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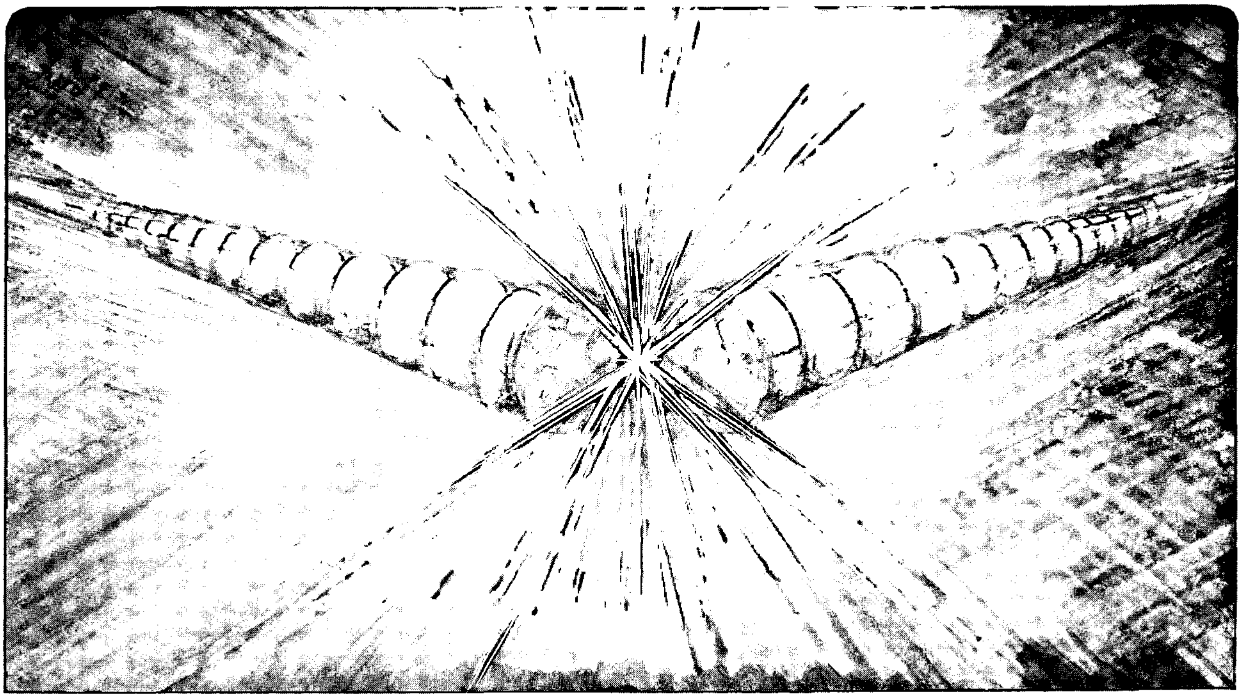

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Design of a 16 T Nb3Sn Twin Dipole with a Window-Frame Conductor Layout*

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Design of a 16T Nb_3Sn Twin Bore Accelerator Dipole with a Window-Frame Conductor Layout

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Abstract --- **A simplified design study of a 16T Nb_3Sn twin bore accelerator dipole magnet is presented. The philosophy behind the study is to design a high field magnet with a coil structure optimized for a reasonable Lorentz-load and easy of construction. The coils are of the rectangular window-frame type with modular flat pancake windings, thus eliminating the need for complex coil return ends. The magnetic and structural design is presented and a comparison is made with existing coil layouts for high field magnets.**

I. INTRODUCTION

When designing accelerator type dipole magnets one is always trying to optimize the maximum field while keeping the conductor volume to a minimum. This need for efficiency is usually driven by the price of the magnet, which is primarily based on the price of the superconductor used. A design optimized for efficiency will almost always result in a so-called "cosine-theta" conductor layout [1], in which the current blocks occupy the free surface of two overlapping ellipses. In the ideal case this will generate a perfect dipole field in the overlapping region. A cosine-theta design uses the least amount of conductor possible to attain a desired field in the bore, but results in complex coil return ends which require careful design and optimization to minimize the mechanical load in case Nb_3Sn is used [2].

If the operating field is pushed higher than about 10 T, the mechanical load on the superconductor becomes a major design factor [3]. By pushing for more and more efficient designs one also increases the Lorentz load on the superconductor due to the fact that the current density is higher and the total conductor volume supporting the load is smaller. This means that above a certain field it becomes interesting again to look at different coil geometries. Although other layouts like block designs or a pipe design [4] might not make efficient use of the superconductor, they may decrease the mechanical load and load to easier coil construction, thus resulting in cheaper magnets.

This paper describes a simplified design study done to determine the feasibility of a block design for a twin bore 16 T accelerator type dipole magnet. Special emphasis is put on the simplicity of the coil ends and keeping the Lorentz load on the superconductor within reasonable limits. A short mechanical analysis is presented, followed by a harmonic optimization at full operating current.

II. COIL RETURN ENDS

The primary idea behind the design of a twin bore accelerator dipole magnet using flat pancake windings is the fact that the coil ends in cosine-theta designs usually cause many problems. The return ends in dipole magnets must support a high compressive load due to the Lorentz forces trying to stretch the coil when the magnet is energized. These forces scale with the square of the current, and are in the order of 800 kN for the 13 T dipole "D20" [2], and will be about 1.2 MN for a 16 T dipole magnet. The high mechanical load, combined with the complex geometry required to minimize the harmonics in the magnetic field and to keep the field from peaking in the ends, results in a difficult engineering problem. Fig. 1 shows a typical coil end for a cosine-theta design dipole magnet.

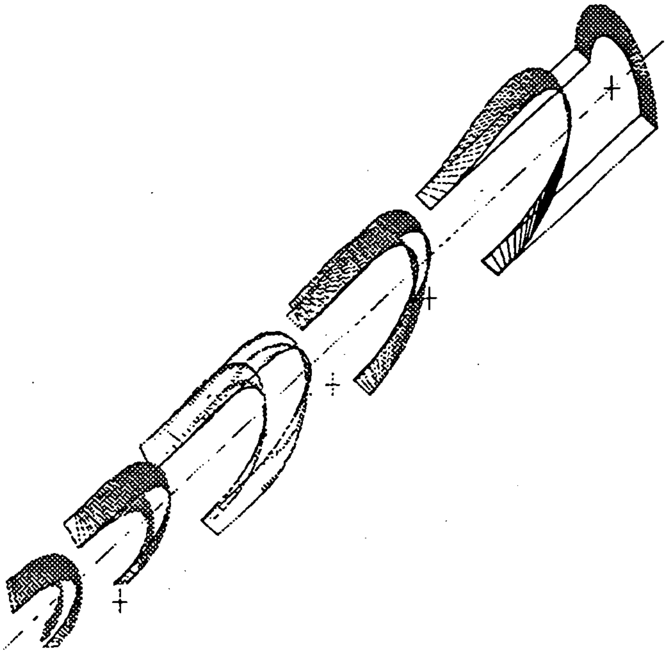

Fig.1. A typical set of coil return pieces for a cosine-theta layout.

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Several different design philosophies have been developed for the coil ends. An elegant pragmatic solution of wrapping the cables around the pole supported by thin stainless steel sheets, then filling the voids with ceramic material before reaction, and replacing the filler after reaction is reported in [1]. Other solutions are based on a predetermined path for each cable, i.e. based on constant perimeter curves or by approximating the path of a sheet of solid material [5]. The latter methods usually result in mathematically smooth coil return ends that will not fit the real cable very well, thus resulting in additional strain on the conductor. Furthermore, construction of the filler pieces for such end designs require complex 5-axes NC-machining operations, thereby considerably increasing the total price of the magnet.

To avoid the problem of complex coil ends completely one can design the coil windings to stay clear of the beam-pipe at all times. If the conductor does not have to intersect the beam-pipe, no complex turns have to be made, and the winding design is reduced to a stack of flat pancake windings. By allowing the correct amount of spacing between the pancakes one can tune the harmonics in the longitudinal direction and smooth out any peaks in the magnetic field at the ends. The end pieces required for the conductor spacing are simple flat parts requiring only one axis for cutting.

III. A 16T TWIN BORE BLOCK DESIGN

The goal of this design is to demonstrate the feasibility of a 16 T twin bore accelerator dipole magnet using flat pancake windings. Further restrictions are the maximum compressive load on the superconductor is limited to 150 MPa and the fact that the coils cannot intersect the beam pipe. The field goal of 16 T is chosen as a logical step for a next generation of accelerator dipole magnets.

The magnet design consists of the following steps :

1) the rough magnetic layout yielding 16 T in a 58 mm bore with 180 mm spacing between the beam pipes, no iron;
2) a rough finite element analysis of the mechanics of such a design;
3) further analysis of the magnetic design, including optimization of the field harmonics and a finite permeability rectangular iron yoke.

The rough magnetic layout without iron is performed with a custom written code using analytical functions describing the magnetic field in the complex plane. This method is used to speed up the iteration process, but does not provide for an accurate description of the field near the conductors.

Next, a 2D coil geometry is analyzed for its mechanical design using finite element analysis in ANSYS [6]. Two possible constraining methods are checked, one using an aluminum shrink-bar and a stainless-steel wire wrapped around the coil to control prestress, the other using an aluminum shrink cylinder around the entire structure.

TABLE I
MECHANICAL ANALYSIS SUMMARY : LOADS

Location	At 4.2 K [MPa]	Energized [MPa]
A (inner coil left)	40	130
B (inner coil right)	50	145
C (outer coil left)	40	110
D (outer coil right)	50	125
E (top beam pipe)	70	290
F (top return coil)	60	110

The wire-wind method seems to be the best method to load the structure, since it is controllable for accurate prestress, and reversible in case of unforeseen problems during the process. Table I. lists the mechanical analysis results for the simplified coil design shown in Fig.2 using a wire-wind prestress mechanism and an aluminum shrink-bar.

With the rough mechanical analysis showing the load on the conductor being within reasonable limits, a further optimization of the coil structure is performed. The goal is to reduce the amount of conductor used to a minimum while keeping the maximum Lorentz load below the set limit of 150 MPa. Also the field harmonics are optimized to below one unit (1 unit = $B_n \times 10^4 / B_0$ with B_n the n^th^ multipole).

After the coil is optimized for minimum conductor volume and the field harmonics are within limits, the finite permeability iron is introduced, and the multipoles are optimized again to solve for slight changes due to the saturation effects in the iron yoke. A fluxline plot for the real iron case is shown in Fig.3. The results from the multipole optimization are shown in Table 2.

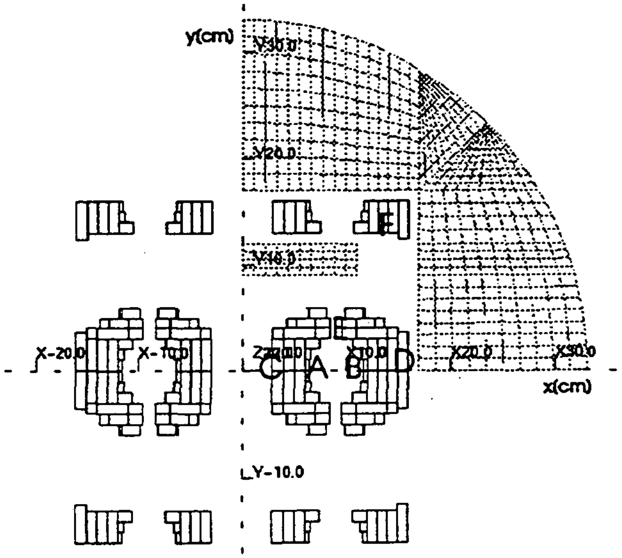

Fig.2. Twin-bore coil layout : stress analysis listed in Table. I.

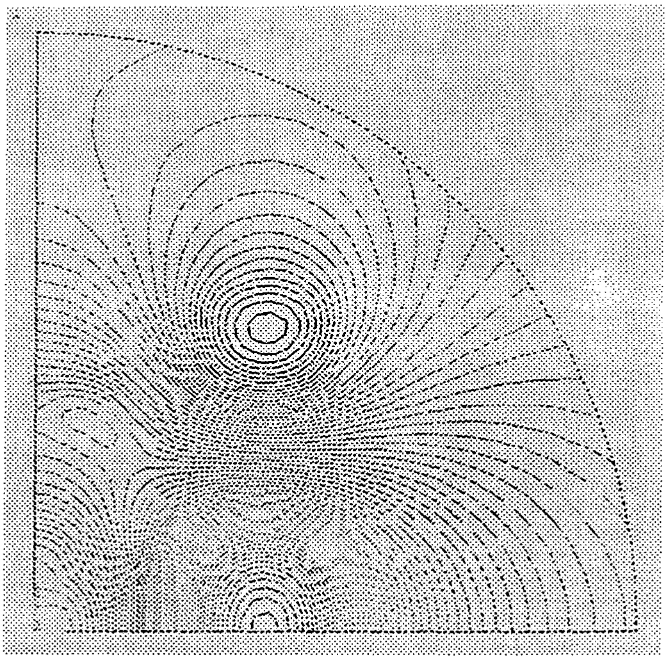

Fig.3. Fluxline plot with real iron yoke.

The change of the multipoles with the current is controlled by adjusting the current in the outer layer to minimize the harmonics. A full study of the change in the harmonics remains to be done; however, the design will use two currents with current programming to keep the multipoles within the set tolerances.

The layout of the fully optimized magnet is shown in Fig.4. and Fig.5. Fig.4 shows the cross-section of the coils and iron yoke with the calculated y-component of the magnetic field, while Fig.5 illustrates the direction of winding of the separate coils. All horizontal windings that would normally be bent up over the beam pipe in the ends are rotated by 90° and returned vertically. The horizontal coils that would not interfere with the beam pipe in the first place are returned directly. The geometry requires more superconductor volume to reach the same bore field compared to a cosine-theta design, but the compressive forces are lower and the coil ends can be constructed without difficulty.

TABLE II

FIELD HARMONIC ANALYSIS

Skew	[units]	Normal	[units]
		B_y (dipole field)	16.061
A_2	0.480	B_2	0.874
A_3	-0.205	B_3	-0.730
A_4	0.062	B_4	-0.160
A_5	0.032	B_5	0.006
A_6	0.024	B_6	0.002
A_7	0.017	B_7	0.0004
A_8	0.014	B_8	0.0007
A_9	0.008	B_9	0.0002

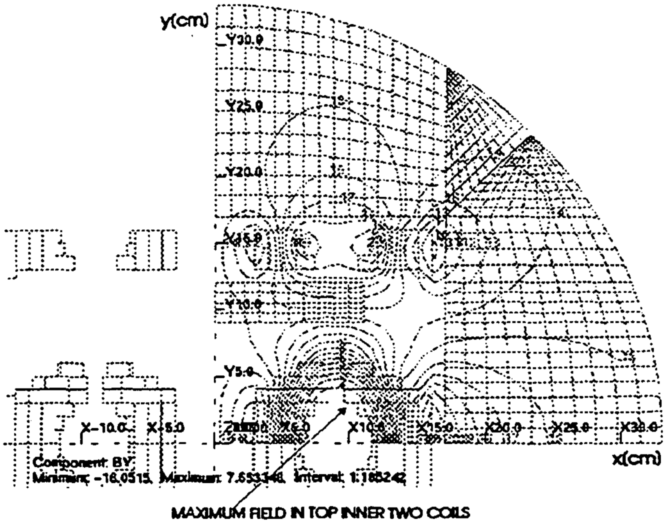

Fig.4. Coil and iron yoke cross-section with calculated y-component of the magnetic field

The magnetic field reaches its maximum value at the conductor in the top inner two coils, and peaks at 16.015 T. The design uses three different cables with each separate current densities, and requires two currents. The overall current densities are 730 A/mm^2 at 13 T for the middle blocks, 400 A/mm^2 at 14.6 T for the outer blocks and 220 A/mm^2 at 16 T for the inner blocks near the bore. With the present performance of Nb_3Sn cables these values a realistic for use in this design [7],[8]. No cable size has been fixed for this design yet. Fig. 6 shows the y-component of the magnetic field from the center through the coils.

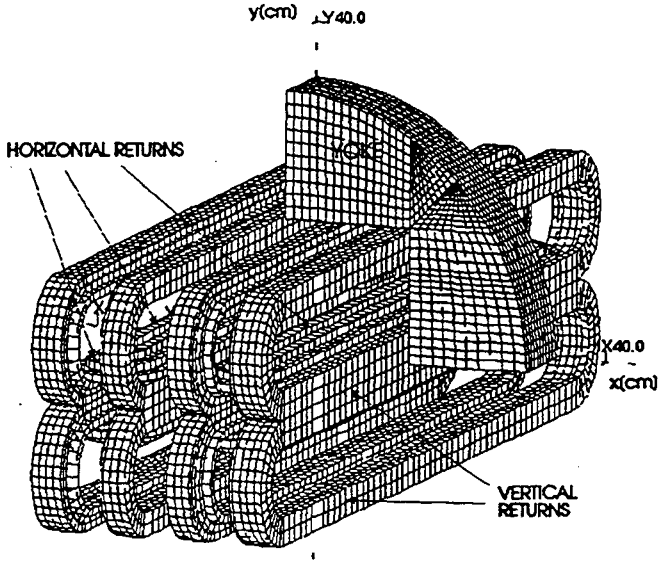

Fig.5. Layout of the coil windings. Note the vertical return of the outer segments and the horizontal return of the top inner segments.

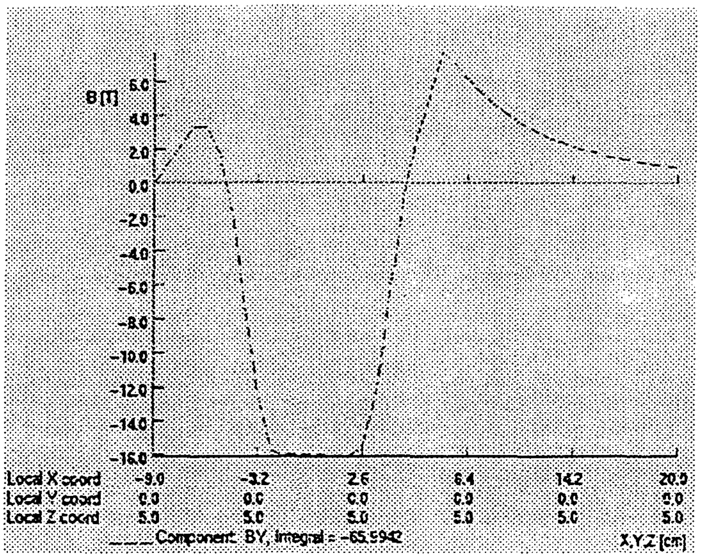

Fig.6. B_y-component of the magnetic field from the center of the magnet to the edge of the iron yoke.

IV. CONCLUSIONS

This design study shows that one should not automatically adhere to proven magnet designs for higher field accelerator dipoles. A viable alternative design is shown with the mechanical loads within set limits at the expense of some more conductor volume compared to a cosine-theta design.

It is possible to minimize the higher field harmonics by shaping the coil; however, when operating at lower currents, the effects from the iron yoke dominate, thereby creating the need for current programming with two currents to keep the multipoles within limits.

The design and construction a 16 T accelerator dipole is possible with existing Nb_3Sn conductor material, however, to create a more compact design a higher critical current density at 16 T would be desired.

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