CERN
CH-1211 Geneva 23
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the
Large
Hadron
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project

LHC Project Document No.
LHC-BPM-ES-0004 rev 2.0

CERN Div./Group or Supplier/Contractor Document No.
SL/BI

EDMS Document No.
327557

Date: 2002-02-11

Functional Specification

MEASUREMENT OF THE BEAM POSITION IN THE LHC MAIN RINGS

Abstract

This Functional Specification covers the Beam Position Measurement System (BPM System) distributed along the LHC rings. The observables provided by the BPM System are the beam trajectories, the closed orbits, the beam oscillations measured at one azimuth in the machine and optionally the bunch currents. The beam parameters that can be calculated from these observables are identified. The requirements arising from LHC beam dynamics are used to set tolerances on the beam parameters. Given typical LHC operations scenarios, these requirements and tolerances are translated into specifications for the BPM System.

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History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
1.0	2001-10-25	1-22	Submitted for approval.
2.0	2002-01-28	1-24	Released with the following changes: • **Table 3**: extension of the range of bunch length and update of Pb parameters. • Table 10 suppressed: information obsolete; new information not available. • The scope 1 excludes explicitly non-distributed measurements. • Section 5.1.5 added to cover the BPM's in IR4 needed to measure the tunes with the dampers acting as AC dipoles and to measure the angle of the trajectories at the SR undulators. • Update of the section 5.7 (sum signal) following the recommendations of the LHC Instrumentation Review.

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1. SCOPE

This Functional Specification covers the Beam Position Measurement System (BPM System) distributed along the two LHC rings and the beam measurements based on it. Other documents will cover the beam position monitors either not installed in the main rings (SPS to LHC transfer lines, LHC Dump ejection lines) or not dedicated to the measurement of the distributed observables described in Section 2. Consideration on the BPM's for the RF feedbacks, the measurement of the growth rate or modes of transverse collective instabilities, the measurements of the tunes, chromaticities, amplitude detunings, resonance driving terms,… are to be found in these other documents.

This specification complements the Conceptual Design Report of the LHC Instrumentation [2].

2. DESCRIPTION OF THE BEAM OBSERVABLES

The primary observables of a BPM are the electric signals collected by the four pick-up electrodes. These signals are combined, normalized and linearized to provide the beam position. The following analysis and specification start at this latter level and consider as observable the beam position. It should be noted that the linearization carried out at the signal level should take into account the dynamic range of the beam positions defined in chapter 5.3.

The BPM System as a whole is meant to measure three fundamental beam observables:

- the single pass trajectory (beam positions versus machine azimuths),
- the beam oscillation sampled at one or several azimuths (beam positions versus time),
- the closed orbit (average beam positions versus machine azimuths).

A by-product is the beam current intensity measured at each monitor from the sum signal of the electrodes.

3. DESCRIPTION OF THE RELATED BEAM PARAMETERS

Even-though the beam observables are of direct use for basic machine monitoring and corrections, the operation of modern storage rings requires their processing to give access to more involved beam parameters. The latter are relevant to this specification in that they are likely to be more demanding to the instrumentation, particularly in terms of precision. We list our selection of such beam parameters in Tables 1 and 2 together with their typical uses. It should be pointed out that these lists do not include parameters foreseen to be measured by special BPM's (e.g. the tunes, chromaticities, amplitude detunings, resonance driving terms which are assumed to be measured with dedicated high-sensitivity beam position monitors in IR4). The parameters in bold are those deemed to be the most important for LHC operations and performance. The tolerance on these beam parameters are evaluated and converted into specifications of the BPM System in the references listed in the tables. We quote only the results of these studies in this Functional Specification.

Observables: TRAJECTORY and OSCILLATIONS		
Parameter	*Use*	*Ref.*
Trajectory	Visual inspection	TR1
	Beam threading	TR2[4]
	Close trajectory on itself	TR3[4]
Position error at injection	**Subtract orbit from trajectory and compute x,px,y,py at injection**	TR4[4]
Momentum error	**Deduce momentum from trajectory averaged over the azimuth**	TR5[19]
b and m	Visual check of linear optics	TR6
	Search for focusing imperfections	TR7[20]
Local chromaticity	**Dependence of b and m on momentum for the measurement of b3 versus azimuth**	TR8[20]
Local impedance	Dependence of μ on beam intensity	TR9
Local coupling	Identify the local 4D transport	TR10
Transverse spectrum	**Check on the presence and amplitude of harmonics of the betatron oscillation**	TR11[21]
Fast Tune	Fast measurement of the tunes with all the BPM's	TR12
Phase space	Measure the phase space portrait for visual inspection	TR13
Frequency maps	Variation of (fast) tunes with initial conditions for visual inspection of the non-linearity	TR14

Table 1: Beam parameters related to trajectories and oscillations

Observable: AVERAGE BEAM ORBIT		
Parameter	*Use*	*Ref.*
Closed orbit	Visual inspection	CO1
	Correct to minimize the aperture requirement	CO2[5]
	Monitor/Log the closed orbit	CO15
Beam position at critical points	**Fine control of the orbit at the aperture limits (collimators, TDI…) and orbit feedback**	CO3[18, 5]
	Fine control of the orbit at the interaction points	CO4[5]
Alignment and BPM errors	Search for misalignments and BPM errors. Beam-based alignment of the low-β straight-sections.	CO5
Integer tunes	Fourier analyse the closed orbit	CO6
Position at injection	**Subtract orbit from trajectory and compute x,px,y,py at injection**	CO7[4]
Momentum error	**Deduce momentum error from averaged closed orbit**	CO8[19]
Dispersion	**Closed orbit versus momentum deviation**	CO9[5]
β and μ	Closed orbit displacement after a dc kick for visual checks	CO10
	Search for optics imperfections	CO11
Linear optics model	Measure β and μ, BPM resolution, corrector calib. a la Safranek.	CO12
b2/a2 to b5	Measure the arc multipoles	CO13
b2/a2 to b4/a4	**Measure the low-b multipoles (orbit and tune response to bumps)**	CO14[22]

Table 2: Beam parameters related to the closed orbit

4. MEASUREMENT SCENARIOS

The operations of LHC can be expected to be more involved than present accelerators. A very small fraction of the nominal beam can indeed quench the super-conducting magnets. To avoid this situation, it is foreseen to divide the set-up of LHC into several steps. At each step the beam intensity is progressively increased to match the efficiency expected from the collimation system. This efficiency depends on the precision of the beam measurements used to position the collimators. The precision of the beam measurements depends themselves on the beam intensity. The definition of reference operations scenarios is therefore an important element in specifying the instrumentation.

In addition to the above nominal situation, special beams will be used in LHC:

- a beam with a three times larger bunch spacing to prevent the build-up of an electron cloud when the machine is turned on,
- a large spectrum of beams for physics in addition to the nominal high intensity proton beam: TOTEM proton beam and various ion beams.
- for machine studies, operations with a nominal beam in one ring and a `weak' beam (about one tenth of the nominal intensity) in the other ring can be foreseen for beam-beam studies or for disentangling single beam effects from beam-beam effects.

In all cases, the beam instrumentation must work at full performance.

To summarize, the specification of the instruments depends on the measurement scenarios defined by:

- the two beams (structure and intensity),
- a machine operation stage (operation goals),

which are discussed hereafter.

4.1 BUNCH AND BEAM PARAMETERS

4.1.1 EXPECTED RANGE OF BEAM PARAMETERS

The ranges of the LHC beam parameters shown in Table 3 are taken or calculated from the v6.2 parameter list [24] and [3] and from the latest information on LHC v6.4 [33]. The parameters of other lighter ions are not yet available.

Particle	*Bunch charge*	*Number of bunches*	*Bunch spacing*	*RMS Bunch length*
	q		*ns*	*ns*
proton	5 10^9 → 1.7 10^{11}	1 → 2808	24.95 -> 88925	.28 -> .62-> 1.25
Pb	5.6 10^9→ 8.2 10^9	592	100	

Table 3: Range of LHC beam parameters

The first range for the RMS bunch length is related to the energy dependence. The second range arises from RF settings in the SPS which can be used to measure the dispersion matching between BT and LHC [38]. In a beam, not all bunches are separated by the same amount: the injection and abort gaps indeed cause some bunch spacings to be multiples of the nominal one. The exact nominal beam structure may be consulted in [25] and [12]. In the machine regions common to the two beams, the bunch spacing *as seen by a BPM* is further reduced, depending on its machine azimuth. It varies between 0 and 1/2 of the nominal one.

The range of bunch lengths quoted includes the expected transients at injection [32], [8].

4.1.2 BEAM IMPERFECTIONS

The preparation of the LHC beams in the injector chain is complex and may give rise to various types of imperfections:

- unequal charges or positions of the different bunches, batches or beams,
- missing bunches,
- nominal intensity bunches in wrong buckets,
- ghost bunches between the nominal ones,
- presence of a small continuum of debunched beam between the bunches.

These imperfections and their possible magnitude are described in [12].

4.2 OPERATIONS SCENARIOS

The operations scenarios for protons are taken from [13]. The set up of LHC is expected to be done in three steps, using one of the beams defined in Table 4:

- A circulating beam is established with the `pilot beam'. The BPM system is used to thread the beam and obtain a few turns. Closing the first and second turns normally yields a circulating beam. A possible momentum deviation is checked. The closed orbit is measured and roughly corrected. The collimators are positioned at 8σ.
- The intermediate (25 or 75) beams may then be injected to tune the machine. The instrumentation is assumed to have reached full performance. At the end of this stage, the orbit is corrected and the collimators in their final positions.
- The nominal beam intensity can then be accumulated and accelerated. For commissioning, set-up or studies, the intermediate beam may be ramped and put in collision as well.

Type of Beam	*Number of bunches*	*Bunch charge*	*Bunch spacing*
		q	*ns*
Pilot beam	1	$5\ 10^{9}$	88925
Intermediate 75	24	$5\ 10^{9}$ -> $8.5\ 10^{10}$	74.85
Intermediate 25	72	$5\ 10^{9}$ -> $3\ 10^{10}$	24.95
Nominal 75	936	$1.1\ 10^{11}$	74.85
Nominal 25	2808	$1.1\ 10^{11}$	24.95
Ultimate	2808	$1.7\ 10^{11}$	24.95
TOTEM	36	$1.1\ 10^{11}$	2470

Table 4: Expected LHC beams

5. FUNCTIONAL REQUIREMENTS

5.1 AZIMUTHAL DISTRIBUTION OF THE BPM’S

5.1.1 NOMINAL DISTRIBUTION IN THE LHC RINGS

A BPM monitor measuring the horizontal **and** vertical positions of the beam is required near each LHC quadrupole in each ring, at the place where the orbit deviations reach their maximum. The monitors are spaced on average by a betatron phase advance of 45 degrees.

There are several justifications for this distribution, all linked to the LHC cell phase advance close to 90 degrees:

- Assuming a BPM failure rate of 5%, the global closed orbit correction does not prevent the aperture criterion (orbit peak of 4 mm) to be exceeded on average at 25 locations around each ring would the number of BPM’s be halved [27]. With the nominal BPM distribution, the probability of exceeding the aperture criterion becomes negligible, in the somewhat optimistic scenario where each faulty BPM can be identified and disabled.
- If a pair of successive focusing or defocusing quadrupoles is misaligned identically, a BPM at each quadrupole inside the bump is needed to disentangle wrong BPM’s from quadrupole alignment errors. Such a local misalignment was indeed experienced in LEP [28],[16].
- The measurement of the β-beating, important in a machine with a small beam aperture, requires sampling the trajectory at each quadrupole if the cell phase advance is 90 degree [7].

This distribution was approved [31].

5.1.2 LOW-BETA TRIPLETS

Due to the rapid oscillation of the β-function in the triplets, the beam trajectory oscillates (by several millimeters for the crossing angle trajectory) even-though the betatron phase advances by less than one degree. The sampling theorem shows that 2 BPM’s are necessary for a minimal sampling. A third BPM is advisable to yield a modest over-sampling and some robustness. The favourable positions for the BPM’s are:

1. at Q1 towards the IP to calculate with a minimum error the beam position and angle at the IP.
2. between Q2a and Q2b to sample the maximum of the orbit in one plane; a fall-back position could be between Q1 and Q2a (75% of the maximum extent of the orbit but significant sensitivity to the polarity of the focusing),
3. between Q3 and D1 to sample the orbit maximum in the other plane.

It should be noted that the position between Q2b and Q3 is not optimal. The measured beam position due to the crossing angle is there insensitive to the sign of the low-β focusing. The interpolation of the orbit between this BPM and the neighbouring ones is not possible without an external information on the magnet polarity. Given the fact that this interpolation is needed to yield the peak orbit extension in the machine, this position is certainly inappropriate from the machine operation point of view.

The fine azimuthal position of the BPM’s should be adjusted to avoid the azimuths of the long-range beam-beam interactions where the time interval between the two counter-rotating beams vanishes. This would indeed maximize the electronic coupling between the two beam positions. The condition to fulfil is given in section 5.2.

5.1.3 JUNCTIONS OF THE RINGS WITH THE TRIPLETS

Like in the case of the triplets, the small betatron phase advance over the D1/D2 section may mask the local complexity. At least two BPM's placed towards both ends of the D1/D2 drift space are recommended:

1. to tune accurately the D1/D2 separation/recombination,
2. to decouple the closed orbit correction in the two rings and in the common section. This would be done by constraining the orbit positions at these two BPM's.

5.1.4 COLLIMATOR REGIONS

In order to measure accurately the beam position at each collimator, BPM's are installed on each side of each warm quadrupole, i.e. on each side of the drift spaces where collimators are installed [17]. Given the number of collimators, this is the minimal configuration of BPM's which allows a linear interpolation of the beam position, dispersion and β-functions at the collimators.

5.1.5 INSTRUMENTATION AREA IN IR4

The IR4 straight-section will receive many of the beam instruments or beam excitation devices. Some of them need additional BPM's:

- The transverse dampers used as AC dipoles [35] may be used to measure the betatron tunes without beam blow-up due to the excitation. A promising method yet to be studied consists in measuring the betatron phase advance around the damper and to correct it for the calculated phase advance inside the damper, thus providing the total tune. For that purpose, BPM's are needed on either side of the horizontal and vertical dampers. The possible effect of coupling not being analysed as yet, they should be foreseen to measure in both planes.
- The undulator system foreseen for the measurement of the beam profiles requires a reasonably precise control of the orbit angles to extract the synchrotron light. The prescription is ±0.1 mrad [36]. The above-mentioned BPM's on either side of the dampers are in the same straight-section and allow a precise extrapolation of the orbit angles at the undulators. A second requirement is to measure the β-function accurately (about 1%) in order to convert the beam sizes into emittances. The minimum requirement is a BPM at the undulator or two BPM's in the straight-section. The 4 BPM's already foreseen around the dampers provide a redundancy which is welcome given this tight requirement. BPM's specific to the profile monitors are thus not needed.

5.1.6 PREFERED AZIMUTHS FOR THE BEST MONITORS

If all BPM's do not turn out to be equally performing or if the transfer function of a subset is more accurately measured, there is a case to install the best ones at preferred positions in the machine:

- at the junctions of the arcs and of the straight-sections at, in order of preference Q7, Q6, Q8 (BPM's with lowest non-linearity),
- at the junctions of the rings and of the common sections, i.e. Q4, Q5 (BPM with the largest accuracy for the closed orbit).

This amounts to a few percent of the BPM positions. In the common sections, all positions are equally important.

5.2 TIME RESOLUTION OF THE MEASUREMENT

5.2.1 BPM'S IN THE RINGS

The complex preparation of the LHC batches makes it possible to observe imperfections in the beam, i.e. different parameters depending on the bunch position in the beam pattern (intensity, position, emittance) [12]. In this case, a bunch-by-bunch measurement at least at a few azimuths is required to diagnose the situation.

The bunch to bucket injection of the SPS batches into the LHC buckets requires a tight control of the momenta of the batches [1]. The momentum measurement using the BPM's requires that the average trajectory of each batch be measurable.

The long-range beam-beam interaction is another mechanism the strength of which depends on the bunch position in the beam. This effect is presently estimated to be the first limit for the LHC performance (see, e.g. [29]). It is therefore necessary to measure the beam on a bunch-by-bunch basis in the common sections of the LHC (i.e. in the triplets) and at least at two BPM's per ring at the junction of the common sections and of the rings, near Q4, Q6 and Q7.

The most demanding requirement for the BPM System is thus to be able to measure beams from a single bunch (11.25 KHz) to the nominal 25 ns spacing (40Mhz) through all possible intermediate rates and bunch patterns.

5.2.2 BPM'S IN THE COMMON SECTIONS

In the machine part that is common to the two beams, the spacing between passages of a bunch of any beam may vary from 0 to 1/2 of the bunch nominal spacing assumed identical for the two beams. The bunch spacing vanishes at azimuths equal to k×3.74 m from the interaction points and reaches its maximum of 12.5 ns at azimuths equal to (2k+1)×1.87 m for the nominal spacing of 25 ns. The positioning of the BPM's should be such as to minimize the parasitic coupling between the beam signals to provide the highest specified precision and reliability in this critical machine section.

5.3 DYNAMIC RANGE AND PRECISION

The concepts of dynamic range and precision are inter-linked and defined in [6]. We take as the dynamic range of an instrument the domain of variation of the observable or of influence parameters within which a measurement of the observable can be made with a given precision goal.

For the BPM System, the bunch charge is the influence parameter with the most demanding domain of variation. The machine requirements and BPM technology are consistent with a sub-division of its dynamic range into two sub-ranges with different precision goals:

1. the coarse precision, for low intensity beams such as the pilot pulse,
2. the nominal high precision for the intermediate to ultimate beam intensities (see section 4.2 for a definition of pilot, intermediate and nominal beams).

The two precision goals are defined in Table 7.

5.4 DYNAMIC RANGES

5.4.1 BEAM POSITION

The useful domain of variation of the beam position is the composition of the expected domain of variation of the closed orbit and of the super-imposed betatron oscillations.

We can distinguish three ranges:

- Range for nominal machine operation (R1): a non-vanishing closed orbit arises due to the imperfections, the momentum deviation of the beam and the crossing angle separation. We have taken the standard values for the above from [17]. The standard measurements of the linear optics require an oscillation amplitude small enough to be negligible.
- Range for studies (R2): the collimation system leaves a beam aperture around the closed orbit of 7σ maximum. This range is relevant for beam dynamics studies requiring the nominal high precision of the BPM's.
- Ultimate range (R3): between 7σ and 10σ, only a short-lived halo of particles is expected to circulate. Some degradation of the precision in this range is acceptable if it allows an improved accuracy in the other two ranges.

The range of beam positions at a given BPM depends on the focusing of the near-by quadrupole and on the energy. We take the largest domain for the purpose of specification.

Table 5: Ranges of beam positions

	Closed orbit	Momentum Dev.	Crossing angle	Beam σ	Range for operation R1	Range for Studies R2(7σ)	Ultimate Range R3(10σ)
Standard BPM's	± 4 mm	± 2 mm	0	1.2 mm	± 6 mm	± 14.5 mm	± 18 mm
Low-β BPM's	± 4 mm	± 1 mm	± 7 mm	1.5 mm	± 12 mm	± 22.5 mm	± 27 mm

5.4.2 BUNCH LENGTH

The BPM System precision should not be sensitive to the bunch length in a range of 0.2 to 0.8 ns, taken from Table 3 and adding a small safety margin.

5.4.3 BUNCH INTENSITY

The BPM system shall be able to measure bunches in the range of 5 10^9 to 1.7 10^{11} charges, i.e. from the pilot proton pulse to the ultimate proton bunch current. The lowest ion current corresponds to the pilot bunch intensity. A safety margin by a factor of 2 or more should be foreseen towards the low end of the range with a degraded accuracy (by about a factor of two) would the Pb ion current be weaker than expected. The dynamic range may be subdivided into two sub-ranges with differing precision goals:

1. 5 10^9 to 3 10^{10} : coarse precision for injection
2. 3 10^{10} to 1.7 10^{11}: high precision for set-up and other operations.

It should be noted that the nominal intensity of the Pb beam corresponds to the coarse precision of the BPM System. The beam dynamics with such very low intensities is less critical and its understanding or control is not expected to require the high precision [23].

5.5 PRECISION

The terminology defined in [6] is briefly recalled here. The ***error*** of a BPM measurement is generally the combination of an offset (Δ), a scale error (k), a roll (y), a non-linearity and a noise (e). The resolution is the smallest increment that can be discerned and is either set by the noise level or by a systematic effect.

$$x_{measured} - x_{true} = \Delta + kx_{true} + y\,y_{true} + \sum_{k=2}^{\infty}\sum_{j\le k} a_{kj}\, x_{true}^{k-j}\, y_{true}^{j} + e$$

The measurement method sets how many of these terms combine to produce the measurement error. A difference measurement for instance is not sensitive to the offset. The noise of the system summarizes the influence of uncontrolled parameters and the limitations of the physical model used in the measurement.

The ***uncertainty*** is one of the parameters of the estimated error distribution. In calculations, it is taken to be the rms error while specifications require tolerances, i.e. the peak value of the error for a given confidence level. We assume a ratio of 2 between rms and peak values, corresponding to a confidence level of 95% for a Gaussian distribution and 100% for a rectangular one. In calculating tolerances, the maximum perturbation due to non-linearities is retained; for $x_{true} \in [-X, X]$ and $y_{true} \in [-Y, Y]$, the tolerance is given by:

$$|\Delta| + |k| X + |y| Y + Max\left(\left| \sum_{k=2}^{\infty} \sum_{j \le k} a_{kj} x_{true}^{k-j} y_{true}^{j} \right|, x_{true} \in [-X, X], y_{true} \in [-Y, Y] \right) + 2e_{rms}$$

To avoid any ambiguity, tolerances are quoted as ranges, e.g. ± 1mm while rms uncertainties are quoted by their positive rms values.

Table 6 summarizes the requirements on the BPM precision identified in studying the measurement of the beam parameters quoted in Tables [1] and [2]. The calculations, estimates and discussions are to be found in the corresponding references. In several instances, exhaustive calculations on small quantities are either not realistic in view of the unknowns or too time-consuming. They are best replaced by `educated' guesses.

The calculated or estimated requirements are therefore open for discussion in case they could not be reached.

Whenever the precision is not expected to be a limitation, the breakdown of the uncertainty is not carried out and the global uncertainty specified.

Column *P* of **Table 6** marks the measurements relevant to the pilot beam which only require the coarse precision as defined in section 5.4.3. The ranges R1 and R2 are the position ranges defined in **Table 5**.

The requirements of **Table 6** are based on the beam dynamics. It is therefore not possible to distinguish and specify the various sources contributing to the same component of the precision. For instance, offsets due to a misalignment, to the electronics or to any other source can only be globally specified.

Measurement	*P*	*Range*	*Accuracy*	*Scale error*	*Offset*	*Non-linearity*	*Resolution*
			peak	*peak*	*peak*	*peak*	*rms*
TR2	*	R2	±2000μm	+	+	+	+
TR3	*	R1	±500μm	+	NR	+	+
TR4	*	R1	±500μm	+	NR	+	+
		R1	±50μm	+	NR	+	+
TR5	*	R1	±1500μm	+	NR	+	+
		R1	±250μm	+	NR	+	+
TR7/TR8	*	± 1 mm ⊂ R1	±400μm	+	NR	+	+
			±50μm	±4%	NR	+	+
TR11		R2		NR	NR	±500μm	50μm
CO2	*	R1	±500μm	+	±250μm (±750μm)	+	+
CO3		± 1 mm ⊂ R1	±20μm	NR	NR	NR	+
CO4		± 1 mm ⊂ R1	±30μm	+	+**	+	+
CO7		R1			±100μm	±200μm over ±4mm	1000μm
CO8		R1	±250μm	+	NR	+	+
CO9 IP		± .1 mm ⊂ R1	±15μm	+	NR	+	+
other		± 1 mm ⊂ R1	±175μm	+	NR	+	+
CO14		± .1 mm ⊂ R1	±10μm	+	NR	+	5μm

Table 6: Precision required either on the trajectory (TR) or on the closed orbit (CO) according to the measurement goals and conditions.

+ : component included in the calculation of the accuracy
NR: non-relevant or negligible
**: difference between beam1 and beam2 positions (low-β triplets)

Table 7 summarizes the requirements for the two dynamic sub-ranges relevant to the beam intensity

Precision goal	*Coarse (pilot pulse)*	*High (other beams)*
Scale error	NR	±4%
Roll	NR	±1 mrad
Offset	±750μm	±100μm (relative offset < ±30μm in IR's)
Non-linearity	NR	±200μm over ±4mm, ±500μm over R1
Resolution	200μm rms	50μm rms (traj.), 5μm rms (orbit)

Table 7: Specification for the accuracy of the BPM's

5.5.1 SCALE ERROR

The linear scale error does not appear to be an important issue in any of the methods investigated provided it is smaller than about 5%. The spread from BPM to BPM is more serious than the average scale error.

5.5.2 OFFSET AND ALIGNMENT

In LHC, the non-linear corrections are not exactly local (in azimuth). Likewise, the collimation is carried out over long machine stretches. This makes the absolute BPM alignment more important than in other machines. The efficiency of operation will be improved if the absolute value of an orbit or trajectory can be relied upon. The spread in BPM offsets is more important than the average value that can be measured in the arcs. For these reasons, special attention should be given to minimize the offsets (survey or electronic) with respect to the **reference orbit** of the surveyors (not necessarily defined by the magnetic axes of the near-by quadrupoles). Alternatively the individual offsets should be measurable.

In the machine sections common to the two beams, the relevant quantity is the difference between the offsets of beam1 and beam2 at each BPM station.

5.5.2.1 AZIMUTHAL POSITION VERSUS THE QUADRUPOLE CENTER

The azimuthal distance between the BPM and the magnetic center of the near-by quadrupole sets the accuracy to which the K-modulation techniques allows to measure the BPM offset.

For the assumed 4 mm peak orbit, the maximum orbit divergence is about 50 μm per meter of distance in the regular part of the machine ($\approx 4mm/\sqrt{b(s)b_{\max}}$). The requirement on the offset (**Table 7**) sets this maximum distance to about 2 m.

5.5.2.2 ROLL

In the amplitude range R1, a roll of ± 2 mrad produces a signal in the other plane about equal to the resolution required and is therefore acceptable. The same prescription requires only ± 1 mrad for the low-β BPM's due to the presence of the crossing angle. Requiring the same prescription in the range R2 does not seem justified.

5.5.3 NON-LINEARITY

The non-linearity impacts on the measurement precision in two different ways: an uncertainty on the transfer-function that limits the resolution; the presence of artificial harmonics in the spectrum of the measured signal. While the first aspect does not require a detailed knowledge of the non-linearity, the second does. We have used the measurement of the BPM electronics under development showing a dominant third-order harmonic [Coq1]. We have assumed the three-point calibration already foreseen for the system [Coq1].

5.5.4 RESOLUTION

A resolution of 5μm is either sufficient or satisfactory for all measurement methods studied. A further reduction of the ultimate resolution would be beneficial for the measurement of the multipoles by the bump method (CO13 and CO14) but other more sensitive observables may be found. It would of course be taken advantage of only if the machine were stable with the same precision over about 10 seconds. This is presently not known. A guarantied resolution of 5µm with an ambition of reaching a few µm would seem an appropriate goal.

5.5.5 REPEATABILITY AND REPRODUCIBILITY

5.5.5.1 FROM BUNCH TO BUNCH

Assuming that all bunches in one beam are on the same trajectory, the measured trajectories may differ due to transients in the BPM electronics. These errors should not exceed:

- ± 400 µm in the coarse accuracy dynamic range (corresponding to 10% of the assumed closed orbit range),
- ± 0.1σ in the high accuracy dynamic range; this corresponds to ± 30 µm for the rings and ± 100 µm in the common sections; such orbit differences are expected for the PACMAN bunches [14]; they were found in other colliders to give just detectable consequences [10], [26], [15].

5.5.5.2 OVER SECONDS

Several measurements of beam parameters require subtracting orbits or trajectories measured typically over seconds up to one minute. The tolerance on the repeatability of the beam position measurement over such short times should be negligible as compared to the resolution.

5.5.5.3 FROM RUN TO RUN

The reproducibility from run to run is an essential component of operations efficiency. The reproducibility of the magnetic system is not expected to be sufficient and the reproducibility of the machine will rely largely on the beam instrumentation. It is difficult to specify to what accuracy a `golden' orbit should be reproduced, as the concept itself hides a lack of knowledge of why an orbit is `golden'. We rather take as a criterion the collimation system. A reproducibility of ±100 µm (≈σ/2 at 7 TeV) is a minimum requirement which allows to position rather well the beam with respect to preset collimators and save set-up time. A reproducibility of ± 20 µm would potentially allow avoiding a collimator set-up on every run if the emittance can be controlled to the same accuracy. This is presently not expected.

5.6 RESPONSE TO BEAM IMPERFECTIONS

The BPM system shall be as much as possible tolerant to the imperfections of the beam patterns described in section 4.1.2. Possible limitations should be explicit.

5.7 MEASUREMENT OF THE BEAM INTENSITY

The measurement of the beam intensity versus azimuth is found by experience [39] a very valuable tool, recognized as providing more reliable information than the Beam Loss Monitors (calibration issue). It is however useful only for commissioning or re-commissioning. A cheap solution, even not operational on a daily basis should be studied and proposed. If the cost cannot be made marginal, it would be wise to equip one or two BPM's per arc, e.g. one on each side of the IR's. This would provide a minimal redundancy for a rough crosscheck of the BLM's and a capability of detecting unexpected losses mainly when the pilot beam circulates only a few turns. An accuracy in the 10% range is appropriate.

5.8 STORAGE OF DATA AT THE BPM LEVEL

The decoherence of the beam oscillations limits in practice the usefulness of the turn-by-turn trajectory data. Due to the non-linearity, the incoherent tune spread is expected to lie between 1 10^{-3} and 5 10^{-3} after correction. This would yield between 200 and 1000 useful turns. The head-tail damping may further reduce this time for positive chromaticities. On the other hand, the use of an AC dipole [30], not decided yet, may overcome this limitation.

A memory depth of 16K data acquisitions seems a reasonable compromise between the nominal situation with an expected coherence over a few hundred turns and accurate measurements with an AC dipole which would then allow a gain by a factor 4 to 10 on the statistical resolution. By acquisition, we mean either the trajectory of a given bunch or the average of all (or a subset) of the bunches. This memory could be used as well to monitor 16 different bunches over 1000 turns.

The Post-Mortem option (see section 5.12) may require additional storage for transient recording of the trajectories and closed orbits. Its location (at the BPM level or centralized) is not an issue for these specifications.

5.9 INTEGRATION TIME FOR THE CLOSED ORBIT

The integration time of the closed orbit shall be compatible both with the required resolution and with possible residual forced beam oscillation which were observed in LEP to be significant at 50Hz. The chosen integration time of 224 turns [1] fulfils these criteria. It shall be possible to change the integration time from the control room to investigate the influence of this parameter.

5.10 SYNCHRONISATION WITH EXTERNAL EVENTS

The measurement of the trajectories or closed orbits shall be made in synchronism with any machine event (injection, start of ramp, energy, timing,…), operator request and in combination with other beam instruments, such as the BPM System of the transfer lines or the beam exciters, independently in Ring1 and Ring2. The BPM system being able to resolve the bunches, the resolution in the synchronisation time shall be better than 25 ns.

For studies of the interaction of the two beams, it shall be possible to record beam oscillations, trajectories or orbits measured simultaneously in Ring1 and Ring2.

A logging mode is foreseen for the closed orbit, whereby a measurement must be carried out and logged at a frequency of 10Hz. In case of a conflict with an asynchronous measurement request, the latter should be given priority.

In order to increase the reliability of the measurement and the ability to detect dysfunction or errors, it shall be possible optionally to trigger the measurement with a positive or ***negative*** delay with respect to the event. For example, the trajectory should be measured a few turns before the beam is kicked. The dead time after a trigger shall be less than one turn.

5.11 DATA FLOWS AND RESPONSE TIME

At the specification level, we define the logical data flows the response times acceptable for an efficient operation of the machine.

In the vast majority of the cases, the BPM system will be used to measure the trajectories and orbits ***averaged over all bunches***. For machine studies, the most precise measurements will be made on a single bunch. In these two dominant modes of operating the BPM System, the logical information blocks are similar:

- The average trajectory is the series of horizontal and vertical positions (average and variance) and of BPM status (and/or the sum signal as well) versus BPM number in the ring, collected over a few turns (mostly one turn, but say up to 10 turns).
- The average beam oscillations at one BPM is the series of horizontal and vertical positions (mean and variance), possibly the sum signal as well, versus turn number over typically 1000 turns and up to the maximum capability of the BPM memory.
- The closed orbit data include the average horizontal and vertical beam positions (mean and variance), the BPM status and optionally the sum signal (proportional to the beam intensity) versus BPM number as well as the absolute time with an accuracy of 1ms.
- The combined measurement of the average trajectories/oscillations for all BPM's is used e.g. in the measurement CO10, CO11 and CO13. The processing time of close to 10^7 numbers should make the transmission time uncritical.

For studies, an exact identification of the turn and bunch number(s) is critical for a proper analysis of the measurements, using timing information common to all LHC systems (TTC). For commissioning, the system should be tolerant to a missing timing. The calculation of the closed orbit indeed does not require the knowledge of the turn and bunch numbers. For the correction of the injection errors, it is important to tag with a high reliability the first and second turns.

	Information block	Response	Methods
Single shot measurement	1 orbit or trajectory	1 s	TR2,3,5,7,11,CO2,5,8
Difference measurement	2*(orbit or trajectory)	2 s	TR4,8,CO9
Repeated diff. measurements	*n**(orbit or trajectory)	*n* s	TR9
Monitoring	orbit	5 ms	TR7,8,11,CO2'
Snapshot	trajectories/orbits	~2 s	CO9,13,14

Table 8: Typical modes for the information transfers and response times

In the monitoring mode, the information is transferred at a maximum rate of 10Hz. The acquisition time at the level of local computers able to carry out local orbit corrections shall not exceed 5 ms to leave 95 ms for the orbit correction and power converter change. The fast 10 Hz rate is essentially useful in special cases: i) during the snap-back, ii) when another machine parameter is modified, iii) continuously at the collimators.

In the snapshot mode, the 224 consecutive trajectories (one bunch or average of all bunches) needed to compute a closed orbit are acquired, followed by an optional gap of *n* turns; this process is iterated until the BPM memory is filled up (50 to 100 orbit measurements). The closed orbits are then computed and transferred. This mode is especially useful when another machine parameter is changed over one or a few seconds, typically an RF frequency change, an orbit bump…

5.12 TRANSIENT RECORDING AND POST-MORTEM

The BPM System shall be able to recognize two external events:

- total beam loss,
- partial beam loss,

and take appropriate action, using the BPM memory's as transient recorders.

The memories corresponding to these two kinds of events should be separate to avoid any loss of information in case of a total beam loss.

The actions to be carried out in case these events are received are under definition by the Post-Mortem Working Group, whose documentation should be consulted [post].

Provisionally, it is foreseen, in case of a total beam loss event, to

- freeze the BPM memory where trajectories are accumulated 124 turns after the trigger and retain the last 1024 values (900 before the trigger, 124 after),
- freeze the closed orbit buffer to record the last 1000 orbits before the trigger and 24 orbits after the trigger.

6. DESIGN CONSTRAINTS

6.1 GEOMETRICAL APERTURE

In LHC, the estimate of the geometrical aperture available for the beam results from a two-dimensional calculation based on the shape of the beam halo [17], taking into account various imperfections. A simple criterion may therefore not be specified. If the geometry of the BPM detector restricts the beam aperture as compared to the neighbouring upstream and downstream machine sections, the LHC Working Group on Aperture shall be consulted for advising.

6.2 HEAT LOAD

The heat inleaks due to the BPM System are estimated to be about 15% of the total static heat load in the SSS at 4.6-20 degrees K. In the nominal dynamic mode (with beam), the values for LHC V6.2 are reported in **Table 9**. Any change in the BPM System design liable to modify the heat inleaks should be submitted to the LHC Working Group on Heat Loads.

Table 9: Heat Load in SSS from [11]

Source of Heat Load	Temperature levels		
	50-75 K	4.6-20 K	1.9 K
	Watt		
BPM	0	.57	0.3
Total	41.23	19	4.2

6.3 MACHINE IMPEDANCE

The presently obsolete impedance budget [32] shows that the BPM's amount to a significant fraction of the total budget, especially at low frequency. A new budget is under work [34].

Any change to the body geometry which might create a spurious cavity or to the detectors, buttons or antennas interacting with the beam electro-magnetic field shall be submitted to the LHC Working group on Impedance.

6.4 RADIATION

The experimental insertions and the collimation straight-sections are exposed to potentially high radiation doses. A first consequence is the possible perturbation of the beam signal by a synchronous flux of charged secondaries in the vacuum chamber and by the interaction of scattered or secondary particles with the material of the instrument. Other consequences are the ageing of the materials and the restricted access and maintenance possibilities.

To optimize the design, the latest radiation estimates should be consulted in the project documentation system. The present latest document is LHC-PM-ES-0002.00 rev 1.1 (April 1999).

6.5 INB

The LHC has been classified as an "Installation Nucleaire de Base" by the French Authorities. Within this context CERN has to establish traceability & waste management procedures and maintain a radiological and zoning system.

In order to meet these requirements, information such as:

- material content
- location history
- sub-assemblies
- etc.

shall be supplied by the Contractor and will be maintained in a CERN database.

CERN has created a set of procedures and conventions as part of the Quality Assurance System for LHC which will also be used to facilitate these INB requirements. The relevant quality documents are listed below and shall be applied by the Contractor during the production, testing and assembly of components.

- "The Equipment Naming Convention"
- "The LHC Part Identification"
- "The Manufacturing and Test Folder"

7. RELIABILITY, AVAILABILITY AND MAINTAINABILITY

The BPM system is critical for machine operations and performance. It must be always available at a 90% to 100% level. The operations efficiency will depend critically on the level of confidence in this system. It must thus offer checking possibilities.

7.1 ROBUSTNESS IN OVER-SAMPLING

The over-sampling of the closed orbit by about a factor of 4 gives robustness to the system as long as the orbit is a pure betatron oscillation. However, two consecutive faulty BPM's may hide a significant orbit distortion and three consecutive faulty may hide a complete π-bump of arbitrary amplitude. In both cases, a quenching hazard arises. An adequate grouping of the electronics in chassis or crates which minimizes the probability of several consecutive faulty BPM's will increase the availability (e.g. every other BPM in another chassis/crate minimizes the probability of two or more consecutive faulty BPM's).

7.2 CALIBRATION

The calibration and self-tests foreseen for the system should be easily doable by the operations team, scheduled at regular intervals and their results logged and accessible to the operations team. The possibility of calibrating the system with beam in the dump `hole' would be an asset, as it would allow carrying checks at top energy before doing potentially dangerous machine parameter changes. It is recommended if feasible.

7.3 DATA CONSISTENCY CHECK

The simultaneous calculation of the closed orbit and of its variance and their storage in the same file provides a significant help to identify erratic measurements, either on-line or during off-line analysis.

8. SAFETY AND REGULATORY REQUIREMENTS

The Beam Position Instrumentation must meet the safety guidelines put forward by the CERN Technical Inspection and Safety Commission (TIS). TIS have issued safety documents in compliance with LHC-PM-QA-100 rev1.1, and the guidelines in these documents will be incorporated into the Beam Position Instrumentation design.

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