# SUMMARY OF SESSION 5: FROM LEP TO LHC, SOME IMPORTANT ISSUES

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### *Abstract*

The aim of this session is to introduce some important concepts of LHC related to performance and beam dynamics: very high energy and luminosity (Lyn Evans), super-conducting magnets and consequences on field quality (Luca Bottura), sensitivity to beam losses (Jean-Bernard Jeanneret), machine optics, parameters and most important beam dynamics issues (Jean-Pierre Koutchouk, Daniel Brandt and Werner Herr). The overall impression may be one of complexity. In this summary, we bring together the issues and the solution(s) adopted.

## 1 INTRODUCTION

The LHC is a hadron machine designed for wide-band exploration and discovery. For that purpose, it must run at the highest energy possible in the LEP tunnel (7 TeV×7 TeV) and at the very high luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The first requirement is fulfilled by using super-conducting magnets cooled at 1.9° K. Due to the large energy range (450 GeV to 7 TeV), the magnets are operated at low current at injection. The dc and ac magnetization of the cables causes relatively large multipolar field components which are significant for the beam dynamics.

The second requirement (high luminosity) imposes a very large number of bunches in each beam with important consequences for the beam-beam effect.

The overall impression may be that of complexity, further amplified by the requirement to foresee all hardware in advance as the compact design makes any late modification difficult and expensive. The main issues have however been studied over years and experience of the former or existing hadron colliders has been taken into account to anticipate new requirements and investigate the robustness of the chosen machine parameters.

## 2 SINGLE PARTICLE ISSUES

### *2.1 Effect of the Multipolar Content of the Magnetic Fields*

The situation is rather contrasted. On the one hand, the total relative field errors of the dipoles versus the transverse position expressed in $\sigma$'s are not so different when comparing LEP to LHC magnets (factor 3 at most). On the other hand, the multipolar content of the LHC dipole field is much richer. Significant components extend to the decapole in the dipoles and to the 20-pole in the quadrupoles. Altogether, the beam motion is unstable at a few $\sigma$'s if no corrective actions were made.

The cures have been of three types:

- improvement of the field quality (adjustment of coil position, compensation between different sources of imperfections, strategy in the assembly),
- comprehensive set of multipolar correctors,
- use of the optics (integer tunes or cell phase advance) to avoid the strongest resonances.

  A target field quality could be defined and it is now reached. The dynamic aperture reaches $12\sigma$ at $10^5$ turns in LHC version 6. This should give at least the required $6\sigma$ for the actual machine.

### *2.2 Variation in Time of the Multipoles*

The movie on field quality showed convincingly the large variation in time and with $\dot{B}$ of the multipoles (up to 30%).

The perturbation of the beam dynamics is such as to cause a beam loss. The cures are as follows:

- magnetic models based on bench measurements and physics of the magnets, predicting the magnetic field given the current, its variation and the magnetic history. The predictability is now about 80%,
- reference magnets with on-line multipole measurement,
- a slow start of the ramp,
- feedback from the beam if the reproducibility is insufficient.

### *2.3 Variations with the Magnetic History*

The strength of the multipoles, the amplitude of the decay and snap-back change drastically with the magnetic history. This is minimized as follows:

- a one-hour degauss cycle,
- strict operational procedures,
- logging of the magnetic history and use of the magnetic model.

### *2.4 Mechanical Aperture*

The mechanical aperture is about $9\sigma$ without collimation and $6\sigma$ with the collimators in place. These figures include rather tight tolerances on the imperfections (alignment, closed orbit,…) A special effort is being carried out to meet the tolerances and maximize the space available to the beam. The constraint of a sufficient mechanical aperture is included at the optics design stage, i.e. as a matching constraint. The LHC aperture is indeed smaller then that of LEP but larger than in HERA.

### 2.5 *Sensitivity to Beam Losses*

Depending on the circumstances (energy, time constant of the loss, ...), a quench may be produced by 0.001 to less than 1 ppm of the LHC beam intensity. To face this challenge, the following solutions have been adopted:

- pilot pulses to set up the machine, with an intensity such that quenches will be unlikely,
- two very complete collimator sets (betatron, momentum) with a safety margin of 100, requiring tight control of the local orbit (a small fraction of $\sigma$=0.3mm at top energy).

The collimators should be the first aperture restrictions. They will be equipped with loss detectors to help protecting the machine.

## 3 COLLECTIVE EFFECTS

In this field, LHC is not notably different from other machines. The dynamics was studied already long ago. It is not expected to limit the LHC performance. A new effect (for LHC) was however identified recently: the build-up of an electron cloud. It is reported in a dedicated session. With the gradual design and construction of the beam environment, the impedances which were estimated need now to be calculated/measured for the actual structures. Presently, the longitudinal impedance is well below the threshold above which instabilities would occur. The decision was made not to build a feedback. The transverse impedance however is expected to cause several single bunch and coupled-bunch head-tail modes to become unstable. Great care is required to keep it within tolerance (Cu plating, ...) The transverse instabilities are damped by a transverse feedback for the dipole mode and by two families of octupoles for the higher-order modes.

An interesting issue concerning the shielding properties of thin resistive layers was recently confirmed. An experiment in EPA showed that a ceramic chamber coated with a layer much thinner than a skin depth did indeed provide efficient shielding provided care is taken to avoid any low impedance by-pass. These shielding properties will actually by used for the LHC dump kickers and possibly by the LHC experiments.

## 4 BEAM-BEAM ISSUES

The beams crossing at an angle, two qualitatively different phenomena should be considered: head-on and long-range interactions, further complicated by the PACMAN effect.

### 4.1 *Head-on Interaction*

Apart from the crossing angle, the parameters of the head-on collisions are those of the Sp$\bar{p}$S, with a total beam-beam tune shift less than 0.01. They allow reaching the nominal luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

### 4.2 *Long-Range Interactions*

There are 120 of these interactions, where the beam separation is mostly in the range of 7 to 13$\sigma$. They produce linear effects, like closed orbit distortions and tune shifts and more subtle non-linear effects. The latest findings seem to show that they limit the stability of the motion at large amplitude, while the head-on interaction does not give rise to an instability.

To minimize the linear tune shift, the plane of crossing is horizontal in one point and vertical in the other. The crossing angle may still be increased by 20% if it would become necessary.

### 4.3 *PACMAN bunches*

Due to the kicker gaps in the bunch train, some bunches do not experience the same number of long-range interactions as the nominal bunches. This gives a spread in orbits, tunes,...

The linear tune spread is cancelled by alternating the crossing angles. The orbit spread gives rise to a beam separation of about 0.2$\sigma$, at the limit of significance. A further increase of the crossing angle decreases as well the 'PACMAN' spread.

### 4.4 *Coherent Beam-Beam Oscillations*

At nominal performance, the $\pi$-mode is shifted away from the incoherent beam-beam frequencies and becomes potentially unstable. This may easily be avoided by selecting different betatron tunes for the two rings: one ring could be operated on the nominal tune (close to 3rd-order resonances) while the other could be tuned close to 4th-order resonances.

## 5 CONCLUSION

To reach a very high performance level, the LHC beam dynamics is involved. Solutions(s) have been devised to reach the nominal performance in a reliable way. The margins are not as large as in other machines and require a continuous follow-up of the actual hardware parameters. Some flexibility is implemented in the machine (mainly in its optics) to face new requirements. The beam observation and control systems will be important issues for an accurate control of the machine and beam parameters.