# A 5 Tesla Solenoid for SiD

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A conceptual design study for a 5 Tesla superconducting solenoid for the Silicon Detector (SiD) [1] has been undertaken. Utilizing the existing Compact Muon Spectrometer (CMS) [2] magnet conductor as an appropriate starting point for such a magnet, a winding design has been prepared which generates the desired magnetic field for the detector. Finite element analysis shows the resulting magnet does not greatly extrapolate beyond the CMS design in overall mechanical stress in the coil. An iron yoke which also contains a muon tracking system is provided in the design and the resulting decentering forces on the coil are shown to be manageable.

## 1. INTRODUCTION

The SiD, a particle detector that utilizes silicon tracking and calorimeters enclosed within the magnetic field, is being considered for the future electron-positron International Linear Collider (ILC). The important features of the SiD are excellent overall hermeticity, overall compact design, a 5.0 Tesla central solenoidal field, fine grained ECAL with energy resolution ~ 15%/√E, and a dense well-optimized HCAL, both enclosed inside the magnet warm bore, and muon identification and tracking embedded in the steel flux return outside the magnet cryostat.

The specification of 5 Tesla central field for the solenoid that provides a clear bore 5m in diameter and 5 m long undisputably makes the magnet novel. In this paper a conceptual design of the solenoid has been undertaken which indicates that consideration of such a magnet is not unrealistic, and that the cost of its design and fabrication can be estimated within reasonable tolerances.

## 2. REFERENCING THE STATE-OF-THE ART

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

The CMS solenoid, 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. We find that in many ways this magnet provides an "almost proof-of-concept" for the SiD solenoid. We say "almost" 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 standard 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.

[1] The CMS magnet will be commissioned late in 2005

## 2.1. Safety

The safety of a magnet which stores a great deal of energy is paramount -- cryogenic and electrical upsets 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 Figure 1 the stored energy per unit cold mass is plotted against the stored energy for many detector solenoids:

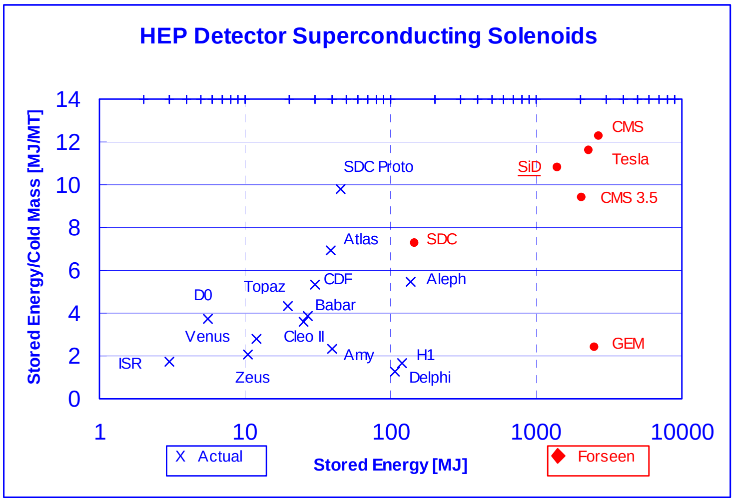


Figure 1: Stored Energy per unit Cold Mass vs. Stored Energy for Detector Solenoids

All magnets marked with “X” are operating or have operated in the past. Except for CMS, all the magnets marked with a dot are “Forseen” only. As can be seen, the SiD magnet lies comfortably within the bounds of CMS in both plotted variables. This suggests that although novel, the SiD magnet is not unthinkable. It can be anticipated that a proper analysis of the quenching behavior of the SiD magnet will surely show that it can be discharged safely without damaging itself.

# 3. CHOOSING DESIGN FEATURES

The winding radius for the SiD coil (2.645 m) is not so dissimilar from that of CMS (3.095 m), and the optimum operating current of the magnet is likely not to be substantially different (~ 20 kilo Amperes), so 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.

## 3.1. Conductor and Winding Design

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

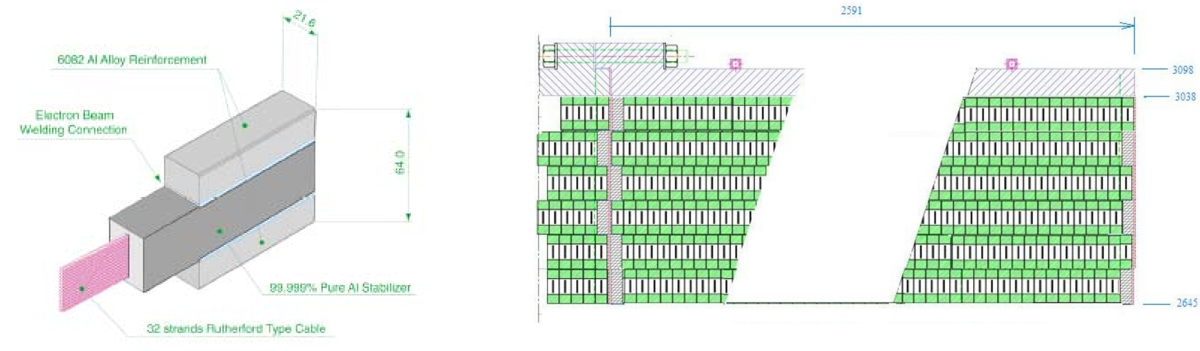


Figure 2: The CMS conductor and coil winding design

CMS achieves its design field with four winding layers; SiD will require six layers using the CMS 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 Figure 2.

## 3.2. Operational Stability

The operational stability of the magnet is of paramount interest – it must charge readily, discharge safely, and never quench unexpectedly. For CMS, detailed modeling analysis [4] indicates 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 shows that the MQE is essentially unchanged if a single turn of conductor, or the entire four winding layers, are allowed to participate in the heat absorption. This indicates that the increase in the number of winding layers for SiD, even thou 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 of the order of ~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.

## 3.3. Stress Analysis

A figure-of-merit (FOM) for the radial magnetic loads on the coil, based on the hoop stress $\sigma$ 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 might be lower than those for SiD (even considering the lower CMS field). The radial fields determine the axial loads on the coil. 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, 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 windings 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.

The chief interest of course is the state of stress in the high purity aluminum near the conductor cables. As seen in figure 3, these stresses (Von Mises) peak at about 22.4 MPa (3.2 ksi). This stress certainly places the soft aluminum in the plastic regime, but this is very comparable to that calculated for CMS (22 MPa).

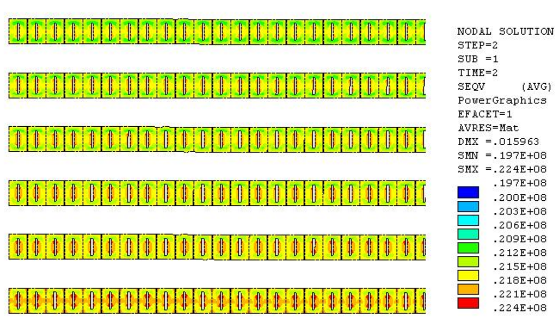


Figure 3: Von Mises stresses from the FEA modeling of the SiD winding cold and energized

### 3.4. 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, and a system of end gussets created to support the barrel shells from one another. The rather simple concept for the central barrel, where the gussets are staggered on the two ends to allow muon detectors to be slid axially into the gaps and rearranged for high hermeticity, was shown sufficiently stiff to support the barrel steel, and the solenoid and the calorimeters inside it. The central 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.

### 3.5. Field Shape

Two-dimensional and three-dimensional magnetic field calculations of the magnet have been made, and the resulting field shape is seen in Figure 4. In Figure 4 the outer iron barrel layers are not shown. The inner radius of the magnet vacuum cryostat is at R = 2.645 m and it extends to Z = 2.80 m.

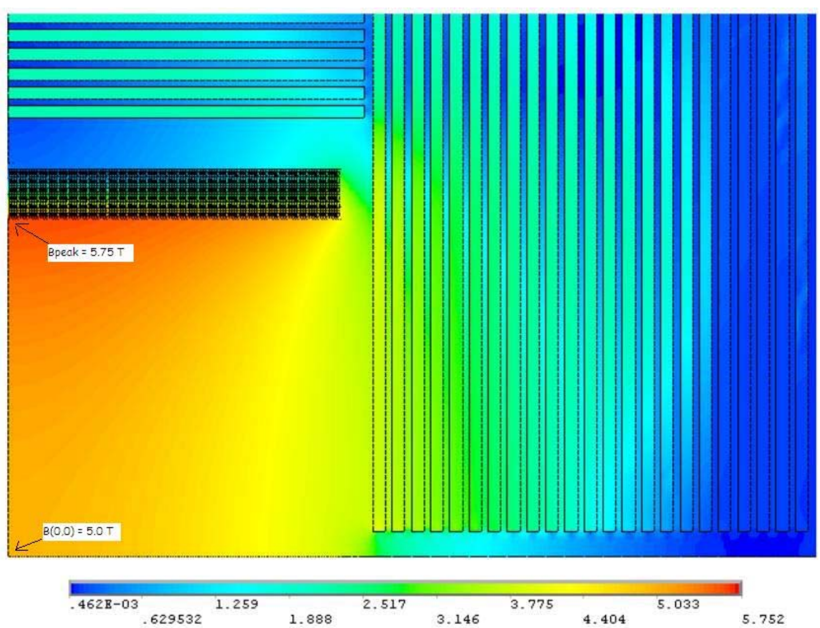


Figure 4: SiD field shape

### 3.6. General Mechanical Comparisons

From the FEA 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 |

## 3.7. Cryostat

No effort has been spent to design a cryostat and cooling system. The requirements for each 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.

# 4. CONCLUSIONS

The conceptual design study has indicated that the realization of the SiD solenoid is not 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 conductor design and choice of operating current. Likewise the requirements of the muon system will evolve and influence the details of the iron design. Since none of these efforts apparently need stray very far from the general approaches taken for CMS, the CMS fabrication and cost experiences can guide the planning for SiD.

## Ackowledgments

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## References

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