A Five Tesla Solenoid with Detector Integrated Dipole for the Silicon Detector at the International Linear Collider

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***Abstract*—A conceptual design study for a 5 Tesla superconducting solenoid for the Silicon Detector (SiD) of the International Linear Collider (ILC) has been undertaken. Utilizing the existing Compact Muon Spectrometer (CMS) magnet conductor as the starting point, a winding design has been proposed for the magnet. Finite element analysis shows the resulting magnetic stresses in the coil do not greatly extrapolate beyond those of CMS, and decentering forces to the muon steel are shown to be manageable. For compensation of finite crossing angles of the ILC beams, a dipole coil integrated with the solenoid is examined.**

***Index Terms*—superconducting, solenoid, magnet, particle physics detector, detector integrated dipole**

I. INTRODUCTION

THE SiD[1], a particle detector that utilizes silicon tracking and calorimeters enclosed within the magnetic field, is being optimized for particle physics at the future ILC. The SiD offers excellent hermeticity and compact design, an undisputably novel 5.0 Tesla solenoid magnet 5 m in diameter and 5 m long, a fine-grained electromagnetic calorimeter with jet energy resolution ~ 30%/√E, and a dense hadron calorimeter, both enclosed inside the magnet warm bore, and muon identification and tracking embedded in a steel flux return outside the magnet cryostat. In addition, to provide optimum compensation for finite beam crossing angles, a dipole coil is integrated with the solenoid [2].

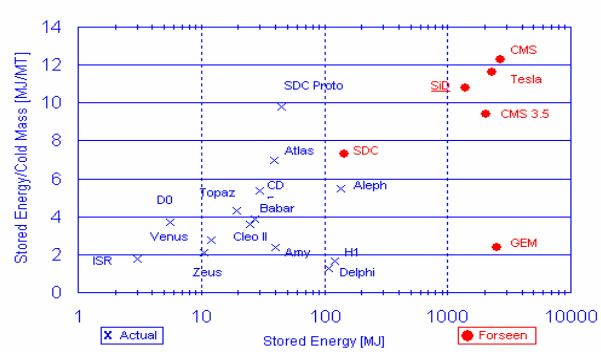
A. Extrapolating from the State of the Art

A large 5 Tesla superconducting solenoid unquestionably transcends present experience. It has been suggested by at least one author [3] that mechanical considerations lead to an upper limit of about 60 T^2m for the figure-of-merit B^2R for superconducting solenoids. For the SiD solenoid this quantity is 62.5 T^2m, suggesting that the feasibility of such a magnet is best determined by appeal to experience and careful engineering extrapolation from thence where required.

The CMS solenoid [4], nearing completion at the CERN Large Hadron Collider, will provide a 4 T field in a bore 5.9 m in diameter and 13 m long. This magnet provides a substantial proof-of-concept for the SiD solenoid. We say substantial because the CMS solenoid is yet to be operated[1]. Although providing 20% lower field than the SiD solenoid, the CMS solenoid is physically larger and stores 2.6 Giga-Joules (GJ) magnetic energy vs. 1.4 GJ stored by the SiD solenoid. As with the CMS detector, no special field uniformity beyond that of a uniformly wound solenoid is required by SiD, and the radiation transparency of the magnet is not a constraint. As has become common with large detector solenoids, the CMS coil is wound inside a thin support cylinder which is cooled by forced-flow two-phase helium circulating in tubing welded to the support cylinder. These general approaches were selected for the SiD solenoid.

B. Reliability and Safety Foremost

The safety of a magnet which stores a great deal of energy is paramount – quenching of the magnet due to cryogenic or electrical upset must not lead to harm of the magnet or of the detector. One figure-of-merit for characterizing the safety of a large magnet is the ratio of stored energy to cold mass; the less cold mass able to absorb the stored energy deposited during a quench, the more likely damage to the magnet is to occur in such an upset. In Fig. 1 the stored energy per unit cold mass is plotted against the stored energy for many detector solenoids:



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[1] The CMS magnet will be commissioned early in 2006

Fig. 1. Stored Energy per unit Cold Mass as a function of Cold Mass for Particle Physics Detector Superconducting Solenoids.

All magnets marked with "X" in Fig. 1 are operating or have operated in the past. Except for CMS, all the magnets marked with a dot are "Forseen" only. Note the SiD magnet lies comfortably below CMS in both plotted variables. This suggests that although novel the SiD magnet is not unthinkable.

II. Choosing design features

The winding radius for the SiD coil (2.645 m) is not so dissimilar from that of CMS (3.160 m), and the optimum operating current of the magnet is likely not to be substantially different (~20 kilo Amperes) from CMS, that it was straightforward to attempt to utilize the CMS conductor design without change. Likewise the key features of the CMS winding design were also seen as likely to provide a credible proof-of-concept for SiD.

A. *Conductor and Winding Design*

The CMS conductor consists of a 32-strand NbTi cable, stabilized by a coextrusion of high-purity aluminum, which is welded to two bars of strong aluminum alloy. The conductor is shown in Fig. 2.

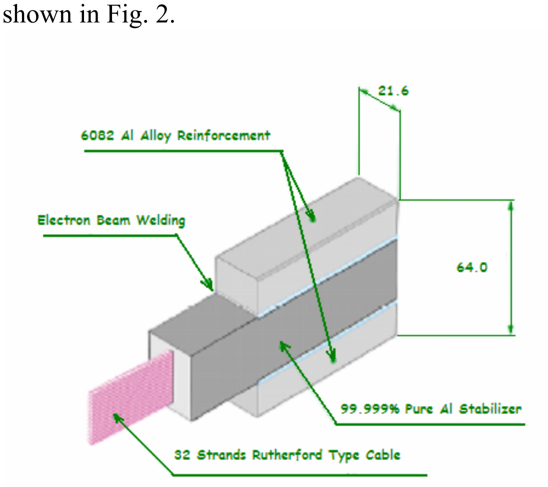

Fig. 2: The CMS conductor design

CMS achieves its design field with four winding layers; SiD will require six layers using the same conductor. The smaller aspect ratio (magnet length divided by diameter) of SiD vs. CMS -- approximately one for SiD but more than two for CMS -- means that more linear current density than simple proportionality of the higher field is required. CMS operates at 19.5 kilo-Amperes (kA) and its windings provide a linear current density of approximately 3500 A/mm; SiD requires 4800 A/mm, a factor of almost 1.4 more than CMS for a field only 25% more intense. CMS has demonstrated that conductor piece lengths of 2.7 km are possible, and to ensure no conductor joints within a winding layer CMS subdivided the coil into five modules each 2.5 m long. The modules are independently wound inside their support cylinder segments, impregnated and cured, then transported to the assembly site where they are bolted together at the interface plane between the modules at bosses provided in the outer support cylinder segments.

The SiD winding design chooses two modules, each 2.5 m long, joined as does CMS. Each winding layer consists of 116 turns, and as with CMS, the interturn insulation is 0.64 mm thick and the interlayer insulation 1.04 mm thick. The SiD winding design is shown in Fig. 3.

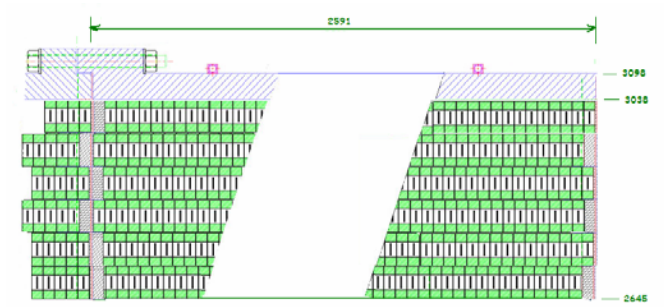

Fig. 3: The SiD coil winding design

B. *Operational Stability*

The operational stability of the magnet is paramount – it must charge readily, discharge safely, and never quench unexpectedly. For CMS, detailed modeling analysis [4] indicated the Minimum Quench Energy (MQE -- that pulse of energy absorbed by the coil that is just able to initiate quenching) is of the order 0.5 – 1.0 J. Such an energy pulse might come from e.g. epoxy cracking, etc. The analysis showed that the MQE is essentially unchanged if a single turn of conductor, or the entire four winding layers, was allowed to participate in the energy absorption. This indicates that the increase in the number of winding layers for SiD, even though it moves the innermost layer 50% farther from the cooling piping than does CMS, is not expected to reduce its stability from that of CMS, if the critical current margins of the superconductor are not less than those of CMS.

For CMS the peak field on the conductor is 4.6 T and the conductor achieves a critical current of ~59 kA at 5 T. The "fraction of short-sample" is approximately 19.5/59 = 0.33 (ignoring small corrections for the magnet peak field vs. the conductor test field, and the magnet operating temperature vs. the conductor test temperature -- the two corrections tend to offset each other). For SiD the conductor operates at 18000 Amperes and the peak field on the conductor is 5.8 T. The first factor increases the margin by ~19.5/18 = 1.08; the second decreases it by ~0.79. Evidently only small changes in the CMS conductor design (e.g. increasing the number of strands in the cable) might be necessary to provide the same or even greater operating margin than the CMS conductor.

C. *Stress Analysis*

A figure-of-merit (FOM) for the radial magnetic loads on the coil, based on the hoop stress σ in a thin-walled pressure vessel, is $FOM = 2\mu_o\sigma = B^2R/t$, where $B^2/2\mu_o$ is the magnetic pressure in the magnet bore, R the mean radius of the coil, and t the thickness of the coil. For CMS this FOM is 160 and for SiD it is 158. This indicates that a detailed calculation of the hoop stresses should be very similar for both solenoids. For CMS the end iron yokes are partly "reentrant" into the magnet bore. This suggests that the radial fields at the ends of the coil, which determine the axial loads on the coil, might be lower than those for SiD (even considering the lower CMS field). An axial stiffness FOM for the coil is the fraction Rt/L, where L is the half length of the magnet. For SiD this FOM is about 3 times that of CMS, suggesting that SiD is better able than CMS to resist the axial loadings on the coil, thereby helping to reduce the shear on the epoxy bond between the coil and the outer support cylinder.

A detailed finite-element model of the SiD coil was created with ANSYS [6], incorporating the details of each turn, to evaluate the stresses and strains in the coil generated by cool down and energization. The model shows the expected cool down strains (uniform displacement inward radially and axially) and the expected energization strains (which bow the cylindrical coil into a barrel shape, fatter at Z = 0 than at the ends, and overall axial displacement of the ends of the windings towards Z = 0. The net peak outward radial strain (cold, energized) is about 6 mm at Z = 0 and 3 mm at Z = 2.5 m; the net axial strain at Z = 2.5 m is about 3 mm towards Z = 0.

Of interest is the state of stress in the high purity aluminum near the conductor cables. As seen in Fig. 4, these stresses (Von Mises) peak at about 22.4 MPa (3.2 ksi) nearest the superconducting cables. This stress places the soft aluminum in the plastic regime, but this is very comparable to that calculated for CMS (22 MPa).

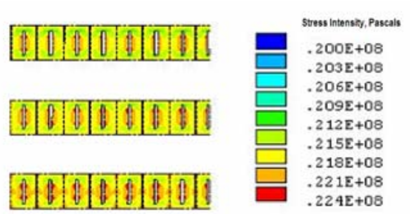

Fig. 4: Detail of Von Mises stresses in the High Purity Aluminum, SiD cold and energized (outer 3 layers omitted from figure)

D. Iron Yoke

An iron yoke, consisting of an octagonal barrel and endcaps of steel plates 10 cm thick, with 5 cm gaps for muon chambers, was provided in the conceptual design. A total of 23 layers of steel was chosen for both the barrel and the endcaps. A system of end gusset plates, staggered on the two ends to allow the insertion of muon detectors into the gaps, supports the barrel shells from one another and the solenoid and calorimeters inside. The barrel extends from R = 3.428 m to R = 6.828 m and is 5.6 m long in Z. The end steel plates are flush with the central barrel plates, i.e. they do not "reenter" the bore of the solenoid. They extend from Z = 2.847 m to 6.247 m.

E. Field Shape

Two-dimensional and three-dimensional magnetic field calculations of the magnet have been made with ANSYS, and the resulting field shape is seen in Fig. 5. In Fig. 5 the outer iron barrel layers are not shown. The inner radius of the magnet vacuum cryostat is at R = 2.5 m and it extends to Z = 2.80 m.

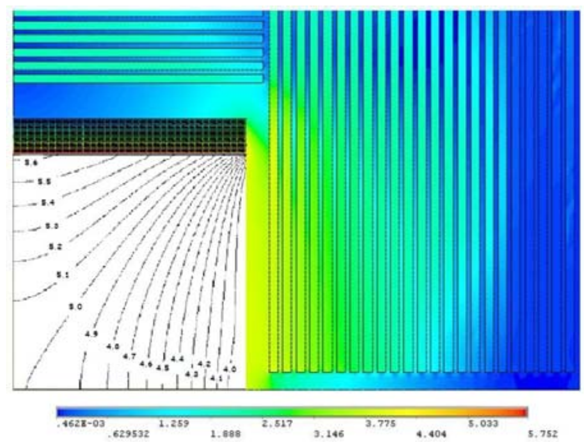

Fig. 5: SiD central field contours in |B|, fields in the iron shown by intensity scale. Outer layers of barrel steel omitted from the figure.

F. General Mechanical Comparison

From the ANSYS studies the following comparisons can be made to similar analysis made for the CMS solenoid. The stresses in the coil shown in Table I are evaluated after cooldown and energization.

TABLE I: COMPARING SID AND CMS

Quantity	SiD	CMS
Von Mises Stress in High Purity Aluminum	22.4 MPa	22 MPa
Von Mises Stress in Structural Aluminum	165 MPa	145 MPa
Von Mises Stress in Rutherford Cable	132 MPa	128 MPa
Maximum Radial Displacement	5.9 mm	~5 mm
Maximum Axial Displacement	2.9 mm	~3.5 mm
Maximum Shear Stress in Insulation	22.6 MPa	21 MPa
Radial Decentering Force	38 kN/mm	38 kN/mm
Axial Decentering Force	230 kN/mm	85 kN/mm
Stored Energy	1.4 GJ	2.6 GJ

G. Cryostat

The requirements for the cryostat and cold mass support system don't appear to differ strongly from CMS so likely similar design approaches would be taken – long metallic axial members and tangential radial members at each end in the vacuum space of the cryostat for cold mass support, and cooling by forced-flow two-phase helium – thermosiphon or pump assisted.

III. Detector Integrated Dipole

Beam particles entering the detector at a finite horizontal crossing angle will deviate in the vertical plane. This deviation can be corrected by a special dipole field at the intersection region. For maximum efficiency this special field can be provided by saddle coils mounted on the outer support cylinder of the solenoid. This Detector-Integrated-Dipole (DID) corrector can also be used to compensate for rotation of the beam polarization or beam size growth due to synchrotron radiation [2]. Locating the DID coils on the solenoid outer support cylinder offers an ideal environment for them. There is minimal solenoidal field in that region, a slight increase in the size of the solenoid cryostat readily provides for the dipole coils, and the large winding radius of the dipole coils ensures a high quality dipole field on the beam axis with modest attention to the dipole winding geometry. Approximately 550 kA-turns are required for the required ~ 600 G dipole field from each of the coils. In Fig. 6 is seen the DID coil geometry superimposed on the solenoid coil:

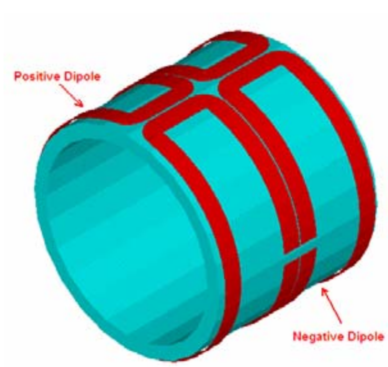

Fig. 6 Detector-Integrated-Dipole Saddles

The field provided by the DID coils is seen in Fig. 7:

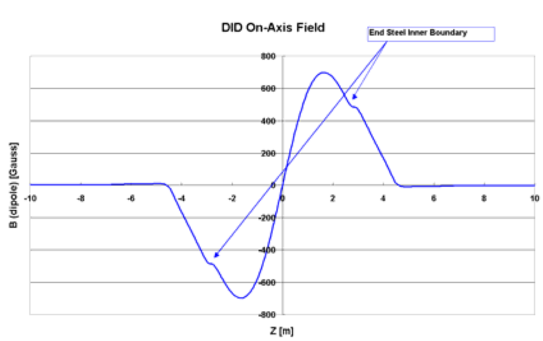

Fig. 7. The DID field on the colliding beam axis

The DID coils couple modestly to the solenoid and some attention must be given to their mutual behavior during upsets. The forces on the DID coils are also modest as seen in Fig. 8 and the required support should be relatively straightforward to engineer.

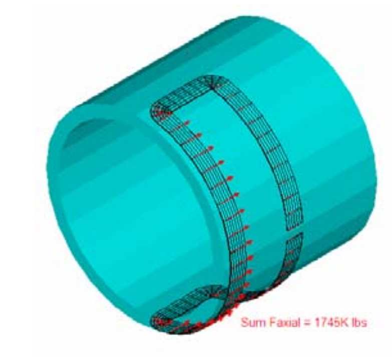

Fig. 8 Axial forces on the DID coil

The axial forces on each saddle coil sum to 1745 K lbs and relatively small bosses on the solenoid support cylinder placed in shear stress would provide adequate support. A similar plot of radial loads on a saddle coil shows they sum to 435 K lbs but they are generated principally on the segment of the saddle next to the adjoining saddle where the radial forces are in the opposite direction.

IV. Conclusions

The conceptual design study has indicated that the realization of the SiD solenoid is not greatly less credible than that of CMS. Detailed study is required to quantify the stability and safety of the winding design, and to select the optimum final conductor design and choice of operating current. Likewise the requirements of the muon system will evolve and influence the details of the iron design. Detailed engineering study is required to confirm the reality of the proposed DID system. Since none of these efforts for the solenoid apparently need stray very far from the general approaches taken for CMS, the CMS fabrication and cost experiences can guide the planning for SiD.

References

[1] J. E. Brau, M. Breidenbach, Y. Fujii, "The Silicon Detector (SiD) and Linear Collider Detector R&D in Asia and North America", Amsterdam ECFA/DESY Study April 2003, DESY-PROC-2004-01, DESY-04-123G, March 2004.

[2] B. Parker, A. Seryi, "Compensation of the Effects of Detector Solenoid on the Vertical Beam Orbit in NLC", LCC-0143, SLAC-TN-04-044, BNL-MDN-637-40, June 3, 2004.

[3] F. Kircher, "Magnetic Field Geometries", 42^{nd} INFN ELOISATRON Workshop, Erice, IT, Sept 28, 2003.

[4] A. Herve, et.al., "Status of the Construction of the CMS (Compact Muon Spectrometer) Magnet", Proc. Eighteenth Intern. Conf. Magnet Technology, V 14, No 2, pages 548—551, IEEESup, June 2004.

[5] F-P. Juster, et. al, "Stability of Al-stabilized Conductors for LHC Detector Magnets", IEEE Trans App Superconductivity (June 1977), Sup Vol 7 N2, 633-637.

[6] Swanson Analysis Systems, Houston, PA, USA