US LHC ACCELERATOR RESEARCH PROGRAM HIGH-FIELD MAGNET R&D

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Abstract

The US LHC Accelerator Research Program is a collaboration of four US National Laboratories (Fermilab, BNL, LBNL and SLAC) which has been formed to work with CERN on the commissioning, accelerator physics, and upgrades of the LHC. The largest single part of this program is planned to be the development of the next generation of high field superconducting magnets, made with Nb3Sn, for a new interaction region that would be part of an LHC luminosity upgrade.

1. INTRODUCTION

The US LHC Accelerator Research Program (US LARP) is a collaboration of four US National Laboratories (Fermilab, BNL, LBNL and SLAC), which has been formed to work with CERN to advance the performance of the LHC by helping commission the machine, conducting accelerator physics research, and doing R&D towards upgrades of the LHC. The goals of this program are:

To advance high energy physics:

- Help bring the LHC on and up to design performance quickly.
- Improve LHC performance by advances in understanding and instrumentation.
- Use LHC as a tool to gain deeper knowledge of accelerator science and technology.
- Extend LHC as a frontier high energy physics instrument with a timely luminosity upgrade.

To advance U.S. accelerator science and technology:

- Keep skills sharp by helping commission the LHC.
- Conduct forefront accelerator physics research and development.
- Advance U.S. capabilities to improve the performance of our own machines.
- Prepare U.S. scientists to design the next generation hadron collider.
- Develop technologies necessary for the next generation of hadron colliders.

To advance international cooperation in high energy accelerators, which is crucial for the future of high energy physics.

The major elements of the US LARP are 1) to help commission the LHC, both hardware commissioning, principally of the equipment that the US National Laboratories are providing for the LHC, and commissioning of the full LHC complex with beams; 2) development of beam instrumentation and second generation collimators to help commission the LHC and bring it to design performance; 3) to use the LHC as a vehicle for fundamental accelerator physics research, and 4) to perform accelerator physics studies and advanced magnet R&D directed towards a timely luminosity upgrade. The US LARP high-field magnet R&D program is the main subject of this paper.

2. NEW INTERACTION REGIONS FOR A LUMINOSITY UPGRADE

The final focus system in the interaction regions (IR) is expected to be among the systems that will eventually limit the performance of the LHC, and replacing them with new higher performance magnets, possibly with a new layout or optical configuration, is expected to be one of the main routes

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to higher luminosity. A survey of possible new IR's has been presented in [1], and a detailed study of all of the options for increasing the LHC luminosity beyond its nominal value is reported in [2].

Three major factors drive the designs of new IRs: minimizing β^*, minimizing the effects of long-range parasitic beam-beam interactions, and the large radiation power due to the pp collisions (9 kW/beam at 10^{35} cm^{-2} s^{-1}) directed towards the IRs. The first two factors point towards maximizing the magnet apertures and minimizing their distances to the IP, and the solutions to the third must be considered in designing the new configuration. The two main types of final focus systems under consideration – quadrupoles first or dipoles first - determine the principle magnet requirements which in turn drive the magnet R&D program.

The first type, shown in Fig. 1, essentially duplicates the existing IR design, in which the quadrupole triplet is the closest set of magnet to the interaction point (IP), and the two beams, which collide with a small crossing angle on the order of 0.5 mrad, pass through the same single aperture quadrupoles. Use of Nb_3Sn superconductor allows a considerably higher pole-tip field than in the baseline NbTi quadrupoles. This permits a larger aperture (up to 110 mm[3] versus 70 mm in the baseline design) for the same 200 T/m operating gradient, which finally allows a smaller β^* to be achieved. About a factor of 3 reduction in β^* appears possible by this route[1]. A pair of dipoles deflect the beams into the twin-aperture magnets that make up the rest of the machine. The first, single aperture dipole of this pair is shown in Fig. 1. Use of Nb_3Sn here allows this magnet to be very strong (up to 15 T), which separates the beams more quickly than in the baseline design and modestly reduces the number of parasitic beam-beam interactions. Since this magnet can be very short, much of the collision debris exits the magnet rather than being absorbed in it.

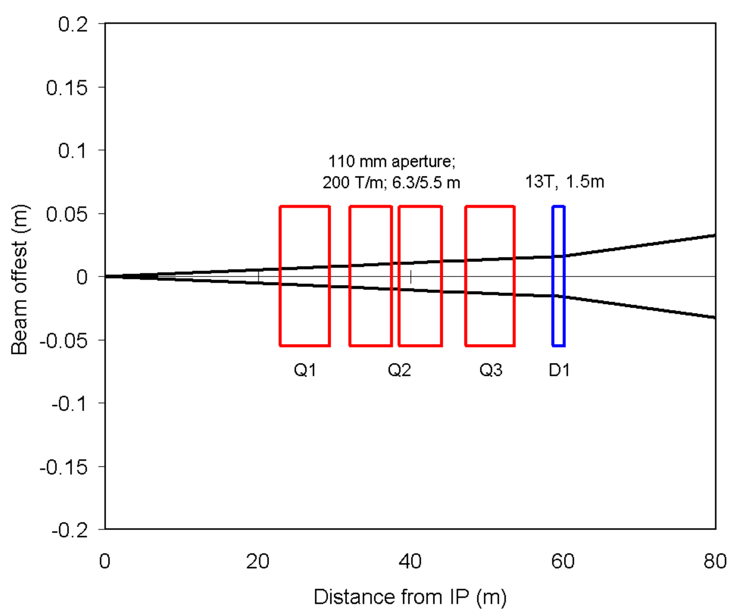

Fig. 1 Quadrupoles-first interaction region.

In the second type of IR, show in Fig. 2, the beam separation dipoles and quadrupole triplet are exchanged. The early separation of the beams reduces the number of parasitic collisions by more than a factor of three. Also, correction of quadrupole field errors is more robust, since the beams pass through the quadrupoles on axis and independent correction elements can be used for each beam. However, the quadrupoles are considerably farther from the IP, increasing β_{max} for a given β^*. The D1 also suffers very large energy deposition from collision debris, since the majority of the forward charged particles will be swept into it by the large magnetic field [4]. An added challenge is to maintain good field quality in the D2 with strong coupling between the two close, high-field apertures.

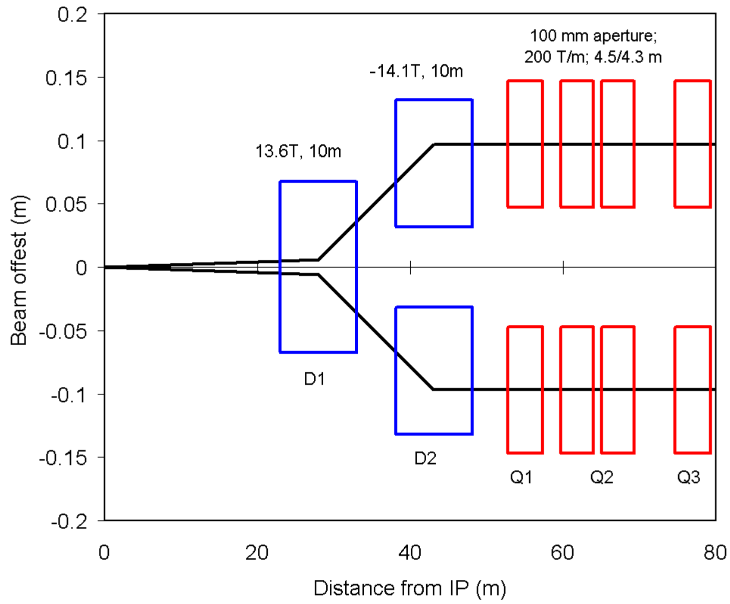

Fig. 2 Dipoles-first interaction region.

Energy deposition and radiation are major issues for the new IRs, which will determine the designs of the magnets and place significant restrictions on the usable materials. Figure 3 shows the peak density and total power deposited in a quadrupole-first IR as a function of position along the beam at L = 2.5 x 10^{34} cm^{-2} s^{-1}[5]. Scaling this result to the goal of 10^{35} cm^{-2} s^{-1}, the peak power density is more than 4 mW/g. At this radiation level, the lifetime of G11-CR is less than six months. The peak linear power density of at least 120 W/m and the total power deposition in the inner triple of at least 1.6 kW will be major challenges for the magnet design and for the cryogenic system.

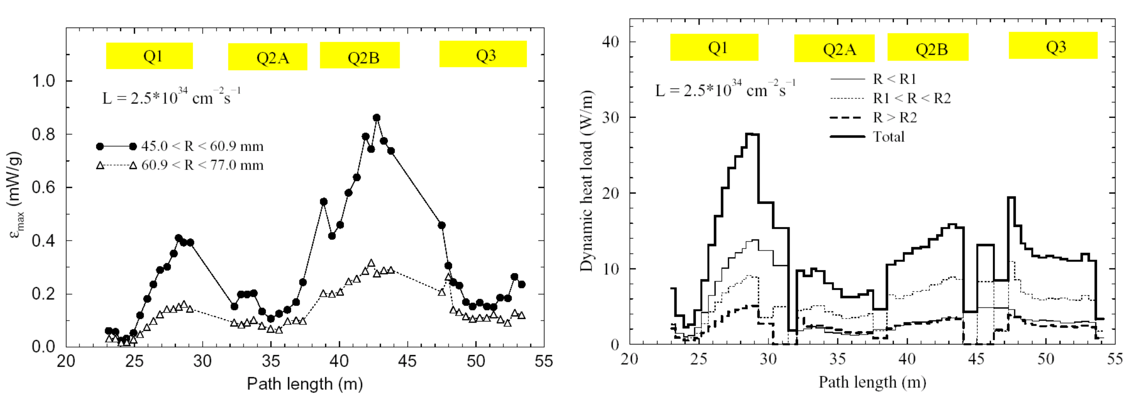

Fig. 3 Peak local power deposition (left) and linear power density (right) in a quadrupole-first IR at L = 2.5 x 10^{34} cm^{-2} s^{-1}.

The problem is even more severe in a dipole first IR. Figure 4 shows the power density in a cross-section at the non-IP end of the D1 dipole for two different dipole design concepts[4]. The peak deposition occurs on the mid-plane, as most forward charged particles from the p-p collisions are swept out of the beam by the high magnetic field. The peak power density at L = 10^{35} cm^{-2} s^{-1} is on the order of 50 mW/g, more than an order of magnitude above the quadrupole first case at the same luminosity, and more than two orders of magnitude above the peak levels expected to be encountered in the baseline IR magnets. The total power deposited in this one 10-m long magnet is calculated to be 3.5 kW. Clearly only the most radiation-hard materials can be used, and "exotic" designs, such as the one shown on the right of Fig. 4 which has no material on the mid-plane in the coil region, may be required.

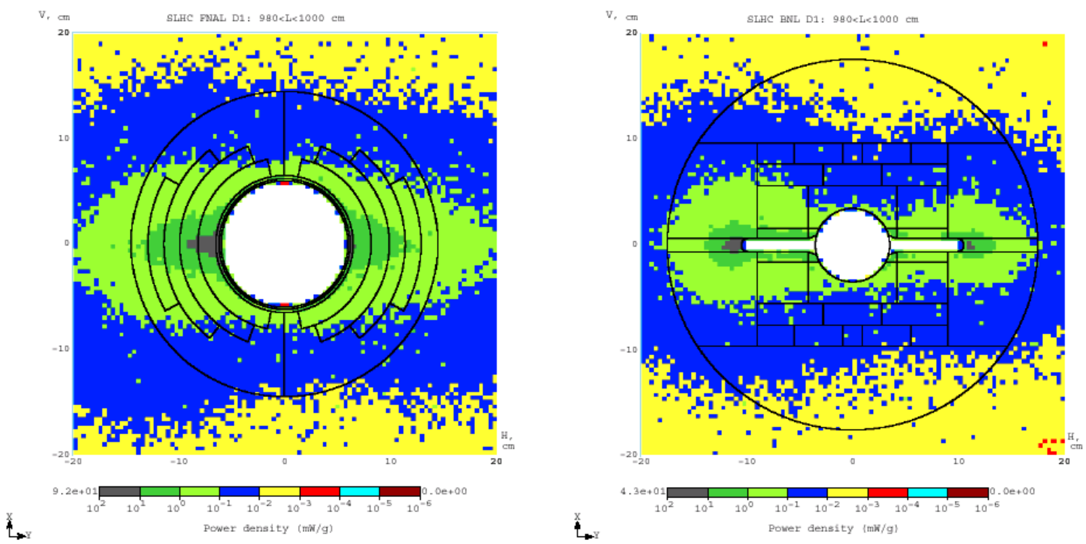

Fig. 4 Power density isocontours (mW/g) at the non-IP end of two different design concepts for a D1 in a dipole-first IR at L = 2.5 x 10^{34} cm^{-2} s^{-1}.

2. MAGNET R&D FOR A LUMINOSITY UPGRADE OF LHC

The actual form of the upgraded interaction regions will not be decided until there is a reasonable amount of running experience with the LHC, which will indicate which factors are most important in limiting the machine performance, and therefore which design will offer the best route to higher luminosity. In order to explore the range of magnet designs that may be required, the US LARP, working in close collaboration with CERN, will initially pursue R&D on both quadrupoles and dipoles. In particular, the aim is to develop quadrupoles with the largest possible aperture with operating gradient >200 T/m, as required for any new IR, and large-aperture dipoles of the highest possible field that can operate in the extreme radiation environment of a dipole-first IR. The goal of this program is to complete R&D leading to one or more accelerator-ready designs, ready for production in the early part of the next decade, which we anticipate as being the time scale required for a luminosity upgrade. Certainly a vigorous program to develop Nb_3Sn technology will be required to support this goal.

The main phases of this program are the following:

2004-05:
- Accelerator physics studies of IR issues and designs.
- Magnet design studies to identify feasible designs and critical R&D issues.
- Begin technology R&D focused on the critical topics.

2006-09:

- Model magnet R&D to develop quadrupole and dipole technologies and learn what are feasible goals for IR upgrade designs.
- Continue focused technology development.
- Continue accelerator physics studies, including beam studies once the LHC is operational.
- Choose upgrade IR design in 2009 or 2010.

2010-2012:

- Develop final designs to a production ready state, including assembly of one or more prototypes.
- Prepare for magnet production for the new IR.

Initial conceptual design studies have begun on both dipoles and quadrupoles. For example, Fig. 5 shows magnetic field calculations comparing race-track coil and $\cos 2\theta$ quadrupole designs[6]. The more conventional shell-type magnet has a coil aperture of 110 mm, which is the largest that can achieve an operating gradient of 200 T/m with a 20% operational margin assuming a Nb_3Sn critical current density of 3000 A/mm^2 at 12 T and 4.2 K[3]. The race-track coil has an aperture across the poles of 92 mm, which yields approximately the same physical aperture for two beams with a horizontal or vertical crossing plane as the 110 mm circular aperture quadrupole. Results of this very preliminary study indicate that the gradient that can be achieved with the race-track design, for the same peak field in the coil, is only a few percent less than with the $\cos 2\theta$ design. However, the superconductor volume is almost 60% larger in the race-track design, the stored energy per unit length is almost twice as large, and the field quality appears to be more sensitive to random conductor placement errors. The race-track coil is attractive for use with the difficult and brittle Nb_3Sn superconductor, and this could may outweigh the disadvantages of superconductor volume and stored energy, but it certainly cannot be used in a twin-aperture design, due to the much greater width of the coils on the mid-plane.

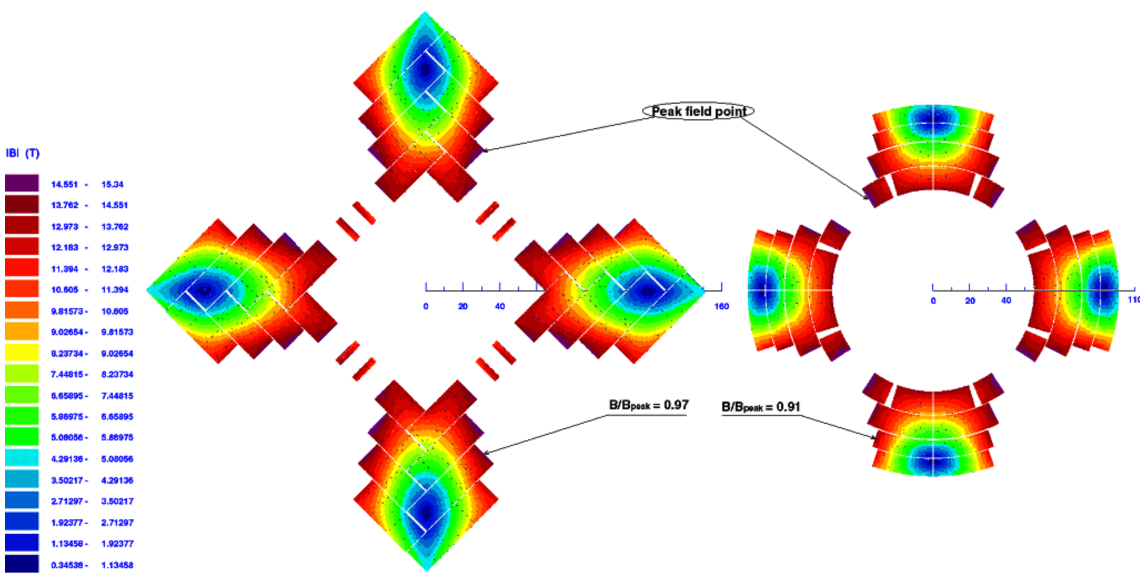

Fig. 5 Coil cross-sections of 92 mm race-track and 100 mm $\cos 2\theta$ quadrupole conceptual designs.

Design studies for a 15 T dipole with an open coil mid-plane, as required for the extreme radiation environment of a dipole-first IR, are at a very early conceptual stage. For example, Fig. 6 shows a concept for a block-type coil, built into a steel support structure which holds the upper and lower coils apart[7]. The closest material along the mid-plane is well outside the coil region, and, in this example, is an absorber held at a higher temperature than the coil to minimize the refrigeration cost. Clearly, this will be a very difficult magnet, with regard to achieving field strength as well as field quality. The gap height is a key parameter: the smaller the gap the more straightforward it is to achieve field strength and field quality, but the higher the energy deposition in the coil from the forward-going collision debris. The required height of the gap must take into account the width of the forward cone of collision debris, the divergence of the beam, and alignment and orbit errors. It may be advantageous to include some sort of low-mass "bridge" between the upper and lower coils, which could reduced deflections under the magnetic forces, but not initiate full hadronic showers.

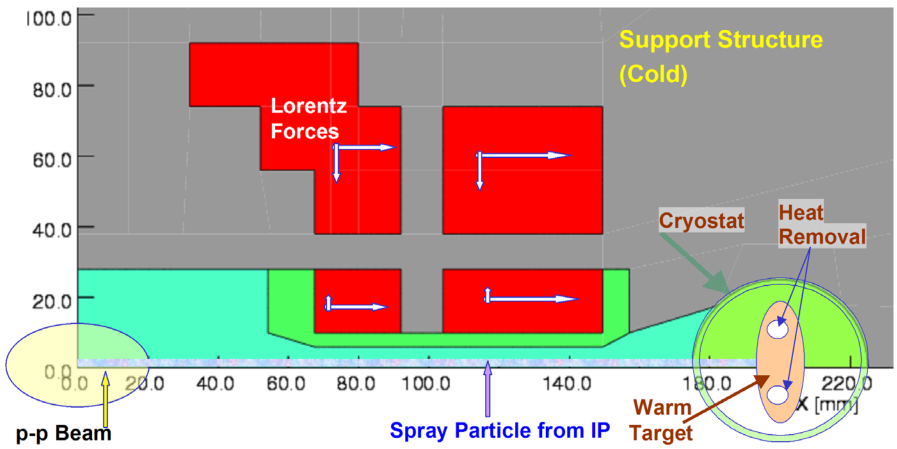

Fig. 6 Design concept for a 15 T dipole with block-type coils and an open mid-plane..

While Nb_3Sn offers a clear and promising path to the magnet parameters required for a luminosity upgrade of the LHC, this is far from a mature technology. Thus technology development will be a crucial aspect of the US LARP magnet R&D program. Among the issues that must be addressed are the superconductor itself, where achieving high J_c with small effective filament size and good strain tolerance remains a challenge, cabling, coil winding and reaction procedures, conductor-friendly coil and support structure designs, and radiation hard materials for coil impregnation and support structures. An important tool for technology development is the so-called "sub-scale" model program[8], which utilizes small racetrack coils, about 15 cm long, assembled in pairs in a "common coil" geometry as shown in Fig. 7. These allow relatively inexpensive and quick tests of various superconductor, fabrication, material, and instrumentation issues.

Over the next one to two years the top priorities of the US LARP magnet R&D program are to do coordinated magnet conceptual design and accelerator physics studies, to determine the most likely IR upgrade options and the boundary conditions on them, to develop the superconducting cable and other technologies for the new magnets, and to build and test a simplified model quadrupoles and, if possible, dipole. The first model will be a quadrupole, which will be made from two layers of an eventual four-layer magnet, which will most likely be assembled using the "bladder and key" method[9], as shown in Fig. 8. When resources permit, a simplified open mid-plane dipole will be constructed possibly using coils from the HD-1 dipole (see below). Figure 8 shows a cross-section of concept for this magnet[10].

3. US BASE PROGRAM IN HIGH FIELD MAGNET R&D

The US LARP magnet R&D builds on a base program at BNL, FNAL and LBNL in the development of high-field accelerator magnets for future hadron colliders. Indeed, the ambitious goal of US LARP, to develop magnet designs to a production ready state using the difficult Nb_3Sn superconductor, have a good chance to success only because the LARP is supported by the base program.

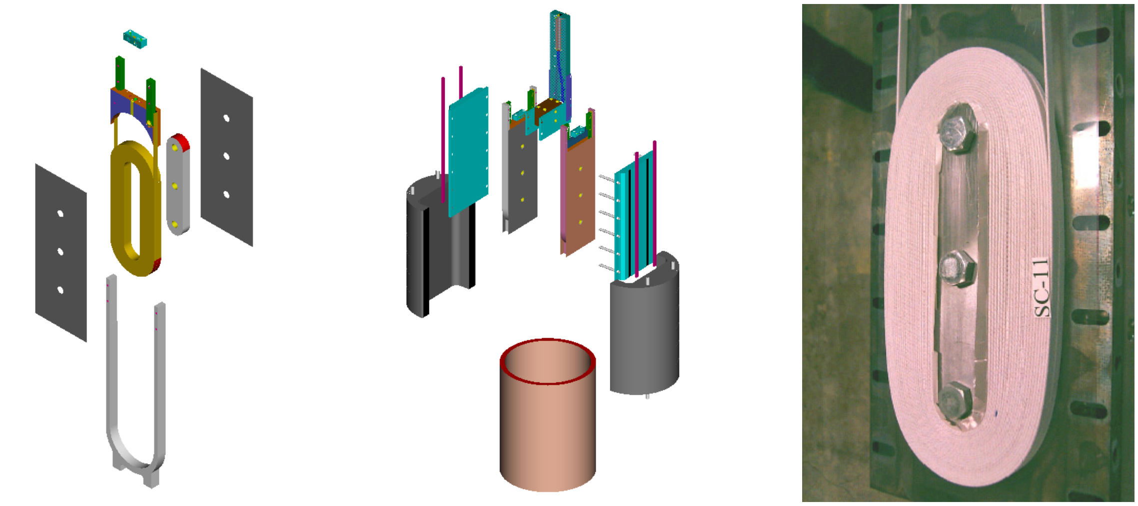

Fig. 7 Sub-scale models. Left: 3D CAD model of an individual race track coil. Center: 3D CAD model of a 2-coil subscale model assembly. Right: Photograph of an actual subscale coil.

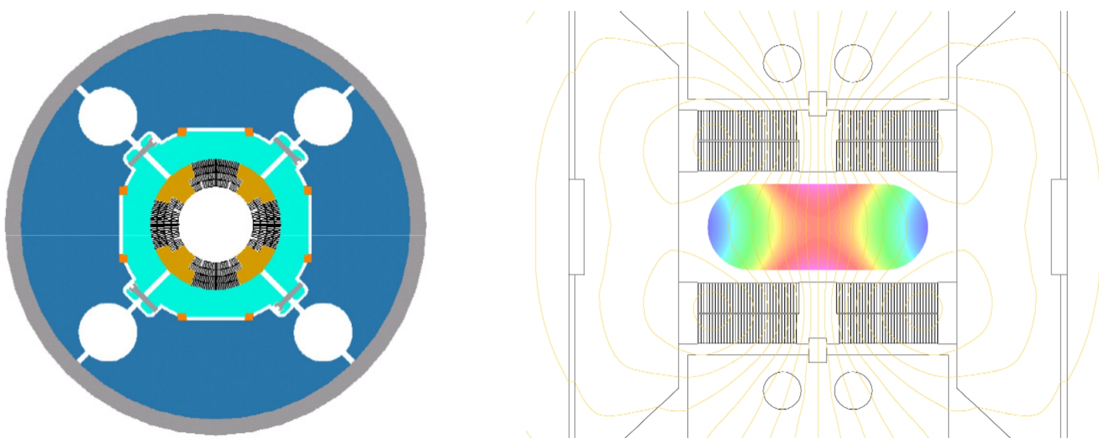

Fig. 8 Design concepts for simplified quadrupole (left) and dipole (right) models.

The programs at the three US Laboratories, while not explicitly coordinated, nonetheless complement each other. The emphasis of the LBNL program is the development of new technologies with the goal of achieving the highest possible field, without, however, initially being concerned about the practicality of the configuration for use in an accelerator. The Fermilab program focuses on development of practical designs for accelerator applications that would operate at moderately high fields in the range of 10-12 T. BNL is directed towards development of react-and-wind technology for both Nb_3Sn and high temperature superconductors (HTS).

The LBNL magnet group has built a sequence of magnets in different geometries which have each, in turn, reached a world-record field for accelerator-like magnets. D20 was a $\cos\theta$ coil, which reached 13.5 T[11]. This was followed by RD-3b, which achieved 14.5 T in a common coil configuration[12]. The current record field of 16 T is held by HD-1, a block-coil magnet (see Fig. 9)[13]. This magnet illustrates the LBNL approach, in that it makes very efficient use of the superconductor and support structure to demonstrate the high-field capability of Nb_3Sn. But with only a 10 mm aperture and little attention paid yet to field quality, it is relatively far from what would be required for use in an accelerator. The next step in LBNL's plan is to reconfigure the mechanical support of the HD-1 coils to allow it to go to higher field by operating it at 1.8 K. They are currently planning a larger bore block-type dipole capable of reaching similar field strength to HD-1, but with a larger coil bore and spacers to address field quality. A cross-section of such a coil is shown in Fig. 9[14]. Note the very large volume of superconductor required to achieve this very high field with a practical bore size for an accelerator beam.

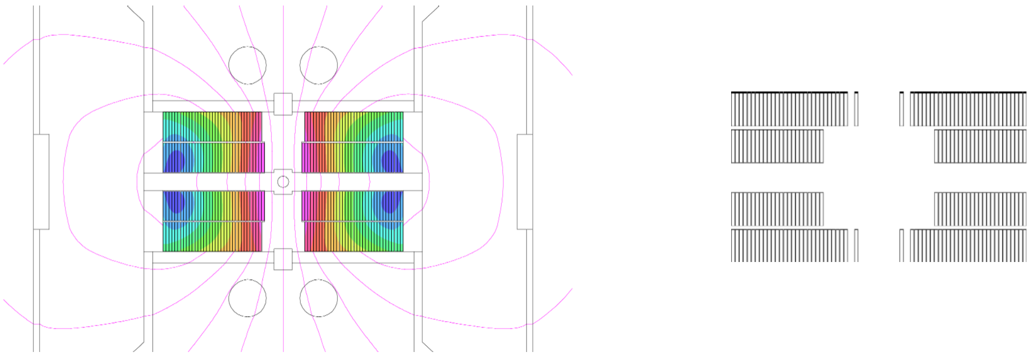

Fig. 9 Cross-section of the HD-1 coil (left), which reached 16 T and of a proposed HD-2 (right), which would achieve a similar field with larger bore.

Fermilab is pursuing two basic dipole coil designs (see Fig. 10), considering practical apertures, field quality, and manufacturability as key goals. Based in large part on the judgment that magnets of the highest possible field are unlikely to be economical for large-volume applications, such as the arcs of a future hadron collider, Fermilab is focusing on a more "modest" operating field of 10-12 T (12-14 T at the conductor limit). The first design is a conventional shell type coil, which due to the small bending radii at the coil ends, requires a wind-and-react approach. The second is a block-type design in a common coil configuration. Here the bending radii at the ends are set by the (vertical) aperture spacing and hence this design is amenable to the react-and-wind approach. The first models of both types failed to reach their design field. It is now understood that this resulted from superconductor instability due to the large effective filament size of the 1 mm modified jelly roll wire used. A program to understand the instability issue has been launched, involving both short-sample wire and cable tests and sub-scale models. A recent sub-scale coil made from 1 mm diameter powder-in-tube conductor with an effective filament size around 50 μm has achieved its short-sample limit, as expected by the instability threshold calculations[15]. With this issue at least partially understood, Fermilab will now return to testing full-featured model magnets, while continuing to quantify the understanding of the instability question.

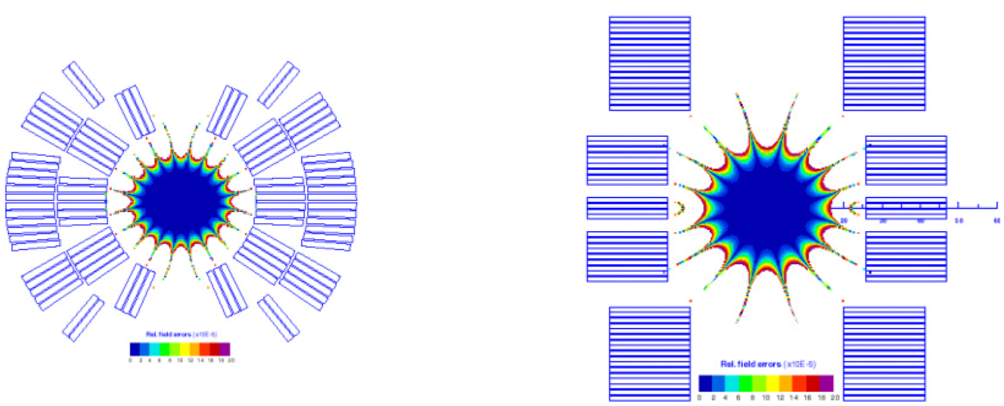

Fig. 10 Shell-type (left) and common-coil block type (right) Nb_3Sn dipoles.

BNL bases much of its development of conductors and methods for react-and-wind assembly on small 10-turn racetrack coils, similar to the sub-scale models described above. Figure 11 is a recent 10-turn coil made from BSCCO 2212 HTS cable. They use a set of Nb_3Sn racetrack coils in a common-coil configuration to provide a background field in which they insert strand or cable samples, or 10-turn test coils, as shown in Fig. 11[16]. Although HTS is still rather far from being suitable for use in a more application oriented program such as the US LARP, its continued progress suggest that it may eventually be useful at least in specialized applications, for example, in regions of high heat load such as in a dipole-first interaction region.

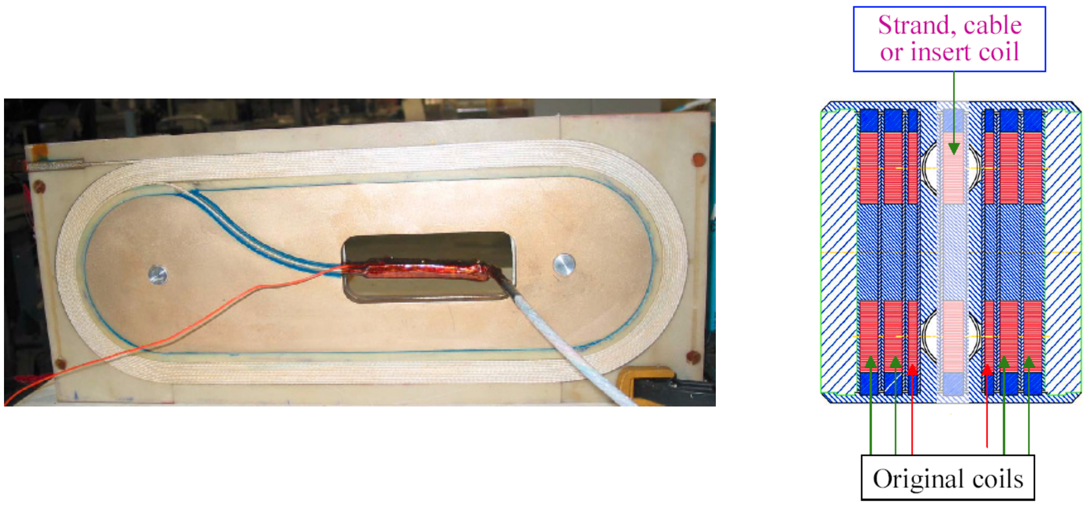

Fig. 11 Ten-turn HTS coil (left), and common-coil magnet (right) used to provide background field for conductor tests.

3. SUMMARY

The US LHC Accelerator Research Program will be an important part of the world effort to advance both high energy physics and accelerator physics and technology which underpin particle physics. The US LARP collaboration is working with CERN to advance the LHC by helping to commission the machine, developing advanced beam instruments and second generation collimators, performing fundamental accelerator physics calculations and experiments, and conducting accelerator physics studies and magnet R&D aimed at a timely luminosity upgrade. The magnet R&D program focuses on the development of a large aperture (≥100 mm) quadrupole with operating gradient ≥ 200 T/m, and a large aperture, high field (~15 T operating field) dipole suitable for the extreme radiation environment of a dipole-first IR. The goal is to develop at least one of these to a production ready state by about 2012, to permit a luminosity upgrade to be implemented in the middle of the next decade. The LARP magnet R&D program builds on a vigorous base program at LBNL, Fermilab and BNL, which is developing high-field magnets for the next generation of accelerators. The current world record field in an accelerator-type magnet is held by HD-1 at LBNL. The Fermilab program aims at developing practical designs, and is currently addressing conductor stability issues. BNL is focusing on react-and-wind technology development for both Nb_3Sn and HTS coils.

4. ACKNOWLEGEMENTS

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