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CONCEPTUAL SPECIFICATIONS

[DRAFT] CONCEPTUAL BPM SPECIFICATIONS FOR THE HL-LHC

Abstract

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

TRACEABILITY

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1 INTRODUCTION

The BPM is expected to be upgrade 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. The LHC BPM system has been specified in the document [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 [5]. Optics corrections are also more difficult due to larger peak β-function in Point 1 and 5. The present performance of the LHC system and the functional specifications have been discussed in [7-9].

The document resumes the concepts and specifications for LHC, which are still valide, 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 finaly accuracy required. The document does not include hardware specifications needed to obtained the requested performance.

2 MEASURENENT SCENARIOS

2.1 Beam parameters

The expected beam parameters are show in Table 1 and taken or calculated from [3, 4] for protons and ions. Doublet proton bunches might be used at injection for scrubbing runs [TODO Beam parameters].

Table 1: Beam Parameters

Particle	Bunch Charges [q]	Max Number of bunches	Min bunch spacing [ns]	Bunch length FWHM [ns]
Proton	$5\ 10^{9} \rightarrow 2.3\ 10^{11}$	2760	25	0.7→1
Pb	$(5\ 10^{9}) \rightarrow 1.6\ 10^{10}$	1170	100	0.7→1

BPM in the low-β insertions are special in terms of range of measurand since the closed orbit is large in presence of a crossing angle and in terms of bunch spacing since due needs of detecting the counter-rotating beams.

2.2 BPM families

We can distinguish two BPM families. The one in the arcs that measure 1 beam at the time over a limited range of orbit excursion and the BPM in the triplet are that observes the BPMs of both beams (with an effective small beam separation) and large orbit excursion due to crossing angles.

Table 2: BPM Types

Type	Two beams	Range Operation [mm]	Max Range Studies [mm]	Bunch spacing (Signal) [ns]
Arc	No	±4 mm	±18 mm	25
Triplet Point 2, 8	Yes	±15 mm	±27 mm	5.ns
Triplet Point 1, 5	Yes	±20 mm	±58 mm	3.5 ns

For the BPM in the triplet in Point 1/5, the minimum bunch spacing as seen from the two different ports of a stripline BPM (12 cm length) by placing the BPM center at least 57 cm from a beam-beam parasitic encounter (e.g. 51 cm from the closest port) [6].

Triplet BPMs might need special features in case of Pb-p run to cope with different revolution frequency.

2.3 Measurement types

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

1. Bunch-by-bunch turn-by-turn for orbit oscillations (TR)
2. High resolution averaged position (CO)

TR mode aims at measuring optics parameters and bunch dependent orbit (e.g. long-range beam-beam depedent effects) in dedicated machine measurements. CO measurement types aim at knowing the average orbit continuously to set-up orbit and stabilize operations, and in dedicated orbit response measurements (e.g. k-modulations).

The error of a single isolated measurement of a BPM can be described by [1,2]:

$$x_{\text{measured}} - x_{\text{true}} = \Delta + k x_{\text{true}} + \psi y_{\text{true}} + \sum_{k=2}^{\infty} \sum_{j \le k} \alpha_{kj} x_{\text{true}}^{k-j} y_{\text{true}}^{j} + \varepsilon\,,$$

and depends on a combination of offset (Δ), scale error (k), tilt (ψ), non-linearieties (α_{kj}), and noise (ε), which is assumed to be random. In [1], it is not specified what it is x_{true}. A naïve defition is that x_{true} is the beam position w.r.t to the ideal machine reference frame. In this case however the offset will depend on the alignment accuracy of the BPM and the extent of the ground motion.

The relation from uncertainty and tolerance is given by:

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

where X and Y is the applicable range of the measurand. The resulting target of accuracy in [1] are very demanding and probably not achieved in the LHC.

A BPM measurement is never used in isolation and machine measurement always involve a series of BPM reading. 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. In this document we assume that the component of measurement error may depend on BPM, bunch population, bunch pattern and average orbit.

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 can distinguish between reproducibility between consecutive measurents in the time scale:

Table 3: Types of reproducibility

Reproducibility	Usage
Bunch-by-bunch	Beam-beam effects [1]
Stable beam	IP position control [9]
Entire fill	Keep consistent during optics change
Fill to fill	Find collisions after a refill

2.3.1 Optics measurement and correction

For instance TR measurements are used taking syncrhonized horizontal/ vertical readings (x_{bjk}, y_{bjk}) from all bpms (b) bunch-by-bunch (j) turn-by-turn measurement for thousands turns (k) during AC dipole exicitaiton for some bunches. Data is further transformed in

$$X_{bj}(Q) = \sum_k \mathrm{x_{bjk}} \mathrm{exp}^{i2\pi Qk}$$

for certain Q close to the tune for optics measurements. Typical excitation with the AC dipole is 5 σ, and with ADT and full beam up to 1 σ;

2.3.2 Orbit measurements and correction

Orbit measurements are needed to keep golden orbit from injection till stable beam, have a reproducible collapse process to avoid ending up with a large separation (no luminosity signal or instabilities), keep beams colliding with required separation within 0.2 σ to avoid luminosity losses or spikes.

3 HL-LHC SPECIFICATIONS

3.1 Specifications

Table 4: Specifications

Goal	Tolerance LHC	Tolerance HL-LHC
Scale error	±4%	±1%
Roll	±1 mrad	±1 mrad
Offset	±100 µm (±30 µm Triplet)	±100 µm (±30 µm Triplet)
Non-linearity	±200 µm over ±4 mm, ±500 µm over OP range	±200 µm over ±4 mm, ±500 µm over OP range
Resolution	±50 µm (TR), ±5 µm (orbit)	±50 µm (TR), ±5 µm (orbit), ±5 µm (orbit triplet)

3.2 Orbit correction

Table 5: Orbit measurements ranges

Goal	Arc BPM	Triplet BPM
Accuracy [1]	±100 µm	±30 µm
Reproducibility bunch-by-bunch (0.1 σ) [1]	±30 µm	±100 µm
Reproducibility stable beam [7]	0.1 σ	±2 µm (0.1 σ IP)
Reproducibility fill to fill [9]	±100 µm	±10 µm
Reproducibility during the year [9]	±100 µm	±30 µm
Resolution [9]	±5 µm	±1 µm

Accuracy and reproducibility values are taken from

The reproducibility during stable beam is needed mostly to keep collision. In this case difference between Q1 left – Q1 right response matters most.

3.3 Optics measurements

Table 6: Optics Measurements

Measurements	BPM	Observable	Uncertainty
Optics from phase	Arc	$\angle X_{bj}(Q)$	≤1 10^{-3}
Optics from amplitude	Arc	$\lvert X_{bj}(Q)\rvert$	≤ 1 10^{-2}
β* from phase	Triplet	$\angle X_{bj}(Q)$	≤ 1 10^{-4}
β* from amplitude	Triplet	$\lvert X_{bj}(Q)\rvert$	≤ 1 10^{-2}

For β* measurements the difference of scale error between Q1-left, Q1-right matter most.

3.4 Data flows and response time

Table 7: Data flow and response time

Measurements	Frequency	Delay	Quantity
Orbit mode	12.5 Hz	5 ms	Continous
Trajectory	~0.5 Hz	~1 s	All bunches, 20 k turns

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