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FERMILAB HIGH-FIELD OPTION
POPAE DIPOLE - MAGNETOSTATICS

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Summary

Magnetic field computations have been performed for a four-inch coil aperture 45 kG dipole magnet that may be utilized in a high-field option of POPAE.[1] A cold iron version utilizing flat pancake coils has been explored to determine the magnetostatic effectiveness of a simple coil geometry. Suitable locations have been found for rectangular blocks of conductors each consisting of 280 turns of .040 in by .040 in conductor.

Design

Since the POPAE storage device is operated with direct current, the wire chosen for the coil winding may be reasonably small. A convenient choice is .040 in by .040 in carrying about 200 A which gives a comfortable current density of about 125 kA/in^2. The field accuracy requirement for a storage ring is tighter than that required in an accelerator. Hence, it was felt that accurately positioned blocks of current might be preferable to a monolithic random wound coil. A flat pancake was chosen for the individual block as being the simplest coil to wind. Before potting to the final shape the ends are turned around elliptically and bent up at an incline. This gives a coil package consisting of flat pancake blocks .420 in by 1.177 in each bent up along inclined planes at the ends such that they nest onto a cylindrical bore tube, the length of each block being chosen to minimize the longitudinally integrated multipole contribution.

The field in the transverse section has been calculated using a complex variable method.[2] A search mode is employed which minimizes the energy content within the reference radius of a preselected number of multipoles higher than the dipole. The parameter varied is the horizontal location of the inside edge of each flat pancake coil. Since the ends occupy only a small part of the magnet length relatively few trials with varying positions for the turn around centers suffice to minimize the higher multipole coefficients of the longitudinally integrated fields.

Tables 1-3 are self-explanatory. Table 4 refers to the longitudinally integrated fields in which inclined elliptical turn around ends are used, the turn centers being separated by the length indicated. The entries T(N), S(N), and R(N) refer to coefficients in a multipole expansion of the longitudinally integrated magnetic field. Successive terms give ΔB at the reference radius for the dipole, sextupole, decapole, etc. The contribution due to the currents with no shield is T(N), the contribution from the iron shield is S(N), and R(N) is the ratio T(N)+S(N) divided by T(1)+S(1). Table 5 is similar calculation in which the contribution from the ends is omitted and the length set equal to one inch. The median plane field in the transverse section is given by BT. Columns BA, BS, and BN give respectively the contribution in the absence of the shield and the total field normalized to unity at the center. The entry DELR(N) is an estimate[3] of the magnitude of the change in R(N) induced by saturation effects in the iron shield. Finally the net flux entering the iron is given from which one sees that if average fields less than 18 kG are desired in the iron the magnet diameter is about 22 inches.

*Operated by the Universities Research Association, Inc., under contract with the U.S. Energy Research and Development Administration.

References

1. T.L. Collins, D.A. Edwards, J. Ingebretsen, D.E. Johnson, S. Ohnuma, A.G. Ruggiero, L.C. Teng, Fermilab Technical Note TM-547 (Feb. 1975)

2. W.W. Lee and S.C. Snowdon, IEEE Trans. on Nucl. Sci., NS-20, 726 (1973)

3. M.A. Green, Kernforschungszentrum Karlsruhe External Report 3/71-7, June 1972

Table 1. Performance Parameters

Field Strength	45 kG
Effective Field Length	237 in
Good Field Width	3.0 in
Field Quality($\Delta B/B$ at 1in Rad.)	±.01%

Table 2. Design Data

Conductor Current (45 kG)	212 A
Cond. Size(no insulation)	.040 in by .040 in
Effective Current Density	132.5 kA/in^2
Total Number of Turns	3360
Insulation Thickness	.001 in
Iron Shield Inner Radius	4.25 in
Outside Dimension of Iron	22 in by 14 in
Total Length of Iron	252 in

Table 3. Critical Fields, Stored Energy, and Forces

Maximum Field in Conductor	48 kG
Stored Energy	1 MJ
Inductance	47 Hy
Effective Rad. of Cond. Blocks	2.875 in

Traction at Effective Radius

Angle (Deg)	x-traction (lb/in^2)	y-traction (lb/in^2)
0	1005	0
40	1465	-823
50	1475	-695
90	0	0

Displacement Force

(x-displ. = .010 in)	29 lb/in
(y-displ. = .010 in)	29 lb/in

Table 4. POPAE DIPOLE WITH PANCAKE COILS AND CIRCULAR SHIELD

ORDER OF POLE	=	1	CALCULATIONAL MODE	=	1	NUMBER OF BLOCKS	=	6
HIGHEST MULTIPOLE ORDER	=	19	CONDUCTOR CURRENT(A)	=	212.0	CONDUCTOR WIDTH(IN)	=	.0400
CONDUCTOR HEIGHT(IN)	=	.0400	INSULATION THICKNESS(IN)	=	.0010	REFERENCE RADIUS(IN)	=	1.0000
INNER IRON RADIUS(IN)	=	4.2500	SIMPSONS RULE X-INCREM.(IN)	=	.0080	SIMPSONS RULE Y-INCREM.(IN)	=	.0080
HORIZ. PLOT INCREM.(IN)	=	.1000						

BLOCK	TURNS	LAYRS/BLK	CURDEN (KA/IN/IN)	SPACER (IN)	XOBLK (IN)	YOBLK (IN)	ALPHBLK (RAD)	LENGTH (IN)
1	28.00	10.00	132.500	.0000	2.1725	.0000	.2500	252.0000
2	28.00	10.00	132.500	.0000	2.0937	.5000	.2500	248.0000
3	28.00	10.00	132.500	.0000	1.8812	1.0000	.2500	244.0000
4	28.00	10.00	132.500	.0000	1.7028	1.5000	.2500	240.0000
5	28.00	10.00	132.500	.0000	1.2625	2.0000	.2500	236.0000
6	28.00	10.00	132.500	.0000	.6422	2.5000	.2500	232.0000

MULTIPOLE COEFFICIENTS

T(N)	=	7.425E+03	9.347E+00	-7.235E-01	-1.469E-01	5.104E-02	4.465E-02	6.309E-03	1.537E-04	-9.709E-05	-4.990E-07
S(N)	=	3.251E+03	-7.045E+00	4.513E-02	4.028E-03	-4.669E-05	5.797E-06	2.894E-09	-3.396E-09	4.554E-11	-1.327E-12
R(N)	=	1.000E+00	2.156E-04	-6.354E-05	-1.339E-05	4.777E-06	4.182E-06	5.909E-07	1.439E-08	-9.094E-09	-4.674E-11

X(IN)	BT(KG-IN)	BA(KG-IN)	BS(KG-IN)	BN
.00000	10675.75819	7424.92197	3250.83622	1.00000
.10000	10675.78114	7425.01537	3250.76577	1.00000
.20000	10675.84917	7425.29467	3250.55450	1.00001
.30000	10675.95976	7425.75720	3250.20256	1.00002
.40000	10676.10856	7426.39833	3249.71023	1.00003
.50000	10676.28925	7427.21134	3249.07792	1.00005
.60000	10676.49339	7428.18724	3248.30615	1.00007
.70000	10676.71067	7429.31506	3247.39560	1.00009
.80000	10676.92980	7430.58268	3246.34712	1.00011
.90000	10677.14094	7431.97923	3245.16172	1.00013
1.00000	10677.34072	7433.50012	3243.84060	1.00015
1.10000	10677.54206	7435.15685	3242.38522	1.00017
1.20000	10677.79157	7436.99432	3240.79725	1.00019
1.30000	10678.19304	7439.12039	3239.07866	1.00023
1.40000	10678.98526	7441.75354	3237.23172	1.00030
1.50000	10680.55596	7445.29690	3235.25906	1.00045
1.60000	10683.61235	7450.44867	3233.16368	1.00074
1.70000	10689.30930	7458.36029	3230.94901	1.00127
1.80000	10699.47228	7470.85332	3228.61897	1.00222
1.90000	10716.87996	7490.70197	3226.17799	1.00385
2.00000	10745.60861	7521.97749	3223.63112	1.00654
2.10000	10791.41315	7570.42909	3220.98405	1.01083

Table 5. POPAE DIPOLE WITH PANCAKE COILS AND CIRCULAR SHIELD

ORDER OF POLE	=	1	CALCULATIONAL MODE	=	0	NUMBER OF BLOCKS	=	6
HIGHEST MULTIPOLE ORDER	=	19	CONDUCTOR CURRENT(A)	=	212.0	CONDUCTOR WIDTH(IN)	=	.0400
CONDUCTOR HEIGHT(IN)	=	.0400	INSULATION THICKNESS(IN)	=	.0010	REFERENCE RADIUS(IN)	=	1.0000
INNER IRON RADIUS(IN)	=	4.2500	SIMPSONS RULE X-INCREM.(IN)	=	.0080	SIMPSONS RULE Y-INCREM.(IN)	=	.0080
HORIZ. PLOT INCREM.(IN)	=	.1000						

BLOCK	TURNS	LAYRS/BLK	CURDEN (KA/IN/IN)	SPACER (IN)	XOBLK (IN)	YOBLK (IN)	ALPHBLK (RAD)	LENGTH (IN)
1	28.00	10.00	132.500	.0000	2.1725	.0000	.2500	1.0000
2	28.00	10.00	132.500	.0000	2.0937	.5000	.2500	1.0000
3	28.00	10.00	132.500	.0000	1.8812	1.0000	.2500	1.0000
4	28.00	10.00	132.500	.0000	1.7028	1.5000	.2500	1.0000
5	28.00	10.00	132.500	.0000	1.2625	2.0000	.2500	1.0000
6	28.00	10.00	132.500	.0000	.6422	2.5000	.2500	1.0000

MULTIPOLE COEFFICIENTS

T(N) =	3.136E+01	3.168E-02	-2.082E-04	-3.622E-05	1.215E-04	1.839E-04	2.582E-05	1.405E-07	-4.858E-07	3.861E-09
S(N) =	1.375E+01	-3.165E-02	2.034E-04	1.811E-05	-2.874E-07	2.697E-08	9.059E-11	-1.516E-11	2.113E-13	-4.295E-15
R(N) =	1.000E+00	5.445E-07	-1.059E-07	-4.013E-07	2.687E-06	4.077E-06	5.725E-07	3.115E-09	-1.077E-08	8.559E-11
DELR(N)=	8.392E-02	1.549E-03	5.145E-05	2.034E-06	8.760E-08	3.968E-09	1.859E-10	8.919E-12	4.357E-13	2.158E-14

X(IN)	BT(KG-IN)	BA(KG-IN)	BS(KG-IN)	BN
.00000	45.10800	31.35924	13.74876	1.00000
.10000	45.10800	31.35955	13.74844	1.00000
.20000	45.10800	31.36050	13.74750	1.00000
.30000	45.10800	31.36209	13.74591	1.00000
.40000	45.10800	31.36430	13.74370	1.00000
.50000	45.10800	31.36714	13.74086	1.00000
.60000	45.10801	31.37062	13.73739	1.00000
.70000	45.10802	31.37472	13.73330	1.00000
.80000	45.10805	31.37946	13.72859	1.00000
.90000	45.10813	31.38486	13.72327	1.00000
1.00000	45.10833	31.39100	13.71733	1.00001
1.10000	45.10881	31.39801	13.71079	1.00002
1.20000	45.10985	31.40619	13.70366	1.00004
1.30000	45.11204	31.41610	13.69594	1.00009
1.40000	45.11638	31.42874	13.68764	1.00019
1.50000	45.12461	31.44584	13.67878	1.00037
1.60000	45.13965	31.47028	13.66936	1.00070
1.70000	45.16610	31.50669	13.65941	1.00129
1.80000	45.21109	31.56215	13.64894	1.00229
1.90000	45.28519	31.64721	13.63797	1.00393
2.00000	45.40347	31.77695	13.62653	1.00655
2.10000	45.58653	31.97190	13.61463	1.01061

MAX. FIELD ON IRON(KG) = 28.4271 IRON PERMEABILITY AT BMAXFE= 3.4682 FLUX IN IRON(KG-IN) = 115.4958