Magnets for the Very Large Hadron Collider

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Initial work toward a proton-proton collider with energy much higher than the LHC at CERN is now underway. Study groups are looking at magnets, accelerator physics, and other accelerator systems for a vlhc (very large hadron collider). Magnet R&D, underway at several locations, is summarized.

I. INTRODUCTION

Early in 1998, a steering committee was set up in the U.S. to look at a proton-proton collider with center of mass energy significantly above that of the LHC. The steering committee was set up in response to one of the recommendations of the 1997-1998 HEPAP Subpanel report on the future of U.S. High Energy Physics. The steering committee chose a temporary name for the machine, very large hadron collider (vlhc), a nominal set of machine parameters (from Snowmass '96) and appointed working groups on accelerator physics, magnets technologies, and accelerator systems. Each working group was asked to hold at least one workshop per year and to make an annual report to the steering committee. This note summarizes the first workshop on magnet technologies, held in Port Jefferson, NY, last November. The available talks can be accessed via the BNL magnet group Web site (http://magnets.rhic.bnl.gov) or via the vlhc Web site (http://vlhc.org). The vlhc Web site also has links to the proceedings of the other two workshops, which were held in February, and information about the annual vlhc meeting (June 28-30 in Monterey, California).

The working group on magnet technologies was asked to focus on innovative concepts that would result in significant cost reductions. Activities are to be coordinated with other working groups and include encouraging progress in superconducting materials. Work on new types of magnets, some with new types of superconductors, is underway at BNL, Cornell, Fermilab, LBNL, and Texas A and M. This work was discussed in detail at the workshop. Overview talks on the Snowmass '96 parameters, accelerator physics, and superconductors provided a framework for the magnet activity.

The pp colliders studied at the DPF Snowmass '96 workshop had center of mass energy 100 Gev and luminosity $10^{34} cm^{-2} sec^{-1}$. Three colliders, characterized by differing magnetic fields, were studied. One collider was based on a dipole magnetic field of 12.5 T. Such a machine would have a circumference of 100 km and a synchrotron radiation damping time for the beam emittance of 1.3 hours. Since the familiar NbTi superconductor has a critical field of 10 T, magnets for such a machine would require a new type of superconductor, such as Nb_3Sn or high temperature superconductor (HTS). The second collider was based on the use of NbTi to achieve a dipole field approaching 10 T. None of the work reported at the magnet workshop was based on this type of magnet. The third collider was based on a low field ($\sim 2T$), iron-dominated magnet. Such a machine would have nominal circumference $\sim$ 550 km and no synchrotron damping.

II. SUPERCONDUCTORS

Superconductor characteristics place fundamental limits on magnet design, so it is useful to summarize them. Important parameters of the familiar NbTi are the current-carrying capacity in the superconductor (J_c), the diameter of the superconducting filaments, the critical field (H_c), and the critical temperature (T_c). Additional parameters are needed to describe the new materials. Nb_3Sn and HTS are brittle. For HTS materials, the engineering current density (J_e) must be considered because a significant fraction of the conductor cross section is non-superconducting structural support. Also, HTS conductors retain some residual resistance even at low temperatures.

NbTi is suitable for a low field vlhc magnet. Nb_3Sn can be used at high fields, since it has $H_c \sim 18T$, but it has lower J_c than NbTi and costs much more. Nb_3Sn has not had the benefit of nearly as much development as NbTi. With interest in it for use in vlhc magnets, R&D has resumed on a modest scale and improvements are expected. Magnet designers must choose between "wind and react" (which requires ovens large enough to accommodate the magnet coils) and "react and wind" (which requires that the cable bend radius be larger than $\sim$ 2.5 cm).

The most common type of HTS material is BSCCO (oxides containing Bi, Sr, Ca, Cu), which can be a cable or tape. At present, BSCCO's J_e is too low, and its cost too high, to make it a candidate for large-scale use in magnets. However, J_e has been increasing linearly with time for the last eight years. Further, R&D funds from DOE and the electric utilities are being spent to improve both cost and performance, so it may yet be an asset for a vlhc. Because of the stringent requirements on reaction conditions, the initial BSCCO coils have been "react and wind." YBCO is another possible HTS material. It has a high J_c, but needs higher J_e, longer piece length, and reduced cost. The non-vanishing resistance of all HTS materials will make the persistent current and quench propagation behaviors of these conductors different than those of the low temperature superconductors.

III. MAGNET R&D

Six groups in the U.S. are actively engaged in magnet R&D for a vlhc. Groups at Brookhaven and Berkeley are using a new type of coil configuration called "common coil." Two groups are Fermilab are working on magnets, one on a high field, cosine theta design, the other on a low field, iron-dominated transmission line type of magnet. A group at Texas A&M is working on a high field magnet whose conductor blocks are individually supported.

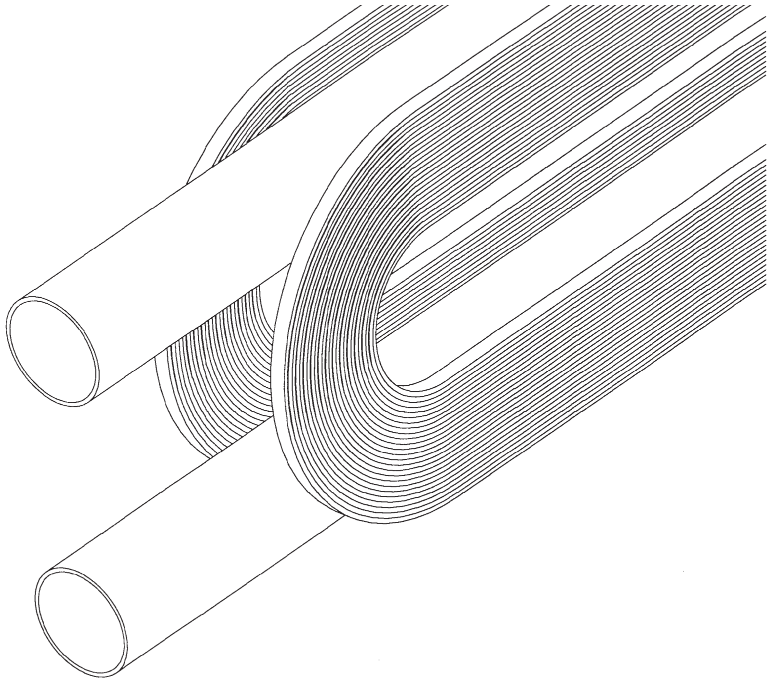

FIG. 1. Arrangement of two racetrack coils to produce dipole fields in two apertures.

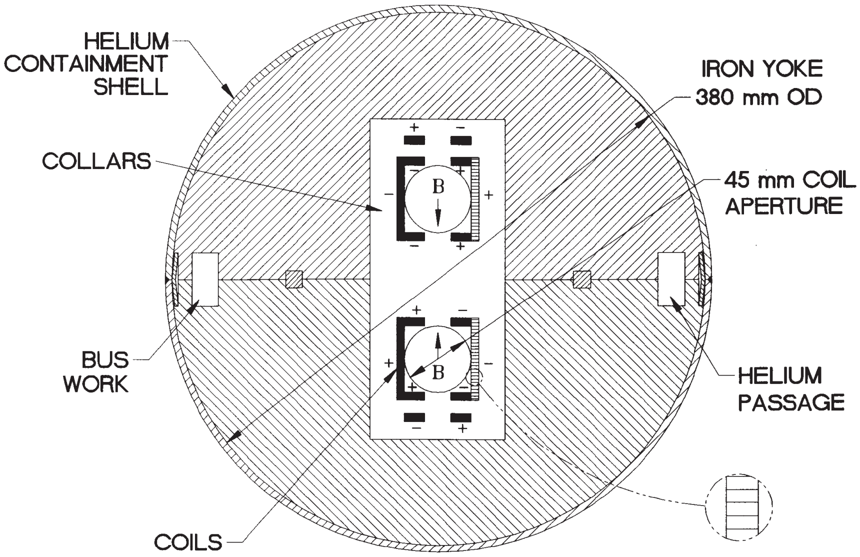

FIG. 2. Cross section of common coil magnet including racetrack coils, yoke, and correction coils.

Common coil magnets are designed for a two-aperture collider [1]. The design uses two "racetrack" coils arranged so that each coil contributes to the field in both apertures (Fig. 1). For brittle materials, there is a two-fold advantage to the use of this design. First, the conductor does not have to bend in three dimensions as it does in a saddle coil. Second, the spacing between the two apertures, not the aperture diameter, sets the minimum bend radius of the conductor. The current in one coil is opposite the current in the other coil so that the magnetic fields in the aperture add together. The magnet can reach 12.5 T with a compact iron structure (400 mm o.d.). A cross section of the magnet with trim coils is shown in Fig. 2.

The Brookhaven group has built a common coil R&D yoke about 1 m long. NbTi cable from the SSC program was resized at Berkeley so that it could be wound in a racetrack coil configuration. Assembled in the R&D yoke, two of these coils produce a 6 T background field for tests of HTS and Nb_3Sn coils, which produce an additional 1 T. (Nb_3Sn is of interest because it has the same dependence of critical current on strain as HTS.) Thus far, the NbTi and Nb_3Sn coils have been run successfully [2]. Work is underway to improve the assembly and quench performance before construction of the 1 m HTS coils. In parallel, small HTS coils have been made and tested as single windings. A racetrack coil and a quadrupole saddle coil have worked well. The quadrupole coil was a joint purchase with Cornell and Fermilab and made in industry [3].

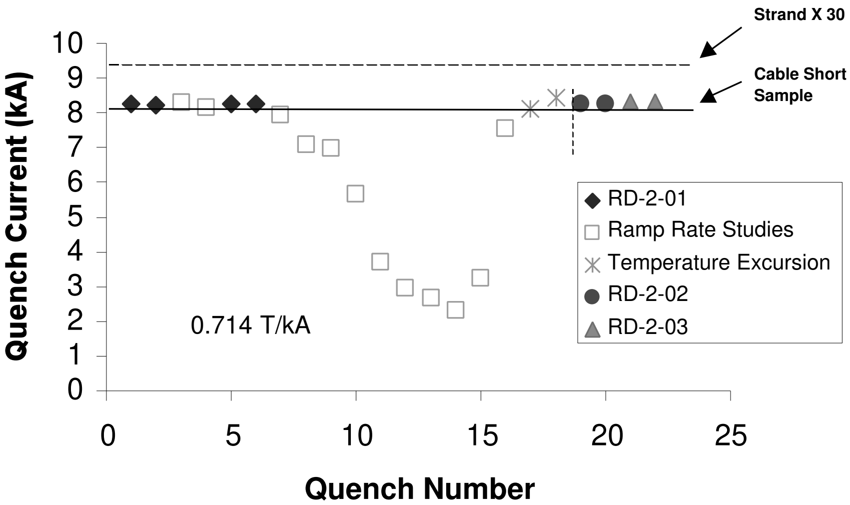

FIG. 3. Quench performance of 1 m LBL common coil magnet.

The Berkeley group has had quite good success with its first common coil magnet, which was made using Nb_3Sn cable left over from the ITER program [4]. The coils, which were made using a wind and react method, are about 1 m long. The magnet reached a central field of 6 T, the limit of the current-carrying capacity of the superconductor, without training (Fig. 3). The initial assembly of the magnet was with high vertical and horizontal preload, to limit conductor motion under Lorentz forces to a small value. After its initial test, the magnet was reassembled three times, with reduced vertical and horizontal preload, and with a weakened interior support piece. In spite of the reduced preload, the magnet continued its excellent quench performance.

An extension of the common coil design to four apertures is now being examined [5]. The yoke shown in Fig. 2 is extended vertically at the top and bottom to include apertures above and below the two main apertures. The field in these apertures would be limited to 2 T. As such, it would be produced primarily by the iron ("iron dominated") and require little extra superconductor. With the appropriate ramping, the beam could, in principal, be transferred from a low-field aperture to a high-field ("conductor dominated") aperture. This would extend the dynamic range of the magnet and avoid time-dependent field effects due to magnetization currents in the superconductor.

Low-field magnet R&D has been underway at Fermilab for three years. The magnet uses one turn of superconductor, carrying 75 kA, to generate current in two apertures of a warm iron yoke (Fig. 4). The vacuum chamber is at room temperature. It is made from an extrusion that may require a large volume outside the magnet aperture to provide sufficient pumping. The current return and helium transport are in a separate cryostat under the magnet (Fig. 5). There is R&D on components of the design and a 2 m section of iron has been powered. The group is presently setting up a loop for testing 4 m sections of cable and a 50 m test section of magnet [6].

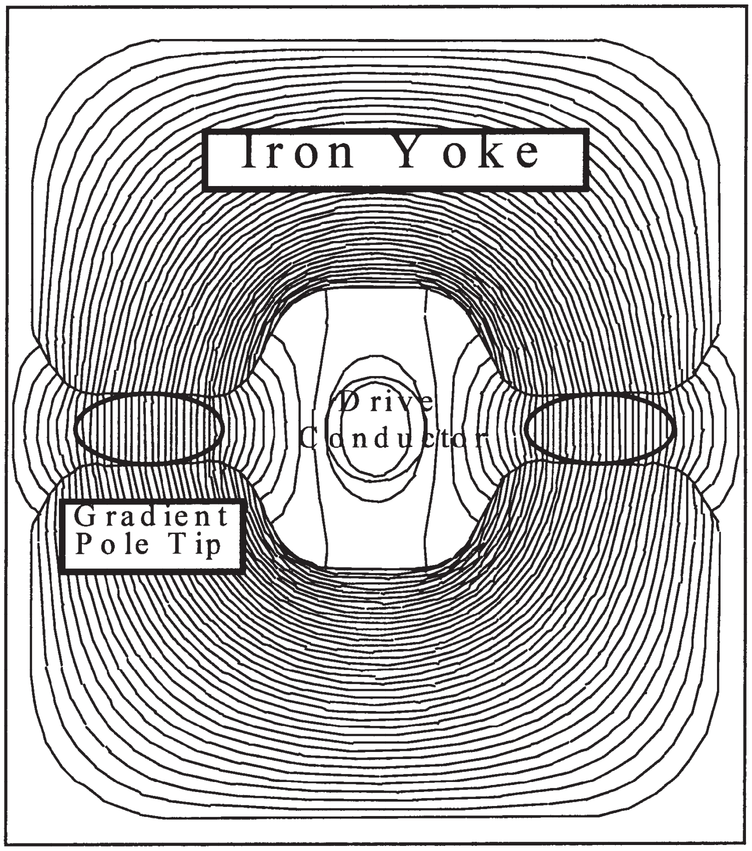

FIG. 4. Yoke and conductor for transmission line magnet, showing lines of flux.

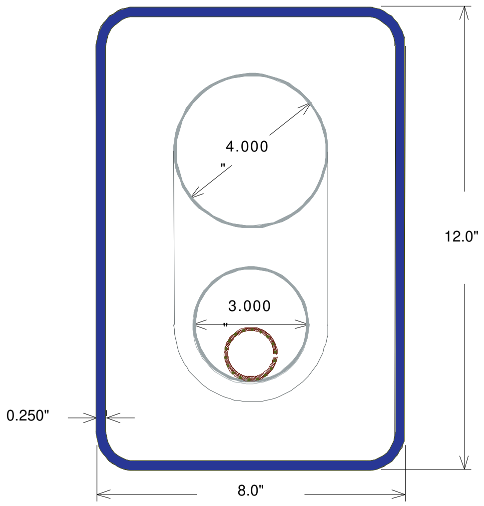

FIG. 5. Cross-sections of the helium supply and return and current return for the transmission line magnet.

High-field magnet R&D at Fermilab increased significantly last year. Plans are centered on a two layer cosine theta cold iron dipole made with Nb_3Sn cable [7]. The nominal superconductor specification would produce a central field of 11.8 T in a 50 mm bore (Fig. 6). Substantial capacity for reacting and testing Nb_3Sn has been installed at Fermilab and much computational and lab work is underway. The group plans a 1m magnet for the fall of 2000.

The magnet group at Texas A&M has designed a 16 T dual bore magnet in which the individual blocks of Nb_3Sn superconductor are supported against the Lorentz forces (Fig. 7). (In contrast, the azimuthal forces in cosine theta magnets accumulate from the pole to the midplane.) A frame of Inconel steel (Fig. 8) surrounds each conductor block. For ease of assembly, the Inconel frame is slightly larger than the conductor block. A special spring fills the remaining space in the frame. The Inconel structure transmits the force that accumulates on a group of blocks to a supporting structure outside the coil. Currently, the group has R&D projects underway to develop the individual components, such as the special spring, for the magnet. Also, a mechanical model using NbTi cable has been assembled [8]. Testing of R&D magnets will be simplified because the coil blocks needed for one bore in a dual bore magnet can be used to make a single bore magnet, saving time and materials costs.

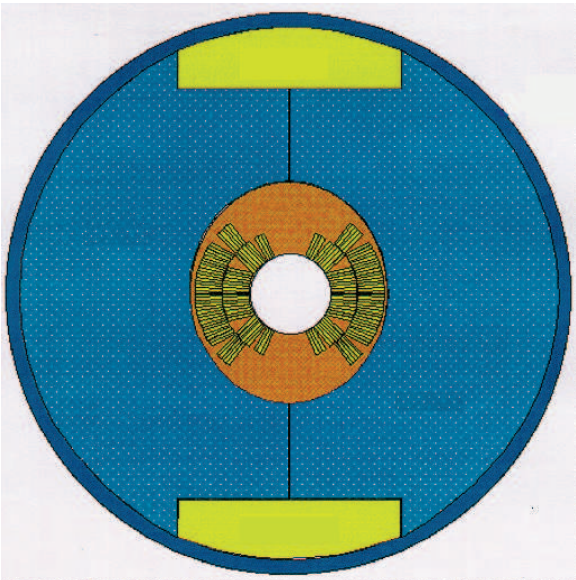

FIG. 6. Initial design cross section for a high-field Nb3Sn cos-theta dipole.

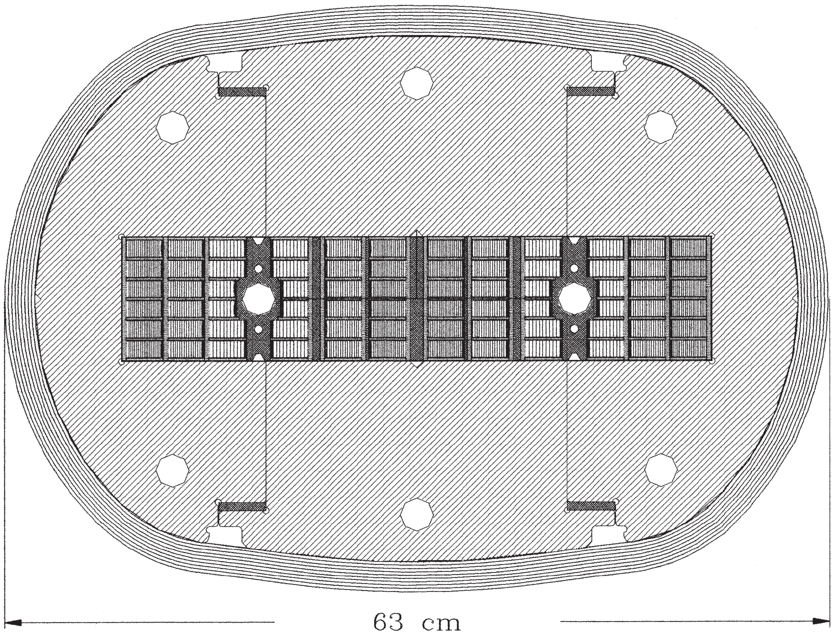

FIG. 7. Cross section of high-field dual bore block dipole.

The three groups that are using Nb_3Sn cable are working with industry to develop a set of specifications that are as much alike as possible. The labs and industry are working to increase critical current and decrease filament size. With ITER no longer making large purchases of superconductor, high energy physics will need to support much of the development formerly carried by the fusion program.

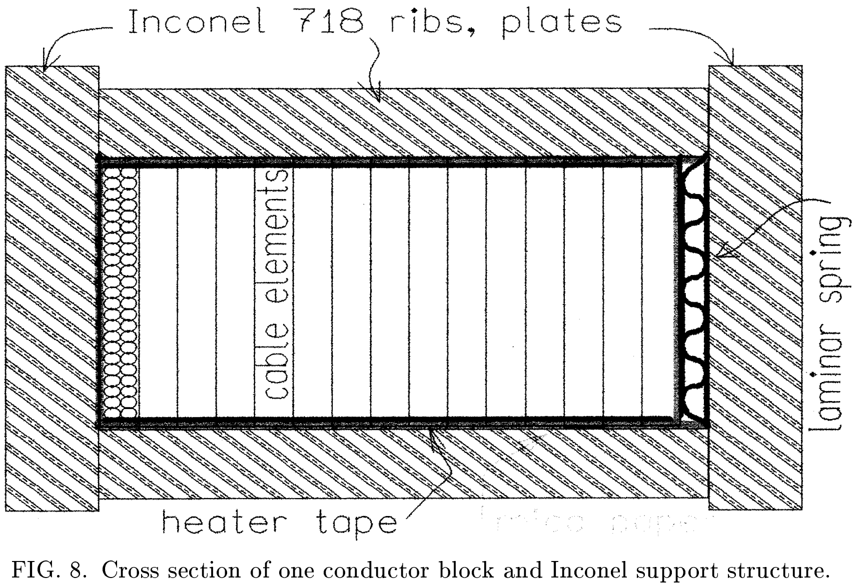

FIG. 8. Cross section of one conductor block and Inconel support structure.

IV. CONCLUSION

The vlhc magnet workshop demonstrated that the groups are working with new ideas for both superconductor and magnets, as will be needed for a pp collider beyond the LHC. Both cost and technical performance are receiving attention.

V. ACKNOWLEDGEMENTS

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