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HiLumi Beam Halo Monitor Review: Report from the Review Panel

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Abstract

The HiLumi Beam Halo Monitor Review took place at CERN on 18 December, 2024. The main goals of this review were to present the LHC beam halo monitoring functional specifications and to evaluate the performance and limitations of the beam instruments presently being studied (and developed where applicable) to meet these specifications. The evaluation is expected to assess the clarity, completeness, and consistency of the specifications, as well as to advise on the monitors' architecture and proposed implementation. It should also highlight the main risks for successfully deploying the system in the LHC during Long Shutdown 3 (LS3), considering both budget and schedule factors.

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Contents

1 Introduction

1.1 Event and Panel Composition

The HiLumi Beam Halo Monitor Review took place on 18 December 2024 at CERN and featured a full day program to review motivations and functional specifications for halo monitoring diagnostics in LHC during the Hilumi operation, as well as to analyse the different possible instruments currently under consideration for this function. The Review Panel was composed by Ubaldo Iriso (ALBA), as Panel Chair, Giovanni Rumolo (BE-ABP), Jörg Wenninger (BE-OP), and Markus Zerlauth (ATS-DO). The linkperson was Federico Roncarolo (SY-BI).

1.2 The charge questions

The Review Panel members are asked to answer the following charge questions:

1. Are the functional specifications comprehensive and clear? Is there any ambiguity, excessively stringent specification, or other inconsistency in the final document?

2. For each proposed technical solution:
   (a) Does the monitor meet all functional specifications?
   (b) Are budget and schedule clearly explained?
   (c) Is the proposed strategy and are the milestones to address remaining technical issues or unknowns well-defined and aligned with implementation during LS3?
3. Are the pros and cons of the different technical solutions properly addressed?
4. Are there changes to the functional specifications that could increase the chances of success in terms of budget and schedule?

1.3 Background material

A Working Group on LHC Beam Halo Monitoring was set up at the beginning of 2024 and met regularly from March to August 2024, producing a draft document with definitions and functional specifications for the HiLumi Beam Halo Monitor. The table, compacted, simplified and with some numbers amended is also reported here, see Table 1.

Parameter	**Unit**	**Collimation**	**MP**	**Beam-beam**
Range of Interest	σ with $\varepsilon_n = 2.5\mu$m	[4.7, 6.7] or [6.5, 8.5]	[4.7, 6.7] or [6.5, 8.5]	[3.5, 8.5]
Contrast		10^{-4} at 4.7σ	10^{-6} at 6.7σ	5×10^{-5} at 7σ
Relative integral		[0.2%, 5%]	[0.1%, 0.4%]	
Absolute integral	p in RoI	10^{12} for full beam	$[1,4] \times 10^{10}$ for 48 bunches	
Charge	p in RoI	Required	Required	Not required
Profile	-	Desirable	Not required	Required
2D Image	-	Desirable	Not required	Required
Acq. time	sec	60	10	60
Gating and integration	-	Beam	48 bunches	Bunch-by-bunch
Multi-turn integration	-	OK	OK	OK
Interlocking	-	No	Desired	No

Table 1: Functional specifications for Beam Halo Monitor. MP stands for "Machine Protection".

Reply to charge question 1:
Are the functional specifications comprehensive and clear? Is there any ambiguity, excessively stringent specification, or other inconsistency in the final document?
Yes, the specifications are comprehensive and seem to cover all relevant cases. Some inconsistencies have been spotted, discussed with the experts and corrected.

2 Executive Summary

At the time of the review, none of the four presented instruments has been demonstrated to fully meet the specification for halo measurements as detailed in Table 1, even when focusing on what the review panel would consider the two most relevant use-cases for collimation and machine protection.

The panel considers the BSRH to be the instrument with the best prospects of meeting the specification, with options for cross-calibration with BSRT and WS. The BSRH budget estimate is compatible with the present HL-LHC allocations and with a schedule that allows for an operational instrument as of the start of Run 4. The implementation of a second SR extraction (BSRTMBs) and optical line routing until the UA galleries is supported, which will come at the benefit of both the existing LHC beam instruments (BSRT, BSRA) as well as the sensitivity reach of the BSRH.

The BGI is equally part of the HL-LHC baseline, but comes today at considerable technical risk still. Additional studies should be done with high priority throughout 2025 to ensure the issues observed in the PS and SPS system are overcome in order to proceed with the installation of a prototype system in the LHC during the YETS 2025/26. The panel supports the addition of a gas injection system to enhance the sensitivity of the present baseline design.

Low density materials are considered a promising future development, with the potential of providing benchmark measurements at injection and at lower beam intensities. Due to its limitations and the still ongoing R&D phase, this option is not recommended to be retained within the baseline for HL-LHC. It is nevertheless considered an interesting evolution of the present wire scanner technology that promisees benefits for the entire accelerator complex, in particular to allow emittance measurements of the full LIU beam at the SPS top energy.

The BGC has shown interesting potential as a profile monitor, which in combination with BLM measurements may provide for a valuable complement as well in terms of halo measurements. Two more monitors are within the presently approved scope of HL-LHC UK2, and the panel supports to pursue the installation of a standalone monitor as well for B2, however outside the scope and resources of HL-LHC and with priorities that will not jeopardize the timely completion of the baseline deliverables of WP13.

3 Comments and Findings

3.1 Setting the scene

Halo formation seems to originate partly from the injectors and the beam transfer to the LHC, but also from mechanisms in the LHC itself like nonlinear motion, beam-beam and e-cloud.

- Diffusive models are being developed to explain the mechanisms observed in the LHC. Island trapping + transport is being investigated as a possible alternative halo depleting technique.
- To gain information where the halo is mostly generated, it would be highly valuable to measure it repeatedly at several points during an LHC fill, e.g. at injection, end-of-injection, flat top, start of stable beams and before dumping.

R1: It is recommended to continue MDs (or end of fill studies) during Run 3 to gain a deeper insight into halo population and re-population dynamics throughout the entire LHC cycle, in particular for higher bunch intensities approaching the nominal HL target.

R2: It is recommended to ensure that the selected beam halo measurement tool is able to measure the halo along the entire LHC cycle.

There is currently no active mitigation measure for halo depletion foreseen in the HL-LHC baseline. The Hollow Electron Lens (HEL), which would have worked as a halo cleaning device, will not be implemented during LS3 but can be considered as a post-HL item to be installed in one of the following long shutdowns, should safe operation require it. In absence of an active halo cleaning device it is even more important to be able to measure the halo population as of the start of Run 4, to be able to trigger mitigation measures/interlock signals in case of excessive halo population.

Typical ranges of interest for halo population are beyond 3σ or within 2σ from the primary collimator (TCP) position.

- Two possible operational settings are assumed for collimators, tight and relaxed, which define different halo regions. The latter are helpful for halo and impedance. Relaxed collimator settings is the baseline for the entirety of Run 4, allowing to reach a minimum beta* of 20 cm at the end of Run 4. Tight collimator settings are currently planned to be used operationally only as of Run 5.

Halo measurements have been executed by moving collimators into the beam and then use the Fast Beam Current Transformers (FastBCT) and calibrated Beam Loss Monitor (BLM) signals. However, these are destructive, time-consuming and loss generating measurements. Furthermore, as collimator jaws get close to the beam during these measurements, the beam can get unstable and so perturb the measurements. During operation, this method can be potentially used only as an End-of-Fill (EoF) tool and is limited today to only a few bunches at flat-top in order to allow movement of the collimator jaws outside the nominal settings.

- Such measurements performed before LS2 showed values of up to 5% in terms of relative integral (tail population above 3σ normalized to full beam population), however only up to 1.5% after LS2, when a new beam production scheme was put in place after the LHC Injectors Upgrade (LIU) project implementation and a dedicated "halo optimisation" campaign was implemented in 2024.
- BLMs allow for an increased dynamic range (contrast), whereas bunch-by-bunch measurements are possible with the FastBCT.
- Some correlations were found, e.g., one can see less populated halo for colliding bunches and depending on the number of collisions, while bunches with more e-cloud have more populated halos and exhibit slower repopulation.

The main drivers for halo monitoring are the collimation team, the Machine Protection (MP) team and machine physicists for beam-beam measurements.

- The collimation team requires that the total beam energy stored within 2σ from the primary collimator stays below 1 MJ for the full HL-LHC beam in order to avoid risks of magnet quenches or damage to other parts of the machine due to particle showers. This translates into a limit for the tail population (absolute integral) of 10^{12} protons.
- From simulations of fast failures, the MP team requires that the halo population (absolute integral) stays between 10^{10} and 4×10^{10} p over 48 bunches. The lower limit is due to the fact that the generation of interlock signals relies on the BLM response, which may not be fast enough if the halo is too depleted. The required range corresponds to 0.1-0.4% relative integral.
- Accelerator physicists who study the different bunch-by-bunch loss patterns and their correlations with beam-beam or e-cloud would benefit from reconstructing the q-values of the distributions and estimate the halo populations (beyond 3σ) bunch-by-bunch.

R3: Unlike the two first use cases, the beam-beam use case is oriented to the optimisation of luminosity production with no direct machine protection

implications. Priority shall be given to commission for the start of Run 4 a working instrument complying with the collimation and MP specifications. Additional features shall be considered only after demonstrating this core functionality.

Interlocks could be attached to halo measurements and therefore will require the signal to be available with adequate reliability.

There is some flexibility to change the optics in IP4 and enlarge the beta functions at the position of the beam size/halo monitoring devices.

- While not much flexibility is available at injection due to aperture constraints, aperture is not a problem anymore further along the cycle and at flat top. This flexibility is currently used to keep the optics unchanged from injection until the end of leveling. This optics was also chosen to keep the beams round at the location of the electron lenses (which since have been dropped from the baseline).
- For the BSRT the increase of beta function should always remain compatible with the requirement on the mirror position.

R4: As the e-lenses might still be considered for installation at a later moment of the HL era, it is recommended to maintain the constraint of round beams at the present installation location of the e-lens, and ensure compatibly with other optics changes proposed for IR4, e.g. optimizations of beam sizes for other BI instruments.

3.2 Beam Synchrotron Radiation Halo monitor or BSRH or coronagraph

The BSRH is receiving the light from the BSRT mirror. An occulter is used to remove the light from the beam core. The extraction mirror edge is a source of diffracted light, in particular in the horizontal plane. The BSRH is cross-calibrated with the BSRT using the full profile without occulter.

During MDs in 2024, low intensity bunches were first scraped on the primary collimators to $\approx 3\sigma$ before being blown up by the ADT to generate controlled tails. The BSRH did manage to track the halo population after subtraction of the diffraction offset. The BSRH results were consistent with the wire-scanners and tracked well the estimated beam halo. While absolute measurements bear more challenges, the relative tracking was found to be very consistent.

The device will be further developed in Run 3, in particular to achieve mostly automated halo measurements during regular fills.

A new extraction mirror design, tested for impedance in previous years, will be produced and installed for the BSRH. This will provide a second light source (BSRTMB) which will be available for tests in 2025.

The optical tables for the various instruments relying on the SR light are installed in a crowded optical box below the beam line. One possible option for the future is to transport the light to the UA service area and install the an additional optical table in that area away from the beam line.

Reply to charge question 2:

1. Does the monitor meet all functional specifications? No. In combination with a new SR extraction line, this instrument is however deemed to show the most potential to ultimately meet the required specifications for halo measurements all along the LHC cycle. Measurements at injection might require the addition of undulator in he future (>=LS4)
2. Are budget and schedule clearly explained? The BSRH is an HL-LHC baseline instrument. The present budget allocation is deemed sufficient for an operational deployment by the start of Run 4. The realization of a 2nd optical line, which will bring considerable operational flexibility and ease access and maintenance, is estimated at 300 kCHF. Due to the benefit for existing beam instrumentation devices (BSRA, BSRT) this cost could be proposed as share with LHC-CONS.
3. Is the proposed strategy and are the milestones to address remaining technical issues or unknowns well-defined and aligned with implementation during LS3? Additional studies and simulations are vital to be performed in 2025 and 2026 towards the ultimate goal of absolute halo measurements of adequate precision with the BSRH. The risks were however clearly identified and an R&D path defined to address them.

R5: The implementation of a 2nd SR light source and extraction line are supported by the panel, as this will not only benefit the performance reach of the BSRH but also increase operational flexibility and maintenance for the existing SR light based instruments. Cost sharing with LHC-CONS could be sought.

3.3 Wire Scanner

The wire-scanners are an important baseline instruments for the LHC, in particular to normalize all other emittance measurement devices. Due to the interaction between wires and beam, the presently installed WS can typically only be used for a limited number of bunches, around 300 at injection and around 12 at 6.8 TeV. At injection, the limit is given by wire damage while at high energy it is defined by the prevention of magnet quenches due to the induced beam losses.

Wire scans were successfully used in Run 3 to estimate the non-Gaussianity of the beams (Q-gauss fits), but this does not extend beyond $\approx 4\sigma$. The intensity limitations also apply, limiting the capabilities of the WS beyond cross-calibration. Presently, the contrast is in the range of 1e-3. As a reminder, the WS can only provide a 1D profile. Bunch-by-bunch measurements are also possible.

The development of thinner wires based on C-nanotubes (CNT-wires) could help raise the intensity limits in the HL-LHC era. This technology is currently still in a rather preliminary R&D phase. The limited contrast of 0.01 to 0.001 will limit the ability to observe the reliable observation of the far tails.

It is the understanding of the panel that such a device cannot be relied upon for tail measurements at the required 10-4 level, given the current state of development and that several fundamental technical challenges remain to be demonstrated. While this technology evolution is overall a promising development (as a vital benchmark for other instruments and tail measurements at injection), even an upgraded Wire-Scanner system will not allow for profile measurements to be done with physics beams or beam intensities representative for nominal physics beams. The requirement for measurements all along the LHC cycle and in all beam conditions is considered a must, ideally with a single instrument.

In the LHC, the technique could potentially work from 8.5 to $3.5{\cdot}\sigma$, requiring however much more R&D efforts with a timeline beyond LS3.

Reply to charge question 2:

1. Does the monitor meet all functional specifications? No, the instrument will remain limited to be used at injection with up to a few 100 bunches at most and not reach the desired contrast.
2. Are budget and schedule clearly explained? The budget for an operational device has been tentatively estimated at 1.16 MCHF (including 720 kCHF of M4P). If the R&D on the CNT wires over the upcoming 3 years leads us to a CNT that can withstand full intensity of the LHC beam without triggering quenches of downstream elements, the wire could be retrofitted in the new linear BWS design (at no additional costs). If the R&D on the CNT still points to a partial beam scan, then a new instrument, based on the new Linear BWS design should be studied to allow for absolute position measurements of the wire (post LS3).
3. Is the proposed strategy and are the milestones to address remaining technical issues or unknowns well-defined and aligned with implementation during LS3? No, still in a rather preliminary R&D phase. While a first wire valida-

tion is planned by the end of 2025 in HighRadtMat, a final and operationally usable system is not expected to be ready before 2031.

R6: While not considered a viable baseline choice for halo measurements in the HL-LHC era, the technology evolution promises benefits for an increased performance reach of the present WS system in the LHC and in particular in the injector complex. It appears therefore of general interest to the organisation to pursue this development in the scope of a consolidation project or similar.

3.4 Beam Gas Curtain monitor

The Beam Gas Curtain monitor was developed as an integral part of the hollow e-lens (HEL) which is no longer part of the LHC baseline today (ex Russian contribution). For this reason, the present devices are optimized in terms of their design as overlap monitors for the e-beam of the HEL, not as standalone devices for emittance/halo measurements. The UK collaboration is committed to deliver two more series units as part of the UK-2 agreement, but with mostly unchanged design with respect to the delivered prototype.

One device (prototype) is today installed on B1 of the LHC in a stand-alone configuration. A second device is foreseen to be installed on B2, this is however not part of the baseline HL-LHC scope today and therefore not funded through the project. The BGC has demonstrated good performance for emittance measurements but only for very long integration times (minutes). The contrast (peak/tail) is currently around 2% with an integration time of 30 sec, and could be pushed down to 1% for an integration time of $\sim$10min, which is however still considered insufficient for halo diagnostics. Unless significant additional effort is done to improve this low SNR (new detection system, other gas...), this technique is not deemed suitable to measure halo at the required precision levels, even less so on a bunch by bunch basis. Some alternatives and design optimisations are currently under study (i.e. increase of the gas jet density, increase light collection, use other gas species...). These promise to improve the contrast, but the integration time would still be in the order of minutes to reach a contrast of $\sim 1\%$. In addition, radiation load to downstream equipment for increased gas jet densities as well as background losses increasing due to accumulated gas in the region would have to be studied in detail.

To reuse the concept of gas jet for halo monitoring, the idea would be to detect the beam losses induced by the nuclear collisions between the protons of the beams and the gas jet. To be able to probe the halo, the gas curtain would have to be restricted to the beam halo, with the possibility to scan the position of the gas jet. The concept is simple, but relies on a "sharp" edge gas jet. This is however a very recent concept with many open questions and in a very preliminary state of R&D. The timeline presented to complete the studies by 2026 to conclude if the device is suitable for HL-LHC is judged optimistic by the panel in view of the remaining development, engineering and validation effort. In terms of schedule, a timely installation in LS3 only seems realistic if a considerable increase of resources required for simulation and engineering is granted. The cost for the required infrastructure and integration for a stand-alone installation is not part of the HL-LHC baseline.

Reply to charge question 2:

1. Does the monitor meet all functional specifications? No, the present devices provided through UK in-kind have been optimized as overlap measurement devices for their integration in the hollow e-lens. Devices show potential for profile measurements, but are limited in resolution in terms of halo monitoring and cannot for example provide bunch by bunch measurements.
2. Are budget and schedule clearly explained? Yes, UK-2 will provide two additional (slightly improved) BGC series units, one of which is proposed for a standalone installation on beam 2 of LHC. The budget and resources for a standalone installation are however not part of today's HL-LHC baseline.
3. Is the proposed strategy and are the milestones to address remaining technical issues or unknowns well-defined and aligned with implementation during LS3? Partially. The present strategy foresees additional beam tests and studies (in combination with BLMs that were installed in the YETS 2024/25) as well as modifications to the present installation on B1 to further explore the performance reach. Likely to remain as interesting option for profile measurements but not for halo measurements.

R7: While the BGC is considered an interesting option to be pursued for future beam profile measurements, the panel considers the technique not a viable choice as baseline instrument for halo measurements due to the inherently limited performance reach. Resources and efforts to continue the foreseen R&D and validation plan for this instrument are considerable and should be appropriately prioritized wrt to the baseline deliverables of WP13.

3.5 Beam Gas Ionization monitor or BGI

The BGI is relying on the collection of electrons ionized from the rest gas by the beam. The device requires a sufficiently high magnetic field (0.6T) to ensure that the electrons are collected with a limited distortion of the reconstructed profiles.

The BGI is the baseline HL-LHC emittance device, already installed in the injector chain in PS and SPS, but never operationally deployed. The PS devices (horizontal and vertical) were prototyped under LIU during Run 2 and then implemented during LS2. They are not yet operational after 4 years of continued commissioning. The SPS device was installed in one plane during the YETS 2023-24, but caused significant orbit perturbation and suffered from beam coupling impedance issues that have so far limited its deployment and use. These issues are expected to be resolved through hardware modifications implemented during the 2024-25 YETS. In the LHC, first BGI's were installed in Run 2 but had to be taken out in the 2017-18 YETS, as they suffered from excessive heating due to beam coupling impedance. It is now claimed that a new compact design equipped with cooling should prevent this problem from re-appearing. Other technical and performance limitations (e.g., inhomogeneous aging of components, limit above 4 TeV) have also been supposedly addressed.

The BGI is intrinsically providing a 1D measurement. Without gas injection at the location of the monitor, both size and halo (particles beyond 3.5σ) measurements could be made at an acquisition rate of 10 kHz. Measurements at 5 MHz could be obtained with gas injection, in which case the halo alone would be measured by blinding out the central region of the Timepix detector in order to avoid saturated signals. Gas injection would further provide an option for bunch-by-bunch measurements at a rate of almost 2 kHz per bunch.

Reply to charge question 2:

1. Does the monitor meet all functional specifications? Unclear, especially for the 2σ range from the primaries, but it would have a high chance to comply with a majority of the requirements if a gas injection system was to be added to the current design.
2. Are budget and schedule clearly explained? The BGI is already a baseline instrument of HL-LHC (as profile monitor, replacing the previously foreseen BGV). The available budget is deemed sufficient for now, an extra material budget of 135 kCHF would have to be included for an additional gas injection system. Several technical risks remain to be overcome (beam coupling impedance, background) that still require validation after further development in the injectors and an LHC prototype installation. If the 2025 tests in the SPS are successful, an identical installation would be planned in the LHC for beam tests in 2026.
3. Is the proposed strategy and are the milestones to address remaining technical issues or unknowns well-defined and aligned with implementation during LS3? See prior point. Schedule risk largely depends on a timely resolution

of technical issues. If the fundamental problems are not solved in 2025, the final instrument can only be validated as of the re-start of SPS with beam in 2029, i.e. only 1 year before the start of Run 4 in the LHC.

R8: The BGI is already the baseline device for emittance measurements for HL-LHC, ans is considered a promising "back-up" option for halo measurement. It is recommended that the system design is made compliant with an additional gas injection to maintain this option viable.

R9: In view of the remaining technical risks with the BGI, a hold point should be set towards the mid of 2026 to decide on its deployment in the LHC during LS3, i.e. namely after the operational validation of the improvements in the injector systems and first beam experience with a setup in the LHC.

4 Additional observations

4.1 Wrap-up and concluding remarks

The best estimates of expected performance for the considered technologies have been summarised in Fig. 1.

Reply to charge questions 3 and 4:

1. Are the pros and cons of the different technical solutions properly addressed? Yes, as far as the analysis in the previous section shows.
2. Are there changes to the functional specifications that could increase the chances of success in terms of budget and schedule?
   No change in the functional specifications is recommended, a clear focus should be given to the use-cases for collimation and machine protection however (see recommendation 3).

4.2 Alternative techniques

Recently, Refs. [1, 2] showed a new method to obtain the transverse 2D characterization using synchrotron radiation using multi-aperture (and non-redundant) masks. This method is based on radio-astronomy techniques, which also offer the possibility to measure beam halo.

R10: We recommend to look at this technique in the framework of the coronagraph, as powerful radio interferometry concepts can be applied to

Performance Metric	Required Range	Use Case(s)	BSR	BGI	BGC (imaging)
Contrast	10^-4 to 10^-6	Collimation: 10^-4 at upper bound	Under study	Signal = 10 kHz (residual gas) or 5 MHz (injected gas) Background = tbd.	~1%
		MP: 10^-6 at 6.7σ			
Relative Integral	0.2% to 5%	Collimation: 5% to 0.25% (2700 bunches)	<0.1%	See slide #14 BGI pres	tbc
		MP: 0.4% to 0.1% (48 bunches)			
Absolute Integral	10^10 to few 10^12	Collimation: 1.5×10^12	During MD: 1.5% of tot intensity → 1.6e9 , tb studied for full beam	See slide #14 BGI pres	tbc
		MP: (1-4)×10^10			
1D Profile Capability	Yes/No	Required for Beam-Beam	Yes	Yes	Yes
2D Image Capability	Yes/No	Required for Beam-Beam	Yes	No	No
Max. Acquisition Rate	10-60 seconds	MP: ~10s	~20Hz (time for full beam depends on the gated sample - >100s for full machine bunch per bunch, around 3s for 48b., limited by data processing)	5 MHz with injected gas → 1800 electron / bunch / s.	1 min
		Others: ~60s			
Bunch-by-Bunch Gating	Yes/No	Required for Beam-Beam	Yes	B-b-B via electrons timestamp	no
Number of Turns Needed	-	All cases accept multi-turn	Yes	With gas injection 5 MHz → 440 samples / turn.	-
Interlock Capability	Yes/No	Required for MP	tbc	tbc	SW

Figure 1: Best estimates of expected performance for the considered technologies.

synchrotron radiation interferometry in accelerators. With the given BSRH sketch, 2D beam size and halo measurements could be achieved by adding a multi-aperture mask instead of the diaphragm, and keeping the Lyot stop in the coronograph system.

4.3 Interlocks

Some candidate devices require many seconds of integration to provide a meaningful signal: in that case, and in particular for early operation in Run 4, an interlock by software is perfectly adequate. Most likely **a software based interlock** is acceptable also for future regular physics operation.

5 Summary of recommendations

R1: It is recommended to continue MDs (or end of fill studies) during Run 3 to gain a deeper insight into halo population and re-population dynamics throughout the entire LHC cycle, in particular for higher bunch intensities approaching the nominal HL target.

R2: It is recommended to ensure that the selected beam halo measurement tool is able to measure the halo along the entire LHC cycle.

R3: Unlike the two first use cases, the beam-beam use case is oriented to the optimisation of luminosity production with no direct machine protection implications. Priority shall be given to commission for the start of Run 4 a working instrument complying with the collimation and MP specifications. Additional features shall be considered only after demonstrating this core functionality.

R4: As the e-lenses might still be considered for installation at a later moment of the HL era, it is recommended to maintain the constraint of round beam at the present installation location of the e-lens, and ensure compatibly with other optics changes proposed for IR4, e.g. optimizations of beam sizes for other BI instruments.

R5: The implementation of a 2nd SR light source and extraction line are supported by the panel, as this will not only benefit the performance reach of the BSRH but also increase operational flexibility and maintenance for the existing SR light based instruments. Cost sharing with LHC-CONS could be sought.

R6: While not considered a viable baseline choice for halo measurements in the HL-LHC era, the technology evolution promises benefits for an increased performance reach of the present WS system in the LHC and in particular in the injector complex. It appears therefore of general interest to the organisation to pursue this development in the scope of a consolidation project or similar.

R7: While the BGC is considered an interesting option to be pursued for future beam profile measurements, the panel considers the technique not a viable choice as baseline instrument for halo measurements due to the limited performance reach. Efforts to continue the foreseen R&D and validation plan for this instruments are considerable and should be appropriately prioritized wrt to the baseline deliverables of WP13.

R8: The BGI is already the baseline device for emittance measurements for HL-LHC, and is considered a promising "back-up" option for halo measurement. It is recommended that the system design is made compliant with an additional gas injection to maintain this option viable.

R9: In view of the remaining technical risks with the BGI, a hold point should be set towards the mid of 2026 to decide on its deployment in the LHC during LS3, i.e. namely after the operational validation of the improvements in the injector systems and first beam experience with a setup in the LHC.

R10: We recommend to investigate the Multi-Aperture interferometry technique in the framework of the coronagraph, as powerful radio-astronomy concepts can be applied to synchrotron radiation in accelerators. With the given BSRH sketch, 2D beam size and halo measurements could be achieved by adding a multi-aperture (non-redundant) mask instead of the diaphragm, and keeping the Lyot stop in the coronograph system.

Acknowledgments

The panel members would like to express their gratitude to the organisers as well as all speakers and participants of his review for the excellent presentations, open discussions and offline follow-up that enabled the editing of this report and recommendations.

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