Nb_3Sn Accelerator Magnet Development Around the World

Michael J. Lamm

Abstract— During the past 30 years superconducting magnet systems have enabled accelerators to achieve energies and luminosities that would have been impractical if not impossible with resistive magnets. By far, NbTi has been the preferred conductor for this application because of its ductility and insensitivity of Jc to mechanical strain. This is despite the fact that Nb_3Sn has a more favorable Jc vs. B dependence and can operate at much higher temperatures. Unfortunately, NbTi conductor is reaching the limit of it usefulness for high field applications. Despite incremental increases in Jc and operation at superfluid temperatures, magnets are limited to approximately a 10 T field. Improvements in conductor performance combined with future requirements for accelerator magnets to have bore fields greater than 10 T or operate in areas of large beam-induced heat loads now make Nb_3Sn look attractive. Thus, laboratories in several countries are actively engaged in programs to develop Nb_3Sn accelerator magnets for future accelerator applications. A summary of this important research activity is presented along with a brief history of Nb_3Sn accelerator magnet development and a discussion of requirements for future accelerator magnets.

***Index Terms*— Superconducting accelerator magnets, Superconducting cables, Superconducting filaments and wires.**

I. Introduction

Particle accelerators require the use of specialized dipoles and quadrupoles to repeatedly steer and focus the beams through the accelerating RF systems and then guide and focus the particles into collision. These magnets are typically several meters in length with apertures on the order of 50 mm with very uniform transverse fields. As the accelerator radius is often fixed by practical real estate considerations, the fields and gradients of these magnets ultimately set the energy and luminosity limit for these accelerators. Throughout the history of particle accelerators there has been a strong interplay between HEP goals for energy and luminosity and what can be practical achieved with present or future accelerator magnet technology. Up to now, accelerators have relied on NbTi technologies to achieve the highest field magnets. As shown in Fig. 1, using a working value of 2000 A/mm^2 critical current, NbTi conductor has a limit at 1.9 K of ~10 T, and is completely unusable at 12 T. On the other hand, HTS and "A15" conductors such as Nb_3Sn can operate in fields in excess of 12T[1]. As shown in Fig. 1, one can achieve 2000 A/mm^2 critical currents with a 12 Tesla field or higher. Furthermore, these materials have the added advantage of operating with a higher T_c than NbTi (9 K for NbTi, 18K for Nb_3Sn), which is advantageous for applications in a high heat load environment. The price for choosing these materials over NbTi is that the conductor is difficult to work with; it is extremely brittle, has very long reaction times requiring special high temperature, gas inert ovens, and is expensive to manufacture relative to NbTi. For this reason, NbTi has been used for all accelerator magnets to date [2].

Of the higher field materials, Nb_3Sn has been the most widely used to date, because of its combination of Jc, continuous piece length and lower production cost. In fact, several one-of-a-kind accelerator model magnets have been built with Nb_3Sn conductor over the past 40 years.

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II. Brief history of Nb_3Sn Magnet development

Prior to using superconductor materials, accelerator magnets were iron core magnets with water-cooled copper conductor. The field strength of these magnets is limited to ~2 T due to iron saturation. Furthermore, the power consumption of these resistive magnets became enormous, finally becoming the largest single power consumer during operation [3].

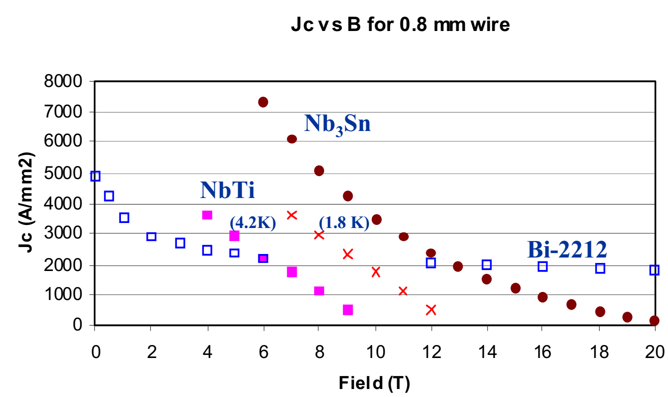

Fig. 1. Critical Current vs. Field, for various conductors at 2002 technologies (Courtesy of R. Scanlan)

Major advancements in the development of class II superconductors in the 1950-1960 made it possible to consider this material for accelerator magnet applications [3][4]. In 1962, Nb_3Sn materials had been developed that could achieve a Jc of 100 A/mm^2 in an external field of 2.5 T [3].

During the 1960's through the 1980's programs in the US and Europe developed Nb_3Sn magnet models as an alternative to NbTi. As early as 1967, a 20 cm long Nb_3Sn quadrupole magnet was built and tested at BNL using Nb_3Sn react and wind tape. The magnet had a wide 70 cm bore and achieved a gradient of 85 T/m, with 3 T peak field in the conductor and 400 A/mm^2 critical current [5]. Later in 1979, 80 mm aperture dipoles were made with react and wind "Isabelle braid" cables achieving bore fields comparable to Tevatron NbTi dipoles at (4.8T at 4.6K) and could operate in helium gas at lower fields up to 17 K [6]. At CEN/Saclay, a two-layer dipole, similar in design to the Tevatron arc dipole achieved 6 T [7]. While these magnets demonstrated promise of Nb_3Sn, NbTi magnets with comparable or better field and quench performance were chosen for large-scale projects [8][9].

In the 1980's interest in Nb_3Sn magnets was renewed with the proposal to replace the LEP electron/positron ring with a hadron collider. There were two competing ideas for the upgrade, one was to make Nb_3Sn magnets operating at 4.2 K, the other was to make NbTi magnets operating in superfluid. The former involved continue R&D in Nb_3Sn while the latter required a significant cryogenic upgrade for CERN. Through a collaboration of ELIN and CERN, model dipole coils using the wind and react technology, culminating the successful construction of a 10.5 T dipole [10]. Despite these successes, the decision was to made to adopt the NbTi at 1.9K approach.[11]

In the 1990s, Nb_3Sn research in "LHC" type dipoles was largely centered in Twente and LBL, with significant progress made in quench and mechanical performance. Both programs utilized a "cosine " design with wind and react Rutherford cables. In 1997 Twente reported a record field of of 11 T [12][13][14] followed the later that year by a 12.8 T at 4.4K and 13.5 T at 1.8K. [15]

Perhaps bolstered by these results as well as the requirements for future accelerators requirements, several institutions started or rejoined their efforts in the Nb_3Sn magnet technology towards the end of the decade and into the present, including Fermilab, TAMU, BNL, as well at LBL, Saclay and University of Twente.

III. Present and Future Magnet Requirements

Nb_3Sn will likely be featured in future accelerator projects involving higher energy or higher luminosity. Examples of these future projects with Nb_3Sn accelerator magnets are proposed new or upgraded hadron accelerators [16][17], muon colliders [18][19], high luminosity interaction regions for Linear or hadron synchrotron accelerators [20][21] and even a hydrotest facility [22].

The most immediate goals for energy and lumpiest are set by the world's future largest hadron collider, the LHC [23]. The LHC will collide 7 TeV x 7TeV protons with a maximum design luminosity of 10^{34} cm^{-2}s^{-1}. Operation of this machine requires dipoles and quadruples of 50-70 mm apertures with peak bore fields of 8.4 T and gradients of 220 T/m. These magnets have a peak field in the conductor of approximately 9-10 T which can be accomplished by utilizing NbTi conductor operating in superfluid. After a long technology development program, all the magnets for the LHC are in production [24].

Already there are discussions for upgrades for this machine as well as plans for a possible Very Large Hadron Collider (VLHC), colliding protons at several hundred TeV center of mass energy. Upgrades for the LHC in the 10-15 year horizon center around improving the luminosity by a factor of two by increasing the machine's *[25]. One scenario calls for replacing the first generation LHC IR 70 mm quadrupoles with a larger 90 mm aperture quadrupole with the same gradient [26]. The time scale for an energy upgrade for the LHC is further in the future, and would require replacing the arc dipoles with magnets with field of >17 T along with a correspondingly strong arc quadrupole [17]

The VLHC is being considered for this longer 20-30 year time frame. In 2000, a VLHC study group was formed, and after a several month design study, a report was written on a possible VLHC [16]. In order to reach a collision energy of several hundred TeV, a 233 km circumference tunnel was proposed. Fig 2 shows a possible tunnel layout. The report suggests that the following general principles are needed for accelerator magnets to reach these highest energies: 1)operating field range up to 10 T for both arc and DS dipoles, 2)gradients of 45-400 T/m for arc and DS, quadrupoles, with coil apertures >40 mm sufficient for beam screen and vacuum pipes, 3)finally the magnet must be robust and must come an affordable price.

IV. Design Considerations

Magnets developed for these programs can be categorized in two broad categories, "cos(" and "block coil". The cos(is the traditional single aperture design used in the Tevatron and continued through every operational magnet to date. An example is shown in fig. 3a. The cable is arranged in an approximate "cos(" arrangement by using keystoned Rutherford cable and non-magnetic spacers. The cos(gives the most efficient utilization of conductor. As the magnet is single aperture, there is no restriction on coil placements in dual aperture magnets. As the coil requires tight bend in the pole end regions, the coils are most likely fabricated using the "wind and react" method. This requires that all internal coil pieces, i.e., insulation, conductor & spacers must be able to withstand the high reaction temperatures. The block design, as the name implies, places cables in parallel arrangement as shown in Fig. 3b. This block arrangement keeps the conductors parallel and unkeystoned, allowing for local cable support. An important variation of this design is the "common coil" design where each coil supplies current to two apertures. This eliminates the need for tight conductor bends in the pole region. In this case, it may be possible to utilize a cable the follows the "react and wind" approach.

Fig.2. Proposed tunnel layout for VLHC utilizing Nb_3Sn dipoles

The design of these superconducting accelerator magnets are guided by general principles of mechanical stability against spontaneous quenches, field quality across the magnet aperture and protection against excessive coil voltage and temperature as a result of a spontaneous quench. For magnets made with Nb_3Sn conductors, there are several problems in achieving these goals beyond those encountered with NbTi magnets.

Mechanical stability is difficult due to the extreme sensitivity of reacted Nb_3Sn to strain. Nb_3Sn coils are given added mechanical support by vacuum impregnating the coils with epoxy. The downside of impregnation is that the coils can no longer by directly cooled by LHe and are thus can be sensitive to beam induced heating.

Field quality is also a challenge. Reacting of the coils and impregnation make it more difficult to control the final position of the cable conductors. It is estimated that the conductor positioning is on the order of 50 microns, or 2-3 times worse than with NbTi magnets [27]. The state of the art superconductor has 50 micron filament sizes, a factor of 5-10 larger than NbTi conductor. If not properly compensated for, this leads to large magnetization effects, which are proportional to filament diameter. Short of reducing the filament diameters, passive correction schemes have been shown to significantly reduce this effect [28]. Finally, the reaction process leads to small interstrand resistances, which results in larger eddy current losses. Inserting a stainless steel core in the cable is a strategy for reducing these losses.

Magnets must be self-protected against a spontaneous quench. Once the quench occurs, the magnet leads are effectively shorted together and the quench protection heaters discharged. For any practical accelerator application, the stored energy must be dissipated with the magnet. This can lead to large non-uniform thermal expansions which can cause cracking in the coil epoxy, thus degrading the coil support.

This problem is exacerbated by the large stored energy in many of the magnet designs and the very long magnet lengths proposed (>10 m VLHC). Solving these problems is a major challenge faced by the many Nb_3Sn programs. For example, computer models for quench propagation and heat transfer have been incorporated into the ANSYS ™ program to simulate the thermo mechanical effects in the quench protection process [30]. Data from the model test programs can be used as empirical parameters for these models or to validate the model calculations. Results from model tests indicate that heater efficiencies are very good despite the coil impregnation [30]. Also "Quench back" should contribute significantly to the quench propagation after the quench protection heaters are fired. Finally studies of quench propagation and heat transfer can be performed directly on short sections of cables in high magnetic fields [31].

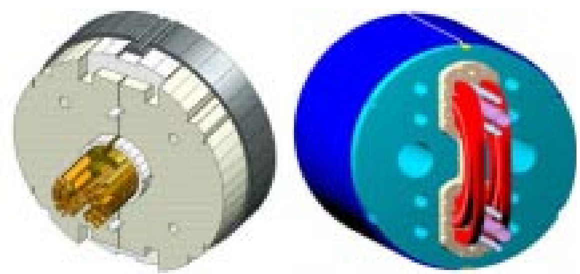

Fig. 3. a) Cos magnet design b) Common Coil design

V. Conductor and Cable R&D

As the accelerator performance is ultimately limited by the performance of the magnets, the magnet designs in particular coil design and coil mechanical support, are driven by the characteristics of the best available conductor and cable. Recognizing this need, there is a vigorous cable and conductor program concurrent with the magnet programs.

Of primary consideration for conductor is critical current Jc. Strand diameter, piece wise lengths, degradation due to mechanical strain, and of course production costs are also important considerations. Figure 4 shows a summary of the progress made over the past 20 year in Jc of Nb_3Sn conductor. Through the 1980's much of the conductor development was been driven by magnet requirements for the International fusion program [33]. These rapid cycling magnets were most concerned about eddy current effect coupling, and less concerned about high Jc and magnetization effects due to large strand diameters. However, in the 1990's, a renewed effort has been made to develop strand for high field magnets.

One example has been the development in the Netherlands of powder in tube conductor the University of Twente [33]. They have been successful in developing with industry a powder in tube conductor with good Jc and very small filament diameter and very low degradation during cabling.

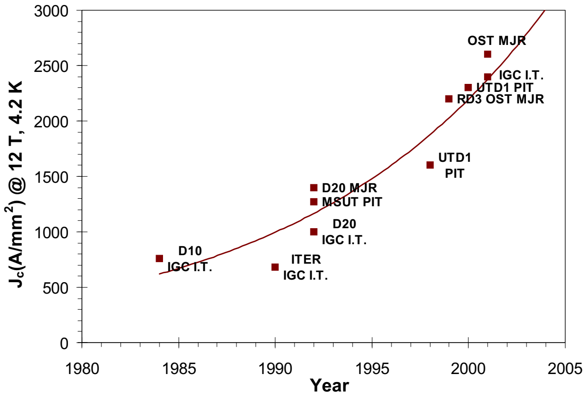

Fig. 4. Summary of Nb_3Sn conductor development over the past 20 years (Courtesy of R. Scanlan)

In 2000, a program called the US/HEP Conductor Development Program was formed. Its goal is to provide cost effective high performance Nb_3Sn conductor that could be used in a future accelerator magnet application [34]. This effort is a collaboration let by LBNL with participation among industrial conductor vendors, national laboratories and university research facilities. For example, through HEP participation with industry, LBNL has worked with OST who has increased the Jc to >2600 A/mm^2 at 12 T, which is a new world record. As part of this program, Fermilab has worked with vendors to characterize the Nb_3Sn materials with regards to Jc, magnetization RRR and strain tolerance. Modifications of the heat treatment cycle indicate improvements in magnetization strain tolerance and Jc and reduction of the heat treatment times. Table I shows a summary of the state-of-the-art conductor [35]. As can be seen, the program is well on its way to meeting its goals.

TABLE I
CONDUCTOR GOALS AND PRESENT STATUS

Specification	Target Value	Present Achieved
Jc (noncopper, 12T, 4.2K)	3000 A/mm2	2600-2900 A/mm2
Effective filament size	Less than 40 microns	100-120 microns
Minimum piece length	> 10 km	250-1000m
Wire cost	Less than $1.50/kA-m (12T, 4.2K)	$5.0-7.75/kA/m
Heat treatment times	Less than 200 hrs	148 hours

Along with the conductor development there have been several innovations in the cabling process that have improved the conductor performance. For example, the inclusion of a stainless steel core greatly reduces the AC losses by minimizing the interstrand cross over resistance. Another very interesting idea is to mix strands of pure copper with Nb_3Sn, thus reducing the cost of the manufacturing process but reducing the number of Nb_3Sn strands [36]. Finally, a program to create "react and wind" cables is being carried out at LBNL, BNL and Fermilab. Utilizing pre-reacted strands in a 6-around-1 cable makes a flexible Nb_3Sn cable that has good strain sensitivity [37].

VI. MAGNET R&D PROGRAMS

The Fermilab program, following its production oriented tradition, has the goal of developing "accelerator quality" magnet with dipole fields between 10-12 T and wide aperture quadrupoles in the range of 200-300 T/m. Magnets operate in 4.3-4.5 T with large critical temperature margin for use in high heat load environments. "Accelerator quality" magnets mean magnets that are cost effective, robust fabrication design, with highly uniform bore fields that are reproducible through a large production series. There are two parallel lines of development, a cos ( ) design and a common coil design.

The two layer cos ( ) design dipole is shown in fig. 3a. It utilizes a keystoned Rutherford cable of 28 1 mm diameter strands. Cable is wound with stainless steel core to minimize the cross over resistance. The two layers are wound and reacted together eliminating the need for the inner/outer coil splice. Mechanical support of the impregnated coils is accomplished through a stainless steel skin through aluminum spacers.

Several models have been built and tested [30]. Magnet quenches have not reached their short sample limit due to quenches near the NbTi to Nb_3Sn transition. Despite not reaching full fields and quench propagation, heater efficiencies have been studied and applied to the quench models. The magnet program has been very successful in achieving its goals for field quality. The harmonics for the models are low, and consistent with expected coil displacements [27]. The use of a stainless steel core in the conductor was very successful in reducing interstrand resistance. Finally, a study of passive corrector greatly reduced the low current magnetization effects.

A cos(2 version of this magnet is being considered as a possible candidate for an LHC IR upgrade [26]. The design constraints for the magnet are that it must operate in 4.5K helium or superfluid helium and have an outer diameter and operation current compatible with the existing LHC IR system and have a 90 mm bore with 250 T/m peak gradient. The proposed cross section is shown in Fig. 5. One interesting feature of this design is the large cut outs in the cold iron which on the one hand provide cooling and still provide suppression of the iron saturation effect. Note that LBNL is also working on designs for this upgrade and are being presented at this conference [38]

A parallel approach has been to develop a common coil dipole as shown in Fig. 3b [39]. This magnet has a maximum nominal field of 11 T at 4.5 K with a 40 mm aperture. The coils are single layer, enclosed in a laminated collar structure. The "bridge" piece between the apertures is designed to accommodate the expected 750 MPa peak pressure during excitation. The wide separation of the two apertures allows for a wide bends in the ends thus making it possible to consider a conductor with the "react and wind" approach. In order to achieve the necessary amp-turns for a single layer magnet, a cable with a large width to thickness aspect ratio is required. This cable has been constructed from ITER conductor and cabled at Berkeley. Construction of a 1 meter model is on going. It is expected to be built and tested during the Fall 2002.

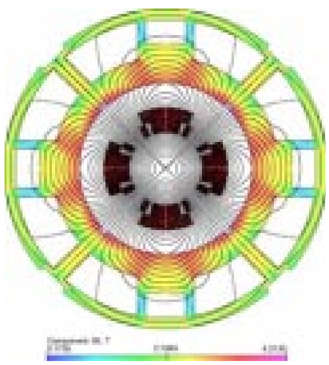

Fig 5. Fermilab design for future LHC design (Courtesy of A. Zlobin)

Supporting the "react and wind" approach is the "race track" coil structures [40]. Two layers of impregnated react and wind coils are tested together in a bolt mechanical structure. This structure is very useful for understanding mechanical coil support, insulation schemes and quench heater efficiency.

The high field magnet program at the Lawrence Berkeley National Laboratory (LBNL) has centered on this common coil approach, after a very successful cos- program [15]. The programs effort is divided into three efforts, the "RD" program which geared towards accelerator field quality dipoles, the "HD" program whose goal is to build the highest field dipoles using simple coil designs and less emphasis on field quality and the "SM" program which produces short coils. The RD program is geared towards accelerator quality common coil dipoles. The magnets are characterized by one or more pancake coils. Last year, the RD3b, a three layer coil, reached a field of 14.7 T a new record of accelerator dipoles. The most recent RD3c is shown in Fig 6. It consists of a double layer pancake with a set of auxiliary coils for improved field quality. Results are presented at this conference [41].

The SM and HD programs support the main program. The SM program are 1/3 scale magnets, with a field range of 9-12 T, which allow to test new ideas such as new fabrication and cabling techniques. The HD program idea is to make flat coils with very simple geometries to push the limits of conductors and materials. The first HD magnet, set for construction and test in 2003 has an expected short sample limit of 15 T, with future magnets proposed to max the Nb_3Sn limit.

BNL, with its long tradition of Nb_3Sn development has embarked on a program to build high field magnets out of new high field materials. The central approach has been to use the "react and wind" cable technology outline above and to incorporate innovative magnet designs to fit the conductor capabilities [44]. There are two parallel magnet programs. The first is relies on the aformentioned Flexible "6 around 1" flexible cable using the slotted magnet developed for the RHIC Spin Program. This construction technique relies on a slotted collar structure, which divides the coil into many independently supported sectors, each sector can be used to control the Lorentz forces, as shown in Fig 7 [43]. The second program is ultimately geared toward HTS materials but the same principles apply to Nb_3Sn. The design is similar to those used at LBNL, with simple race track coils. Innovative ideas for coils include a very high gradient flat coil quadupole. Like the LBNL "SM" program, they have initiated a short model test coil program to conductor, cable and insulation scheme. As part of this process, a 12 T common coil react and wind Nb_3Sn dipole is being designed and built to provide a background field for these test coils. This Nb_3Sn magnet is expected to be built and tested next year [44].

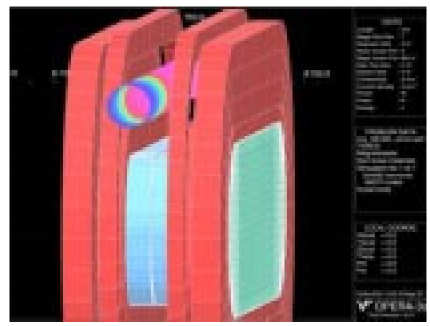

Fig 6. LBNL RD3c (Courtesy of S. Gourlay)

The block design is used in a single aperture dipole design at the Texas A&M University. The goal here is to build a 12 T dipole with 30 mm aperture using wind and react conductor. The magnet consists of four pancake coils arranged in approximate cos- geometry. The most unique feature of this magnet is the support structure. Each coil has its own support system so that stress cannot accumulate between blocks. Progress towards building this magnet will be reported at this conference [45]

The University of Twente is also heavily engaged in a program of developing high field dipoles. Following their success with the 11 T wind and react MSUT dipole, their goal since 1998 has been to build a 10 T 88 mm dipoles that could be used as a future upgrade to the LHC D1 separation dipole. Much of the effort up to this point has been in developing the conductor for this magnet which utilzes the powder in tube technology. The magnet is under construction and should be available for test next year [33].

Finally, work continues on Nb_3Sn quadrupoles at Saclay. Their proposed magnet has the some cross section as the LHC arc quadrupoles but with a Nb_3Sn conductor. This magnet is be used for application as insertions quadrupole for project such as the Tesla interaction regions [20].

Fig 7. BNL slotted collar dipole design (Courtesy of E. Willen)

VII. Conclusion

Accelerator magnets utilizing Nb_3Sn have been studied for the last 30 years and have never been overshadowed by their NbTi counterparts. Future accelerator applications are beyond the field reach of NbTi, thus making Nb_3Sn attractive. There has been significant progress in the past years in all phases of conductor development. Cabling techniques and coil designs take advantage of these innovations to create magnet designs with high fields with accelerator quality field homogeneity. The next test is to produce magnets suitable for use in an actual accelerator. This requires improvements in conductor costs, ease of manufacturing and reproducibility of the high field quality.

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References

[1] R. Scanlon et al., "Development of Cost-Effective Nb_3Sn Conductors for the next generation hadron colliders", *Adv. In Cryo Eng.,* vol. 614, pp.949-957

[2] M. Wilson, "Superconducting Magnets for Accelerators; a review, IEEE Tarns. Appl. Supercond., 7(2), 727-732, 1997

[3] J. E. Kunzler and M. Tanenbaum, "Superconducting Magnets", *Scientific American,* vol. 206, no. 6., New York, 1962, pp.60-67.

[4] H.J. Kolm and A. J. Freeman, "Intense Magnetic Fields", *Scientific American*, vol. 212, no. 5, New York, 1965, pp. 66-78.

[5] W. B. Sampson, "Superconducting Magnets for Beam Handling and Accelerators", *Proceedings for the Second International Conference on Magnet Technology*, H. Hadley, Ed. Oxford, 1967, pp. 575-578.

[6] W.B. Sampson et al., "Nb_3Sn Dipole Magnets", *IEEE Trans. Magnetics,* vol. Mag-15, no. 1, pp. 117-118., Jan. 1979.

[7] J. Perot, "Construction and Test of a Synchrotron Dipole Model Using Nb_3Sn Cable", *IEEE Trans. Magnetics,* vol. Mag-19 no. 3, pp. .1378-1380, May 1983.

[8] "Superconducting Accelerator Design Report", Fermi National Accelerator Laboratory (1979)

[9] "HERA , A proposal for a large electron proton colliding beam facility at DESY", *DESY Hera81-10,*1981

[10] A. Asner, R. Perin, et al., "First Nb_3Sn 1 m long superconducting dipole magnet for LHC break the 10 Tesla field threshold", *Proc. of the 11th Intl. Conf. on Magnet Technology,* Tsukuba, Japan,1989, pp. 36-41.

[11] LHC Conceptual Design Report, LHC Study Group 2000-11-01

[12] H. H. J. ten Kate et al., "Development of an experimental 10 T Nb_3Sn Dipole Magnet for the CERN LHC", *IEEE Trans on Mag.*, vol. 27, no 2., pp. 1996-1999, Mar. 1991

[13] A. den Ouden et al., "An experimental 11.5 T Nb_3Sn LHC type of dipole magnet", *IEEE Trans on Mag.,* vol. 30., no. 4, pp. 2320-3, July, 1994.

[14] A. den Ouden et al., " Application of Nb_3Sn superconductors in accelerator magnets", *IEEE Trans. Appl. Superconductivity*, vol 7, 1997

[15] A.D. McInturff, "Test Results for a high field (13T) Nb_3Sn Dipole", Pac 97, Vancouver, May 1997.

[16] P. Limon et al., "Design Study for a Staged Very Large Hadron Collider Working Group Summary", Fermilab TM-2149, June 2001.

[17] T.M. Taylor, "Superconducting Magnets for a Super LHC", submitted to EPAC 2002, Paris

[18] B. Parker et al., "Magnets for a muon storage ring", submitted to PAC01, Chicago, June 2001

[19] M. Zisman, "Status of Muon Collider and Neutrino Factory R&D", submitted to PAC-01, Chicago, June 2001.

[20] A. Devred et al., "Development of a Nb_3Sn quadrupole magnet model", IEEE Trans. Appl. Supercond. 11(1), March 2001 2184

[21] LHC IR Upgrade Collaboration Meeting, CERN, March 13-14, 2002, http://lhc-proj-ir-upgrade.web.cern.ch/lhc-proj-IR-upgrade/.

[22] N. Andreev et al., "Magnetic Design of Large-Bore Superconducting Quadrupoles for the AHF", 4LC06, this conference

[23] The Large Hadron Collider, CERN/AC/95-05 (LHC) 1995

[24] R. Schmidt, "Status of the LHC" submitted to EPAC 2002 Paris, June 2002.

[25] T. Sen et al., "Beam Physics issues for a possible 2nd generation LHC IR", EPAC 2002, Paris June 2002.

[26] A. Zlobin et al., "Conceptual Design Study of Nb_3Sn Low-beta Quadrupoles for 2nd generation LHC IRs", 2lC04 this conference

[27] E. Barzi et al., "Field Quality of the Fermilab Nb3Sn cos-theta Dipole Models", submitted to EPAC 2002, Paris.

[28] V.V. Kashikhin et al., "Passive Correction of the Persistent Current Effect in Nb3Sn Accelerator Magnets", 2LC08, this conference

[29] R. Yamda et al., "Stress Effects of Quenches on Epoxied Nb3Sn High Field Magnets and their Limitations", 1LJ06, this conference

[30] N. Andreev et al., "Development and Test of Single-bore cos-theta Nb3sn Dipole Models With Cold Iron Yoke", MT17, Geneva, Sept. 2002

[31] L. Imbasciati et al, "Effect of Thermo-Mechanical Stress during quench on Nb3Sn magnet performance", 1LM06, this conference

[32] N. Mitchell et al, "Conductor Designs for the ITER Toroidal and Poloidal Magnet Systems," *IEEE Trans on Mag.* 30, pp 1602-7 (1994).

[33] A. den Auden et al., "Component properties of a 1 m ,10 T Nb_3Sn Dipole Magnet", 3LA04 this conference.

[34] R. Scanlan et al., "Progress and Plans for the High Energy Physics Conductor Development Program, 5LA04, this conference

[35] E. Barzi et al., Studies of Nb_3Sn Strands for High Field Accelerator Magnets at Fermilab, 5MJ05, this conference

[36] M. Coccoli et al., "Fabrication and Performance of Nb_3Sn Rutherford-type cable with Cu Added as a separate component", 1LM02, this conference

[37] N. Andreev et al., Development of Rutherford Cables for High Energy Accelerator Magnets at Fermilab", 3LA06, this conference

[38] S. Caspi et al., "Nb3Sn Quadrupole Magnets for the LHC IR", 2LC03, this conference

[39] I. Novitski et al., "Development of a Single-Layer Nb3Sn Common Coil Dipole Model",2LC05, this conference

[40] G. Ambrosio et al., "Fabrication and Test of a Racetrack Magnet using Pre-reacted Nb_3Sn Cable", 3LA03, this conference

[41] A.F. Lietzke et al., "Test Results for RD3c, a Nb3Sn Racetrack Dipole Magnet", this conference, 3LA05

[42] R. Gupta et al., "R&D for Accelerator Magnets with React and Wind High Temperature Superconductors"., MT17, Geneva, Sept. 2002

[43] E. Willen, "Construction and Test of Nb3Sn Coil MCA003", BNL SC Div. Note, MDN-612-32 (AM-MD-313) January 2002

[44] R. Gupta, private communication

[45] P.M. McIntyre et al., "Construction and Testing of Block-coil High-field Dipoles for Future Hadron Colliders", 4LC04, this conference