PROFILE MONITORS, INJECTION MATCHING MONITOR AND SYNCHROTRON LIGHT MONITORS

Stephane Bart Pedersen, Andrea Boccardi, Enrico Bravin, Gerard Burtin, Stephane Burger, Bernd Dehning, Jonathan Emery, Alan Fisher, Ana Guerrero, Adam Jeff, Jan Koopman, Thibaut Lefevre, Aurelie Rabiller and Federico Roncarolo, , CERN, Geneva, Switzerland

Abstract

A set of different beam instruments have been developed and installed on LHC to provide transverse profile monitoring. Imaging systems using intercepting screens are currently used in the transfer lines from SPS, in the dump lines and in the LHC injection regions. Betatron matching oscillations would be investigated using Optical Transition Radiation screens and fast framing cameras, installed in Point 4. Wire scanners, provide high-resolution profile measurements from injection to top beam energies, but they cannot handle the full beam intensity. Thus, for continuous beam imaging as well as abort gap monitoring, synchrotron light monitors have been developed and installed. This paper gives a brief description of the different systems and presents the first results obtained during the beam commissioning in 2009.

PROFILE MONITORS

Since the first day of the LHC beam commissioning, beam images and transverse profiles are acquired in the transfer lines (injection and dump) and in the ring using the so-called 'BTV' system [1]. Depending on the beam intensities, they rely on the use either a chromium doped alumina luminescent screen (for low intensities) or an Optical Transition Radiation (OTR) screen in titanium (for higher beam charge). 10 out of the 19 BTV systems installed on LHC are equipped with radiation-hard cameras capable to withstand integrated doses up to 3Mrads. An upgrade is already planned to replace the remaining CCD camera by Radiation Hard camera during the next shutdown.

During the normal operation of the machine, screens are not inserted in the beam path and their positions are interlocked in such a way that the beam cannot be injected in the machine if a screen is 'in'. When requested, the screens can be inserted but this implies a specific mode of operation where the beam circulates in the machine for few turns and is dumped afterwards. A very wide screen denominated 'BTVDD' [2] and located just in front of the dump, is an exception to this rule. The screen is fixed and permanently used to verify that the LHC beam dumping system is performing as expected. An example of a typical beam image as seen by the BTVDD is shown in Figure 1. When the beam is getting dumped, a serie of horizontal and vertical kickers are triggered in order to dilute the beam density over a large area (40cm). The resulting beam painting has an 'e' shape as visible on Figure 1. The theoretical track of the particle during the dilution has been superimposed to the measured image. In general the overall system has worked very reliably.

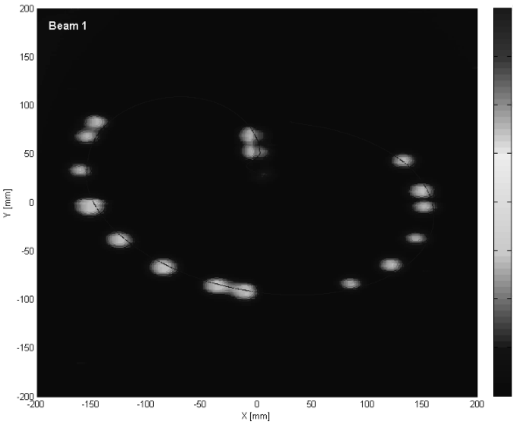

Figure 1: Beam 1 with 16 bunches getting dumped as seen by the BTVDD. *Courtesy of B. Goddard*

INJECTION MATCHING MONITORS

For Betatron matching measurements, two imaging systems, called BTVM, have been installed in the point 4 of LHC. They will provide turn-by-turn (11kHz) acquisition using an OTR screen observed by a fast framing camera [3]. A photograph of the BTVM is presented in Figure 2. The system has not been used in 2009.

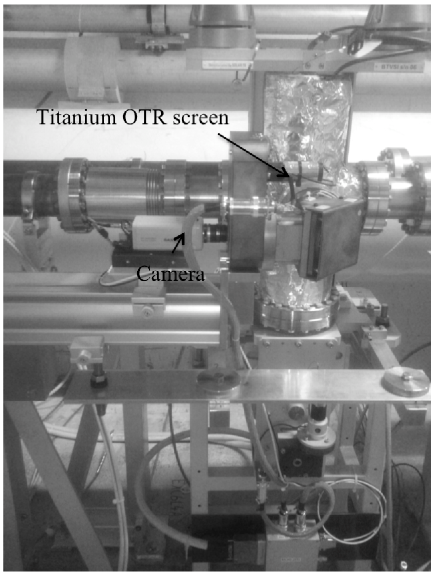

Figure 2: BTVM in the point 4 of LHC.

The fast camera is less sensitive than classical CCD cameras and in the LHC at injection energy, a minimum of 10^{10} protons per turn would be required to observe an image with an adequate signal to noise ratio.

A similar system was already tested on the SPS in 2008 [4] but has shown that the operation of the fast camera has operational limitations. The camera is sensitive to radiation. It was observed that single upset event induces perturbations, which would require the camera to be rebooted from time to time. Secondly, because the camera is not radiation hard, it cannot be left in the tunnel without an appropriate shielding for long periods. This would limit the use of this fast camera to an operation mode requiring an access to the tunnel to install the camera, which would need to be removed after the measurements.

WIRE SCANNERS

The LHC beam wire scanner design is based on the second generation of SPS linear wire-scanners with an actualized control electronic and position measurement. The 36 µm carbon wire attached to the moving fork is crossing the beam at a constant speed of 1 m/s. The wire position is acquired with a high precision potentiometer, which is also used for the position control during movement. It allows a high accuracy beam profiling when fraction of the total beam intensity is present in the machine [5]. The secondary particle shower generated by the interaction with the beam is measured with a detector consisting of scintillator, variable attenuators and photomultiplier. A typical scan is presented in Figure 3.

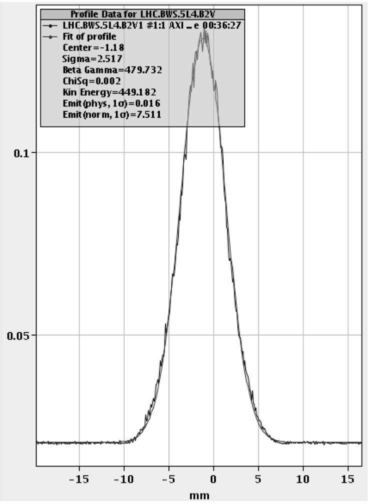

Figure 3: Vertical beam profile measured with a wire scanner on Beam 2

There are 2 sets of horizontal/vertical wire-scanner per beam. The second set is used as a backup for continuation of operation in case of a broken wire on the first set. The powering/control of the four scanners of one beam is multiplexed to one movement control and acquisition system with multiplexer boxes installed in the tunnel. This layout allows optimized space integration. The acquisition function is flexible to allow beam synchronous acquisition at beam revolution frequency with adjustable phase (e.g. pilot bunch) as well as higher frequency up to the bandwidth of the acquisition chain (100 kHz) for beam envelope when multi-bunch operation. A bunch by bunch acquisition system is also installed in parallel of the normal acquisition chain and is foreseen to be finalized in the following year using the 40 MHz integrator mezzanines used in various beam instrumentation systems (IBMS card).

SYNCHROTRON LIGHT MONITORS

Synchrotron radiation is used in LHC for continuous beam imaging and for monitoring the proton population in the 3 microseconds abort gap. Depending on the beam energy different synchrotron light sources must be used. A dedicated superconducting undulator has been built for low beam energies [6] (450 GeV to 3 TeV), while edge and centre radiation from a beam separation dipole magnet, namely the D3, are used respectively for intermediate and high energies (up to 7 TeV).

Figure 4: The Synchrotron radiation telescope

The emitted visible photons are collected using a retractable mirror, which sends the light into an optical system as shown on Figure 4 and described in details here [7]. The telescope is installed below the beam pipe on a vibration-free optical table. The first mirror on the table is remotely controlled and is used to correct for mechanical misalignments. Based on our first experience, the overall error was smaller than 300µrad. A 3m long adjustable optical line can be then used to focus our optical system on the desired the source of radiation, choosing between the undulator or the dipole D3. Two spherical mirrors provide the required image demagnification (0.3) and a pair of remotely controlled horizontal slits can be used to optimize the image quality. The light intensity is controlled using a set of optical density filter wheels, providing attenuation up to 10^5. An additional 30m long optical line is also installed on the optical table, to serve as a calibration line. A target is illuminated and is used to characterize the optical performance of our telescope, providing the magnification and the point spread function. In case of problems, it helps to investigate if the system is still operational.

Abort Gap Monitoring (AGM)

The LHC beam dump system relies on extraction kickers that need 3 microseconds to rise up to their nominal field. As a consequence, particles crossing the kickers during this rise time will not be dumped properly. The proton population during this time should remain below quench and damage limits at all times. A specific monitor has been designed to measure the particle population in this gap. It is based on the detection of Synchrotron radiation using a gated photomultiplier. Between the two spherical mirrors, a beam splitter reflects 90% for the imaging system and transmits the rest for the AGM. The detection is done using a photomultiplier (PMT) placed at the focal plane of the first spherical mirror. The PMT (Hamamatsu R5916-50) uses a micro-channel plate rather than dynodes, so that it can be gated. The gate allows it to sensitively detect the small gap signal without saturating from the large population elsewhere. The 3-μs gap is monitored in 30 100-ns bins. Using the emission per particle, the quench thresholds, and the spectral properties of the PMT and optics, we find that it is possible to measure a threshold population to 5% accuracy in 100 ms. Since the quench and damage limits change with the beam energy, the acceptable population in the abort gap and the settings of the monitor must be adapted accordingly.

On of the first signal observed by the abort gap monitor is shown on Figure 5. There was only one bunch circulating in the machine and the trigger timing of the gated PMT was modified to observe it. Each dot on the plot corresponds to a 100ns integration time. Since a bunch is shorter than a nanosecond, it appears here as a single point. The white zone displays the 3-μs gap, when the PMT is gated on. The grey zone gives an indication of the noise level on the electronics when the PMT is off.

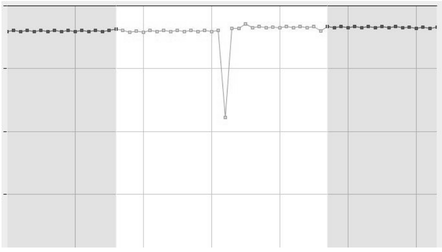

Figure 5: First signal seen on the Abort Gap monitor on Beam 2 at 450GeV.

Transverse profile monitoring

The continuous monitoring of the transverse beam sizes relies on the use of synchrotron radiation and intensified video cameras.

The camera is a Proxicam HL4 S NIR with a red-enhanced S25 photocathode and an image intensifier. A typical image is presented in Figure 6. It corresponds to a pilot bunch of 5 10^9 protons circulating in the machine at injection energy, with an integration time of 20ms, approximately 224 turns.

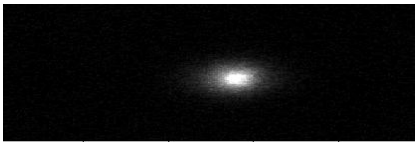

Figure 6: First image see on Beam 2 at injection energy

Beam images are recorded at 10Hz and published to the control system every second. Beam images are analyzed in order to provide vertical and horizontal beam profiles and the corresponding beam sizes using a Gaussian fit. The amplitudes of both profiles are also measured and published.

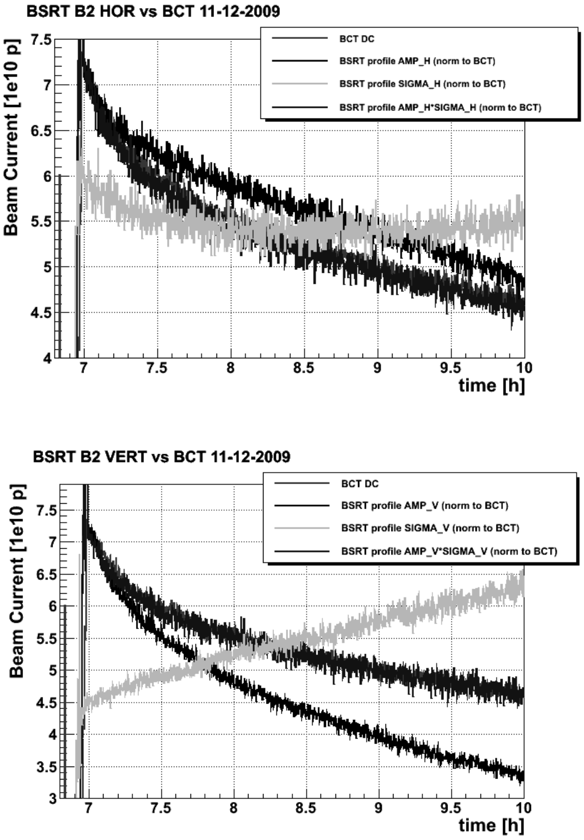

Figure 7: Comparison between the fast Beam Current Transformer and the Synchrotron Light Monitors

Figure 7 presents a comparison between the beam intensity as measured by a fast current transformer and the data from the SR images. The first plot used horizontal profiles and the second vertical ones. The beam intensity using the synchrotron radiation profile is calculated by multiplying the amplitude of the beam profile by the sigma of the Gaussian fit. In both cases, the agreement between the intensity seen by BCT and by the SR profiles is very good. It is in addition possible to follow the variation of the beam size as the beam circulates. A vertical blow-up of the beam is clearly observed but not understood yet.

A set of profile measurements was also cquired using the wire scanners at different moments during the cycle. The results are displayed on Figure 8 and compared with profiles obtained using the synchrotron light monitors. On this plot, beam emittances have been calculated using the measured beam profiles and assuming the theoretical β values for the positions of the SR monitor and the wire scanners. The agreement is within 10-20% but there is still a correction to be done by taking into account the measured β values instead of the theoretical ones. The absolute calibration of both the wire scanners and the synchrotron light monitors has not been studied in details and systematic measurements would be done during the run in 2010 to optimize performances. Nevertheless, the relative variations observed on both systems agree very well.

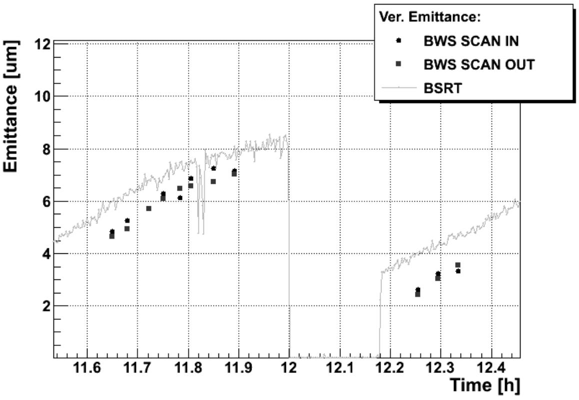

Figure 8: Beam emittance as measured by the Wire Scanner and the Synchrotron Light Monitors

CONCLUSION AND PERSPECTIVES

The wire scanners and the beam observation system using screens and cameras have proven to be robust and reliable, providing useful information since the first day of operation.

Some work has recently been initiated to review the expected performances and the mode of operation of the matching monitors. Radiation-hard solutions are envisaged but will provide profile measurements only.

The synchrotron light monitors have been commissioned successfully. As designed, they need to have the superconducting undulator at nominal current (450A) in order to reach optimal performances at injection beam energy. The commissioning of the synchrotron light monitors for Beam 1 was only possible at 1.18TeV because the undulator for Beam 1 was not available in 2009. Systematic comparisons between the synchrotron light monitors and other beam instruments have been done and have shown a very satisfying agreement. The system needs nevertheless to be commissioned further for different beam energies. The ultimate goal will be then to operate the synchrotron light monitors in an automatic mode, where depending on the beam energy and intensity, the system will adapt in order to provide reliable data under any conditions.

A turn-by-turn and bunch-by-bunch imaging system is also currently being developed as an additional synchrotron light monitor. This device uses a gated image intensifier coupled to the 'Redlake HG-100k' camera, capable of acquiring images at 100kHz. A minimum gate of 5ns will provide the bunch selection, which will be then followed turn-by-turn using the fast framing cameras.

In addition to these existing detectors, longitudinal density monitors are currently being developed. They should provide a longitudinal profile of the LHC beams with a high dynamic range and a 50ps time resolution. This would allow for the precise measurement both of the bunch shape and the number of particles in the bunch tail or drifting into ghost bunches. A solution is proposed based on counting synchrotron light photons with two fast avalanche photodiodes (APD) operated in Geiger mode. One is free•running but heavily attenuated and can be used to measure the core of the bunch. The other is much more sensitive, for the measurement of the bunch tails, but must be gated off during the passage of the core of the bunch to prevent the detector from saturating.

REFERENCES

[1] S. Burger *et al*, "A New TV Beam Observation System for CERN', DIPAC 2005, Lyon, France, pp.214

[2] T. Lefevre, C. Bal, E. Bravin, S. Burger, B. Goddard, S. Hutchins and T. Renaglia, "A Large Scintillating Screen for the LHC Dump Line", Proceeding of the DIPAC Conference, Venice, Italy, (2007), CERN-AB-2007-023

[3] Model HG-100k: http://www.redlake.com/

[4] E. Bravin and T. Lefevre, Private communication, 2008

[5] M. Sapinski, and Tom Kroyer, "Operational limits of wire scanners on LHC beam", Proceeding of the Beam Instrumentation Workshop, Lake Tahoe, California, (2008), pp383

[6] R. Maccaferri, M. Facchini, R. Jung, D. Tommasini and W. Venturini Delsolaro, "The 5-T Superconducting Undulator for the LHC Synchrotron Radiation Profile Monitor", LHC Project Report 731, EPAC, 5-9 July 2004, Lucerne, Switzerland

[7] A.S. Fisher, A. Goldblatt and T. Lefevre, "The LHC Synchrotron Light Monitors", Proceeding of the DIPAC Conference, Basel, Switzerland, (2009), CERN-BE-2009-030