SSCL-Preprint-4

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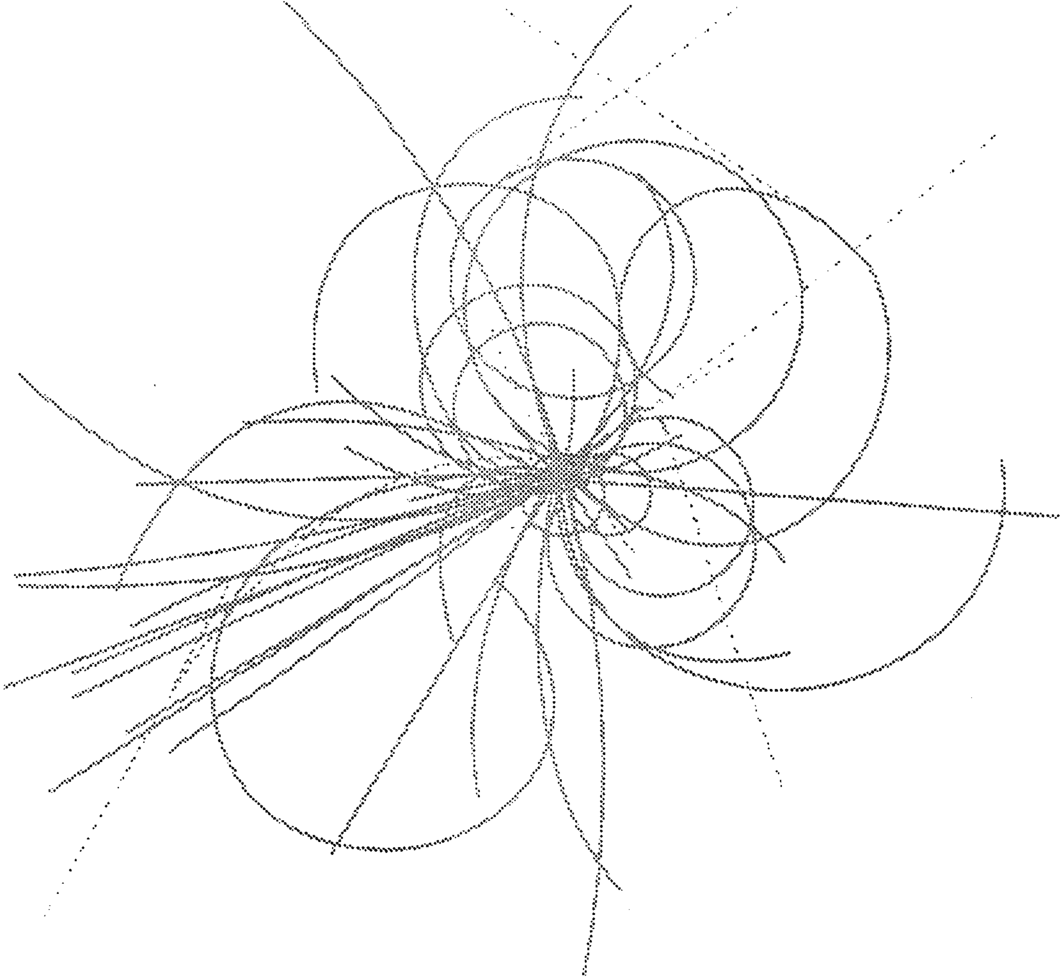
Superconducting Super Collider Laboratory



Methods for Field Computations for the Development of SSC Superconducting Magnets

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Abstract—The Superconducting Super Collider Program will require a large number of superconducting dipole and quadrupole magnets with a variety of designs. Analysis methods are being developed to facilitate rapid and accurate calculation of fields and optimization of design. 2-D and 3-D field computations are fully developed for analysis of coils in the straight section and ends. These are being linked to structural codes and CAD software for design optimization and studies. Other codes have been developed for coil errors, and for persistent and eddy current effects. The attempt is underway to integrate all the codes into a design software package.

I. INTRODUCTION

The Superconducting Super Collider (SSC) will have two counter-rotating proton beams with energies up to 20 Tev, in collider rings of about 87 km [1] in circumference. The two proton beams will be brought into collision in two interaction regions by vertically bending and focussing the beams at the collision point. The beams themselves will originate from an ion source and will be accelerated to 200 Gev in a series of accelerators and finally to 2 TeV in the High Energy Booster (HEB) ring with a circumference of about 11 km. The dipole and quadrupole magnets for the Collider and HEB will be made with superconducting coils, as will most of the magnets in the Interaction Region (IR). Specifications require a bending dipole magnet field integral of 100.088 T/m (6.6 T, 15.165 m) with an aperture of 50 mm, and a quadrupole strength of 1070 T (210 T/m and 5.1 m) with an aperture of 40 mm. The corresponding numbers for the HEB are: Dipole—6.4 T, 15.165 m, 50 mm aperture; Quad—200 T/m, 1.25 m, 50 mm aperture. The IR region of magnets will have bending magnets from 4.4 T to 6.6 T with aperture up to 100 mm and quads with a gradient of 230 T/m strength or above, if possible, and apertures from 30 mm to 60 mm.

A total of about 9000 dipoles and about 2000 quadrupoles will be required for the SSC project, with stringent requirements on quench performance and field qualities comparable to DESY/HERA and FNAL/Tevatron. Typical reliability requirements are also extremely stringent for these magnets.

With these requirements and with the possibility that about 10–20 different magnet designs may have to be generated, an attempt is underway in the Magnet Systems Division to have a strong analysis capability which lends itself to rapid calculations for design generation/iteration, trade studies, and fault analyses. Where available, commercial software has been used. One of the key approaches being taken is to define and develop an integrated design/analysis package through use of efficient codes which are interlinked as far as possible. The overview of analyses needs and the hierarchy of calculations are shown in Fig. 1. Two aspects of EM field computations are involved in the design and analysis of superconducting magnets; one is related to field quality and quench margins for the ideal design characteristics, and the other is related to field quality effects due to deviations from the ideal design. The computations also, of course, fall into the natural categories of 2-D and 3-D analyses.

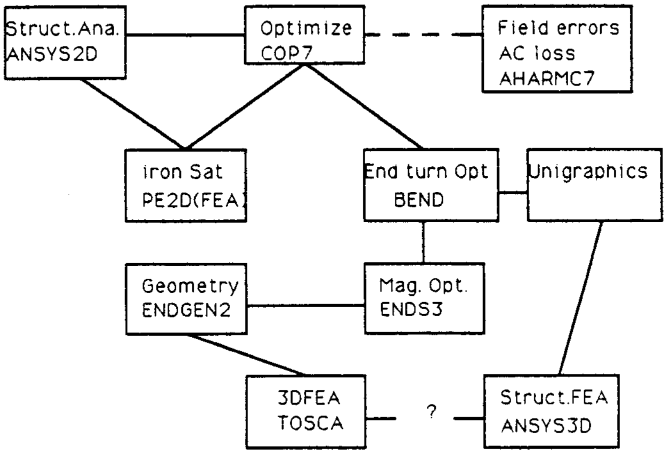

Fig. 1. Design/Analysis flow and codes in use.

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II. 2-D FIELD COMPUTATIONS

A. Design Optimization/Analysis

The design of the magnet begins with coil turn/wedge optimization directly using the expression for the multipole field for a local current line element infinite in the *z* direction and situated inside an iron yoke of infinite permeability, while the field is computed in the *x*-*y* plane. Following the SSC notation (1) the dipole component due to a current sheet is given by

$$H_0 = -\frac{I}{2\pi}\left[\frac{\ln(Z_2/Z_1)}{Z_2 - Z_1} + \frac{Z_2^* + Z_1^*}{2R^2}\right] \qquad (1)$$

and the higher order multipole fields are given by

$$H_n = \frac{I}{2\pi(Z_2 - Z_1)}\left[-\frac{1}{nZ^n} + \frac{(Z^*)^{n+2}}{B(n+2)R^{2(n+1)}}\right]_{Z_1}^{Z_2} \qquad (2)$$

where Z are complex notations for coordinates = (x+iy), Z is the coordinate of the field point, Z_1 and Z_2 are the edges of the current sheet (e.g., the inner and outer radii of the coil), I is the operating current, and $B = (Z_2-Z_1)^*/(Z_2-Z_1)$. (The normal multipole coefficients b_n are given by $\mathrm{Re}(H_n)/\mathrm{Re}(H_0)$ and the skew components a_n by $\mathrm{Im}(H_n)/\mathrm{Re}(H_0)$. The units are in 10^{-4} cm^n.) The conductor size, number of coils and wedges, yoke iron inner radius, and current range are specified, and the rest of the geometry is optimized for number of turns using the least- square technique. The turns are simulated with two current sheets along the centers of the two layers of strands in the turn. The number and location of the turns and the wedge locations are optimized using infinite iron approximation for the cold mass yoke. After optimization the conductor peak field is calculated using Ampere's law and the superconductor margin to quench field for different layers of coils is calculated using empirical relations for the critical surface. The optimization technique has been exercised to obtain varieties of dipole and quadrupole designs for the SSC, and several trade studies have been carried out to select designs for different magnets.

A universal file of conductor and wedge locations is then created by adding the yoke details to the conductor locations and current densities from COP7. This file is directly read by the code PE2D[2] which calculates fields, including the effect of iron saturation. A flux plot for the Collider dipole design obtained this way is shown in Fig. 2.

The field multipole coefficients are obtained by using the PE2D postprocessor HARM, which Fourier-analyzes the field along an arc, which, in turn, can be obtained from the post-processor in PE2D. The accuracy of the procedure has beenverified by comparing the results on the multipoles and for peak fields by comparison with an alternative code, POISSON[3]. For the SSC Collider dipole the results are in agreement within 0.001% for the dipole transfer function and within 0.1 unit for the sextupole component; the difference for higher multipoles is very small. The agreement on peak fields and superconductor margin is within 0.5%.

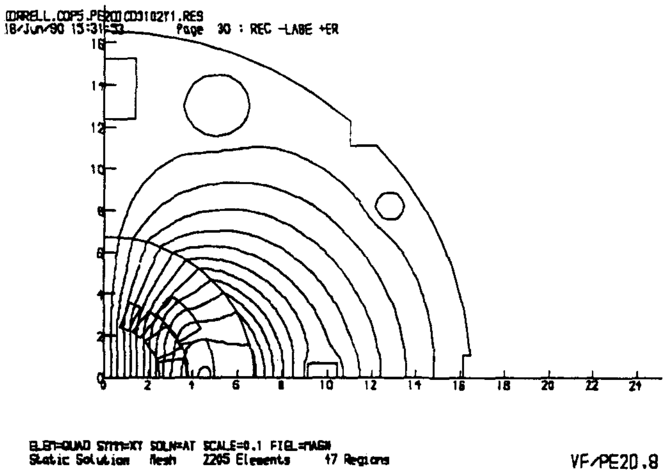

Fig. 2. Flux plot (PE2D) for the collider dipole magnet.

The above method is also used for studying non-ideal effects, e.g., magnetization of collars and beam tube, by adding appropriate features or changing material properties [4].

B. Field Errors Due To Deflections

A link between the universal file and the structural finite element code ANSYS [5] has been established which permits calculation of systematic multipoles due to coil deflections caused by collaring, yoking, cooldown, and energization of the magnet. Since the ANSYS model with separate turns and gap elements would require very large computational time for solutions and since structural characteristics of individual turns in a typical cured coil are not well known, it was decided to limit the calculation to deflection of the blocks of turns between wedges. The coordinates of the edges and the middle points of the block after the deflection are fed back into the geometry file for PE2D. Fig. 3 shows the deflected coil geometry for the Collider dipole at full field compared to uncollared (free) shape, as calculated on ANSYS, using boundary conditions and loading appropriate to the SSC dipole assembly and operating conditions. Table 1 gives the value of normal sextupole (b_2 in SSC notation) components calculated for various stages of assembly and operation (unit = 10^{-4} cm^{-2} @ 1 cm). Comparison with actual measurement indicates that some general trends can be observed. More detailed comparison taking into account all field quality effects (iron saturation, superconductor magnetization, etc.) is underway. Presently the method has been exercised only for 90° models (for cases which have symmetric deflections with respect to x and y axes).

TABLE I

Current (Amps)	b_2 units (@ 1cm)
warm	- 0.548
0	- 1.360
2000	- 1.393
4000	- 1.511
5000	- 1.600
6000	- 1.699
6500	- 1.762

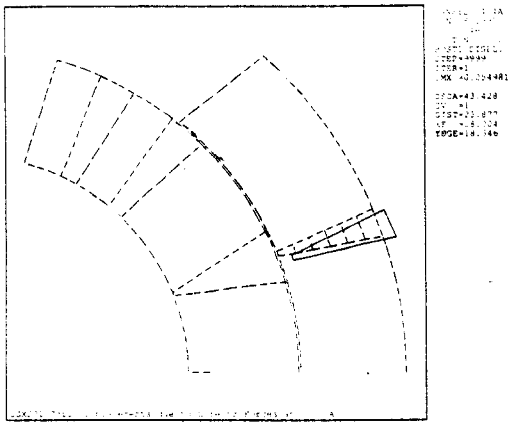

Fig. 3. Collider dipole coil deflections with I = 6500 A.

C. Multipoles Due To Geometric Errors

One of the important purposes of field analyses is to determine the effect of geometric errors in the coil(s) due to manufacturing errors. The magnet specifications place upper limits on the average as well as on the spread in the value of these multipoles over many magnets, since these affect the dynamic aperture and lifetime of the beam. These errors fall into two categories: one that is reproduced in all magnets, such as the systematic error (the effect of assembly and operational deflections described above would also fall under this category), and the other a magnet-to-magnet variation causing a distribution of values in multipoles. The former, once identified, can in most cases be iterated out with a simple design or process change, while the latter requires careful examination and control of the manufacturing process. In order to aid both these activities with a rapid turnover, a field quality analysis code, AHARMC7, has been written. The code calculates the fields with a 360°-model consisting of a full complement of coils, to enable study of geometric errors which are not symmetric about any axis. Each coil (defined here as one layer of turns and wedges on one side of the pole) is moved or changed either independently or as coupled motion (correlated or anti-correlated) with another coil to simulate coil size and coil location errors. For example, the azimuthal or radial size of the coil can be varied or the radius of the coil may be varied. The geometry of the coil is now externally input, but efforts are underway to couple this code into COP7, which will obviate this necessity. While this analysis would aid in the design iteration process, the control on the RMS width of the multipole errors caused by magnet-to-magnet variation in manufacturing requires an understanding of the spread in multipoles. A Monte-Carlo option in AHARMC7 allows a random selection of geometric coil errors, and an RMS error is determined by a set of a thousand movements with weight and coupling of coil motions as input variables. Table II shows an example of the results of calculation for the Collider dipole with random variations in azimuthal movement, azimuthal compression, and radius change in all the coils of 0.025 mm and asystematic error of 0.075 mm in azimuthal dimension of both coils. (For details of coupling of movements see [6].) The selection of the location error and the coupling of coils and the maximum amplitude of the errors can, in principle, be derived from part tolerances and from a detailed knowledge of assembly procedure. The RMS prediction (Root Mean Square error) provided by such an analysis then gives indications of the source of the error by comparing the RMS values for different multipoles. Conversely, for given specification on the RMS spread permitted, one can obtain the maximum coil error and, therefore, tolerances on parts.

TABLE II

	RMS		Specification	
n	b_n	a_n	b_n	a_n
1	0.60	1.57	0.50	0.50
2	0.80	0.48	1.15	0.35
3	0.036	0.095	0.16	0.32
4	0.072	0.019	0.22	0.05

D. Persistent Current Multipoles

During the ramping of the superconducting magnet, additional currents which resist the penetration of fields in the superconducting filaments are induced in the filaments. These currents, which consist of surface currents and currents in the bulk of superconductor, persist for long durations because the currents ideally decay only through flux creep. The surface current and the so-called "H_{c1} magnetization" is reversible (it retraces magnetization curve when the ramp direction is reversed), while the bulk magnetization is hysteritic and reverses magnetization value when the ramp direction is reversed. The field errors are those caused by current doublets at the location of the filaments. These multipoles are usually large and can significantly lower the dynamic aperture of the beam at injection.

The two components of magnetization are given by

$$M_1 = \frac{4}{3\pi} a J_c \left(1 - \frac{J}{J_c}\right)$$

$$M_2 = H_{c1} - \frac{\ln(H - H_{c1})\phi}{\ln(H_{c2} - H_{c1})\phi} \qquad (3)$$

where a is filament radius, H_{c1} and H_{c2} are lower and upper critical fields, J and J_c are operating and critical current density for the superconductor, and Φ is the flux in a single vortex. The multipole fields due to the total magnetization $M = M_1 + M_2$ are given by the expression

$$H_n = -\frac{n\Gamma e^{i\alpha}}{2\pi i} Z_c^{-(n+1)} \quad . \tag{4}$$

The multipole components due to the image current doublet corresponding to an infinite permeability iron of the yoke are given by

$$H_n' = -\frac{n\Gamma e^{i(\pi-\alpha)}}{2\pi i} \frac{(Z_c^*)^{n-1}}{R^{2n}} \quad , \tag{5}$$

where α is the inclination of the plane of the doublet to the x axis and Z_c is the complex coordinate of the conductor, $\Gamma = \pi a^2 M$. (The assumption of infinite permeability for iron is adequate for the region of interest, the low beam injection field.) The above expressions are also coded into AHARMC7 and therefore use the same coil geometry as described in the geometric error section. The calculation is carried out by dividing the coil region into about 1000 elements, each of which has a magnetization weighted by the volume and which corresponds to the local value of the field at that element. The calculations are similar to those reported in Green [7]. The total magnetization hysterisis curve is unsymmetric about the field axis due to the fact that the H_{c1} magnetization is reversible. The calculated persistent current sextupole component for the Collider dipole is shown with the measurements on a model magnet in Fig. 4. The measured values were obtained by subtracting the estimated geometric error. Within the variation in superconductor characteristics and error in the estimates on geometric error, the agreement is good.

AHARMC7 also calculates the AC losses for a given coil geometry for a given ramp rate by taking into account the hysterisis losses in the superconductor and yoke, eddy current loss in the strands, and eddy current loss due to strand-to-strand coupling. The details of the calculations are given in Ref. [8]. Fig. 5 shows the comparison between AC loss calculations and measurements for a model dipole.

The calculated field distribution in the superconducting coils (in ideal conditions) is also used for quench propagation studies.

AHARMC7 is being incorporated into COP7 and will use the same universal file and can be invoked as needed. The eddy current part of the code is also being incorporated into the calculation of multipole field errors and quench propagation caused by changing fields.

E. Eddy Current Analyses

Several parts of superconducting magnets experience rapidly varying magnetic fields, particularly during quench. Analyses are carried out, particularly with regard to forces experienced, on the effect of these currents. Examples of these are metallic parts used in clamping end turns (the collars in the straight section are laminated) and the beam tube, which is made from stainless steel with high-conductivity copper plating. Commercial code PE2D is used for modelling these phenomena. Fig. 6 shows the results of calculation on the beam tube [9]. These calculations were carried out with varying copper resistivity within the quench event, taking into account the dependence of resistivity on the field and temperature (since the tube heats up during the quench), by using polynomial fits. The calculations shown were carried with the boundary condition that eddy currents close at the ends of the beam tube. From these calculations the required thickness of the beam tube and limit on the electrical conductance of the copper plating can be specified. Results of these calculations have been used to study structural requirements for potential designs of synchrotron radiation intercept for an accelerator like the SSC.

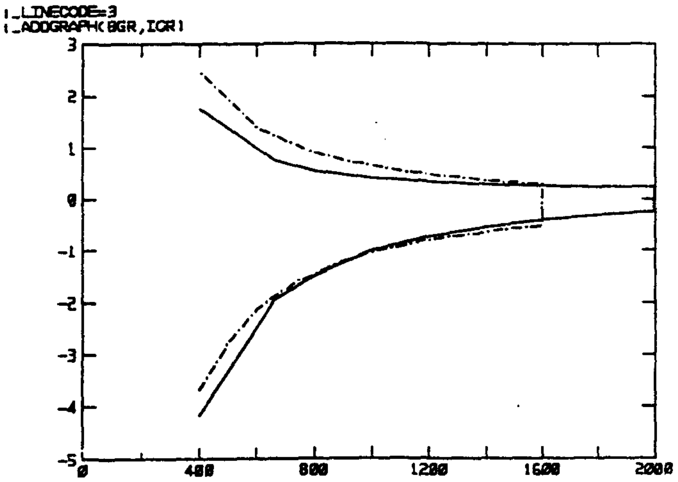

Fig. 4. Comparison of calculated (dashed line) and measured (solid line) values of sextupole units vs current (A) for collider dipole magnet.

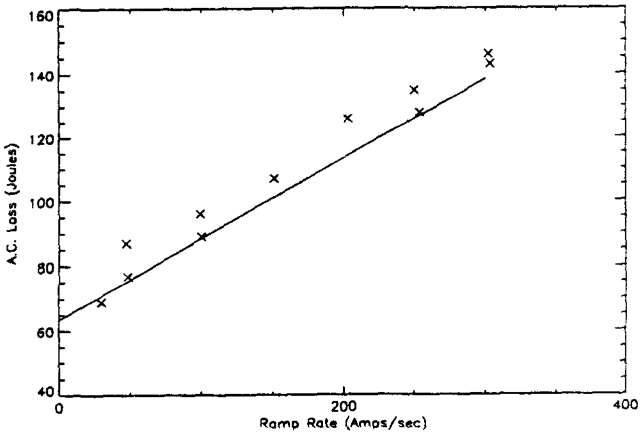

Fig. 5. AC losses in model dipole: calculated (dashed line) and measured (-x-).

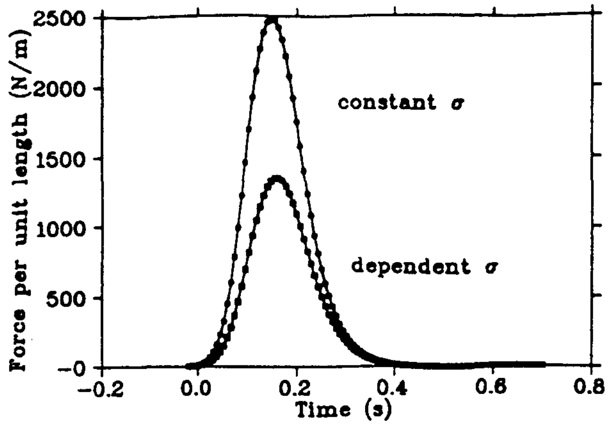

Fig. 6. Force on beam tube due to collider dipole quench.

III. 3-D CALCULATIONS

The design of superconducting magnets requires a careful examination and optimization of coil ends. The coil ends are complex areas, where the superconducting cable is bent around in three dimensions and the winding shape has to be optimized to minimize stresses (strain) in the cable. Meanwhile, the integrated multipole field error induced by the end turns has to be simultaneously minimized. Additional optimization criteria that can be placed are the minimization of peak field at the conductor and the minimization of the end physical length. Since the conductor support is always questionable at the ends and is more prone to manufacturing quality problems compared to the straight section, the design of the ends has to provide a less sensitive and reproducible winding that satisfies quench and field quality requirements.

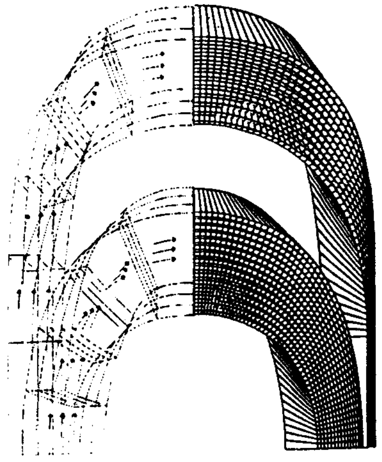

Fig. 7. Coils as modelled by ENDS3/BEND (right) and TOSCA/ENDGEN2 (left).

The 3-dimensional field analysis at the ends is carried out using in-house resources and the commercial finite element code TOSCA [10]. The end turn shapes are optimized by using a strain optimization code BEND [11], which produces the so-called "grouped ends" and constructs the end turn around an infinitely thin guiding strip. The position of the guiding strip is varied to find a surface with the least strain for a chosen turn of a group of windings (turns between two wedges). The other turns stack against this turn. By varying the position of the guiding strip, the overall strain energy is minimized. The program BEND outputs files CENTROID and CORNER containing the coordinates of the end turns. These and other files are used for generating UNIGRAPHICS II drawings and for generating end part designs.

The code ENDS3, which uses Biot-Savart formulation, reads the file CORNER and calculates the fields on a circle of 20 mm radius and calculates the harmonics, without including the effect of iron. In the first approximation ENDS3 is used to adjust the turn geometry (by adjusting the straight section of the group) to minimize the harmonics generated by the end turns. The finite element 3-D saturable iron calculations are then carried out to refine the geometry and to calculate superconductor fields and fringe fields. The CORNER and CENTROID files are used by the program ENDGEN2 to generate the TOSCA geometry. The output of the program BEND (see Fig. 7 (right)), which has 50 sets of points per turn, is converted into corners and centroids of the group of conductors. Cubic spline fits are generated to the lines connecting the four corners of the cross section of the group of conductors, the line connecting the center of the faces, and the line connecting the the center of each conductor in the group. A number of planes perpendicular to the current are generated at evenly spaced intervals in this 3-D geometry. Five to six segments defined by these planes are used per group of conductors. The choice of five segments has been found to give satisfactory agreement between ENDS3 and TOSCA results for the case of no iron. The segments are further divided into three sections to model current density variation in the cable. Each section is then modelled with a 20-noded brick element. Fig. 7 (left) shows the TOSCA model for turns. Fig. 8 shows a view of the TOSCA model, and Figs. 9 and 10 show the field values at the end. Fields at the end turns have also been calculated. It is also noted that there is good agreement between the calculated sextupole value calculated by TOSCA and PE2D at the straight section. Recently, these calculations have been compared with measurements on magnets [12], and excellent agreement has been obtained.

Fig. 8. TOSCA model of the collider dipole ends.

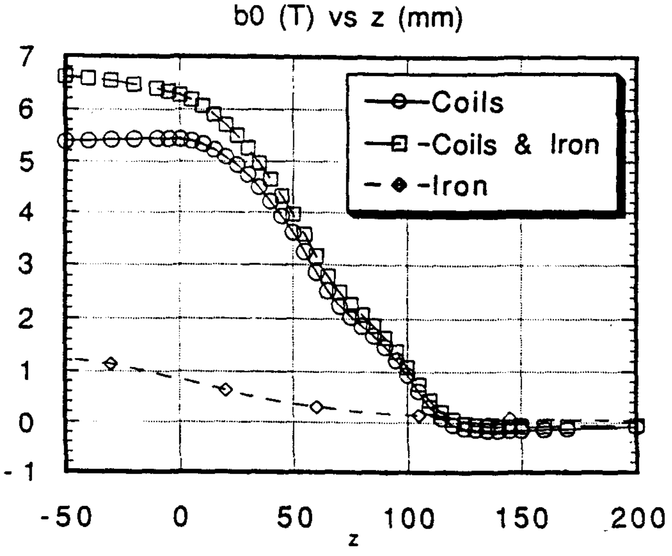

Fig 9. Dipole field as a function of axial distance for the collider dipole at the ends. z = 0 marks end of yoke.

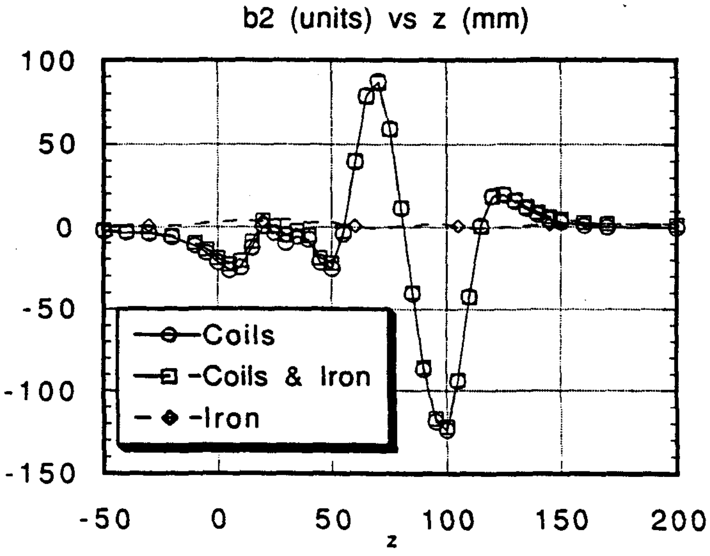

Fig. 10. Sextupole component (units) as a function of axial distance for collider dipole. z = 0 marks end of yoke.

IV. WORK IN PROGRESS

The SSCL Cold Mass Analysis group is actively pursuing faster and more accurate field analysis techniques. Work on 2-D and 3-D volume element codes which can be coupled to COP7 and ENDS3 is being initiated. This will facilitate geometry generation and will require less time by the analyst, perhaps at a cost of some accuracy or additional computation time due to the full matrix nature of the integral codes. The structural analysis code ANSYS is now partially coupled to the UNIGRAPHICS II files. Although some work is continuing on the structural analysis of end turns using this interface to BEND, work on directly linking ENDS3/TOSCA to ANSYS3D is recognized to be complicated. Options are being explored to enable structural analysis of end turns under Lorentz force as calculated by TOSCA. Work on integrating the various codes into user-friendly design software for use by SSCL subcontractors is also in progress.

V. CONCLUSIONS

The SSC Laboratory (SSCL) has a reasonably complete suite of codes for field calculations, and these have been linked together for minimizing analyst intervention to give quicker and error-free analysis. Commercial softwares are used where available, and SSCL codes are generated where necessary. These codes have been exercized extensively for optimization and analysis of Collider dipoles, Collider quadrupoles, HEB dipoles and quadrupoles, and IR magnets. The results have been reliable, and initial results of measurements on actual magnets indicate that the methods give correct results. Integral methods to speed up field computations are being created. The effort to create an integrated design and analysis package has started yielding results and is expected to be available to SSCL subcontractors in due time.

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