Chapter 8

Beam instrumentation

8.1 Beam position measurement

A complete list of the beam position monitors associated with orbit and trajectory measurements is given in table 8.1. There are three types of monitor: 24 mm button electrode monitors, 34 mm button electrode monitors, and 120 mm stripline monitors. These are assembled in 13 different types of housing, depending on the vacuum chamber dimension and the interface with neighbouring equipment. The orbit and trajectory measurement system has been developed to fulfill the functional specifications described in [39]. The system consists of 516 monitors per ring, all measuring in both the horizontal and vertical planes. The acquisition electronics is capable of 40 MHz bunch-by-bunch measurements and will provide closed orbit feedback at 1 Hz.

Table 8.1: List of beam position monitor types in LHC.

Type	**Electrode Type**	**Name**	**Number**
Standard Arc	24 mm Button	BPM	720
Dispersion suppressor & Q7	24 mm Button	BPM	140
Standard BPM for vertical beam screen	24 mm Button	BPMR	36
Enlarged Aperture BPM for horizontal beam screen	34 mm Button	BPMYA	24
Enlarged Aperture BPM for vertical beam screen	34 mm Button	BPMYB	12
Warm LHC BPM for MQWA	34 mm Button	BPMW	36
Enlarged Warm LHC BPM for ADTV/H	34 mm Button	BPMWA	8
Enlarged Warm LHC BPM for D2	34 mm Button	BPMWB	16
Combined Button & Shorted Stripline BPMs	24 mm Button + 150 mm Stripline	BPMC	16
Cryogenic Directional Stripline Coupler for Q2	120 mm Stripline	BPMS	8
Warm Directional Stripline Coupler for Q1	120 mm Stripline	BPMSW	8
Warm Directional Stripline Coupler for D1	120 mm Stripline	BPMSX	4
Warm Directional Stripline Coupler for DFBX	120 mm Stripline	BPMSY	4
	TOTAL		1032

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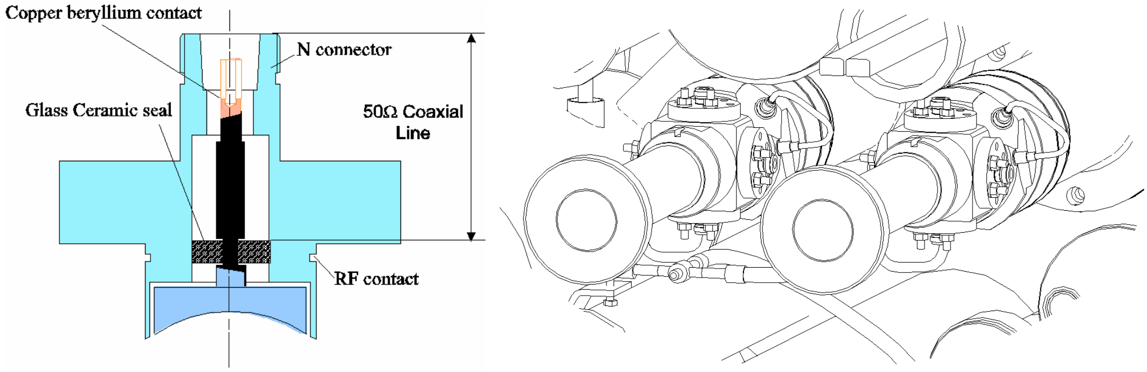

Figure 8.1: (a) 24 mm button electrode, (b) Mounted BPM bodies.

The majority of the LHC beam position monitors (860 of the 1'032) are of the arc type (see figure 8.1) consisting of four 24 mm diameter button electrode feedthroughs mounted orthogonally in a 48 mm inner diameter beam pipe. The electrodes are curved to follow the beam pipe aperture and are retracted by 0.5 mm, to protect the buttons from direct synchrotron radiation from the main bending magnets. Each electrode has a capacitance of 7.6 ±0.6 pF, and is connected to a 50 Ω coaxial, glass-ceramic, UHV feedthrough.

The inner triplet BPMs in all interaction regions are equipped with 120 mm, 50 Ω directional stripline couplers (BPMS×), capable of distinguishing between counter rotating beams in the same beam pipe. The location of these BPMs (in-front of Q1, in the Q2 cryostat and after Q3) was chosen to be as far as possible from parasitic crossings to optimise the directivity. The 120 mm stripline length was chosen to give a signal similar to the button electrode, so allowing the use of the same acquisition electronics as for the arcs. All cold directional couplers use an Ultem® dielectric for use in a cryogenic environment, while the warm couplers use a Macor® dielectric to allow bake-out to over 200°C.

The cleaning insertions in Points 3 and 7 are equipped with warm 34 mm diameter button electrode BPMs (BPMW) fitted either side of the MQWA magnets. The electrodes are an enlarged version of the arc BPM button. The same button electrodes are also used for the cold BPMs in the matching sections either side of the four interaction regions as well as for the warm BPMs located near the D2 magnets and either side of the transverse damper (ADTV/H). The BPMC, installed in Point 4, are combined monitors consisting of one BPM using standard 24 mm button electrodes for use by the orbit system, and one BPM using 150 mm shorted stripline electrodes for use in the transverse damper system.

The LHC orbit and trajectory acquisition system is based on a Wide Band Time Normaliser (WBTN) [40] capable of processing the analogue signals from the pick-up at 40 MHz. The resulting signal is transmitted via a fibre-optic link, treated, digitised using a 10-bit ADC and processed by a VME64x Digital Acquisition Board (DAB) developed by TRIUMF, Canada. The performance of the WBTN electronics with intensity is shown in figure 8.2. The system is expected to function with between 2×10^9 and 2×10^{11} charges per bunch. A summary of the expected performance of the complete acquisition system for standard arc BPMs is presented in table 8.2.

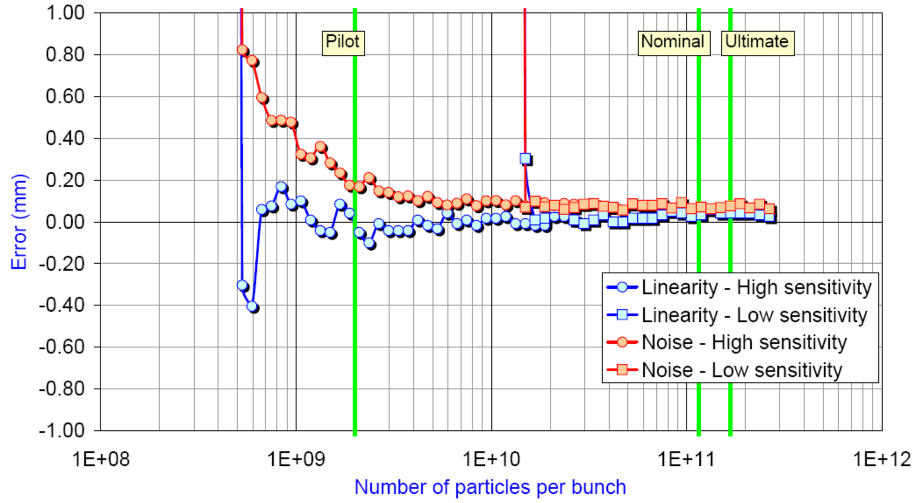

Figure 8.2: Performance of the LHC WBTN system as a function of intensity.

Table 8.2: Expected performance of the LHC BPM system for standard arc BPMs.

Range of Operation (±6mm)	Pilot Bunch (5x10^{9})		Nominal Bunch (1.1x10^{11})		Ultimate Bunch (1.7x10^{11})	
	Single	Average over 224 turns	Single	Average over 224 turns	Single	Average over 224 turns
Resolution (μm rms)	130	9	50	5	50	5
Non-Linearity (±μm)	100					
Scale Error (±%)	1					
Calibrator Offset (±μm)	50					
Intensity Offset (±μm)	25					
BPM & Gauge Mechanical Offset (±μm)	125					
Survey Measurement Precision (μm rms)	50					
Electrical Axis Offset (±μm)	113					
Uncertainty of MA wrt GA (μm rms)	150					
Geometric Non-Linearity (±μm)	100					
Total Offset (±μm)	363					
Relative Accuracy [offset ignored] (±μm)	302	155	183	154	183	154
Global Accuracy (±μm)	472	394	406	393	406	393

8.2 Beam current transformers

Beam current transformers of two different kinds will provide intensity measurements for the beams circulating in the LHC rings, as well as for the transfer lines from the SPS to LHC, and from LHC to the dumps. The transformers will all be installed in sections where the vacuum chamber is at room temperature and where the beams are separated.

The fast beam current transformers (FBCTs) will be capable of integrating the charge of each LHC bunch. This provides good accuracy for both bunch to bunch measurements and average measurements, intended mainly for low intensity beams, for which the DCCT accuracy will be limited. For redundancy, two transformers, with totally separated acquisition chains, will be placed in each ring. These will be located in Point 4. Each beam dump line will also be equipped with two redundant FBCTs, using the same acquisition electronics, for monitoring the ejected beam. In order to get good performance, there will be a DC restoration with a successive integrator and S/H circuitry used in the ring. The result of integration is digitized and stored in memory. Beam synchronous timing with 40 MHz frequency is used to trigger the system. The measurement precision for the pilot beam of 5×10^9 protons in a single bunch is expected to be around 5% (worst-case 10%), and for the nominal beam, below 1%. The transformer cores will use low droop, radiation hard material, with a specified droop below 2%/μs, and with the sensitivity approx. 1.25 V/A. Once injection is completed, the transformers will be used to measure the circulating bunches, by averaging the acquired bunch intensities over 20 ms, yielding to approximate precision of 1% for pilot beams.

The DC current transformers (DCCT) are based on the principle of magnetic amplifiers and will measure the mean intensity or current of the circulating beam and they can be used to measure the beam lifetime. Because of their operational importance, two of the devices will be installed in each ring. Currently a resolution of 2 μA can be reached but a 1 μA is targeted corresponding to 5×10^8circulating particles. The temperature dependence of the output current is $\sim$5 μA per degree which makes either temperature stabilisation or frequent re-adjustment of the offset a necessity. With an intensity of 4.8×10^{14}protons and a lifetime of 25 h driven by proton-proton collisions the decay rate is 5×10^9 protons/s. With a measurement time of 10 s this decay should be seen with 1% precision. A resolution of 1 μA is, however, insufficient for measurement of the pilot beam which can only be achieved with the fast transformers. The front-end electronics generating the DC transformer feedback current should be placed as close as possible to the sensor in the ring. However, the radiation induced by the beam and by the RF cavities during their conditioning will be an issue. If the finest resolution is required for measuring the beam over the whole dynamic range, then an ADC of at least 20 bits, located in the front-end electronics is required. The data will be transmitted to the front end computer (DSC) installed in a surface building.

8.3 Beam loss system

The loss of a very small fraction of the circulating beam may induce a quench of the superconducting magnets or even physical damage to machine components. The detection of the lost beam protons allows protection of the equipment against quenches and damage by generating a beam dump trigger when the losses exceed thresholds. In addition to the quench prevention and damage protection, the loss detection allows the observation of local aperture restrictions, orbit distortion, beam oscillations and particle diffusion.

The loss measurement is based on the detection of secondary shower particles using ionisation chambers located outside of the magnet cryostats. The secondary particle energy flux is linear with the initiating protons parameters. To observe a representative fraction of the secondary particle flux detectors are placed at likely loss locations. The calibration of the damage and quench level thresholds with respect to the measured secondary particle energy deposition is simulation based.

The criteria used to define the dynamic range are given by the calculated damage and quench levels and the expected usage. The observation time range is defined by the fastest possible use of a beam dump trigger signal by the beam dump itself and the response time of the helium temperature measurement system. Different families of BLM monitors are defined to ease the monitor design (see table 8.3) [41].

Table 8.3: Functional families of BLM.

Type	Area of use	Dangerous consequences in the case of failures	Time resolution
BLMC	Collimation sections	yes	1 turn
BLMS	Critical aperture limits or critical positions	yes	1 turn
BLMA	All along the rings	no	2.5 msec
BLMB	Primary collimators	no	1 turn bunch-by-bunch

8.4 Transverse profile measurement

User requirements led to the definition of four functional modes to be mapped on the different types of hardware monitors:

- A single-pass monitor of high sensitivity (pilot beam) with a modest demand on accuracy and few restrictions on the beam blow-up due to the traversal.
- A "few-pass monitor" (typically 20 turns) dedicated for the intermediate to nominal intensity range of the injected beam for calibration or matching studies. The blow-up per turn should be small as compared to the effect to be measured.
- A circulating beam monitor, working over the whole intensity range. No blow-up is expected from such a monitor.
- A circulating beam tail monitor optimised to scan low beam densities. In this mode, one may not be able to measure the core of the beam. The measurement should not disturb the tail density significantly.

The monitor types include wire scanners, residual gas ionisation monitors and synchrotron light monitors using light from D2-type superconducting dipoles. Synchrotron light monitors are also under development for using light from superconducting undulators in each ring. Point 4 is the default location for all instrumentation.

8.5 Longitudinal profile measurement

This measurement is a dual application of the Transverse Profile Monitor light source [42] with the aim of using synchrotron light to measure bunch profiles with a dynamic range of 10^5, enabling measurements and monitoring of bunch lengths, tails, un-bunched beam, ghost bunches and the abort kicker rise time gap. A part of the synchrotron light generated by the superconducting dipoles and undulator magnets of the Transverse Profile Monitor is collected by a separate fixed mirror offset behind the transverse optics. It is estimated that 2×10^6 photons will be collected per passage of each 1.1×10^{11} proton bunch. This intensity remains reasonably constant from injection energy up to 7 TeV. However, the spectral distribution changes with beam energy. At injection energy the undulator produces a distribution peaked around 950 nm but at higher energies the spectral profile extends from 200 nm to 2'000 nm, although only a part of this range can be used by the instrument. The photon flux reliably mimics the beam in both time and intensity. Two detection methods are under study at Lawrence Berkeley Laboratory.

An alternative system is to use an array of fast Single Photon Detectors (SPD) and time-of-flight recorders, continuously detecting the photon flux with the data being accumulated into registers.

8.6 Luminosity monitors

The nominal LHC luminosity for ATLAS (Point 1) and CMS (Point 5) is 10^{34} cm^{-2}s^{-1}, for beams of 2'808 bunches of 1.1×10^{11} protons each. The other two interaction regions will have lower nominal luminosities of the order of 10^{32} cm^{-2}s^{-1} for LHCb (Point 8) and 10^{30} cm^{-2}s^{-1} for ALICE (Point 2). With different filling patterns and optics, the global luminosity range is from 10^{26} to 10^{34} cm^{-2}s^{-1} and for the ion runs between 10^{24} cm^{-2}s^{-1} and 10^{27} cm^{-2}s^{-1}.

The proton beams are bunched with a bunch-to-bunch distance of 25 ns (or a multiple of 25 ns). This corresponds to a maximum bunch crossing frequency of 40 MHz. Under nominal conditions the beams do not collide head on, but with a small angle of the order of 150-200 μrad to avoid unwanted collisions near the interaction point. The plane containing the two beams (collision plane) can be rotated and be different in the four interaction regions.

The aim of the machine luminosity monitors [43] is to measure the interaction rates for the setup, the optimisation and the equalisation of the beams at the interaction regions. The monitors must be simple, fast and robust and preferably be of one design for all four interaction points. The requirements on accuracy go from around 10% for the beam finding mode to 0.25% for the collision feedback. Measurement times also vary from minutes in beam finding mode (very low luminosity) to one second at nominal luminosity. The monitors should also allow the measurement of the crossing angle with an accuracy better than 10 μrad in the range 0-200 μrad.

In order to detect and correct eventual bunch-by-bunch effects, a bunch-by-bunch luminosity measurement is also required. The detectors, readout and acquisition systems must therefore be capable of operating with a useful bandwidth of 40 MHz.

The machine luminosity monitors are flux monitors installed in the TAN absorbers 141 m away on both sides of the high luminosity IR1 and IR5 and at equivalent positions in IR2 and IR8. They measure the flux of the showers generated by the neutral particles created in the collisions (neutrons and photons). Neutral particles are chosen in order to suppress the background related to beam losses. The radiation dose to the detectors is very large, 170 MGy/yr, and poses a constraint on the choice of the technology. The detectors have a rectangular surface $\sim$10 cm $\times$ 10 cm. and each detector consists of four rectangular fast, pressurised, gas ionisation chambers, assembled in a 2×2 array, which is placed behind $\sim$30 cm of copper at the shower maximum inside the TAN. An alternative technology that is still under investigation consists of the use of polycrystalline CdTe discs in a 2×5 array.

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8.7 Tune, chromaticity, and betatron coupling

Reliable measurement of betatron tune, and the related quantities tune-spread, chromaticity and betatron coupling, will be essential for all phases of LHC running from commissioning through to ultimate performance luminosity runs. For injection and ramping, the fractional part of the betatron tune must be controlled to ± 0.003, while in collision the required tolerance shrinks to ± 0.001. With the exception of Schottky scans and the "AC-dipole" excitation outside the tune peak, all tune measurement techniques involve some disturbance to the beam. The resulting emittance increase, while acceptable for some modes of running, has to be strongly limited for full intensity physics runs. Different tune measurement systems are therefore envisaged.

8.7.1 General tune measurement system

Use of standard excitation sources (single kick, chirp, slow swept frequency, and noise). It should operate with all filling patterns and bunch intensities and be commissioned early after the LHC start-up. Even with oscillation amplitudes down to 50 μm, a certain amount of emittance increase will result, limiting the frequency at which measurements can be made. It will therefore probably be unsuitable for generating measurements for an online tune feedback system.

8.7.2 AC dipole

This emittance-conserving beam excitation was studied at BNL for adiabatic resonance crossing with polarised hadron beams and it was realised that the same principle could be used to diagnose the linear and non-linear transverse beam dynamics. The principle is to excite the beam coherently at a frequency close to, but outside its eigenfrequencies, by an oscillating dipole field. Hence the name AC dipole is given to the exciter. In the simplified model of a linear oscillator, the beam is expected to oscillate at the exciter frequency with a phase shift of $\pi/2$. The energy of the coherent oscillation does not couple with the incoherent oscillations of the individual beam particles. There is therefore no change of beam emittance. The forced beam oscillation amplitude is inversely proportional to the difference of the betatron tune and the exciter frequency, which is the major parameter in the design of the AC-dipole strength. Ideally, one would like to create large oscillation amplitudes, which requires the excitation frequency to approach the betatron tune, but a certain difference has to be maintained to preserve the emittance.

8.7.3 High sensitivity tune measurement system

The beam is excited by applying a signal of low amplitude and high frequency to a stripline kicker. This frequency is close to half the bunch spacing frequency (40 MHz for the nominal 25 ns bunch spacing). The equivalent oscillation amplitude should be a few micrometers or less for a β-function of about 200 m. A notch filter in the transverse feedback loop suppresses the loop gain at this frequency, where instabilities are not expected to be a problem. If the excitation frequency divided by the revolution frequency corresponds to an integer plus the fractional part of the tune, then coherent betatron oscillations of each bunch build up turn by turn (resonant excitation). A batch structure with a bunch every 25 ns "carries" the excitation frequency as sidebands of the bunch spacing harmonics. A beam position pick-up is tuned to resonate at one of these frequencies.

8.7.4 Chromaticity measurement

The chromaticity is measured by varying the mean radial position (or energy) of the beam by changing the RF frequency and measuring the tune.

At injection the linear chromaticity must be controlled to better than $\Delta Q' = \pm 1$ unit. This relaxes to ± 3 units in collision. During the "snap-back" phase of the magnet cycle at the beginning of the ramp, the b_3 multipole in the main dipoles can generate a chromaticity change of up to 2.7 units per second. Feed-forward, on-line reference magnet measurements and modelling will be used to control "snap-back".

8.7.5 Betatron coupling measurement

The working point of the LHC will be close to the diagonal and coupling compensation may be needed before making tune and chromaticity measurements. Two classical methods can be used to measure betatron coupling. The first method is the "closest tune approach" method and the second is the "kick" method.

8.8 Long-range beam-beam compensation

Due to the small bunch spacing, the LHC beams experience 15 'near-misses' on each side of every collision point. In IP1 and IP5, the beam separation is 9.5σ on average. In the other two collision points, the normalised separation is larger and their contribution to the long-range beam-beam effect can be neglected. The non-linear part of the long-range interactions is the dominant mechanism for single particle instability [44], even though the tune spread is small enough. A very fast diffusion in amplitude is observed for beam amplitudes of 6 to 8σ. The topology of the long-range interactions in LHC makes it possible to devise a simple but accurate weak-strong model where the weak beam, assumed round, is perturbed by currents flowing in wires on either side of the crossing points (strong beam). This model leads naturally to a compensation system [45] made of genuine wires, excited by a constant current for the average compensation of the bunches, or by a pulsed current in an option where the bunches would be individually corrected. It is planned to place these wires along the beam at positions where the beams are already in separate channels. They should be placed between the two channels for a horizontal crossing, and above or below for a vertical crossing. The beam-wire distance should be equal to the beam separation at the long-range interaction points (9.5σ). Studies of robustness show that they can be further retracted to 12σ, i.e., well in the shadow of the collimators. The wire excitation is 83 A m on each side of every crossing point. The β-function is not relevant (provided it is the same in both planes). The phase advance between perturbation and correction must be as small as possible, to correct all linear and non-linear terms. The strong focusing of the LHC low-β sections allows suitable positions to be found at 112 m from the crossing points, and space has been reserved.

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