Chapter 8
Superconducting Magnets in Accelerators

Abstract Particle accelerators and high field superconducting magnets had been the greatest promoters of each other. In accelerators, RF power is used to boost the beam energy through the use of superconducting (RF) cavities. Bending, focusing and steering of the beam is provided by superconducting magnets. Fundamentally, an accelerator can either be of circular type or linear. Circular accelerators like LHC (Large Hedron Collider) are suitable for heavy ions like protons because the energy loss caused by synchrotron radiation in a circular accelerator varies inversely to the fourth power of the mass of the ion. Brief discussion on the superconducting colliders built and operated, namely, Tevatron, HERA, SSC, RHIC prior to LHC have been given in the chapter. LHC magnets have been discussed in greater details. LHC, world's most powerful particle accelerator has been in operation since 2009 and has yielded vast data and has confirmed the existence of Higgs boson. Parameters of the collider magnet system and the specifications of the conductor used are presented. Innovative magnet designs and development of superior conductors have been included. Linear accelerator, is the choice for light particle like electrons and positrons. An international effort has been made to build a 31 km long linear collider named ILC (International Linear Collider) for colliding electrons and positrons with a collision energy of 500 GeV ($\sim$1 TeV in future). The chapter ends with a brief description of the magnets in cyclotrons. World's first superconducting cyclotron of the class K-500, world's biggest cyclotron, K-1200 (both at MSU) and the world's biggest ring cyclotron, RIKEN SRC K-2500 have been described. K-1200 can accelerate U to 90 MeV and the SRC K-2500 up to 350 MeV.

8.1 The Accelerators

Great advancement made in the development of superconducting magnet technology led to their application to particle accelerators enabling them to go to higher and higher beam energy. High energy accelerators, in turn, have been responsible for the unprecedented growth in the production of superconducting cables carrying

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several thousands of ampere current with high stability and low a c losses. It looks, as though, the two technologies have been moving in tandem.

In an accelerator, the beam is accelerated by pumping RF through superconducting radio frequency (SCRF) cavities (mostly Nb) to produce high voltage gradient. High energy accelerators built are mainly either of circular or linear configuration. In both types of accelerators the beam is accelerated in an array of SCRF cavities but differ in several other aspects. In a circular accelerator, the beam travels through the SCRF cavities arranged in a nearly circular path. Dipole magnets are used for bending the beam by producing appropriate and very precise field transverse to the beam path. As the beam particles travel through the cavities repeatedly they gain energy and their velocity increases. The accelerating field in the cavity too is adjusted accordingly. For higher energy the magnetic field has to be adjusted to keep the particle moving in the same trajectory. Once the velocity approaches relativistic value equal to the speed of light, c, the RF frequency stays constant. This design of accelerator has been followed in colliders in which two energetic beams traveling in opposite directions collide to produce particles that were not seen before. The most famous of such colliders is the LHC (Large Hadron Collider) build and operated at CERN (European Organization for Nuclear Research) to accelerate two protons traveling in counter clockwise directions to acquire an ultimate energy of 7 TeV and collide to produce a collision energy of 14 TeV. LHC installed in a 27 km long tunnel used earlier by the LEP (Large Electron-Proton Collider) has been successfully operating since Sept. 2009. The first collision between two 3.5 TeV beams was observed in March 2010 and the long sought after Higgs boson was observed in Nov. 2012.

The difficulty with the circular accelerators, however, is that the relativistic particles emit radiation while traveling perpendicular to the field in the bending region. This results in a significant loss of energy as the energy loss is found to be proportional to E^4. The size of the machine is therefore greatly increased. Further, the energy loss also scales with the rest mass of the radiating particle as $1/m^4$. For this reason alone the energy in LEP never reached beyond 200 GeV even after up-gradation till it was retired in Nov. 2000. Circular accelerator are thus suitable to accelerate heavy particles only, like protons in LHC.

Linear accelerators (linac) are preferred to accelerate light particles like electrons and positrons. Here the beam is accelerated in a straight line trajectory. The energy is proportional to the accelerator length as the beam travels through a cavity only once. In a linear collider two beams are accelerated in two opposite directions and made to collide at the intersection point (IP) and discarded into the beam-dump. A new bunch is used each time. The advantage of the linac is that there is no energy loss due to synchrotron radiation. The energy is proportional to the number of RF cavities and the gradient of each cavity but does not depend on particle mass. Maximum luminosity is obtained by increasing the frequency of collision and reducing the area cross-section of the beam.

Cyclotrons are yet another type of accelerators which can accelerate heavy ion like U to high energies up to 350 MeV and the superconducting magnets again play a pivotal role in achieving such high energies. The ion circulate spirally under the influence of a vertical magnetic field and an RF across two gaps between two dees. The RF frequency matches with the cyclotron frequency of the charged particle and accelerate it each time it crosses the gap. The beam is finally extracted through an extraction system and used to bombard targets for the production of radio isotopes.

In this chapter we will focus on the role of superconducting magnets in both these types of accelerators with special reference to LHC and the future ILC.

8.2 Role of Superconducting Magnets in Accelerators

Superconducting magnets have become the essential part of all types of accelerator design. Successful operation of LHC owes much to the high field superconducting magnets used along its 27 km circumference. LHC is using more than 1,600 superconducting dipole and quadrupole magnets in addition to other magnets. The future ILC (International Linear Collider) will have as many as 715 superconducting quadrupole magnets and 1,374 correctors. Besides many other types of magnets, the dipole magnets and quadrupole magnets constitute the backbone of any high energy accelerator. To achieve transverse field the dipoles are made of long saddle shaped coils or the simpler racetrack coils and are installed in two halves all along the entire curved part of the ring. Quadrupole superconducting magnets are used to keep the beam well-focused. In addition, there are higher order magnets, the correctors, to compensate for the field errors arising in the main dipoles and quadrupoles. These field errors are caused by the persistent magnetization currents generated in superconducting filaments during field ramping and also by the manufacturing errors/tolerances.

Circular accelerators are built in long underground circular tunnels so that the beam keeps circulating to get repeated acceleration in SRF cavities by the accelerating voltage. The beam energy obtainable in a relativistic accelerator is approximately given by the equation $E = 0.3\ B_{\text{dipole}} \times R$, where E is the energy in TeV, B_{dipole}, the dipole field in tesla and R the effective radius of the tunnel in km. For high energies, therefore it is imperative to have very long tunnels and high magnetic field depending on the budget available. All pervading Nb–Ti/Cu cables have been used in almost all the modern high energy accelerators. This superconductor has an upper limit of producing field of 9 T when operated below 2 K. For field 10–15 T, attempts are being made to develop Nb_3Sn magnets. Some proto type Nb_3Sn dipoles and quadrupoles have already been built and tested primarily at Fermi Lab. (USA).

An excellent and comprehensive book has been written by Mess, Schmuser and Wolff [1] on all aspects of superconducting accelerator magnets. Readers will find detailed description of field calculations, design and construction of the magnets, quench protection, electromagnetic forces, mechanical and field accuracies, collaring and warm and cold yoke. A useful review article had also been published earlier by Schmuser [2].

8.3 High Energy Accelerators Using Superconducting Magnets

Below we give a brief account of all the superconducting accelerators built prior to LHC. The experience gained through the operation of these accelerators led to the design and construction of the most powerful accelerator LHC which promises to unravel the mystery of matter.

8.3.1 Tevatron

Tevatron was the first high energy hadron collider built at Fermi National Accelerator Laboratory (FNAL), near Chicago, USA using superconducting magnets and commissioned in 1983. It was a proton–antiproton collider which achieved an energy of 1 TeV. It had warm iron yoke putting less low temperature load but high heat input to the cold mass. The entire EM forces are taken by the collars. It accelerated protons and anti-protons in a ring of 6.3 km circumference. By 1987, it attained a beam energy of 0.9 TeV thus a collision energy of 1.8 TeV, the highest energy ever attained till that time. It used 774 dipoles each 6 m long, 224 quadrupoles magnets and several correcting magnets. The dipoles generated a field of 4.4 T at 4.4 K. Cu/Nb–Ti cables had been used for magnet coils. Tevatron has been shut since September, 2011 especially because Large Hadron Collider (LHC) at CERN started operation and will be producing much higher collision energy (7 + 7 TeV). Nevertheless, Tevatron has become a trend setter for building high energy beam colliders using high field superconducting magnets. Over more than two and half decades of operation, this collider yielded profound data of 500 trillion collisions from year 2001 onwards. The analysis of the data led the Fermi Lab. team of researchers to believe strongly the possible existence of all illusive Higgs Boson which has since been confirmed from LHC's data.

8.3.2 HERA (Hadron Electron Ring Accelerator)

Soon, the technology of building hadron collider using superconducting magnet was adopted by DESY (Deutsches Electronen Synchroton), Hemberg, Germany to built their electron—proton beam collider, HERA. The accelerator started operations in 1989 and continued until it was shut down in 2007. Unlike the Tevatron the HERA had a cold iron yoke enclosing the high strength Al-alloy ($AlMg_{4.5}Mn$) collars. It was installed in a tunnel 6.3 km long and up to 25 m deep underground. It had two storage rings mounted one at the top of other. Normal room temperature magnets had been used in the electron storage ring which ran below the proton storage ring. Superconducting magnets have, however, been used in the proton ring only. The proton ring employed 422 main dipole magnets to provide 5.3 T field for beam bending and 244 main quadrupoles for beam focusing. Four dipoles, four quadrupoles, six sextupoles and correction magnets were grouped together as one 47 m long module along the curved path. These magnets had two layered coils and operated at 4.2 K. The electron ring used conventional magnets, 456 main dipoles providing a field of 0.17 T and 605 main quadrupoles. One dipole, one quadrupole, one sextupole and a few correction dipoles were grouped into a 12 m long module. Old accelerators were used to pre-accelerate the proton beam. The last accelerator was PETRA which accelerated the electron beam to 14 GeV before injection into HERA. Sixteen four cell cavities with an accelerating field of 5 MV/m were used to accelerate the beam to a final energy of 0.92 TeV.

8.3.3 SSC (Superconducting Super Collider)

The SSC was the most ambitious collider project conceived during mid 1980s in USA and finally sanctioned in 1991. The project was, however, abandoned due to high cost involved, just 2 years later. It was aimed at accelerating proton to 20 TeV energy thus producing a collision energy of 40 TeV. It was to be a chain of five accelerators pre-accelerating proton to 2 TeV before being finally injected into the SSC. It was to be a two race track like rings with 70 cm separation. More than a total of 9,600 superconducting magnets were envisaged to be used. These included 7,860 main dipoles, 1,360 main quadrupoles, many corrector magnets and 648 special magnets for directing beams to six collision points. The design and development work on dipoles was carried out by Fermi Lab. and BNL (Brookhaven National Lab). The R&D work on quadrupoles was done by LBL (Lawrence Berkeley Laboratory). The dipoles were 16.6 m long to produce a field of 6.6 T at 4.35 K, whereas the quadrupoles were 3.3 m long and to produce a field gradient of 230 T/m at 4.35 K. The dipoles were two layered Cosine θ coils wound using Cu/Nb–Ti cable with an inner diameter of 4 cm. Coils were collared and closed with a split yoke consisting of lamination of the arc accurately die-punched sheets of low carbon steel and 1.5 mm thick. Yoke too formed the part of the cold mass cooled by supercritical helium at 4.15 K at 4 atm. pressure. Many full scale magnets were built and tested successfully for their critical performance as per the quality assurance codes. Many problems related to quench and training were solved. Alas ! the project was dropped soon after it was sanctioned for lack of funds.

8.3.4 RHIC (Relativistic Heavy Ion Collider)

RHIC was built by Brookhaven National Lab, (BNL), Upton, USA. It has been under operation since 1999. Until 2010 it was the highest energy collider in the world, now taken over by LHC at CERN. But it is the only collider which accelerates spin polarized protons. Positively charged heavy ions and/or protons circulate in opposite directions at 99–99.5 % of the speed of light, in two independent rings, hexagonal-shaped and 3.8 km in length. A total of 1,740 superconducting magnets have been used in the two rings. Dipoles produce a field of 3.46 T at an operating current of 5.1 kA. Out of 1,740 magnets, 396 are the main dipoles and 492 quadrupoles. Rest of the magnets are the corrector magnets. The dipole magnet is 9.45 m long, the coil I.D. 80 mm and O.D. 100 mm. The inner and outer diameters of the yoke are 119.4 and 266.7 mm respectively. An important feature of the magnets of RHIC is that there are no separate collars between the coils and the yoke. The yoke itself serves the purpose of collars and provide required pre-stress to the coil. The yoke is the part of the cold mass. The collision between gold ions resulted in a record temperature of more than 4 trillion K creating conditions that might have existed moments after the 'big-bang'. It has six intersection points where the heavy ions up to gold collide and produce an energy of 0.1 TeV per beam. RHIC upgrade will facilitate collisions between positively charged and negatively charged particles.

8.3.5 LHC (Large Hadron Collider)

LHC is the world's largest particle accelerator, built by CERN at Geneva Switzerland. It has a tunnel 27 km long and 50–175 m deep underneath the border between France and Switzerland. At full potential it will accelerate proton beams rotating in opposite directions to an energy of 7 TeV. Two proton beams will then collide at four intersection points and produce a collision energy of 14 TeV. LHC has so far attained a level of 4 TeV/beam. It will attain its full potential of 7 TeV/beam by the end of 2014. Proton beams are pre-accelerated by old SPS (Super Proton Synchrotron) to 450 GeV before being injected into the LHC. SPS uses normal magnets. The yearly data generated is several peta-bytes which is analyzed in 140 computing centres spread over 36 countries and connected by the world's largest computing grid.

The LHC has used about 6,000 superconducting magnets, out of which 1,232 are the main dipoles along the curved path of the beam pipe. These are 15 m long with 56 mm inner diameter. The number of quadrupole magnets is about 400 and the rest are different types of magnets including multi-pole corrector magnets. All the magnets are divided into 8 sectors for operation powered by 8 power supply systems. Each sector has 154 main dipoles and 45 quadrupoles. The dipoles produce a field of 8.34 T. To produce such high fields using Cu/Nb–Ti cables the magnets are operated at a reduced temperature of 1.9 K using superfluid ^{4}He. The conductor is a Rutherford cable 15.2 mm wide with 36 strands of 0.825 mm diameter and each strand having 6,425 filaments of 6 μm dia. One unique feature of LHC is that the main magnets around the two beams are collared together and contained in one yoke. This makes the cold mass a compact system and much economical.

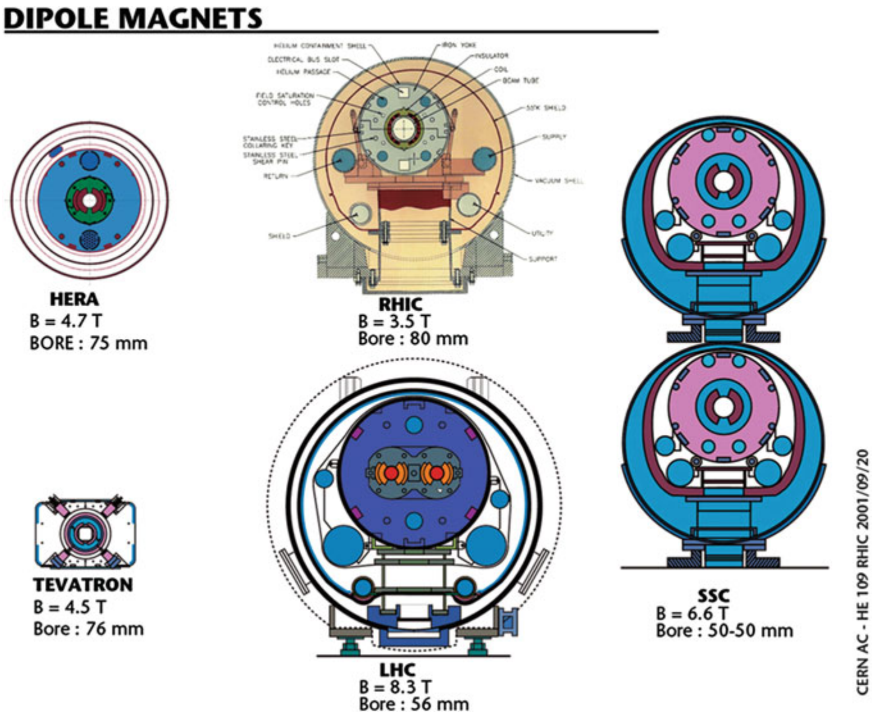

Fig. 8.1 Schematic cross-section of the main dipoles of the five accelerators discussed in Sect. 8.3 (*Source* [3]) (*Courtesy* Lucio Rossi, CERN Photo Library and with permission from "CAS")

Schematic cross-sections of the main dipole magnets of these accelerators are reproduced in Fig. 8.1.

8.4 Unique Features of the Accelerator Magnets with Special Reference to LHC

In this section we will discuss important characteristics of the accelerator magnets with a special reference to LHC which has been built with several new features over the past accelerators. A good number of papers have been published by Lucio Rossi of CERN on all aspects of LHC magnets and cryogenic system. I refer to a few of them [3–7]. The magnets are the most critical components of any accelerator. A dipole magnet is far more longer than its aperture, the conductor therefore runs parallel to the beam except a small part which bends at the coil ends. It is built in two halves with current flowing in opposite directions and producing required field in a direction transverse to the beam as shown in Fig. 8.2. Dipole magnets are not straight, instead they follow the curvature of the beam pipe. The deviation from a

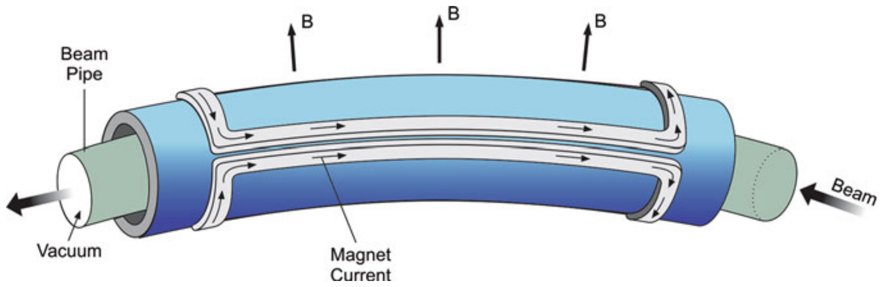

Fig. 8.2 Dipole magnets produce transverse field to bend the beam along the curved path. Current in the two halves of the coil flows mostly longitudinally except short coil ends and in opposite directions

straight line is, however, so small in comparison with the dipole magnet length that it is hardly noticed. This curvature makes the design of the magnets quite complicated and difficult. Computer codes like TOSCA, ANSYS, POISSON, DXF and ROXIE have been developed and used for magnet designs. ROXIE (Routine for the Optimization of magnet X-sections, Inverse software programme Package) was developed by Rossenschuk [8, 9] for LHC magnets and is widely used by many institutions for magnet design. It is a versatile and easy to use programme. It is used to give integrated design of a superconducting magnet, including the conceptual design, optimized field, coil ends design, end spacers, cross-sections of the coils, collars and the iron yoke and produces detailed drawings. 'End spacers' design is interfaced with CAD-CAM for the five axes CNC milling machines to produce these pieces. It has the capability of tracing manufacturing errors which affects the field quality.

8.4.1 The Coil Geometry

A perfect dipole field can be produced [1] by a current sheet with surface current density distribution of azimuthal type varying as Cosine ($n\varphi$). One obtains dipole, quadrupole and sextupole field for n = 1, 2, and 3 respectively. For perfect dipole field such a coil geometry is obtained by the intersection of two cylinders [10] and also by the intersection of two ellipses (shaded parts) carrying equal volume current densities but in opposite directions as shown in (Fig. 8.3a, b). A perfect quadrupole field can similarly be obtained by the intersection of two crossed ellipses as shown in Fig. 8.3c each quadrant carrying equal current densities but reversing the current polarity in alternate segments. A very common and well known geometry of the current shell generating dipole field is shown in Fig. 8.4a and the current shell generating quadrupole field is shown in Fig. 8.4b. The value of the limiting angle φ of a dipole is kept 60° which eliminates sextupole (n = 3) but higher multipoles like decapole (n = 5) and 12-pole do exist. These higher multipoles can only be

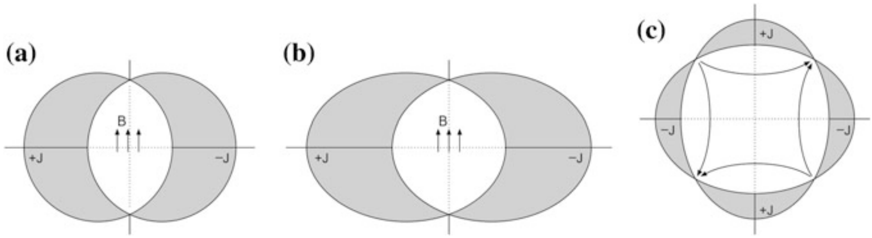

Fig. 8.3 **a** A perfect dipole field by intersecting two cylinders or, **b** a perfect dipole field by two intersecting ellipses (both carrying uniform current but in opposite directions), **c** a quadrupole field generated by the intersection of two crossed ellipses

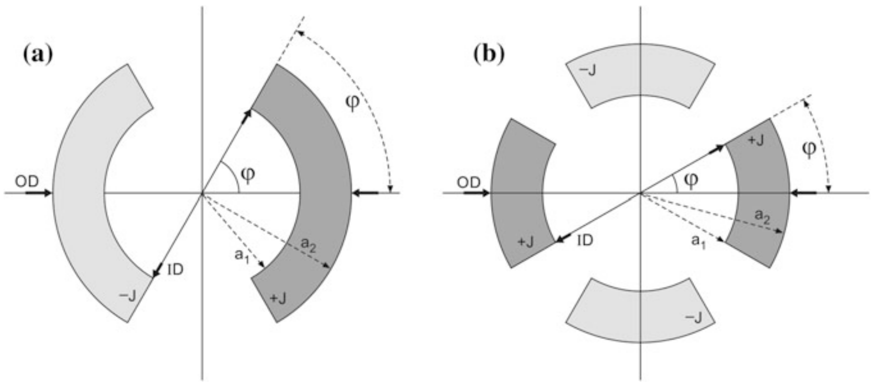

Fig. 8.4 **a** Current shell geometry with dipole symmetry and **b** quadrupole symmetry

eliminated of by winding the shells in two layers. Similarly, the quadrupole current shells are wound in two layers to eliminate higher order multipoles (Fig. 8.4b). The limiting angle of the quadrupole shell φ is 30° and for a sextupole 20°. The field homogeneity is further improved by introducing longitudinal wedges in the windings.

In a perfect dipole with a current density of $J\cos\varphi$, the field B is proportional to J and ΔR $(B \propto J \times \Delta R)$ where ΔR is the coil thickness. To keep the volume of the coils within reasonable limits, we have to look for high J_c conductor for a given beam aperture. Further, these magnets are wound in two layers and since the outer layer experiences lower field, one can operate the outer coil at much higher current compatible with the field. This reduces the coil volume too. Operating the two coils at different current levels will, however, be complicated because it requires two separate power systems and quench protection/detection systems.

Designing the coil ends is difficult as these are raised above the longitudinal winding. Bending of the conductor at the ends has to be carried out accurately and should be below the permissible strain limit of the conductor. The bends are of the shape of a saddle. To keep the end winding in position suitable spacers machined from fiberglass-epoxy composites are inserted. Coil ends are impregnated with resin to fill the gaps between spacers and the winding and to obtain good finished surface for collaring.

8.4.2 The Collars

The Dipole magnet-coils are wound in two halves over the beam tube, both repelling each other. At high J_c and high field these coils experience huge lateral force ($=J \times B$) with a large horizontal component, which is not self supported like in a solenoid winding. This force is huge, of the order of several MN at the level of the field produced. The two halves are thus held together mechanically by strong clamps referred to as collars. Collaring is carried out in a large press to compress the coils to 100–120 MPa so that the collars remain compressed to a pressure of 60–90 MPa after the pressure is released. In LHC, the two dipoles around the two beam pipes, are housed in a single cold mass system. Both the dipole coils are collared together and called “twin”. The collars used in LHC are made of stamped laminations of austenitic steel. HERA at DESY has used collars made of laminations of a strong Al–Mg–Mn alloy. The two halves are held in position together using pins and dowel rods The collar material has to remain non-magnetic even after thermal cycling to LHe temperatures, cold worked during stamping or after welding. Protection sheets have been used between the coils and the collars which also provide ground insulation. Sometimes, very thin 3–5 mm skin spacers have been used in place of collars and all the compression to the coil is provided by the outside yoke. The field enhancement too increases because of closer proximity of the yoke with the coil. Quadrupole coils are collared individually.

8.4.3 The Yoke

The compression by collars is further enforced by the iron yoke fitted outside the collars. The yoke is used to reduce the fringe field out side the magnet to below 10 mT. At the same time, the yoke also enhances the magnet field. Warm (room temperature) as well as cold (cooled to LHe-magnet temperature) yokes have been used in different accelerators. Enhancement of field is higher when the yoke is part of the cold mass because of the close proximity of the yoke with the coil. Cold yoke only require more cryogen and the magnet system takes little more time to cool down, which is not very important because accelerator magnets are not warmed-up and cooed-down frequently. Moreover fast cooling is not desirable to prevent excessive thermal stresses. Enhanced field, however, allows the use of smaller operating current in the coil, which results in the reduction of stored energy and the consequent enhancing protection against quench. One drawback of the cold yoke is that the shrinkage in soft iron yoke is larger than in the coil after cool-down and therefore larger pressure has to be applied while compressing the yoke. Second problem could be the saturation of the yoke which may generate higher order poles and distort the field. This has to be well accounted for during the design stage itself. Recall that RHIC does not use collars at all, instead, the coils are compressed directly by the yoke.

In LHC, the yoke is 600 mm thick and made into two halves and put around the collars. The yoke is of cylindrical shape consisting of 1.5 m long packs of stamped laminations compressed together to a density of 98.5 %. A cylindrical shell in two halves and of 10 mm thick 316 LN steel then surrounds the yoke. Welding is carried out simultaneously on top and bottom parts under a pressure of 400 tons. After mounting electrical systems in place the two end parts too are welded. All along the length of a dipole a total welding of 16 m is carried out. This 316 LN SS cylinder also forms part of the LHe-cryostat.

8.4.4 The Magnets

The magnets constitute the most critical part of an accelerator and more so the dipoles which produce high field, quite close to the limit of Nb–Ti conductor. These magnets operate at high current. To minimize heat input to the cryostat the number of current leads are cut down to minimum. All the magnets in one sector are therefore connected in series and powered by a single sector power system using only one pair of current leads. The twin magnets and common collar and the yoke are installed in the same liquid helium cryostat. This whole assembly is commonly referred to as the “cold mass”. A schematic cross-section of the cold mass is shown in Fig. 8.5. The dipole characteristic parameters are tabulated in Table 8.1. The stringent requirement of all the dipole magnets in the lattice is that they ought to produce almost identical field in magnitude as well as in quality. The field strength and the harmonic contents of all the dipoles must be same within the range of the order of 10^{-4} (one unit). This means that the coils of two poles (top and bottom) of each dipole have to be identical and so should be for all the dipoles built at different locations. Each coil is wound in two layers using two different cables running at different current densities but same operating current. The geometrical dimensions of the two layers of all the magnets have to match within a variation of less than 100 μm. Small variation can cause appreciable change in the main field and the higher harmonics. These requirements call for precision winding and should be perfectly reproducible in all magnets.

The photograph in Fig. 8.6 shows the cutaway cross-section of the twin aperture dipole magnet used in LHC. Each dipole is about 15 m long. All the dipole magnet systems (cold mass) alone occupy close to 20 km length of the tunnel.

The stringency of field uniformity equally holds for quadrupoles which too are wound in two layers and using the same cable as used for winding the outer layer of the main dipoles. A small shortfall (<10 %) in the focal strength of a magnet can, however, be compensated by successive quadrupoles.

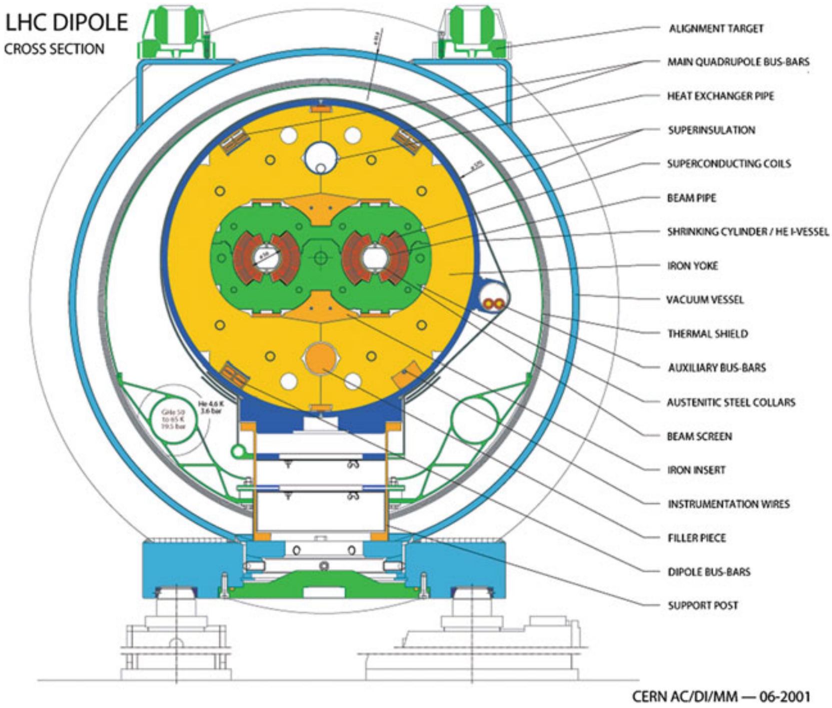

Fig. 8.5 The cross-section of the compact cold mass of the main LHC dipole. The two dipoles of the two oppositely circulating beams are coupled together by a single austenitic steel collar and compressed within the same iron yoke [3] (*Courtesy* Lucio Rossi, CERN Photo Library and with permission from "CAS")

Table 8.1 Important parameters of the main LHC dipole (data compiled from [5, 6])

Parameter	Unit	Value
Operating field	T	8.33 (can operate up to a max. 9.00 T)
Operating current	kA	11.85
Operating temperature	K	1.9
Coil aperture	mm	56
Distance between the two aperture axes	mm	194
Stored energy/channel	MJ	3.5 @ 8.33 T
Magnet length	m	14.3
Cold mass length	m	15.18
Cold mass O. D.	mm	570

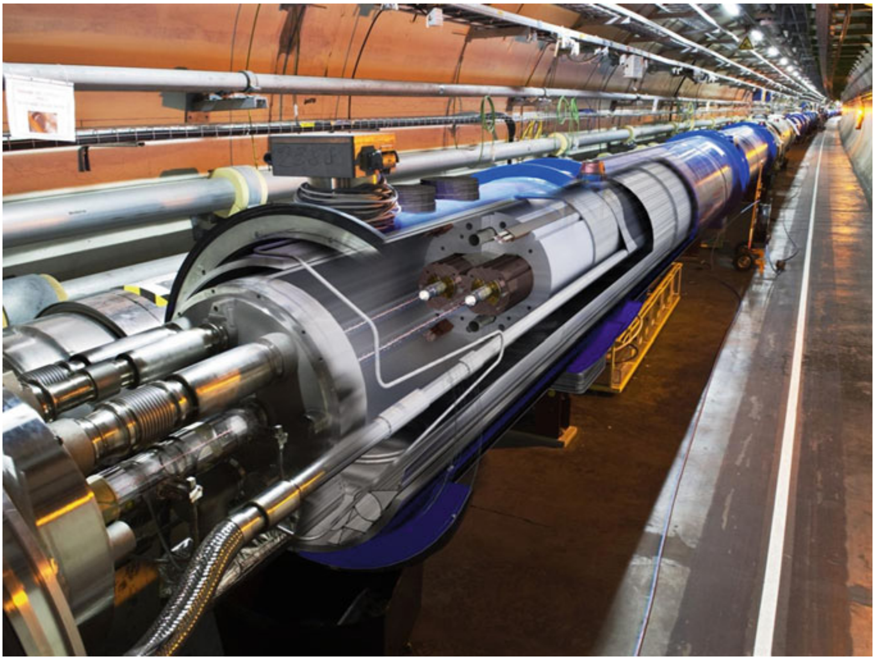

Fig. 8.6 A cutaway cross-section of a twin aperture dipole magnet mounted in a 27 km long tunnel. All the dipoles together occupy nearly 20 km length of the tunnel (CERN Photo courtesy Ph. Lebrun)

8.4.5 The Superconductors

So far, the most favoured superconductor for all the accelerator magnets have been the Cu/Nb–Ti (Rutherford type) cables because of its superior mechanical properties and comparative insensitivity to stresses. The production procedures for manufacturing large quantities of Nb–Ti conductor are well established and standardized since the material is being produced commercially over last four decades. In an accelerator, the quantity of conductor used for winding large number of magnets is huge and cannot be supplied by a single manufacturer. For field uniformity and field reproducibility, the total quantity of conductor produced by all the manufacturers has to be uniform within a small tolerance limit. LHC has used something like 1,200 tons of cable, out of which the Nb–Ti is about 400 tons.

The quality control of the conductor starts from the compositional uniformity of the basic material, Nb–Ti, its processing, uniformity of filament size, the strand size and finally the braided cable dimensions. The strand diameter has to be uniform within 1 μm and the cable size to ±6 μm. The uniformity of the size of the cable is crucial to the conductor positioning in the coil and ultimately the field profile. To prevent degradation in the overall I_c of the cable, the strands must be compacted to no less than 90 %. Equally crucial is the uniform distribution of current among the strands and the inter-strand resistance of a cable. CERN has devised an ingenious and cost effective technique for the production of Rutherford cable used for LHC. The strands are coated with a Sn–Ag alloy before they are cabled. The cable is then oxidized by heating it under controlled conditions in air. The technique, in fact, has proved a turning point in the successful production of Rutherford cable for LHC. The contact resistance is low also because the coil is pre-stressed to 80–100 MPa.

The most important parameter of the cable is its over-all critical current density, J_c usually referred to as J_{Eng} (engineering critical current). This takes into account the total cross-section of the cable which consists of superconducting and non-superconducting components like, copper, filament barrier and bronze in case of Nb_3Sn. The microstructure of Nb–Ti is to be well controlled to benefit from the effective flux pinning. For stability, a copper to Nb–Ti ratio of 1.5–2 has been used for accelerator magnets. To boost J_{Eng} further, a much lower ratio of 0.7–0.8 is being planned for future magnets with no deterrent to conductor stability and/or the quench protection.

To keep the inductance and the stored energy within limits these magnet coils are optimized for high currents somewhere in the range of 10–13 kA. One has to keep in mind that the transverse field produced by (cosine θ) type coils is smaller than that produced by a simple solenoid coil for the same J_c and same coil thickness. The field in a solenoid is $B = \mu_0 J t$ whereas for a cosine θ coil it is $B = ½ \mu_0 J t$ (cos θ). Here J is current density and t the winding thickness. Rutherford cable capable of carrying such large current have invariably been used for accelerator magnets. Each cable has few tens of strands with high I_c value, braided together in a rectangular shape (see Fig. 6.10). The cable has a high compaction density of about 90 %. The main parameters of the cable and the strand used for LHC dipoles are tabulated in Table 8.2.

Well microstructured Nb–Ti with effective pinning optimally has been serving well as high I_c conductor for accelerator magnets, nevertheless, suffer from the big problem of persistent (magnetization) current which can distort the field. These superconductors retain magnetization even when the field from its maximum value of 8.33 T is ramped down to the lowest injection value of 0.54 T. Since the critical current density is very high of the order of 10 kA/mm^2, the persistent magnetization current can be significant and can damage the field quality drastically. The magnetization scales as $M \propto J_c D_{eff,}$ where D_{eff} is the effective diameter of the filament

Table 8.2 Parameters of the strands and the Cu/Nb–Ti Rutherford cable used for LHC dipoles (data compiled from [5, 6])

Strand			Cable		
Parameter	Unit	Value	Parameter	Unit	Value
Diameter	mm	0.825	Width	mm	15.1
Filament diameter	μm	6	Thickness @ 70 MPa	mm	1.48 ± 0.006
No. of filaments		6,425	No. of strand		36
Cu/Nb–Ti ratio		1.9–2.0	Inter-strand resistance	μΩ	20–80
I_c @ 1.9 K	A	380 @ 7 T	I_c @ 1.9 K	kA	12.97 @ 7 T

and J_c the critical current density. D_{eff} sometimes can be much more than the geometrical diameter, if the filaments touch each other or are coupled together in metal matrix due to small inter-filament separation. In such cases the filaments are usually cladded with a barrier like Nb. Since we cannot afford a drop in J_c, we must reduce the filament diameter to the extent possible. For LHC application a filament diameter of 6–7 μm was found ideal and selected. Still smaller filament diameter leads to much lower J_c values.

8.4.6 Training

Training of accelerator dipoles assumes special importance because of the low Cu: Nb–Ti ratio of the conductor used and the coil running at very high current density. It is almost impossible that the magnet attains its peak field and the peak operating current in the virgin run. The large EM forces cause some movement in the coil winding, the strand or the cable and quench the magnet at a current which may be much lower than the maximum operating current for which the magnet is designed. In successive runs the magnet quenches at increasingly high currents. After a few cool down cycles the magnet reaches a saturation point where the maximum current and field are achieved. The magnets are therefore 'trained' before being installed at their designated locations. The final quench current and the quench field so attained after training should be reproducible each time the magnet is operated and thermally recycled to room temperature. All the magnets are operated at a level little below the quench current values to make allowance for small variation in the performance of such a large number of magnets.

The training process is most expensive one as it involves huge quantity of liquid helium for such a large number of magnets but cannot be done away with. It is important that the training is irreversible and the magnets do not quench after their installation below the quench current value. A premature quench in a single dipole may cause a chain reaction, of the sort, and affect rest of the 154 dipoles which are connected in series in one sector. If one magnet quenches, energy from all other magnets in the sector has to be discharged safely. A quench in one magnet may result in the increase of temperature of all other magnets in a sector, above T_c, turning them normal. LHC did face this problem in Sept. 2008 within 9 days of its first operation, when one main dipole magnet in sector 3–4 quenched due to a faulty electric connections and consequent mechanical damage and release of LHe. This resulted in the damage of 50 expensive magnets. It took 14 months to repair the damage and to bring back LHC to life in Nov. 2009.

At last, LHC succeeded in discovering all evasive Higgs Boson, first predicted by Peter Higgs together with five other physicists in 1964. The first indication came in July. 2012 and the final announcement of the confirmation of Higgs particle was made in March 2013. Peter Higgs and Francois Englert were awarded the 2013 Nobel Prize in physics. The particle has a mass 125 GeV/c^2, zero spin and zero electric charge. Its decay time is found to be 1.56×10^{-22} s.

8.4.7 The Quench Protection

Since quench cannot be ruled out in a superconducting magnet it is very important to provide a most reliable and fool-proof quench protection system for accelerator magnets especially when the magnets are operating at high field. No sooner the hot spot is detected, the current should decay fast and the stored energy should spread over the entire coil so as not to allow excessive heating at the hot spot. Quench protection in LHC type magnets is tricky because each magnet has large stored energy and a large number of them, 154 are connected in series and energized by a common source. Normal protection systems were found inadequate. LHC magnets have superconducting bus bars in parallel with magnet coils. In the event of a quench Joule heat dissipation starts at the hot spot and the voltage increases. As soon as the voltage exceeds the opening voltage of the by-pass diodes, the current gets diverted into the superconducting bus bars. This prevents excessive heating and rise in temperature beyond acceptable limit of room temperature. The current decays over a time constant ($=L/R$) which in LHC magnets is too large, R being very small. R is kept small because the quench propagation in the LHC conductor is slow at 20 m/s and $dR/dt = 10$ mΩ/s. Large time constant means it will take a long time to stop heat dissipation at the hot stop risking the magnet safety.

Dumping energy in an external resistor will need high resistance (~ 1 Ω) for LHC magnets which will induce high voltage of the order of 10 kV across the magnet which is too high and well above the prescribed limit of 1 kV. LHC magnets are protected by activating the SS strip heaters mounted between the coil winding and the collars. This helps in spreading the quench to the larger part of the coil and rather fast. The resistance R rises and the time constant decreases. The stored energy thus spreads uniformly across the whole coil without excessively increasing the temperature at the hot spot. This also avoids thermal gradients and consequent unwanted stresses in the coil. Since the resistive voltage and the inductive voltage have opposite polarity, they balance each other to great extent. As a result, the voltage rise in LHC during the quench does not exceed beyond 600 V.

The main parameters of all the superconducting colliders discussed above are summarized in Table 8.3.

8.5 High Field Magnets for Future Accelerators

The quest of high energy community to achieve higher beam energy has never ceased. While world's largest accelerator, LHC at CERN was being built R&D on developing still high field superconducting magnets had continued at CERN and other places notably in USA. The aim has been to build 15 T magnets in immediate future and 20 T magnets for a distant future. Obviously, in today's scenario, the only conductor available is the brittle A-15 Cu/Nb_3Sn composites. The next candidate for fields higher than 15 T could be Nb_3Al [11] of the same family. Other

Table 8.3 Summery of the superconducting collider

Parameter	Unit	Tevatron FNAL (USA)	HERA[a] DESY (Germany)	SSC TEXAS (USA)	RHIC BNL (USA)	LHC CERN (Europe)
Year of operation		1987	1989	Proposed 1991	1999	2009
Present status		Shut 2011	Shut 2007	Dropped 1993	Working	Working
Tunnel length	km	6.3	6.3	87.1	3.8	27
Colliding species		p^+–p^-	e^-–p^+	p^+–p^+	Ions-proton	p^+–p^+
Collision energy	TeV	1.8	0.92	40	0.2 (Au-p^+)	14
Main dipoles		774	422 proton ring only)	7,860	396	1232
Main quadrupoles		224	244 (proton ring only)	1,360	492	400
Dipole field	T	4.4	5.3	6.6	3.46	8.34
Operating temp.	K	4.4	4.2	4.35	4.6	1.9
Conductor used		Cu/Nb–Ti	Cu/Nb–Ti	Cu/Nb–Ti	Cu/Nb–Ti	Cu/Nb–Ti
Collar used		Yes	Yes	Yes	No, yoke only	Yes
Yoke (iron)		Warm	Cold	Cold	Cold	Cold

[a] HERA has proton ring and electron ring one over the above. Proton ring has superconducting magnets and the electron ring normal magnets. The electron ring has 456 normal dipole magnets (1.7 T) and 605 quadrupole magnets

option is to use high T_c superconductors like Bi-2223 or 2G YBCO after they are produced in sufficient lengths by cost effective technique and meet the stringent characteristic parameters set for accelerator magnets. Major efforts in this direction have been going on at several places like CERN, FNAL, BNL, LBNL, University of Twente (NZ) and other such places individually as well through mutual collaborations. So far these efforts have been directed towards using Nb_3Sn superconductor albeit produced by different techniques.

8.5.1 The Nb_3Sn Conductor for Accelerator Magnets

The biggest challenge to High Field Accelerator Magnet (HFAM) programme stems from the brittle nature of the Nb_3Sn. The conductor is manufactured in preformed (Nb filaments in a Sn composite matrix) state. It is only after the coil is wound that the superconducting compound Nb_3Sn is formed in the final stage through a controlled heat treatment, what is generally termed as “wind and react” technique. So far, this reaction temperature is quite high in the range of 650–700 °C which poses several problems related to electrical insulation and application of pre-stress etc. The “react and wind” technique which is feasible for HTS like Bi-2223 and YBCO tape conductors is being pursued at some places. Extensive R&D efforts are being made to study the effect of bending dia. on J_c of Nb_3Sn. One option being tried is to react the cable under bend position at a certain diameter so that the degradation by final diameter winding is cut significantly.

Nb_3Sn also suffers from poor ultimate tensile strength as compared to Nb–Ti and therefore needs re-enforcement. Cables with SS core have been produced and used for accelerator magnets. Conductors produced by four different techniques, namely, the MJR (Modified Jelly Roll), the ITD (Internal Tin Diffusion), PIT (Powder-In-Tube) and RRP (Restack Rod Process) have been used for making model dipoles and quadrupoles by FNAL or in collaboration with BNL and LBNL [12]. We have discussed these techniques in some detail in Chap. 6. Conductors with $J_c \sim 2{,}500$ A/mm^2 with a filament dia. of less than 50 μm and a Cu/Nb_3Sn ratio between 1 and 1.5 have been used for magnet fabrication. To keep persistent current under control the filament dia. should be reduced further to $\sim$20 μm or still below. Further, the Cu/Nb_3Sn ratio needs to be brought down to 50–60 % which in turn demands very effective quench protection procedures. Fine filaments seems to be possible with PIT technique. After over a decade of extensive research it is now feasible to have magnets producing a nominal field of 12 T and the maximum field of 15 T. More R&D efforts are needed to build 15 T nominal field magnets. These studies have generated plethora of useful data on coil design, conductor evaluation, mechanical structure, coil pre-stress, quench performance, field quality and coil performance. These studies will go long way in establishing a reliable Nb_3Sn technology for 15 T and higher accelerator magnets.

8.5.2 Nb_3Sn Accelerator Magnets Development at FNAL

In the context of Nb_3Sn magnet development programme for future high energy accelerators it will be appropriate to discuss the high field programmes pursued at Fermi Lab. [12] for LHC IR upgrade, Muon Collider Storage Ring and future high field accelerators. Fermi Lab. while developing this technology also had collaboration with BNL and LBNL. It built approximately 20 dipoles and 35 quadrupole magnets in 1, 2 and 4 m lengths and later another 14 quadrupoles, all 4 m long. Magnets have performed well up to a nominal field of 12 T and a maximum field of 15 T. Vast data with regard to cable parameters, collaring technique, pre-stress, mechanical structure, field quality and quench behaviour has been generated. This data has indeed laid the foundation for future development of Nb_3Sn accelerator magnet programme.

Fermi Lab. built base line dipoles for VLHC (Very Large Hadron Collider), generating 10–11 T field @ 4.5 K, in an aperture of 43.5 mm. The coil was two layer shell type with a mechanical structure which had a cold iron yoke 400 mm thick and a SS skin 10 mm thick but had no collars. It also developed Nb_3Sn quadrupoles for the LHC luminosity upgrade under the US-LARP (LHC Accelerator Research Programme) having an aperture of 90 mm and providing a nominal field gradient of 200 T/m. This value is the same as in the 70 mm aperture of the present LHC Nb–Ti quadrupoles. These magnets will also be operated at 1.9 K. These quadrupoles too have a two layer shell type coils with a 25 mm thick SS collar, a 400 mm thick cold iron yoke and a 12 mm thick SS skin.

For dipoles, keystoned Ruherford cable 14.24 × 1.8 mm size with 27/28 strands of dia. 1 mm was used. For quadrupoles, similar cable of the dimensions 10.05 × 1.26 mm, with 27 strands of 0.7 mm dia. each was used. The keystone angles of the two cables were 0.9 and 1.0° respectively. The maximum field generated by the dipoles was 12.05 T @ 4.5 K and a peak field of 12.6 T at the coil. The quench current was 21.06 kA. The quadrupoles operated at 1.9 K provided a field gradient of 233 T/m with a peak field of 12.1 T at the coil. These values were obtained at a quench current of 14.07 kA. The characteristic parameters of the cables used and the performance parameters of the dipoles and quadrupoles [12] are given in Table 8.4. To prevent persistent currents caused by magnetization, the filament size should be kept below 20 μm without lowering J_c. The eddy current effects are dependent upon the twist pitch of the strand and of the cable, the matrix resistivity and the inter-strand resistivity. These effects have been suppressed by the insertion of a SS core in the cable which increases the inter-strand resistance and also by having well twisted strands.

The strands used in cables for the magnets were made following three different methods, namely, MJR, PIT and RRP. The J_c of the strands produced by the three techniques was in the range of 2–2.8 kA/mm^2 and filament size 50–100 μm. The insulation studied, were the ceramic tape, S-2 glass sleeve and E-glass tape. Ceramic insulation proved to be the best from the coil fabrication point of view but it is rather thick and more expensive of the three. Ceramic tape was used for all the dipoles and S-2 and E-glass sleeve for quadrupole magnets.

Table 8.4 Characteristic parameters of the Nb_3Sn cables and the performance parameters of the model dipoles and quadrupoles built at FNAL cables used are produced by MJR, PIT and RRP techniques (data compiled from [12])

Parameter	Unit	Dipoles	Quadrupoles
Cable (keystoned Rutherford) size with SS core	mm	14.24 × 1.80	10.05 × 1.26
Keystone angle	degrees	0.9	1.0
Number of strand		27/28	27
Strand diameter	mm	1	0.7
Filament dia.	μm	~20	~20
Maximum field @ 4.5 K	T	12.05	
Field gradient @ 1.9 K	T/m		233
Peak field at the coil	T	12.6 (4.5 K)	12.1 (1.9 K)
Quench current	kA	21.6	14. 07

To handle the coil processing, FNAL used a ceramic binder which after curing holds rigidly all the components of the coil like wedges, pole blocks etc. and enhances the mechanical strength of the electrical insulation. During heat treatment, this binder turns into fine ceramic particles serving as filler material during the impregnation of the coil. So far the magnets have been impregnated with epoxy CID 101 K. Efforts are on to find an epoxy which is more resistant to hard radiation.

Brittle Nb_3Sn coils and the need for pre-stress pose serious challenge to the mechanical structure design. A thick SS shell structure was used for some magnets and a SS collar supported by SS skin for others. Two Al-clamps pre-stress the dipole coils to 20 MPa at room temperature. The final pre-stress of 100–120 MPa at 4 K is provided by the yoke and the skin. In quadrupole magnets, the coils are stressed to 30–35 MPa by the collars and to final pre-stress of 110–150 MPa by the SS skin. Control spacers have been used to prevent over-compression during yoking.

8.5.3 EuCARD Nb_3Sn Dipole Magnets

The EuCARD (European Coordination for Accelerator R&D) project is aimed at developing technologies for future accelerators in Europe with higher energies and higher luminosities. Its Work Package-7 relates to the development of high field Nb_3Sn magnets for accelerators. One of the key objectives of this work package is the fabrication of a 1.5 m long dipole magnet with a 100 mm aperture and a bore field of 13 T. This will replace the present Nb–Ti based dipole magnet of FRESCA, the Cable Test Facility at CERN and has been code named as FRESCA-2. The magnet was put under operation in 2013.

The detailed design of the model FRESCA-2 dipole has been given by Milanese et al. [13] and a status report at the end of 2012 has been published by Ferrasin et al. [14]. A block layout has been preferred for the coil design in place of a cos θ configuration. It has two coils each having two layers. The first coil (inner) consisting of layer 1 and layer 2 has 36 turns and is wound over a Ti pole with 100 mm diameter hole. The second coil (outer) consisting of layer 3 and layer 4 is wound with 42 turns around an iron-pole. Each coil has a double pancake structure and wound using single length of the conductor, reacted and impregnated separately. Insulating inter-layer shims (0.5 mm) and inter-coil shims (1.5 mm) are used. The coil ends are bent upwards at an angle of 17° to make room for the 100 mm aperture as shown in Fig. 8.7. The bent coil ends are supported by steel wedges.

FRESCA2 design phase has been funded by the European Commission under the framework of EuCARD under the Grant Agreement n° 227579.

The salient feature of the design of FRESCA-2 is the use of the so-called ‘bladder and key’ concept developed earlier by LBNL. Horizontal and vertical pads have been used between the coils and the yoke made of 5.8 mm iron laminations compressed by SS end-plates. The pads transfer the entire force to the split iron yoke. The iron yoke covers the entire coil length and is fitted into a 65 mm thick pre-tensioned (with bladders) cylindrical shell made of a 7075 Al-alloy. Ultimately,

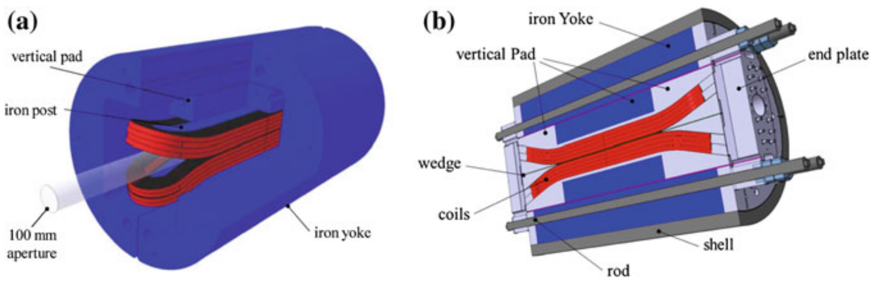

Fig. 8.7 **a** A cutaway sectional view of the FRESCA-2 dipole coils and the beam aperture. The coil ends are bent upwards supported by wedges [13], **b** a longitudinal cross-section of the FRESCA-2 dipole coils (© CEA/IRFU, P. Manil, J.F. Millot)

the entire force is taken care of by the shell. The shell shrinks more than the other parts of the assembly during cool-down and pre-compresses the coil further. The mechanical support design of FRESCA-2 ensures sufficient pre-compression on the coil to counter Lorentz force effectively as the current keeps rising during the energization of the magnet. It also keeps the peak stress under limit in the cool-down state. In the cool-down state the maximum horizontal stress observed is 150 MPa at 13 T field.

The presence of iron vertical pads close to the second coil (layer 3 and 4) and the iron yoke makes a significant impact on the field strength inside the bore as well as on the peak field at the coils. The target field of 13 T is achieved at a magnet current of 10.8 kA instead of at 12.8 kA, that would have been required without iron. It also reduces the peak field from 13.9 to 13.2 T. Lorentz force, however, remains unaffected. The fringe field at a distance of 1 m, too, decreases from 150 to 100 mT.

The cable used for winding is a Rutherford cable of the size 20.90 × 1.82 mm (pre-reacted) with 40 strands of 1 mm diameter. Each strand contains 192 filaments of ~48 μm diameter and a Cu/Nb_3Sn ratio of 1.3. Strands are produced by PIT method as well as by the RRP technique. The magnet design takes into account the cable size increase during reaction. The cable size after reaction turns 21.32 × 1.89 mm. The strand reaches a critical current density, J_c = 2,450 A/mm^2 (4.2 K, 12 T) and 1,400 A/mm^2 (4.2 K, 15 T). Cabling brings down the J_c by about 5 %. The cable is insulated with a 0.2 mm thick braided S2 glass fiber. The strand and cable parameters are given in Table 8.5.

The stored energy of the FRESCA-2 magnet is extremely high, 4.6 MJ (Table 8.5) and therefore quench protection system becomes a critical part of this project. An efficient protection system, based on dump resistors and quench heaters, has been provided. The external dump resistor is of 95 mΩ so that the voltage at the magnet terminals does not exceed 1 kV. The heaters are SS strips 25 μm thick and 12 mm wide. These heaters are mounted on the outer surface of each layer covering nearly 50 % of the surface area available. The response time from the initiation of quench to activating heaters is expected to be less than 40 ms and the maximum temperature to be 150 K.

Table 8.5 The parameters of the magnet and strand/cable used for FRESCA-2 dipole produced by PIT technique (data compiled from [12–14])

Cable/strand parameters	Unit	Value	Magnet parameters	Unit	Value
Cable type		Rutherford	Aperture diameter	mm	100
Cable size (before reaction)	mm	20.9 × 1.89	Outer diameter of the magnet	m	1.03
Cable size (after reaction)	mm	21.32 × 1.89	No. of turns in layer 1 and layer 2		36
No. of strands		40	No. of turns in layer 3 and layer 4		42
Strand diameter	mm	1	Bore field (4.2 K)	T	13
No. of filaments		192	Magnet current at 13 T	kA	10.9
Filament dia.	µm	~45	Stored energy (13 T)	MJ	4.6
Cu:SC ratio		1.3	Quench protection		Resistors and heaters
Strand J_c (4.2 K, 15 T)	A/mm^2	1,400	Coil fabrication		Wind and react

8.6 Common Coil High Field Dipole Magnets—A New Approach (LBNL)

Although Nb_3Sn based dipole magnets are being built and tested for future VLHC application, a parallel programme of looking for altogether a new innovative design for the high field dipoles has been going on at few select places. The motivation for a new design stems from the requirement of reducing the cost of the superconducting magnets. In particle accelerators, a dipole magnet is the single most expensive component and challenging from fabrication point of view. So far, all the dipoles have been built on cos θ design which involves many complicated steps till the final assembly. The factors on which the new design should take into account are that the design should be simpler, cost effective and should yield desired high field with minimum quantity of the conductor. At the same time, the new design should aim at minimizing field harmonics and the peak field. It should have a much simplified and compact mechanical structure. The design must be of modular form enabling easy coil repair or replacement when required.

An innovative design, the so called "Common Coil Design" earlier proposed by Gupta [15, 16] is being pursued actively at LBNL. This design is also sometimes referred to as 2-in-1 dipole. The salient feature of the common coil design is that the coils are of simple racetrack type and a single pair of coils provides opposing high field to both the apertures aligned now in vertical direction (one over the other), making it most cost effective. The bend diameter of the coils is thus much larger than in LHC design as this is now determined by the separation between the two apertures and not by the small aperture diameter. This is extremely crucial for the

Nb_3Sn conductor which is very brittle. Use of “React and Wind” Nb_3Sn conductor also becomes a possibility. LBNL has already demonstrated [17] successfully a 6T prototype dipole magnet (RD-2) based on common coil design and using Nb_3Sn conductor. This magnet used a Rutherford cable of the size 12.34 × 1.45 mm containing 30 strands of Nb_3Sn 0.808 mm dia. manufactured by Teledyne Wah Chang Albany. The strand J_c was only 610 A/mm^2 (12 T, 4.2 K). This was the precursor to the later 15–16 T racetrack dipole magnets built at LBNL.

LBNL built and tested [18] its first 14 T racetrack common coil dipole (RD-3) using Nb_3Sn conductor with a J_c of 2,000 A/mm^2 supplied by Oxford Technologies. At 14 T the total horizontal Lorentz force turns out to be ~12 MN over a 780 mm coil length which tries to push the coil windings apart. The mechanical support structure was designed to withstand such large forces. The inflatable bladder and interference key system has been employed for RD-3. The design of the cross-section of the RD-3 dipole is shown in Fig. 8.8. The bladders installed between the coil pack and the iron yoke work as an internal press compressing the coil packs to 70 MPa. It also provides a tension of 155 MPa to the surrounding 40 mm thick aluminum shell. Next, the keys are inserted and the bladders are deflated and removed leaving a tension of 140 MPa on the aluminum shell. This stress rises to 250 after cool-down due to the thermal mismatch between the yoke and the shell. The magnets use 3 modular coils. The two 10 mm aperture beam pipes are inserted between the coils.

During training, first quench occurred at 8.1 T and the field reached 14 T after 35 quenches. No quench occurred up to this field after thermal cycling. Quenches below 13.7 T were found to be caused by conductor movement in the inner coil module located in high field region and quenches above this field originated in the outer coil modules. A record field of 14.7 T was achieved which was close to the

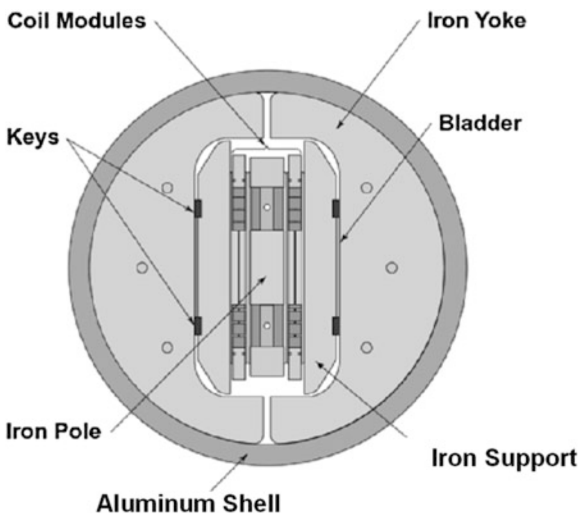

Fig. 8.8 The cross-section of the 14 T common coil dipole magnet built at LBNL (RD-3) [18] (*Courtesy*, Lawrence Berkeley Nat’l Lab)

short sample limit of the conductor in the two coils. No degradation in J_c was thus observed by cabling or due to Lorentz forces. The mechanical structure too withstood the forces as per the prediction made by TOSCA and ANSYS models.

8.7 The 15 T HD-2 Dipole

LBNL continues to carry forward the common coil dipole development programme with the ultimate aim of generating a field of 16 T in a bore of 40 mm dia. LBNL built one racetrack type dipole, code-named HD-1 which generated 16 T in a bore dia. of 8 mm. The next target was to increase the bore dia. to 35 mm and generate a field of 15 T. LBNL achieved [19, 20] 15 T in a 36 mm dia. bore field in a 1 m long dipole, code-named HD-2. The design is again based on the simple racetrack coil geometry, the block-coil module configuration and the bladder-interference key technology. The cross-section of HD-2 is shown in Fig. 8.9. HD-2 has two double layer coil modules. Each module has two layers. Coil 1 is wound on a Ti-alloy pole having a central cut-out for the bore pipe and has 24 turns. Coil 2 has 30 turns wound on another Ti-alloy pole. The coil ends are flared and supported by Al-bronze wedges with a central cut-out for the beam pipe. The two coils are separated by a SS mid-Plane sheet 1.37 mm thick.

A Rutherford Nb_3Sn cable (22 × 1.4 mm) of 'Wind and React' type consisting of 51 strands of 0.8 mm dia., Cu/SC ratio 0.94 has been used. Strands were supplied by 'Oxford Superconducting Technologies' and the cable was fabricated at LBNL. The strand with 54/61 sub-elements was produced by RRP technique. Strand J_c was 2,800–3,000 A/mm^2 (4.2 K, 12 T). The support structure is quite similar to the

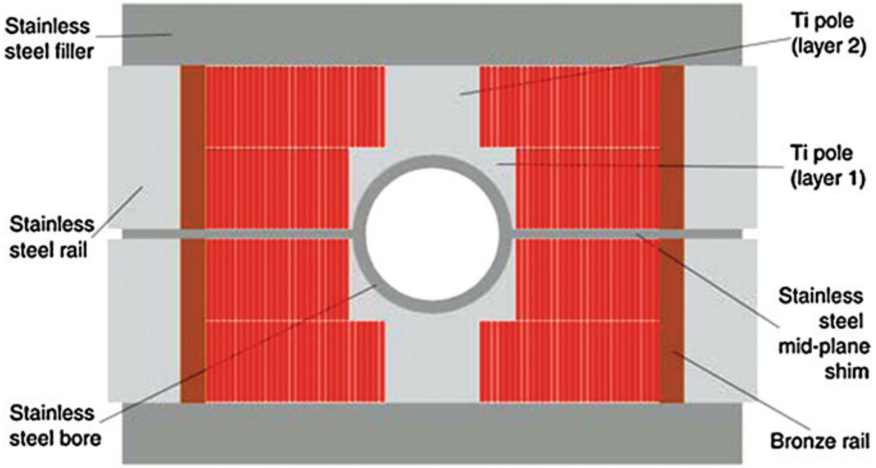

Fig. 8.9 The schematic of the cross-section of the HD-2 dipole magnet [20] (*Courtesy*, Lawrence Berkeley Nat'l Lab)

dipole RD-3 and consists of the outer 41 mm thick Al-shell pre-tensioned using inflatable bladders and the interference keys. The iron yoke is made in two halves with 50 mm thick laminations.

HD2 produced an accelerator quality bore field of 15 T at 4.2 K. Field harmonics have been suppressed to acceptable level. The design could suppress persistent current induced effects quite significantly.

8.8 Work on the Design of 15 T Nb_3Al Dipole

Yet another programme on the design and development of a 15 T dipole [21] based on coil block concept is going on using Nb_3Al superconducting cable. This work is being carried out under a collaboration between FNAL (Fermi National Accelerator Laboratory), NIMS (National Institute for Material Science) and KEK (High Energy Accelerator Research Organization). A Rutherford cable (13.93 × 1.84 mm) containing 28 strands (1 mm Dia.) of Nb_3Al produced by the so called, RHQT (Rapid Heating Quench and Transformation) process is slated to be used for the dipole. The RHQT technique has already been discussed in Sect. 6.5.4, Chap. 6. The strand has a non-Cu J_c of 1,000 A/mm^2 (15 T, 4.2 K). The filament dia. is 50 μm and the Cu ratio 0.5. Nb_3Al is known to have much larger B_{c2} and has better stress tolerance than the Nb_3Sn conductor. NIMS has already produced a field of 19.5 T in a background field of 15 T using this material. The dipole has been designed using ROXIE and the stress analysis carried out using ANSYS. The total stress at the mid-plane due to Lorentz force is 85.4 MPa and the horizontal stress at the outer surface of the block coils is 67 MPa at 4.5 K. Both are well within the tolerance limit of the conductor.

We thus find that even after the successful operation of LHC efforts continue to go to higher fields and higher energies. Unconventional simple and cost-effective coil designs are being investigated. A-15 Nb_3Sn magnets might replace Nb–Ti magnets in near future and focus then might shift to Nb_3Al for certain applications. HTS like 2G YBCO conductors may also become candidate for accelerator magnets once they meet the established criteria for accelerators and their reliability is proven. Production cost too has to be within affordable limits. The biggest fall-out of accelerator programme has been the emergence of the state-of-art technologies for the manufacture of high current efficient superconductors.

8.9 Linear Colliders with Special Reference to ILC

As discussed in Sect. 8.1, linac is a preferred option for accelerating light particles like electrons and positrons, as the energy loss due to synchrotron radiation is no longer a major problem. In 2004, the International Committee on Future Accelerator (ICFA) had recommended superconducting RF cavity (SCRF) technology for future accelerators. The three large accelerators, namely, NLC (Next Linear Collider) at SLAC, GLC (Global Linear Collider) in Japan and TESLA (Terra Electronvolt Energy Superconducting Accelerator) in Germany decided to pool their efforts together and build ILC (International Linear Collider). In ILC, electrons and positrons will be accelerated in linear accelerators in opposite directions and collide with a collision energy of 500 GeV which could be up-graded to 1,000 GeV (1 TeV) later. It will be 30 km long to start, with a provision of extending up to 50 km. The site of location of the ILC is expected to be one of the two sites selected in Japan's mountainous regions, Kitakami (Tohoku Prefecture) or Sefuri (Kyushu Prefecture). A schematic diagram of ILC [22] is shown in Fig. 8.10. Electrons are produced by striking a gallium-arsenide photocathode with a nanosecond laser. The electrons are also made to move through a helical undulator to create photons. These photons in turn produce a pair of electron and positron when they strike a titanium target. The positrons proceed to be accelerated in the main linac whereas the electrons and the remaining photons are dumped. Positrons are accelerated in a separate linac. After acceleration both the beams collide and the fragments are picked up by two detectors.

Evidently the collision energy of the ILC, initially at 500 GeV, is much smaller than the collision energy of LHC, but use of smaller particles, electrons and positrons with higher accuracy results in an unprecedented precision. It is expected that the ILC can analyze the data accurately and can verify if the Higgs boson is the same as predicted by the Standard Model of particle physics.

8.9.1 Superconducting Magnets in ILC

The ILC Reference Design Report (RDR) [23] was presented in 2007. As per the design report superconducting magnets will be used in ILC to transport beam all along the accelerator length. ILC will use 2,333 superconducting magnets out of a

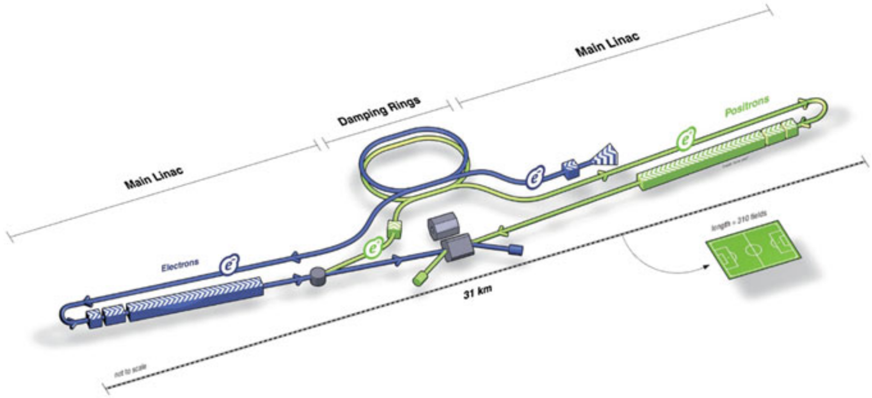

Fig. 8.10 A schematic layout of the ILC [22] ILC conceptual diagram (© ILC GDE)

total of more than 13,000 magnets which will be used in the entire machine. The main superconducting magnets are: 715 quadrupoles to focus the beam and 1,374 dipole correctors to steer the beam. In addition, there are 12 sextupoles, 14 octupoles, 16 simple solenoids, 160 wigglers and 42 undulators. To a large extent, the success of the collider will depend upon the precision with which the magnets are designed, manufactured and positioned. The field quality for most of the length of the collider should be few parts in 10^4 the beam size being only 6 nm × 600 nm. In a linear accelerator, the magnets must meet several stringent requirements such as discussed below.

The magnet centre field stability should stay within an accuracy of 5 μm during the operation of the quadrupoles and the beam based alignment (BBA) process up to a 20 % change in the focusing field. Beam alignment is extremely critical in this accelerator to keep on track such a small size beam for collision. Horizontal and vertical dipole correctors are used in the quadrupole magnets to correct all magnet centre deviations caused by field variation and the BBA.

The magnetic centre stability is influenced by a number of factors such as the mechanical misalignment of the magnets, the magnetization effects in the magnets, the hysteresis effects in the iron core and its saturation, thermal deformations in magnet on cooling, Lorentz forces and the coupling between the coils of the quadrupole and dipole. The dipole correctors need to be programmed to restore magnet centre under all circumstances.

Since the magnets are mounted close to SCRF cavities they have to be effectively shielded to limit the fringe field on the cavities below 1 μT during cooling. This is required to prevent flux trapping in the cavities. During normal operation, the fringe field should not exceed 10 μT. A cut-view of the cross-section of ILC cryomodule can be seen in Fig. 8.11. The cavity and other components of the cryomodule are seen in the picture.

Fig. 8.11 A cut-view of the cross-section of ILC cryomodule. Cavity and other components are seen in the *picture* (© Rey.Hori/KEK)

8.9.2 The ILC Quadrupole and Dipole Correctors

We have just seen in the last section that the quadrupole/dipole corrector magnets play a crucial role in the success of the beam transport in ILC. Superferric quadrupole magnet design has been chosen by RDR for ILC. In this design the field is substantially enhanced even after the iron core is saturated. The design and fabrication of the model quadrupole magnet has been carried out by Kashikhin et al. [24] at the Fermi Lab. The field in the quadrupole is produced by a set of 4 rectangular race track coils. The design optimization has been done using OPERA 2-D and 3-D codes. Since field region of interest is limited to 5 mm radius only, the core and coil positions are not very critical. The conceptual cross-section of the Q pole magnet is shown in Fig. 8.12.

The details of the Q-pole magnet and the conductor used for winding are given in Table 8.6. The coils wound are of race track geometry which have the advantage of showing low superconducting magnetization effect. The coils have been wound using a single strand Nb–Ti wire with a filament size of 3.7 μm. The winding is done on a SS former with channels. Kapton insulation is provided to the winding to prevent ground shorts. The coil of each pole consists of 700 turns. The coil is vacuum-pressure impregnated with epoxy inside a mould. The yoke is made of laminations precisely cut out of a 1.5 mm thick sheet of AISI 1006 steel. Two (single lamination) flat iron sheets are fixed at the two ends of the magnet for magnetic shielding to limit the fringe field on the SCRF cavities to 1 μT. The quadrupole magnets will be mounted inside the cryomodules close to the SCRF cavities. As shown in the conceptual design in Fig. 8.13 the quadrupole is mounted below the centre support. Some SRF cavities including one 9-cell cavity and the Q-pole magnets are also shown in the figure.

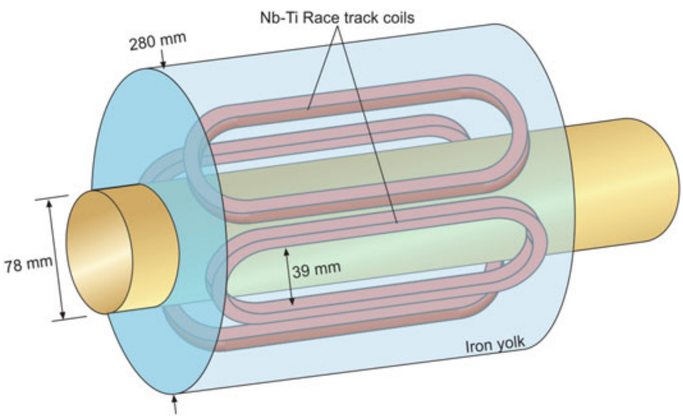

Fig. 8.12 A conceptual design of the quadrupole magnet for ILC consisting of four race track coils around the beam pipe (concept from [24])

Table 8.6 The quadrupole magnet parameters and conductor specifications for a beam energy of 250 GeV (data compiled from [24, 25])

Quadrupole magnet parameters and conductor specifications		
Parameter	Unit	Value
Magnet aperture	mm	78
Magnet length	mm	680
Yoke outer diameter	mm	280
Integrated field strength	T	36
Peak gradient	T/m	54
Peak current in Q-pole and dipole correctors	A	100
Magnet stored energy	kJ	40
Magnet centre stability at BBA	μm	5
Field non-linearity at 5 mm radius	%	0.05
Conductor used		Nb–Ti
SC wire dia.	mm	0.5
Filament dia.	μm	3.7
Cu/Nb–Ti ratio		1.5
Coil maximum field	T	3.3
SC wire I_c @ 5 T and 4.2 K	A	200
Operating temp.	(K)	2
No. of turn/pole of Q-pole coil		700
No. of turns/pole of dipole corrector		100

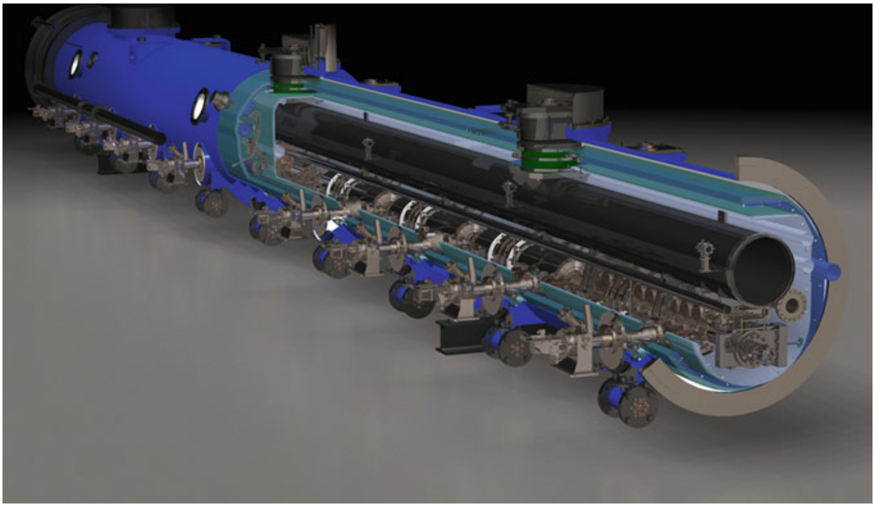

Fig. 8.13 ILC showing the location of SCRF cavities and the quadrupoles focusing magnets inside the cryomodule (*Courtesy* Fermi Lab.)

The model quadrupole magnet has been tested at Fermi Lab. by Kashikhin et al. [25]. The magnet centre stability shifts by ±2.5 μm for a current range of 3–10 A. The studies on the coupling effects between quadrupole and dipole corrector coils have been carried out by connecting them in series. This eliminates current imbalance between the two sets of coils. The magnet needs multiple training because of the multiplicity of various Lorentz forces. The magnet is protected against quench by an external resistor of 10 μΩ and coil heaters. The quench is detected by voltage taps in 50 ms with a heater response time of 100 s. The maximum temperature raise during quench is restricted to safe limit, 74 K. and the induced voltage to below 1 kV.

Recently, Kashikhin et al. [26] at Fermi Lab. have come out with an innovative design and fabricated a split-quadrupole magnet with the same dimensions. The need for modifying the design arose from the requirement of assembling the magnet under extremely clean conditions as they are installed between the SCRF cavities inside the cryomodules. In the new design the magnet is split along the vertical plane and is installed around the beam line without exposing the beam pipe to room temperature contamination. A four race track and superferric coil design was followed. In the new design the magnet is not cooled in a liquid helium bath but is conduction cooled using cryomodule liquid helium supply and gas return lines. The newly designed quadrupole produced 20 % higher field gradient than the rated value. The design is being improved further to reduce magnet centre shift.

Of late, Kashikhin [27] has come out with an interesting proposal to reduce the number of power supplies needed for operating the ILC quadrupole/corrector magnets. This proposal can improve the magnet centre stability and significantly enhance the operational reliability of the magnets. In the RDR design each magnet in the accelerator runs on a dedicated power supply and separate sets of bus-bars and current leads. In the new approach suggestion has been made to group a certain number of magnets and power the group with a single power supply. Further, the magnets, quadrupoles and dipole correctors should run in persistent mode using superconducting persistent switches. In this arrangement each magnet is energized to the required field level by a single power supply by opening the persistent switch and locking after regulating the magnet current by closing the switch. The process is repeated for every individual quadrupole as well as for the dipole corrector and are put in persistent mode of operation one by one. The new design will not only reduce the cost but will also add to the reproducibility and reliability of operation as the field stability in persistent mode is extremely high.

8.9.3 The Wiggler Magnets

The luminosity performance of the ILC requires extremely low emittance e^- and e^+ beams with high bunch charges. As per the RDR, ILC will use damping rings equipped with superconducting wiggler magnets to damp the beams effectively.

A wiggler magnet provides a sequence of transverse fields with alternate polarity and forcing the charge particles (e^- and e^+) to wiggle up and down emitting EM radiation. Crittenden et al. [28] have developed an OPERA based finite element ILC model for the design of the wiggler magnets. They followed a CESR (Cornell Electron Storage Ring) wiggler magnet design with a few changes in the parameters. About 54 magnets, each 2.2 m long, with a peak field of 1.51 T for 5 Hz mode and 2.16 T for the 10 Hz mode will be used to provide damping for the required horizontal emittance in each ring. These magnets will operate at 4.5 K. The wiggler magnets are of the superferric type where the coil is wound over a iron pole. There are 14 poles, 30 m period and a pole gap height of 7.62 cm.

8.9.4 The Undulator

The superconducting undulator will be used to generate positron source using the electron beam in the linac itself. The helical undulator will be placed in the main electron accelerator at a point of 150 GeV beam energy. The undulator produces synchrotron radiation and polarized photons which in turn produce positrons by impinging on a Ti target. Model coil is a double helical coil wound on a copper tube of ID 5.85 mm and OD 6.35 mm which produces helical transverse field. The undulator has 42 modules each with two magnet coils. The length of the field is 2×1.74 m. The axial field is 0.86 T at a nominal current of 250 A. The period is 11.5 mm. The tolerances to maintain alignment are very tight because of the small aperture. The winding is done on a SS former with grooves using a 0.4 mm dia. Nb–Ti wire. A SS yoke has been used which enhances the field by 10 % and also provide mechanical support.

8.9.5 Other Superconducting Magnets

In addition to the magnets discussed above, the collider will have 12 sextupoles, 14 octupoles and 16 solenoids serving the interaction region (IR), the beam delivery system (BDS), the e^-–e^+ source region and the ring to main linac (RTML) region.

The fabrication and installation of such a large number of magnets with great precision is a big challenge. The design details discussed above are as per the RDR which was largely based upon concepts and is subjected to modification. The 'ILC Final Design Report' has been submitted to ICFA on June 12, 2013 simultaneously at Tokyo, Geneva and Chicago, the representative cities of three continents, Asia, Europe and USA. Several modified versions of the focusing magnets are being studied at BNL, Fermi Lab. and SLAC laboratories.

8.10 Superconducting Magnets in Cyclotron

8.10.1 The Cyclotron

Superconducting magnets have played equally important role in the development of yet another type of particle accelerators, the cyclotron. Cyclotrons have been very successful in accelerating light to very heavy particles like U to high energies equivalent to K values of 2,500 MeV. Here K value represents the energy in MeV of a proton to which it can be accelerated in a cyclotron. Since a nuclei contains many protons and neutrons the nuclei energy will be much smaller. The beam injection in a cyclotron is done using either a linear accelerator or an ECR source. This class of accelerators have been very popular in the study of nuclear physics, production of radioisotopes used as tracer elements and particle therapy for the treatment of cancer.

A cyclotron uses a pair of hollow electrodes which are of the shape of 'D' (dee) arranged in opposite configuration with a gap as shown in Fig. 8.14. These electrodes are held between the poles of a magnet which produces a uniform vertical

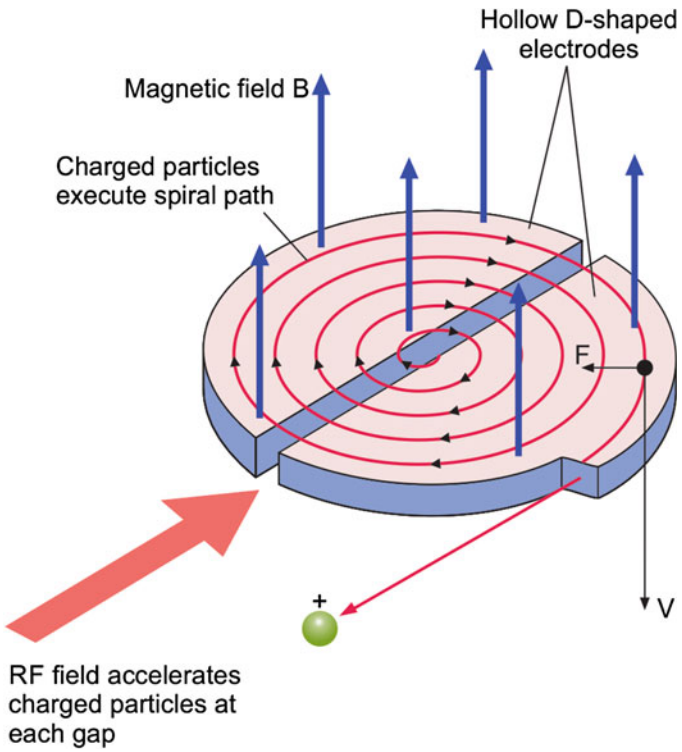

Fig. 8.14 In a cyclotron a charged particle executes a spiral trajectory under the influence of a RF field and a perpendicular uniform magnetic field

field. An alternating voltage, in MHz range, is applied to the electrodes. An ion source kept in the gap at the centre produces ions which get attracted by the first electrode. The ions execute circular motion inside the electrode (in magnetic field) and get attracted across the gap by the second electrode when they emerge from the first electrode because of the opposite polarity of the second electrode. The ions again execute circular motion in the second electrode and get accelerated in the gap by the first electrode. Ions after acceleration gain energy and move in a larger circle. This process of acceleration in gaps continues and the ions continue to travel in circles of increasing radii till they exit from the dee through an extraction route. To achieve this condition the RF frequency must match the cyclotron resonance frequency so that the ions are in phase with the RF to get repeated acceleration. This intense beam can be used to bombard a variety of target materials to produce rare radioisotopes or to conduct nuclear physics experiments. Powerful cyclotrons need high magnetic field which can be provided by a superconducting magnet alone.

The orbital motion to the ions in a magnetic field such as in a cyclotron, is provided by the Lorentz force which acts as the centripetal force:

$$qvB = mv^2/r \tag{8.1}$$

$$r = mv/qB \tag{8.2}$$

where r is the radius of the dee, m mass of the particle, v the particle velocity, q the charge of the particle and B the magnetic field. The time taken by the ion to execute half a circle in a dee will be

$$t = \pi r/v \quad = \pi m/qB \tag{8.3}$$

The cyclotron time period thus will be

$$T = 2t = 2\pi m/qB \tag{8.4}$$

And the cyclotron frequency

$$f = qB/2\pi m \tag{8.5}$$

The maximum kinetic energy can be obtained by calculating the maximum velocity at the periphery of the dee, that is, by replacing 'r' by 'R' the radius of the dee:

$$E_{max} = \tfrac{1}{2}\left(mv^2\right) = \tfrac{1}{2}\left(mq^2B^2R^2/m^2\right) \tag{8.6}$$

$$= q^2B^2R^2/2m \tag{8.7}$$

This cyclotron frequency (8.5) is constant only for low non-relativistic velocity where 'm' is constant. For high velocities the relativistic mass increases and therefore the cyclotron frequency decreases. For continuous acceleration either the frequency has to decrease like in a synchrocyclotron or the magnetic field be increased as the particles move towards the perimeter of the dees. So the cyclotron is now isochronous wherein the magnetic field increases with radius to keep the angular frequency of the particle constant.

8.10.2 Cyclotron Magnet

A cyclotron has 4 major subsystems [29], the injection system, the magnet system, the RF system and the extraction system. Each of these subsystems have to be compatible with others and are designed through a sustained iteration process till the construction stage. Our discussion will be restricted to magnet part which certainly is the most critical subsystem of the cyclotron as a whole. As shown [29] in Fig. 8.15 the magnet is a long solenoid nested in a rather thick iron yoke and having top and bottom iron pole caps and a large gap. In an isochronous cyclotron the magnet provides axial field to the particle for circular motion as well as an axial focusing to the beam which becomes critical as the velocity approaches relativistic values (>0.5 c). For axial focusing the field should increase azimuthally as the spiral radius increases. This is achieved by creating hills (high field) and valleys (low field) at the pole tips which too are spiraled to improve focusing further. In a superconducting magnet and high field region the pole tips are fully saturated which results in the enhancement of field at the hills by 1.5 T, higher than the field in the valleys. This saturation or the complete alignment of the magnetic moments is in fact equivalent of a surface current of 450 kA on a 250 mm thick ordinary steel pole

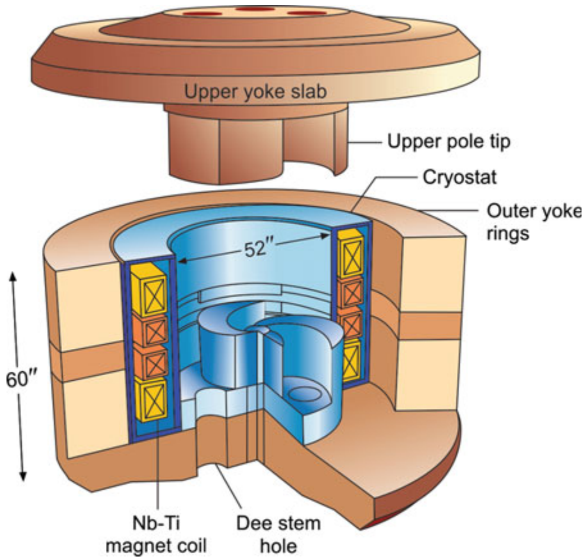

Fig. 8.15 A sketch and dimensions of the MSU cyclotron K-500, world's first superconducting cyclotron [29, 30] (*Courtesy* Marti Felix and Gelbke Konrad, NSCL, Michigan State University)

tip and with no cost. The azimuthal width of the valley and the hill is kept same so as to benefit from maximum focusing effect.

The next consideration about the magnet design is the number of hills or the so called ‘sectors’. The thumb rule is that good axial focusing at the centre is obtained by a smaller number of sectors but to operate the cyclotron at high beam energies a larger number of sectors are needed. For example, 200 MEV/nucleon seems to be the upper limit to which the K-800 cyclotron of MSU, with three sectors, can accelerate a beam. For higher energies one has to use either four sectors or three inner sectors breaking into six outer sectors. To keep the magnetic field to be isochronous and maintain azimuthal field variation for focusing, trim coils are often used. For variable energy, the magnetic field profile has to remain synchronous so that the beam does not go out of phase with the accelerating voltage. This may need large adjustment in the radial field increase ranging from almost 1–20 % in K-800 class of cyclotron depending on the beam being accelerated. This is best achieved by dividing the main coil into two or more no. of coil pairs symmetric to the median plane and exciting them at different currents.

8.10.3 Some Landmark Superconducting Cyclotrons

We list below some of the well known superconducting cyclotrons built and operated in Europe, Japan and USA.

1. K-500 NSCL, MSU (USA) 1982
2. K-520 Chalk River (Canada) 1985
3. K-500 (TAMU) Texas A&M Uni. (USA) 1985
4. K-1200 NSCL, MSU (USA) 1989
5. K-800 LNS, Catania (Italy) 1994
6. K-600 (AGOR), KVI (Orsey-Groningen), 1996
7. K-2500 RIKEN Ring Cyclotron, RIKEN (Wako, Japan), 2006
8. K-500 VECC (Kolkata, India) (First beam line acceleration 2009)

Below we discuss three trend setting cyclotrons, namely, K-500, K-1200 and K-2500 mentioned above.

8.10.3.1 K-500 Cyclotron at NSCL (Michigan State University)

World’s first superconducting cyclotron K-500 was built and operated at National Superconducting Cyclotron Laboratory, MSU, USA in Nov. 1981 and the first beam was extracted in August 1982. Since then many cyclotrons have been built ranging up to very high energies up to K-2500. Some of these cyclotrons have been listed in the previous section. The MSU design of the cyclotron got popularity and was followed by a number of laboratories. The schematic diagram of the cross-section of the cyclotron is shown in Fig. 8.16. The cyclotron is 2.184 m tall and

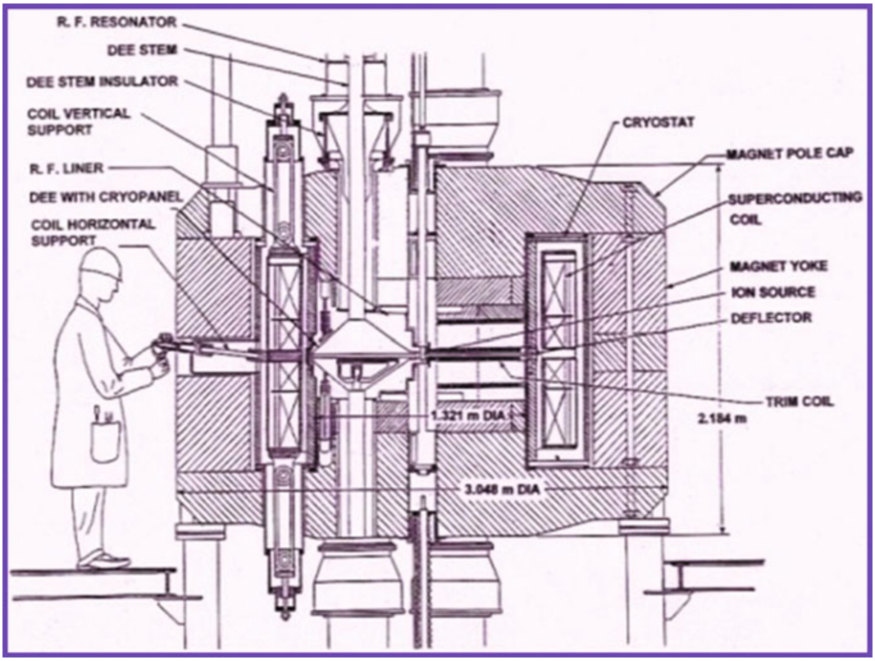

Fig. 8.16 The schematic cross-section of the K-500 cyclotron (MSU) [29] (*Courtesy* Marti Felix and Gelbke Konrad, NSCL, Michigan State University)

3.048 m wide (dia.). The magnet has two pairs of superconducting coils on either side of the median plane placed symmetrical, namely, α coils close to the centre and β coils away from the centre. The α and β coil sets are energized independently which allows proper adjustment of the isochronous field for all the beam energies and the central field. The magnet is installed in an annular cryostat with thermal shields and diagnostic tools. After welding, the magnet becomes an integral part of the annular cryostat as a single unit. The magnet operates in liquid helium at 4.2 K and produces field up to 5 T. The gap between the two coil sets allows different type of radial insertions in the median plane especially the extraction elements.

8.10.3.2 K-500 Cyclotron (VECC, Kolkata)

The K-500 superconducting cyclotron built at VECC [31], Kolkata is based upon the MSU design already shown in Fig. 8.15. The design parameters of the cyclotron are given in Table 8.7. The main magnet is divided in four coils, two identical pairs of α coils and β coils on either side of the median plane. Both the α coils and β coils are energized by two different power supplies. The α coils are short coils placed closure to the median plane and the larger β coils away from the median plane.

Table 8.7 The design parameters of the α and β coils of the main magnet of the K-500 (VECC, Kolkata [31]) (data compiled from PPT presentations)

Parameters of the α coils			Parameters of the β coils		
Parameter	Unit	Value	Parameter	Unit	Value
No. of α coils		2	No. of coils		2
Inner dia.	mm	1,521	Inner dia.	mm	1,521
Outer dia.	mm	1,793	Outer dia.	mm	1,793
Coil height	mm	162	Coil height	mm	327
No. of layers/coil		36	No. of layers/coil		36
No. of turns/coil		1,083	No. of turns/coil		2,234
Inductance of coils	H	13.8	Inductance of coils	H	27.6
Designed coil current	A	800	Designed coil current		800
Weight of coil	kg	690	Weight of coil	kg	1,410
Aluminum banding	mm	2.48 × 5.13	Aluminum banding	mm	2.48 × 5.13
No. of layers		10	No. of layers		10
No. of turns/layer		62	No. turns/layer		32
Total cold mass				ton	8
Main magnet frame dimensions (height)				mm	2,184
Main magnet frame dimensions (dia.)				mm	3,048
Weight of the main frame				ton	100
Total stored energy				MJ	22

All the coils have same inner and outer diameter and wound on a common SS former. The α and β coils are separated by an insulating 10 mm thick glass epoxy laminate spacer which has six segments of 60° each. The spacer has alternate grooves spaced at 2° pitch for liquid helium flow and for lead entry and exit. The former surface is electrically insulated with layers of mylar followed by a layer of 40 mil × 13 mm wide NEMA G-10CR laminate placed at a gap of 13 mm to allow the flow of liquid helium. Flange spacers of G-10 glass epoxy laminate with grooves of 2° pitch and 13 mm wide alternating ducts are used at the two ends of the former. These ducts provide liquid helium cooling channels. For inter-layer insulation also G-10 spacers, (180 in number) have been used, providing axial flow channels. Since during operation the winding is subjected to large EM forces, to prevent cable movement the winding is carried out under tension of 2,000 psi. The terminal of the magnet coils and the current leads are taken out through the top flange of the former. The two α coils and the β coils are connected in series to form two pairs and are operated using two separate power supplies. After insulating the coils with several layers of mylar, ten layers of aluminum (5052—H34 grade) banding (2.48 mm × 5.13 mm) were wound on the coils at a high tension of 20,000 psi. This banding increases the compressive stress on the coils significantly. The space between the two pairs of coils in the median plane is used for a variety of horizontal inserts.

The magnet former is welded shut inside the annular helium vessel such that the former itself acts as the inner wall of the helium container. The helium container is surrounded by an annular 80 K thermal shield and finally suspended inside a vacuum tank using G-10 vertical and horizontal support links. Many ports such as vacuum port, refrigeration ports and ports for current leads and other diagnostic tools are provided at the top of the vacuum container. The helium container is shown in Fig. 8.17a. The whole assembly is now positioned in a magnet frame which is one half of the iron yoke and weighs about 100 tons. The yoke carries top and bottom pole caps and three pole tips of sector shape, spaced at 120°. The lower half of the yoke is shown in Fig. 8.17b. Each pole tip has 13 trim coils wound over them for fine tuning of the field for different radii. A forged steel of AISI 1020 grade has been used for the fabrication of the yoke components including pole caps. All the components have been machined to a precision of 1.6 μm for perfect mating. Cylindrical symmetry around the axis and mirror symmetry of the two halves on either side of the median plane has been achieved using VTB machine.

The conductor used is a 1.2 mm multifilamentary wire of Nb–Ti (46 %) composition. The complete specifications of the conductor used are given in Table 8.8. The wire is embedded in the groove of a copper bar of dimensions 2.794 × 4.978 mm and filled with Pb–Sn soft solder. Since the maximum single length of the cable available was limited to 6 km three joints were made in each β coil and two joints in α coils. Special technique was developed to prepare low resistance joints. A total of 35 tons of cable has been used. The VECC cyclotron machine with beam line system is shown in Fig. 8.18. First beam acceleration took place in August 2009.

The quench protection system uses external dump resistors and consists of two independent circuits one each for α and β coils. The circuit (Fig. 8.19) enables the dumping of the stored energy in the resistors either in a slow-dump mode (4 A/min) or in a fast-dump mode (15.3 A/s) in different situations. The slow dump is activated in the event of a power failure. However, whenever some cryostat parameters exceed the acceptable limit such as liquid helium level, current lead voltage or

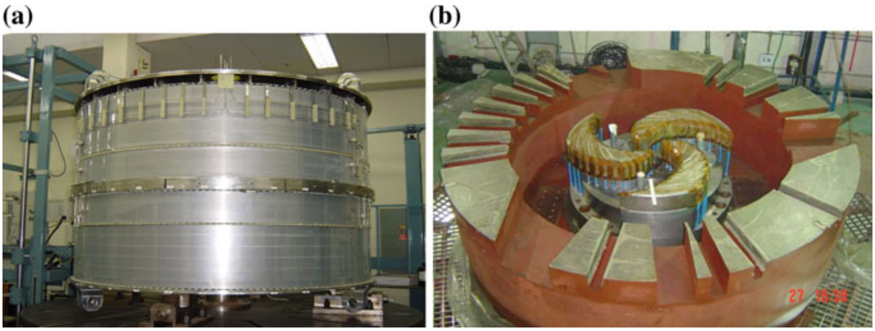

Fig. 8.17 **a** The annular helium vessel housing the magnet coils. **b** Lower half of the yoke with bottom pole caps and three sector shaped pole tips. Each pole tip has 13 trim coils (*Courtesy* D. Srivastava and S. Saha, VECC, Kolkata)

Table 8.8 The specifications of the conductor used for winding coils for K-500 (VECC, Kolkata, [31]) (data compiled from PPT presentations)

Parameter	Unit	Value
Type of conductor		MF (Nb–46 % Ti) wire soldered in a Cu-channel
Cable outer dimensions	mm	2.794 × 4.978
MF–Nb–Ti wire dia.	mm	1.20
No. of filaments		500
Filament dia.	μm	40
Cu/SC ratio in the wire		1.3
Overall Cu/SC ratio in the cable		20
Overall current density	A/mm^2	58
Critical current @ 5.5 T, 4.2 K	A	1,030
Conductor yield strength	MPa	117
Max. conductor single length	km	6
Total length of conductor used	km	35

Fig. 8.18 VECC superconducting cyclotron with beam line system (first beam line acceleration in August 2009) (*Courtesy* D. Srivastava and S. Saha, VECC, Kolkata)

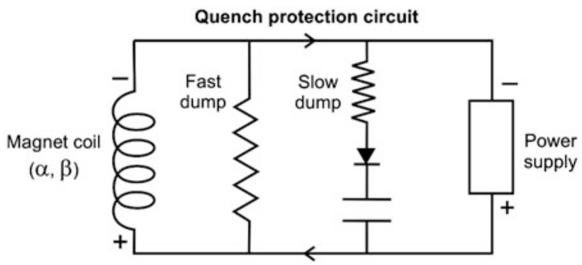

Fig. 8.19 Quench protection circuit provides slow and fast discharge of energy in external dump resistors in different situations

strain related force etc. the energy will dissipate in fast dumping resistors. The magnet system was first operated in 2009. A field of 4.8 T was achieved at the pole tips (hill region) at a radius of 0.55 m by charging α and β coils to 550 A current.

8.10.3.3 K-1200 Cyclotron (NSCL, MSU)

NSCL built yet another powerful cyclotron, K-800 [32, 33] as a booster to K-500 which went into operation in 1988. The new cyclotron performed superbly and provided excellent focusing power and was renamed K-1200 a year later in 1989. K-1200 continues to be world's highest energy superconducting cyclotron in its class. The design envisaged a beam energy of 200 MeV/nucleon for fully stripped light ions and 30 MeV/nucleon heavy ions depending upon the charge state of the ions injected. Even though, the design was based upon the use of K-500 as an injector yet the option was kept to operate K-1200 in stand alone mode using ECR ion source injector. All important parameters of the cyclotron and the conductor used in magnet construction are given in Table 8.9.

The design of K-1200 is similar to K-500 but differs in respect of several parameters. For example, the pole diameter was increased from 2.05 to 2.1 m, hill gap increased from 62.5 to 75 mm and the hill width from 46° to 51° at the outer radii. The distance between the two α coils increased from 75 to 100 mm making larger space for radial insertions especially for the magnetic channels of the extraction system. The pairs of α and β coils are powered by two independent power supplies like in K-500 to adjust the isochronous field for all ions and the main magnetic field. For most relativistic ions and for energies approaching focusing limit, current in β coils may be negative with respect to α coil and the average field increases by 20 % from $R = 0$ to $R = 1$ m. For non-relativistic ions these coils are positive with respect to α coils and the average field B_{ave} is almost constant with radius. Figure 8.20 is a photograph of K-1200 during the assembly procedure. The picture shows the lower half of the yoke with several radial penetrations related to the beam extraction system and other diagnostic tools. The coil and lower hills too are visible.

Table 8.9 Important parameters of K-1200, the magnet coils and the conductor (data compiled from [32])

Parameters of K-1200 cyclotron, the magnet and conductor		
Parameter	Unit	Value
Operating field	T	3–5
Pole diameter	m	2.1
No. of sectors used		3
Minimum hill gap	mm	75
Maximum valley gap	mm	900
Yoke inner diameter	m	2.95
Yoke outer diameter	m	4.375
Yoke height	m	2.875
No. of trim coils		22
Max. current in any trim coil	A	400
Max. power in any trim coil	kW	70
Peak dee voltage	kV	200
K value at 5 T		1200
RF frequency range	MHz	9–27
Number of coil pairs		2 (α and β)
Inner coil diameter	m	2.275
Outer coil diameter	m	2.575
Height of α coil (closer to median plane)	mm	400
Height of β coil (away from median plane)	mm	262.5
Separation between α coils	mm	100
Al-alloy banding thickness	mm	50
Inner dia. of vacuum tank	m	2.1125
Outer dia. of vacuum tank	m	2.925
Total height of cryostat	m	1.725
Conductor used (embedded in Cu-channel)		Nb–Ti (monolithic)
Conductor dimensions	mm	5.175 × 3.75
Overall Cu:SC ratio		25:1
Max. nominal current	A	1,000
Total inductance including mutual inductance at J_α = 3,500 A/cm^2	H	88.8
Total stored energy	MJ	61
Weight of the magnets	ton	280

The magnet operated in a range of 3–5 T field with a magnetic rigidity of 5 T m (K-1200). The magnet coils were run at a maximum current density of 3,500 A/cm^2. A monolithic Nb–Ti wire of the size 1.1 mm × 1.65 mm embedded in a copper channel (in a groove filled with solder) has been used for winding. The dimensions of the cable are 5.175 mm × 3.75 mm. A set of 21 trim coils have been used to have required B_{ave} v/s R slope. These coils have been wound on the pole

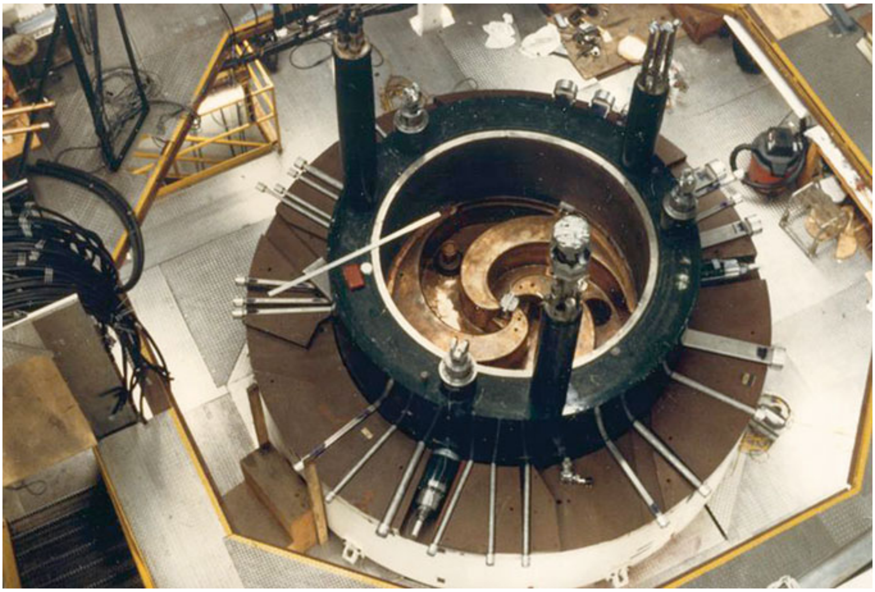

Fig. 8.20 K-1200 during the assembly process, the return yoke, the penetrations associated with the extraction elements (radial tubes) and the coil as well as the lower hills are seen in the *picture* (*Courtesy* Marti Felix and Gelbke Konrad, NSCL, Michigan State University)

tips using conventional copper conductor. A set of thick and heavily spiraled steel pole tips with three-fold symmetry provides vertical focusing. The gap between the valleys is 0.9 m. The sector area has a central hole of 175 mm which increases to 250 mm in the poles. This cyclotron happened to be first to have used a vertical injection and a ECR source for injection. There are 42 holes of dia. 18.75 mm, on the two sides of the each hill for the leads from the 21 trim coils. Holes have also been provided for feeding RF. The number of trim coil layers has been reduced from two to one and the gap between the hills increased to 75 mm. This enables easy slide of the deflector inwards at lower fields and helps in the extraction system. Nine magnetic channels and two electrostatic deflectors have been used in the extraction system.

The cyclotron went on stream and the first beam of $^{20}Ni_{3+}$ with 18 MeV energy was extracted successfully on June 6, 1988. The cyclotron performance was in excellent agreement with design calculations and the beam followed the highly intricate trajectory accurately. The beam spot was 4 mm well within the calculated value of 5 mm. The construction of the cyclotron was indeed most challenging because of much larger EM forces, a very intricate extraction system, much tighter pole tip spiral and a much larger size isochronous cyclotron with a magnet rigidity of 5 T m.

In 2001, K-1200 was coupled [34] to k-500 at the injection stage through an intermediate coupling line with a magnetic system. An ECR source injects the beam into K-500 which accelerates the beam to 17 MeV/nucleon which in turn is injected into K-1200. The ions pass through a thin foil stripper which increases the charge state by a factor of 2.5. The beam is finally accelerated to 200 MeV/nucleon. It thus became possible to accelerate light ions to high intensities and heavy ions to large energies. This upgraded version can accelerate the U beam to 90 meV/nucleon and in stand alone mode can accelerate U beam to 25 MeV/nucleon. The cyclotron can as well be operated in stand-alone mode using ECR source producing very high charge state. The cyclotron produces radio active ion beam and is used by a vast community of nuclear scientists from across the globe.

8.10.3.4 K-2500, RIKEN Superconducting Ring Cyclotron

The RIKEN superconducting ring cyclotron (SRC) is the most important accelerator of the RIKEN radioactive ion beam factory (RIBF) project in Japan. The beam energy from the old ring cyclotron K-540 is boosted using a cascade of ring cyclotrons with K values of 570, 980 and 2,500 MeV. The final beam energy goes up to 440 MeV/nucleon for light ions like carbon and 350 MeV for very heavy ions like U. The high energy beam of heavy ions are then converted into high intensity radioactive ion beam through the fragmentation of stable isotopes. RIBF is world's unique facility which provides most intense radioactive ion beams of all the elements across the periodic table. Figure 8.21 is a complicated picture showing the organization of sector magnets and various other components constituting the ring.

The K-2500 SRC [35, 36] is 19 m in diameter and 8 m in height. The main components of the SRC are six sector magnets, one flat-top RF cavity, four main RF cavities, an injection system and an extraction system. The beam from the previous cyclotron is injected into the SRC at a radius of 3.56 m. Important parameters of the SRC and the sector magnets are given in Table 8.10. Each sector magnet is 7.2 m long, 6 m in height and has a sector angle of 25°. Each sector magnet module comprises of a pair of main coils, four sets of superconducting trim coils, thermal shield, thermally insulating supports and the cryostat. The magnet is operated at 4.5 K. In addition, there are 22 pairs of normal conducting trim coils, warm poles and warm yoke. Each sector magnet weighs $\sim$800 tons. The total cold mass of all the six sector magnets is 140 tons which needs three weeks to cool to 4.5 K from room temperature. A unique feature of the construction of the SRC is the use of 1 m thick iron slabs for an effective radiation and magnetic shielding. These slabs cover the valley regions between the two adjacent sector magnets and also vertically along the sides between the top and bottom slabs. This minimizes the inverse-direction stray field which influences beam deflection power in the valley. The decrease in leakage field brings down the magneto-motive force at the peak bending power. In all, the iron slabs weigh around 3,000 tons. The SRC itself becomes massive weighing 8,300 tons. The beam is finally extracted at a radius of 5.36 m. The maximum field produced is 3.8 T which accelerates U^{+88} to an energy of 350 MeV and is a world record.

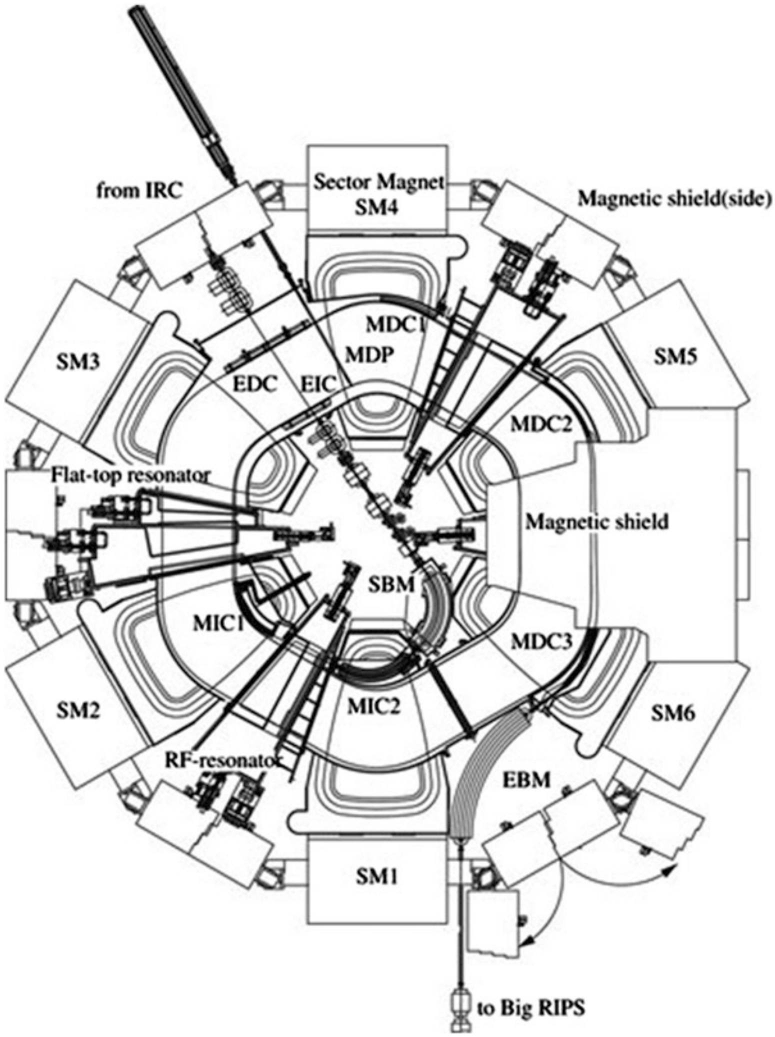

Fig. 8.21 The layout of the six sector magnets of the RIKEN K-2500 superconducting ring cyclotron (SRC) [35] (*Courtesy* Hiroki Okuno and with permission of Oxford University Press on behalf of Physical Society of Japan)

The cable used for winding the main coils of the sector magnet and the superconducting trim coils is of a Nb–Ti Rutherford type with an outer dimensions of 15 mm × 8 mm. The stabilizing cladding material is an aluminum alloy containing about 1,000 ppm Ni which increases the yield strength of this alloy from 44 to 55 MPa. The maximum operating current for the main magnet is 5,000 A and for the trim coils 3,000 A. The main coil has a solenoid winding with 396 turns and generates a magneto-motive force of 4×10^4 AT (Ampere Turn). Inter-turn and inter-layer fiberglass reinforced plastic (FRP) spacers have been used in the

Table 8.10 Important parameters of RIKEN K-2500 SRC and the magnet (data compiled from [35, 36])

Parameter	Unit	Value
Outer dia. of SRC	m	19
Height of SRC	m	8
Injection radius	m	3.56
Extraction radius	m	5.36
Total weight	ton	8,300
No. of sector magnets		6
Sector angle	degree	25°
Poles and yoke		Warm
No. of main coils		2
No. of SC trim coils		4 sets
Max. sector field	T	3.8 @ 5 kA
Total stored energy	MJ	235
Length of sector magnet	m	7.2
Height of sector magnet	m	6
Weight of a sector magnet	ton	800
Conductor used		Nb–Ti
Type of conductor		Rutherford
Cable outer dimensions	mm	15 × 8
Jacket material		Al-alloy
Yield strength of Al-alloy	MPa	55

horizontal and vertical gaps to insulate the conductor electrically as well as to provide cooling channels for the conductor. About 50 % area of the cable is left exposed. For trim coils also the same conductor has been used. Four sets of trim coils, installed in the beam accelerating area of the sector magnet, are wound in a double pancake structure. The wide and thin trim coil is sandwiched between two Al-alloy plates having grooves. These grooves serve as cooling channels for the forced flow of two phase helium. A control dewar mounted at the top of the SRC supplies liquid helium to all the six sector magnets in a close loop mode. A refrigerator with a capacity of 620 W at 4.5 K and 400 W at 70 K has been used which is far more than the heat load of the total cold mass (140 tons).

The injector system too has a superconducting bending magnet (SBM) [37] for bending the beam before injection into K-1200. This magnet generates a field of 3.8 T along the beam trajectory having a curvature of 1.21 m at a current of 363 A. The special features of the magnet are the flat coil geometry, iron poles used as former for coil winding and the iron yoke in two parts, one H-shaped cold yoke and another C-shaped warm yoke. The total cold mass is only 3 tons. A monolithic Nb–Ti conductor of the dimensions of 2.4 mm × 0.8 mm has been used for winding. The coil is finally vacuum epoxy impregnated.

The demand for superconducting magnets for application to accelerators will continue to grow. Focus, however, may shift to A-15 class of superconductors like

Nb_3Sn and Nb_3Al for their superior performance and to the high T_c superconductors in the near future. MgB_2 is a new superconductor which is economical and stands chance of becoming a good candidate for application to accelerators. High T_c superconductors and MgB_2 have the added advantage that they can operate on cryo-coolers in place of liquid helium.

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