LHC Beam Instrumentation

R. Jones
CERN, CH - 1211 Geneva 23, Switzerland

ABSTRACT
The instruments and diagnostic systems considered for the LHC are presented and their specifications and expected performance discussed. Their task will be to measure the essential beam properties, establish diagnosis, and give information on beam behaviour. The diagnostic systems will be essential during the running-in period. Precise and reliable information from them are a prerequisite for operational optimization. The present description of beam instrumentation and diagnostics is based on the most recent set of nominal LHC parameters.

1. BEAM POSITION MEASUREMENT

The Beam Position Measurement System is a key element of the instrumentation of any accelerator. In the case of the LHC, equal attention will be given to the system for the rings and the transfer lines, as the latter is itself an installation nearly as large as the present orbit system of the SPS. The specifications for both systems are very similar and hence a common approach for the readout electronics and for the calibration system is planned. The pick-ups themselves are based on button electrodes, but whereas the ring pick-ups are nearly all at cryogenic temperatures all the transfer line pick-ups are at room temperature. For each transfer line 26 horizontal and 27 vertical monitors are required, giving a total of 106 monitors. For the main rings about 1000 monitors are needed, all of them measuring in both planes. A certain number of monitors around the experimental insertions have to be built directional, as both beams pass in the same beam tube.

1.1. Signal processing

The signal processing has to cope with a dynamic range of bunch currents from 5×10^9 to 1.7×10^{11} protons, and a number of bunches which can vary from 1 to 2835. The beam position measurement system would need to have a particularly large dynamic range of 90 dB, if the system were designed to integrate the beam current over a full revolution. Technically this could only be achieved with adjustable gain stages, a solution that in many designs of other machines creates a continuous worry for the maintenance and the calibration of the system. On the contrary, if one looks at the dynamic range that is covered by the single bunch intensities one finds only 31dB. Allowing for another 9 dB in variation in the sum signal of two opposing electrodes, for a position variation within 50% of the BPM aperture, results in a total dynamic range of 40 dB. A phase processor can cover this range. The circuit to be used, called a wide-band time normaliser, is a completely new design developed at CERN [1] in order to achieve the required bandwidth of 40 MHz. With a bandwidth of 40 MHz, a measurement of the trajectory or the orbit of any individual bunch will be possible. This is of particular interest for injection studies and for beam-beam studies with the beams in collision.

The overall performance of the system is summarised in Table 1.

2. BEAM LOSS MONITORS (BLM)

Beam losses must be monitored carefully in the LHC since as little as 10^7 p/s lost at 7 TeV on a superconducting magnet can induce a quench. For that reason the beam halos will be cleaned by means of multiple collimators in the two insertions at IP3 and IP7. The optimisation of this cleaning will require dedicated beam loss monitors located close to all collimators. The tertiary halo which will escape from the cleaning insertions will be lost in the rest of the machine (over 26 km) where it will be concentrated around the quadrupoles due to the large beam envelope in their centers. All BLMs, of which there will be ~3000, will be permanently surveyed in order to dump the beam to prevent magnet quenches.

2.1. Monitors for the cleaning sections

These monitors will have a huge dynamic range to cover extreme cases and a bandwidth, which extends from zero to 40 MH**z.** There are various solutions to this problem using fast particle detectors. One difficulty though might be the high level of radiation reached in the two cleaning sections LSS3 and LSS7. Fast losses due to beam instabilities or equipment failures will be detected in the cleaning sections and result in a quick dumping of the beams. In LSS7 there will be 8 primary collimators for the two beams, while in LSS3 there will be 2.

Bunch Type		***Pilot Bunch***		***Bunches of Nominal Intensity***		
Mode of Operation		**Trajectory** (single shot)	**Orbit** (224 turn average)	**Trajectory** (single shot, single bunch)	**Trajectory** (single shot, average of all bunches)	**Orbit** (average of all bunches over 224 turns)
ELECTRONICS	**Resolution**	200μm	20μm	50μm	5μm	5μm
	Accuracy	500μm				
MECHANICAL	**Alignment Error**	700μm				
	Residual after k-modulation	~50μm				

Table 1. Summary of the resolution and accuracy of the LHC orbit system**.**

2.2. Monitors for the arcs

Smaller and slower losses might concentrate elsewhere on the circumference and quench a dipole or a quadrupole. In the adiabatic case, superconducting cables cannot stand more than a loss of 10^7 p in 20 ms and, with helium convection cooling, the slow quench limit is 10^8 p in 30 s. A distributed BLM system must be able to give alarms in both cases. Standard ionisation chambers could be used and would offer a linear dynamic range of 10^6, which is perfectly adequate for fast losses. When operating in integration mode their output signal is proportional to the dose deposited in the magnets. Small PIN diodes could also be used and, with a high counting rate, they would offer a dynamic range of 10^5 for fast losses and of 10^8 for slow losses. The choice of detector is still to be made. Beyond giving alarms to dump the beams, the distributed BLM system will be used for beam dynamic studies and should provide live displays of the azimuthal and time distributions of losses. Some of the data will be logged in a permanent database for off-line treatment but all data will also be permanently filed in cyclic memories for post-mortem analysis after any event of interest.

3. INTENSITY MEASUREMENT

Beam transformers will not only measure the intensities of the beams passing through the transfer lines (from the SPS to the LHC, and from the LHC to the dumps) but also the circulating current in the two LHC rings. All of them will be installed in places where the vacuum chamber is at room temperature and the circulating beams are separated. For the measurement of the intensity at injection, first-turn and bunch-to-bunch, a bunch-to-bunch transformer will be used. The precision will be typically 2% for the pilot beam of 5.10^9 protons in a single bunch. For any higher intensity the precision will improve. For circulating the fast beam transformers will serve to determine the number of protons contained in each bunch. DC transformers will be used to measure the circulating current and will require a dynamic range which covers 1 μA (10% of the pilot bunch) to 0.54 A.

3.1. Lifetime measurements

Using the DC monitor will require analogue to digital conversion with a minimum of 21 bits, which is currently commercially available for low bandwidth. There will however be a signal to noise problem when measuring the pilot bunch. With the bunch-to-bunch transformer this is possible for a few bunches (as in LEP), but will be difficult to perform at 40 MHz.

4. TUNE AND CHROMATICITY MEASUREMENT

The betatron tune, Q, needs to be measured with high precision throughout the cycle. Related quantities (tune-spread, chromaticity and coupling) also are of great relevance for the behaviour of the beam. Several methods of measurement are being investigated. Some of them cause an emittance increase and can therefore be used only occasionally and with great care on an operational beam. On low-intensity pilot beams, however, they can be used without constraint, and the measured values may be assumed to be valid also for high-intensity beams.

4.1. Tune measurement

So called Q-kickers will be installed which are capable of exciting transverse oscillations of 50 μm -1.6 mm at injection or 3 -100 μm at 7 TeV, at a maximum repetition rate of 2Hz. The tune is then measured by FFT techniques. This obviously falls into the category of measurement that blows up the emittance, and will therefore not be possible for extended periods on an operational beam.

Another method of transverse excitation is by injecting a parasitic signal, such as a swept frequency ("chirp"), with the transverse feedback system. Again this will lead to significant emittance blow up if used continuously. R&D is therefore currently underway to produce a high performance system capable of providing a continuous tune measurement in the presence of strong transverse damping and without excessive emittance blow-up.

4.2. Chromaticity measurement

The tight tolerance on beam parameters for successful LHC operation implies a good knowledge of the chromaticity throughout the cycle. There are two methods that will be implemented in the LHC for measuring the chromaticity. The first involves measuring the tune change due to a change in beam momentum (achieved by altering the RF frequency); the second obtains the chromaticity by measuring the head-tail phase shift in a single bunch after transverse excitation.

4.2.1. Variation of tune with momentum

The classical method of measuring chromaticity involves varying the beam momentum and looking at the induced changes in the betatron tune. This change in beam momentum can be achieved by modulating the RF frequency. In the LHC the maximum allowed $\Delta p/p$ variation is limited to 10^{-3} which, when combined with a resolution of 10^{-3} in measuring the betatron tune, allows a variation of 1 unit in chromaticity to be detected. The betatron tune can be measured using any of the methods described in Section 4.1.

4.2.2. Head-tail phase shift measurements

This method allows the chromaticity to be calculated after several hundred turns from the turn-by-turn position data of a single bunch after transverse excitation. This so-called head-tail chromaticity measurement [2] relies on the fact that for non-zero chromaticity a dephasing/rephasing occurs between the head and tail of a bunch with a frequency equal to the synchrotron frequency. By measuring the turn-by-turn position data from two longitudinal positions in a bunch, it is possible to extract the relative de-phasing of the head and the tail, and so to determine the chromaticity. The transverse excitation can be obtained using the Q-kickers, allowing the measurement to be performed in parallel with the tune measurements described in Section 4.1.

Information on the transverse position along the bunch would be obtained using the strip-line coupler pick-up, digitised using a fast (>2 GS/s) ADC with a high analogue bandwidth (>1 GHz). The advantage of this technique is that a single chromaticity measurement can be performed in one synchrotron period (150 to 450 turns for the LHC), and is virtually energy independent when operating well above the transition energy. There is however the disadvantage that the transverse excitation required to observe the head-tail phase shift results in a considerable emittance increase. On operational beams this type of measurement may therefore only be carried out a limited number of times if excessive emittance growth is to be avoided.

5. BEAM PROFILE AND EMITTANCE MEASUREMENTS

The transverse profiles of the beams will be measured at several convenient locations to provide information on beam size and on emittance. The precision of the emittance calculation depends critically on the knowledge of the amplitude function at the location of the profile measurement, the measurement of which will not be described here.

5.1. Screens in transfer lines, for first turn and beam dumping checks

Screen monitors are foreseen to give a precise measurement of the beam size and position, together with direct visual information, in the transfer lines and for the first turn in LHC. Approximately twenty screens are foreseen in total for TI2, TI8. In each LHC ring, eight screens are foreseen for first turn studies. The images will be acquired either with TV type detectors for observing the batches or with 32 strip photomultipliers for bunch to bunch acquisitions.

5.2. Injection matching monitors

Emittance preservation in the whole accelerator chain is a major concern in the LHC project. An OTR screen monitor will be installed in the LHC to help achieve this goal. This monitor will measure the profiles of the injected beam over several dozen turns [3]. The absence of profile modulation indicates that the matching from SPS to LHC is perfect. The method will allow the determination and correction of the mismatch, in order to reduce the emittance blow-up by filamentation, to less than a few percent. The blow-up and the losses induced by this monitor during the measurement are negligible over the number of turns required.

5.3. Synchrotron light monitors

Synchrotron light monitors operating at near-UV wavelengths are considered as the basic instrument for measuring continuously the profiles from 0.45 to 7 TeV. The design is based on the monitor which has proven its capabilities over the years in LEP1 [4]. Two major technical difficulties in LHC are the small amount of light emitted at injection energy and the small beam size at top energy. It is proposed to install four monitors. One pair of monitors will be located close to IP4 and have a light source generated in a specially installed mini-wiggler made up of four 1 m long super-conducting magnets creating a localised bump. This will be capable of measuring the beam size from 450 GeV to 2 TeV.

To have a precise measurement at collision energy, it is proposed to install another two monitors around IP5. The light will be generated in the D2 magnets and extracted towards the arcs as close as possible to Q5, the start of the arc cryostat. This monitor will be able to measure the beams from 2 to 7 TeV, with the best precision achieved at 7 TeV in collision where the beam sizes will be comfortably large, $\sigma_H \sim 0.5$ mm and $\sigma_V \sim 0.9$ mm, with respect to diffraction.

5.4. Rest gas ionisation monitor

A rest gas instrument makes use of the ions or electrons produced from the ionisation of the rest gas by the circulating beam. These are accelerated onto a Multi Channel Plate (MCP) followed by a phosphor screen. TV cameras observe the resulting light bands, and generate both top and side views of the beams. A local nitrogen pressure bump as low as 5.10^{-8} Torr is sufficient to act as rest gas, and results in a negligible increase of the average pressure. This monitor would be used in conjunction with the synchrotron light monitor of IP4, for measurements between 450 GeV and 2 TeV.

5.5. Wire scanners

All these monitors suffer potentially from some sort of imprecision and need to be cross-checked with a reference monitor. Wire scanners are considered for these cross calibration purposes using lower density beams, as they have proven to be the most precise and robust monitors for profile measurements of limited intensity beams. Medium speed wire scanners are considered as the basic calibration instrument for the other circulating beam profile measuring devices. They will be located close to the other profile monitors for cross-calibration purposes, so as to depend as little as possible on the precise knowledge of the LHC optics functions over a large fraction of the circumference.

6. LUMINOSITY MONITORING

The nominal LHC luminosity is 10^{34} cm^{-2}s^{-1} with two beams of 2835 bunches each containing $\sim 10^{11}$ protons, colliding in the low-β^* interaction points IP1 and IP5. Lower luminosities are foreseen in IP8 (10^{32} cm^{-2}s^{-1}), and IP2 (10^{30} cm^{-2}s^{-1}). A bunch-by-bunch luminosity monitoring is mandatory for an efficient diagnosis of the collision overlap and to help to identify other possible effects which might limit the overall performance of the collider. The luminosity detectors and the associated front-end electronics are therefore to be conceived with the following in mind:

- Availability in all Ips.
- Integration into TAN absorbers → very high radiation doses.
- Absolute luminosity from cross calibration against experiments.
- Bunch-to-bunch (40 MHz bandwidth) luminosity diagnostics.

6.1. Instrumentation

In the frame of the US/LHC collaboration, LBNL is responsible for providing TAS and TAN absorbers for the IR1 and IR5 high luminosity regions. LBNL has developed a proposal for instrumenting, with appropriate detectors, the absorbers at the high luminosity IPs to provide adequate tools for luminosity diagnostics and optimisation. Several detector candidates capable of fulfilling the speed requirements for bunch by bunch measurement are currently being considered, namely:

- Gas ionisation chambers.
- CdTe crystals.
- Displacement current in a dielectric.

7. TIMING REQUIREMENTS

The timing requirements for LHC instrumentation fall into two main categories:

- Fast pulsed signals: these include the LHC injection pre-pulse, the LHC radio frequency (400 MHz), the LHC bunch frequency (40 MHz), and the LHC revolution frequency (11 kHz).
- Slow encoded signals: these consist of a 1 ms clock, event codes, beam synchronous distributed commands and the time of day.

The beam synchronous distributed command system will be based either on a modified LEP Beam Synchronous Timing (BST) system [5], or the Timing, Trigger and Control (TTC) system [6] currently under development for the LHC experiments, or a combination of both. The system will provide the 11 kHz LHC revolution frequency, the 40 MHz LHC bunch frequency and will also allow the transmission of encoded signals for beam synchronous commands such as injection warnings, instrument triggers, real-time settings and post-mortem synchronisation to freeze acquisitions. The main requirements for the timing infrastructure come from the beam position monitor system and the beam loss monitor system, which will make use of all the above signals with the exception of the 400 MHz RF signal. This will necessitate the distribution of timing signals to equipment crates located around the whole ring as well as those in the TI2 and TI8 transfer lines. Fibre-optic cables will be used to transmit the timing signals to all the LHC pits and alcoves. Subsequent transmission from the alcoves to the equipment within the tunnel will either be by fibre-optic links or via copper cables.

REFERENCES

[1] D. Cocq. The wide band normaliser - a new circuit to measure transverse bunch position in accelerators and colliders, NIM A416 (1998) 1-8.

[2] D. Cocq, O.R. Jones, H. Schmickler. The Measurement of Chromaticity via a Head-Tail Phase Shift, 8th Beam Instrumentation Workshop: BIW '98 Stanford, CA, USA; 4 - 7 May 1998.

[3] C. Bovet, R. Jung. A new diagnostic for betatron phase space matching at injection into a circular accelerator, LHC Project Report 3, March 1996, and Proceed. of EPAC 96, Sitges, Spain.

[4] R. Jung, Precision Emittance measurements in LEP with imaging telescopes, comparison with wire scanner and X-Ray detector measurements, CERN SL/95-63 (BI), June 1995, and KEK Proc. 95-7, Sept. 1995 A.

[5] G. Baribaud et al. The Beam Synchronous Timing System for the LEP Instrumentation, Proceedings of the International Conference on Accelerator and Large Physics Control Systems, Vancouver, Canada, 1989.

[6] B.G Taylor. TTC Distribution for LHC Detectors, IEEE Trans. Nuclear Science, Vol. 45, June 1998, pp. 821- 828.