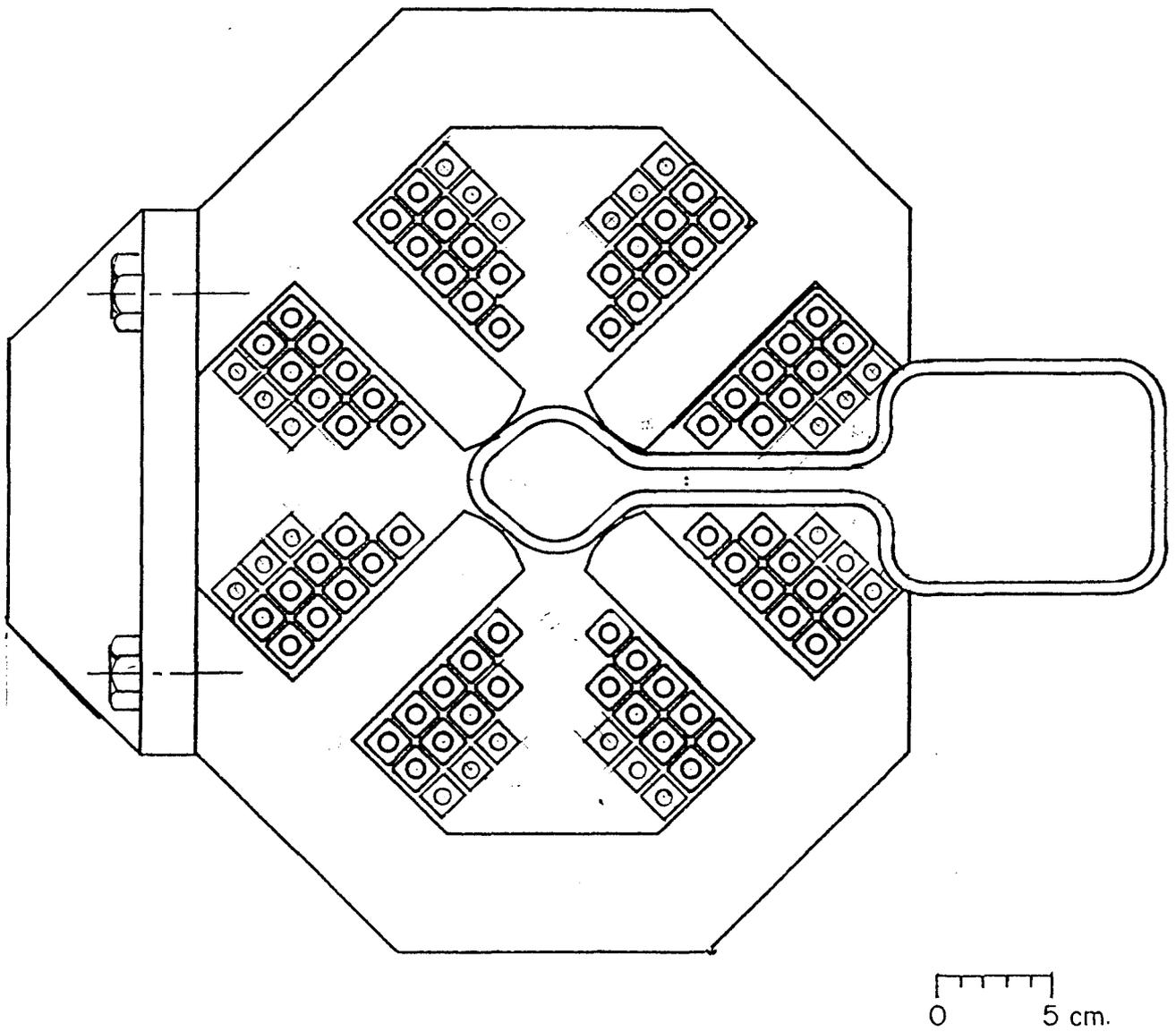


Figure 2 - Storage Ring QF5/QD6 Quad and Vacuum Chamber

TABLE IV
Storage Ring QF5/QD6 Quad Design

1	<u>DESIGN PARAMETERS of MAGNET SYSTEM:</u>		
2			
3	Number of magnets	=	<u>96</u>
4	Type of magnet	=	<u>Quadrupole</u>
5	Type of excitation	=	<u>Simple AC</u>
6	Repetition frequency	(Hz)=	<u>0</u>
7	Maximum multipole field gradient	(G/cm)=	<u>1200</u>
8			
9	<u>DESIGN and OPERATING PARAMETERS of a SINGLE MAGNET:</u>		
10			
11	*Vacuum chamber*		
12	Chamber type	=	<u>None</u>
13	*Gap*		
14	Effective length of field along gap axis	(cm)=	<u>70</u>
15	Total width of pole	(cm)=	<u>3.705</u>
16	Total bore radius	(cm)=	<u>3.25</u>
17	*Core*		
18	Distance from-Field edge to-Core end	(cm)=	<u>1.414</u>
19	-Coil to-Pole face	(cm)=	<u>0</u>
20	-Pole side	(cm)=	<u>.15</u>
21	-Top yoke	(cm)=	<u>0</u>
22	-Side yoke	(cm)=	<u>2</u>
23	-Endplate end	(cm)=	<u>2</u>
24	Pole radius	(cm)=	<u>3.705</u>
25	Angle of pole	(deg)=	<u>60</u>
26	Angle between pole axis and pole side	(deg)=	<u>0</u>
27	Maximum field density at pole edge	(G)=	<u>5015</u>
28	Maximum average field density inside yoke	(G)=	<u>15000</u>
29	Ratio of side to top yoke thicknesses(S/T)	=	<u>0</u>
30	Overall core-Height	(cm)=	<u>41.77</u>
31	-Width	(cm)=	<u>31.3</u>
32	-Length	(cm)=	<u>67.2</u>
33	Total mass of magnetic core	(kg)=	<u>383</u>
34	Lamination thickness	(cm)=	<u>.15</u>
35	Lamination stacking method	=	<u>Parallel</u>
36	End plate thickness	(cm)=	<u>1.5</u>
37	End plate material	=	<u>Magnet st.</u>
38	*Coil*		
39	Conductor material	=	<u>Copper</u>
40	Conductor-Height	(cm)=	<u>1.5</u>
41	-Width	(cm)=	<u>1.5</u>
42	-Hole diameter	(cm)=	<u>.8</u>
43	-Corner radius	(cm)=	<u>.15</u>
44	Conductor min. bend radius(inside edge)-Width	(cm)=	<u>5</u>
45	Insulation-Tape-Thickness-Turn	(cm)=	<u>.05</u>
46	-Ground	(cm)=	<u>.1</u>
47	-Width-Turn	(cm)=	<u>2.5</u>
48	-Ground	(cm)=	<u>2.5</u>
49	Insulation total thickness-Turn	(cm)=	<u>.1</u>
50	-Ground	(cm)=	<u>.2</u>
51	Average turn length	(cm)=	<u>154.2</u>
52	Hydraulic bend factor	=	<u>1.1</u>
53	Magnetic efficiency	(%)=	<u>90</u>
54	Ampere-turns per pole	(Amperes)=	<u>5603</u>

TABLE IV
(Continued)

55	Coil configuration definition	=	Manual
56	Number of layers of conductors per pole	=	<u>6</u>
57	Number of conductors per layer per pole	=	<u>2</u>
58	Effective number of turns per magnet	=	48
59	Number of turns per cooling circuit	=	<u>48</u>
60	Number parallel connected conductors per magnet	=	1
61	Coil-Height	(cm)=	10.6
62	-Width	(cm)=	3.8
63	*Electrical*		
64	Stored energy	(J)=	997
65	Total inductance	(mH)=	9.15
66	Total coil resistance	(mOhms)=	7.96
67	Supply current	(Amperes)=	466.9
68	Voltage across magnet	(Volts)=	3.718
69	Overall magnet-Height	(cm)=	41.77
70	-Width	(cm)=	31.3
71	-Length	(cm)=	78.8
72	Min. length from gap center to magnet edge-Vert.	(cm)=	20.88
73	-Horiz.	(cm)=	15.66
74	Total mass of an assembled magnet	(kg)=	547
75			
76	<u>OPERATING PARAMETERS of the MAGNET SYSTEM:</u>		
77			
78	*Cooling circuit*		
79	Coolant supply temperature	(C)=	38
80	Coolant temperature gradient	(C)=	3.458
81	Pressure gradient	(psi)=	100
82	Coolant flow	(gpm)=	184
83	*Power losses*		
84	Electrical losses in magnets	(W)=	166674
85	Electrical power to operate coolant pumps	(W)=	11433

TABLE V
Unit Cost and Effort for the Storage Ring Quads

1	<u>MISCELLANEOUS ASSUMPTIONS AND FABRICATION PARAMETERS:</u>		
2			
3	Number of lamination parts	=	2
4	Number of stamping operations per lamination part	=	1
5	Number of core edges to machine	=	2
6	Number of coil pottings per pole	=	1
7	Core is potted	=	No
8	Mass of miscellaneous components	(kg)=	10
9	Average shipping distance	(km)=	1448
10	Shipping costs	(\$/kg)=	0
11	Effort efficiency for work calculated in mhrs	(%)=	80
12	Operating life	(yr)=	10
13	Duty factor during operation	(%)=	50
14	Contingency	(%)=	0
15			
16	<u>RAW MATERIAL COSTS:</u>		
17			
18	Magnetic steel sheet	(\$/kg)=	1.76
19	Low carbon steel	(\$/kg)=	1.1
20	Copper conductor	(\$/kg)=	4.4
21	Insulation tape-Turn	(\$/cm)=	.001969
22	-Ground	(\$/cm)=	.001969
23	Coil potting epoxy	(\$/kg)=	3.52
24	Electric power	(\$/kW-hr)=	.06
25			
26	<u>FABRICATED PARTS COSTS:</u>		
27			
28	Lamination parts	(\$/unit)=	.8
29	Low-carbon steel end plates	(\$/unit)=	500
30	Miscellaneous coil fittings	(\$)=	200
31	Miscellaneous assembly fittings	(\$)=	1.4
32			
33	<u>TOOLING FABRICATION COSTS:</u>		
34			
35	Lamination die	(\$)=	20000
36	Core stacking fixture	(\$)=	8000
37	Lamination edge machining fixture	(\$)=	2500
38	Vapor degreaser for laminations	(\$)=	6000
39	Coil-Winding fixture	(\$)=	6000
40	-Potting fixture	(\$)=	8000
41	Vacuum impregnation consumable hardware	(\$)=	100
42	Alignment fixtures	(\$)=	0
43			
44	<u>EXCESSES INCLUDED:</u>		
45			
46	Minimum number of spare magnets	(%)=	0
47	Low carbon steel	(%)=	0
48	Magnetic steel sheet	(%)=	1
49	Outer surface trim per machined side	(cm)=	1
50	Laminations	(%)=	.5
51	Coil end lengths	(cm)=	61
52	Copper conductor	(%)=	10
53			
54	<u>MISCELLANEOUS MATERIALS USAGE:</u>		
55			

TABLE V
(Continued)

56	Coil potting epoxy per insulation volume	(%)=	75
57			
58	<u>LABOR COSTS:</u>		
59			
60	Technical staff(TS)	(\$/mmo)=	0
61	Drafting(DR)	(\$/mmo)=	0
62	Machinists(MA)	(\$/mhr)=	35
63	Technician(TE)	(\$/mhr)=	35
64	Riggers(RG)	(\$/mhr)=	35
65			
66	<u>FABRICATION EFFORT PER PROJECT:</u>		
67			
68	Magnet design-TS	(mmo)=	1
69	-DR	(mmo)=	1.5
70	Procurement & QC-TS	(mmo)=	0
71	Core stacking fixture-Design-TS	(mmo)=	.2
72	-DR	(mmo)=	.5
73	-Assem. & align.-TS	(mmo)=	.2
74	-TE	(mhr)=	.5
75	Coil tooling design-TS	(mmo)=	.2
76	-DR	(mmo)=	.5
77	Core tooling design-TS	(mmo)=	.3
78	-DR	(mmo)=	.6
79	Project administration-TS	(%)=	0
80			
81	<u>FABRICATION EFFORT PER MAGNET:</u>		
82			
83	Core-Stacking-TE	(mhr/unit)=	.012
84	-Edge machining-MA	(mhr)=	8
85	-Welding-MA	(mhr)=	8
86	-Assembly-TE	(mhr)=	16
87	-Moving-RG	(mhr)=	4
88	-Supervision-TS	(mmo)=	.05
89	Coil-Application of turn insulation-TE	(mhr/wrap)=	.003
90	-Winding-TE	(mhr/bend)=	.25
91	-Brazing of cooling & elec. joints-TE	(mhr/joint)=	4
92	-Application of ground insulation-TE	(mhr/unit)=	1
93	-Potting-TE	(mhr/unit)=	16
94	-Tests-TE	(mhr/unit)=	2
95	-Supervision-TS	(mmo)=	.05
96	Magnet assembly-Coil installation-TE	(mhr)=	2
97	-Cooling & elec. connections-TE	(mhr)=	8
98	-Tests-TE	(mhr)=	8
99	-Moving-RG	(mhr)=	2
100	-Supervision-TS	(mmo)=	.05

TABLE VI
Major Costs for Fabricating Storage Ring QF5/QD6 Quad

Cost estimates for 96 magnets.

COSTS FOR FABRICATING THE MAGNETS:

Purchased Materials and Parts	Quantity	Cost (K\$)
Magnetic steel	77622 kg	134.4
Laminations	82539	66.0
End plate fabrication	192	96.0
Copper conductor	12225 kg	53.8
Tape insulation	5314965 cm	10.5
Epoxy	650 kg	2.3
Misc hardware	960 kg	28.9
Shipping	91457 kg	0.0
	Subtotal	391.9

Effort	TS	DR	MA	TE	RG	Cost (K\$)	
		(man-months)					
Core-Machining			5.5			33.6	
-Assembly			5.5	14.5	2.8	138.9	
Coil-Winding				33.5		203.7	
-Insulating				2.8		16.8	
-Assembly				8.3		50.4	
-Potting				44.2		268.8	
-Testing				5.5		33.6	
Magnet-Assembly			5.5	6.9		75.6	
-Testing				5.5		33.6	
Moving					1.4	8.4	
			16.5	121.2	4.2	Subtotal 863.4	

COSTS DISTRIBUTED OVER ENTIRE PROJECT:

Design-Tooling	.7	1.6				
-Magnet	1.0	1.5				
Tooling-Fabrication						50.5
-Assembly	.2			.3		2.1
Supervision	14.4					
	16.3	3.1		.3		Subtotal 52.6

Administration
Contingency

Grand Total 1307.9x 1.1 = 1438.7
(1985K\$)

Effort totals 16.3 3.1 16.5 121.5 4.2

To build and operate for 10 years at 4380 hours each is \$1776 K.

Costs to Engineer-Design-Inspect-Administrate are 0% of the costs to build.

TABLE VII
Some Design Parameters and Fabrication Costs

<u>Magnet Type</u>	<u>Number Req. 'd</u>	<u>Current (A)</u>	<u>Voltage (V)</u>	<u>ΔT ($^{\circ}C$)</u>	<u>Total Mass (Tonne)</u>	<u>Total Power (kW)</u>	<u>Total Water Flow (gpm)</u>	<u>Total Fabrication Costs (K\$(85))</u>
M	64	792	16.5	19.5	323	837	164	2027.5
QD1	32	467	1.5	0.8	6	22	101	430.0
QF2	32	493	8.5	12.6	43	134	41	660.0
QD3	32	493	6.1	7.7	31	97	48	593.1
QD4	64	467	2.9	2.3	29	86	141	908.1
QF5/QD6	96	467	3.7	3.5	52	167	184	1438.7
QF7	32	467	4.0	3.8	<u>21</u>	<u>59</u>	<u>59</u>	<u>521.1</u>
Totals for Ring					505	1402	738	6578.5

TRIM CALCULATIONS

To address the field errors of the dipole magnets, we have done several magnetic field calculations. A TRIM calculation was done for a flat pole version of the magnet. This utilized a relatively high resolution mesh that could be altered at a later date to incorporate some edge shims. The mesh generated is shown in Figure 3 and a plot of the field lines is shown in Figure 4. The calculated midplane vertical field strengths across the gap are shown in Figure 5 (followed by tabulated values). The right hand edge of this plot also represents the shape of the end field. Figure 6 shows an expanded view around the gap center. Also a plot was made for the radial field component, at $y = 1.5$ cm, near the gap center as shown in Figure 7 (followed by tabulated values). This TRIM run also provided the forces on the coils. The TRIM data tape could also be used to calculate the forces between the poles so a more accurate calculation of the pole deflections could be carried out in the future.

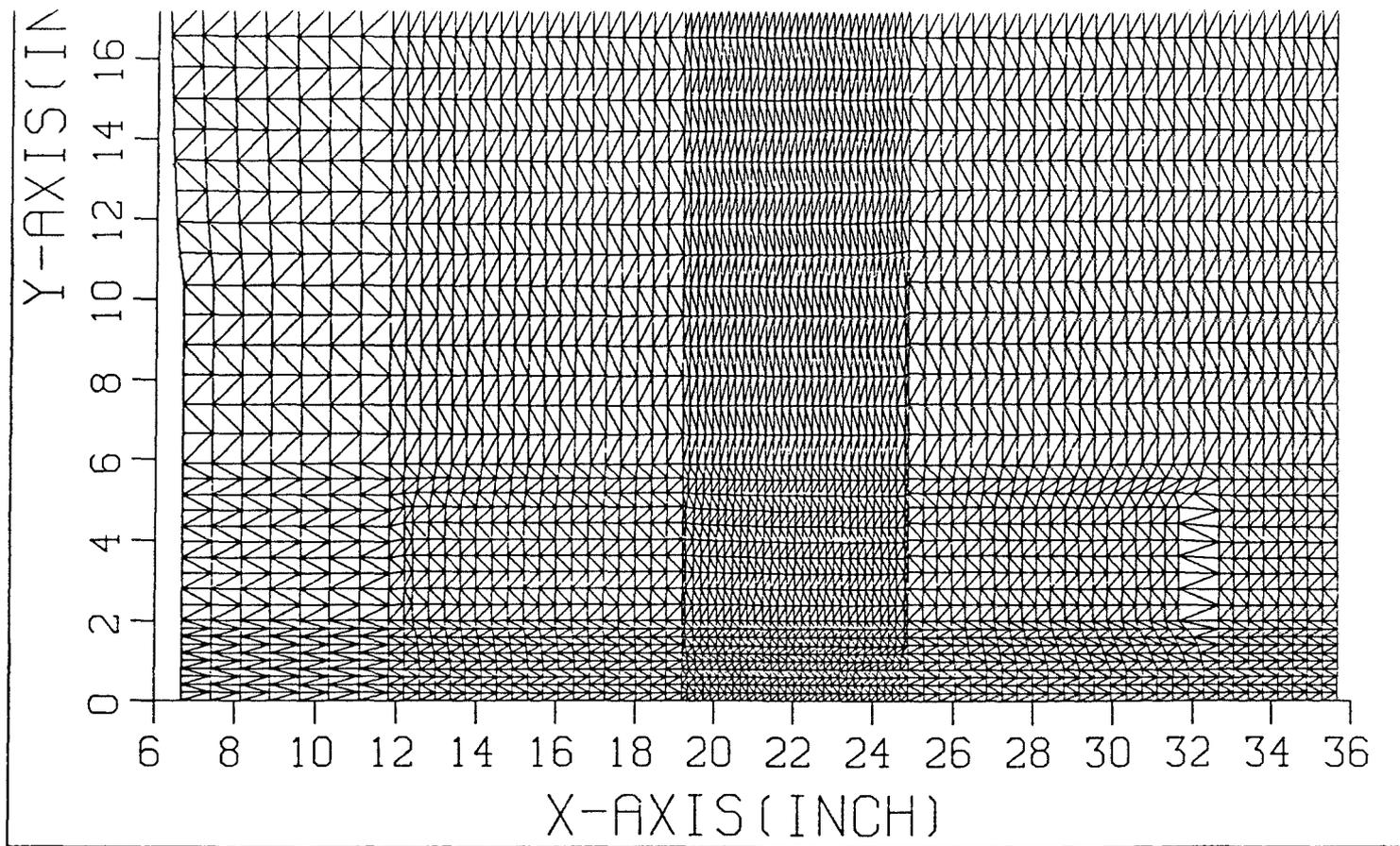


Figure 3 - Mesh for the Storage Ring Dipole

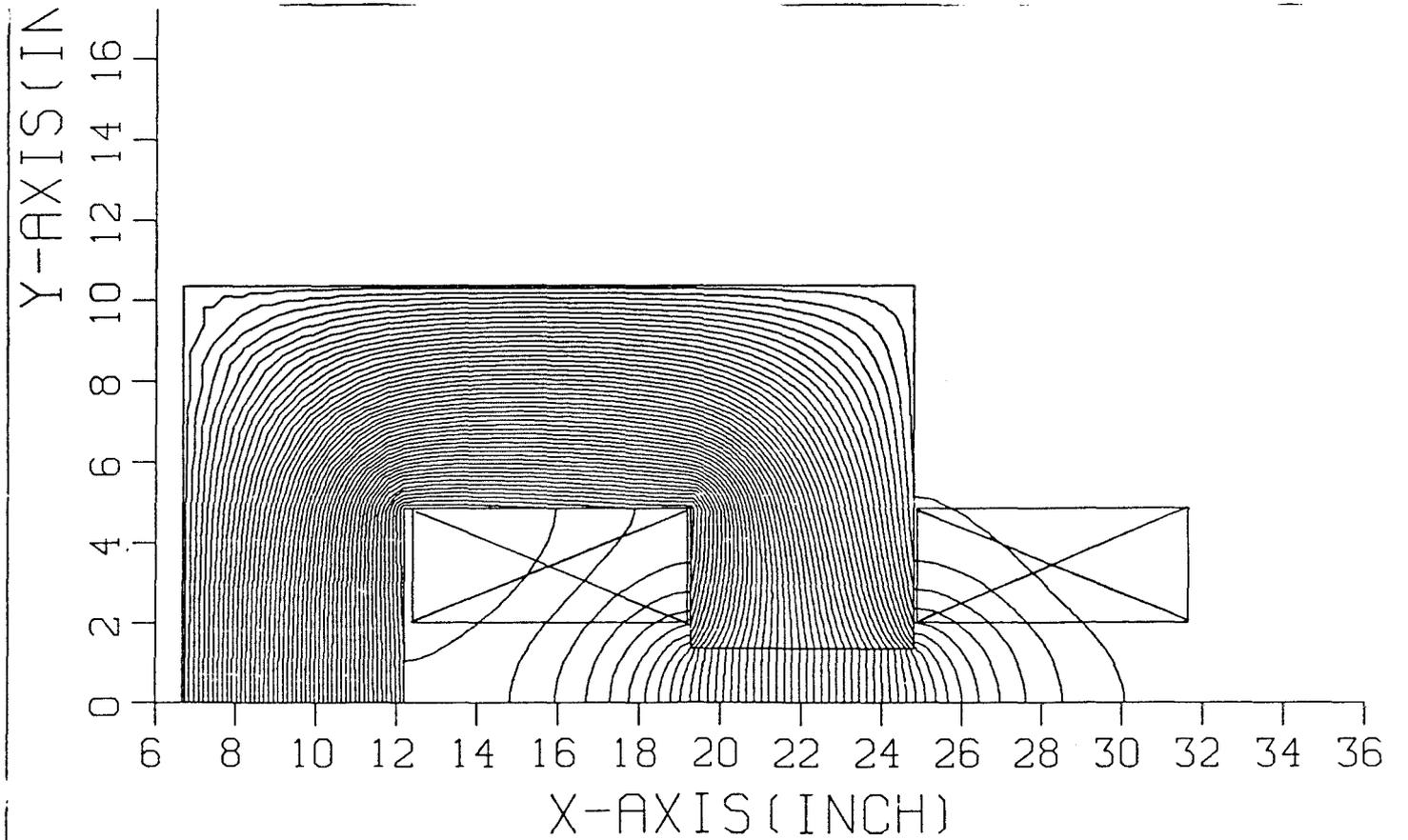


Figure 4 - Field Lines in the Storage Ring Dipole

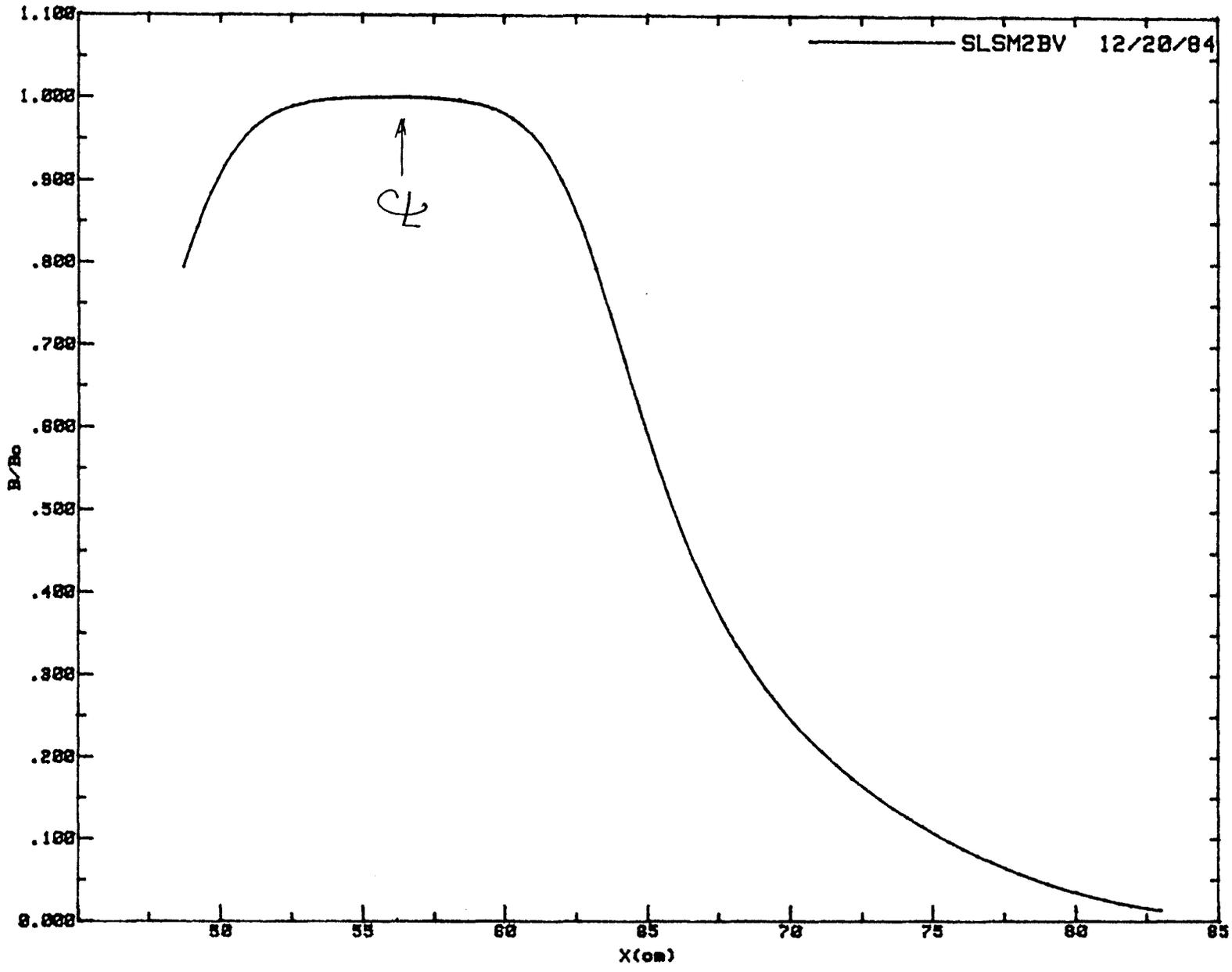


Figure 5 - Vertical Field along a radial line in the midplane of the Storage Ring Dipole

Vertical field strengths on the midplane
as calculated with TRIM

SLSM2B 6.5cm x 14cm Gap + 14cm Yoke VERTICAL

The value of B_0 used in the following list is 6661.99.

The input coordinate pairs are (X,B) and pairs to be plotted are (X,B/ B_0):

#	X	B(Gauss)	X(cm)	B/ B_0
1	48.7000	5292.6600	48.7000	0.79446
2	49.1833	5615.9600	49.1833	0.84299
3	49.6666	5891.9600	49.6666	0.88441
4	50.1499	6113.1600	50.1499	0.91762
5	50.6332	6281.2900	50.6332	0.94285
6	51.1165	6403.8600	51.1165	0.96125
7	51.5998	6490.4200	51.5998	0.97425
8	52.0831	6550.1500	52.0831	0.98321
9	52.5667	6590.6700	52.5667	0.98929
10	53.0500	6617.8000	53.0500	0.99337
11	53.5333	6635.7600	53.5333	0.99606
12	54.0167	6647.4900	54.0167	0.99782
13	54.5000	6654.9900	54.5000	0.99895
14	54.9833	6659.5500	54.9833	0.99963
15	55.4667	6661.9900	55.4667	1.00000
16	55.9500	6662.7400	55.9500	1.00011
17	56.4333	6661.9400	56.4333	0.99999
18	56.9167	6659.4600	56.9167	0.99962
19	57.4000	6654.8400	57.4000	0.99893
20	57.8833	6647.2900	57.8833	0.99779
21	58.3667	6635.4800	58.3667	0.99602
22	58.8500	6617.4100	58.8500	0.99331
23	59.3333	6590.1500	59.3333	0.98922
24	59.8167	6549.4500	59.8167	0.98311
25	60.3000	6489.4600	60.3000	0.97410
26	60.7833	6402.5100	60.7833	0.96105
27	61.2667	6279.2900	61.2667	0.94255
28	61.7500	6110.0500	61.7500	0.91715
29	62.2333	5887.0200	62.2333	0.88367
30	62.7167	5608.2700	62.7167	0.84183
31	63.2000	5281.1800	63.2000	0.79273
32	64.1900	4543.0700	64.1900	0.68194
33	65.1800	3817.0000	65.1800	0.57295
34	66.1700	3185.0000	66.1700	0.47809
35	67.1600	2664.0000	67.1600	0.39988
36	68.1500	2241.0000	68.1500	0.33639
37	69.1400	1897.0000	69.1400	0.28475
38	70.1300	1613.0000	70.1300	0.24212
39	71.1200	1374.0000	71.1200	0.20624
40	72.1100	1170.0000	72.1100	0.17562
41	73.1000	994.0000	73.1000	0.14920
42	74.0900	839.0000	74.0900	0.12594
43	75.0800	702.0000	75.0800	0.10537
44	76.0700	581.0000	76.0700	0.08721
45	77.0600	473.0000	77.0600	0.07100
46	78.0500	378.0000	78.0500	0.05674
47	79.0400	296.0000	79.0400	0.04443
48	80.0300	226.0000	80.0300	0.03392
49	81.0200	168.0000	81.0200	0.02522
50	82.0100	122.0000	82.0100	0.01831
51	83.0000	87.0000	83.0000	0.01306

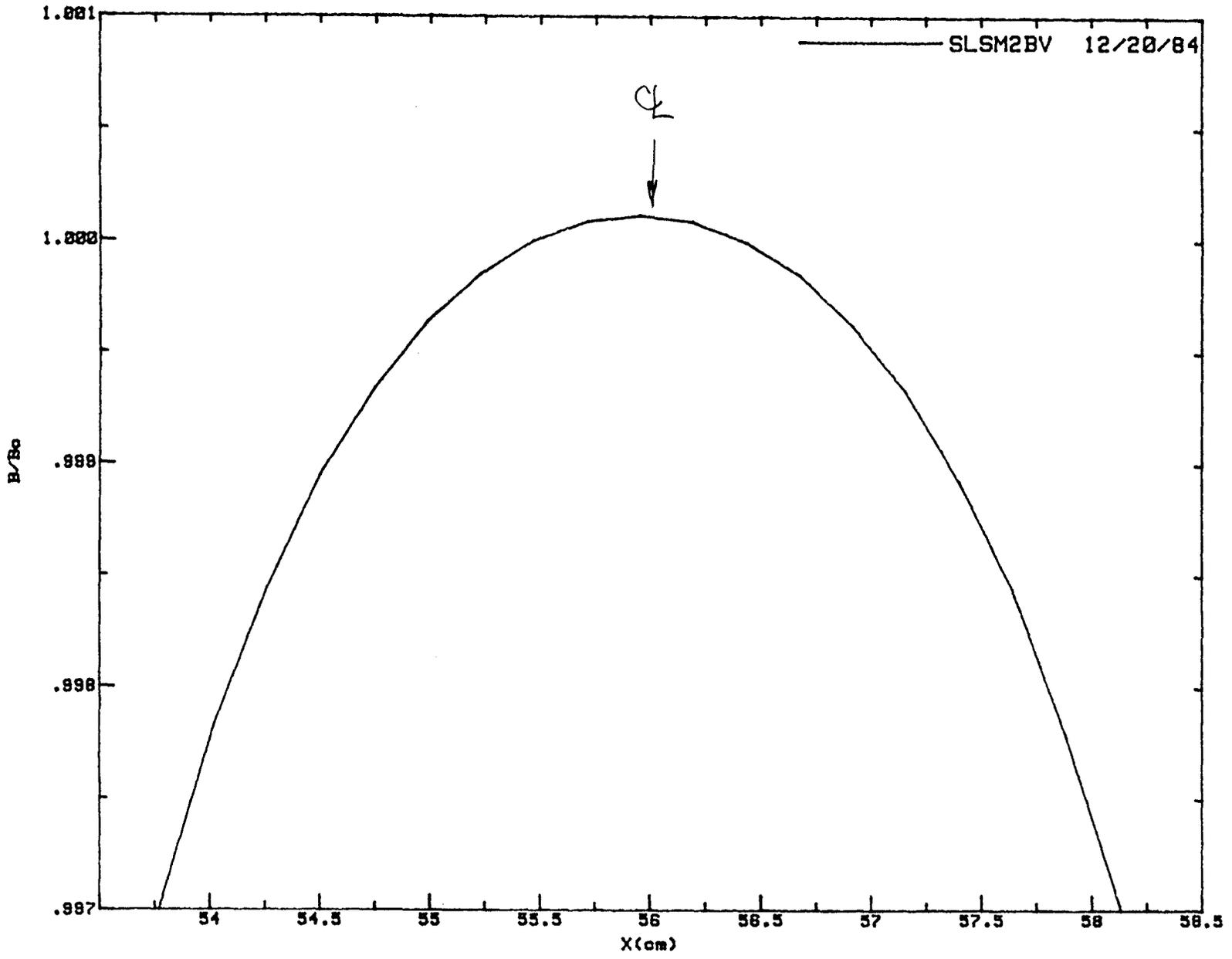


Figure 6 - Vertical Field (expanded) along a radial line on the midplane and near the center of a Storage Ring Dipole

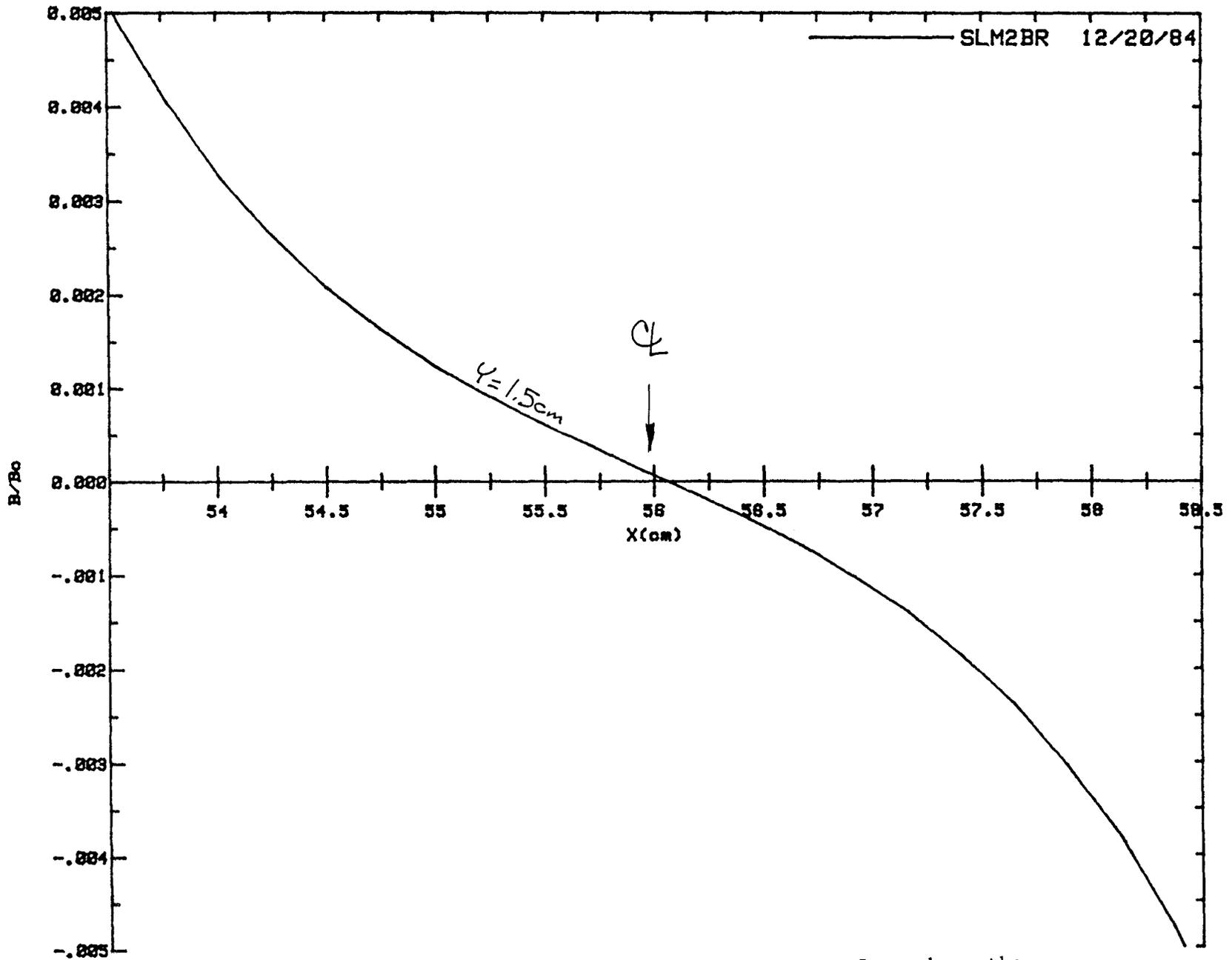


Figure 7 - Radial Field along a radial line, at 1.5 cm above the midplane, in a Storage Ring Dipole

Radial field strengths at $y = 1.5$ cm above
the midplane as calculated by TRIM

SLM2BR 6.5cm x 14cm Gap + 14cm Yoke RADIAL Z=.5

The value of B_0 used in the following list is 6661.99.

The input coordinate pairs are (X,B) and pairs to be plotted are (X,B/ B_0):

#	X	B(Gauss)	X(cm)	B/ B_0
1	53.0500	22.4700	53.0500	0.00337
2	53.5333	15.0500	53.5333	0.00226
3	54.0167	10.0500	54.0167	0.00151
4	54.5000	6.6200	54.5000	0.00099
5	54.9833	4.2100	54.9833	0.00063
6	55.4667	2.3800	55.4667	0.00036
7	55.9500	0.8300	55.9500	0.00012
8	56.4333	-.7300	56.4333	-.00011
9	56.9167	-2.5600	56.9167	-.00038
10	57.4000	-4.9800	57.4000	-.00075
11	57.8833	-8.4200	57.8833	-.00126
12	58.3667	-13.4300	58.3667	-.00202

PE2D CALCULATIONS

In addition to the TRIM magnetic field calculations, the computer program PE2D was used to check these results and we tried to utilize the TRACKING feature to track electron through the end field. Preliminary tracking results are shown below. The field values are given in TABLE VIII and plotted in Figure 8 for both the area under the pole and the end field region. They agree with TRIM to a reasonable accuracy.

```

TRACK STARTING PARAMETER
FIELD FACTOR= 1 00 TOL= 0 0100000 STEP= 0 1000
MAX NO OF STEPS= 200 ZMAX= 40 000 ZMIN= 0 000 IFLDT= 1
TRACK Z0 X0 U THETA PHI MASS AMPS
1 0 010 38.950 6 000E+09 90 000 0 000 0 000 1 00000
NIT= 0 NITD= 0
General ray tracing option
Fields from PE2D
Magnetic field
Electrons
RFAC= 1.000
TOLERANCE= 0 0100
STARTING PARAMETERS VOLTS= 6 000E+09 ANGLE= 90 000 PHI= 0 000
X0= 38 950 Z0= 0 010 VELOCITY= 2 998E+08 M/SEC
TRACK NUMBER 1

```

ISTEP	T	Z	X	PHI	ANGLE	BZ	BX
0	0 000000	0 010000	38 9500	0 000000	90 0000	6660 98	-0 15180
3	10 3 34E-11	0 010000	39 9500	0 014476	90 0000	6658 37	-1 57566
	20 6 67E-11	0 010000	40 9494	0 056469	90 0000	6648 29	-4 35194
	30 1 00E-10	0 009999	41 9481	0 123931	90 0000	6621 50	-11 2060
	40 1 33E-10	0 009996	42 9457	0 214938	90 0003	6554 81	-27 0664
	50 1 67E-10	0 009986	43 9416	0 327423	90 0010	6397 32	-60 6018
	60 2 00E-10	0 009956	44 9357	0 459400	90 0027	6060 72	-117 046
	70 2 33E-10	0 009894	45 9274	0 608094	90 0060	5421 97	-175 030
	80 2 67E-10	0 009742	46 9171	0 770234	90 0107	4687 98	-192 003
	90 3 00E-10	0 009514	47 9047	0 942490	90 0158	3905 50	-174 520
	100 3 34E-10	0 009200	48 8903	1 12142	90 0204	3219 09	-144 197
	110 3 67E-10	0 008811	49 8742	1 30436	90 0246	2667 20	-114 806
	120 4 00E-10	0 008358	50 8567	1 48920	90 0280	2230 40	-91 7007
	130 4 34E-10	0 007853	51 8379	1 67438	90 0308	1877 13	-73 9364
	140 4 67E-10	0 007303	52 8179	1 85873	90 0331	1589 50	-60 5202
	150 5 00E-10	0 006716	53 7970	2 04142	90 0350	1355 60	-50 8616
	160 5 34E-10	0 006098	54 7751	2 22178	90 0369	1156 42	-43 3752
	170 5 67E-10	0 005452	55 7527	2 39930	90 0383	984 383	-37 5014
	180 6 00E-10	0 004781	56 7296	2 57366	90 0397	836 288	-32 8340
	190 6 34E-10	0 004029	57 7059	2 74452	90 0409	705 954	-29 0113
	200 6 67E-10	0 003378	58 6818	2 91173	90 0419	589 876	-25 6930

End of track
OK

TABLE VIII-A

(cm)	$B_y (y = 0)$	$B_y (y = 1.5)$	B_x	(GAUSS)	$B_y (y = 3.0)$	B_x
X position	Value	Value	Value		Value	Value
31 9500	5226 28	5450 23	1249 24		6655 49	4360 30
32 4500	5750 86	6132 04	965 178		8403 10	1776 80
32 9500	6028 86	6384 69	675 299		7638 22	670 038
33 4500	6236 28	6519 22	448 907		7224 77	303 910
33 9500	6383 19	6588 27	290 392		6995 01	156 443
34 4500	6483 14	6624 51	185 087		6863 24	86 8878
34 9500	6549 10	6643 08	116 520		6786 12	50 1020
35 4500	6592 02	6652 81	73 1099		6740 00	30 1290
35 9500	6619 60	6658 43	45 5580		6711 98	18 3911
36 4500	6636 91	6661 70	28 3500		6694 89	11 1673
36 9500	6647 64	6663 58	17 4251		6684 28	6 73057
37 4500	6654 37	6664 67	10 3883		6677 97	4 00117
37 9500	6658 22	6665 28	5 81848		6674 32	2 20156
38 4500	6660 20	6665 51	2 53010		6672 27	0 899289
38 9500	6660 97	6665 64	-0 101800		6671 50	-0 209888
39 4500	6660 37	6665 62	-2 67961		6672 07	-1 16854
39 9500	6658 34	6665 36	-5 84786		6673 96	-2 22562
40 4500	6654 50	6664 92	-10 2854		6677 40	-3 71544
40 9500	6648 23	6664 21	-17 0491		6683 54	-6 07600
41 4500	6637 84	6662 87	-27 6441		6693 64	-9 83560
41 9500	6621 34	6660 50	-44 4728		6710 49	-15 6620
42 4500	6595 16	6656 43	-71 2847		6738 24	-25 4003
42 9500	6554 24	6648 66	-114 016		6784 02	-42 0960
43 4500	6491 02	6633 61	-181 399		6861 40	-71 5110
43 9500	6395 28	6603 24	-286 378		6996 04	-127 089
44 4500	6254 33	6540 32	-445 497		7242 19	-244 113
44 9500	6054 34	6410 60	-673 000		7731 07	-534 940
45 4500	5786 20	6154 40	-960 080		8842 86	-1429 21

FIGURE 8A

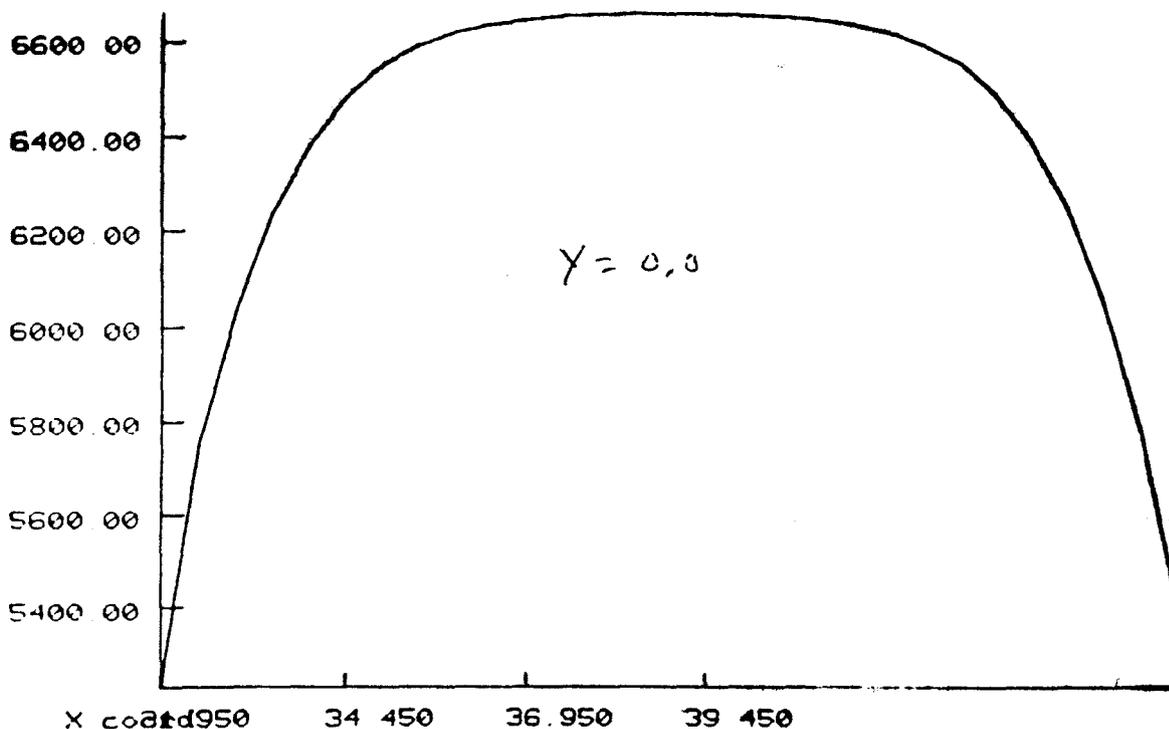


FIGURE 8B

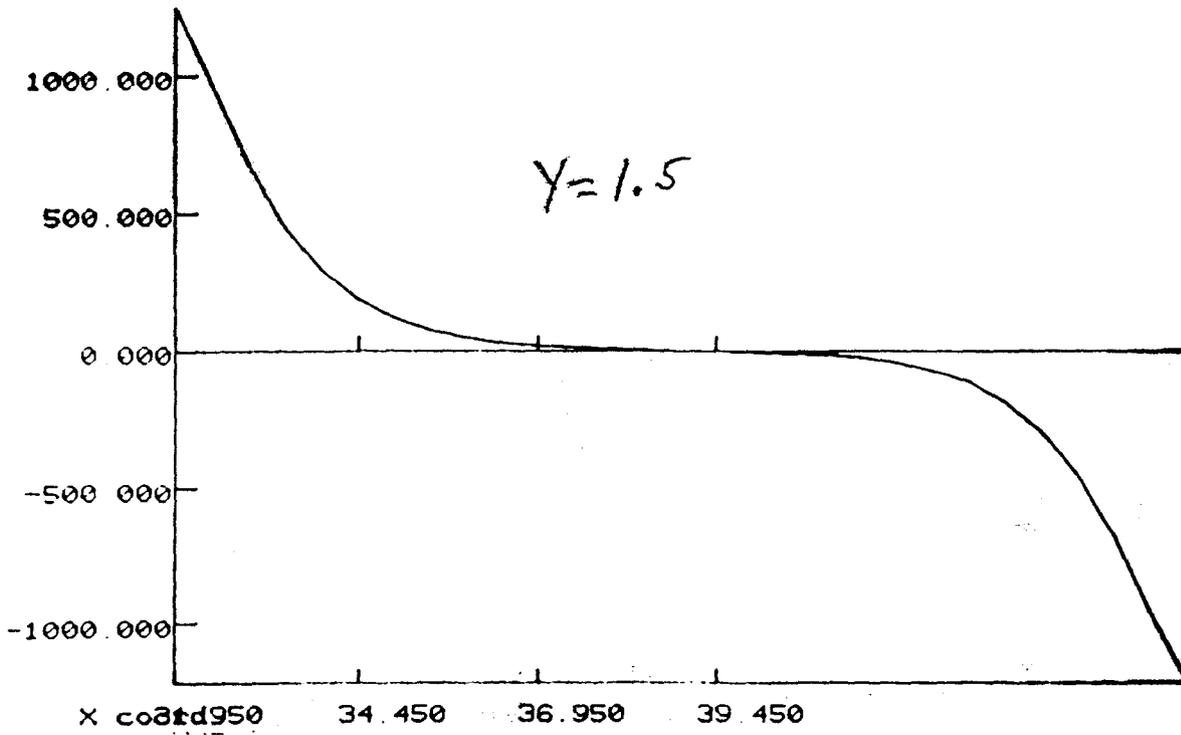
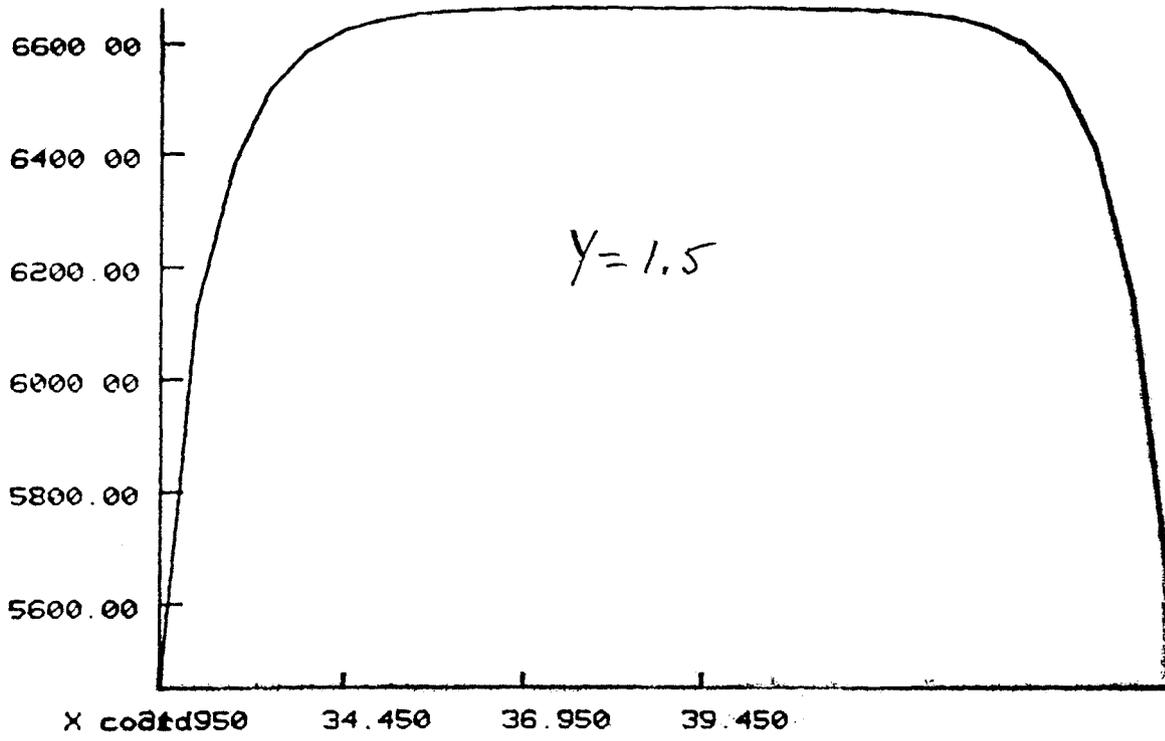
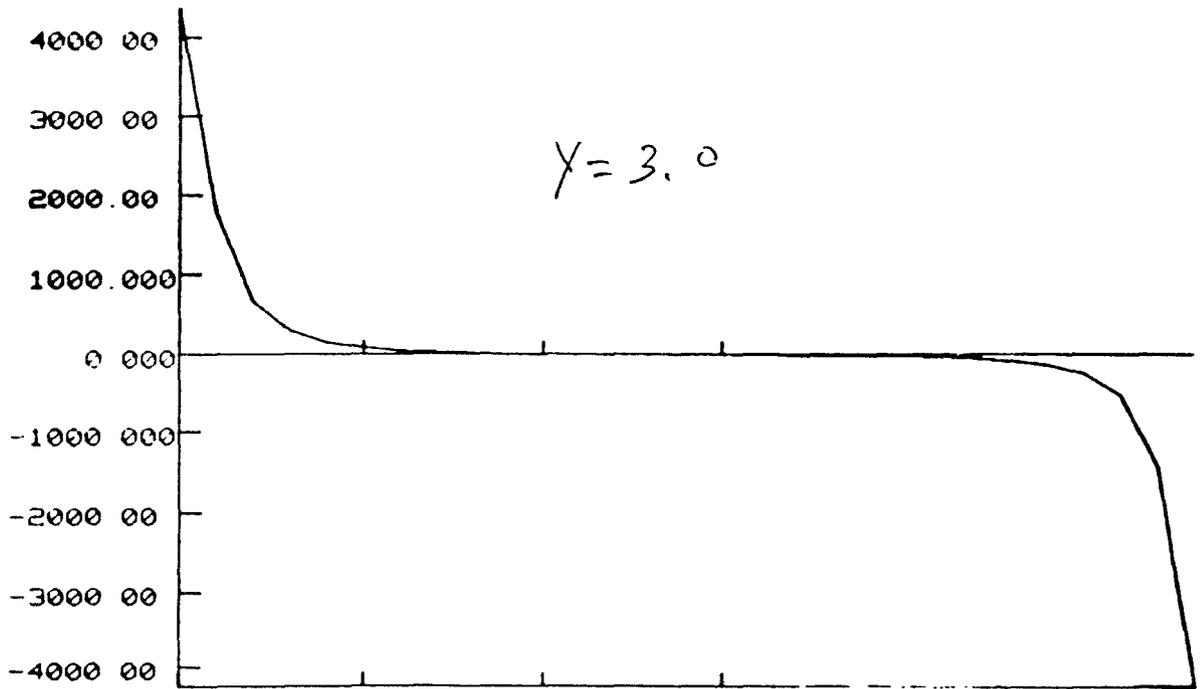
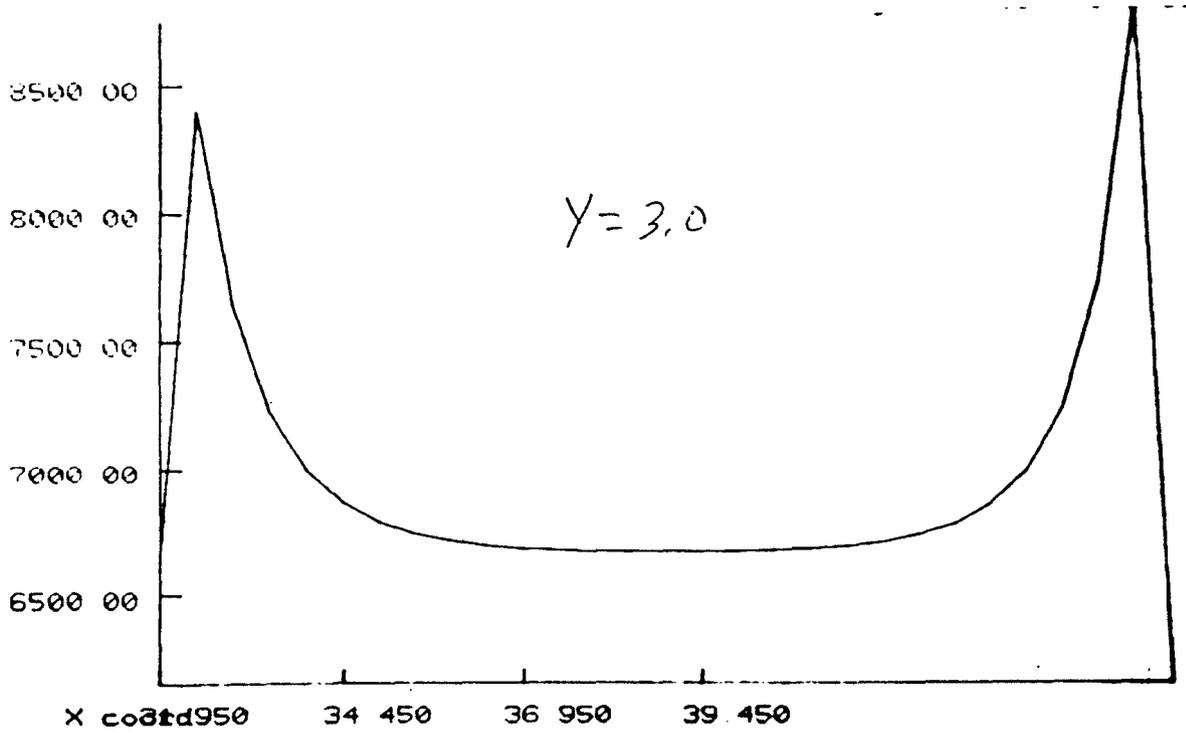


FIGURE 8C



reactive control system quota exceeded process priority has been lowered

(cm)	$B_y (y = 0)$	$B_y (y = 1.5)$	B_x	(GAUSS)	$B_y (y = 3.0)$	B_x
position	Value	Value	Value		Value	Value
32 9500	6650 37	6665 64	-0.101800		6671 50	-0.202320
39 9500	6658 34	6665 36	-5.84786		6673 96	-2.22562
40 9500	6648 23	6664 21	-17.0491		6623 54	-6.07600
41 9500	6621 34	6660 50	-44.4728		6710 49	-15.6620
42 9500	6554 24	6643 66	-114.016		6784 02	-42.0960
43 9500	6395 28	6603 24	-286.378		6996.04	-127.089
44 9500	6054 34	6410 60	-673.000		7731.07	-534.940
45 9500	5404 37	5634 60	-1224.30		6160.01	-4251.30
46 9500	4661 32	4821 50	-1307.77		4075.37	-3247.14
47 9500	3871 30	3722 88	-1139.93		3062.27	-2320.92
48 9500	3179 68	3020 20	-914.803		2490.04	-1720.20
49 9500	2631 63	2504 34	-713.227		2120.94	-1323.38
50 9500	2193 60	2096 39	-566.918		1822.13	-1048.46
51 9500	1839 69	1767 29	-456.852		1566.72	-851.066
52 9500	1556 90	1504 21	-374.010		1355.30	-707.309
53 9500	1322 60	1292 56	-314.889		1171.20	-599.278
54 9500	1123 11	1092 19	-269.242		1005.92	-516.850
55 9500	953 201	929 021	-232.886		860.634	-451.949
56 9500	805 809	786 067	-204.694		730.511	-399.383
57 9500	675 266	652 452	-181.296		611.044	-356.161
58 9500	560 193	545 239	-160.469		502.796	-318.103
59 9500	459 137	445 060	-141.620		404.788	-282.418
60 9500	369 816	356 016	-123.811		315.736	-248.241
61 9500	292 523	278 791	-105.684		237.394	-212.408
62 9500	223 828	210 529	-87.3798		169.564	-173.324
63 9500	170 010	158 120	-69.9417		121.436	-136.544
64 9500	131 260	120 828	-55.0478		88.9042	-104.349
65 9500	99 8953	91 5049	-42.5021		66.3911	-79.4392
66 9500	73 8070	67 2870	-32.0678		47.6297	-59.7414
67 9500	52 9940	47 8360	-24.2670		32.8699	-44.4417
68 9500	39 2080	35 3107	-18.4840		24.0470	-33.8477
69 9500	27 7387	24 8557	-13.7824		16.3170	-25.4343
70 9500	18 2808	16 6532	-10.4374		10.2856	-19.0543
71 9500	12 3770	11 2090	-7.94970		6.42776	-14.5563
72 9500	7 90496	6 67679	-5.93617		3.03662	-10.9924
73 9500	4 13366	3 17901	-4.53010		0.450518	-8.29949
74 9500	1 50183	0 783658	-3.45046		-1.27722	-6.32280

FIGURE 8D

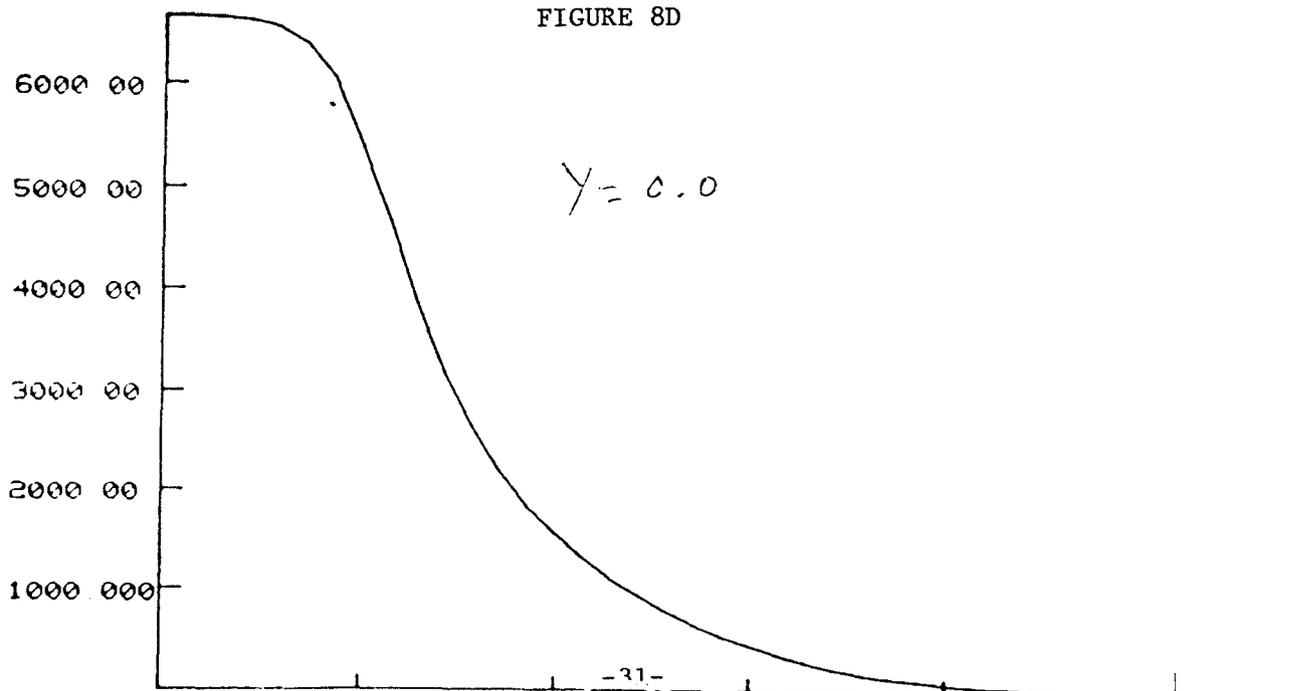


FIGURE 8E

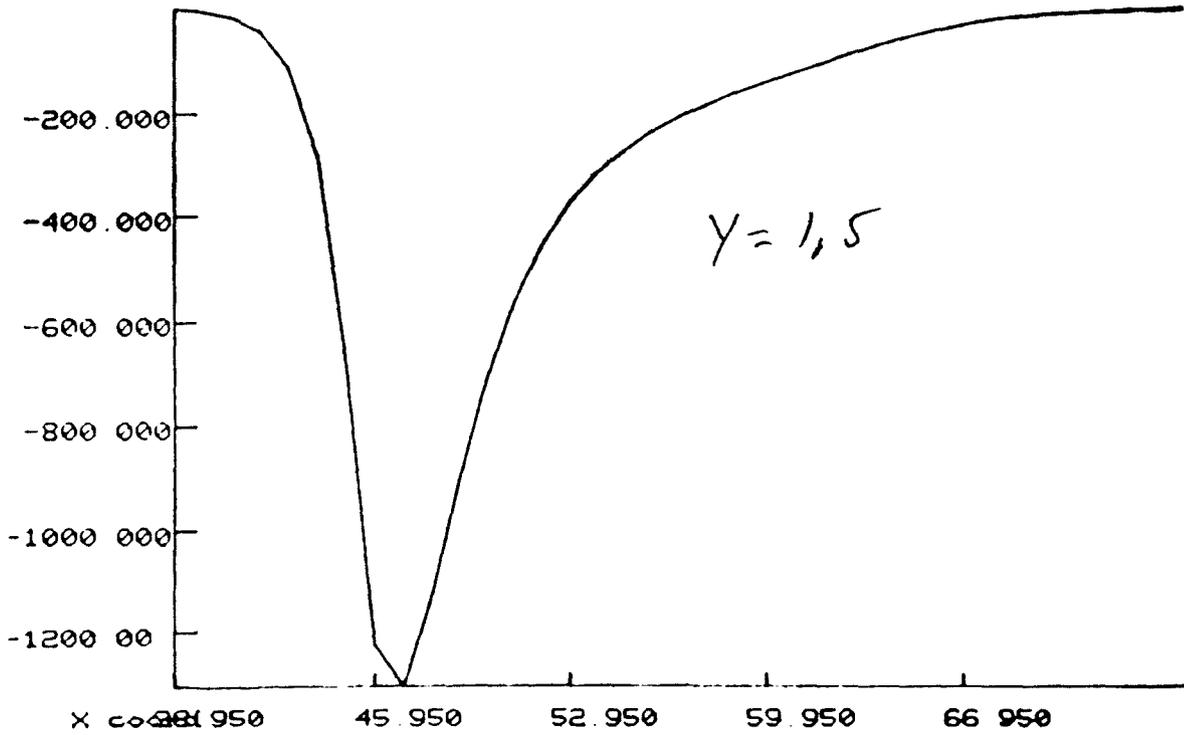
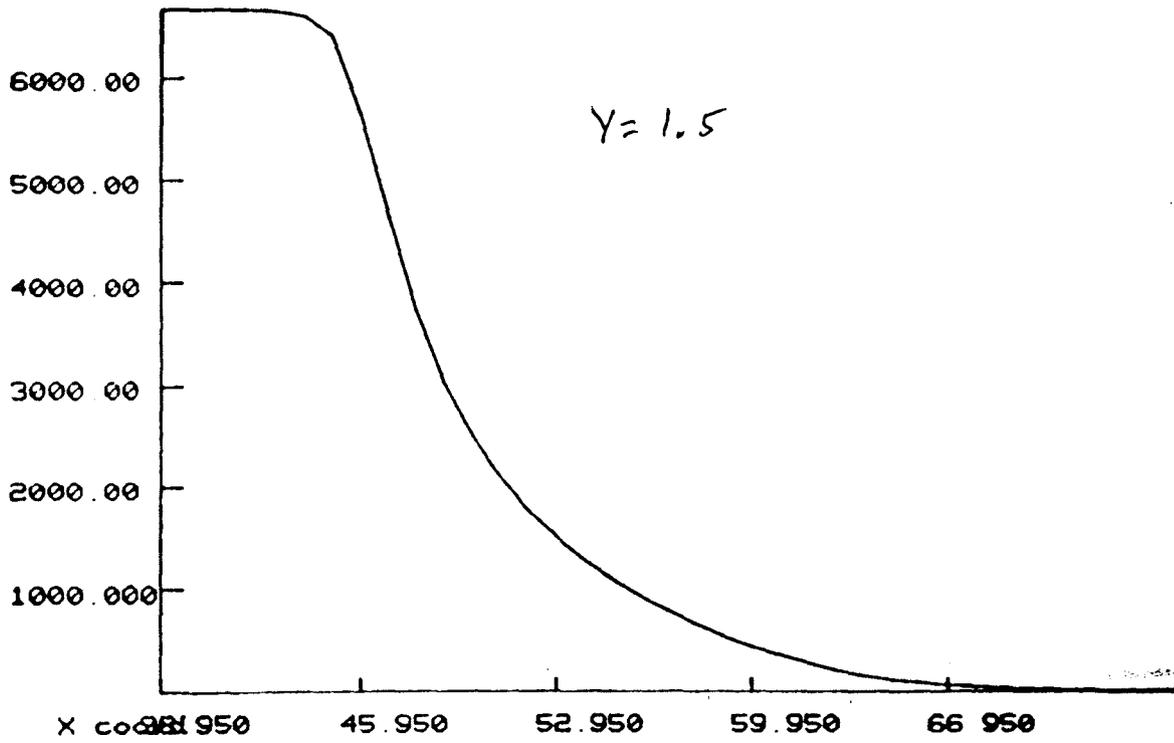
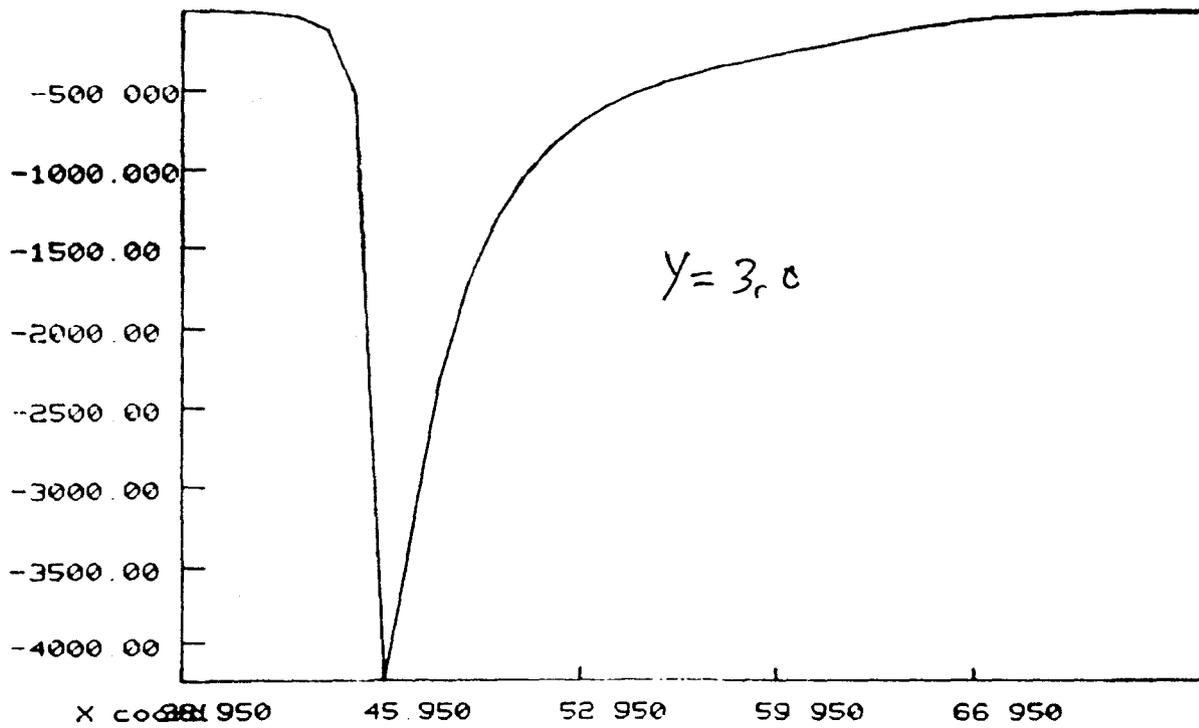
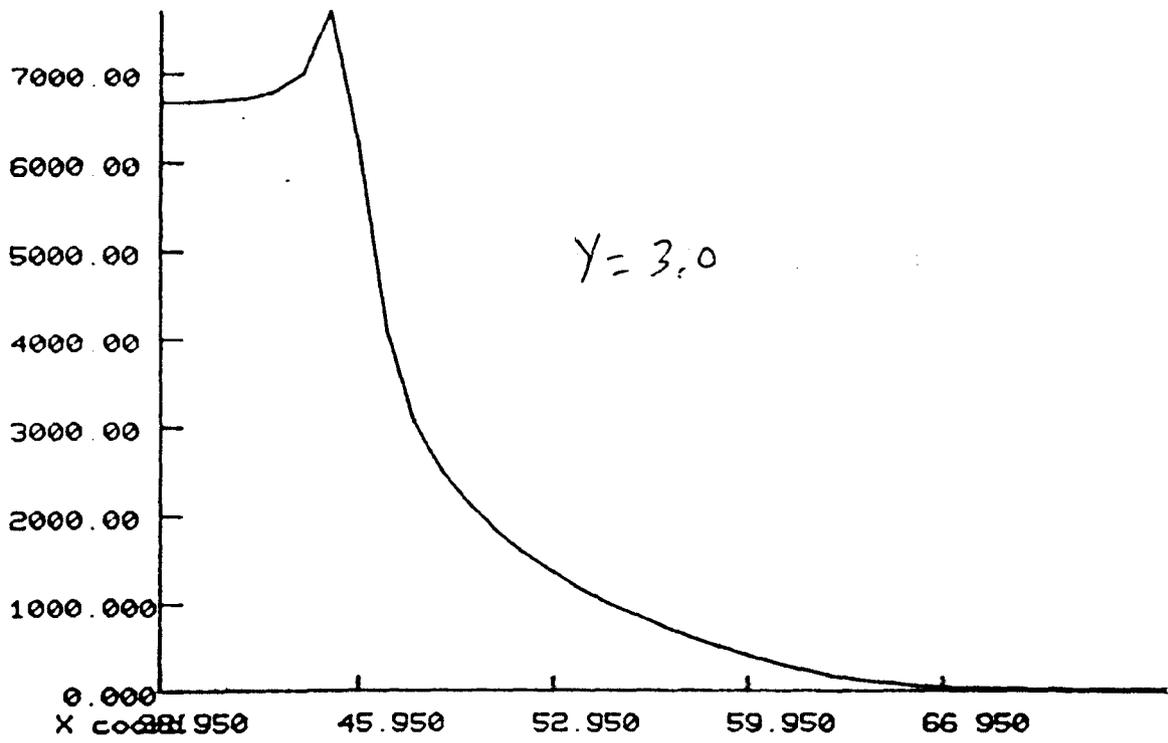


FIGURE 8F



POISSON CALCULATIONS

POISSON is a next generation of TRIM and the mesh is set up in a similar manor. It has one feature in it that TRIM does not have, namely, the field can be analyzed in terms of the harmonic content. For a dipole field with symmetry, only the odd harmonics can be present, namely $m=1$ (dipole), 3 (sextupole), 5,7, etc. A calculation that was not fully converged (due to other problems) had the harmonic fields as shown in TABLE IX.

TABLE IX
Harmonic content in the storage ring dipole

N	B _n (at $r_0=2.54$ cm)
1	6634.7
3	6.6
5	15.6
7	2.1
9	7.5

Remember, that at a smaller radius, the field will fall off as $(r/r_0)^{N-1}$ so the higher harmonics fall off very fast as the radius decreases. For a fully converged solution, these higher harmonics should be smaller.

FUTURE CALCULATIONS

There still is more that can be done to fine tune the designs for the storage ring magnets. The cores and coils must be optimized to some degree. Shims could be developed for the edges of the poles in the dipoles. This can be done in a fairly short time (1 week) for the dipoles, but doing it for the quadrupoles would be more time consuming since there are four different designs and the geometry is much more complex to set up than for a dipole. A 3 dimensional calculation using TOSCA would be needed to calculate the harmonics due to the edge fields of the magnets.