FCC CDR Volume 2 - Hadron Collider (Concise, short)

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Chapter 2

Collider Design and Performance

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Chapter 3

Collider Technical Systems

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3.1 Requirements and Design Considerations

3.2 Main Magnet System

3.2.1 Introduction

The magnetic system of the FCC will heavily profit of the experience gained with the LHC, which has demonstrated the feasibility and effectiveness of operating a large number of superconducting magnets in a superfluid helium bath, at 1.9 K. With respect of the LHC, the FCC magnets will be about 4 times more numerous and the field amplitude produced by the arc dipoles will increase by almost a factor of two, keeping a similar beam aperture size and twin configuration. The field increase will be enabled by using Nb_3Sn superconductor instead than NbTi as in the LHC arc dipoles. This technology, though not yet extensively used in particle accelerators, is being implemented for the LHC HiLumi project in both dipole and quadrupole configurations operating at peak fields between 11 and 12 T. It is believed that, through an appropriate R&D program, within a decade this technology will be ready to start a production of 16 T magnets as required for the FCC.

3.2.2 Superconducting Main Dipole

The MD (Main Dipoles) of the FCC are twin-aperture magnets of cosinetheta layout assembled in a common helium tight structure CM (Cold Mass), integrated in a cryostat: a cross section of the system is pictured in PICT1. The design field is 16 T produced by a current of 11240 A, the coil physical aperture is 50 mm, the distance between the axis of the two apertures is 204 mm, and the operational temperature is 1.9 K. The main parameters of the MD, included the expected field quality, are listed in Table 3.1.

Each MD aperture is made of 200 cable turns distributed in one upper pole and one lower pole, each pole of two double layer coils, an inner coil and an outer coil Pict2. The inner coil is made of 32 turns of a 0.5° keystoned Rutherford cable, made of twenty-two 1.1 mm diameter strands, the outer coil of 68 turns of a 0.5° keystoned Rutherford cable, made of thirty-seven 0.7 mm diameter strands. As the two coils are supplied in series and the relevant cables have different size, the current density in the outer coil is larger than the one in the inner coil. This design exploits the so-called grading concept, which consists of increasing the current density where the magnet field is lower resulting in a considerable saving of conductor amount for a given magnet margin on the load-line, which for the FC MD has been set to 14%. The force containment structure is based on the so-called key and bladders concept and on the use of an aluminium cylinder surrounded by a stainless steel welded shell. The aluminium cylinder

Table 3.1: Main parameters of the dipoles

Operational field	T	16.0
Physical coil aperture	mm	50.0
Operating current	A	11240
Operating temperature	K	1.9
Magnetic length @ 1.9K	mm	14300
Stored energy at 16T (entire magnet)	MJ	0
Self-inductance at 16T (entire magnet)	mH	0
Field margin on the load-line at 16T	%	14
Distance between aperture axes at 1.9K	mm	204
Number of coil turns per aperture		400
Cold mass length beam pipe flange-to-flange at 1.9K	mm	15600
Mass of the cold mass	kg	0
Mass of the cryostat	kg	0
Geometric field harmonics b2,b3,b5	units	
Contribution of persistent currents b2,b3,b5	units	
Contribution of saturation b2,b3,b5	units	
Total field harmonics b2,b3,b5 at injection (1.05T)	units	
Total field harmonics b2,b3,b5 at nominal field (16T)	units	

provides the required increase of coil loading from assembly to the operational temperature and during magnet energization, and the stainless shell helium tightness, alignment and support for the magnet end covers. The CM is installed in a cryostat structure composed of a radiation shield at 5K, a thermal screen at 70K and a vacuum vessel, and is supported by three feet made of composite material and having a cold flange bolted to the vacuum vessel. All parts between the beam vacuum chamber walls and the shrinking cylinder of the CM are immersed in superfluid helium at atmospheric pressure and cooled by means of a heat-exchanger tube, in which two-phase low-pressure helium circulates. The CM for the FCC MD is straight, with a total length, from the two extremities of the beam pipe flanges, of 15.6 m, and a magnetic length of 14.3 m.

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Temperature levels, cooling scheme, operating modes, transients, cryo-distribution, instrumentation

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Refrigeration cycle, transients, operating [?] modes

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Glossary

Arc A circular collider is composed of bent cells called arcs that are separated by straight sections (see LSS). An arc half-cell forms the periodic part of the arc lattice (see lattice).

Beam pipe Volumes of different shape (e.g. cylindrical, conical, flanges and bellows) and material (e.g. metallic, ceramic) used to transport the beam. The contained ultrahigh-vacuum reduces beam-gas interactions to a level at which the beam lifetime is acceptable.

Beam screen Perforated tube inserted into the cold bore of the superconducting magnets in order to protect the cold bore from synchrotron radiation and ion bombardment.

Beamline A series of functional elements, such as magnets and vacuum pipe, which carry the beam from one portion of the accelerator to another.

Beta function An optical function proportional to the square of the local transverse beam size. The beta function details how the beam width changes around the accelerator. There are separate Îš functions for the x and y planes.

Bunch A group of particles captured inside a longitudinal phase space bucket.

CERN European Organisation for Nuclear Research.

Collimator A device that removes beam particles at large amplitudes. They are used to keep beam-losses low and to protect critical elements of the accelerator.

Collision A close encounter of particles during which dynamic quantities such as energy, momentum, and charge may be exchanged.

Critical temperature Temperature Tc below which characteristics of superconductivity appear. The value varies from material to material and depends on the magnetic field.

Cryo magnet Complete magnet system integrated into one cryostat, including main magnet coils, collars and cryostat, correction magnets and powering circuits.

Cryogenic system A system that operates below a temperature set by convention at 150 K (-123.15°C).

Dark matter Invisible matter that makes up 26% of the universe and which can only be detected from its gravitational effects. Only 4% of the matter in the Universe are visible. The remaining 70% are accounted to dark energy.

Dipole A magnet with two poles, like the north and south poles of a horseshoe magnet. Dipoles are used in particle accelerators to keep particles moving in a circular orbit.

Dynamic aperture Maximum transverse oscillation amplitude that guarantees stable particle motion over a given number of turns. If the motion amplitude of a particle exceeds this threshold, the betatron oscillation of the particle will not have any bounds, and the motion will become unstable, leading to loss of the particle. It is expressed in multiples of the beam size together with the associated number of turns. Unlike the physical aperture, dynamic aperture separating stable and unstable trajectories is not a hard boundary.

Electron-cloud A cloud of electrons generated inside an accelerator beam pipe due to gas ionization, photoemission from synchrotron radiation, or âĂIJbeam-induced multipactingâĂİ via electron acceleration in the field of the beam and secondary emission. Electron clouds may cause single- and multi-bunch beam instabilities as well as additional heat load on the beam screen inside the cold magnets.

Electroweak symmetry breaking Although electromagnetism and the weak force have the same strength at high energies, electromagnetism is much stronger than the weak force in our everyday experience. The mechanism by which, at low energies, a single unified electroweak force appears as two separate forces is called electroweak symmetry breaking.

Emittance The area in phase space occupied by a particle beam. The units are mm-milliradians for transverse emittance and eV·sec for longitudinal emittance.

Experimental insertion region Place in the particle collider foreseen to host the interaction region in which the two beams are brought to collision and the surrounding particle physics experiments.

FCC Future Circular Collider is a feasibility study aiming at the development of conceptual designs for future energy and high-intensity frontier particle colliders based on a technically feasible and affordable circular layout permitting staged implementation.

FCC-hh Future circular energy-frontier hadron-hadron collider reaching up to 100 TeV centre-of-mass collision energies at luminosities of $5 - 10x10^{34}cm^{-2}s^{-1}$. Operation with protons and ions is envisaged.

Hadron A subatomic particle that contains quarks, antiquarks, and gluons, and so experiences the strong force. The proton is the most common hadron.

Higgs boson An elementary particle linked with a mechanism to model, how particles acquire mass.

HL-LHC High Luminosity upgrade of the LHC to a levelled constant luminosity of $5x10^{34}cm^{2}s^{-1}$. A dedicated FP7 design study (HiLumi LHC DS) precedes the upgrade implementation.

HTS High Temperature Superconductors have critical temperatures above 77 K.

Impedance A quantity that characterizes the self-interaction of a charged particle beam, mediated by the beam environment, such as the vacuum chamber, RF cavities, and other elements encountered along the accelerator or storage ring.

Kelvin Unit of measurement for temperature (K) using as null point the absolute zero, the temperature at which all thermal motion ceases. 0 K = -273.15°Celsius.

Lattice The arrangements of quadrupoles, dipole magnets, drift spaces and higher-order magnetic elements in the optical description of an accelerator.

LEP The Large ElectronâĂŞPositron Collider, which was operated at CERN until 2000.

Lepton A class of elementary particles that do not experience the strong force. The electron is the most common lepton.

LHC The Large Hadron Collider is a circular particle collider for protons and heavy ions with a design centre-of-mass energy of 14 TeV for proton-proton collisions at a peak luminosity of $1x10^{34}cm^{2}s^{-1}$ at CERN in Geneva, Switzerland.

Linac A LINear ACcelerator for charged particles in which a number of successive radiofrequency cavities that are powered and phased such that the particles passing through them receive successive increments of energy.

LSS Long Straight Section: quasi-straight segments of a circular collider, which are available for beam interactions or utility insertions (e.g. injection, extraction, collimation, RF).

LTS Low Temperature Superconductors have critical temperatures below 77 K.

Luminosity Luminosity is the rate of collision events normalized to the cross section. It is expressed as inverse square centimetre and inverse second ($cm^{-2}s{-}1$) or barn (1 barn = $10^{-24}cm^2$).

MDI The Machine Detector Interface refers to the topics and regions where the beamlines of the accelerator overlap with the physics experimentâĂŹs detector. Key elements include mechanical support of final beamline elements, luminosity monitoring, feedback, background suppression and radiation shielding.

Nb3Sn A metallic chemical compound of niobium (Nb) and tin (Sn). A LTS with TC = 18.3 K that can withstand magnetic field intensities up to 30 Teslas.

NEG Non-Evaporable Getter materials are mostly porous alloys or powder mixtures of Al, Zr, Ti, V and iron (Fe). They help to establish and maintain vacuums by soaking up or bonding to gas molecules that remain within a partial vacuum.

Optics An optical configuration refers to a powering scheme of the magnets. There can be several different optics for a single lattice configuration. Different optics exist for instance for injection and for luminosity operation corresponding to different $\beta*$ values in the experimental insertions.

Phase Space A six-dimensional space consisting of a particle's position (x, y, z) and divergence (x/, y/, z/). Phase space is represented in two dimensions by plotting position on the horizontal axis and the corresponding divergence on the vertical axis.

Quench The change of state in a material from superconducting to resistive. If uncontrolled, this process damages equipment due to thermal stress induced by the extremely high-currents passing through the material.

RAMS Reliability, Availability, Maintainability and Safety. Four non-functional key characteristics that determine the performance and total cost of technical systems.

RF cavity An electromagnetically resonant cavity used to convey energy (accelerate) to charged particles as they pass through by virtue of the electric field gradient across the cavity gap(s). Radio Frequency is a rate of oscillation in the range of around 3 kHz to 300 GHz.

SC coating A very thin layer of SuperConducting material on normal-conducting material (e.g. copper). Used for various purposes such as quench avoidance of a neighbouring superconductor, reduction of production costs due to use of cheaper support material and impedance reduction.

Standard Model The Standard Model explains how the basic building blocks of matter interact, governed by four fundamental forces.

Strand A superconducting strand is a composite wire containing several thousands of superconducting filaments (e.g. Nb_3Sn) dispersed in a matrix with suitably small electrical resistivity properties (e.g. copper).

Strong force One of four known fundamental forces (the others are the weak force, electromagnetism and gravity). The strong force is felt only by quarks and gluons, and is responsible for binding quarks together to make hadrons. For example, two up quarks and a down quark are bound together to make a proton. The strong interaction is also responsible for holding protons and neutrons together in atomic nuclei.

Superconducting cable Superconducting cables are formed from several superconducting strands in parallel, geometrically arranged in the cabling process to achieve well-controlled cable geometry and dimensions, while limiting the strand deformation in the process. Cabling several strands in parallel results in an increase of the current carrying capability and a decrease of the inductance of the magnet, easing protection.

Superconductivity A property of some materials, usually at very low temperatures that allows them to carry electricity without resistance.

Synchrotron A circular machine that accelerates subatomic particles by the repeated action of electric forces generated by RF fields at each revolution. The particles move in constant circular orbits by magnetic forces that continually increase in magnitude.

Synchrotron Radiation Electromagnetic radiation generated by acceleration of relativistic charged particles in a magnetic or electric field. Synchrotron radiation is the major mechanism of energy loss in synchrotron accelerators and contributes to electron-cloud build-up.

Tesla Unit of magnetic field strength. 1 T is the field intensity generating one newton (N) of force per ampere (A) of current per meter of conductor.

TeV Tera electron Volts (10^{12} eV). Unit of energy. 1 eV is the energy given to an electron by accelerating it through 1 Volt of electric potential difference.

Tevatron A 2 TeV proton on anti-proton collider that was operated at Fermilab in Batavia, Illinois (USA) until 2011. The top quark was discovered using this collider.

Vacuum Pressures much below atmospheric pressure.

Weak force A force carried by heavy particles known as the W and Z bosons. The most common manifestation of this force is beta decay, in which a neutron in a nucleus is transformed into a proton, by emitting an electron and a neutrino. Weak neutral current is a very weak interaction mediated by the Z boson that is independent of the electric charge of a particle. Particles can exchange energy through this mechanism, but other characteristics of the particles remain unchanged.

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