SiD SUPERCONDUCTING MAGNET DESIGN AND SUPERCONDUCTING CABLE DEVELOPMENT FOR SiD and BEYOND

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EXECUTIVE SUMMARY

Continued development of the SiD superconducting magnet along with its superconducting cable is essential because it is a very costly item, and it is the highest risk item associated with the detector. The advanced superconducting cable development is deemed to be the higher priority task as it has the greatest chance of significantly reducing cost, risk and construction time. Conductor choice is the driver for all other magnet design decisions and needs to be done first. Three advanced conductor designs are proposed. A successful advanced conductor could be used for all other high field, large bore solenoids (e.g. 7 T to 9 T MRI magnet now in use and being considered) to minimize cost and risk.

Development of the conductor and SiD magnet design issues on a reasonable time line would require Wes Craddock 60%, John Hodgson 15%, and Marco Oriunno 15% of their time for approximately 2 years. It is anticipated that Bob Wands of Fermilab would continue his magnet field analysis. Material cost is expected to be quite small in the first year and modest in the second year with the manufacture and testing of small samples. University materials science partners would be sought during the first year. Commercial coextruders or superconducting cable manufacturers would be sought at the end of the first year for possible SBIR development. At the end of this time a conductor will be selected for development with extruders and superconducting wire manufacturers if no SBIR partner is found. A new SiD magnet design incorporating the advanced conductor will be written.

INTRODUCTION

The current baseline design for the SiD superconducting solenoid is to use the identical superconducting cable in CMS and to use many of the CMS solenoid design and construction techniques. SiD like CMS, BaBar and most other very large solenoids employ an indirectly cooled high purity aluminum stabilized superconductor wound inside a support cylinder. In principal this would result in a buildable and working magnet, but the difficulties and costs would be high. In particular the conductor winding would be an enormous undertaking. The CMS magnet including the iron yoke is a 100 M $US item. Although smaller, the SiD magnet will cost in the same range. It behooves us to spend some design and research time early on to try to reduce costs and construction time. We have CMS experience and other additional conductor R&D since CMS to guide us. A brief comparison of SiD and CMS relevant to these particular topics is listed below.

ITEM	SiD	CMS
Stored Energy	1.4 GJ	2.6 GJ
Stored Energy per Unit Cold Mass	10.8 kJ/kg	11.6 kJ/kg
Central Field	5.0	4.0
Peak Field on Conductor	5.8	4.6
Number of Layers	6	4
Warm Bore Inner Radius	2.5 m	3.0 m
Conductor Inner Radius	2.645 m	3.16 m
Magnetic Length	5.6	12.5 m
Current (amps)	18000	19100

12 kJ/kg is close to the upper bound that this type of large aluminum dominated magnet can be operated in a fail safe manner if the quench detection or energy extraction circuit were to fail. This specific energy density yields an average magnet temperature of 130 K. For CMS only half the energy is extracted during a fast discharge with a temperature rise to 80 K. Thus for the SiD solenoid with nearly the same energy density, the total volume of aluminum stabilizer/structure can not be reduced by much from the present baseline design. The problem with the CMS conductor is that it is very stiff in bending and is difficult to wind. The smaller inner radius of SiD will only make matters worse. Although the final outcome was a fabulous CMS conductor, it still would take great effort to recreate this process at a much latter date. CMS winding took 2 years of pre industrialization activity and 1 ½ years of setup before winding started.

A picture of the CMS conductor is shown below. Notice the electron beam weld joints. The high strength 6082 aluminum was welded in the T51 underaged, softer state and then aged to T6 during the impregnation cure.

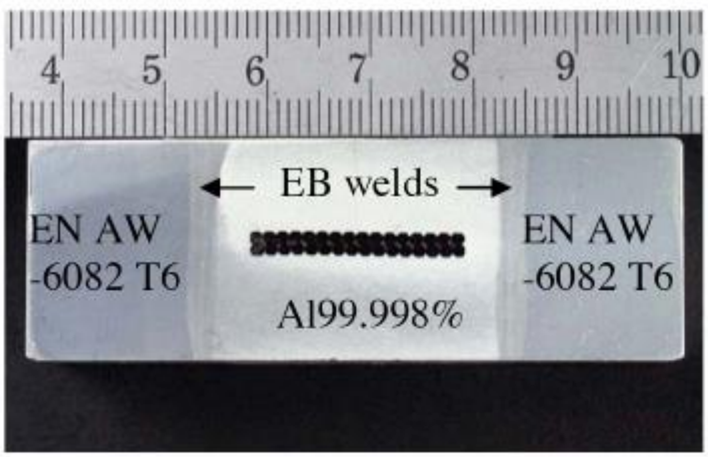

Fig. 3. Cross-section of the CMS conductor. The material grades used for the present conductor are shown in the picture. The EB weld seams join the insert and the reinforcement sections. The Rutherford cable is co-extruded with the insert. The insert (conductor) cross section is 30 mm x 21.6 mm (64 mm x 21.6 mm). The cross section of the NbTi-Cu stabilized Rutherford cable is 20.68 mm x 2.34 mm. 21 lengths of 2.6 km of conductor have been produced for CMS.

ROAD MAP FOR SiD SOLENOID DEVELOPMENT

Much of the solenoid design work stopped in 2006 with the death of Rich Smith at Fermilab. Since then Bob Wands at Fermilab has completed additional magnetic field analysis with different iron configurations to reduce fringe fields. Continuation of SiD solenoid development will require resumption of standard superconducting magnet engineering analysis and examining advanced concepts. Standard superconducting magnet analysis involves the following tasks:

1) Finite element magnet field, force and stress analysis
2) Conductor stability
3) Quench propagation and energy extraction
4) Conductor thermal cooling
5) Magnet current and conductor optimization
6) Mechanical design of supports, current leads, radiation shields, cooling tubes, liquefier interfaces, etc
7) Power supply, dump breaker, dump resistor, instrumentation and other electrical issues

The basic goals in reducing complexity and cost are the following:

1) Optimize the conductor with respect to operating current and each layer
2) Try to reduce the number of layers from six to five or less.
3) Find an easier to manufacture and wind conductor

These three goals have the chance of significantly reducing cost and construction time. All of the other standard superconducting magnet tasks are needed to assure success, but they will have minimal bottom line impact on cost.

GOAL 1:

For any given superconducting wire, aluminum stabilizer material and conductor reinforcement, the conductor can be optimized with respect to operating current and the amount of superconducting wire in each layer. For example, a larger superconducting cable in the first layer with the highest field would enable an overall higher current which then could be used to reduce the number of layers. There is some concern that the large number of layers will significantly complicate winding and reduce the radial stiffness of the coil package to an unacceptable level. The radial magnetic pressure of the SiD solenoid is 50% greater than CMS. Although this goal falls under standard superconducting magnet design, it has the potential for cost reduction.

GOAL 2:

Layer reduction might be achieved by conductor optimization. If layer reduction can be achieved by optimization, there is only so far one can go without sacrificing fail safe magnet protection. It was stated above the ~ 12 kJ/kg of cold mass is the prudent limit for a magnet of this type. Assuming that conductor stability would permit this option, the outer supporting/winding cylinder might be made much more electrically conductive, enhancing the so called quench back mechanism. This might be achieved by imbedding ultra high purity aluminum cable in the winding mandrel. Then in the event of a quench or fast discharge, a larger fraction of the energy would be inductively coupled into the cylinder reducing conductor hot spot temperature and local thermal stresses.

GOAL 3:

Advanced conductor design holds the promise of the greatest cost reduction. The first part of this goal would be to reduce conductor bending stiffness to simplify winding. The second part would be to eliminate the welded structural reinforcing alloy and also reduce bending stiffness. Significant R&D work on advanced conductors has been done since the start of CMS. It centers on replacing the ultra high purity aluminum with Al-0.1%Ni and replacing the 6082 aluminum structural alloy with higher strength aluminum 7020.

The Al-0.1%Ni alloy was developed for ATLAS. Nickel has very low solubility in aluminum. The supersaturated nickel atoms precipitate and form intermetallic compounds during heat treatment. The small number of remaining nickel atoms has relatively small impact on the aluminum resistivity. This alloy has a 4.2 K yield strength of 85 MPa (12.3 ksi) after a 15 hour 130 C coil epoxy curing cycle. For a 20% cold drawn alloy the 4.2 yield strength is 110 MPa (16.0) ksi and the residual resistivity ratio (RRR) is an excellent 590. CMS stability requires RRR > 800 but requires aluminum billets to have a RRR > 1500. Much of this RRR is lost during thermal cycling. One additional big advantage to Al-0.1%Ni stabilizer is that it would remain well within its elastic limit and would loose no RRR during cycling. Other alloys have been tested up to Al-2.0%Ni with very good results. Cerium and antimony are also candidates to replace the Ni.

Two other reinforcement techniques might also be employed, either separately or in combination. The first is replacing the nickel intermetallic precipitates with more traditional metal matrix fillers such as Al_2O_3, carbon fibers, SiC whiskers, and newly developed nanoparticles. No information on ultra high purity aluminum with metal matrix fillers has been found so far. It seems reasonable that if 0.1% nickel can have such a significant impact on strength with fairly limited impact on RRR, these other fillers might be as good or better. If a large enough percent of these materials could be added without reducing the RRR to far, a single aluminum alloy with reduced stiffness could be developed.

The next technique to eliminate the aluminum reinforcing is to coextrude extra reinforcing right into the aluminum stabilizer along with the superconducting cable. This reinforcement could be stainless steel, beryllium copper alloys, nickel alloys or other materials. It most likely would be in the form of a round ropes or flat cables above and below but close to the superconducting cable in order to minimize bending stiffness. If it is found that the reinforcing starts to push through the soft high purity aluminum, the Al-0.1%Ni alloy or aluminum matrix concept might be used in combination. It should be noted that the superconducting cable with electromagnetic forces appears to stay in place. Once the basic material properties are found or measured, finite element plastic analysis can be used before mechanical testing.

ROAD MAP FOR CONDUCTOR DEVELOPMENT

1a) Research the Al-Ni alloys and contact the individuals who developed these materials. Investigate the higher nickel percent aluminum alloys.

1b) Research the properties and possibility of using more typical aluminum matrix reinforcing materials.

2) Design and perform ANSYS analysis on the internal rope/cable reinforcement concepts

3) Obtain information from extruders and metal matrix specialists about the possibility of producing these different conductors.

4) Make or obtain small samples of these materials. Mechanically test them at least at room temperature and measure the RRR ratio.

5) Try to establish university material science and metallurgy partnerships.

6) Look for commercial partners for SBIR development

7) Make or obtain small samples of these materials. Mechanically test them at least at room temperature and measure the RRR ratio.

8) Incorporate the best conductor concept into a new SiD magnet design

9) Pursue actual conductor development and production with commercial partners. Patent?

ADVANTAGES OF AN ADVANCED CONDUCTOR

SiD and other large diameter high field solenoids need substantial mechanical reinforcement to withstand the radial burst pressure. Historically this was always done with an outer reinforcing cylinder or internal banding. However, with the very large diameter and very high field superconducting magnets now in use and being developed, self supporting windings seem the only prudent way to go. High field solenoids are being developed for MRI and other applications. A standard single aluminum alloy stabilizer/structure with or without extra internal reinforcement would be a huge advantage to the high energy physics community as well as the superconducting magnet industry. One could then specify a conductor and procure a high strength, high RRR aluminum stabilized conductor with not much more effort than the standard high RRR aluminum stabilized conductor provided by industry today.