

HIGH FIELD MAGNET DEVELOPMENTS

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Abstract

High field magnet developments based on Nb₃Sn towards future accelerator applications in the next era have been intensively pursued. Fundamental R&D efforts with Nb₃Al and HTS conductors have been also underway. This paper will try to summarize these activities.

INTRODUCTION

Particle accelerators utilizing superconducting magnets, firstly realized at Tevatron, followed by HERA, RHIC and LHC, have been able to attain higher particle energies in given circumferences and have played very important role in the high-energy physics and the nuclear physics. Superconducting low-beta insertion quadrupole magnets in LEP and KEKB also contributed to enhance beam luminosities significantly. Demands of superconducting magnets would increase in future accelerator applications.

Development of magnet technology with multi-filamentary superconducting NbTi wires in last several decades has enabled to realize “accelerator quality” magnets fulfilling the following requirement: good field quality and its reproducibility, mechanical endurance to firmly support substantial Lorentz forces, reliable operation without spontaneous quenches. The mature, robust NbTi superconductors have been already pushed to its performance limit, as demonstrated in LHC where the nominal field of the main dipole magnet is 8.3 T at 1.9 K [1]. However, planned future accelerator programs expect more performance for the superconducting magnets to generate 10 T and higher field. The NbTi technology cannot be adopted for such applications.

Instead, A15 type superconductors have been considered to be promising materials for the high field magnets. Especially, intensive R&D efforts on Nb₃Sn superconductors for the ITER fusion reactor and future accelerator applications have been made. Further future accelerators such as High Energy LHC (HE-LHC) [2] and Muon Collider [3] must require very high field in excess of 20 T. This means that utilization of HTS (high Tc superconductors) would be the only possible solution.

Nevertheless, it is known that these advanced superconductors are not mechanically robust in comparison with the practical NbTi superconductors and the performance is influenced by mechanical stress and strain. In addition, magnetization effects caused by larger effective filament diameters may compromise the field quality particularly at the beam injection. The magnet developments to overcome these issues are still ongoing.

NB3SN MAGNET R&D

Nb₃Sn superconductors have intrinsic advantages over NbTi in critical field (B_{c2} at 4.2 K ~ 23 T) and critical temperature (T_c at 0 T ~ 18 K). In addition, the

commercially available Nb₃Sn superconducting wires such as Powder-in-Tube (PIT) wire by Bruker-EAS and Restack Rod Process (RRP) wire by Oxford Superconducting Technology (OST) show sufficiently high non-copper J_c of 2500 ~ 3000 A/mm² at 12 T, 4.2 K. Due to these attractive properties, Nb₃Sn has been considered as an adequate choice for the high field magnet or the magnet operated under high heat load in the next era. Nevertheless, Nb₃Sn superconductor needs to be transformed at high temperature (~650 °C) and heat-reacted conductors become brittle and strain (stress) sensitive. R&D efforts to build the magnet with new design concepts and new fabrication processes were necessary.

In terms of the fabrication process, there are two possible options: React-and-Wind and Wind-and-React technologies. The React-and-Wind technology, where the Nb₃Sn cable is heat-reacted in advance and the critical heat reaction of the wound-coil can be avoided, is beneficial to succeed the well-developed magnet technology with NbTi superconductors to date. In particular, use of polyimide films can ensure the electrical insulation system. Nevertheless, a saddle-shaped coil for the accelerator magnet forces to tightly bend the brittle Nb₃Sn cable in a small radius at the coil end, and excessive strain and serious damage of Nb₃Sn filaments could spoil the magnet performance. For this reason, the recent Nb₃Sn magnets have been mostly based on the Wind-and-React technology where the heat-reaction is made after the coil winding. Careful mechanical designs have been taken into account the behavior of the structure and the Nb₃Sn coil including anisotropic transformation all through the heat reaction process. The magnet technologies to utilize inorganic insulation in the heat reaction and vacuum impregnation with epoxy resin to improve the mechanical robustness and electrical insulation of the reacted coil have been developed.

In the 1990s, CERN firstly developed the 1-m long cos θ -type dipole magnet with Nb₃Sn Rutherford-type cable that generated a field of 9.5 T at 4.3 K in an aperture of 50 mm [4]. Subsequently, the MSUT dipole magnet at University of Twente achieved 11 T at 4.4 K [5], and D20 dipole magnet at LBNL reached 12.8 T (13.5 T) at 4.4 K (1.8 K) [6].

Fermilab started High Field Magnet program in 1998 aiming Very Large Hadron Collider (VLHC) and built a series of HFDA dipole models [7]. Differing from the previous model magnets [4]-[6], the HFDA was oriented to demonstrate the cost effective magnets applicable for the future industrialization of full-scale magnets. Though the HFDA02-04 reached only 7 T at highest and quenches were concentrated around the coil leads near Nb₃Sn/NbTi cable splice in low fields, further study could reveal that the poor quench performance resulted from the low field

instability of the Nb₃Sn wire having very high J_c and a larger effective filament diameter. Shortly thereafter, this important lesson was reflected in the next model, HFDA05, with Nb₃Sn PIT superconductor having an acceptable stability at low fields. The HFDA05 successfully exhibited improved quench performance: the training quench at 4.5 K reached the short sample limit corresponding a bore field of 9.5 T [7].

Apart from the cosθ-type magnet development described above, fundamental R&D programs using with simple racetrack coils have also been carried out in the different laboratories. Fermilab and BNL have made efforts to explore the possibilities of the React-and-Wind technology with racetrack coils within a scope of a common coil configuration. Three 1-m long racetrack magnets, HFDB01-03, and a common coil dipole magnet, HFDC01, were built by Fermilab, and they reached 60 to 75 % of the short sample limit. It was concluded that the J_c degradation of the brittle Nb₃Sn cable was higher than expectation and more efforts will be necessary to improve the conductor properties, mechanical design and fabrication procedure [7].

In LBNL, a number of model magnet with racetrack coils was developed so far. An important milestone for the high field magnet development was that a block type dipole magnet, HD1, successfully achieved 16 T in a clear bore of 8 mm [8]. Moreover, the design concept and the fabrication process demonstrated in HD1 development have been a good reference in the later development programs [9].

A unique approach to manage high stress in the block-type dipole coil has been conducted at Texas A&M University. In “stress management strategy”, the segmented coil blocks are individually supported by rigid matrix structure of ribs and plates, and the accumulation of Lorenz force can be limited within the single coil block. Though fabrication process was much complicated, the TAMU2 magnet with a maximum design field of 6.8 T successfully reached 95 % of the short sample limit [10]. As a next demonstrator, development of TAMU03 with a design field of 14 T has been underway.

NB₃SN MAGNET DEVELOPMENTS FOR PRACTICAL APPLICATIONS

Low-beta Quadrupole Magnets for LHC Upgrade

High field magnet developments beyond the present LHC has been intensively carried out in US laboratories and CERN aiming the practical application in the High Luminosity LHC upgrade (HL-LHC) to achieve the design luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ for the ATLAS and CMS experiments [11]. One of the major upgrade items in the HL-LHC will be the replacement of the present NbTi inner triplet quadrupole magnets for the final beam focusing, and the high performance Nb₃Sn magnet is considered as a promising substitution.

Development of Nb₃Sn quadrupole magnets for the LHC luminosity upgrade started at 2004 under the framework of US LHC Accelerator Research Program

(US-LARP) formed by BNL, Fermilab and LBNL [12]. Following fundamental magnet R&D based on subscale race track coils with Nb₃Sn conductors (SQ) [13], a series of 1-m long “Technology Quadrupoles” (TQ) with a coil aperture of 90 mm and a target field gradient of 200 T/m was fabricated and tested [14], [15]. Two different mechanical design concepts using the virtually identical coil sets were evaluated in the TQ development.

In the “TQC” model magnets, the Nb₃Sn coils were mechanically supported by stainless steel collars, iron yokes, and welded stainless shell. This design concept can be considered as a sort of a natural extension of the mechanical structure of the current NbTi magnets, and extendability on precise alignment feature of Nb₃Sn coils in the longer magnet was expected. The other model magnets, “TQS”, mechanically relied on the most outer aluminum shell, surrounding the Nb₃Sn coils and iron yokes, and hydraulic pressure system using bladder and key. Thanks to larger thermal contraction of aluminum in comparison with other magnet structures, an adequate stress increase during cool-down can be provided. This feature results in lower assembly pre-stress while keeping the same level of the coil stress as TQC before excitation at cold. A shell-based structure with bladder and key technology has also an advantage that the magnet can be easily assembled and disassembled and this feature is quite cost effective in the development phase.

A number of excitation tests was performed for both TQC and TQS 1-m long model magnets and a field gradient of 200 T/m in 90 mm aperture corresponding the coil peak field of 10 T were consistently demonstrated [14], [15]. Especially, the latest TQS model using RRP 108/127 Nb₃Sn conductor successfully achieved 240 T/m at 1.9 K. Stress limit of Nb₃Sn coils was investigated by changing the coil pre-stress for 4 cases using same coils. Although the highest quench current was not recovered, degradation of quench performance was only 5 % even after the coil experienced the maximum stress of 260 MPa at the median plane. Furthermore, quench performance was not degraded through a fatigue test with 1000 excitation cycles [16].

As a next step toward the LHC luminosity upgrade, two parallel R&D programs aiming a magnet length scale-up (LQS) and a higher field gradient model in an increased aperture (HQ) were started. Fruits of the TQ program served as a basis for both LQS and HQ models.

For the 3.7-m long LQS models with an aperture of 90 mm, some modifications were introduced to the coil design and fabrication technology in order to improve the fabrication of long coils. The structure was mainly based on the TQS, but newly adopting a segmented aluminum shell from the long racetrack development (LRS) [17]. The LQS models with OST RRP 54/61 Nb₃Sn conductor successfully demonstrated the same level of quench performance exceeding 200 T/m as 1-m long TQ models though the quench currents seemed to be limited by a local enhanced instability of the conductor in one coil [18]. The new coils with more stable RRP 108/127 Nb₃Sn

conductor will be fabricated for the new LQS model and improved performance will be evaluated.

The HQ was determined to have a large coil aperture of 120 mm, which is necessary for improving the beam performance in the LHC luminosity upgrade and is same as the CERN's developing NbTi quadrupole model magnets MQXC [19] while generating higher field gradient. This design choice resulted in technological challenge to cope with the higher Lorentz force and the requirement of higher coil pre-stress at cold. It was judged that aluminum shell-based structure with bladder and key technology demonstrated in the TQS was adopted for the HQ because the appropriate pre-stress controlled by the shell thickness can be applied to the coil and risk of over stress at the assembly can be avoided. Apart from the TQS, the coil alignment feature needed to be implemented in the HQ.

The HQ model consisted of two layer Nb₃Sn cos2θ coils, aluminum collars, iron pads, yokes and outer aluminum shell. The aluminum collars with alignment keys provided the coil alignment feature with respect to the yoke and the shell. The coil used the 15 mm wide Rutherford cable with 35 RRP 108/127 strands. The magnet was designed to reach a "short sample" field of 14.9 T at 1.9 K, corresponding to the field gradient of 214 T/m, at a current of 19.0 kA, with assuming J_c of 2900 A/mm² at 12 T, 4.2 K [20]. A first series of excitation tests showed that the HQ reached 157 T/m at 4.2 K and it was already higher than the performance limit of the MQXC NbTi quadrupole models [19].

However, the initial HQ01 coils have suffered electrical insulation problems. Possible causes might be thinner cable insulation than that of TQ, high compaction of the coil in the heat reaction cavity, and mismatched end spacer design. A new series of the HQ02 coils to address these issues will be fabricated and tested soon.

11 T DS Dipole for LHC Collimation Upgrade

In order to achieve nominal and ultimate beam intensities in the LHC, additional collimators to improve the collimation efficiency by a factor of 15 or higher are planned to be installed in the dispersion suppressor (DS) region. To provide a longitudinal space of about 3.5 m for the collimator, replacement of a 14.3-m long 8.33 T LHC main dipole magnet (MB) with a pair of 5.5-m long 11 T Nb₃Sn dipole magnets is considered. CERN and Fermilab started a joint development program to build a series of dipole magnets: initiated with a 2-m long single-aperture demonstrator followed by a 2-m long twin-aperture demonstrator and a 5.5-m long prototype [21], [22].

The 2-layer cosθ coil layout and the electrical insulation scheme are identical for both the single-aperture and the twin-aperture magnets. Though the iron yoke of the twin-aperture magnet needs to have a 550 mm outer diameter, which is same as the MB, the single aperture magnet will use the existing 400 mm yoke from the HFDA of Fermilab [7]. The coil cross-section was determined to generate 11 T at 11.85 kA in a 60 mm aperture with 20 % operation margin and to suppress

geometrical field errors below 10⁻⁴ level. The key-stoned 14.8 mm wide and 1.3 mm thick Rutherford type cable consisting with 40 Nb₃Sn RRP 108/127 strands were used for the coil. Following magnetic and mechanical designs, the first 11 T single-aperture demonstrator has been fabricated at Fermilab with a participation of CERN for the technology transfer. The development status will be presented in this conference [22].

Since a pair of 5.5-m long 11 T DS dipole magnet will be powered in series with the other existing MB magnets, precise adjustment of the magnetic length of this pair to be same as the MB magnets in the whole range of the operation currents would be one of the major items to be addressed.

EuCARD High Field Dipole Model for FRESCA2

Within a framework of European Coordination for Accelerator Research Development (EuCARD), co-funded by the EC-FP7, superconducting high field magnet development for higher luminosities and energies in future accelerators has been pursued by the collaboration with the 12 European institutes. Development of a 13 T, 1.5-m long, 100 mm aperture dipole model, so-called Fresca2 dipole magnet, using Nb₃Sn Rutherford cable was motivated to upgrade the present 10 T NbTi dipole magnet in the Fresca cable test station at CERN [23]. In the Fresca2 development, assets of the previous high field magnet development program, Next European Dipole (NED) in the Coordinated Accelerator Research in Europe (CARE) project [24], is effectively employed: high performance Nb₃Sn 1.25 mm PIT strand (J_c of 1500 A/mm² at 15 T, 4.2 K, a filament diameter of 50 μm, RRR > 150) accomplished by the NED program was a basis of the conductor utilized for the Fresca2 coils. Design central field is 13.0 T at 10.7 kA and target field homogeneity is within 1 % at 2/3 of the aperture. It turns out that the diameter of magnet and the stored energy will be 1.03 m and 3.6 MJ/m, respectively. Design features of the Fresca2 dipole magnet are as follows;

- 4-layer block-type coil configuration with flared ends, inspired by HD2 of LBNL [9].
- Continuous double pan-cake coil winding for each the 1st-2nd layer and the 3rd-4th layer.
- Mechanical support by outer aluminum shell,
- Assembly using bladder and key technology.

In parallel with cabling study to evaluate the performance degradation of the strands, particularly in J_c and RRR, by changing the cable dimension, engineering design to start the fabrication are in progress. Highlight of the relevant R&D results obtained so far was that the Short Model Coil (SMC) with racetrack configuration to validate the cable performance and the fabrication process for the Fresca2 magnet showed the excellent quench performance to reach the coil peak field of 12.6 T at 4.2 K, corresponding the short sample limit. This result strengthens the success of the Fresca2 magnet development.

Development Items to be Addressed

The high field magnet development projects mentioned in this chapter has been performed with substantial efforts, in particular, coping with high stress in the fragile Nb₃Sn coils. In order to achieve “accelerator quality” in the Nb₃Sn magnet, the following R&D items should be further emphasized even though they were already started.

To attain acceptable field quality with reproducibility, the scheme of coil geometry control as well as fine alignment feature with respect to the outer structure needs to be established. Furthermore, field variation during the excitation induced by magnetization effects should be improved by reducing the filament diameter appropriately.

Small inter-strand contact resistances of the Rutherford cable due to the heat reaction at high temperature induce significant eddy-currents that compromise the quench performance and the dynamic field quality. Development of the cored cable (stainless steel, fiber cloth) and feasibility test in the coil should be performed.

As the Nb₃Sn performance is fully exploited, the stored energy of the magnet becomes quite larger. The quench protection study is very crucial especially for the large-scale magnet.

The low-beta insertion quadrupole magnets for future hadron colliders, such as HL-LHC, will be exposed by very severe radiation of $\sim 10^{22}$ p/m² and ~ 100 MGy. Radiation resistance of conductors (Nb₃Sn and copper stabilizer) as well as impregnation resin should be evaluated to recognize the operation limit. It should be noted that very common epoxy resin used for the current Nb₃Sn coil cannot withstand such high radiation and new radiation resistant resins should be adopted for the magnet fabrication.

Extension of the magnet length is expected in future accelerator. The heat reaction process to accommodate the different thermal expansion of structures as well as anisotropic transformation of the Nb₃Sn coil is more critical for the longer coil. However, mechanical design of the coil and the structure still seems to be empirical at present. Thorough understanding of the mechanical behavior in the heat reaction process is inevitable to realize a 10-m long class magnet.

NB3AL MAGNET R&D

Since Nb₃Al has a much better stress and strain tolerance than Nb₃Sn, Nb₃Al has been also considered as the possible candidate for the high field magnet. Thanks to a rapid heating/quenching and transformation (RHQ) process developed by NIMS, J_c of Nb₃Al has been improved at high field [25]. KEK has been promoting to develop Nb₃Al conductor for accelerator applications in collaboration with NIMS, CERN, Fermilab and LBNL. R&D efforts have been primarily dedicated for the conductor development, including a 13 T sub-scale magnet to demonstrate the feasibility of Nb₃Al Rutherford cable [26]. The sub-scale magnet is being built and will be tested soon.

Furthermore, KEK has conducted the fundamental study to investigate the strain behavior of the advanced superconductors in collaboration with JAEA, NIMS and Tohoku University. In parallel with the ordinary J_c dependence measurement on the external applied strain, the direct observation of the strain of the superconductor crystal in the advanced conductor in various conditions has been experimentally made at the pulsed neutron diffractometer, TAKUMI, of J-PARC MLF [27], [28]. As a reference, spatial distribution of the internal strain in the Nb₃Sn CIC conductor for the ITER-TF coil was determined by TAKUMI diffractometer [29]. By using a newly developed cryogenic load frame, the internal strain measurement of impregnated Nb₃Al Rutherford cable stacks under transversal compressive stress simulating the accelerator coil is planned.

HTS MAGNET R&D

There are two possible HTS conductors to be applicable for the high field accelerator magnets: Bi-2212 round wire and ReBCO (YBCO or GdBCO) coated conductor. Both conductors can keep engineering current densities (J_e) around several 100 A/mm² at 4.2 K up to 45 T [30]. In particular, Bi-2212 round wire can be formed in Rutherford cable and use in the cos(nθ) coil layout is in principle possible.

NHMFL has promoted the HTS high field solenoid insert coil development programs for both conductors: the 32 T YBCO insert coil and the 25 T Bi-2212 insert coil [31]. A number of HTS solenoid insert coils have been built and tested. As a typical successful result, the YBCO insert coil with a background field of 31 T generated a central field of 33.8 T with J_{ave} of 400 A/mm² under estimated hoop-stress beyond 300 MPa. Other US laboratories have also conducted the HTS coil development with a solenoid or a block-type configuration for the future particle accelerator [32]-[34]. Even though both HTS conductors intrinsically show the excellent performance, there are technological challenges to realize the high field accelerator magnet.

Bi-2212 round wire requires heat treatment like Nb₃Sn, but it is very complicated process: the heat treatment must be performed in oxygen, and the precise control of the peak temperature (~ 890 °C) within a few °C and the homogeneous oxygen distribution for the whole coil structure must be necessary to achieve the full performance. Furthermore, leakage of molten Bi-2212 frequently occurs depending on the ambient materials and compromises the magnet performance [34].

In the ReBCO coated conductors, superconducting layer is formed on thin tape (a few μm thick, typically 5 mm wide) and J_c shows strong angular dependence. This means that magnetic design particularly for the cos(nθ)-type accelerator coil should take into account the anisotropic property of the transport current of the coated conductors [35]. Since a single superconducting layer is wide enough, substantial magnetization effect is observed and this would be an issue for the accelerator applications.

One of the measure may be the utilization of the Reobel cable [33]. A very thin superconducting layer is mechanically reinforced by the Ni-alloy substrates (Hastelloy), which eventually determine the mechanical strength of the coated conductor. While the coated conductors shows high strength against axial tension, debonding of the substrate can be easily induced by the interfacial shear stress and practically limits the mechanical strength of the coil [36].

As common issues for both HTS conductors to realize large-scale high field magnets, the quench protection scheme has not been established yet and an available unit conductor length is still limited.

SUMMARY

Requirement of the LHC performance upgrade strongly drives the high field magnet development program based on Nb₃Sn technology below 15 T. While there are still R&D items to be addressed, the “accelerator quality” Nb₃Sn magnet would be developed in very near future.

For realization of the high field magnet beyond 15 T, intensive R&D on the HTS conductors is still needed. Substantial demands of the HTS conductors from big scientific projects like Tevatron and LHC for NbTi and ITER for Nb₃Sn would be the necessary driving force for the further performance improvement.

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