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LHC Accelerator Physics and Technology Challenges

L.R. Evans

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The Large Hadron Collider (LHC) incorporates many technological innovations in order to achieve its design objectives at the lowest cost. The two-in-one magnet design, with the two magnetic channels integrated into a common yoke, has proved to be an economical alternative to two separate rings and allows enough free space in the existing (LEP) tunnel for a possible future re-installation of a lepton ring for e-p physics. In order to achieve the design energy of 7 TeV per beam, with a dipole field of 8.3 T, the superconducting magnet system must operate in superfluid helium at 1.9 K. The LHC will be the first hadron machine to produce appreciable synchrotron radiation which, together with the heat load due to image currents, has to be absorbed at cryogenic temperatures. A brief review of the machine design is given and some of the main technological and accelerator physics issues are discussed.

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LHC Accelerator Physics and Technology Challenges

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Abstract

The Large Hadron Collider (LHC) incorporates many technological innovations in order to achieve its design objectives at the lowest cost. The two-in-one magnet design, with the two magnetic channels integrated into a common yoke, has proved to be an economical alternative to two separate rings and allows enough free space in the existing (LEP) tunnel for a possible future re-installation of a lepton ring for e-p physics. In order to achieve the design energy of 7 TeV per beam, with a dipole field of 8.3 T, the superconducting magnet system must operate in superfluid helium at 1.9 K. The LHC will be the first hadron machine to produce appreciable synchrotron radiation which, together with the heat load due to image currents, has to be absorbed at cryogenic temperatures. A brief review of the machine design is given and some of the main technological and accelerator physics issues are discussed.

1 INTRODUCTION

The LHC, now under construction at CERN, will provide proton-proton collisions with a centre-of-mass energy of 14 TeV and an unprecedented luminosity of 10^{34} cm^{-1} s^{-2}. The machine will also operate for heavy (Pb) ion physics at a luminosity of 10^{27} cm^{-2} s^{-1}. Some of the main parameters are given in Table 1.

Table 1: Machine parameters

Energy	(TeV)	7.0
Dipole field	(T)	8.3
Coil aperture	(mm)	56
Distance between apertures	(mm)	194
Luminosity	(cm^{-2} s^{-1})	10^{34}
Beam-beam parameter		0.0032
Injection energy	(GeV)	450
Circulating current/beam	(A)	0.530
Bunch spacing	(ns)	24.95
Particles per bunch		1 x 10^{11}
Stored beam energy	(MJ)	332
Normalized transverse emittance	(µm)	3.75
R.m.s. bunch length	(m)	0.075
Beta values at I.P.	(m)	0.5
Full crossing angle	(µrad)	300
Beam lifetime	(h)	22
Luminosity lifetime	(h)	10
Energy loss per turn	(keV)	6.9
Critical photon energy	(eV)	45.6
Total radiated power per beam	(kW)	3.7

Many accelerator physics issues must be taken into consideration in the machine design. The first is a sound and flexible lattice, robust against inevitable perturbations and able to cater for changes in layout demanded by hardware builders and particle physicists. The interaction of the beam with its immediate environment and with the other beam can produce many undesirable effects. Incoherent single particle effects include the beam-beam interaction due to the influence of the electromagnetic field of one beam on the particles in the other, and intrabeam scattering, multiple Coulomb scattering between the particles in the same beam. Collective effects include single bunch instabilities driven by short range wakefields and coupled bunch effects due to the large number of bunches and small separation. Since the unavoidable imperfections in superconducting magnets produce non-linear field errors, the issue of dynamic aperture, the maximum useful betatron amplitude of particles over a long time duration, is also of fundamental importance.

The attainment of 7 TeV in the existing LEP tunnel also presents some considerable technological challenges. The small tunnel cross section as well as the need for cost reduction imposes a two-in-one magnet design for the main dipoles and quadrupoles. The 8.3 T operating field can only be obtained at an acceptable cost by cooling the magnets to 1.9 K, below the lambda point of helium. This presents serious challenges to both the magnet designers and cryogenic engineers.

After a brief description of the machine layout and status, some of these issues are discussed.

2 MACHINE LAYOUT

The basic layout mirrors that of LEP, with eight long straight sections, each approximately 500 m in length available for experimental insertions or utilities. Two high luminosity insertions are located at diametrically opposite straight sections, Point 1 (ATLAS) and Point 5 (CMS). One more experiment, optimised for heavy ion collisions (ALICE), has now been approved and will be located at Point 2. A fourth experiment (LHCb) is in an advanced stage in the approval procedure and will be located at Point 8. The two detectors at Points 1 and 5 require a substantial amount of new civil engineering infrastructure, whilst the other two will be integrated into existing LEP caverns. The beams cross from one ring to the other only at these four locations. Points 2 and 8 also contain the injection systems for the 450 GeV/c beams provided by the SPS.

The other four long straight sections do not have beam crossings. Points 3 and 7 are practically identical and are used for collimation of the beam halo in order to minimise the background in the experiments as well as the beam loss in the cryogenic parts of the machine. Consequently, they only contain classical resistive magnets robust against the inevitable beam loss and secondary shower from the collimators. Point 4 contains the RF systems which are independent for the two beams, where the beam separation must be increased from 194 mm in the regular arcs to 420 mm in order to provide the transverse space needed.

Finally, Point 6 contains the beam abort system, where the two beams are extracted using a combination of fast pulsed magnets and steel septa and are transported to the external beam dumps.

3 OPTICS

The regular arc cell is 106.9 m in length and contains six dipoles, each of 14.3 m magnetic length. The lattice quadrupoles, 3.1 m in length, are integrated into “short straight sections” containing a combined orbit correction dipole and chromaticity sextupole and space for another short corrector, either a trim quadrupole, skew quadrupole or octupole, depending on its position in the lattice. The dipoles and quadrupoles are powered independently, with different gradients in the two quadrupole apertures allowing a tune split of up to ten units in order to render the machine insensitive to linear coupling.

The four collision insertions have a similar layout. Moving out from the interaction point (IP), one first encounters the inner triplet. The distance from the IP to the first element of the triplet is 23 m, with the IP at Point 8 displaced longitudinally by 11.22 m with respect to the centre of the experimental hall due to the asymmetric geometry of the LHCb detector. After the triplet, the beams are separated. In the high luminosity insertions 1 and 5, the separation dipoles are not superconducting due to the very high particle flux from the IP. In the other two insertions they must be superconducting due to the restricted longitudinal space available because of the presence of the injection systems.

The long straight section terminates with a twin aperture dipole to bring the beams into the two magnetic channels and a set of four independently powered matching quadrupoles. Between the long straight section and the regular arc there is a dispersion suppressor approximately 171 m long, where the dispersion function is matched to that of the arc. The first three quadrupoles in the dispersion suppressor are also independently powered in order to increase flexibility. All matching quadrupoles are of a special low current design. The other four long straight sections have special optics depending on their role.

4 ACCELERATOR PHYSICS ISSUES

4.1 The Beam-Beam Interaction

The beam-beam interaction is an inevitable consequence of bringing the beams into collision. The particle trajectories in one beam are perturbed by the electromagnetic field of the other beam. This non-linear interaction excites betatron resonances and also produces a variation of tune with amplitude, generating a tune spread in the beams which makes it more difficult to steer clear of these resonances [1].

The strength of the interaction is parameterised by the linear tune shift ξ given by

$$\xi = \frac{r_p}{4\pi}\frac{N}{\varepsilon_n}$$

where r_p is the classical proton radius, N the bunch population and ε_n the normalized emittance. The tune shift is independent of the value of the β^* at the crossing point. The total tune spread is approximately equal to the product of the tune shift and the number of experiments illuminated, independent of their luminosity. However, since the LHC will operate with a 25 ns bunch spacing, there must be a small crossing angle at the collision point to prevent other unwanted collisions when the beams are travelling in the same vacuum chamber. The long-range interactions cannot be suppressed and accounts for about 20% of the total tune spread. Experience in the SPS has shown that the beam lifetime is strongly reduced when particles straddle resonances of order less than 12. The tune footprint, the image of the beam in the tune diagram, must therefore be small enough to fit in between these resonances.

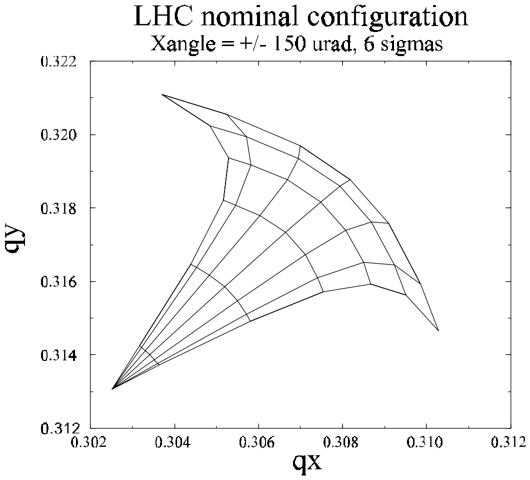

Figure 1: The LHC lattice tune footprint for two insertions illuminated and the nominal tune shift.

The LHC working point can be safely placed close to the diagonal between 3rd and 10th order resonances provided the tune footprint stays below 0.01 [2]. The corresponding value of the beam beam parameter of .0032 with two insertions illuminated is very close to that achieved routinely in the SPS collider.

4.2 Intrabeam Scattering

Intrabeam scattering, or multiple Coulomb scattering between particles in the same bunch can give rise to a redistribution of the energy of oscillation between the different degrees of freedom. Roughly speaking, the bunch can be thought of as a relativistic gas which is not in thermal equilibrium. Due to the Lorentz contraction, the longitudinal phase plane is much “colder” than the transverse planes, so a transfer of energy takes place between betatron and synchrotron motions. This should result in slow damping of transverse emittance and increase in energy spread. However, due to the dispersion, there is a heating term in the radial phase plane that dominates the damping term. Intrabeam scattering therefore results in an increase in radial emittance that can rapidly degrade the luminosity [3] unless remedial action is taken. The transverse emittance growth can be strongly reduced by diluting the 6-dimensional phase space density by artificially increasing the longitudinal emittance. In the LHC, the emittance will be increased from its injection value of 1 eV.s to 2.5 eV.s at collision energy. This fixes the maximum RF voltage of 16 MV per beam in order to give sufficient bucket area.

4.3 Dynamic Aperture

The beam-beam interaction generates resonances due to the non-linear nature of the beam-beam force and can limit the available aperture during collision. However, superconducting magnets also have non-linear field errors coming from many sources including persistent currents, small errors in coil geometry and redistribution of current between the strands during ramping. These errors are dominant at the injection field level where the beam must survive for many minutes. The dynamic aperture is defined as the maximum stable amplitude of oscillation in the presence of these errors combined with other effects such as tune ripple and closed orbit distortion.

At the present time the only quantitative ways to investigate the dynamic aperture are by computer simulation and by experiments on existing machines. For the LHC, a computer farm has been dedicated to this activity, where particles are tracked through sample machines in which the non-linearities are statistically distributed, for up to 10^6 turns [4].

In order to check the reliability of the results, extensive experiments have been launched at the CERN SPS and at HERA. They have shown that the simulations agree with the experimental results at the level of 10-20% if all known details like closed orbit errors, coupling and tune ripple are taken into account.

The final objective is to obtain a dynamic aperture from the simulations of at least 12 σ in order to be sure that in the real machine particles will be stable up to the collimator settings of 6 σ. This requires a very close interaction between accelerator physicists and magnet designers in order to define the tolerable errors during series production of the magnets and to define the small correctors needed to compensate for systematic non-linearities, especially the sextupole and decapole fields generated by persistent currents.

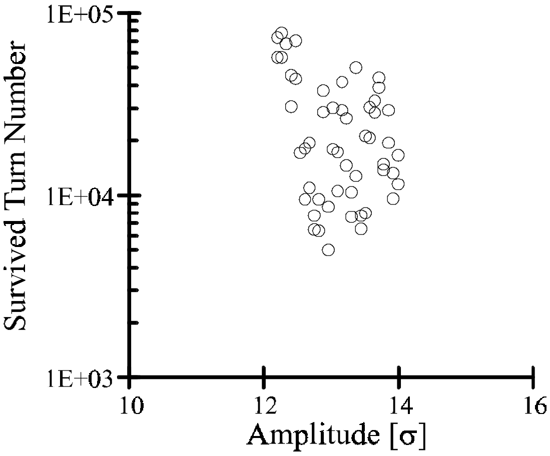

Figure 2: Survival plot for 10^5 turns. The open circles represent the amplitude at which particles were lost.

4.4 Collective Effects

Collective effects can be broadly separated into single bunch effects, where bunch instability is driven through the short range wakefields generated by the interaction of the beam with its environment, and multibunch instabilities generated by the long range wakefields .

The most common of the single bunch instabilities is the transverse slow head-tail instability. This can be suppressed for the rigid dipole mode m=0 by operating the machine with a small positive chromaticity. Another instability driven by the broadband impedance is caused by coupling between transverse modes and is potentially much more dangerous since it cannot be suppressed in this way. However, this instability, unlike the head-tail, shows a threshold behaviour which occurs at about twice the nominal beam current for the LHC [5]. The longitudinal equivalent of the transverse mode-coupling instability is known as the microwave instability. Due to the very low coupling impedance, the threshold for onset of this instability is also well above the nominal bunch current.

The most important multibunch effect in the LHC is the transverse resistive wall instability. Its growth rate is proportional to the square root of the resistivity of the beam pipe and to the inverse cube of its radius. The instability exhibits no threshold behaviour but its growth rate can be reduced by coating the inside of the beam screen with a 50 μm layer of copper and cooling it to below 30K where its resistivity is further reduced. The e -folding time for the most dangerous mode at a frequency of a few kHz then exceeds 100 turns, which can easily be damped with an active feedback system.

Although a great deal is now known about collective effects and how to combat them, the LHC will also be equipped with the ultimate panacea to tackle the unknown, a set of octupoles which can provide Landau damping if necessary.

4.5 Vacuum Effects

Normally one would not expect vacuum problems in a machine with the beam pipe at cryogenic temperature. However, the two main heat inputs, synchrotron radiation and beam image currents cannot be taken at the 1.9 K temperature of the cold bore of the magnets (1 W at 1.9 K requires 1 kW at room temperature). Therefore, the vacuum chamber must be fitted with an inner liner at a high enough temperature to be thermodynamically efficient at absorbing the heat flux and at the same time cold enough to have a low enough resistivity to combat the resistive wall instability. A convenient temperature level available in the cryogenic system is 20 K. At this temperature the cryopumping capacity is strongly reduced and it has been shown that gas, particularly hydrogen, desorbed from the body of the liner by the synchrotron radiation, accumulates on the surface and gradually deteriorates the vacuum. The solution adopted to combat this is to punch holes in the liner over about 2% of the surface so that the cold bore at 1.9 K can pump away the gas, while being protected from the synchrotron radiation.

Another important effect that needs to be taken into account is caused by electrons, mainly produced by photoelectric emission. These electrons can be accelerated across the chamber by the electric field of the bunches, reaching a few hundred volts before striking the wall, creating a further source of heat for the cryogenic system to absorb [6]. This has been taken into account in defining the capacity of the cryogenic plants. A potentially dangerous situation can arise if the secondary emission coefficient of the surface is too high. A resonant build-up of the electron cloud due to the influence of the following bunches can occur, loading the cryogenic system even more and provoking an instability due to the interaction of the beam with the electron cloud. In order to avoid this under nominal beam conditions, the secondary emission coefficient of the liner surface must be kept below 1.4. Work is therefore in progress to choose the best coating for the liner surface, giving simultaneously a low secondary emission coefficient and quantum efficiency.

5 TECHNOLOGICAL CHALLENGES

In order to reach its design energy inside the existing LEP tunnel, the LHC must operate at a field level (8.3 T) considerably higher than achieved in previous superconducting accelerators. To achieve this with affordable Nb/Ti technology, use must be made of the 3 T shift in critical field obtained by cooling the superconductor from 4.2 K to 1.9 K. The construction of the magnet system and the associated cryogenics present two of the major technological challenges in this project.

5.1 Magnets

The LHC will be the first accelerator in which the magnet system is cooled with superfluid helium. Superfluid helium as an engineering material presents some interesting properties that can be used to advantage to compensate for the considerable disadvantage in working with superconductors at very low temperature. The main disadvantage is the very large, more than a factor of 5, reduction in specific heat of the superconducting material and its associated copper matrix between 4.2 K and 1.9 K. Quenches below the critical field in the superconductor are most often caused by microscopic movement of superconductor strands under the enormous electro-magnetic forces (up to 500 tons/m in the LHC dipoles). These movements create heat through friction, locally taking the material above its critical temperature and provoking a quench. Due to the very low specific heat, the adiabatic temperature rise for a given amount of frictional energy is very much higher at 1.9 K than at 4.2 K, making these magnets much more sensitive to training.

The very strange properties of superfluid helium can be used in part to compensate for this disadvantage. The most well known property of this material is the complete absence of viscosity of the superfluid component, but for the purpose of magnet design, more important properties are the very large specific heat (about 4000 J/kg.K compared with 0.03 J/kg.K for copper), and the enormous thermal conductivity (several thousand times higher than OFHC copper, depending on the heat flux). It is therefore very important to get the helium to permeate the strands of the cable so that it can contribute to absorbing energy and transporting heat away from the coil. Great attention has therefore been paid to the insulation of the superconducting cable in order to render it porous and to the characteristics of the cable itself in order to allow maximum penetration of helium between the strands.

The development of superconducting two-in-one dipoles and quadrupoles has itself proven to be a considerable challenge. This work has been done both at CERN, where many short models have been built, and in industry, where a total of eleven 10-metre long prototypes have been constructed. The first full length dipole (14.3 m magnetic) made in Italian industry as a joint CERN/INFN collaboration recently arrived at CERN. It is now being prepared for cold testing.

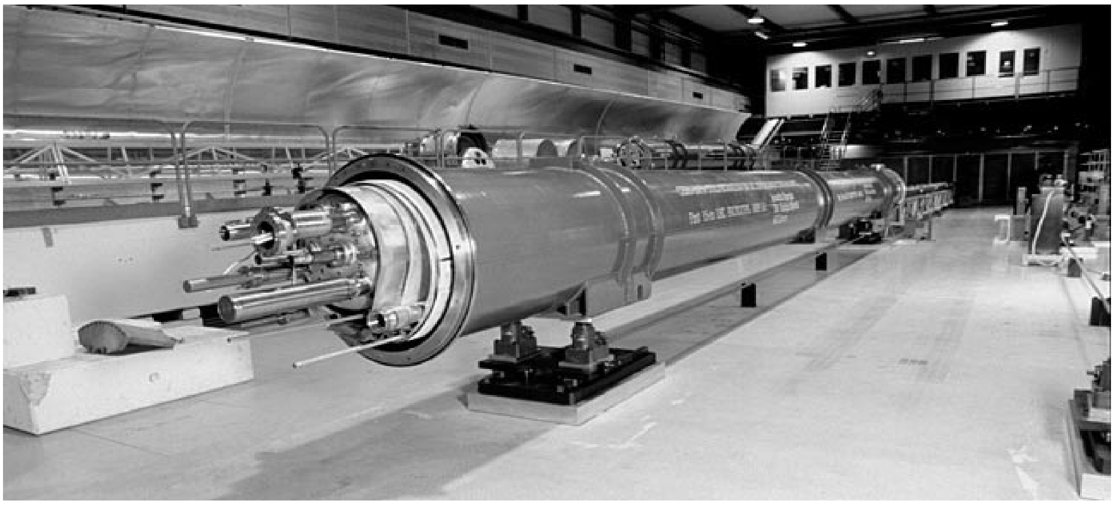

Figure 3: The first full length dipole built in collaboration with INFN.

5.2 Cryogenics

Cooling more than 31,000 tons of material spread over 26.7 km to below 2 K presents a considerable technological challenge [7]. The most convenient way to cool helium to below its critical temperature is by reducing the vapour pressure above the liquid bath. At 50 mbar the liquid crosses the lambda point at 2.17 K and it is necessary to reduce the pressure to below 20 mbar to achieve the 1.9 K operating temperature of the LHC magnets. The magnets are first cooled to 4.2 K with boiling helium at atmospheric pressure. A linear heat exchanger pipe inside the magnet cold mass, extending over a full period containing six dipoles and two quadrupoles carries a flow of saturated helium II which absorbs heat by gradual evaporation of the liquid phase, slowly cooling the helium in the magnet until it also crosses the lambda point. The magnets are therefore cooled with pressurised helium II at 1 bar, avoiding the severe drawbacks of helium at low saturation pressure, i.e. the risks of dielectric breakdown and contamination by air inleaks.

In order to create the superfluid helium at 1.9 K, it is necessary to compress helium gas at cryogenic temperature from 16 mbar up to atmospheric pressure. The only efficient way to achieve this is by multi-stage compression using hydrodynamic compressors in the lower stages. CERN has therefore undertaken an R&D programme with three manufacturers of such compressors to develop a prototype device capable of compressing 18 g/s of helium at 4 K and 10 mbar up to 30 mbar. Three compressors using different designs have now been tested and excellent results have been achieved [8]. Work is now under way to specify the requirements of complete cold compressor boxes with 3 to 5 compression stages, each handling 125 g/s. In all, eight cold compressor boxes, one for each refrigerator, will be required.

6 CONCLUSIONS

From the point of view of accelerator physics, the LHC machine design rests on a sound base, with a great deal of accumulated knowledge from previous projects to guide the choice of parameters and the steps needed to combat undesirable effects. On the hardware side, the LHC represents a technological step forward, stimulated by the need to achieve the best possible performance within the constraints of the existing infrastructure and at the lowest possible cost.

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