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*Abstract*

Knowledge of the longitudinal distribution of particles is important for various aspects of accelerator operation, for example to check the injection quality and to characterize the development of ghost bunches before and during the physics periods. A new detector, the LHC Longitudinal Density Monitor (LDM) is a single-photon counting system measuring synchrotron light by means of an avalanche photodiode detector. The unprecedented energies reached in the LHC allow synchrotron light diagnostics to be used with both protons and heavy ions. The LDM is able to longitudinally profile the whole ring with a resolution close to the target of 50 ps. On-line correction for the effects of the detector deadtime, pile-up and afterpulsing allow a dynamic range of $10^5$ to be achieved. The LDM operated during the 2010 lead ion run and during 2011 with protons. Measurements from both runs are presented in this contribution along with an analysis of the LDM performance and an outlook for future upgrades.

## INTRODUCTION

The LHC currently accelerates and collides protons with a center-of-mass energy up to 7 TeV. The RF cavities operate at 400 MHz. In the ultimate LHC filling pattern, 1 in 10 RF buckets will be filled with a bunch. Thus, the minimum bunch separation will be 25 ns, with additional gaps left to account for the rise-time of injection and extraction kicker magnets in the LHC and its injector complex.

However, a small proportion of the beam can often be found in satellite bunches adjacent to the main bunches, which are either an artifact of bunch manipulations in the LHC injectors or poor RF capture in the LHC. In addition, some off-momentum particles are not trapped in a bucket. This 'debunched' beam then drifts around the ring and can be recaptured later to produce very small ghost bunches spread around the whole ring.

These satellite and ghost bunches can collide at the interaction points and create background noise for the experiments. In addition, they cause problems in the calibration of other instruments, and in extreme cases could cause machine protection problems. It is therefore very important to know the level and distribution of the ghost and satellite bunches.

Synchrotron Radiation (SR) is an excellent tool for particle beam diagnostics as it is non-disruptive and carries information on both the transverse and longitudinal particle distribution. It is widely used in electron storage rings [1] where the SR intensities are very high. Since the SR power emitted is proportional to the fourth power of the relativistic $\gamma$, the intensity of SR from a proton beam is 13 orders of magnitude lower than an electron beam at the same energy and with the same radius of curvature. Nonetheless, synchrotron radiation has been used for diagnostics at the highest-energy proton accelerators [2].

A number of methods exist to convert synchrotron light into longitudinal profiles. As well as direct measurement with a photodiode and an oscilloscope, there are streak camera techniques, non-linear mixing of the synchrotron light with light from a pulsed laser [3], or Single Photon Counting (SPC). SPC is a relatively low-cost solution which is capable of measuring the full LHC ring with high dynamic range. SPC also compares favorably in this respect with electromagnetic measurements of the beam, such as Wall Current Monitors (WCM) or Beam Current Transformers (BCT), where the dynamic range is usually limited due to noise and small mismatches in the impedance of the acquisition chain.

## PRINCIPLE OF THE DETECTOR

Single-photon counting is used in order to achieve a high dynamic range. The system is illustrated schematically in figure 1. Each particle bunch passes the LDM once every revolution (turn) with the light attenuated in such a way that statistically the chance of detecting a photon from each bunch on any turn is less than one. In order to make a meaningful bunch profile the data have to be collected over thousands of turns. The avalanche photodiode (APD) detects incoming photons and produces an electrical pulse. This is time-stamped by a time-to digital converter (TDC) and a histogram of arrival times is created. The longer the acquisition, the more counts are added to the histogram, and the higher the dynamic range of the measurement.

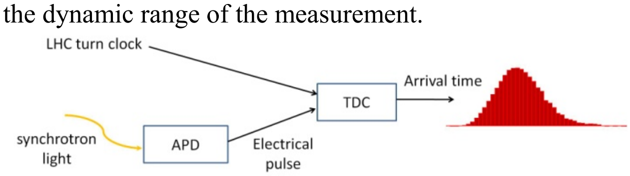


Figure 1: Schematic of the longitudinal density monitor.

The detector used for the LDM is the Photon Detection Module (PDM) from Micro Photon Devices. This is a silicon APD operated in the Geiger mode [4]. The detection efficiency is ~35% averaged over the visible range, however the active area of the APD is only 50

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microns and this leads to a substantial coupling loss. The time resolution is 50 ps FWHM. The PDM uses an active quenching circuit with a deadtime of 77 ns.

The TDC used is an Acquiris TC890 (also called Agilent U1051A) which has a minimum bin width of 50ps. A START pulse is provided at the revolution frequency by the LHC Beam Synchronous Timing system. The STOP signals are the electrical pulses generated by the PDM. The TC890 is a multi-stop TDC so that the time stamps of many STOP pulses can be given relative to each START. The minimum separation of two STOPs is 15ns; since this is less than the deadtime of the PDM it has no effect on the measurements.

## SIGNAL CORRECTION

An APD operated in Geiger mode has a certain deadtime due to the need to quench the avalanches. As well as limiting the maximum count rate, this introduces a distortion to the pulse shape. If a photon is detected from the first part of the pulse, the detector will be blind to any further photons. The measured pulse is thus skewed towards earlier time. In typical single-photon counting applications, the count rate is kept so low that this effect is negligible. However, in order to keep the integration time to a minimum it is desirable to have a higher count rate, and thus correction for the effect of deadtime is necessary.

In order to correct the number of counts in bin *i*, the total number of counts in the previous 77 ns of the histogram is found, and divided by the number of turns that were integrated over. This gives the probability that the APD was in deadtime during bin *i*. A correction can then be calculated,

$$C_i = \frac{x_i}{P(ready)_i} = x_i \frac{N}{N - \sum_{j=i-d}^{i-1} x_j}$$

where $x_i$ is the number of photons counted in bin *i* over N turns, d is the deadtime in bins and $C_i$ is the number of photons which would be counted by a detector with no deadtime [**5**].

This procedure was tested in the laboratory using a pulsed LED as the light source. The pulse shape was measured with a high arrival rate (>1 photon per pulse) and the correction applied. A neutral density filter with transmission of 0.01% was then placed in front of the detector and the pulse shape measured again. In this case the count rate was low enough to make the deadtime effect negligible and no correction was applied. As shown in figure 2, the two measurements agree closely.

When the APD's operating voltage is restored it has an increased chance of producing a spontaneous avalanche caused by charge carriers trapped in the silicon. These correlated false counts or 'afterpulses' are most likely to occur at the end of a deadtime but can spread over several µs with probability decreasing further from the original count. The probability of an afterpulse occurring has been found experimentally to be approximately 3%, and its time distribution is best fitted by multiple exponentials, with the main components having time constants of 25 and 45 ns. The afterpulses can therefore be statistically eliminated by subtraction of a sequence of infinite impulse response filters.

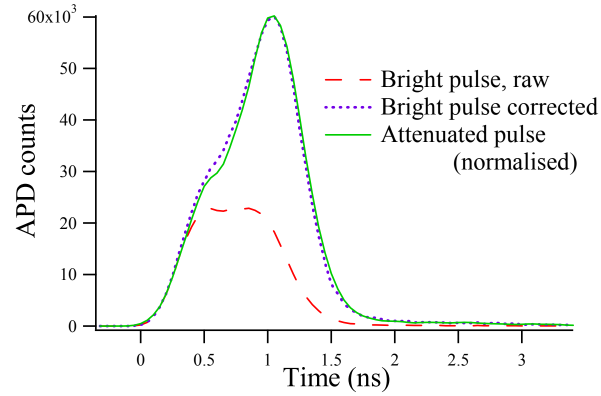


Figure 2: Skew due to deadtime can be compensated with an appropriate correction algorithm. The raw measurement shows that the pulse shape is considerably misrepresented; the correct pulse shape is restored after correction.

A third correction is applied to account for the possibility of two photons arriving during the same bin. The probability of this occurring is small but not negligible for the peak bins of each bunch. Since the two photons produce only one count, the effect is to slightly flatten the peak. The arriving photons follow a Poissonian distribution, so the appropriate correction is

$$P_i = -\ln(1 - C_i/N)$$

where $P_i$ is the number of photons emitted during bin *i*, which is directly proportional to the particle density.

## RESULTS

Measurements were taken with the LDM during both proton and lead ion runs. In the case of lead ions, the lower relativistic γ means that the SR is almost entirely in the infra-red at injection, and measurements with the LDM were only possible above 350 GeV/u (equivalent to 900 GeV for protons). To illustrate the large dynamic range that can be achieved with correction, examples of typical profiles for both protons and heavy ions are shown in figure 3. Ghost bunches can be distinguished with a dynamic range close to $10^5$. In this case, a long integration time of several minutes was used in order to make a high-dynamic range profile showing satellites, but profiles showing only main bunches can be made in approximately 10 seconds. The importance of adequate correction is illustrated in figure 4.

In the case of protons, almost all the satellites are spaced at 5 ns intervals, and so are thought to originate in the LHC injector chain where a lower RF frequency is used. In the case of heavy ions, small ghost bunches spaced at 2.5 ns (i.e. occupying the LHC RF buckets) spread around the ring with population slowly decreasing far from the full bunches, in addition to the larger 5 ns satellites near to the full bunch. This pattern of satellites, with the largest occurring 15 ns before the bunch, was reproduced in most lead ion fills. This came from the modulation of the RF voltage at injection to optimize capture for newly injected bunches, which led some particles from previously injected bunches to leak out of the bucket. These particles were subsequently recaptured once the RF voltage was again increased.

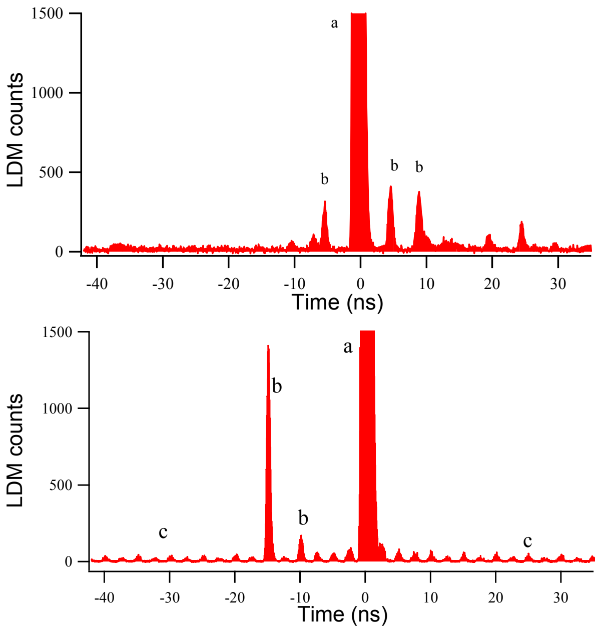


Figure 3: Typical pattern of satellites in an LHC fill with protons (above) and with lead ions (below) showing a) main bunch with peak at 1.3 x $10^5$ counts, b) satellites, and c) ghost bunches.

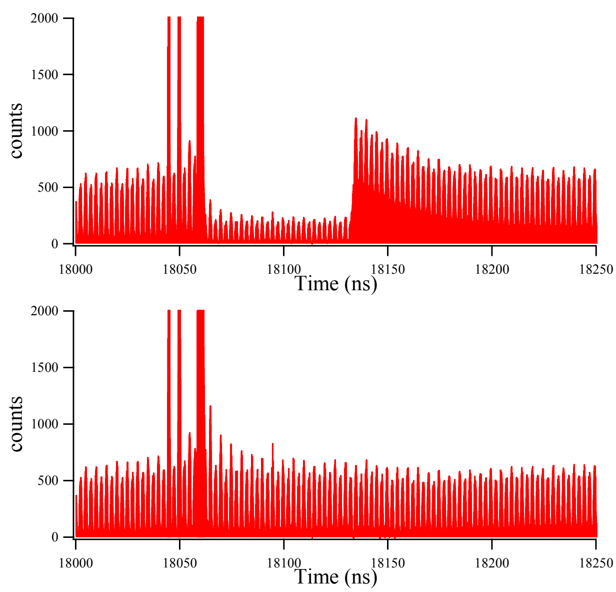


Figure 4. Lead ions with 500 ns bunch spacing. The main bunch arrives at 18060 ns and is preceded by two satellites; ghost bunches spaced at 2.5 ns are present throughout the ring. Above: Raw signal. The count rate is reduced immediately after the bunch for 77 ns (deadtime) after which sensitivity is restored and the noise level increases (afterpulsing). Below: corrected signal.

Due to the dependence of the coupling efficiency on very precise steering of the light onto the LDM, it has been impossible to establish an absolute calibration factor. However, the relative bunch-by-bunch and bunch to satellite populations can be easily extracted. The bunch-by-bunch populations can be compared to those measured by fast beam current transformers and are found to agree to within 2%. Similarly, the bunch length can be found by fitting a Gaussian to the LDM profile, and this is found to be in close agreement with the bunch length measured by the LHC wall current monitor.

## CONCLUSION

It is shown that a photon-counting method can produce high-resolution longitudinal beam profiles. The method is suitable for the low intensity synchrotron light found in high energy hadron accelerators and has been demonstrated with both protons and heavy ions. A high count rate (and consequently a shorter integration time) can be used provided that suitable correction is applied. Although the results are so far mostly qualitative, it has been shown that the statistical subtraction of afterpulses allows a high dynamic range of up to $10^5$ with a few minutes integration time. Work remains to be done to fine tune the correction parameters, which depend on the probability of afterpulsing with respect to time. Ultimately the dynamic range is limited by the uncertainty in the determination of this probability and its stability at varying count rates.

Early results from the LHC Longitudinal Density Monitor show that it is in good agreement with existing instruments. However, it exceeds them in sensitivity and has already proven itself as a useful tool for machine optimisation.

## ACKNOWLEDGEMENTS

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