MEASUREMENT OF SATELLITE BUNCHES AT THE LHC

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Abstract

The RF gymnastics involved in the delivery of proton and lead ion bunches to the LHC can result in satellite bunches of varying intensity occupying the nominally empty RF buckets. Quantification of these satellites is crucial for bunch-by-bunch luminosity normalization as well as for machine protection.

We present an overview of the longitudinal density monitor (LDM) which is the principal instrument for the measurement of satellite bunches in the LHC. The LDM uses single photon counting of synchrotron light. The very high energies reached in the LHC, combined with a dedicated undulator for diagnostics, allow synchrotron light measurements to be made with both protons and heavy ions. The arrival times of photons are collected over a few million turns, with the resulting histogram corrected for the effects of the detector's deadtime and afterpulsing in order to reconstruct the longitudinal profile of the entire LHC ring.

The LDM has achieved a dynamic range in excess of 10^5 and a time resolution of 90 ps. Example results are presented and the successful modification of the system to prevent dependence on the transverse beam size is shown.

INTRODUCTION

Each ring of the LHC is divided longitudinally into 35640 buckets, most of which do not contain a bunch. These nominally empty buckets can in fact contain small populations of particles, which are then called satellite bunches (if they are within the same 10-bucket slot as a nominal bunch) or ghost bunches (if they are in an empty slot). These definitions are illustrated in Fig. 1 with an example profile from the heavy ion run 2010.

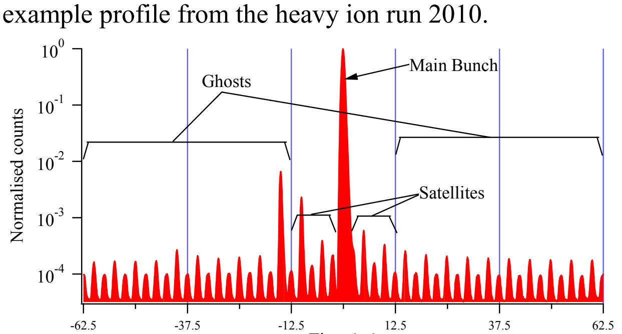

Figure 1: An example LDM profile showing the definition of ghosts and satellites. Longitudinal profile in logarithmic scale.

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Relative bunch-by-bunch currents in the LHC are measured by the fast Beam Current Transformer (fBCT), and must then be normalized to the absolute current measurement performed by the DC Current Transformer (DCCT) [1]. Any slots which do not exceed the fBCT noise threshold, i.e. empty slots, are set as zero. In reality, these slots contain ghost charge. Therefore, the ghost charge proportion must be allowed for when normalizing the fBCT to the DCCT, which integrates all charges circulating in the machine. Knowledge of the ghost charge fraction is then critical for bunch current measurement, and thus for luminosity calibration.

DESCRIPTION OF THE DETECTOR

The LHC is equipped with two sets of synchrotron radiation (SR) monitors, one for each beam, known as the BSRTs. SR is emitted in a purpose-built undulator and in the D3 separation dipole immediately downstream. Approximately 7% of the SR is directed to the LDM, the rest being used for transverse imaging [2] and abort gap monitoring [3]. The LDM line is equipped with filter wheels and translation stages allowing the attenuation and alignment to be controlled independently of the other BSRT instruments.

The LDM uses time-correlated single-photon counting (TCSPC) to produce a longitudinal profile. Each bunch passes the LDM once every turn and a photon could be detected from anywhere in the bunch, or not at all. In order to make a meaningful bunch profile the data have to be collected over many turns. Incoming photons are detected by a silicon avalanche photo-diode (APD). The APD is operated in Geiger mode, so that each photon (if detected) produces a measurable electrical pulse. A time-to-digital converter (TDC) then time-stamps the arrival of the pulse relative to the LHC turn clock. The histogram of arrival times which is built up is then the longitudinal beam profile (Fig. 2). The LDM system is described in more detail in [4].

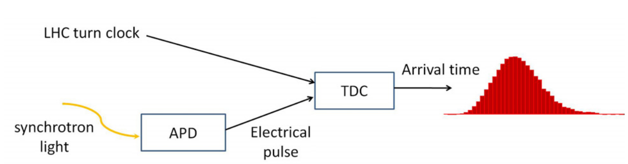

Figure 2: Schematic of the LDM system.

The longer the acquisition, the more counts are added to the histogram and the higher the dynamic range of the measurement. An integration time of 10 s (~10^5 turns)

ISBN 978-3-95450-115-1

allows the shape, length and relative populations of the main bunches to be measured. Quantifying the satellite and ghost fractions requires an integration time of at least 5 minutes (~3×10^6 turns). A dynamic range of better than 10^5 has been reached with an even longer integration time.

The APD used is the PDM from Micro Photon Devices [5]. The PDM has a FWHM time resolution of 40 ps. However, the time response has a long tail due to photons incident in the diffusion region of the APD. All Geiger-mode APDs have a deadtime due to the need to quench the self-sustaining avalanche. The PDM has a deadtime of 77 ns.

During an avalanche, charge carriers may become trapped in impurities in the silicon. These trapped carriers will be released some time later, when they can cause a new avalanche. This is known as afterpulsing and is the dominant source of noise for the LDM detector.

The photon-counting histogram was measured for 10^8 pulses of a diode laser, and the response is shown in Fig. 3, illustrating the diffusion tail, deadtime and afterpulsing.

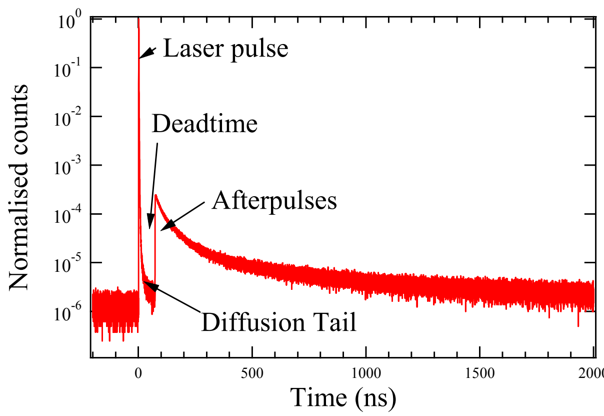

Figure 3: Photon-counting response histogram of the APD, measured in the lab for 10^8 cycles of a pulsed laser.

SIGNAL PROCESSING

The deadtime of the detector introduces a distortion to the measured bunch shape, since in general only the first arriving photon is detected in each pass. In filling schemes where the bunch separation is less than the deadtime, an additional inter-bunch distortion occurs.

The average count rate can be controlled by attenuating the light with neutral density filters. The actual number of photons arriving at each pass follows Poissonian statistics. If the average count rate is very low (<<1 photon / bunch / turn) the probability of seeing two photons is very small and the distortion is then negligible; however the integration time necessary to achieve a high dynamic range would be prohibitively long. On the other hand if the average count rate is too high (>2 photons / bunch / turn) then very few photons can be detected from the end of the bunch. An optimal compromise is reached around 0.5 photons / bunch / turn. In this regime the distortion due to deadtime is significant, but a correction can be applied in order to restore the true bunch shape.

In order to achieve a high dynamic range, noise subtraction is carried out in two steps. First, correlated noise due to afterpulsing is removed by subtraction of a series of infinite impulse response filters [6]. Second, the remaining baseline is removed. The baseline is a combination of APD dark counts, background light and incomplete subtraction of afterpulses.

In order to calculate the baseline, we take the mean of all the bins at the junction of two buckets (the bucket separatrix). In normal operation we do not expect any beam to be present close to the separatrix, which lies approximately 4σ from the bunch centre. Unfortunately, however, this assumption means that the LDM is unable to measure any debunched beam, since it would be subtracted with the baseline.

The corrected histogram is separated into slots. Each slot is approximately 499 bins long. The exact length changes slightly with energy, as does the LDM's phase with respect to the turn clock, due to the change in RF frequency and in the dominant synchrotron light source, respectively. The exact phase and width are therefore calculated each time, by using the center of Gaussians fitted to the first and last bunch in the histogram.

Next, 'average slot' histograms are created by adding the slots together bin by bin. Separate histograms are created for the filled slots and the empty slots. Examples are shown in Fig. 4 and 5 respectively.

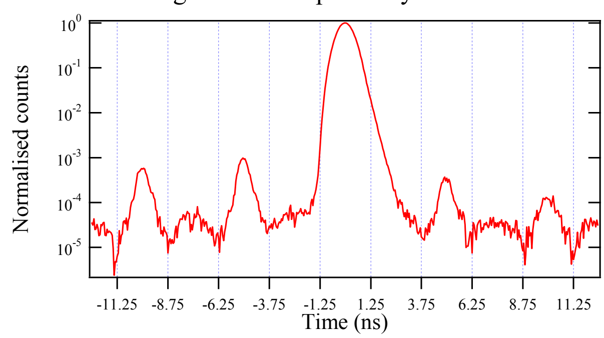

Figure 4: Averaged filled slot. From the beam 1 longitudinal profile during lead ion fill 2292 (November 2011)

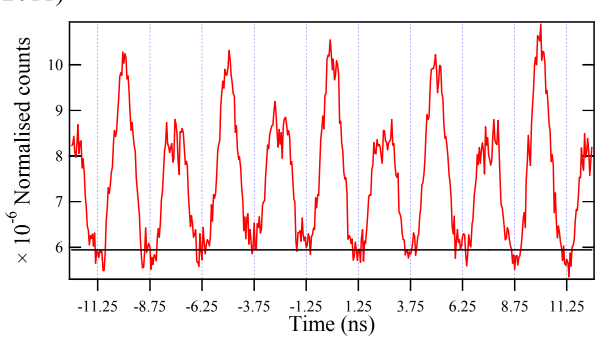

Figure 5: Averaged empty slot. From the beam 1 longitudinal profile during lead ion fill 2292 (November 2011). The baseline level is shown.

From these average histograms it is simple to calculate the fraction of the beam population contained in the main bunch, the satellites and the ghost bunches.

It can be seen in Fig. 4 that the diffusion tail of the APD means that the bucket immediately following the main bunch is swamped by the diffusion tail from the main bunch. Any satellite in this bucket cannot be distinguished. This bucket is not counted in the satellite proportion, nor are the separatrices each side of the main bunch counted in the baseline calculation.

MODIFICATIONS TO ELIMINATE EMITTANCE DEPENDENCE

The active area of the APD has a diameter of only 50 µm. The beam spot produced by the synchrotron light telescope is roughly Gaussian with a sigma between 100 and 500 µm depending on the emittance of the beam. This reduces the coupling efficiency since only a fraction of the beam spot can be sampled. In addition, it creates a dependence of the coupling efficiency (and therefore the measured beam population) on the transverse size of the bunch, and therefore on the bunch emittance. If the detector is centered in the beam spot, then bunches with larger emittance will appear to have lower population. Conversely, if the detector position is away from the beam center, bunches with larger emittance will appear to have a larger population.

If the transverse emittance of the satellite / ghost bunches is systematically different from that of the main bunches, this will result in an incorrect estimation of their population.

The optical line for the beam 2 LDM has been modified during the winter stop 2011/12 in order to reduce to a minimum the dependence on transverse beam size. The new setup is shown in Fig. 6. A diffuser with a Gaussian point spread function (PSF) scatters the incident light. This produces a beam spot with size

$$\sigma_{After\ Diffuser}{}^2 = \sigma_{Original}{}^2 + \sigma_{PSF}{}^2$$

The diffuser is chosen with $\sigma_{PSF} >> \sigma_{Original}$, so that the dependence of the spot size after the diffuser on the original beam size is negligible. The large size of the beam spot causes an unacceptable loss of coupling efficiency, so a lens is used to increase the amount of light captured.

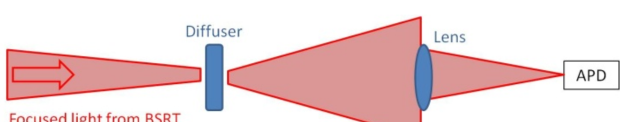

Figure 6: Modification of the optical line to eliminate dependence on transverse beam size.

The effect of the transverse emittance on the measured bunch population was investigated during dedicated machine development sessions before and after the changes to the optical line. Some bunches had their emittance blown up by insertion of a screen in the SPS to LHC transfer line or by use of the transverse dampers, giving a much larger than usual spread in emittance. Fig. 7 shows that the use of the diffuser almost completely eliminates the dependence on emittance.

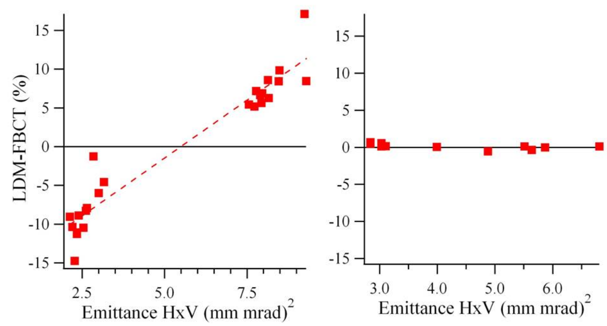

Figure 7: Effect of bunch emittance on the population measured by the LDM, compared to that measured by the fast BCT. Left, original setup. Right, with diffuser and lens.

CONCLUSION

The Longitudinal Density Monitor can measure satellite and ghost bunches circulating in the LHC with a dynamic range of 10^5. Signal correction algorithms rectify the distortion caused by the APD's deadtime and subtract both correlated and random noise.

A dependence of the measured population on the bunch emittance has been identified and eliminated by the addition of an optical diffuser.

ACKNOWLEDGMENTS

A. Jeff is a member of the DITANET Marie Curie network, supported by the E.U. under contract PITN-GA-2008-215080.

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ISBN 978-3-95450-115-1