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ISABELLE DIPOLE AND QUADRUPOLE COIL CONFIGURATIONS*

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Summary

The coil configurations of the ISABELLE dipole and quadrupole magnets have been reviewed and a number of improvements were suggested for incorporation into the final design. The coil designs are basically single layer multiple block approximations to cosine current distributions, wound from a high aspect ratio non-keystoned braided conductor. The blocks are separated by knife-edge wedges to maximize the quench propagation velocity. The current density variation is obtained by an appropriate distribution of the spacer turns and, to a lesser degree, by the wedge locations. The use of inert turns is necessary to minimize the peak field enhancement both in the ends and in the two dimensional section. Schemes for deriving turns distributions yielding harmonic coefficients satisfying the stringent ISABELLE tolerances on field uniformity, while allowing for simplicity in winding and taking into account quench propagation considerations, will be discussed, as well as our approach to the coil end configuration.

Introduction

The coil configurations for the ISABELLE[1] dipole and quadrupole magnets are single layer multiple block approximations to cosine current distributions, wound from a high aspect ratio non-keystoned braided conductor. The current blocks are separated by wedges with knife-edge to maximize the quench propagation velocity. The current density variation is obtained by an appropriate distribution of braided inert spacer turns. The 2-dimensional field distribution includes built-in sextupole and decapole terms to compensate for saturation-induced terms at high field. Presently the end harmonics are compensated by end spacers located in the dipole coil ends, although the alternative possibility exists to compensate for the end effects by appropriately modifying the 2-D current distribution. The use of inert turns is also desirable for minimizing the peak field enhancement in the ends as well as in the two-dimensional section.

The present paper reviews a number of improvements recently proposed for incorporation in the two-dimensional coil design. The design characteristics addressed were primarily those which lead to:

a) Simplifications in coil winding

b) Optimum quench propagation

c) Field distribution meeting storage ring tolerances.

The ground rule for the design review limited the modifications to those compatible with the winding techniques developed over the past several years, with minimal effect on existing cooling.

We first review briefly the computational procedure used in designing the ISABELLE coil configuration generally. Next we discuss several stages of revision of the cross section of the dipole which, though still somewhat tentative, has been the principal focus of attention. (Note that the design considerations discussed here, i.e., items a through c above, do not address the equally critical area of magnet training and coil support.) Finally, the status of the main lattice quadrupole design is briefly indicated.

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Computational Methods, Dipole Configuration Generally

There are two conceptual approaches to achieving a uniform field (or gradient) by the so-called sector coil geometry. The Beth[2] approach is based on sectors of equal azimuthal extent, with variable current density, and separated by sharp wedges. This may be approximated with inert spacer turns and a non-keystoned block geometry. In a practical design, rounding off to integral turns introduces wedges of finite thickness, which may be replaced by additional inert turns. The Coupland-Halbach[3,4] approach is based on sectors of unequal azimuthal width, carrying uniform current density. The ISABELLE magnets in the past have been basically designed according to the former (modified Beth) scheme. Typically, the dipole winding scheme, Fig. 1, consists of six blocks. Quadrufilar turns (i.e., one superconducting turn co-wrapped with three inert turns) are repeated a number of times in block no. 1 (counting from the pole). Proceeding to block 2, inert turns are discarded, leaving in the succeeding blocks bifilar and monofilar turns in varying proportions as demanded by the field shape. An undesirable feature of this design solution has been the presence of so-called inert turn restarts in several of the blocks, as a consequence of the aforesaid integral turn constraint, wherein a sequence of monofilar turns is periodically interrupted by the reintroduction of a discrete bundle of bifilar turns adjacent to a (sharp) wedge. These "bifilar islands" or discontinuities complicate the winding process and, more importantly, seriously impede the azimuthal propagation of the normal zone in case of a quench. Moreover, the multifilar turns, while advantageous with regard to minimizing peak field enhancement, and contributing to coil stability, require manual applications of the fiberglass insulation.

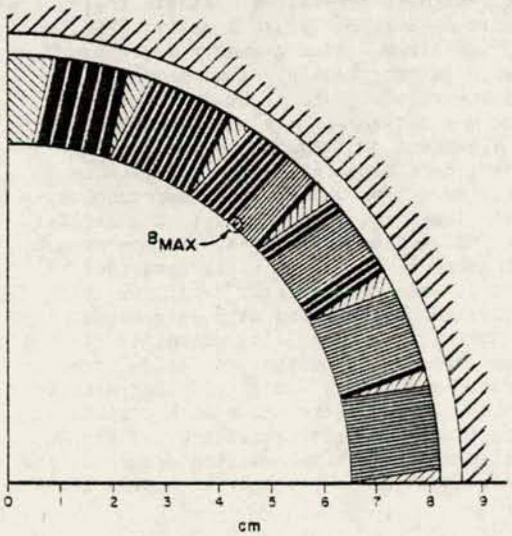

Fig. 1. Present design for ISABELLE dipole cross section.

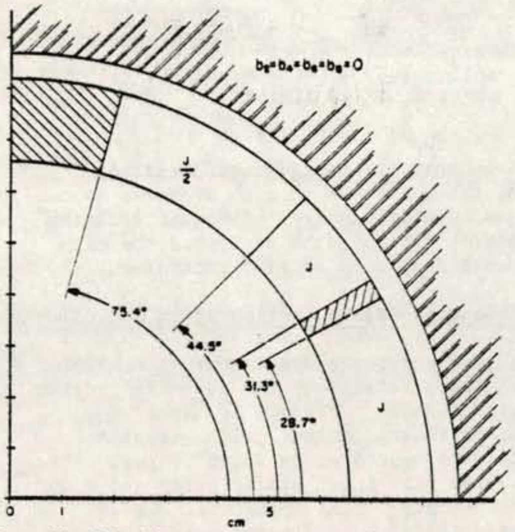

Fig. 2. Idealized sector geometry for revised dipole configurations.

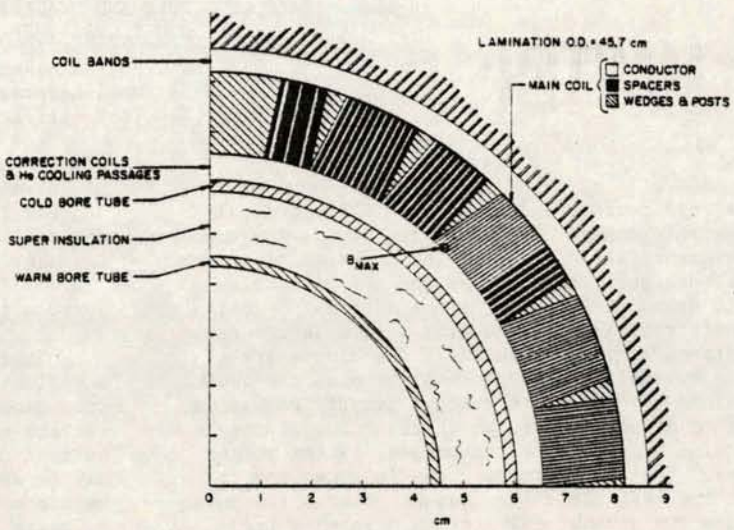

Fig. 3. Six-block ISABELLE dipole geometry with single inert turn restart. The ISABELLE magnet bore tube components are also indicated.

The design solutions discussed here incorporate various simplifications and improvements in the coil design, achieved by augmenting the numerical computational design procedure -- which is performed with the aid of the computer program MAGFLD[5] -- with an analytical calculation as the starting point[6] assuming an idealized current distribution of a sector geometry, an example of which is shown in Fig. 2. The angular extent of the sectors are chosen such that $b_2 = b_4 = b_6 = b_8 = 0$, where b_n is defined by the following expansion of the vertical field on the median plane of a dipole without random errors:

$$B_y = B_o(1+b_2x^2+b_4x^4+...) \qquad (1)$$

To allow for the non-keystoned conductor the analytical solution assumes the current density to vary inversely with radius.

Possible Dipole Designs

Idealized sector geometry solutions of the type discussed above may be implemented in practice by a block geometry utilizing knife-edge wedges. Figure 3 is a six-block design incorporating a single inert turn restart, compared to 3 in our present design (Fig. 1). The underlying idealized sector geometry for this particular design is not precisely that shown in Fig. 2, due to the requirements of quadrufilar turns in block 1, but one not shown here which includes a sector with J/4 current density. Note the presence of an inert (copper) turn adjacent to the post. Recent ISABELLE magnets have been wound with a superconducting turn in this location, in contrast to the earliest members of our "MK" series of magnets. We now attach considerable importance to the stability provided by locating copper in this particularly sensitive coil region. This design can be wound with very minor changes in the present tooling. Its principal advantages over the present design are, aside from being considerably simpler to wind: ~ 2% increase in transfer function; field distribution more compatible with present estimates of iron saturation and (by simple alteration in the bifilar winding sequence) end effects; near optimum quench propagation characteristics.

In a variant on the Fig. 3 design, not shown, a single restart remains, but the quadrufilar sequence of turns in block 1 is eliminated by adopting a five block geometry with only bifilar turns in blocks 1 and 2; the single restart occurs at the edge of block 3 closest to the mid-plane. This design approach also yields harmonics of storage ring quality.

Two closely related five block design represent our most recent effort in the direction of coil simplicity, shown in Figs. 4 and 5. Both eliminate restarts while retaining ISABELLE field quality by the introduction of a single (metal) wedge of finite thickness. The Fig. 4 geometry is based on bifilar and monofilar turns only. That in Fig. 5 assumes a conductor of twice the present nominal ISABELLE braid thickness* in blocks 1 and 2. The reduction in current density in this region should considerably enhance coil stability. With the possibility of implementing either of these designs in mind, an experimental investigation of the quench propagation characteristics of the necessary thick wedge has been undertaken.

The central field transfer function as well as the leading allowed harmonics generated by the designs in Figs. 1, 3, 4 and 5 are listed in Table I.

Table I

	Fig.1	Fig.3	Fig.4	Fig.5	Systematic Tolerances	
B_o/I	13.59	13.88	13.93	13.93		G/A
b_2	-206	-243	-186	-190	a	$\times 10^{-6}/cm^2$
b_4	-114	239	153	199	a	$\times 10^{-8}/cm^4$
b_6	-50	9	48	21	63	$\times 10^{-10}/cm^6$
b_8	1000	830	-700	-700	1016	$\times 10^{-12}/cm^8$

a) correction coils available.

Here the "built-in" values of b_2 and b_4 are of appropriate magnitude and sign (for the Figs. 3, 4, and 5 designs, in contrast to that of Fig. 1) to compensate for present estimates of iron saturation effects, and the harmonics are compatible with the harmonic contributions from the ends as presently compensated.

* Presently 0.028 in (insulated). We expect the thickness will grow to 0.030" in forthcoming magnets.

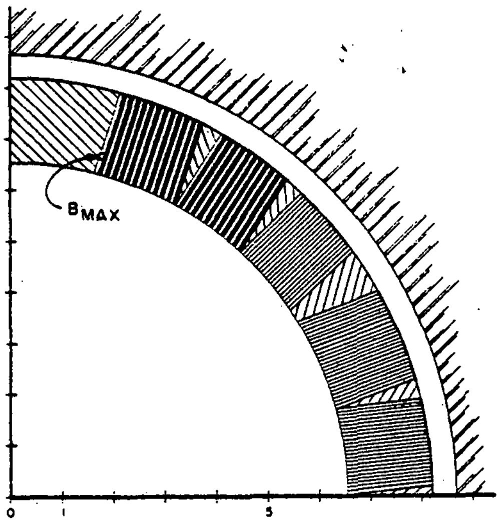

Fig. 4. Five-block dipole geometry without inert turn restarts, based on bifilar and monofilar turns only.

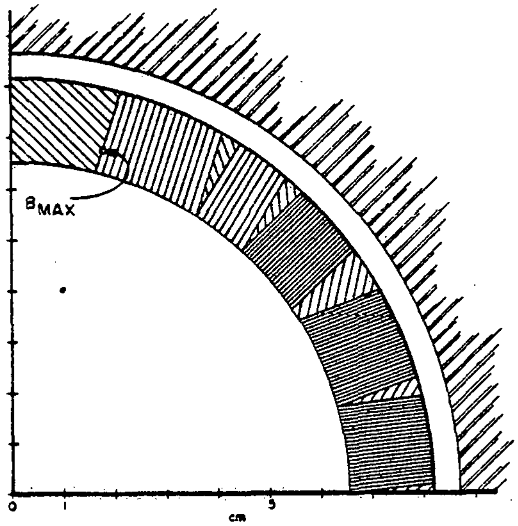

Fig. 5. Five-block dipole geometry without inert turn restarts and reduced current density in blocks 1 and 2.

A rather serious consequence of the 5-block design alternatives is an increase in the peak field ratio. Whereas for the geometry of Fig. 1 the (two-dimensional) enhancement, or B_{max}/B_o, is 3%, for the geometry of Figs. 4 and 5 this enhancement is 7.8% and 7.4%, respectively. Therefore, it may be necessary to incorporate spacers in the coil ends to prevent the end peak field from becoming excessive. Alternatively it has been suggested[7)] that the peak field problem be eliminated by incorporating aluminum spacers between the iron laminations in the end region of the iron core, thus effectively reducing the iron permeability here.

One further variant on the Fig. 3 cross section should be noted, shown in Fig. 6. It retains the original six blocks, with the number of multifilar and monofilar turns per block altered somewhat, and has no inert turn restarts. Elimination of the restart in the 6-block geometry is at the expense of some deterioration of field quality which is, however, quite adequate for R&D magnet purposes. Since, moreover, the tooling for the design remains basically unaltered, all our recent R&D dipoles are being wound according to this design.

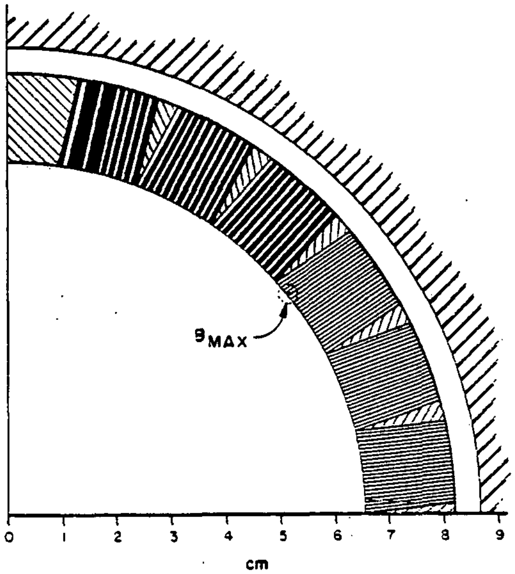

Fig. 6. Six-block dipole geometry for ISABELLE R&D dipoles.

Quadrupole Configuration

The ISABELLE quadrupole design is based on a 3-block cosine current distribution, employing the same conductor and similar inert turn scheme as in the dipole for grading the current density. The present design, Fig. 7, relies on inert turn restarts for obtaining the required field shape with the use of sharp wedges, also analogous to the dipole case. By means of the analytic-numerical computational approach indicated we have re-examined the quadrupole design with the simplifications noted earlier in mind. Fig. 8 shows the resulting conceptual sector geometry, from which the practical design of Fig. 9 was obtained. The most recent pre-production prototype quadrupoles are now being wound according to this design. The central gradient transfer function, as well as leading harmonics, for this quadrupole and that of Fig. 7, are listed in Table II.

Table II

	Figure 7	Figure 9	Systematic Tolerances	
G_o/I	1.63	1.70		$G/cm\ A^{-1}$
b_5	-6.2	13.0	a	$x10^{-8}/cm^5$
b_9	-1.2	-2.5	3.8	$x10^{-10}/cm^9$

a) correction coils available.

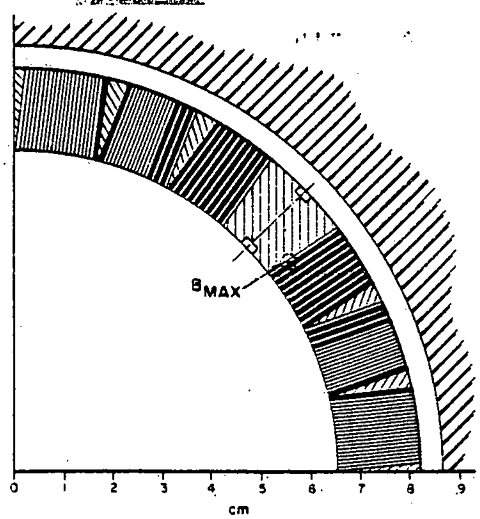

Fig. 7. Present design for ISABELLE quadrupole cross section.

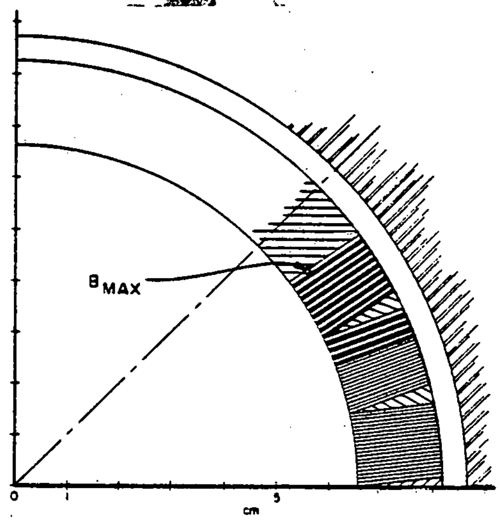

Fig. 9. Revised coil configuration for ISABELLE prototype quadrupoles.

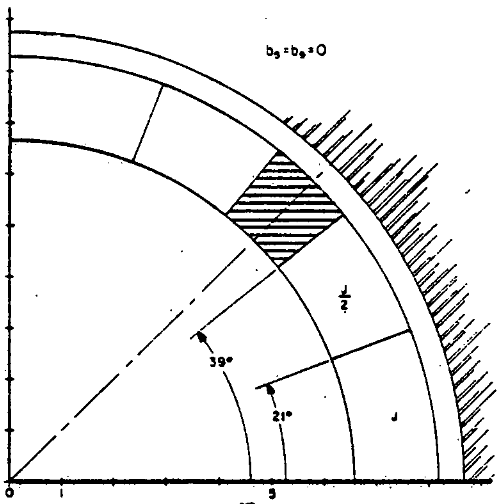

Fig. 8. Conceptual sector geometry for revised quadrupole configuration.

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