T2 Working Group Summary Report

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1. Introduction

The T2 Working Group has reviewed and discussed the issues and challenges of a wide range of magnet technologies: superconducting magnets using NbTi, Nb_3Sn and HTS conductor with fields ranging from 2–15 T and permanent magnets up to 4 T. The development time of these technologies varies significantly, but all are considered viable, providing an unprecedented variety of choice that can be determined by a balance of cost and application requirements.

One of the most significant advances since Snowmass ’96 is the increased development and utilization of Nb_3Sn. All of the current US magnet programs (BNL, FNAL, LBNL, and Texas A&M) have programs using Nb_3Sn. There are also active programs in HTS development at BNL and LBNL. A DOE/HEP sponsored program to increase the performance and reduce the cost of Nb_3Sn is in its second year. The program has already made significant advances. The current funding for this program is $500k/year and an increase to $2M has been proposed for FY02.

2. US Magnet Programs

2.1. Brookhaven National Laboratory

The primary goal of the magnet R&D program at BNL is to develop magnet designs and technology where high temperature superconductors (HTS) play a major role. The performance and availability of high temperature superconductors has reached a level that one can start serious magnet R&D. HTS has many potential advantages that include operating at elevated temperature in an environment where a large amount of energy is deposited by decay particles. This makes HTS particularly attractive for interaction region magnets of various colliders and for storage ring magnets of muon colliders. The other major advantage is that, unlike low temperature superconductors (LTS), HTS retains most of its current carrying capacity at high fields.

Despite above-mentioned advantages, HTS is a difficult material to work with, as it is brittle in nature and requires a precisely controlled reaction environment. It would require several years of R&D before a magnet based on HTS can be used in particle accelerators. The magnet designs must be “conductor friendly.” BNL is developing several designs (including the common coil design concept for VLHC) that are based on racetrack coils with a large bend radius suitable for “React & Wind” technology. BNL is also building racetrack coil magnets with open midplane gaps for neutrino factory storage rings. A new design, where ends provide skew quadrupole focusing, eliminates wasted space in the ends. In addition, the quadrupole magnets for VLHC interaction regions and the LHC interaction region upgrade are also being developed using the same general technology.

Apart from developing several new magnet designs, BNL has also developed a magnet R&D program with rapid turn-around. It has made and tested many short HTS and Nb_3Sn coils based on cables and tapes. The performance of HTS coils has been very encouraging so far. The next phase of the program would be to test these HTS coils in the field of a 12 T magnet generated by Nb_3Sn superconductor.

The HTS material development is being carried out at industry by a large funding from places other than High Energy Physics (HEP). The industry has made major advances in terms of producing longer length wires/tapes, large-scale production, and improvements in material properties.

2.2. Fermi National Accelerator Laboratory

The superconducting (SC) magnet R&D program at Fermilab has two major directions with a common strategic goal: the construction of a new hadron collider at ultra-high energies. One program targets cost-effective high-field magnets with advanced superconductors to reach the highest possible energy in a fixed-size tunnel. A parallel program concentrates on inexpensive low-field magnets designed to provide the lowest cost per unit bend field using conventional superconducting materials. Both magnet types are an essential feature in a *staged* approach to the next ultra-high energy hadron collider, in which a stage I machine is based on low field magnets in a large tunnel, and a stage II machine is based on high field magnets in the same tunnel using the stage I machine as an injector. This approach allows attainment of the highest energies in a series of affordable steps, providing a healthy and exciting future for HEP. Both SC magnet R&D programs are supported by expanding superconductor and cable R&D performed in collaboration with universities and industry.

The high field magnet R&D program includes generic conceptual design studies of different *accelerator* magnets (dipoles, quadrupoles, IR magnets, correctors) for VLHC and other applications (e.g., LHC IR upgrades and BTeV) as well as model magnet development and tests. Conceptual designs of various double-aperture cos-è dipoles have been developed, which explore vertical vs horizontal bore arrangements, and cold vs warm iron yokes. These designs utilize two-layer low current or single-layer high current coils and provide nominal fields of 11-12 T in 40-50 mm apertures. Conceptual designs of a common coil high field dipole, based on single-layer low or high current coils have also been developed. These designs provide a nominal field of 10-11 T in a magnet bore of 40-50 mm. All the designs were optimized with respect to the maximum bore field, field quality, and minimum coil/yoke/magnet size. Arc quadrupoles and correctors matching corresponding dipoles have also been developed which incorporate the major design and technological features of dipole magnets.

Model magnet R&D includes both cos-è and common coil dipole models made of Nb_3Sn cables. The development and study of single-bore cos-è dipole models based on two-layer coils is now a most advanced activity. With these models, accelerator-quality fields up to 12 T in a 43-mm diameter bore will be achieved. Due to the small bending radii, the cos-è type coils require using the wind-and-react techniques in order to avoid a large degradation of the cable critical current during coil winding. Several practice coils and mechanical models have been fabricated and tested in order to verify the fabrication technology and magnet mechanical parameters. Two types of high temperature insulation (ceramic and S2-glass) with liquid ceramic binder and some new technologies for the magnet end-part design and fabrication have been successfully tested during coil fabrication. Three 1-m long models of this magnet have been fabricated and two of them were cold tested. The engineering design of a short common coil dipole magnet has also been completed. Simple single layer coils and large cable bending radii allow using wind-and-react techniques that offer the potential for reduced fabrication costs. A fabrication of the first short model is in progress. Experimental studies of different aspects of react-and-wind techniques are underway using flat racetrack coils.

The low field magnet program concentrates on cost reduction using existing SC materials in a simple and lightweight transmission line magnet design. This is a single-turn, warm-iron, 2-in-1 superferric magnet built around a high-current SC transmission line. In the past year, the transmission line conductor development was successfully completed with the operation of a 100-kA SC test loop. Five candidate conductors were successfully tested and a baseline design meeting all requirements was chosen. Samples tested included conventional NbTi Rutherford cable-in-conduit conductor, a Nb_3Al conductor that operated above 11 K, and the preferred option: a novel coaxial braid-in-conduit conductor. Optimization and test of the iron shape has arrived at a workable 2D profile, which provides adequate field quality above 1.9 T. This design is the basis for industrially fabricated iron cores/cryopipe assemblies, which have been ordered for the multi-magnet system tests under construction at Fermilab. 100 kA power supplies and current leads for this test are also under construction.

The combined function transmission-line magnet, single-layer common coil dipole, and cos-è quadrupole became a baseline for the VLHC Design Study [1] recently performed at Fermilab.

2.3. Lawrence Berkeley National Laboratory

The LBNL superconducting magnet program is primarily directed towards development of high field magnets for future accelerators. At present, accelerator magnet technology is dominated by the use of NbTi superconductor. To achieve fields above 10 Tesla requires the use of A15 compounds, the most practical and available of which is Nb_3Sn. In a practical geometry, magnets based on Nb_3Sn technology should be able to exceed fields of 14–15 Tesla at 4.2 K. The challenge lies in incorporating the intrinsically brittle, strain sensitive material into a realistic magnet where it is subjected to stresses that could exceed 150 MPa. Advances in fabrication techniques and materials have allowed us to reinvestigate simple racetrack coil geometries that have advantages in support structure design and fabrication.

In FY 98, the emphasis of our high-field magnet work shifted from “proof of principle” to a broad-based search for a cost-effective magnet solution for the next generation collider beyond the LHC. This shift is consistent with the recommendations of the High Energy Physics Advisory Panel (HEPAP) subpanel on Planning for the Future of U.S. High Energy Physics, also known as the Gilman Panel. These recommendations include a statement that “an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC” is desirable. This slightly more focused approach fits within the overall goal of the program to “write the book on magnets.”

In particular, we are concentrating on the common coil configuration for its potential simplicity of construction and consequent cost effectiveness. The design concept consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions. This geometry is intrinsically suited for a collider, but modifications of this design can be used for single-aperture applications as well.

2.4. Texas A&M University

The accelerator physics group's magnet program is based on interdependent avenues of approach to a future machine magnet ring based on high field, high current density, wind and react, and *internally stress managed* windings. The first avenue of approach is that of 14–16 T block-type dipoles and quadrupoles with bore size range in the 30 to 40 mm diameter. These designs are based on racetrack coils, which contain internal high strength (Inconel 708, and Titanium) support structures to limit stress integration and intercept it across the winding packages. Possible applications are a "Tevatron Tripler" with dipole fields of 12–13 T, the "Muon Collider" ring concept and its associated large heat load and a small aspect aperture block magnet for VLHC.

Concurrently, during the 1999 to 2000 year period the group constructed one block-coil magnet, which was subsequently tested at LBNL. The windings utilized NbTi conductor, but included all the material except the A15 superconductor and most of the techniques necessary to produce an A15 conductor winding with a "wind & react" procedure) as well as the stress management internal structure. This prototype performed very satisfactory achieving "short sample" 6.7 T, 4.3 K in six spontaneous quenches. The present prototype design under construction is a 12–13 T "Tevatron Tripler" type Nb_3Sn winding with a single aperture. The first phase is utilizing "ITER" project surplus conductor in order to benchmark and trouble shoot the various processing lines and fixtures developed as well as the presently foreseen winding procedures. The next set of coils will be a complete set of both inner and outer windings using high performance Nb_3Sn/Cu conductor in a mixed strand cable conductor (a cost reduction configuration). The outer support structure is an aluminum outer shrink ring tube over the vertically split iron return yokes loaded against the winding package with metal filled pressurized stainless steel bladders transmitting the "Lorentz Loads" to the outer structure.

3. High Field Collider Magnets

Magnet applications for future accelerators come in two major categories: upgrades of existing facilities such as the LHC and Tevatron, and new facilities. With the constant drive for higher energy machines, there is a premium for achieving the highest field magnet possible in an upgrade scenario. In the case of a new facility, the parameters are much more open. Issues such as tunneling, cryo systems, logistics, and location are important considerations in addition to magnet performance and cost.

The magnet requirements for the various machines generate some common issues. Cost is a pervasive consideration, but it prevails in the case of dipoles for the VLHC. Some cost issues include magnet length, aperture, conductor efficiency, and complexity. In terms of the next large-scale application of magnet technology, there is an implicit goal to reduce the cost per Tesla-meter by at least a factor of two relative to the SSC dipoles. Conventional approaches have reached a plateau, and meeting expectations on cost reduction demand consideration of alternate magnet designs and technologies or innovative applications of old technologies. Smaller-scale applications, such as IR quads for both linear and hadron colliders, have operational requirements that demand very high performance levels. In these cases, cost is not a significant factor. During the Snowmass

Workshop, many design options and issues related to cost and performance were identified.

At the present time four superconducting accelerators/colliders, the Tevatron (FNAL), HERA (DESY), Nuklotron (JINR) and RHIC (BNL) are in operation, and LHC (CERN) is under construction. All these machines utilize different superconducting magnets based on NbTi superconductor and cooled by LHe at a temperature of 1.9 K (LHC) or 4.5 K. A recently completed design study for a VLHC based on a two stage scenario in a 233 km tunnel demonstrated the feasibility of a pp collider with a center-of-mass energy of 40 TeV in the first stage using 2 Tesla superconducting magnets and 175-200 TeV center-of-mass energy in the second stage with 10 Tesla magnets [1].

Work on high field accelerator magnets for present and future hadron colliders is performed in several U.S. and European Labs and universities.

3.1. Collider Magnet Design Requirements

Based on previous experience and present vision of a future hadron collider, the high field magnet parameters for this machine can be summarized as follows:

- Operating dipole field range from 1 to12 Tesla
- Good field quality over the operating range inside a 20 mm physical aperture (reference harmonics as for SSC or LHC magnets)
- Coil aperture ≥40 mm, sufficient for the installation of beam screen
- Operation temperature range 4.5-5.5 K
- Sufficient critical current and critical temperature margin for reliable operation under high heat load from synchrotron radiation
- Restricted temperature and voltages during quench
- Robust mechanical design at affordable magnet cost

3.2. VLHC-2 magnet system

The VLHC-2 magnet system consists of superconducting arc dipoles, quadrupoles and corrector magnets as well as special superconducting magnets such as dispersion suppressor magnets. These magnets, described in [1], meet the above requirements.

The 10 Tesla arc dipoles use a design based on the common coil approach and cold iron yoke. This common coil dipole design is a simple single-layer coil divided into three blocks by wide spacers. It allows the use of reacted brittle Nb_3Sn cable, solving mechanical problems, and at the same time achieving excellent field quality. The 400 T/m arc quadrupole magnet with vertical bore arrangement and FF or DD functions matches the arc dipole magnet. The magnet design is based on a two-layer shell-type coil and cold iron yoke. The arc correction system includes dipole, quadrupole and sextupole correctors combined in two packages: a) 2.3 T·m dipole and 0.74 $T{\cdot}m/cm^2$ sextupole package for the arc cells and b) 2.3 T·m dipole and 0.95 T·m/cm skew-quadrupole package for Dispersion Suppression cells. The baseline approach is based on well-developed technologies for NbTi correctors.

To protect the dipole and quadrupole magnets with large stored energy, an active quench protection system based on quench heaters is used. Quench heaters installed in the magnets distribute the stored energy deposition throughout the coil, protecting it from overheating and preventing insulation damage from high voltage and thermo-mechanical stress.

With a proton energy of 87.5 TeV per beam and a bending radius of 29.9 km, the synchrotron radiation power emitted by the two beams is 9.4 W/m. A beam-screen with an aperture of 20 mm is used inside the magnet cold bore to intercept this power. The beam-screen is perforated over its surface for cryopumping to the 5 K cold bore surface.

The dipole and quadrupole cryostats are 958 mm wide and 1012 mm high. Their lengths are approximately 17 m and 9 m and total estimated weight is 42 tons and 22 tons respectively. The spool nominal length is 2.5-3 m. Spools exist in several varieties, e.g. with and without vacuum breaks, with and without high-current dipole and quadrupole leads, etc. All the large cold pipes and most of the electrical bus are placed in a separate transfer line to simplify magnet interconnects.

Magnets are cooled by a flow of supercritical, 4.5 K helium. Allowing a 1 K rise in the helium flow through the magnet string avoids the use of re-coolers or two-phase helium. An 80-110 K helium stream cools the thermal shields and beam screens.

3.3. Collider Magnet Designs

The large circumference of hadron colliders and the large number of superconducting magnets makes it vitally important to simplify their design and develop manufacturing technology, aimed at high reproducibility of parameters and cost reduction.

3.3.1. Coil designs

The coil is the most critical part in a conductor-dominated high field accelerator magnet. The design goals are to reach a field of 10-12 Tesla in a 40-50 mm bore Nb_3Sn dipole magnet using single-layer or double-layer coils based on shell-type or block-type geometries with minimal coil volume [2,3]. Examples of such coils are shown in Figure 1.

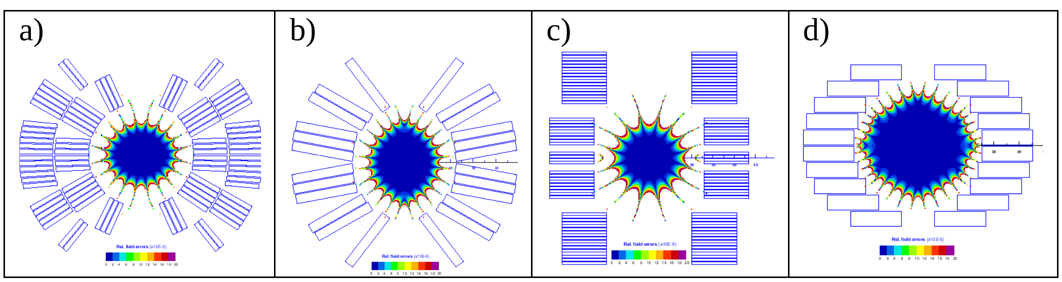

Figure 1: Coil geometry and field quality:
a) and b) – cos-theta type coils; c) and d) – block-type coils.

The cross-section of a two-layer cos-theta coil is shown in Figure 1a. The coil bore diameter is 43.5 mm. The coil shown in Figure 1b is a single-layer cos-theta coil with minimal number of turns. The coil bore diameter of 45 mm and the target field of 12 T defines the cable thickness of 3.942 mm and width of 26.717 mm for 0.25-mm thick insulation. The slightly elliptical coil bore enhances field quality with respect to the round bore. The cross-section of a single-layer common coil is shown in Figure 1c. The gap between pole blocks is 40 mm and determines the maximum magnet aperture. In Figure 1d is a single-layer block type coil with minimal number of turns. All turns are positioned horizontally and stacked in one block. The cross-sectional area of two intersecting ellipses is approximated with only ten turns. The position of turns in all the coils was optimized for the best field quality in the bore. All of them provide a field of ~12 T and accelerator field quality in the reference area.

3.3.2. Coil support structures and fabrication techniques

Coil support structures of high field collider magnets are based on the traditional approach utilizing collar laminations, direct coil support by the yoke and skin or both [3,4,5]. The examples of coil mechanical structure are shown in Figure 2.

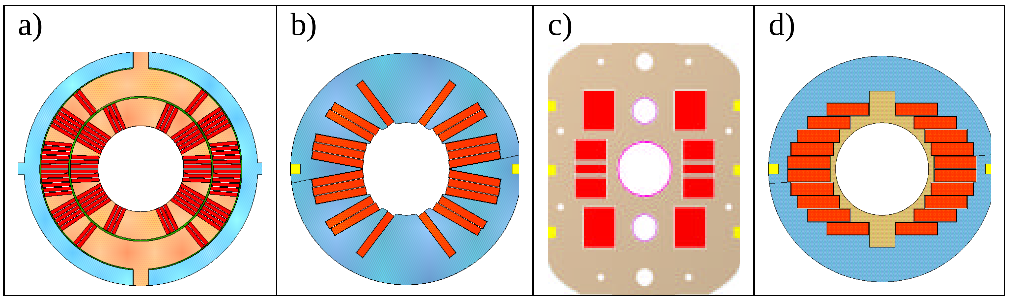

Figure 2: Examples of coil mechanical structures: a) two-layer epoxy-impregnated cos-theta design; b) single-layer high-current cos-theta design; c) single-layer low-current block (common coil) design; d) single-layer high current block design.

Due to small bending radii of turns in the cos-theta coil ends designs shown in Figure 2a and b, these coils are better suited for the wind-and-react fabrication technique due to the brittleness of Nb3Sn. Two-layer cos-theta half-coils are wound from a single cable piece. After winding and curing, two half-coils are assembled, reacted and epoxy impregnated together. This approach avoids expensive collars and a delicate collaring procedure. Coil prestress and support is provided by the yoke and skin.

In the case of single-layer cos-theta coil each half-coil is wound directly into the coil support structure. After that, the two collared half-coils are assembled around the mandrel and the collars are locked together by keys, providing some small radial prestress in the midplane blocks. After reaction, the collared coil will be impregnated with epoxy.

The horizontal turn orientation in block-type coils shown in Figure 2c and d makes them well suited for the react-and-wind fabrication technique in the common coil configuration. In this case, two Nb_3Sn coils are wound simultaneously into the coil support structure, slightly prestressed in vertical and horizontal directions, and impregnated with epoxy. A separate coil block based on this geometry and a wind-and-react approach are also feasible although with the possibility of more complex ends.

3.3.3. Strands and Cables

Rutherford-type cables are widely used in collider magnets due to their excellent electrical and mechanical properties. Examples of traditional Rutherford-type cables used in the single-layer common coil and in the two-layer cos-theta dipoles described above, and Nb_3Sn strands produced using different technologies are shown in Figure 3 [6].

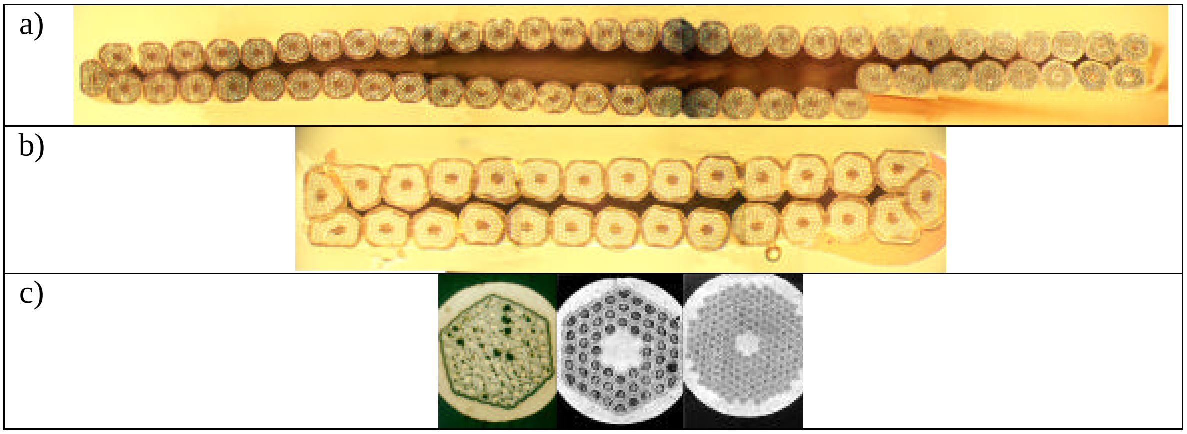

Figure 3: Examples of Rutherford-type cables and Nb_3Sn strands used in collider magnets: a) 60-strand flat cable for the single-layer common coil dipole in Figure 2c; b) 28-strand keystone cable for the two-layer cos-theta dipoles in Figure 2a; c) Internal Tin (IT), Modified Jelly-Roll (MJR) and Powder-in-Tube (PIT) Nb_3Sn strands.

The cables used in the designs shown in Figure 2b and d require quite large strands of 2-3.5 mm in diameter and are a factor of 2-3 larger than currently used [3,7]. As a result, such cables may have rather high mechanical rigidity that could create some problems during winding in coil ends. In case of the react-and-wind approach, the large strand diameter would require excessively large bending radii or lead to unacceptable critical current degradation. In order to avoid these problems and decrease the Nb_3Sn strand diameter to a level convenient for magnet fabrication, a multistage cable with sub-strands as shown in Figure 4 can be used. Such strands allow reducing the strand diameter to a level of 0.7-0.45 mm, a reasonable diameter for strand production, thereby increasing the cable flexibility and minimizing bending degradation. Mixing low-Cu Nb_3Sn strands and Cu strands provides a Cu:nonCu ratio in the cable required for magnet quench protection at a lower strand volume and cable cost. Samples of such cables are shown in Figure 4.

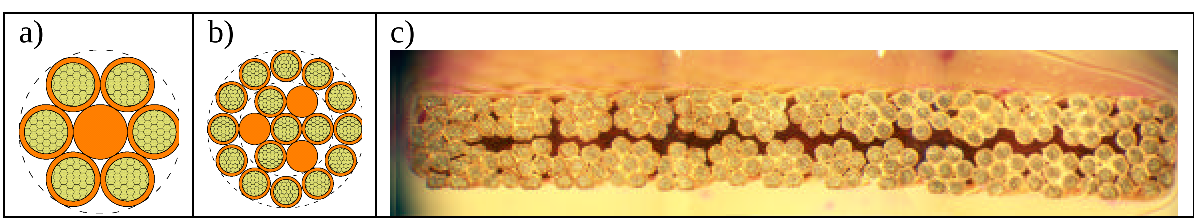

Figure 4: Examples of combined Cu/Nb_3Sn strands, and 28-strand cable made of such strands.

3.3.4. Iron yoke and cold mass

Collider storage rings can be designed based on single-aperture magnets placed in separate cryostat (SSC) or more effectively based on double-aperture magnets with a common iron yoke and cryostat (LHC). The latter approach allows reducing the size, weight, and cost of the magnet and cryostat. The 2-in-1 approach was used with both horizontal and vertical bore arrangements. A reduction of the total magnet cross-section and weight was achieved by minimizing the bore separation distance in each configuration and optimizing the iron yoke design and cross-section parameters [7,8].

The examples of optimized cross-sections of the 2-in-1 dipole magnets based on the two-layer cos-theta Nb_3Sn coils (Figure 2a), with cold and warm iron yokes and with horizontal and vertical bore arrangements as well as single-layer common coil dipole are shown in Figure 5. Magnets with the same iron yoke cross-sections can also be used with the other coils shown in Figure 2b and d.

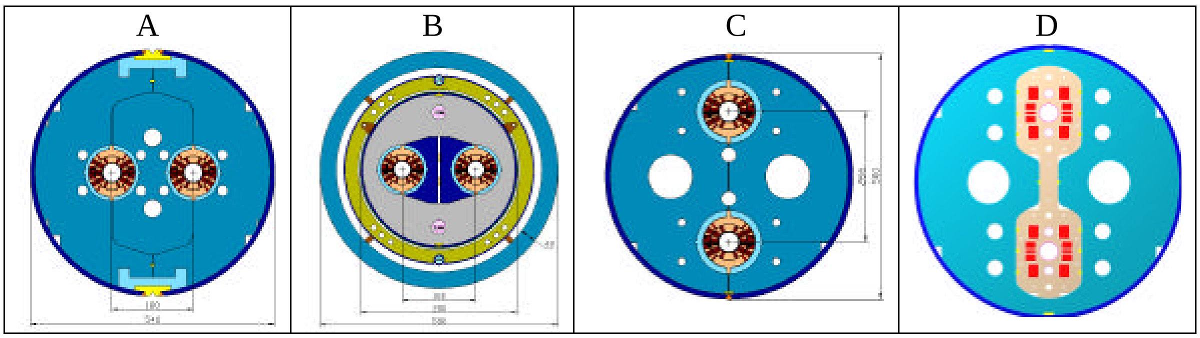

Figure 5: 2-in-1 dipole magnets based on the cos-theta (A-C) and block-type (common coil configuration) Nb_3Sn coils: A, C and D - cold yoke; B - warm yoke; A,B – horizontal apertures; C,D – vertical apertures.

In design A, two collared coils are placed side by side in a cold iron yoke with a nominal aperture separation of 180 mm. This parameter can vary within a range of 160-200 mm at the same yoke size without noticeable deterioration of field quality. The iron saturation effect is suppressed by introducing special holes and by optimizing the yoke inner and outer diameters. The yoke is vertically split into three pieces to allow assembly of two collared coils in the common yoke. The collared coils are prestressed horizontally by the yoke and the stainless steel skin. Since two horizontal components of the Lorentz force acting on the left and right sides of both coils are compensated inside the cold mass, a 10 mm thick skin is sufficient to provide an adequate coil support. An open gap, designed to be parallel to the flux lines, minimizes the reduction of coil prestress after cool down and the effect of gap size variation on the field quality. This design concept is similar to the LHC dipole design.

In design B, two collared coils are placed inside the cylindrical yoke with the same as above aperture separation of 180 mm. A magnetic coupling between the two coils results in a fairly large quadrupole field component which is compensated in each aperture by the geometrical quadrupole component of opposite sign generated by a left-right asymmetry introduced in the position of coil blocks. The inner radius of warm iron is chosen to be sufficient to accommodate such cryostat elements as the support system, the thermal shield, and the vacuum vessel. A support structure based on aluminum rings and stainless steel inserts provides the collared coil prestress and mechanical support. The cold mass skin is thin since it is not a part of the coil support structure. The aperture separation for this design could be reduced to 120 mm and the yoke OD to 500 mm.

In design C, two symmetric collared coils are placed inside the cold yoke one on top of the other. To reduce magnetic coupling between them a minimum aperture separation is 266 mm. To minimize the size of cold mass, the yoke is divided in two parts – cold and warm (warm part is not shown in Figure 5c). The iron saturation effect is suppressed by the holes in the cold iron, and by optimizing the cold and warm yoke inner and outer radii. The cold part of the yoke is vertically split in two pieces for assembly the collared coils. The coil prestress is provided by the yoke and 20-mm thick stainless steel skin. The skin thickness is a factor of two thicker than in design A, since horizontal components of the Lorentz force applied to each coil are not compensated but added. The warm part of the yoke is remote in order to accommodate the cryostat elements as in design B. This approach allows reducing magnet size by 25% with respect to the cold yoke design.

Designs B and C require a proper alignment of the cold mass inside the warm yoke to reduce the force imbalance and the misalignment effect on the field quality. Analysis shows that the alignment requirements are quite modest and can be easily met.

In design D, collared common coils are placed inside a vertically split iron yoke. A bore separation of 290 mm in this design is determined by minimal cable bending radius provided small cable degradation for the reacted brittle Nb_3Sn cable. Skin thickness in this design is the same as for design C for the same reasons.

3.4. Superconductor for Collider Magnets

The superconductor used in magnets has substantial influence on performance and cost. Many years experience with present collider magnets shows that NbTi dipoles can reach ~7 T nominal operating field at 4.5 K and up to 9 T operating field at 1.9 K. These values are determined by the NbTi critical parameters such as B_{c2}(0K)~14 T and T_c(0T)~9.5 K. Small filament diameters in state-of-the-art composite NbTi strands allows expanding the magnet dynamic range to15-20. Thanks to the excellent mechanical properties of NbTi, traditional electromagnet technologies were used in the construction of these magnets. NbTi accelerator magnets have been mass-produced in Laboratories (Tevatron, Nuklotron) and in industry (HERA, RHIC) at affordable costs.

In order to reach nominal fields above 10 Tesla at an operational temperature of 4.5 K, future hadron colliders will require the use of alternative superconductors such as A15 materials (Nb_3Sn or Nb_3Al), and HTS (BSCCO) as well as different design and technological approaches.

Nb_3Sn has a B_{c2}(4.2K)=23-24 Tesla and T_c(0T)=18 K. Formation of the Nb_3Sn phase and its brittleness determine two possible fabrication techniques: wind-and-react or react-and-wind. In the past 5 years, a feasibility of fields above 10 Tesla at 4.3 K in Nb_3Sn accelerator magnets made using the wind-and-react technique has been demonstrated experimentally. The Twente University group (Netherlands) achieved 11.5 Tesla at 4.3 K with a two-layer cos-theta dipole model. The LBNL group built a four-layer cos-theta [9] dipole model that reached fields above 12.4 T at 4.3 K and above 13 T at 1.9 K. A common coil Nb_3Sn racetrack structure at LBNL recently reached 14.7 Tesla at 4.3 K [10].

The use of Nb_3Sn conductor typically results in significant coil magnetization effects in high field magnets due to large effective filament diameters. A simple passive correction technique based on iron strips installed in the magnet bore or inside the magnet coil has been developed in order to reduce this effect [11]. This approach might lead to a significant increase in the dynamic range of Nb_3Sn accelerator magnets and relax the requirements on the effective filament size in Nb_3Sn strands.

Available HTS materials include BSCCO-2212, with $T_c(0T)$~85 K, and BSCCO-2223, having $T_c(0T)$~110 K. Kilometer-length quantities of these materials have been made in the form of multifilamentary tapes or round strands, suitable for a magnet using a flat racetrack coil design. Very high critical current densities have been achieved at high fields in YBCO short samples. However, commercial production of this material lags well behind BSCCO. The cost of all HTS material is very high and the production rate at present is too low.

3.5. Summary

Progress in raising the critical current of Nb_3Sn strands and in developing magnet technologies for brittle superconductors make it possible to design *cost-effective* high-field Nb_3Sn accelerator magnets with a nominal field above 10 Tesla with sufficient operating margin, accelerator field quality and reliable quench protection.

A magnet system configuration with a vertical bore arrangement, adopted in the VLHC Stage-2 design, dictated the configuration of the superconducting magnets described above. Arc dipole magnets are based on the common coil design and react-and-wind fabrication technique. This is regarded at this time as the most innovative and cost effective approach, although it requires significant effort to prove it experimentally. Arc quadrupole magnets are based on the traditional shell-type coil design and wind-and-react fabrication technique.

Dipole magnets based on the shell-type and block-type single-layer coils with minimum number of turns have been developed. All designs achieve an 11-12 Tesla field level with Nb_3Sn coils and provide accelerator field quality. A simple, single-layer coil geometry and minimum number of turns allows significant reduction of manufacturing time and cost that is essential for magnet mass production. The collar structures, also used as a coil-winding fixture, provide precise conductor positioning and support. Magnet designs are well suited for both wind-and-react and react-and-wind techniques. Coils with low inductance simplify magnet quench protection and allow substantial increases in magnet length. Optimization of the iron yoke design in a 2-in-1 configuration allows minimizing the bore separation distance, and the yoke and magnet size as a whole in each case of cold or warm yoke and horizontal or vertical bore arrangements. The magnet design with a horizontal bore arrangement and warm yoke allows a minimal bore separation (~120 mm) and a significant reduction of magnet size (<500 m) without a noticeable degradation of its characteristics.

4. Very High Field Superconducting Magnets

The natural trend in accelerator magnet development has been towards higher fields, sometimes out of necessity and sometimes due to considerations of tunneling, logistics, infrastructure, etc. Consequently, there is considerable activity in this area.

Aside from the challenges inherent in the construction of magnets using the brittle and strain sensitive materials required for high fields, other important issues come into play. The energies being considered for new accelerators along with the small arc-bend radii lead to significant synchrotron radiation loads. As fields increase, costs increase as well. Magnet designs that meet cost reduction requirements will need to depart significantly from the present "conventional" designs now in use. These and other issues must be evaluated and compared with other options in the context of the proposed application.

Progress in high field accelerator magnets began when Nb_3Sn superconductor was first introduced as a possible substitute for NbTi. Starting 20 years ago with fields of 5 Tesla, Nb_3Sn dipoles are now approaching a central field of 15 T (Figure 6).

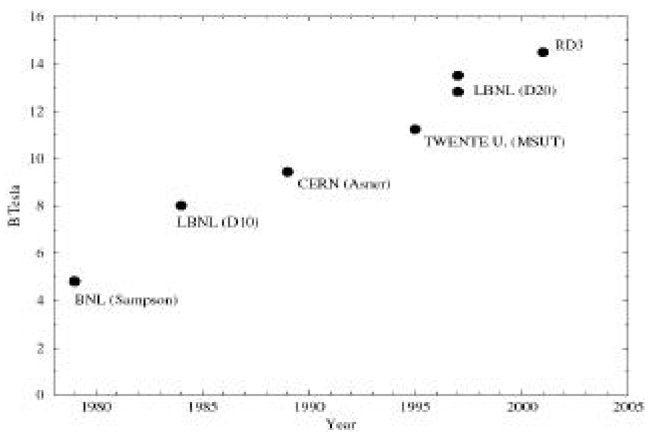

Figure 6: Progress in Nb3Sn dipole magnets in the past 20 years.

It is quite likely that in the next few years, the conductor development program [12] will yield J_c's of 3000 A/mm^2 @12 T, making it possible to achieve dipole fields of 16 Tesla in a realistic coil geometry. An increase in J_c to 5,000 A/mm2 and operation at 1.8K could yield an ultimate field of 18 Tesla. Given a situation where very high fields are required, practical magnets operating between 15 and 16 Tesla are possible.

4.1. *Copper Current Density*

Copper current density is usually a magnet protection issue. However, as the operating field is raised along with the J_c, copper current densities decrease. For example, J_{Cu} at 18 T with J_c as high as 5000 A/mm2 will not exceed 1400 A/mm^2. It should be noted that in the LBNL RD-3 dipole [10], with a conductor J_c of 2,200 A/mm^2 the J_{Cu} reached 1150 A/mm^2 at a short sample of 14.7 T. It was observed that during a quench the magnet temperature did not rise above 200 K. This is good news both from a protection as well as a cost point of view, as it will allow a reduction of the amount of copper in each strand from the current ~50% level to 20%. Incorporating low copper ratios in strand production will therefore raise J_{Cu} to values that are only as high as 2,500 A/mm^2 and the use of any additional external copper may not be needed.

4.2. *Training*

In addition to the excellent high field properties of Nb3Sn, it also has the advantage of a higher critical temperature. There is some indication that it may be reasonable to expect construction of magnets that exhibit little or no training. On the contrary, the highest field (13.5 and 14.7 Tesla) magnets trained considerably. However, the LBNL group has had two examples of magnets that did not train, one at 6 Tesla and another at 12 Tesla [13,14]. An 11.5 Tesla magnet built by the University of Twente [15] also reached short sample without training. The cost of training is high, increasing operating margins and wasting expensive conductor. Investigating the origin of training and ways to avoid it should therefore take top priority as we try to push towards higher fields.

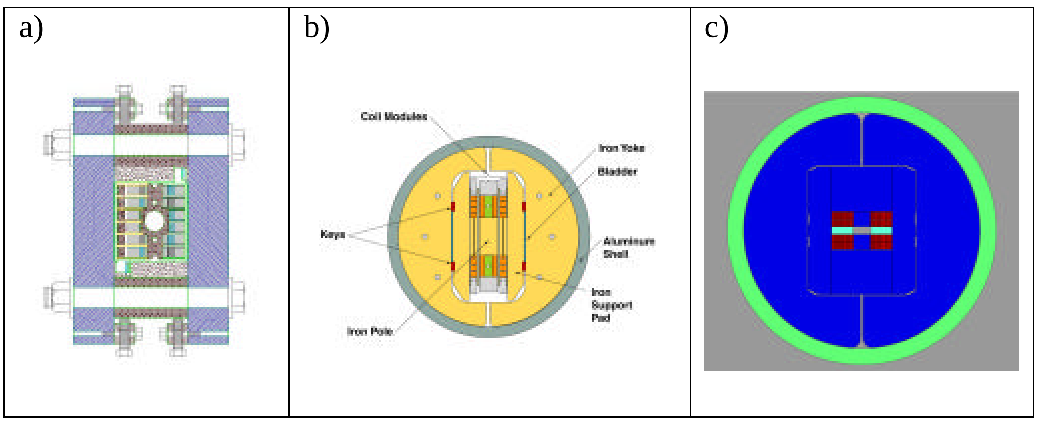

Figure 7: a) Texas A&M Block design, b) LBNL RD-3 common coil, c) LBNL single-bore, high field dipole with a conductor-free mid-plane.

4.3. *Lorentz Forces and Structure*

Raising the field from 10 to 15 T has doubled the Lorentz force. That value doubles again in dual-bore geometries such as the common coil. Construction and assembly procedures of very high field magnets are undergoing substantial changes compared with technologies inherited from NbTi magnets. The use of bladders [16] as an internal press to preload the coils and elimination of structural material in the bore region will contribute to a substantial cost reduction. The increase in the Lorentz forces can be accommodated with new structures, some of which could be made even less expensive than those currently used with NbTi at lower fields. Figure 7a is a block coil configuration by Texas A&M [17] and Figure 7b is a cross-section of LBNL's RD-3 [10], a common coil design utilizing the bladder-loaded support structure. One of the issues concerning high field magnets is the synchrotron heat load that must be extracted from the cryogenic environment. Figure 7c, shows an LBNL design of a 15 Tesla, single-bore racetrack magnet with conductor-free mid-plane that would minimize the heat load on the conductor.

5. Synchrotron Radiation

A serious technological issue for any post-LHC hadron collider is synchrotron radiation (SR). Any future energy-frontier hadron collider, using high field magnets, will produce several W/m of SR power. The recently proposed VLHC in its 2^{nd} stage, for example, would produce 5 W/m/beam of peak SR power [1], which is ~50 times as much as the current LHC. This power is to be extracted from a cryogenic environment, making total cryogenic power requirements of the collider a top priority issue. We know solutions to the problem of extracting SR power from cryogenic magnets: cooled beam-screens and/or photon-stops. Both solutions have limitations, which are briefly summarized here. A more detailed discussion can be found in [18,19,20]. The beam screen and photon stop designs proposed in the recent VLHC study are presented more thoroughly in [1] and [21].

Beam screens, much like that of the LHC, consist of a perforated, cooled liner, operated at a temperature slightly higher than the magnet cold-bore. The liner thus serves as the higher temperature baffle to the cryo-pump constituted by the cold bore surface, and shields the cryosorbed gas from redesorption by SR. The higher temperature operation allows extraction of the SR power at higher Carnot efficiency, reducing the overall cryo-power requirement of the accelerator. An important issue arising in the presence of SR power much larger than in the LHC is whether one can absorb the SR at temperatures up to 100 K or more in order to reduce the cryogenic power requirements. The optimal temperature, i.e. the temperature at which the total cryo-power requirement is minimized, rises quickly with increased SR load and reaches ~100 K at ~10 W/m. A second important issue is the growing size of the cooling channels required to extract the SR power heat load, forcing a minimum aperture size upon the magnets.

Photon stops are water-cooled fingers protruding into the beam pipe from one side, placed after every bending magnet, which can be driven toward the magnet axis to intercept the SR emitted by the beam. At high SR power levels, photon stops are preferred to a beam screen, because they extract the SR heat load at room temperature and thus at optimal Carnot efficiency. An R&D program is currently underway at Fermilab and ANL to test a first prototype under an SR load. Critical issues of the photon stop design are primarily geometrical in nature and are related to the size of the ring and the magnet length and aperture. Photon stops are only practical in machines with large enough aperture magnets and a large enough arc radius. The minimum magnet aperture required for photon stop operation is slightly less than for the cooled beam screen.

We presently, however, consider it most prudent to use a combination of beam-screen and photon-stop, with the photon-stop absorbing most of the SR power to minimize the machine cryopower, and the beam-screen providing mostly the vacuum function.

6. Permanent Magnets

The use of permanent magnets as components of proposed machines looks promising. A significant step leading to the present interest in permanent magnets is the experience of the Fermilab Recycler, which made extensive use of hybrid permanent magnets. In a hybrid magnet, the iron poles determine the magnetic field quality while the permanent magnet material acts to excite the magnetic field. Quadrupole, dipole, and combined function magnets were fabricated, installed in the Fermilab Main Injector tunnel, and commissioned with beam [22]. This project consisted of a 0.75-km long 8 GeV beamline and the 3.3-km circumference Recycler, whose name reflects its function to recycle antiprotons at the end of each collider for re-use in the following store. The Recycler, built at low cost ($12M), represents the largest use of permanent magnets for accelerator components and is the 5th largest synchrotron in the world. Permanent magnets were selected because the energy was fixed at 8 GeV and the required field was < 0.5 T. Other advantages of permanent magnets are no power supplies and no cooling water. Strontium ferrite was chosen because it is the lowest-cost permanent magnet material per BH (Energy Product), and has high availability because of extensive use in automobiles. It has documented good stability over time, temperature, and radiation exposure. The beam line and Recycler magnets were optimized to operate the magnetic material at $B \quad 0.5\ B_r$. This extracts the maximum field energy from the permanent magnet material and corresponds to a point on the load line of about 45 degrees. Another important point is to be sure to stay away from the demagnetization "knee" in order to avoid sensitivity to temperature or de-magnetization.

Two characteristic properties of Strontium Ferrite had to be dealt with. The first was that Strontium Ferrite has a temperature coefficient of –0.2%/ºC. Since controlling the Main Injector tunnel temperature was impractical, this would result in unacceptable variations in field strength. The problem was solved by incorporating Iron–Nickel alloy with compensating temperature behavior. The second property of Strontium Ferrite to be accounted for is that the material varies by about 10% in its magnetic properties. The technique that solved this problem was to build the magnet and then adjust its strength using measurements. The amount of Ferrite was adjusted to attain the desired integrated field strength. Since the Recycler is a storage ring, the field quality requirement of dB/B is less than 0.01% of total field defect across the 2-inch by 3-inch aperture. This requirement was met by EDM machining of custom end shims determined from the magnetic measurements.

Another great advantage of the use of permanent magnets was demonstrated in the 8 GeV Line and Recycler projects by the fact that over 500 magnets were produced by a 12-person crew at a rate of 3.5 magnets per day. Installation in the tunnel was carried out at a rate of 12 magnets per day.

One of the new applications of permanent magnets is the design of adjustable quadrupoles for the Next Linear Collider (NLC). This joint effort by Fermilab, SLAC, and LBL was initiated about 2 years ago, and has resulted in five models for the quads for the Main Linacs of the NLC. The NLC design had initially used electro-magnets. Advantages of permanent magnets were stated as 1) elimination of power supplies and water cooling, 2) substantial reduction in cabling, 3) lower operating cost and 4) probably lower magnet cost. Disadvantages were 1) difficulty in meeting one micron stability of quad center during strength adjustment, 2) uncertainty in long term stability and 3) limitation on field strength. The most severe requirement is the stability of the quad center during beam-based alignment. This is a feedback system that requires the adjustment of the individual quad strength by up to 20% in several steps based on beam position monitor signals.

Permanent Magnet Materials

Ferrite	*Sm-Co*	*Nd-Fe-B*
Strontium or Barium Ferrite	Sm-Co 1:5, 2:17	
Inexpensive	Expensive	Cheaper than Sm-Co
Radiation resistant	Radiation resistance (2:17 good, 1:5 worse)	Radiation resistance needs further work
Low Br, 0.38 T	High Br, 1.14 T	Highest Br, 1.43 T
Temp Coef = –0.2% / Cº	Temp Coef = -0.03%/ Cº	Temp Coef = –0.1%/ Cº

Based on the above table Sm-Co was selected for the initial magnet models. Nd-Fe-B will be investigated as a later step in particular to reduce cost. After looking at a list of possible permanent magnet candidates, about 50% looked viable for permanent magnet implementation, i.e., about 3321 magnets.

Of the four permanent magnet quad models tested so far, the rotational quad gives the best result for the stability of the quad center during strength change [23]. It consists of 4 identical quad sections. Each section is a permanent magnet Sm-Co(1:5) quadrupole. All sections are placed on a V block support and the two central sections can be rotated in counter directions by simple mechanics, providing 20% integrated gradient strength adjustment. Each section is provided with an adjustment in its center by the use of iron shunts. The average field gradient of the assembly is 100 T/m and the aperture is 12.7 mm. The first test run confirmed the design and showed magnetic axis stability in X direction of about 1 micron and about 4.5 microns in the Y direction with good reproducibility. The accuracy of the measurement system for center offset is better than 1 micron.

The Magnet-in-Magnet (MiM) concept was presented in order to increase the field strength of the 2 Tesla VLHC Superferric superconducting (SSM) magnet. The magnetic field strength of 2 Tesla is limited by a field distortion due to saturation of the iron pole of the magnet. To avoid the saturation, a compact Halbach type 2.1 Tesla permanent magnet (PM) dipoles are inserted inside of both SSM air gaps. The material of the PM where the external filed opposes to the magnetization direction of the PM material can be chosen so that it does not demagnetize. The field strength of the SSM is 2.0 Tesla in bipolar mode. The resultant field changes from 0.1 Tesla to 4.1 Tesla. The diameter of the PM inserts is roughly 100 mm and the necessary SSM excitation current is about 250 kA. The field stability of the MiM magnet can be performed by feedback to the power supply. The cost of the PM is modest and comparable to the SSM.

One of the challenging issues of using permanent magnets in future accelerators is their stability to radiation. It was proposed to start at FNAL investigation of radiation damage of permanent magnets. Two magnets with a known load line one with high coercivity material and another with lower coercivity material should be built and irradiated until a noticeable change in the field is observed. The lower coercivity magnet should show loss in field with less radiation than the higher coercivity magnet. The magnets should then be disassembled and the magnetic material re magnetized. The field after re-magnetization should be the same as the original field. Similar magnets should also be built and not irradiated to measure the effects of aging in the magnetic system. The manufacture of the magnetic material should be carefully controlled at all steps to ensure uniform and small grain size.

Brian Watson (Hitachi Magnetics Corp.) covered permanent magnet materials and showed large progress in magnetic properties of rare-earth materials during the past decade. The maximum energy product increases from 200 kJ/m3 to 400 kJ/m3. He showed the technological process of permanent magnet production and noted that large permanent magnet applications decrease the cost of permanent magnets production. Future projects can use new materials with high properties.

Ross D. Schlueter as part of the IEEE NPSS Technology Courses gave a short course on Permanent Magnets in which he summarized the theoretical basis for the design of permanent magnets useful for bending and focusing of charged particle beams. He covered the basis of magnetostatics and pure permanent magnet theory in which he presented significant detail. He also showed a recent application in designing a permanent magnet corrector ring capable of providing any desired harmonic mix and which is insert able at any desired location along a beam. Such rings are in present use to null the harmonics of the Q2 system quadrupole for the SLAC B-factory. He reviewed the earlier work on permanent magnets, starting with that by Klaus Halbach and others on the design, testing, and use of magnets using rare earth materials. He then emphasized the development of the theory for calculating the design of ferrite-based hybrid permanent magnets, which contributed to the design of the Fermilab 8 GeV Line and Recycler.

7. Magnets for Hadron Collider Interaction Regions

Particle beams are brought into collision using interaction region (IR) magnets. IR magnets include high field dipoles for steering and beam separation, and high gradient focusing quadrupoles. The field requirements and proximity to the collision region make their operational requirements more stringent than for arc magnet counterparts. The following issues have been identified as important to interaction region magnet design:

1) *High gradient/field and large aperture*
   As these magnets form the final focus, they are located as close as practically possible to the interaction regions. This requires high gradients to achieve the required β^* with a limited focusing lever arm. Large apertures are needed to accommodate large dynamic apertures and transverse beam separation from the beam-crossing angle. For example, in the LHC IRs, a 200 ìrad crossing angle results in a beam separation of 4 mm at the front face of the first quadrupole. The aperture is further restricted by absorbers in the beam pipe, required to intercept the large radiation/heat deposition due to interaction debris.

2) *Excellent field quality*
   This is driven by the need for large crossing angles and high luminosity. Both result in beam trajectories away from the magnetic axis, thus making the beam susceptible

to error harmonics in the magnetic field. The goal is to limit unallowed field harmonics at the upper end of injection and beta squeeze to one unit or less. Harmonics of this order can be compensated by a scheme of local correctors.

3) *High radiation environment/heat deposition*
The proximity of the magnets to the IP puts a significant radiation load on the magnet. For the LHC, ~900 Watts/side of debris is generated at nominal luminosity and energy. Of this, 200 Watts is deposited in the cryogenic system through the beam tube and beam tube liner. Aside from the cryogenic load, some of this debris will interact directly with the magnet, which can result in a rise in the magnet temperature and cause a quench. The radiation can degrade the magnet components (7 years of LHC operation translates into 20 MGy, which causes the epoxy in G-11CR to disintegrate) and can cause activation of magnet and shielding.

4) *Alignment and mechanical stability*
Magnet alignment contributes in three major ways to the proper operation of the accelerator. First, misalignment leads to luminosity loss, by steering the beams to the wrong location in the IP. Second, misalignment causes the beam to populate off- axis areas of the aperture and thus become susceptible to harmonic errors that grow in powers of the radius. This leads to a decrease in dynamic aperture if not properly accounted for with local correction. Finally, transverse misalignment can lead to a reduction in physical aperture, as beam pipe apertures are already reduced by absorber materials to ameliorate the problems listed in item 3. Typical transverse alignment goals are 300-500 microns, 1-2 mm longitudinally, 1 mR in roll and 100 microradians in pitch and yaw.

5) *Powering and quench protection*
The protection goals for IR magnets are comparable to other superconducting magnets: namely limiting the peak voltage to ground to 1000 V and limiting the peak temperatures to 400 K. These goals are challenging because of the high field/large aperture, which translates into high currents and/or large inductances and large stored energies. Inner triplet magnets are typically powered in series, with the possibility of varying the field in one of the triplet quadrupoles for accelerator studies.

Several types of IR magnets are in prototype or R&D phases, while others are under consideration for future machines. These include:

- LHC IR quads: Fermilab and KEK has completed a model magnet program, tested the first full-length prototype, and is gearing up for a 36-unit production run
- LHC IR quad upgrades (Nb_3Sn): a future replacement the NbTi LHC IR quads. The combination of high current density and large temperature margin would allow the LHC IRs to operate at high luminosities.
- LHC IR HTS quadrupoles: Proposed at BNL as an alternate LHC IR upgrade. Add to the existing NbTi IR triplet, a doublet of compact very high gradient HTS quadrupole.
- VLHC-1 IR quads (Nb_3Sn): VLHC-1 requires 3x the LHC energy at comparable luminosities. This could be accomplished by making a quadrupole similar to the

LHC IR upgrades, with a small aperture but larger gradient.

- VLHC-2 IR quads (BNL Nb_3Sn or HTS): 400 T/m single aperture or 600 T/m double aperture magnets in a very high radiation environment.
- Permanent quadrupole magnets for future IR Quads: Magnets could be used alone or in combination with other electromagnet focusing elements.

The IR quadrupoles for existing or near term projects such as the LHC utilize coils made from Rutherford style NbTi cables. The 70-mm aperture LHC inner triplet quadrupoles operate in superfluid with a peak operating gradient of 215 T/m. Future accelerator applications as listed above will require a combination of higher gradient, possibly larger aperture and higher heat loads. This means building magnets with Nb_3Sn or High Tc materials.

The upgrade for the LHC IRs is an excellent opportunity to use Nb_3Sn technology for a production series of accelerator magnets. The experience from all phases of the magnet production, from cable procurement through construction and test will be invaluable for the VLHC program.

Any future IR magnet program including those mentioned above will required a detailed understanding of the operational conditions, the field strength requirements and the radiation heat load. The key issues for radiation are:

- Radiation heat depositions (transverse and longitudinal distributions)
- Radiation load on different elements of magnet design
- IR component activation

8. Magnetic Measurements

Magnetic measurements are an essential part of the R&D program for magnets for new facilities. Some magnets will only need an extension of present techniques; others will require a certain amount of development of new measurement tools.

8.1. Measurement activities at Magnet R&D centers

Activities at Fermilab from which we should continue progress toward measurement requirements for future magnets include:

- *LHC IR quadrupoles*: we have built a new test stand for horizontal tests of the LHC Q2a/Q2b IR triplet quadrupoles. The test stand has the capability to provide superfluid He to the magnets. The stand is long enough to accommodate 2 quads in a single cryostat; this implies we are gaining valuable experience in testing magnets or magnet strings up to ~16 m in length.
- *Nb3Sn model magnets*: the measurements of these magnets are being done at the Vertical Magnet Test Facility, which has been operational for the last few years. This allows us to test short models, typically 1-2 m cold masses, in an LHe dewar. Two magnet designs have active test programs; these are the cos (θ) and racetrack (common coil) designs.
- *VLHC Stage-1 prototype*: Tests of the SC transmission line have been done and the concept has been validated. Some prototyping of measurement devices is

ongoing, including a multi-element Hall array for transverse field shape measurements, and a rotating coil as described below.

Activities at other labs are also very strong. SLAC has made good progress on making small diameter rotating coils for strength and alignment studies of permanent and electromagnet designs for main linac NLC quads. The CERN measurement group has been very active in main arc dipole and quad measurements for LHC; they have been developing probes using ceramic materials which can be used in cold bore measurements. Texas A&M and LBNL are vigorously pursuing very high-field magnets.

8.2. VLHC Stage-2 magnets

For the VLHC Stage-2 magnets, we can expect to use the techniques developed for the LHC and older types of magnets. That is, a combination of rotating coils to measure the harmonic content with stretched wire systems to measure integral strength and alignment will probably work. The present high-field magnet program, based on the use of Nb_3Sn superconductor, requires simpler (less expensive) cryogenics than the superfluid LHC IR quads, only needing a 4.5 K operating temperature. The 40 mm aperture may present some challenges for a rotating coil system, since lower coil radius will result in reduced signal size. The effective aperture size for a probe may be further reduced by the presence of a beam screen. This may be mitigated by the very large signal one will expect for a 10 T field. Warm measurements, however, will have greatly reduced signal size, but we have already gained experience in measurement of small signals, e.g., we routinely make corrector strength measurements in warm Tevatron spools.

8.3. Arc dipoles for VLHC Stage-1

R&D for measurements of VLHC Stage-1 arc dipoles will of course have to make rapid and significant progress in the next few years, because of the parameters associated with these magnets. The parameters affecting measurements include:

- Magnet length of 65 m
- Aperture (on center) of 20 mm
- Gradient profile (~5-9%/cm)

A first sketch on how to measure these magnets was developed for the VLHC Design Study. This uses rotating coils inserted into the open part of the C magnet from the side. Two probes, one for each aperture, are attached to a strong back, which is mounted to the top of the magnet laminations and provides precision positioning. The probes could be made nominally with a length of 6.5 m, which means that by sliding the probe along 10 longitudinal positions, the entire magnet length could be measured.

8.4. Permanent magnets

Fermilab has been very active in permanent magnet technology since the Recycler development, which used thermally compensated Sr-ferrite ceramic magnets. More recent activities include using high-field SmCo (and also NdFeB) permanent magnets to do R&D for NLC main linac quads. Measurements have focused on the severe alignment requirements of these magnets (~1 μm). We have used the single stretched wire technique with promising success: with our current stages, we have been able to obtain precision measurements on the order of a few microns. Further investment in high accuracy stages will be necessary to achieve the measurement goals.

9. Quench Protection

The following briefly discusses quench protection issues in new generations of low and high field superconducting magnets for future colliders on the basis of the magnets and related quench protection systems proposed recently in the context of a study for a two-stage Very Large Hadron Collider [1].

9.1. *Low Field Superconducting Magnets*

In the low-field, stage-1 VLHC design [1], the low inductance (3 μH/m), and low stored energy of the magnet system permit the entire ring to be energized with a single power supply. Quench detection is performed by a single circuit located at the power supply terminals [24]. When a quench is detected, the power supply is ramped down and the magnetic energy is extracted from the magnet system with a 1 second time constant by cryogenic dump resistors spaced at 20 km intervals around the ring. The peak temperature of the conductor, given an effective copper cross-section in the conductor of 3 cm^2, is kept to less than 250 K and the peak pressure below 40 bar. The spacing of the extraction resistors is chosen such as to limit the peak to ground voltage to less than ±3 kV. The overall system is drastically simpler than LHC-style quench protection, which requires multiple crates of electronics under every dipole around the circumference of the ring.

9.2. *High Field Superconducting Magnets*

The large stored energy and high inductance of superconducting high field magnets requires active quench protection systems, such as those used in the Tevatron, HERA, and LHC. The quench is detected by voltage rise, and heaters are fired to spread the quench throughout the magnet. The energy stored in the unquenched parts of the machine is bypassed around the quench cell by diodes and is absorbed in an external resistor.

Higher fields and the use of new materials, such as Nb_3Sn, with higher current densities, however, will require adaptations of this quench protection technology regarding in particular heater coverage and coil inductance. The dipoles for the high field stage of the recently proposed VLHC [1], for example, use Nb_3Sn superconductor to achieve high fields of the order of 10-12 T. They use cables with approximately the same cross-section as the LHC dipoles, but operate at double the current taking advantage of the higher critical current density of Nb_3Sn with respect to NbTi. Other Nb_3Sn magnet R&D projects aim at even higher fields.

The addition of copper stabilizer is often erroneously perceived as the best remedy to high temperatures during quenches, but it affects peak temperatures only in a limited way, and rather results in a dilution of the overall current density in the coils.

Adding more heaters is a more efficient way to deal with this problem. While the LHC covers 12% of the coil surfaces with heaters, the dipoles proposed for the second stage VLHC [1] would require, according to a preliminary analysis, up to 100% heater coverage [25]. Heater redundancy, which is definitely required, becomes a difficult task for a heater coverage >50%. On the other hand, new experimental evidence of strong quench-back in LHC- and LBL-Nb_3Sn- magnets, raises the hope that quench-back could in the future be an integral part of quench protection designs, thus allowing a reduction of the amount of heaters installed and allowing for redundancy.

Increased heater coverage results in faster magnet discharges causing larger inductive voltages. Low inductance magnet designs were recently proposed and developed, such as the base-line dipole for the second stage VLHC [1].

The higher current in the high field Nb_3Sn magnets, and especially in the low inductance designs, will require more bulky and complicated bypass diode systems to cope with 20 kA or more.

Another issue that is currently perceived as important, is the problem of thermo-mechanical stresses during quenches, that could result in a permanent degradation of the critical current in brittle Nb_3Sn. R&D is on the way to establish the maximum allowable peak temperatures to prevent this effect.

10. Superconducting Magnets for a Muon Collider or Neutrino Factory

A muon collider or a neutrino factory requires the extensive use of superconducting magnets. The two types of muon machines are similar in their design. The primary difference lies in the muon cooling system and the acceleration system for the two types of machine. It is said that the neutrino factory can be the front end of a muon collider. The primary difference between the front end of a muon collider and the front end of the neutrino factory is the extent to which the muons are cooled before acceleration. The front end of both types of machines is a string of superconducting solenoids that both direct and focus the muon beam.

The front ends of both a muon collider and a neutrino factory start with a 20 T capture solenoid around a target that is impinged by a high intensity (1 to 4 MW) proton beam. This magnet is a hybrid magnet that operates in an extremely high radiation environment. The capture solenoid is DC, so the outsert portion of the magnet is a superconducting solenoid that develops an induction that is as high as 14 T in its own right. The field in the capture system decreases adiabatically as one moves down the channel away from the target. As one moves downstream from the target all of the solenoids are superconducting. Room temperature shielding keep the superconducting magnets from turning normal under the high radiation load from the target. It is proposed that at least some of these solenoids be made using a cable-in conduit conductor.

Once the pions produced at the target are captured, they must go through phase-rotation. The phase-rotation process slows down the high-energy particles and speeds up the low-energy particles. Phase-rotation can be accomplished using low frequency RF cavities or using an induction accelerator. In both cases, the particles are directed using a solenoidal field. High current density superconducting solenoids that produce an on axis induction of 1.25 T to 3 T are needed inside the RF cavities or the induction accelerator. These solenoids can be challenging from a cryogenic standpoint because there is very little room for the cryostat and the magnet cryogenic services.

Once the muons have been phase-rotated, they must be cooled to a low emittance so that they can be accelerated to high energy. The degree to which the muons must be cooled depends on the size needed for the final beam. A muon collider requires much more muon cooling than does a neutrino factory. Ionization cooling has been proposed for cooling the muons. Ionization cooling has alternating acceleration and absorption method. The absorption removes both longitudinal and transverse momentum. The acceleration phase puts back the longitudinal momentum lost in the absorber. Hopefully, multiple scattering during the absorption phase does not heat the beam more than a cell can cool the beam. Several cooling schemes have been studied. All of the schemes require RF cavities that are in a magnetic field. The absorber, which is smaller than the RF cavity, is also in a magnetic field. A number of the cooling approaches will require that the field be flipped within either the RF cavity or the absorber. The solenoids in the cooling section will be challenging because there are large forces on the coil. Later stages of muon cooling will require large on axis fields. The highest on axis fields that have been discussed approach 30 T. The point in the cooling channel where the highest field occurs is where the magnet aperture is the smallest. The cooling channel solenoids begin to resemble accelerator dipoles in that the highest current density conductor is needed in the highest field region of the cooling channel. The continued development of A-15 and HTS conductors will benefit the muon collider. The cooling channel for a neutrino factory does not push the superconductor as much.

The first stages of muon acceleration will use solenoidal focusing as part of a superconducting linac. As one moves up in beam energy solenoidal focusing is replaced by quadrupole focusing. The size of the focusing magnets and bending magnets in the acceleration section is dictated by the size of the muon beam leaving the muon cooling system. The final stages of muon acceleration will either occur in a re-circulating linac or an FFAG. The peak field for any of these magnets is about 7 T. The acceleration section will see some heating from muon decay (about 1 W per meter of length). The decay product heating can be reduced using a room temperature water-cooled liner.

The storage ring for either the muon collider or the neutrino factory requires relatively high field accelerator type magnets to bend and focus the beam. In both cases, it is desirable to reduce the length of the bending sections of the storage ring. From a practical standpoint bending magnets that produce a central induction of 6 to 10 T would be attractive. High gradient quadrupoles are probably not needed for the neutrino factory storage ring, but they are needed in the collider storage ring in the region around the collision point. The dominant factor in either the muon collider or the neutrino factory storage ring is the heating due to muon decay. Depending on the type of machine and its design, this muon decay heating will be from 0.1 kW to 3 kW per meter of magnet length in the storage ring. The portion of this heating entering the cryogenic region of the magnets must be less that 1 or 2 W per meter. This has lead to some unusual magnet designs or large aperture magnets that have a room temperature beam absorber within the magnet bore. Some of the magnet designs proposed for the muon storage ring require the use of niobium tin or some other high field conductor. The development of the muon storage ring will benefit from continued development of high current density conductors that operate at fields above 12 T.

Since the magnets in the muon collider or neutrino factory use high current density conductor, the key magnets in the system should be built and be tested. Training is a potential issue even for superconducting solenoid magnets. The magnets in the phase rotation system and the cooling system should be modeled. The magnets for the re-circulating linacs and the storage ring will be a challenge; so model magnets should be built. If the muon collider or the neutrino factory is going to be a part of the future of high energy physics in the United States, the superconducting magnet modeling work should be done along with conductor development. Conductor development for the high field magnet work in the United States will benefit the muon collider and neutrino factory as well as the VLHC.

11. Superferric Magnets

The superferric magnets are a very attractive approach for the future staged colliders. One of the proposed options for future VLHC is to build as large as possible in perimeter tunnel, install there superferric magnets of Stage I and upgrade later the accelerator with help to Nb_3Sn high field magnets to the maximum possible energy. P.J. Limon presented VLHC Design Study Report [1] based on this scenario at the Snowmass plenary meeting.

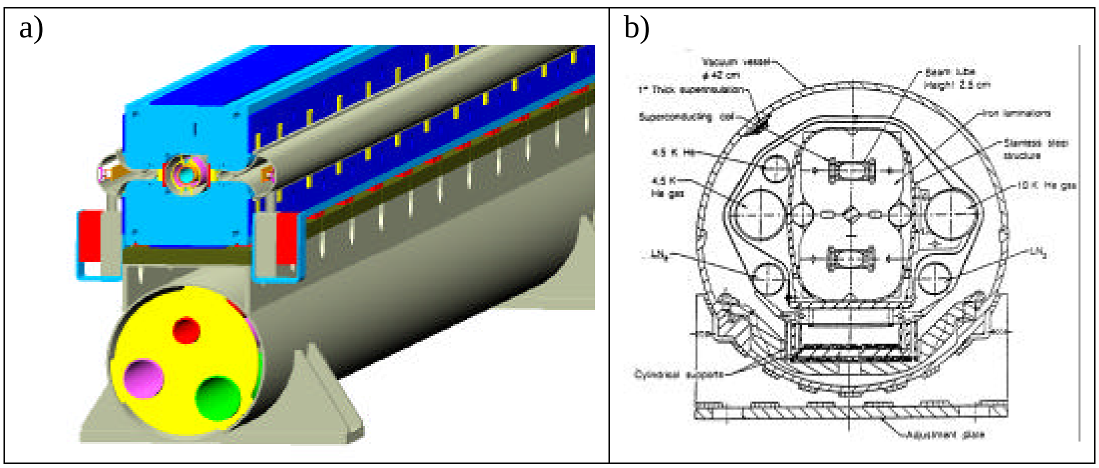

Figure 8: a) VLHC 2 Tesla Superferric Magnet; b) SSC 3 Tesla Superferric Magnet.

The 2 Tesla superferric magnet for VLHC Stage 1 was discussed, which is under design and model tests at Fermilab. Good quality 2 Tesla fields are achievable using holes in poles to correct saturation effects. Several short models were tested. The test stand for two 6-m length magnets, Hall probe array, 100 kA power supply, and current leads is now under construction. The promising concept of a 3 Tesla transmission line magnet with a cold iron core [26] was also discussed. A single turn winding and small pole-correction coils give the possibility to correct iron saturation effects. It was also proposed to install permanent magnet rotational multipoles inside each half-cell as correction elements to reduce the correction system cost.

3 Tesla superferric dipole magnets with cold iron cores were proposed for SSC and investigated in the past by the Texas A&M. Four 34-m length magnets were built and tested with good results. For this design (window frame magnet with cold iron), it is possible to increase the field level up to 6 Tesla. The saturation effects for these magnets are eliminated by separate winding coils excited by 3 different power supplies.

The cost analysis for a future VLHC 1 was presented in the Design Study report. The magnet field range of 2–5 T should be carefully investigated. A careful comparison of all designs, using cost optimization and analysis of the whole accelerator structure, is needed to choose the optimal magnet for the VLHC.

12. R&D Issues and Planning

Future R&D work should involve developing new designs and technology and understanding the issues involved with the present technology in a systematic way so that it can be pushed towards cost effectiveness. High field magnet development can be divided into two categories: first, where the performance is a major issue (for example IR magnets) and second, where the cost is a major issue (for example arc dipole magnets). The design and technology should be optimized accordingly.

Due to recent advances, dipole magnets with fields in the range of 2 – 15 Tesla can be considered as possible options. However, the time and resources required to develop the technologies vary significantly. For example, low-field superferric magnets such as the FNAL Transmission-line magnet or the Texas Accelerator Center (TAC) magnet could be brought into production in less time than it would take to dig a tunnel for a new machine. High field magnets based on Nb_3Sn would require longer development time, on the order of 10 years, depending on funding levels.

During the workshop, many design options and issues related to cost and performance were identified and have been described in this report. Some examples are:

- **Aperture:** With higher energy machines, there is a trend towards smaller apertures. Cost savings come from a reduction in the quantity of conductor required for a given field and support structure. Eliminating beam screens, which take up precious aperture, and dealing with beam instabilities are the challenges.
- **Magnet length**: By reducing the number of magnets and hence the number of expensive interfaces, increasing the magnet length has clear cost saving advantages. The issues involved (which can only be studied by building magnets) are: mechanical stability and alignment, transport and magnetic measurements.
- **Coldmass design:** Several magnet geometries have been presented, but a lot of work, integrated with input from accelerator physicists, is required to evaluate all the options and choose the right combination of cost and performance.
- **Field quality:** Cable size control during heat treat process for Nb_3Sn, cross-section designs that reduce persistent current effects and extending dynamic range (iron saturation control) are a few of the issues needing study.
- **Support systems (cryo, quench protection, etc.):** Designing magnets that do not require complex support systems has obvious cost saving potential. Helium inventory, heat loads, warm- vs cold-iron designs, quench protection requirements (active vs passive), and copper current density are all topics for intensive study.

- **Large scale production and testing:** Large scale, industrial production is an absolute necessity when considering fabrication of thousands of magnets. Significant R&D effort is necessary to provide manufacturability designs. Experience has demonstrated a lack of sufficient consideration of the value of robust mechanical designs. Both SSC and LHC magnet designs were not adequately prepared for industrial fabrication.
- **High gradient IR quads (conductor development (HTS) and radiation hardness):** High gradient quadrupoles represent the greatest challenge in terms of performance. High fields and very large heat loads require either innovative use of Nb_3Sn or of HTS, whose viability still needs to be demonstrated.
- **Magnetic measurements:** Long magnets with smaller bores require development of new techniques for magnetic measurement.
- **Conductor cost (Nb_3Sn)**
- **Superferric magnets:** Further development of superferric magnets includes fabricating prototypes of 2 Tesla Transmission-line magnets, explore a 3 Tesla cold-iron option based on the Texas Accelerator Center magnet design and MgB_2 transmission lines at 20 K.
- **Permanent magnets:** Permanent magnets have now become a viable alternative for a wide variety of applications. A large number of topics needs more development: thermal and radiation stability, active and passive correction systems, adjustability, hybrids, and cost optimization.

Currently, there are four programs in the US that focus on accelerator magnet development: Fermilab, Lawrence Berkeley National Lab, Texas A&M and Brookhaven National Lab.

The U.S. programs, complementary in their approaches, manage to pursue a significant subset of the major R&D issues. However, given the relative importance of magnet sub-systems, either as significant cost drivers and/or providing a critical function, the current level of R&D effort is disproportionately low. For example, development work on medium-field magnets as a VLHC alternative is non-existent. In the case of other options, most notably high field magnets, progress towards achieving a technological base from which to launch a development program has been hampered due to lack of adequate support. Realistic evaluation of the broad range of magnet technologies, ranging from permanent magnets to high field, superconducting dipoles, requires a more aggressive program. The formula for success requires a substantial increase in the base magnet program along with an increase in collaboration (sharing lessons learned and facilities) between magnet programs in the U.S. and abroad. A 10 – 15% per year increase for the next 3 – 4 years seems modest considering the scope, but would have a significant impact on productivity. An integrated approach, combining input from accelerator physicists and evaluated using a standard cost model is necessary to arrive at a cost/performance optimized design. It was suggested that the RHIC model be generalized and used as a basis for design comparisons. The very successful VLHC Design Study is an excellent example of the combined approach (and effort) needed to evaluate accelerator/magnet options, and it should be expanded to include other possibilities.

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