

Synchrotron Radiation Measurements at the CERN LHC

**S. Bart Pedersen; A. Boccardi; E. Bravin; A. Guerrero; A. Jeff:
T. Lefevre; A. Rabiller; F. Roncarolo**
CERN – Geneva/CH

A. S. Fisher
SLAC, Menlo Park; CA - USA

Abstract

The CERN LHC is equipped with two systems (one for each beam) designed to image the synchrotron radiation emitted by protons and heavy ions. After their commissioning in 2009, the detectors were extensively used and studied during the 2010 run. This allowed preliminary limits in terms of sensitivity, accuracy and resolution to be established. The upgrade to an intensified video camera capable of gating down to 25ns permitted the acquisition of single bunch profiles even with an LHC proton pilot bunch ($\sim 5 \times 10^9$ protons) at 450 GeV or a single lead ion bunch ($\sim 1 \times 10^8$ ions) from about 2 TeV. Plans for the optimization and upgrade of the system will be discussed. For the last few months, part of the extracted light is deviated to the novel Longitudinal Density Monitor (LDM), consisting of an avalanche photo-diode detector providing a resolution better than 100 ps. The LDM system description will be complemented with the promising first measurement results.

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SYNCHROTRON RADIATION MEASUREMENTS AT THE CERN LHC

F. Roncarolo*, S. B. Pedersen, A. Boccardi, E. Bravin, A. Guerrero, A. Jeff, T. Lefevre, A. Rabiller, CERN, Geneva, Switzerland
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The CERN LHC is equipped with two systems (one for each beam) designed to image the synchrotron radiation emitted by protons and heavy ions. After their commissioning in 2009, the detectors were extensively used and studied during the 2010 run. This allowed preliminary limits in terms of sensitivity, accuracy and resolution to be established. The upgrade to an intensified video camera capable of gating down to 25ns permitted the acquisition of single bunch profiles even with an LHC proton pilot bunch ($\sim 5 \times 10^9$ protons) at 450 GeV or a single lead ion bunch ($\sim 10^8$ ions) from about 2 TeV. Plans for the optimization and upgrade of the system will be discussed. For the last few months, part of the extracted light is deviated to the novel Longitudinal Density Monitor (LDM), consisting of an avalanche photo-diode detector providing a resolution better than 100 ps. The LDM system description will be complemented with the promising first measurement results.

INTRODUCTION

The two BSR systems [1] are installed about 30 m downstream of the D3 cryostats hosting the D3 dipole and an undulator. The latter has been built to provide enough synchrotron radiation (SR) at low beam energies. As the beam energy reaches 1.2-1.5 TeV, most of the useful SR power starts to be generated first by the D3 edge and then by the D3 centre. A retractable extraction mirror deviates the light below the beam pipe where an optical system performs the imaging of the beam spot on CCD cameras.

The optical system is shown in Fig. 1 and is equipped with remote control in order to

- focus on the different SR sources by adjusting the optical delay line length;
- tune the light average angle and position at the telescope entrance, in order to centre it on the detectors' sensitive areas;
- adjust the neutral and chromatic optical filters that are installed in front of the detectors, according as the beam intensity and energy change;
- select the light coming from a short section of the D3 magnet by means of movable slits.

The total SR power is shared between the Abort Gap Monitor (AGM), the Longitudinal Density Monitor (LDM) and the two cameras dedicated to transverse profiles, the Beam Synchrotron Radiation Transverse

Slow (BSRTS) and Fast (BSRTF) systems. This paper mainly contains the results obtained so far with the BSRTS and LDM systems. More information about the AGM can be found for example in [2].

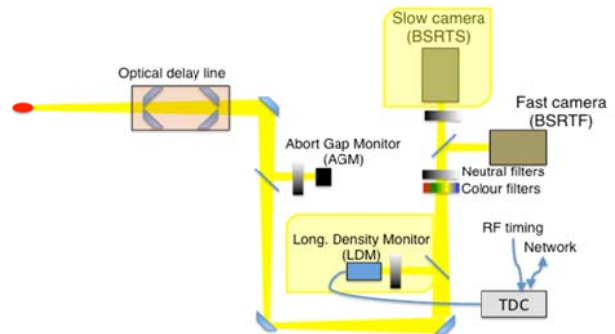


Figure 1: Schematic drawing of the BSR telescope system sitting below the LHC beam pipe.

TRANSVERSE PROFILE MEASUREMENT SYSTEMS (BSRT)

BSRTS System Description

The BSRTS systems (one per LHC beam) are equipped with Proxitronic Nanocam HF4 S 25N NIR [3] cameras, intensified via a MCP between the photocathode and the camera sensor. They are read out by 50 Hz electronics. Two operation modes are possible:

- Continuous or DC mode: each acquisition corresponds to the integration for 20 ms of all circulating bunches;
- Gated or Pulsed mode: each acquisition corresponds to the integration over all the time windows (gates) programmed in 20ms.

When the camera is in Pulsed mode, the minimum gate length is 25 ns and the maximum gate repetition rate is 200 Hz. This means that it is possible to measure a single LHC bunch for a single turn, sampled every 55 turns.

The SR power generated by protons and the system efficiency are such that there are no intensity limitations for proton beams: a single pilot ($\sim 5 \cdot 10^9$ protons) gives a signal well above background even when measured on a single turn (89 us). A minimum of about 30 lead ion bunches ($\sim 3 \cdot 10^9$ Pb82 ions) averaged for 20 ms (DC mode) are necessary to have enough light at injection energy. This is due to the shift in frequency into the infra-red of the undulator light generated by ions.

*federico.roncarolo@cern.ch

BSRTS Measurements

The BSRTS systems calibration is done at first with a calibration target installed in the BSR telescope at an optical distance equal to the distance between the BSR detector and the centre of the undulator. This allows measurement of the optical system magnification, presently set at about 0.3. The absolute and relative calibration can then be studied with beam-based measurements aiming at comparing the BSRTS with the Wire Scanner (WS) monitors. These monitors can be used only below a maximum beam intensity (of the order of few 10^{13} protons) above which wire damages or quenches of the downstream magnets can occur. The BSRTS-WS cross-calibration yields BSRTS correction factors intended to compensate for aberration, diffraction and depth of field errors. At the moment, the best correction is believed to be in quadrature on the measured BSRTS beam size. An example of WS-BSRTS cross-calibration is shown in Fig. 2, where the two monitors have been used to measure the horizontal emittance of 24 nominal bunches ($\sim 1.1 \cdot 10^{11}$ p/bunch) at 450 GeV in one of the LHC rings (Beam 2).

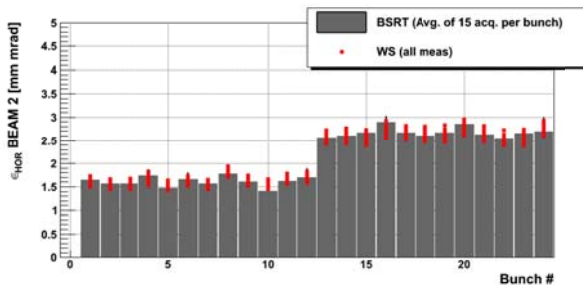


Figure 2: Bunch per bunch horizontal normalized emittance as measured by BSRTS (average over 15 acquisitions per bunch) and WS (8 consecutive scans) in one of the LHC rings.

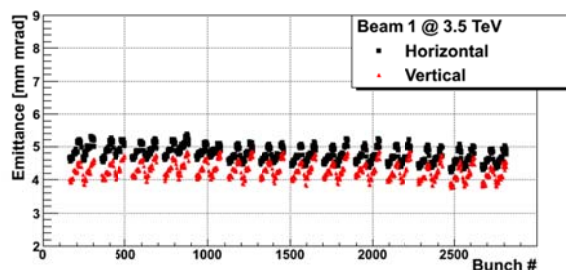


Figure 3: Bunch per bunch emittance as measured by the BSRTS, showing the non-uniformity among bunches inherited from different settings in the PS booster rings.

The measurement was performed during a dedicated machine development period, in which the first 12 bunches were injected with normalized emittances $\epsilon_{x,y} < 2$ mm mrad and the last 12 with $\epsilon_{x,y} > 2$ mm mrad. The BSRTS measured beam sizes (varying from 0.8 to 1.2 mm) have been corrected in quadrature for the same factor 0.65 mm. After the correction, WS and BSRT agree on the bunch per bunch emittance at the 1% level.

Similar results have been achieved for Beam 2 vertical and for Beam 1 and Beam 2 at 450 and 3500 GeV. A detailed analysis is in progress to understand the absolute values of the calibration factors that allow the BSRTS systems to match the WS measurements at the two beam energies.

Fig. 3 shows an example of bunch per bunch emittance measured by the BSRTS during an LHC physics fill at 3.5 TeV. The measurement revealed systematic differences among bunches that were correlated to different settings in the 4 PS Booster rings.

BSRTF

The BSRTF systems consist of a Redlake HG-100K camera [4] whose sensor is coupled via optical fibers to a Photek MCP125 [5] intensifier equipped with a GM200-3 gate module. The maximum acquisition rate of 100 kHz with a minimum gate size of 3 ns allows a bunch-per-bunch turn-per-turn mode. Presently the systems are in the commissioning phase, in the first place to investigate whether the purpose-made optical fiber coupling provides enough intensification.

MEASURED SR POWER COMPARED TO SIMULATIONS

The simulation code SRW [6] has been used to simulate the expected light at the AGM and BSRTS detectors, taking into account the detectors' spectral response. This has been done for protons and ions as function of the LHC beam energy. The comparison between the simulations and measurements with the AGM for beam energies between 450 and 3500 GeV is shown in Fig. 4. In particular, the AGM measured intensity per charge for both protons and Pb ions is compared to the expected visible photons per charge.

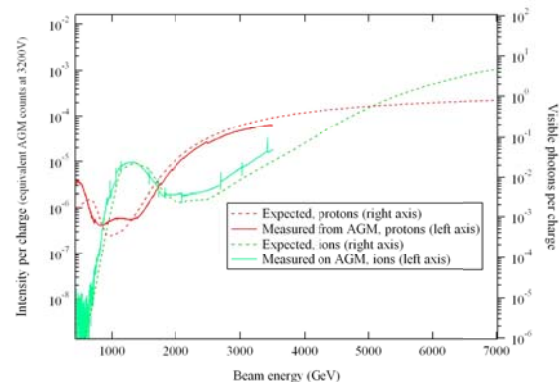


Figure 4: Synchrotron radiation intensity per primary charge as simulated (dashed lines) and measured by the AGM detector (solid lines) as function of beam energy, for both protons and Pb ions.

The simulation evidences the shift to higher energies of the undulator peak from protons to ions, well reproduced by the measurements. It is also evident that at the LHC injection energy (450 GeV) the amount of detectable light emitted by protons is a factor 10^4 higher than for ions.

LONGITUDINAL DENSITY MONITOR

The LDM monitors are designed to monitor the LHC beam longitudinal distribution. The system's large dynamic range and high time resolution allow characterisation of the main bunches length as well as the presence and extent of the *satellite* and *ghost* bunches. Satellites can develop due to capture/splitting errors in the injectors (e.g. the SPS 200 MHz RF can give satellite bunches separated by 5 ns) whereas ghosts can arise from capture/splitting errors in the LHC (the 400 MHz RF system can produce ghosts separated by 2.5 ns).

The LDM is based on avalanche photodiodes (APD) from id-Quantique [7] and Micro Photon Devices [8] connected to a Time Digital Converter (TDC) from Agilent [9]. The detector can resolve single photons with a time resolution of the order of 50 ps, the TDC also has a resolution of 50 ps. The APD presents a short dead-time used to quench the avalanche (tens of ns) and there is also a small probability (~3%) that at the end of this *dead-time* trapped electrons or holes will trigger a new avalanche producing an *after-pulse*. These effects, together with the dark count rate, although small, are corrected with a statistical algorithm. The probability of a photon triggering an avalanche per bunch-crossing must be maintained below a certain level (60-70%) otherwise the error on these corrections becomes too large. This has an impact on the maximum counting rate and thus on the integration time required for acquiring a profile with sufficient resolution. In fact the integration time required depends on what is being observed; if the aim is just to measure the core parameters of a bunch (mainly the bunch length) a few seconds are sufficient; on the other hand if the population of ghosts and satellites has to be measured an integration of several minutes may be required. The dynamic range observed in 2010 was of the order of 10^5 with an integration time of 500 s.

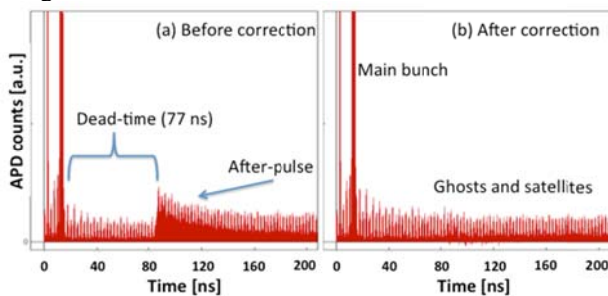


Figure 5: Example of an LDM measurement before and after the correction for the dead-time and after-pulse.

Measurements

An example of the effectiveness of the dead-time and after-pulse correction algorithm is shown in Fig. 5. Without correction, both effects would definitely compromise the measurement accuracy. Fig. 6 shows the result of a measurement that allowed evidencing the presence of both satellite and ghost bunches. At the moment the LDM is the only monitor able to retrieve

such information. This particular measurement triggered a campaign optimization in the LHC and in the injectors.

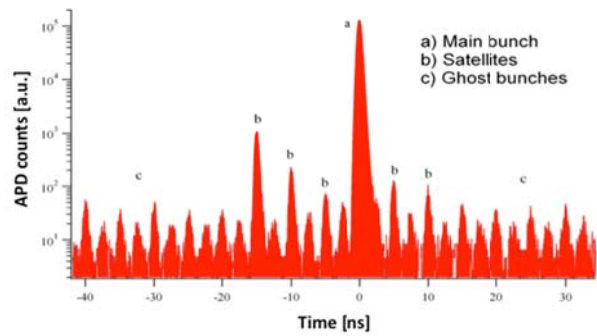


Figure 6: LDM measurement with sufficient integration time to clearly identify satellite and ghost bunches.

CONCLUSIONS AND OUTLOOK

The LHC BSRTS systems allow monitoring the bunch-per-bunch emittances by gating a single bunch at a time, at a maximum frequency of 1 Hz. To reduce statistical errors it is normally required to gate on each bunch from 2 to 5 seconds. The absolute calibration is for the moment based on cross-calibration with respect to WS. During synchronized measurements, applying a correction factor to the BSRTS, the difference between the two monitors is at the 1% level. This was achieved during a dedicated beam study period, during which experts tuned the WS and BSRTS to their optimal settings. More studies are on-going to understand the correction factors and to bring the BSRTS always to optimal settings during operation.

The BSRTF systems are being commissioned and aim at single turn – single bunch monitoring.

The LDM detectors are still in the commissioning phase, but already served to improve the LHC operation, being the only device able to characterize the longitudinal beam distribution with a resolution of the order of 50 ps and a wide beam intensity range.

ACKNOWLEDGEMENTS

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