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BEAM INSTRUMENTATION AND DIAGNOSTICS FOR HIGH LUMINOSITY LHC

M. Krupa*
CERN, Geneva, Switzerland

Abstract

The High Luminosity LHC project aims to increase the integrated luminosity of the LHC experiments by an order of magnitude. New and upgraded beam instrumentation is being developed to cope with much brighter beams and to provide the additional novel diagnostics required to assure safe and efficient operation under the new LHC configuration. This contribution discusses the various ongoing developments and reports on the results obtained with prototypes for transverse position, intra-bunch position, transverse size and profile, and beam halo monitoring.

INTRODUCTION

Since the first beam injection in 2008, the Large Hadron Collider (LHC) has delivered around 190 fb^{-1} of integrated luminosity to each of the two large experiments, ATLAS and CMS. This has led to numerous advancements in particle physics, the most notable being confirming the existence of the Higgs boson in 2012. To fully exploit the discovery potential of the LHC, the High Luminosity LHC (HL-LHC) project aims to achieve an additional 3000 fb^{-1} of integrated luminosity over twelve years of operation from 2026 which necessitates significant upgrades to the accelerator [1].

The two high-luminosity Interaction Regions (IR) of the LHC housing the ATLAS and CMS experiments will undergo major changes during the HL-LHC upgrade. The main change will be a complete replacement of the low-beta Inner Triplets (IT), with higher gradient quadrupoles to allow a further squeezing of the beams to produce even smaller beams at the collision point. In order to reliably collide these exceptionally small beams, extraordinary control of the beam orbit will be necessary.

Moreover, transverse deflecting RF cavities, referred to as crab cavities, will be installed on each side of ATLAS and CMS to perform bunch crabbing. Each bunch will be exposed to a modulating RF field, tilting the bunch transversely to allow the bunches to cross head-on at the collision point even for they approach each other at an angle. After the collision the bunches are rotated back to their original orientation by the crab cavity on the other side of the experiment. This operation maximises the geometric overlap between the colliding bunches which would otherwise be reduced due to the crossing angle.

In the high luminosity era, the LHC bunch intensity will be increased by a factor of two leading to much higher power stored in the beams. The machine protection requirements will therefore become stricter. This particularly concerns the allowed beam halo population since it will become possible to lose the entire halo within a very short timescale in case of a crab cavity failure. Furthermore, increased radiation levels due to the higher beam intensity and the increased luminosity pose additional requirements on any equipment installed for HL-LHC.

To cope with the above challenges, both new and upgraded beam instrumentation is under development with the initial plans and early progress described in [2] and [3]. The following sections review the current state of these projects.

BEAM POSITION MONITORING

Interaction Regions

There are currently four types of Beam Position Monitors (BPMs) under development for the HL-LHC with their arrangement shown in Fig. 1. The seven BPMs closest to the collision point on each side of the experiments are installed in the new higher gradient, inner-triplet quadrupoles, in a region where both beams circulate in a common vacuum chamber. They must be able to clearly distinguish between the positions of the two counter-propagating particle beams, for which the solution is to use directional couplers. In such beam position monitors the passing particle beam couples to four long antennas (often called striplines) parallel to the beam axis. Each antenna is connectorised on both ends, and has the particularity that the majority of the beam signal is visible only on the upstream end with only a much smaller parasitic signal leaking to the downstream end. This feature, referred to as directivity, allows both beams to be measured by a single array of antennas, and is achieved by a careful RF design complemented by 3D electromagnetic simulations [4]. A 3D model of the most complicated HL-LHC directional coupler BPM is shown in Fig. 2.

To reduce the cross-talk between the signal from one beam and the other due to the limited directivity of such a stripline BPM, the HL-LHC directional coupler BPMs will be intentionally installed in locations where the bunches of the two beams arrive at different times. With bunches separated by 25 ns the maximum time difference between two counter-propagating beams arriving at a given position is 12.5 ns. Due to the HL-LHC beam optics and hardware constraints, it is not possible to install all the BPMs at ideal locations. However, the temporal separation between the beams at a BPM location will always be greater than 3.9 ns which is approximately 3 times longer than the bunch length.

Besides the directive couplers, a set of more conventional capacitive button BPMs is also under development.

The superconducting IT magnets incorporate tungsten shielding blocks which protect them from the high-energy collision debris [5]. Likewise, some of the cryogenic BPMs

* michal.krupa@cern.ch

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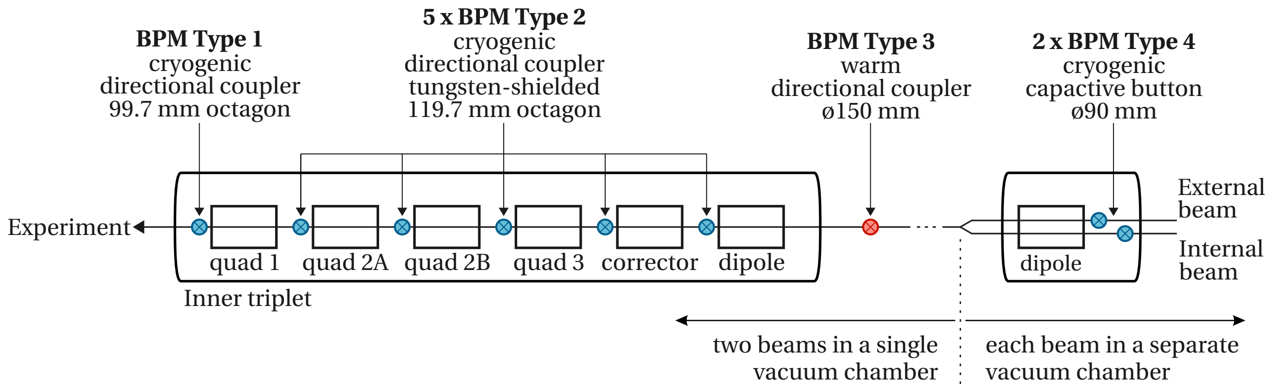

Figure 1: Schematic layout of BPM under development for HL-LHC.

installed between these magnets, also need to feature 6 mm thick tungsten absorbers located in the horizontal and vertical planes of the monitor. The electrodes of these tungsten-shielded BPMs are therefore installed at 45° and 135° instead of the typical 0° and 90°.

Besides absorbing collision debris, the cryogenic BPMs will have to cope with other sources of heat load, the most significant being that caused by electron cloud effects. After a series of extensive macroparticle simulations [6] it was concluded that internal amorphous carbon coating will be applied to the cryogenic BPMs to minimise the total heat load due to electron cloud. Coating of the BPMs and the adjacent drift vacuum chambers more than halves the estimated head load for the cryogenic circuits from 532 W to 238 W.

The heat deposited on the cryogenic BPMs will be evacuated by an active cooling circuit. Capillaries carrying liquid helium will be welded to the BPM body and connected to the main magnet cooling circuit. The design was verified with thermomechanical simulations to guarantee appropriate performance of the BPM under realistic thermal conditions. For tungsten shielded BPMs, the absorbers will also be cooled using thermal links brazed to the capillaries. To improve heat transfer along the body, the BPMs will be internally coated with 100 µm of copper.

Collimators

With ever increasing power stored in the LHC beams, it becomes indispensable to protect the accelerator against

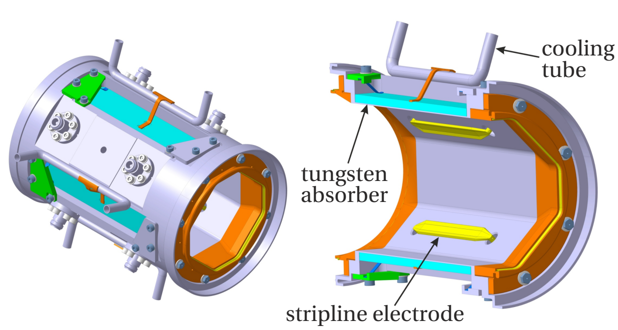

Figure 2: Tungsten-shielded cryogenic directional coupler BPM design for HL-LHC.

beam which cannot be safely contained within the vacuum chamber. The LHC uses a hierarchical system of collimators distributed around the accelerator which intercept particles deviating too much from the allowed beam aperture.

Following the very successful first deployment in 2013 [7], all new collimators feature embedded BPMs to expedite centring the jaws around the beam. The jaws incorporate a 10 mm diameter button electrode installed on each end resulting in four electrodes per collimator. The buttons are retracted by 8.5 mm from the active surface of the jaw to protect them from a possible beam impact. Moreover, some collimators feature two additional buttons in the non-collimated plane to improve transverse alignment of the instrument.

Incorporating BPMs into a highly radioactive, beam intercepting device poses several engineering challenges. In particular all materials used need to be carefully selected to withstand the radiation levels while being UHV compatible and able to withstand a vacuum bakeout cycle to 250°C. This had led to the use of Special vacuum-tight coaxial cables using silicon dioxide dielectric and a fast plug-in coaxial cable assembly for remote installation.

DIAGNOSTICS FOR CRAB CAVITIES

The crab cavities for the HL-LHC will enhance luminosity by countering the geometric reduction factor caused by a large crossing angle. These cavities will be installed around the high luminosity experiments (ATLAS and CMS) 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.

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Head-tail Monitor

Head-Tail monitors (HT) are specialised BPMs optimised for high-frequency performance, and used to monitor beam instabilities by measuring the position distribution of particles within a bunch. The beam induced signals are processed by a passive 180° RF hybrid producing analogue sum and difference signals, proportional to the bunch intensity and the position, respectively. The hybrid signals are then digitised with a high-frequency, high-resolution oscilloscope.

Such a HT monitor, installed in the CERN-SPS, was extensively used in the testing of prototype crab cavities with beam. Figure 3, shows the results obtained after processing the data from the SPS HT monitor demonstrating the first successful crabbing of a proton bunch with a crab cavity [8].

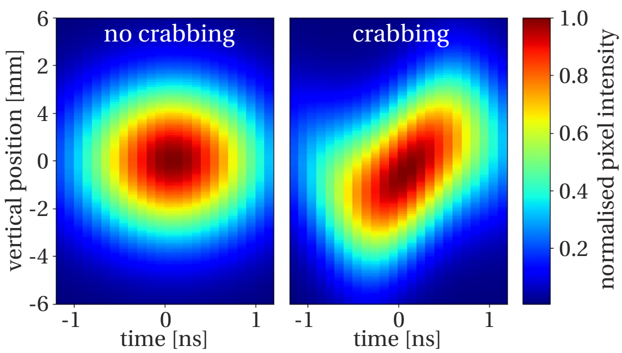

Figure 3: World's first successful crabbing of a proton bunch as seen by the SPS HT monitor.

Such monitors are also installed in the LHC, where they are mainly used for instability diagnostics. However, while HT monitors were successfully used in the SPS as crab cavity diagnostics, they are limited in both resolution and bandwidth, which poses a problem for the shorter bunches and much lower deflections to be measured for HL-LHC. This is why alternative technologies are being investigated to address these shortcomings.

Electro-optic BPM

A higher frequency alternative to the HT monitor is a BPM based on electro-optic detection, being developed in collaboration with Royal Holloway, University of London. The technique relies on the ultrafast response of birefringent crystals to encode the electromagnetic field of a passing bunch onto a laser beam. When exposed to an electric field, the crystal rotates the polarity of any light passing through it. The rotation amplitude is correlated with the strength of the electric excitation field. Therefore, by measuring the polarity of the light it is possible to reconstruct the electric field seen by the crystal [9]. This technique has often been used to determine the longitudinal beam profile of short bunches using a single crystal. To measure the intra-bunch position, two crystal are placed on either side of the beam. By comparing their response, the position variation along the bunch can be determined.

Such an elementary configuration can be further improved with interferometric methods as shown in Fig. 4. The laser beam is split and only a part of it travels through the crystal whilst the remaining light does not experience any polarisation change. Upon recombination both light beams are superimposed causing interference. By correct adjustment of the system only the fraction of light whose polarisation was rotated by the crystal is then detected by the photodetector. Such a setup was successfully tested with beam in the CERN SPS in 2018 [10].

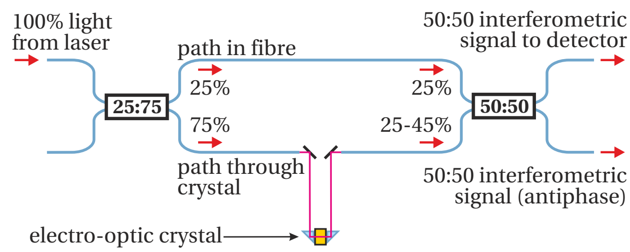

Figure 4: Principle of operation of the fibre interferometer electro-optic BPM.

Until now, all the electro-optic systems developed at CERN placed their crystals within the beam vacuum. Such an approach has proved to be very challenging from the engineering point of view, requiring both fibre-to crystal and air-to-vacuum fibre coupling, or a compact free-space optical system.

Recently, however, a proposal has been made for an out-of-vacuum design that would significantly simplify this technique. Electromagnetic simulations have shown that it is feasible to place all optical components outside of the beam vacuum over a metal electrode embedded in a brazed ceramic window. Although these results are very encouraging a significant amount of work remains to be done before a final HL-LHC electro-optic BPM design emerges.

HALO DIAGNOSTICS

The energy stored in the HL-LHC beams will reach approximately 700 MJ per beam. Since the safe, continuous dissipation of power into the collimation system is limited to 1 MW, controlling beam losses will become even more fundamental. An important mechanism for slow losses consists of populating the beam "halo", i.e. populating the periphery of transverse phase-space with particles at large amplitudes. Measurement of the beam halo distribution is therefore necessary for understanding such losses. A new beam loss mechanism will also be introduced by installation of the crab cavities. In case of their failure, it will be possible to lose the entire beam halo over a short timescale, making beam halo measurements crucial for adequately adapting the machine protection systems.

Most of the LHC transverse beam profile diagnostics could be adapted for beam halo measurement. However, using synchrotron radiation seems the most promising, with a coronagraph under development for the HL-LHC.

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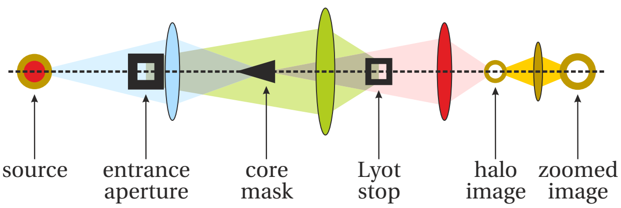

Figure 5: Principle of operation of a coronagraph.

A prototype coronagraph is currently installed in the LHC using optics mostly provided by KEK [11]. Its principle of operation is depicted in Fig. 5. An objective lens creates a real image of the beam and its halo, with the bright core of the beam blocked by a core mask. However, diffracted light from the edges of entrance aperture of the first lens will at this stage still dominate the halo image. To reduce this effect a second lens and Lyot stop are used. The Lyot stop is a well-dimensioned mask placed at the location where the diffraction fringes from the entrance aperture are re-imaged by the second lens, blocking their further propagation. Further lenses are then used to re-image the halo. Instruments applying this principle have been used in astronomy to observe the corona of the sun since the 1930s.

First successful beam halo measurements using the LHC coronagraph demonstrator were obtained in 2016 using synchrotron radiation produced by an undulator. The beam was blown up in a controlled manner with measurements taken at different transverse emittance values clearly showing the change in halo population as shown in Fig. 6.

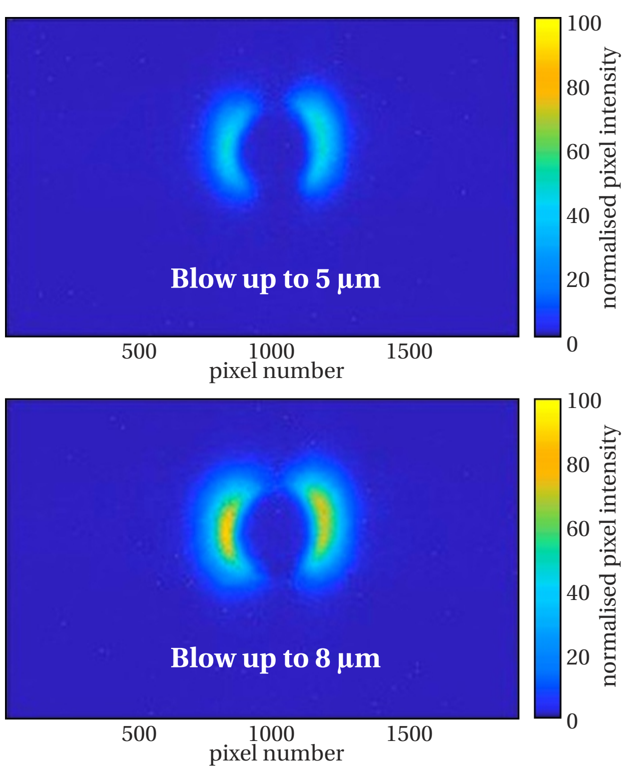

Figure 6: Beam halo measurements during controlled beam emittance blow up.

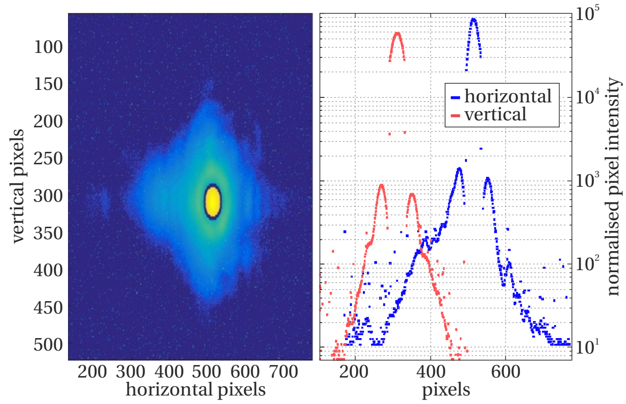

Figure 7: 2D profile of an LHC bunch obtained by combining measuremetns from the coronagraph prototype and synchrotorn light monitor

A coronagraph's figure of merit is its contrast, i.e. the ratio of the measurable halo intensity to the core intensity at the image plane. The instrument currently installed in the LHC has demonstrated a contrast of around 10^{-4}. Figure 7 shows a 2D beam profile obtained by combining measurements obtained with the coronagraph (for the halo) and with other synchrotron light based diagnostics (for the core). However, the halo monitor for HL-LHC is required to observe beam halo at the level of 10^{-5} of the peak bunch intensity. Further improvement will therefore be necessary to achieve the specified contrast. In particular, a design exploiting a Cassegrain reflector telescope to increase the magnification is underway. This new prototype will replace the existing prototype and is scheduled to be tested with beam in 2021–2023. Moreover, for the HL-LHC era, a dedicated coronagraph light extraction path is foreseen to minimise the number of optical elements spoiling the signal quality and to make the instrument independent of the other synchrotron radiation based diagnostics used in the LHC.

BEAM PROFILE MEASUREMENTS

A remaining limitation of the existing LHC beam instrumentation is the lack of reliable emittance measurements throughout the whole acceleration cycle with a full physics beam. Besides the ongoing efforts to improve the performance of the existing instruments, alternative measurement techniques are also being investigated to provide continuous emittance monitoring in the HL-LHC.

The Beam Gas Vertex (BGV) monitor is one such candidate instrument [12]. Conceptually, it resembles the vertex (VELO) detector of the LHCb experiment which successfully proved that beam-gas interactions can be used to reconstruct the transverse profile of the beam circulating in the LHC [13]. Such a technique presents the appealing potential to provide high-resolution bunch-by-bunch profile measurements in three dimensions using a minimally-intercepting (gas target) out-of-vacuum detector. However, the particle track reconstruction required implies an immense amount of data processing which is challenging to accomplish.

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The HL-LHC BGV specification calls for a measurement resolution of 5% for a single bunch and an absolute accuracy of 2% for the whole beam, i.e. the superposition of all bunches, within an integration time of one minute. Furthermore, the instrument should provide measurements throughout the entire LHC cycle, from injection, through acceleration, to collision.

A BGV demonstrator, developed in collaboration with École Polytechnique Fédérale de Lausanne, LHCb, and RWTH Aachen, was installed in the LHC in 2014. The gas target volume is filled with neon at a pressure of approximately $5 \cdot 10^{-8}$ mbar. The secondary particles exit the vacuum chamber through a thin aluminium window and are measured by two tracking detectors based on scintillating fibre modules. Additionally, hardware and software triggers are used to discard false-positive readings coming from regular beam losses. The readout and data acquisition systems are based on those used at LHCb. The LHC BGV demonstrator is schematically shown in Fig. 8.

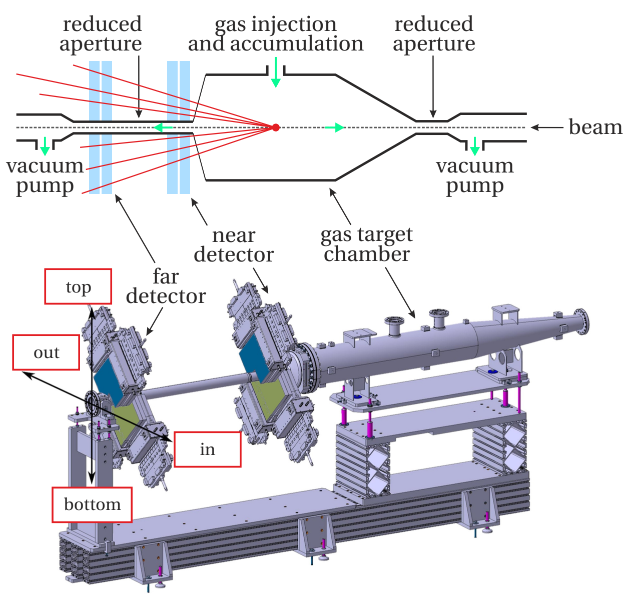

Figure 8: LHC BGV demonstrator principle of operation.

Through beam measurements, the LHC BGV demonstrator has proven its ability to measure the beam size in both planes with an achieved precision better than 3% for an integration time of less than one minute [14]. It has also demonstrated the ability to continuously measure the beam size during the entire LHC cycle. An example of beam size measurements obtained with the BGV demonstrator during the LHC energy ramp is shown in Fig. 9.

These encouraging results have led to continued R&D for a final version of such a system to be implemented for HL-LHC. Improvements being studied include: the investigation of alternative tracking technologies to optimise resolution with respect to coverage and cost; the use of standard beam instrumentation data acquisition modules for ease of future maintenance; the addition of a third detector plane to simplify the identification of tracks and ease with alignment;

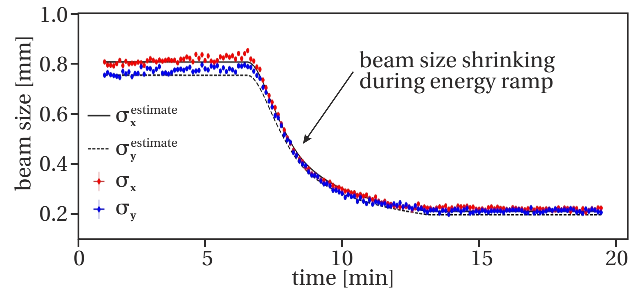

Figure 9: LHC BGV demonstrator measurements during the LHC energy ramp.

replacing the voluminous gas target by a planar gas jet to reduce the uncertainty on the longitudinal beam-gas interaction coordinate. A full, final design proposal is expected to be ready by the end of 2020.

LUMINOSITY MEASUREMENTS

Both the ATLAS and CMS experiments at the LHC measure their respective instantaneous luminosities independently. However, these measurements are often not available to LHC machine operation during machine study periods or when the accelerator is not fully tuned.

To overcome these operational limitations, fast ionization chambers, referred to as BRAN [15] (Beam RAte from Neutrals) detectors, are installed to complement the experiment luminosity monitoring. Installed in the neutral absorbing block on either side of the high luminosity experiments, they sample the showers of secondary particles produced by forward neutral particles and photons originating from the high energy collisions in the region where the two LHC beams move from a single vacuum chamber into two separate chambers.

To cope with the higher luminosity, the increased radiation levels, and the re-design of the neutral absorbing block, new detectors are foreseen for the HL-LHC era. Fused silica rods generating Cherenkov radiation are being considered as a replacement for the ionization chambers [16]. Rods made of different compositions of fused silica were recently tested in the LHC to evaluate their performance under realistic irradiation conditions. The loss in light yield after two years of operation is plotted in Fig. 10. Two sharp absorption centres can be seen in the UV range, which unfortunately coincide with the wavelength range where most of the Cherenkov light is generated. Nevertheless, rod darkening was seen to occur only within the first 10 fb^{-1} of integrated luminosity, remaining stable afterwards. Such silica rod based detectors are therefore maintained as viable candidates to replace the ionisation chambers for HL-LHC.

In order to avoid parasitic collisions outside of the experiments, the two beams collided at an angle. The plane in which this crossing angle is applied is referred to as the crossing plane. For HL-LHC it is currently foreseen that a horizontal crossing is used in ATLAS and a vertical crossing used in CMS. This crossing angle is also foreseen to be

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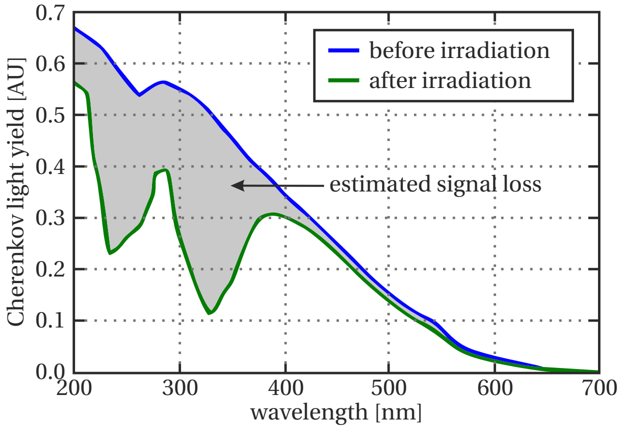

Figure 10: Cherenkov light yield before and after irradiation of fused silica rods.

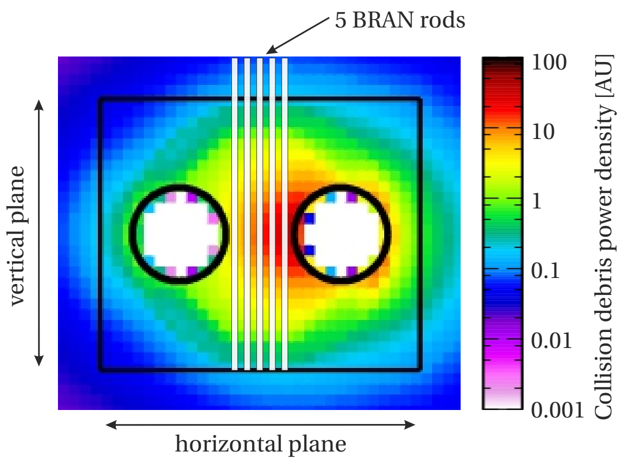

Figure 11: 2D section view of the power density of the neutral particle shower at the location of the BRAN detector for a horizontal crossing angle.

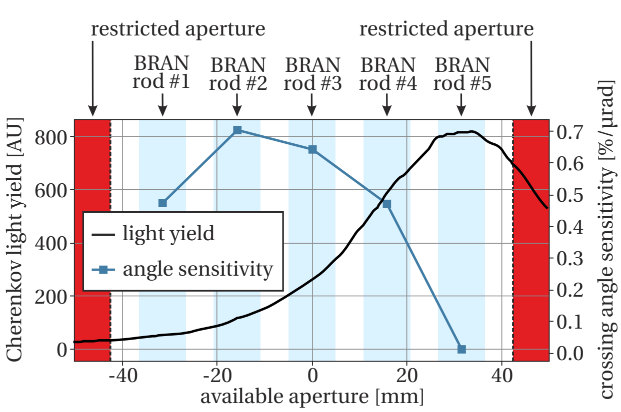

Figure 12: Cherenkov light yield from the neutral particle shower and the effect of the horizontal crossing angle on the HL-LHC BRAN monitors.

varied during a physics fill to maintain a constant luminosity as the beam intensity reduces. The HL-LHC BRAN should therefore be able to provide relative luminosity measurements in all of these conditions. While this is the case for vertical crossing, it can be seen in Fig. 11 that for horizontal crossing the secondary shower is transversely misaligned with the instrument exposing each of the rods to a particle flux which depends on the crossing angle as well as the instantaneous luminosity (Fig. 12). This can affect the BRAN signal by up to ~10% for a 15 µrad change in the crossing angle, making it difficult to use the system for collision optimisation during a crossing angle change. Different signal processing options are therefore being investigated to minimise this sensitivity.

GAS JET DIAGNOSTICS

A Hollow Electron Lens (HEL) is under study for beam halo control as a possible upgrade to the LHC collimation system in the scope of the High Luminosity LHC upgrade [17]. The HEL generates a hollow, cylindrical electron beam which is concentrically overlapped with the high energy proton beam in a 3 m long superconducting solenoid. Any halo particles from the high energy proton beam migrating into the electron beam are slowly kicked to higher amplitudes where they are extracted by the collimation system. Efficient operation of the HEL necessitates a good transverse alignment of the high energy proton and hollow electron beams. To address this need a Beam Gas Curtain (BGC) fluorescence monitor is being developed in collaboration with GSI (Germany) and the Cockcroft Institute (UK) to provide a minimally invasive way to monitor the concentricity of both beams [18].

The BGC generates a thin, supersonic gas curtain tilted at 45° with respect to the beam axis. Beam-gas interactions excite the gas, leading to the spontaneous emission of photons which are observed as fluorescence by an optical system linked to an intensified camera. This creates a 2D image of both beams in a similar fashion to that obtained with a traditional, solid scintillating screen. Using fluorescence rather than ionisation electrons or ions, allows the system to be used in the proximity of the strong solenoid field. The principle of operation of the BGC is sketched in Fig. 13.

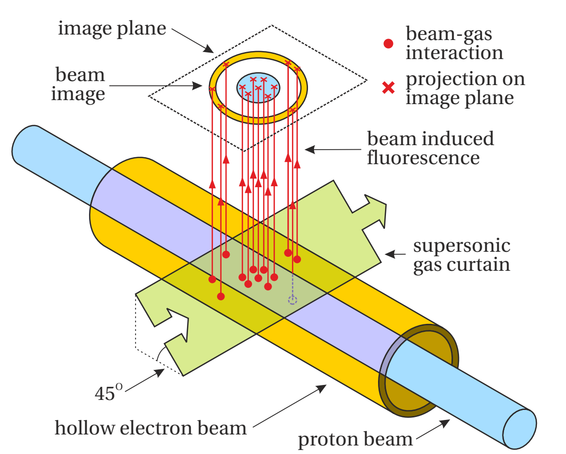

Figure 13: Principle of operation of the Beam Gas Curtain fluorescence monitor.

Several considerations affect the choice of working gas. A sufficient fluorescence signal is required from interaction with both a keV electron beam as well as a TeV proton beam. Spectral lines of a neutral atom or molecule are favoured to avoid image distortion from the strong background electromagnetic self-fields of the beams. Moreover, the working gas should be fully compatible with the LHC ultra-high vacuum environment and NEG coated chambers.

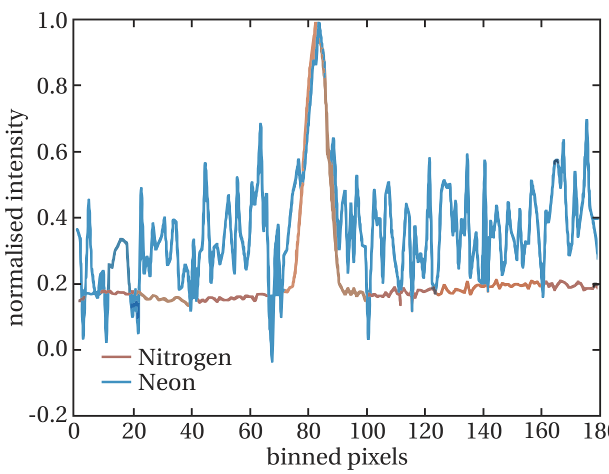

Figure 14: A comparison of beam-induced fluorescence from nitrogen and neon for the same integration time.

A prototype BGC has been built at the Cockroft Institute to test nitrogen (N_2), neon (Ne), and argon (Ar) with a 5 keV, 0.65 mA electron beam. Beam-induced fluorescence was observed with all three gases [19]. Measurements obtained with nitrogen and neon over a 4000 s integration window are shown in Fig. 14. As the fluorescence cross section of nitrogen for 5 keV electrons is two orders of magnitude higher than that for neon, it produces a much cleaner signal. However, nitrogen has limited compatibility with the LHC vacuum system and the lines observed come from charged molecules. Neon is therefore at the moment still preferable despite the lower signals obtained. It should be noted that the HEL electron beam will be operated at 5A, a factor 10000 higher than the Cockroft test beam, so reducing proportionally the overall integration time required. A full prototype system will be installed in the LHC during the next run to verify both the vacuum compatibility and verify the expected fluorescence cross-sections with high energy proton beams.

SUMMARY

With the high luminosity upgrade the extensive array of existing beam instrumentation and diagnostics in the LHC will be upgraded and complemented by new developments.

The design of new stripline beam position monitors is well underway, with optimised directivity and incorporated tungsten absorbers for shielding the magnets from collision debris. A novel electro-optic BPM has been tested to assess the feasibility of using this technique for fast intra-bunch position measurements, with continued R&D ongoing to simplify the construction and enhance the sensitivity. Results from a prototype HL-LHC coronagraph are promising with a contrast of 10^{-4} demonstrated. A second prototype using a Cassegrain telescope configuration is foreseen for installation next year, with a view to approaching the HL-LHC requirement for a contrast of 10^{-5}.

The Beam Gas Vertex monitor has been shown to be a real candidate to address the lack of sufficient LHC instrumentation to monitor the beam emittance throughout the entire LHC cycle, with a conceptual design of a final system for HL-LHC foreseen by the end of 2020.

To cope with the increased luminosity and higher radiation levels an upgrade to the LHC luminosity monitors is also foreseen. Recent results from the irradiation of fused silica rods producing Cherenkov radiation have validated this technique for replacing the existing ionisation chambers, with studies now ongoing to address remaining issues.

Finally, the possible addition of the Hollow Electron Lens to the LHC collimation system and its particular need for beam overlap diagnostics, has initiated a very fruitful collaboration for the development of a minimally invasive Beam Gas Curtain monitor. A prototype of such a monitor, combined with the observation of beam-induced fluorescence, has been successfully tested with low energy electron beams, and it is now planned to install a full prototype system in the LHC to verify the expected fluorescence cross-sections with high energy proton beams.

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