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DESIGN OF SUPERCONDUCTING HIGH ENERGY BEAM LINE DIPOLE-MAGNETOSTATICS

S.C. Snowdon
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

Summary

Three relatively distinct designs of superconducting beam line dipoles have evolved at Fermilab. Two follow from Energy Doubler/Saver considerations and one from POPAE considerations. Suitable end arrangements are placed on each coil to eliminate the field rise in the end conductors. An adjustment of the conductor locations within the body of the magnet then permits the elimination of sextupole and decapole terms in the longitudinally integrated magnetic field. The three designs being presently pursued are presented.

Magnetic Design of Beam Line Dipoles

Warm iron shields have been adopted for the Fermilab Energy Doubler/Saver dipoles.[1] It was natural, therefore, to consider a warm iron design for beam line magnets. These dipoles must have useable apertures about twice that of the doubler and for component replacement reasons must be about 10 feet long or about one half the length of the ED/S. Three designs are being explored.[2] The earliest one (A) followed (Fig. 1) from an early ED/S design.[3] In this design an attempt is made to make the vertical aperture smaller than the horizontal aperture by introducing a horizontal displacement between the shells in the first and fourth quadrants and the shells in the second and third quadrants. The next design (B) follows from a design (Fig. 2) to use flat pancakes as had already been employed successfully by Desportes[4] and were further treated in the POPAE design.[5] Although the conductors may be easier to wind in this design the rectangular shape of each coil does not lend itself to an efficient use of space. Hence a third design (C) is considered (Fig. 3) which is based on the present E-series ED/S design[1] which utilizes a concentric shell design for the conductor.

Each of the designs produces a longitudinally integrated field of 4800 kG-in. For designs A and C the ends of each shell are developed from a flat wound coil with circular ends spaced out with a maximum of .050 in between turns to reduce the field rise. This flat coil is then wrapped down on a cylinder of appropriate radius (mathematical description only). The coil ends for design B are developed from flat wound coils by bending up the coils at each end using a 60-degree bend for all blocks except the top most which is only bent up by 30 degrees.

Table 1 lists the main design parameters for each of the three designs. Table 2 gives the location of the conductors in first quadrant of each magnet. The designation LENGTH is the distance between bend centers of the inner turn at each end of the coil. Note that layer 2 of design A designates the location of 6 conductors that are parallel to the midplane but otherwise may be considered in layer 1. Note also that layer 4 in design C designates two turns in the same layer (#5) that have extra insulation. Hence designs A and C have only four shells.

Finally the field quality is given by B_n/B_1 in Table 3 where $B = B_1 + B_3 + B_5 + \cdots$, each successive term in the sum representing the dipole, sextupole, decapole, etc. contributions to the field at the reference radius which is taken to be 1 inch. Four cases are distinguished. Low field excitation or unsaturated iron in the region of the magnet center (2D) and the longitudinally integrated field including the magnet ends (3D). Similar information is listed at full excitation where the effects of finite permeability may be seen. The magnetostatic design[6] generates a two-dimensional conductor distribution that minimizes the (3D) multipole contribution using ends that are selected to reduce the field rise. The effects of finite permeability are determined using LINDA.[7]

References

1. The Energy Doubler, Progress Report for the Energy Doubler/Saver Collider Project, Fermilab Publication, June 1976
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3. D.A. Edwards et al., "Progress Report on the NAL Energy Doubler Design Study", Proc. of the IXth Intern. Conf. on High Energy Accelerators, SLAC, May 2-7, 1974
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Table 1. Design Data for Beam Line Dipoles

	Displaced Shell	Block	Shell
Central Field (kG)	44.65	46.91	43.32
Effective Length (in)	107.5	102.34	110.79
Conductor Current (A)	1996	2327	3719
Total Number of Turns	420	512	294
Conductor Size (in by in)	.144 by .044	.219 by .078	.344 by (.089/.081)
Effective Current Density (kA/in^2)	315	136.2	127.2
Maximum Field at Conductor (kG)	47	50.8	46.0
Horizontal Offset (in)	±1.00		
Conductor Aperture (in by in)	6.6 by 4.6	6.5 by 6.5	7 in by 7 in
Inner Iron Radius (in)	5.75	7.00	8.00
Lamination Size (in by in)	26 by 17	33 by 22	32 by 20
Weight of Iron (lb)	10450	18650	14300
Weight of Conductor (lb)	192	625	660
Stored Energy (MJ)	.74	1.05	1.06
Inductance (H)	.41	.39	.15
Force on Conductors in First Quadrant			
F_x(lb/in)	3930	8140	6300
F_y(lb/in)	-2120	-3000	-3260
Force on Coils due to Displacement of .010 in			
F_x(lb/in)	25	15	13
F_y(lb/in)	19	15	13

Table 2. Location of Conductors in First Quadrant

Displaced Shell Layer	Turns	θ_s (Deg)	θ_f (Deg)	R_o (in)	R_1 (in)	Wrap (in)	Length (in)
1	64	.1199	86.1991	2.312	2.468	.006	107.00
2	6	91.1985	99.1744	2.312	2.468	.006	104.00
3	61	.1113	76.0548	2.497	2.653	.006	104.00
4	38	.1038	44.2245	2.682	2.838	.006	98.00
5	41	.0973	44.7171	2.867	3.023	.006	96.00

Block Block	Turns/ Layer	Layers/ Block	x_o (in)	y_o (in)	Length (in)	F_x (lb/in)	F_y (lb/in)
1	16	2	3.5000	.050	110.625	585	-74
2	16	2	3.2597	.616	108.625	819	-157
3	16	2	3.2069	1.182	106.625	745	-300
4	16	2	2.9314	1.748	104.625	893	-378
5	16	2	2.6480	2.314	102.625	971	-480
6	16	2	2.1432	2.880	100.625	1197	-472
7	16	2	1.6569	3.446	98.625	1344	-540
8	16	2	.9881	4.012	95.125	1584	-602

Shell Layer	Turns	θ_s (Deg)	θ_f (Deg)	R_o (in)	R_1 (in)	Wrap (in)	Length (in)
1	49	.1557	78.5076	3.500	3.858	.007	105.112
2	45	.1408	64.4313	3.891	4.249	.007	103.944
3	32	.1284	42.2632	4.282	4.640	.007	102.775
4	2	.1180	2.5963	4.673	4.037	.010	101.597
5	19	2.5963	25.9411	4.673	4.031	.007	101.506

Table 3. Field Homogeneity (B_n/B_1 at 1-in Radius)

	Unsaturated		Finite Permeability	
Displaced Shell	(2D)	(3D)	(2D)	(3D)
Dipole	1.00000	1.00000	.99068	.9907
Sextupole	.00174	-.00014	.00174	-.0001
Decapole	-.00003	-.00003	-.00004	.0000
14-pole	-.00001	.00000	-.00002	.0000
Block				
Dipole	1.00000	1.00000	.99166	.9917
Sextupole	-.00206	.00002	-.00192	.0002
Decapole	-.00006	-.00005	-.00011	-.0001
14-pole	.00000	.00000	.00000	.0000
Shell				
Dipole	1.00000	1.00000	.98696	.9870
Sextupole	.00061	.00000	.00097	.0004
Decapole	.00003	.00000	-.00015	-.0002
14-pole	.00000	.00000	.00007	.0001

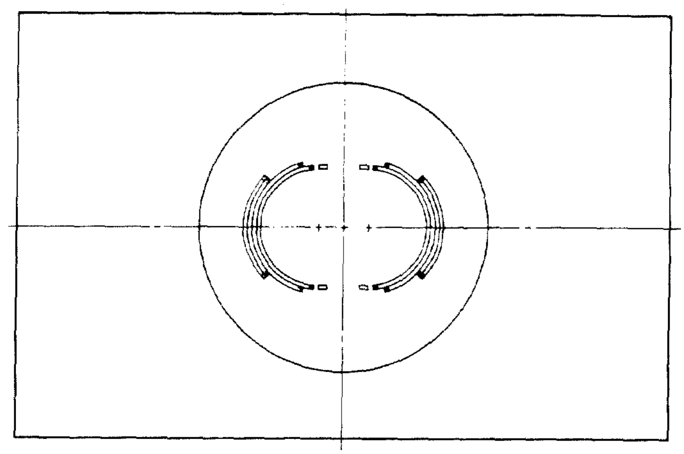

Fig. 1 Cross Section of Displaced Shell Design

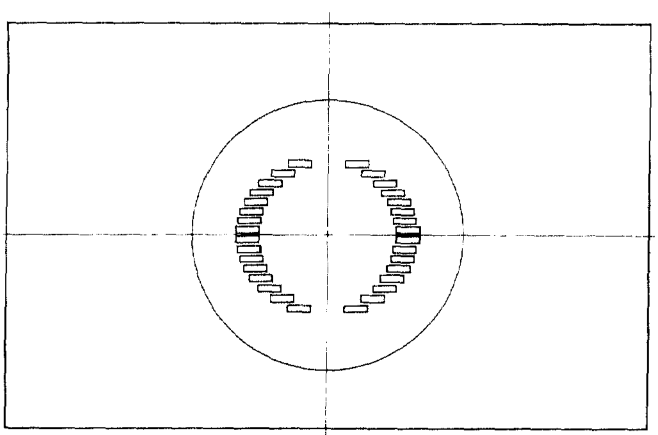

Fig. 2 Cross Section of Block Design

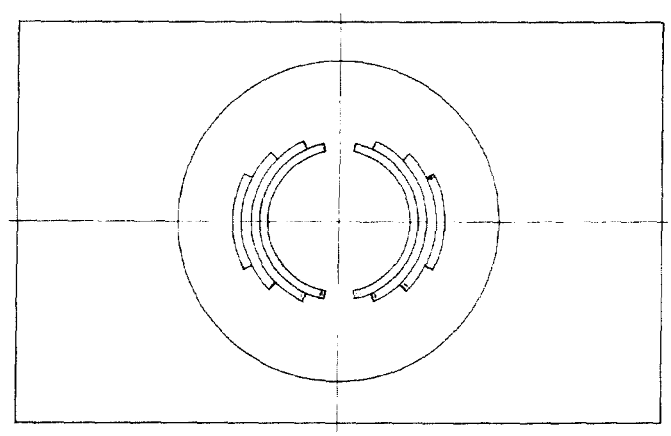

Fig. 3 Cross Section of Shell Design