

# Chapter 16

## Nb<sub>3</sub>Sn Accelerator Dipole Magnet Needs for a Future Circular Collider



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**Abstract** The Future Circular Collider (FCC), or the High-Energy Large Hadron Collider (HE-LHC), would require bending magnets operating at 16 T. The large quantity of high-performance conductor required for these projects can only be satisfied by using Nb<sub>3</sub>Sn superconductor. This chapter summarizes the main design approaches and parameters for these dipole magnets.

### 16.1 Introduction

A new proton collider representing a step forward with respect to the Large Hadron Collider (LHC) would provide collisions at a center-of-mass energy of the order of 100 TeV. This could be achieved, as proposed by, the Future Circular Collider (FCC) study (CERN 2013), with bending magnets operating at 16 T in a 100 km long circular machine. Magnets operating in the same field range could also be considered, should interest arise in doubling the energy of the LHC (Todesco and Zimmermann 2011).

With respect to the LHC, this quest for a doubling of the field requires a change of superconducting material, because the upper critical field  $B_{c2}$  of Nb-Ti at 1.9 K is limited to, at most, 13.5 T (Bottura 2000), limiting the ultimate field amplitude of Nb-Ti accelerator magnets to about 10 T. A field level of 16 T is also 5 T higher than the field in the Nb<sub>3</sub>Sn magnets currently being developed for the High Luminosity LHC (HL-LHC or Hi-Lumi LHC) (Ferracin et al. 2016; Savary et al. 2017). Once installed, they will be the first high-field Nb<sub>3</sub>Sn magnets ever operated in a particle collider. It will be shown below that the Nb<sub>3</sub>Sn compound is appropriate for 16 T accelerator dipole magnets operating at 1.9 K with a similar margin (14% on the load line) to that used for the LHC magnets. The field amplitude range between 10 T and 16 T is of interest not only for the HL-LHC, the High-Energy LHC (HE-LHC), and

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the FCC, but also for several other initiatives such as, for example, the 100 km long version of the Super Proton-Proton Collider (Gao 2016), a Very Large Hadron Collider (Bhat et al. 2013), or for muon colliders (Kashikhin et al. 2012; Zlobin et al. 2013).

With respect to the LHC dipole magnets, the higher field level yields increases of the forces, size, weight, and stored energy. For magnet cross-sections optimized for using a minimum amount of high-performing conductor, the larger forces also result in greater stress levels in the coil and in the structural components, making the structural design, the magnet's integration into a cryostat, and installation in the accelerator challenging. Finally, the management of the larger stored energy imposes increased challenges in magnet and circuit protection, in particular for the dielectric strength of the coil insulation.

The next sections summarize and discuss the baseline design choices and parameters of these magnets.

## 16.2 Conductor

### 16.2.1 Superconductor

As anticipated, the required field amplitude of 16 T cannot be achieved with coils made of Nb-Ti. According to Larbalestier (2017), unless a major discovery is made in the next decade, the candidate conductor materials are to be selected from Nb<sub>3</sub>Sn, BSCCO (in particular Bi-2212: Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8</sub>), and REBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>, where RE stands for rare earth element (REBCO). We exclude MgB<sub>2</sub> due to its low critical field  $B_{c2}$ , though the situation may change if the results obtained with thin films (Dai et al. 2011) can be extended to practical conductors. We also have to exclude Fe-based superconductors, mainly because it is not clear whether the limitations of the connectivity between grain boundaries can ever be overcome. We remark, however, that a new development of MgB<sub>2</sub>- or Fe-based superconductors may, especially for the latter, open new cost-effective, high-performance opportunities. With regret, however, at this stage there is no basis for considering these materials for high-field accelerator magnets.

Both BSCCO and REBCO can carry engineering current densities of practical use for magnets at field amplitudes well beyond a target field amplitude of 16 T: for that field level, however, their cost cannot yet compete with that of Nb<sub>3</sub>Sn. Indeed, a moderate performance increase of the critical current density of Nb<sub>3</sub>Sn (in the order of 2300 A/mm<sup>2</sup> at 16 T and 1.9 K, which we will define as the FCC target) with respect to the best state of the art (Larbalestier 2017) would effectively fulfill the requirements for these magnets in terms of conductor current density. To support this statement we consider as an example the 16 T cos-theta magnet operating with a 14% margin on the load line being developed by Istituto Nazionale di Fisica Nucleare (Sorbi 2017). In this design, using the FCC target conductor, the critical current density of the inner coil layers at the short sample peak field (18.7 T) and at

an operating temperature of 1.9 K is about 1200 A/mm<sup>2</sup>. It will be shown below that to protect the magnet in case of a quench in this configuration, about half of the conductor should contain copper. An additional increase of current density would require a larger fraction of copper, so it would not be linearly exploited in terms of engineering current density. For the outer coil layers, where the short sample peak field is limited to about 14–15 T, the amount of copper needed for magnet protection represents about two times the amount of the non-copper part of the conductor. For example, a 15% further increase of  $J_c$  of the outer layer conductor allows a reduction of the amount of superconductor in the wire by 15%, but, as the amount of copper remains the same, it represents a decrease of the wire size by only about 5% (in reality a bit more because a smaller coil is electromagnetically more efficient).

In summary, the FCC target performance for Nb<sub>3</sub>Sn seems to be a sufficient conductor for these 16 T magnets: any other option should be considered only if it is more cost-effective. If the target nominal field was higher than 16 T (or if a larger margin would be needed) then the situation would be different: this will be discussed in Sect. 16.3.3.

### 16.2.2 Nb<sub>3</sub>Sn Wire and Cable

An overview on the development of Nb<sub>3</sub>Sn wires and cables focused on high-field accelerator magnets can be found in Chap. 3 of this book, and a discussion on targets for research and development (R&D) programs can be found in Ballarino and Bottura (2015).

The wire and cable characteristics and sizes are a compromise between what is required for an optimized electromagnetic design and the achievable electro-mechanical performance of the conductor once submitted to the different manufacturing (including wire cabling and magnet coil winding) and operational phases. For these high-field magnets, there is an interest in using large wires and cables to allow for large currents, and therefore keeping the magnet inductance within reasonably low limits, as required for magnet and circuit powering and protection. Furthermore, the effective filament diameter of the wire should be reasonably small in order to reduce the wire magnetization, which has an impact on the magnet field quality at low fields, on conductor stability against flux jumps, and on the energy losses to be cooled by the cryogenic system. The issue of producing large wires with a small effective filament size has been tackled in two development programs started in the US in 1999 (Scanlan 2001) and in Europe in 2004 for the Next European Dipole program (NED) (Devred et al. 2004). Target values for the effective filament size were < 40 μm for the US program and < 50 μm for NED, and for a strand diameter of up to 1.25 mm in the case of NED. These target values have now been approached, and just recently achieved in critical current density on limited unit lengths (Xu et al. 2019). The 16 T design options explored within the European Circular Collider (EuroCirCol) program (Tommasini et al.

2017) are presently considering a target effective filament size of 20  $\mu\text{m}$  and a maximum strand diameter of 1.20 mm.

The maximum number of strands in a cable is not only dependent on the cabling capacity (presently up to 40 strands in Europe and up to 60 strands in the US), but also on the cable stability during winding and magnet assembly. For example, it is expected that winding a cos-theta geometry with a large cable is more challenging than winding a racetrack coil for a common-coil geometry.

Finally, the maximum allowed reversible and irreversible stress limits for impregnated Rutherford cables at ambient temperatures and cryogenic temperatures represent severe bounds imposed upon the magnet design and may, for example, preclude the use of collared assemblies for dipole magnets in the 16 T field range. For the abovementioned EuroCirCol program, these stress limits have been set at 150 MPa and 200 MPa at ambient and cold temperatures, respectively.

### 16.2.3 Cost

The target conductor cost set in 1999 for the abovementioned US program was <US \$1.50 per kA.m at 12 T, 4.2 K. When scaled to 16 T, 4.2 K, this corresponds to about US\$3.5 per kA.m. The target cost currently considered in view of the FCC was set in 2016 at €5 per kA.m at 16 T, 4.2 K (Schoerling et al. 2017).

## 16.3 Design Parameters

Both the present design of the FCC machine and a possible energy upgrade of the LHC are based on scaling up the LHC machine. The required bending field integral for the FCC is about 1.0 MT.m to achieve a proton–proton center-of-mass energy of 50 + 50 TeV with 66 km of bending length, which, for a 100 km closed orbit length, corresponds to the same filling factor as in the LHC. Considering the same magnetic length of 14.3 m per magnet as in the LHC, the FCC reference lattice needs about 4600 magnets, producing a field of 16.0 T.

### 16.3.1 Magnet Aperture

The required physical magnet aperture depends on beam dynamics requirements, the beam screen, and the field quality at the reference radius.

For the FCC the physical magnet aperture has been set to 50 mm. A larger aperture would provide more margin for the dynamic aperture as well as for the design and integration of the beam screen: furthermore, it would also make it easier to achieve a given magnetic field quality at a given reference radius (17 mm for the

FCC). A smaller aperture would impose more stringent constraints on the magnets' field quality, the beam screen design and integration, and the magnets' alignment in the accelerator. Besides the fact that the physical aperture has an impact on the magnet stored energy, thus upon the powering and protection scheme, it also determines the amount of conductor needed for the coils. For the FCC it has been estimated (Schoerling et al. 2017) that, for an aperture of around 50 mm, the relative variation of amount of conductor is similar to that of the variation of the aperture: i.e., 10% less aperture corresponds to about 10% less conductor.

Considering the presence of the beam screen and vacuum pipe, such a small reduction of physical aperture would, however, considerably reduce the beam aperture.

### ***16.3.2 Operating Temperature***

The choice of the operating temperature has a strong impact on the magnet design and cost as well as on the cryogenic production and distribution system. Operation at 1.9 K, as in the LHC, allows easier and more effective cooling of the magnet coils, and a considerable saving of the amount of conductor needed for producing the 16 T field amplitude when compared to the alternative of working in supercritical helium. Furthermore, operation at 1.9 K greatly simplifies the beam screen design because it enables effective cryo-pumping (Baglin et al. 2013). On the other hand, producing superfluid helium requires additional cold compressors and more energy. It has been estimated (Schoerling et al. 2017) that the additional capital cost and the difference in operation cost over 10 years for cooling the magnets at 1.9 K compared to cooling at 4.5 K is largely compensated for by the savings in the cost of conductor.

### ***16.3.3 Field Level and Margin***

Considering the FCC target performance of the conductor discussed above, 16 T seems to be the highest field level that is still economically and technically interesting when the same margin (14%) on the load line of the LHC is considered and the operational temperature is set at 1.9 K. A comparison between optimized designs of different magnet cross-sections, cos-theta, block coils, and common coils, operating at 16 T with 18% and 14% margin on the load line, and using the FCC target performance for the conductor, has been performed in the frame of the EuroCirCol study (Gourlay 2016, 2017). In all cases, the coil cross-sections that were designed with 18% margin were using up to 30% more conductor than the cross-sections designed with 14% margin. At a lower field amplitude the relative difference between margin and field amplitude decreases, due to a combination of the variation of the critical current density with field amplitude and the quantity of copper required to protect the magnet in the case of a quench.

The concept of load line margin is the one most used when comparing magnets performance, because it gives a theoretical performance percentage given by a conductor's electromagnetic characteristics. The load line margin does not, however, have an immediate physical meaning as, for example, in the case where the temperature margin, the enthalpy margin, or the current margin are considered. The use of these latter concepts is, however, not necessarily more representative of magnet performance than using the margin on the load line, it is just different. For example, at a given margin on the load line and a given operating temperature, Nb<sub>3</sub>Sn magnets have a much larger temperature margin than Nb-Ti, but not necessarily better performance. At 20% of the load line and 1.9 K the temperature margin for Nb-Ti is 2.1 K and for Nb<sub>3</sub>Sn it is 4.5 K; and at 4.2 K it is 1.2 K and 3.0 K for Nb-Ti and Nb<sub>3</sub>Sn, respectively. Concerning enthalpy margins, for Nb<sub>3</sub>Sn these are typically three times larger than for Nb-Ti for the same conditions of load line margin and operational temperature (Todesco 2017).

### 16.3.4 Field Quality

The field quality required has an impact on the selection of the conductor, on the manufacturing and assembly tolerances of the magnet and other relevant parts, and on the degrees of freedom in the design of the magnet cross-section and the magnet ends.

We assume that the required control limits for tune and chromaticity are similar to those of the LHC, i.e., in the order of 0.001 of tune and 1 unit of chromaticity (Todesco et al. 2016).

In a hadron collider like the HE-LHC or the FCC, the quadrupole component is mainly due to the two-in-one magnet design, and varies along the powering ramp due to the saturation of the ferromagnetic yoke. To keep these effects small with respect to the force generated by the lattice quadrupoles and to preserve the dynamic aperture at injection, the magnet design should minimize the quadrupole component at the lowest field amplitude. At the highest fields this can be considerably relaxed because the tune of the two beams can be controlled separately as the two quadrupole apertures are individually powered. Indeed, referring to the field error in terms of units (parts of the main field in  $10^{-4}$  at a reference radius two-thirds of the physical aperture), for the FCC the allowed quadrupole component of the dipoles is up to several tens of units at full energy. This limit allows for the design of 16 T dipoles with inter-beam distances in the range 200–250 mm.

Concerning the sextupole component, the main difficulty comes from the fact that controlling 1 unit of chromaticity corresponds to controlling a few percent of units for the sextupole component. For high intensity beams (i.e., during nominal operation), the chromaticity cannot be measured in real time during the magnet ramp, thus requiring an accurate magnetic model to predict the sextupole component during the ramp. Establishing such an accurate model is possible only if the behavior of the sextupole component during the ramp is accurately predictable, i.e., reproducible in

time and amplitude. The quality of the prediction depends, on the spread of the conductor characteristics responsible for the sextupole variation during the magnet ramp, and on the shape and amplitude of the variation itself. For the LHC the field model, after several iterations and corrections from ad hoc measurements at low fields, can predict the sextupole component in the dipoles during the ramp by about 0.1 units (Todesco et al. 2016) for a total sextupole variation from injection to a nominal energy of about 10 units.

With respect to the filament diameter of 7  $\mu\text{m}$  and 6  $\mu\text{m}$  in the inner and outer coil layers, respectively, of the LHC dipoles (Rossi 2003), the effective filament size of the best-performing Nb<sub>3</sub>Sn conductors is almost one order of magnitude larger. The associated sextupole component due to strand magnetization, decay, and snapback is also therefore much larger, due to both the higher critical current density and the larger filament size. Fortunately, it has been shown that several methods can be effective in mitigating these effects (Izquierdo Bermudez et al. 2016; Kashikhin and Zlobin 2016).

### 16.3.5 *Structural Parameters*

Major difficulties for Nb<sub>3</sub>Sn with respect to Nb-Ti magnets are related to the lower strain and stress allowed in the brittle Nb<sub>3</sub>Sn conductor, and to the higher rigidity of the impregnated Nb<sub>3</sub>Sn coils with respect to non-impregnated Nb-Ti coils, which imposes tighter assembly tolerances. These difficulties are enhanced by the higher forces to be handled in a higher field magnet with respect to a lower field magnet, which also yields higher stresses for similar engineering current densities.

The design options explored within the EuroCirCol initiative (Schoerling et al. 2019) show that, by using a conductor with the FCC target performance, the maximum stress in the conductor reaches values in the range of 150 MPa during magnet assembly and of 200 MPa during operation at cold.

As anticipated above, Nb<sub>3</sub>Sn coils are in general stiffer than non-impregnated Nb-Ti coils: for example, the average elastic modulus of the coils of the LHC magnets is about 10 GPa (Couturier et al. 2002), and the elastic modulus of the coils built so far for the Hi-Lumi project is in a range between 25–40 GPa. This makes the magnet design and the assembly tolerances of Nb<sub>3</sub>Sn magnets more challenging than those of Nb-Ti magnets because, for a given geometric error or deformation, the associated stress variation increases considerably.

Finally, as the performance and integrity of Nb<sub>3</sub>Sn is particularly sensitive to strain, the magnet assembly requires particular care in every detail, at the risk of potentially introducing a local discontinuity.

### 16.3.6 Quench Protection

According to the Hi-Lumi experience (Marinozzi et al. 2016), a conductor hot-spot temperature in the order of 350 K during a quench can be sustained by Nb<sub>3</sub>Sn accelerator magnets without degradation. In reality, the epoxy-based impregnation system should allow the reaching of, for short periods, much higher temperatures, in the order of 450 K. In this direction, a study of the effects of high temperatures during quenches performed on a small Nb<sub>3</sub>Sn racetrack magnet (Imbasciati et al. 2004) suggested that the temperature threshold could be increased to at least 400 K.

Concerning the protection aspects, with respect to Nb-Ti magnets the higher magnetic field produced by Nb<sub>3</sub>Sn magnets engages larger stored energies, which have to be managed in the case of a quench, or a fault, at the magnet and at the circuit level. Considering as a reference that a quench is spread within a time delay of about 40 ms (20 ms for detection and 20 ms for having the coil quenched), the maximum voltage to ground during a quench of a typical EuroCirCol 16 T design option is of the order of 1 kV (Salmi et al. 2017), and the turn-to-turn voltage of the order of up to 100 V. An additional 1 kV should be added to this for the whole circuit, totaling the requirement of an operational dielectric insulation to ground of 2 kV. This is about twice the value of the LHC magnets, and certainly represents an important technological issue to keep in mind.

Both the Hi-Lumi magnets and the EuroCirCol options show that the use of quench heaters and the so-called coupling-loss-induced quench (CLIQ) system (Ravaioli et al. 2015), either in combination or alone, appears appropriate for ensuring reliable protection during a quench.

Concerning the integration of the magnet in a circuit string, a strong limitation comes from the maximum voltage to ground that one is ready to accept in case of a quench. A study performed for the FCC (Prioli et al. 2019) has shown that, if a single magnet can be protected, a string of magnets can also be protected within given constraints (in particular voltage withstand levels and the time constant of the circuit) by a proper subdivision of a powering sector in multiple circuits.

### 16.3.7 Conductor Grading

In a dipole cross-section the field amplitude is reduced over the coil width as the radius increases. This allows splitting the coil into layers, with the superconductor operating at increasing current densities thanks to the field decrease. This approach, called grading, allows an efficient use of conductor by moving the operating point of each graded layer closer to the conductor critical surface, at the expense of the complication of using and splicing different cables in a coil. Considering an Nb<sub>3</sub>Sn conductor with the FCC target performance and at an operational temperature of 1.9 K, the interest in grading arises when the short sample peak field exceeds about 15 T (corresponding to a magnet with an operational field amplitude in the range of

13 T). For lower field levels the critical current density of the superconductor is already in a range (about 3000 A/mm<sup>2</sup>) requiring a large fraction of copper for quench protection (two to three times the amount of superconductor), so that the coil size becomes no longer dominated by the conductor performance. For higher field amplitudes we consider the case of a 16 T magnet with 14% of margin on the load line: at the short sample peak field of 18.7 T and at an operating temperature of 1.9 K the FCC target superconductor can carry about 1200 A/mm<sup>2</sup>. At this current density, as much copper as superconductor is required to ensure magnet protection in case of a quench. If the coil is graded at a magnetic field of around 3 T lower than the peak field, the critical current density has already doubled, requiring about twice the quantity of copper with respect to the quantity of superconductor. Additional grading levels at a lower field require a larger and larger fraction of copper to non-copper. Therefore, in terms of magnetic efficiency of the magnet cross-section, for a 16 T magnet with 14% margin there is a strong interest in having one or even two grading levels. A further increase of the number of grading levels is of limited interest, because the engineering current density of the conductor does not increase linearly with the number of grading levels. In terms of cost, the raw ingredients of the superconductor material do not currently represent the major component of the conductor cost, but the situation may change in the case of optimized conductor production, requiring that an optimal compromise be found between the technical complexity of additional grading and conductor cost.

Finally, we recall the opportunity of grading with different types of superconductor, towards lower or higher fields. An apparently “cheap” way to grade towards lower fields can be performed using Nb-Ti, which we can imagine being used at 1.9 K and, with some margin, at around 8 T. If this additional grading level is achieved through an internal splice this should, however, be compared to performing the same grading with Nb<sub>3</sub>Sn or not performing it at all. At a field amplitude of 8 T plus margin, let us say 10 T, the critical current density of Nb<sub>3</sub>Sn at 1.9 K is extremely high, exceeding 5000 A/mm<sup>2</sup>: the cost of the superconductor in these conditions may become competitive with that of Nb-Ti.

### ***16.3.8 Quench Performance***

A superconducting magnet may not reach its operational field the first time it is powered due to the occurrence of a quench. In most cases, the quench current increases at each subsequent powering until a limiting maximum current (ideally the short sample limit) is reached, going through what is referred to as “training.” Provided that the magnet is designed, manufactured, and protected to withstand the occurrence of quenches during its life, depending on the specific situation, we can accept, or not, a certain degree of training. For example, in the case of a single or a few units individually powered, we may decide to accept to perform a few training quenches once the magnet is installed and cooled down before operating the magnet in the facility, if the infrastructure is capable of performing the training campaign.

On the other hand, in the case of a large number of magnets connected in series, the probability that a single magnet unit needs a training quench before reaching its operational field should be minimized. Achieving this objective becomes increasingly expensive as the allowed probability that a magnet needs training quenches becomes smaller. Directions for decreasing the probability of needing training quenches to reach nominal field are: (1) a robust design (typically requiring long and expensive R&D programs); (2) an increased margin (requiring more conductor and also resulting in a larger magnet); and (3) the insertion of training campaigns within the magnet acceptance tests.

In the case where all magnets are individually trained, as should ideally be for a large accelerator, an important element to consider is the so-called “memory,” i.e., the ability of a magnet to retain its performance achieved after training in cases where the magnet is submitted to a thermal cycle. A magnet with good memory will not train again once installed and operating in the particle accelerator. Ideally, the training campaign performed during the acceptance tests should include a “thermal cycle” to re-check the performance on a trained magnet after a warm-up and subsequent cool-down.

## 16.4 Present Development Programs

In these years, the development of the magnets for the Hi-Lumi project will for the first time demonstrate the use of Nb<sub>3</sub>Sn magnets in a particle accelerator. To prepare for the next step at higher fields, towards a HE-LHC or a FCC, new R&D programs are being established in the US through the US Magnet Development Program (MDP) (Gourlay et al. 2016), and in Europe through the FCC 16 T development program and the European Circular Collider (EuroCirCol) study (Schoerling et al. 2015; Tommasini et al. 2018). These programs are tackling the main R&D issues in preparation for the large use of high-field Nb<sub>3</sub>Sn magnets in a particle accelerator, from conductor development to the training performance and design options. Block type (Felice et al. 2019), common coil (Toral et al. 2018), cos-theta (Valente et al. 2018; Zlobin et al. 2018), and canted cos-theta (Caspi et al. 2017; Montenero et al. 2019) are being studied as design options for twin-aperture dipole magnets accessing the 16 T field range. As a magnet’s cost is heavily dependent on the amount of conductor used, for a large number of magnets the cos-theta and block coil options would be preferable because, for the same margin on the load line, they are more efficient than the other two options. The favorable stress management of a canted cos-theta magnet or the regular simple coil geometry of a common-coil magnet may, however, allow these configurations to operate at a lower margin on the load line. This may possibly partially or totally compensate for their lower efficiency in terms of conductor use.

## 16.5 Conclusions

In the operational field range between 10 T and 16 T the most appropriate, and probably the only, conductor for producing a large series of accelerator magnets is Nb<sub>3</sub>Sn. Its present performance is very close to what is ideally required, and its cost should still have a considerable margin of decrease if large-scale production is performed.

At this stage, an operational field range up to about 12 T is becoming reality in the Hi-Lumi project. The operational range between 12 T and 16 T has still to be explored and proven experimentally, showing that the outstanding challenges of stress management and training can be effectively overcome.

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