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MAGNETOSTATIC DESIGN OF 85KG SUPERCONDUCTING DIPOLES

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Summary

Extension of the present Tevatron dipole to 85kG has been considered by Wilson.[1] An accelerator utilizing such dipoles has been designated as the Pentevac since it would permit 5 TeV protons to circulate within the boundaries of the Fermilab site. The present note contains results of magnetic field, force, and mechanical stress calculations for one possible Pentevac dipole.

Choice of Superconductor

Originally Nb_3Sn was considered for the higher field application. However, recent developments,[2,3] indicate that the ternary alloy NbTiTa with about 25 percent by weight of tantalum has a critical current density at 120kG and 2K that exceeds that of Nb_3Sn at 120kG for any temperature. The critical current density is plotted in Figure 1 against magnetic induction for two temperatures. If one uses sub-cooled helium as a refrigerant, then NbTiTa admits of substantially higher critical current densities than NbTi without tantalum additions. For example,[3] at 120kG addition of 25 percent by weight of tantalum gives a 75 percent increase in J_c. In the following, these new developments are exploited in the magnetic design of 85kG dipoles. Generally, the construction features follow those found useful in Tevatron dipoles.[4] Thus, a warm iron magnetic shield and a non-structural cold bore are assumed.

Number of Shells

From Figure 1 the critical current achieved at 90kG and 2K is about the same as that obtained[5] with NbTi in Tevatron dipoles at 50kG and 4.2K. Hence, for the Pentevac dipole, it will be necessary to use wider cable or more than two shells. Wider cable would require substantially different winding and forming techniques than those used in the Tevatron. Hence four shells of Tevatron cable will be used in this dipole to produce 85kG operating at 85-90 percent of critical current.

Four Shell Case

At first an attempt was made to keep the four shell magnet similar to the Tevatron dipole so that as many construction features as possible could be transferred. In this case, one would nest two two-shell coils, each pair having a cross section similar to that in the Tevatron. However, when this is done, the peak stress in the collar is about 47,000 psi. Measurements by Koepke[6] indicated that about 10^8 cycles of the magnetic force was achieved in Tevatron collars by reducing peak stress levels. Since the peak stresses in the Tevatron dipole are about 25,000 psi, it seems prudent to choose this level for the Pentevac dipole. Reducing the stress level from 47,000 psi to 25,000 psi without enlarging the outside diameter of the collar requires utilization of the cantilevering action that may be obtained if the conductors are distributed as in Figure 2. This more efficient use of collar space requires giving up the notion of nesting two Tevatron coil pairs.

Table 1 contains the magnet design parameters. All magnetostatic calculations are carried cut using theory presented previously.[7] Mechanical stresses are estimated from an elastic model that takes into account the preload condition, thermal cooldown, and magnetic forces.[8] The collaring force is calculated after a preload has been found that just reduces the compression to zero at the point of minimum stress in the conductor. In this determination, the magnet is cooled down and excited to 85kG. Further reduction of the preload causes regions of tension to appear in the conductor. By assumption, the conductor cannot support tensile stress. Integrating the stresses across the conductor or the collar at room temperature with no field gives the collaring force.

In this design, only fields in a two dimensional section have been employed. The effects of coil end terminations can be included after magnet lengths have been determined. In general, conductor placements can be obtained including end effects that yield the same multipole purity as that found for the two dimensional section.

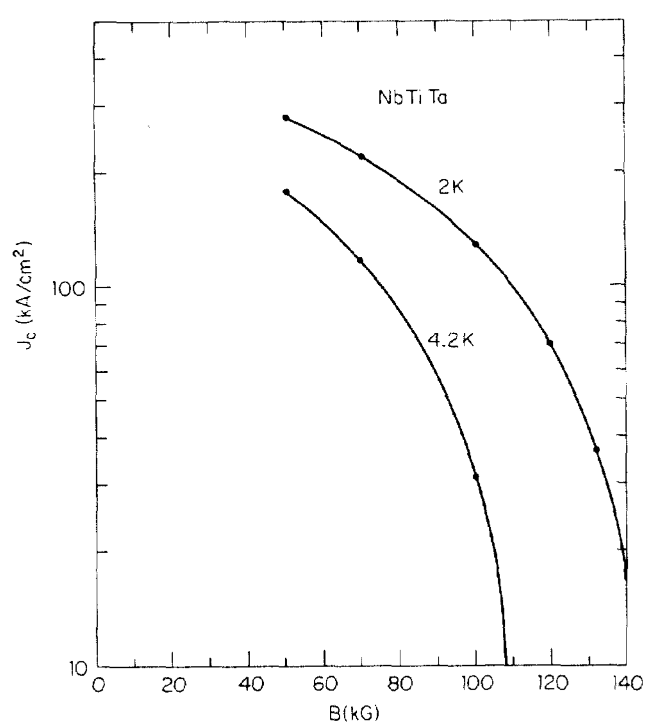

Figure 1. Critical Current Density vs. Magnetic Induction in NbTiTa.

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TABLE 1

Design Parameters for Four-Shell Dipole

Central Magnetic Field	85kG.
Bore Diameter	2.5 in.
Radius of Iron Shield	5.00 in.
Conductor Strand Diameter	.025 in.
Strands per Cable	23
Cable Size (overall without insulation)	.307 in. by .050 in.
Cable Keystone	+.005/-.005 in.
Cable Wrap (effective)	.0035 in.
Cable Current	4523 A
Peak Field on Conductor	87.5kG
Critical Current Density (Fig. 1)	165kA/cm^2
Copper to Superconductor Ratio (by volume)	1.8 ÷ 1
Filling Factor of Cable	.9
Average Current Density (86% ss)	295kA/in.^{2}

Conductor Placement

Layer	Turns/Quadrant	θ_s(Deg)	θ_f(Deg)	R_1(in.)	R_2(in.)
1	33	.20	77.58	1.250	1.564
2	31	.16	57.80	1.585	1.899
3	27	.14	41.49	1.920	2.234
4	22	.12	29.48	2.255	2.569

Peak Field on Inner Surface of Iron Shield	19.4kG
Field Quality ($\Delta B/B$ at ±.75 in.)	±.01 per cent

Multipole Quality (B_n/B_1 at ± 1 in.)

Harmonic	B_n/B_1	Harmonic	B_n/B_1
1	1.000000	11	.000636
3	.000000	13	-.000484
5	.000000	15	.000234
7	.000000	17	-.000115
9	-.000855	19	.000031

Off-Center Displacement Force

F_x (per inch of length per .010 inch displ)	16 lb/in.
F_y (per inch of length per .010 inch displ.)	16 lb/in.

Force on Conductors (first quadrant)

F_x (average per conductor)	86 lb/in.
F_y (average per conductor)	-52 lb/in.

Collar Outer Radius	4.00 in.
Collaring Force	5100 lb/in.
Peak Stresses	
Conductor	-7400 lb/in.^{2}
Collar	25000 lb/in.^{2}

Conductor Motion due to Magnetic Field

Radial : ΔU_r(in.) = .0002 + .0016 cos 2θ

Azimuthal : ΔU_θ(in.) = - .0020 sin 2θ

Longitudinal: ΔU_z(in.) = .09

Multipoles Introduced by Conductor Motion ($\Delta Bn/B_1$ at ± 1 in.)

Pole	Harmonic	$\Delta Bn/B_1$
Dipole	1	-.0002
Sextupole	3	-.0002

Stored Energy (effective length of 252 in.)	1.6 MJ
Magnet Size	22 in. by 15 in.

Problem Areas

A comparison of the parameters with those of the Tevatron dipole indicates areas in which additional effort will be needed. First, the collaring force being about 4 times that required in the Tevatron[9] may be excessive for the insulation system. Corrective measures will undoubtedly increase the space allotted for conductors and hence reduce the effective current density. Secondly, the suspension system must counteract an off-center displacement about twice as large as that in the Tevatron. The stiffer suspension must be longer to reduce an otherwise increased heat load. Thirdly, the stored energy for the same length magnet is about 4 times as large as that in the Tevatron. Quench protection will be a correspondingly greater problem. Finally, operation at 2K instead of 4.2K requires a reconsideration of the cooling system. While the radial thickness allotted to the cryostat and suspension system is only 1 inch, increasing this to 1.5 inches only requires a 2 percent increase in current in which case the magnet would be operating at 88 percent of critical current. Since less flux is returned through the iron, the overall magnet size remains the same.

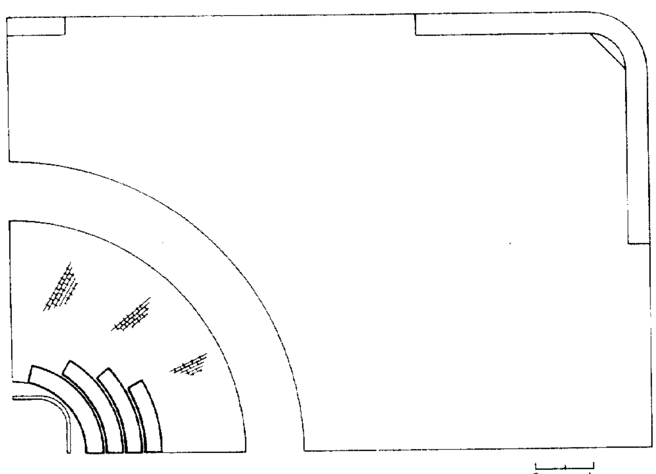

Figure 2. Possible Four Shell 85kG Dipole Magnet Cross Section (first quadrant).

Undoubtedly the list is much longer, but the advent of the alloy NbTiTa overcomes a few problems in attempting to obtain higher magnetic fields.

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