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Author

Sabbi, Gian Luca

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Status of Nb₃Sn Accelerator Magnet R&D

Gian Luca Sabbi

¹*Abstract*--Excellent mechanical and electrical properties of multifilamentary NbTi have made it the conductor of choice in superconducting accelerators starting from the Tevatron. However, the LHC operating field of 8.33 T is close to limit for NbTi technology. In order to advance to higher fields, a superconductor with higher upper critical field is needed. At present, Nb₃Sn is the most suitable material in terms of properties, availability, and cost. In contrast to NbTi, Nb₃Sn is brittle and strain sensitive. Magnet R&D programs are underway worldwide to develop technologies that can take advantage of Nb₃Sn properties while coping with the associated challenges. Status and accomplishments of the different programs are reviewed in the context of the requirements of next-generation accelerator facilities and possible upgrades to present ones.

I. INTRODUCTION

SUPERCONDUCTING accelerator magnets have supported advanced programs in experimental high-energy physics for the past 20 years. The ductile Niobium-Titanium alloy (NbTi) allows simple fabrication methods for wires and cables, and has been the superconductor of choice in all projects to date [1]. Significant increase of NbTi critical current density resulted from improved understanding of the factors controlling the microstructure [2]. However, NbTi performance is ultimately limited by its upper critical field $B_{c2}=10.5$ Tesla at 4.2 K. A 3 Tesla increase of B_{c2} can be obtained by lowering the temperature to 1.9 K. This method, which presents considerable engineering challenges, has been adopted by the Large Hadron Collider (LHC), presently under construction at CERN, to achieve 14 TeV collision energy at a nominal dipole field of 8.33 T [3]. While this requirement is close to the limit for NbTi technology, several next-generation facilities demand significantly higher fields. Design studies for a high-field Very Large Hadron Collider (VLHC) have been developed, based on 10-12.5 T dipoles [4]-[6]. High-field magnets operating under severe radiation load are needed for the Muon Collider and Neutrino Factory [7]. A Tevatron energy upgrade has been proposed, with operating field of 12 T [8]. In addition, all future facilities as well as upgrades of present ones [9], [10] require powerful dipoles and quadrupoles for beam steering and focusing at the Interaction Points.

Among the potential conductors for high-field applications, Niobium-Tin (Nb₃Sn) is in the most advanced state of development. Nb₃Sn wires are available in long lengths and carry currents comparable to NbTi wires of the same size at



Fig. 1: RD3-B, a 14.7 Tesla Nb₃Sn dipole [19].

more than twice the field. Nb₃Sn is a brittle intermetallic compound belonging to the A15 crystallographic family, with a critical field of 24-25 T at 4.2 K. Because of its brittleness, Nb₃Sn cannot be drawn to thin filaments like NbTi, but has to be formed in the final geometry by high-temperature heat treatment (650-700 C). In the fully reacted state, Nb₃Sn is extremely sensitive to mechanical stress. In order to use this material effectively, the design concepts and fabrication techniques developed for NbTi magnets need to be modified. In particular, tight bending of the conductors at the coil ends results in unacceptable critical current degradation. A first approach (wind-and-react) is to wind coils using un-reacted cable, when components are still ductile, and perform the heat treatment after coil winding. This technique requires the use of special insulation and coil structural components that can withstand the high reaction temperatures. A second approach (react-and-wind) is to modify the coil design to avoid sharp bending, allowing the use of pre-reacted cable. In particular, the “common coil” arrangement for twin-aperture dipoles achieves a significant increase of the bending radius using a pair of racetrack coils shared between both apertures [11].

Early work on Nb₃Sn accelerator magnets was performed at BNL [12], CEA [13], CERN [14]-[15], LBNL [16]. In the mid-90s, the dipoles MSUT (Twente University) and D20 (LBNL) reached fields of 11-13 T using wind-and-react technology [17]-[18]. Recently, the LBNL dipole RD3-B (Fig. 1) has achieved a record field of 14.7 T [19]. Nb₃Sn magnet R&D programs are presently underway at Twente University, CEA, Texas A&M University, KEK, FNAL, BNL and LBNL. Primary goals of these programs are developing magnets which satisfy all accelerator quality requirements, and exploring new concepts allowing simplifications and cost reductions. Recent accomplishments are reviewed along with the main challenges lying ahead.

II. CONDUCTOR AND CABLE

Progress towards higher fields in superconducting magnets is directly correlated to improved conductor properties, the critical current density J_c being the most important parameter. After a phase of Nb_3Sn development driven by magnetic confinement fusion applications (ITER, KSTAR, LDX), renewed interest by conductor manufacturers and research groups in the needs of the HEP community has produced impressive results (Fig. 2). Three fabrication processes have demonstrated J_c above 2 kA/mm^2 at 12 T, 4.2 K: Powder in Tube (PIT) [20], Internal Tin (IT) [21] and Modified Jelly Roll (MJR) [22]. PIT wires are developed by Shape Metal Innovation (SMI) in collaboration with Twente University. Internal Tin and Modified Jelly Roll are developed, respectively, by Intermagnetics General (IGC) and Oxford Superconducting Tecnology (OST) under the guidance of the US DOE conductor development program [23]. Parameters for the best samples of each type are listed in Table I, together with the goals set by the DOE program. The cost goal is $1.5 \text{ \$/kA-m}$ at 12 T. While present prices for small batch R&D are considerably higher, analysis based on raw material cost and large process units shows that this goal is realistic [21]. Scale up processes and cost reduction will be the focus of the second phase of the conductor program.

TABLE I
WIRE PERFORMANCE PARAMETERS

Parameter	Goal	PIT	IT	MJR
J_c (12T,4.2K) [kA/mm^2]	> 3.0	2.1	2.4	2.6
d_{eff} [μm]	< 40	20-50	100-150	80-100

Optimization of Nb_3Sn Rutherford cables presents serious challenges. High compaction is required to insure mechanical integrity during winding, in particular for designs with complex and tight bending patterns at the coil ends, but results in plastic deformation leading to critical current degradation. Wire processing and layout has considerable impact on cabling degradation. A detailed study was conducted by Fermilab and LBNL for both flat and keystone cables in a wide range of compaction [25]. At a field of 12 T, MJR and high-tin IT strands showed degradation in the range 5-11%, while PIT strand showed degradation in the range 36-60%. Early PIT wire procured for the Twente program also showed strong degradation after cabling. However, optimization of the strand design allowed to reduce cabling degradation to 5-7% [26].

Critical current degradation due to bending in react-and-wind applications has been the subject of a study conducted by Fermilab in collaboration with LBNL and NHMFL [28]. Cables of different designs, fabricated using ITER-IT strand, were reacted bent and tested straight in background field of 8 to 11 T. Comparison with reference samples which were reacted straight showed that for the typical parameters of interest in common coil magnets (minimum end radius 70-90 mm) it is possible to achieve bending degradation below

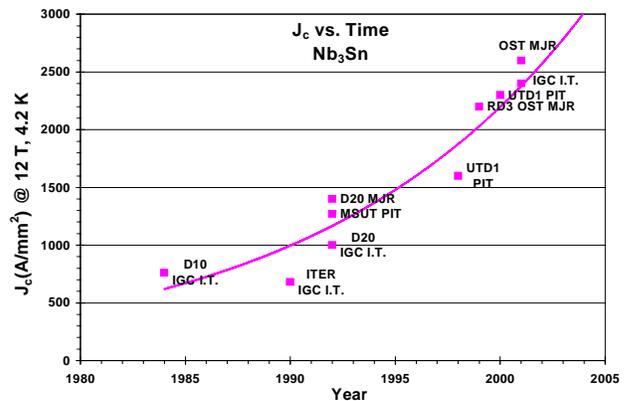


Fig. 2: Advances in Nb_3Sn critical current density [24].

10%. A synthetic oil lubricant was applied during cabling to prevent sintering at strand crossovers during reaction. As a result, the two layers behave independently limiting the bending strain to 0.2% for a strand diameter of 0.7 mm, and high contact resistance is obtained preventing large eddy current effects during ramping. The use of stainless steel strips between layers was also investigated, but handling of reacted cables with cores proved problematic and resulted in higher bending degradation. The opposite is true in wind-and-react applications, where thin ($25 \mu\text{m}$) cores do not pose significant cabling or winding issues and have been proven effective in suppressing eddy current effects.

Nb_3Sn wires and cables are also strongly affected by applied pressure. Significant improvement is obtained by filling the voids in the cable with epoxy resin to avoid stress concentration. Measurements of cable I_c under transverse and edge loading show that maximum pressure in operation to maintain the degradation below 10% is in the range of 100-185 MPa depending on wire and cable design [28] [29]. The limit for permanent degradation is 150-200 MPa.

Mixed-strand Rutherford cables alternating low-copper superconducting strands and pure copper strands have been proposed as a cost-effective strategy to control the overall copper fraction [23]. The development and test of mixed-strand cables is being actively pursued at LBNL. Initial attempts were not successful due to different mechanical properties of the strands resulting in hi-low patterns and a tendency to decable. Good results have been recently obtained by adjusting the relative diameter of the strands in order to compensate for the different elastic properties (Fig. 3). Next step in the program is verification of the stable operation of the mixed-strand cables in a high current density regime, using a subscale structure specifically designed for technological studies. Current sharing among Nb_3Sn strands during ramping and current transfer to the pure copper strands in case of a quench also need to be studied experimentally.



Fig. 3: Mixed strand cable (courtesy R. Scanlan, LBNL).

III. MAGNET DESIGN

A. Coil layout

Shell-type ($\cos\theta$) coils using keystoneed Rutherford cable have been adopted in most accelerator magnet designs to date, due to their self-supporting Roman-arch structure and optimal use of superconductor in the typical parameter range of interest. Wind-and-react technology allows to successfully extend this approach to Nb_3Sn dipoles and quadrupoles. However, several considerations are prompting magnet designers to explore alternative schemes based on rectangular (block-type) coil geometry with flat cables.

The arc dipoles are a major cost driver for next-generation colliders. In order to limit the stored energy, magnetic forces and conductor volume, the magnet aperture should be reduced from the 50-70 mm of previous machines to 40 mm or less. From the beam physics standpoint, a reduction of the aperture is allowed by smaller beam size at higher energy. Limitations come from synchrotron radiation and vacuum issues, in particular at the highest energies being considered [30]. As field increases and aperture decreases, the advantages of shell-type coils are progressively lost. Since cable keystoneing is limited by degradation at the narrow edge, a larger fraction of the coil has to be allocated to wedges, decreasing the magnetic efficiency. Winding issues become critical due to tight bending radii at the ends. Azimuthal force accumulation results in high stress levels at the midplane.

Conversely, interest in block-type coil geometries arises from the following factors: higher conductor packing in small aperture dipoles; use of flat cables with minimal degradation; simplification of end part design and fabrication, coil winding procedures, support structures, assembly techniques; modularity of the coil package; efficient coil grading thanks to lower field in the outer layers; physical separation between high-field and high-stress points; compatibility with force bypasses preventing stress accumulation. In addition, the common coil arrangement for twin-aperture dipoles (Fig. 4, right) has large end bending radius allowing to wind coils using pre-reacted cable, with significant cost saving potential.

Disadvantages of block-coils are the loss of high-field magnetic aperture to provide structural material for internal coil support against prestress, and generation of large horizontal forces. Also, deviations from the simplicity of planar racetrack coils may be necessary to address issues of conductor efficiency and field quality. Specific disadvantages of the common coil arrangement are the low ratio of magnetic to physical length in the end regions, which also present magnetic optimization challenges to achieve low peak field and good field quality in a simple layout; and the vertical bore arrangement where the return flux from one aperture decreases the field in the other.

Block-type magnets with split coils are being developed at Texas A&M [31] and BNL [32] for use in the muon collider and neutrino factory, where high radiation loads are present due to electrons generated by muon decay. Split racetracks

allow the decay products to be absorbed at higher temperature, away from the coil. In addition, the BNL design uses partially overlapping top and bottom coils to achieve a combined function design allowing tight lattice packing.

High-gradient quadrupoles for beam focusing at the Interaction Points are a promising near-term application of Nb_3Sn technology. In order to accommodate large beam envelope excursions during final focus and thick absorbers to shield secondaries from beam-beam collisions, these magnets tend to have large bores, favoring the use of shell-type coils. However, special block-coil designs have been proposed in order to achieve the extreme field gradients required by VLHC designs with 50-100 TeV/beam [33].

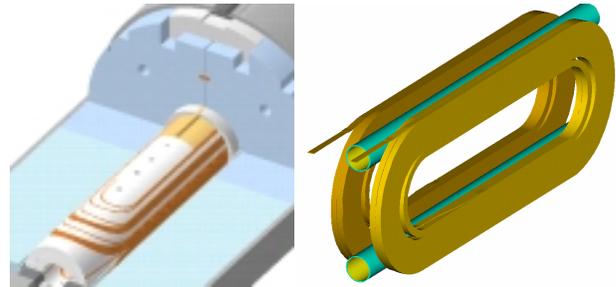


Fig. 4: Coil designs. Left: shell-type [47]; Right: common coil [27].

B. Magnetic efficiency and field quality

Field quality optimization of shell-type coils is well understood. Minimization of the size and number of wedges and end spacers is a primary figure of merit to improve magnetic efficiency and simplify fabrication. Block-type coils can also provide high field quality, but the trade-offs between design simplicity, conductor efficiency and field quality are more complex. In single aperture block-coil magnets, conductor placement in the vicinity of the coil midplane is desirable for magnetic efficiency but leads to complications at the coil ends, where the conductors have to clear the magnet bore. This configuration is best suited for applications where it is acceptable to remove conductors from the coil midplane (small aperture, high radiation load). In common coil magnets, simple flat coils on each side of the bore do not provide adequate field quality. Auxiliary coils in the pole region can balance the harmonics generated by the main coils but are difficult to support mechanically [34]. Some designs incorporate the auxiliary coils in the main coil package. For example, the inner layer of a double pancake coil can be used as an auxiliary coil [35], or the conductor blocks in the pole regions of the main coils can be shifted horizontally inwards [36]. Auxiliary coils also cause complications at the coil ends, where the conductors have to clear the magnet bore. A planar geometry can be maintained but results in a loss of physical aperture. In small aperture dipoles adequate field quality can be achieved using flat coils, but spacers have to be inserted at the magnetic midplane, again causing a loss of efficiency [37]. Further analysis as well as feedback from model magnet fabrication and test are required to select the best options.

Field errors due to persistent current effects are a primary concern in superconducting accelerator magnets. Nb₃Sn wires exhibit large magnetization due to high critical current density and large filament size. Among the Nb₃Sn fabrication processes capable of high J_c, PIT can achieve the smallest filaments (20 μm). This value is still several times larger than in NbTi wires, but is acceptable for special magnets which do not constitute a significant fraction of the accelerator. Compensation of persistent current effects by saturation of carefully designed iron inserts is actively explored [37]-[40]. Such schemes do not address persistent current decay and snap-back, but are well matched to VLHC scenarios allowing single turn injection. Compensation of the magnetization harmonics can also be achieved by coil geometry [40]. This strategy counteracts both static and dynamic effects, with some loss of conductor efficiency.

C. Support structures

Large electromagnetic forces are generated in high-field Nb₃Sn magnets and several new design concepts are being developed to provide adequate coil support. A specific requirement is to minimize stress on the conductor at all stages of magnet fabrication and operation. Thermal shrinkage differentials among elements of the support structure are often exploited to maintain or even increase prestress during cooldown, in spite of the high thermal contraction coefficient of the coil. This allows to limit the peak coil stress during assembly, and to minimize the amount of structural material taking advantage of its increased strength at lower temperature.

The Twente University shell-type separation dipole for LHC relies on laminated collars, with additional support provided by a welded stainless steel shell surrounding the yoke [26]. In the Fermilab cosθ dipole (Fig. 4, left), strong aluminum clamps lock the vertically split yoke supporting the coil, again in combination with an outer shell [41]. An aluminum spacer between coil and yoke protects the coil from high stress during assembly. Twin-aperture, warm yoke designs have also been developed at Fermilab. Coil support is provided by thick aluminum rings and stainless steel inserts allowing to maintain prestress during cooldown.

In block-type dipoles, the main challenge is represented by large horizontal forces. The 0.8 m long, twin-aperture dipole RD3-B (Fig. 1) generates 12 MN at 14 T. A special support structure was developed for this magnet, based on the use of water-pressurized bladders (Fig. 3) to compress the coil pack while tensioning a 40 mm thick aluminum shell [42]. When the shell reaches a tension of 140 Mpa, interference keys are inserted and the bladders deflated and removed. During cooldown, the stress in the shell almost doubles due to



Fig. 3: A bladder made of stainless steel sheets [42].

differential thermal contraction relative to the iron yoke. A similar approach has been adopted for the Texas A&M block-coil dipole [39]. However, the bladders are pressurized with melted liquid metal and remain as part of the structure, following a technique successfully developed at LBNL [43]. The Texas mechanical design also integrates a high-strength support matrix of Inconel ribs and plates within the coil structure to intercept Lorentz stress and prevent its accumulation on the conductor. Foil springs sandwiched inside each coil block control conductor preload. Finally, the Fermilab single-layer common coil dipole uses strong collars with horizontal bridges which withstand a large portion of the Lorentz forces and minimize coil displacement during excitation [44]. Horizontal preload is provided by an outer stainless steel skin.

D. Quench protection

Protection of Nb₃Sn magnets is complicated by high levels of stored energy, high current densities in the conductor and high critical temperature requiring more heater power and increasing heater delays. In addition, epoxy cracking or even damage to the conductor may result from the stress generated during a quench. Modelling efforts are underway to study the thermo-mechanical behaviour of the coil package during a quench and the heat propagation from heater to coil [45][46]. Analysis of temperature and voltage distributions as function of Cu/Sc ratio, cable RRR, heater coverage and delay time show that peak temperatures below 400 K and peak voltages below 1 kV can be achieved in long magnets operating at 10 T. However, extensive heater coverage is required, and small margins are available to account for failure modes. Higher field magnets are even more challenging and new approaches may be required. It should be noted that little experimental data is available to verify these calculations and the assumptions upon which they are based. Results from model magnet testing are thus needed to progress in this area.

IV. PROTOTYPE FABRICATION AND TEST

A. Shell-type dipoles and quadrupoles

Model dipoles and quadrupoles of the shell type are presently being developed at Twente University, Fermilab and CEA-Saclay using the wind and react approach.

Goal of the UT program is to fabricate a second generation separation dipole for the LHC Interaction Regions, with 88 mm bore and a nominal field of 10 T [9]. A successful conductor R&D program has resulted in PIT strands with J_c (12 T, 4.2 K)=1.9 kA/mm², d_{eff}=20 μm and degradation due to cabling of 5-7% [26]. Two dummy coils were fabricated, the first using Nb₃Sn to study the effect of heat treatment on the coil, the second using NbTi to test all phases of coil production, including the installation of heaters between coil layers, vacuum impregnation and instrumentation. Coil fabrication is now underway with the goal of testing the magnet at CERN in May 2002.

Shell-type dipoles are being developed at Fermilab, in collaboration with KEK and LBNL, for use in VLHC. The first series of models have single bore, cold iron yoke, 43.5 mm aperture and a nominal field of 11 T using MJR conductor. The coil design has two layers wound from the same length of cable. A ceramic tape is used for cable insulation and a ceramic binder is applied to preform the coils and facilitate their handling through the reaction phase [47]. Three models have been fabricated to date and the last two have been cold tested. Unfortunately, both showed premature quenching [48]. Geometric harmonics are within a few units at 10 mm reference radius, and small eddy current effects are observed thanks to the use of a 25 μm thick stainless steel core in the cable [49]. Persistent current harmonics are large, as expected from measurements of strand magnetization.

A Nb_3Sn quadrupole magnet is being fabricated at CEA-Saclay, with parameters suitable for application in the final focus of the TESLA collider [50]. Nominal field gradient is 211 T/m in a 56 mm aperture. The coil design is the same as for the LHC arc quadrupole, also developed at Saclay. This choice simplifies the design but constrains the cable and insulation dimensions. The cable uses ITER-type Internal Tin strand by Alstom/MSA, with J_c (12 T, 4.2 K)=750 A/mm² and d_{eff} =19 μm . Extracted strand measurements show cabling degradation within 10%. Several technology studies were carried out in preparation for magnet fabrication: special insulation was developed using a thin (60 μm) quartz fiber tape [51]; thermo-mechanical properties of 10-stack samples were measured to verify that coil dimension can be controlled to the required accuracy, and to provide input for the mechanical analysis; and a splicing technique using intermediate Nb_3Sn -NbTi connections was developed. Magnet test is planned for March 2003.

B. Block-coil and common coil magnets

The magnet program at Texas A&M University develops block-coil, single aperture high-field magnets with several innovative features: a support matrix in the coil to prevent stress accumulation; mixed-strand cables for conductor grading; planar steel boundary with current programming for control of persistent current and iron saturation effects [39]. A first model has been built using NbTi conductor, incorporating the same features that will be adopted in the high-field Nb_3Sn dipole. The magnet has been recently tested at LBNL, reaching short sample at 7 T with minimal training [52]. Fabrication of a 12 T Nb_3Sn dipole is now underway.

Twin-aperture common coil dipoles are developed at BNL, Fermilab and LBNL. The BNL program focuses on react-and-wind technology. A 10-turn coil program is in progress to evaluate different approaches to coil fabrication [53]. The reference cable has 30 strands of 0.8 mm diameter, and is wound on an iron bobbin with 70 mm radius. Test results for the first two sets of Nb_3Sn coils were very encouraging. A conductor-limited plateau was reached with minimal training, at a current level corresponding to bending degradation of 8

to 13%. Two additional sets of coils were recently fabricated and tested. In this case, however, only a fraction of the expected short sample current was obtained, indicating severe damage to the conductor. Testing of cable samples showed that the damage occurred during or immediately after reaction [54]. Though disappointing, this result confirms the validity of a low-cost, rapid turnaround R&D approach to develop procedures suitable for handling reacted conductors.



Fig. 6: BNL 10-turn coil for react-and-wind studies [53].

The Fermilab react-and-wind common coil dipole for VLHC has a nominal field of 11 T with 40 mm coil spacing [55]. Characteristic features of this magnet are: the use of a single-layer coil to simplify fabrication and reduce magnet inductance; shifted pole blocks and internal spacers for field quality optimization; a coil geometry providing compensation of persistent current effects. Both coils were wound directly inside the collars to allow insertion of horizontal bridges for coil support. A mechanical model has been assembled to check winding procedures, choose the best collar design and measure the stress in warm and cold conditions. At the same time, react-and-wind technology is being developed using simple racetrack coils in back-to-back configuration. Test results of the first model showed premature quenching. A second set of coils is being fabricated.

The primary goal of the LBNL program is to push accelerator magnet technology towards the highest fields. A series of common coil dipoles have been fabricated, using wind-and-react technology to maximize performance. The latest dipole in the series, denoted RD3-B, has reached 14.7 T at 4.5 K using MJR conductor [11]. The coil package consists of three double-pancake windings: an inner module comprising the 25 mm thick bore plate and two outer modules, one on each side of the bore. A low first quench and slow training was observed in RD3-B, with all quenches below 14 T occurring in the inner module. This behaviour was attributed to stick slip motion in the mica slip planes between the inner layer and the bore plate, due to imperfect shear release after impregnation. No conductor degradation due to cabling or stress was observed. The capability to fabricate flat Rutherford cables for racetrack coils with no degradation was already demonstrated in previous tests [27]. The absence of performance degradation due to stress can be explained by noting that the high stress point (120 MPa) occurs in a region of the outer layer where the critical current margin is high. The new assembly procedure based on pressurized bladders has proved successful and accurate in providing very large horizontal prestress, and facilitates magnet assembly and disassembly. This last feature is well

matched to the modular coil design and allowed quick recovery from a first unsuccessful test of RD3, when an insulation failure resulted in arc damage to the coils. Fabrication of a new inner module (RD3c) is presently underway, with the goal of providing geometric field quality at 11 T field level with 40 mm coil spacing.

V. CONCLUSIONS

Intensive programs are underway worldwide to develop high-field Nb₃Sn magnets for future accelerators. Cost effective designs have been developed, meeting accelerator quality requirements. A new record dipole field of 14.7 T has been established, and further progress to 15-16 T is already made possible by improvements in critical current density of Nb₃Sn wires. At the same time, several results from prototype fabrication and test reconfirm the difficulties associated with Nb₃Sn technology. Continued R&D efforts are necessary to demonstrate its feasibility in large accelerator projects.

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