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HL-LHC BPM SYSTEM DEVELOPMENT STATUS

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Abstract

The demanding instrumentation requirements of the future High Luminosity LHC (HL-LHC) require 44 newly designed Beam Position Monitors (BPM) to be installed around the ATLAS and CMS experiments in 2026–2028. Three BPM types are now in pre-series production, with two more variants under design. Close to the collision point, a set of cryogenic directive coupler BPMs equipped with a brand new acquisition system based on nearly-direct digitization will resolve the position of the two counter-rotating LHC beams occupying a common vacuum chamber. Other new button and stripline BPMs will provide not only the transverse beam position, but also timing signals for the experiments, and diagnostics for the new HL-LHC crab cavities. This contribution summarizes the HL-LHC BPM specifications, gives an overview of the new BPM designs, reports on the pre-series BPM production status and plans for series manufacturing, outlines the foreseen acquisition system architecture, and highlights the first beam measurements carried out with the proof-of-concept electronics for the directive stripline BPMs.

INTRODUCTION

The High Luminosity LHC (HL-LHC) project aims to significantly boost the LHC performance with a series of major upgrades scheduled to take place in 2026-2028 [1]. Most notably, the two regions housing the large ATLAS and CMS experiments will be overhauled including a complete replacement of the low-beta Inner Triplets (IT) with higher gradient focusing magnets to produce an even smaller beam size at the Interaction Points (IP) where the LHC beams collide. Further increase of the instantaneous luminosity will be possible thanks to crab cavities (CC) installed on each side of ATLAS and CMS. The CC installed upstream from the IP will tilt each circulating bunch transversely such that at the IP it collides head-on with the counter-rotating bunch. The CC on the other side of the IP will reverse this tilt to cancel out any transverse oscillation outside of the crabbing region between two CCs.

SYSTEM OVERVIEW

The HL-LHC ITs will require a set of new Beam Position Monitors (BPM) to reliably control the orbit of extraordinarily small beams. Moreover, additional specialized BPMs are needed near the CCs to tune and monitor the crabbing process as well as to watch for any beam instabilities [2]. In total, 44 new BPMs of 5 types will be installed as part of the HL-LHC project. Figure 1 shows the arrangement of the new BPMs on each side of the IP in the HL-LHC era.

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The six BPMs closest to the IP (BPMQSTZA and BPMQSTZB types) are installed inside the continuous cryostat of the new HL-LHC IT where both counter-rotating beams will circulate in a common vacuum chamber. Therefore, these BPMs must be able to distinguish the position of each beam independently. Such a feature, referred to as directivity, is typical of directional coupler BPMs in which the passing beam induces signals on four long antennas (commonly called striplines) parallel to the beam motion axis [3]. The striplines are connectorised on each end and are designed such that the majority of the beam signal couples only on the upstream port with a much smaller (around 5%) parasitic signal leaking to the downstream output. To further reduce the cross-talk between the two beams, the HL-LHC directional couplers will be installed in locations where bunches of both beams arrive at different times with the temporal separation ranging from 3.9 ns (approximately 3 times larger than the bunch length) up to 10.5 ns depending on the BPM location. The measurement error due to the presence of the other beam will also be reduced through digital signal processing with a new dedicated fast-sampling data acquisition system [4]. All HL-LHC directional coupler BPMs will operate at a cryogenic temperature within the 60–80 K range. Moreover, the BPMQSTZB type BPMs will be equipped with shielding blocks made out of tungsten to decrease the ionizing dose received by the nearby superconducting magnets [5].

Further away from the IP, after the separation-recombination dipoles, both beams circulate in separate vacuum chambers. A standalone double-aperture cryogenic dipole will be equipped with two capacitive button BPMs (one per beam, BPMQBCZA/B type) installed within the magnet's cryostat and operating at 4.5–20 K. The signals of these BPMs will be measured by the currently used LHC BPM data acquisition system [6].

The remaining three room-temperature BPMs installed after the CCs will not become part of the main LHC BPM system but will instead serve very special users. The two BPTQR type BPMs will replace the initially foreseen APWL pick-ups as the main diagnostic monitors for the crab cavities. These BPMs will be connected to dedicated electronics and will combine three different BPMs in a single unit:

- a set of capacitive buttons for phasing the CCs with the beam and for filtering the CC antenna signal,
- a pair of 94 mm-long stripline antennas for the CC amplitude and noise feedback at the 800 MHz component,
- a pair of Electro-Optical (EO) buttons [7] or a pair of 400 mm-long stripline antennas for wideband measurements of beam instabilities introduced by the CCs.

The detailed BPTQR design is not yet frozen, and some technical decisions (e.g. the choice between EO buttons and stripline antennas) will be taken in the following years.

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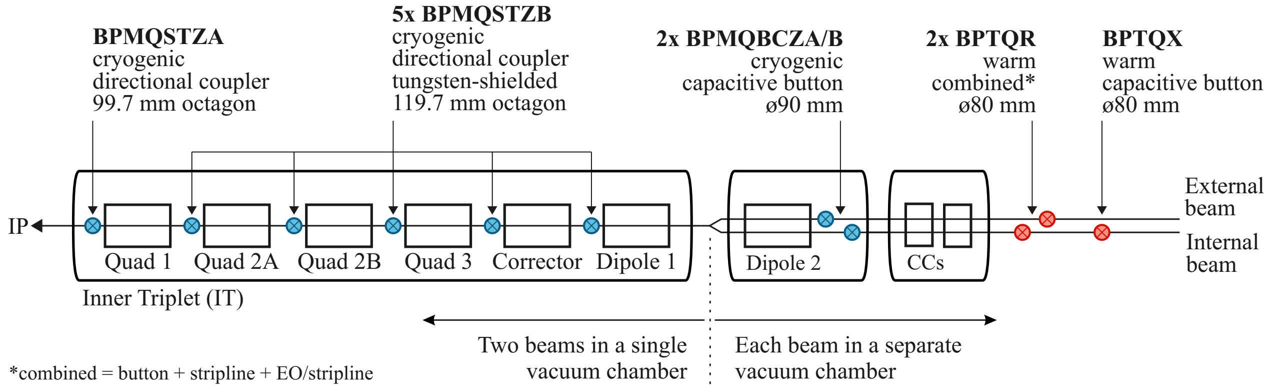

Figure 1: New BPMs foreseen to be installed in the HL-LHC era on each side of the ATLAS and CMS experiments.

The final BPTQX type BPM will replace the currently used BPTX pick-up which is part of the ATLAS and CMS experiments' trigger and timing system [8]. These capacitive button BPMs are installed only on the vacuum chamber carrying the beam travelling towards the IP and are connected to dedicated electronics managed by the experiments.

With the increased bunch intensity in the HL-LHC era, the beam-induced heat loads on accelerator components have to be managed even more carefully than in the LHC. The inner surfaces of all HL-LHC BPMs will be coated with 100 µm-thick layer of copper to improve heat transfer along the body and a thin layer of amorphous carbon to reduce the power generated due to electron cloud effects [9]. Moreover, all cryogenic BPMs will be actively cooled with liquid helium to efficiently maintain them at the temperature of the adjacent vacuum components.

PERFORMANCE SPECIFICATIONS

The LHC BPM system has three main users whose requirements drive the performance specification:

- the accelerator operators who continuously monitor and control the average beam orbit, predominantly through an automated feedback system,
- the accelerator physicists who rely on bunch-by-bunch turn-by-turn position data to measure and correct the accelerator optics as well as to tune its performance,
- the LHC experiments who calibrate the luminosity through van der Meer scans using the average beam orbit measured by the BPMs closest to the IP.

The users' requests for the HL-LHC era BPM system performance have been collected in a detailed document which currently serves as a baseline conceptual specification [10]. Table 1 provides an excerpt of some of the most demanding performance requirements for the IT BPMs. With a reduced BPM sensitivity due to the increased vacuum chamber aperture, some of the requests (e.g. one-turn one-bunch precision) call for an effective improvement by over an order of magnitude when compared to the currently used LHC BPM data acquisition system. Detailed studies spanning theoretical analysis and practical measurements are ongoing to evaluate if the requested performance can be achieved.

Table 1: Users' Requests for the HL-LHC IT BPM

Parameter	Value
Bunch charge	0.8–36 nC
Minimum bunch spacing	25 ns
Turn period	89 µs
Measurement range	±29 mm
Scale error	0.8%
Non-linearity	0.1%
Gain stability (24 h)	0.1%
Measurement offset	50 µm
One-turn one-bunch precision	15 µm
Two-beam cross-talk	0.05%

PRODUCTION OF BEAM PICK-UPS

All cryogenic HL-LHC BPMs will be integrated within the respective magnet's cryostat. The BPM installation is, therefore, one of the many steps in a long magnet assembly sequence. As the series production of HL-LHC IT magnets is already ongoing or starting soon [11, 12], the BPM manufacturing must also be carefully scheduled to ensure that the pick-ups are available when needed. Overall, 38 cryogenic BPMs (32 to be installed in the accelerator and 6 spares) will be manufactured by the CERN Main Workshop in the coming years. Figure 2 shows the most complex BPM type to be built, BPMQSTZB, which features an octagonal aperture, tungsten shielding blocks, brazed thermal links, welded cooling capillaries, and conflat knife-edges machined on a solid 316LN stainless steel body. All cryogenic HL-LHC BPMs will interface the adjacent vacuum components via custom aperture-adapting transitions made out of OFE copper.

Due to the high complexity of the cryogenic HL-LHC BPMs, their manufacturing has been split into three phases: prototyping (simplified units to test specific manufacturing methods), pre-series production (2 units per type), and series production (32 units of 3 types in total). The prototyping phase was completed by the end of 2021 and currently 6 fully-featured pre-series units are being manufactured at CERN. One of the BPM bodies after gold plating and copper coating can be seen in Fig. 3.

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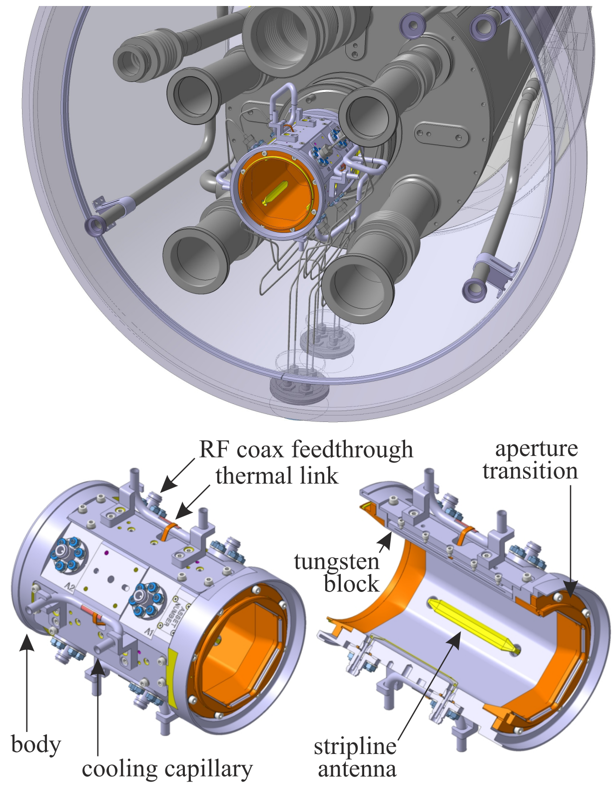

Figure 2: BPMQSTZB-type cryogenic directional coupler BPM in a magnet's cryostat (top) with its most important features marked (bottom).

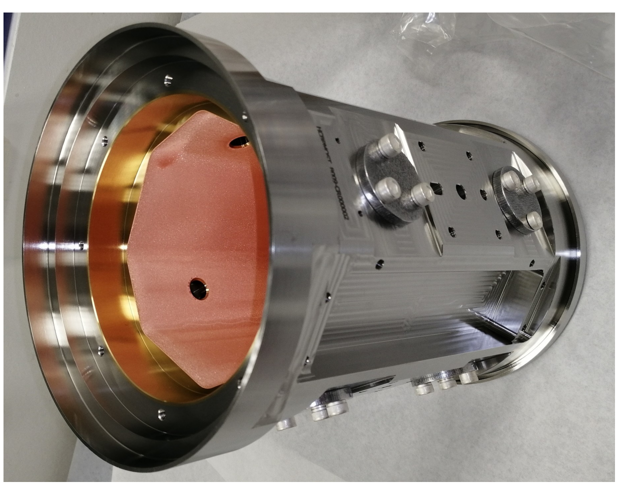

Figure 3: Gold- and copper-coated pre-series body of the BPMQSZTB-type BPM

The series production of the remaining cryogenic HL-LHC BPMs is foreseen to start once the pre-series units have been fully validated through vacuum, cryogenic, electrical, and mechanical integration tests. Installation of the first BPMs in cryogenic magnets is foreseen to take place in June 2023 and launch a campaign lasting until early 2026.

The production schedule of the room-temperature BPMs of types BPTQR and BPTQX is more relaxed as their installation is scheduled to take place only in 2028. Nevertheless, their mechanical designs are expected to be completed in 2022 (BPTQX) and 2023 (BPTQR) with production to start in 2024. Due to their simpler design and a reduced number of value-adding features, the warm BPMs are expected to be easier to manufacture than the cryogenic BPMs.

In parallel, the Mechanics and Logistics section of the CERN Beam Instrumentation Groups is designing and manufacturing a vast amount of custom tooling for BPM assembly, 3 coating procedures, quality control (mechanical, electrical, vacuum), handling, and storage.

DATA ACQUISITION SYSTEM FOR DIRECTIONAL COUPLERS

Independently of the BPM pick-up design and production, a new data acquisition platform for the cryogenic directional couplers is under development in collaboration between CERN and the University of Oxford. In contrast to the acquisition electronics used by the current LHC BPM system which relies on precise analogue signal conditioning (through amplitude-ratio to time-difference conversion), the new electronics will exploit nearly-direct digitisation of the BPM-generated signals with minimum analogue pre-processing. Due to the high radiation levels in the HL-LHC IT area, it is not possible to house the acquisition electronics directly next to the BPMs. However, favourable locations with radiation levels considered safe for commercial-grade electronics have been identified in the nearby technical galleries with the maximum cable length between a BPM pick-up and its acquisition electronics not exceeding 100 m.

Numerical studies have demonstrated that precise beam position measurements based on direct digitisation in the LHC require a sampling rate in the order of a few gigasamples per second (GSps) and a vertical resolution with an Effective Number of Bits (ENOB) reaching 10 [13]. The Xilinx Zynq UltraScale+ RFSoC [14] has recently been identified as a compelling solution for modern beam instrumentation systems [15–18]. These devices integrate multiple high-performance analogue-to-digial converters (ADC) and digital-to-analogue converters (DAC) together with a feature-rich platform which includes Digital Signal Processing (DSP) blocks, a general-purpose processor, and programmable logic on a single chip. Given its excellent datasheet performance, tests are ongoing to verify if the new data acquisition system for the HL-LHC directional coupler BPMs can be based on the RFSoC technology.

In October 2021, beams briefly circulated in the LHC for the first time after a three-year-long shutdown in order to test various systems before the accelerator fully restarted in April 2022. This period was also used to parasitically acquire preliminary beam data with an off-the-shelf ZCU111 evaluation board connected to one of two existing directional coupler BPMs installed 30–60 m away from the CMS experiment. The ZCU111 board is equipped with a Generation-1 RFSoC featuring 8 ADCs (sampling at up to 4.096 GSps with ENOB $\approx$ 9.5) which is sufficient to acquire all the signals generated by one directional coupler BPM. However,

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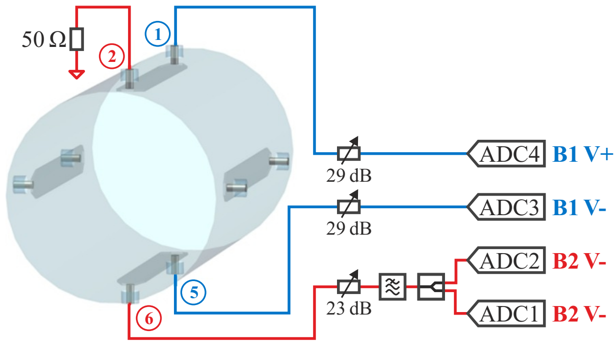

Figure 4: One of the configurations used in 2021 to acquire beam-induced BPM signals with a ZCU111 board.

due to some prototype firmware limitations, only four of the available ADCs could be used during the tests.

Even though direct digitisation calls for the signal source to be connected directly to the ADC, such an approach is not possible for the LHC BPMs. The broadband nature of beam-induced BPM signals as well as their amplitudes reaching several hundreds of volts exceed the input capabilities of even the most modern digitisers. Some limited analogue signal conditioning is therefore unavoidable and even desirable to match the BPM signals well to the ADC input capabilities. During the aforementioned 2021 beam tests, the analogue front-end consisted of a fixed 23–29 dB attenuator and a custom-made non-reflective low-pass filter with a 3 dB cut-off at 170 MHz and a sufficient anti-aliasing insertion loss (exceeding 60 dB for frequencies above 900 MHz).

The data were acquired using five different configurations, with one of them set out in Fig. 4. In this case, the vertical plane of Beam 1 BPM (ports 1 and 5) was connected without additional filtering to the ADC channels 3 and 4, while the remaining ADC channels 1 and 2 measured the split filtered signal of Beam 2 BPM bottom output (port 6) with the top port terminated with 50 Ω. The split signal measurements are particularly interesting as they allow the acquisition electronics' resolution to be evaluated independent of the real beam movement. The other tested configurations employed unsplit signals from one of two different pick-ups with or without filters and with different levels of attenuation.

As will be the case in the final system, the ADC clocks were free-running and asynchronous to the beam but phase-locked among the four used ADCs. A standard LHC timing signal was used to define the acquisition window with respect to the revolution period. All measurements were carried out with only a few well-separated bunches in each beam organized such that none of the bunches of the counter-rotating beams arrived at the BPM location near each other.

In total, nearly 700 thousand traces have been recorded in a two-day measurement period. In order to reliably compare various considered data processing and correction algorithms, no DSP was applied online and all ADC samples were saved as raw data for fully offline processing. The signals typically covered 30% to 50% of the ADC dynamic range.

The comprehensive analysis of the acquired data will be the subject of another, future manuscript. However, some preliminary results indicate that an RFSoC-based acquisition system might be the right choice for the HL-LHC directional couplers. The data acquired with a split signal hints that a one-turn one-bunch precision of under 30 μm could be achievable with the input signal covering noticeably less than half of the ADC dynamic range. An extensive analysis of waveforms synthesized such that the two beams arrive at the BPM location with the expected temporal separation proves that the developed two-beam cross-talk correction algorithm (so-called *power compensation* [4]) can efficiently minimize the impact of the pick-up's limited directivity. The analysis also substantiated that signal reflections due to imperfections in cables and connectors lead to a quantifiable reduction of the measurement precision and might require a dedicated correction procedure.

As the 2021 tests proved invaluable for the development of the new data acquisition systems for the HL-LHC directional couplers, a further data-taking campaign is foreseen in 2022. With dedicated beam time, it will be possible to configure the two beams to even better mimic the conditions expected in the HL-LHC era. Most importantly, the temporal difference between the arrival of bunches from both beams at the BPM location will be controlled through a process commonly called RF cogging.

SUMMARY AND OUTLOOK

As part of the HL-LHC project, 44 new BPM pick-ups of 5 brand new types will be installed to fulfil the ever increasing beam instrumentation and diagnostics needs of the BPM system users. Pre-series production of the most urgently needed pick-ups is already ongoing, with the remaining units to be manufactured in the coming years.

The cryogenic directional couplers are closest to the IP and see both beams circulating in a common vacuum chamber. In addition to the reduction of the two-beam cross-talk at source, a new data acquisition system based on nearly-direct digitisation and advanced DSP to reduce the measurement error is under development for those BPMs. Currently, the focus is on testing commercially available evaluation boards to qualify the RFSoC technology as viable for the HL-LHC direction couplers. Manufacturing of the first custom-made prototype boards is planned for 2024-25, with the series production expected to take place in 2026-27.

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