Mini Torus Magnet for CLAS

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1.0 Conductor

EXPERIENCE FROM HIGH ENERGY PHYSICS CENTERS

The correct choice between different water cooling hollow conductors such as copper or aluminum depends on physics requirements and parameters of the magnet: current density, cooling conditions, volume of the magnetic field, power supply, magnetic forces. Aluminum conductor can be produced with very long length without additional joints and copper conductor allows to generate more current densities and to decrease the power consumption. Conventional magnets operate at low water speed rate of 3-10 m/sec with Reynolds number >> 2400 turbulent flow. Water speed higher than 10 m/sec may lead to conductor erosion and corresponding protective test should be done.

CURRENT DENSITIES

Coils with cooling water copper conductors may have average optimum current densities of 500-2000 A/cm^2. Studies carried out at CERN indicated that current densities of 600-1000 A/cm^2 give the optimum magnet-power supply system [1,2,3] for copper. For aluminum in big detector magnets (L3, OPAL, SLD) current densities of 50-350 A/cm^2 were used[4]. The optimum current density for copper used in ANL is about 5000 A/in ^{2} [5].

Compact coils with higher average current densities need better insulation, more extensive cooling, leads also to a high power dissipation and operational cost. Low voltage has some advantages in safety of operation. An aluminum conductor requires either higher power costs or larger coil cross section.

HEAT DISSIPATION

An important parameter for the magnet cooling is a heat transfer coefficient h. For short length, a heat transfer coefficient for conductor and cooling water of 4 W/cm^{2}C is achievable for the length more than 20 m and water speed 3-4 m/sec the heat flux of only 0.1-0.5 W/cm^{2}C can be utilized [1,6].

CEBAF EXPERIENCE in Thermal Tests of Septum Magnets

Low current with small cross sections and short lengths hollow copper conductors were tested at CEBAF. The achieved heat dissipations were:

Conductor 1: h=2.64 W/cm^{2}C, Current density in conductor J=26.15 A/mm^2

Conductor 2: h=2.02 W/cm^{2}C, Current density in conductor J=5.24 A/mm^2

Conductor 3: h=2.2 W/cm^{2}C, Current density in condductor J=27.2 A/mm^2

The main parameters and test results of conductors are presented in attachment 1.

2.0 Mini Torus Magnet

The magnet has some peculiarities:

1. The current density is not uniform. A short length of the conductor 17 cm after machining in each turn will have 1/4 area of the initial cross section. This region will be a weak point of the magnet and the heat dissipation higher, than in any place of the coil.

2. The environment temperature has to be stabilized at 22 ^{0}C.

3. To minimize a background in operating regions of the detector, the coils have to be produced from aluminum.

4. To organize the circular current each turn in the sections must be shorted with neighbor.

If we use the water cooling aluminum conductor with 55 x 19 mm^2 with a hole diameter of 11 mm the estimations can be done for the first turn of the section with the smallest cross section after machining. For estimations relations from [6] will be used.

A pressure drop across the pipe is given by:

$$\Delta P = \frac{5 \cdot l \cdot V^{1.75}}{d^{1.25}}, \frac{N}{m^2}$$

where length l and hole diameter d expressed in m, V is a water velocity in m/sec. The heat transfer coefficient h for turbulent flow through cylindrical tubes for single-phase flow of water:

$$h = \frac{2 \cdot 10^3 \cdot (1 + 1.5 \cdot 10^{-2} \cdot T_m) \cdot V^{0.87}}{d^{0.13}}, \frac{W}{m^2 K}$$

$$T_m = 0.9 \cdot T_b + 0.1 \cdot T_w ,$$

where T_b and T_w are water and conductor temperatures.

The water temperature rise through the passage is given by:

$$\Delta T = 4 \frac{W}{\pi V d^2 C \rho}$$

where W is a power in W; $\frac{\pi d^2}{4}V$ is a mass flow, m^3/ sec; $C\rho$ - heat capacity, J/m^3K

One turn was divided into five regions.The results of calculations are listed in Table 1 for aluminum and Table 2 for copper. Where, l_1 - l_5 is the length of conductor, cm; S_1 - S_5 cross section of conductor, cm^2; R_1 - R_5 resistivity of the conductor, 10^{-6} Om; H_1 - H_2 the current heat dissipation, $h = R_0 J^2 S / \pi d$, W/cm^2; W_1 - W_2 the power dissipation, W; dT_1 - dT_2 the temperature rise of the cooling water with a speed of 3 m / sec, dp = 0.33 kg/cm^2; DT_1 - DT_5 the temperature rise of the cooling water with a speed of 10 m / sec.

TABLE 1. Al, R_0=2.8 10^{-6} Om cm

#	l, cm	S, cm^2	R, Om^{-6}	H,W/cm^2	W, W	dT, C	DT, C
1	41	9.5	12.1	3.8	543	0.46	0.14
2	42	6	19.6	6.1	880	0.74	0.22
3	17	2.5	19.0	14.6	853	0.72	0.21
4	34	6	15.9	6.1	714	0.6	0.18
5	206	9.5	60.7	3.8	2725	2.29	0.7

The resistivity of one turn is R = 127.3 10^{-6} Om, the magnet applied voltage U = 26.6 V, power W = 171 kW, at water pressure drop 0.33 atm. with total water flow 8.5 1 / sec.

TABLE 2. Cu, R_0=1.7 10^{-6} Om cm

#	l, cm	S, cm^2	R, Om^{-6}	H,W/cm^2	W, W	dT, C	DT, C
1	41	9.5	7.3	2.3	328	0.3	0.1
2	42	6	11.9	3.7	534	0.45	0.13
3	17	2.5	11.6	8.8	521	0.44	0.13
4	34	6	9.6	3.7	432	0.36	0.11
5	206	9.5	36.9	2.3	1656	1.4	0.42

The resistivity of one turn is 77.3 10^{-6} Om, voltage applied the magnet U = 15.5 V, power W = 104 kW.

The heat transfer coefficient h = 5.2 W / cm^2K for a water speed 3 m/sec, h = 14.6 W/cm^2K for a water speed 10 m/sec that means that at v = 3 m/sec l_3 piece temperature will be on 3 ^{0}C higher than others.

3.0 Conclusion

For short length aluminum conductor with 55 x 19 mm^2 and hole diameter of 11 mm the water cooling conditions are enough to operate under current 6700 A.

4.0 Stabilization of the temperature

The problem is that a temperature of input water is 32 ^{0}C that is at least 10 ^{0}C higher than required for the environment of the CLAS detector. One possibility to solve this problem is to cover the insulated Mini Torus coils with aluminum screen cooled by water. This screen could stabilize the environment temperature.

For estimations two modes of heat transportation will be used:

1. Heat conduction

$$Q = kS\frac{dT}{dl}$$, where

k - is a thermal conductivity;

S - is an area normal to the heat flow path;

dT / dl - is the thermal gradient of the flow path.

If the aluminum screen area S = 0.6 m^2 for one section, the distance l between screen and coil is 10^{-3} m, dT = 10 K, thermal conductivity of the air is k = 3. 10^{-3} W/m K then : Q = 180 W

A heat is dissipated through a support plastic pins between aluminum screen and the coil, if area of pin is S = 10^{-6} m^2, length is l = 10^{-3} m and a thermal conductivity is k = 0.1 W/m K then Q = 10^{-3} W , that means that for a pin cell 5 x 5 cm: Q = 0.24 W.

The heat transportation through a support screen structure is small.

2. Radiation

The energy from a black body with 100% emissivity (e=1) of area S, at temperature T is proportional to the fourth power of T:

$$Q = e\ k\ S\ T^4, \text{ where } k = 5.67\ 10^{-8}\ W / mm^2K^4$$

In the worse case when the emissivity of two bodies equal e_1=e_2=l, a heat transport between two plane parallel surfaces S = 0.6 m^2 at temperatures T_1 and T_2 is:

$$Q = 5.8\ 10^{-8}\ (310^4 - 300^4)\ 0.6 = 36\ W$$

In reality e_1<0.1 for Al, so the total power transported from the coil to a screen is about 200 W.

If the screen is cooled by the water with a temperature T_1 from one side at the opposite side the temperature will be equal to T_2:

$$T_2 - T_1 = Q\frac{l}{kS} = 8^oC$$

where $Q = 108$ W, $l = 0.05$ m, $S = 3.\ 10^{-3}\ m^2$, $k\ (Al) = 230$ W/m K. If the water cooling screen temperature is 18 ^{0}C less than the coil temperature, then the average screen temperature will be 14 ^{0}C less than the coil temperature. For two side cooling $T_2 - T_1 = 2^0C$.

5.0 Magnetic forces

For Mini Torus designing three modes of magnetic forces are important:

- magnetic forces acting on each section in radial direction;

- nonsymmetric location of each section around the beam axis and in X direction ;

- the Mini Torus interaction with Superconducting Torus.

Radial magnetic forces can be estimated by hand and computer code (attachment 2). This force is about 350 kg.

Nonsymmetric location (attachment 3) create the force 11 kg/cm.

Interaction forces between magnets is negligible (attachment 3).

We would like to thank B. Mecking for the help in magnetic forces estimations, V.Burkert for background estimation, J.O'Meara,W.Tuzel,C.Hutton, A.Guerra for discussion of design and Andrey Kossov for arrangement of text.

6.0 References

1. H. Brechna, Electromagnets for High Energy Physics applications, Proceedings International Symposium on Magnet Technology, SLAC, Sept. 8-10, 1965.

2. H. Brechna, Materials in Electromagnets and their Properties, Proceedings International Symposium on Magnet Technology, Rutherford Lab., 1967.

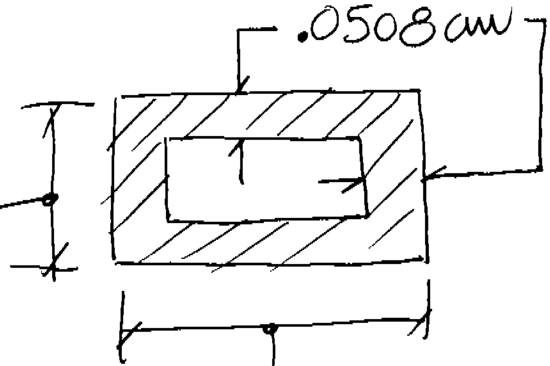
3. C.A. Rama, Some aspects of magnet technology in high energy experimental physics, Proc. Inter. Symp. on Magnet Technology, Slac, Sept. 8-10, 1965.

4. H. Desportes, Recent progress in design and construction of beam and detector magnets, Proc. Inter. Conference on Magnet Technology, MT-9, 1985.

5. L. Pollack, Selection of water-cooled conductors for dc magnets, Proc. Inter. Symp. on Magnet Technology, SLAC, Sept. 8-10, 1965.

6. H. Brechna, Superconducting Magnet System, New York, 1973.

Attachment 1



Calculation Look-up Data Sheet
Thin Septa Magnet Coil Design
Prototype Design Calculations

1 Meter Septum Coil Only		Each Turn		Total
a	**Temperature Coeff. of Rho.E**	**0.0036**	**OHM/C**	
Ac	Area of Conductor	0.02348	cm^2	0.23
Aw	**Area of Water Tubing**	**0.00373**	**cm^2**	
Ax	Heat Transfer Area	36.27	cm^2	
Dh	**Dia of Conductor (width)**	**0.18796**	**cm**	
Dv	**Dia of Conductor (height)**	**0.14478**	**cm**	
f	Friction Factor	0.03435	***	
g	**Gravitational Constant**	**980**	**cm/s^2**	
h	Heat Transfer Coefficient	2.64	W/cm^2C	
HD	**Hydraulic Diameter**	**0.05757**	**cm**	
I	**Current**	**61.4**	**amps**	
J	Current Density	2,615	a/cm^2	
k	Thermal Conductivity of Water	0.00631	W/cm C	
L	**Length of Tube**	**140**	**cm**	
m	Mass Flow	1.16	g/s	12
Mu	Dynamic Viscosity of Water	0.00620	g/cm s	
N	**Coil Turns**	**10**	***	
NI	Amp Turns	614	NI	
Nu	Nusselt Number	24.08	***	
PD	Pressure Drop	58.69	lb/in^2	58.69 (95psi)
Qf	Volumetric Water Flow	0.0184		0.18
Qj	Joule Heat	41.74	WATTS	417.40
Qm	Sensible Heat	41.68	WATTS	
Qx	Exchanged Heat	41.74	WATTS	
Rc	Resistance of Conductor	1.11E-02	OHM	
Re	Reynolds Number	2,889	***	
Rho	Density of Water	0.99686	g/cm^3	
Rho.E	**Resistivity**	**1.7E-06**	**OHM*cm**	
Tb	Bulk Temperature of Water	37.41	C	
Ti	**Water Inlet Temperature**	**33.10**	**C**	
To	Water Exit Temperature	41.72	C	
Tw	Wall Temperature	42.16	C	
V	**Water Velocity**	**312**	**cm/s**	
VD	Voltage Drop	0.67981	Volts	6.80
WP	**Wetted Perimeter**	**0.25908**	**cm**	

Highlighted parameters are given. Balance of data is a product of 20 iterations

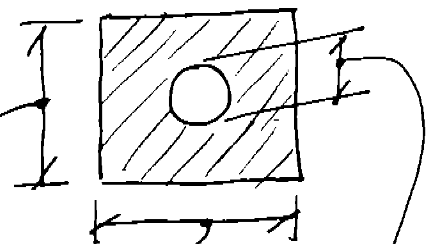
Heat Exchanger Routine

Iteration	Tw	Tb in	Rc	Qj	Rho	Cp	m	Tb out	Mu	Re	Pr	Nu	k	h	(Tw-Tb)	f	PD
	41.720	37.410	1.11E-02	41.7	0.9969	4.1740	1.1583	41.709	0.00624	2,868	4.2834	24.0159	0.0063	2.63	0.4367	0.03436	58.7
1	42.146	42.582	1.11E-02	41.7	0.9952	4.1740	1.1591	41.727	0.00620	2,883	4.2531	24.0510	0.0063	2.64	0.4363	0.03435	58.6
2	42.163	37.632	1.11E-02	41.7	0.9969	4.1740	1.1595	41.725	0.00620	2,889	4.2519	24.0857	0.0063	2.64	0.4357	0.03435	58.6
3	42.160	37.630	1.11E-02	41.7	0.9969	4.1740	1.1597	41.723	0.00620	2,889	4.2521	24.0852	0.0063	2.64	0.4357	0.03435	58.6
4	42.159	37.629	1.11E-02	41.7	0.9969	4.1740	1.1598	41.722	0.00620	2,889	4.2522	24.0850	0.0063	2.64	0.4357	0.03435	58.6
5	42.158	37.629	1.11E-02	41.7	0.9969	4.1740	1.1598	41.722	0.00620	2,889	4.2522	24.0849	0.0063	2.64	0.4357	0.03435	58.6
6	42.158	37.629	1.11E-02	41.7	0.9969	4.1740	1.1598	41.722	0.00620	2,889	4.2523	24.0848	0.0063	2.64	0.4357	0.03435	58.6
7	42.158	37.629	1.11E-02	41.7	0.9969	4.1740	1.1599	41.722	0.00620	2,889	4.2523	24.0848	0.0063	2.64	0.4357	0.03435	58.6
8	42.157	37.629	1.11E-02	41.7	0.9969	4.1740	1.1599	41.722	0.00620	2,889	4.2523	24.0848	0.0063	2.64	0.4357	0.03435	58.6
9	42.157	37.629	1.11E-02	41.7	0.9969	4.1740	1.1599	41.722	0.00620	2,889	4.2523	24.0847	0.0063	2.64	0.4357	0.03435	58.6
10	42.157	37.629	1.11E-02	41.7	0.9969	4.1740	1.1599	41.722	0.00620	2,889	4.2523	24.0847	0.0063	2.64	0.4357	0.03435	58.6

Case: **1 Meter Septum Coil Only**

Mass Transfer Routine

Iteration	Trial T	Tb	Rc	Qj	Rho	Cp	m	Tb
	50	41.550	1.14E-02	42.8	0.9956	4.1740	1.1583	41.959
1	45.980	39.540	1.12E-02	42.3	0.9963	4.1740	1.1591	41.837
2	43.908	38.504	1.11E-02	42.0	0.9966	4.1740	1.1595	41.775
3	42.842	37.971	1.11E-02	41.8	0.9968	4.1740	1.1597	41.743
4	42.292	37.696	1.11E-02	41.8	0.9968	4.1740	1.1598	41.726
5	42.009	37.555	1.11E-02	41.7	0.9969	4.1740	1.1598	41.718
6	41.864	37.482	1.11E-02	41.7	0.9969	4.1740	1.1598	41.713
7	41.788	37.444	1.11E-02	41.7	0.9969	4.1740	1.1599	41.711
8	41.750	37.425	1.11E-02	41.7	0.9969	4.1740	1.1599	41.710
9	41.730	37.415	1.11E-02	41.7	0.9969	4.1740	1.1599	41.709
10	41.720	37.410	1.11E-02	41.7	0.9969	4.1740	1.1599	41.709



Calculation Look-up Data Sheet
Thick Septa Magnet Coil Design

2 Meter, Back Coil Only		Each Turn	Total
[illegible]	**Temperature Coeff. of Rho,E**	**0.0036 OHM/C**	
Ac	Area of Conductor	1.16877 cm^2	28.05
Aw	Area of Water Tubing	0.02413 cm^2	
Ax	Heat Transfer Area	140.46 cm^2	
[illegible]	**Dia of Conductor (width)**	**1.09220 cm**	
[illegible]	**Dia of Conductor (height)**	**1.09220 cm**	
f	Friction Factor	0.03149 ***	
[illegible]	**Gravitational Constant**	**980 cm/s^2**	
h	Heat Transfer Coefficient	2.02 W/cm^2C	
HD	**Hydraulic Diameter**	**0.17526 cm**	
[illegible]	**Current**	**612 amps**	
J	Current Density	524 a/cm^2	
k	Thermal Conductivity of Water	0.00630 W/cm C	
[illegible]	**Length of Tube**	**255 cm**	
m	Mass Flow	7.22 g/s	173
Mu	Dynamic Viscosity of Water	0.00637 g/cm s	
[illegible]	**Coil Turns**	**24** ***	
NI	Amp Turns	14,688 NI	
Nu	Nusselt Number	56.25 ***	
PD	Pressure Drop	29.77 lb/in^2	29.77
Qf	Volumetric Water Flow	0.115	2.75
Qj	Joule Heat	150.95 WATTS	3,622.76
Qm	Sensible Heat	150.70 WATTS	
Qx	Exchanged Heat	150.95 WATTS	
Rc	Resistance of Conductor	4.03E-04 OHM	
Re	Reynolds Number	8,228 ***	
Rho	Density of Water	0.99681 g/cm^3	
[illegible]	**Resistivity**	**1.7E-06 OHM*cm**	
Tb	Bulk Temperature of Water	37.51 C	
[illegible]	**Water Inlet Temperature**	**35.00 C**	
To	Water Exit Temperature	40.01 C	
Tw	Wall Temperature	40.54 C	
[illegible]	**Water Velocity**	**300 cm/s**	
VD	Voltage Drop	0.24665 Volts	5.92
WP	Wetted Perimeter	0.55082 cm	

Highlighted parameters are given. Balance of data is a product of 20 iterations

Case: 2 Meter Back Coil Only

Mass Transfer Routine

Iteration	Trial T	Tt	Ro	Dj	Rho	Cp	m	Tb
	90	62.500	4.70E-04	176.0	0.9855	4.1808	7.1352	40.899
1	65.450	50.225	4.37E-04	163.6	0.9920	4.1740	7.1825	40.455
2	52.952	43.976	4.20E-04	157.2	0.9947	4.1740	7.2017	40.230
3	46.591	40.796	4.11E-04	154.0	0.9958	4.1740	7.2101	40.117
4	43.354	39.177	4.07E-04	152.4	0.9964	4.1740	7.2140	40.060
5	41.707	38.354	4.05E-04	151.5	0.9966	4.1740	7.2159	40.031
6	40.869	37.935	4.03E-04	151.1	0.9968	4.1740	7.2168	40.017
7	40.443	37.721	4.03E-04	150.9	0.9968	4.1740	7.2173	40.009
8	40.226	37.613	4.03E-04	150.8	0.9969	4.1740	7.2175	40.005
9	40.116	37.558	4.02E-04	150.7	0.9969	4.1740	7.2176	40.003
10	40.060	37.530	4.02E-04	150.7	0.9969	4.1740	7.2177	40.002

Heat Exchanger Routine

Iteration	Tw	Tb in	Ro	Dj	Rho	Cp	m	Tb out	Mu	Re	Pr	Nu	k	h	(Tw−Tb)	f	PD
	40.060	37.530	4.02E-04	150.7	0.9969	4.1740	7.1352	40.002	0.00642	8,161	4.4060	56.0695	0.0063	2.01	0.5332	0.03152	29.80
1	40.536	41.069	4.03E-04	150.9	0.9957	4.1740	7.1825	40.035	0.00637	8,218	4.3700	56.2021	0.0063	2.02	0.5323	0.03149	29.74
2	40.567	37.784	4.03E-04	151.0	0.9968	4.1740	7.2017	40.022	0.00637	8,232	4.3677	56.2623	0.0063	2.02	0.5318	0.03149	29.76
3	40.554	37.777	4.03E-04	151.0	0.9968	4.1740	7.2101	40.016	0.00637	8,230	4.3687	56.2572	0.0063	2.02	0.5318	0.03149	29.76
4	40.548	37.774	4.03E-04	151.0	0.9968	4.1740	7.2140	40.013	0.00637	8,229	4.3691	56.2549	0.0063	2.02	0.5318	0.03149	29.76
5	40.545	37.772	4.03E-04	150.9	0.9968	4.1740	7.2159	40.012	0.00637	8,229	4.3693	56.2539	0.0063	2.02	0.5318	0.03149	29.76
6	40.544	37.772	4.03E-04	150.9	0.9968	4.1740	7.2168	40.011	0.00637	8,228	4.3694	56.2534	0.0063	2.02	0.5318	0.03149	29.76
7	40.543	37.771	4.03E-04	150.9	0.9968	4.1740	7.2173	40.011	0.00637	8,228	4.3695	56.2531	0.0063	2.02	0.5318	0.03149	29.77
8	40.543	37.771	4.03E-04	150.9	0.9968	4.1740	7.2175	40.011	0.00637	8,228	4.3695	56.2530	0.0063	2.02	0.5318	0.03149	29.77
9	40.542	37.771	4.03E-04	150.9	0.9968	4.1740	7.2176	40.011	0.00637	8,228	4.3695	56.2529	0.0063	2.02	0.5318	0.03149	29.77
10	40.542	37.771	4.03E-04	150.9	0.9968	4.1740	7.2177	40.010	0.00637	8,228	4.3695	56.2529	0.0063	2.02	0.5318	0.03149	29.77

Calculation Look-up Data Sheet
Thick Septa Magnet Coil Design

1 Meter, Back Coil Only		Each Turn	Total
	Temperature Coeff. of Rho,E	**0.0036 OHM/C**	
Ac	Area of Conductor	1.16877 cm^2	28.05
Aw	Area of Water Tubing	0.02413 cm^2	
Ax	Heat Transfer Area	85.38 cm^2	
Dh	**Dia of Conductor (width)**	**1.09220 cm**	
Dv	**Dia of Conductor (height)**	**1.09220 cm**	
f	Friction Factor	0.03163 ***	
	Gravitational Constant	**980 cm/s^2**	
h	Heat Transfer Coefficient	1.99 W/cm^2C	
HD	**Hydraulic Diameter**	**0.17526 cm**	
I	**Current**	**612 amps**	
J	Current Density	524 a/cm^2	
k	Thermal Conductivity of Water	0.00627 W/cm C	
	Length of Tube	**155 cm**	
m	Mass Flow	7.22 g/s	173
Mu	Dynamic Viscosity of Water	0.00659 g/cm s	
N	**Coil Turns**	**24 *** **	
NI	Amp Turns	14,688 NI	
Nu	Nusselt Number	55.49 ***	
PD	Pressure Drop	18.18 lb/in^2	18.18
Qf	Volumetric Water Flow	0.115	2.75
Qj	Joule Heat	91.14 WATTS	2,187.45
Qm	Sensible Heat	90.99 WATTS	
Qx	Exchanged Heat	91.14 WATTS	
Rc	Resistance of Conductor	2.43E-04 OHM	
Re	Reynolds Number	7,950 ***	
Rho	Density of Water	0.99710 g/cm^3	
	Resistivity	**1.7E-06 OHM*cm**	
Tb	Bulk Temperature of Water	36.51 C	
	Water Inlet Temperature	**35.00 C**	
To	Water Exit Temperature	38.02 C	
Tw	Wall Temperature	38.56 C	
	Water Velocity	**300 cm/s**	
VD	Voltage Drop	0.14893 Volts	3.57
WP	Wetted Perimeter	0.55082 cm	

Highlighted parameters are given. Balance of data is a product of 20 iterations

Case: 1 Meter Back Coil Only

Mass Transfer Routine

Iteration	Trial T	Tb	Re	Qj	Rho	Cp	m	Tb
	90	62.500	2.86E-04	107.0	0.9855	4.1808	7.1352	38.586
1	64.293	49.646	2.64E-04	99.1	0.9923	4.1740	7.1844	38.303
2	51.298	43.149	2.54E-04	95.1	0.9950	4.1740	7.2040	38.161
3	44.730	39.865	2.48E-04	93.0	0.9962	4.1740	7.2124	38.091
4	41.410	38.205	2.46E-04	92.0	0.9967	4.1740	7.2162	38.055
5	39.733	37.366	2.44E-04	91.5	0.9969	4.1740	7.2180	38.037
6	38.885	36.942	2.44E-04	91.2	0.9971	4.1740	7.2189	38.028
7	38.457	36.728	2.43E-04	91.1	0.9971	4.1740	7.2194	38.024
8	38.240	36.620	2.43E-04	91.0	0.9971	4.1740	7.2196	38.021
9	38.131	36.565	2.43E-04	91.0	0.9972	4.1740	7.2197	38.020
10	38.075	36.538	2.43E-04	91.0	0.9972	4.1740	7.2197	38.020
	^	^						^

Heat Exchanger Routine

Iteration	Tw	Tb in	Re	Qj	Rho	Cp	m	Tb out	Mu	Re	Pr	Nu	k	h	(Tw-Tb)	f	PD
	38.075	36.538	2.43E-04	91.0	0.9972	4.1740	7.1352	38.020	0.00665	7,882	4.5632	55.3012	0.0063	1.98	0.5389	0.03167	18.20
1	38.558	39.097	2.43E-04	91.1	0.9964	4.1740	7.1844	38.039	0.00659	7,944	4.5238	55.4593	0.0063	1.99	0.5377	0.03163	18.17
2	38.577	36.789	2.43E-04	91.1	0.9971	4.1740	7.2040	38.031	0.00659	7,953	4.5223	55.4977	0.0063	1.99	0.5374	0.03163	18.18
3	38.569	36.784	2.43E-04	91.1	0.9971	4.1740	7.2124	38.028	0.00659	7,951	4.5230	55.4945	0.0063	1.99	0.5374	0.03163	18.18
4	38.565	36.783	2.43E-04	91.1	0.9971	4.1740	7.2162	38.026	0.00659	7,951	4.5233	55.4931	0.0063	1.99	0.5374	0.03163	18.18
5	38.563	36.782	2.43E-04	91.1	0.9971	4.1740	7.2180	38.025	0.00659	7,951	4.5234	55.4924	0.0063	1.99	0.5374	0.03163	18.18
6	38.563	36.781	2.43E-04	91.1	0.9971	4.1740	7.2189	38.025	0.00659	7,950	4.5235	55.4921	0.0063	1.99	0.5374	0.03163	18.18
7	38.562	36.781	2.43E-04	91.1	0.9971	4.1740	7.2194	38.025	0.00659	7,950	4.5235	55.4920	0.0063	1.99	0.5374	0.03163	18.18
8	38.562	36.781	2.43E-04	91.1	0.9971	4.1740	7.2196	38.025	0.00659	7,950	4.5235	55.4919	0.0063	1.99	0.5374	0.03163	18.18
9	38.562	36.781	2.43E-04	91.1	0.9971	4.1740	7.2197	38.025	0.00659	7,950	4.5235	55.4919	0.0063	1.99	0.5374	0.03163	18.18
10	38.562	36.781	2.43E-04	91.1	0.9971	4.1740	7.2197	38.024	0.00659	7,950	4.5235	55.4918	0.0063	1.99	0.5374	0.03163	18.18

Calculation Look-up Data Sheet
Thick Septa Magnet Coil Design

1 Meter, Front Coil Only		Each Turn	Total
[illegible]	**Temperature Coeff. of Rho,E**	**0.0036 OHM/C**	
Ac	Area of Conductor	0.22516 cm^2	5.40
Aw	Area of Water Tubing	0.02413 cm^2	
Ax	Heat Transfer Area	71.61 cm^2	
D?	**Dia of Conductor (width)**	**0.60960 cm**	
D?	**Dia of Conductor (height)**	**0.40894 cm**	
f	Friction Factor	0.03074 ***	
[illegible]	**Gravitational Constant**	**980 cm/s^2**	
h	Heat Transfer Coefficient	2.20 W/cm^2C	
HD	**Hydraulic Diameter**	**0.17526 cm**	
I	**Current**	**612 amps**	
J	Current Density	2,718 a/cm^2	
k	Thermal Conductivity of Water	0.00641 W/cm C	
[illegible]	**Length of Tube**	**130 cm**	
m	Mass Flow	7.21 g/s	173
Mu	Dynamic Viscosity of Water	0.00538 g/cm s	
N	**Coil Turns**	**24 *** **	
NI	Amp Turns	14,688 NI	
Nu	Nusselt Number	60.08 ***	
PD	Pressure Drop	14.78 lb/in^2	14.78
Qf	Volumetric Water Flow	0.115	2.76
Qj	Joule Heat	413.99 WATTS	9,935.76
Qm	Sensible Heat	410.39 WATTS	
Qx	Exchanged Heat	413.99 WATTS	
Rc	Resistance of Conductor	1.11E-03 OHM	
Re	Reynolds Number	9,716 ***	
Rho	Density of Water	0.99498 g/cm^3	
[illegible]	**Resistivity**	**1.7E-06 OHM*cm**	
Tb	Bulk Temperature of Water	41.88 C	
[illegible]	**Water Inlet Temperature**	**35.00 C**	
To	Water Exit Temperature	48.76 C	
Tw	Wall Temperature	51.39 C	
[illegible]	**Water Velocity**	**300 cm/s**	
VD	Voltage Drop	0.67645 Volts	16.23
WP	Wetted Perimeter	0.55082 cm	

Highlighted parameters are given. Balance of data is a product of 20 iterations

Case: 1 Meter Front Coil Only

Mass Transfer Routine

Iteration	Trial T	Tb	Rc	Qj	Rho	Cp	m	Tb
	90	62.500	1.24E-03	465.7	0.9855	4.1808	7.1352	50.611
1	70.306	52.653	1.17E-03	439.3	0.9909	4.1740	7.1741	49.671
2	59.988	47.494	1.14E-03	425.5	0.9932	4.1740	7.1913	49.176
3	54.582	44.791	1.12E-03	418.3	0.9944	4.1740	7.1994	48.919
4	51.750	43.375	1.11E-03	414.5	0.9949	4.1740	7.2034	48.785
5	50.268	42.634	1.10E-03	412.5	0.9952	4.1740	7.2054	48.715
6	49.491	42.246	1.10E-03	411.4	0.9953	4.1740	7.2064	48.679
7	49.085	42.042	1.10E-03	410.9	0.9954	4.1740	7.2069	48.660
8	48.872	41.936	1.10E-03	410.6	0.9954	4.1740	7.2072	48.650
9	48.761	41.880	1.10E-03	410.5	0.9955	4.1740	7.2074	48.644
10	48.703	41.851	1.10E-03	410.4	0.9955	4.1740	7.2074	48.642
	^	^						^

Heat Exchanger Routine

Iteration	Tw	Tb in	Rc	Qj	Rho	Cp	m	Tb out	Mu	Re	Pr	Nu	k	h	(Tw−Tb)	f	PD
	48.703	41.851	1.10E-03	410.4	0.9955	4.1740	7.1352	48.642	0.00560	9,351	3.8396	59.1750	0.0064	2.16	2.6587	0.03092	14.88
1	51.300	53.959	1.10E-03	413.9	0.9902	4.1740	7.1741	48.821	0.00539	9,657	3.6984	59.8146	0.0064	2.19	2.6410	0.03077	14.73
2	51.462	43.231	1.11E-03	414.1	0.9950	4.1740	7.1913	48.795	0.00538	9,726	3.6899	60.0990	0.0064	2.20	2.6291	0.03073	14.78
3	51.424	43.212	1.11E-03	414.0	0.9950	4.1740	7.1994	48.778	0.00538	9,720	3.6919	60.0865	0.0064	2.20	2.6295	0.03073	14.78
4	51.408	43.204	1.11E-03	414.0	0.9950	4.1740	7.2034	48.770	0.00538	9,718	3.6928	60.0810	0.0064	2.20	2.6297	0.03073	14.78
5	51.399	43.200	1.11E-03	414.0	0.9950	4.1740	7.2054	48.766	0.00538	9,717	3.6932	60.0783	0.0064	2.20	2.6298	0.03074	14.78
6	51.395	43.198	1.11E-03	414.0	0.9950	4.1740	7.2064	48.763	0.00538	9,717	3.6934	60.0769	0.0064	2.20	2.6298	0.03074	14.78
7	51.393	43.197	1.11E-03	414.0	0.9950	4.1740	7.2069	48.762	0.00538	9,716	3.6935	60.0762	0.0064	2.20	2.6298	0.03074	14.78
8	51.392	43.196	1.11E-03	414.0	0.9950	4.1740	7.2072	48.762	0.00538	9,716	3.6936	60.0759	0.0064	2.20	2.6299	0.03074	14.78
9	51.392	43.196	1.11E-03	414.0	0.9950	4.1740	7.2074	48.761	0.00538	9,716	3.6936	60.0757	0.0064	2.20	2.6299	0.03074	14.78
10	51.391	43.196	1.11E-03	414.0	0.9950	4.1740	7.2074	48.761	0.00538	9,716	3.6936	60.0756	0.0064	2.20	2.6299	0.03074	14.78

Calculation Look-up Data Sheet
Thick Septa Magnet Coil Design

2 Meter, Front Coil Only		Each Turn	Total
a	**Temperature Coeff. of Rho,E**	**0.0036 OHM/C**	
Ac	Area of Conductor	0.22516 cm^2	5.40
Aw	Area of Water Tubing	0.02413 cm^2	
Ax	Heat Transfer Area	126.69 cm^2	
Dx	**Dia of Conductor (width)**	**0.60960 cm**	
Dy	**Dia of Conductor (height)**	**0.40894 cm**	
f	Friction Factor	0.02998 ***	
g	**Gravitational Constant**	**980 cm/s^2**	
h	Heat Transfer Coefficient	2.37 W/cm^2C	
HD	**Hydraulic Diameter**	**0.17526 cm**	
I	**Current**	**612 amps**	
J	Current Density	2,718 a/cm^2	
k	Thermal Conductivity of Water	0.00654 W/cm C	
L	**Length of Tube**	**230 cm**	
m	Mass Flow	7.19 g/s	173
Mu	Dynamic Viscosity of Water	0.00464 g/cm s	
N	**Coil Turns**	**24 *****	
NI	Amp Turns	14,688 NI	
Nu	Nusselt Number	63.65 ***	
PD	Pressure Drop	25.45 lb/in^2	25.45
Qf	Volumetric Water Flow	0.115	2.76
Qj	Joule Heat	759.55 WATTS	18,229.13
Qm	Sensible Heat	753.20 WATTS	
Qx	Exchanged Heat	759.55 WATTS	
Rc	Resistance of Conductor	2.03E-03 OHM	
Re	Reynolds Number	11,254 ***	
Rho	Density of Water	0.99262 g/cm^3	
Rho,E	**Resistivity**	**1.7E-06 OHM*cm**	
Tb	Bulk Temperature of Water	47.65 C	
Ti	**Water Inlet Temperature**	**35.00 C**	
To	Water Exit Temperature	60.31 C	
Tw	Wall Temperature	62.83 C	
V	**Water Velocity**	**300 cm/s**	
VD	Voltage Drop	1.24109 Volts	29.79
WP	Wetted Perimeter	0.55082 cm	

Highlighted parameters are given. Balance of data is a product of 20 iterations

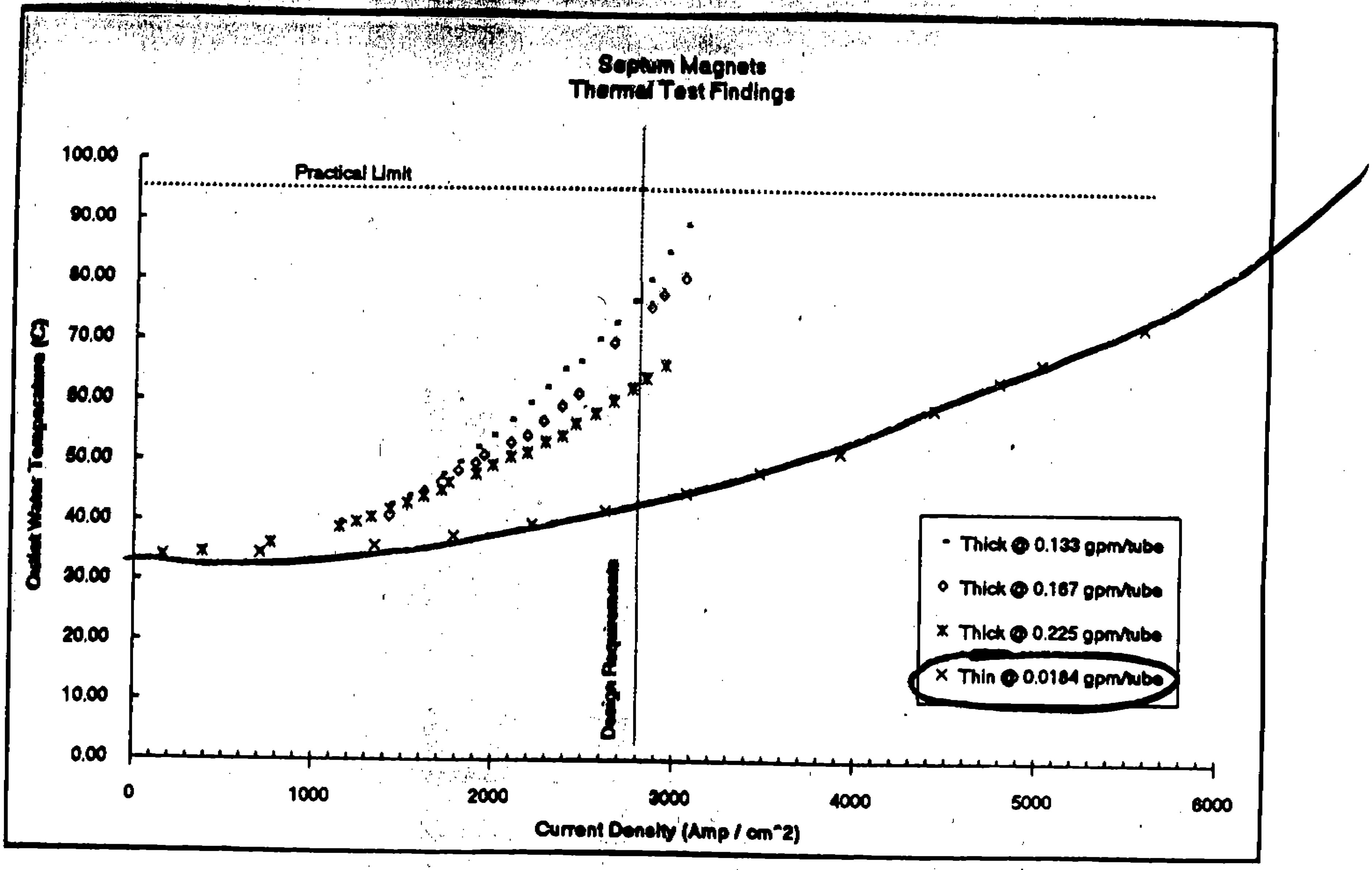
Case: 2 Meter Front Coil Only

Mass Transfer Routine

Iteration	Trial T	Tb	Rc	Qj	Rho	Cp	m	Tt
	90	62.500	2.20E-03	823.9	0.9855	4.1808	7.1352	62.620
1	76.310	55.655	2.11E-03	791.5	0.9893	4.1754	7.1630	61.463
2	68.887	51.943	2.07E-03	773.9	0.9912	4.1740	7.1766	60.835
3	64.861	49.930	2.04E-03	764.4	0.9922	4.1740	7.1835	60.492
4	62.677	48.838	2.03E-03	759.2	0.9927	4.1740	7.1871	60.307
5	61.492	48.246	2.02E-03	756.4	0.9929	4.1740	7.1890	60.207
6	60.849	47.925	2.02E-03	754.9	0.9931	4.1740	7.1900	60.153
7	60.501	47.750	2.01E-03	754.0	0.9931	4.1740	7.1905	60.123
8	60.312	47.656	2.01E-03	753.6	0.9932	4.1740	7.1908	60.107
9	60.210	47.605	2.01E-03	753.3	0.9932	4.1740	7.1910	60.099
10	60.154	47.577	2.01E-03	753.2	0.9932	4.1740	7.1911	60.094
	^	^						^

Heat Exchanger Routine

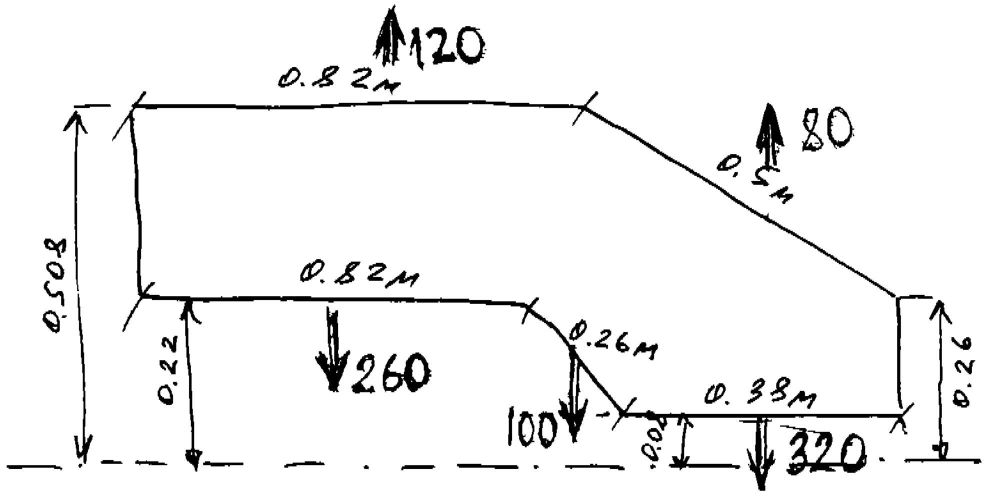
Iteration	Tw	Tb in	Rc	Qj	Rho	Cp	m	Tb out	Mu	Re	Pr	Nu	k	h	(Tw−Tb)	f	PD
	60.154	47.577	2.01E-03	753.2	0.9932	4.1740	7.1352	60.094	0.00479	10,895	3.2881	62.8471	0.0065	2.33	2.5480	0.03015	25.61
1	62.642	65.190	2.03E-03	759.1	0.9839	4.1828	7.1630	60.335	0.00465	11,129	3.1887	63.1440	0.0065	2.35	2.5456	0.03004	25.28
2	62.881	48.941	2.03E-03	759.7	0.9926	4.1740	7.1766	60.360	0.00463	11,260	3.1794	63.6667	0.0065	2.37	2.5256	0.02997	25.45
3	62.886	48.943	2.03E-03	759.7	0.9926	4.1740	7.1835	60.336	0.00463	11,261	3.1792	63.6681	0.0065	2.37	2.5256	0.02997	25.45
4	62.862	48.931	2.03E-03	759.6	0.9926	4.1740	7.1871	60.322	0.00464	11,258	3.1801	63.6610	0.0065	2.37	2.5258	0.02997	25.45
5	62.847	48.924	2.03E-03	759.6	0.9926	4.1740	7.1890	60.314	0.00464	11,256	3.1807	63.6567	0.0065	2.37	2.5259	0.02998	25.45
6	62.840	48.920	2.03E-03	759.6	0.9926	4.1740	7.1900	60.310	0.00464	11,255	3.1810	63.6544	0.0065	2.37	2.5260	0.02998	25.45
7	62.836	48.918	2.03E-03	759.6	0.9926	4.1740	7.1905	60.307	0.00464	11,254	3.1812	63.6532	0.0065	2.37	2.5260	0.02998	25.45
8	62.833	48.917	2.03E-03	759.6	0.9926	4.1740	7.1908	60.306	0.00464	11,254	3.1812	63.6525	0.0065	2.37	2.5260	0.02998	25.45
9	62.832	48.916	2.03E-03	759.5	0.9926	4.1740	7.1910	60.306	0.00464	11,254	3.1813	63.6522	0.0065	2.37	2.5260	0.02998	25.45
10	62.832	48.916	2.03E-03	759.5	0.9926	4.1740	7.1911	60.305	0.00464	11,254	3.1813	63.6520	0.0065	2.37	2.5260	0.02998	25.45



Septum Magnets
Thermal Test Findings
Practical Limit
Outlet Water Temperature (C)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Design Requirements
0
1000
2000
3000
4000
5000
6000
Current Density (Amp / cm^2)
Thick @ 0.133 gpm/tube
Thick @ 0.167 gpm/tube
Thick @ 0.225 gpm/tube
Thin @ 0.0184 gpm/tube

Attachment 2

$$B = \mu_0 \frac{NI}{2\pi r} = \frac{4\pi \cdot 10^{-7} \cdot 2 \cdot 10^{5}}{2\pi \; r} = \frac{4 \cdot 10^{-2}}{r}$$



$$B_1 = \frac{4 \cdot 10^{-2}}{0.22} = 0.18\,T \qquad F = \frac{1}{2} \; B \cdot I \; dl$$

$$B_3 = \frac{4 \cdot 10^{-2}}{0.08} = 0.5\,T \qquad I = 5 \cdot 6700 = 3.35 \cdot 10^{4}\ At$$

$$B_4 = \frac{4 \cdot 10^{-2}}{0.26} = 0.154\,T$$

$$B_5 = \frac{4 \cdot 10^{-2}}{0.508} = 0.08\,T$$

$$F_{\downarrow} = \frac{1}{2} \cdot 3.35 \cdot 10^{4} \left(0{,}82 \cdot 0{,}18 + \frac{0.34 \cdot 0.26}{1.4} + 0.38 \cdot 0.5 \right) =$$

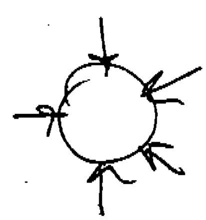
$$= 0.26 \cdot 10^{4} + 0.1 \cdot 10^{4} + 0.32 \cdot 10^{4} = 260\,kg + 100\,kg + 320\,kg = 680\,kg$$

$$F_{\uparrow} = 1.7 \cdot 10^{4} \left(0.8 \cdot 0.5 \cdot 0.12 + 0.82 \cdot 0.08 \right) = 0.08 \cdot 10^{4} + 0.12 \cdot 10^{4} =$$

$$= 80\,kg + 120\,kg = 200\,kg$$

$$F_{\uparrow} - F_{\downarrow} = 480\,kg$$

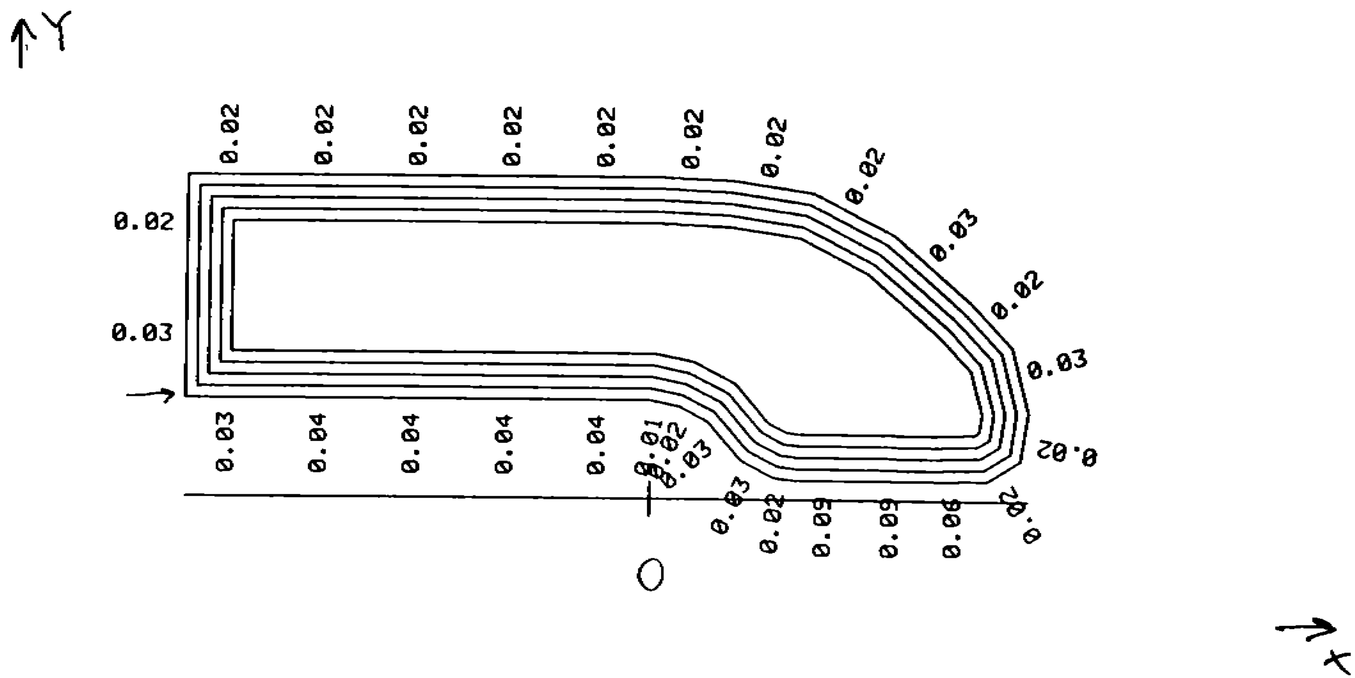
F_r forces acting on a single section



21-SEP-93 In-plane forces (abs.)

Total Force	0.3	-0.0	-0.0	tons
Inward Force	0.6	-0.0	0.0	tons
Outward Force	-0.2	-0.0	-0.0	tons

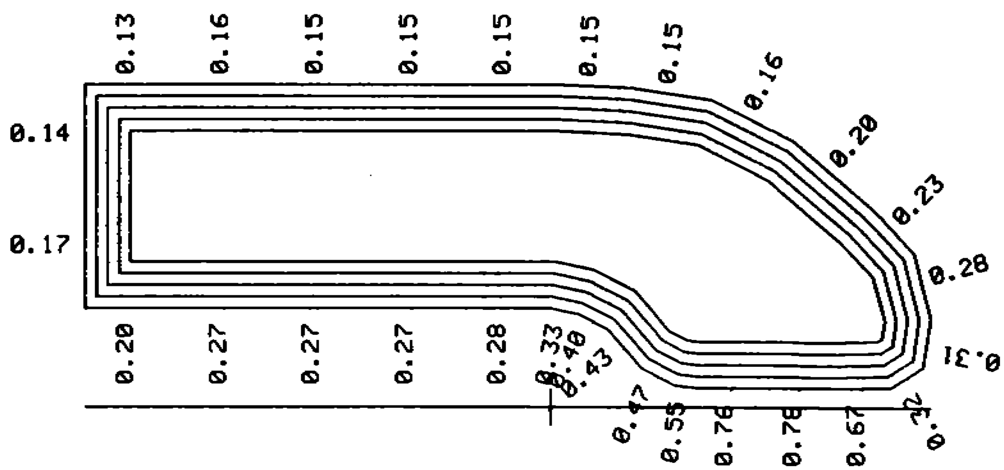
F_r, T



21-SEP-93 In-plane forces (norm.)

Total Force	0.3	-0.0	-0.0	tons
Inward Force	0.6	-0.0	0.0	tons
Outward Force	-0.2	-0.0	-0.0	tons

F_r, T/M



1	11	0.0330	0.4400	0.0833	0.0068	0.0000
1	12	0.0340	0.5500	0.0797	0.0054	-0.0001
1	13	0.0525	0.6285	0.0401	0.0016	-0.0010
1	14	0.1125	0.6635	-0.0124	-0.0001	0.0007
1	15	0.2105	0.6550	-0.0506	0.0010	0.0038
1	16	0.3030	0.6050	-0.0672	0.0032	0.0034
1	17	0.4000	0.4990	-0.0850	0.0082	0.0069
1	18	0.4950	0.3670	-0.0900	0.0087	0.0043
1	19	0.5400	0.2145	-0.0933	0.0091	0.0013
1	20	0.5530	0.0765	-0.0969	0.0088	0.0004
1	21	0.5560	-0.0730	-0.0987	0.0111	0.0000
1	22	0.5560	-0.2390	-0.0992	0.0112	0.0000
1	23	0.5560	-0.4050	-0.0990	0.0112	0.0000
1	24	0.5560	-0.5710	-0.0969	0.0109	0.0000
1	25	0.5560	-0.7370	-0.0738	0.0083	0.0000
1	26	0.4595	-0.8200	-0.0755	0.0000	-0.0099
1	27	0.2665	-0.8200	-0.0651	0.0000	-0.0085
1	28	0.1700	-0.7360	-0.0485	-0.0054	0.0000

OUTPUT OF MAIN S H O F O R C E

#	X3	X1	FORCE3	FORCE1	SUM	THETA
	X, M	Y, M	Fx	FY	$\sqrt{F_x^2+F_y^2}$	angle
1	-0.5740	0.1700	0.0000	0.0452	0.0452	90.0000
			0.0000	0.2757	0.2757	
2	-0.4100	0.1700	0.0000	0.0448	0.0448	90.0000
			0.0000	0.2729	0.2729	
3	-0.2460	0.1700	0.0000	0.0447	0.0447	90.0000
			0.0000	0.2728	0.2728	
4	-0.0820	0.1700	0.0000	0.0463	0.0463	90.0000
			0.0000	0.2825	0.2825	
5	0.0250	0.1650	0.0033	0.0167	0.0171	78.6901
			0.0658	0.3282	0.3347	
6	0.0750	0.1475	0.0101	0.0202	0.0225	63.4349
			0.1802	0.3605	0.4030	
7	0.1300	0.1015	0.0293	0.0263	0.0394	41.8452
			0.3262	0.2921	0.4379	
8	0.1900	0.0530	0.0143	0.0286	0.0320	63.4349
			0.2131	0.4262	0.4765	
9	0.2400	0.0355	0.0028	0.0224	0.0226	82.8750
			0.0694	0.5551	0.5594	
10	0.3200	0.0330	0.0000	0.0915	0.0915	90.0000
			0.0000	0.7628	0.7628	
11	0.4400	0.0330	0.0000	0.0936	0.0936	89.9990
			0.0000	0.7804	0.7804	
12	0.5500	0.0340	-0.0013	0.0672	0.0672	91.1478
			-0.0135	0.6722	0.6723	
13	0.6285	0.0525	-0.0114	0.0185	0.0217	121.5514
			-0.1699	0.2767	0.3247	
14	0.6635	0.1125	-0.0269	0.0041	0.0272	171.3045
			-0.3131	0.0479	0.3167	

15	0.6550	0.2105	-0.0318 -0.2770	-0.0086 -0.0749	0.0330 0.2869	195.1240
16	0.6050	0.3030	-0.0175 -0.1718	-0.0166 -0.1625	0.0241 0.2365	223.4089
17	0.4990	0.4000	-0.0242 -0.1301	-0.0286 -0.1540	0.0375 0.2016	229.7998
18	0.3570	0.4950	-0.0113 -0.0716	-0.0230 -0.1452	0.0256 0.1619	243.7587
19	0.2145	0.5400	-0.0031 -0.0214	-0.0221 -0.1527	0.0223 0.1542	262.0382
20	0.0765	0.5530	-0.0009 -0.0070	-0.0208 -0.1560	0.0208 0.1561	267.4170
21	-0.0730	0.5560	0.0000 0.0000	-0.0259 -0.1560	0.0259 0.1560	270.0000
22	-0.2390	0.5560	0.0000 0.0000	-0.0260 -0.1565	0.0260 0.1565	270.0000
23	-0.4050	0.5560	0.0000 0.0000	-0.0261 -0.1573	0.0261 0.1573	270.0000
24	-0.5710	0.5560	0.0000 0.0000	-0.0275 -0.1659	0.0275 0.1659	270.0000
25	-0.7370	0.5560	0.0000 0.0000	-0.0230 -0.1383	0.0230 0.1383	270.0000
26	-0.8200	0.4595	0.0282 0.1461	0.0000 0.0000	0.0282 0.1461	0.0000
27	-0.8200	0.2665	0.0337 0.1749	0.0000 0.0000	0.0337 0.1749	0.0000
28	-0.7380	0.1700	0.0000 0.0000	0.0331 0.2016	0.0331 0.2016	90.0000

y z x

SF	0.3562E+00	-0.3227E-08	-0.6727E-02
SFI	0.6033E+00	-0.2243E-08	0.8217E-01
SFO	-0.2481E+00	-0.9845E-09	-0.8890E-01

MAGNETIC FIELD OF MINI-Torus
INPUT DATA: 21-SEP-1991

I	J	X(1) Y [M]	X(3) X [M]	BTOT(2) Bz	FORCE(1) Fy,T	FORCE(3) Fx,T
5	1	0.2500	-0.5740	0.2228	0.0248	0.0000
5	2	0.2500	-0.4100	0.2214	0.0247	0.0000
5	3	0.2500	-0.2460	0.2213	0.0247	0.0000
5	4	0.2500	-0.0780	0.2206	0.0258	0.0000
5	5	0.2432	0.0421	0.2158	0.0100	0.0020
5	6	0.2180	0.1128	0.2280	0.0113	0.0057
5	7	0.1662	0.1794	0.2736	0.0112	0.0125
5	8	0.1242	0.2265	0.3437	0.0080	0.0040
5	9	0.1143	0.2543	0.3664	0.0053	0.0007
5	10	0.1130	0.3225	0.3515	0.0275	0.0000
5	11	0.1130	0.4396	0.3516	0.0285	0.0000
5	12	0.1138	0.5380	0.3594	0.0189	-0.0004
5	13	0.1167	0.5801	0.4934	0.0023	-0.0014
5	14	0.1346	0.5859	0.3658	0.0012	-0.0079
5	15	0.1880	0.5782	0.2837	-0.0039	-0.0145
5	16	0.2537	0.5415	0.2468	-0.0089	-0.0094
5	17	0.3372	0.4494	0.2151	-0.0192	-0.0162
5	18	0.4226	0.3230	0.2038	-0.0168	-0.0083
5	19	0.4614	0.1989	0.1984	-0.0171	-0.0024
5	20	0.4731	0.0719	0.1942	-0.0168	-0.0008
5	21	0.4760	-0.0739	0.1924	-0.0215	0.0000
5	22	0.4760	-0.2390	0.1920	-0.0217	0.0000
5	23	0.4760	-0.4050	0.1922	-0.0217	0.0000
5	24	0.4760	-0.5710	0.1951	-0.0220	0.0000
5	25	0.4760	-0.6970	0.2237	-0.0131	0.0000
5	26	0.4195	-0.7400	0.2194	0.0000	0.0169
5	27	0.3065	-0.7400	0.2296	0.0000	0.0176
5	28	0.2500	-0.6980	0.2467	0.0141	0.0000
4	1	0.2300	-0.5740	0.1387	0.0155	0.0000
4	2	0.2300	-0.4100	0.1377	0.0153	0.0000
4	3	0.2300	-0.2460	0.1376	0.0153	0.0000
4	4	0.2300	-0.0790	0.1368	0.0158	0.0000
4	5	0.2236	0.0378	0.1302	0.0056	0.0011
4	6	0.2004	0.1034	0.1420	0.0065	0.0033
4	7	0.1500	0.1671	0.1905	0.0078	0.0087
4	8	0.1064	0.2174	0.2666	0.0074	0.0037
4	9	0.0946	0.2507	0.2969	0.0053	0.0007
4	10	0.0930	0.3219	0.2850	0.0225	0.0000
4	11	0.0930	0.4397	0.2849	0.0231	0.0000
4	12	0.0938	0.5410	0.2885	0.0163	-0.0003
4	13	0.1006	0.5922	0.3349	0.0044	-0.0027
4	14	0.1291	0.6053	0.2605	0.0012	-0.0080
4	15	0.1937	0.5974	0.1859	-0.0029	-0.0106
4	16	0.2660	0.5574	0.1542	-0.0060	-0.0063
4	17	0.3529	0.4618	0.1254	-0.0114	-0.0096
4	18	0.4407	0.3315	0.1163	-0.0100	-0.0049
4	19	0.4811	0.2028	0.1114	-0.0099	-0.0014
4	20	0.4931	0.0731	0.1072	-0.0094	-0.0004
4	21	0.4960	-0.0737	0.1053	-0.0118	0.0000
4	22	0.4960	-0.2390	0.1048	-0.0118	0.0000
4	23	0.4960	-0.4050	0.1050	-0.0118	0.0000
4	24	0.4960	-0.5710	0.1077	-0.0122	0.0000
4	25	0.4960	-0.7070	0.1379	-0.0099	0.0000
4	26	0.4295	-0.7600	0.1332	0.0000	0.0120
4	27	0.2965	-0.7600	0.1440	0.0000	0.0130
4	28	0.2300	-0.7080	0.1630	0.0115	0.0000
3	1	0.2100	-0.5740	0.0819	0.0091	0.0000
3	2	0.2100	-0.4100	0.0811	0.0090	0.0000
3	3	0.2100	-0.2460	0.0811	0.0090	0.0000

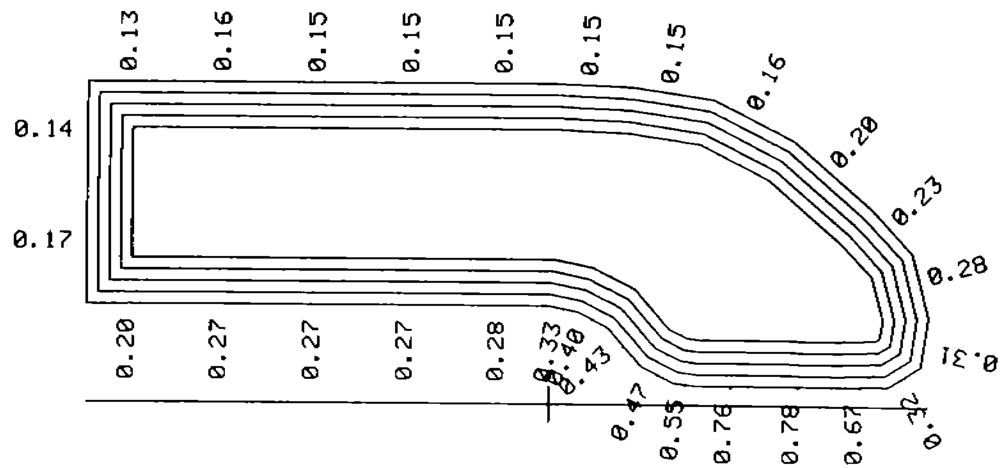
turn No →

3	4	0.2100	-0.0800	0.0803	0.0092	0.0000
3	5	0.2041	0.0335	0.0724	0.0029	0.0006
3	6	0.1828	0.0939	0.0833	0.0035	0.0017
3	7	0.1339	0.1547	0.1325	0.0054	0.0060
3	8	0.0886	0.2082	0.2096	0.0067	0.0033
3	9	0.0749	0.2471	0.2479	0.0052	0.0006
3	10	0.0730	0.3212	0.2427	0.0194	0.0000
3	11	0.0730	0.4398	0.2426	0.0197	0.0000
3	12	0.0739	0.5440	0.2425	0.0146	-0.0003
3	13	0.0846	0.6043	0.2474	0.0054	-0.0033
3	14	0.1235	0.6247	0.1790	0.0011	-0.0071
3	15	0.1993	0.6166	0.1157	-0.0020	-0.0073
3	16	0.2784	0.5732	0.0894	-0.0037	-0.0040
3	17	0.3686	0.4742	0.0641	-0.0059	-0.0050
3	18	0.4588	0.3400	0.0567	-0.0051	-0.0025
3	19	0.5007	0.2067	0.0524	-0.0048	-0.0007
3	20	0.5131	0.0742	0.0482	-0.0043	-0.0002
3	21	0.5160	-0.0735	0.0462	-0.0052	0.0000
3	22	0.5160	-0.2390	0.0457	-0.0052	0.0000
3	23	0.5160	-0.4050	0.0459	-0.0052	0.0000
3	24	0.5160	-0.5710	0.0486	-0.0055	0.0000
3	25	0.5160	-0.7170	0.0777	-0.0067	0.0000
3	26	0.4395	-0.7800	0.0737	0.0000	0.0077
3	27	0.2865	-0.7800	0.0647	0.0000	0.0088
3	28	0.2100	-0.7180	0.1037	0.0087	0.0000
2	1	0.1900	-0.5740	0.0243	0.0027	0.0000
2	2	0.1900	-0.4100	0.0238	0.0026	0.0000
2	3	0.1900	-0.2460	0.0237	0.0026	0.0000
2	4	0.1900	-0.0810	0.0231	0.0026	0.0000
2	5	0.1845	0.0293	0.0149	0.0006	0.0001
2	6	0.1651	0.0846	0.0244	0.0009	0.0005
2	7	0.1177	0.1424	0.0707	0.0029	0.0032
2	8	0.0708	0.1991	0.1425	0.0052	0.0026
2	9	0.0552	0.2436	0.1880	0.0045	0.0006
2	10	0.0530	0.3206	0.1904	0.0154	0.0000
2	11	0.0530	0.4399	0.1903	0.0155	0.0000
2	12	0.0539	0.5470	0.1876	0.0120	-0.0002
2	13	0.0686	0.6164	0.1611	0.0049	-0.0030
2	14	0.1180	0.6441	0.0968	0.0007	-0.0047
2	15	0.2049	0.6358	0.0460	-0.0009	-0.0032
2	16	0.2907	0.5891	0.0247	-0.0011	-0.0012
2	17	0.3843	0.4866	0.0032	-0.0003	-0.0003
2	18	0.4769	0.3485	-0.0028	0.0003	0.0001
2	19	0.5204	0.2106	-0.0066	0.0006	0.0001
2	20	0.5330	0.0754	-0.0106	0.0009	0.0000
2	21	0.5360	-0.0732	-0.0125	0.0014	0.0000
2	22	0.5360	-0.2390	-0.0130	0.0015	0.0000
2	23	0.5360	-0.4050	-0.0128	0.0014	0.0000
2	24	0.5360	-0.5710	-0.0104	0.0012	0.0000
2	25	0.5360	-0.7270	0.0161	-0.0016	0.0000
2	26	0.4495	-0.8000	0.0132	0.0000	0.0016
2	27	0.2765	-0.8000	0.0241	0.0000	0.0028
2	28	0.1900	-0.7280	0.0422	0.0041	0.0000
1	1	0.1700	-0.5740	-0.0620	-0.0069	0.0000
1	2	0.1700	-0.4100	-0.0624	-0.0070	0.0000
1	3	0.1700	-0.2460	-0.0624	-0.0070	0.0000
1	4	0.1700	-0.0820	-0.0630	-0.0070	0.0000
1	5	0.1650	0.0250	-0.0700	-0.0024	-0.0005
1	6	0.1475	0.0750	-0.0622	-0.0021	-0.0011
1	7	0.1015	0.1300	-0.0230	-0.0009	-0.0010
1	8	0.0530	0.1900	0.0341	0.0014	0.0007
1	9	0.0355	0.2400	0.0763	0.0021	0.0003
1	10	0.0330	0.3200	0.0833	0.0068	0.0000

21-SEP-93 In-plane forces (norm.)

Total Force	0.3	-0.0	-0.0	tons
Inward Force	0.6	-0.0	0.0	tons
Outward Force	-0.2	-0.0	-0.0	tons

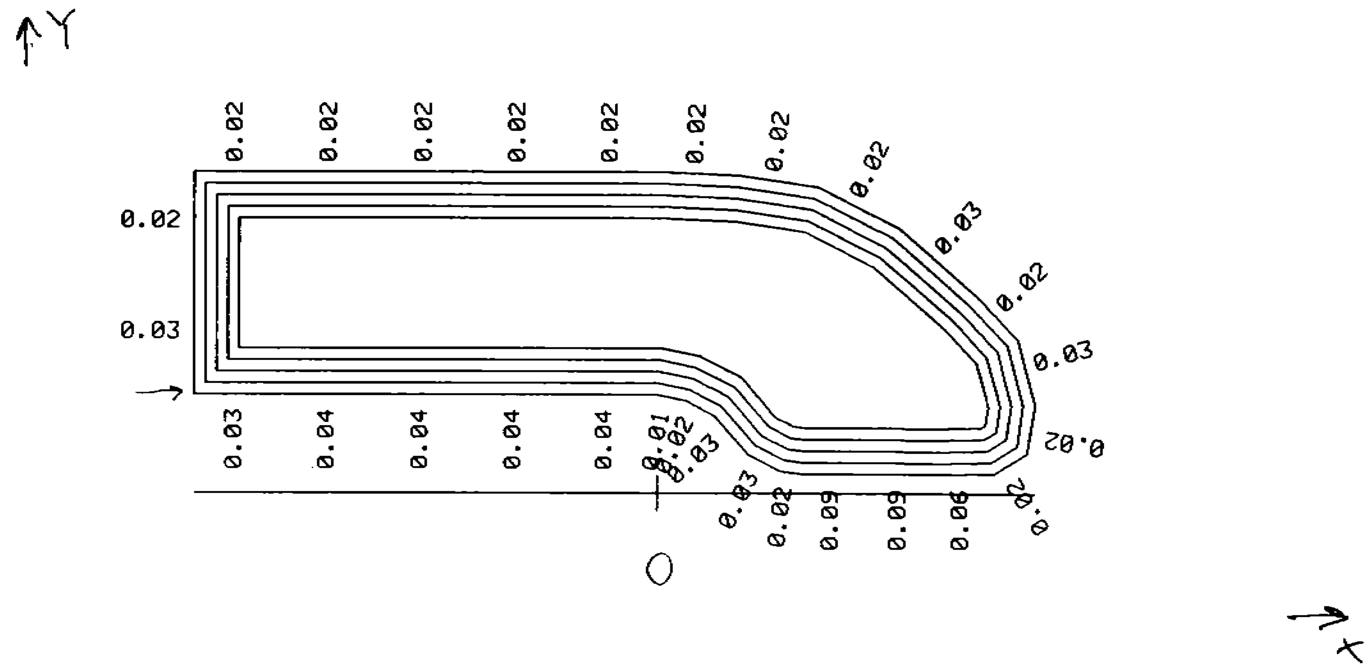
F_r, T/M



21-SEP-93 In-plane forces (abs.)

Total Force	0.3	-0.0	-0.0	tons
Inward Force	0.6	-0.0	0.0	tons
Outward Force	-0.2	-0.0	-0.0	tons

Fr, T



15	0.6550	0.2105	-0.0318	-0.0086	0.0330	195.1240
			-0.2770	-0.0749	0.2869	
16	0.6050	0.3030	-0.0175	-0.0166	0.0241	223.4089
			-0.1718	-0.1625	0.2365	
17	0.4990	0.4000	-0.0242	-0.0286	0.0375	229.7998
			-0.1301	-0.1540	0.2016	
18	0.3570	0.4950	-0.0113	-0.0230	0.0256	243.7587
			-0.0716	-0.1452	0.1619	
19	0.2145	0.5400	-0.0031	-0.0221	0.0223	262.0382
			-0.0214	-0.1527	0.1542	
20	0.0765	0.5530	-0.0009	-0.0208	0.0208	267.4170
			-0.0070	-0.1560	0.1561	
21	-0.0730	0.5560	0.0000	-0.0259	0.0259	270.0000
			0.0000	-0.1560	0.1560	
22	-0.2390	0.5560	0.0000	-0.0260	0.0260	270.0000
			0.0000	-0.1565	0.1565	
23	-0.4050	0.5560	0.0000	-0.0261	0.0261	270.0000
			0.0000	-0.1573	0.1573	
24	-0.5710	0.5560	0.0000	-0.0275	0.0275	270.0000
			0.0000	-0.1659	0.1659	
25	-0.7370	0.5560	0.0000	-0.0230	0.0230	270.0000
			0.0000	-0.1383	0.1383	
26	-0.8200	0.4595	0.0282	0.0000	0.0282	0.0000
			0.1461	0.0000	0.1461	
27	-0.8200	0.2665	0.0337	0.0000	0.0337	0.0000
			0.1749	0.0000	0.1749	
28	-0.7380	0.1700	0.0000	0.0331	0.0331	90.0000
			0.0000	0.2016	0.2016	

	y	z	x
SF	0.3552E+00	-0.3227E-08	-0.6727E-02
SFI	0.6033E+00	-0.2243E-08	0.8217E-01
SFO	-0.2481E+00	-0.9845E-09	-0.8890E-01

1	11	0.0330	0.4400	0.0833	0.0068	0.0000
1	12	0.0340	0.5500	0.0797	0.0054	-0.0001
1	13	0.0525	0.6285	0.0401	0.0016	-0.0010
1	14	0.1125	0.6635	-0.0124	-0.0001	0.0007
1	15	0.2105	0.6550	-0.0506	0.0010	0.0038
1	16	0.3030	0.6050	-0.0672	0.0032	0.0034
1	17	0.4000	0.4990	-0.0850	0.0082	0.0069
1	18	0.4950	0.3570	-0.0900	0.0087	0.0043
1	19	0.5400	0.2145	-0.0933	0.0091	0.0013
1	20	0.5530	0.0765	-0.0969	0.0088	0.0004
1	21	0.5560	-0.0730	-0.0987	0.0111	0.0000
1	22	0.5560	-0.2390	-0.0992	0.0112	0.0000
1	23	0.5560	-0.4050	-0.0990	0.0112	0.0000
1	24	0.5560	-0.5710	-0.0969	0.0109	0.0000
1	25	0.5560	-0.7370	-0.0736	0.0083	0.0000
1	26	0.4595	-0.8200	-0.0755	0.0000	-0.0099
1	27	0.2665	-0.8200	-0.0651	0.0000	-0.0085
1	28	0.1700	-0.7380	-0.0485	-0.0054	0.0000

OUTPUT OF MAIN S H O F O R C E

#	X3 X, M	X1 Y, M	FORCE3 Fx	FORCE1 FY	SUM $\sqrt{F_x^2+F_Y^2}$	THETA angle,
1	-0.5740	0.1700	0.0000 0.0000	0.0452 0.2757	0.0452 0.2757	90.0000
2	-0.4100	0.1700	0.0000 0.0000	0.0448 0.2729	0.0448 0.2729	90.0000
3	-0.2460	0.1700	0.0000 0.0000	0.0447 0.2728	0.0447 0.2728	90.0000
4	-0.0820	0.1700	0.0000 0.0000	0.0463 0.2825	0.0463 0.2825	90.0000
5	0.0250	0.1650	0.0033 0.0656	0.0167 0.3282	0.0171 0.3347	78.6901
6	0.0750	0.1475	0.0101 0.1802	0.0202 0.3605	0.0225 0.4030	63.4349
7	0.1300	0.1015	0.0293 0.3262	0.0263 0.2921	0.0394 0.4379	41.8452
8	0.1900	0.0530	0.0143 0.2131	0.0286 0.4262	0.0320 0.4765	63.4349
9	0.2400	0.0355	0.0028 0.0694	0.0224 0.5551	0.0228 0.5594	82.8750
10	0.3200	0.0330	0.0000 0.0000	0.0915 0.7628	0.0915 0.7628	90.0000
11	0.4400	0.0330	0.0000 0.0000	0.0936 0.7804	0.0936 0.7804	89.9990
12	0.5500	0.0340	-0.0013 -0.0135	0.0672 0.6722	0.0672 0.6723	91.1478
13	0.6285	0.0525	-0.0114 -0.1699	0.0185 0.2767	0.0217 0.3247	121.5514
14	0.6635	0.1125	-0.0269 -0.3131	0.0041 0.0479	0.0272 0.3167	171.3045

MAGNETIC FIELD OF MINI-Torus
INPUT DATA: 21-SEP-1991

I	J	X(1) Y [M]	X(3) X [M]	BTOT(2) B_Z	FORCE(1) F Y T	FORCE(3) F X T
5 (turn No →)	1	0.2500	-0.5740	0.2228	0.0248	0.0000
5	2	0.2500	-0.4100	0.2214	0.0247	0.0000
5	3	0.2500	-0.2460	0.2213	0.0247	0.0000
5	4	0.2500	-0.0780	0.2206	0.0258	0.0000
5	5	0.2432	0.0421	0.2158	0.0100	0.0020
5	6	0.2180	0.1128	0.2280	0.0113	0.0057
5	7	0.1662	0.1794	0.2736	0.0112	0.0125
5	8	0.1242	0.2265	0.3437	0.0080	0.0040
5	9	0.1143	0.2543	0.3664	0.0053	0.0007
5	10	0.1130	0.3225	0.3515	0.0275	0.0000
5	11	0.1130	0.4396	0.3516	0.0285	0.0000
5	12	0.1138	0.5380	0.3594	0.0189	-0.0004
5	13	0.1167	0.5801	0.4934	0.0023	-0.0014
5	14	0.1346	0.5859	0.3658	0.0012	-0.0079
5	15	0.1880	0.5782	0.2837	-0.0039	-0.0145
5	16	0.2537	0.5415	0.2468	-0.0089	-0.0094
5	17	0.3372	0.4494	0.2151	-0.0192	-0.0162
5	18	0.4226	0.3230	0.2036	-0.0168	-0.0083
5	19	0.4614	0.1989	0.1984	-0.0171	-0.0024
5	20	0.4731	0.0719	0.1942	-0.0168	-0.0008
5	21	0.4760	-0.0739	0.1924	-0.0215	0.0000
5	22	0.4760	-0.2390	0.1920	-0.0217	0.0000
5	23	0.4760	-0.4050	0.1922	-0.0217	0.0000
5	24	0.4760	-0.5710	0.1951	-0.0220	0.0000
5	25	0.4760	-0.6970	0.2237	-0.0131	0.0000
5	26	0.4195	-0.7400	0.2194	0.0000	0.0169
5	27	0.3065	-0.7400	0.2296	0.0000	0.0176
5	28	0.2500	-0.6980	0.2467	0.0141	0.0000
4	1	0.2300	-0.5740	0.1387	0.0155	0.0000
4	2	0.2300	-0.4100	0.1377	0.0153	0.0000
4	3	0.2300	-0.2460	0.1376	0.0153	0.0000
4	4	0.2300	-0.0790	0.1368	0.0158	0.0000
4	5	0.2236	0.0378	0.1302	0.0056	0.0011
4	6	0.2004	0.1034	0.1420	0.0065	0.0033
4	7	0.1500	0.1671	0.1905	0.0078	0.0087
4	8	0.1064	0.2174	0.2666	0.0074	0.0037
4	9	0.0946	0.2507	0.2969	0.0053	0.0007
4	10	0.0930	0.3219	0.2850	0.0225	0.0000
4	11	0.0930	0.4397	0.2849	0.0231	0.0000
4	12	0.0938	0.5410	0.2885	0.0163	-0.0003
4	13	0.1006	0.5922	0.3349	0.0044	-0.0027
4	14	0.1291	0.6053	0.2605	0.0012	-0.0080
4	15	0.1937	0.5974	0.1859	-0.0029	-0.0106
4	16	0.2660	0.5574	0.1542	-0.0060	-0.0063
4	17	0.3529	0.4618	0.1254	-0.0114	-0.0096
4	18	0.4407	0.3315	0.1163	-0.0100	-0.0049
4	19	0.4811	0.2028	0.1114	-0.0099	-0.0014
4	20	0.4931	0.0731	0.1072	-0.0094	-0.0004
4	21	0.4960	-0.0737	0.1053	-0.0118	0.0000
4	22	0.4960	-0.2390	0.1048	-0.0118	0.0000
4	23	0.4960	-0.4050	0.1050	-0.0118	0.0000
4	24	0.4960	-0.5710	0.1077	-0.0122	0.0000
4	25	0.4960	-0.7070	0.1379	-0.0099	0.0000
4	26	0.4295	-0.7600	0.1332	0.0000	0.0120
4	27	0.2965	-0.7600	0.1440	0.0000	0.0130
4	28	0.2300	-0.7080	0.1630	0.0115	0.0000
3	1	0.2100	-0.5740	0.0819	0.0091	0.0000
3	2	0.2100	-0.4100	0.0811	0.0090	0.0000
3	3	0.2100	-0.2460	0.0811	0.0090	0.0000

3	4	0.2100	-0.0800	0.0803	0.0092	0.0000
3	5	0.2041	0.0335	0.0724	0.0029	0.0006
3	6	0.1828	0.0939	0.0833	0.0035	0.0017
3	7	0.1339	0.1547	0.1325	0.0054	0.0060
3	8	0.0886	0.2082	0.2095	0.0067	0.0033
3	9	0.0749	0.2471	0.2479	0.0052	0.0006
3	10	0.0730	0.3212	0.2427	0.0194	0.0000
3	11	0.0730	0.4398	0.2426	0.0197	0.0000
3	12	0.0739	0.5440	0.2425	0.0146	-0.0003
3	13	0.0846	0.6043	0.2474	0.0054	-0.0033
3	14	0.1235	0.6247	0.1790	0.0011	-0.0071
3	15	0.1993	0.6166	0.1157	-0.0020	-0.0073
3	16	0.2784	0.5732	0.0894	-0.0037	-0.0040
3	17	0.3886	0.4742	0.0641	-0.0059	-0.0050
3	18	0.4588	0.3400	0.0567	-0.0051	-0.0025
3	19	0.5007	0.2067	0.0524	-0.0048	-0.0007
3	20	0.5131	0.0742	0.0482	-0.0043	-0.0002
3	21	0.5160	-0.0735	0.0462	-0.0052	0.0000
3	22	0.5160	-0.2390	0.0457	-0.0052	0.0000
3	23	0.5160	-0.4050	0.0459	-0.0052	0.0000
3	24	0.5160	-0.5710	0.0485	-0.0055	0.0000
3	25	0.5160	-0.7170	0.0777	-0.0067	0.0000
3	26	0.4395	-0.7800	0.0737	0.0000	0.0077
3	27	0.2865	-0.7800	0.0847	0.0000	0.0088
3	28	0.2100	-0.7180	0.1037	0.0087	0.0000
2	1	0.1900	-0.5740	0.0243	0.0027	0.0000
2	2	0.1900	-0.4100	0.0238	0.0026	0.0000
2	3	0.1900	-0.2460	0.0237	0.0026	0.0000
2	4	0.1900	-0.0810	0.0231	0.0028	0.0000
2	5	0.1845	0.0293	0.0149	0.0006	0.0001
2	6	0.1651	0.0845	0.0244	0.0009	0.0005
2	7	0.1177	0.1424	0.0707	0.0029	0.0032
2	8	0.0708	0.1991	0.1425	0.0052	0.0028
2	9	0.0552	0.2436	0.1880	0.0045	0.0006
2	10	0.0530	0.3206	0.1904	0.0154	0.0000
2	11	0.0530	0.4399	0.1903	0.0156	0.0000
2	12	0.0539	0.5470	0.1875	0.0120	-0.0002
2	13	0.0685	0.6164	0.1611	0.0049	-0.0030
2	14	0.1180	0.6441	0.0968	0.0007	-0.0047
2	15	0.2049	0.6358	0.0460	-0.0009	-0.0032
2	16	0.2907	0.5891	0.0247	-0.0011	-0.0012
2	17	0.3843	0.4866	0.0032	-0.0003	-0.0003
2	18	0.4769	0.3485	-0.0028	0.0003	0.0001
2	19	0.5204	0.2106	-0.0066	0.0006	0.0001
2	20	0.5330	0.0754	-0.0106	0.0009	0.0000
2	21	0.5360	-0.0732	-0.0125	0.0014	0.0000
2	22	0.5360	-0.2390	-0.0130	0.0015	0.0000
2	23	0.5360	-0.4050	-0.0128	0.0014	0.0000
2	24	0.5360	-0.5710	-0.0104	0.0012	0.0000
2	25	0.5360	-0.7270	0.0161	-0.0018	0.0000
2	26	0.4495	-0.8000	0.0132	0.0000	0.0016
2	27	0.2765	-0.8000	0.0241	0.0000	0.0028
2	28	0.1900	-0.7280	0.0422	0.0041	0.0000
1	1	0.1700	-0.5740	-0.0620	-0.0069	0.0000
1	2	0.1700	-0.4100	-0.0624	-0.0070	0.0000
1	3	0.1700	-0.2460	-0.0624	-0.0070	0.0000
1	4	0.1700	-0.0820	-0.0630	-0.0070	0.0000
1	5	0.1650	0.0250	-0.0700	-0.0024	-0.0005
1	6	0.1475	0.0750	-0.0622	-0.0021	-0.0011
1	7	0.1015	0.1300	-0.0230	-0.0009	-0.0010
1	8	0.0530	0.1900	0.0341	0.0014	0.0007
1	9	0.0355	0.2400	0.0763	0.0021	0.0003
1	10	0.0330	0.3200	0.0833	0.0068	0.0000

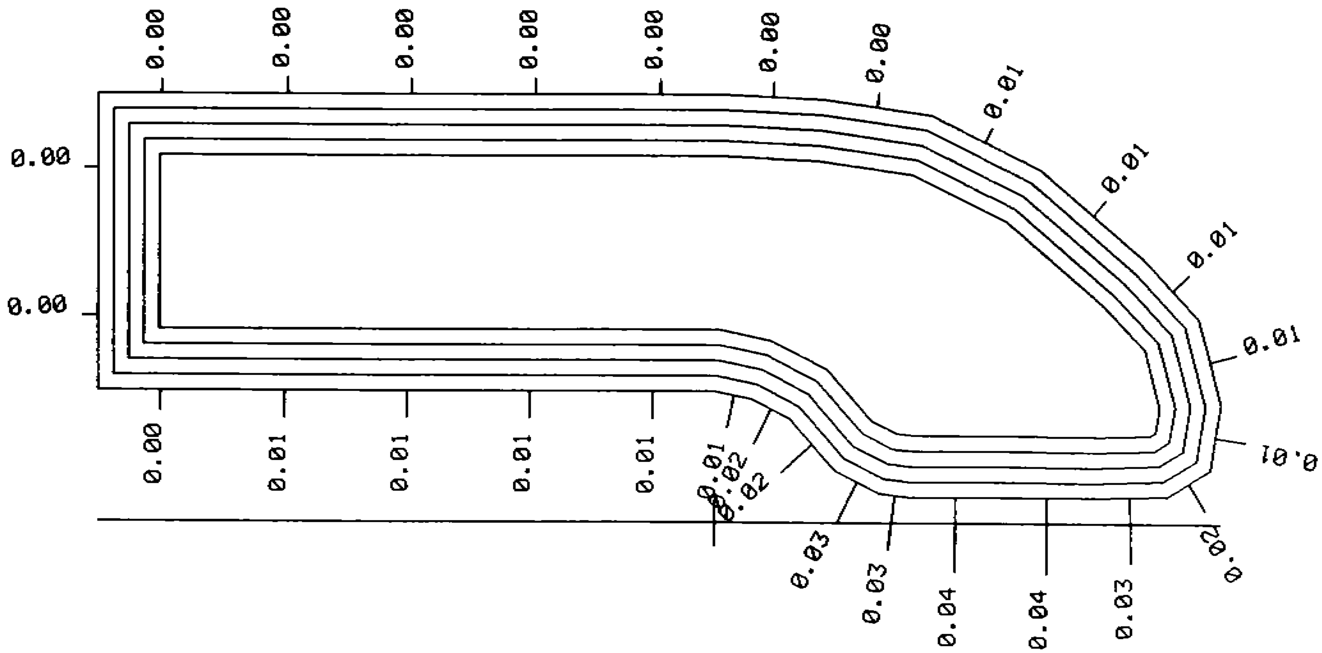
Data file MINI.DAT Attachment 3

```
CIRCE: FIOFAC=2
9-MAY-1989
RMAX      X3MIN     X3MAX     SHIFT1    SHIFT2    DISMIN
5.0       -3.0      4.5       0.0       0.0       0.20
LOOPS     COILS    (FIOFAC =1 FOR TOROID, =2 FOR SHOBINT AND SHOTRAC)
005       006
CUR[MA]   FIOFAC    CENT1     CENT2     BA(1)     BA(2)     BA(3)
0.2       2.00
BEGIN     1       1. loop
18.       1.0
0.17      -0.82
0.17      0.0
0.16      0.05
0.135     0.10
0.068     0.16
0.038     0.22
0.033     0.26
0.033     0.50
0.035     0.60
0.070     0.657
0.155     0.67
0.266     0.64
0.34      0.57
0.46      0.428
0.53      0.286
0.55      0.143
0.556     0.01
0.556     -0.82
END
BEGIN     2                   2. loop
15.       1.0       -.020
END
BEGIN     2                   3. loop
15.       1.0       -.040
END
BEGIN     2                   4. loop
15.       1.0       -.060
END
BEGIN     2                   5. loop
15.       1.0       -.080
END
0123456789012345678901234567890123456789012345678901234567890
```

All neighboring coils shifted by $\Delta\phi = 5°$

22-SEP-93 Transverse Forces (norm.)

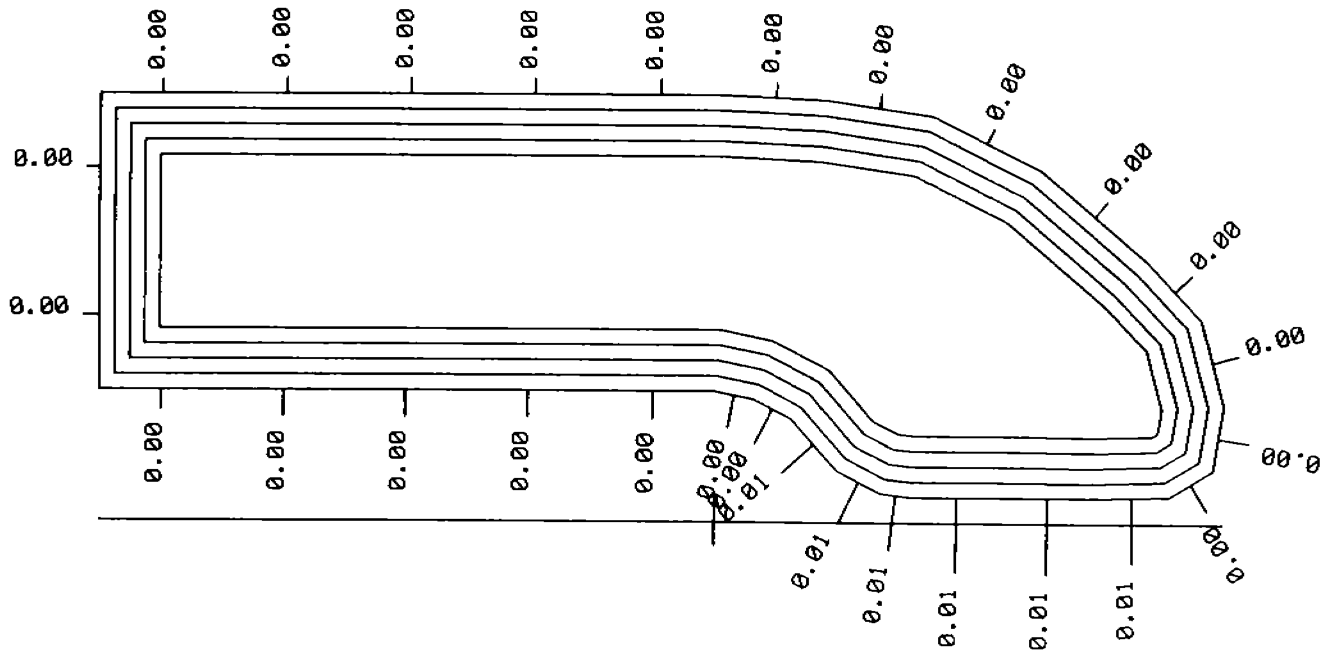
Total Force	0.355	0.057	-0.006	tons
Inward Force	0.604	0.041	0.082	tons
Outward Force	-0.248	0.015	-0.089	tons



all neighboring coils shifted by 2° in ϕ

22-SEP-93 Transverse Forces (norm.)

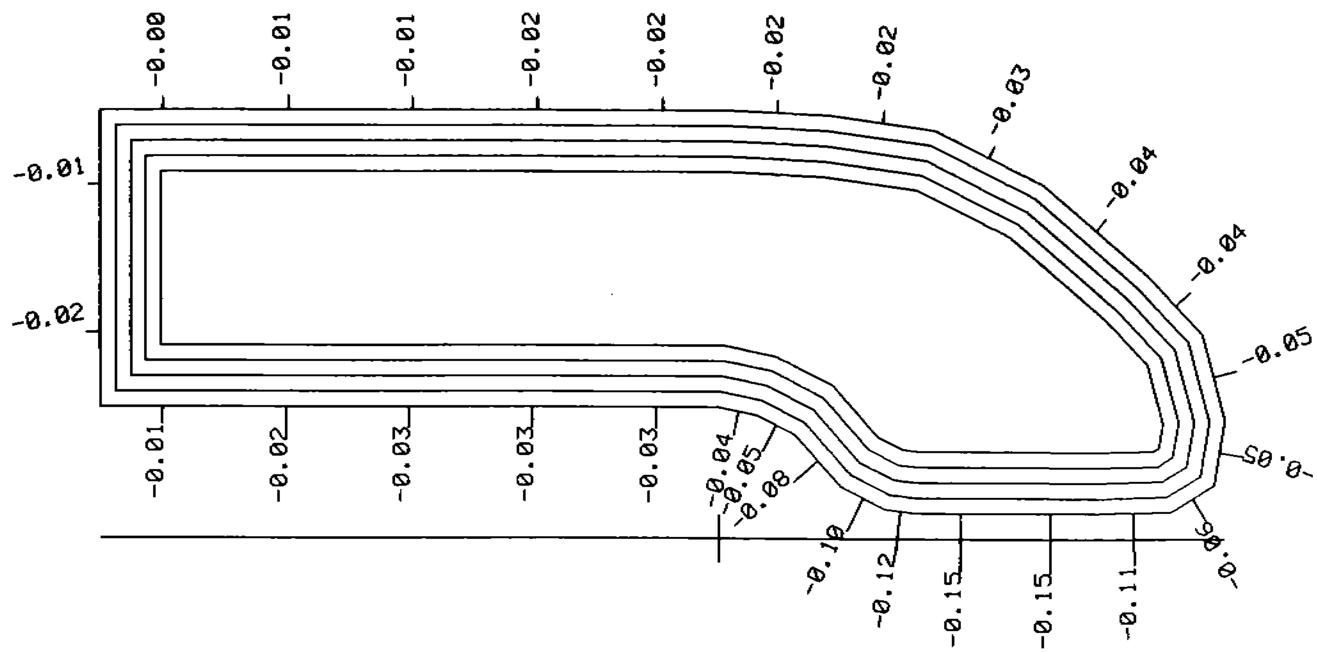
Total Force	0.355	0.022	-0.006	tons
Inward Force	0.603	0.016	0.082	tons
Outward Force	-0.248	0.006	-0.088	tons

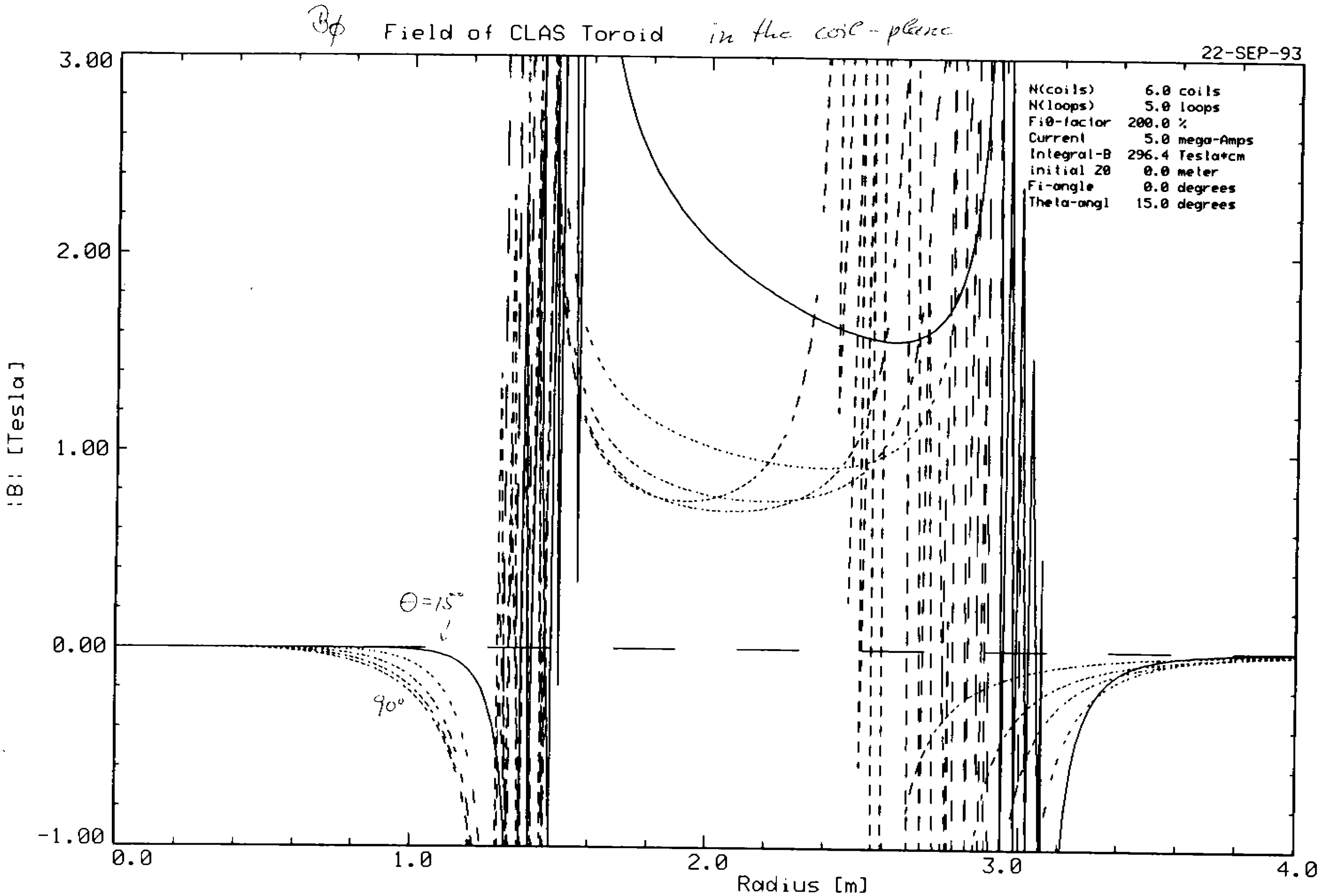


neigboring coil switched off !!

22-SEP-93 Transverse Forces (norm.)

Total Force	0.262	-0.160	-0.006	tons
Inward Force	0.474	-0.115	0.068	tons
Outward Force	-0.212	-0.044	-0.074	tons

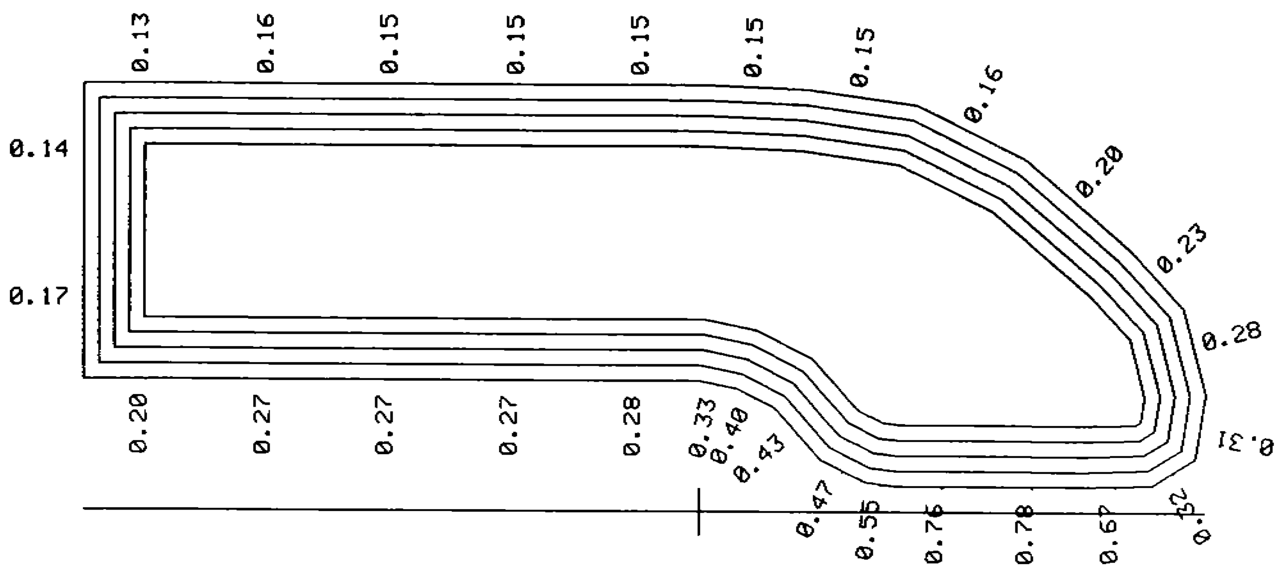




Bϕ
Field of CLAS Toroid
in the coil-plane
22-SEP-93
N(coils) 6.0 coils
N(loops) 5.0 loops
Fi0-factor 200.0 %
Current 5.0 mega-Amps
Integral-B 296.4 Tesla*cm
initial Z0 0.0 meter
Fi-angle 0.0 degrees
Theta-angl 15.0 degrees
θ=15°
90°
3.00
2.00
1.00
0.00
-1.00
|B| [Tesla]
0.0
1.0
2.0
3.0
4.0
Radius [m]

22-SEP-93 In-plane forces (norm.)

Total Force	0.355	-0.000	-0.006	tons
Inward Force	0.603	-0.000	0.082	tons
Outward Force	-0.248	-0.000	-0.088	tons



Attachment 4