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Chapter 18

Beam Instrumentation and Diagnostics

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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 that are currently being addressed.

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. In addition to replacing the current directive stripline beam position monitors, which allow independent measurement of both beams in a single aperture, eight 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, as part of the HL-LHC upgrade, implies new instrumentation in order to allow for the optimisation of their performance. This requires intra-bunch measurements 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 possibility prospect of using a hollow electron lens for cleaning the beam halo [see Chapter 8] 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 a halo at a level of 10^{-5} of the core intensity, while a gas curtain monitor is under development 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 the hollow electron beam and the proton beam 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. While wire-scanners work with low intensity beams, and the synchrotron light monitor provides the relative beam size for all beams at a fixed energy, there is currently no system that can provide accurate beam size measurements for all beams throughout the cycle. Such a measurement is essential to understand and combat emittance growth. Developments are therefore underway to provide such a monitor, with a prototype beam gas vertex detector being tested with beam in the LHC as part of the high luminosity LHC upgrade.

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

2. Beam Position Monitoring for the HL-LHC

With its 1070 monitors for orbit control, the LHC Beam Position Monitor (BPM) system is the largest BPM system in the world [1]. Based on the Wide Band Time Normalizer (WBTN) principle [2], 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 two LHC physics runs has been excellent.

2.1. *Current performance and limitations*

The position resolution of the LHC arc beam position monitors has been determined to be better than 150μm when measuring a single bunch on a single turn and better than 10μm for the average position of all bunches [3]. The main limitation on the accuracy of the BPM system 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 micrometers 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 exhaustive electro-magnetic simulations, with the aim of bringing the residual error down to below 20μm over most of the useable BPM aperture [4]. Developed to be able to distinguish between the positions of two counter propagating beams in the same beam pipe, these BPMs also suffer from non-optimal decoupling between the beams, which is something that is being addressed for HL-LHC.

2.2. *A high-resolution orbit measurement system for HL-LHC*

At the start of the HL-LHC era the existing BPM system will have been operational for over 15 years, using components which are over 20 years old. A completely new system is therefore being developed to replace these ageing electronics. This will be a fully digital system, directly sampling opposite electrode outputs on a single channel and making use of recent advances 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.

2.3. *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. Directional strip-line pick-ups are therefore used to distinguish between the positions 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, which can then be used to collect the signal from the beam travelling in the opposite direction. However, when the two beams pass through the BPM at nearly the same time, there is still some interference due to imperfect directivity (some signal still appearing at the downstream port) of the strip-line. In the current design 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 offset. This effect can be minimised by installing the BPMs at a location where the two counter-propagating beams do not meet, which is a constraint included in both the current and future layout. In addition, for the HL-LHC BPMs in front of the Q2a, Q3 and triplet corrector package magnets, there is the additional constraint that tungsten shielding is required at the level of the cold bore to minimise the heat deposition due to collision debris in these magnets. A mechanical re-design (see Figure 1) coupled with extensive electro-magnetic simulations have therefore been performed to optimise the directivity under these constraints, aiming at a factor 20 or more isolation between the signals from the counter propagating beams.

2.4. *Beam Position Measurement at the HL-LHC Collimators*

All next generation collimators in the LHC will have button electrodes embedded in their jaws for on-line measurement of the jaw to beam position [5]. These are fitted with an orbit measurement system based on a compensated diode detector scheme [6], which has already 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.

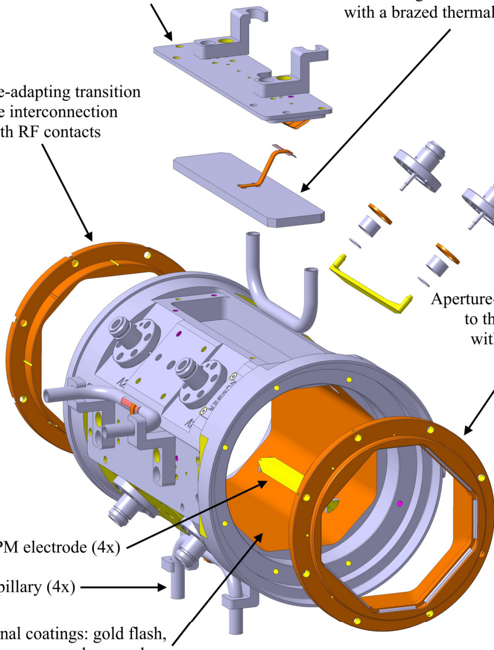

Fig. 1. Mechanical design of the Q2 directive stripline beam position monitor for HL-LHC.

3. Beam Loss Monitoring for the HL-LHC

Monitoring of beam losses is essential for the safe and reliable operation of the LHC. The beam loss monitoring (BLM) system provides knowledge of the location and intensity of such losses, allowing an estimation to be made of the energy dissipated in the equipment along the accelerator. The information is used for machine protection, to optimise beam conditions and to track the radiation dose to which equipment has been exposed. This is provided using nearly 4000 ionisation monitors distributed around the machine. These are located at all probable loss locations, with the majority mounted on the outside of the quadrupole magnets, including those in the inner triplet regions. There are also a few, fast diamond loss detectors located in the injection, dump and collimation regions to provide loss information on a bunch-by-bunch basis. 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. Although qualified for use in the low radiation environments of the LHC arcs the current electronics cannot be located close to the detectors in the higher radiation insertion regions. Development has therefore begun to implement these 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 existing 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 10μs integration time, and a targeted radiation tolerance of 1MGy.

This ASIC will use standard 130 nm CMOS technology (known to be radiation tolerant to 2MGy) 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.

4. Emittance Measurement for the HL-LHC

The LHC is currently fitted with a host of beam size measurement systems used to determine the beam emittance. These different monitors are required in order to overcome the specific limitation of each individual technique.

Wirescanners are used as the absolute calibration reference but can only be operated with a low number of bunches due to intensity limitations linked to wire breakage at injection and the quenching of downstream magnets at top energy.

A synchrotron light monitor [7] provides measurements during normal operation, delivering bunch-by-bunch beam size. However, this has limitation coming from the small beam size at top energy, the multiple sources of synchrotron radiation required to produce sufficient light over the whole energy range (undulator, D3 edge radiation, central D3 radiation), and the long optical path required to extract the light. This means that the correction needed to extract an absolute value of the transverse beam width is of the same order of magnitude as the beam width itself. An excellent knowledge of all error sources is therefore required to obtain meaningful results, something that can currently only be achieved through regular cross-calibration with wirescanners at a fixed energy.

The third system installed is an ionisation profile monitor. Originally foreseen to provide beam size information for lead ions at injection, where there is insufficient synchrotron light, this monitor has also been used for protons. However, with the intense proton beams, this monitor suffers from space charge effects at high energy, and recently had to be removed due to excessive, impedance related, radio-frequency heating.

Whilst efforts are ongoing to improve the performance of all the above systems, alternative techniques to measure the bunch-by-bunch transverse beam size and profile are under study for the HL-LHC.

4.1. *A Beam Gas Vertex Emittance Monitor for the HL-LHC*

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 [8]. 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 quantity 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.

This technique is based on the reconstruction of beam gas interaction vertices from the charged particles produced in inelastic beam gas interactions that are subsequently detected with high-precision tracking detectors (Figure 2). By reconstructing enough vertices, a complete two-dimensional transverse beam profile can be obtained. In order to acquire enough vertices in a reasonable time, a dedicated gas-injection system is required to provide a local pressure bump in the vicinity of the detectors. The pressure and type of gas

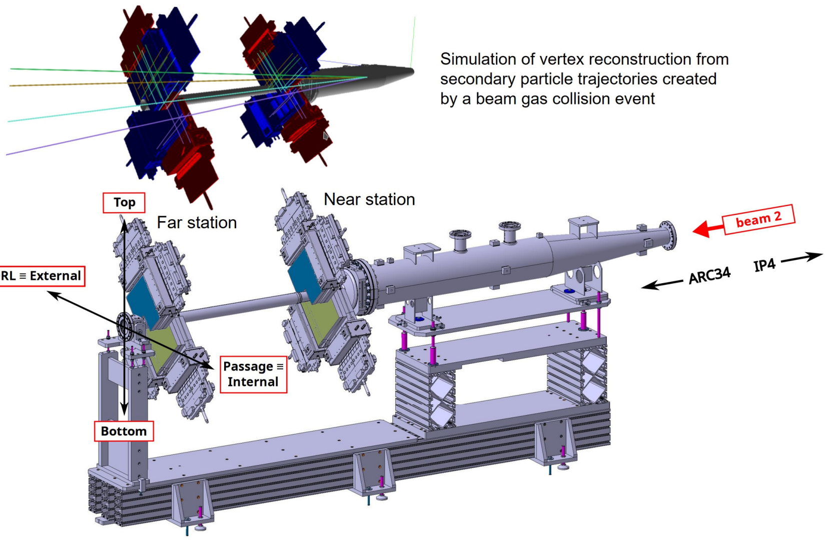

Fig. 2. The principle and design of the prototype LHC beam gas vertex detector.

used are of principal importance for the statistical and systematic uncertainties of the measured beam profiles. Prototyping of such a detector began in 2012 in collaboration with the LHCb experiment, the École Polytechnique Fédérale de Lausanne and RWTH Aachen, with the system installed in 2015 and fully operational for data taking in 2017-2018.

The installed prototype (Figure 3) 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 [9]. This allows beam size monitoring during all operational phases, including the energy ramp for which there is currently no other instrument that can make an absolute measurement of the beam size for high intensity physics beams. These encouraging results will lead to continued R&D on such a detector, to develop a fully optimised system for installation in the HL-LHC.

4.2. *Halo Diagnostics for HL-LHC*

One of the major challenges for high intensity accelerators is the control of beam losses. In the case of 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

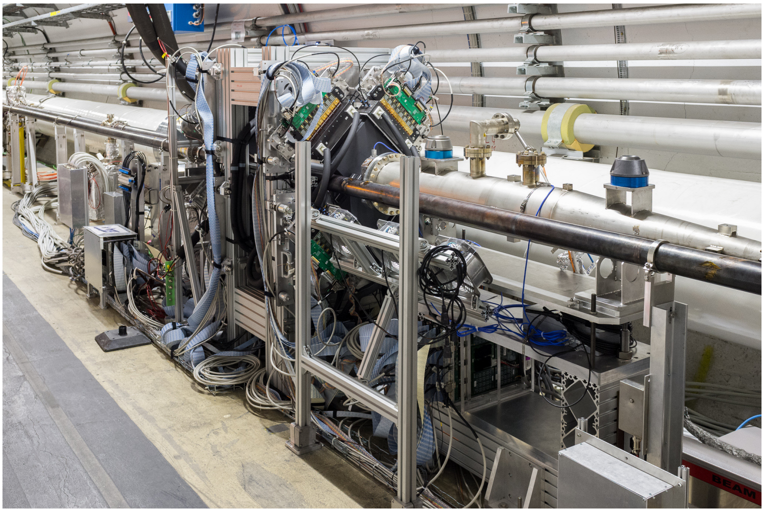

Fig. 3. The prototype LHC beam gas vertex detector

continuous power deposition. For this reason, it is very important 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 the non-linearity of the optics until they hit a collimator. Measurement of the beam halo distribution is important for understanding this mechanism to allow a minimisation of its effects. 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 HL-LHC should thus be able to observe the halo at a level of 10^{-5} of the peak bunch intensity.

There are two main ways of measuring the beam halo: either measuring the whole transverse space with a high dynamic range monitor, or sampling only the tails using a monitor with a standard dynamic range. Both methods have already been attempted in other machines offering a good example of what can be achieved. A third technique often used to measure the halo consists in removing it by scraping the beam and recording the loss rate during the process. This technique is, however, not suitable for the intense nominal HL-LHC beams and can only be used in dedicated low intensity experiments.

There are considerable challenges involved in adapting the standard diagnostics used for transverse beam profile measurement for halo measurements, due to the large dynamic range required and the need for continuous, non-invasive monitoring. Ionisation profile monitors and the new technique based on beam-gas vertex reconstruction provide non-invasive measurement but would require very long integration times to provide enough statistics to build-up a picture of the transverse beam tails, during which time the beam needs to remain extremely stable. Halo measurement using synchrotron radiation therefore seems the most promising technique as it can provide high dynamic range, while being non-invasive and allowing continuous monitoring of the beams at the bunch-by-bunch level.

4.2.1. *Halo measurement using Synchrotron Radiation Imaging*

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

- high dynamic range cameras [10]
- core masking and standard cameras [11]
- 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, in principle, be mitigated with an appropriate surface treatment and a clean and hermetic setup, although diffusion by scratches and defects on the optical components cannot be entirely removed. Diffraction, however, is a fundamental physics limitation.

To overcome the problem of diffraction, halo measurement using a coronagraph technique is under study, and a prototype based on a similar system installed on the Photon Factory at KEK is currently installed in the LHC [12]. Figure 4 shows the result of a test where the LHC beam was artificially blownup, with the halo being formed clearly visible when difference images are analysed. 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 5). This shows that the current 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 foresees to replace the first prototype for testing during LHC Run 3. Optimised versions will then be installed for both beams on new, specifically built synchrotron radiation lines using the light from the D4 separation dipoles in LSS4.

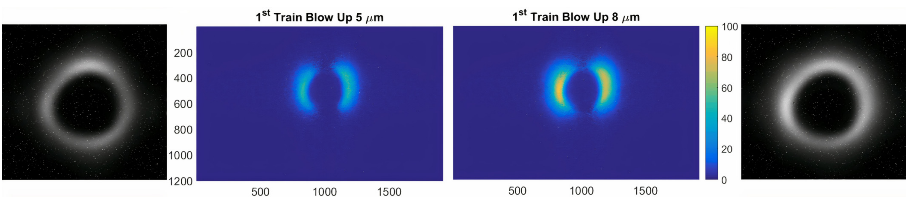

Fig. 4. Halo measurement during artificial beam blow-up. From left to right: original image, difference image after 1st blow-up, difference image after 2nd blow-up, final image.

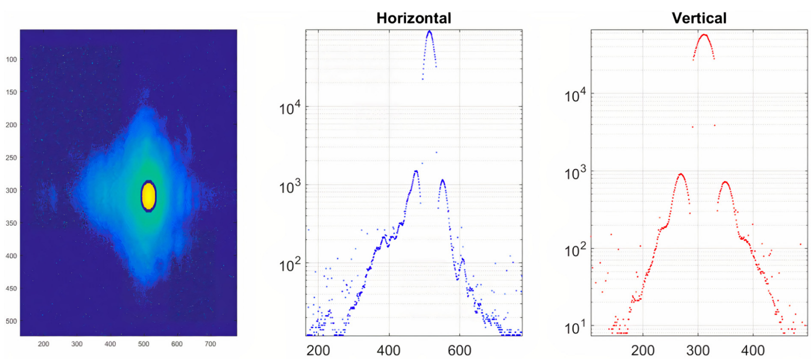

Fig. 5. Combined core and halo measurement showing a dynamic range of ~10^{-4}.

5. Diagnostics for Crab Cavities

The crab cavities for the HL-LHC will counter the geometric reduction factor caused by a large crossing angle to enhance luminosity. These cavities will be installed around the high luminosity interaction points (IP1 and IP5) and used to create a transverse intra-bunch deflection (head and tail of the bunch deflected in opposite directions) such that opposing bunches coming in at an angle to collide overlap fully at the interaction point. These intra-bunch deflections are compensated by crab-cavities acting in the other direction on the outgoing side of the interaction region. If the compensation is not perfect the head and tail of the bunch will travel on slightly different closed orbits around the ring and can be intercepted by the collimators or other aperture restrictions in their path. Monitors capable of measuring this orbit difference and any head-tail rotation or oscillation outside of the interaction regions are therefore required.

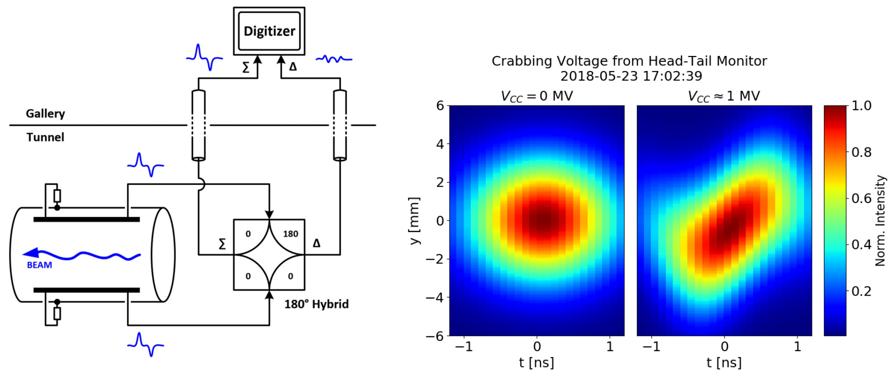

Fig. 6. Head-Tail monitor – principle of operation and reconstruction of the transverse position of the bunch with crab cavities off (left picture) and on (right picture).

5.1. *Bunch shape monitoring using electro-magnetic pick-ups*

Electromagnetic monitors for intra-bunch diagnostics are already installed in the LHC [13]. These so-called “Head-Tail” monitors mainly provide information on instabilities and have a bandwidth of 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 HL-LHC prototypes in the CERN-SPS accelerator (see Figure 6).

To better understand instabilities in HL-LHC and to help with the tuning of the crab-cavities a higher granularity within the bunch (bandwidth of ~10 GHz) is desirable, along with an improved position resolution. Studies are therefore ongoing to improve the existing electromagnetic pick-ups, which include optimisation of the pick-up design and the testing of faster acquisition systems.

In addition to the standard electromagnetic monitors, pick-ups based on electro-optical crystals in combination with laser pulses are also being considered [14]. Such pick-ups have already demonstrated an extremely fast time response, in the sub-picosecond range. Developed mainly for linear accelerators, this technology is now also being considered for circular machines, with a prototype recently tested on the CERN-SPS in collaboration with Royal Holloway University of London, UK [15].

5.2. *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) [16]. Usually only one transverse axis is acquired, with the other used for the streaking (temporal profile). Using sophisticated optics, it is however possible to monitor both axes at the same time, as was demonstrated at the Large Electron Positron (LEP) collider at CERN [17].

Streak cameras 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 50Hz, 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 can 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.

The longitudinal resolution of around 50ps required for 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:

(1) 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.

(2) 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 therefore 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.

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, shielded, hutch. The latter would imply an optical line to transport the synchrotron light from the machine to the camera.

Another point to consider is the synchrotron light source. At the moment two synchrotron light telescopes are installed in the LHC, one per beam, using radiation from the D3 separation magnet in the RF insertion region of the LHC at Point 4. These telescopes already share their light amongst three different instruments, the synchrotron light monitor, the abort gap monitor and the longitudinal density monitor. It will therefore be difficult to integrate yet another optical beam line for the streak camera. The installation of additional light extraction mirrors will therefore be necessary to provide the light for the streak cameras and the halo diagnostics mentioned in the previous section. Integration studies are currently underway to incorporate a second synchrotron radiation line per beam, using the radiation produced by the D4 separation magnet near the RF insertion in Point 4. Since the crab cavities are only needed at high energy, dipole magnets can be used as the source of the visible synchrotron radiation for the streak cameras, with no need for the installation of additional undulators that are only required at injection energy, where the dipole radiation is in the infra-red. The efficient detection of the crabbing is also dependent on the accelerator optics, requiring a favourable phase advance between the crab cavities and the synchrotron light source used.

6. Luminosity Measurement for HL-LHC

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 beam collision process. Simple, reliable collision rate monitors are therefore needed for HL-LHC, similar to those currently 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 at the point where the two beams are separated back into individual vacuum chambers. These detectors are installed inside absorbers whose role it is to avoid that the neutral collision debris, and the secondary showers induced, reach and damage downstream machine components. As these absorbers will be re-designed for the completely different HL-LHC geometry in this region, new, adapted luminosity monitors will need to be produced.

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 HL-LHC. Prototypes, with Cherenkov radiation produced in both air and in 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, with a continuous degradation of the mirrors used in the Cherenkov in air monitor, and a change in transmission of the Cherenkov light produced in the fused silica rods observed. 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 for detection. This technology therefore looks promising as the baseline for the luminosity monitors of the HL-LHC.

7. Gas Curtain Diagnostics

With a hollow electron lens actively being studied as an addition to the HL-LHC collimation system, research and development is also 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 collection of charged particles as an observable.

An instrument is therefore 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 for a traditional solid screen beam observation system. The instrument consists of the following main components:

- a gas generation stage consisting of a supersonic gas nozzle followed by three skimmers which select and shape the gas jet into a thin gas curtain
- an interaction chamber where the high energy proton beam and low energy hollow electron beam interact with the gas curtain
- an optical system for image generation
- an exhaust chamber which pumps the residual gas of the curtain.

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, LHC ultra-high vacuum system, 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. Total integration times of the order of 1 s are thus expected for neon or argon as working gases.

Formation of the gas stream in the nozzle and subsequent selection and shaping in the skimmers define the gas curtain density at the interaction point with the beam. A predictive design of the gas curtain requires simulation of a continuous gas flow with a pressure range of 14 orders of magnitude, from the gas nozzle at 10 bar to the LHC machine vacuum at 10^{-10} mbar.

A hybrid simulation approach to this problem is being taken, using Computational Fluid Dynamics (CFD) from the supersonic nozzle up to the first skimmer opening and Test-Particle Monte Carlo (TPMC) assuming a quasi-molecular flow downstream of the first skimmer. This has resulted in an optimised design (Figure 7), currently undergoing laboratory testing, with promising results having already been obtained with nitrogen gas (Figure 8).

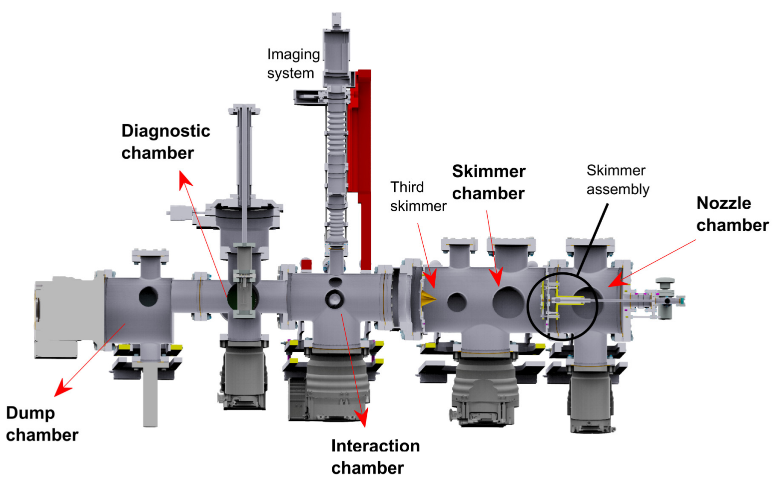

Fig. 7. Layout of the laboratory prototype gas curtain monitor.

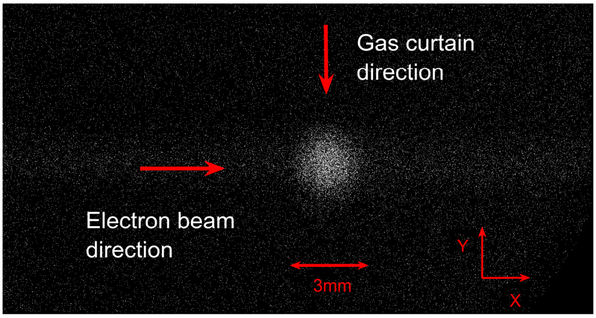

Fig. 8. Two-dimensional luminescence profile of an electron beam produced using a gas curtain.

This laboratory design must now be adapted for installation in the LHC, posing a number of additional challenges. Beam impedance concerns must be addressed by using a copper shielded sleeve with regular slots for vacuum conductance. The distance between the gas nozzle and interaction point needs to be compatible with the LHC tunnel dimensions, with the final instrument also required to fit into the 200 mm longitudinal gap between the two solenoid cryostats of the hollow electron lens. A prototype taking into account all these considerations is currently under construction with plans for installation and operation on the high energy proton beams during Run 3 of the LHC.

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