

# BEAM INSTRUMENTATION AND DIAGNOSTICS FOR HIGH LUMINOSITY LHC

R. Jones, E. Bravin, B. Dehning, T. Lefevre, H. Schmickler, CERN, Geneva, Switzerland

## Abstract

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 instrumentation that will be discussed in this contribution.

## INTRODUCTION

The following sections will describe the main beam instrumentation and diagnostic developments underway or foreseen as part of the High Luminosity Upgrade Project of the LHC, HL-LHC [1].

## BEAM LOSS MEASUREMENT

Monitoring of beam losses is essential for the safe and reliable operation of the LHC. While the existing system [2] is believed to meet the needs of the HL-LHC for the arc regions, this will no longer be the case for monitors in the high luminosity interaction points, and for monitors located in high radiation areas.

### Beam Loss Monitors for the Triplet Magnets

The HL-LHC high luminosity insertions region magnets will be subjected to an enhanced continuous radiation level due to the increase in collision debris resulting from the higher luminosity. With the presently installed configuration of ionisation chambers in this region, outside of the cryostats, the additional signal from any quench provoking accidental loss would be completely masked by that coming from collision debris.

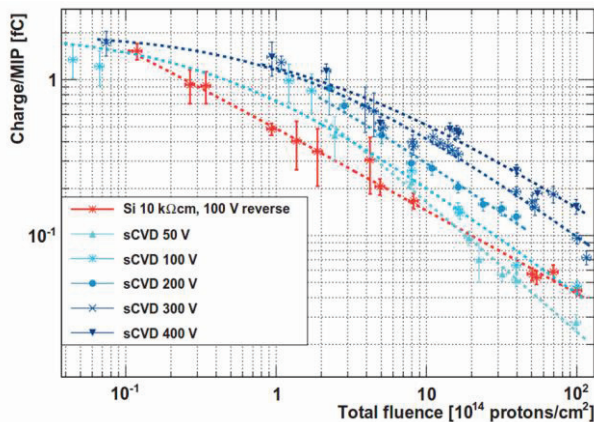


Figure 1: Charge collection efficiency for silicon and diamond detectors with increasing radiation fluence in a cryogenic environment.

The option of placing radiation detectors inside the cryostat of the triplet magnets as close as possible to the superconducting coils is therefore under study. The dose

measured by such detectors would correspond more precisely to the dose deposited in the coils, which ultimately sets the quench level. Three detectors have been investigated as candidates for operation in a high radiation, cryogenic environment [3]: single crystal chemical vapour deposition (CVD) diamond; p+-n-n+ silicon wafers; liquid helium ionisation chambers.

Irradiation at cold up to several Mega-Gray showed a degradation of the charge collection efficiency by a factor of 15 in both CVD diamond and silicon (Fig. 1). The major downside of silicon compared to diamond at room temperature, its much higher leakage current when irradiated, is seen to disappear at liquid helium temperatures. Tests of detectors mounted inside the cryostats of existing LHC magnets are currently ongoing with the aim of gaining experience with the long term performance of such detectors under operational conditions.

### Radiation Tolerant Beam Loss Monitor ASIC

The quench levels estimated for 7 TeV running are, for some detectors, very close to the noise level of the acquisition system. The noise is mainly determined by the length of cable required to bring the signal from the radiation hard detector to the less radiation tolerant front-end electronics. Development has started to implement this electronics in a radiation hard Application Specific Integrated Circuit (ASIC). This ASIC 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 (Fig. 2). The technique employed allows the digitisation of bipolar charge over a 120dB dynamic range (40fC - 42nC) with a 40µs integration time and an adjustable, temperature compensated conversion current reference [4].

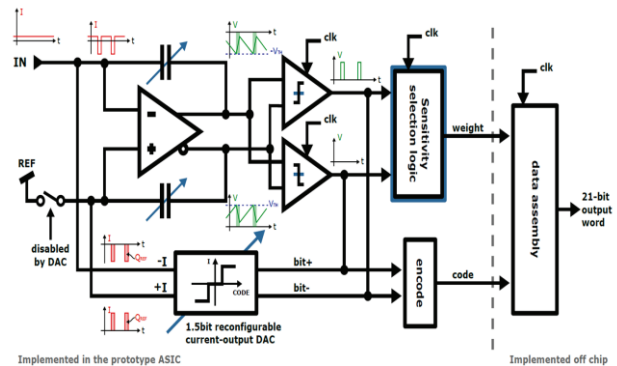


Figure 2: Schematic of the BLM ASIC implementation.

Total Ionizing Dose (TID) effects have been investigated using an X-ray beam with 20 keV peak energy. The characteristics of the device were measured

up to 10 Mrad (Si) and showed that functionality was always preserved, with the conversion offset remaining below 1 LSB and the value of the full scale charge drifting by less than 3%.

Development is now continuing to address the issues found with the prototype and to implement more advanced logic blocks within the ASIC.

## BEAM POSITION MONITORING

With its 1070 monitors, the LHC Beam Position Monitor (BPM) system is the largest BPM system in the world [5]. Its performance to date has been excellent and there are currently no requests for significant improvements to the global system for HL-LHC.

The main changes required for HL-LHC are therefore linked to the upgrade itself, with the addition of new equipment requiring new beam position monitors.

### 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 [6]. This provides a fast and direct way of positioning the collimator-jaws and allows constant verification of the beam position at the collimator location.

Eighteen such collimators are already installed in the LHC, with the BPM signals acquired through a new, high resolution orbit measurement system. This electronics, making use of a compensated diode detector scheme [7], is simple, robust and provides a position resolution down to the nanometre level.

### High Directivity Strip-line Pick-ups

Directional strip-line pick-ups are used to distinguish between the positions of the counter-rotating beams near the interaction regions. When the beams pass through the BPM at the same time, their signals interfere due to the limited directivity of the strip-line, leading to an error in the measured position. This effect can be minimised by installing the BPMs at a location where the two beams do not overlap completely, which is a constraint included in both the current and future layout. However, this cannot be maintained for all BPM locations.

The HL-LHC BPMs located in front of Q2a, Q3 and the corrector package, will also have to accommodate tungsten shielding at the level of the cold bore to minimise the heat deposition in these magnets. Extensive electro-magnetic simulations have therefore started to optimise the directivity under these constraints [8], which will lead to a complete mechanical re-design of the beam position monitors in this region.

## BEAM SIZE MEASUREMENT

The LHC is currently fitted with a host of beam size measurement systems used to determine the beam emittance. Wire scanners are used as the absolute calibration reference, but can only be operated with low intensity due to limitations linked to wire breakage and

the quenching of downstream magnets. A synchrotron light monitor is therefore used to provide beam size measurements during nominal operation. However, the small beam sizes achieved at 7 TeV, the multiple sources of synchrotron radiation (undulator, dipole edge radiation, central dipole radiation), and the long optical path required to extract the light mean that the correction which has to be applied to extract an absolute measurement with this system is of the same order as the size itself. This implies an excellent knowledge of the error sources to obtain meaningful results. Ionisation profile monitors are also installed to provide beam size information for the lead ion runs.

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

### Beam Gas Vertex Detector

The beam gas vertex (BGV) detector [9] is one such instrument, currently being prototyped on one of the LHC beams through collaboration between CERN, EPFL Lausanne (Switzerland), and RWTH Aachen (Germany). This non-invasive beam gas interaction detector is based on developments for the LHCb experiment to measure 3D beam profiles during collisions [10].

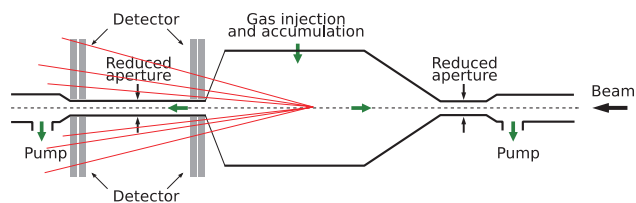


Figure 3: Principle of the beam gas vertex detector for transverse beam profile measurement.

Unlike LHCb, where the detector is placed very close to the beam and can only be used during stable collision conditions, the aim with the BGV detector was to design a robust instrument that could be used for beam size measurements at all times in the LHC cycle. Its final specifications are to provide a relative bunch width measurement with 5% accuracy within 1 minute and an absolute average beam width measurement to an accuracy of 2% within the same time.

The principle of the device is shown in Fig. 3. The LHC proton beam interacts with an injected gas volume to produce secondary particles. These are peaked in the forward direction and are tracked using a set of tracking detectors. By tracing back from the detected tracks the original vertex can be located, provided that the quantity of intervening matter is small enough to limit the amount of multiple-scattering. By reconstructing a sufficient number of vertices it is then possible to build-up a picture of the beam profile.

The main subsystems are: a neon gas target at a pressure of  $6 \times 10^{-8}$  mbar, a thin aluminium exit window, tracking detector based on scintillating fibre modules read

out by silicon photomultipliers, hardware and software triggers, and a readout and data acquisition system based on that used for LHCb. As the tracking detectors are external to the vacuum chamber, no movable parts are needed. The final design is shown in Fig. 4.

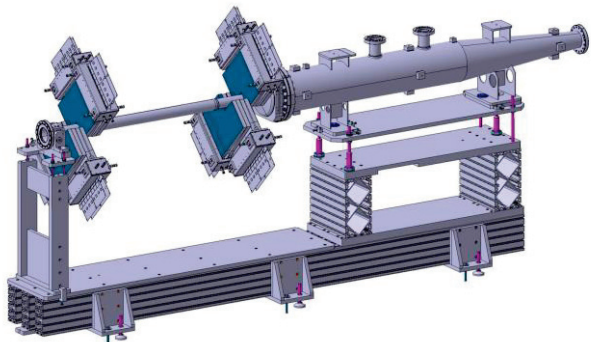


Figure 4: The demonstrator Beam Gas Vertex detector.

## HALO DIAGNOSTICS

Populating the beam “halo”, i.e. the periphery of the transverse phase-space, can lead to beam loss spikes from the collimation system due to small orbit variations. Overpopulation in the tails is also dangerous when using crab cavities, as foreseen for HL-LHC, where the failure of a crabbing module may result in a very quick loss of the halo, which could seriously damage the collimation system or other machine components.

In order to monitor such halo formation an instrument capable of detecting transverse tails at the level of  $10^{-5}$  of the core bunch intensity is required. There are two main ways of doing this: measuring the whole transverse space with a high dynamic range monitor or sampling only the tails using a monitor with a standard dynamic range.

### *Halo Measurement Using Synchrotron Radiation*

Techniques based on imaging synchrotron light seem the most promising for halo monitoring, as they are non-invasive and therefore allow for continuous measurement. A variety of options are available, with a coronagraph and high dynamic range imaging combined with apodization currently being studied.

The limiting factors in both cases are likely to be: the presence of diffused synchrotron light coming from reflections in the vacuum chamber or optics; diffusion by dust particles; 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. The third source is a physical limitation and its effects have to be studied and corrected for very carefully.

## INTRA-BUNCH MONITORING

### *BPMs for Intra-bunch Monitoring*

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 higher resolution within the bunch a bandwidth of 10 GHz or more is desirable. Pick-ups based on electro-optical crystals in combination with laser pulses are therefore being studied. Developed mainly for linear accelerators, this technology has already demonstrated a time response in the picosecond range [11].

### *Streak Cameras for Intra-bunch Monitoring*

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 [12].

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. Measurement of the absolute transverse beam size will not be very precise as the beam width is affected by diffraction due to the large relativistic gamma of the beam, with the diffraction disk typically of the same order as the beam size. However, the centroid motion (i.e. the centre of gravity) is not directly affected by the diffraction and therefore the resolution for this type of measurement will be significantly better.

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.

## SUMMARY

The LHC was constructed with a comprehensive suite of beam diagnostic devices, which play an important role in its safe and reliable operation. HL-LHC will push the performance of the LHC even further, requiring a deeper understanding of beam related phenomena. This 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.

## REFERENCES

- [1] HL-LHC Preliminary Design Report: Deliverable: D1.5, CERN-ACC-2014-0300, November 2014; <http://cds.cern.ch/record/1972604>

- [2] B. Dehning et al., “The LHC Beam Loss Measurement System”, PAC’07, Albuquerque, USA (2007).
- [3] C. Kurfuerst et al. “Radiation Tolerance of Cryogenic Beam Loss Monitor Detectors”, IPAC’13, Shanghai, China (2013).
- [4] G. Venturini, F. Anghinolfi, B. Dehning, M. Kayal “Characterization of a wide dynamic-range, radiation-tolerant charge-digitizer ASIC for monitoring of Beam losses, IBIC’12, Tsukuba, Japan (2012).
- [5] E. Calvo et al, “The LHC Orbit and Trajectory System”, DIPAC 2003, Mainz, Germany (2003).
- [6] C. Boccard et al., “Embedded Collimator Beam Position Monitors”, MOPD18, DIPAC’11, Hamburg, Germany (2011).
- [7] M. Gasior et al., “BPM electronics based on compensated diode detectors - results from development systems”, BIW’12, Newport News, USA (2012).
- [8] D. Draskovic et al., “Electromagnetic design and optimization of directivity of stripline beam position monitors for the high luminosity large hadron collider”, these proceedings, IPAC’15, Richmond, USA (2015).
- [9] P. Hochev et al., “A Beam Gas Vertex detector for beam size measurement in the LHC”, IPAC’14, Dresden, Germany (2014).
- [10] LHCb Collaboration, J. Instrum. 7 P01010 (2012).
- [11] Y. Okayasu et al, “The First Electron Bunch Measurement by Means of Organic EO Crystals”, IBIC’12, Tsukuba, Japan (2012).
- [12] E. Rossa, “Real time single shot three-dimensional measurement of picosecond photon bunches”, BIW’94, Vancouver, Canada (1994).