Chapter 13

Beam instrumentation and long-range beam–beam compensation

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13 Beam instrumentation and long-range beam–beam compensation

13.1 Introduction

The extensive array of beam instrumentation with which the LHC is equipped has played a major role in its commissioning, rapid intensity ramp-up and safe and reliable operation. Much of this equipment will need consolidation by the time the LHC enters the High-Luminosity (HL) era, while the upgrade itself brings a number of new challenges.

The installation of a completely new final focus system in the two high-luminosity LHC insertions implies the development of new beam position monitors to equip the upgraded quadrupole magnets. As well as replacing the 10 current beam position monitors, six additional beam position monitors will be added per interaction region, to further improve beam control at the collision point.

The use of crab cavities for luminosity enhancement implies a need for new instrumentation in order to allow for the optimisation of their performance. This requires intra-bunch measurement of transverse position on a turn-by-turn basis. Several diagnostic systems are being investigated as candidates to perform this task, including very high bandwidth pick-ups and a streak camera installation making use of synchrotron light.

The installation of a hollow electron lens for cleaning the beam halo has added to the beam diagnostic challenges of high-luminosity LHC. Not only must the beam halo be measured, but a good concentricity and alignment between the electron and proton beam must be ensured. A coronagraph based on synchrotron light is therefore under study with the aim of being able to image the halo at a level of 10^{-5} of the core intensity, while a gas curtain monitor is being developed to align the electron and proton beams within the hollow electron lens. The latter will use a high-density, supersonic, gas sheet to allow a two-dimensional image of both beams to be created via luminescence.

Upgrading the LHC also provides the opportunity of developing new instrumentation to address areas identified as currently lacking adequate diagnostics. This includes a non-invasive, beam-size measurement system capable of delivering data throughout the LHC acceleration cycle, with a prototype beam gas vertex detector already being tested for this purpose.

An upgrade or consolidation is envisaged for several other systems, including the main beam position monitoring system, the beam loss measurement system, the luminosity measurement system, and the synchrotron light monitor.

This workpackage also covers the study of possible technologies for long–range beam-beam compensation.

13.2 Beam loss measurement

Monitoring of beam losses is essential for the safe and reliable operation of the LHC. The beam loss monitor (BLM) system provides knowledge on the location and intensity of such losses, allowing an estimation to be made of the energy dissipated in the equipment throughout the accelerator. This information is used for machine protection, to optimise beam conditions, and to track the radiation dose to which equipment has been exposed. The BLM system consists of nearly 4000 ionisation monitors distributed around the machine [1]. These are located at all probable loss locations, with the majority mounted on the outside of quadrupole magnets. While the existing system is globally believed to meet the needs of the HL-LHC, some upgrades will nevertheless be required.

The quench level signals estimated for 7 TeV running are, for some detectors, very close to the noise level of the acquisition system. This is mainly determined by the length of cable required to bring the signal from the radiation hard, ionisation chamber detector to the radiation sensitive front-end electronics. This is not an issue for the detectors in the arcs, as the current electronics are qualified for use in low radiation environments and can therefore be placed close to the detectors. For the detectors in the interaction and collimation regions, however, this is not the case, with some 250 channels affected. Development has therefore begun to implement the readout electronics in a radiation hard Application Specific Integrated Circuit (ASIC) that could sit near each detector, eliminating the need for long cables.

Two technologies are being studied for this ASIC, current to frequency conversion, as is used in the standard LHC ring beam loss system, and a sigma-delta implementation. The final ASIC will need to cover a 180 dB dynamic range (corresponding to a current range from 1 pA – 1 mA) with a 10 μs integration time and target a radiation tolerance of 1 MGy. This ASIC will use standard 130 nm CMOS technology (known to be radiation tolerant to 2 MGy) and be housed in a standard 64 pin Quad Flat Package (10 × 10 mm). Each chip will have two analogue readout channels, triplicated digital circuitry with majority voting, and double communication channels for redundancy [2].

13.2.1 Changes from the initial HL-LHC TDR

In the original TDR it was proposed to investigate possible options for placing radiation detectors inside the cryostat of the triplet magnets as close as possible to the superconducting coils. The dose measured by such detectors would then correspond much more precisely to the dose deposited in the coils, allowing the system to prevent quenches and distinguish between beam loss and luminosity debris. Silicon and diamond detectors were investigated for this purpose, with both shown to be capable of operating in such an environment [3]. However, recent studies using the updated HL-LHC optics and including the tungsten shielding in the beam screen, have demonstrated that there is little difference in the loss patterns measured by such detectors and the standard beam loss monitors external to the cryostat [4]. The option of installing cryogenic beam loss monitors in the HL-LHC triplets is therefore abandoned.

The prototype beam loss monitor ASIC described in the original TDR used what is now outdated 250 nm CMOS technology. A complete redesign was therefore required to use standard 130 nm technology. This gave the chance to investigate alternative topologies, with both a sigma/delta and current to frequency method now being studied. The final choice of technology will be taken after fully testing prototype versions of each ASIC.

13.3 Beam position monitoring

With its 1070 monitors, the LHC Beam Position Monitor (BPM) system is the largest BPM system in the world [5]. Based on the Wide Band Time Normalizer (WBTN) principle [6], it provides bunch-by-bunch beam position over a wide dynamic range (~50 dB). Despite its size and complexity (3820 electronic cards in the accelerator tunnel and 1070 digital post-processing cards in surface buildings) the performance of the system during the first LHC physics runs has been excellent.

13.3.1 Current performance and limitations

The short-term reproducibility of orbit measurements using the LHC beam position monitors has been determined to be better than 20 μm [7]. The main limitation on the accuracy is linked to temperature dependent effects in the acquisition electronics, which can generate offsets of up to a millimetre if left uncalibrated. Temperature controlled racks have been installed to limit this effect, but drifts of several tens of micrometres are still observed. The non-linearity of the BPMs located near the interaction points has also proven to be problematic, in particular for accurate measurements during the beta-squeeze and during machine development periods. A new correction algorithm has therefore been developed, based on electro-magnetic simulations, with the aim of bringing the residual error down to below 20 μm over ~70% of the useable BPM aperture [8]. As they detect both beams, these BPMs also suffer from cross-coupling of the signals induced, which is something that is being addressed for the HL-LHC.

13.3.2 A high-resolution orbit measurement system for the HL-LHC

At the start of the HL-LHC era, the existing BPM system will have been operational for over 15 years, using components that are over 20 years old. A completely new read-out system is therefore being developed to replace these ageing electronics. It will be heavily based on digital signal processing, directly sampling opposite electrode outputs on a single channel, making use of recent advancements in high resolution, fast sampling analogue to digital conversion technology and the radiation hard, high speed optical transmission systems developed for the LHC experiments. The aim will be to provide a high reliability system with improved long-term stability and reproducibility.

13.3.3 High directivity strip-line pick-ups for the HL-LHC insertion regions

In the BPMs close to the interaction regions, the two beams propagate in the same vacuum chamber. Strip-line pick-ups acting as directional couplers are therefore used to provide the position signals of both beams. The particularity of such a BPM is that signal from the beam only appears at the upstream port, with little contribution at the downstream port. The same BPM can therefore be used to measure both beams. However, when the two beams pass through the BPM at nearly the same time, there is still some interference due to the imperfect directivity (some signal still appearing at the downstream port) of the strip-line. In the current strip-line BPMs there is only a factor 10 isolation between the upstream and downstream signals, making it difficult for such a BPM to measure beams with significantly different intensities or large position offsets. The effect can be minimised by installing the BPMs at a location where the two counter-propagating beams do not meet. This is a constraint included in both the present and future layout, but which cannot be satisfied for all BPM locations. The ideal longitudinal location corresponds to $(1.87 + N \times 3.743)$ m from the IP where N is an integer, providing a maximum separation of 12.5 ns between signals. Any deviation from this will diminish the ability of the system to distinguish one beam from the other. For the current HL-LHC layout the temporal separation between the two beams at the locations of the BPMs varies from 3.9 ns, for the BPMs installed on the Q1 and Q2a magnets, up to 10.5 ns for the BPM installed on the corrector package.

As part of the critical beam position system required to maintain optimised collisions in the HL-LHC these components need to be highly reliable and maintenance-free. The system should be able to measure the average beam position (i.e. orbit) for each beam with a resolution of 1 μm and with a medium term (fill to fill) reproducibility of 10 μm [7].

The BPMs in front of the Q2a, Q2b, Q3, the triplet corrector package, and D1 magnets require tungsten shielding close to the beam screen aperture to minimise the integrated radiation dose deposited in these magnets due to luminosity debris. This implies rotating the electrodes by 45° to allow the insertion of tungsten shielding in the median planes of both horizontal and vertical axes. A mechanical re-design, coupled with extensive electro-magnetic simulation, is therefore being performed to optimise the directivity under these constraints.

Six directional strip-line BPMs of three different types are foreseen on each side of the high-luminosity insertions. A cold BPMQSTZA without tungsten shielding in front of Q1; 5 cold BPMQSTZB (Figure 13-1) with tungsten shielding: in front of Q2A, between Q2A and Q2B, in front of Q3, between Q3 and the corrector package, and in front of D1.

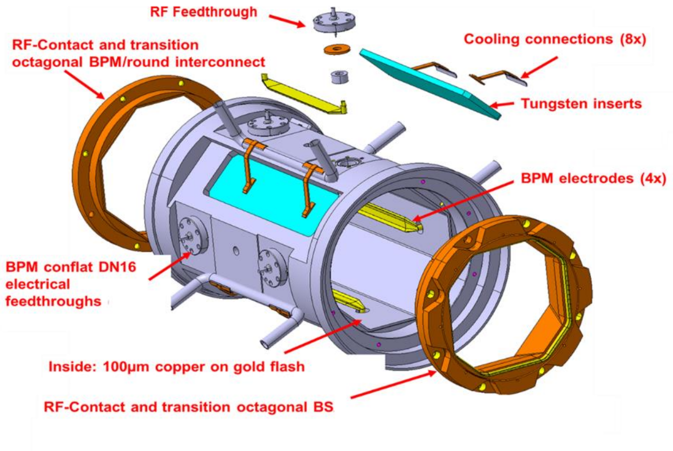

Figure 13-1: Mechanical design of the BPMQSTZB stripline beam position monitor for the HL-LHC.

The signal from all of these BPMs will be extracted using eight semi-rigid, radiation-resistant coaxial cables per BPM. Two feedthroughs with four coaxial cable connections each will be integrated into the cryostats of the Q1, Q2a, Q2b, Q3, corrector package and D1 magnets. The outputs of these feedthroughs will be connected to standard ½″ coaxial cables taking the signal to the electronics in the UJ/US.

A total of 24 new strip-line BPMs will be installed in the high-luminosity insertions as part of the HL-LHC upgrade (Table 13-1).

13.3.4 Button electrode beam position monitors for the HL-LHC insertion regions

Two new, cold, button BPMs will be added inside each D2 cryostat, liberating space currently taken by warm button BPMs in front of the D2 magnet. Two different types, for the internal / external beam, may be required due to asymmetric welding interfaces. The BPTX trigger BPM for the experiments, currently in front of Q4, will need to be redesigned or relocated due to aperture considerations.

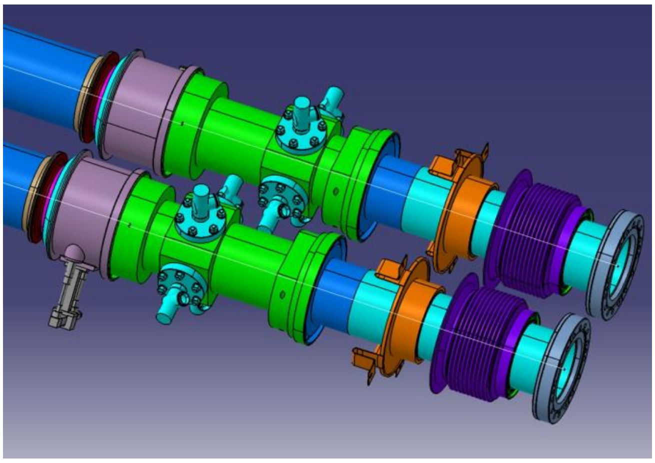

Figure 13-2: Layout of the BPMQBCZA and BPMQBCZB D2 button beam position monitors for the HL-LHC.

A total of 8 new button BPMs will be installed in the high-luminosity insertions as part of the HL-LHC upgrade (Table 13-1).

Table 13-1: Summary of Q1-Q5 BPM locations and types Left and Right of IP1 and IP5 for the HL-LHC

Code	Location	Distance from IP (m)	Aperture (mm)	Warm or cold	Stripline or button	Tungsten shielding	Electrode position	Parasitic bunch crossing timing (ns)	New or existing
BPMQSTZA	Q1 (IP side)	21.853	Octagonal 101.7 / 99.7	Cold	Stripline	No	0° / 90°	3.92	New
BPMQSTZB	Q2B (IP side)	33.073	Octagonal 112.7 / 119.7	Cold	Stripline	Yes	45° / 135°	3.92	New
BPMQSTZB	Q2B (IP side)	43.858	Octagonal 112.7 / 119.7	Cold	Stripline	Yes	45° / 135°	6.82	New
BPMQSTZB	Q3 (IP side)	54.643	Octagonal 112.7 / 119.7	Cold	Stripline	Yes	45° / 135°	9.72	New
BPMQSTZB	CP (IP side)	65.743	Octagonal 112.7 / 119.7	Cold	Stripline	Yes	45° / 135°	10.52	New
BPMQSTZB	D1 (IP side)	73.697	Octagonal 112.7 / 119.7	Cold	Stripline	Yes	45° / 135°	7.36	New
BPMQBCZA BPMQBCZB	D2 (arc side)	151.930	Round Ø 90	Cold	Button	No	0° / 90°	N/A	New
BPTX	Between crabs & Q4	169.024 (not final)	Round Ø 80	Warm	Button	No	0° / 90°	N/A	Existing
BPMYA BPMYB	Q4 (arc side)	182.312	Round Ø 61	Cold	Button	No	0° / 90°	N/A	Existing
BPMYA BPMYB	Q5 (arc side)	210.171	Round Ø 61	Cold	Button	No	0° / 90°	N/A	Existing

13.3.5 Collimator beam position monitors

All next generation collimators in the LHC will have button electrodes embedded in their jaws (Figure 13-3) for on-line measurement of the jaw to beam position [9]. These are fitted with an orbit measurement system based on a compensated diode detector scheme [10], which has been demonstrated to be simple and robust, and to provide a position resolution at the sub-micron level. This will provide a fast and direct way of positioning the collimator-jaws and subsequently allow constant verification of the beam position at the collimator location, improving the reliability of the collimation system as a whole.

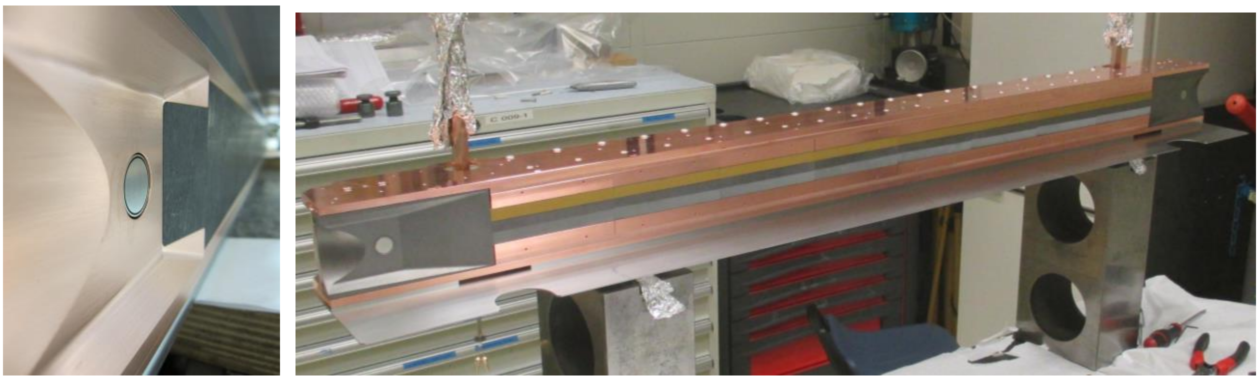

Figure 13-3: Photograph of TCSP collimator button BPM (left) and a test assembly (right).

The collimator BPM hardware, i.e. the button electrode located in the jaw, the cable connecting the electrode to the electrical feedthrough mounted on the vacuum enclosure, the feedthrough itself, the quick connect flange on the support and the cable connections to the standard cable patch panel, have all been chosen to withstand the radiation dose of 20 MGy expected during the lifetime of the collimator.

13.3.6 Changes from the initial HL-LHC TDR

The following changes have been made with respect to the original TDR:

- New BPMs are not required for Q4 and Q5 due to the decision to re-use the current magnets.
- The warm BPMs of D2 are moved into the cryostat to free additional space in front of D2.
- The warm BPMQSWZA after D1 is removed as it brings little additional information and is difficult to incorporate into the fully remote alignment system.
- Tungsten shielding is added to all BPMs of type BPMQSTZB to reduce the number of variants and simplify production. This more than offsets the additional cost of adding the tungsten to all these BPMs.
- The baseline electronic acquisition system is now based on digital signal processing techniques, directly sampling opposite electrode outputs on a single channel and making use of recent advancement in high resolution, fast sampling analogue to digital conversion technology and the radiation hard, high speed optical transmission systems developed for the LHC experiments.

13.4 Beam profile measurements

The LHC is currently fitted with a host of beam size measurement systems used to determine beam emittance. These different monitors are required in order to overcome the specific limitations of each individual system. Wirescanners are used as the absolute calibration reference but can only be operated with a low number of bunches in the machine due to intensity limitations linked to wire breakage and the quench limits of downstream magnets. A cross-calibrated synchrotron light monitor is therefore used to provide beam size measurements, both average and bunch-by-bunch, during nominal operation. However, the small beam sizes achieved at 7 TeV, the multiple sources of synchrotron radiation (undulator, D3 edge radiation, and central D3 radiation), and the long optical path required to extract the light imply that the correction needed to obtain an absolute value is of the same order of magnitude as the value itself. This relies on an excellent knowledge of all error sources to obtain meaningful results and excludes continuous measurement during the energy ramp.

A third system initially installed was an ionisation profile monitor foreseen to provide beam size information for lead ions at injection, where there is insufficient synchrotron light. However, with intense proton beams the monitor suffered from excessive, impedance related, radio-frequency heating and had to be removed.

Whilst efforts are ongoing to improve the performance of all the above systems, alternative techniques to measure the transverse beam size and profile are also under study for the HL-LHC, in particular during the ramp, as this is crucial for understanding the emittance evolution of the beam throughout the acceleration cycle and hence to optimise the final luminosity achievable.

13.4.1 A beam gas vertex profile monitor

The VELO detector of the LHCb experiment has shown how beam gas interactions can be used to reconstruct the transverse beam profile of the circulating beams in the LHC [11]. Currently under study is whether a simplified version of such a particle physics tracking detector can be used to monitor the beams throughout the LHC acceleration cycle. Such a concept has, up to now, never been applied to the field of beam instrumentation, mainly because of the large amount of data treatment required. However, the advantages compared to standard beam profile measurement methods are impressive: high-resolution profile reconstruction, single-bunch measurements in three dimensions, quasi non-destructive, no detector equipment required in the beam vacuum, high radiation tolerance of the particle detectors and accompanying acquisition electronics.

Unlike LHCb, where the detector is placed very close to the beam and can therefore only be used during stable beams, the aim with the Beam Gas Vertex profile monitor (BGV) is to design a robust instrument that can be used for beam size measurements throughout the LHC cycle. Its final specifications are to provide:

- transverse bunch size measurements with a 5% resolution within 1 minute;
- average transverse beam size measurements with an absolute accuracy of 2% within 1 minute.

Prototyping of such a detector began in 2012 in collaboration with the LHCb experiment, the École Polytechnique Fédérale de Lausanne and RWTH Aachen. The system was installed on the left-hand side of LHC IP4 on Beam 2 in 2015 (Figure 13-4) and made operational for data taking in 2017–2018. The main subsystems are: a neon gas target at a pressure of $\sim 5 \times 10^{-8}$ mbar; a thin aluminium exit window; tracking detector based on scintillating fibre modules read out by silicon photomultipliers; hardware and software triggers; and a readout and data acquisition system based on that used for LHCb. As the tracking detector is external to the vacuum chamber, no movable parts are required.

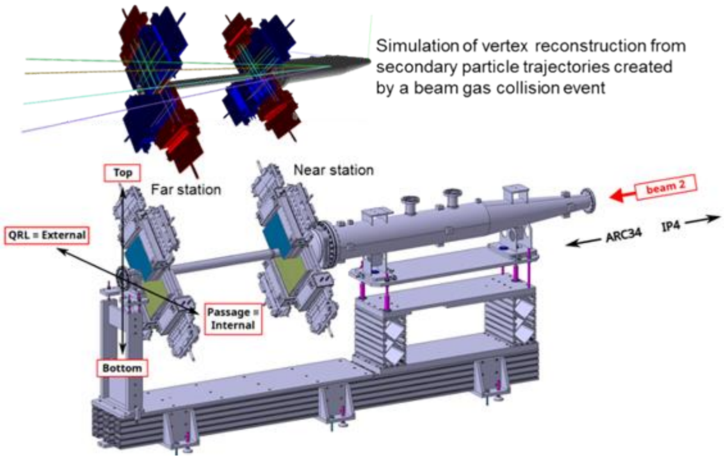

Figure 13-4: The principle and design of the prototype LHC beam gas vertex detector.

The installed prototype has demonstrated the ability to measure both the horizontal and vertical beam size independently, with a precision better than 3% for an integration time of less than a minute [12]. This allows beam size monitoring during all operational phases, including the energy ramp, for which there is currently no other instrument that can make a measurement of the beam size for high intensity physics beams.

The encouraging results and experience gained with the prototype has led to continued R&D on such a monitor, to develop two, fully optimised systems for installation on both beams as part of the baseline HL-LHC project. Various new concepts are being investigated [13] including the possibility to confine the gas target using gas-jet technology already being developed for the HL-LHC (see Section 13.8), using three tracking planes incorporating multi-pattern gaseous detectors and deploying a radiation tolerant readout electronics using standard components that can be maintained in the longer term.

13.4.2 Changes from the initial HL-LHC TDR

In the original TDR it was foreseen to install a copy of the first system during LS2, so as to equip both beams. Instead, since the initial system is not maintainable for the longer term, the project will now fund two new systems that will be optimised for performance and maintainability and installed during LS3.

13.5 Halo diagnostics

One of the major challenges for high intensity accelerators is the control of beam losses. In the case of the HL-LHC, the stored energy per beam is of the order of 700 MJ while the collimation system can sustain a maximum of 1 MW continuous power deposition. For this reason, it is vital to study and understand loss dynamics. An important mechanism for slow losses consists of populating the beam “halo”, i.e. populating the periphery of the phase-space with particles at large amplitudes (by IBS, beam-gas collisions, resonances etc.). These halo particles then gradually increase their amplitude due to the non-linearity of the optics until they hit a collimator. Measurement of the beam halo distribution is important for understanding this mechanism and hence to minimise its effect. Moreover, in the HL-LHC, crab cavities will be used to counter the geometric luminosity loss factor introduced due to the increased crossing angle. In case of failure of a crab cavity module the whole halo may be lost in a few turns. If the halo population is too high this can cause serious damage to the collimation system or to other components of the machine. The total halo population that can be absorbed by the collimation system in case of a fast loss is of the order of few 10^{-5} of the nominal beam intensity. The halo monitor for the HL-LHC should thus be able to observe the halo at a level of 10^{-5} of the peak bunch intensity.

Most diagnostics used for transverse beam profile measurement could be adapted for halo measurement. For the LHC this consists of beam imaging using synchrotron radiation, wire-scanners, ionisation profile monitors and the new technique based on beam-gas vertex reconstruction. However, halo measurements using synchrotron radiation seem the most promising.

13.5.1 Halo measurement using synchrotron radiation imaging

Halo measurement using synchrotron radiation can be achieved using one of the following techniques:

- High dynamic range cameras
- Core masking and standard cameras
- Performing an X-Y scan of the image plane with a photo-detector located behind a pinhole
- Single photon counting with a pixelated photo-detector

The limiting factor in all cases is likely to be the unavoidable presence of diffused synchrotron light coming from reflections in the vacuum chamber or optics, diffusion by dust particles, and diffraction. The first two can be mitigated with an appropriate surface treatment and a clean, hermetic setup, although diffusion by scratches and defects on the optical components cannot be entirely removed. Diffraction, however, is a physical limitation.

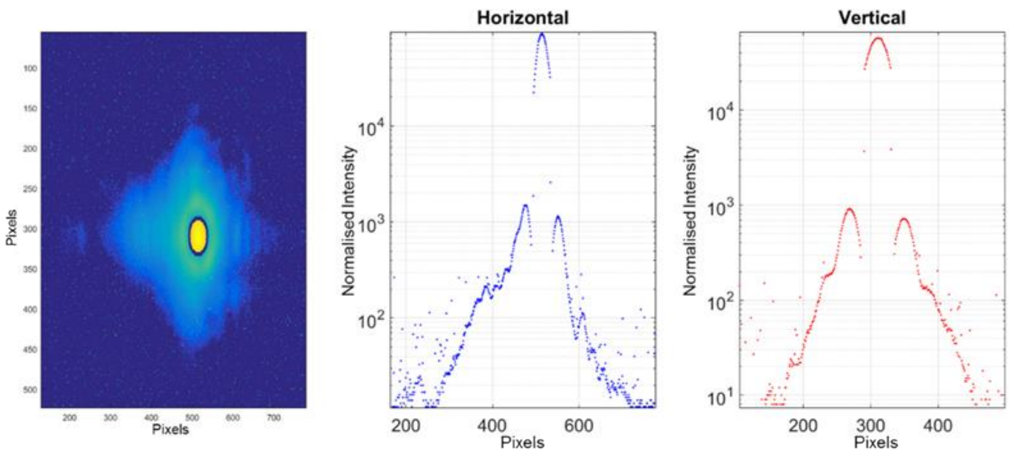

Figure 13-5: Combined core and halo measurement showing a dynamic range of ~10^4.

To overcome the problem of diffraction, halo measurement using a coronagraph technique is under study, and a prototype, using components from a similar system installed on the Photon Factory at KEK, is currently installed in the LHC [14]. By combining a core image (without the coronagraph mask in place) with a halo image (with the coronagraph mask in place) a combined beam profile measurement is obtained (Figure 13-5). This shows that the current, prototype system is capable of detecting halo at the level of 10^{-4}. In order to push this further a new design is underway, exploiting a Cassegrain reflector telescope to allow for higher magnification, and therefore capable of achieving the specified contrast of 10^{-5}. This is foreseen to replace the first prototype for testing during LHC Run 3, on the existing optical table exploiting the light from the D3 magnet (at top energy) and undulator (at injection energy).

To measure the halo at this very low level, a dedicated light extraction path is mandatory to minimise the number of optical elements. The current prototype installation can therefore only be used during machine development periods when the standard beam size observation is not required. The final, optimised versions of the coronagraph will require new, specifically built synchrotron radiation lines. Integration studies are currently underway to incorporate a second synchrotron radiation line per beam, using the radiation produced by the D4 separation magnets near the RF insertion in Point 4. The light will be extracted via an in-vacuum mirror to a new optical table located below the beampipe (as is currently the case for the existing lines). This will only provide halo measurements at top energy as, in the absence of an undulator near the D4 magnet, there is insufficient light generated at injection energy. The option of installing an undulator (at present not in the baseline) upstream of D4 is retained to allow additional diagnostics at injection energy, with the possibility of using permanent magnets being considered.

13.6 Diagnostics for crab cavities

The crab cavities for the HL-LHC will enhance luminosity by countering the geometric reduction factor caused by the large crossing angle. These cavities will be installed around the high-luminosity interaction points (IP1 and IP5) and used to create a transverse bunch rotation at the IP. The head and tail of each bunch is kicked in opposite transverse directions such that the incoming bunches will cross parallel to each other at the interaction point. These position bumps which vary along the length of the bunch are closed by crab-cavities acting in the other direction on the outgoing side of the interaction region. If the bumps are not perfectly closed the head and tail of the bunch will travel on different closed orbits around the ring which could lead to unwanted emittance blow-up, and more importantly to beam loss at locations with aperture restrictions. Two monitors capable of measuring the closure of the head-tail bump and any head-tail rotation or oscillation outside of the interaction regions are therefore included in the HL-LHC baseline: an electromagnetic monitor; a streak camera using synchrotron light, which is also capable of providing accurate longitudinal profiles.

13.6.1 Bunch shape monitoring using electro-magnetic pick-ups

Electromagnetic monitors for intra-bunch diagnostics are already installed in the LHC [15]. These so-called “Head-Tail” monitors mainly provide information on instabilities and have a bandwidth up to several GHz. Similar monitors were essential to understand and optimise the first ever use of crab cavities in a proton synchrotron during the 2018 tests of the HL-LHC prototypes in the CERN-SPS accelerator.

To better understand instabilities in the HL-LHC and to help with the tuning of the crab-cavities a higher granularity within the bunch (bandwidth > 5 GHz) is desirable, along with better position resolution. The current HL-LHC baseline foresees the installation of pick-ups based on electro-optical crystals in combination with laser pulses, with a prototype recently tested on the CERN-SPS in collaboration with Royal Holloway University of London, UK [16]. Four such monitors, two per beam with 90° phase advance between pick-ups, are foreseen be installed in LSS4. The exact locations will depend on the final optics configuration.

Studies are also continuing to improve the existing electromagnetic pick-ups, including the optimisation of the pick-up design and the testing of faster acquisition systems, which would become the fallback option should the electro-optical pick-ups not reach the required sensitivity and resolution.

13.6.2 Bunch shape monitoring using streak cameras

The use of synchrotron light combined with a streak camera is complementary to electromagnetic or electro-optical pick-ups for high-resolution temporal imaging, being able to also provide detailed longitudinal bunch profile information. Using an optical system to re-image the synchrotron light at the entrance of a streak camera allows the transverse profile of the beam to be captured in one direction (horizontal or vertical) with a very fast time resolution (below the picosecond level). Such a system can be used to observe a number of beam parameters simultaneously: bunch length, transverse profile along the bunch, longitudinal coherent motion, head-tail motion etc. The main limitations of the streak camera are the repetition rate of the acquisition, typically less than 50 Hz, and the limited length of the recorded sample, which is given by the CCD size. The latter can be improved by using double scan streak cameras. Considering a CCD with 1000 × 1000 pixels working at 50 Hz and adjusting the optical magnification and scan speed such that the image of each bunch covers an area of about 100 × 100 pixels one could record a maximum of 100 bunch images per 20 ms, i.e. 5000 bunches per second. This is clearly just an optimistic upper limit with other factors likely to reduce this value but indicates that a complete snapshot of all circulating bunches could be acquired within a reasonable time.

The longitudinal resolution of around 50 ps required for the HL-LHC is rather easy to achieve using streak cameras, where measurements down to the sub-picosecond are now possible. In terms of transverse resolution two distinctions have to be made:

- The resolution when measuring beam width. This is affected by diffraction due to the large relativistic gamma of the beam, with the diffraction disk of the same order as the beam size. Measurement of the absolute transverse beam size will therefore not be very precise.
- The resolution when measuring centroid motion, i.e. the centre of gravity of the beam. This is not directly affected by the diffraction, which produces a symmetrical blur, and therefore the resolution for this type of measurement will be much better.

As head-tail motion is essentially a centroid motion, the streak camera should be able to achieve the resolution of a few percent of the beam sigma necessary to quantify any residual non-closure of the crab cavity bumps. However, in order to measure this, the phase advance between the crab cavities and the light extraction point would need to be optimised which is not the case with the current HL-LHC optics. It is therefore still being investigated how much of an effect could be detected with such a system.

Streak cameras are expensive and delicate devices not designed for the harsh environment inside an accelerator. Radiation dose studies are therefore required in order to verify if a streak camera can be installed directly in the tunnel or if it has to be housed in a dedicated hutch in an equipment gallery. The latter would imply an optical line to transport the synchrotron light from the machine to the camera, for which initial integration studies have already been performed.

13.7 Luminosity measurement

The measurement of the collision rate at the luminous interaction points is very important for the regular tuning of the machine. Accurate information about the instantaneous luminosity is provided by the LHC experiments once stable collisions are established, but this information is often not available during commissioning, machine development periods or during the initial process of bringing the beams in collision. Simple, reliable, collision-rate monitors are therefore needed for the HL-LHC, similar to those presently available for LHC operation. This measurement is currently provided by measuring the flux of forward neutral particles generated in the collisions using fast ionisation chambers installed inside the TAN neutral collision debris absorbers. As these absorbers will be re-designed for the completely different HL-LHC geometry in this region (TAXN), new, adapted luminosity monitors will need to be produced. Integration in the TAXN is not trivial due to space constraints, and the measurement is complicated by the fact that the shower is asymmetric for horizontal crossing, leading to a dependence of the measured flux on the crossing angle (Figure 13-6).

There are several drawbacks with the current ionisation chambers, notably the need for a circulating gas circuit and the fact that the front-end amplifiers have to be placed as close as possible to the detector in a very high radiation area, making repairs difficult. A different technology, Cherenkov radiation, is therefore being studied to provide this measurement for the HL-LHC. Prototypes, with Cherenkov radiation produced in both air and fused silica rods, have been tested in the LHC during Run 2 to try to qualify the system for use in a region where the radiation dose will reach 180 MGy per year. The results indicate that the high radiation affects both systems, leading to a continuous degradation of the mirrors used in the air monitor, and a change in transmission of the fused silica rods. However, almost all of the transmission loss in the fused silica occurs within the first 10 fb^{-1}, with transmission remaining stable beyond this while still producing sufficient light. This technology therefore looks promising as the baseline for the luminosity monitors of the HL-LHC [17].

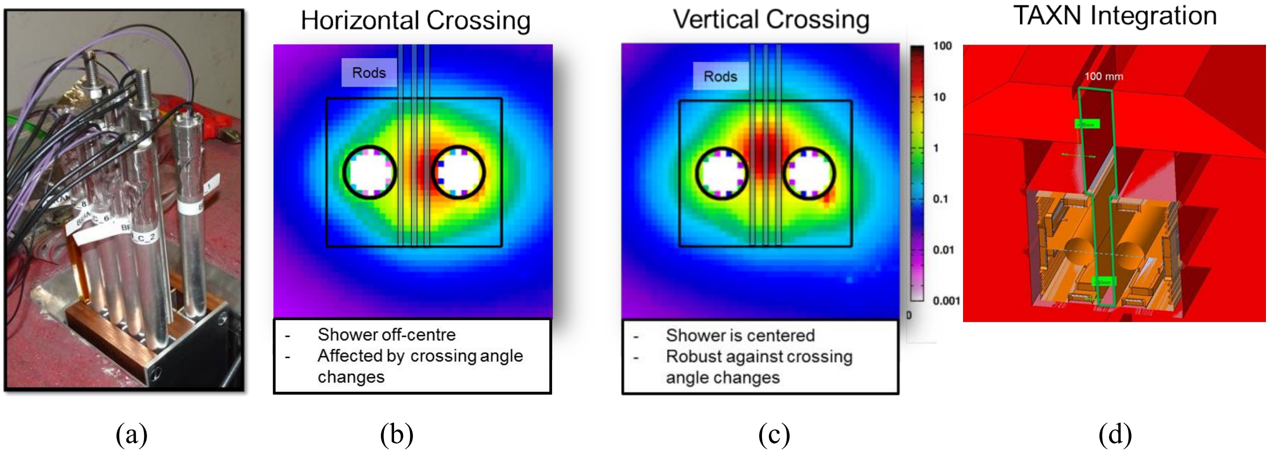

Figure 13-6: (a) Prototype installation in the LHC TAN; (b & c) Secondary shower map at the TAXN for horizontal and vertical crossing; (d) Space for integration of the Cherenkov rods in the TAXN

13.7.1 Changes from the initial HL-LHC TDR

In the original TDR it was foreseen to install ionisation chambers similar to those already operating in LHC. However, the disadvantages of these monitors led to R&D on new techniques, resulting in a successful validation of Cherenkov detectors, which are now the baseline for the luminosity monitors of the HL-LHC.

13.8 Gas jet diagnostics

With a hollow electron lens being added to the HL-LHC collimation system, research and development is underway to ensure that such an electron lens can be fitted with adequate diagnostics. One requirement is the on-line monitoring of the position of both the electron and proton beams, to ensure that the low energy, hollow electron beam is always concentric about the high-energy proton beam. This requires a non-invasive monitor capable of providing a simultaneous, two-dimensional image of both beams. In addition, this measurement must be made in close proximity to the solenoid field constraining the electron beam, preventing the use of charged particles as an observable.

An instrument is being developed through collaboration with GSI (Darmstadt, Germany) and the Cockcroft Institute/University of Liverpool (UK) to image fluorescence generated by the interaction between these beams and a thin, supersonic, gas curtain [18]. By tilting this ‘Beam Gas Curtain’ (BGC) with respect to the beam axis, a two-dimensional image of both beams can be obtained in much the same way as with a traditional, solid screen beam observation system. The instrument consists of the following main components:

- a gas generation stage with a supersonic gas nozzle followed by three skimmers which select and shape the gas jet;
- an interaction chamber where the high energy proton beam and low energy hollow electron beam interact with the gas jet;

- an optical system for image generation;
- an exhaust chamber which pumps the residual gas jet and contains gas jet diagnostics.

There are a number of key developments required for this instrument. It is important to select a working gas that is compatible with the NEG-coated, ultra-high vacuum system of the LHC, whilst still producing an adequate fluorescence signal from the interaction of both keV electrons and TeV protons, preferably from the spectral line of a neutral atom or molecule to avoid image distortion from electric and magnetic fields. It is also necessary to study the production of a dense supersonic gas curtain whilst minimising the background gas load to the vacuum system, and to develop a radiation-hard imaging system that is efficient for both the electron and proton excited fluorescence signals.

Although no fluorescence cross-section data exists for protons impacting neutral gases at 7 TeV, extrapolation from lower energy experiments indicate that for the gases of choice, neon, or argon, these will be between 20-30 times lower than for the low energy electrons. This, however, is compensated by the small transverse size of the proton beam, with detection of a few hundred photons considered sufficient to assess the proton beam position and shape. The electron beam is distributed over a much larger area, and it is therefore estimated that ~10^4 photons will be needed for the same purpose. Since the total electron and proton beam currents are of the same order of magnitude (~5 A for electrons and ~1 A for protons) the total integration times should be similar and of the order of 1 s.

A prototype is currently under construction with plans to install and validate this technology for operation on high energy proton beams during Run 3 of the LHC (see Figure 13-7).

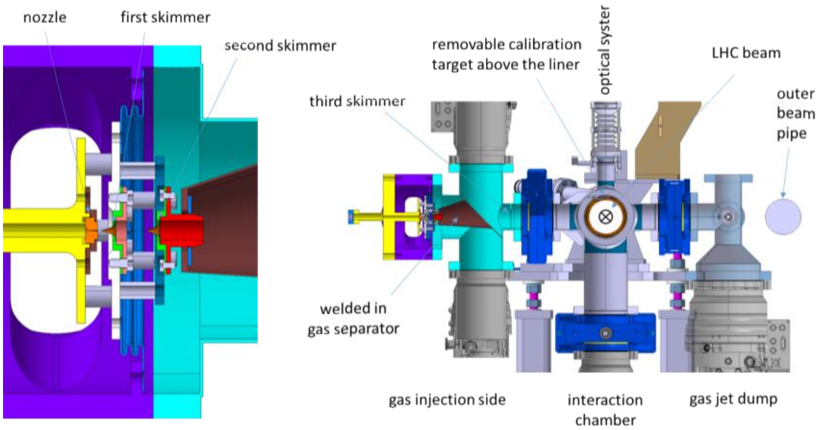

Figure 13-7: Exploded view of prototype to be installed for testing in the LHC during Run 3.

13.9 Long-range beam–beam compensation

The simulated strong effect of the LHC long-range interactions on beam stability led to a proposed long-range beam-beam compensation for the LHC based on current-carrying wires [19]. As of today, this equipment is not part of the HL-LHC baseline, however studies, construction of a number of prototypes, tests in LHC with beam, and a final conceptual design for the HL-LHC are supported by the project. The aim is to be ready with a validated solution in case of need, e.g. for operation with flat beams and/or if there is a shortfall in crab cavity performance.

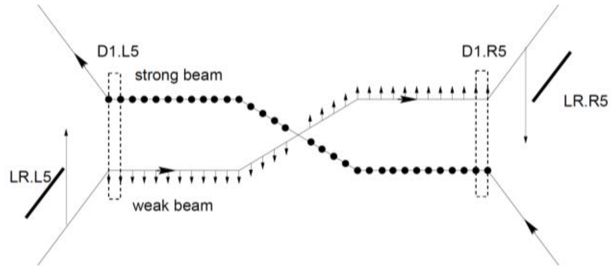

Figure 13-8: Illustration of the compensation principle. Here LR.L5 and LR.R5 indicate schematically the potential position of compensating wires.

13.9.1 Long-range beam–beam demonstrator

One of the few solid objects that can approach the beam accurately to within 10 σ or less are the LHC collimators. By embedding a wire in such a collimator, it is possible to use the collimator as a host for a demonstrator version of a long-range beam-beam compensator. The best compensation effect in this scenario is obtained by a wire in the tertiary collimators (TCT) located just in front of the D2 magnet. A 1 m long wire at this location would require a DC current of some 180 A at a distance of 9.5 σ to the beam or over 200 A at a distance of 11 σ. These values correspond to a symmetric layout with one compensator left of the IP and another on the right-hand side, a set-up that is necessary since the ratio of the horizontal and vertical beta functions are not equal at the TCT locations.

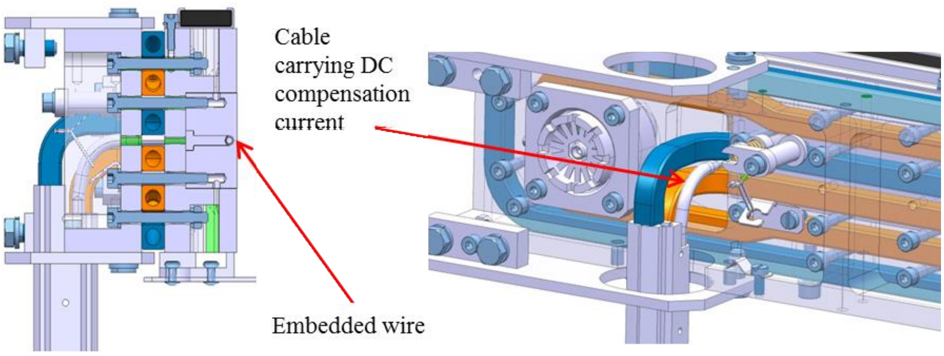

Figure 13-9: Technical drawing of the wire-in-jaw collimator design.

Integration of DC-powered wires into collimator jaws (Figure 13-9) was the only possibility to make realistic beam tests before embarking on a final implementation of the wires for high-luminosity operation. This integration itself required the solution of many important technical issues:

- no interference of the wires with the nominal operation of the collimators;
- transfer of 1 kW resistive heat loss in the wire by heat conduction to the water-cooled collimator jaw;
- shielding of the wire from the beam with a thin metallic layer for impedance reasons.

These were all successfully solved with four such wires now installed for testing in the LHC, along with the necessary DC cables and power converted infrastructure [20].

Machine experiments performed in 2017 and 2018 with these wires have clearly demonstrated long-range compensation [21]. Studies are therefore ongoing to complete a conceptual design for optimised beam-beam compensators for the HL-LHC.

13.10 Changes from the initial HL-LHC TDR

In the original TDR it was foreseen to study a high current electron beam as an alternative to a solid, current carrying wire in order to allow a much closer approach to the beam. However, recent results from the wire-in-jaw long-range compensators in the LHC accompanied by updated simulations, show that this is not necessary, and that adequate compensation can still be achieved at distances compatible with the collimation hierarchy. This favours the possibility of using of solid wires for the final system, a technology that is much cheaper and easier to integrate than high current electron beams.

13.11 References

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