Chapter 20

Beam Instrumentation and Diagnostics for the LHC Upgrade

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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. High Luminosity LHC (HL-LHC) brings with it a number of new challenges in terms of beam instrumentation that will be discussed in this chapter. The beam loss system will need significant upgrades in order to be able to cope with the demands of HL-LHC, with cryogenic beam loss monitors under investigation for deployment in the new inner triplet magnets to distinguish between primary beam losses and collision debris. Radiation tolerant integrated circuits are also being developed to allow the front-end electronics to sit much closer to the detector. Upgrades to other existing systems are also envisaged; including the beam position measurement system in the interaction regions and the addition of a halo measurement capability to synchrotron light diagnostics. Additionally, several new diagnostic systems are under investigation, such as very high bandwidth pick-ups and a streak camera installation, both able to perform intra-bunch measurements of transverse position on a turn by turn basis.

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. In addition to all of this existing diagnostics HL-LHC brings a number of new challenges in terms of beam instrumentation that are currently being addressed.

The beam loss system, designed to protect the LHC from losses that could cause damage or quench a superconducting magnet, will need a significant upgrade in order to be able to cope with the new demands of HL-LHC. In particular, cryogenic beam loss monitors are under investigation for deployment in the new inner triplet magnets to distinguish between collision debris and primary beam losses. Radiation tolerant integrated circuits are also under

development to allow the front-end electronics to sit much closer to the detector, so minimizing the cable length required and reducing the influence of noise.

The proposed use of crab cavities implies new instrumentation in order to allow for optimization of their performance. Several additional diagnostic systems will therefore be investigated, including very high bandwidth pick-ups and a streak camera installation. These would be able to perform intra-bunch measurements of transverse position on a turn-by-turn basis.

An upgrade to several existing systems is also envisaged, including the beam position measurement system in the interaction regions and the addition of a halo measurement capability to synchrotron light diagnostics.

2. Beam Loss Measurement for 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 qualify the collimation hierarchy, to optimize beam conditions and to track the radiation dose to which equipment has been exposed. This is currently done using nearly 4000 ionization monitors distributed around the machine and located at all probable loss locations, with the majority mounted on the outside of the quadrupole magnets, including those in the inner triplet regions. Around one third of the arc monitors have recently been relocated in order to optimize the system for protection against fast beam losses believed to be caused by dust particles falling into the vacuum pipe. While the existing system is expected to meet the needs of the HL-LHC for the arcs, this will no longer be the case for the high luminosity interaction points.

In the HL-LHC high luminosity insertions the magnets will be subjected to a greatly enhanced continuous radiation level due to the increase in collision debris resulting from the higher luminosity. With the presently installed configuration of ionization chambers in this region the additional signal from any dangerous accidental losses would be completely masked by that coming from collision debris. This is a critical issue for LHC machine protection and therefore R&D has started 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 be used once again to prevent a quench or damage.

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 detector to the more 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 also started to implement this electronics in a radiation hard Application Specific Integrated Circuit (ASIC).

2.1. Beam loss monitors for the HL-LHC triplet magnets

Three detectors are currently under investigation as candidates for operation at cryogenic temperatures inside the cryostat of the triplet magnets [1]:

- Single crystal chemical vapor deposition (CVD) diamond with a thickness of $500\text{ }\mu\text{m}$, an active area of 22 mm^2 and gold as the electrode material.
- $\text{p}^+\text{-n-n}^+$ silicon wafers with a thickness of $280\text{ }\mu\text{m}$, an active area of 23 mm^2 and aluminium as the electrode material.
- Liquid helium ionization chambers.

Fig. 1. Charge collection efficiency for silicon and diamond detectors with increasing radiation fluence in a cryogenic environment.

Experiments have already been performed to observe the behavior of such detectors in a cryogenic environment and on the radiation effects at such temperatures for silicon and single crystal diamond. Irradiation up to several Mega-Gray showed a degradation of the charge collection efficiency in both CVD diamond and Si by a factor of 15 (see Fig. 1). The major downside of silicon compared to diamond, its much higher leakage current when irradiated, has been observed to disappear at liquid helium temperatures, with the leakage current remaining below 100 pA at 400 V, even under forward bias for an irradiated diode. Further experiments combining irradiation with cryogenic temperatures will be necessary to optimise the final detector design. These experiments will be accompanied by tests of detectors mounted inside the cryostats of existing LHC magnets with the aim of gaining experience with the long term performance of such detectors under operational conditions.

2.2. *A radiation tolerant ASIC for the HL-LHC beam loss monitoring system*

The front-end electronics design for both solid state and ionization chamber beam loss detectors gives rise to several challenges, namely the requirement for a wide dynamic range, a relatively short conversion time and a low offset current. Additionally, particularly in the case of the HL-LHC, this electronics needs to be as close as possible to the detector, meaning that it is exposed to the same ionizing radiation as the detector itself.

The current front-end electronics for the LHC BLM system, while providing a 40 μ s integration time, is limited in the dynamic range it can handle and is not radiation tolerant. The latter implies the use of long cables in the higher radiation LSS regions, which further limits the dynamic range and in some cases brings the noise floor close to the quench level signal at 7 TeV. Instead of the discrete component currently used, an optimized ASIC is therefore under development. This is still based on the current to frequency conversion used in the existing system, but packaged in a compact, radiation-tolerant form with an increased dynamic range. The technique employed allows the digitization of bipolar charge over a 120 dB dynamic range (corresponding to an electric charge range of 40 fC–42 nC) with a 40 μ s integration time and a conversion reference provided by an adjustable, temperature-compensated current reference [2].

Figure 2 shows the block diagram of the integrated circuit. It is composed of a bipolar, fully-differential integrator that converts the charge received from the detector into a voltage input for a synchronous comparator system. A three-level Digital-to-Analogue Converter (DAC) drives the discharge current for the

Fig. 2. Schematic representation of the ASIC implementation currently under development.

Table 1. Characteristics of the prototype HL-LHC BLM system ASIC.

A/D converter			
Integration time	40μs	Linearity error	< ±5 %
Input current range	−1.05 mA to 1.05 mA	Peak S/N ratio	53 dB
Input charge range	−42 nC to 42 nC	SFDR at 999Hz, 1mA	50 dB
Offset	< 40 aC, 40μs integration	Total ionizing dose	10Mrad(Si)
	< 1 pA	Supply voltage	2.5 V
Default LSB step	50 fC ±20 %, adjustable	Clock	12.8 MHz
Dynamic range	120 dB	Power	40 mW
Reference charge			
Drift with TID	3 % at 10Mrad(Si)	Drift with temperature	< 600 ppm/°C

integrator and is connected in a feedback loop to the comparator output. A first logic block is used to select the gain in the integrator, the current step in the DAC and the threshold in the comparators, while a second logic block encodes the output signal from the comparators. The results of both of these are used by a third block to assemble the final, correctly weighted output word.

The prototype ASIC is designed in commercial CMOS technology and has two Analogue-to-Digital (A/D) channels and a sensitivity selection logic that can be disabled to implement the circuitry externally. This strategy has been useful for testing the device and improving the algorithm. Its measured characteristics are listed in Table 1.

The measured linearity is limited by transistor matching imperfections in the DAC, introducing an error at the transition between the sensitivities. However, overall the error is less than 5% and well inside specification (<10%).

Fig. 3. Measurements of the Signal-to-Noise ratio as a function of the input current.

Figure 3 shows the measured Signal-to-Noise (S/N) ratio versus input amplitude for a sinusoidal current stimulus at 91 Hz. In the figure, the measurement is compared with the theoretical peak S/N ratio for fixed resolution A/D converters (horizontal lines) and with the measured S/N ratio of each sensitivity setting (dashed lines extrapolated from the saw-tooth shape of the output). The S/N ratio for this conversion principle results in a saw-tooth waveform: the S/N ratio increases with the amplitude as the input current increases until saturation occurs and the interface switches to the next range, increasing the full-scale of the conversion.

Total Ionizing Dose (TID) effects on the ASIC have been investigated using an X-ray beam with 20 keV peak energy. The characteristics of the device were measured up to 100 kGy (Si), followed by a 1-week annealing cycle at 100 °C. From the beginning to the end of the irradiation cycles, the functionality was always preserved, with the conversion offset remaining below 1 Least Significant Bit (LSB) and the value of the full scale charge drifting by less than 3%.

Development will now continue to address the issues found using the prototype and to implement more advanced logic blocks within the ASIC.

3. Beam Position Monitoring for the HL-LHC

With its 1070 monitors, the LHC Beam Position Monitor (BPM) system is the largest BPM system in the world [3]. Based on the Wide Band Time Normalizer

(WBTN) principle [4], 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 last three years has been excellent, with greater than 97% overall availability.

3.1. *Current performance and limitations*

The position resolution of the LHC arc BPMs is better than $150\ \mu\text{m}$ when measuring a single bunch on a single turn and better than $10\ \mu\text{m}$ for the average position (orbit) of all bunches [5]. 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 millimeter over a timescale of hours. On-line compensation was introduced to limit this effect during operation and temperature controlled racks are currently being installed with the hope of eliminating this limitation from the Run II start-up in 2015.

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 electromagnetic simulations, with the aim of bringing down the residual error to below $20\ \mu\text{m}$ over most of the useable BPM area [6]. 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 will need to be addressed for HL-LHC.

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

Originally developed to process signals from BPM buttons embedded in LHC collimator jaws, orbit measurement using a compensated diode detector scheme [7], has already been demonstrated to be simple and robust, and to provide a position resolution down to the nanometer level. A comparison of the orbit measured on a single BPM during a van der Meer scan by the current orbit system and the new diode orbit system is presented in Fig. 4, where the resolution of the new system can be seen to be over 50 times better. All new LHC collimators will have BPMs using this acquisition system installed with them, with plans to also equip the BPMs in all four LHC interaction regions. It is important to note, however, that the new system does not provide the bunch-by-bunch measurement capability of the existing system.

Fig. 4. Comparison of the new LHC orbit system electronics with the existing system during a van der Meer scan.

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. It is therefore likely that a completely new system will need to be installed during HL-LHC running. One candidate would be to extend the new diode orbit system to the whole machine for accurate global orbit measurements, and complement this with a system capable of providing the high-resolution bunch-by-bunch, turn-by-turn measurements required in particular for optics studies and the many other accelerator physics experiments that will be needed to understand and optimize HL-LHC performance.

With the higher bunch intensities foreseen, the dynamic range of the BPM system for HL-LHC would need to be increased accordingly. The present system implements two sensitivity ranges, optimized for pilot and nominal bunch intensities. Issues have been observed in the first three years of operation with BPMs providing large errors when reaching the limit of their dynamic range. For the interlock BPMs located in Point 6, this can trigger false beam dumps, which clearly has an impact on machine availability. Although improvements have already been made to this interlock system for Run II, any consolidation of the LHC BPM system will need to include developing dedicated electronics for this system, optimized for both high reliability and availability.

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. Directional strip-line pick-ups are therefore used to distinguish between the positions of both beams. When the two beams pass through the BPM at nearly the same time, the two signals interfere due to the limited directivity of the strip-line, which in the present design, only gives a factor of 10 isolation between the two incoming signals for the same bunch intensity. This effect can be minimized by installing the BPMs at a location where the two beams do not temporally overlap, which is a constraint included in both the present and future layout, but which cannot be maintained for all BPM locations. In addition, for the HL-LHC BPMs in front of the Q2a, Q3 magnets and the triplet corrector magnet package, there is the additional constraint that tungsten shielding is required at the level of the cold bore to minimize the heat deposition in these magnets. A mechanical re-design coupled with extensive electromagnetic simulations is therefore necessary to optimize the directivity under these constraints.

3.4. *Collimator BPMs*

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. This is expected to 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. The design of such a BPM was intensively simulated using both electromagnetic (EM) and thermomechanical simulation codes. In order to provide the best accuracy, the BPM readings must be corrected for the non-linearity coming from the varying geometry of the collimator jaws as they are closed and opened, for which a 2D polynomial correction has been obtained from EM-simulations and qualified with beam tests in a prototype system installed in the CERN-SPS [8].

The collimator BPM hardware, i.e. the button electrode located in the jaw, the cable connecting the electrode to the electrical feed-through mounted on the vacuum enclosure and the feed-through itself, has been chosen to withstand the radiation dose of 20 MGy expected during the lifetime of the collimator.

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 system. Wire-scanners 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 at injection and the quenching of downstream magnets at 7 TeV. A 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, central D3 radiation), and the long optical path required to extract the light mean that the correction needed to be applied to extract an absolute value is of the same order of magnitude as the value itself. This implies an excellent knowledge of the error sources to obtain meaningful results. The third system installed is an ionization 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, the system can currently only measure the average size of all bunches and suffers from space charge effects at high energy.

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 also under study for the HL-LHC.

4.1. *A beam gas vertex emittance monitor for the HL-LHC*

The vertex detector (VELO) 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 [9]. The new concept under study is to see whether a simplified version of such a particle physics tracking detector can be used to monitor the beams throughout the LHC acceleration cycle. This concept has up to now never been applied to the field of beam instrumentation, mainly because of the high level of data treatment required. However, the advantages compared to the standard beam profile measurement methods listed above 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.

Such a beam shape measurement technique is based on the reconstruction of beam gas interaction vertices, where the charged particles produced in inelastic beam gas interactions are detected with high-precision tracking detectors (Fig. 5). Using the tracks left in the detectors, the vertex of the particle-gas interaction can be reconstructed so, with enough statistics, building up a complete 2-dimensional

Fig. 5. A sketch demonstrating the beam gas vertex measurement concept.

transverse beam profile. The longitudinal profile could also be re-constructed in this way if relative arrival time information is additionally acquired by the system, something which is not currently planned.

In order to obtain a reasonable time for reconstruction of the profile 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 used are of principal importance for the statistical and systematic uncertainties of the measured beam profiles.

The prototyping of such a detector is currently underway in collaboration with the LHCb experiment, EPFL (Lausanne, Switzerland) and RWTH (Aachen, Germany), with the aim of developing a system capable of providing:

- 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.

The envisaged measurement times and accuracy will allow meaningful measurements to be performed during the LHC ramp and provide a direct calibration for other beam size measurement instruments.

Fig. 6. Conceptual layout of the beam gas vertex emittance monitor. The two major sub-systems are the gas target (vacuum chamber, gas injection and pumping systems), and the tracking detectors.

A proof-of-principle demonstrator is foreseen for installation on the left side of LHC IP4 within the next few years. The basic layout is shown in Fig. 6. This relies on a gas target with a length of 1–2 m and tracking detectors external to the vacuum chamber. There are no moving parts and the aperture is defined to ensure that the chamber does not become a local aperture restriction. The chamber impedance is taken into account in the chamber design.

5. Halo diagnostics for the HL-LHC

One of the major issues 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 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 gradually increase their amplitude until they hit a collimator. Measurement of the beam halo distribution is important for understanding this mechanism to allow a minimization of its effects. Moreover, in the HL-LHC, crab cavities will be used to counter the geometric loss factor introduced by the increased crossing angle, which reduces the luminosity. In case of failure of a crab cavity module the whole halo can be lost in a single turn. 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 10^{-5} of the nominal beam intensity. The halo monitor for HL-LHC should thus have a dynamic range of at least 10^5 .

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 at 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.

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

5.1. *Halo measurement using synchrotron radiation imaging*

This technique seems the most promising, as it is non-invasive and allows the continuous monitoring of the beams. Halo measurement could be achieved by using, as examples, one of the following techniques:

- High dynamic range cameras (like the SpectraCam from ThermoFisher) [10].
- Core masking and standard cameras (possibly with adaptive masks based on micro mirror arrays) [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.

A variety of options are therefore available, but 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, while the third source is a physical limitation and its effects have to be studied carefully.

5.2. *Halo measurements using wire-scanners*

Halo measurement using wire scanners is possible by measuring the induced signal as the wire is moved into the tails of the beam. For very high sensitivity the downstream shower detector could be used in counting mode instead of the usual pulse height mode if needed. The problem associated with this method is that the wire has to be brought quite close to a high intensity beam with inherent safety issues. Another problem is the possibility of burning the wire by just exposing it to the electromagnetic field of the beam (RF heating). A modified version of the wire scanner, the so-called vibrating wire scanner, can also be used to monitor the faint halo around the core [12]. The advantage of this instrument is the high sensitivity, but it again involves moving the wire to a very small distance from a very intense beam.

5.3. *Halo measurements using ionization profile monitors*

Ionization profile monitors use the electrons or ions generated by beam collisions with residual gas to image the transverse beam profile. This technique again has the advantage of being quasi non-invasive and allowing continuous monitoring. Solutions for a high dynamic range readout could possibly be found by, for

example, using a mask on the multi-channel plate (MCP) input. In reality in order to obtain a measurable signal for the tails the gas pressure has to be much larger than for just a core measurement. This would lead to the generation of large losses and hence enhanced radiation levels in these locations. Another problem arises from the fact that many ions and electrons generated by the core of the beam will drift outward under the influence of the beam space charge creating a background difficult to remove or correct for.

5.4. Halo measurement summary

Looking at the diagnostics that have been used to date for the measurement of beam halo, synchrotron radiation imaging seems to be the best candidate for halo monitoring for the HL-LHC. Work will start soon to study this in more detail in particular to identify the final potential of such techniques and any related problems.

6. Diagnostics for Crab Cavities

The crab cavities for the HL-LHC are proposed to counter the geometric reduction factor and so to enhance luminosity. 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 directions by the crab cavities such that the incoming bunches will cross parallel to each other at the interaction point. These intra-bunch bumps 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 follow different orbits along the ring. Monitors capable of measuring the closure of the head-tail bump and any head-tail rotation/oscillation outside of the interaction regions are therefore required.

6.1. Bunch shape monitoring using electromagnetic pick-ups

Electromagnetic monitors for intra-bunch diagnostics are already installed in the LHC. These so-called “Head-Tail” monitors mainly provide information on instabilities and have a bandwidth of some 2 GHz. To go to a higher resolution within the bunch a bandwidth of 10 GHz or more is desirable. This will be important to better understand instabilities in HL-LHC and to help with the tuning of the crab cavities. Several of these systems are therefore foreseen for installation around the interaction points. In addition to studies aimed at

improving the existing electromagnetic pick-ups, which include optimization of the pick-up design and the testing of faster acquisition systems, pick-ups based on electro-optical crystals in combination with laser pulses are also being considered [13]. Such pick-ups have already demonstrated fast time response in the picosecond range [14]. Developed mainly for linear accelerators, this technology is now also being considered for circular machines, with a design for a prototype to be tested on the CERN-SPS recently initiated.

6.2. *Bunch shape monitoring using streak cameras*

The use of synchrotron light combined with a streak camera may be an easier alternative to electromagnetic or electro-optical pick-ups for high resolution temporal imaging. 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 (X or Y) with a very fast time resolution (below the picosecond level). Only one transverse axis can be acquired with a given setup, while the other is used for the streaking. Using a sophisticated optical setup it is however possible to monitor both axes at the same time, as was performed in the CERN-LEP accelerator [15].

Streak cameras can be used to observe a number of parameters simultaneously: bunch length, transverse profiles along the bunch, longitudinal coherent motion, head-tail motion etc. The main limitation of the streak camera is the repetition rate of the acquisition, typically < 50 Hz, and the limited length of the recorded sample, given by the CCD size. Double scan streak cameras also exist that allow an increase in the record length. By using 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 50 ps 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 beam width 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 centroid motion (i.e. the center of gravity) 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 only the average position along the bunch is of importance in this measurement and not changes to the beam size, 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, which seems more likely, 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, something for which an integration study is required.

Another point to consider is the synchrotron light source. At the moment two synchrotron light telescopes are installed in the LHC, one per beam. These telescopes already share their light amongst three different instruments, the synchrotron light monitor, the abort gap monitor and the longitudinal density monitor, and in the future will also have to accommodate the halo monitor. It will therefore be difficult to integrate yet another optical beam line for the streak camera. The installation of additional light extraction mirrors may therefore be necessary to provide the light for the streak cameras. Since the crab cavities are only needed at high energy, dipole magnets can be used as the source of this visible synchrotron radiation, with no need for the installation of additional undulators which are only required at injection energy, where the dipole radiation is in the infra-red.

7. 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. The LHC experiments can certainly provide accurate information about the instantaneous luminosity, but this information is often not available until stable collisions have been established, and is often missing altogether during machine development periods. For this reason simple and reliable collision rate monitors, similar to those now used in LHC, are also needed for HL-LHC. The collision rate is currently obtained by measuring the flux of forward neutral particles generated in the collisions using fast ionization chambers installed at the point where the two beams are separated into individual vacuum chambers. The detectors (BRAN) are installed inside the neutral shower absorber (TAN) whose role is to avoid that the neutral collision

debris, and the secondary showers these induce, reach and damage downstream machine components. The luminosity monitors therefore already operate in a very high radiation area, which for HL-LHC is anticipated to be a further ten times the nominal LHC value. For this reason the technology chosen for HL-LHC is likely to be based on the radiation hard LHC design [16], with the geometry adapted to the new TAN design. In order to further increase the radiation resistance some current features, such as bunch to bunch measurement capability, may need to be sacrificed and redundancy added.

8. Summary

The LHC was constructed with a comprehensive array of beam instrumentation. This played an important role in the early commissioning of the accelerator and is essential for its safe and reliable operation. In addition, a full understanding of this complex machine cannot be achieved without having dedicated, specialized instruments available for the measurement of nearly every conceivable accelerator parameters. HL-LHC will push the performance of the LHC even further, requiring an even deeper understanding of beam related phenomena, which can only be delivered through its beam instrumentation. The upgrade of many of the existing systems in conjunction with the development of new diagnostics will therefore be mandatory to address the specific needs of the HL-LHC.

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