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Final Report Magnet Technical Review Panel

The Superconducting Super Collider

TABLE OF CONTENTS

	<u>Page</u>
Abstract.	iii
I. Introduction.	1
I.A Meetings in 1984.	1
I.B Meetings in 1985.	2
I.C Overview.	4
II. Present Status of Magnet Technology	7
II.A Conductor Technology.	7
II.B Conductor Support Structure	15
II.C Quality Control and Field Errors.	21
II.D Quench Protection	31
II.E Cryostat Design and Performance	34
III. Description of Various Magnet Systems	39
III.A Style D	39
III.B Style B	44
III.C Style A'.	51
III.D Style C	53
III.E Style C*.	60
IV. Development of Superconducting Wire and Cable	63
V. R&D Program	69
V.A Introduction.	69
V.B Cosine Theta Style Magnet R&D Program (BNL, FNAL, LBL Response)	76
V.C Superferric Style Magnet R&D Program (TAC Response)	92

APPENDICES

Appendix A Charge to the Technical Magnet Review Panel October 19, 1984	99
Appendix B Charge to the Technical Magnet Review Panel April 23, 1985	101
Appendix C Magnet Measurements.	103
References	131

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ABSTRACT

The Magnet Technical Review Panel has had two series of meetings. The first occurred in the fall of 1984, and in an extensive series of meetings lasting more than ten days, carried out a review of the magnet R&D program for the SSC. The accomplishments of FY84 and the plans of FY85 were studied, and an Interim Report summarizing our studies was written. A by-product of this series of meetings was the proposal for a new style magnet, type D, by a consortium of BNL, FNAL, and LBL.

In April, 1985, Dr. M. Tigner again convened the panel with slightly different membership to review the state of cable development, to report on the state of development of the individual styles of magnet, and to enumerate the time and manpower effort to complete the preprototype R&D prior to style selection.

The committee finds that:

1. The R&D program for superconducting wire and cable has produced spectacular results. The current density of commercially available NbTi cable equals 2600 A/mm^2 , and may become even higher. Magnets using this conductor and operating at 4.2K routinely achieve fields greater than 6 T.
2. The technology for superconducting magnet design has a solid base. Good computer codes exist for magnet stress analysis, the behavior of a magnet under quench, and for relating random and systematic errors in magnetic field to the magnet structure. The technological base is widespread, and good communication exists between the various R&D centers.

3. No magnet-related problems were found that would threaten achieving a successful design for the SSC. The present technology is such that any of the proposed magnets can be successfully evolved to the preproduction stage. However, the remaining R&D is style specific and has a strong interaction with the overall accelerator design. If a style choice can be made now, it will narrow the scope of the remaining engineering R&D and thus conserve funds, make optimum use of the available intellectual resources, and expedite the design of the SSC.

Although the committee did agree on the R&D program necessary to bring any specific magnet design to a preproduction stage, it did not come to a consensus for estimates of the time and manpower required. In retrospect this was probably predictable. The future evolution of the magnet is inextricably tied to questions of machine lattice, aperture, operation, and cost--all of which were outside of the scope of the charge to this committee. A major advantage of the style selection will be to allow all of the resources to focus the engineering R&D on a single magnet style in a manner coherent with the overall machine design program. This is badly needed if the SSC program is to proceed in a timely and aggressive manner in the light of the presently approved funding for FY86.

I. Introduction

I.A. Meetings in 1984

The Technical Magnet Review Panel was first appointed by Dr. Maury Tigner, Director of the Central Design Group, in the fall of 1984. The charge and membership of that committee are given in Appendix A, and the charge is given below:

- 1) Delineate for each design type that minimal set of technical data which is needed for the design type selection process and which can only be obtained from models and prototypes.
- 2) Review critically and report progress, from October, 1983, to date, of each of the three major design types.
- 3) Review critically plans for FY85 in light of (1) and, as appropriate, suggest changes which may enhance their effectiveness.
- 4) Write a report setting forth the results of (1), (2), (3), in a systematic fashion.

A series of ten meetings in October and November, 1984, were held at Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley Laboratory (LBL), and Texas Accelerator Center (TAC), and an interim report was produced in response to the charges set forth above.

The meetings served as an excellent forum for the major participants to review and discuss R&D techniques common to all the various styles of magnets.

I.B. Meetings in 1985

In April, 1985, the committee with a slightly different membership was again called into session. The membership is given in Appendix B and the charge reproduced here:

1. Review magnet and cable development programs at FNAL, LBL, and TAC.
2. Write a report evaluating the technical status of dipole and quadrupole magnet design and development work for the 1-in-1 and 2-in-1 low and high-field magnet styles. For each style enumerate the R&D remaining before each style can prudently be carried to the full-scale prototype stage. This enumeration should include an estimate of the time and manpower effort needed to complete the pre-prototype R&D. The report should include a detailed account of model tests for the various designs.
3. Evaluate and report on the status of superconducting cable development and enumerate further development objectives which could reasonably be expected to be complete in time to have a beneficial impact on SSC magnet cost, reliability and ease of operation. The report should be complete by July 25, 1985.

We have held two meetings: the first was at TAC, July 1-2, and the second at BNL, July 11-12.

I.B.1 Meeting Held July 1-2 at TAC

At the first meeting, the progress on magnets was again reviewed. A new design, D, proposed by a consortium of BNL, FNAL, and LBL was reviewed. This magnet is a $\cos \theta$, cold iron, 6.5 T magnet with a 4-cm bore and uses collared coils.

This made five different designs of magnets to be considered. They are:

1. Design D 1-in-1, cold iron, 6.5 T, 4-cm bore. Consortium BNL FNAL, and LBL.
2. Design B 1-in-1, no iron, 5.5 T, 5-cm bore. FNAL revised.
3. Design A 2-in-1, cold iron, 6.5 T, 4-cm bore. BNL, and LBL.
4. Design C 2-in-1, superferric, 3 T, 3.5 cm x 2.5 cm. TAC.
5. Design C* 1-in-1; superferric, 3 T, 3.5 cm x 2.5 cm. TAC.

The committee concentrated its attention on types D and C. The reason for this is that the designs for these two styles are the most advanced. In addition all of the cos θ style magnets now propose to use collared coils and thus the variations in these three magnets appear in the cryostat design and for case A in the magnetic coupling between the two apertures. Therefore, programs for types A and B were viewed as perturbation of the program proposed for D. Design C* is viewed as a perturbation of C, since the magnetic coupling is minimal in this design, and if anything, the assembly may be easier. Very little effort has gone into specific C* design.

After reviewing each of the two styles, the committee spent considerable time reviewing the status of each design and what areas remained to be clarified by further R&D. A list was made by the committee of those areas for each style that would require more R&D. The various "proponents" of each style were then asked to respond in writing at the BNL meeting on their view of how and when this R&D would be carried out.

I.B.2 Meeting Held July 11-12 at BNL

The body of the report was constructed at BNL. There was good agreement among the members concerning the areas of each design that would require further engineering R&D information to bring it to the level of preproduction prototype if it were selected. We include this information in tabular form as well as the "proponents" written responses mentioned above.

However, while we could reach agreement as to where the R&D effort would be needed, we found it impossible to reach agreement upon how much may be required to bring an individual style to the preproduction stage. Thus, the programs presented in Section V are only illustrative of a program that does not get hung up on a knotty problem. This report fails in giving any estimate of the contingency required in the various programs. In addition the committee declined to present here the range of views held by its various members.

I.C. Overview

Section II of this report reviews the status of superconducting magnet technology. The thrust of this section is that the general principles that underlie the design of a magnet are now well understood and widely dispersed within the community. References are given where possible to either published data or data on file with the Central Design Group (CDG).

Section III includes a brief description of the various magnet styles. These descriptions are abstracts in the case of B and D of documents on file with the CDG at LBL. Style A and C are described in the Reference Designs Study.

Section IV is a report on the status of the superconducting wire and cable development.

Section V presents a discussion of the R&D programs necessary to bring the individual designs to a preproduction stage. The appendices contain some of the documentation used in preparing this section.

It is the opinion of the committee 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.

The successful construction of large numbers of accelerator quality superconducting magnets has been demonstrated by the successful operation of the Tevatron. It was emphasized during the reviews carried out by the committee that the technology of magnet fabrication is now widely spread and well understood at the major U.S. centers for magnet development: BNL, FNAL, LBL, and TAC.

The R&D program after the style choice will be directed toward using this broad technical base in collaboration with industry to develop a preproduction prototype of a magnet that has manufacturability and meets the requirements of the SSC. It is the purpose of the next section to document that the technological base is competent to carry out this task.

II. PRESENT STATUS OF MAGNET TECHNOLOGY

Superconducting magnet technology can be broken down into the following areas:

1. Cable/conductor technology.
2. Conductor support structure.
3. Quality control and field errors.
4. Quench protection.
5. Cryostat design and cryogenics.

In the following we will give a brief overview of these subjects with the intention of demonstrating the widespread, high-level technology that has been developed within the community. It is the invaluable heritage of the extensive superconducting magnet R&D program that has been pursued in the U.S. over the last ten years and an asset that permits constructing the SSC with confidence.

II.A. Conductor Technology

Spectacular progress has been made in increasing the current density that is commercially practical to achieve in a NbTi superconducting cable (Ref. 1). This is documented in Fig. II.1. which shows the critical current density versus magnetic field for several conductors. The Tevatron cable is the lowest curve. The last two years have seen the fruition of an R&D program supported by the DOE and involving industry, national laboratories, and the University of Wisconsin. The result has been a much better understanding of the metallurgy involved in producing NbTi filaments.

Figure II.2a shows photomicrographs of the NbTi filaments in the new cable versus that typical of the Tevatron shown in Fig. II.2b. The much smoother, more uniform filament shown in Fig. II.2a presents the possibility of drawing the wire down to a smaller filament size. Multi-stage heat treatments have

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Fig. II.1 Curves showing progress in raising the J_c of NbTi.

Fig. II.2a SEM micrograph of filaments from Billet CB1710 at 4 μ m filament diameter. $J_c(5T) = 2640 \text{ A/mm}^2$

Fig. II.2b SEM micrograph of filaments showing uneven filament diameter and large nodules of intermetallic.

increased the current density at 5 T and 4.2 K by almost 50 per cent (2700 A/mm^2) compared to the FNAL cables (1800 A/mm^2); this has been accomplished commercially on a large scale for superconducting strand with 20μ filaments. Commercial production of cable with filaments less than 5μ in diameter and current densities of 2600 A/mm^2 looks very promising.

The above represents a good example of the impact of magnet style on the R&D program. All magnets benefit from the increased current density in the superconductor. The $\cos \theta$ style will also benefit from a smaller persistent current sextupole field at injection if the filament size is reduced since the value of b_2 is proportional to filament diameter. However, other techniques are readily available for correcting this field, and the R&D must be directed at comparing the commercial cost of producing wire with small filaments versus the cost of adding distributed superconducting correction coils. If the superferric magnet style is chosen, further development of small filament size would not be necessary for the dipoles.

The cable used in magnets is made from many strands of composite conductor. In addition it must be "keystoned" in order that it will fit like wedges in an arch if it is used in a $\cos \theta$ style magnet. After the keystoning operation, the cable is insulated with a Kapton wrap. Regardless of the magnet style this cabling operation must produce a well insulated package with precisely controlled dimensions and one in which the current-carrying capacity is not degraded by having filaments broken during the manufacturing process. Research at LBL in collaboration with industry has resulted in cables with as many as 36 strands compared to the 23 strand cable used in the Tevatron. Modern cable with higher current as well as higher current density has resulted in SSC model magnets that operate at over 6.5 T at 4.5K compared to the Tevatron that operates at about 4 T.

The conductor R&D program has produced excellent facilities at the National Laboratories for making measurements on short samples of the various properties of the conductor (Ref. 2). Widespread agreement exists on the measuring techniques to be used and on the interpretation of the data. This represents an important step in the ability to accurately define the specification of the conductor for industrial production.

An example showing the sophistication in instrumentation presently available is given in Fig. II.3. These measurements were made by clamping a hairpin of cable in a fixture and inserting the assembly into a dipole. B may be oriented either perpendicular or parallel to the wide face of the cable. The voltage drop across the cable versus the current through the cable is measured. Near the critical current the resistance of the sample increases very rapidly from the superconducting state and follows an expression of the form $R = KI^n$. The value of I_c is defined as that current where the resistivity of the cable is 10^{-14} ohm-meters. The printout shown in Fig. II.3 gives the date, the value of n, I_c , B and the temperature. Figure II.4 shows the results for a 30 strand cable prepared at LBL and tested at BNL for style D magnets. Two directions of B are measured and compared with 30 times the current measured for a single strand of virgin wire. Some degradation due to cabling is evident as well as dependence upon the direction of B. High quality measurements such as those shown in Fig. II.4 are important in studying the effects of compaction during manufacture on the current-carrying capacity of the cable (Ref. 3). In addition they provide the most effective way to effect quality control on the superconductor strand as well as the completed cable. Finally for magnets constructed with presently developed techniques there is a good correlation between the short sample test of a cable and how it performs in a completed magnet (Ref. 4).

RUN 3823 TAC B:SP00L Sp: 3 Probe:B 6-5-85

Field = 50kG Dia. = .0268in. C/S = 1.21 Mfr C/S = 1.3

Amps	μ Volts	Rho	Amps	μ Volts	Rho	Amps	μ Volts	Rho
1.0	1.7	74.2	350.4	1.6	.2	442.7	11.1	1.2
59.8	1.0	.7	382.0	.6	.1	446.4	14.0	1.5
105.3	1.4	.6	401.8	1.8	.2	450.9	23.0	2.5
155.8	1.6	.4	414.4	1.0	.1	454.5	32.9	3.5
201.0	1.2	.2	427.6	2.0	.2	459.2	54.0	5.7
256.7	.6	.1	434.0	4.9	.5	461.6	70.2	7.4
300.8	.7	.1	438.7	7.1	.8	463.2	84.4	8.6

$I_{c1} = 441.7$ $I_q = 465$ $n = 45.1$ $J_c = 2683 \text{ A/mm}^2$

Fig. II.3 Sample data sheet from BNL wire critical current measurement. The upper graph shows V in μ V vs. I in A. The lower graph shows $\log \rho$ vs. $\log I$.

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Fig. II.4 Critical current vs. magnetic field results for outer Design D cable XT-013-3012HH and component wire.

II.B. Conductor Support Structure

In order to achieve an accurately shaped magnetic field, the conductors must be located very accurately. They also must not move with thermal or magnetic stress. The cos θ magnets and superferric magnets are considerably different in the magnitude of the forces that must be constrained and the dependence of the field shape on coil and support dimensions; therefore, we will consider the two styles separately and contrast their differences.

II.B.1. Cos θ Support Structure

The forces on the conductor in a cos θ magnet excited to 6 T are very large as the pressure inside the coil package exceeds 2000 psi. The coil collars must support these forces without allowing appreciable conductor motion if the field quality is to be maintained during excitation. A complicating factor is that the differential contraction of the various components as the temperature is lowered to 4.5K may either increase or decrease the built-in preload on the coil package.

These two problems have been investigated extensively in the cos θ magnet R&D program and detailed calculations using finite element stress analysis have been verified by measurements of collar deflection for this style magnet (Ref. 5). The ANSYS printout for a B style collar as calculated at Fermilab is shown in Fig. II.5.

Extensive measurements showing the behavior under load of the cable plus insulation composite have also been made (Ref. 5.1). Recently LBL has measured the stress history in a coil package during cooldown, Fig. II.6a, and during excitation, Fig. II.6b, of a 1 meter model magnet (Ref. 6). The different curves in Fig. II.6b show the relief of internal stress during training of a magnet and its I^2 dependence during excitation.

ANSYS
85/ 7/ 9
14.6250
PLOT NO. 2
POST1
STEP=1
ITER=10
STRESS PLOT
SIGE

ORIG SCALING
ZV=1
DIST=2.61
XF=1.63
YF=.875
EDGE
DMAX=.00274
OSCA=95.3
MX=11334
MN=35.1
INC=800

Fig. II.5 ANSYS output for style B collar.

Fig. II.6a Change in pressure at the key during cool down from room temperature as measured by stress gauges located as shown in the insert. The collars were aluminum and contracted during cool down more than the coil package with a resulting increase of preload.

Fig. II.6b Coil clamping pressure at the points B shown in Fig. 6a. The different curves exhibit the decrease in pressure at the key proportional to I^2 as expected. When the coil quenches, the internal stress is redistributed and the coil "trains."

This detailed understanding of the mechanical properties of the coil package has lead to extremely well clamped coils which exhibit a minimum amount of training (Ref. 7). The detailed data base now available on the structural properties of the coil matrix at both room temperature and 4.5K, modern instrumentation to measure preload, and the existence of verified stress analysis programs has virtually eliminated the problem of training caused by lack of sufficient clamping forces. Figure II.7 shows training curves typical of SSC model magnets and to illustrate the progress that has been made, a curve for an early 1-ft model magnet from FNAL (circa 1977) is included.

II.B.2 Superferric Support Structure

In the superferric magnet, the iron yoke serves the dual function of supporting the conductor and positioning it accurately. Since the field is smaller by a factor of two, the magnetic forces are much smaller, and as a result this design is not strongly influenced by magnetic loading forces. However, one must be concerned with obtaining high enough loading at the parting plane of the laminations to insure that the gap is adequately closed or the field quality at injection will suffer. The assembly procedure must also control accurately the vertical position of the conductor if the terms a_1 and b_2 are to be kept small. And, finally, thermal stresses during cool down must be calculated and carefully measured.

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Fig. II.7 Training history of two SSC-style 4.5 meter models compared to a very early Tevatron 1-foot model magnet. The arrows indicate the expected short sample limit.

II.C. Quality Control and Field Errors

Controlling the quality of the magnetic field in the dipoles and quadrupoles of the SSC is one of the primary concerns of the magnet program. The magnitude of the random and systematic errors is measured by the coefficients a_n and b_n in the expansion for the field on the median plane of the dipole

$$B_y = B_0 \sum_{n=0}^{\infty} b_n x^n \quad b_0 = 1$$

$$B_x = B_0 \sum_{n=0}^{\infty} a_n x^n$$

Similar equations exist for the gradient inside a quadrupole.

Calculations show that extraordinarily uniform fields are possible if the conductors are placed in the correct location; however, in the real world, a number of effects leading to both systematic and random error fields must be dealt with in magnet design. These effects are different for each style magnet and will be discussed separately below. Systematic errors are considered first and involve primarily the properties of the superconductor and of magnet iron which are amenable to measurements in the laboratory. These data can be used quite successfully with computer codes to calculate the systematic error fields.

Random errors are a more difficult problem. They depend not only on the magnet style, but also its size and the intimate details of the processes and tooling used in its manufacture. A "general model" for a given style may be useful at the early stages of the machine design for estimating the aperture

required. However when the manufacturing has began, a specific error model is required in order to determine the specifications and set the tolerances for all of the components consistent with having the final magnet meets its design criteria.

We show below that general models are available for the different designs. A specific error model will only come as the manufacturing process for the final magnet is defined.

II.C.1 Systematic Errors

For the $\cos \theta$ style the major systematic error is the sextupole and decapole fields at injection due to persistent currents in the superconducting filaments. For the superferric magnet, these two multipoles also dominate the systematic errors, but they are most important at high field and are caused by saturation of the iron plus the intrinsic field from the coils after the iron is saturated (Ref. 12). Methods exist for correcting these fields in both cases.

For the $\cos \theta$ magnets, a straight forward bore tube correction coil such as was successfully tested for CBA magnets could be used. Alternatively since these fields are proportional to the filament diameter, it is possible to reduce them by manufacturing strand with smaller size filaments. A great deal of R&D effort has gone into understanding the effects of persistent currents and constructing a model that accurately predicts their effects (Ref. 9). BNL has the facility to measure the magnetization of a sample of superconductor. Data from such a measurement are shown in Fig. II.8. The measured magnetization data from BNL shown in Fig. II.9a are used to predict b_2 for a model magnet constructed and measured at LBL. A comparison of the measured and calculated values of b_2 is shown in Fig. II.9b.

Fig. II.8 The results of reversible and hysteresis effects on the magnetization of samples with two different filament sizes (3μ m and 20μ m).

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Fig. II.9a Magnetization data used to predict b_2 for the magnet shown in Fig. II.9b.

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Fig. II.9b C5 (Design D) magnetization sextupole field.

Magnetization moment per unit volume versus filament diameter is shown in Fig. II.10 and demonstrates a linear relation. If the filaments can be sufficiently reduced in size then distributed correction coils may be unnecessary.

Also, a superconducting correction winding that is simply shorted at its terminals, instead of being powered from an external source, is energized inductively and has been shown to correct field distortions nearly completely (Ref. 21).

Finally, it may be possible to correct these fields using passive methods. It has been suggested by G. Fisk and B. Brown at FNAL that some additional passive superconductor can be placed around the beam pipe in such a way that its magnetization will cancel the b_2 and b_4 of the superconductor in the coil package. Tests have indicated that this is possible and that there is agreement between theory and experiment (Ref. 17). Also, a superconducting correction winding that is simply shorted at its terminals, instead of being powered from an external source, is energized inductively and has been shown to correct field distortions nearly completely (Ref. 21).

We see again that here is an area in which, if the $\cos \theta$ style is chosen, the R&D program will be directed at the specific problem of minimizing the overall cost of the system used for correcting the systematic error fields and persistent currents. There is no threat to the SSC: a distributed correction coil can be built and will certainly work; however, other schemes are available for performing the same function.

The superferric magnets have three different windings and through control of the total current, plus the two independent ratios, the central field can be set to a given value and the systematic values of b_2 and b_4 tuned out.

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Fig. II.10 Variation of measured magnetization with filament size for samples with transport current $J_c \approx 2500 \text{ A/mm}^2$ (Ref. 9b).

Thus the systematic errors in b_2 and b_4 will depend on how accurately the three currents can be made to track each other and how accurately they can be specified in order to get these two harmonics to equal zero. Figure III.8 shows the calculated values for these three currents as a function of B . Calculations at TAC indicate that if these ratios are controlled to 0.01% then the systematic errors for b_2 or b_4 are negligible (see Table II.2).

An indication of the accuracy of the computer programs when used to calculate the behavior of a C type magnet is given in Table II.1 (Ref. 12).

Table II.1

B_0 T	b_2			b_4		
	Meas.	Pred.	Δ	Meas.	Pred.	Δ
.756	-58.2	-59.5	1.3	-28.4	-30.5	2.1
1.498	-89.7	-88.3	-1.4	-37.5	-38.4	0.9
2.349	-135.8	-131.	-4.8	-25.8	-25.2	-0.6
2.981	-35.2	-35.2	0	-14.9	-16.0	1.1

Calculations and measurements of b_2 and b_4 as a function of B_0 are shown for a case when I_3 was equal to zero and large values for these coefficients would be expected. The agreement between measurement and calculation to a few units in b_2 and b_4 indicates the present accuracy of the computer codes in a case where the iron at 3 T is highly saturated. More work is required to test the ability to predict the current ratios required for setting b_2 and b_4 equal to zero. An additional systematic effect that has not been studied is that of the residual magnetization on the shape of the injection field.

II.C.2 Random Errors

The model for random errors in $\cos \theta$ magnets has received much attention.

The data bases are:

1. Tevatron magnets - 800 dipoles - 250 quadrupoles (Ref. 10).
2. CBA preproduction - 10 dipoles in test string (Ref. 7).
3. Model magnets - 50-100 using various designs.

Considerable effort has gone into generating a random error model that applies to magnets with aperture sizes between 3 cm and 7.5 cm (Ref. 11). The work at FNAL during the production of the Tevatron magnets has furnished a good data base on the dimensional tolerances that can be expected from industrial production of cable, Kapton film insulation and collar laminations. This model work has been the basis for projecting the errors used in the studies of required aperture in the SSC high-field magnets. If this style is chosen, this model and its data base will be used to guide the design of tooling for the magnet production and for writing specifications for industrial production of components of the magnet.

The superferric style magnet has errors at low field that are determined by the accuracy that one can achieve in stamping laminations and in controlling the air gaps at the points where the laminations meet. In addition, careful control of the μ of the iron is necessary. At high excitation, part of the field at the orbit comes from the magnetization of the iron and part from the direct field of the coils, and therefore the field errors arise from fluctuations in the magnetization of the iron and from errors in mechanical placement of the conductor.

An error model covering the above effects has been developed at TAC (Ref. 12) using the programs POISSON and MAGNUS. Table II.2 shows the results of these calculations as they existed in July, 1985. Additional work is in progress to compute the missing numbers, i.e., odd b_n and even a_n .

The degree of confidence one can have in these calculations was discussed in connection with the results shown in Table II.1. More measurements

Table II.2 (Table taken from Ref. 12)

	B_0		b_2		b_4		b_6		a_1		a_3	
Tesla	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3
HMC	0		0.25	0.02	0.007	0.005	0.004	0.002	0.004	0	0	0
VMC	0	0	0.08	0.3						0.28	0.18	0.08
GS	1.5	13	2.7	0.18	0.03	0.02	0.3	0.003	0	0	0	0
CR	0	0	0.37	1.1	0.2	0.004	0.035	0.001	0	9	0	0
MV	0.01	39		0.3		0.022						
MM	0	12	0.01	0.4	0.01	0.13	0.005	0.4				
SFV	0	155	0.002	2.4		0.07		0.013				
SFM	0	71	0.004	6.3	0.004	0.36	0.005	0.22				

HMC - Horizontal misplacement of conductors (1 mil; 4)
 VMC - Vertical misplacement of conductors (3.8 mil total; 1)
 GS - See 1 gap spacing (0.2 mil; 2 for b_n , 4 for B_0)
 CR - Current ratio (0.01%; 2)
 MV - μ variations (2% at 0.15T, 0.13% at 3T; 1)
 MM - Up-down μ mismatch (2% at 0.15T, 0.18% at 3T; 1)
 SFV - Stacking factor variations (0.1%; 1)
 SFM - Up-down stacking factor mismatch (0.1%; 1)

The numbers in parentheses are the accuracies with which we believe that the corresponding error can be controlled, and the rms number of occurrences. The calculated sensitivities of the harmonic components to each error for the WF2C model are shown in the table (Ref. 12).

are clearly needed to verify the accuracy of these predictions. To date, eight magnet model bores have been measured; two 2-in-1 magnets and four 1-in-1. The magnets are of varying design and not all harmonics are available for studying errors.

If this style magnet is selected, future R&D work will involve studies of how accurately the magnetization iron can be controlled, on average, over the magnet. The precision of lamination stampings, the pressure required to close the gap at the parting plane, and the errors in conductor placement will all need more study.

II.D. Quench Protection

Quench protection for SSC magnets is necessary regardless of the style finally chosen. None of the magnets can afford the luxury of a cryostable conductor due to the high current density required. The Tevatron represents the existence proof that a large system can be protected adequately (Ref. 13); it has over 10^8 cm of cable--each centimeter of which must be monitored and protective action taken if it goes normal due to an instantaneous temperature increase from frictional motion, beam loss, or lack of refrigeration. The Tevatron uses an "active" system of protection. If a quench is detected, a subsection of the magnet system is shorted with an SCR, and a heater is fired inside the shorted magnets driving them normal. Enough conductor must be driven normal so that all of the stored energy in the subsection can be absorbed as an increase of the enthalpy of the conductor without producing a temperature increase so high that the winding is damaged.

A passive system was developed for the CBA magnets and is being studied for the SSC (Ref. 7). This system utilizes cold diodes to bypass the current around the normal-going magnet and relies on quench propagation within the

magnet to spread the energy loss over sufficient conductor to limit the temperature rise to safe values.

The R&D program is concentrating on obtaining good values for the quench wave velocity within the magnet structure. Once these values are known, comparison can be made between quench code predictions and actual measurements made on magnets equipped with small heaters at various spots in the magnet to trigger quenches. In the case of the $\cos \theta$ dipole data on several magnets (Ref. 14) verify these computer codes. Extrapolation from the present length magnets of about 6 meters to 16.6 meters and higher fields can be made with a certain degree of confidence.

A complicated time dependence for the magnet currents can exist if there is more than one inductively coupled loop such as occurs when the top and bottom coils of a $\cos \theta$ magnet are separately protected or, in the case of the superferric magnets, where three different loops are magnetically coupled non-linearly. This effect, if present, must be included in the quench protection code.

The calculated curves of current versus time for a passively protected 105 m long superferric magnet are shown in Fig. II.11. Calculated temperatures are in the table under Fig. II.11 (Ref. 8). At present the quench velocity has been measured in a 1 meter model and used in the computer program.

The present computer codes give an upper limit for the temperature rise of the conductor since they all use an approximation that neglects any heat removal due to vaporization of the helium in contact with the conductor. The amount of this helium is not accurately known as it depends on the compaction

XBL 857-11228

4x35 Dipole-Magnets Section Outer Coil Quench

	<u>T(s)</u>	<u>θ(K)</u>	<u>NM</u>	<u>R(Ohm)</u>	<u>V(volts)</u>	<u>VQ(m/s)</u>	<u>Fraction</u>
OUTER	1.0	672	44	0.0537	140	12.0	0.23
INNER		552	41	0.0561	151	15.0	0.34
TRIM		97	4	0.2492	105	24.0	1.00

Fig. II.11 Calculated currents vs. time for the three currents in a 105 m long Type C superferric magnet. The calculated maximum temperature and voltage is shown in the table above (from Ref. 8).

of the winding and its porosity. The quench codes in use require knowledge of the longitudinal and transverse velocity of the quench zone. It is fairly easy to directly measure these two velocities once the structure of the magnet is fixed (Ref. 15). As mentioned above, these codes when compared with experiment give temperatures somewhat higher than are observed, and thus gain a conservative estimate. Their accuracy is acceptable for guiding the design of the quench protection system.

The length of magnet that can be protected in a "quench protection cell" is a function of the energy stored per unit length, the heat capacity of the cable, and the velocity of quench propagation. Thus it is magnet specific. Engineering R&D will be necessary after the style and aperture are chosen to define details of the magnet protection.

II.E. Cryostat Design and Performance

The SSC Reference Designs all required greatly improved cryostat performance relative to the Tevatron. It has been necessary to document that this increased performance was achievable. The R&D program for this study has been centered at FNAL. Three separate facilities have been constructed:

1. 12 meter model cryostat assembly.
2. 6 meter model with Tevatron style collared coil assembly to study transient magnetic eddy current effects in the intermediate heat shields during a magnet quench.
3. LHe dewar instrumented to accurately measure the heat leaks in a wide variety of support devices.

In addition, a model was constructed to measure distortions caused by stress from thermal gradients that are encountered during cooldown.

This program has given a great deal of confidence that predicted and measured performance of a typical cryostat are in excellent agreement (Ref. 16). Table II.3 gives the results measured on the 12-m model cryostat. With the exception of the 4.5K load, which is difficult to measure on a single magnet because of its very small value and large end effects, the agreement is excellent.

Table II.3 Heat Leak Model - Preliminary Thermal Performance Results.

<u>Heat Gain</u>	<u>Analytical Prediction</u>	<u>Measured Value</u>	<u>Measurement Method</u>
80K	- End vessels (measured)	22.0W	Boil-off
	- Thermal radiation (calculated)	8.3	
	- Support conductor (calculated)	21.2	
		<u>51.5W^a</u>	
10K rise	- Thermal radiation (calculated)	0.7W	Gas steam temperature
	- Support condition (calculated)	1.54W	
		<u>2.28W</u>	
		<u>2.28W</u>	
4.5K	- End vessels (measured)	450mW	Boil-off
	- Thermal radiation (calculated)	2mW	
	- Support conduction (calculated)	440mW	
		<u>892mW^a</u>	
		<u>1060mW^a</u>	

^a Total heat gain to model ... includes end vessels

This measurement is complemented by measurements in the instrumented dewar which allows a single support to be studied and the very low losses at 4.5K to be easily measured. Figure II.12 shows the results of one such measurement. Note the very small values that can be measured between the 4.5K point and the first heat intercept and their good agreement with predictions.

Fig. II.12 Cryogenic support post heat leak measurements.

The performance of the multilayer insulation between the 80K shield and room temperature depends on the insulating vacuum. Figure II.13 shows that the MLI blankets used in these tests perform considerably better (i.e., work at a higher pressure) than previous data would indicate.

The measurements on supports and MLI are applicable to any style of magnet and indicate that the heat load budget proposed in the Reference Designs Study can be met; however the information obtained concerning distortion caused by cool down thermal stress is only applicable to magnets in the length range of 10-15 meters. Longer magnets such as proposed for the type C of ~100 meters still must be studied as no measurements of thermal distortions in such long structures exist.

PRESSURE VS. BOILOFF
FOR SSC MLI BLANKETS
VS. PUBLISHED DATA

Fig. II.13 Performance of multilayer insulation vs. vacuum.

III. DESCRIPTION OF VARIOUS MAGNET SYSTEMS

III.A. Style D - A High Field 1-in-1 Cold Iron Magnet

This section summarizes the 1-in-1 collared dipole design for SSC Reference Design D, a collaborative effort of BNL, LBL, and FNAL (Ref. 18).

Overall Design. The dipole is a cold iron (and cold bore), 1-in-1 magnet of 16.6 m magnetic length, utilizing a two-layer cosine theta coil of 4.0 cm aperture (coil i.d.). It is designed for an operating field in the range 6.0-6.5 T. (The SSC ring circumference corresponding to a guide field of 6.5 T is 90 km, and the number of dipoles in Reference Design D is approximately 8000.) The design operating temperature is 4.5K, obtained with forced circulation of high pressure supercritical (single phase) helium; the cryogenic system encompasses 12 refrigerators equally spaced around the ring and periodic re-coolers within each cryogenic loop. At this time only a conceptual design exists for the regular quadrupoles for this machine option: a one-layer coil with an inner diameter matching that of the outer layer in the dipole and utilizing the same conductor. It would have a cold-iron yoke without collars, a magnetic length of about 6.6 m, and a maximum gradient of about 140 T/m matched to 6.5 T in the dipole. Design D calls for approximately 1500 quadrupoles in the regular arcs.

Bore Tube Assembly. The high vacuum chamber, or cold bore tube, is a stainless steel tube of 3.3 cm i.d., copper coated on the inside to minimize the electrical resistance of the wall to image currents. On the outside of the bore tube are mounted superconducting sextupole and decapole correction coils. Several prototype designs well suited for mass production are under development. Between these and the main dipole coil are longitudinal plastic insulator-spacer strips spaced to furnish annular helium cooling passages.

Fig. III.1 Cos Θ style collared coil.

Coil. The collared coil subassembly is shown in Fig. III.1. Both coil layers are wound from partially keystoneed (about 1.8 degree) flat "high homogeneity" NbTi cable of the Rutherford type. Mechanical stability and optimal conductor placement in the completed coil package are achieved by inclusion of copper wedges in the coil cross section. Since the field in the outer coil is lower, the cable is graded according to current density, with the inner layer (16 turns) wound from a 23-strand cable of Cu:SC ratio 1.3:1 and the outer layer (20 turns) from a 30-strand cable (1.8:1). The two layers are powered in series, with approximately 6 kA corresponding to a central field of 6 T. The cable insulation consists of a double wrap of Kapton followed by one layer of fiber glass impregnated with B-stage epoxy; the latter serves to hold the coil together during handling. (A possible coil fabrication procedure without fiber glass epoxy is also being studied.) The individual coil sections are wound under computer control on a precision laminated convex mandrel, and subsequently epoxy-cured in a laminated concave fixture under pressure. During assembly additional insulation is introduced: Kapton on the mid-plane and Kapton and Teflon (the latter serving as a slip plane) between coil layers. The coil ends are flared out from a minimum i.d. in the straight section of 4.0 cm to about 8.9 cm. An advantage of this feature is a reduction of the peak end field associated with straight saddle coils without resorting to the usual spacers between end turns. Recent experiments have indicated that a flared end is not needed for NbTi conductor and if further development confirms this finding, then straight ends, as used in the Tevatron, would become standard.

Collars. The coils are compressed with 1.5 cm wide collars of fully austenitic, non-magnetic stainless steel pre-assembled in packs from 1.5 mm

thick laminations. The collars simplify subsequent assembly in the iron yoke and provide the necessary restraint to maintain the coil under a compressive stress of about 8 kpsi. The relatively thin radial width minimizes the loss in contribution to the magnetic field from the yoke (a loss of about 0.2 T in B_0 at high field); conversely, a benefit from collars is a sharp decrease in the effect of iron saturation on the allowed harmonics (a shift less than one 2×10^{-4} for b_2 in the present design). The coils are insulated from the collars with several layers of Kapton sheet.

Cooling Scheme. The high pressure (4 atm) supercritical helium flows through the annular space between the trim coils and the main coil (where part of the heat load intercepted is due to synchrotron radiation), through passages between the collars and yoke, and through larger channels in the yoke. The bulk of the helium mass flow, 100 g/sec, flows through the yoke bypass channels; about 1 g/sec is needed in the coil region to act as a transfer medium for heat from the bore tube.

Yoke and Cryostat. The yoke, 26.67 cm (10.5 in.) in o.d., is assembled from modular blocks fabricated from laminations of low carbon steel, mounted in the helium containment shell as in Fig. III.2. The laminations are punched with keyways for accurately locating the collared coil assembly within the yoke. The two large rectangular slots carry the main and diode bypass electrical bus (top) and correction element leads (bottom). The four large holes are the channels for helium flow; the smaller holes near 40 degrees are for tensioned alignment rods. The tolerances on yoke length and weight are met with the aid of a select number of filler laminations and proper compression of the lamination stack. The helium vessel is fabricated from stainless steel half shells, welded shut on the mid-plane with the top and bottom sub-assemblies held in contact under pressure. Holes are provided in the containment shells for the insertion of fiducial marking plugs into recessed slots in

Fig. III.2 Completed helium containment cross section.

the yoke (Fig. III.2), used as magnet survey markers during installation in the tunnel.

Vacuum Vessel Assembly. The cold mass subassembly, at 4.5K, is surrounded by concentric aluminum heat shields maintained at 10-20K and 80K, by helium gas and liquid nitrogen, respectively, with intervening thermal insulation consisting of layers of aluminized Mylar and fiber glass mats. Three cryogenic headers are located in the annular space between the cryostat and inner heat shield: a recooler supply pipe, a helium gas return pipe, and an additional helium gas pipe welded to the heat shield. A fourth pipe, welded to the 80K shield, carries liquid nitrogen. The cold mass and the ancillary cryogenic components are supported vertically and constrained horizontally at four locations relative to external supports. A compact post design for accomplishing this is shown in Fig. III.3 together with a complete cross section. The cylindrical vacuum vessel is constructed from low carbon steel. The magnet stands will be simple pedestals with adjustment screws, surveyed into position by the fiducial marks and grouted to the tunnel floor. Interconnections between magnets include beam tube, 4.5K helium pipe, heat shield connections, electrical buswork including thermal contraction loops and quench-protection diodes, and insulating vacuum. The connections utilize automated welding procedures and incorporate bellows to facilitate installation and compensate for thermal contraction.

III.B. Style B - The Ironless Cosine θ Option For The SSC

The most prominent and distinguishing features of Reference Design B are its particular style of magnet. Separate cryostats are used for each of the two collider rings, arranged one above the other. The magnet is proposed as 5.5 T, 1-in-1 design, using warm shielding iron located far from the coils. The dipole length is 12 m and the mechanical aperture of the coil is 5 cm.

Fig. III.3 Completed cryostat and vacuum enclosure.

The magnet design aims at achieving the SSC performance and cost-effectiveness objectives with a minimum extension beyond the technology demonstrated by the Tevatron. The design B dipole magnet concept has evolved since the Reference Designs Study of May, 1984, to take advantage of R&D developments since then. Improvements are the result of a continuing program of design studies and laboratory investigations and include:

1. An increase in central field to 5.5 T.
2. A more effective use of multilayer insulation.
3. A redesigned support post.
4. Lower magnetic decentering force and smaller transient deflections due to eddy currents.

A cross section and an elevation are shown in Figs. III.4 and III.5.

Superconductor. The inner and outer shells are wound from Kapton-insulated, Rutherford-style cable. Copper wedges are included to improve the field uniformity and to reduce the amount of keystoneing required of the cable. Winding parameters are listed below:

	<u>Inner</u>	<u>Outer</u>
Number of turns	25	18.5
Number of strands in cable	25	23 (both use 0.76 mm strand)
Copper to superconductor ratio	1.8	2.5

The design has assumed that superconducting strand will be available with critical current density of 2500 A/mm^2 at 5 T and 4.2K.

Collared Coil Assembly. The Kapton-insulated cable is dry wound onto a collapsible mandrel in one complete operation. The aluminum collars are installed, closed incrementally, and keyed together as the mandrel is withdrawn. A 3-mm thick stainless shell installed over the collars completes

Fig. III.4 Design B completed cryostat and vacuum.

Fig. III.5 Magnet style B.

1 * DISTANCE BETWEEN ENDS OF EFFECTIVE FIELDS.
2 * SEE SHEET 2 OF 3 FOR TYP. CROSS-SECTION.
3 * SEE SHEET 3 OF 3 FOR CROSS-SECTION THRU POST.

NOTES:

the collared coil assembly. The collared coils are similar to type D except for the larger bore of 5 cm.

Cryostat. As can be seen in the cross-section view of Fig. III.4, the collared coil assembly is supported at four posts formed from concentric cylinders of epoxy fiber glass. These posts are rigidly attached to the collared coil assembly but are free to slide longitudinally with regard to the warm iron vacuum vessel. These support posts provide the thermal intercepts and attachment points for two intermediate temperature heat shields. Both shields are formed from aluminum extrusions and rolled shapes. Multilayer insulation blankets as shown are used to reduce the heat leak.

The vacuum vessel is made from mild steel and serves to return some of the magnetic flux from the collared coil. Its dimensions are such that it has negligible effect on the central field and neither magnetic properties nor dimensional tolerances are critical. The R&D to support this cryostat design is given in Ref. 16.

Interconnections. The required interconnections between magnets are:

Cryogenic

- beam tube vacuum
- main helium coolant containment tube
- cryogenic lines for helium
- liquid nitrogen shield lines
- insulating vacuum

Electrical

- magnet current bus bars (1 pair)
- quench bypass bus bars (1 pair)
- quench protection diodes installed in every half cell and instrumentation leads, quench detection voltage taps, and correction coil leads.

To obtain the most reliable leak tight connections all internal fluid connections are welded stainless-steel joints made by automatic welding equipment. Joints in the beam tube that separate the single phase helium flow from the beam vacuum are made with double wall bellows having an intermediate space for leak interception. Electrical connections are made within the feedthroughs except where necessary at the quench heaters. Connections are supported by insulating bars and junction boards. Expansion joints are provided in the bus to accommodate thermal expansion which is of the order of an inch.

Quadrupole. The quadrupole coil uses the same conductor specified for the dipole; the inner coil has 8 turns and the outer has 14. At a current of 6600 A (5.5 T in the dipole) the quadrupole has a gradient of 154 T/m. Except for its shorter length, the quadrupole cryostat is essentially the same as the dipole cryostat.

Correction Coils. Persistent currents flowing within the superconductor during magnet excitation give rise to a current dependence in the sextupole and decapole moments for all cosine theta superconducting dipole designs. By using conductor with a filament size of less than 3 μm , persistent current induced multipoles may be small enough to permit the corrections to be made by the usual relatively short correction magnets located near the quadrupoles. If small filaments cannot be made satisfactorily, it is necessary to correct locally these unwanted field components to obtain reasonable magnetic aperture for injection and acceleration of the beam. A model of this effect has been developed and tested with current-dependent data obtained from Tevatron dipoles (Ref. 17). Alternatively, bore tube mounted correction windings applicable to all high field magnets styles are being developed (see Style D) and could be used.

III.C. Style A' - The High Field 2-in-1 Coil Iron Design

Style A' incorporates 2 collared coils of the Style D design in a single yoke and cryostat to form a 2-in-1 magnet with horizontally aligned bores. The only significant difference between the dipoles of type D and A' is the 2-in-1 yoke in the latter design (Ref. 20). As a consequence of the assumed identical collared coils, the performance characteristics of the two magnets, e.g., peak field, transfer function etc., are about the same. The systematic multipoles in style A' are approximately the same as for style D. An overall cross section of the A' cold mass is shown in Fig. III.6. The cryostat concept shown in this figure illustrates a ring girder support system that is different than the pedestal supports shown for styles A and B, and is shown in this figure to illustrate a slightly different cryostat concept. Here the yoke o.d. is 35.56 cm (14 in.), with center-to-center separation between the two apertures of 16.51 cm (6.5 in.), determined primarily by the minimum practical separation between the collared coils in the flared ends, and the minimum allowable thickness of the outer return leg in the yoke. (In this particular design, the return leg is heavily saturated at full field, with twice as much flux crossing from one aperture to the other as is returned through the outer leg.)

The two cut-outs on the vertical center line at either pole are for accommodating heavy strong backs; the four rectangular slots at 40 degrees from the horizontal axis are for the electrical bus. The two large holes on the vertical center line replace the four helium bypass channels in Design D. In a 2-in-1 dipole, the quadrupole harmonic is an allowed term in the absence of left-right symmetry; the magnitude of this term was minimized by adjusting the size and location of the two bypass holes.

Fig. III.6 Magnet style A helium containment cross section.

III.D. Style C - Superferric Magnet Option for the SSC

The basic superferric idea for the SSC started at Snowmass in the summer of 1982. A concentrated effort began in March of 1984 when the Texas Accelerator Center was formed.

As currently conceived (Ref. 8), the main ring of the SSC would be made up of 1330-115 meter units, plus the necessary straight sections and interaction regions, and have a total circumference of 162 kilometers. Each of the 115 meter units would be made up internally with three 35 meter dipoles, a 4.7 meter quadrupole, and a 4.3 meter spool piece containing correction elements, position monitors, expansion joints, and heat exchangers. It is proposed that the 35 m unit dipoles, quadrupoles, and spool pieces would be assembled individually at various industries throughout the country. These units would be shipped to the SSC site and assembled above ground into a single 115 meter unit. Externally this would be a 16-3/4 in. diameter pipe serving as the vacuum chamber for the full unit. The insulating vacuum would be pumped and then sealed off. These units would then be inserted into the main tunnel at four locations and welded together to make up the arcs of the accelerator. The magnets would be transported by a specially made self-propelled vehicle that could follow a guide wire located in the floor.

Magnet design. Figure III.7 is a cross section of the 3 T superferric magnet. The magnet has three independent windings: I_1 are the four turns closest to the horizontal plane, I_2 are the four turns farthest from the horizontal plane, and I_3 is the trim coil on the edges of the pole face. The main dipole field is set by the sum of the three currents, $I_1 + I_2 + I_3$; the systematic b_2 (sextupole) is adjusted to zero by the ratio I_1 to I_2 , and the systematic b_4 (decapole) is adjusted to zero by I_3 . The systematic b_6 multipole is the first nonzero coefficient for this design. Its

Fig. III.7 The 2-in-1 3 Tesla superferric magnet is enclosed in a vacuum chamber of 16-3/4 in. o.d. The iron is 1/16 in. laminations. The two magnet channels are magnetically independent. The vertical gap of the magnet is 1 in. and the calculated good field is greater than 2 cm diameter. The support in the figure is made of two concentric fiber glass cones, one between 10K and 80K and the other between 80K and 300K. There is a support every 24 feet. The small pipes are for liquid helium and nitrogen and the larger ones for helium gas. Sixty layers of superinsulation are between 80K and 300K (From Ref. 8).

XBL 857-11227

Fig. III.8 The calculated values of the three independent currents as a function of magnetic field (Ref. 8).

magnitude is about 1 unit which may be corrected if necessary by the correction elements at the end of each dipole. The odd b_n multipoles and all of the a_n multipoles are zero by symmetry. Figure III.8 gives the computed current as a function of field for all these currents.

The iron of the magnet is made of 0.06 in. laminated steel (1008). A unique aspect of this magnet is the iron magnetic shunt located between I_3 and I_1-I_2 in the magnet. This 0.060 in. steel shunt between the pole faces saturates at very low field. Its purpose is to reduce sensitivity of the field quality to cable placement errors and to reduce the magnetic field at the cable for a given field in the gap. Calculations indicate a 15% reduction.

The electric circuit for the magnets is shown in Fig. III.9. When a quench occurs in the magnet the main current is bypassed every 105 meters of dipole. The stored energy in 105 meters of dipole is 525 kJ per channel. There will be six power supplies around the ring for each circuit. The three independent current circuits are magnetically coupled.

Figure III.10 illustrates what happens when a magnet quenches. As mentioned in the figure caption, the maximum temperature calculated in the superconducting cable is 565K.

The cryogenic system as currently proposed consists of 12 refrigeration circuits around the ring and the calculated cryogenic loads which must be taken care of are listed in Table III.1. The liquid helium is fed down through the magnets to a distance of 1/24 of the ring. At that point part of the liquid helium is expanded through a Joule Thompson valve to cool it giving a two phase helium, and the other part of the liquid is returned in a separate pipe. Between every cell, that is, every 230 meters, there is a heat exchanger where the returned and cold gas are combined to heat exchange with the helium coming down through the magnets. In this manner, the full length of magnets is kept

XBL 857-11232

Fig. III.9 There are four electrical circuits around the ring. This figure shows one-half of one circuit (Ref. 8).

Fig. III.10 Model calculations of currents during a quench. The quench that produces the highest temperature in any conductor occurs at full current and in I_2 (shown). Normally quenches will occur by beam loss in I_1 . The quench occurs at $t=0.0$, and in this model the power supply is removed at $t=0.1$ seconds. The diode in circuit I_2 begins to bypass current at $t=0.2$ seconds (fires at 4 V). The trim current I_3 diode fires at $t=0.2$ seconds and the whole I_3 circuit quenches at $t=0.3$ seconds. The diode in circuit I_2 fires at $t=0.4$. Calculations indicate that the warmest spot in I_1 is 565K, in I_2 472K and in I_3 40K (Ref. 8).

Table III.1 Calculated Steady State Heat Loads in W/Meter.

	<u>300-80</u>	<u>80-10</u>	<u>4.5K</u>
Radiation	0.75	0.066	0.0124
Shield Support System	0.114	--	--
Closure Bellows	0.12	--	--
Magnet Supports	0.63	0.080	0.0040
Magnet Connections	0.16	0.040	0.0200
Refrig. Station ^a	0.06	0.031	0.0800
Contact Resist	--	--	0.0032
Synchrotron rad.	--	--	0.0579
TOTALS	1.834	0.217	0.1055
TOTAL/REFRIG. STATION	23,842	2,822	1,366
TOTAL FOR RINGS	286,100	33,864	16,396

^aIncludes allowance for valves.

cool. A shield will be at a temperature of about 10K. When a quench occurs, the warm helium in that magnet or magnets is removed at the next spool piece where there are cryogenic valves that allow this warm helium to be put into the return lines.

III.E. Style C* - 1-in-1 Superferric Magnet Option for the SSC

The design of the 1-in-1 superferric magnet option is derived from the 2-in-1 Design C. Only differences in the design will be presented in this section. Figure III.11 is a cross section of the magnet.

The magnetic and electrical properties are identical to the 2-in-1 magnet. The principal problem is to support the magnet. We have used a double fiber glass epoxy support similar to the 2-in-1 design. The thickness of the cylinders is one-half that of the 2-in-1; however, there are twice as many, so the conductive heat leak is approximately the same. The moment of inertia of the structure has been increased by adding the beam structure on the bottom of the magnet. It has been shaped to give maximum moment of inertia and to allow placement of necessary cryogenic lines. The diameter of the vacuum vessel is 12 in. compared to 16-3/4 in. for the 2-in-1. Thus the total surface area is 1.4 times the 2-in-1. The number of independent end boxes is twice the 2-in-1. The total cryogenic load is estimated to be 1.4 times the 2-in-1.

Fig. III.11 Superferric style C* 1-in-1 magnet.

IV. DEVELOPMENT OF SUPERCONDUCTING WIRE AND CABLE

This is a summary of the status of development of superconducting wire and cable for SSC magnets (Ref. 1).

For a small-bore (4-5 cm), high-field (6-6.5 T) magnet, current density must be significantly improved over that of the Tevetron cable. Because of the SSC interest, the technology to realize this was very rapidly developed over the past two years; rapid large-scale commercialization was aided by a successful collaboration between the University of Wisconsin, who did much of the fundamental work on metallurgy of Nb-Ti, Teledyne Wah Chang, the major world supplier of Nb-Ti alloy, Intermagnetics General Corp., who processed billets into wire, and LBL, who organized the industrial part of the effort.

Fortunately, the key process changes involve only homogenization (via heat treatment) of the Nb-Ti billet at a large size and one additional heat treatment of the wire during processing; no new equipment or costly process is required, and, therefore, the cost is not significantly increased. The details of this development are given in Refs. 1e and 18.

Material now being produced commercially for SSC model magnets has current density between 2500 A/mm^{2*} and 2700 A/mm^{2*} depending on strand size. Improved heat treatments produce at least 3000 A/mm^{2*} in laboratory pilot tests; thus, further improvements are expected in production. Figure IV.1 shows J_c vs. field for several Nb-Ti composites.

For reference, the Tevatron specification was 1800 A/mm^2 . For the Reference Designs, an anticipated J_c of 2400 A/mm^2 was assumed; this has now been exceeded. The most recent Design D model magnets** use material with 2500 A/mm^2 in layer 1 and 2650 A/mm^2 in layer 2, and reach 6.6 Tesla.

* A/mm^2 at 5 T, 4.2K, for an equivalent resistivity of 10^{-12} ohm-cm .

**4.5 m models at BNL and 1 m models at LBL.

XBL 856-2862

Fig. IV.1 Progress in raising the J_c of Nb-Ti.

After 15 billets for a total of about 5,000 lbs. (including LBL, Fermilab, and TAC orders), the following can be concluded regarding large-scale production:

- (1) The original SSC specification of 2400 A/mm^2 can be exceeded.
- (2) The spread in J_c of the wire appears to be less than that for "old" material.
- (3) Extremely long wire piece lengths are produced (very few breaks occur due to wire flaws.)

Changing magnetic fields induce persistent currents in superconducting filaments; these currents cause distortion of the field for the SSC; the distortion must be either corrected with windings in the bore of each magnet, or reduced to a manageable level by reducing the size of the filaments. Therefore, development of composites with 2-3 μm Nb-Ti filaments has been done during the past year. Results to date have been very encouraging. Figure IV.2 shows some recent current density results on pilot lots of small wire made commercially.

A practical problem to be solved in producing fine filament Nb-Ti for the SSC is to devise a method of stacking a large number (15,000-50,000) of elements to produce the end product. There are at least three promising approaches.

First, one can stack a large number of rods in a single billet; this is the approach being investigated by Supercon. To date, they have stacked a 12-in. billet with approximately 4,000 rods and have completed the extrusion successfully. The second phase will consist of another 12 in. diameter billet with a 1.8:1 Cu:SC ratio and a filament number yet to be specified. A third phase billet would contain approximately 40,000 filaments and yield a final filament size of 2 μm .

Fig. IV.2 Recent fine filament Nb-Ti results.

IGC is investigating a double extrusion approach and has completed an initial 6 in. diameter billet with 7 Nb-Ti rods and a second 6 in. billet with 7 x 858 Nb-Ti filaments. Approximately 100 lbs. of this material should be drawn to final wire size by July, 1985, and will be cabled in order to produce samples for I_c and magnetization measurements. IGC is proceeding with two 10-in. first stage billets. Material from these billets will then be restacked to produce a 10-in. billet of inner layer and a 10-in. billet of outer layer material. This wire should be ready for cabling in December, 1985. If this phase is successful, there will be enough cable for one 16.6-m model dipole and several 1-m models. In addition, BNL is procuring material with 5 μ m filaments for use in another 16-m model magnet.

A promising alternative to the use of conventional hot extrusion with diffusion barriers is cold hydrostatic extrusion. One can process approximately the same weight of material using hydrostatic extrusion as can be produced from a 10 in. diameter conventional extrusion; however, the yield of useful material can be much higher in the hydrostatic extrusion case because of reduced end losses. This factor is especially important in a double extrusion process.

Three billets are being assembled at LBL for extrusion at the National Standard Facility in Glasgow (there is no U.S. hydrostatic press). In addition orders have also been placed with OST and Furukawa for wire with 5 μ m filaments for later delivery. At the conclusion of this R&D phase in November, 1985, there will be a data base on both cost and technical feasibility of various fine filament options as well as enough material to test in magnets.

Cable development has been proceeding along two paths-cabling experiments at LBL and process improvements at NEEW (New England Electric Wire Co., the sole U.S. supplier of this service). An experimental cabling machine at LBL

can produce long continuous lengths of cable about 5,000 ft at production speeds (e.g., 12 ft/min.). After developing the critical parameters on the experimental machine, a total of approximately 8,000 ft of cable was fabricated at NEEW and 12,000 ft of cable was made at LBL at a speed of 10-12 ft/min. and a yield of over 95%. This speed is comparable to that used at NEEW on Doubler/ CBA cable and the yields are better than 95% vs. about 80%. The increased yield is due (1) to improved wire lengths and quality, and (2) to improved cabling parameters and techniques. At this time, it is felt that the Design D cable can be made for the same cost, or perhaps less, than the Doubler/CBA cable. Several new cables are being investigated which could have advantages, including two level cables, internal wedge cables, and internal flat cables.

The strand used in the TAC 3 T magnet is made from the same billet as the inner cable of Design D except it is drawn to a slightly smaller diameter and soldered to a copper core for stabilization and quench protection.

Other important activities include measurement of magnetization, critical current, mechanical properties, and basic metallurgical investigations. Improvements in wire and cable performance has been very promising; further improvements can be incorporated into the SSC program at any time without redesign of the magnets.

V. R&D PROGRAM

V.A. Introduction

This section will discuss the program necessary to bring each magnet style up to the "preproduction stage." We define this stage to mean:

1. A detailed design and set of specifications exist for the magnet.
2. Enough models have been constructed and tested so that there is a reasonable expectation that the magnet in No. 1 can be built.
3. There has been enough R&D effort on manufacturability so that the magnet described in No. 1 can be mass produced at minimum cost using techniques that either exist or can be developed in the industrial environment.

We do not address here the selection of which style magnet should be chosen for the SSC as that is outside the scope of our charge. Rather we try and outline the program that will have to be implemented once the choice has been made.

Following the style choice, the next most important decisions are the size of the aperture and the machine lattice. At this point a detailed design of the machine will start to evolve, and R&D past and future will be used during this design evolution to create a magnet with acceptable cost that will function in the SSC in a highly reliable manner. In particular, the R&D program will be directed toward making comparisons between various alternatives and fixing parameters in a cost-effective way. Thus, for example, a general model for errors in superconducting magnets will no longer be of interest, but only a model for errors generated by a specific proposed fabrication procedure.

The data base we have at present varies with the style, and it is for this reason that R&D programs shown below for the different styles differ; however, the position of the committee is that sufficient data exist to make a style choice now, and the most economical path for the future will be to concentrate the R&D on the particular engineering problems that are associated with developing a specific magnet for the SSC.

The problem of gas desorption by synchrotron radiation affects the development program of all the magnets in that a bore tube liner may be required within the magnetic aperture. The necessary R&D to evaluate the seriousness of this problem has not been done. Basic coefficients for photodesorption of molecules from cold surfaces as a function of photon energy and incident angle of synchrotron radiation have not yet been measured. However, an experiment at the NSLS is underway and will give a preliminary measure of the magnitude of the effect by August, 1985. From this early experiment, it should be possible to estimate whether liners in the bore tube are necessary.

Following the early experiments, more refined experiments to measure the effect of the radiation on the final bore tube surface will hopefully be conducted. Since the overall magnitude of the problem is uncertain by many powers of ten, it is premature to speculate on the significance of the factor of two difference in radiated power in a low-field versus a high-field magnet system.

In summary, this problem should not be viewed as a threat to the viability of the SSC. The solution to the problem is to install a bore tube liner. The impact of this decision is that more magnet aperture may be required. This is another example of where the engineering R&D will be most economically used if it is directed at solving the problem specifically for the magnet style to be used.

A few general comments on the R&D program after style selection are in order. First, the work on spool pieces and quadrupoles is not very advanced for any style magnet, although a great deal of generic information is available from the Tevatron. Much work remains to be done on these components, and it is very specific to magnet style and machine lattice. Funding is badly needed to allow the design of these components to proceed in a timely manner after the style is fixed. There will be enough trained personnel within the magnet centers to undertake this program if funds are available.

A second point concerns the time delay in the program if a decision is made to change the size of the aperture of the magnet from that presently being produced. It was generally agreed by the committee that such a change will result in an additional 9-12 months delay before modified magnets become available for test. Tooling must be changed, many calculations redone, and the "component supply lines" refilled with different size components. If an aperture change is made, one could anticipate that the present size magnets would continue to be produced and appropriate measurements made using them until the modified magnets are brought into production. Experience with such a scenario occurred when BNL, FNAL, and LBL decided to concentrate their collective efforts on the D style 4 cm aperture magnet. In what follows, we break the magnets into two different categories: (1) $\cos \theta$ and (2) superferric. Since all of the $\cos \theta$ magnets use collared coils; they have many similarities and a few differences.

1. Type D; 1-in-1; high field, cold Fe.
2. Type B; 1-in-1; high field, no Fe.
3. Type A; 2-in-1; high field, cold Fe magnetically coupled apertures.

Type D is discussed in detail first and the other two treated as perturbations. It was estimated that switching from D to type A would add six months to the program due to the additional studies required because of the magnetic coupling between apertures.

1. Type C; 2-in-1; low field; cold Fe; no magnetic coupling.
2. Type C*; 1-in-1; low field; cold Fe.

In this case the major design effort has been concentrated on the type C although models of C* were used in early tests of this style magnet.

An explanation of the remaining part of the section is in order. The presentations given are those of the "proponents" for the various style magnets. The time schedule is only for purposes of illustration, and it should be noted that all of the resources of the community are expected to become available for a concentrated program after the choice of style has been made. The schedules shown do not reflect this fact, and the committee did not feel it was in the scope of its charge to focus on how the resources will be deployed in the future.

In our Texas meeting, we considered each design and tried to establish the extent of the necessary R&D to bring it to the preproduction prototype level. Each magnet design was graded as to the status of its development relative to each of the following areas:

1. Stress Analysis
 - a. Collars or magnet yoke in superferric case.
 - b. Cryostat support system
 1. Mechanical loading
 2. Shipping loads
 3. Thermal induced stress
2. Electrical System Performance Analysis
 - a. Electrical insulation
 - b. Transients during quench and excitation of magnets
 - c. Regulation of currents if more than one circuit is involved.

3. Vacuum System Performance Analysis
 - a. Bore tube vacuum studies
 - b. Synchrotron light gas desorption
 - c. Insulating vacuum
4. Cryogenic System Performance Analysis
 - a. Adequate conductor cooling
 - b. Synchrotron radiation heat removal
 - c. Initial cooldown
 - d. Behavior under quench, maximum pressure, recovery time.
5. Quench Behavior
 - a. Maximum temperature in coil package
 - b. Active or passive system suitable
 - c. Voltages induced during quench
 - d. Quench detection system
6. Bore Tube Plating Feasibility
7. Interconnections Design
 - a. Mechanical
 - b. Electrical
8. Model Tests for Future R&D
 - a. Training
 - b. Field level
 - c. Systematic errors
 - d. Random errors
 - e. Quench heating
 - f. Alignment and support
9. Status of Production Engineering Design
 - a. Manufacturing plan
 - b. Development of tooling
10. Design Review
 - a. Internal
 - b. External
11. Correction Coil Design
 - a. Lumped
 - b. Distributed
12. Current Lead Design
13. Status of Production Testing Instrumentation
14. Maintenance and Replacement Considerations

The problem involving synchrotron radiation gas desorption affects all the designs and has been split off and described above. It is to be viewed as possibly requiring an increase in aperture with the consequent delay mentioned above.

For each of the styles the three most significant engineering R&D areas were identified. In addition there were ten to twelve areas identified that would require continuing effort and that affected either the magnet itself or the magnet as installed in a system. Some of these issues were common to all designs, and some were design specific. The committee tried to come to a consensus and give a quantitative estimate of how much work remained in each area for each magnet design, but unfortunately, although as a committee we could agree on the areas requiring attention, it was apparent that there was no possibility of reaching agreement on how much engineering R&D remained or the contingency that should be assigned to cover any remaining uncertainty.

As a result, at the end of our TAC meeting, each "proponent" was asked to respond in writing about how he would direct the R&D in those areas that were brought into question. At our final meeting at BNL, we took those responses as the basis of the required R&D program--the three most significant areas are broken out and discussed explicitly, and the continuing engineering R&D tasks are listed in table form. The written responses are also included and give more complete information than the Tables V.1 and V.2.

The panel was thus not able to respond to its charge of providing an "estimate of the time and manpower needed to complete the preproduction R&D." The estimates in the following sections are those of the "proponents" and should only be viewed as indicating a plausible scenario in the eyes of the proponents. The contingency that should be applied to these programs is obviously very different due to the fact that much more experience exists with

the cos θ style magnets as used in the Tevatron, than with any of the others. The key issue of assigning a rational contingency to the other designs must take place in a broader forum than one just restricted to magnet technology which is the case for this committee. Invariably in debating this issue the committee would get involved in questions concerning SSC machine lattice or aperture, machine operation, or total project cost--all of which were areas outside the charge, but clearly have a strong bearing on the future magnet development program. With this preamble we go on to the proponents' R&D programs.

V.B. Cos Θ Style Magnet R&D Program (BNL, FNAL, LBL Response)

BNL, FNAL, and LBL working together in a collaborative effort have, since January, 1985, emphasized Design D as the most effective approach to the resolution of major R&D issues for all of the high-field cos Θ designs. In fact, we believe that all of the key issues involved in the demonstration of a successful cos Θ design have been identified and are either resolved or will be resolved by the end of FY85. We further contend that by this time, as a result of the successful 1 meter dipole program at LBL (8 magnets), the 4.5 meter program at BNL (6 magnets), the already completed cryostat development work at FNAL, and the superconductor wire development at LBL, the University of Wisconsin and in industry, we will have demonstrated by model tests all of the critical features of Design D. In addition, we will have accumulated a sufficient data base to begin an aggressive program leading up to the production in the laboratories and in industry of prototype models of the SSC dipole magnets in FY87 in accordance with existing manufacturing plans and production approaches which have been successfully demonstrated.

This program of solid accomplishment coupled with the base of knowledge and experience achieved through the design, construction, and operation of the Tevatron along with the demonstration of manufacturability of high-field cos Θ magnets at Fermilab, BNL, LBL, Europe, Japan and the Soviet Union establishes the data base for an in-depth assessment of the technical status of the D style magnet. Following the completion of this FY85 effort, the final confirmation of the Design D systems approach will occur during the preliminary string test of a half cell at FNAL in about one year. With these results, the laboratory and industrial prototype magnets fabrication experience and the incorporation of cost optimization features to be developed in FY86 and FY87, fabrication of initial production magnets can begin in FY88.

With regard to funding and resources, the technical data discussed below under item 1 will, in the main, be completed this fiscal year without additional funds. Assuming FNAL, BNL, and LBL receive the same funding in FY86 as they have in FY85, the half cell preliminary string test can be completed with existing personnel resources shown in Fig. V.1. With additional funding, personnel resources exist to develop more, such as quadrupole and spool piece design and modeling, cost optimization R&D and industrial involvement. A possible schedule is included in the Appendix.

Finally, should Design A or B be chosen, the overall cos θ program would be delayed three to six months due to tooling changes and if the aperture were changed the delay would be nine to twelve months. Additional R&D is addressed below.

DESIGN D DIPOLE SCHEDULE

FY 85

FY 86

SUPERCONDUCTOR
COST OPTIMIZATION

FINE FILAMENTS

CABLE

1m MODELS

4.5 m MODELS
3.2 cm 2 in l

4.0 cm 'D'

16 m MODELS

COMPONENT TESTS

16 m CRYOSTATS

PRELIMINARY
STRING TEST

Fig. V.1 FY 1986 schedule for Design D dipoles.

V.B.1. Significant Engineering R&D Questions for Design D. Significant Engineering R&D Questions to be Resolved in the Next Two to Three Months to Establish Final Magnet Design Basis for Design D follow.

a. Quench Behavior. Good progress has been made in the past year in our ability to predict the temperature upon quench in the cos θ magnet (Ref. 14a) and in fact magnets can be built that are adequately protected. The predicted temperatures are generally somewhat higher than measured values probably because the simple analytic model ignores the effect of the helium cooling. We expect to make several tests on a 4.5 m Design D magnet in the next few months. These measurements will enable us to make a decision regarding active or passive quench protection in this design.

b. Model Tests - Training. Two D model have been tested at BNL, and have reached 6 T with one quench or less and leveled off at a maximum field of 6.6 T after three to five quenches. Similar results have been obtained in four 1-m models test at LBL. The most recent model at LBL quenched first at 6.4 T and leveled off at 6.6 T. In the next few months, several additional training curves will be obtained from 1-m and 4.5-m models. We expect the recent excellent results to continue, thus allowing the training of the magnets to be conveniently done in long strings after installation in the tunnel if required.

c. Distributed Correction Coil Design. BNL has an active program to develop externally powered distributed correction coils for D. The early 4.5-m models contain coils manufactured at BNL and their performance is being ascertained. Later 4.5-m models and the 16-m models will contain correction coils of the multiwire type, a derivative of printed circuit technology that promises to be particularly

cost effective in production. Samples of such coils 4.5-m long are already in hand and meet the required specifications for accuracy and include the necessary bonding agents and electrical performance characteristics when installed on the magnet bore tube. At FNAL (Ref. 17) and LBL (Ref. 21), programs are underway to develop passive distributed correction coils and have given promising results, but further engineering development will be required to integrate these concepts into SSC models.

BNL has extensive experience in the problems of distributed trim coils by virtue of having fully developed and tested externally-powered distributed correction coils for the CBA magnets, of more complicated design (3 multipoles) than needed for SSC. It is anticipated that fully developed coils will be included in at least some of the 16 m magnets scheduled for next year. Should the development of small filament superconductor negate the need for distributed trim coils, their further development and the associated costs would be curtailed.

V.B.2 Continuing Engineering R&D Studies for Design D. Continuing R&D issues to be resolved for magnet Design D (plus A and B) is summarized in Table V.1.

Table V.1 R&D Status (Response by BNL, FNAL and LBL).

^a <u>Item</u>		<u>Status</u> <u>For Design D</u>	<u>Expected Completion Date</u> <u>For Design D</u>
1)	a) Collar stress analysis	R&D work nearly completed; 8T at 2K operation demonstrates adequate safety margin	Last Quarter FY85
	b) Other stress analysis	Underway; will be verified in test of first 16.5 m magnet	Mid FY86 for analysis; verification in late FY86 on PST ^b
2)	Electrical system performance analysis and test	Analysis underway	Experimental verification in late FY86 on PST
3)	Vacuum system performance analysis and test	Analysis underway	Experimental verification in late FY86 on PST
4)	Cryogenic system performance analysis and test	Design and Calc. near completion	Performance verification in full length unit early FY86. System performance from PST in late FY86.
6)	Bore tube coating	R&D for plating	1st samples late FY85 full length samples FY86
7)	Interconnections		Design nearing completion verification in PST.
8d)	Random errors	FY85 effort will provide additional input for errors used in aperture studies	Will continue through production
8f)	Alignment and Suspension	Prototype studies completed in FY85 as part of the cryostat development.	Verification first long models by mid FY86
15)	Quadrupole development	Preliminary design complete, engineering design could begin immediately	Schedule to be determined by optimum resource allocation

^a The numbers in the first column refer to the numbers in the list of R&D items given in Section V.A.

^b FNAL preliminary string test

V.B.3. Additional R&D Needed for Reference Design A. Assymmetric iron requires additional calculations using existing codes and subsequent experimental verification particularly with the use of collars and with model magnets of the required aperture. The 3.2 cm 2-in-1 magnet test data (4 each 4.5 m 2-in-1 models), however, does establish an excellent data base to build on if a Type A magnet is chosen. In other respects, the R&D requirements are identical for those of Design D.

V.B.4. Additional R&D Requirements for Reference Design B. There is no additional R&D, beyond that discussed for Design D, required for Design B.

V.B.5 Response to R&D Questionnaire Discussion of Remaining R&D
For SSC Reference Design D - Engineering Development

Report to Magnet Technical Review Panel

July 11, 1985

1a) Basic clamping or collar stress analysis. Extensive calculations have been performed at BNL (using the finite element program ANSYS), FNAL, and at LBL. The results of these calculations closely predict the final measured deflections of the collar at room temperature while under load at the required prestress. Measurements at LBL using strain gauge instrumentation have confirmed the expected changes in shape upon cool down and due to Lorentz forces when the magnet is powered. Still to be done are calculations on the dynamic behavior of the collar-press system during the actual collaring operation. This would aid in refining the press contact points on the collar so as to better control the deflections during collaring, thereby perhaps permitting the possibility of increased prestress on the coil upon completion of collaring.

1b) Other stress analysis, including shields. With collars containing the Lorentz forces, the remaining forces acting in the magnet are small. The stainless-steel skin forming the helium containment around the outside of the iron yoke is stressed upon completion of the welding operation and further stressed upon cool down due to differential contraction of the stainless steel relative to the iron. These welds have been designed to withstand the required relatively small forces that act to keep the iron yoke firmly closed at the midplane. The large section of the final weldment gives the structure sufficient rigidity to counteract the anticipated bending and torsional forces provided the structure is assembled straight in the first place, as planned.

Engineering analyses of these possible deflections exist and no problem has been found which could lead to later trouble. The remaining development in this category is to measure final deflections when a 16 m cold mass is built. For the cryostat assembly and shield system, FNAL (Ref. 16) has performed extensive calculations and has made measurements on full-length engineering models to verify the correctness of the calculations. From this work, the forces and deflections are well understood, and even the availability of the first full-length magnet will not impact significantly the advanced state of development here.

2) Electrical system performance analysis and test. The electrical system performance analysis for the proposed D magnet system is straightforward owing to the very great electrical similarity of the proposed magnets to the Tevatron and CBA systems. The single approximately 6000 A current leads to an uncomplicated design. The inductance of the 16 m magnets is similar to that of the CBA 5-m magnets, which were extensively tested in an exhaustive string test in the tunnel. Nevertheless, development can only be said to be complete when performance of final magnets is studied in the proposed string tests. The diode protection system needs 7000 A diodes versus the 5000 A diodes exhaustively tested for CBA. These are similar and available, and a test program is underway to confirm their suitability.

3) Vacuum system performance analysis and test. Final engineering development must await the results of the synchrotron radiation experiments currently being conducted at the NSLS. It may be necessary to incorporate a liner in the bore tube to guard against vacuum degradation from the impact of synchrotron radiation at 20 TeV. Other vacuum aspects of the proposed magnet system, such as the pump-down speed following magnet replacement, all meet acceptable parameters of performance.

4) Cryogenic system performance analysis and test. Testing at FNAL (Ref. 16) during the past year has confirmed that the low heat leaks specified in the Reference Designs Study are possible. Whether the anticipated low heat leaks for a complete system of magnets is possible must await the results of the long string test, where end effects will not mask the measured performance. The tests will begin on the preliminary string test at FNAL when two or more magnets are available for interconnection, but the sensitivity of the PST may not be sufficient to finally resolve all the questions.

5) Quench behavior analysis. Good progress has been made in the past year in our ability to predict the temperature upon quench in a $\cos \theta$ magnet. The predictions invariably give too high a temperature, probably because it is not possible to construct an analytic model of the effect of the helium cooling. The effective quench velocities are believed to be higher than thus far measured. By normalizing to direct temperature measurements (Ref. 14a) during controlled quenches on CBA models and on SSC 3.2-cm models, the calculations indicate the Design D is safe for passive diode protection. Measurements on 4.5-m D models will soon be made and will provide another normalizing point for the calculations, but the final answer can only come from measurements on the early 16-m models. If passive quench protection is acceptable for this design, a whole host of questions concerning the reliability, complexity, and expense of an active system immediately disappears, and the active heaters now incorporated and being tested in the D magnets can be removed from the design and from future magnets.

6) Bore tube plating feasibility. BNL currently has two R&D contracts with two experienced firms to develop an acceptable copper plating technique. Short samples are already on hand and longer samples are expected later in the year. The two proposed techniques differ from one another (one uses deposition

from a solution containing copper and the other depends on deposition via chemical transport from a copper electrode) and the resulting plated tubes will have a different set of surface characteristics. If successful, these techniques will avoid a welded bore tube which has been shown to always have some (variable) magnetic characteristics. When longer plated bore tubes arrive at BNL, they will be tested for the desired characteristics and if possible, tested in the experiment at the NSLS. Some thought is being given to rf impedance measurements but it may not be possible (or necessary) to measure the precise value of the (expected) very low rf impedance without developing new instrumentation and techniques; guidance and support from the CDG are needed here.

7a) Interconnections design - mechanical. The detailed design of the interconnection region between magnets is proceeding, including layouts, sizing and availability of bellows expansion joints, support structures, etc. Much of this detail will be included and will be proven in the construction of the PST at FNAL, where extensive experience with the Tevatron exists.

7b) Interconnections design - electrical. The electrical system is in detailed design and interconnection layouts are being prepared. Conservative criteria are being used to size the copper interconnection bus work. The current requirements are somewhat higher than for the Tevatron and CBA and similar to those of HERA, where an experienced electrical engineering firm (BBC) is helping to define the design. BNL is watching this evolving design closely. The bus expansion joints are modifications of the exhaustively tested joints developed for CBA. The engineering development will be complete only when a "final" system is assembled and tested in the PST at FNAL and later more thoroughly in the long string test. The detailed work that has been done indicates a non-trivial amount of hardware and a substantial cost

impact for a fully-detailed and acceptable system -- an aspect not completely appreciated until detailed design was undertaken.

8a) Model Tests - training. Two D models have been tested at BNL and have reached 6 T with one quench or less and leveled off at the maximum current after five quenches or less. Similar results have been obtained in five 1-m models tested at LBL. This is considered acceptable performance for the specifications of the magnet. Additional models soon to be tested at BNL will give further information on the stability of the result. The coil prestress will be varied in some future models to study the effect of this parameter on quench behavior.

8d) Model tests - random errors. Extensive random error calculations at the three laboratories collaborating in this design (Refs. 22, 10c, 10d) agree closely with one another and with the performance of the CBA and Tevatron magnets. It is felt that the calculations are conservative and that the measured random errors may not be as large as the calculations indicate. There is some evidence that this will be the case from the results of the first BNL model, where every unallowed multipole was substantially less than the rms value predicted. In this design, the random errors are dominated by coil construction errors. Utilizing previous experience, BNL has designed and constructed a new curing press of great strength and exact dimension. The press is constructed of laminated form blocks which are more precise than the former single-piece machined form blocks. It is anticipated that coils molded in this device will be close duplicates of one another as already indicated by the small random error content in the first 4.5-m magnet, which is constructed of four individual coils fabricated with this new press. Measurements of the upcoming models will give a clearer picture of the random errors that can be expected.

Also expected to help this problem are the new precision cabling techniques being developed at LBL and the work to measure and perhaps control cable dimensions being conducted at FNAL.

8e) Quench heating. The technique for direct temperature measurement via Cu resistivity at various points in the coil for a variety of temperature and energy deposition conditions has been by now well developed at BNL. It remains to make these measurements in a future D 4.5-m magnet and a confirmation measurement in a future 16 m magnet. The 4.5 m measurement should be available late in the summer and has not yet been done because of the higher priority accorded the tests for quench behavior and magnetic field quality.

8f) Alignment design. The D design has included special consideration of the necessity for precision from the start. Thus, a careful review of the design features of the D cross section will reveal that the coil is keyed to the collars, the collars to the iron yoke, and the iron yoke via special fiducial apertures in the lamination stamping, to the cold mass support system. An error budget of maximum possible error at each of these interfaces reveals a system well within the required alignment precision. The stiff cold mass assembly, unburdened with unsymmetrical and unbalanced forces, gives confidence that the required alignment precision will be retained in service. Verification of dipole field angle alignment should be possible with the initiation of horizontal testing at FNAL next year, using the "mole" under development at BNL.

9) Production engineering design, manufacturing plan, and testing plan. The extensive production facilities and expertise at FNAL, BNL and continuing discussions with industrial firms have made it possible to make extensive progress in this area. FNAL has extensive experience in this regard, having assembled all the Tevatron and antiproton source magnets in-house from

industrially produced sub assemblies. The Laboratories have engineering talent in-house with extensive industrial manufacturing experience and, utilizing this talent, has developed complete manufacturing plans for CBA and SSC reference design. Engineers from GD, Westinghouse, and BBC have visited BNL and FNAL. General Dynamics completed a contract to develop an example manufacturing plan. The SSC reference design manufacturing plan was reviewed by GD and BBC under contract and found to be reasonable. BNL has purchased industrially manufactured magnets for RHIC and has worked with BBC and DESY on the manufacturability of the HERA magnet.

With the difficult R&D for Design D taking place at three laboratories, a fully developed set of blueprints will be available for a magnet to be manufactured by industry with a minimal need for changes in the design. Experience shows that change orders, no matter how trivial, can be expensive.

A further consideration in this category is the modularity of the basic magnet design. Such modularity is extremely desirable from a manufacturing perspective, for it allows greater automation and minimizes the need for synchronization of component fabrication. Molded coils can be built with tooling designed specifically for this one function and need not interact with yoke assembly, for instance. The collar assembly, yoke stacking, and helium containment operations likewise can all be accomplished on automated machinery dedicated to these functions. The manufacturability of the design has always been a prime consideration in the evolution of the D magnet and has been greatly aided by the knowledgeable engineers who participated in its design. The "expensive tooling" necessary to build early R&D models will translate into less expensive production magnets, and the pay-off promises to be large indeed. These considerations are not so obvious to R&D physicists accustomed to thinking in terms of one-of-a-kind detectors but thanks to the

experienced engineers at BNL, FNAL and LBL, are included in the current D magnet.

11a) Lumped correction coils. As part of the Tevatron, a system of five hundred lumped superconducting correction coils was built and has operated in a very reliable way at FNAL. There has been little recent effort in this area, because the requirements for lumped correctors will depend on a forthcoming detailed lattice design. For the Reference Designs Study, a conceptual drawing of a possible corrector design was prepared, using the best information available at the time. It did not then appear that there were any particularly difficult problems in this area.

11b) Distributed correction coil design. BNL has an active program to develop externally powered distributed correction coils for D. The early 4.5-m models contain coils manufactured at BNL and their performance is being ascertained. Later 4.5-m models and the 16-m models will contain correction coils of the MULTIWIRES type, a derivative of printed circuit technology that promises to be particularly cost effective in production. Samples of such coils 4.5 m long are already in hand and meet the required specifications for accuracy and include the necessary bonding agents and electrical performance characteristics when installed on the magnet bore tube. At FNAL (Ref. 17) and LBL (Ref. 21), programs are underway to develop passive distributed correction coils and have given promising results, but further engineering development will be required to integrate these concepts into SSC models.

BNL has extensive experience in the problems of distributed trim coils by virtue of having fully developed and tested externally-powered distributed correction coils for the CBA magnets, of more complicated design (3 multipoles) than needed for SSC. It is anticipated that fully developed coils will be included in at least some of the 16 m magnets scheduled for next year. Should

the development of small filament superconductor negate the need for distributed trim coils, their further development and the associated costs would be curtailed.

13) Status of production testing instrumentation. Production testing instrumentation can only realistically be undertaken when the magnet design is ready for industrial production. The items which fall into this category, e.g. gauges, calipers, micrometers, sizing and alignment jigs, CODEX machines, etc., are all standard industrial items. A rigorous quality control program will be essential, and will be possible because of the extensive design effort, testing, and intimate knowledge of detail presently being accumulated in the three laboratories involved in the D collaboration.

15) Quadrupole design. A design has been developed and engineering drawings are currently being prepared for an acceptable quadrupole for the lattice. This problem appears susceptible to straightforward development work and no serious problems are anticipated. Given the required characteristics, R&D models could be designed and built in approximately one year. The experience at FNAL in building high gradient quadrupole magnets for SLAC will prove useful.

V.C. Superferric Style Magnet R&D Program (TAC Response)

The Texas Accelerator Center has been working with General Dynamics on a design that was fixed February 15, 1985. We believe this design is mechanically, electrically, and magnetically sound. The design permits very easy assembly with simple tooling. Industry is already assembling the magnet. By the end of CY85 ten channels of 1-m magnets, two channels of 7-m magnets, and 6 channels of 28-m magnets will have been constructed and tested. The funding for this program (except for the testing) has already been committed from FY85 resources. This will provide a sufficient data base to construct 24 35-m magnets in industry during CY86. This could be accomplished with the same level of resources allocated to the FY85 total magnet program.

This program of solid accomplishment coupled with the long experience with iron magnet accelerators and colliders will provide a magnet design ready for SSC production in industry by 1987.

The attached schedule shown in Fig. V.2 for superferric magnet production, indicates that the SSC preproduction dipole magnets could be completed by the end of CY 1986. This assumes participation by all laboratories, for example, TAC overseeing magnet production in industry, lab 1 measuring magnets, lab 2 responsible for spool piece production, and lab 3 helping on smaller items (position monitors, etc.)

V.C.1. Significant Engineering R&D questions to be Resolved for Design C

- a. Field calculations. The programs used by the TAC for magnetic field calculations are POISSON and MAGNUS (Ref. 12). POISSON is the standard 2-dimensional program and predicts Design C multipoles to about $5/n$ units (parts in 10^4). We plan improvements in this program in two areas, first the permability and its derivatives are

Schedule for Superferric Magnet Production

Fig. V.2 FY 1986 schedule for Design C.

not always treated properly and, second, the meshes used in the program could be improved. MAGNUS is a 3-dimensional program which is being used at TAC for the superferric magnet design. Some auxiliary subroutines are needed for interpretation of the solutions. Necessary modifications to these programs will be completed before the end of this year.

- b. Control and measurement of permeability. TAC has a program outlined to measure the permeability of the iron used in the magnets. Samples of individual magnet laminations as well as each 6 in. pack of iron laminations will have the permeability measured at 2 points (mid and high field) and the remanent field for injection. Shuffling of the 6 in. packs such that the equivalent permeability averages to the same value within a few parts of 10^3 over each 10 meters length will permit control of multipoles (the effect due to permeability) to a few parts in 10^5 . This technique will be verified in the next 12 magnet channels that will be assembled in this manner.
- c. Continued testing of models. The final design of the superferric magnet has been fixed since February 15, 1985. Four each 1-in-1 one meter models have been constructed and tested. By the end of CY85 an additional 4 each 2-in-1 one meter, at least 1 each 2-in-1 seven meter, and 3 each 2-in-1 twenty-eight meter magnets will be constructed and tested. The three long magnets will be assembled at General Dynamics and tested at TAC. Measurements of multipoles, quenching characteristics, cryogenics and alignment will be done.

V.C.2 Continuing Engineering R&D Studies for Design C. Table V.2 is similar to Table V.1 in showing the areas of continuing R&D program as foreseen at TAC. The detailed response is given in the following section.

Table V.2 R&D Status (Response by TAC).

^a <u>Item</u>	<u>Status for Design C</u>	<u>Expected Completion Date For Design C</u>
1. Collar stress analysis	G.D. Contract Being Negotiated	6 Months After Start
2. Electrical system performance analysis and test	Under Analysis	Half Cell Test (begins 1-86)
3. Vacuum system performance analysis and test	Analysis Underway	Experimental Verification in Late 86 (half cell test)
4. Cryogenic system performance analysis and test	Design and Analysis	Experimental Verification Half Cell Test
5. Quench behavior	Analysis Nearly Done	Experimental Verification in Half Cell Test
6. Bore tube coating	Samples Being Made	First Samples in Late FY85; Full Length Samples FY86.
7. Interconnections	Design Underway	Mechanical Mock-up 1st Quarter FY86; Prototype Interconnection Tests Included in Half Cell
8d. Random errors	Model Tests	Continue Through Production
8f. Alignment and suspension	7-m model	Continuous
15. Quad development	Design	1 Meter Model By 1st Quarter FY86

^a The numbers in the first column refer to the numbers in the list of R&D items given in Section V.A.

V.C.3 Response to R&D Questionnaire by TAC Discussion of Remaining R&D
For SSC Reference Design C

Report to Magnet Technical Review Panel
July 11, 1985

1. Stress analysis.

A contract with General Dynamics-Convair for complete stress analysis of the superferric magnet is being negotiated now. Once started, it will be complete in six months.

2. Electrical system performance analysis test.

The 3 T superferric magnet system has four independent currents, two 12,000 A loops and two 3,000 A loops. These permit independent control of the dipole, quadrupole, sextupole, and decapole magnetic multipoles. Test of these systems will be done when the half-cell tests begin in January, 1986.

3. Vacuum system performance analysis and test.

Final engineering development must await the results of the synchrotron radiation experiments currently being done at the NSLS. Experimental verification in late CY86 on half-cell test.

4. Cryogenic system performance analysis and tests.

The vast experience of CCI, the superferric cryogenic designers, on helium service and, in particular, the FNAL Energy Doubler, gives confidence that the cryogenic system will perform as calculated. Only operation of the magnet string will confirm this. Experimental verification in late CY86 on half-cell test.

5. Quench behavior.

Two independent computer programs have been used to predict quench behavior. These are required to verify the temperature in the cable. Experimental verification in late CY86 on half-cell test (Ref. 8).

6. Bore tube coating.

University of Wisconsin with industry is developing a method of rolling copper onto stainless steel and then forming a tube. Short samples have been done. Actual bore tubes will be done next, in FY86.

7. Interconnections design.

The 105 m superferric magnet contracts 33 centimeters during cool down. Mechanical mock-up of conductor coils and bellows containing cryogens will be tested by the end of the year. Prototype will be tested during FY86 on the half cell test.

8d. Model tests - Random errors.

Twelve of the final design magnet channels will be measured over the next six months. This program will continue throughout the entire production (Ref. 12).

8f. Model tests - Alignment.

During the next six months one 7-m magnet and three 28-m magnets will be tested and studied.

11. Spool pieces - Correction elements, etc.

Conceptual design has been done. Detailed design needs to be done.

13. Production testing instrumentation.

The superferric magnets would be tested cold, since there are only 1330 units that go in the tunnel. Full testing (needs studying) would be done.

15. Quadrupole design.

Computer designs are being generated now. The first 1-meter quad should be complete by the end of this year. Full length quadrupoles by mid FY86.

APPENDIX A

CHARGE TO THE TECHNICAL MAGNET REVIEW PANEL October 19, 1984

Members

Alvin Tollestrup, Chairman

Dr. T. Elioff, LBL

Dr. P.J. Reardon, BNL

Prof. F.R. Huson, TAC

Dr. C. Taylor, LBL

Dr. P. Limon, CDG

Dr. R. Watt, SLAC

Dr. R. Lundy, FNAL

Mr. R. Yourd, CDG

Dr. R. Neal, SLAC

1. Delineate for each design type that minimal set of technical data which is needed for the design type selection process and which can only be obtained from models and prototypes.
2. Review critically the report progress, from October, 1984, to date, of each of the three major design types.
3. Review critically plans for FY85 in light of (1) and, as appropriate, suggest changes which may enhance their effectiveness.
4. Write a report setting forth the results of (1), (2), (3), in a systematic fashion.

APPENDIX B

CHARGE TO THE TECHNICAL MAGNET REVIEW PANEL April 23, 1985

Members

Alvin Tollestrup, Chairman

Prof. H. Hirabayashi, KEK

Dr. C. Taylor, LBL

Prof. F.R. Huson, TAC

Dr. R. Watt, SLAC

Dr. R. Lundy, FNAL

Mr. R. Yourd, LBL

Dr. P.J. Reardon, BNL

1. Review magnet and cable development programs at BNL, FNAL, LBL, and TAC.
2. Write a report evaluating the technical status of dipole and quadrupole magnet design and development work for the 1-in-1 and 2-in-1 low- and high-field magnet styles. For each style enumerate the R&D remaining before each style can prudently be carried to the full-scale prototype stage. This enumeration should include an estimate of the time and manpower effort needed to complete the pre-prototype R&D. The report should include a detailed account of model tests for the various designs.
3. Evaluate and report on the status of superconducting cable development and enumerate further development objectives which could reasonably be expected to be complete in time to have a beneficial impact on SSC magnet cost, reliability, and ease of operation. The report should be complete by July 25, 1985.

APPENDIX C. TEST DATA

This appendix contains the results of model magnet measurements as of the end of July, 1985. An updated set of data will be available before the end of August for use by the Basic Magnet Type Selection Panel. The data collected here have not been digested and are only provided as illustrations of the type of data being obtained by the various centers. The data for type D from BNL show the training curves and harmonics as a function of current for the first two 4.5-meter models.

The data from LBL are for two 1-meter models using the D-type collars.

The data from FNAL are room temperature measurements made on four 1-meter models with a 5 cm bore using the "dry winding" technique. The shims were not correct and, hence, the large value of b_2 . The tables are interesting in that they show the quality of coil achieved by the dry winding technique. A good measure of the random errors are given by the a_n and the odd b_n . In addition these data illustrate the quality of measurements that can be achieved at room temperature with a rather simple test setup. The monitoring of magnet production at room temperature provides one of the most effective means for component and construction quality control.

Data from TAC are for the first two 1-meter models and were obtained early in the program. The tables show three successive runs and these numbers can be compared for reproducibility of the data. Later the magnet design was modified from two windings to three independent coils. Data from this style magnet near 3 T with currents adjusted so that b_2 and b_4 are nearly cancelled are given in the table. Extrapolation of these data by means of a least squares linear fit yields a value for the current where $b_2 = 0$ of 11,202 A and for where $b_4 = 0$ of 11,180 A. The predicted value from the computer is 11,260 A. The data are from GD1.

4.5 m DIPOLES FOR BNL REFERENCE DESIGN D: PERFORMANCE UPDATE

Tests on the second 4.5 m long model dipole for Reference Design D (1-in-1, collared coils, 4.0 cm aperture) started on July 15, with a first quench at 6.03 T (5894A) and a quench plateau (at 4.5 K) of about 6.60 T (6520A) reached with negligible training. This plateau is virtually identical to that observed with the first dipole at this temperature, as is evident from the two enclosed graphs showing field vs. quench number for the two magnets. It is also in reasonably good agreement with the "short sample" prediction at 4.5 K--i.e., the quench field expected from laboratory measurements on short samples of the conductor utilized in the magnets. At the time of writing, the second magnet had not yet attained a clear-cut quench plateau in sub-cooled (2.5K) helium (dipole #1 reached a maximum field of 8.05 T at this temperature).

Similarly, field quality results reported here are also somewhat preliminary. Table I summarizes the allowed (two-dimensional, not integrated) harmonics. Here column 2 gives the calculated (design) values at 1 cm radius (a "unit" is the multipole field at 1 cm radius, normalized to 10^{-4} of the dipole field), obtained with a finite element, variable- μ program with a current of 2 kA (or B_0 2T). Columns 3 and 4 list the measured values, and column 5 the corresponding r.m.s. random multipole errors calculated by Herrera et al. for assumed 0.05 mm (0.002 in.) radial and azimuthal conductor placement errors. Table II summarizes similar data for the skew and normal nonallowed harmonics. As can be seen, the measured harmonics are small, with individual values differing from the design values by no more than an r.m.s. width and showing a magnet-to-magnet variation also well within the r.m.s. band.

BNL DATA

Table I

Allowed Harmonics ($10^{-4}B_0$) at 1 cm)

b_n	Calculated Value	Measured, Dipole No.1	Measured, Dipole N.2	Expected rms Errors
b_2	3.56	1.3	0	2.6
b_4	-0.44	-0.3	-0.6	0.68
b_6	0.17	0	0	0.08
b_8	0.83	0.9	0.8	0.02
b_{10}	-0.02	0	0	0.003
b_{12}	-0.04	0	0	-

Table II

Forbidden Harmonics ($10^{-4}B_0$) at 1 cm)

b_n, a_n	Measured, Dipole No.1	Measured, Dipole No.2	Expected rms Errors
b_1	0.1	-0.4	1.8
b_3	-0.1	-0.1	0.57
b_5	0	0	0.06
b_7	0.1	0	0.02
b_9	0	0	0.004
a_1	-1.5	-2.4	3.3
a_2	0.3	0.1	0.65
a_3	-0.4	-0.3	0.73
a_4	0	0.1	0.15
a_5	-0.1	0	0.26
a_6	0	0	0.05
a_7	-0.1	0	0.04
a_8	0.1	0.1	0.008
a_9	0	0	0.009

BNL DATA

Comparison of First Two D Dipoles $B_0 = 2.07$ T

	Calculation	SLN008	SLN009
b_1	-	+0.10	-0.40
b_2	3.56	-1.30	-2.5
b_3	-	-0.10	-0.10
b_4	-0.44	0	-0.20
b_5	-	0	0
b_6	+0.17	0	0.1
b_7	-	+0.10	0
b_8	+0.83	0.90	0.90
b_9	-	0	0
b_{10}	-0.02	0	0
b_{12}	-0.04	0	0
a_1	0	-1.5	-2.4
a_2	0	+0.30	+0.10
a_3	0	-0.40	-0.30
a_4	0	0	+0.10
a_5	0	-0.10	0
a_6	0	0	0
a_7	0	-0.10	0
a_8	0	+0.10	+0.10
a_9	0	0	0
a_{10}	0	0	0
a_{12}	0	0	0

SSC REFERENCE DESIGN D DIPOLE #1
(4.5m LENGTH, 4cm APERTURE, 4.5K)

Test Data from first two BNL SSC type D dipoles SLN008 and SLN009.

SSC REFERENCE DESIGN D DIPOLE #2

(4.5m LENGTH, 4 cm APERTURE, 4.5K)

Test Data from first two BNL SSC type D dipoles SLN008 and SLN009.

MAGNET MEASUREMENTS ANALYSIS
TESTING & MEASURING GROUP

Date: July 18, 1985

Magnet: SLN008

Data: Summary

Description: 4 cm aperture, 4.5 m length, C5 cross section, dogbone ends, SS collars, reusable yoke, clamped SS shell, BNL trim coil heater strip

Tested: June 1985

Comments:

1. First model of BNL/FNAL/LBL collaboration for SSC magnets.
2. Cable manufactured by NEEW
3. A measuring coil centering correction is not applied to these data; because of the small value of the multipoles, a centering correction does not appear necessary.
4. The measuring coil was miscentered vertically in the magnet $\sim 4"$. Thus $\int B dl$ and harmonics including ends are unreliable.

(This Magnet Test Note consists of 1 sheet)

SLN008 EM 07/16/95 22.56.06. HERRERA/WILLEN ANALYSIS

QUENCHES: N.1(A)= 1 5507 2 5932 3 6317 4 6232 5 6239 20 8106(MAX) TOTAL= 41
 BITI= 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000

DC EXC ENDS .476JK 07/11/95 MEASURED ON 20-JAN-95 COIL.MAG= 22.4 RZ.OM= 0.00 0.0

B1 AND A1(E-4) EVALUATED AT X= 1.0 CM

I	BO	BO/I	ALP	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
A	T	G/A	MR	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
100	.1035	10.350	-1	.7	-11.4	.5	6.6	.1	-.2	.1	.7	-.0	-.2	.0	-.0
				-2.5	1.7	-.9	1.1	-.3	-.1	-.0	.1	-.0	-.0	.0	-.0
500	.5168	10.337	-2	.0	-16.0	.0	2.3	-.0	.1	.1	1.2	.0	-.1	-.0	-.0
				-1.5	.1	-.6	.2	-.2	-.0	-.0	.1	-.0	-.0	-.0	-.0
1000	1.0350	10.350	-0	-.1	-5.5	-.0	.6	-.0	-.0	.1	1.0	-.0	-.1	-.0	-.0
				-1.1	.3	-.4	-.0	-.3	.0	-.0	.1	-.0	-.0	-.0	-.0
1200	1.2424	10.353	-2	-.4	-4.1	-.1	.4	-.0	.0	.1	1.0	-.0	-.0	-.0	-.0
				-1.2	.4	-.4	.0	-.2	.0	-.0	.1	-.0	-.0	-.0	-.0
2000	2.0711	10.355	-1	.6	-2.0	-.1	.1	-.0	.0	.1	.9	-.0	-.0	-.0	-.0
				-1.2	.3	-.4	-.0	-.2	.0	-.0	.1	-.0	-.0	-.0	-.0
3000	3.1061	10.354	-3	.1	-.9	-.1	-.0	-.1	-.0	.1	.9	.0	-.0	-.0	-.0
				-1.3	.4	-.5	-.0	-.2	.0	-.0	.1	-.0	-.0	-.0	-.0
4000	4.1390	10.347	-3	-.1	.1	-.2	-.1	.0	-.0	.1	.9	-.0	-.0	-.0	-.0
				-1.1	.4	-.4	-.1	-.2	.0	-.0	.1	-.0	-.0	-.0	-.0
5000	5.1548	10.310	-2	-.1	1.1	-.1	-.1	.0	-.0	.1	.9	.0	-.0	-.0	-.0
				-1.1	.2	-.3	-.0	-.2	.1	-.0	.1	-.0	-.0	-.0	-.0
5400	5.5501	10.278	.1	-.1	1.4	-.1	-.2	-.0	-.1	.1	.9	.0	-.0	-.0	-.0
				-1.3	.1	-.4	-.1	-.1	.0	-.0	.1	-.0	-.0	-.0	-.0
7401	7.3881	9.983	2.3	.2	1.0	-.1	-.1	-.0	-.1	.1	.9	.0	-.0	-.0	-.0
				-1.4	.3	-.5	-.1	-.2	.0	-.0	.1	-.0	-.0	-.0	-.0

DC INC ENDS-COIL 4 .2767R 07/02/95 MEASURED ON 20-JAN-95 COIL.MAG= 22.4 RZ.OM= 0.00 0.0

B1 AND A1(E-4) EVALUATED AT X= 1.0 CM

I	BO	BO/I	ALP	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
A	T	G/A	MR	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
100	.1035	10.354	-2	-.5	3.4	.4	5.5	.0	-.1	.1	.6	-.0	-.2	-.0	-.0
				-3.8	.8	-.7	.9	-.2	-.1	-.0	.1	.0	-.0	.0	-.0
500	.5170	10.340	-2	-.6	-3.0	.1	1.7	.0	.2	.1	1.0	-.0	-.1	-.0	-.0
				-2.9	.9	-.3	.2	-.2	-.0	-.1	.0	.0	-.0	.0	-.0
1000	1.0352	10.352	-1	-.3	6.9	.0	.1	.0	.1	.1	.9	-.0	-.1	-.0	-.0
				-3.0	.9	-.3	-.0	-.1	.0	-.1	.0	-.0	-.0	.0	-.0
1200	1.2425	10.354	-1	-.3	8.1	.0	-.0	.0	.1	.1	.8	.0	-.0	-.0	-.0
				-3.0	1.0	-.3	-.0	-.1	-.0	-.1	.0	-.0	-.0	.0	-.0
2000	2.0711	10.355	-1	-.3	10.3	-.0	-.3	.0	.1	.1	.8	-.0	-.0	-.0	-.0
				-3.0	1.0	-.3	-.1	-.2	.0	-.1	.0	-.0	-.0	.0	-.0
3000	3.1048	10.349	-2	-.3	11.3	-.0	-.5	.0	.1	.1	.8	-.0	-.0	-.0	-.0
				-3.0	.9	-.3	-.1	-.2	-.0	-.1	.0	-.0	-.0	.0	-.0
4000	4.1341	10.335	-2	-.1	12.1	-.0	-.5	.0	.1	.1	.8	-.0	-.0	-.0	-.0
				-3.0	.9	-.3	-.1	-.1	-.0	-.1	.0	-.0	-.0	.0	-.0
5000	5.1430	10.286	-2	-.2	13.1	-.1	-.5	-.0	.1	.1	.8	-.0	-.0	-.0	-.0
				-3.2	1.0	-.3	-.1	-.1	.0	-.1	.0	-.0	-.0	.0	-.0
5400	5.5356	10.251	.0	-.3	13.4	-.0	-.6	.0	.1	.1	.8	.0	-.0	-.0	-.0
				-3.0	.9	-.2	-.1	-.2	.0	-.1	.0	-.0	-.0	.0	-.0
7401	7.3660	9.953	2.3	-.2	13.0	-.1	-.6	.0	.0	.1	.8	.0	-.0	-.0	-.0
				-3.2	.9	-.3	-.1	-.1	.0	-.1	.0	-.0	-.0	.0	-.0

NOTE: BO AND BO/I NORMALIZED AT 2000.0 A FACTNM= 1.1253 EFFECTIVE LENGTH= 0.0000 M

CURRENT(A), INTEGRAL BOL(TM), EFF LEN(M)= 500.0 0.0000 0.0000
 CURRENT(A), INTEGRAL BOL(TM), EFF LEN(M)= 2000.0 0.0000 0.0000

BNL DATA

+	SLN008.476JK	22 4	0.0	0.0	1.000
	UP CYCLE				
□	SLN008.477JK	22 4	0.0	0.0	1.000
	DOWN CYCLE				
△	SLN008.2767R	22 4	0.0	0.0	1.125
	LONG COIL				

2 SLN008 Transfer function

3 SLN008 Quench history

4 SLN008 Quench history

5 SLN008 Dipole amplitude

6 SLN008 Dipole angle

7 SLN008 Normal dipole fractional coefficient

8 SLN008 Skew dipole fractional coefficient

9 SLN008 Quadrupole amplitude at 1.00 cm

10 SLN008 Quadrupole angle

11 SLN008 Normal quadrupole fractional coefficient at 1.00 cm

12 SLN008 Skew quadrupole fractional coefficient at 1.00 cm

13 SLN008 Sextupole amplitude at 1.00 cm

13 HERRERA-WILLEN SLN008.476JK 477JK 2767R ZQ 07/15/85 16.12.09.

14 SLN008 Sextupole angle

28 HERRERA-WILLEN SLN008.476JK 477JK 2767R ZQ 07/15/85 16.12.10.

15 SLN008 Normal sextupole fractional coefficient at 1.00 cm

43 HERRERA-WILLEN SLN008.476JK 477JK 2767R ZQ 07/15/85 16.12.10.

16 SLN008 Skew sextupole fractional coefficient at 1.00 cm

58 HERRERA-WILLEN SLN008.476JK 477JK 2767R ZQ 07/15/85 16.12.11.

17 SLN008 Octupole amplitude at 1.00 cm

18 SLN008 Octupole angle

19 SLN008 Normal octupole fractional coefficient at 1.00 cm

20 SLN008 Skew octupole fractional coefficient at 1.00 cm

21 SLN008 Decapole amplitude at 1.00 cm

22 SLN008 Decapole angle

23 SLN008 Normal decapole fractional coefficient at 1.00 cm

24 SLN008 Skew decapole fractional coefficient at 1.00 cm

25 SLN008 Dodecapole amplitude at 1.00 cm

26 SLN008 Dodecapole angle

27 SLN008 Normal dodecapole fractional coefficient at 1.00 cm

28 SLN008 Skew dodecapole fractional coefficient at 1.00 cm

29 SLN008 14-pole amplitude at 1.00 cm

30 SLN008 14-pole angle

31 SLN008 Normal 14-pole fractional coefficient at 1.00 cm

32 SLN008 Skew 14-pole fractional coefficient at 1.00 cm

33 SLN008 16-pole amplitude at 1.00 cm

34 SLN008 16-pole angle

35 SLN008 Normal 16-pole fractional coefficient at 1.00 cm

36 SLN008 Skew 16-pole fractional coefficient at 1.00 cm

37 SLN008 18-pole amplitude at 1.00 cm

38 SLN008 18-pole angle

39 SLN008 Normal 18-pole fractional coefficient at 1.00 cm

40 SLN008 Skew 18-pole fractional coefficient at 1.00 cm

41 SLN008 20-pole amplitude at 1.00 cm

42 SLN008 20-pole angle

43 SLN008 Normal 20-pole fractional coefficient at 1.00 cm

44 SLN008 Skew 20-pole fractional coefficient at 1.00 cm

45 SLN008 22-pole amplitude at 1.00 cm

46 SLN008 22-pole angle

47 SLN008 Normal 22-pole fractional coefficient at 1.00 cm

48 SLN008 Skew 22-pole fractional coefficient at 1.00 cm

49 SLN008 24-pole amplitude at 1.00 cm

50 SLN008 24-pole angle

51 SLN008 Normal 24-pole fractional coefficient at 1.00 cm

52 SLN008 Skew 24-pole fractional coefficient at 1.00 cm

53 SLN008 26-pole amplitude at 1.00 cm

54 SLN008 26-pole angle

55 SLN008 Normal 26-pole fractional coefficient at 1.00 cm

56 SLN008 Skew 26-pole fractional coefficient at 1.00 cm

LBL DATA

LBL SSC Model Dipoles
 Multipoles at $r=1$ cm in SSC models, D-12C- 2, 3, 4
 $C_n=b_n + iA_n$ in units (10^{-4} dipole)

	3kA $\approx$ 3 Tesla			2kA $\approx$ 2 Tesla			4 kA $\approx$ 4 Tesla		
	C-2	C-3	C-4	C-2	C-3	C-4	C-2	C-3	C-5
b ₁	-1.51	2.96	0.30	-1.52	2.69	0.32	-1.53	3.08	0.27
a ₂	-0.55	0.25	0.09	-0.48	0.62	-0.01	-0.59	0.05	0.16
b ₂	6.33	12.01	16.54	5.78	11.73	15.87	6.30	11.35	16.68
a ₂	0.54	0.92	0.09	0.64	1.36	0.08	0.52	0.75	0.09
b ₃	0.05	-0.24	0.28	0.05	-0.24	0.33	0.04	-0.25	0.27
a ₃	0.12	0.25	-0.02	0.11	0.43	-0.04	0.13	0.18	0.01
b ₄	1.00	1.24	-0.03	1.05	1.35	0.02	0.94	1.20	-0.06
a ₄	0.22	0.20	-0.02	0.24	0.23	-0.04	0.22	0.19	-0.02
b ₅	-0.08	-0.09	0.03	-0.07	-0.09	0.05	-0.08	-0.10	0.03
a ₅	-0.04	0.04	0.04	-0.04	0.05	0.05	-0.03	0.03	0.03
b ₆	0.36	0.38	0.13	0.37	0.40	0.14	0.35	0.37	0.13
a ₆	0.06	0.03	0.02	0.07	0.04	0.02	0.05	0.02	0.02
b ₇	-0.27	0.10	-0.04	-0.26	0.08	-0.04	-0.26	0.10	-0.04
a ₇	-0.16	0.20	0.01	-0.16	0.19	0.01	-0.15	0.20	0.01
b ₈	0.84	0.78	0.62	0.85	0.78	0.63	0.84	0.78	0.62
a ₈	0.12	0.08	0.06	0.12	0.09	0.07	0.12	0.07	0.06

N.B. b₂, b₄, b₆, b₈ are allowed terms. b₁ may come from feeddown of b₂ and non-centering of mean-coil.

FNAL DATA

Room Temperature Measurements of S cos θ Style Model Magnets at FNAL
(Multipoles for 5 cm Dry Wound Coils at 1 cm)

	<u>SG1003</u>		<u>SG1004</u>	<u>SG1006</u>	<u>SK1001</u>	<u>SJ1003</u>
b_1	0.23	± 1.5	-1.42	0.069	-2.36	0.26
a_1	-1.89	± 2.0	0.69	4.78	-1.30	0.85
b_2	42.98	± 0.5	43.44	43.81	15.58	7.16
a_2	0.42	± 0.15	1.14	-0.397	-2.06	-0.81
b_3	0.02	± 0.10	-0.12	0.115	0.20	0.50
a_3	-0.47	± 0.30	0.035	0.422	-0.30	0.82
b_4	2.24	± 0.20	2.32	2.30	1.59	-0.20
a_4	0.002	± 0.10	-0.040	-0.066	0.116	-0.163
b_5	0.031	± 0.05	0.062	-0.007	-0.007	0.042
a_5	0.204	± 0.05	0.036	-0.165	0.145	0.015
b_6	-0.456	± 0.05	-0.470	-0.433	-0.314	-0.295
a_6	-0.02	± 0.02	-0.019	-0.004	-0.007	-0.016
b_8	0.042	± 0.05	0.045	0.046	0.014	0.0056
a_8	0.0003	± 0.005	0.001	0.0002	-0.0014	0.0031

TAC DATA

Table b_n for TAC001.

<u>B(T)</u>	<u>b_1</u>	<u>b_2</u>	<u>b_3</u>	<u>b_4</u>	<u>b_5</u>	<u>b_6</u>	<u>b_7</u>	<u>b_8</u>
0.01161	17.8	-156.0	24.5	-43.8	7.5	-8.4	2.9	3.9
0.14526	1.9	-0.1	2.1	6.2	0.9	1.4	0.4	-0.5
0.25329	1.3	-0.2	1.2	6.1	0.3	1.8	-0.1	0.8
0.51360	0.6	0.2	1.2	4.8	0.4	1.7	0.4	1.2
1.03262	0.5	-0.4	1.1	5.1	0.7	2.3	0.5	1.3
1.77290	0.1	-0.5	0.4	7.2	0.0	2.9	0.5	0.8
2.53527	0.3	-0.1	0.0	2.2	0.2	2.8	0.3	0.9
2.93804	0.3	0.3	-1.3	-16.7	-0.2	-0.5	0.0	0.7
0.01158	24.5	-156.0	26.0	-51.3	4.0	-12.6	7.8	10.7
0.14570	3.4	-0.7	2.6	5.3	1.5	1.1	1.7	-2.5
0.25401	1.8	0.0	1.0	6.5	0.2	2.4	0.3	0.5
1.03333	0.3	-0.3	0.7	4.6	0.0	2.3	0.0	1.2
1.77397	-0.2	-0.2	0.5	7.4	-0.1	2.5	0.9	-0.2
2.53723	-0.3	0.0	-0.1	2.2	0.4	2.9	0.1	0.8
2.98844	0.5	0.1	-1.3	-17.5	0.1	-0.8	1.2	0.7
0.01170	25.0	-155.6	29.0	-47.6	12.3	-8.4	3.2	4.7
0.14579	3.4	-0.7	2.5	5.6	1.3	0.8	1.5	1.5
0.25364	1.3	-0.2	2.1	5.6	0.9	2.0	0.1	1.5
1.03322	0.5	-0.4	0.9	5.1	0.1	2.1	0.4	1.0

TAC DATA

Table b_n for TAC002.

	<u>b_1</u>	<u>b_2</u>	<u>b_3</u>	<u>b_4</u>	<u>b_5</u>	<u>b_6</u>	<u>b_7</u>	<u>b_8</u>	<u>b_9</u>
0.01145	-2.4	158.8	0.0	47.6	2.9	-7.8	2.5	11.6	-0.8
0.14473	-0.1	0.3	1.6	5.7	0.5	2.1	-0.2	1.1	-0.3
0.25295	-0.3	-0.4	1.4	4.7	0.7	1.4	0.8	0.4	0.7
0.51206	-0.7	0.9	0.9	5.0	0.3	2.0	0.2	1.3	-0.4
1.03050	-0.5	0.0	1.0	4.9	0.5	2.0	0.1	0.7	-0.1
1.76895	-0.9	-0.7	1.2	6.2	1.0	2.4	0.6	0.7	-0.3
2.53050	-0.7	-1.1	0.4	1.6	0.7	2.7	0.6	0.7	-0.2
2.98316	-0.4	-0.3	-1.8	-17.8	0.1	-0.8	0.0	0.5	0.0
0.01153	4.6	156.3	3.0	46.4	3.0	-8.2	-3.2	-1.1	2.1
0.14481	0.4	0.7	1.3	5.8	1.0	1.3	0.2	0.6	0.1
0.25328	-0.1	-0.2	1.4	5.0	0.8	1.8	0.6	0.4	0.7
0.51199	-0.6	0.9	0.9	5.0	0.7	1.6	0.8	0.1	0.5
1.03036	-0.4	0.0	1.1	4.9	0.5	2.0	0.2	1.0	-0.1
1.76867	-0.7	-0.6	1.0	6.6	0.5	2.9	0.2	1.0	-0.1
2.53047	-0.4	-1.2	0.8	1.3	1.1	2.4	0.6	0.7	-0.1
2.98307	-0.4	-0.5	-1.8	-17.4	0.0	-0.8	0.0	1.0	-0.1
0.01154	-0.1	-156.6	4.8	-45.7	3.6	-10.0	-2.5	6.6	-0.4
0.14468	0.4	0.7	1.9	5.4	0.8	1.6	0.0	0.2	-0.3
0.25290	0.2	0.0	1.4	4.5	1.0	2.0	-0.3	1.0	0.8
0.51190	-0.5	0.9	0.8	5.0	0.7	1.7	0.5	0.4	0.1
1.03032	-0.4	-0.1	1.2	4.5	0.5	2.1	0.1	0.9	0.7
1.76854	-0.6	-0.7	1.2	6.4	0.7	2.8	0.1	1.4	-0.3
2.53060	-0.4	-1.1	0.5	1.6	0.9	3.0	0.1	0.7	0.2
2.98384	-0.7	-0.2	-1.9	-17.4	0.1	-1.0	0.3	0.7	0.3

Table a_n for TAC001.

<u>B(T)</u>	<u>a_1</u>	<u>a_2</u>	<u>a_3</u>	<u>a_4</u>	<u>a_5</u>	<u>a_6</u>	<u>a_7</u>	<u>a_8</u>
0.01161	-106.7	+4.6	-35.1	-4.0	-0.8	-1.4	-5.4	-3.6
0.14526	-3.5	1.8	-0.8	0.0	0.6	-0.2	-0.2	1.2
0.25329	1.2	0.8	0.5	1.0	-0.2	0.5	0.2	-0.6
0.51360	2.8	1.2	1.0	0.1	0.6	0.1	0.5	0.4
1.03262	4.6	0.4	2.1	0.3	0.9	0.2	0.5	-0.9
1.77290	4.8	0.4	2.1	0.4	0.7	0.7	0.0	0.6
2.53527	3.7	0.3	1.0	0.4	0.6	0.6	0.0	1.0
2.93804	2.4	-0.2	-2.2	-0.5	-0.3	0.3	-0.6	0.8
0.01153	-151.8	6.6	-49.2	-6.4	-6.0	-5.3	+2.2	-4.3
0.14570	-5.6	1.1	-0.3	-0.7	-0.2	1.9	0.6	-2.3
0.25401	-0.2	0.9	0.4	0.8	0.7	1.2	-0.2	-1.0
1.03333	3.9	0.8	1.8	0.0	0.9	0.3	0.5	0.3
1.77397	4.5	0.9	1.8	0.8	0.2	1.1	-0.2	0.9
2.53723	3.2	0.5	0.5	0.4	0.5	0.8	-0.3	0.6
2.98844	2.6	-0.2	-1.9	-1.0	-0.4	-0.4	0.4	0.3
0.01170	-162.3	0.0	-53.7	-3.7	-7.4	0.0	0.7	2.8
0.14579	-5.6	1.1	-2.1	-0.1	-0.3	-0.9	2.4	-1.7
0.25364	-1.6	1.0	0.1	0.2	0.9	0.7	-0.8	0.5
1.03322	3.7	0.7	1.6	0.0	0.7	0.3	0.2	0.1

Table a_n for TAC002.

	<u>a_1</u>	<u>a_2</u>	<u>a_3</u>	<u>a_4</u>	<u>a_5</u>	<u>a_6</u>	<u>a_7</u>	<u>a_8</u>	<u>a_9</u>
0.01145	27.0	-16.7	11.6	-5.2	2.7	1.8	5.4	0.8	-0.4
0.14473	-2.7	-2.1	-2.1	-0.5	-0.9	-0.4	-0.3	-0.4	0.2
0.25295	-3.3	-1.7	-1.8	0.3	-0.8	-0.4	-0.4	0.3	-0.6
0.51206	-3.4	-1.4	-2.0	-0.2	-0.7	-0.2	-0.1	-0.3	0.0
1.03050	-3.8	-1.3	-2.1	0.1	-0.6	-0.1	0.2	-0.4	0.1
1.76895	-3.8	-1.4	-2.7	0.5	-1.2	0.0	-0.3	-0.9	0.6
2.53050	-3.5	-1.1	-1.4	0.0	-1.2	-0.2	-0.3	-0.5	0.4
2.98316	-2.7	-0.6	3.1	-0.8	0.4	-0.2	0.2	-0.3	0.1
0.01153	31.7	-18.6	15.9	-4.7	3.5	2.8	-1.4	5.6	0.3
0.14481	-2.9	-2.1	-2.4	0.2	-0.7	-0.7	-0.5	0.5	0.0
0.25328	-3.0	-1.3	-2.1	-0.2	-0.8	0.0	-0.4	-0.2	-0.5
0.51199	-3.7	-1.3	-2.1	-0.2	-0.6	0.0	-0.1	-0.4	-0.3
1.03036	-3.5	-1.3	-2.1	-0.1	-0.7	0.0	-0.3	-0.3	0.4
1.76867	-3.6	-1.3	-2.5	-0.1	-1.0	0.1	-0.6	-0.1	0.0
2.53047	-3.2	-1.2	-1.3	0.1	-1.2	0.3	-0.5	-0.4	0.5
2.98307	-2.5	-0.8	3.2	-0.9	0.4	-0.1	-0.1	-0.8	0.3
0.01154	39.3	-18.7	19.2	-3.2	-0.8	5.5	0.8	-3.6	0.3
0.14468	-2.1	-2.0	-2.5	-0.2	-0.5	0.0	-0.3	0.1	0.3
0.25290	-2.7	-1.6	-1.7	0.2	-0.7	-0.2	-0.3	0.1	0.3
0.51190	-3.4	-1.4	-1.8	-0.2	-0.5	-0.1	0.1	-0.6	0.3
1.03032	-3.5	-1.2	-2.0	0.0	-0.8	0.1	-0.4	-0.2	0.1
1.76854	-3.5	-1.7	-2.3	0.1	-1.0	0.0	-0.8	0.0	-0.1
2.53060	-3.4	-1.1	-1.2	-0.1	-1.0	0.2	0.1	-0.7	0.3
2.98384	-2.8	-0.5	3.0	-0.4	0.2	-0.3	0.0	-0.5	0.4

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