COLD IRON COS Θ MAGNET OPTION FOR THE SSC*

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Introduction

In this paper we review first the evolution over the past several years of a cold iron, high field cos θ magnet design option for the SSC. We note the collaborative approach pursued by BNL and LBL on the 2-in-1 option, and the culmination of this effort in the tests of the BNL 4.5 m model magnets. Next, we discuss the subsequent 1-in-1 option being pursued jointly by BNL, Fermilab and LBL.

During the initial period, 1983-84, the cold iron SSC program progressed in several stages, all based on the 2-in-1 (two coils in a common iron yoke) concept: first, and basically a BNL effort, a 2-in-1 dipole of 3.2 cm aperture was developed, to accommodate either NbTi or Nb_3Sn to achieve an eventual field of 6.5 T to 7.5 T, respectively. We designate this SSC Design Ao. A modified version of this later became the workhorse of the BNL/LBL collaboration, namely a geometrically similar dipole of 4.0 cm aperture, based on the high homogeneity NbTi conductor then under development at the University of Wisconsin and with industry, with an expected field of about 6.5 T. This magnet was featured in SSC Reference Design A. Finally, in the last quarter of 1984 Design A underwent an important modification, with the addition of stainless steel collars. This collared 2-in-1 dipole of 4.0 cm aperture we designate SSC Design A'.

Meanwhile, a parallel development of an ironless cos θ magnet at Fermilab, described in an earlier paper by E. Fisk, became the basis for Reference Design B, a medium-field SSC option. In the winter of 1984-85, the three laboratories, in order to minimize technical options at this stage and to more efficiently use scarce R&D funds, adopted a common cos θ cold iron design incorporating the most promising features of Designs A' and B. This paper ends with a brief status report of this SSC Design D option, a 1-in-1 cold iron, collared dipole of 4.0 cm aperture which is expected to achieve 6.5 T.

Magnet Features

The thrust of the cold iron cos θ magnet program has been predicated on three design concepts for minimizing the cost of the SSC. One, a high operating field, to be achieved first by exploiting improved NbTi conductor with the longer-range hope of substituting prereacted Nb_3Sn. To allow for this later possibility, yet retaining the smallest possible magnet aperture (the second basic design concept) it was necessary to flare out the coil ends to increase the minimum coil bending radius (due to the brittle nature of niobium tin) and clamp these "dog bone" ends in stainless steel. (A secondary benefit of flared ends is reducing the peak end field associated with straight coils without resorting to the usual spacers between end turns.) The coil aperture in the initial 2-in-1 model magnets is 3.2 cm.

Reference Designs A and its modified version A', as well as Design D, call for an aperture of 4.0 cm. Although these later designs all presuppose NbTi, the flared ends were retained in the models as a strictly provisional design feature; ongoing R&D should settle the need, if any, for flared ends with NbTi.

In a 2-in-1 dipole, the two adjacent coil systems bending the counter-rotating beams in a pp collider are mounted side-by-side in a common yoke, with one bore serving as the return path for the flux from the other bore. Due to the need for less iron, the total weight of iron is just slightly more than for each of the single magnets in a conventional 1-in-1 design. There would be additional savings in cryostats and vacuum vessels--albeit with the possible penalty of a relatively more complicated magnet and less flexibility during the operating phase of the accelerator due to the coupled machines. A further important design parameter from the point of view of overall cost, obviously, is the magnet length (magnet ends are expensive, as stressed by R. Huson). In the designs discussed here the effective length will be 16.6 m. The SSC ring circumference corresponding to a guide field of 6.5 T is 90 km, and the number of 2-in-1 dipoles in Reference Design A is approximately 4000.

Magnet Details

Figure 1 shows a cross section of the 2-in-1, 3.2 cm aperture dipole, discussed in some detail by Dahl et al elsewhere in these proceedings. The yoke o.d. is 33.0 cm, and the center-to-center spacing between bores is 15.2 cm. In the present R&D phase, the bolted stainless steel yoke support vessel (which is also the helium cryostat) allows repeated reuse of the same yoke, and facilitates coil repair, if necessary. In a production design this vessel would be closed by automatic welding along the midplane as indicated in Figure 2 which shows the dipole of Reference Design A (the 4 cm aperture version). The flared coil ends are evident in Figure 3. The two-layer coils are wound from a 23-strand NbTi cable geometrically similar to that used for the CBA magnets and the Tevatron, insulated with a double wrap of Kapton followed by a layer of fiberglass-epoxy. In fact, three of the four magnets constructed utilized basically the same available cable, except with additional keystoning due to the smaller 3.2 cm aperture. One magnet model was wound from an early sample of high homogeneity NbTi cable. In Reference Design A (as well as D) optimum superconductor usage in the two-layer coil, where the field in the outer coil is lower, is realized by grading the cable according to current density. In the 3.2 cm aperture models this is simulated by separately powering the two coil layers.

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Magnet construction follows procedures developed in the CBA program. The individual coil sections are wound automatically on a convex mandrel, and then epoxy-cured under pressure in a precision mold. The yoke is pre-assembled from module blocks of glued laminations. During final magnet assembly, azimuthal prestress is applied to the coil package via the split, tensioned support shell, the shell being closed in a press by either bolting or welding. Friction is minimized by Teflon slip planes located between the yoke and support shell.

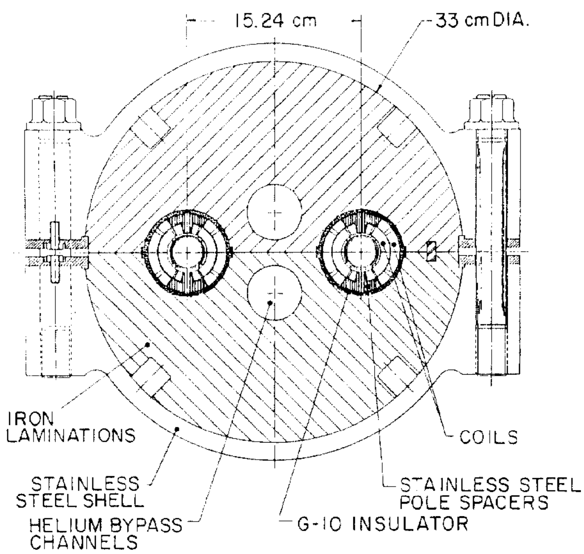

Figure 1. Cross section of 2-in-1 dipole of 3.2 cm aperture.

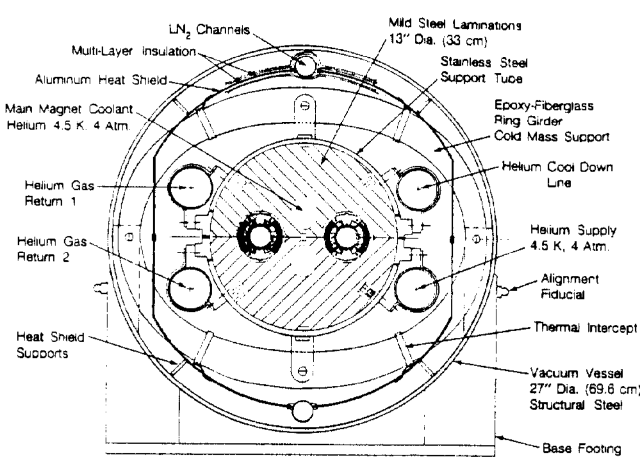

Figure 2. Dipole of Reference Design A, including cryostat, vacuum vessel and conceptual design for magnet support assembly.

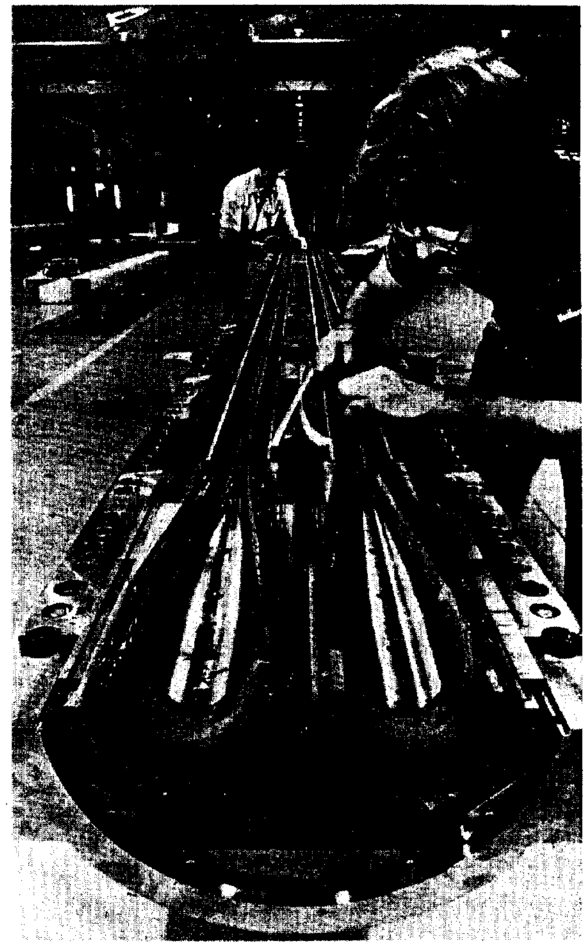

Figure. 3 Two-in-one dipole under construction, showing lower coil-in-yoke subassembly. The flared ends are very evident in this view.

Performance of Model Magnets

Four 4.5 m long NbTi dipoles of the 2-in-1, 3.2 cm aperture design have been constructed and tested; one of these is shown in Figure 4. Since these tests are discussed elsewhere, only the highlights of the results are touched on here. The training performance of the four magnets is summarized in Figure 5. At a liquid bath temperature of 4.5 K all four reached their conductor short sample performance, which varied from magnet to magnet due to available cable, with very little or no training. In the case of magnet no. 3, wound with the new successful high homogeneity conductor, this limit was 6.5 T; for the others it was less. In subcooled (~ 2.5 K) liquid, correspondingly higher fields were reached (7.8 T for no. 3) albeit with more training being required. Field quality was not an explicit objective in the first three dipoles. Thus, there were variations in assembly shims and other construction details, as well as rather large built-in (by design) allowed harmonics. The measured allowed harmonics were

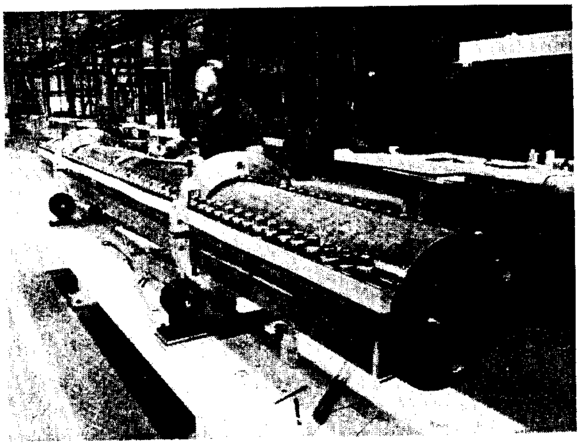

Figure 4. First 2-in-1 dipole undergoing inspection prior to testing.

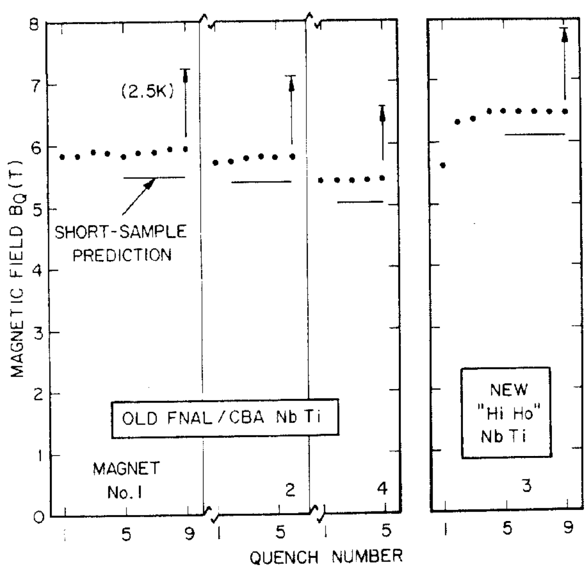

Figure 5. Quench performance of four 2-in-1 dipoles. "Old FNAL/CBA" indicates the use of NbTi conductor available from the Tevatron/CBA projects; "Hi Ho" indicates new high homogeneity conductor.

nevertheless within a few x 10^{-4} of the design values over the full excitation range from injection to operating field, as shown for the sextupole harmonic of either bore in Figure 6. In the fourth magnet the coil configuration was altered slightly, basically by removing two turns from the upper and lower coils, respectively, (thus reducing B_0/I and mainly accounting for the lower quench plateau of this magnet in Figure 5). The new built-in harmonics were only a few percent of the previous values, as shown for b_2 (and b_4) in Figure 7. A histogram of all unallowed harmonics through the 12-pole term for this magnet is shown in Figure 8. The results of this model program strengthen our belief that for the cos θ SSC option, one is able to accurately predict magnet performance with codes already developed.

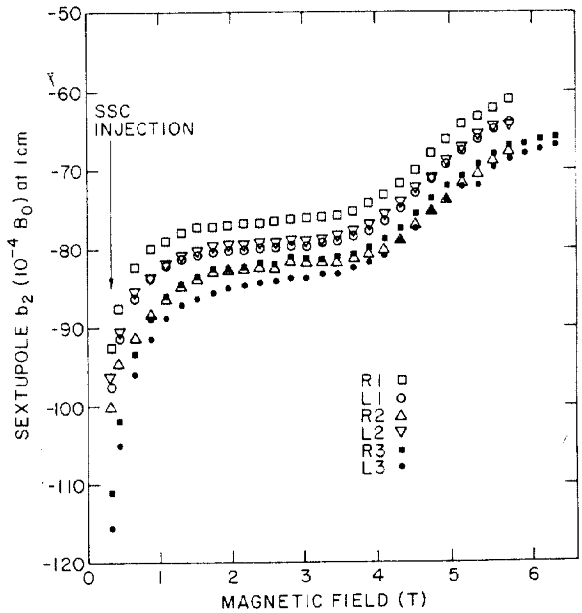

Figure 6. Sextupole harmonic vs. field for three 2-in-1 dipoles.

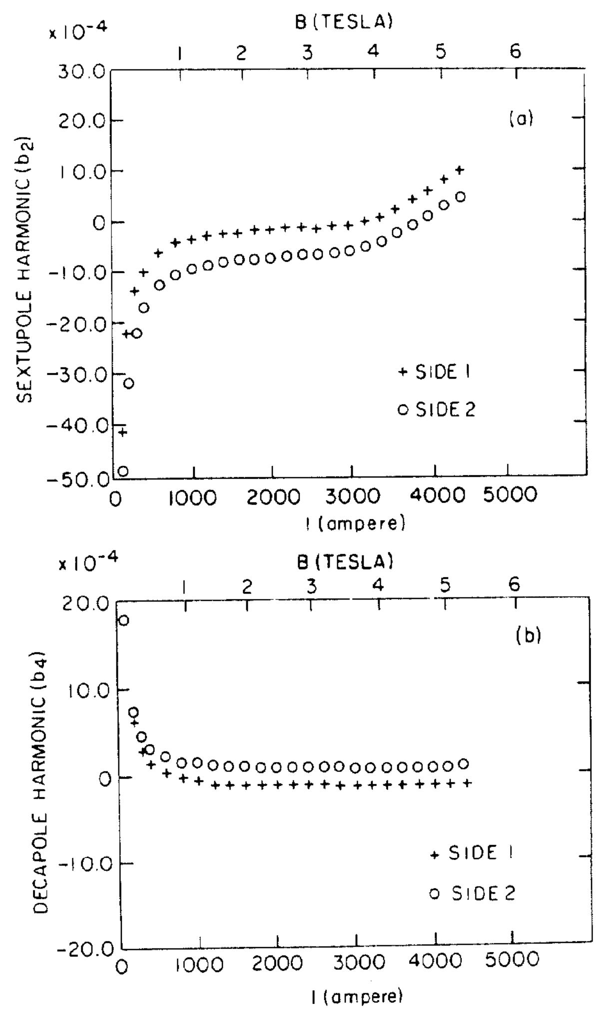

Figure 7. Sextupole and decapole harmonics in fourth 2-in-1 dipole.

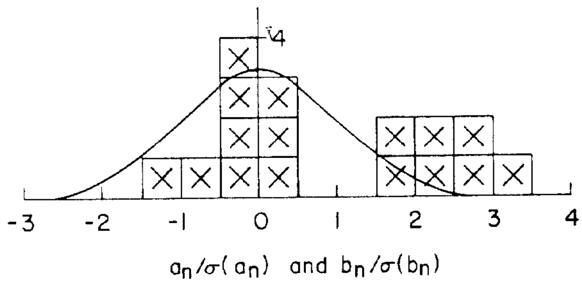

Figure 8. Unallowed multipoles in fourth 2-in-1 dipole, normalized to expected rms multipoles (Herrera et al, these proceedings).

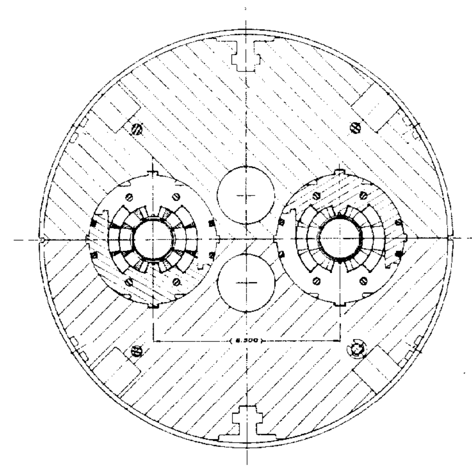

Figure 9. Cross section of collared version of 2-in-1 dipole (Design A').

3.2 cm Aperture Program: Remaining Work

With successful testing of the fourth 4.5 m dipole of this series (the last dipole was built primarily to study in detail cross talk between the bores in 2-in-1 magnets), the NbTi phase of the 2-in-1 model program has essentially been concluded--further iterations of the various design features passing on to Design D, below. The Nb_3Sn program continues, however, with lower priority. As of May, six inner and six outer 4.5 m long Nb_3Sn coils sized for 3.2 cm aperture magnets have been wound, awaiting close inspection in the R&D group for mechanical integrity before undergoing full-scale tests in the 2-in-1 magnet configuration. More Nb_3Sn cable is on hand for additional magnets, pending the outcome of the first tests.

Design D

As noted in the Introduction, the SSC cold iron cos θ magnet underwent a fairly rapid evolution, from a 2-in-1 dipole of 3.2 cm aperture to one of 4.0 cm, and then to the incorporation of coil collars (Figure 9). Collars simplify assembly in the iron yoke, especially in a 2-in-1 dipole, and provide the necessary restraint to maintain the coil under adequate compressive stress. Although (non-magnetic) collars result in some inevitable loss in contribution to the field from the iron yoke, an additional benefit from their presence is a decrease in the effect of iron saturation on the allowed harmonics. Since early 1985 the U. S. cold iron cos θ program, now joined by Fermilab, has focused on a 1-in-1 version of the 4 cm aperture collared magnet. This program will furnish an excellent data base for the basic cos θ option if the field or aperture should change in the course of fine tuning the SSC machine design. The continuing R&D on Design D will be largely applicable to either a 2-in-1 cold iron magnet (which, in view of the successful model series, we consider to be adequately demonstrated), a 1-in-1 cold iron magnet, or even a 1-in-1 warm iron magnet.

A cross section of the cold mass for dipole Design D, including collared coil, yoke and yoke containment vessel, is shown in Figure 10, and some basic magnet parameters associated with this option are summarized in Table I.

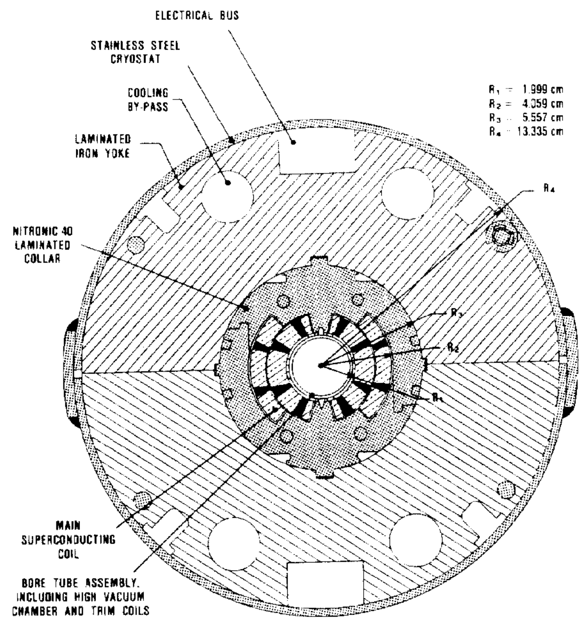

Figure 10. Cross section of dipole for Reference Design D.

Table I
SSC Design D
Basic Magnet Parameters

Operating Field	6.5 T
Operating Current	6.44 kA
Magnetic Length	16.60 m
Number of Dipoles	7740
Bore Tube ID	3.3 cm
Coil ID	4.0 cm
Collar Thickness	1.5 cm
Yoke OD	26.7 cm
Vacuum Vessel OD	61.0 cm

Responsibilities for the various aspects of the continuing R&D program concerned with this magnet have been allocated among the collaborating laboratories essentially as follows: (1) BNL: conductor measurements, fabrication of 4.5 m models and 16.6 m demonstration magnets, magnet testing; (2) Fermilab: cryostat development and fabrication, exploratory lower cost production techniques by fabrication of 1 meter models of improved cross section; (3) LBL: superconductor R&D, 1 m model magnets to demonstrate superconducting wire and cable performance. New production-oriented laminated coil winding and curing fixtures for the 4.5 m program are now operational at BNL, with a first set of coils completed. The collaring press, as well as yoke assembly press, are nearly completed, with assembly of the first magnet expected in mid-June and tests later that month. Five more 4.5 m magnets are to follow between then and October 1. Preparations for a full length prototype magnet have also started, with good progress in a number of areas. These include the cryostat design, progressing well at Fermilab, full length fixture fabrication, and R&D on the overall bore tube assembly, including trim coils based on a promising ("Multiwire") commercial procedure. Progress also continues in laying out a magnet test facility incorporating MAGFLD, an existing magnet production test facility at BNL. A key component in testing full length SSC magnets will be the traveling field probe or "mole" also under development (Figure 11).

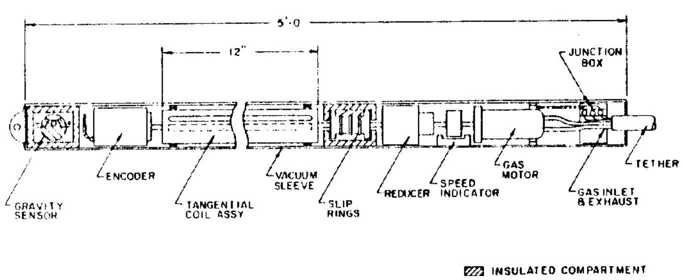

Figure 11. Traveling field probe under development.

Note added in proof: In the third week of June, tests were underway on the first 4.5 m dipole of Reference Design D, with a quench plateau of about 6.6 T attained at 4.5 K -- a performance closely reproducing that of a 1 m model tested earlier at LBL and wound from similar conductor.

Acknowledgements

In this short space, I have been unable to describe the comprehensive work being done at the University of Wisconsin, BNL, LBL and industry on the provision of advanced NbTi wire and cable. The results of this outstanding work make the high field option extremely cost effective and very attractive. The work at LBL on 1 meter models of the Design "D" cross section has been very effective in establishing its basic features and is described elsewhere. The highly successful cryostat development studies at Fermilab coupled with the outstanding ongoing performance of the Energy Doubler round out the data base required to demonstrate the success of an SSC built using the cos θ option. The resources of the three major laboratories, coupled with the production experience achieved with the Energy Doubler and the CBA models as well as the SSC technology transfer to industry planned for FY86, makes the cold-ion cos θ SSC option a formidable contender. In FY86 the R&D program will concentrate on cost optimization studies and systems testing of six full length magnets.

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