# BEAM PHYSICS AT LHC

L.R. Evans, CERN, Geneva, Switzerland

### *Abstract*

The design of the Large Hadron Collider incorporates the accumulated knowledge obtained from previous generations of hadron colliders. Among the well known effects limiting machine performance are intrabeam scattering, the beam-beam interaction and stability against collective motion. Simulations and recent experiments in the SPS have shown that the electron cloud effect observed in the B-factories will be present both in the LHC and in its injector. All of these phenomena are discussed together with the measure taken in the machine design to overcome them.

## 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 stored energy per beam at design energy is 350 MJ. 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 25 ns bunch spacing can give rise to a new effect, now known to be a limiting factor in the B-factories. Electrons, produced by synchrotron radiation or by ionisation of rest gas, can be accelerated to the walls of the vacuum chamber, producing secondaries which can themselves be accelerated by following bunches. This can give rise to a rapid build-up in the "electron cloud" and is a source of heat deposition into the cryogenic system, emittance blow-up and even instability

## 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) 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 400 MHz 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.

## 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

0-7803-7739-9 ©2003 IEEE

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.

In addition to the normal lattice correctors for chromaticity and orbit control, a number of different multipole correctors are included to compensate for field imperfections and to control instabilities. All dipoles contain a sextupole spool piece to correct for persistent current effects and residual sextupole errors. Half of the dipoles also contain a ganged octupole and decapole corrector to compensate unwanted field harmonics. In about half of the main quadrupole cold masses, octupoles are included to provide Landau damping against transverse instabilities. The inner triplets contain their own corrector packs in order to correct multipole errors locally in the very sensitive regions where the beta function is very large in collision.

## ACCELERATOR PHYSICS ISSUES

### *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.

Due to the small (25 ns) bunch separation and crossing angle, the effect of long-range beam-beam interactions must also be taken into consideration. It has been shown that the most optimum situation is obtained by alternating the crossing angle between horizontal and vertical in adjacent collision points. In the initial commissioning phase of the LHC, it is foreseen to have a 75 ns bunch separation available. This minimises the effect of long-range interactions and will also eliminate the electron cloud effects mentioned below.

### *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 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 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.

### *Dynamic Aperture and Field Quality*

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. These results are used to define limits for multipole field components in the main magnets.

During production, magnet field quality is continuously monitored directly at the factory as soon as the coils are collared. This allows errors in fabrication (for example, missing shims) to be detected and corrected at an early stage. It also allows trends in field quality and magnetic length to be continuously monitored and corrected much earlier than results are available from cold tests of assembled dipoles would allow.

Figure 1 shows the measured sextupole component in the main dipole for the first 80 collared coils [1] (160 apertures) produced in three firms. Early dipoles showed b3 to be substantially out of the tolerance band.

After nine dipoles, it was decided to make a downward correction of b3 by small modifications of the wedges in the coil cross section. This correction fed through after dipole number 30. The new cross section has a lower sextupole component which is on the upper edge of the tolerance band due to the fact that the b3 drifted slightly upwards after the correction was computed. This geometry is perfectly acceptable from the point of view of dynamic aperture and will be maintained for the whole of the first octant of dipoles in order not to introduce too much spread in b3. It will be possible to introduce a correction in the second octant by changing slightly the thickness of the mid-plane insulation although a final decision has not yet been taken. The main interest in a last correction is to increase the margin for further possible upward drift in b3 which may make the chromaticity correction more difficult.

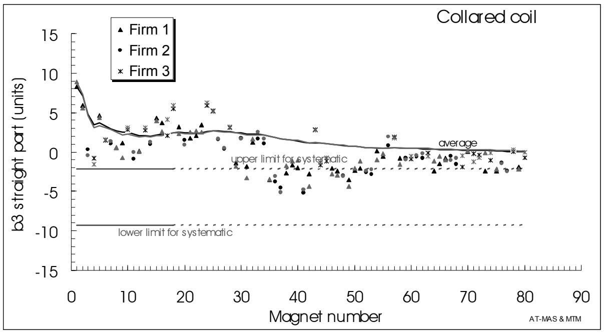

Figure 1: Sextupole component of the collared coils of 80 dipoles.

Field quality is also measured on the cold test benches up to nominal field, where other important effects such as snapback and dynamic behaviour of multipoles can be studied. Solid warm-cold correlations have also been established for the most important multipoles, validating the procedure of computing corrections on the collared coils, where data is available many months before the cold measurements are performed.

## *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.

Collective effects are not only important in the LHC. The injector chain, which includes the PS and SPS must deliver stable beams with well defined characteristics. In particular, before 2002, the beam in the SPS exhibited a strong microwave instability due to its large coupling impedance. An intensive programme of impedance reduction has been implemented, removing all obsolete equipment from the ring, damping essential equipment like kickers and septa and smoothing vacuum chamber discontinuities with sleeves. The results [2] have been quite spectacular. Figure 2 shows the bunch length as a function of intensity on the injection plateau before and after the impedance reduction. The data after the intervention is consistent with inductive wall bunch lengthening, emittance is preserved. Figure 3 shows the quadrupole mode frequency shift as a function of intensity. The improved quality of the data is immediately apparent. From this data, the impedance (Z/n) is estimated to be about 5 ohms, approximately a factor of 3 reduction.

The result is that stable beam can be maintained at nominal intensity with an emittance of less than 0.7 eV.s which, with the 7 MV available in the SPS at 200 MHz, will allow clean transfer and capture by the LHC 400 MHz system without the need for the sub-harmonic capture cavities originally foreseen.

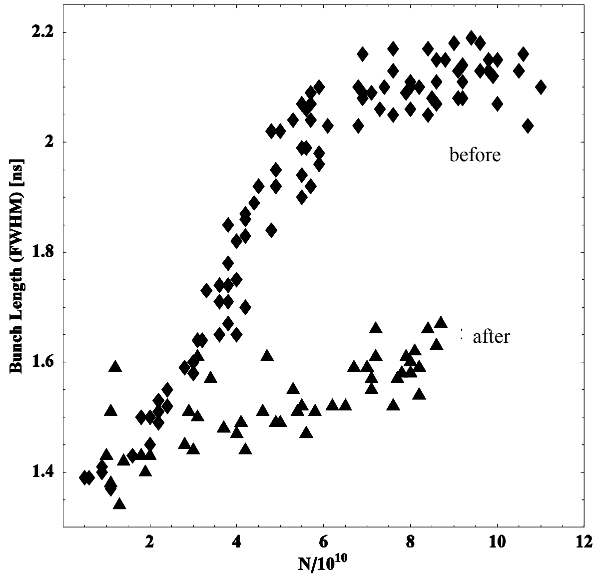

Figure 2: Bunch length as a function of intensity in the SPS before and after the impedance reduction.

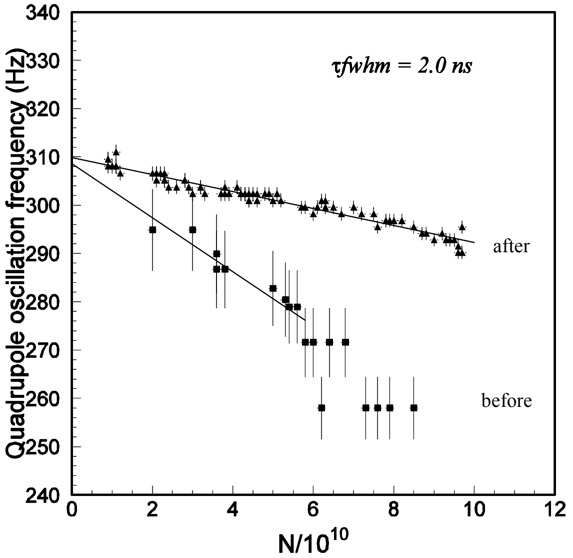

Figure 3: Coherent frequency shift of the longitudinal quadrupole mode in the SPS before and after the impedance reduction.

## VACUUM

The high intensity beams in the LHC will deposit heat into the cryogenic surface surrounding the beam through a number of effects, including 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 of the magnets at 1.9 K can pump away the gas while being protected from the heat source. Heat can also be produced by inelastic scattering of protons with the residual gas molecules. This cannot be intercepted by the screen and must be transported away by the superfluid helium.

Another effect that can result in considerable heat input into the cryogenic system and vacuum degradation is due to beam induced multipactoring by the electric field of successive bunches as first observed [3] in the ISR. It arises through a resonant motion of secondary electrons bouncing back and forth between the walls of the beam screen. If the secondary electron yield is sufficiently large, this can lead to an exponential build-up, stimulating gas desorption and heating of the beam screen. This effect is known to limit the performance of the B-factories and has received much attention in recent years. It has now been clearly observed in the SPS for LHC beam conditions [4]. As the electron bombardment of the surface proceeds, it has a conditioning effect, reducing the secondary electron yield and cleaning the surface of the chamber.

Recent experiments at the SPS have clearly demonstrated this cleaning effect. Figure 4 shows a measurement of the vacuum pressure during a four day "scrubbing" run. A reduction of 4 orders of magnitude over the scrubbing period can be observed. This is accompanied by a reduction of the secondary emission coefficient of the surface (see Fig. 5).

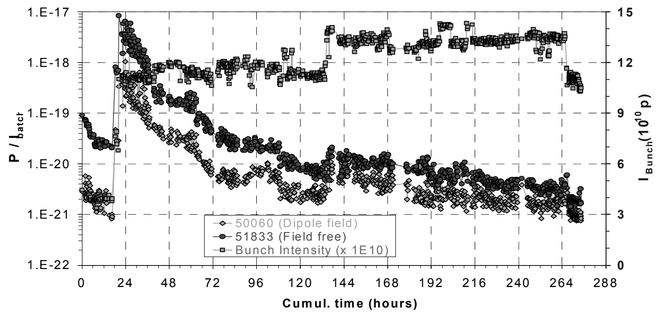

Figure 4: Evolution of vacuum pressure with time during the SPS "scrubbing" run.

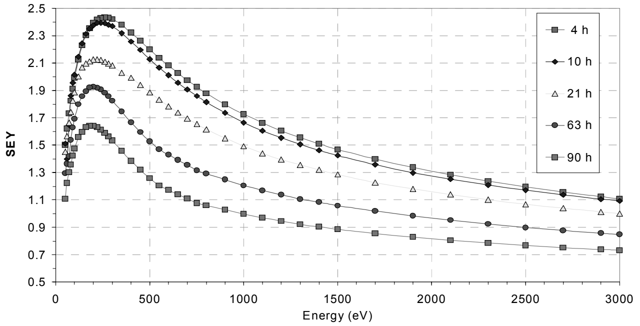

Figure 5: Reduction of the secondary emission yield on the SPS vacuum chamber during the scrubbing process.

Experimental results have been compared with multiparticle simulation of the process [5]. For example, in a dipole field the simulation code predicts that the electron bombardment should be concentrated in two stripes on the top and bottom of the vacuum chamber where the separation varies linearly with bunch intensity. Figure 6 shows a measurement of this effect in the SPS together with the most recent simulation results.

The scrubbing of the SPS vacuum chamber, together with the impedance reduction programme previously mentioned has allowed the SPS to accelerate the full LHC beam to 450 GeV. Further experiments are planned to investigate the efficiency of the scrubbing process on cold surfaces similar to the situation in the LHC itself.

In the warm regions of the LHC, the electron cloud effect can be suppressed by coating the chamber with a new non-evaporable getter (NEG) material developed at CERN [6]. This material (TiZrV) can be activated at 200° C, a temperature lower than for conventional getters. Once activated, the secondary electron yield is very low and, as shown in SPS experiments, the electron cloud effect is suppressed. These chambers also contribute to the production of ultra high vacuum due to their ability to pump gas.

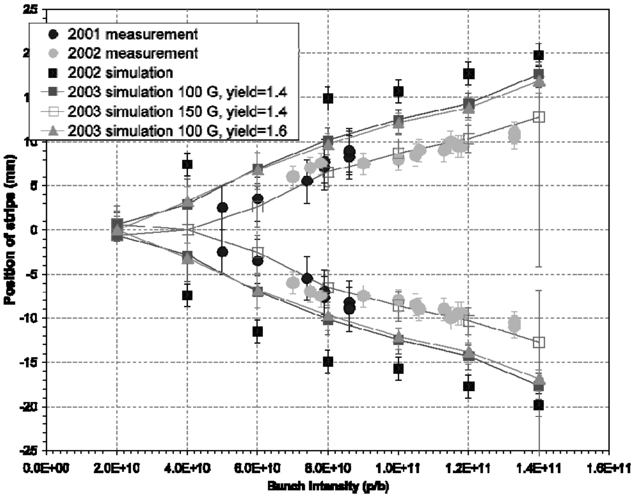

Figure 6: Distance between the two strips as a function of intensity compared with simulation results.

## OPERATION WITH PB IONS

In addition to high-luminosity proton-proton collisions, the LHC must provide Pb-Pb ion collisions with a luminosity of up to $10^{27}$ $cm^{-1}$ $s^{-1}$. This poses a number of special problems. The PS injector chain must be supplemented by an intermediate accumulation and cooling ring in order to achieve the Pb ion beam of the required brightness. This will be achieved by converting the existing low energy antiproton ring (LEAR) with additional strong electron cooling.

Another problem is that a very large cross section is predicted (~ 300 barns) for electron capture by pair production [7]. This process removes particles from the beams, reducing the luminosity lifetime and may affect the quench behaviour of superconducting magnets of unfavourable locations. The effect is under careful study.

## 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. The most serious new phenomenon revealed is the electron cloud effect, where experiments and simulations have led to a good understanding of how it will be overcome in the LHC.

## ACKNOWLEDGEMENTS

I would like to acknowledge the outstanding work of the LHC team on the machine design and the continuing efforts in understanding performance limitations.

## REFERENCES

[1] E. Todesco, et al., “Controlling field quality in magnet production”, Proceedings of the LHC Performance Workshop, Chamonix XII, Chamonix (2003), p. 104.

[2] T. Bohl, T. Linnecar and E. Shaposhnikova, “Impedance reduction in the CERN SPS as seen from longitudinal beam measurements”, EPAC’02, Paris (2002), p. 1446.

[3] O. Gröbner, “Bunched induced multipacting”, 10th Int. Conf. on High-Energy Accelerators, Protvino (1977).

[4] M. Jimenez, et al., “Electron cloud studies and analyses at SPS for LHC type beams”, these proceedings.

[5] F. Zimmermann, “A simulation study of electron-cloud instability and beam-induced multipacting in the LHC”, CERN LHC Project Report 95 (1997).

[6] C. Benvenuti, et al., “Vacuum properties of TiZrV non-evaporable getter films”, Vacuum, Vol. 60, (January 2001), p. 57.

[7] J. Jowett, et al., “Heavy ion beams in the LHC”, these proceedings.