# BEAM DIAGNOSTIC CHALLENGES FOR HIGH ENERGY HADRON COLLIDERS

E. B. Holzer*, CERN, Geneva, Switzerland

### *Abstract*

Two high energy hadron colliders are currently in the operational phase of their life-cycle, RHIC and LHC. A major upgrade of the LHC, HL-LHC, planned for 2023 aims at accumulating ten times the design integrated luminosity by 2035. Still further in the future, studies in the frameworks of the Future Circulating Collider (FCC) and the Super Proton Proton Collider (SppC) are investigating machines with a center-of-mass energy of up to 100 TeV and with up to 100 km circumference. The existing machines already pose considerable diagnostic challenges, which will become even more critical with any increase in size and energy. Cryogenic environments lead to additional difficulties for diagnostics and further limit the applicability of intercepting devices, making non-invasive profile and halo measurements essential. The sheer size of these colliders requires the use of radiation tolerant read-out electronics in the tunnel and low noise, low loss signal transmission. It also implies a very large number of beam position and loss monitors, all of which have to be highly reliable. To fully understand the machine and tackle beam instabilities, bunch-by-bunch and intra-bunch measurements become increasingly important for all diagnostic systems. This contribution discusses current developments in the field.

## INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) is operating since the year 2000. It accelerates various ion species for symmetric and asymmetric collisions. Furthermore, it has the unique capability of colliding high energy polarized protons to study the spin structure of the proton. The Large Hadron Collider (LHC) is operational since 2009, mostly running p-p collisions, and for four weeks per operational year Pb-Pb or p-Pb collisions. While the maximum RHIC beam energy is 100 GeV/n for ions and 255 GeV for protons, the LHC was running at 3.5 and 4 TeV and is scheduled to run at 6.5–7 TeV beam energy in the coming years. The average beam current at RHIC is well above 100 mA for almost all ions, while at LHC it is around half an Ampere for proton, but much lower for lead ions. The peak luminosity as well as the integrated luminosity per year for heavy ion collisions at LHC is considerably lower than at RHIC. With its proton luminosities, on the other hand, LHC is unmatched with $7.7 \times 10^{33}$ cm$^{-2}$s$^{-1}$. Table 1 (top) gives an overview of RHIC and LHC parameters. The estimated performance is shown for the LHC Run2, which starts in 2015 after the current long shutdown 1 (LS1), and for the planned luminosity upgrade HL-LHC (High Luminosity LHC). HL-LHC is scheduled for Pb ions for 2020, at the start of Run3, and for protons for 2025, at the start of Run4. LHC beam instrumentation experiences during Run1 and challenges for Run2 are discussed in [1] and [2] respectively.

Looking still further in the future, there are currently two studies for hadron colliders, the FCC-hh and the SppC. Bother studies include as a potential intermediate step an electron-positron collider in the same tunnel, called FCC-ee and Circular Electron-Positron Collider (CEPC) respectively. The FCC-hh study considers p-p, Pb-Pb and p-Pb collisions, the SppC p-p collisions. With an envisaged circumference of 80 or 100 km the FCC is somewhat larger than the SppC with 50–70 km. Physics start date (2035–2042), beam energy (25–50) TeV/n and beam current (≈0.5 A) are rather comparable. Table 1 (bottom) summarizes parameters under consideration.

## STORED ENERGY

The energy stored in one LHC beam has reached the record level of 140 MJ during the 4 TeV run. 362 MJ are expected at 7 TeV, 694 MJ at HL-LHC and even 8 GJ for FCC-hh. 10 GJ will be contained in the LHC magnets at 7 TeV. Already one LHC pilot bunch of $5 \times 10^9$ is close to damage limits at 7 TeV. The machine protection system is vital for the survival of these colliders, and must be integrated with the machine design. A dependability analysis comprises reliability, availability, maintainability and safety. It yields the allowed budgets for each subsystem in terms of: probability of component damage due to malfunctioning; downtime due to false alarms; and downtime due to maintenance. There is an inherent conflict between these budgets. By reducing the damage probability (increasing protection) the machine availability will go down due to increased numbers of false dumps and maintenance time. Several beam instrumentation systems are/will be part of machine protection, e. g. beam loss measurement (BLM), beam position measurement (BPM) at critical locations, and a fast measurement of the beam current change.

### *Beam Cleaning and Losses*

The collimation system gets increasingly complex with increasing beam energy and brightness. At the LHC there are already more than 100 collimators installed. At the same time the tolerance for collimator set-up becomes tighter. LHC has installed 18 new collimators with embedded BPM buttons at the tapered ends of both collimator jaws, retracted by 10.6 mm from jaw surface. The new design was successfully tested at the CERN SPS. The readout is via a newly designed compensated diode peak detector electronics. It achieves an excellent resolution of less than 100 nm for centered beams [3]. With this system the collimator alignment will take less than 20 s with an achieved tolerance

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* barbara.holzer@cern.ch

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Table 1: High Energy Hadron Colliders, Top: Current, Bottom: Studies (Parameters under Consideration)

| | | **Circumference [km]** | **Physics Start** | **Maximum Beam Energy [TeV/n]** | **Average Beam Current [mA]** | **Peak Luminosity [cm$^{-2}$s$^{-1}$]** |
|---|---|---|---|---|---|---|
| **RHIC** | pp pol. | 3.8 | 2001 | 0.255 | 257 | $2.1\times10^{32}$ |
| (Brookhaven) | AuAu | | 2000 | 0.1 | 145 | $8.4\times10^{27}$ |
| **LHC** | pp | 26.7 | 2009 | 3.5–4 | 400 | $7.7\times10^{33}$ |
| (CERN) | pp | | 2015 | 6.5–7 | 580 | $1–2\times10^{33}$ |
| | PbPb (pPb in 2012) | | 2010 | 1.38 | 6.8 | $0.5\times10^{33}$ |
| | PbPb | | 2015 | 2.76 | 7.4 | $1\times10^{33}$ (lev.) |
| **HL-LHC** | pp | 26.7 | 2025+ | 7 | 1200 | $5\times10^{34}$ (lev.) |
| (CERN) | PbPb | | 2020 | 2.76 | 22 | up to $7\times10^{33}$ |
| **FCC-hh** | pp | 100 (80) | 2035–2040+ | 50 | 0.5 | $5\times10^{34}$ (lev.) |
| **SppC** | pp | 50–70 | 2042+ | 25–45 | 0.4–0.5 | $2–3\times10^{35}$ |

of 10 $\mu$m [4]. It can be done in parallel for all equipped collimators and without touching the beam. The set-up is two orders of magnitude faster than with the BLM method, where the center of the beam is found by scraping into its tails. The validation of the correct collimator positioning requires the measurement of 'loss maps' with controlled beam blow-up in dedicated low intensity fills, where the leakage of collimation losses into the rest of the machine is measured with the BLM system. The embedded BPMs make constant monitoring of beam to jaw position possible. Hence, tighter collimator settings due to reduced safety margins allow for smaller $\beta^*$ at the experiments, resulting in higher luminosity. As the intensities increase, uncontrolled losses of even the beam halo have to be avoided. Beam size measurements have to evolve in terms of dynamic range to monitor the halo and aid in understanding the mechanisms of its formation. Details of halo monitoring are discussed in this workshop [5] and in previous workshops and schools [6–8].

Beam loss monitoring is one of the key systems in machine protection. When potentially dangerous levels of losses are detected the beam is safely aborted. A system with individual, localized loss monitors is best suited for time and position resolution. On the other hand, all loss locations can not necessarily be predicted at the design stage of an accelerator. At the LHC about one third of the BLMs had to be relocated during LS1, to cover the circumference of the machine more uniformly. During beam operation previously unconsidered beam losses, dubbed 'UFO' losses, had appeared in high numbers all along the machine, also in the cold dipole magnets which had not been equipped with BLMs during Run1. These losses are believed to be caused by beam - dust interactions. Simulations and measurements suggest that at 7 TeV they can quench a magnet. Long, distributed loss monitors would avoid holes in the protection system. The number of monitors and readout channels could be significantly reduced, also reducing the cost. Optical loss monitoring based on the Cherenkov effect in fibers, or individual crystals, is insensitive to synchrotron radiation, which will be copious in machines like the FCC-hh. Noise due to electromagnetic interference can be avoided with optical measurements. At the LHC, significant losses anywhere in the machine are always visible as well at the collimators. At this location the timing of the loss is resolved by a bunch-by-bunch loss measurement, using diamond BLMs with few ns time resolution. To be able to use fiber loss monitors for machine protection, further R&D work is required, in particular for absolute measurements and position and time resolution.

## NON-INVASIVE TRANSVERSE PROFILE MEASUREMENTS

Practically all measurements have to be non-invasive to the beam. This is a particular challenge for transverse profile/emittance measurement. Most non-invasive devices are affected by systematic effects which increase in magnitude with higher brightness and/or smaller physical beam sizes, and often require cross calibration. Absolute profile measurements are nevertheless possible, at least theoretically, with detailed study, and correction procedures. At LHC to date the wire scanner is the only means of absolute beam size measurement. All other profile measurements have to be calibrated against the wire scanner. At injection energy, 450 GeV, a full injection batch of 288 proton bunches will break the wire, the operational limit is about $2.7\times10^{13}$ protons. At top energy the limit of $2.7\times10^{12}$ corresponds to about 20 bunches [9]. At this energy quenching of an adjacent cold magnet limits the beam intensity. The crossover of these two regimes was calculated to be around 4 TeV. Wire aging is dominated by sublimation. A dedicated low intensity run is required to calibrate the other profile/emittance measurements. In addition to the systems mentioned below, other promising or proven devices for (quasi) non-invasive measurements are electron beam scanners, gas screen or gas pencil beams.

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### *Ionization Profile Monitors (IPM)*

RHIC and LHC are equipped with IPMs for both beams and both planes.

IPM measurements in RHIC date back to 1999. After successive design improvements, a new design was put into operation in 2008. The improvements included shielding from upstream losses and electron cloud, increased homogeneity of the electric field, fast signal gating to reduce aging of the multichannel plate (MCP) and shielding the readout electronics, including the MCP, from the beam's image current by putting them in a Faraday cage. Electrons from beam–rest gas interactions are accelerated towards the MCP by an electric field, and guided by a magnetic field, parallel to the electric field. The signal is amplified in the MCP and collected on an anode consisting of 64 strips oriented parallel to the beam axis. Remaining systematic effects could be traced to offset and gain variations between the readout channels and imprecise knowledge of the beam beta functions. A set of calibration measurements, scanning the beam position over the active detector region was used to determine channel offsets. Then, an elaborate calibration procedure for each individual channel gain, described in [10], was performed on the offset corrected profiles, whereby the best gain value was found by minimizing the $\chi^2$s of the Gaussian profile fits. Measurements of the beta functions at the monitor locations for Au-Au at store energy revealed a deviation of the optics model of +8% to -36%. All the corrections applied, absolute emittance measurements are achieved. This could be demonstrated by excellent agreement between horizontal and vertical emittances of both beams under optimized 3D stochastic cooling and by an agreement within 15% with the emittances measured by the experiments STAR and PHENIX [11].

The LHC IPM uses injected Ne gas for signal enhancement and a magnetic guide field of 0.2 T. The electrons created in the beam–gas interactions are accelerated towards an MCP and amplified. A radiation hard camera acquires the optical signal from a phosphor screen behind the MCP [12]. The monitor was primarily designed for the Pb beams, which emit very little synchrotron light at injection energy. The IPM works well in all Pb conditions. The proton profile agrees with wire scanner measurements only at 450 GeV. As the energy increases and the beam size shrinks, the profile is broadened by the space charge of the bunch. This distortion eventually dominates the measurement. Simulations show that increasing the magnetic field to 1 T would solve this problem, but it was not possible to install such a magnet during LS1. Efforts are undertaken to develop a deconvolution algorithm for profile reconstruction [13].

### *Beam Gas Vertex Monitor (BGV)*

The LHCb experiment performed special runs with gas injection to measure 3D beam profiles for absolute luminosity determination during Run1. The inelastic beam gas interactions were reconstructed using the LHCb vertex detector [14]. Based on this concept, the BGV is developed in collaboration with LHCb (CERN), EPFL Lausanne (Switzerland) and RWTH Aachen (Germany) [15]. It uses the LHCb monte-carlo and track reconstruction framework as well as scintillating fiber tracking detectors with SiPMs readout developed for the LHCb vertex detector upgrade [16]. The BGV is being designed to measure absolute values of beam position, angle, profile and relative bunch populations during all of the LHC cycle, unlike the vertex detectors of the experiments, which can only operate during stable beams. It applies a controlled Neon gas pressure bump for sufficient event rate. A prototype is currently being installed at the LHC. The final specifications are to provide within one minute 5% accuracy on the relative bunch width measurement and 2% accuracy on the absolute average beam width. The prototype was designed for providing the same 5% accuracy on the relative bunch width measurement but with an increased measurement interval of five minutes and a relaxed 10% accuracy within one minute.

### *LHC Synchrotron Light Monitor*

At top energy, the imaging of the synchrotron light will be dominated by diffraction. Even with the newly chosen UV wavelength of 250 nm, the contribution from diffraction is estimated to be around 250 $\mu$m compared to a beam size of 180 $\mu$m. Absolute beam size measurement will be very challenging in these conditions. Therefore, interferometric measurement will be performed in parallel, using a new optical line which was designed in collaboration with KEK (Japan), SLAC (US) and CELLS-ALBA (Spain) [17]. This technique is based on diffraction rather than being limited by it. The beam size can be inferred from the visibility of the interference pattern.

### *Transverse Schottky Measurements*

Both RHIC and LHC are equipped with a Schottky system to measure transverse beam parameters. The RHIC detector is a high frequency cavity operated at 2.07 GHz. At CERN a slotted waveguide pick-up operates at 4.8 GHz. The operating frequency has to be high enough for the coherent signals not to dominate the measurements, and low enough that the bands do not overlap. The readout consists in both cases of several stages of filtering, amplification and down-mixing. The CERN system has 25 ns gating for individual bunch measurements, while the RHIC cavity can only provide averaged results.

The RHIC cavity has also been used for completely non-invasive transverse beam size measurements [18]. In this method the cavity is moved transversely to the beam in a range of a few cm, recording the signals at each position. The power measured in the Schottky band around the revolution harmonics (excluding the sharp coherent peak) is compared to the sum of the power in the two betatron side-bands. The first one is proportional to the square of the distance of the orbit from the center of the cavity. The second one is independent of this distance, but proportional to the square of the rms beam size. Hence, an absolute value of the rms beam size can be derived for these measurements. The uncertainty

ISBN 978-3-95450-173-1

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on the emittance measurement reported is 2009 was 20 %. A noticeable reduction in this uncertainty could be possible by using the measured beta function rather than the model and improving the algorithm for extracting the power from the spectrum. Also the improved orbit stability, due to the correction for the 10 Hz triplet vibrations, should reduce the systematic error.

The LHC system aims to provide on-line chromaticity and bunch-by-bunch tune measurements. These measurement were achieved during Run1 for ion beams, where the power in the Schottky bands scales with the square of the ion charge. Proton measurements on the other hand were plagued by large coherent signals at the revolution frequency band and at the betatron bands. The controlled longitudinal beam blow up during the proton ramp makes the signal disappear completely. During LS1, the pick-up design has been modified to avoid deformations, which were seen in Run1. The read-out system will be improved as well.

## MACHINE SIZE, RADIATION AND CRYOGENIC TEMPERATURES

The increase in machine length in itself poses considerable challenges for beam instrumentation, and in particular for the BLM and BPM systems. The number of their monitors increases in proportion to the number of optics cells. The cost increases, but also system maintenance and availability becomes increasingly challenging. More data is produced by the instruments, which needs to be extracted, logged, monitored, analyzed and made available for various online and offline applications. Because of the long distances involved, to keep electromagnetic interferences small, the front-end read-out electronics is often positioned in the accelerator tunnel, close to the instrument. In this case it has to be radiation tolerant, which considerably complicates design and production. To transport the signal to the surface requires low noise, low loss signal transmission. Optical signal transmission and optical diagnostic techniques are preferable in such conditions.

Collimation regions, the vicinity of the interaction points, regions of beam injection and beam extraction have particularly high levels of radiation. This poses i. a. a problem for beam loss monitoring, as a typical loss monitor cannot distinguish between a beam loss and other sources of radiation.

A cryogenic environment makes beam monitoring considerably more complex. BPMs and certain BLMs need to be installed inside the cryostat. Again, this calls for very high dependability of the systems. By placing the loss monitor inside the cryostat, it is closer to the loss location and at the same time shielded from other radiation source. This way it can protect the magnet from quenching due to beam loss even in high radiation areas. Three different technologies are investigated at CERN, liquid helium, silicon and diamond. Prototypes have been installed in the LHC during LS1.

## IMPROVING THE PERFORMANCE

New machines with higher energy and brightness require several beam instrumentation systems to improve in performance, e. g. BPM stability, resolution and precision for fast feedback systems and transverse damping. The same holds for pushing existing machines to higher luminosities. The colliders crucially depend on feed-back systems, on systems which damp beam instabilities and/or on beam cooling. RHIC's orbit, tune and coupling feed-backs were a key to higher luminosities, polarization and integrated luminosity/uptime [19]. During Run1, LHC used an orbit feed-back and during certain periods of the cycle also a tune feed-back. Bunch-by-bunch and intra-bunch measurements are required to diagnose, and eventually avoid, beam instabilities. This section collects a number of recent instrumentation improvements and some which are planned for the near future.

### *Intra-Bunch Measurements*

A new Multiband Instability Monitor (MIM) for the LHC is being developed [20]. It uses a broadband stripline pickup. 16 narrow frequency bands spaced by 400 MHz, covering the frequency range of 0.4–6.4 GHz, are individually monitored. When a bunch starts to oscillate, it's frequency spectrum changes to reflect the oscillation modes of the bunch. The amplitude and phase information of these 16 frequencies might, at a later stage, be used to reconstruct the intra-bunch motion in the time domain. For the time being it is planned to use the MIM to trigger the high rate acquisitions of other systems which can measure instabilities, e. g. the transverse damper system, bunch-by-bunch emittance and intensity measurements and the head-tail monitor. The head-tail monitor shares the same pick-up and uses a wideband oscilloscope to measure in the time domain. The higher sensitivity of the MIM should allow to detect sub-micron oscillations.

### *Wall Current Transformer (WCT)*

A new fast beam current transformer has been developed at CERN for Run2. It aims to improve the bunch-by-bunch resolution, and remove the dependency on beam position and bunch length observed during Run1 [21]. It is designed for a bandwidth of up to ≈100 MHz, for a position dependence of less than 0.1%/mm and for a bunch length dependence of 0.1%.

### *Electron Back-Scattering Detector (eBSD)*

To attain higher polarized proton luminosities in RHIC, partial compensation of the beam-beam effect is planned with the help of electron lenses [22]. A low energy (≈6 keV) and high intensity (≈1 A) electron beam moving in the opposite direction is mixed with the proton beam over a 2 m long interaction region within a field of ≈6 T. The two beams are approximately 300$\mu$m rms and their centers need to be aligned to less than 30–50$\mu$m. The eBSD [23] is a new measurement device for the precise alignment of the two beams. It was successfully commissioned in 2014 with ion

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ISBN 978-3-95450-173-1

beams. Back-scattered electrons are intercepted by a small plastic scintillator in the vicinity of the electron gun. A 1.2 m long light-guide leads to a magnetically shielded photomultiplier tube. An automatic procedure aligns the two beams by maximizing the eBSD counting rates. The alignment is based on a program for maximizing luminosities at the RHIC experiments. An eBSD could possibly be used for hollow electron lens alignment [24]. A hollow electron lens is considered as an option for beam collimation for HL-LHC in the framework of the LARP collaboration.

## WAKEFIELDS AND RF HEATING

In order to limit beam instabilities, the impedance budgets are very strict, in particular for numerous devices like the BPMs. Also for the survival of the instrument a careful management of the beam induced wake functions is crucial. Several LHC system suffered strong heating during Run1 [25]. Injection kickers and forward physics experiments overheated. The beam screen of the injection protection system deformed. RF contact fingers at magnetic interconnects and the extraction mirror of the synchrotron light monitor were heated to the point of failure [26]. The redesigned extraction mirror couples much less to the beam, and the heat dissipation via conduction and radiation should now be sufficient. By installing a camera in the RHIC polarimeter, strong RF heating was discovered at the ends of the thin carbon wire when well outside the beam and even in parking position, explaining the frequent wire breakages [27]. The addition of field-intercepting “fins” have been shown to reduce the heating.

All new instruments installed on the beam have to be validated by EM simulations and/or laboratory test. The incorporation of temperature sensors will be advisable for certain devices. Heating effects can often be observed indirectly by vacuum degradation, increased beam losses or degraded performance of the device. Possibilities for mitigation include: design changes to reduce the build-up of wake fields; adding ferrites to absorb the RF power given there is sufficient cooling for the ferrites; or using multi-mode couplers to extract the power and dissipate it outside of the beam vacuum.

## ACKNOWLEDGMENT

The author wishes to thank in particular O. R. Jones, T. Lefevre, M. Minty and M. Wendt for their valuable input and support.

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