Fermilab

# SSC DETECTOR SOLENOID DESIGN NOTE #105

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ABSTRACT: This Design Note is the draft of the magnet section of the Expression of Interest. A copy of it was given to Larry Price on Mar 9, 1990 to take to the collaboration meeting in Dallas on Mar 11-13.

**FNAL**
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# Superconducting Magnets

## Introduction:

Large superconducting magnets are envisioned to provide field for central tracking and possibly for precision measurement of forward muons. A large solenoidal magnet is planned to provide the magnetic field required for charged particle momentum determination in the central detector. While the exact dimensions of this tracking volume are still under study, the overall scale is understood and significant progress has been made in understanding the engineering details of several possible configuations of such a solenoidal magnet. To date, two basic configurations have been studied. The first configuration studied was that of the Large Solenoid Detector proposed at the 1987 Berkeley workshop. In this configuration, a large solenoidal magnet completely surrounds both tracking volume and calorimetry. This magnet was studied in detail by both US and Japanese groups and writeups of these detailed design studies exist[1] [2]. The conclusion of these studies was that the proposed magnet is technically feasible. However, the magnet's large electromagnetic stored energy (>1.5 GJ) combined with cost, schedule and transportation issues resulting from its large physical size appear to be problems. These difficulties when combined with the problems of operating calorimetry in a confined space and immersed in a 1.5 to 2.0 T field make this configuration look less attractive than configurations which have the calorimetry outside the coil in essentially a field free region. Such a geometry provides the required field in the tracking volume with a coil of minimal physical size and stored electromagnetic energy. It also allows good access to calorimetry for cabling and maintenence. However, this geometry places the material of the coil, support cylinder, and vacuum shells in front of the electromagnetic calorimetry. Nevertheless, by making these items thin in terms of radiation and absorbtion lengths, the effects on electromagnetic energy resolution for physics processes of interest at SSC energies can be made to be small[3]. The presence of a coil with a thickness of $2X_0$ in front of the calorimeter has been shown to have neglible effects on the missing $P_t$ spectrum [4] Furthermore, although studies are still in progress, we believe that careful attention to the calorimetry geometry near the ends of the coil can result in small or neglible degradations of missing $E_t$ resolution and calorimetry coverage. Finally, since eight solenoids of approximately the size required for an SSC detector have been built in the past 8 years (see table 1), we have great confidence that a satisfactory thin coil magnet can be built and in place when SSC experiments begin.

The magnet dimensions will be determined via an optimization proceedure that balances various conflicting requirements on the magnet parameters. As an example, consider the magnet's radius. The desire for the best momentum measurement with plausible extrapolations of existing tracking technology argues for large radius and high field integrals. On the other hand, the desire to minimize coil material in front of the electromagnetic calorimetry and minimize the cost of calorimetry argues for small radius. Although this optimization process is still in progress, its seems likely that a coil with a useful inner radius of 2.0 m $\pm$ 0.3 m and a field integral of 4.0 $\pm$ 0.5 T-m will be chosen. Our design studies most recently have focused on the engineering problems of building a "thin" (in terms of radiation and absorption lengths) superconducting coil of approximately these dimensions. The results of these design studies support the assertion that coils of the desired dimensions and field strengths can be built with material budgets that correspond to 1.2 $\pm$ 0.2 radiation lengths for a particle traversing the coil at 90 degrees to the solenoid axis. These studies considered two magnet options with these dimensions. Each variant has advantages and disadvantages, but we note that many features of the designs are common. We call these two design variants type-L and type-S. Differences in the basic geometries of the two types are illustrated in Figure 1. Both coil types are described in the sections that follow.

The type-L[5] magnet attempts to extend the current sheet as close as possible to a ferromagnetic flux return yoke. This results in a magnet with a very uniform internal magnetic field and neglible fringe fields outside the coil volume. In addition, since the radial field components are small, the resulting compressive force on the coil is small. However, the proximity of the coil to iron return yoke results in it being exposed to axial decentering forces (and to a lesser extent radial decentering forces) that must be resisted via support members from the coil at 4.5 K to the room temperature steel yoke. In addition, since the coil penetrates the calorimetry, care must be taken insure that the calorimetery performance in coil end region is not compromised. Figure 2 is an example of a type-L magnet.

The type-S[6] magnet makes no attempt to have an iron flux return near the end of the coil. This design choice allows the calorimetry to wrap around the end of the coil in a more hermetic way than the type-L design. However, the magnetic field in this type coil is much less uniform than in the type-L design, especially near the ends of the winding, and large fringe fields extend into the volume occupied by calorimetry and other external detectors. The large radial component of the magnetic field that penetrates the current sheet results in a very large magnetic compressive force on the winding that must be resisted without quench causing coil motion. Because of the large distance to the ferromagnetic return yoke, the axial and radial decentering forces are neglible and supports must primarily be designed to carry the weight of coil cold mass. One additional worthwhile feature of such a coil is that it could be tested to full current at a vendors factory since the presence of a return yoke is not required. Figures 3 and 4 shows a type-S magnet.

A summary of qualitative advantages and disadvantages of each configuration appears in Table 2. Quantitative comparisions are much more difficult and are crucial to making such an important design decision. Experience with other large detectors has taught us that wrong magnet decisions made early in the design of a detector can have enormous long term consequences for the experiment. Although we currently believe that either type of magnet is technically feasible, **substantial magnet design and detector simulation studies are required to determine which is the better choice.**

## Thin Solenoid Design Criterion

As stated above, many features of both magnet types are common. One overiding and common consideration is that of the overall design criteria to be used. In particular, for thin solenoids such as these, there are two fundamental, but in a sense opposing, criteria which strongly influence the design of the magnet: "thinness" and reliability. Thinness is measured in radiation and absorption lengths of the coil and cryostat package as a function of pseudorapidity over the angles at which the coil occludes calorimetry. Reliability is difficult to quantify before the fact but is measured in practice by both the short- and long-term availability of the magnet to function as a part of the detector. As an example of the opposing character of these criteria consider the following: The need to minimize the thickness results in the use of aluminum for the conductor stabilizer and for the shells of the vacuum vessel, yet the welding of aluminum is generally recognized to be more difficult and less reliable than welding stainless steel. Similiarly, our studies to date indicate that it would be very desirable to use honeycomb construction and various other "aerospace" construction techniques to minimize the amount of material required for the insulating vacuum vessel. However, since such techniques are new to large magnets, extensive R & D will be required to insure reliable long term vacuum integrity can be maintained. As a further example, the solenoid we plan will be indirectly cooled rather than cooled by immersion of the conductor in a bath of liquid helium which is generally accepted to be more predictable and have better reliability. There are many other examples. The fact that eight thin solenoids have been built and are in service in detectors around the world gives us confidence that, with carefull design engineering, such opposing criteria can be balanced.

We recognize that there are a few basic parameters in which the thinness-reliability trade-off can be clearly seen and through which both can be quantified. These are given below with comments.

Indirectly Cooled Coil. An indirectly cooled design minimizes the required structure due to the absence of large LHe filled pressure vessels. In an indirectly cooled solenoid of the type we are considering LHe does not come directly in contact with the superconducting wire. Instead, LHe flows through a cooling tube attached to the external cylinder that is used to resist the radial magnetic forces on the winding. The LHe cools the superconductor via conduction from this support cylinder through the electrical insulation to the conductor itself. The conductor is stabilized against small releases of heat via the use of very high purity Al stabilizer that surrounds the superconductor and is intended to rapidly spread released heat to prevent the occurance of a propagating normal zone that would quench the magnet.

Quench Reliability and Safety. In the event a quench is detected, the magnet must be discharged as rapidly as possible and mechanisms should be provided to insure that the quench rapidly spreads to as much of the winding as possible to avoid damaging high temperature spots. This is another area where optimization is important since reliability and engineering conservatism argues for more aluminum stabilizer, while physics performance of calorimetry depends on minimizing the amount of high purity Al stabilizer. Again in such designs there is a conflict between material and the ability of the magnet to survive quenches without serious damage or loss of performance. It is generally accepted by superconducting magnet designers that if the maximum temperature reached in the coil following a quench does not exceed about 100 K the performance of the coil will be unaffacted by repeated quenching. Furthermore, the recovery of the coil and cryogenic system back to the operating temperature from 100 K can be relatively fast (few hours). We have chosen a maximum adiabatic hot spot temperature, calculated from an energy balance[7], of 100 K to be the design criteria for this magnet. The temperature-dependent resistivity of the aluminum stabilizer is an input to the calculation of the maximum hot spot temperature. This resistivity is typically characterized by the residual resistivity ratio (RRR) which is defined as the ratio of the room temperature resistivity to that at 4.5 K. The average value of the RRR at the design phase for the eight solenoids already built is 1000; the average measured RRR for the completed coils was about 1600, Figure 5. We therefore believe that RRR above 1500 is a reasonable value to expect for the finished coil but we plan to use RRR=1200 for design purposes. Having chosen the maximum hot spot temperature and the aluminum RRR, the operating current is somewhat of a free variable, with thinner coils associated with higher currents. Because superconductor joint heating and current lead refrigeration demand both increase with current, and because of the room-temperature bus requirements, 10 kA seems to be a practical limit to the operating current. The eight earlier solenoids all operate at about 5 kA.

Conductor Strain. The RRR of the high-purity aluminum used as the stabilizer for the superconductor is determined by the strain in the aluminum and degrades (gets smaller) as the strain and the number of strain cycles increases. We believe that the coil-outer support cylinder package should be designed so that the strain in the high-purity aluminum does not exceed 0.005 (0.5%)

Vacuum Vessel Shells. The standard of the Compressed Gas Association for cryogenic tanks[8] requires that vacuum vessels be designed for a minimum collapse pressure differential of 2 atm. We believe that the cylindrical outer vacuum shell may be designed to this criterion. The cylindrical inner shell experiences a collapsing pressure differential only if the insulating vacuum space goes above atmospheric pressure. We believe that this shell may be designed for a collapsing pressure differential of 0.2 atm (3 psid). This means that the relief device on the vacuum space must be adequate to ensure that the pressure in that space cannot rise above 1.1 atm-absolute (1.5 psig) for any credible failure.

## Research and Development Plans

Because both the type-S and type-L solenoid options are significantly larger that the largest "thin" solenoid built to date, by a factor of about two in stored energy, considerable R & D effort will be required to complete the engineering design of the chosen option. Experience with previous indirectly cooled "thin" solenoids has shown that such magnets are not very forgiving of mistakes and careful and extensive engineering as well as careful construction and testing is required to insure a reliable final product. A great deal of computational work, beyond what has already been done, will lie behind the final choice of magnet type. The following is meant to be a typical, rather than an exhaustive, list of the R & D work required for the solenoid.

Magnetostatics. Preliminary magnetostatic studies have shown that the spatial uniformity of the axial component of the magnetic field in an type-S solenoid can be significantly improved by dividing the main coil into axial regions of different current density, Figure 6. The uniformity could also be improved by the use of trim coils at each end of the mail solenoid. Subdivision of the main coil results in larger fringe fields and axial forces on the coil, Figure 7. More work needs to be done to optimize the parameters of the trim coils and the main coil subdivisions to decide is a useful and cost effective improvement in a type-S solenoid.

Conductor Studies. Studies which quantify the electrical and mechanical properties of aluminum stabilized conductor are needed. The stress-strain behavior of Cu/Nb-Ti/Al composite conductors is not in general well known, and yet it is important in order to achieve a sufficiently low strain state in the final coil. The electrical resistivity of the conductor from 4.5 to 300 K enters into the quench analysis of the magnet in a significant way, Figure 8. and yet it is known only for a few choices of residual resistivity ratios (RRR). This should be measured for the RRR's of interest for this magnet. The present method of making splice joints between lengths of conductor by edge welding must be verified for the conductor under consideration. This is especially needed if the magnet operating current is chosen to be 10 kA, since low-resistance joints would be more important than they have been in the 5-kA solenoids of the past. Regardless of the magnet type chosen, we feel that developing a conductor that consists of high purity aluminum extruded around a multifiliament superconducting cable (as opposed to a monolithic Cu/SC core) is very desirable to avoid local conductor defects that might lead to quenches. It will be necessary to purchase some lengths of conductor of the nearly final dimensions in order to make these tests and a large LHe dewar with a suitable background field magnet and instrumentation is required.

Quench Behavior. Further quench analysis work is necessary to give confidence that the performance of the magnet will be unaffected by an indeterminate number of quenches. The quench behavior of the magnet coil both before and after quench-back must be computer modelled so that the voltage and temperature is known as a function of time after quench initiation. The ability of the magnet to not only survive, but to be unaffected by the failure of the quench detection and fast dump circuit during a quench must be demonstrated computationally.

Honeycomb Vacuum Vessels. There is interest in considering the use of aluminum honeycomb materials rather that aluminum plate for the outer vacuum shell. Certainly the use of honeycomb material will reduce the total radiation thickness (Figure 9), but this reduction will be accompanied by greater risk. In order to assess this risk before committing to the use of honeycomb, it will be necessary to procure an appropriately scaled model of the outer vacuum shell fabricated of the honeycomb material most likely to be acceptable from a fabrication, vacuum tightness and overall reliability point of view.

Reliability Analysis. A thorough reliability analysis must be made of all components and sub-systems which comprise the solenoid magnet. A "what-if" analysis is one way of doing this, in which the question, "What if this item fails?" is considered. If the answer to the question is that the magnet will be made inoperable by the failure, then the design must include backup, or parallel, or redundant methods

Table 1. Summary of existing solenoids for colliding beam experiments, where B = central field, L = radiation thickness, E = stored energy, M = cold mass and R = E/M.

| Experiment | B(Tesla) | $L(X_0)$ | E(MJ) | M(ton) | R(kJ/kg) |
|---|---|---|---|---|---|
| CDF | 1.5 | 0.84 | 30 | 5.6 | 5.4 |
| TOPAZ | 1.2 | 0.70 | 19.5 | 4.5 | 4.3 |
| VENUS | 0.75 | 0.52 | 12 | 4.3 | 2.8 |
| CLEO-II | 1.5 | ? | 25 | 7.0 | 3.6 |
| ALEPH | 1.5 | 2 | 130 | 25 | 5.5 |
| DELPHI | 1.2 | | 109 | 25 | 4.3 |
| H1 | 1.5 | | 120 | 25 | 4.8 |
| ZEUS | 1.8 | 0.95 | 12.5 | 1.9 | 6.54 |

to eliminate inoperability as a consequence. The goal of this analysis is to essentially guarantee that the solenoid magnet will either be available for collider physics during its 10 or 15 year lifetime or can be made available shortly (two or three months) after any credible incident takes it out of service.

Toroid Studies. The present status of the design of the forward muon toroids is such that considerable thought will be required even before the choice between an iron toroid with water-cooled coils and an air-core superconducting toroid can be made. This suggests that the superconducting version must be studied conceptually to the point that a cost estimate can be prepared and compared to that of an iron toroid.

If it is decided to proceed with the superconducting version, the same sort of R & D as mentioned above for the solenoid will be required. The need for "thinness" will probably be less for the toroid than for the solenoid, so studies of aluminum stabilized conductors and honeycomb vacuum shells might not be required. On the other hand, the engineering required to reach the design report stage is much greater for the toroid than for the solenoid. This is simply due to the fact that eight thin solenoids have been designed and built in the last 7 or 8 years, whereas toroids of the style desired for an SSC detector do not exist. It is worth noting however that the superconducting toroids planned for the one CEBAF spectrometer are similiar to those under consideration for this detector[9]. These toroids, are currently in the preliminary design stage. Figure 10 shows an 8 coil toroid geometry which is being investigated.

Table 2. Comparison of Magnet Types.

| | Type-L | Type-S |
|---|---|---|
| B in tracking region | uniform | non-uniform |
| Fringe field | neglible | large |
| Calorimetry Hermeticity | worse? | better? |
| Axial force on coil | small | large |
| Decentering forces | larger | small |
| Test without Yoke ? | partial | full |

Table 3. Coil Parameters

| | Type-S | Type-L |
|---|---|---|
| Inner radius of cryostat (mm) | 1700 | 2250 |
| Outer radius of cryostat (mm) | 1990 | 2650 |
| Total length of cryostat (mm) | 8000 | 15000 |
| Radius of coil at 4.5 K (mm) | 1800 | |
| Weight of the coil and cryostat (tonnes) | 20 | 74 |
| Weight of the coil mass (tonnes) | 16 | 24 |
| Central Field B@Z=0 (T) | 2.0 | 1.7 |
| NI ( MAt) | 13.4 | 20.3 |
| Nominal operating current (A) | 10,000 | 8000 |
| Stored energy $E_o$ (MJ) | 120 | 300 |
| Stored energy/effective cold mass (kJ/kg ) | 7.5 | 12.5 |
| Winding scheme | single layer | single layer |
| Self inductance (H) | 2.4 | 9.4 |
| Superconductor | NbTi/Cu (0.55/0.45) | NbTi/Cu (0.5/0.5) |
| Stabilizer | Al(RRR=750) | Al(RRR>1100) |
| Conductor cross section ($mm^2$) | 5.6 x 46 | 5.7 x 26 |
| Current density in NbTi ($A/mm^2$) | 2300 | 1056 |
| Current density in NbTi/Cu matrix ($A/mm^2$) | 1250 | 528 |
| Overall current density $J_o$ ($A/mm^2$ ) | 45.0 | 51.6 |
| $E_oJ_o^2$ ($J - A^2/m^4$) | $2.4 \times 10^{23}$ | $8.0 \times 10^{23}$ |
| Load line ratio ($I_{op}/I_c$) at 5 K | 80% | 63% |
| Thickness of support cylinder (mm) | 28 | 14 |
| Axial compressive force (tonf) | 1850 | 150 |
| Axial de-centering force ( tonf/cm) | 1.6 | 37.0 |
| Est.total radiation thickness ($X_0$) | 1.12 | 1.18 |
| Total interaction length ($\lambda_0$) | 0.25 | 0.26 |
| Thermal load at 4.5 K | 55 W + 33 L/hr | |

# References


[1] R. Fast et al., Conceptual design report for a Superconducting coil suitable for use in the Large Solenoid Detector at the SSC, SSC Report SSC-N-663 (1989).

[2] S. Mori et al., Conceptual Design Studies of Large Solenoids, Institute of Applied Physics University of Tsukuba, Feb 1990.

[3] Tests of the resolution effects of material in front of the electromagnetic calorimeter performed in the CDF test beam show small effects for up to 3.5 $X_0$ for 20 GeV/c electrons incident. (better ref ?)

[4] E. Wang, Talk presented at the Calorimeter Workshop at Tuscaloosa, March 1989.

[5] S. Mori et al., HCD Hermetic Collider Detector, Institute of Applied Physics University of Tsukuba, Feb 1990.

[6] T. Kondo, An Air-Core Solenoidal Detector (ACS) for high $P_t$ Physics at the SSC, Talk presented at the Fermilab Workshop on Solenoidal Detectors for the SSC, Batavia, September 1989.

[7] M.N. Wilson, "Superconducting Magnets," Clarendon Press (1983), p. 219.

[8] "Standard for Insulated Cargo Tank Specification for Cryogenic Liquids," CGA-381, Compressed Gas Assn., Arlington, VA (1987).

[9] J. O'Meara et al., IEEE Trans. Magnetics 25 (1989) 1902.

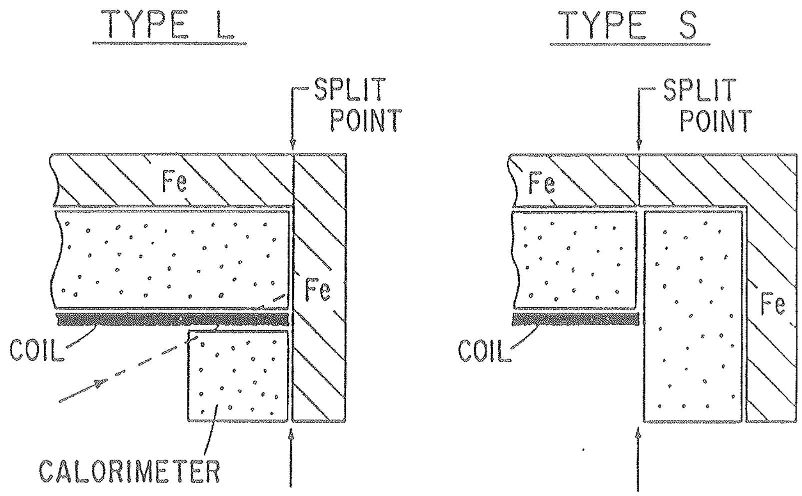


Fig. 1 Coil-iron geometries for type-L and type-S detector solenoids.

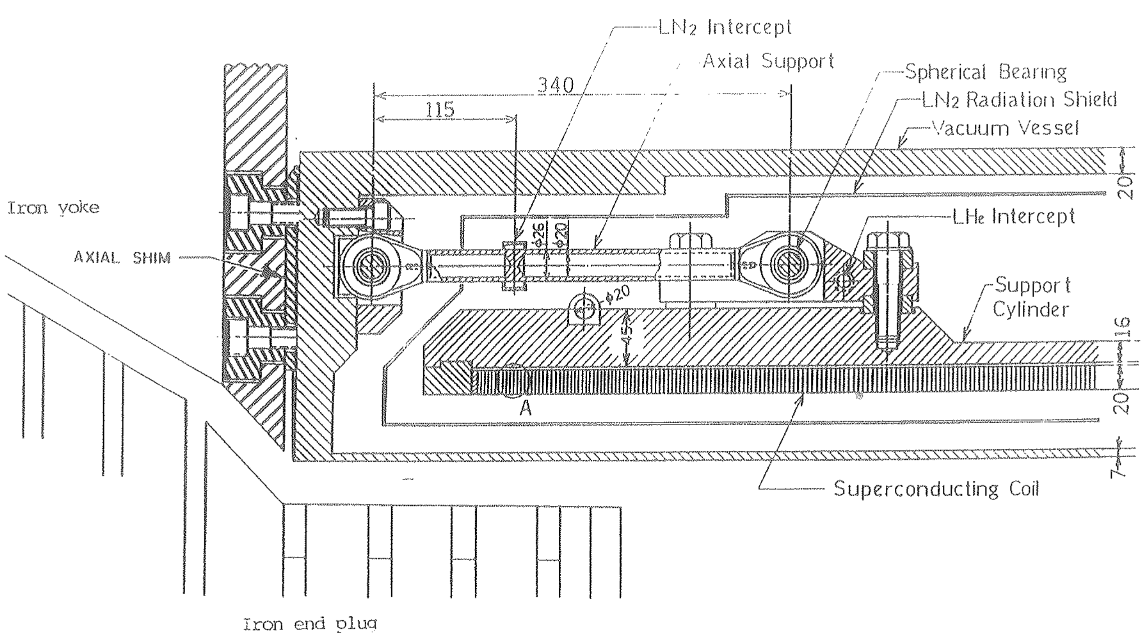


Fig. 2 Example of type-L solenoid: CDF.

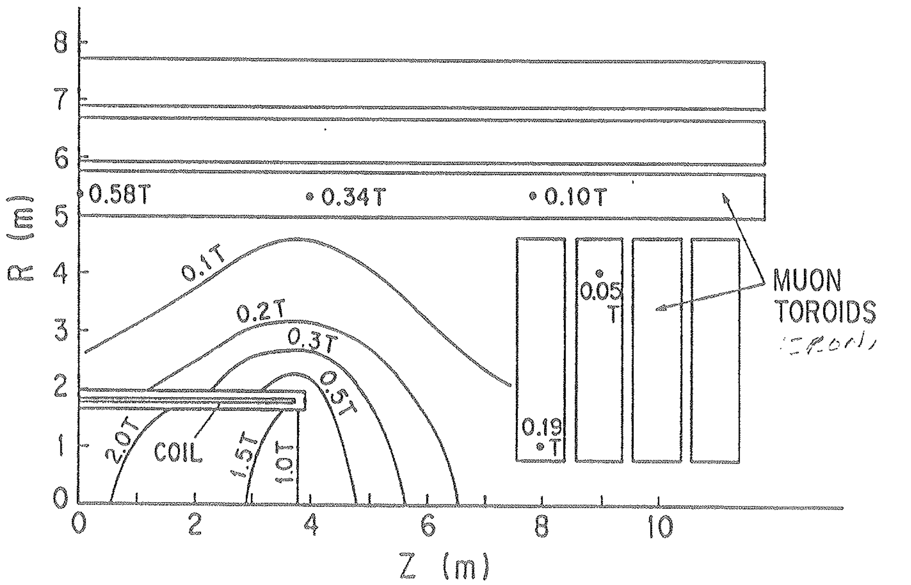


Fig. 3 Type-S solenoid.

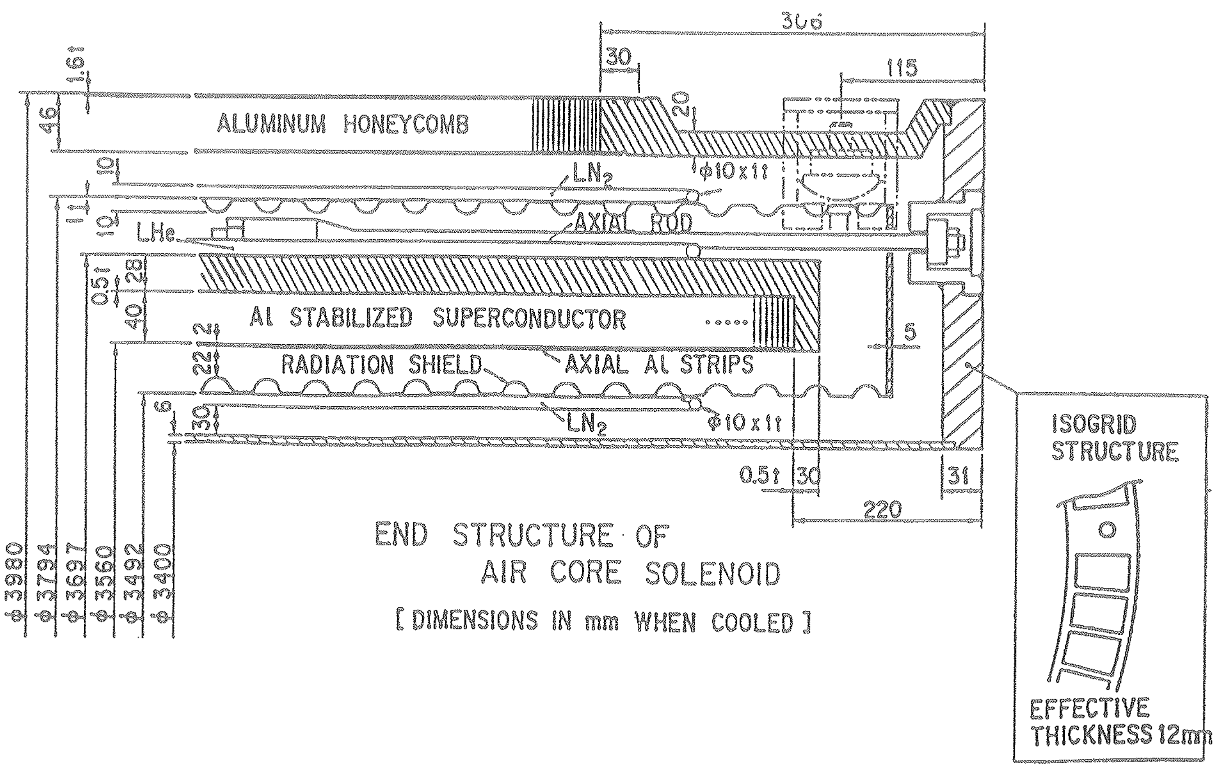


Fig. 4 Cross section of type-S solenoid.

| Magnet | Design | Measured |
|---|---|---|
| CDF | 1000 | 1885 |
| Topaz-KEK | 2500 | 2500 |
| Venus-KEK | 1000 | 1800 |
| Aleph-LEP | 1000 | 2000 |
| Delphi-LEP | 500 | 1160 |
| Cleo II-Cornell | 500 | 1000 |
| Zeus-HERA | 1500 | 1400 |
| H1-HERA | 500 | 1160 |
| Average | 1000 | 1613 |

SSC Detector Solenoid: Design value 1200, Expected value 1500

Fig. 5 RRR of aluminum-stabilized conductors used on large solenoids.

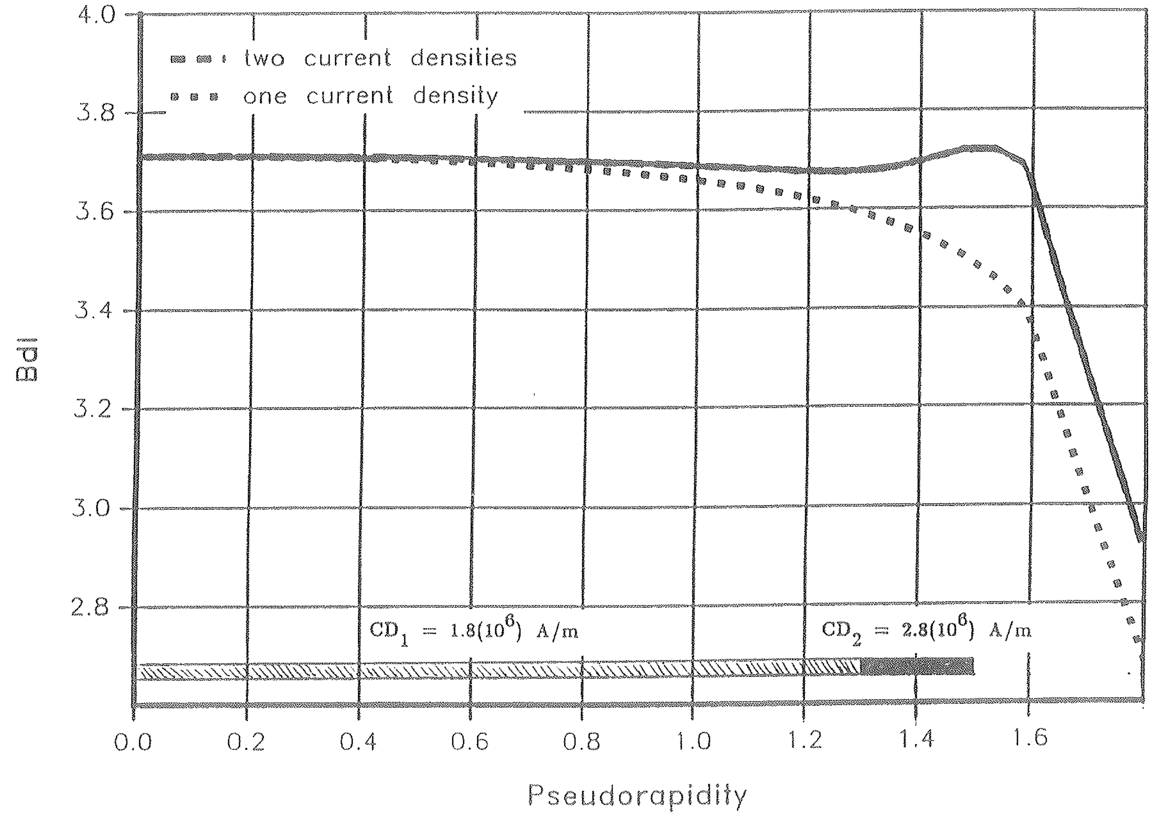


Fig. 6 Improvement in field uniformity by subdividing coil into regions of different current density.

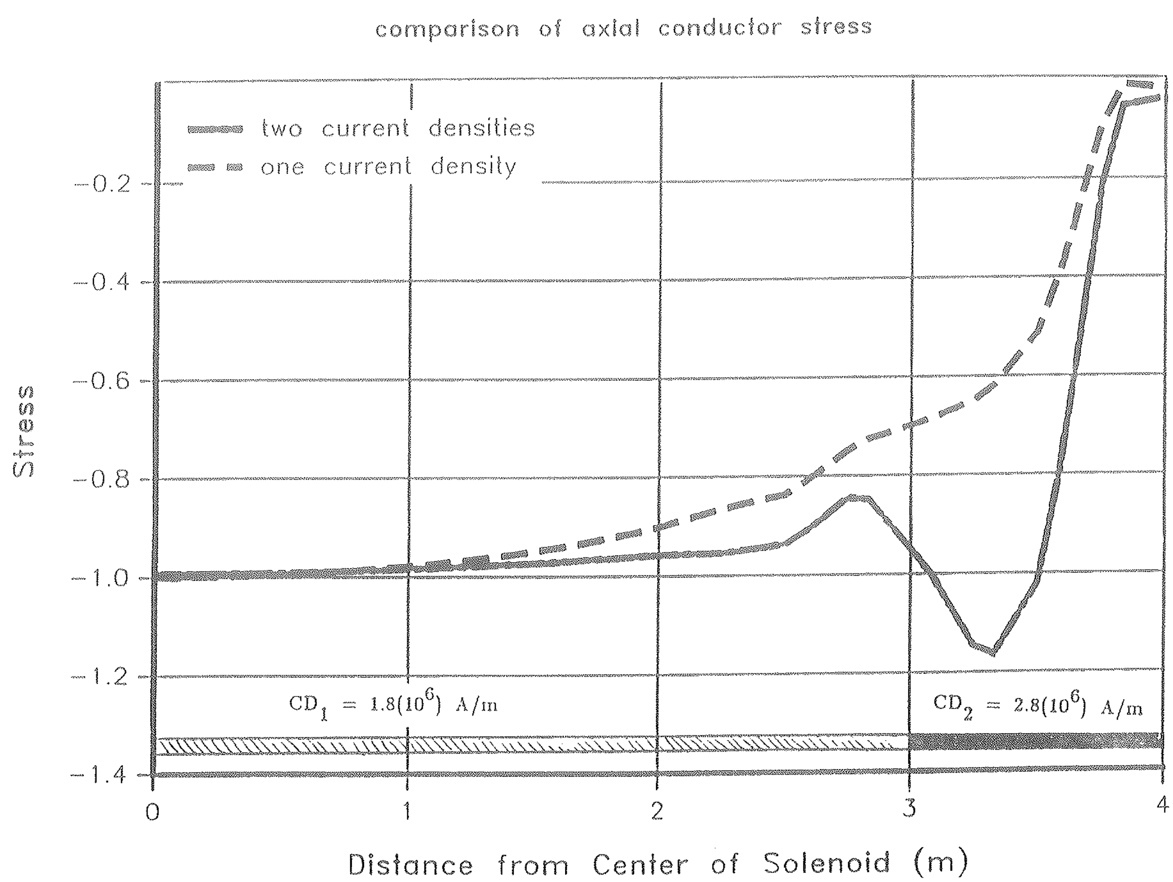


Fig. 7 Comparison of axial stress in coil for uniform and subdivided current density.

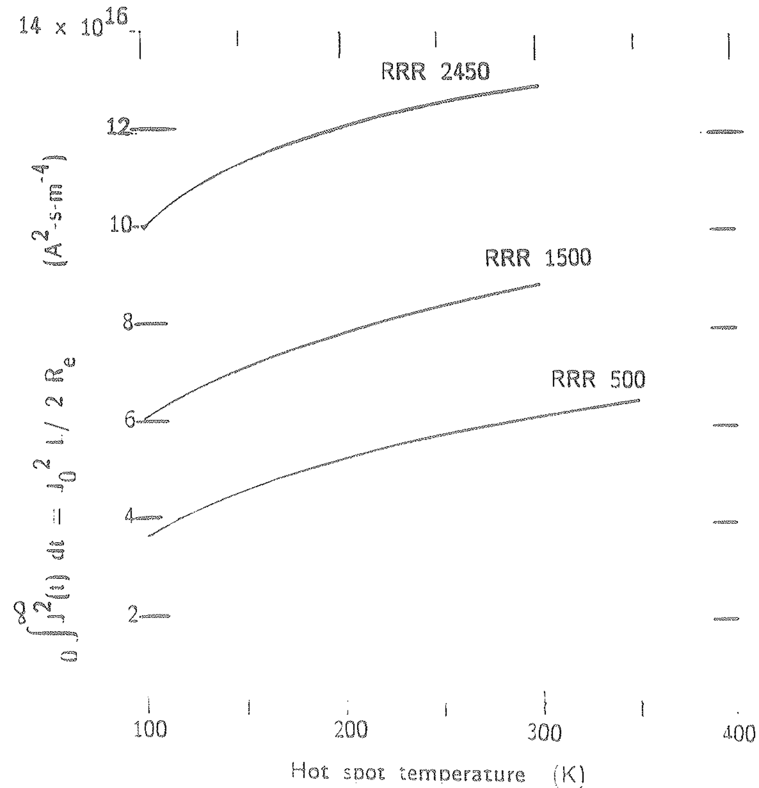


Fig. 8 Hot spot temperature as a function of conductor RRR.

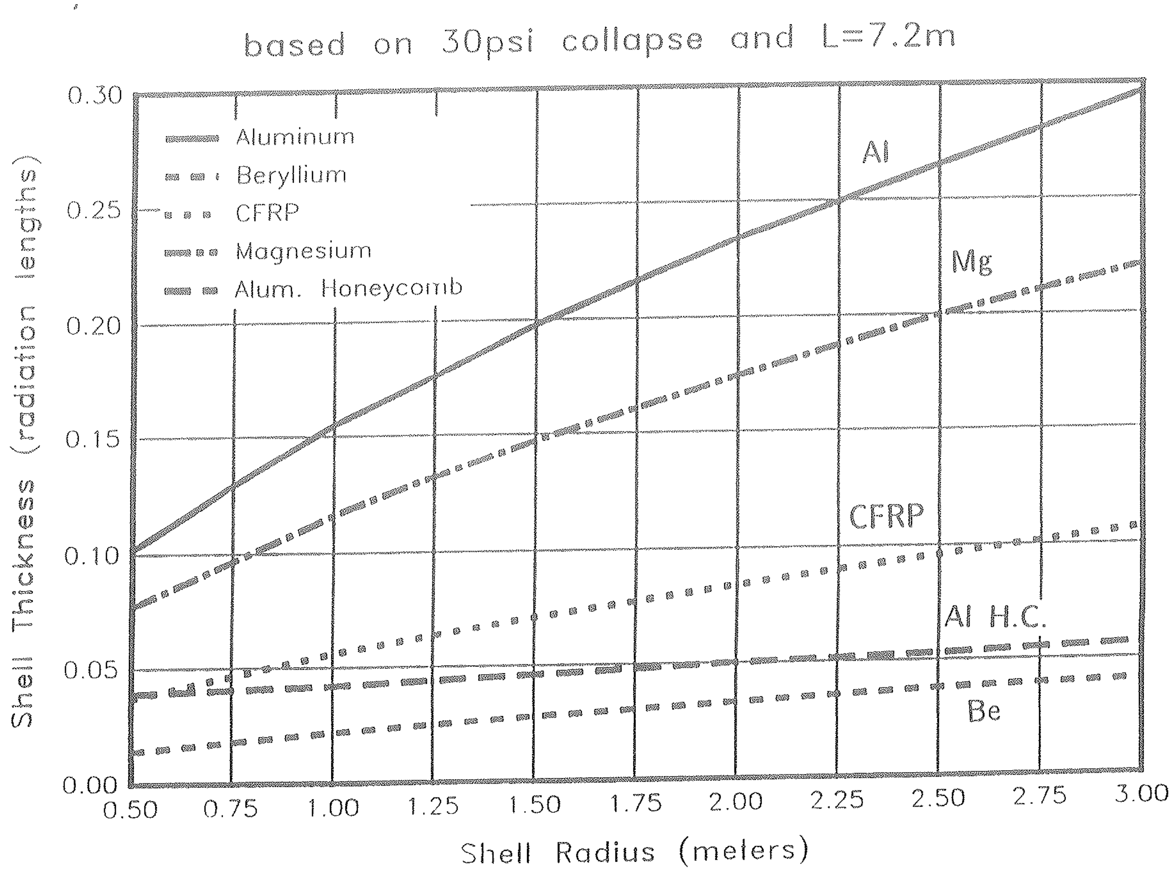


Fig. 9 Outer vacuum shell thickness as a function of radius for different materials.

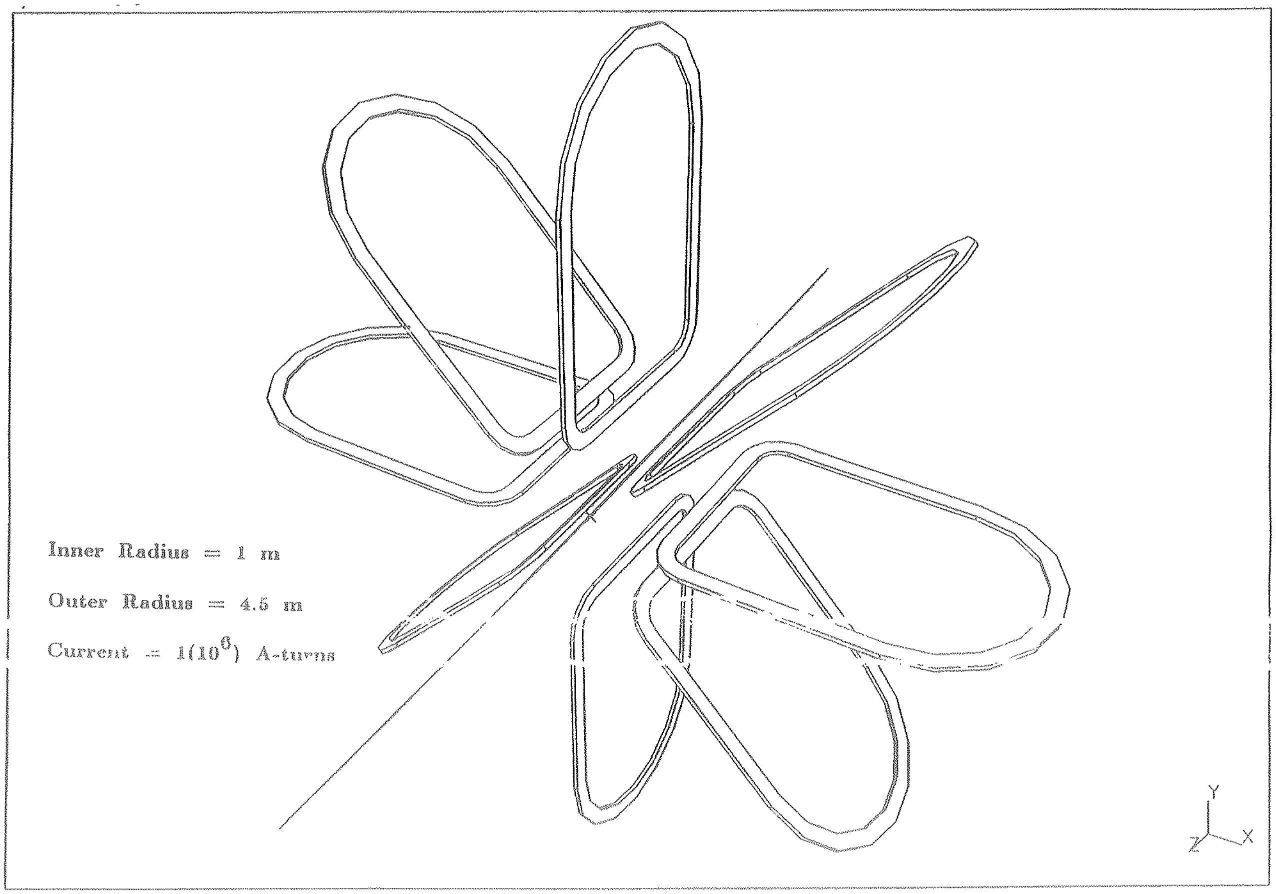


Fig. 10 Eight-coil "bumpy" toroid