EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 370

LHC BEAM INSTRUMENTATION CONCEPTUAL DESIGN REPORT

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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.

During the last years, basic design and parameters of the LHC have evolved continuously. The present description of beam instrumentation and diagnostics is based on the most recent set of nominal LHC parameters.

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Geneva, 22 February 2000

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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.

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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 should be given to the system for the rings and the transfer lines, which latter form 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 different, as the majority of the ring pick-ups is at cryogenic temperatures whereas all transfer line pick-ups are at room temperatures.

For each transfer line 26 horizontal and 27 vertical monitors are required, giving a total of 106 monitors, (Section 8).

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 The Beam Position Monitors (BPM)

The sensitivity limit of the signal processing electronics together with the requirement of obtaining better than 1 mm precision for trajectory (single pass) measurements, dictate the minimum signal to be obtained off the pickups.

Hence the original design was based on strip-line couplers in order to deliver ample signal for a compensation of cable losses, as the signal treatment electronics was located up to 700 m far from the pick-ups. In 1996 it became clear that the radiation levels in most parts of the ring will be so low that the installation of distributed electronics will be possible.

1.1.1 The choice of button electrodes for the arcs

A button electrode of 24 mm diameter, that is the maximum of which four pieces can reasonable be fitted on a beam tube of 44 mm diameter, has a transfer impedance of about 1.5 Ω, to be compared to about 10 Ω for a 20 cm long and 13 mm wide coupler.

Taking as smallest beam intensity the pilot bunch with 5.10^9 particles, an impedance of 1.5 Ω yields a total signal of about 900 mV (peak to peak). This reduces, after a band-pass filter centred at 80 MHz with a bandwidth of 40 MHz, to a signal level which is a factor of 2 higher than the sensitivity limit of a fast discriminator. With this safety margin in mind, 24 mm large button electrodes have been chosen for the LHC ring. An additional advantage of the low signal voltage produced by the button is the negligible amount of electrical loss in the cryogenic cables connecting the pick-up electrodes to the outside of the cryostat. In this case the design of the cryogenic cables can be focused on reducing the cryogenic load due to heat conduction.

A lot of care is given to the reliability aspect of the vacuum properties of the button electrodes and on the electrical contact to the cryogenic cables. The whole beam position monitor is welded to the 6 meter long beam screen, which in turn, together with cryogenic tubing, connects the monitor tightly to the quadrupole. An exchange or repair of broken monitors is very difficult in situ and hence for a repair one will probably have to exchange a whole short straight section. Again this is an advantage of the button design, as at least a broken button electrode could be exchanged in situ.

For the transfer lines, the 34 mm buttons from LEP will be recuperated and installed on a circular beam tube with 60 mm inner diameter. This detector delivers a little more signal than the 24 mm buttons for the rings.

1.1.2 Directional couplers close to the interaction points

Close to the interaction points both beams will circulate in the same beam tube. In order to obtain a beam position reading for each beam, directional couplers are foreseen. These couplers are conventional strip-line couplers, (about 14 cm long), with vacuum feedthroughs on each end. Computer simulations indicate that a separation of 36 dB (~ factor 50), between the signals of the two beams can be obtained. The signal from the couplers is larger than from the button monitors. The excess of signal will be used up in longer signal cables in order to have the electronics in a radiation-shielded alcove.

1.2 Alignment of the arc pick-ups

The requirements for the precision of the mechanical and electrical offset of the BPMs compared to the magnetic quadrupole axis are quite moderate, as for most other proton machines. A tolerance of 0.5 mm rms has been specified, but nevertheless due to the additional difficulties of alignment in case of a superconducting machine, a great effort has to be made to obtain these specifications [1].

In order to verify the quality of the alignment, and in case that during a later stage of the LHC exploitation a higher precision is demanded, installations will be foreseen to measure the alignment with the beams (k-modulation technique).

For this, the strength at each individual quadrupole can be slightly modulated with an additional excitation winding. The excitation frequency is typically around 1 Hz. In case the beams are steered by local bumps through the centre of the modulated quadrupole, no residue of this modulation frequency can be detected on a sensitive monitor somewhere in the ring. The reading of the beam position monitor at the excited quadrupole is then equal to the offset, mechanical and electrical, of the monitor. The precision by what the offset can be determined this way is of the order of 50 μm.

This beam-based offset measurement is a very time consuming procedure. Although many quadrupoles can be excited in parallel by using different excitation frequencies, the first set of BPM corrections can only be expected after some months of machine running. Therefore the beam-based offset measurement is not a tool for improving the closed orbit quality during the first weeks of commissioning of the LHC.

1.3 Signal processing

Table 1 shows the dynamic range of bunch currents respectively total beam currents, which has to be covered by the orbit system. Looking at Table 1, 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.

Filling Scheme	bunch intensity [10^9 charges/bunch]	Number of bunches	Total intensity [mA]
Pilot Bunch	5 := 0 dB	1	0.01 = 0 dB
TOTEM	~10 = ~6 dB	36	~3 = 30dB
Nominal	110 = 26 dB	2835	535 = 95 dB
Ultimate	170 = 31 dB	2835	850 = 100 dB

Table 1:Dynamic range in bunch currents and total currents to be covered by the LHC orbit system.

Technically that 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 bunch intensities one finds only 31 dB. Allowing for another 9 dB 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.

This range could be covered by a phase processor, like the one used in the LEP narrow band system, or by logarithmic amplifiers as proposed for the SSC. Detailed studies [2] on linearity, noise figures, radiation resistance of components, long term stability and cost, have lead to the choice of a phase processor. This circuit, called wide-band time normaliser, is a completely new design made at CERN [3] in order to achieve the requested bandwidth of 40 MHz, which could not be achieved with the old LEP design.

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.

1.4 Acquisition system

The acquisition system will be distributed over 260 electronics stations all around the ring. The position will be underneath the middle dipole of each second half cell, where the estimated radiation dose is of 1 Gy/year. The signals from pickups will be routed through 30 m long cables to the front end electronics. Simulations have shown that for a certain quality of the cables the differential variation of the propagation between one pair of pickup cables does not contribute significantly to the electrical errors of the system.

A significant part of the design and construction of the acquisition system is hoped to be done in collaboration with TRIUMF. Presently a group of people from TRIUMF are designing the prototypes of 70 MHz lowpass filters, a digital acquisition board and software for beam tests of the front end electronics during summer 2000. In case this collaboration will be extended for another five years the above work will continue into the full installation cycle of the LHC orbit system.

The experience in LEP has shown that an orbit system can only be fully exploited with a powerful software in the acquisition system. The standard requirements of single turn trajectories and orbit measurements (i.e. the average of position measurements over a sufficient number of machine turns) can easily be met. It should be clear that not the whole 2835 orbits will be uploaded to the control room. The user will be given the choice of obtaining the average orbit of all bunches, the average orbits of all batches (243 bunches) or the average orbits of up to 16 selected bunches.

In LEP, the possibility of measuring the beam position over more than 1000 consecutive machine turns has led to numerous important applications. For example the measurements of the machine lattice functions, search for machine coupling sources, phase space plots to search for machine resonances and the measurement of the dispersion function by exciting synchrotron oscillations. Such a wide range of application programs will also be implemented for the LHC system.

The acquisition electronics will be made self-triggering on beam signals. As a consequence, only external timing gates for the identification of individual bunches have to be applied. With 25 ns of bunch spacing, a timing jitter of 2 to 3 ns rms and a slow drift due to day/night or summer/winter conditions of 2 ns can be tolerated for these gates. This performance has recently been achieved in LEP by a distribution of a timing reference, via optical fibers all around the ring.

Due to the location of the electronics in the tunnel (not accessible during machine operation), much importance will be given to remote diagnostics of the system.

1.5 Expected performance

Table 2 summarises the expected precision of the BPM system (rms values) in the arcs and has to be interpreted in the following way:

- The overall limiting factor for absolute precision is determined by the mechanical alignment of the BPM with respect to the magnetic axis of the quadrupole. The value of 700 µm has to be added in quadrature to the other electrical errors listed in Table 2.
- The effect of the alignment error can be reduced by more than a factor of 10 after the measurement of the offsets with the k-modulation technique.
  It should be clear that several month of stable machine running will be needed before the offsets of all BPMs will be measured to the quoted precision.
- Two different values describing the precision of the system are listed:
  1) Accuracy: measurement of the beam position including all electrical errors. This value summarises the effects of the calibration system imperfections, stability and tracking errors of the discriminators in the wide band normaliser and the non-linearities of the BPM within a radius of 15 mm.
  2) Resolution: smallest variation in beam position that can be measured. This value is dominated by noise sources in the system and hence depends on the bunch intensity. The above values for accuracy and resolution are listed for the two extreme cases of beam intensity:
  - pilot: bunch intensity close to sensitivity limit of the system.
  - nominal: This is the bunch current for luminosity production. It represents the best conditions for the BPM system.
- The above values for accuracy and resolution are also given for two modes of acquisition:
  1) Trajectory: single beam passage measurement. This figure has to be used for all trajectory measurements and also for measurements of beam oscillations. In the case of the nominal beam we distinguish between a single bunch of nominal intensity and the average of all bunches within a revolution of the machine.
  2) Orbit: beam position measurements averaged over a sufficient number of turns. Most likely a value of 224 turns (corresponding to 20 ms acquisition time) will be chosen like in LEP in order to average over a complete period of the main power supplies. This figure represent the increase in precision compared to single shot measurements following pure statistical laws until the precision becomes limited by various systematic effects.

1.6 Closed orbit feedback

Local orbit feedback is intended for critical sectors of the machine:

- The two cleaning insertions around IP3 and IP7 will have four series of collimators where any closed orbit drift must be eliminated in both planes. A typical local orbit

- feedback system consists of 5 corrector magnets in each plane and, for each beam and in each straight section (from Q6 left to Q6 right), there will be 10 button pickups. Four correctors are enough to determine both the position and the angle of the beam at a given location. The fifth is used for redundancy. The drift of the closed orbit is expected to be less than 0.5 mm per hour. The regulation frequency will be 0.5 Hz which is solely determined by the corrector magnet (R=67 m, L=20 H) and the power supply (±600 A, ±55 V). At present the tolerance requirements for this regulation loop are not clear.

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

Table 2: Expected rms precision of the BPM system.

- At the two injection points in insertion 2 and 8 the closed orbit will also have to be kept in position and angle in both planes, in order to avoid any blow-up of the injected batches. A similar feedback system will have to be provided with 5 correctors in each plane looking at several pick-ups around the injection point. This system will be working during the filling time at 450 GeV.

For the general closed orbit correction of each beam around the whole circumference, a global feedback system will use all 255 correctors in each plane and all 512 pick-ups. Concerning the implementation details of all these feedback systems it is not clear at the moment, whether different installations will be needed or whether all the above functionality can be realized by one central system. All orbit data will be transmitted at a rate of 10 Hz to the PCR and the correction signals to the power supplies can also be applied at a maximum rate of 10 Hz. Hence all orbit feedbacks could be executed in a central computer. The distinction between local feedback or global feedback would be made by the number of pickups and correctors, by the correction algorithm and by the feedback speed.

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 super-conducting 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 middle. All BLMs 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 MHz**.** 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, of about 400 m each. 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, for the two beams, 8 primary collimators and 2 in LSS3. These collimators will have to be equipped with fast detectors of type Aluminium Cathode Electron Multiplier, (ACEM), for which the analogue signal will be sampled at 40 MHz to identify each bunch losses. All collimators, (primary and the following four), will be equipped with an ionisation chamber integrating over the length of a batch (7 µs).

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. Therefore an integration time of 10 ms would be adequate and a sensitivity of 10^5 p per 10 ms would be sufficient for fast losses.

The signal given by the shower which can be detected outside the cryostat is far weaker but it has been computed carefully with the program GEANT, [4]**.** Taking into account the maximum position errors of the beam screens inside a quadrupole and the adjacent dipoles, and the modulation of the beam envelope, it has been possible to localise halo losses over a distance of –7 m to +3 m, measured from the centre of each quadrupole in the direction of the beam [5]. The use of micro-calorimeters to detect the heat deposited close to the vacuum chamber inside the cryostat has been contemplated for some time [6]**.**

However, since most particle losses will happen in the first half of the quadrupoles [5], the induced signal at the downstream end will be too small for temperature detection. Three short detectors will be placed on each side of the cryostat in the plane of the beams at the best longitudinal positions, and the detected signal levels will be at least 5 times higher for the closer beam, which will allow for beam identification.

Standard ionisation chambers [7] 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 [8] would also do 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. Scintillators coupled to a photo-multiplier could also be considered as a solution. Their surfaces can be made much larger than the PIN diode ones and they can be shaped to reach optimum sensitivity. These detectors can be used in either linear (integration) or counting mode. All types of detectors mentioned above have been thoroughly tested [9] and the choice has 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 azimuthal and time distributions of losses. Some of the data will be logged in a permanent data base for off line treatment but all data should also be permanently filed in cyclic memories for post mortem analysis after any interesting event.

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 separated. One will also avoid proximity to perturbing elements, such as magnets and kickers. In the ring, the preferred location is close to IP4, for short transmission lengths of the analogue signals to the electronics racks located in the underground cavern or in the present LEP klystron galleries.

3.1 Bunch-to-bunch (AC) beam monitors

The use of transformers is proposed, in preference to pick-up electrodes, because of their insensitivity to beam losses. In order to obtain a bandwidth of the order of 1 GHz, they will be of a single-turn variant which one commonly calls wall-current-monitor. Ferrite loading will extend the lower cut-off frequency.

One of the tasks is to observe the passage of beams in the transfer lines and in the ring. The other task is to measure the charge of the beams in the lines, on their first turn after injection, and at their ejection to the dumps. This requires integration, which can be done either on the analogue signal, using integrate-and-hold circuits, or by treating the data after digitisation, and has to be done for each bunch individually. 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. This will, however, not permit injection efficiency of full intensity beams to be determined with a resolution corresponding to permissible beam loss.

Once injection is completed and the beams are circulating, the fast beam transformers will serve to determine the number of protons contained in each bunch, again with 1% precision. For practical reasons, this will not be done on a single turn, which is acceptable as this information does not require continuous surveillance.

As complement, an opto-electronic device inserted into the synchrotron light telescope (see Section 5.4.2) is under study. This device is based on single photon detection and will be able to measure the longitudinal charge distribution on a statistical basis by making a histogram of the arrival time of synchrotron light with respect to a stable RF-clock. The main advantage of such a device is the large dynamic range of several orders of magnitude, in principle only limited by the available measurement time.

3.2 DC beam transformers

They are based on the principle of the magnetic amplifier, using a null-method, and will measure the intensity, or current, of the circulating beams. In view of their eminent importance for any kind of operation or machine experiment, at least two will be installed per beam, to assure availability**.** DC beam transformers currently reach a resolution of 1 μA, corresponding to 5.10^8 protons in an LHC ring. The output drift is about 1 μA over 10 s, 2 μA over one day, and 3 μA over a week, but a significant improvement may be achieved before the LHC start-up.

The pilot beam constitutes 9 μA of circulating current, and can thus be measured with a resolution of 10% (against 1% with the fast beam transformers). Any possible improvement is of course welcome.

In summary, the following numbers of beam transformers are foreseen:

Type	2 transfers SPS-LHC	2 transfers to dumps	2 Rings	**Total**	Length
Fast	4	2	4	10	1 m each
DC	0	0	4	4	1 m each

Table 3: Beam transformers needed for both rings

3.3 Lifetime measurements

3.3.1 Use of the DC monitor

A resolution of 1 μA (5.10^8 protons) on the one hand, and a nominal beam intensity of 0.54 A (3.10^{14} protons) on the other, means a dynamic range of 10^6, requiring an analog to digital conversion of 21 bits, which is commercially available for low bandwidth.

When measuring beam decay rate, a reasonable interval between readings is 10 s. In that interval, the output drift corresponds to 5.10^8 protons. Assuming a beam intensity of 3.10^{14} protons and a lifetime of 25 h, the basic decay rate is around 3.10^9 p/s, which is then measured with 2% accuracy in a single 10 s interval, and with correspondingly higher accuracy when averaged over several data points. Excessive increases in the decay can then be detected reliably and an alarm given.

3.3.2 Use of the AC monitor

In LEP the AC monitor is successfully used for the measurement of bunch lifetimes. Although technologically it is more difficult than using the DC-transformer the advantage of having a lifetime reading for each bunch is obvious.

In LEP the bunch current is measured using a peak-and-hold device triggered by an externally applied timing reference with about 1 ns jitter (r.m.s.). Taking into account the 22 μs bunch distance the bunch signal can be filtered before digitisation with a 500 kHz low-pass and in consequence for an average of about 5000 readings ($\cong$ 0.5 s) a resolution as low as 10 ppm is achieved. This performance allows lifetimes of 20 hours to be measured within 10 seconds to better than 10%.

Extrapolating this performance to the LHC and counting on the improvement of two orders of magnitude for the timing reference (already achieved for the LEP streak camera), a similar or slightly worse performance can be expected for the LHC although the bunch distance is only 25 ns.

4 TUNE AND CHROMATICITY MEASUREMENT, DYNAMIC APERTURE STUDIES

4.1 Tune 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 were 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.

Any of the methods described in the following allows chromaticity to be measured by altering the momentum through altering the RF frequency. Details on this and further specific ways of measuring chromaticity are described in a separate paragraph (4.2) on chromaticity measurement.

4.1.1 Use of the transverse feedback system

In the simplest case, for naturally unstable beam conditions, opening the feedback loop or reducing its gain for a short time, say 10-100 ms, will lead to a build-up of coherent oscillations to a measurable level. It is not permissible, however, to tamper with such a vital system in the presence of a high intensity beam.

Alternatively, signals may be injected into the feedback loop, either white noise, for broad-band spectral analysis, or a swept-frequency sine-wave. The latter allows the measurement of the beam transfer-function, i.e. the response in amplitude and phase. The peak of the resonance indicates the Q-value, whereas its width yields information on the chromaticity. This also is a method limited to machine experiments.

In a further variant, the resonant condition of excitation is maintained through a feedback circuit (phase-locked loop, successfully used at LEP and other machines), and the Q-value is then read continuously from the excitation frequency. With such continuous excitation, care must be taken to limit the resulting emittance growth. Using, for highest sensitivity a tuneable resonant pick-up to observe the beam's coherent oscillation, sub-micrometer amplitudes will suffice for measurement. Evidently, continuous Q-measurement during critical phases of the machine cycle, in particular ramping and beta squeezing, is a great help and convenience.

If, through resonant excitation, the amplitude is made to build up to a larger level, the value of the betatron function and the phase advance can be measured all around the ring, with the help of the closed orbit measurement system. With all methods in which a signal is injected into an active transverse feedback loop, one has to be aware of an inherent incompatibility between damping and Q-measurement: the damping action will broaden the tune resonance to an extent precluding the desired precision of 0.001 of the Q-measurement. This incompatibility may be circumvented by introducing in the frequency response of the feedback system a zero-gain notch at a frequency high enough (20 MHz are considered here) that instabilities are not to be expected. For Q-measurement, the beam would be excited, and its resulting coherent oscillation observed with a resonant PU, at an odd harmonic of the notch frequency.

4.1.2 Excitation of coherent oscillations with a kicker

Although this classical method does cause an emittance increase, a very sensitive PU may permit this to be quite small (a betatron amplitude of 50 μm probably is sufficient). On operational beams, a measurement may be carried out only for a limited number of times. The Q-spread is visible in the de-coherence of the PU signal. Kicking the beam offers additional possibilities:

- Coupling is easily measured, applying a single kick in one plane and observing the oscillation amplitude in the other plane.
- The kicks can serve for the measurement of chromaticity, via the head-tail phase shift, as described in a separate paragraph (Section 4.2.2).

Four kickers are needed, a horizontal and a vertical one on each of the two beams. They are made from the same modules as the dump-kickers and will be located in the long straight section 6, two on either side of the intersection point, close to the quadrupoles Q4.

The shape of the kick is a half-sine wave with a superposed 3rd harmonic. Its length covers 1 batch of 243 bunches, in such a way that 80% of the bunches see between 80 and 100% of the peak value, whilst the adjacent batches are unaffected. Given that, for technical reasons, the kick strength can be varied by a factor 64, its range is chosen, for each plane, such that at the resonant PU at Q3, the smallest amplitude at 450 GeV is 0.05 mm (probably the smallest useful value), and the largest amplitude at 7 TeV is 0.2 mm (a safe value for reliable measurement). A repetition rate of 2 Hz is adequate to follow the evolution of Q-values and chromaticity during the critical parts of the cycle.

Data related to Q-kickers are summarised in Table 4.

4.1.3 *Passive methods*

The prominent passive method to measure Q is Schottky-scans. Although these may be feasible on bunched beams, a question which needs further study, use on debunched beams only is considered here. Because of unavoidable beam losses (either due to the absence of a gap in the beam for the ejection kick, or due to the limited efficiency of re-bunching), and because the transverse feedback cannot cope with debunched beams, this method is limited to low-intensity beams. However, it provides a wealth of information: Q, Q-spread, chromaticity, and rms betatron amplitude. This makes it particularly useful for the study of persistent current effects.

Number of kickers (1 H and 1 V per ring)			4		
Overall length per kicker			2		m
Kick shape: half-sine with superposed 3rd harmonic:					
base-length			9.3		µs
between 80 and 100% of peak value			6.3		µs
repetition rate			2		Hz
Approximate values of the β function and amplitudes:			H	V	
β	at kicker	at all energies	200	590	m
β	at PU	at all energies	235	235	m
min. osc. amplitude	at PU	at 450 GeV	0.05	0.05	mm
max. osc. amplitude	at PU	at 450 GeV	3.20	3.20	mm
max. osc. Amplitude	at PU	at 7 TeV	0.20	0.20	mm

Table 4: Q-kickers and related data

Schottky-scans are not rapid; they may take a fraction of a second. It has been checked that energy loss through synchrotron radiation is not an obstacle: even at 7 TeV, the fractional energy loss is only 10^{-5} per second.

Whereas Schottky-scans are based on fluctuations in the incoherent motion of the beam particles, one can also, without any action on the beam, scan the PU signal for coherent modes (so called "pseudo-Schottky-scans"), stemming from residual coherent oscillations. If their amplitude is sufficiently large, Q can be determined. This kind of measurement has the advantage that it can be made on bunched beams.

4.2 Chromaticity[*] measurement

The tight tolerance on beam parameters for successful LHC operation implies a good knowledge of the chromaticity throughout the cycle. Described in the following sections 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.

Other methods of calculating chromaticity include measuring the beam transfer function, and excitation of synchrotron sidebands. These methods are however of limited usefulness for LHC measurements due to their associated problems mentioned below, and will therefore not be discussed any further.

The drawbacks of measuring chromaticity via beam transfer function measurements, i.e. extracting the chromaticity information from the width of the tune resonance (or in time domain from the damping time of the coherent betatron oscillation) are:

- Long measurement time required.
- Requires a good knowledge of how $\Delta p/p$ changes with energy, if the measurement principle should be used during energy ramping.

The drawbacks of measuring chromaticity via synchrotron side-band excitation are:

- Q_S too low for the side-bands to be distinguished from the main tune peak.
- Suffers from resonant behaviour of lattice not linked to chromaticity.

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 [10] 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.

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[*] The chromaticity is defined as dQ/(dp/p), with Q around 60.

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 high frequency or transverse feedback strip-line pick-ups described in Section 7.2, and digitised using a fast (>2GS/s) ADC with a high analogue bandwidth (>1GHz).

The chromaticity can be calculated by reconstructing the betatron oscillations of two positions within a single bunch, one at the head of the bunch and one at the tail. The turn-by-turn phase difference evolution between these two signals is found by performing a Hilbert transformation or a sliding harmonic analysis on the data sets. Once known, the turn-by turn phase difference can be fitted with the theoretical phase difference evolution function to provide a value for the chromaticity. Initial studies at the SPS and HERA suggest that a resolution of 1 in chromaticity is possible using this technique.

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.

4.3 Dynamic aperture scans

The kickers described in Section 4.1.2 used for tune measurement, are not strong enough to perform dynamic aperture scans by kicking the beam. For these studies, deflections of the order of 8 $\sigma_{H,V}$ (rms transverse beam distributions) are required. Investigations made in view of using a single kicker system with enough dynamic range to perform both applications, with deflections from 50 µm at the pick-up at injection energy for Q measurements to 8 $\sigma_{H,V}$ at 7 TeV for dynamic aperture studies, were not successful and led to the conclusion that two independent kicker systems are necessary. Hence kickers with the same dynamic range as the Q kickers but 15 times more powerful were chosen for this application. They will be installed adjacent to the latter.

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. Hence, a measurement of the beta function has to be provided.

5.1 Measurement of the local <β> values

The 1000 turns method used for this purpose in LEP [11] will also be available in the LHC orbit acquisition system as mentioned in Section 1.4. However it presents two main drawbacks: a significant transverse kick of the circulating beam is required and it works marginally when the two beams are colliding. Hence, the feasibility of another method is under investigation in LEP. The average value <β> of the amplitude function within a quadrupole is measured by the gradient variation method, using the hardware installed for k-modulation (Section 1.2). While the quadrupole gradient is modulated, the resulting betatron tune variation is measured over a large amount of samples in phase lock loop (PLL) mode. With this averaging, it is hoped to achieve a precision of the order of 1% on <β>, while keeping the modulation amplitude at a level low enough to induce no noticeable increase of the LHC proton beam emittance. The preliminary tests performed in LEP are encouraging.

5.2 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 a direct visual information, in the transfer lines and for the first turn in LHC. Optical Transition Radiation (OTR) screens are evaluated in the SPS transfer lines and look promising [12,13]. Their advantage is to be made of thin foils, aluminium or titanium of a few microns, which induce a negligible beam blow-up and to generate a light signal following exactly the time structure of the passing proton beam. Hence, these screens give also the time resolved profiles as demonstrated in [13]. The OTR screens will be supplemented by thicker and slower Al_2O_3 (Cr) screens for studies with low density pilot bunches.

Approximately twenty screens are foreseen in total for TI2, TI8 and the LHC injections. In each LHC ring, eight screens are foreseen for first turn studies. A thick screen, made of conventional Al_2O_3 (Cr) material of proper size (~ 40 cm diameter), except may be in the centre where a thin OTR screen could be used, will be installed in front of each dump block for assessing the beam dumping process. A similar application has given good results in LEP [14].

The images will be acquired either with TV type detectors for observing the batches or with 32 strip photomultipliers for bunch to bunch acquisitions.

5.3 Injection matching monitors

Emittance preservation in the whole accelerator chain is a major concern in the LHC project. An OTR screen monitor is installed in the LHC to help achieve this goal. This monitor will measure the profiles of the injected beam over several dozen turns before the beam will be dumped [15]. The absence of profile modulation indicates that the matching from SPS to LHC is perfect. The method will permit to determine and correct the mismatch in order to reduce the emittance blow-up by filamentation to less than a few percents. The blow-up and the losses induced by this monitor during the measurement are negligible over the number of turns required. The detector makes use of a CCD controlled in a dedicated mode. Tests have been carried out in the SPS to evaluate the method and develop further the instrument. The monitor has shown its ability to detect mismatches and to optimise the matching for minimising the blow-up through filamentation to values as small as 0.1% [16]. The preservation of matching can be monitored qualitatively during the filling process with the help of a non-intercepting profile monitor, see Section 5.4.2 and Section 5.4.3, or a quadrupolar pick-up, see Section 7.4.

5.4 Circulating beam profile monitors

Only a limited amount of material can be inserted into a circulating beam, and only for a short time if the obstacle has a density close to that of a solid. Synchrotron light monitors are ideal monitors from this point of view.
Rest gas, ion spectrometer, luminescence and Ion Beam profilometers are, in that order, the next in line of least disturbing monitors and are described later.
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.

Compton scattering, very fast wire scanners, beam-beam and X-ray synchrotron radiation detectors have been considered but were not retained.

5.4.1 Wire scanners

In the light of the LEP experience, medium speed (0.5 to 1 m/s) 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. Experience in LEP and in the SPS leads to the use of an available design of linear wire scanners [17]. The dense core of the beam is traversed at a speed of the order of 1 m/s, and Carbon wires with a diameter below 50 µm are used. Studies made for LHC have demonstrated the interest of increasing the speed of the present wire scanners to 2 m/s, which will permit to measure the profiles of up to 155 bunches of nominal intensity at 7 TeV [18], or more bunches with a modified design [19].

At least four wire scanners, one for each plane and for each particle type, will be located in an area where the beams are farthest separated and where the dispersion is small. Profile monitoring will be done using the secondary emission signal from the wire, if available, or the acquisition of the secondary particles produced by the interaction of the circulating protons with the wire.

5.4.2 Synchrotron light monitors

Synchrotron light monitors operating at near-UV wavelengths are considered as the basic instrument for measuring continuously profiles from 0.45 to 7 TeV. The design is based on the monitor which has proven its capabilities over the years in LEP1 [20]. Two major technical difficulties in LHC are the small amount of light emitted at injection energy and the small beam size at top energy [21]. Work is being done on both topics with theoretical studies and with beam tests in LEP and SPS to predict more precisely and to improve as much as possible the performance of such an instrument. 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. To generate enough light at injection, the magnetic field needs to be at least 1 T at 450 GeV and will be ramped up to about 6 T at 3 TeV, and stay at this level from there onwards. The orbit bump will hence decrease as the energy increases beyond 3 TeV, but with a 40 m drift length, it will be possible to extract enough light even at 7 TeV. The main disadvantage of this monitor is the small beam size at collision energy, where the image broadening due to diffraction will be of the same order as the beam size. A wiggler made with higher field magnets is under consideration, to go beyond the deflection limit at 3 TeV.

To have a precise measurement at collision energy, it is hence 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 where the arc cryostat is starting. To make this possible, it is proposed to enlarge the corresponding vacuum chamber in the electrical Distribution Feed-Box (DFB), to go at least to 50 mm with respect to the centre line and to extract the light through a window at the top of the DFB. With the proposed set-up, this monitor will be able to measure the beams from 2 TeV to 7 TeV, with the best precision achieved at 7 TeV in collision where the beam sizes will be comfortably large, σ_H~0.5 mm and σ_V~0.9 mm, with respect to diffraction. If the light can be extracted close to Q5, the parasitic light originating from D1 should be well enough separated from the D2 light to make low density beam tail measurements possible. Because of the large overlap in beam energy of the two monitor families, a cross-check will be easy, to guarantee the consistency of the results over the whole acceleration cycle. Due to the large bending radii of the beam orbits in both monitors, a major difficulty will be the alignment of the optical elements, typically to better than 0.1 mrad, which will be achieved with dedicated alignment tanks as in LEP.

The cross-calibration with the wire scanners will be made more straightforward than in LEP [11], by installing the wire scanners close to the synchrotron light monitors.

The monitors will provide real-time TV images for direct observation, as well as processed data for precise and possibly turn-by-turn observations, including instabilities and beam tail studies.

An adequate light source is also under consideration to measure longitudinal beam profiles in single photon counting mode and estimate off-bucket populations for machine protection.

5.4.3 Other profile monitors

To overcome the scarcity of synchrotron light around injection energy if the installation of the mini-wigglers close to IP4 is not possible and make continuous beam profile observation nevertheless possible, rest gas monitors, luminescence monitors, ion beam profilometers and ion spectrometers are under consideration. Tests are underway in the SPS to determine which are best suited for LHC, if a complement to the synchrotron light monitors is necessary.

A rest gas instrument made available by DESY [22] is installed in the SPS for evaluation. It makes use of the acceleration onto a Multi Chanel Plate (MCP) followed by a phosphor screen of ions or electrons produced from the ionisation of the rest gas by the circulating beam. Tests making use of the generated electrons together with a focusing dipolar magnetic field are encouraging for providing precision results [23].

A luminescence monitor, making use of the light production of N_2^+ molecules when excited by passing charged particles, has been installed in the SPS and evaluated [24]. The monitor has given good results in the SPS at an energy of 450 GeV with a local Nitrogen pressure bump as low as 5.10^{-8} Torr, which results in a negligible increase of the average pressure. The gas injection can be switched off when the D2 synchrotron radiation monitors generate enough light, i.e. above 2 TeV, or left on occasionally for crosscheck purposes at high energies.

Both monitors generate top and side views of the beams. The resulting light bands are observed by TV cameras. The images are transmitted to the control room for direct observation and processed for profile measurements.

Another possibility is to create a low-density ion-beam and to scan it across the LHC beams [25]. Suitable ion sources, with small diameters of a few tens of microns, are now available at a reasonable cost from the ion implantation industry. The ion-jet is deflected by the circulating beam, and the generated pattern is observed and compared to the pattern without circulating beam to obtain the beam density distribution. Such a monitor is under test in the SPS where it is giving encouraging results [26].

Finally an Ion Spectrometer [27] has been installed and tested in the SPS. It makes use of the acceleration of rest gas ions by the electric potential of the beam bunches and measures their energy by the deflection of the ions in an external magnetic field. The ions are then accelerated onto a MCP and the resulting electron beams impinge on a phosphor screen where the image is acquired with a CCD camera. The analysis of a sharp cut-off in this image yields the standard deviation of the observed LHC beam.

All these monitors can be cross-calibrated continuously with the synchrotron light telescopes up to maximum beam intensity and energy, and with the wire scanners at lower intensity, over the whole energy range.

6 LUMINOSITY MONITORING

The nominal LHC luminosity is 10^{34} cm^{-2} s^{-1}, with beams of 2835 bunches containing each $1.1.10^{11}$ 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 spacing of 7.5 m (25 ns) was chosen to accommodate the timing requirements of the two experiments running in parallel and to optimise the overall accelerator performance. A crossing angle of $\phi = 200$ μrad is required to avoid unwanted collision in the 110m long straight sections at each IP.

6.1 Machine requirements

The structure of the LHC beams involves ‘Pacman-type’ long-range beam-beam effects which will affect the luminosity of the bunches at the beginning and at the end of each train. A bunch-by-bunch luminosity monitoring is then 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 to be conceived for a 40 MHz operation. The basic requirements for the LHC luminosity measurement are summarised below [28].

- Statistical error $\delta L/L \sim 1$ % over ≤ 1s for $L \geq 10^{30}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Absolute luminosity from cross calibration against experiments
- Bunch-by-bunch (40 MHz bandwidth) luminosity diagnostics [29]
- Reasonable acquisition time for 1 % precision over full dynamic range (10^{28} to 10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
- Background less than 10 % of luminosity signal
- Available in all IPs

6.2 Instrumentation

At the nominal luminosity, secondary particles produced in proton-proton inelastic collisions carry about 1 kW beam power. Special purpose absorbers, TAS and TAN, have been designed to prevent this high energy flux from quenching the super-conducting magnets in IR1 and IR5 and provide at the same time a spatial localisation of the induced activation. The TAS copper absorbers, at about 19 m from the IPs, are meant to stop forward collision products (mainly charged pions and photons), escaping from the vacuum pipe in front of Q1. The remaining fraction of charged secondaries is practically captured in the triplets and in the D1 dipoles. About 300W of beam energy released by inelastic p-p collisions is transported by neutrals (essentially photons and neutrons), and absorbed in the TAN neutral beam dumps at about 122 m from IP1 and IP5.

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. Over the past year, LBNL has developed a proposal [30] for instrumenting, with appropriate detectors, the absorbers at the high luminosity IPs to provide adequate tools for luminosity diagnostics and optimisation. Information on bunch-by-bunch luminosity, collision offsets and dynamic beam sizes at the interaction would be available with single-element detectors at the TAN only. Detection of the actual beam-beam crossing angle and of the transverse position of the IP could moreover be implemented by instrumenting the TAS and the TAN elements with segmented detectors.

Luminosity monitors at the other IPs could also be implemented adopting the same philosophy to dummy absorbers in IR2 and IR8.

Decision whether the TAN only, or both the TAN and the TAS, will be instrumented, and whether the low luminosity regions in IR2 and IR8 will be equipped with luminosity monitors, as IR1 and IR5, will be made following the development phase, in a review in the year 2002 [28].

Several detector candidates capable of fulfilling the speed requirements for bunch by bunch measurement are considered:

- Water Cerenkov
- Transition radiation
- Liquid ionisation
- SEM
- Cold silicon detectors
- Gas ionisation chambers
- CdTe crystals
- Displacement current in a dielectric

Reliability considerations for maintenance-free operational conditions as dictated by the high particles flux expected at the absorber locations have reduced the choice to the last three concepts. The CDR [28] Committee report recommended that suitable tests be performed on the SPS test beam in order to characterise the different detectors. The situation should be revisited in the year 2002, after completion of the tests, and decisions taken on further implementations.

7 SPECIAL PICK-UPS

The following devices have been discussed for dedicated observations and studies:

7.1 High frequency pick-up

The purpose of a high frequency pick-up is to detect position and intensity signals for a wide band of frequencies (~ 0.5 to ~ 12 GHz) centred on the cut-off frequency of the LHC vacuum chamber. A smooth-response exponential coupler [31] connected via passive hybrid circuits to short large-diameter air core cables is proposed. The pick-up will be equipped with electrodes in both planes. One unit will be installed per LHC ring. Lower-frequency rigid bunch motion can be observed with standard beam position monitors at any multiple of the bunching frequency.

7.2 Strip-line pick-ups

The transverse feedback and tune measurements will use sensitive strip-line pick-ups. A total of 16, each measuring in the horizontal and the vertical plane, are required, and will be located in the dispersion-suppressors of IR4. The strip-line will have an approximate length of 15 cm and their sensitivity will be six times higher than for the standard buttons.

7.3 Schottky pick-up

Tune and transverse emittance measurements during colliding beam operation may be possible with a bunched beam Schottky pick-up. This can be achieved by observing

Schottky noise at frequencies beyond the bunch spectrum with high impedance tuned cavities operating at high frequency and connected to passive hybrid circuits. Signals will be down-sampled to permit measurement and acquisition at low frequency. Calibration of intensity signals with the standard intensity monitor is required. Such a Schottky pick-up has already been designed and built for the Tevatron in Fermilab [32]**.** Its exploitation was not successful due to perturbing features on the bunch profile. It is expected that these features will not exist on the LHC bunches [33] so that the monitor can correctly be exploited as planned.

7.4 Pick-up for detection of transverse quadrupole oscillations

The state of the betatron matching at injection can be checked with two such monitors per ring, one where β_H is large and β_V small, the other where it is the other way round. This function is important since the emittance conservation in the LHC is a critical issue. The monitors have to be designed and optimised for resolution and dynamic range. The pollution of the quadrupolar signal by dipole oscillations is a basic problem [34]**.** However, the transverse feedback system will damp these oscillations [35] so that the quadrupolar signal will dominate after one damping time constant and can from that moment onwards be observed up to the de-coherence time of the bunches.

7.5 Pick-up for the timing of the experiments

In each LHC ring, upstream each of the four insertion points where an experiment is installed, a pick-up made of one or a pair of button electrodes will be installed to provide each experiment with timing related to the beam passage.

7.6 Resonant coupler for tune measurement

(see Section 4.1.1)

8 TRANSFER LINES

Under this heading are grouped together the instrumentation for transfer to and injection into the LHC, first turn trajectory studies, ejection from the LHC and transfer to the two beam dumps.

8.1 Position pick-ups

The transfer lines TI2 and TI8 from the SPS to the LHC have a total length of about 5 km and in these lines 106 dedicated position pick-ups will be implemented with distributed electronics. This BPM system will differ from the main machine one due to the following characteristics: room temperature**,** only one plane measurement, no multi-turn acquisition, etc., and will therefore require a separate design. The accuracy of the measurement should be ±1 mm for a pilot pulse of 5.10^9 protons and ± 0.3 mm when trains of 81 pulses of 10^{11} protons are injected.

8.2 Profile measurements

Screens observed with cameras have made dramatic progress recently and can replace SEM-grids in most of the cases, while offering a far better spatial resolution. Therefore some screens will be installed in each transfer line, including those carrying the beams to the dumps, to observe beam size and position.

See also Section 5.2.

8.3 Intensity and beam loss (see also Section 3.1)

Measurement of intensity and of transfer efficiency will be made by means of beam transformers located at each end. Beam loss monitors, such as those foreseen for the machine, will be distributed all along TI2 and TI8 and also installed in the last part of these lines, in order to protect the electronics installed inside the transfer tunnels from excessive radiation levels and to prevent losses in direct view of LHC superconducting magnets.

Transfer line	**Pick-ups**		**Small screens**	**Beam transformers**	**Loss monitors**	**Large screens (40 cm)**	**Scintillators**
	H	**V**					
TI2	26	27	10	2	25		
TI8	26	27	10	2	25		
Two Dumps	6 ?	6 ?	6 ?	2		2	2

Table 5: Instruments required for the transfer lines.

9 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 maximum allowed time jitter for each of these signals is summarized in Table 6.

The beam synchronous distributed command system will be based either on a modified LEP Beam Synchronous Timing (BST) system [36], or the Timing, Trigger and Control (TTC) system [37] 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.

Timing System	**Peak-to-Peak Jitter**
400 MHz LHC RF	100 ps
40 MHz LHC bunch frequency	5 ns
11 kHz LHC revolution frequency	5 ns
Beam synchronous distributed commands	10 µs
Time of day	15 µs
Slow machine timing	1 ms

Table 6: Timing requirements for LHC beam instrumentation.

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 around 250 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. The choice of medium will depend on the outcome of current tests into the radiation resistance of fibre optic cables, and on the final specifications of the timing system.

Most of the specific LHC instrumentation will be located around IP4, where all the timing signals will be available, including the 400 MHz RF frequency.

It has not yet been decided whether the RF systems for each of the LHC rings will be coupled or de-coupled during the injection and acceleration of LHC beams. If they were to be de-coupled, two parallel timing distributions would be required to provide the necessary bunch synchronous timing for each ring.

10 LOCATION OF INSTRUMENTS AND ELECTRONICS

The location in the machine of the various instruments is described and justified in [38]. Table 7 summarised the location of the beam position monitors whereas the other instruments are recapitulated in Table 8.

Most of the beam position monitors and of the beam-loss monitors will have their front-end electronics located in stations regularly distributed below dipole magnets inside the machine and the transfer line tunnels. However, for instruments located in the insertion regions where there is no bending magnet, the radiation level will be such that the electronics cannot be left inside the tunnels. For devices, like for example the fast current transformers, which need the presence of close front-end electronics, reservations have been made in the various underground caverns or auxiliary tunnels. Concerning the other instruments, which can accept their electronics to be located at a few hundred meters, space will be available either in the physicists counting-rooms, which, in addition, will ensure accessibility during operation, or in surface buildings.

ACKNOWLEDGEMENT

The contributions of A. Burns, O Berrig, G. Gelato, R. Jones, and M. Placidi to the redaction of this report are gratefully acknowledged. The authors want to acknowledge also the collaboration between DESY and CERN for the development of the front end electronics of the head-tail sampler for chromaticity measurements.

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	Adjacent Quadrupole (number/type)	**Temperature** (K)	**Coil Aperture** (mm)	**Aperture #**	**BPM #**
arcs	360 MQ	1.9	56	2	**720**
Dispersion Suppressors in all insertions:					
Q11	16 MQ	1.9	56	2	**32**
in insertions 3 / 7:					
Q10 / Q9 / Q8	12 MQL	1.9	56	2	**24**
in insertions1/2/4/5/6/8:					
Q10 / Q9 / Q8	36 MQM or MQML	1.9	56	2	**60+12 C** **C=combined** **(DS4)**
Matching Sections					
1/5 Q7	4 MQM	1.9	56	2	**8**
Q6	4 MQML	4.5	56	2	**8**
Q5	4 MQML	4.5	56	2	**8**
Q4	4 MQY	4.5	70	2	**8**
2/8 Q7	4 MQM	1.9	56	2	**8**
Q6	4 MQM	1.9	56	2	**8**
Q5	2 MQY / 2 MQM	4.5	70 / 56	2	**4 / 4**
Q4	4 MQY	4.5	70	2	**8**
Inner Triplets 1/2/5/8					
Q2b	8 MQX	1.9	70	1	**8**
Q1	8 MQX	1.9	70	1	**8** ***bi-direction.strips***
Cleaning Insertions 3/7					
Q7	4 MQ	1.9	56	2	**8**
Q6	4 MQTL	4.5	56	2	**8 cold+4 warm**
Q5	4 MQW	warm	46	2	**16**
Q4	4 MQW	warm	46	2	**16**
RF Insertion 4					
Q7	2MQM	1.9	56	2	**4 C**
Q6	2MQLR	4.5	56	2	**4**
Q5	2MQLR	4.5	56	2	**4**
Q4	2MQR	4.5	56	2	**4**
Q3	2MQR	4.5	56	2	**4**
Dump Insertion 6					
Q5	2 MQY	4.5	70	2	**4**
Q4	2 MQY	4.5	70	2	**4**

Table 7: LHC BPM distribution
(button electrodes except in inner triplets)

	Designation	Code	Location	Approx. Length (m)	Total Number
Two Transfer Lines TI2 & TI8	Beam Current Transformer	BCTI	beginning & end of line	1	**2 per line**
	Beam Loss Monitor	BLMI	distributed outside line	0.10	**20 per line**
	Beam Position Monitor	BPMIH/V BPMI	distributed along line	0.36	**53 in TI2 / 53 in TI8**
	Screen	BTVI	distributed along line	0.36	**10 per line**
Two Injection Points	Screen	BTVI	1 upst. or downst. MSI	0.50	**1 / injection point**
			1 upst.& 1 downst. MKI	0.50	**2 / injection point**
			1 upstr. TDI	0.50	**1 / injection point**
			1 downst. IP between Q5&Q6	0.50	**1 / injection point**
Two Dump Lines	Beam Current Transformer	BCTD	1 at beginning of each line	1	**1 per dump line**
	Scintillator	BSCD	1 downst. dump block TDE	1	**1 per dump line**
	BPM or Screen	BPMD or BTVD	1 upst.septum MSD (in the ring) 1 upst. & 1 downst.diluters MKB	0.50	**3 per dump line**
	Large screen	BTVD	1 larger upst. dump block TDE	1	**1 per dump line**
Two Rings	Beam Current Transformer	BCT	around IP4	5	**1 assemblage / ring**
	Beam Loss Monitor	BLM BLMC	around each quadrupole around collim. blocks in IR3&7	0.10 0.10	**≅ 3000 per ring** **≅ 25 per ring ?**
	Beam Position Monitor:				
	4 buttons	BPM	in arcs, DISS, at Q7	0.50	**438 per ring**
		BPME	in LSS-see table	0.50	**14 per ring**
		BPMR	“	“	**12 per ring**
		BPMW	“	“	**18 per ring**
		BPMYA	“	“	**4 per ring**
		BPMYB	“	“	**6 per ring**
		BPMYC	“	“	**4 per ring**
	4 strip lines	BPMS	in inner triplets at Q1 & Q2b	0.50	**16 for 2 rings**
	Pick-up for eXperi. Timing	BPTX	downstr. D2 in IR1,2,5,8	0.50	**4 per ring**
	Pick-up for Trans. Damp.	BPDTH/V	at Q7and Q9 in IR4	within	**4 per ring**
	Pick-up for Q meas.	BPQH/V	at Q8 in IR4	BPM	**2 per ring**
	Pick-up for Radial Loop	BPRL	at Q10 in IR4	“	**1 per ring**
	High Frequency Pick-up	BPHF	around IP4	1	**1 per ring**
	Schottky Pick-up	BPSCH/V	at Q3 in IR4	1	**1 H & 1 V per ring**
	β Matching Pick-up	BPBMH/V	at Q3 in IR4	1	**1 H & 1 V per ring**
	Resonant Coupler Pick-up	BPRCH/V	at Q3 in IR4	1	**1 H & 1 V per ring**

	Profile Monitors:				
	Synchro. Rad. Telescope	BSRT	Betw.D2 and Q5 in IR1 or IR5	30	**1 per ring**
	SR telescope alignment	BSRTA	upstream Q4 in IR1 or IR5	0.50	**1 per ring**
	Wire Scanner	BWSCH/V	at D2 in IR1or5 & at Q3 in IR4	0.50	**2 H & 2V per ring**
	Under study as options:				
	Synchr. Rad. with Wigglers	BSRW	between Q4 and Q3 in IR4	30 to 40 m	**1 per ring**
	Ion Scanner	BISCH/V	at Q3 in IR4	5	**1 H & 1 V per ring**
	Rest Gas 2	BRGH/V	at Q3 in IR4		**1H & 1 V per ring**
	LUminescence	BSLU	at Q3 in IR4		**1H & 1 V per ring**
	Ion Spectrometer	BISP	at Q4 in IR6	1	**1 per ring**
	Screen for Single Turn	BTV	upstr. Q4 in IR1 & IR5	0.50	**8 per ring**
			between Q6 & Q5 in IR2 & IR8	0.50	
			between Q5 & Q4 in IR3 & IR7	0.50	
			between Q4 & Q3 in IR4	0.50	
			upstr. septum MSD in IR6	0.50	
	Screen for B Matching	BTVMH/V	at Q3 in IR4	1	**1 H & 1 V per ring**
	Q Kicker, Apert. Kicker	MKAH/V MKQH/V	at Q4 in IR6	5 to 10	**1 assemblage/ ring**

Table 8: List of beam instruments