CONCEPTUAL SPECIFICATION

CONCEPTUAL BPM SPECIFICATIONS FOR THE HL–LHC

Abstract

This document specifies the target performance for the BPM system for the HL–LHC.

TRACEABILITY

Prepared by: R. De Maria, D. Gamba, R. Tomás — **Date: 2020-06-02**

Verified by: xxx — **Date: 2020-MM-DD**

Approved by: yyy — **Date: 2020-MM-DD**

Distribution: N. Surname (DEP/GRP) *(in alphabetical order) can also include reference to committees*

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1 INTRODUCTION

A few Beam Position Monitors (BPMs) are expected to be upgraded for the HL–LHC: new BPMs are needed in the Interaction Region (IR) of Point 1 and Point 5 and new electronics will be developed for the rest of the machine [14]. The LHC BPM system was specified in [1, 2].

In the context of the HL–LHC there are more stringent requirements at the Interaction Point (IP) due to the expected smaller beam size [3] and the uncertainty related to possible triplet mechanical stability [7]. Optics corrections are also more difficult due to larger peak β-function in the Interaction Region (IR) in Point 1 and 5 (P1/5). The present performance of the LHC system and the functional specifications have been discussed in [9, 13, 10, 11, 16, 12, 15].

The document resumes the concepts and specifications for LHC, which are still valid, with updated parameters for the HL–LHC where changes are needed. In addition, a specific descriptions on the critical measurements will be provided with the expected finally accuracy required. The document does not include hardware specifications needed to obtained the requested performance.

2 MEASUREMENT SCENARIOS

2.1 Beam parameters

The expected beam parameters for HL-LHC runs are shown in Table 1 and taken or calculated from [3, 4] for protons and ions. A single pilot bunch of 5×10^9 charges or up to 12 bunches are typically used first machine set-up and dedicated studies. Doublet proton bunches will very likely not be used [5].

Table 1: Main Beam Parameters

Particle	Bunch Charges	Number of bunches Min	Number of bunches Max	Min bunch spacing [ns]	Bunch length FWHM [ns]
Protons	5×10^9-2.3×10^{11}	1	2760	25	0.7-1.2
Ions	5×10^9-1.6×10^{10}	1	1232	50	0.7-1.2
Pilot (p or ions)	5×10^9-1×10^{10}	1	3	(25)	0.7-1.2

The ”nominal” ion bunches have similar bunch charge as proton pilots. Therefore ”nominal” ion bunches will also be likely be used during the commissioning.

The BPMs in the low-β insertions deserve special attention as they will need to measure the closed orbit for both counter-rotating beams which will be separated by several mm in presence of a crossing angle.

2.2 BPM families

We can distinguish different BPM families. The BPMs in the arcs measure one beam at the time over a limited range of orbit excursion. Matching section BPM needs to cover additional range due to the presence of crossing angle, separation and offsets bumps. The BPMs in the triplet area observe the positions of both beams (with an effective small longitudinal separation) and large orbit excursion due to the crossing angle orbit bumps. With HL–LHC one should also distinguish between BPMs in the triplet in Point 1/5, which are going to be upgraded, and the ones in Point 1/8 which will not be upgraded. The present layout and location of new BPMs in the IR1/5 is sketch in Fig. 1. Table 2 gives a first classification of the BPMs that will be in HL-LHC. Note that in the BPMQSTZA type BPMs, i.e. the ones installed closest to the IPs in Fig. 1,

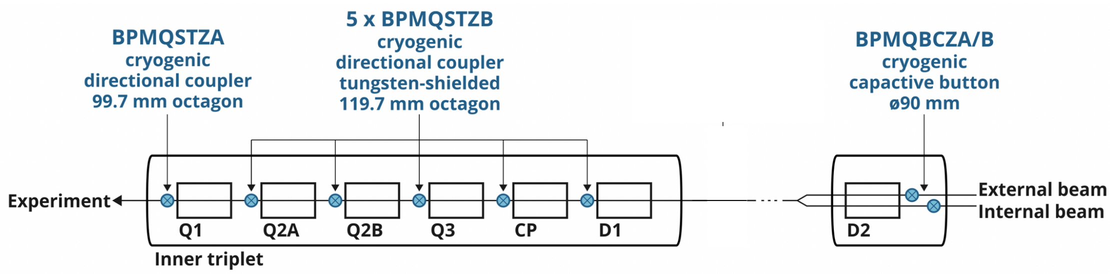

Figure 1: Type and position of new HL-LHC BPMs or IR1/5 [15]

Table 2: BPM Types. The bunch spacing comes from direct computation and from [19]. The max range is defined as the BPM aperture, while operational range as half the max range.

Type	Two beams	Operation Range (OP) [mm]	Max Range for Studies [mm]	Bunch Spacing (Signal) [ns]
Arc	No	± 9	± 18	25
Matching section	No	± 12	± 24	25
Triplet Point 2/8	Yes	± 14	± 27	6
Triplet Point 1/5	Yes	$\pm 29^{\dagger}$	$\pm 58^{\ddagger}$	3.8

† For BPMQSTZA type BPMs this will be $\pm 25mm$

‡ For BPMQSTZA type BPMs this will be $\pm 50mm$

have the electrodes on the horizontal and vertical planes, while the BPMQSTZB type have larger aperture and electrodes at 45deg. The BPM1BCZA/B capacitive button BPMs are also different in design from other button BPMs in the matching section. Despite those differences, no finer classification is assumed for the present specifications. However, it is important to stress that the most important BPMs from a beam dynamics point of view are the ones just next to the IP, i.e. of BPMQSTZA type. In general, the BPM in the triplet in P1/5, the minimum bunch spacing is seen from the two different ports of a stripline BPM (12 cm length) by placing the BPM center at least 57 cm away from a beam-beam parasitic encounter (i.e. 51 cm from the closest port) [8]. A similar computation has been done also for P2/8 BPMs. The “Max Range for Studies” is defined by the aperture of the BPM. The actual operational range for the triplet BPMs is defined by the crossing angle, which separates the beams of about 12 beam sigmas along the whole IR. However, in order to take into account for additional operational knobs (e.g. dispersion bumps, beta-beating bumps) and unforeseen operational bumps (e.g. for avoiding Unidentified Lying Object (ULO)), the “Operation Range” in Table 2 is defined as half the max range.

Triplet BPMs might also need special features in case of Pb-p run to cope with different revolution frequency, but no details are given in this document.

2.3 Measurement modes

Following [1], the measurement modes used during machine measurements can be distinguished in two classes:

1. Bunch-by-bunch turn-by-turn for orbit TRajectories and oscillations (TR)
2. High resolution averaged Closed Orbit (CO)

The TR mode aims at measuring optics parameters and bunch dependent orbit (e.g. long-range beam-

beam effects) during commissioning or machine set-up validation periods, dedicated Machine Development (MD) campaigns, as well as to measure the trajectory of the beam at first injection. The CO mode aims at measuring the average closed orbit continuously to set-up orbit and stabilise it via feedback, and in dedicated machine studies (e.g. kick-response, k-modulations, etc). A hybrid mode (TR+CO) may be needed for PACMAN effect studies [6].

To be pointed out that a BPM measurement is never used in isolation and machine measurements always involve a series of BPM readings. Therefore the correlation between measurement errors have strong impact on the final uncertainty. As also noted in [1], truly random noise has less impact than systematic noise depending on measurements conditions. Therefore, specification on *reproducibility* and *correlation* between different BPM and/or consecutive readings needs to be introduced, because their requirements are stricter than on accuracy. One should therefore distinguish between reproducibility between consecutive measurements over different time scales and purpose of the measurement, see Table 3. In terms

Table 3: Types of reproducibility

Reproducibility Timescale	Usage	Class
Bunch-by-bunch	Optics measurement and correction, steering at Injection [1]	TR
Stable beam (∼10 h)	Keep orbit during optics changes, IP position stabilisation	CO
Fill to fill (∼24 h)	Find collisions after a refill, ensure machine reproducibility	CO

of orbit control, the specifications during stable beam are the most demanding as they meant to keep the beams in collisions, while during the entire fill one is mainly concerned about keeping the beam reasonably well withing the machine aperture. Over longer timescales the requirement is mainly to be able to safely re-inject beam and find back collision.

On top of time-dependent effects, systematic deviations in BPM reading have been seen in LHC as a function of bunch pattern, bunch intensity and temperature variation in the BPM acquisition system racks [11]. Those effects are normally correlated and affect all or groups of BPMs, and are detrimental for reliable operation of the orbit feedback and for beam quality. It is required that those systematic effects will be minimised in the HL-LHC era, such that the reproducibility specification presented here for a single BPM can be considered as the dominant effect.

The expected acquisition frequency for both CO and TR modes are specified in Table 4. The frequency

Table 4: Data flow of measurement acquisition modes.

Measurement	Frequency	Quantity
Orbit mode (CO)	25 Hz	Continuous
Trajectory mode (TR)	∼0.1 Hz	1–3 pilot, 20k turns, on demand

requirement for CO mode comes from its use for the orbit feedback [18], while for TR mode is more for practical reasons, i.e. aiming to minimise the time between two measurements during optics measurement and correction.

3 HL–LHC SPECIFICATIONS

The uncertainty of a single isolated measurement of a BPM described by [1, 2] was:

$$x_{\text{measure}} - x_{\text{true}} = \Delta + k x_{\text{true}} + \psi y_{\text{true}} + \sum_{k=2}^{\infty} \sum_{j \le k} \alpha_{k,j} x_{\text{true}}^{k-j} y_{\text{true}}^{j} + \epsilon \tag{1}$$

and depends on a combination of *uncertainties*: offset (Δ), scale or calibration error (k), tilt (ψ), non-linearities ($\alpha_{k,j}$), and *noise* (ϵ) which is assumed to be random and Gaussian distributed. In [1], it is not specified the definition of x_{true}, which is assumed here to be the beam position w.r.t. to the BPM mechanical center. Note that in this case the offset with respect to the ideal machine reference frame will depend on the alignment accuracy of the magnet/BPM itself and the extent of the ground motion. The *resolution* is defined as the smallest increment that can be discerned. Figure 2 gives a graphical representation of the various linear contribution to the a typical measurement error.

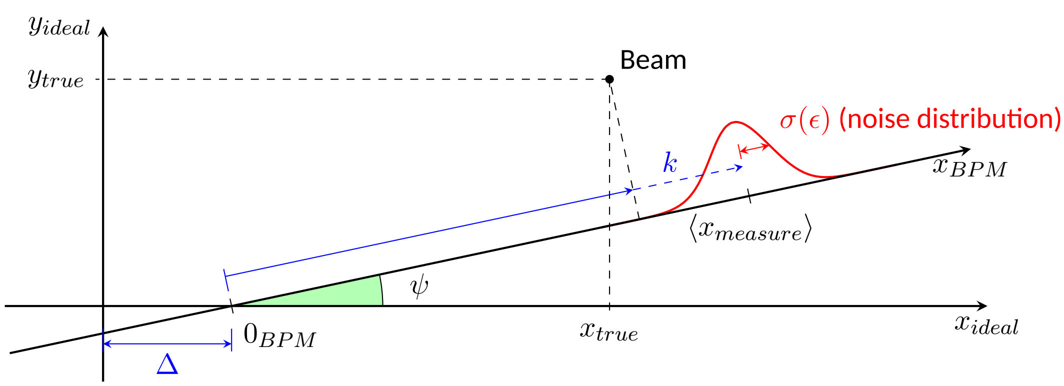

Figure 2: Simplified visualisation of the main linear contributions to BPM measurement error in the horizontal plane only, but showing also the impact of roll.

The maximum error, or *tolerance*, is expressed as a function of the different uncertainties as:

$$|x_{\text{measure}} - x_{\text{true}}| \le |\Delta| + |k|X + |\psi|Y + \max_{x\in[-X,X], y\in[-Y,Y]} \left(\sum_{k=2}^{\infty} \sum_{j \le k} \alpha_{k,j} x_{\text{true}}^{k-j} y_{\text{true}}^{j} \right) + 2\sigma(\epsilon) \tag{2}$$

where X and Y is the applicable range of the measurand, and a ratio of 2 between r.m.s. and peak value is assumed for the random noise. As the other tolerances defined in [1], all values specified in this document are given as range, e.g. $\pm 1mm$, assuming a ratio of 2 between r.m.s. and peak values, unless otherwise specified.

Note that the components of measurement error in Eq. (2) may depend on BPM, bunch population, bunch pattern, average orbit and possibly by environmental conditions.

The resulting target tolerances defined in [1] are very demanding and probably not achieved in the LHC [11]. As mentioned in Sec. 2.3, the reproducibility of a measurement is often more important than its accuracy depending on the use. In the following sections, the two most demanding uses of orbit data are then described together with the required BPM specifications.

3.1 Orbit measurements and correction

CO measurements are needed to keep the beam close to a user-defined *golden orbit* from injection till stable beam, have a reproducible beam separation collapse process to avoid ending up with a too large separation (no luminosity signal or instabilities) which can be quantified in a separation within 4 σ^*, i.e. about 2% of the head-on luminosity, and finally keep beams colliding with required separation within 0.2 σ^* to avoid luminosity losses or spikes above 1%. The reproducibility during stable beam is needed mostly to keep collision. In this case the difference between Q1 left – Q1 right response matters most, while in the arc one can assume a tolerance of about 10% of the beam size.

For the following specifications, a simplified version of Eq. (1) which takes into account time (t) is considered:

$$x_{\text{measure}}(t) = x_{\text{true}}(t) + x_{\text{error}}(t, I_b, T, ...) \tag{3}$$

where x_{error} is a generic function which depends, for example, on bunch intensity (I_b), ambient temperature (T), filling pattern, etc. Here the important requirement is the precision of the measurement, defined as the maximum allowed standard deviation of x_{error} over different time scales. The requirements are summarised in Table 5 for beams of several bunches. The specifications in Table 5 should be considered valid

Table 5: Requirements for orbit measurements expressed as range, assuming a ratio of 2 between r.m.s. and peak values, for luminosity production beams.

Timescale	Arc and MS BPM	Triplet BPM	
		Point 1/5	Point 2/8
Stable beam (∼10 h)	$\pm 20\mu m^‡$	$\pm 2\mu m^†$	$\pm 10\mu m^‡$
Fill to fill (∼24 h)	$\pm 28\mu m$	$\pm 28\mu m^†$	$\pm 28\mu m$

† Number computed from [16].

‡ Number extracted from [1].

over the whole Operational range (OP) specified in Table 2 and bunch intensities specified in Table 1. The ideal acquisition rate is the one specified in Table 4, however the requirements in Table 5 could be achieved by averaging the orbit acquisition over a few seconds, at the expense of orbit feedback bandwidth. The most defined requirements are the ones given for stable beam (∼10 h), which either come from [1] or computed from [16] to ensure a luminosity stabilisation better than 1% only relaying on BPM information. For fill to fill (∼24 h) and possibly longer time scale a generic value of $\pm 28\mu m$ has been computed as the value of $\pm 40\mu m$ for IR1/5 BPMs defined in [16] to ensure to find back collision after a refill with a safety factor of $\sqrt{2}$. The safety factor is justified by assuming that during two or more fills the electrical stability of the BPM and acquisition chain could be of the same order as the mechanical stability of the equipment, which should still be very conservative, at least over relatively short time scales up to a few weeks.

For pilot bunches the requirements in Table 5 would probably be not realistic. In this case a general requirement of $\pm 200\mu m$ resolution from [1] can be assumed for any BPM type and timescale.

The mean value of x_{error}, i.e. normally dominated by the *offset* in Eq. (1), is not so important but for aperture optimisation, for which a good knowledge of the orbit with respect to the nearby magnets is valuable. For this the typical specifications from [1] still hold, and are reported in Table 6.

A special case is the accuracy on the difference between Beam 1 and Beam 2 position measured in the IR BPMs. By profiting of the common BPM hardware and acquisition chain for both beams, one can use this information for a careful measurement of the beam crossing angle and separation, which are particularly

Table 6: General specification for BPM offset, valid for all type of beams.

Goal	**Arc BPM**	**Triplet BPM**	
		Point 1/5	**Point 2/8**
Offset [1]	$\pm 100 \mu m$	$\pm 30 \mu m$	$\pm 30 \mu m$

important for beam-beam effects. The first BPM next to the IP is at about $22m$ from the IP and the minimum half crossing angle is of $180 \mu m$. In order to achieve an accuracy of $\pm 1\%$ on the measurement of the crossing angle one would need an accuracy of $\pm 40 \mu m$ on the Beam 1 and Beam 2 orbit difference, as reported in Table 7.

Table 7: Accuracy requirements on Beam 1 and Beam 2 position difference for crossing and separation estimation better than $\pm 1\%$. Values are expressed as max range, assuming a ratio of 2 between r.m.s. and peak values.

Goal	**Arc BPM**	**Triplet BPM**	
		Point 1/5	**Point 2/8**
$\langle x_{B1} \rangle - \langle x_{B2} \rangle$	n.a.	$\pm 40 \mu m$	$\pm 40 \mu m$

3.2 Optics measurement and correction

In the LHC, and HL-LHC, the measurement of the phase difference between consecutive BPMs when the beam is under an AC dipole excitation is the most accurate method to measure β-beating in most of the machine. Around the IP the most accurate method is k-modulation [17]. An alternative and faster method would be to use BPM amplitude data from AC-dipole measurements, but in LHC this does not give the sufficient accuracy due to limited knowledge of BPM calibration factor (k). This limitation could be overcome in HL-LHC if more accurately calibrated BPMs could be deployed.

Optics measurements requires synchronised horizontal/vertical TR readings ($x_{b,j,k}, y_{b,j,k}$) from all BPMs (b), a few bunches (j) and turn-by-turn (k) for a few thousands turns (N) during AC-dipole excitation. Orbit oscillations are typically induced using the AC dipole, able to induce oscillation up to about 5 σ_{beam}, i.e. able to cover the whole BPM operational range (Table 2), or using the ADT system for oscillations up to about 1 σ_{beam} [17]. The time frame for those measurements is of the order of 20 minutes, and they are typically performed using a pilot bunch or few bunches at different time along the cycle, from injection to top energy, and for different machine optics.

In order to achieve a β^* imbalance better than 5% between IP1 and IP5, the requirements with respect to Eq. (2) are computed and summarised in Table 8.

Note that for β^* measurements the difference of scale error between Q1-left and Q1-right matter the most. In the present specifications the noise is assumed to be white, while coloured noise could be detrimental for AC dipole measurements. In the latter case, more detailed studies might be needed.

The non-linearities of the response of the BPMs play a role in the non-linear measurements in TR mode. If required, studies are needed to obtain more detail specifications than what already specified in [1].

Table 8: Requirements for optics measurements and correction, valid for 1 pilot bunch over between two BPM calibrations [12, 17] and for orbit oscillation amplitude up to the OP range in Table 2. Values are expressed as max range, assuming a ratio of 2 between r.m.s. and peak values.

Goal	Arc BPM	Triplet BPM	
		Point 1/5	**Point 2/8**
Calibration error (k)	3%†	1.6%†	4%‡
Noise (ϵ)	$\pm 100 \mu m$†	$\pm 30 \mu m$†	$\pm 100 \mu m$†

† Number computed from [17].

‡ Number extracted from [1].

3.3 Resulting Specifications

The tolerances identified in Tables 8 and 5, are summarised in Table 9, together with generic tolerances for offset, from Table 6, and the required resolution which, to be consistent with the other specifications, has been set as half the more demanding other requirement. For comparison, Table 9 also report the LHC specifications from [1]. Note that the specifications on roll and non-ineari0.0860ty have been maintained equal to the LHC specifications from [1]. New specifications on those terms could come from new studies on non-linear effects measurements and corrections.

Table 9: Summary specification. Values are expressed as max range, assuming a ratio of 2 between r.m.s. and peak values.

Goal	Tolerance LHC [1]	Tolerance HL–LHC
Calibration error	±4%	±3% (TR, Arc)
		±1.6% (TR, P1/5)
		±4% (TR, P2/8)
Roll	±2 mrad (Arc)	±2 mrad (CO, Arc)
	±1 mrad (Triplet)	±1 mrad (CO, P1/2/5/8)
Offset	±100 μm (Arc)	±100 μm (CO, Arc)
	±30 μm (Triplet)	±30 μm (CO, P1/2/5/8)
Non-linearity	±200 μm over ±4 mm (CO)	±200 μm over ±4 mm (TR tbc)
	±500 μm over OP range (CO)	±500 μm over OP range (TR tbc)
2×Std(x_{error})	±20 μm (CO, Arc)	±20 μm (CO, 10h, Arc)
	±10 μm (CO, Triplet)	±10 μm (CO, 10h, P2/8)
		±2 μm (CO, 10h, P1/5)
		±28 μm (CO, 24h, Arc)
		±28 μm (CO, 24h, P1/2/5/8)
⟨B1⟩-⟨B2⟩	±30μm (CO, Triplet)	±40μm (CO, P1/2/5/8)
Noise	n.a.	±100 μm (TR, Arc)
		±100 μm (TR, P2/8)
		±30 μm (TR, P1/5)
Resolution	±50 μm (TR)	±50 μm (TR, Arc)
		±15 μm (TR, P1/5)
	±5 μm (CO)	±5 μm (CO, Arc)
		±1 μm (CO, P1/2/5/8)

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