Challenges for LHC and Demands on Beam Instrumentation

J. Wenninger, CERN, Geneva, Switzerland

Abstract

The LHC machine presently under construction at CERN will exceed existing super-conducting colliders by about one order of magnitude for luminosity and beam energies for pp collisions. To achieve this performance the bunch frequency is as large as 40 MHz and the range in beam intensity covers $5 \cdot 10^9$ protons to $3 \cdot 10^{14}$ protons with a normalized beam emittance as small as 3 μrad. This puts very stringent demands on the beam instrumentation to be able to measure beam parameters like beam positions, profiles, tunes, chromaticity, beam losses or luminosity.

This document highlights selected topics in the field of LHC beam instrumentation. The examples will be chosen to cover new detection principles or new numerical data treatments, which had to be developed for the LHC as well as aspects of operational reliability for instrumentation, which will be used for machine protection systems.

THE LHC MACHINE

The Large Hadron Collider (LHC) is a proton-proton collider scheduled to start operation in 2007. The LHC will be installed in the existing 26.7 km long LEP tunnel. Its nominal operating energy is 7 TeV/c, with injection from the Super Proton Synchrotron (SPS) at 450 GeV/c. The overall layout of the LHC is shown in Fig. 1. The two beams (rings) of the LHC circulate in separated vacuum chambers that cross in Interaction Regions (IR) 1,2,5 and 8. The two high luminosity experiments are installed in IR1 (ATLAS) and IR5 (CMS). IR3 and IR7 are devoted to beam collimation (beam cleaning). The 400 MHz RF system and most special beam instruments are installed in IR4. The beam dumping system is installed in IR6.

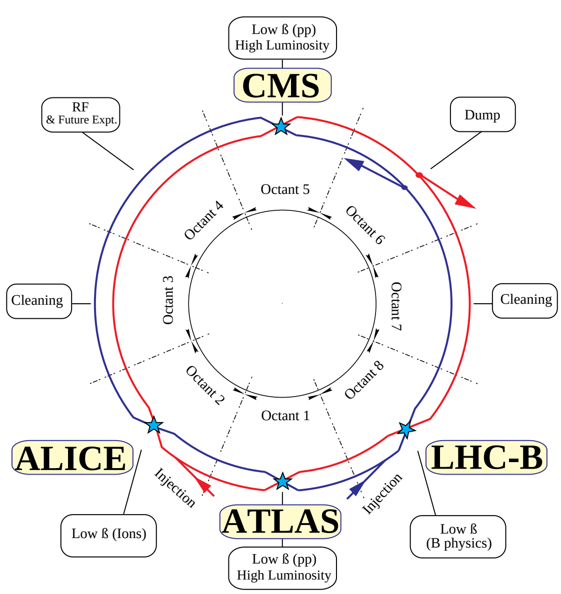

Figure 1: Layout of LHC ring and experiments.

The LHC super-conducting magnets are immersed in a bath of super-fluid Helium at 1.9 K. The nominal operating field of the dipoles is 8.4 T. The main parameters of the LHC for proton operation are summarized in Table 1. Details on ion operation can be found in Ref [2].

Dipole field (at T=1.9 K)	8.39 T
Number of bunches	$1 - 2808$
Bunch spacing	25 ns
Bunch population	$1.1 \cdot 10^{11}$
R.M.S. normalized emittance $\gamma\epsilon_{x,y}$	3.75 μm
Peak luminosity $\mathcal{L}$	10^{34} cm^{-2} s^{-1}
Number of IPs (high $\mathcal{L}$)	4(2)
Crossing angle at IP	300 μrad
Beam-beam tune shift	0.0034
R.M.S. beam size at high $\mathcal{L}$ IP	16 μm
R.M.S. bunch length	7.7 cm
Synchrotron rad. power	3.6 kW

Table 1: Nominal proton beam parameters at 7 TeV [1].

DYNAMIC EFFECTS OF SUPER-CONDUCTING MAGNETS

The transfer function at low field of super-conducting magnets shows a hysteresis caused by the persistent currents, long lasting eddy currents originating in the super-conducting filaments when they are subject to field changes, i.e. during ramps [3]. The effect of persistent currents is particularly strong at low field and their effects appear on all allowed multi-poles (b_1 (dipole), b_3 (sextupole), b_5 (decapole) .. for dipole magnets).

The field contributions from the persistent currents decay during injection with a time constant of $\sim$ 900 s and result in systematic and random (magnet to magnet fluctuations) effects. Fig. 2 gives an example for the b_3 component of the dipoles. The associated chromaticity change is $\Delta Q' \simeq 80$ units. A field ramp of 20 to 30 mT of the dipole field re-establishes the persistent currents to their original configuration before decay. This so-called 'snapback' occurs therefore in the first tens of seconds of the ramp.

The main consequences of the persistent currents are:

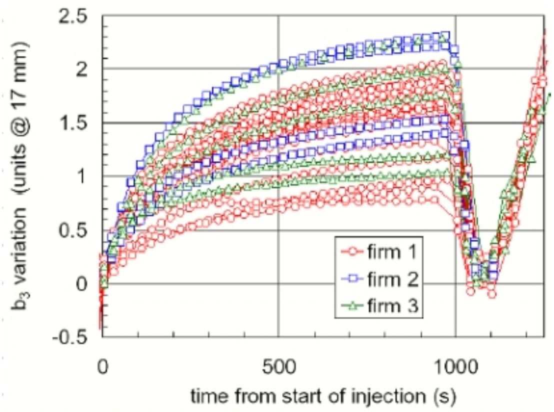

Figure 2: Injection drift of the sextupole field component for a sample of LHC main dipoles due to the decay of the persistent currents [3]. Δb_3 = 1 unit corresponds to $\Delta Q' = 50$ units. The persistent currents 'snapback' to their value before injection during the first seconds of the energy ramp (time = 1000 s).

- Closed orbit changes of ~ 1 mm r.m.s [5].
- Tune changes of $\Delta Q \sim 0.03$ [6].
- Chromaticity changes of $|\Delta Q'| \sim 80$ units (Fig. 2).
- Large coupling changes due to feed-down of the b_3 components from imperfectly aligned sextupole corrector elements.

It is expected that 80-90% of the changes may be anticipated by operating the machine with a reproducible cycle and by measuring the drifts during the injection decay [3]. Operating the LHC with a reproducible magnetic cycle should allow most of the corrections to be feed forward from one cycle to the next.

TUNE, CHROMATICITY AND COUPLING STABILIZATION

The emittance budget of the LHC is very tight, with only about 10% increase allowed from injection to collisions. To achieve this goal, some key parameters must be stabilized within very tight bounds [4]:

- $\Delta Q \simeq \pm(1-3)\cdot 10^{-3}$
- Q' $= 1-2$ units
- Coupling $c \leq 5\cdot 10^{-3}$

To stabilize the tune through the entire cycle, a tune feedback system based on a PLL tune measurement is foreseen. To avoid emittance blowup, a resonant BPM working on oscillation amplitudes of few μm will be used to detect beam oscillations. The chromaticity stabilization is extremely challenging. Measurements based on Head-tail oscillations are foreseen [7], although the required kicks on the beam may affect the emittance significantly. Coupling measurements may be performed with an AC-dipole [8].

PROFILE MONITORS

Precise profile measurements are required to monitor the emittance of the LHC beam throughout the machine cycle. At 7 TeV the emittance of 0.5 nm yields transverse beam sizes of $0.2-0.5$ mm that should be measured with a relative accuracy of a few percent. Synchrotron light monitors are foreseen as not interceptive devices, with precise wire scanners for cross-calibration. The later can only be used with low beam intensities.

Measurements of betatron function are required to transport the beam profiles to other locations in the ring (collimators): such measurement are based on multi-turn BPM data, the beam excitation being performed with single kicks or AC-dipoles.

BEAM-BEAM AND LUMINOSITY

For collisions the IR betatron function is squeezed from the injection and ramp value of 18 m down to 0.5 m at the high luminosity interactions points. The beams collide at an angle (full opening) of 300 μrad to minimize the effects of parasitic encounters in the common beam tube, see Fig. 3. On both sides of the IR, a bunch in the center of a 72-bunch train encounters up to 15 bunches of the opposing beam. The perturbations from those long-range collisions increase the tune spread in the beam and can destabilize particles at amplitudes of a few σ. Bunches at the beginning and end of the trains experience fewer parasitic collisions and are called PACMAN bunches [1, 9]. Such bunches are likely to have lower lifetime and larger emittance.

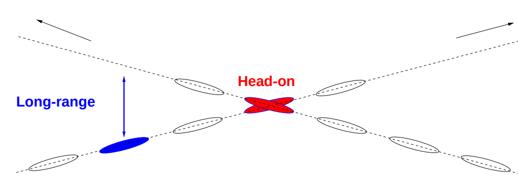

Figure 3: Schematic of long-range collisions.

The effects of the long range collisions depend on the crossing plane combination in the 2 high luminosity IRs [9](both vertical or horizontal, mixed). Fig. 4 shows tune variations along a train due to the long range collisions. The effect on the horizontal beam position at the IR is visible in Fig. 5. Due to the difference in the offsets for the two beams, it is not possible to collide all bunches head-on at the IR. Offsets of ~ 1 μm (for an r.m.s. beam size of 16 μm) cannot be avoided. A challenging compensation scheme based on a wire located near the IRs is foreseen for the LHC to counteract the side effects of the long-range beam-beam [10].

As a consequence of the parameter variations between bunches, all LHC beam instruments should provide bunch-by-bunch measurements: orbit, tune, lifetime and current, emittance (transverse and longitudinal) and, up to a certain extend, beam losses.

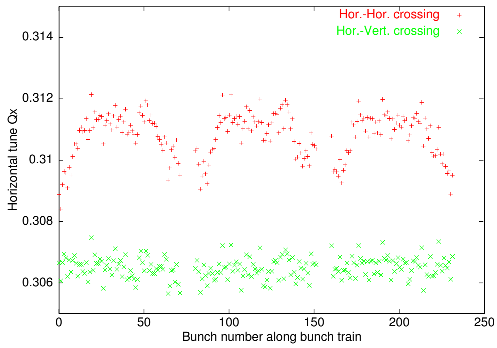

Figure 4: Horizontal tune variation along 3 trains of 72 bunches for the case where the crossing planes are different in the 2 high luminosity IRs (green) and for the case where both crossings are horizontal (red) [9].

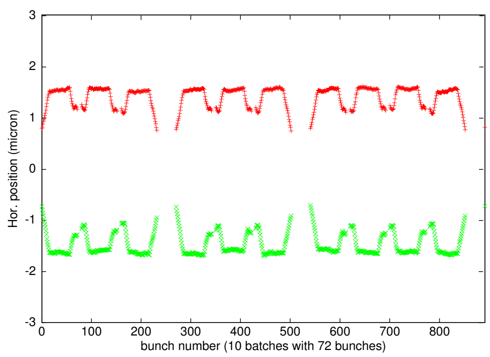

Figure 5: Horizontal beam position variation at the IR along 10 trains of 72 bunches for the 2 counter-rotating beams [9]. The r.m.s. size at the IR is 16 μm.

The fundamental parameter for machine tuning in physics is the luminosity. Luminosity detectors dedicated for machine operation will be installed in all 4 IRs. Those detectors must cover a dynamic range of $\mathcal{L} = 2 \cdot 10^{26}$ to 10^{34} cm^{-2}s^{-}1 (nominal). The lowest $\mathcal{L}$ corresponds to collisions of one low intensity ($5 \cdot 10^9$ protons) bunch per beam and un-squeezed optics. In that case, which is likely to be used during the commissioning phase, the integration time is not critical. Bunch-by-bunch measurements, averaged over a few seconds, should be provided to monitor PACMAN bunches. The monitors should also provide background diagnostics at small angles. The technological choice of the detectors, which are installed in an extremely hostile environment in terms of radiation and heat load, has not been finalized: CdTe detectors [11] or ionization chambers [12].

MACHINE PROTECTION

Both the energy stored in the LHC magnets and in the LHC beams are unprecedented. The 8 LHC sectors covering one arc each are powered separately to limit the energy stored in each circuit to 1.3 GJ at top field. The total energy stored in the LHC magnets is 10.4 GJ [13].

Fig. 6 compares the energy stored in the beams of various accelerators. At 7 TeV the 350 MJ stored in each LHC beam exceed the values at existing machines by 2 orders of magnitude. The transverse energy density increases even by 3 orders of magnitude due to the high beam brightness.

The LHC will be protected by over 10000 interlock channels that are managed by a high performance machine protection system [14]. A significant number of those channels are provided by beam instrumentation as will be discussed below.

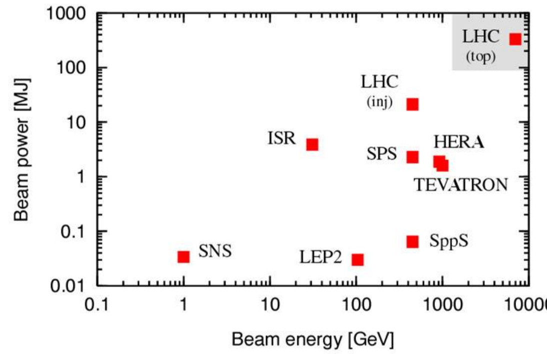

Figure 6: Energy stored in various accelerators.

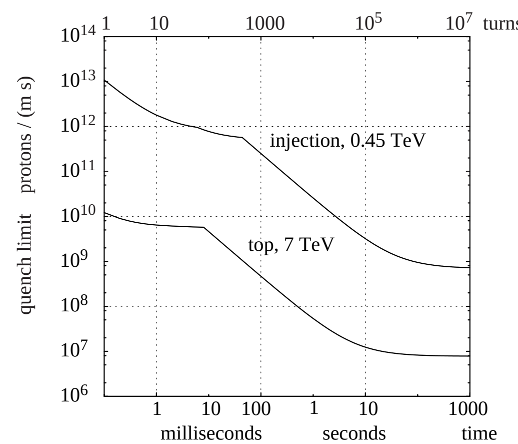

Figure 7: Quench level of the LHC dipoles in lost protons per meter and second as a function of the time scale of the loss.

Beam Collimation

Operating the LHC with beam intensities of 0.5 A or $3 \cdot 10^{14}$ protons per beam requires tight control of the beam losses in the super-conducting magnets. The quench limit of the main dipole magnets is shown in Fig. 7 as a function of beam energy and loss rate. The quench level varies over 6 orders of magnitude from 450 GeV/c to 7 TeV/c and between fast and slow losses. At 450 GeV/c a single low intensity bunch of $5 \cdot 10^9$ protons, the so-called 'pilot' bunch, should not quench the magnets. This pilot bunch will be used to check out and commission the LHC.

Running the LHC requires large beam lifetimes and/or efficient collimation at all stages of operation. With the exception operation at 450 GeV/c with a single pilot bunch, the collimators must be used in all phases of machine operation [15]. The primary collimator aperture must be set between 5 and 8σ. At 7 TeV the opening is only ± 1.2 mm due to the extremely small transverse beam size, see Fig. 8.

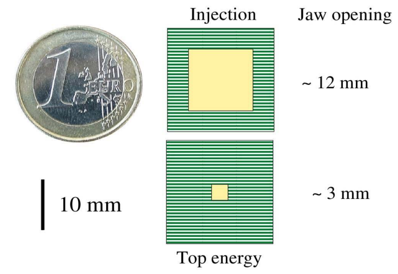

Figure 8: Opening of the LHC primary collimators at 450 GeV/c and at 7 TeV/c. At top energy the opening is equivalent to the size of Spain on the 1 ϵ coin [15].

To maintain a high cleaning efficiency of the collimation system, the orbit must be stabilized to $\sigma/3$ (~ 70 μm at 7 TeV) while the β-beating should not change by more than 5-10% [6]. A local (or global) orbit feedback must be operated at all times in the LHC due to the tight aperture, a somewhat unusual fact in a proton machine [5]. Local β-beating measurement must be provided at the collimators and at the location of the emittance devices to determine precisely the beam size at the collimators.

The tight requirements of the collimation system limits the maximum tolerable oscillation amplitude that can be given to the beam to $\sim 0.5 - 1\sigma$ depending on the total intensity. Such limitations put stringent requirements on the beam position monitor resolution for multi-turn measurements (β-beating...).

Beam Loss Monitors

The extremely high beam energy and density can lead to damage of collimator jaws and other machine components. To protect the machine against un-controlled losses ~ 3000 Beam Loss Monitors (BLMs) will be installed around the ring [16]. The BLMs must cover a dynamic range of loss rates that exceeds 8 orders of magnitude, with a minimum loss rate of $\sim 1\%$ of the lowest quench level (see Fig. 7). Two basic monitors types will be used:

- Arc monitors with a typical reaction time of a 2.5 milliseconds will be installed at each quadrupole.
- Special collimator monitors (BLMC) that must have a reaction time of around 1 LHC turn (89μs) to protect the collimators or other critical apertures against fast beam losses. The role of those collimators will be extremely important to optimize the collimators settings.

The BLMC monitors will be safety critical devices and operation of the LHC will not be allowed whenever they are not operational. They will be able to trigger a beam dump at any time.

The detectors will be based on ionization chambers (1 liter Nitrogen gas) coupled to a first level electronics based on Current-to-Frequency conversion that is capable of covering the entire dynamic range. In the LHC arcs separation of the loss signal of the 2 beams will be extremely useful for operation. Detailed simulations of the loss distribution are required to optimize the detector layout.

Beam Abort Gap Monitor

A 3 μs long beam abort gap free of particles must be provided within the LHC beam to accommodate the rise-time of the beam dump kickers. Un-captured beam (at injection), intra-beam scattering and unavoidable RF noise will populate the beam abort gap [17]. At 7 TeV, the 7 keV/turn energy loss by synchrotron radiation pushes un-captured particles towards the off-momentum collimators and limits the population of the abort gap. Although it is foreseen to clean the abort gap using the transverse damper system, very reliable monitoring of the particle density in the beam abort gap must be provided to ensure that magnets downstream of the dump kickers do not quench during beam abort. The sensitivity of the monitor must be in the range of $2 \cdot 10^5$ protons/m or $6 \cdot 10^4$ protons/ns. This density is 6 orders of magnitude below the peak density inside the LHC bunches.

Beam Dumping System

The limited aperture of the beam extraction septa magnets of the beam dumping system defines a ± 4 mm window on the maximum tolerable orbit excursion around the beam dump area. The position will be stabilized by an orbit feedback, but to ensure that this requirement is always fulfilled, a fast interlock on the beam position will be required. For the fastest magnet/power converter failures, the orbit movement in the dump area will be ~ 60 μm/turn, thus requiring reaction times of a few turns [13]. The same fast position interlock may be required to complement the BLM system for the fastest failures.

Post-mortem Diagnostics

Post-mortem diagnostics, in the form of turn-by-turn information for the last 1000 turns before a beam abort and in the for a lower resolution (1-10 Hz) for the last 20 seconds before beam abort will be required for all critical LHC instruments to diagnose the consequences of beam aborts.

ELECTRON CLOUD

For the 25 ns spacing of the LHC bunches and the vacuum half aperture of 2-3 cm the number of electrons may amplify exponentially during the passage of a bunch train, as has been observed in the SPS [18]. This so-called electron cloud can strongly perturb the beam stability [1]. The associated heat load deposited on the vacuum chamber (Fig. 9) may limit the total beam intensity.

The cloud is generated from a small number of primary electrons liberated by gas ionization, beam loss or syn-

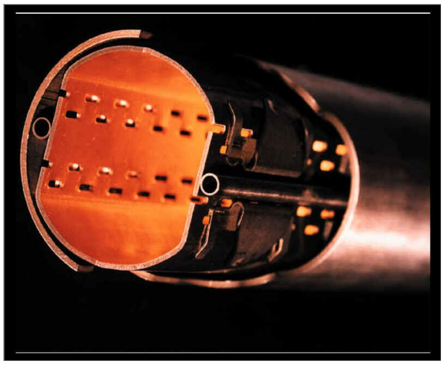

Figure 9: The LHC vacuum chamber and the beam screen (at $4 - 20$ K) that shields the cold mass from synchrotron radiation and image currents. In this figure the chamber is rotated by 90° with respect to its normal orientation.

chrotron light impact, see Fig. 10. The key process for cloud amplification is the secondary emission of electrons, and the most important parameter the secondary emission yield, which is typically peaks around 1 to 2.5 for Copper surfaces. The simulated transverse distribution of an electron cloud in the LHC is shown in Fig. 11.

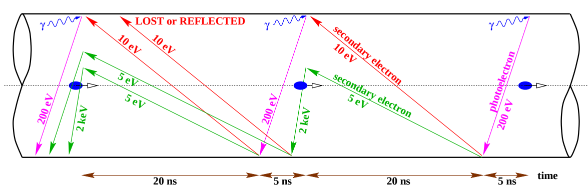

Figure 10: Principle of electron cloud builup.

Measurements at the SPS [18] have shown a strong dependence of the cloud on the magnetic dipoles field, the filling pattern, the bunch population and the bunch length. Diagnostics is required to monitor the state of the LHC vacuum chamber surface. Measurement devices includes strip detector installed inside the vacuum chamber, special devices to determine in situ the secondary emission yield and the power deposited on the chamber.

For the first two years of LHC operation, the bunch spacing will be increased to 75 ns. For such a spacing no electron cloud effect is expected. Nevertheless beam with 25 ns spacing may be stored at injection energy to clean the vacuum chamber surface in preparation for nominal performance.

CONCLUSION

Reliable and safe operation of the LHC requires excellent beam diagnostics and control during all phases of machine operation. The impact of beam-beam effects requires bunch-to-bunch resolution for most LHC beam instruments. High reliability is required from beam loss monitors, abort gap monitors and beam position interlocks. Stabilization of tunes, chromaticity and coupling without emittance degradation of the high brightness beams are required. Closed loop feedbacks on orbit and tune will be mandatory.

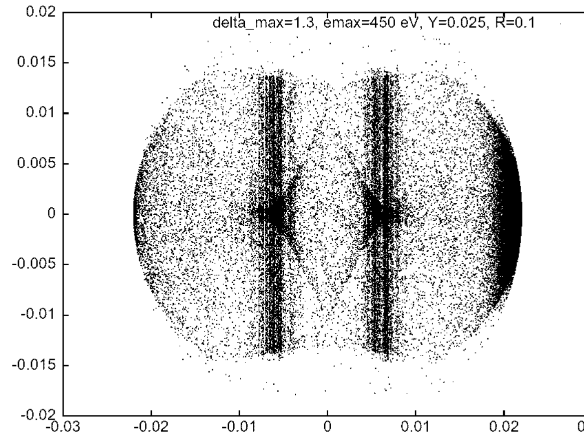

Figure 11: Simulated transverse distributions of electrons due to multi-pacting in the LHC vacuum chamber [1].

REFERENCES

[1] F. Zimmermann, CERN-SL-2002-03 (AP).

[2] K. Schindl, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[3] L. Bottura, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[4] O. Bruning *et al*, LHC Project Report 222 (2001).

[5] J. Wenninger, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[6] R. Assmann *et al.*, *Time Dependent Superconducting Magnet Errors and their Effect on the Beam Dynamics at the LHC*, Proc. of EPAC02, Paris, France.

[7] R. Jones *et al.*, CERN-SL-2001-20-BI (2000).

[8] J.P. Koutchouk, these proceedings.

[9] W. Herr, LHC Project Report 628 (2003).

[10] J.P. Koutchouk, CERN-SL-2001-051-BI (2001).

[11] E. Rossa *et al*, CERN-SL-2002-001-BI (2002).

[12] W.C. Turner, LBNL-42180 (1998).

[13] R. Schmidt, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[14] B. Puccio *et al*, LHC Project Report (2002).

[15] B. Jeanneret, Proc. of the Xth Chamonix Workshop, CERN-SL-2000-007 DI.
R. Assmann, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[16] B. Dehning *et al*, *The Beam Loss Detection System of the LHC Ring*, Proc. of EPAC02, Paris, France.

[17] E. Chapochnikova, Proc. of the XIIth Chamonix LHC Workshop, CERN-AB-2003-008 (2003).

[18] J.M. Jimenez *et al*, LHC Project Report 632 (2003).