Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

LHC ACCELERATOR PHYSICS AND TECHNOLOGY CHALLENGES

L.R. Evans, CERN, Geneva, Switzerland

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. This requires further development of cold compressors similar to those first used at CEBAF. 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. Finally, the LHC is the first major CERN accelerator project built in collaboration with other laboratories. A brief review of the machine design is given and some of the main technological and accelerator physics issues are discussed.

1 INTRODUCTION

The Large Hadron Collider, 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}. In order to achieve this it must operate with more than 2800 bunches per beam and a very high intensity. The machine will also operate for heavy (Pb) ion physics at a luminosity of 10^{27} cm^{-1} s^{-2}.

Many accelerator physics issues must be taken into consideration in the machine design. The first is a sound and flexible optics, robust against inevitable lattice 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). A third experiment, optimised for heavy ion collisions (ALICE) will be located at Point 2. A fourth experiment (LHCb) has now been approved 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 warm 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 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 11.25 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.

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.

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. The LHC working point can safely be placed close to the diagonal between 3rd and 10th order resonances provided the tune footprint stays below 0.01. The value of the beam-beam parameter of .0034 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 Lorenz 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 unless remedial action is not 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 is 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 where the non-linearities are statistically distributed, for up to 10^6 turns.

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 sigma in order to be sure that in the real machine particles will be stable up to the collimator settings of 6 sigma. 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.

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. 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 20 K 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.

5. TECHNOLOGICAL CHALLENGES

5.1 Superconducting Magnets

The LHC will require more than 8000 superconducting magnets of different types. The most challenging are the 1232 superconducting dipoles which must operate reliably at the nominal field of 8.3 Tesla, corresponding to the centre-of-mass energy of 14 TeV, with the possibility of being pushed to an ultimate field of 9 Tesla.

In the early days of magnet development, two technologies for the attainment of fields above 9 Tesla were investigated. The first of these was using Nb_3Sn at 4.2 K. Indeed a dipole model with a first quench at 11 Tesla was built using this technology. However, the coils are very difficult and expensive to manufacture and are not suitable for economic mass production. Nevertheless this technology is still being pursued on a small scale for possible use in selected areas, for example for second generation low-beta quadrupoles.

The other, more economical alternative is to use conventional NbTi technology at reduced temperature. This suffers from the drawback that the specific heat of the superconducting material and its associated copper matrix falls rapidly as the temperature is reduced. For example, the specific heat of copper falls by about a factor of 5, to 0.03 J/kg.K between 4.2 K and 1.9 K. This makes the coil much more prone to premature quenches due to small frictional movements of conductor strands since the adiabatic temperature rise for a given amount of frictional energy is much higher at 1.9 K than at 4.2 K. One can therefore expect more training of these magnets at the highest field levels than at 4.2 K. The important thing is that there is no retraining below the ultimate operational field of 9 Tesla.

The special properties of superfluid helium can be used in part to compensate for this disadvantage. The most well known property of this material is the absence of viscosity but for the purpose of superconducting magnet design, the most important properties are the very large specific heat (about 4000 J/kg.K) and the enormous thermal conductivity at low heat flux. The cable insulation is therefore designed to be as porous as possible to allow penetration of helium whilst maintaining good electrical insulation properties. In this way the helium can contribute to absorbing energy and transporting heat away from the coils.

The development of two-in-one superconducting dipoles and quadrupoles has proved to be a considerable challenge. For the dipoles, this work has been done both at CERN and in industry where a number of long dipoles have been constructed. Recently the coil geometry has been modified from the original 5-block design to improve the field quality and to allow more flexibility for small changes during series production. A number of models using this modified 6-block geometry have performed very well, with first quenches well above 9 Tesla and fast training to the conductor limit of 10 Tesla (Fig. 1). A final full-length prototype with this coil geometry is presently being prepared for testing. Another important outcome of the R&D programme is that the level of compressive prestress applied to the coils can be considerably lowered without loss of performance. This has opened up the possibility of changing from aluminium to stainless steel collars, reducing tolerances and simplifying magnet assembly during series production.

The lattice quadrupoles are designed by CEA/Saclay in collaboration with CERN. To produce the required gradient of 223 T/m the same cable as for the outer layer of the dipole is used in a two-layer geometry. Two prototypes are under construction and the first will be tested before the end of the year.

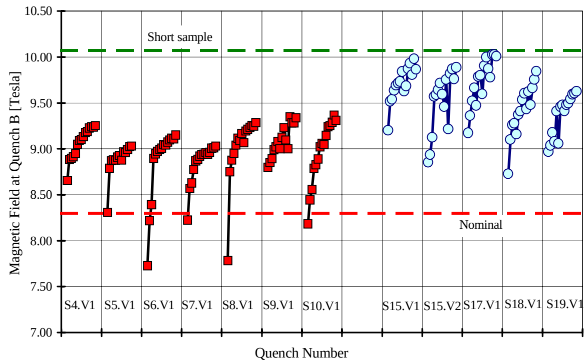

Figure 1: Quench performance of 5-block versus 6-block (open circles) dipole models.

The procurement of some 1200 tons of superconducting cable is a critical path item for the dipole fabrication. The cable will be procured by CERN and supplied to the magnet manufacturers. Contracts for the full supply have been placed with firms in Europe, Japan and the USA. As part of the US contribution to the LHC construction a test facility has been set up at BNL for cable measurement and quality control.

The long straight sections and insertion regions contain many specialised magnets, the most demanding of which are the high gradient (220 T/m), large (70 mm) aperture quadrupoles for the inner triplets of the low-beta insertions. Two versions of this quadrupole have been designed, and prototype models built at KEK and Fermilab. The final integration of both Japanese and US magnets into the inner triplets will be done at Fermilab.

5.2 Cryogenics

Cooling more than 31000 tons of material spread over 26.7 kms to below 2 K presents a considerable technological challenge. The most convenient way to cool helium to below its critical temperature is to reduce 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 reach the 1.9 K operating temperature. In practice, the LHC will operate in a static bath of pressurised superfluid helium at 1.9 K cooled with flowing saturated superfluid helium at 15 mbar through a linear heat exchanger extending over each full 107 m long cell of the machine. In view of the high thermodynamic cost of refrigeration at such a low temperature, most of the system heat loads are intercepted at higher temperature. As a result, the LHC requires a mix of refrigeration duties at several temperature levels. The machine will be cooled by eight cryoplants, each with an equivalent capacity of 18 kW at 4.5 K. Four of these will be the existing LEP refrigerators upgraded in capacity from 12 kW to 18 kW and adapted for LHC duty. The other four new plants, unlike those of LEP, will be entirely installed on the surface, reducing the need for additional underground infrastructure.

In order to create the superfluid helium at 1.9 K, it is necessary to compress cold helium gas from 15 mbar up to atmospheric pressure by the use of cold hydrodynamic compressors attached to the 4.5 K cryogenic plants. CERN has conducted a vigorous R&D effort with three industrial partners with the aim of investigating technological alternatives and validating efficient reliable solutions for these machines. In order to achieve this, three scale 1:5 prototype compressors for the first stage of compression from 10 to 30 mbar have been built and successfully tested (Fig. 2). Orders have now been placed for the eight full-size cold compressors, each handling 125 g/s of helium.

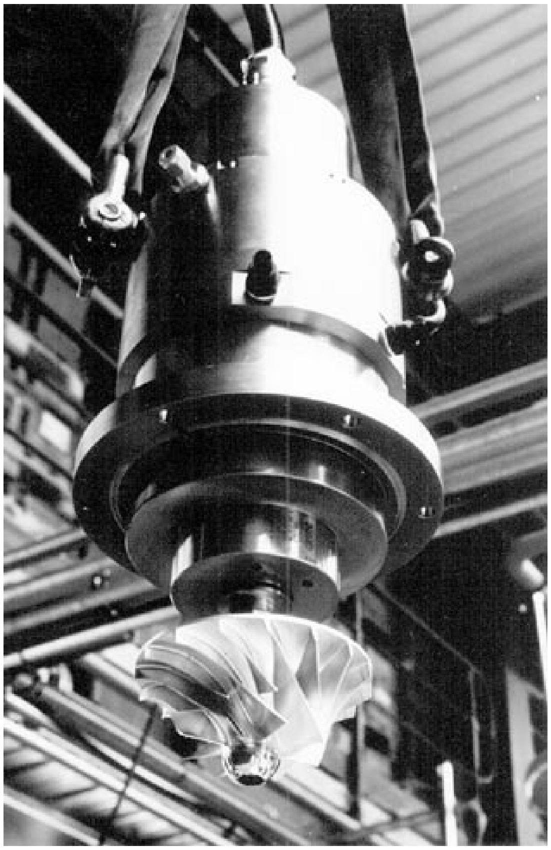

Figure 2: The impeller of a prototype cold compressor stage.

Among the other cryogenic components under development, it is worth mentioning the high-temperature (HTS) current leads. The superconducting magnets have to be fed with a total current of more than 3.5 MA with current ratings from 13 kA (main dipoles and quadrupoles) to 100 A (orbit correctors). The leads for the higher currents, 13 kA to 0.6 kA, will be made using HTS technology in order to reduce the refrigeration requirements for lead cooling. Prototype pairs of such current leads have been ordered from industry. The first of these has been successfully tested up to the design current of 13 kA (Fig. 3).

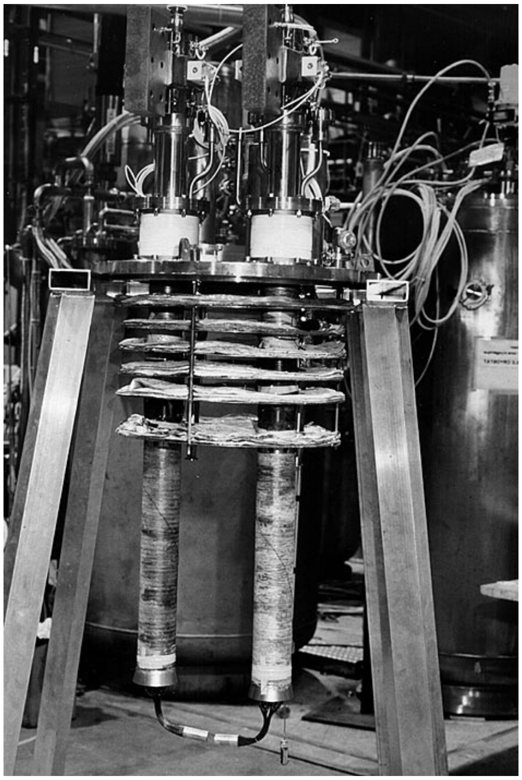

Figure 3: 13 kA HTS current leads.

5.3 Vacuum

The high intensity beams in the LHC will deposit heat into the cryogenic surface surrounding the beam through a number of effects. The most important of these are image currents (up to about 0.8 W/m) and synchrotron radiation (0.6 W/m). These heat loads cannot be taken at 1.9 K and will be intercepted by a beam screen fitted inside the magnet cold bore and cooled by circulation of supercritical helium between 5 K and 20 K. Gas desorbed by the synchrotron radiation cannot be efficiently cryo-pumped by the screen at this high temperature. In order to avoid a catastrophic pressure rise, the screen is punched with small holes over about 2% of its surface so that the cold bore can pump away the gas while being protected from the heat source.

Another effect producing heat is inelastic scattering of protons with the residual gas molecules. This cannot be intercepted by the screen and must be transported away by the superfluid. Recently an additional heat source has been identified, secondary and photoelectrons accelerated across the beam pipe due to the bunched nature of the beam. Under unfavourable conditions, this could result in a resonant build-up of the electron cloud (multipactor), heavily loading the cryogenic system and causing beam instability. In order to avoid this, the secondary emission coefficient of the screen surface must be kept below about 1.4.

5.4 Radiofrequency

The RF frequency, 400.8 MHz, is the highest multiple of the SPS RF frequency (200.4 MHz) compatible with the length of the SPS bunches at transfer. Each beam has a separate system necessitating an increase of the beam separation from 194 mm to 410 mm. Eight single-cell cavities per beam are needed. The maximum operating voltage per cavity (2 MV) corresponds to a very conservative average accelerating gradient of 5 MV/m. The cavities are made from copper with a thin film of niobium sputtered on the inside surface, identical to those of LEP. In order not to lose the technology transferred to firms during the LEP project, these cavities are now being manufactured and the first complete two-cavity unit has been assembled and tested (Fig. 4). The RF coupler is the most critical cavity component with a forward power of 180 kW. It will be an upgraded version of the LEP coupler with a d.c. bias on the inner conductor to suppress multipactoring in the coaxial part.

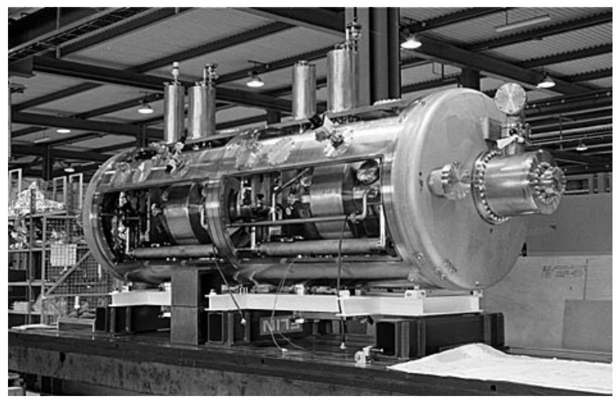

Figure 4: Two LHC 400 MHz superconducting cavities.

5 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.

6 ACKNOWLEDGEMENTS

On behalf of the CERN LHC design team, I would like to acknowledge the enthusiastic collaboration of our colleagues from laboratories in Canada, India, Japan, Russia and the USA as well as from laboratories in the CERN Member States in the realisation of this project.