

Superconducting magnets for accelerators

Alexander V. Zlobin (FNAL) and Daniel Schoerling (CERN)

Abstract—Superconducting magnets have allowed great progress and multiple fundamental discoveries in the field of High Energy Physics. This chapter reviews the use of superconducting magnets in particle accelerators, introduces Nb₃Sn superconducting accelerator magnets and describes their main challenges.

I. CIRCULAR ACCELERATORS AND SC MAGNETS

Circular accelerators are the most important tool of modern High-Energy Physics (HEP) for investigating the largest mass and the smallest space scales. A key element of a circular accelerator is its magnet system [1]. The magnet system is composed of large quantities of various magnets, mainly dipoles and quadrupoles, to guide and steer the particle beams. The function of the majority of the magnets (so called arc magnets which are periodically placed along a ring) is to keep the beam on a quasi-circular orbit and confine them in a relatively small and well-defined volume inside a vacuum pipe. Magnets are also used to transfer beams between accelerator rings in so-called transfer lines, match beam parameters from the transfer line into the injection insertions or into extraction lines and beam dumps, direct or separate beams for the accelerating radio frequency (RF) cavities, and focus beams for collision at the interaction points where the experiments reside.

One of the most important parameters of colliders is the beam energy, as it determines the physics discovery potential. The energy E in GeV of relativistic particles with a charge q in units of the electron charge in a circular accelerator is limited by the strength of bending dipole magnets B in Tesla and the machine radius r in meters

$$E \approx 0.3qBr.$$

Thus, high magnetic fields are an efficient way towards higher energy machines for hadron and ion collision.

The value of magnetic field in a circular accelerator needs to be synchronized with the beam energy. It is achieved by using electromagnets which allow varying the field strength by changing the electric current in the coil. However, the maximum field of traditional electromagnets with copper or aluminum coils is limited by Joule heating which limits the current density in a magnet coil typically to ~ 10 A/mm².

In 1911, the Dutch physicist H. Kamerlingh-Onnes discovered the phenomenon of superconductivity - vanishing of electrical resistance in some metals at very low (< 10 K) temperatures [2]. This discovery inspired him to propose two years later a 100,000 Gauss (10 T) solenoid based on a superconducting coil cooled with liquid helium. He believed that superconductivity would allow increasing the current in a coil and, thus, generating larger magnetic field. Yet, it took more than 50 years of hard work to realize in practice this dream.

The design and construction of superconducting magnets have become possible only after the discovery and development of technical superconductors in the early 1960s. Technical superconductors are defined as a class of

superconducting materials that provide high current densities in the presence of high magnetic fields.

Earlier attempts to use technical superconductors in superconducting magnets failed due to premature magnet transitions to the normal state called quenches. These quenches were caused by the abrupt movement of magnetic flux inside a superconductor, the so-called flux jump effect. The analysis of flux jumps yielded to the development of stability criteria for technical superconductors [3, 4]. Stability with respect to small field or temperature perturbations of the superconducting state can be guaranteed only if the superconductor transverse size does not exceed a maximum transverse size value proportional to the material specific heat and inversely proportional to its critical current density. For example, for an Nb-Ti superconductor at 5 T and 4.2 K the maximum filament size has to be smaller than 50 μ m.

The other main concern was the superconductor protection in case of a quench. All superconductors in normal state have high resistivity. In case of quench, they are likely to be damaged by Joule heating due to the high current density they carry, if no adequate measures for protection are taken. To minimize the heating after a quench, a superconductor should be therefore surrounded by a normal conductor with low resistance.

The two aforementioned conditions (stability and protection) have led to the concept of composite superconductors in which small superconducting filaments are embedded in a normal conducting matrix with low resistance and large thermal diffusivity. The matrix decreases the Joule heating when the superconductor becomes normal, conducts the heat away from the surface of the superconducting filaments thanks to high thermal conductivity, and absorbs a substantial fraction of heat due to high specific heat. To provide stability of a composite superconductor to flux jumps and reduce the eddy currents induced by varying external magnetic fields, the superconducting filaments are twisted along the conductor axis. Flux jumps not only limit the size of the filament but also the size of the multifilament composite wire due to self-field instabilities related to the non-uniform distribution of transport current inside the wire. For example, for an Nb-Ti composite wire at 5 T and 4.2 K the maximum diameter is limited to ~ 2 mm.

A composite superconductor placed in a varying magnetic field becomes magnetized with two components: one is related to persistent currents in superconducting filaments, and the second one is caused by coupling eddy currents between filaments. Both components are diamagnetic in an increasing field and paramagnetic in a decreasing field. The hysteretic behavior of wire magnetization leads to energy dissipation called also Alternating Current (AC) losses. Likewise, the magnetization, the AC loss power in a composite superconductor has two main components one is related to persistent currents in superconducting filaments and the other one to coupling eddy currents in composite wires. The magnetization of composite wires plays an important role in superconducting accelerator magnets,

which have demanding requirements on field uniformity. The AC losses are important for *cryogenic cooling* of superconducting coils during magnet operation and quench, and contribute to the heat load on a magnet cooling system. The critical current density J_c is a key parameter, which controls the current carrying capability, stability, magnetization and AC losses of technical superconductors and, thus, the performance of superconducting magnets. As the resistive transition from the superconducting to the normal conducting state in a composite superconductor is smooth, the definition of J_c is not straightforward [5]. The most commonly used criterion at the present time, in particular for superconducting accelerator magnets, defines J_c at the resistivity of $10^{-14} \Omega\cdot\text{m}$.

Important features of practical materials for superconducting magnets include not only appropriate combination of critical parameters but also their reproducibility in long lengths, compliance with mass production and affordable cost.

Large accelerator magnets are using large high-current cables to reduce the magnet inductance which is an important parameter for magnet protection during a quench. To achieve the required high current level, several strands are connected in parallel and twisted or transposed in the axial direction [3]. Multistrand cables allow reducing the piece length requirement for wire manufacturing, the number of turns in a magnet coil, and also allow for current redistribution between strands in the case of a localized defect of some strands or quench. The Rutherford cable is the most widely used cable type in accelerator magnets [6]. To adapt the cable design to the magnet design, it is produced either with a rectangular or a slightly keystone cross-section. A Rutherford cable is composed of fully transposed twisted composite strands. Strand transposition reduces coupling losses and ensures uniform current distribution, also aided by the electrical contact between the strands. The cable critical current I_c is normally the sum of the strand critical currents, which depend on wire degradation during cabling and current distribution in the cable cross-section. Due to strand coupling inside the cable, its magnetization and AC losses have additional eddy current components controlled by the interstrand resistance and the cable twist pitch.

II. ACCELERATOR MAGNET DESIGN AND OPERATION

A. Magnetic design

The desired magnetic field in SC magnets is produced by a current I in a coil calculated using the Biot–Savart law

$$\vec{B} = \frac{\mu_0}{4\pi} \int_C \frac{Id\vec{l} \times \vec{r}}{r^3},$$

where Idl is a current element and r is the radius vector from the current element to the field point. The total field in a given point of a magnet is obtained by integrating the current elements over the coil volume.

A perfect dipole field can be generated by two infinite slabs, by two intersecting ellipses (cylinders) with uniform and equal currents of opposite direction, or by a cylinder with a cos-theta current density distribution (Fig. 1) [7]. The field strength B in the dipole aperture is defined as follows

$$B \sim J(B)w$$

where w is the slab or cylinder thickness.

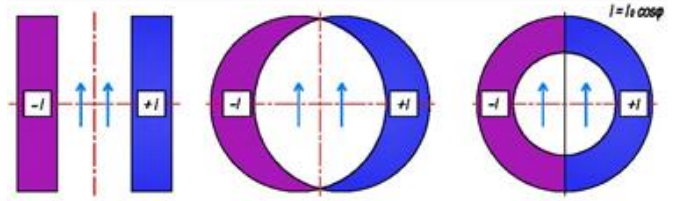


Fig. 1. Pure dipole configurations: two infinite slabs (left), intersecting ellipses (center) and cylinder with cos-theta azimuthal current density distribution (right).

To mimic the ideal current configurations, they are approximated with a number of cables arranged in blocks and separated by wedges [8]. The block positions and cross-sections are optimized to approach the ideal coil cross-section and achieve the required field quality. In practice, in line with the three different types of dipolar configurations in Fig. 1 three coil types are used: block-type, shell-type, and cos-theta type.

Coils of accelerator magnets are usually surrounded by an iron yoke, which serves as a return path for the magnetic flux and contributes to the magnet bore field. Three different classes of magnets can be identified based on the way in which the wanted field is achieved: a) iron dominated or superferric magnets, in which the shape of iron poles determines the field pattern; b) iron-free magnets in which the field configuration is dominated by the coil shape; and c) magnets in which the field configuration is provided by both the coils and the iron yoke.

B. Field quality

Since real coils only approximate the ideal dipole cross-sections, the magnetic field in accelerator magnets is not perfect. Excluding the coil ends, the magnetic field in the bore of long and slender accelerator magnets is two-dimensional and can be represented by the power series [8, 9]

$$B_y + iB_x = B_1 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

where B_x and B_y are the horizontal and vertical transverse field components, B_1 is the dipole field component, and b_n and a_n are the “normal” and “skew” n -pole coefficients, also called field harmonics, at a reference radius R_{ref} . The reference radius is usually chosen at two-thirds of the magnet free aperture.

Due to the symmetry of the magnet cross-section, only normal multipole coefficients allowed by symmetry are expected to be non-zero [7-9]. These so-called allowed multipole coefficients can be minimized by iterating on the coil cross-section parameters. In addition, the magnetic properties of coil and structural materials and geometrical errors produce un-allowed field harmonics. For instance, a top/bottom asymmetry in a dipole magnet produces a skew quadrupole a_2 , while a left/right asymmetry produces a normal quadrupole b_2 . These unwanted harmonics can be minimized by selecting the appropriate materials and improving the precision of coil and structural components, tooling and assembly procedures.

At the magnet design phase, two classes of field errors are distinguished: systematic and random errors. The systematic errors include geometrical errors, which originate from the imperfections of the coil and the iron yoke cross-sections as well as by the iron yoke saturation and the coil magnetization.

The random errors are mainly due to the random variations of the coil geometrical parameters (inner and outer coil radii, coil pole angles, wedges geometry and position, etc.).

To achieve accelerator field quality the coil and the yoke cross-sections and their relative position typically must have an accuracy better than ~ 0.1 mm including coil deformations under the Lorentz forces. The errors from Lorentz forces vary during magnet excitation and their level depends on the rigidity of the coil and magnet mechanical structure. The minimization of these errors is one of the key parts of mechanical structure optimization.

The random errors are typically estimated by means of Monte-Carlo simulations imposing a random displacement of the coil blocks. Since these displacements do not respect the magnet symmetry, they produce a whole spectrum of field harmonics. Based on the random error analysis fabrication tolerances on the main coil and structural components, tooling and assembly process are formulated which need to be provided to achieve the required accelerator field quality.

The iron yoke is saturated when the level of field in the iron exceeds 2 T. The relative magnetic permeability of saturated iron dramatically reduces depending on the field level in each point of the yoke. As a result, the iron contribution is a non-linear function of transport current. In a single-aperture magnet with a symmetrical iron yoke, the saturation effect is mainly observed in the magnet main field B_1 (or magnet transfer function B_1/I) and in the normal sextupole b_3 . The variation of sextupole field due to iron saturation is reduced by optimizing the iron inner and outer dimensions and introducing special holes at appropriate places in the yoke. In a twin-aperture dipole, the central part of the yoke saturates before the outer parts, resulting in left/right asymmetries in the yoke contributions affecting the normal quadrupole b_2 . The saturation effects in b_2 are of opposite sign in the two apertures. This effect is controlled by asymmetrical holes in the iron yoke and by choosing the inter-beam distance large enough to minimize these effects.

The three main components, which add to the field quality distortion from coil magnetization, are the persistent currents in the superconducting filaments, the eddy current between filaments within the strands and the eddy currents between the strands of a cable, so-called interstrand coupling currents. The field distortions produced by coil magnetization are most significant at low fields and become negligible at high fields. The field errors from coil magnetization change sign during current ramp up or down, and as a result, the main field and the allowed lower-order harmonics show ample hysteresis as a function of transport current and magnet excitation history.

The persistent currents in the filaments can be reduced by reducing their filament size. The eddy current component within the strands is controlled by the wire twist pitch, and the interstrand coupling currents depend on the interstrand resistance in the cable. The interstrand resistances should not be too large to allow current sharing among cable strands. If the cable magnetic properties are uniform, only the main field and low order allowed field harmonics (mainly b_3 and b_5) are disturbed. In the case of non-uniform magnetic properties all lower-order harmonics will be affected.

C. Mechanical design

The coil turns carrying a transport current in the magnetic field are exposed to electromagnetic (Lorentz) forces. The Lorentz force per unit length \vec{F}/l of conductor with current I in magnetic field B is

$$\vec{F}/l = \vec{I} \times \vec{B}.$$

The force is directed perpendicularly to the current and field vectors. The value and distribution of forces inside the magnet coils and the associated mechanical stress and deformations depend on the magnet size and configuration, the value of the magnetic field, and the mechanical properties of the coil and the magnet structure. The analysis of mechanical forces, stresses and deformations is a complex task, which is usually performed using finite element codes.

The Lorentz forces in superconducting accelerator magnets are very large [9-10]. To stabilize the magnetic field characteristics in the operating field range and to reduce the probability of spontaneous quenches, it is necessary to ensure the mechanical stability of turns in the coil. Mechanical stability is achieved by applying a pre-load to the coil during magnet assembly and by supporting the compressed coil during operation with a rigid support structure. The required minimum pre-load value is determined by the magnet design, the level of the operating field, and the thermal contraction and mechanical rigidity of the structural materials. The allowed coil pre-stress is limited by the maximum stress the coil can sustain before the superconductor starts degrading or insulation damage. The pre-load applied to the magnet coils at room temperature has to be sufficient to compensate the pre-load decrease due to coil creep after magnet assembly, differences in thermal contraction of the coil and the structure, and coil deformations under Lorentz forces during magnet excitation.

The horizontal component of the Lorentz force bends the coil horizontally with a maximum displacement at the magnet midplane. This bending leads to additional coil stress and to coil deformation which generates field distortions. The coil support against the horizontal component of the Lorentz force is provided by a special stiff support structure placed between the coil and the iron yoke. This structure is optimized to limit the horizontal coil deflections. However, to increase the field enhancement from the iron yoke, it is placed rather close to the coil which limits the thickness and, thus, rigidity of the support structure. To compensate this, the yoke and strong metallic shell outside the yoke or the helium vessel shell are also used as part of the coil support system.

The axial component of the Lorentz force stretches the coil axially increasing stresses and turn displacements in coil ends. To minimize these effects, it is essential to provide a stiff support (and even some initial axial preload to compensate for different thermal contraction of magnet coils and mechanical structure) against the axial component of the Lorentz force using thick stainless steel end plates welded to the shell or connected by thick axial rods.

D. Operation temperature, fields and margins

Superconducting magnets are operated at temperatures well below the superconductor's critical temperature. Usually, liquid helium is used for this purpose, which has a boiling temperature of around 4.22 K at atmospheric pressure [11]. At temperatures below 2.17 K, called the lambda-point, liquid helium turns into superfluid due to a phase transition. The superfluid phase has extremely high thermal conductivity and extremely low viscosity. This combination of properties is beneficial for cooling of superconducting magnets as it allows the superfluid helium to penetrate into a porous coil and magnet structure and to transfer heat from the magnet to a heat sink in a stagnant liquid superfluid helium bath.

The superconductor critical current density is a function of its temperature and the applied magnetic field. Figure 2 shows the dependence of the conductor critical current, defined as a maximum transport current carried through the superconductor area, versus the magnetic field for a given operating temperature T_{op} . The magnet load line describing the dependence of the magnetic field in the coil and the magnet current is also shown. The intersection of these two functions defines the ultimate magnet parameters such as the maximum field B_{SSL} and the maximum current I_{SSL} , called also the magnet short sample limits (SSL).

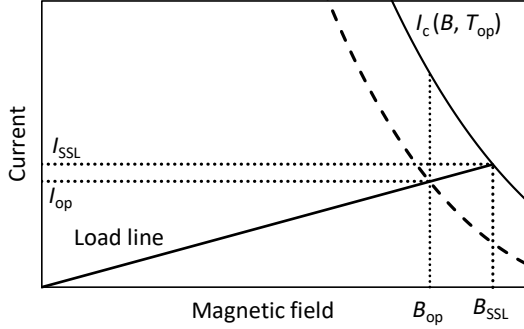


Fig. 2. Conductor I_c vs. magnetic field B and magnet load line.

To ensure stable performance, superconducting magnets operate at currents below the conductor critical current with some margin. Important magnet operation margins include the margin along the load line, defined as the ratio of the operation current to the magnet SSL, $l=I_{op}/I_{SSL}$, and the critical current margin, defined as the ratio of the operation current to the conductor critical current at B_{op} and T_{op} ,

$$i=I_{op}/I_c(B_{op},T_{op}).$$

The magnet temperature margin ΔT , associated with the critical current margin, is defined as the difference between the operation temperature T_{op} and the current sharing temperature T_{cs} at which the operation current is equal to the critical current. Note that the critical current margin and the temperature margin are different for each turn, due to the field and related critical current variations inside the coil.

E. Magnet thermal stabilization

Superconducting magnet coils are exposed to a variety of disturbances such as conductor displacements during excitation, epoxy cracking, AC losses, splice heating, beam-induced heat deposition, fluctuations of the helium temperature in the cryogenic system, etc. These disturbances may raise the coil temperature above the superconductor critical temperature T_c , as the transport current is expelled into the low-resistivity matrix. The main goal of coil thermal stabilization is ensuring its ability to stay superconducting or even to recover superconductivity after a disturbance.

To achieve complete magnet thermal stability with respect to any perturbations the cross-section of the normal stabilizer has to be rather large and well cooled [7, 11]. However, considerations related to cost and performance optimization require reducing the stabilizer cross-section in superconducting accelerator magnets to a minimum dictated by internal stability of the composite wires to flux jumps and quench protection. In this case, complete magnet stability is not provided. Some improvement of magnet stability can be achieved by limiting the conductor motion in a coil by applying coil preload, by coil impregnation (e.g. with epoxy or other suitable agents), and by reducing friction on various

conductor surfaces inside a magnet.

The perturbation spectrum is usually not known for superconducting magnets. In this case, magnet pre-conditioning plays an important role for releasing large perturbations accumulated during magnet fabrication. In early experiments with superconducting magnets it was found that the magnet maximum current before quench gradually increases in consequent quenches. This process is known as magnet training. After a limited number of quenches a magnet often reaches a stable plateau. If the magnet quench current at the plateau is lower than the magnet short sample limit, it indicates a magnet current degradation. Usually magnets remember their training after warming up and cooling down cycles or show only a very short retraining. This memory is extremely important for accelerator magnets, which are installed and connected in series in large-scale accelerators.

Despite the disadvantages associated with possible instabilities and training, partially stabilized accelerator magnets provide the highest engineering current densities in the coils and, thus, enable the most compact magnets and the highest fields at the lowest cost.

In the case of AC losses, radiation-induced heat deposition, splice heating, and other steady or pulsed heat losses, the perturbation power is known and the coil peak temperature T_{coil} is defined by

$$T_{coil} - T_{op} = \frac{q_v A}{hP} \text{ for a steady heat deposition,}$$

or

$$W = \int_{T_{op}}^{T_{coil}} C_p(T) dT \text{ for a pulse heat deposition,}$$

where q_v is the average volumetric heat load, W is the heat pulse energy, A is the cable cross sectional area, h is the heat transfer coefficient, P is the conductor cooling perimeter and T_{op} is the operating temperature. To prevent magnet quenches, the temperature everywhere in the magnet coil should be kept below T_c . Magnet stability is ensured by choosing an appropriate temperature margin and coil cooling conditions.

F. Quench protection

The stored energy in superconducting accelerator magnets is large. In case of a quench, a large portion of this stored energy is typically dissipated in the relatively small coil volume and, thus, the coil is heated to quite high temperatures, which may damage or even destroy the coil. Hence, the magnet and conductor design and the protection system parameters have to be optimized to provide for reliable magnet protection during a quench and to limit the coil temperature, thermal stress and voltages within acceptable values [3, 9, 12].

The peak quench temperature T_{max} is usually estimated using an adiabatic approach by equating the Joule heat in the coil during the quench to the increase of the coil enthalpy:

$$\int_0^{\infty} I(t)^2 dt = \lambda S^2 \int_{T_q}^{T_{max}} \frac{C(T)}{\rho(B,T)} dT,$$

where $I(t)$ is the current decay after a quench; T_q is the conductor quench temperature; S is the total conductor cross-section; λ is the stabilizer fraction in the conductor cross-section; $C(T)$ is the average conductor specific heat; and $\rho(B,T)$ is the conductor normal resistivity. For a given value of the so-called quench integral measured usually in MIITs ($MIIT=10^6 \text{ A}^2\text{s}$), T_{max} can be minimized by reducing the matrix resistivity, or increasing the conductor cross-section

and the average specific heat. The value of the total quench integral is controlled by the quench detection and validation time, the protection circuit response, and the current decay time.

If the quench propagates rapidly inside a magnet, the stored energy can be practically uniformly dissipated in the magnet coil. The magnet will be self-protected if the enthalpy of quenched part of the coil is sufficient to keep the magnet maximum temperature below the acceptable level, usually 300 to 400 K. Quench protection of large accelerator magnets requires a special protection systems based either on traditional resistive quench heaters or on the recently developed Coupling Loss Induced Quench (CLIQ) system [13]. Both approaches provide a rapid quench of a large coil volume sufficient to absorb the magnet storage energy without coil overheating.

Protection heaters are usually made of thin stainless-steel strips, which are placed on the coil surface. Since the heaters are electrically insulated from the coil, the heater electrical insulation introduces a thermal barrier. As a result, there is a delay between the heater excitation and the coil quench. The heaters and their integration into the coil structure are optimized to reduce this delay. For the CLIQ system capacitor banks are discharged over parts of the coil, inducing eddy currents which quench the coil quasi-instantaneously.

The natural quench propagation in the coil, as well as the heat transfer between the quenched coil and the magnet support structure, increases the effective magnet volume involved in the energy dissipation and allows dissipating some fraction of the stored energy outside the coil. It reduces the hot spot temperature and the temperature under the quench heaters. In some cases, the magnet current decay is fast enough so that eddy currents induced in the conductor may also quench superconducting parts of the coil. This phenomenon, known as the ‘quench-back’ effect, evidently helps reducing the peak coil quench temperature. Using a protective heating system also helps to provide more balanced temperature and voltage distributions, and reduce the thermal and electrical stresses in the coil.

III. NB-TI ACCELERATOR MAGNETS AND TECHNOLOGIES

The work on Nb-Ti superconducting magnets for accelerators started in the late 1960s [14] and culminated by construction of a series of large superconducting accelerators in the USA and in Europe [15-18] in 1980s-2000s. These powerful superconducting accelerators have enabled several fundamental discoveries including the charm and top quarks, the tau lepton, the gluon, the Z- and W-bosons, and the most recent Higgs-boson that have shaped and confirmed our understanding of the Particle Physics Standard Model.

A. Nb-Ti composite wire

The superconducting Nb-Ti alloy, discovered in the 1960s, is the most successful practical superconductor. Since the 1970s, it has been the workhorse for the superconducting accelerator magnets, thanks to its ductility, high current carrying capability and successful industrialization of composite wires based on this material. Its critical temperature at zero magnetic field, T_{c0} , is 9.8 K and the upper critical magnetic field at zero temperature, B_{c20} , is 14.5 T.

The Nb-Ti composite wires are manufactured by a co-drawing process with intermediate heat treatments to achieve an optimal critical current density. The final anneal provides

a high Residual Resistivity Ratio (RRR) of the copper stabilizer. A thin Nb barrier separates the Nb-Ti alloy from the copper to avoid formation of brittle CuTi intermetallic composite during the high-temperature extrusion and the annealing heat treatments.

Diameters of practical wires are in the range of 0.1 mm to 3 mm and piece lengths are of a few km. The number of filaments in a wire may reach $\sim 10^5$ and the filament diameter is typically 5-20 μm (the practical low limit is ~ 1 -2 μm). The filament size is determined mainly by stability criteria and by hysteresis magnetization or AC loss requirements. The critical current density in superconductor at 5 T and 4.2 K of Nb-Ti composite wires used in accelerator magnets increased from $\sim 1.5 \text{ kA/mm}^2$ to more than 3 kA/mm^2 today. The typical RRR values of the copper matrix are in the range of 50-200.

B. Nb-Ti accelerator magnet designs and technologies

The first large superconducting accelerator based on Nb-Ti magnets was the Tevatron (1983-2011) at Fermi National Accelerator Laboratory (FNAL, USA). It was followed by the Hadron Elektron Ringanlage (HERA, 1991-2007) at the Deutsches Elektronen-Synchrotron (DESY, Germany), the Relativistic Heavy Ion Collider (RHIC, since 2000) at Brookhaven National Laboratory (BNL, USA) and the Large Hadron Collider (LHC, since 2008) at CERN.

Cross-sections of the Nb-Ti dipole coils used in arc dipoles in those projects are shown in Fig. 3. Coil and cable parameters are summarized in Table 1.

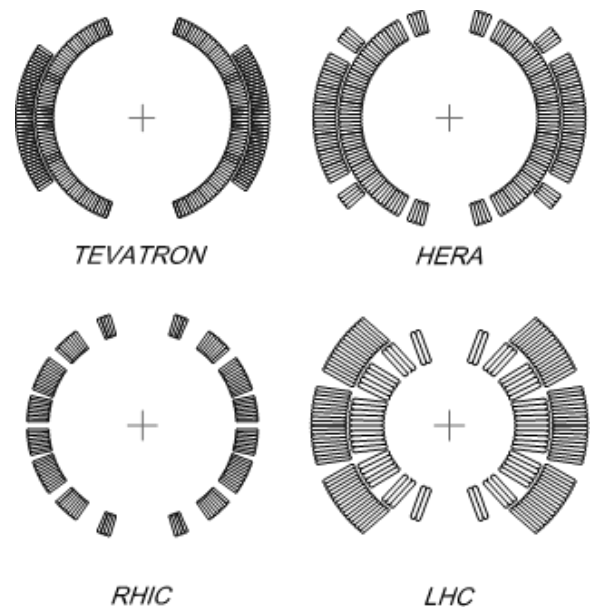


Fig. 3. Magnet coil cross-sections.

Table 1. Coil and cable parameters

	Tevatron	HERA	RHIC	LHC
Coil aperture (mm)	76	75	80	56
Number of turns	35/21*	32/20*	31	15/25*
Strand diameter (mm)	0.68	0.84	0.65	1.065/0.825*
SC filament diameter (μm)	9	14	6	7/6*
Cu:SC ratio	1.8	1.8	2.25	1.65/1.95*
Number of strands in cable	23	24	30	28/36*
Cable thickness (mm)	1.26	1.48	1.16	1.9/1.48*
Cable width (mm)	7.77	10.0	9.7	15.1/15.1*

* Inner/Outer layer

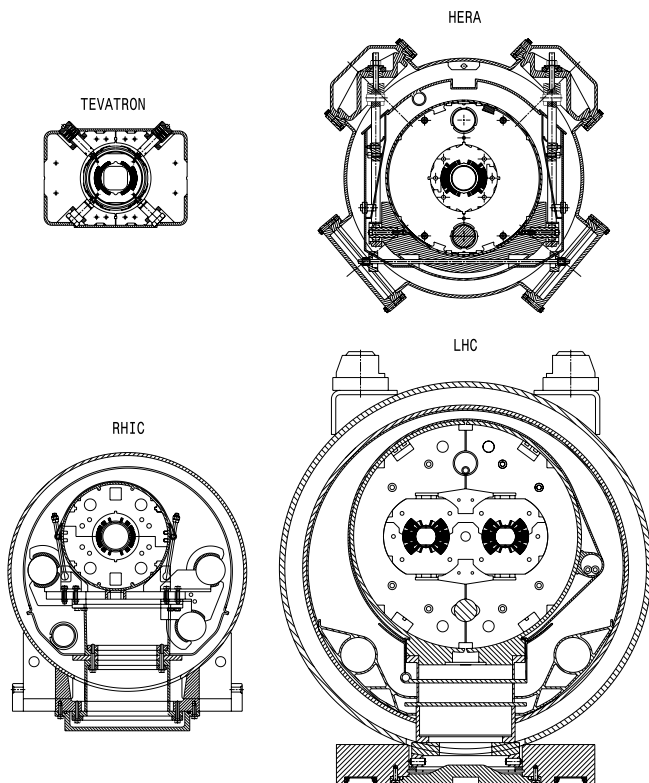


Fig. 4. Accelerator dipole cross-sections.

Table 2. Arc dipole parameters

	Tevatron	HERA	RHIC	LHC
Aperture (mm)	76	75	80	56
Magnetic length (m)	6.1	8.8	9.45	14.3
Nominal bore field (T)	4.3	5.3	3.5	8.3
Nominal current (kA)	4.3	5.7	5.1	11.9
Stored energy at I_{nom} (MJ)	0.30	0.94	0.35	6.93
Operation temperature (K)	4.6	4.5	4.3-4.6	1.9

Figure 4 shows cross-sections of the dipole magnets in their cryostats, so-called cryo-magnets. Main arc dipole parameters are shown in Table 2. These figures and the data in Tables 1 and 2 show the main tendencies in the evolution of the coil and the magnet designs.

The Tevatron was the highest-energy hadron collider until its shutdown in 2011. It had a circumference of ~ 6.9 km and consisted of 774 dipoles and 240 quadrupoles, as well as more than 200 corrector spool pieces. A key element for the success of the Tevatron was the use of superconducting dipoles wound from Rutherford cables as two-layer shell-type coils. The mechanical structure was based on precise stainless steel collars to apply coil azimuthal prestress and radial support. To ensure protection, quench heaters were used to accelerate the normal zone propagation in the coil during a quench. Tevatron magnets also featured a compact cryostat design with a warm iron yoke. This approach led to some problems with centering and alignment of the collared coils inside the warm iron yoke and to quite large heat leaks to the helium vessel through the short plastic supports. The alignment problem was solved by the invention of spring-loaded smart bolts. However, the high level of heat leaks through the support system did not allow achieving the design operation temperature and, thus, the target beam energy of 1 TeV. Despite these small hick-ups, the design and production of the Tevatron superconducting magnets opened the era of large superconducting accelerators.

The next large superconducting accelerator HERA comprised a 30 GeV electron storage ring (SR) with conventional electromagnets and an 820 GeV superconducting proton storage ring. The 820 GeV ring had a circumference of ~ 6.3 km and consists of 422 main dipoles and ~ 225 main quadrupoles, along with approximately the same number of SC correcting elements. The dipole magnets of the proton ring were developed at DESY, while the quadrupole magnets were developed at CEA/Saclay (Commissariat à l'Energie Atomique at Saclay near Paris, France). HERA dipoles, designed to produce 4.7 T at 4.6 K, operated later at 5.5 T by reducing the magnet operation temperature below 4 K. The HERA dipoles used thick free-standing aluminum collars and a cold iron yoke. The selected cold iron yoke design greatly simplified the collared coil alignment inside the yoke and reduced heat leaks to the magnet cold mass by using long plastic suspensions and better thermal insulation at the expense of a much larger cold mass. The HERA arc dipoles were manufactured in industry, which required a significant improvement of magnet technology, technology transfer to industry and providing reliable quality control throughout the magnet production. This brave and cost saving step was adopted later by the next large accelerator projects.

The RHIC is designed to collide beams of nuclei as heavy as gold, accelerated in two identical storage rings to energies between 7 and 100 GeV per beam and per unit of atomic mass. RHIC beams are guided by 3.5 T dipole magnets. Each of the two separate SC storage rings is ~ 3.8 km in circumference and they intersect in six points. Each ring consists of $\sim 1,740$ SC magnets, including 264 arc dipoles and 276 arc quadrupoles. An important goal of the RHIC magnet design was to minimize magnet cost, which was achieved by using a single-layer shell-type coil design, thin plastic coil-yoke spacers instead of expensive metallic collars, and a cold iron yoke close to the coil which adds $\sim 30\%$ to the field in the bore. The coils, surrounded by glass-reinforced phenolic spacers, are preloaded and supported by a horizontally split iron yoke and a stainless steel skin. The magnet cold mass is installed inside a vacuum vessel on SSC-type plastic support posts used later also in LHC magnets. Several improvements in the dipole design included the optimization of the magnetic field in operation field range in the presence of a saturated iron yoke, high- J_c superconducting strand with 5-6 μm filaments and 10 mm wide Rutherford cable. As for HERA, the RHIC dipoles were produced by industry including systematic warm magnetic measurements for quality control.

The LHC is the largest superconducting proton-proton collider in the world, with a storage ring of ~ 27 km in circumference and the highest operation dipole field of 8.33 T. It is located in an underground tunnel previously constructed and used for the Large Electron-Positron Collider (LEP). The ring is filled with 1,276 SC dipoles and ~ 425 quadrupoles. The dipole magnets were developed at CERN while the quadrupole magnets were developed at CEA/Saclay. The dipole design is based on two-layer shell-type graded coils with two 15 mm wide Rutherford cables in the inner and outer layers. The coils are preloaded with thick stainless-steel collars and supported by a vertically split cold iron yoke. The LHC dipoles adopted for the first time a two-in-one design concept in which two apertures with opposite field directions are placed inside a common collar and iron yoke. The LHC magnets use high-performance composite wires made of high-homogeneity Nb-Ti alloy and are cooled

by superfluid helium at 1.9 K, which allows further enhancing the performance of Nb-Ti conductor and, thus, increasing the magnet operating field. As HERA and RHIC magnets, all the LHC dipoles were produced in industry. The production for the LHC dipoles was shared by three European companies.

In parallel with the development and construction of superconducting magnets for HERA, in 1980s until the early 1990s Nb-Ti magnets were developed for the 3 TeV Accelerator and Storage Complex UNK (from Russian - Uskoritel'no Nakopitel'nyj Kompleks) in Protvino, near Moscow (Russia) at the Institute for High Energy Physics [19] and for the 40 TeV Superconducting Super Collider (SSC) near Waxahachie, Texas (USA) [20]. Both dipole designs were similar to the HERA dipole. The UNK dipoles had 80 mm aperture and were designed to operate at a nominal field of 5 T at 4.5 K. The magnets used circular stainless steel collars. The magnet cold masses were suspended inside the vacuum vessel using long Ti-alloy rods. The SSC dipoles had 50 mm aperture (the initial design had 40 mm aperture) and a nominal operation field of 6.6 T at 4.3 K. Special plastic posts were developed for the SSC magnets to support cold masses inside the vacuum vessel. Although series of short dipole models and full-scale prototypes have been produced and successfully tested in the framework of both projects, these two projects have been terminated in the middle of the 1990s.

IV. NEXT GENERATION OF SC ACCELERATOR MAGNETS

The field of ~ 10 T is considered as the practical limit for Nb-Ti accelerator magnets. As it was shown earlier, using magnets with higher field is the most efficient way to achieve higher collision energies in those accelerators. To produce higher fields, new superconducting materials with better properties are needed. The only practical material that is readily available on an industrial scale is an intermetallic Nb₃Sn compound, which belongs to the A15 crystallographic family.

A. Nb₃Sn composite wires

The superconducting properties of the Nb₃Sn compound, as the Nb-Ti alloy, were also discovered in the 1960s. The work on Nb₃Sn accelerator magnets started practically immediately in the late 1960s motivated by the better critical parameters of Nb₃Sn. The critical temperature T_{c0} of Nb₃Sn is 18 K and the upper critical magnetic field B_{c20} is 28 T.

Nb₃Sn composite wires are presently produced using three main methods: bronze, Internal Tin, and Powder-in-Tube [4]. The bronze process is based on a large number of Nb filaments dispersed in a Sn-rich bronze matrix. The bronze route provides the smallest filament size (~ 2 -3 μm), but has a relatively low critical current density due to the limited Sn content in bronze available for reaction to Nb₃Sn. The Internal Tin (IT) process is based on assembling a large number of Nb filaments and pure Sn or Sn-alloy rods in a copper matrix. Restacking of assemblies allows reducing the final subelement size. Due to the optimal amount of Sn, this process provides the highest critical current density, but limits the minimum subelement size achievable in the final wire currently to ~ 40 -50 μm . The Powder-in-Tube (PIT) process is based on stacking thick-wall Nb tubes, filled with fine NbSn₂ powder in a high-purity Cu matrix. This method provides reasonable combination of small filament size (< 50 μm) and high critical current density comparable with the IT process. However, the cost of PIT wire is still

considerably higher than the IT wire cost. In all the methods, the Nb₃Sn phase is produced during a final multistage high-temperature heat treatment with a maximum temperature ~ 650 -700° C for 50-100 hours.

As the accelerator construction cost is driven by the ring circumference, superconducting magnets for particle accelerators rely on the highest possible current density to minimize the coil volume and magnet cost. Thus, IT and PIT composite wires are the most appropriate for the use in high-field accelerator magnets. The highest value of the critical current density at 12 T and 4.2 K in state-of-the-art Nb₃Sn composite wires developed for use in accelerator magnets exceeds 3 kA/mm².

Nb₃Sn composite wires are compatible with the Rutherford cable design and technologies making Rutherford cable a primary option for the use in Nb₃Sn accelerator magnets. However, due to the more delicate structure and mechanical properties of the Nb-Sn precursor, forming the compact keystoneed cable cross-section is challenging without degrading the strand critical current. This problem as well as strand fusing in cables during high-temperature heat treatment of coils under pressure requires special attention and optimization.

B. Design issues of Nb₃Sn accelerator magnets

All the abovementioned accelerators with Nb-Ti magnets have been built based on the shell-type (a.k.a. cos-theta) designs. This design is also suitable for use with Nb₃Sn superconductor. In this design, keystoneed Rutherford cables are wound in blocks, which are spaced with wedges, around a circular bore. The number of cables in each block and the dimensions of the wedges are selected such that field errors and the ratio (conductor peak field to bore field) are minimized. Thanks to the Roman arch principle, no internal support structure is required in the cos-theta structure. Consequently, no valuable real estate inside the aperture is lost.

An alternative, block coil design is based on racetrack coils with vertical turn position and flared ends. Usually, a special support structure is required in high-field dipoles to support pole blocks and flared ends. In the late 1990s a common-coil approach, first proposed for low-field Nb-Ti magnets in early 1980s, was considered for high-field dipole magnets. The common-coil design is a twin-aperture version of the block-type dipole with vertically positioned apertures. Flat racetrack coils in this design are shared between the two apertures. This coil arrangement and simple coil geometry provide some technological advantages. In particular, the coil radii in this design are defined by the distance between apertures rather than by aperture size, making it suitable for winding of brittle conductors such as Nb₃Sn.

In the late 1990s, it was postulated that the block-type coil design is better suited for high-field Nb₃Sn magnets than the cos-theta design [21]. This statement started to be intensively disputed within the accelerator magnet community. The main debate points are the coil winding issues (racetrack coils with flared ends vs. coils wound around a cylinder), the relative position of high-field and high-stress areas (cos-theta magnets have the highest stress in the coil mid-plane where the field level is also large whereas block coils have the largest stress level in the low-field parts), the possibility of using wider cables in block coils than feasible in the cos-theta coils allowing for smaller inductance and larger operating

current, and the amount of conductor required to achieve the same field level.

All the three different coil types based on Nb₃Sn Rutherford cables have been designed, manufactured, and tested. In the following chapters, they are thoroughly described and discussed. The question which of these options is suited best for the hadron collider continues to be passionately debated within the scientific community.

C. Nb₃Sn magnet technology

Manufacturing of Nb₃Sn magnets is a complicated process due to the delicate processing, brittleness, stress/strain sensitivity of Nb₃Sn composite wires and cables. It imposes serious limitations for the use of reacted Nb₃Sn conductors for coil winding (react-and-wind technology). To overcome the limitations of working with brittle conductors, the so-called wind-and-react technology was introduced. In this approach a coil is wound with a ductile conductor containing the Nb-Sn precursors. Afterwards, the coil is reacted at temperatures of up to 650–700°C for several days to form the brittle superconducting Nb₃Sn phase. The high temperature during the coil reaction excludes using organic materials for cable and coil insulation as well as for various coil components.

The phase transition during the formation of the Nb₃Sn leads to a radial and azimuthal coil expansion after reaction. In axial direction, this effect is compensated by the coil contraction due to a release of stress accumulated in the strand matrix during cable fabrication. In practice, the exact dimensional changes of the coil depend on the cable compaction and on the insulation used. No empirical fitting-law for the exact prediction of the dimensional change of the conductor during reaction has yet been established. It is determined for each cable and coil design empirically in trial coil cross-sections. The empirical data for each specific project need to be established and considered during coil assembly and preloading.

Nb₃Sn conductor, if exposed to strain/stress, shows a degradation of the critical current density. Depending on the stress/strain value the degradation is reversible or irreversible. Stress/strain analysis and optimization of the magnet assembly process are important parts of magnet design and technology development. For example, applying excessive prestress during magnet assembly, to compensate for pre-stress lost during magnet cooling down to the operation temperature, could cause irreversible degradation of Nb₃Sn coils. Engineering of mechanical structures using materials with different thermal contraction coefficients to avoid prestress lost or even to achieve pre-stress increase is important to explore the potential of Nb₃Sn accelerator magnets.

Good field quality discussed earlier, is mandatory in accelerator magnets. All the major components - geometric, iron saturation and coil magnetization effects - require special attention in Nb₃Sn magnets. Geometric field errors, controlled by the position of the coil turns, are impacted by the turn expansion and possible displacements during coil reaction as well as turn motion under large Lorentz forces. The iron saturation effects are larger due to larger field level and larger field variations in the yoke. Persistent current field errors are larger due to the large superconductor filament sizes and higher critical current density in Nb₃Sn filaments. In addition, the field errors related to the interstrand eddy

currents in cable can be also very large due to strand fuse during coil reaction.

Lastly, due to the large scale of future circular hadron colliders, the cost optimization of Nb₃Sn magnets becomes of high importance.

D. Magnet performance test

Sophisticated analysis tools, available at the present time to the magnet designers, allow for accurate magnet analysis (magnetic, mechanical, thermal) and the exact definition of the magnet target parameters based on the properties of materials and the operation conditions. However, many uncertainties in material properties as well as variations of technological procedures inevitably affect the magnet performance. As a result, the difference between the real magnet performance and the magnet target parameters can be significant. Therefore, detailed material characterization, quality control during all production steps and final comprehensive magnet tests are important components of the successful magnet development and production process.

Before performing the final magnet tests at the nominal operation conditions typically tests at ambient temperature are conducted. The final magnet tests are performed at nominal operation conditions. Both magnet production and final cold tests not only provide the final performance parameters but their reproducibility from magnet to magnet in large series. During the R&D phase, these tests provide very important feedback for optimization of magnet design, technology and performance.

The main objectives of the magnet cold tests are the examination of all magnet design parameters including the quench performance study, magnetic measurements, quench protection studies, and measurements of magnet mechanical properties. The list of tests, their sequence and conditions are defined in a magnet test plan, which is prepared for each magnet. This plan consists of the standard test procedures common for all magnets of a given series, as well as some specific tests for each magnet.

To measure the magnet performance parameters each magnet is equipped with appropriate instrumentation. Some elements of the instrumentation (voltage taps, strain and temperature gauges, heaters, etc.) are implemented during magnet assembly, where as the other ones are placed inside the magnet bore (quench antenna coils, Hall probes or rotating coils for magnetic measurements) or on the magnet skin and end plates (strain gauges, bullet gauges, thermometers).

The following examples illustrate the importance of magnet final tests and the important feedback provided by magnet tests. Quenches below the magnet short sample limit point to possible energy depositions in the magnet coil due to turn frictional motions under the Lorentz force, heat dissipation from losses in the cable, or non-uniform current distribution among cable strands. The non-uniform distribution of the transport current in the cable is also visible in longitudinal oscillations of the field harmonics. The current imbalances may be caused by non-uniform properties of strands in the cable, non-uniform solder joints connecting the coils to the current leads, or large eddy current loops formed by small local interstrand resistance.

Other effects which are observed during cold tests of superconducting accelerator magnets and the way they are being addressed during the magnet development phase will be presented and discussed in the next chapters of this book.

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