Superconducting Super Collider Laboratory

The SSC Dipole: Its Conceptual Origin and Early Design History

P. F. Dahl

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AND EARLY DESIGN HISTORY

P. F. Dahl

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, Texas 75237

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1.0 INTRODUCTION

The magnet system for the Superconducting Super Collider will likely remain the most ambitious—and challenging—application of superconducting technology for the foreseeable future (save possibly for the Large Hadron Collider initiative at CERN). The centerpiece of the system is the behemoth collider dipole magnet. Its design, still evolving in its detailed features, dates from the mid-1980's when it emerged as the winner in an early technical showdown that occupied the fledgling SSC project. However, some of its gross features can be traced back to three path-breaking superconducting accelerator initiatives under way a decade earlier—on the East Coast, on the West Coast, and in the Midwest. Other features have a still earlier legacy.

In the present report we chronicle the origins and chief milestones in the development of certain SSC dipole design concepts. Unfortunately, the chronicle must remain incomplete, with the design not yet frozen as we go to press and still subject to important modifications as the SSC Laboratory settles in near its future home in Ellis County, Texas, hard on the heels of a wide-ranging design review in the closing days of the SSC Central Design Group in (CDG) Berkeley [1-1]. Be that as it may, in what follows we concentrate on the early years in an attempt to recapitulate the birth of the dipole, taking as our point of departure the SSC Reference Designs Study (RDS) of 1984 (Section 2). In Section 3 we touch on the background for the various RDS options, including ISABELLE/CBA and the Tevatron. In Section 4 the narrative focuses on the two final protagonists, a high-field cosine theta (cos \theta)magnet and a low-field superferric magnet. Section 5 recounts the circumstances surrounding the selection of a particular magnet “style” for further development, and the ups and downs of the first model magnets. We conclude (Section 6) with a smattering of progress highlights in refining the design during the final push under the reign of the CDG. Beyond that, the ongoing chronicle must be left for others to amplify and complete.

2.0 RDS OF 1984

The momentous recommendation in July of 1983 by a subpanel on new facilities to DOE’s influential High Energy Physics Advisory Panel (HEPAP) [2-1] “that a major new project be initiated to design and build a proton-proton colliding beam facility exploiting our superconducting magnet technology with an energy goal of 10 to 20 TeV per beam...” led to a chain of events that culminated in December of 1983 when DOE and the directors of the high energy laboratories (L. Lederman, B. McDaniel, P. Panofsky, and N. Samios) chartered a Reference Designs Study to review in detail the technical and economic feasibility of such an ambitious undertaking. In chartering the study, the laboratory directors suggested a set of primary design objectives in terms of maximum beam energy (20 TeV), luminosity, and other parameters that would henceforth remain the sine qua non of the collider’s technical specifications. They also suggested that a range of superconducting magnet options be explored since the system of choice seemed sure to hinge on some economic optimum between magnet field strength and machine tunnel circumference.

As a result, some 150 scientists and engineers from the national laboratories and various universities converged on Lawrence Berkeley Laboratory (LBL) which had offered to host the study, starting in February of 1984. The study team, under the leadership of Maury Tigner of Cornell University, selected three dipole designs for pursual that embodied a variety of design concepts and spanned a range of field strengths from 3.0 to 6.5 T: a high-field “two-in-one” dipole, a medium-field “iron-less” alternative dipole, and a third, low-field “superferric” option. As we shall see presently, each option represented a distinct lineage in one of several ongoing
superconducting magnet development programs at the various laboratories. In what follows, it is not intended to trace the general chronology of all three options in all their variegated aspects and minutiae, nor treat them with equal weight, but to unabashedly emphasize the origins of the most prominent features of the dipole design philosophy that gradually evolved into the design adopted for the conceptual design of the SSC. For a complete description of the competing designs, the reader is referred to the Report of the Reference Designs Study Group issued in May of 1984 [2-2].

2.1 High Field Option A

The high-field end of the competition was represented by a design that was the result of a collaborative effort between Brookhaven and Lawrence Berkeley Laboratory. LBL contributed both superconductor expertise and R&D input from its well established model magnet program, while Brookhaven was responsible for the overall magnet design. Its key feature was a magnet concept resurrected from one pursued in the waning days of Brookhaven's ill-fated Colliding Beam Accelerator (CBA); in Design A, this took the form of a "two-in-one" dipole of 6.5 T central field with two closely spaced, horizontally aligned beam tubes encased in a common circular iron yoke and suspended in a single cryostat. The magnet cross section is shown in Figure 2-1, and an illustration depicting the magnet in perspective is shown in Figure 2-2.

Figure 2-1. Cross section of Reference Design A dipole, including cryostat and support assembly.
Only in proton-proton colliders, with two counter-rotating particle beams of the same electrical charge, are two-in-one magnets feasible since two apertures are required—one with the field vector pointing up and the other with the vector pointing down. In these magnets the field lines from one aperture are returned, not through the midplane of the yoke, but across the other magnetic aperture located beside the first. The total weight of iron is about the same as would be required for each of the single magnets in a collider based on magnetically decoupled rings; another advantage is the compactness of the design, which renders it practical in cramped accelerator tunnels (as in CERN's LEP tunnel). The price to pay for the scheme includes greater complexity in magnet assembly and loss of flexibility in machine operation. We will further consider historical origins of this interesting concept in Chapter 3.

The coils in each aperture of Design A were two-layer approximations to “cosine theta” coils (strictly speaking, to constant current density, intersecting ellipse configurations) of 40 mm inner coil diameter, wound from two layers of partially keystoned niobium titanium (NbTi) superconducting cable—the venerable Rutherford Cable nowadays the well-nigh universally preferred conductor configuration for accelerator applications. Named for the laboratory where it was invented [2-3], the cable was optimized and first utilized on a large scale for the Tevatron [2-4]. It consists of a flat cable produced from an initially hollow cable of twisted multifilamentary superconducting strands which is shaped by compaction into an approximately rectangular cross section. Design A, as well as designs B and C, assumed as a “design goal” a critical current density for the NbTi alloy of 2400 A/mm²; note that this does not correspond to the design operating value, but to the expected test value for an individual cable strand measured at a resistivity of $1 \times 10^{-4} \Omega \cdot \text{m}$ at 5.0 T and 4.2 K. By way of comparison, the alloy specification for the Tevatron conductor was 1800 A/mm². The high-homogeneity alloy becoming available by the time of the RDS was the fruit of a collaborative effort on improving $J_c$ involving the Lawrence
Berkeley Laboratory, the University of Wisconsin, Teledyne Wah-Chang, and Intermagnetics General; the key to higher $J_c$ was Teledyne Wah-Chang's modified alloy fabrication procedures, resulting in a product with much improved homogeneity [2-5]. The conductors for Design A were "graded" with the 30-strand cable of the outer layer, where the field is lowest, having a higher operating current density than the 23-strand cable of the inner layer.

Design A incorporated another interesting feature: the coil ends were flared out conically ("dog boned"). The combination of a wide, high-aspect-ratio conductor and small coil aperture made it desirable to increase the winding radius locally in the coil end region to improve the "lay" of the conductor here. Flared ends are also a way of minimizing the peak end-field enhancement. Moreover, at the time of the RDS the mechanically more challenging (but superior with regard to superconducting properties) intermetallic compound niobium tin (Nb$_3$Sn), was an active candidate for eventually replacing NbTi in this particular SSC dipole option. This could only come to pass if the strain-induced reduction in $J_c$ could be checked by suitably flaring the ends. Indeed, flared ends had their legacy in much earlier saddle-coils dating from the first decade of practical high-field superconductivity when the ubiquitous flat Nb$_3$Sn ribbons, produced commercially by vapor-deposition or diffusion, held sway [2-6]. Such ends were revisited two decades later, first in several meetings held during the Fall of 1983 when a subpanel of HEPAP chaired by W. K. H. Panofsky reviewed the various requests to carry out relevant R&D and recommended that, among other things, high-field (8 to 10 T) magnets based on niobium-tin be pursued.

The required SSC main ring circumference based on this magnet would be 90 km.

### 2.2 Medium Field Option B

The prominent feature of Fermilab's medium-field contribution, Design B, was the avoidance of iron in close proximity to the coils. As shown in Figure 2-3, the essential element of the Tevatron Dipole, the **collared coil**, formed the basis for Design B, with the cosine theta coils constrained by aluminum collars. (Note that Design A did not use collars; rather, coil compression relied on a tensioned stainless steel yoke support shell, which also served as the helium containment vessel). In Design B, the warm iron at a large radius was merely sufficient to shield one coil from the field in the other (its wall thickness varied as cos $\theta$). In addition, it served as the vacuum vessel for the cryostat. The design operating field, 5 T, was chosen because it led to coil dimensions similar to that of the proven Tevatron magnets with cable available in production quantities. The combination of warm iron and collared coil resulted in a design offering minimum cold mass ensuring rapid cooldown and warmup, ease of assembly, low-heat leak, and little iron saturation. Aluminum collars were believed to be more cost-effective than stainless steel, and aluminum was chosen for its high thermal expansion coefficient as well.

Finally, Reference Design B, in contrast to A and C, incorporated fully decoupled magnet rings, both cryogenically and magnetically; the one-in-one magnet feature allowed great flexibility in machine operation and in the spacing of the magnet rings.

A drawback of the nearly iron-less design was the high force between the iron-walled vacuum vessel and coil package which, if off-centered with respect to each other, required a robust coil support structure which negated to some extent the low-heat leak. Designing a strong support with concomitant low-heat leak was a major challenge for all three contending magnets, but particularly for the medium-field dipole.

The required SSC main ring circumference based on this magnet would be 113 km.
2.3 Low Field Option C

The low-field region was represented by an iron-dominated, 3-T quasi-2-in-1 “superferric”
dipole—the antithesis to Design B—proposed by the fledgling Texas Accelerator Center (TAC) near
Houston. The term superferric implies that the iron yoke contributes a dominant fraction (about
two thirds in TAC’s design) of the magnetic field, and that the field shape is dictated mainly by the
profile of the iron pole face by (a) limiting the central field and (b) exploiting a particular conductor
geometry in the form of simple current sheets delineating the vertical boundaries of an
approximately rectangular good-field region. While a relatively recently coined term, the concept
itself exploited one long championed by G. Danby in his “window frame” approach to accelerator
dipole designs, as we shall see.

TAC’s superferric version, as shown in Figure 2-4, consisted of separate beam tubes, coils,
and (more-or-less) separate yokes in an over-under configuration, within a common cryostat. The
conductor proposed for the magnet was the cable developed for the Tevatron low-beta
quadrupoles. Below 2 T the field of such a magnet is fully determined by the iron. Above 2 T
saturation gradually sets in, and nonlinear field contributions would require substantial corrections.
An anticipated method for alleviating the burden of the correction system foresaw the use of
gradually saturating pole face “crenelations” for effectively tailoring the pole face with increasing
field (an old practice with conventional magnets).

This design is more sparing in the use of superconductor and iron than its high-field,
conductor-dominated counterparts, and because of the over-under arrangement, there is little flux
linkage between the two magnet rings. Major cost savings were envisaged by its proponents by
Figure 2-4. Cross section of Reference Design C superferric dipole and cryostat.
installing such magnets in very long units (up to 35 m each), thus minimizing the number of magnet ends and interconnecting cryostat sections which tend to be particularly costly. (Similar arguments dictated the maximum credible overall lengths of dipoles A and B, specified as 17.5 m and 12 m, respectively.)

The required main ring circumference based on Design C would be 164 km.

2.4 Conclusion of Study

The Reference Designs Study was completed at the end of April 1984. The report on the study [2-7] concluded that “The basic principles of design used successfully for existing accelerators [could] be conservatively extended to a proton-proton collider having the SSC primary specifications of energy and luminosity.” “Furthermore,” reads the voluminous report,

...each of the three reference magnet styles studied could serve as the foundation for an SSC facility meeting these specifications. A vigorous R&D program of approximately three years duration will be required to refine the cost estimates for the magnets, to determine their actual performance, to determine their manufacturability and reliability, and to develop cost-effective methods for their assembly and quality assurance. It is anticipated that the magnet options can be narrowed to a single design during an early phase of the R&D program. An important R&D goal will be to produce, using mass-production methods, a significant number of magnets of the chosen style. These magnets would then be thoroughly tested under conditions simulating actual collider operations.

The report was favorably reviewed by DOE during May 8-11, and in August DOE Secretary Hodel authorized proceeding with the recommended SSC R&D.

3.0 BACKGROUND FOR RDS OPTIONS

While the Reference Designs Study was still going on, the DOE contracted with Universities Research Association, a consortium of leading research universities that had managed Fermilab from its inception, under contract to the AEC (later DOE), to oversee the forthcoming R&D phase of the SSC program. URA, in turn, established a Central Design Group (CDG) to lead and coordinate the far-flung R&D effort, the burden of which would obviously mainly fall on the national laboratories. LBL extended its hospitality to the CDG, and the freshly organized group settled in “on the hill” with Tigner continuing at the helm. By October 1, 1984, not only was the CDG open for business, but work on model magnets was already under way at Brookhaven, Fermilab, LBL, and the newly established Texas Accelerator Center at the Woodlands, Texas. Some model work, in fact, had been going on for well over a year.

3.1 BNL

3.1.1 Demise of the CBA

Strictly speaking, Brookhaven’s superconducting magnet R&D program [3-1] had its origins in the early 1960’s or shortly after J.E. Kunzler’s path-breaking niobium-tin solenoid [3-2], (as does LBL’s). However, the large-scale, focused magnet program at BNL today is the legacy of the ill-fated CBA project, nee ISABELLE. ISABELLE was to be a 200 x 200 GeV proton-proton collider, the first of its kind, 2.9 km in circumference and predicated on 4-tesla superconducting dipoles and matching quadrupoles; subsequently the beam energy was raised to 400 GeV,
necessitating, among other things, raising the operating field to 5 T. The detailed features of these particular magnets [3-3] are not particularly relevant to the present inquiry: it suffices to note that the single-layer dipole coils were wound from a flat conductor, braided from multifilamentary NbTi wires, and insulated with fiberglass-epoxy tape, and the assembled coil was clamped in a non-split (helium-cooled) iron yoke by a clever--albeit tricky--shrink-fitting technique. In the event, early promising model magnets were followed by a painful, protracted period dominated by disappointing magnet performance—in short, excessive training. The way out of the technical quagmire was shown by Robert Palmer in 1981. Palmer’s inspiration lay in proposing to adopt the Tevatron cable, unaltered in every respect including its Kapton wrap, for the ISABELLE magnets. By happenstance, the radial width of the cable was nearly half the width of the braid, enabling a two-layer coil to be wound from the cable and neatly substituted for the original single-layer coil without otherwise perturbing the magnet cross section significantly. Among additional modifications introduced, one entailed abandoning the awkward shrink-fitting coil-in-yoke insertion procedure in favor of one in which the laminated iron yoke, now split on the midplane, captured the coil by simply bolting the two yoke halves together.

Short- and full-length (4.6-m) model magnets exhibited equally flawless performance, exceeding 5 T with no training. Thus rejuvenated, the Magnet Division of the renamed Colliding Beam Accelerator project forged ahead. By the Summer of 1983, 30 prototype dipoles and 11 quadrupoles were in hand [3-4]. Their performance, including that of 10 “field quality” dipoles built in as nearly identical a manner as possible using the construction techniques envisioned for production magnets, demonstrated that the machine could be constructed, and was so certified by a review panel. A string of magnets (six dipoles and two quadrupoles, comprising a “full cell”) had been subjected to a major test sequence with satisfactory results in the largely completed 3.8-km CBA tunnel on the Brookhaven site, and the on-site magnet production and testing facilities were ready for use. Alas, it was too late; the HEPAP subpanel’s recommendations of June-July, 1983 included terminating the CBA project in favor of an all-out push on the SSC [3-5].

3.1.2 Redirected R&D Effort

Despite the hard blow of losing the CBA at the 11th hour, Brookhaven resolutely mounted a new initiative on SSC magnet development, starting in July of 1983, with the intention of capitalizing on the available in-house wealth of superconducting magnet experience. Two parallel paths were chosen for initial pursual, eventually to merge into a single candidate magnet suitable for the SSC. The magnets would follow the basic CBA design concept, but would be of the two-in-one type, and require a higher field and a smaller aperture. The key to substantially higher fields (say 8 T) lay in substituting, when the time was ripe, Nb3Sn cable outwardly identical to the FNAL/CBA cable (save for a greater keystone). A sharply reduced aperture, ~32-mm coil i.d., and the brittle nature of prereacted niobium-tin could only be accommodated with flared coil ends, as noted earlier. (The prereacted conductor remained uniquely Brookhaven’s approach to niobium-tin, in contradistinction to a “wind and react” approach pursued elsewhere.) Promising discussions were held with Teledyne Wah-Chang, a producer of Nb3Sn by the “expanded metal” process, and with Intermagnetics General whose production was then based on the “internal tin” diffusion process.

Paralleling this effort would be a joint development with LBL of a similar lower-field (6.5 T) 2-in-1, small-aperture dipole based on NbTi--this being magnet A featured in the Reference Designs Study the following spring.
As these initiatives got under way a full-length (5-m) CBA two-in-one dipole was tested for the first time with promising results, the concept having been introduced as a possible cost-cutting option in the course of the CBA project. (A 5-ft model dipole was successfully tested a year earlier.) In fact, the 2-in-1 concept was first suggested by J.P. Blewett in 1971 while considering very high-energy (1 TeV) storage rings using superconducting magnets. Blewett showed that two intersecting rings run adjacent to each other could be contained in a single dewar system by operation of adjacent air-core dipoles with contiguous circular apertures [3-6]. R. A. Beth subsequently solved the problem, in closed form, the same year for apertures which are the adjacent halves of a circle [3-7].

The year 1984 began with the production of magnet tooling, cabling of conductor (both NbTi and Nb3Sn), and lending a hand with the ongoing Reference Designs Study as well. Late spring saw the first 5-m, 2-in-1 NbTi dipole (Figure 3-1) tested with excellent results (even though reworked Tevatron/CBA cable had to serve in lieu of high-homogeneity conductor for the time being). A second dipole followed in mid-summer. These magnets nominally conformed to Design A, save for a smaller aperture and flared ends, still in anticipation of switching to Nb3Sn. However, in August Design A was critically reviewed, and the decision was made to implement stainless steel keyed collars--the Tevatron’s legacy--in the magnet assembly (Figure 3-2), rather than relying on the tensioned yoke-support shell for providing coil prestress as was heretofore the practice. A collared coil, it was realized, would greatly simplify the assembly of full-length (17 m) magnets, and had the undoubted additional advantage of reducing iron-saturation effects at high field (at the tolerable expense of a slight loss in field).

Even more drastic design changes were not long in coming when, in the waning weeks of the year, a mutual agreement was reached between BNL, LBL, and FNAL to proceed in unison with a single magnet design, designated Reference Design D, devised by borrowing design concepts from Reference Designs A and B in the interest of “minimizing technical options and to more efficiently use scarce R&D funds.” The result (Figure 3-3), incorporating the best features of A and B, was a 1-in-1 dipole featuring a two-layer cosine theta coil clamped with stainless steel collars, and the collared subassembly captured in a split iron yoke, also at helium temperatures. (Cryostatic studies had satisfied the Fermilab contingency that cooldown and warmup times for cold-iron magnets would be reasonable.) The inner coil diameter remained 40 mm (a compromise between BNL’s 32 mm and Design B’s 50 mm) and the magnet length remained approximately 17 m—the maximum length deemed practical in view of numerous constraints, many of them non-quantifiable, including accelerator physics issues, magnet design aspects, and handling and transportation considerations.

3.2 FNAL

3.2.1 Triumph of Tevatron

The superconducting magnet program at the new National Accelerator Laboratory (as it was initially known) had its start nearly a decade after Brookhaven’s and from its inception had a much more focused goal. The idea of adding a superconducting ring to the recently authorized 200-BeV accelerator at NAL, possibly for a “beam stretcher” or as a storage ring, was first floated in 1967.
Figure 3-1. First stage in assembly of 2-in-1 dipole. Note the flared coil ends.
Figure 3-2. Modified Reference Design A dipole cold mass with stainless steel collars.
Figure 3-3. Cross section of 1985 version of Reference Design D dipole cold mass.
discussions among the accelerator design staff, temporarily housed at Oak Brook, Illinois. As the design work on the conventional accelerator gathered momentum, Robert R. Wilson felt obliged to prohibit active work on superconducting magnets until the design of the accelerator was in hand [3-8].

The concept of a superconducting energy "Doubler" was fairly widespread by 1971 when NAL's 200-GeV main ring was approaching completion. That summer the AEC requested that Wilson and his staff "perform the necessary work in the coming fiscal year to clearly define the scope of this undertaking and to ascertain whether the inclusion of energy doublers could be achieved within the $250 million authorized for this project" [3-9]. With the attainment of 200 GeV in the spring of 1972, Wilson could lift his edict. In September, he established an informal working group that met on a weekly basis on various technical issues. By that time, the first small model dipole magnets were being made and refrigeration studies were under way. The Doubler group was formally incorporated into the Accelerator Division under Paul Reardon the same year. However, Wilson continued to dominate the discussions, and the Doubler's priority remained rather low.

Despite various bureaucratic hurdles, several important technical decisions were made at this time; two in particular were important. The first was to adopt a dipole design based on "warm" iron—that is, on one in which the iron yoke is mounted outside the magnet cryostat. The LBL group also opted for warm iron for ESCAR, its Experimental Superconducting Accelerator Ring project, the very same year. In contrast, ISABELLE's magnets utilized a helium-cooled yoke in close proximity to the coil winding. While warm iron magnets produce less field for the same excitation current, due to the intervening cryostat structure, by the same token they are practically free of field distortions from iron saturation effects. An advantage of cold iron designs, in addition to their higher transfer function (gauss per ampere), is the inherent simplification and ease of fabrication made possible by relying partially or entirely on the massive yoke for structural coil support.

The second major design decision reached in 1974 was to adopt the Rutherford cable for the conductor (as had ESCAR) in a two-layer coil design. The primary reason for Brookhaven's eschewal of the Rutherford cable at the time, was the importance attached by ISABELLE's magnet designers to a single-layered coil winding, something only possible with a wide ribbon-like conductor of very high aspect (width-to-thickness) ratio—a ratio considered too high to be feasible with the Rutherford cable.

Alvin Tollestrup, on taking charge of the program in the spring of 1975, introduced several more technical innovations that proved pivotal. One was the novel scheme of interlocked, stainless steel collars for providing well-controlled mechanical coil prestress, replacing the ubiquitous metal clamping rings or bands in universal use until then. Crucial to the success of this scheme was the co-discovery of the feasibility of keystoning the Rutherford cable slightly, without degrading its superconducting properties. Another modification seemed rather more mundane when it was proposed, but in hindsight proved to be perhaps the single most important feature of the reworked Fermilab magnets; it also provided the key to the poor performance of their Brookhaven counterparts. Hitherto the bare Rutherford cable (and the ISABELLE braid) had been spirally wrapped with fiberglass tape insulation impregnated with epoxy resin—the turn-to-turn bonding agent, when cured after coil winding. Still concerned about electrical shorts in the Doubler coils, however, Tollestrup introduced a layer of Kapton film insulation, spirally wrapped around the bare cable before application of the fiberglass-epoxy tape. Behold, not only did the Kapton improve the electrical performance, but the training performance improved drastically as well. Apparently, the reasoning, direct contact of the superconductor with epoxy resin tends to promote
microcracks and heat generation by friction associated with conductor (wire) movement even on the micrometer scale, whereas an intervening layer of Kapton or Mylar shields the superconductor from such heat and may have other mechanical benefits as well.

Still, even with the highly successful adaptation for Doubler R&D of the on-site magnet factory, the project was by no means out of the woods. No sooner had L. Lederman filled the footsteps of Wilson who resigned in 1978, than he was faced with a hard choice of whether to scrap the Doubler and embark instead on a project aimed at obtaining proton-antiproton collisions in the main Fermilab ring, as urged voicefully in certain quarters. The upshot of a marathon session with Fermilab staff, convened by Lederman to thrash the question over, was a decision to go for a pp collider, but only after completion of the Doubler which now became Fermilab's highest priority despite DOE's demural. In 1979 DOE acquiesced, raising the project status from that of an R&D project to an “energy saver” construction project. In September of 1980, the dipole design was frozen. Following a successful test of a sector of magnets in the spring of 1982, magnet installation began in earnest that summer and was completed the following spring.Cooldown began in May of 1983, and commissioning followed in June. On July 3, beam was accelerated for the first time, and a month later was extracted out of the ring. That month, August 1983, the CBA project was officially terminated.

3.2.2 New Challenges

Fermilab lost no time in launching an SSC Magnet Development Program, being in the enviable position of possessing a first-rate superconducting accelerator magnet test bed, the Tevatron with its magnets, supported by the magnet fabrication and test facilities. Naturally, the Tevatron collared coil was the starting point. Already in the spring of 1983 design calculations were under way on 10-Tesla collared dipoles of 50-mm coil aperture, wound from improved NbTiTa cable [3-10]; a year later the design had matured in the less ambitious form of Reference Design B. By that time, a number of short first-generation dipole (and quadrupole) magnets were also in the works, albeit of 76-mm aperture dictated by available tooling, intended as test vehicles for improving magnet quality and cost effectiveness [3-11]. Coil fabrication variables included copper-to-superconductor ratio, superconductor filament size, alloy composition, cable critical current, and interstrand resistance. Collar options included stainless steel vs. aluminum.

By late spring of 1985 a new series of 1-m models took center stage (Figure 3-4), now featuring the 50-mm coil aperture [3-12]. After some initial shakedown problems, several models were tested with good results in regard to quench currents as well as field quality. An additional, interesting feature of these models was all-Kapton cable insulation and coil winding by a "dry" technique (i.e., one not relying on epoxy resin) with the aid of an expandable mandrel--an insulation scheme and fabrication technique adopted for Reference Design B.

Paralleling these efforts were preparations for the first half-length (6 m, the longest collared coil possible with Tevatron tooling) model nominally of Design B. The Magnetic Effects Model featured an aluminum-collared Tevatron coil in a cryostat with an iron vacuum vessel. An efficient SSC cryostat had become a major priority at Fermilab and this model incorporated the first version of the now familiar SSC cryostat, including two-phase cryogenic headers, intermediate-temperature heat shields with interposed superinsulation blankets, and particularly the post-type magnet support system based on FRP tubing with metallic end connections and heat intercepts. In the event, magnet tests [3-13] provided indispensable data on cryostat thermal performance, off-centering forces, and shield heating and deformation during quenching--questions of paramount relevance to Design B.
Figure 3-4. Model of Reference Design B dipole, showing dry Kapton insulation and aluminum collars.
Figure 3.5: Heat Leak Model during assembly.
To further ascertain the performance of the cryostat concept, a 12-m Heat Leak Model was contrived, utilizing a makeshift dummy cold mass (Figure 3-5). Though measured heat leaks at 80 K, 10 K, and 4.5 K were 50% above the goals (e.g., one-tenth the Tevatron heat load at 4.5 K), the results agreed with calculations, lending added confidence in the soundness of the basic cryostat design [3-14].

By this time, the decision had been made at the CDG to proceed with a joint effort on Design D. The decision was nailed down in a memorandum from R. Lundy (Fermilab), Reardon (then at Brookhaven), and C. Taylor (LBL) to Tigner dated December 7, 1984. Indeed, Fermilab tooling for dry-winding coils of 40-mm aperture had been started as soon as that decision was reached. However, in the interim, until tooling and coil parts would be available, the development program would continue on 50-mm models [3-15].

3.3 LBL

3.3.1 Post-ESCAR Initiatives

Like Brookhaven's, LBL's superconducting magnet program dates from the mid-1960's when it initiated a program involving pulsed solenoids and beam-line magnets [3-16], but again like BNL, the Berkeley group's strength in high-field superconducting accelerator magnets owes its legacy to an ill-fated accelerator project of the mid-1970's--in LBL's case ESCAR. Launched as a first serious test bed for a full-blown superconducting accelerator system in 1974, various circumstances led to its scope being drastically scaled down in midstream, to a test of the superconducting magnet system alone, albeit a curtailed one at that. A string of twelve dipoles, half of ESCAR's design inventory, was put through an extensive series of tests ending in the spring of 1978. As such, ESCAR did provide considerable operational experience with superconducting magnet and cryogenic systems--experience that honed the expertise of the magnet team ensconced in Berkeley.

No sooner had ESCAR been laid to rest than the Berkeley team, viewing the 4 to 5-tesla magnets of the ESCAR, ISABELLE and Doubler era as accomplished state-of-the-art, set its sight on more ambitious accelerator magnets, say in the 8 to 10-tesla range [3-17]. Invaluable to the forthcoming program at LBL was its prescient development of a pressurized superfluid (He II) test capability at 1.8 K (in 1979). Thus fortified, two parallel paths lay open to higher fields: NbTi at 1.8 K (exploiting multi-layered saddle windings) and Nb3Sn at 4.2 K (exploiting “external tin”-processed material in flat pancake coils via the “wind and react” approach). By late 1982 practice winding of such coils had begun [3-18], and by mid-1984 promising results were being obtained both for NbTi and Nb3Sn [3-19].

3.3.2 Approach to SSC Magnets

Under the agreement with BNL, to pursue jointly a high-field reference design option, LBL now refocused its model-magnet program in conformance with Design A. By early fall of 1984 several one-meter models designed for 6.5 T at 4.5 K were completed and tested; they featured a two-layer coil wound from Rutherford cable, 40-mm coil aperture, flared coil ends, and all-Kapton insulation [3-20]. Model no.1 utilized a ring collet for structural coil support, replaced by a split iron support system in subsequent models of this genre. However, with the aforesaid decision that August to adopt collars à la Fermilab, a new series of one-meter models was promptly inaugurated,
Figure 3-6. LBL collared coil assembly undergoing testing before installation in iron yoke.
exploring alternatively aluminum and stainless steel collars (Figure 3-6). These magnets constituted the first models of Reference Design D, soon embraced by BNL/LBL in consort with Fermilab [3-21].

A critically important aspect of LBL’s growing superconducting magnet R&D for the SSC has been noted earlier: its assuming a major, leadership role, with the cooperation of industry and the University of Wisconsin, in specifying and procuring superconductor for the SSC magnet program [3-22].

3.4 TEXAS ACCELERATOR CENTER (TAC)

3.4.1 Establishment of TAC

The Texas Accelerator Center was formally created in March of 1984 for the purpose of fostering accelerator R&D and training students in accelerator physics and engineering. Located in the Woodlands, Texas, the center is operated by the Houston Area Research Center, a research consortium of Rice University, Texas A&M University, The University of Texas at Austin, and the University of Houston.

Superferric magnets for accelerator applications are but one of the many R&D projects pursued at TAC. Other projects include superferric NMR magnets, conductor development for magnetic energy storage, high-\(T_c\) magnet lead research, and various other accelerator R&D topics (e.g., ion source development).

3.4.2 Superferric Concept

The term “superferric” was coined relatively recently, though the concept exploits one long championed by G. Danby and his group at Brookhaven (initially with conductors of cryogenically cooled, pure aluminum). Their superconducting “window frame” magnets were baptized under fire in the 8° bending magnets for the 30 GeV/c extracted proton beam from the AGS to the 7-ft bubble chamber (employing a 60-MJ superconducting Helmholtz coil). The pair of two-meter, 4-tesla dipoles was installed in 1973 and operated successfully in the radiation environment of the beam line for a decade [3-23]. Subsequently, Danby’s group showed that the advantages of the concept can be exploited, not only in low- or medium-field applications, but at high fields as well by increasing the coil aspect ratio (ratio of aperture gap height-to-width) and tailoring the iron pole tip shape somewhat at the highest fields, say 10 T [3-24].

The inspiration for adopting the superferric principle for SSC magnets specifically is generally credited to R. Wilson and R. Huson at the DPF Snowmass Meeting in 1982 [3-25]; indeed, the SSC concept itself that emerged from the building groundswell that year to leapfrog ongoing accelerator efforts can be said to have its origins at the heated discussions amidst the craggy Snowmass peaks. Wilson, in particular, based his argument, in part, on results from a one-foot superferric model sketched by himself and hastily thrown together and tested at Fermilab at the time of Snowmass ‘82 utilizing Tevatron cable and mild steel [3-26]. He also refers to, but provides no reference, an old article by I. A. Shelaev of Dubna which apparently covered much of the same ground.

3.4.3 First Magnet Models

The first two TAC-built one-meter, 1-in-1 superferric models were tested (at Brookhaven) during October-November, 1984. Quench performance was excellent, with the magnets reaching the 10-kA limit of the power supply with essentially no training. The first 7-m, 2-in-1 model was
tested at TAC in April of 1985, and the first and only 28-m, 2-in-1 dipole tested one year later. (Three of these gargantuan units were actually completed at General Dynamics in San Diego and trucked to Texas before TAC's program in this area was phased out.) Short models were also built at Intermagnetics General, New York, and at Meyer Tool of Chicago. Altogether, approximately 25 models were constructed and tested in the course of the program. Figure 3-7 depicts one of these being prepared for tests at TAC.

4.0 OPTIONS NARROWED

4.1 Alternative Superferric Option C*

Despite their many virtues, two-in-one magnets suffer various drawbacks as well, among them a decided complexity in magnet assembly and, worse, loss of flexibility in accelerator commissioning and operation [4-1]. For instance, a collider based on 2-in-1 magnets cannot be operated with full field in one aperture and no field, or a much lower field, in the other. Thus, the possibility of, say, beam studies in one ring while cool-down is under way in the other is precluded. The loss of beam in one ring (other than at injection) would require refilling both beams. Moreover, the need to match a focusing quadrupole in one aperture with a defocusing quadrupole in the other implies an antisymmetric lattice in contrast to the symmetric lattice possible with one-in-one magnets.

For reasons such as these, TAC considered it prudent to add a one-in-one variant of its superferric candidate, Design C*, as a design option. Though most design effort continued to be expended on Design C, the main-line 2-in-1 option (which after all embodied most of C*'s features anyway), a majority of the model magnets actually constructed and tested were in fact one-in-one magnets.

4.2 High Field Option D

As noted in Section 3.1.2, BNL, LBL and FNAL joined forces in the winter of 1984-85 on a single one-in-one proposal of their own, Design D. BNL's task in the short run, according to the agreement of December 7, 1984, was to make Design D demonstration magnets on the same schedule as in the former two-in-one plan, push bore tube development, and develop magnet measuring hardware. FNAL would concentrate on its "dry-wound" coil insulation scheme, and take responsibility for "long" cryostats. LBL, in turn, would adapt its one-meter model program to the new initiative, with particular focus on (non-flared) coil ends, and continue its oversight role in the area of wire and cable. During the first quarter of 1985 available resources were mainly concentrated on honing the magnet design and on the fabrication of tooling and components of the first 5-m model dipole at BNL. At the same time, a first production run of high-homogeneity cable arrived from New England Electric Wire, just in time for the new coils. ("Hi-Ho" cable was first introduced in the third two-in-one dipole.) The new tooling became operational during April-May, and the first of the new dipoles, SLN-008 (Figure 4-1), was ready for pool-boiling tests in June--
Figure 3-7. Preparing a 1-meter model superferric magnet for tests at TAC.
Figure 4-1. Yoke assembly of SLN-008 in May of 1985. Note enlarged collars over flared coil ends.
hard on the heels of the fourth and last of the two-in-one dipoles to be tested. SLN-008’s performance was about as good as could be expected, reaching a short sample quench plateau (6.5 T) in four quenches and 8 T in subcooled helium. Four more dipoles were funneled through the test dock in time for the all-important deliberations of the SSC Magnet Selection Advisory Panel late in the third quarter of 1985.

Among other things, preparations for constructing the first 17-m dipole also made steady progress in this period. Coincidentally, the decision was made (based on coil winding tests) to henceforth (or as soon as tooling could be converted) forego flared ends, a lingering feature of all BNL-produced NbTi SSC dipoles until that time. To which might be added that a first prereacted niobium-tin coil section was produced and co-mounted with niobium-titanium sections in a reusable yoke in late Fall of 1984. Not surprisingly, this first, fragile coil exhibited strain-induced damage. Though a start was made on appropriately altering the coil winding and curing procedures to circumvent excessive strain in further trials, limited resources and the press of the main-line NbTi program soon necessitated shelving the Nb3Sn program, if only for the time being.

4.3 Magnet Technical Review Panel

To pave the way for the selection of a particular design for “further development to a stage where a responsible SSC conceptual design could be prepared,” CDG Director Tigner now convened--actually reconvened--a Magnet Technical Review Panel under the Chairmanship of A. Tollestrup. The panel had, in fact, held a first series of meetings in the fall of 1984 at, successively, BNL, FNAL, LBL and TAC, where program accomplishments in FY ’84 and plans for FY ’85 were reviewed. A byproduct of these meetings was the proposal for a new style magnet, Type D, by a consortium of BNL, FNAL, and LBL.

In April of 1985 the committee, still under Tollestrup but with a slightly altered membership, was again called into session to review the status of all designs in the offing to “ensure that enough technical information would be available to fairly choose a magnet style by the end of that summer”; the CDG also set in motion several task forces to collect and evaluate specialized information pertinent to the magnet selection [4-2]. The reconstituted panel held two back-to-back, two-day meetings in early July, first at TAC where the progress on all five magnet designs, A, B, C, C* and D, was again reviewed, and then at BNL where the body of the final report was constructed [4-3].

It is the opinion of the committee [concluded the report] that a sufficient R&D base now exists for a style choice and that if the selection is made now it will narrow the scope of the R&D effort. This will conserve funds, make optimum use of the intellectual resources available in the community, and will result in expediting the technical feasibility for the SSC.

5.0 MAGNET SELECTION

5.1 Magnet Selection Advisory Panel

The actual magnet selection, to be made by M. Tigner himself, would rely heavily on the recommendation of an SSC Magnet Selection Advisory Panel appointed by Tigner and chaired by F. Sciulli of Columbia University [5-1]. Charged with the task of submitting”... a report to the
Director [of the Central Design Group] containing the Panel’s recommendation in the form of an ordered list of these five basic magnet styles ...,” the Sciulli panel met for four days in late August of 1985 at the CDG in Berkeley, and heard testimony from proponents of the various styles as well as presentations on technical, operational, and cost issues by CDG staff. Though requested to consider all five basic magnet types, most of the discussion centered on Designs C and D, these being “most strongly advocated by the proponents,” thereby obviating the need for an “ordered list or ranking.” The panel’s final report to Director Tigner is dated September 9, 1985 [5-2]. Of “the two principal magnets placed in competition,” the panel was “unanimous in recommending D as the design basis for an SSC dipole element.”

The hope of two years ago that the superferric magnet would provide a less complicated and less costly SSC has not become true. The Panel believes that there is a real possibility that an SSC based on superferric magnets would be more costly than currently estimated. On the other hand, the cos θ design has proceeded smoothly and met all expectations. For these and other reasons ... the Panel believes that the cost of an SSC based on cos θ magnets is predictable.

The panel justified its recommendation on two different grounds. The cosine theta style magnet was favored for being “a well understood magnet with reliably predictable costs and production schedules. The reliability of the predictions rest on a large base of data developed in building and operating one large accelerator and developing models and prototypes for several others.” Highfield was recommended in light of machine operational as well as capital cost penalties associated with the larger circumference ring based on magnets of Style C.

... The work with the superferric style [adds the panel] has shown it to be more complex than foreseen two years ago. As a result only models of one-meter length have been extensively tested so far. In the panel’s opinion, this style has not displayed the simplicity and ease of construction and operation it originally promised. Of course, if the superferric style held out the promise of substantial construction cost saving to outweigh the additional R&D costs required to develop it for production, it would be a strong candidate despite its less mature status of development. Although its proponents argued that this was the case, the panel is convinced that, as cost studies done by the CDG suggest, the contrary is true. Use of the superferric style, in the panel’s opinion, is likely to result in higher total project costs, exclusive of R&D.

In view of these findings, the panel recommends that the choices between the two styles be made now and that the cos θ Style D be chosen.

On September 13, Maury Tigner concurred with the recommendation of the Sciulli Panel, cautioning that what had been selected was “a style, not a finished design. Production of an optimized and industrially producible design is the next order of business” [5-3]. On that note, the stage was set for the various R&D teams to proceed in unison henceforth. By mutual agreement (in the official CDG language), LBL would concentrate on superconducting cable development and short model magnets, BNL on longer models and the fabrication of full-length prototypes, FNAL on cryostat development and testing of full-length magnets, and TAC on quench protection and magnet correction systems (as well as phasing out the superferric magnet program). Concurrently, the Central Design Group and the four laboratories would initiate a multi-phased magnet technology program involving industry, leading to industrial engineering, production tooling,
demonstration of preproduction \textit{fait accompli}, and ultimately culminating in mass production of the 10,000-odd magnets required.

5.2 Long Magnets: A Precarious Start

The first visible fruit of the consolidated R&D program set in motion by the magnet selection process was the aforesaid series of six five-meter type D model magnets constructed at Brookhaven and tested there with good results between June and November of 1985. All reached a stable quench plateau at the SSC design operating field (6.6 T) in pool boiling helium--albeit the conductor limit achievable at that time--with modest training, and displayed field uniformity by and large meeting SSC specifications \cite{5-4}. So far, so good.

To be sure, LBL’s magnet R&D program based on one-meter models, was by no means idle in this period. A noteworthy advance was made in January of 1986, with that group’s demonstration of a scheme dubbed “conditioning” of magnets. The accepted explanation for training being heat generation from conductor motion under Lorentz forces at progressively higher $J \times B$ excitation levels, one might expect the superior heat transfer and higher temperature margin provided by operating at subcooled (superfluid) helium bath temperatures would allow such heat generation without causing a runaway temperature rise, or quench. Such proved to be the case, opening the interesting possibility of training high-performance superconducting magnets without actually quenching them \cite{5-5}.

Brookhaven’s full-length tooling became operational in January of 1986 as well. The first 17-meter coils were wound and cured in February, and a first long type D cold mass, D0001, was ready in April \cite{5-6}. Late that month it journeyed to Fermilab, strapped to a 60-ft trailer bed encased in a refrigerated box (Figure 5-1). (D0002 followed in May.) At Fermilab D0001 was mounted in its waiting cryostat \cite{5-7} and prepared for cold tests at the laboratory’s Magnet Test Facility, scene of past Tevatron magnet production testing. D0001 was powered up in late August. In the event, its performance was a qualified success at best, with encouraging field quality results (integrated field harmonics, angle of dipole field) but flawed training performance compared to that of its shorter forerunners (excessive training to an unstable quench plateau well short of the conductor limit). D0002, tested in the waning days of 1986, proved only marginally better \cite{5-8}.

Yet, viewed as learning vehicles in an unprecedented magnet development program, scarcely a year old, the magnets provided the essential cornerstone for the conceptual design of the SSC that came into being in 1986 in the guise of the massive, multivolumed CDR tome under J. D. Jackson’s editorship \cite{5-9}.

5.3 Superferric Options Laid to Rest

In fact, the last word had not been heard from proponents of superferric magnets when, in April of 1986, as D0001 was being readied for its journey to Illinois, TAC submitted “new information” to the DOE. Based on their now largely completed program in the superferric area, the authors maintained “that the superferric design is the best and least expensive choice for the SSC,” and that “we are prepared to demonstrate that the superferric magnet is industrialized and ready for construction, and that the project cost can be reduced by $1$ billion compared to the high-field design” \cite{5-10}. Accordingly, DOE was compelled to set in motion a reexamination of TAC’s program and consider the wisdom of reopening the magnet selection process with the aid of yet another HEPAP subpanel, this time chaired by Burton Richter of the Stanford Linear Accelerator Center. However, it required the subpanel but a month of investigation to convince itself “that TAC’s] claim to be able to do the job better, cheaper, and faster with superferric magnets is not
borne out by the information supplied to the Subpanel.” Specifically, the subpanel concluded [5-11]:

The TAC magnet R&D program is still about two years behind the high-field magnet program. The TAC magnet is not ready for industrialization.

Cost uncertainties in TAC technical components are large, and superferric magnet costs cannot be estimated with confidence at the present state of R&D.

We do not believe that the new information presented warrants reexamination of the CDG magnet-selection decision.

With the superferric option finally laid to rest, all available resources, as they were, could be brought to bear on “the SSC dipole,” the designation design D no longer pertinent (Figure 5-2). Even so, the SSC dipole was not yet out of the woods, but the path out was well defined.

6.0 THE SSC DIPOLE

6.1 Slow Progress

1987 is remembered mainly for the unremarkable performance of two new long magnets--neither of which did substantially better than D0001 or D0002, for a new series of short magnets (the DSS magnets) for quantifying performance questions, for a blur of Magnet Systems Integration Meetings, and for the tireless goading of the Central Design Group’s “Gang of Four” (V. Karpenko, P. Limon, E. Goldwasser, and Tigner himself).

6.2 Performance Picks Up

Of the four long magnets tested in 1988, two passed muster. Both DD0012 and DD0014 featured, among other things, azimuthal shims between collar and yoke for reducing coil axial and azimuthal motion, firmer coil end support (stiffer “end plates”), and one (DD0014) LBL’s innovative tapered key collars. The next year, 1989, did better with four out of five qualifying. In large measure the improvement reflected further successes in controlling the interaction between coil, collar, yoke, and yoke support “skin.” The development of a mechanical finite-element analysis capability, coupled with a high level of strain gauge and voltage tap diagnostic instrumentation in the later magnets, was paying off. The shorter one-meter LBL and BNL’s 1.8-meter models served as vehicles for expeditiously proofing design features and modifications suggested by the mixed performance of the full-length prototypes, the latter naturally requiring much longer lead time to test new ideas. Design concepts were honed by engineering analysis at Brookhaven, Fermilab, and Berkeley, and thrashed out in wearisome MSI meetings which rotated on a regular basis between the laboratories.

6.3 Refinements

On that rather uncertain note we end our chronicle of the development of the principal design features that characterized the adolescent SSC dipole ca. 1989, without dwelling upon its multitude of technical details: a high-field, small-bore collared cosine theta dipole, fully 17- meters long,
Figure 5.2. Cross section of the cryostated SSC dipole ca. 1986, indicating its various principal features.
wound from state-of-the-art NbTi Rutherford cable. Two developments during 1989-90 have to be reckoned with in contemplating the near-term health of the magnet program, yet bode well for a sound SSC dipole in the long run: the establishment and rapid growth of the SSC Laboratory in Texas with its attendant Magnet Systems Division based to some extent on fresh engineering talent, and the decision-- not made lightly-- to enlarge the magnet's coil aperture from 40 mm to 50 mm (as well as incorporating several other modifications intended to improve the reliability of the design). Considerable time will obviously be required to implement the revised design and verify its soundness. However, with new resources and initiatives being marshalled to the task, with continued support of the laboratories that brought the 40-mm baseline magnet to fruition, and with a strategy of backups and parallel paths devised to ensure the success of the revamped magnet, there is every reason for optimism.

APPENDIX

Chronology of Magnet R&D Leading to SSC Collider Dipole

1961    High-field Nb$_3$Sn solenoid (J.E. Kunzler et al.).
1964    NbTi conductors mature.
1965-67  Various stability criteria
1968    Intrinsically stable filamentary NbTi.
1970-72  Rutherford cable.
1971 "Two-in-one" dipole concept. 
    Half-meter Doubler model quadrupole.
1973    First 1-m model dipoles for ISABELLE. 
    First short model dipoles for Fermilab Doubler. 
    "Window frame" dipoles, precursors to superferric magnets, operational at Brookhaven's Alternating Gradient Synchrotron.
1974    Warm iron and Rutherford cable adopted for Doubler magnets. 
    Warm iron adopted for ESCAR, LBL's Experimental Superconducting Accelerator Ring, conceived that year.
1975    First full-scale (4.25 m) ISABELLE model dipole (4T, braided conductor, single-layer coil, shrink-fitting yoke support scheme). 
    Kapton cable insulation and stainless steel collars adopted for doubler magnets.
1976    ISABELLE MkV reaches 5 T.
1977    First 5-T dipoles for 400 x 400 GeV ISABELLE.
1978    ESCAR dipole string test.
1978-80  Performance problems beset ISABELLE.

1979  Pressurized superfluid magnet test facility at LBL.

1980  Doubler dipole design frozen.

1981  First "Palmer" dipole for ISABELLE overcomes problems (Rutherford cable, two-layer coil, bolted yoke).

First magnets installed in Doubler ring.
Superferric dipoles proposed for SSC.

1982-83  Revamped prototype dipoles and quadrupoles for CBA (Colliding Beam Accelerator, formerly ISABELLE).

1983  CBA magnet string test.
First 5-m CBA 2-in-1 dipole.
Doubler/Saver completed, became operational.
HEPAP recommends terminating CBA, all-out push on SSC.

1984  Reference designs study pursues three options.
Design A (high field, 2-in-1, 40-mm coil i.d., flared coil ends, collared coil introduced subsequently).
Design B (medium field, 1-in-1, collared coil, quasi-iron free).
Design C (low field, 2-in-1 cryostat, superferric magnet).
Model magnets at LBL (Design A; NbTi and Nb3Sn; aluminum and stainless steel collars).
Model magnets at FNAL (Design B, 50 mm coil i.d.).
First 5-m 2-in-1 Design A dipole at BNL (32 mm coil i.d.).
TAC established, first 1-m model magnets (Design C).
First laboratory quantities of high-homogeneity NbTi.
Reference Design D created from Designs A and B (1-in-1, collared coils, 40 mm coil i.d.).

1984-85  Magnet Technical Review Panel convenes in several sessions.

1985  Magnetic Effects Model, Heat Leak Model at FNAL.
First 5-m Design D dipole at BNL; five more follow.
First 7-m 2-in-1 Design C dipole, at TAC.
First production run of high-homogeneity cable.
Magnet Selection Advisory Panel recommends Design D dipole design;
M. Tigner accepts recommendation.

1986  25-m 2-in-1 Design C dipole tested at TAC.
Superferric option re-examined by HEPAP subpanel; MSAP recommendation sustained.
First 17-m SSC model dipole (D0001) completed at BNL, tested at FNAL; performance poor.
Magnet "conditioning" scheme devised at LBL.

1987
More 17-m dipoles; performance lackluster.
DSS (1.8m) model magnets initiated.
Tapered key collaring scheme devised at LBL.

1988
Improved 17-m dipole performance: DD0012 (collar-yoke shims, enhanced coil end support); DD0014 (ditto, first tapered collar keys); DD))15 (low-friction collar-yoke interface option).

1989
Additional short and long dipoles exploiting design concepts of 1988 exhibit good performance; design and performance analysis capabilities sharpen.
Collider Dipole Review Panel at CDG.
SSC Laboratory established in Texas. Genesis of new magnet team.

1990
50-mm coil i.d. program initiated.

NOTES AND REFERENCES
2-4. The cable was also used in the magnets for LBL’s Experimental Superconducting Accelerator Ring (ESCAR) as well as BNL’s Colliding Beam Accelerator(CBA).
2-5. At the time of the RDS, early 1984, the possible potential for improving $J_c$ based on multiple heat treatments had been verified on laboratory quantities of conductor but not yet tested in production. Central Design Group presentations to SSC Magnet Selection Advisory Panel, August 25, 26, 1985; C. Taylor, “Peak Operating Field Adjustments for Cosine Theta Dipole Magnets,” SSC-N-23 (August, 1985).


3-5. Cited arguments against CBA approval included diminished physics potential resulting from the costly two year’s hiatus associated with the late technical hurdles, recent dramatic developments elsewhere in high energy physics (discoveries of the charged and neutral intermediate bosons in CERN’s pp collider), and expected operation of Fermilab’s own collider one to two years before the CBA and at over twice its energy.


4-2. These included an Aperture Task Force, A Cost Comparison Task Force, and an Operations and Commissioning Task Force (Ref. 4-1, above).


5-1. Panel members were as follows: Frank Sciulli, Chairman (Columbia University); Eberhard Keil (CERN); Neal F. Lane (University of Colorado); Michael S. McAshan (Stanford University); John R. Rees (SLAC); E. Parke Rohrer (Rohrer Associates, Inc.); Alvin V. Tollestrup (FNAL); Bjorn Wiik (DESY). Industrial consultants to the panel were Ray. F. Beuligmann (VP Research and Engineering, General Dynamics Convair Division); Cord- Henrich Dustmann (Group Leader for Marketing and Development of Superconducting Magnets, Brown-Boveri & Cie, Mannheim); John K. Hulm (Director of Corporate Research, Westinghouse R&D Center).


5-10. F. R. Houson and P.M. McIntyre to W. Wallenmeyer, April 7, 1986.