DESIGN FOR A LONGITUDINAL DENSITY MONITOR FOR THE LHC

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Abstract

Synchrotron radiation is currently used on the LHC for beam imaging and for monitoring the proton population in the 3 microsecond abort gap. In addition to these existing detectors, a study has been initiated to provide longitudinal density profiles 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 photo-diodes (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 measurement of the bunch tails, but must be gated off during the passage of the bunch to prevent the detector from being swamped. An algorithm is then applied to combine the two measurements and correct for the detector dead-time, afterpulsing and pile-up effects. Initial results from laboratory testing of this system are described here.

INTRODUCTION

The longitudinal density monitor (LDM) will be installed alongside the existing synchrotron light monitors at point 4 of the LHC [1]. The objective is to produce a complete longitudinal profile showing individual bunch lengths as well as the particle density in the nominally empty buckets. Ideally, the bunch lengths would be available with an integration time of the order of 1ms, in order to allow the study of synchrotron oscillations which have a period of around 40ms. Although such diagnostics have been used before in synchrotron light facilities, the intensity of light available in a proton machine such as LHC is many orders of magnitude lower.

Given the small amount of light available and the fast time resolution required, it is proposed to use time-correlated single photon counting to construct the profile. Avalanche photo diodes (APD) operated in the Geiger mode will be used as they are capable of detecting single photons with high time resolution. However, they suffer from a number of limitations, notably deadtime, which must be corrected for to produce a true proton density profile.

DESCRIPTION OF THE SYSTEM

Specifications

The LDM should be capable of producing a longitudinal profile with a time resolution of 50ps. Two functionalities are requested. Firstly there should be a fast integration mode which can measure the bunch parameters (bunch length, density distribution) with an integration time of 1ms. Secondly, there should be a high-sensitivity mode which can produce a full longitudinal profile with a sensitivity of 5×10^5 protons per 50ps bin. This implies a dynamic range of more than 30,000 compared to the maximum density at the centre of the bunch. Of particular importance is to measure the bunch tails and the nominally empty spaces between bunches [2].

Amount of light available

The amount of light hitting the extraction mirror varies strongly with the particle energy. It can be computed using the simulation code SRW, [3]. This is in close agreement with calculated values [4]. For protons, it is at a minimum at the cross-over point around 1TeV, where the light from the undulator has passed into the UV but the light from the bending magnet still peaks in the IR. The dependence on beam energy has been verified up to 3.5TeV using the Abort Gap Monitor (AGM); this is presented separately at this conference [5] and will not be discussed further here.

The LDM should also operate with lead ions. For ions the minimum light intensity is at the injection energy of 177 GeV per nucleon, where the light from both the undulator and the dipole peaks in the IR. It will then be necessary to increase the integration times considerably.

Table 1. Photons predicted at the extraction mirror. Approximately 1% of these can be diverted to the LDM, the rest being used for the AGM and BSRT.

	Beam energy	**Photons / s**
Protons, pilot bunch	1 TeV	5×10^7
Protons, full ring	1 TeV	5×10^{12}
Protons, full ring	7 TeV	2×10^{16}
Lead ions, pilot bunch	177 AGeV	8×10^4
Lead ions, full ring	177 AGeV	5×10^9
Lead ions, full ring	2.7 ATeV	2×10^{17}

SIGNAL CORRECTION

Because the signal is time-varying, the deadtime causes a distortion of the signal [6]. The detector is more likely to be ready ('up') to receive a photon at the start of the bunch than at the end, since the detector will be in its deadtime ('down') if a photon has been received at any time earlier in the bunch. This causes a skewing of the signal towards the front of the bunch, which is more

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pronounced the higher the photon arrival rate. In order to reduce the integration time, the arrival rate should be high, so the distortion will be significant and must be corrected.

To this end a Monte Carlo simulation was made using C++ to quantify the extent of the distortion and to test a correction algorithm. The number of photons seen by the detector is histogrammed over many turns of the LHC. To calculate the number of photons C_i counted by an ideal detector (i.e. one with no deadtime) in a particular bin i, the number of photons counted by our (non-ideal) detector is summed over all the bins i-d to i-1, where d is the deadtime of the detector divided by the bin width. Dividing this by the number of turns that were integrated over gives the probability that the detector was down during bin i. Then

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

where x_i is the number of counts given by the non-ideal detector in bin i over N turns. Figure 1 shows that the correction is effective even when the deadtime is much longer than the bunch separation of 25ns.

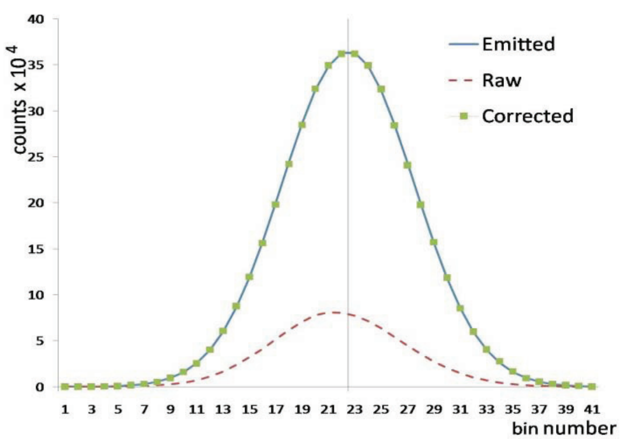

Figure 1. Simulated performance of the APD and correction algorithm. Each bin is 50ps. The photon arrival rate is 0.5 per bunch per turn and the deadtime is 195ns. The centre of the bunch is marked to show the skew of the raw APD signal towards the front of the bunch. After correction the signal exactly matches the number of photons emitted.

A second correction can be applied to account for afterpulsing. However, since the afterpulses are spread over a long period, the adjustment per bin is small and a substantial amount of noise is introduced.

The third correction accounts for pile-up. Even an 'ideal' photon counter operates in a binary mode, that is, each bin either contains a photon or does not. This leads to underestimation of the signal if more than one photon arrives during one bin. The effect only becomes significant at high photon arrival rates since the chance of two photons arriving in the same bin is otherwise negligible.

In order to correct for this, the probability of two photons arriving at the same time must be estimated. The emission of synchrotron radiation is a stochastic effect involving a very large number of particles, each with a very small chance of emitting a photon within the acceptance of the detector. The photons can thus be considered to have a Poissonian distribution. If the number of counts expected in a particular bin (given the proton density) is λ, then the probability of having a given number k of photons emitted is

$$p(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

If C/N is the probability that the ideal detector would see at least one photon then

$$p(0) = 1 - C/N = e^{-\lambda}$$

The expected number of photons is then given by

$$\lambda = -\ln(1 - C/N)$$

which is now directly proportional to the proton density in that bin. As expected this is approximately equal to C/N for $(C/N) \ll 1$.

GATED APD FOR INCREASED DYNAMIC RANGE

Limit to the dynamic range of the APD

The correction algorithm described above is effective up to a photon arrival rate of a few photons per bunch. When the arrival rate becomes very high, however, the probability of the detector still being up in the later part of the bunch is almost zero. In this case no information is available about the end of the bunch and correction is impossible. The detector can then be said to be saturated.

In order to achieve the desired sensitivity in the tails and ghost bunches, however, it would be desirable for the detector to capture as much light as possible. The specifications state that the system should be sensitive to a ghost bunch of 5×10^5 protons. In order for just one photon from this ghost bunch to reach the detector during a 10s integration, the arrival rate must be 3 photons per full bunch. There is then a large probability that the detector would be down anyway when the photon from the ghost bunch arrives. In practice, of course, more than one photon would be needed to stand out above the noise level, and the arrival rate from the full bunch would then need to be above saturation of the detector.

Solution using two APDs

To overcome this limitation it is proposed to use two APDs. The synchrotron light would again be split. One branch would go to a free-running (i.e. always on) APD via a controllable attenuator. This detector would be capable of measuring the core of the bunch but would be blind to the much fainter signals of the tails and ghosts. The second branch would go to a fast gated APD. This APD would be switched off during the arrival of photons from the bunch and would thus be able to receive much more light from the tails without becoming saturated (figure 2).

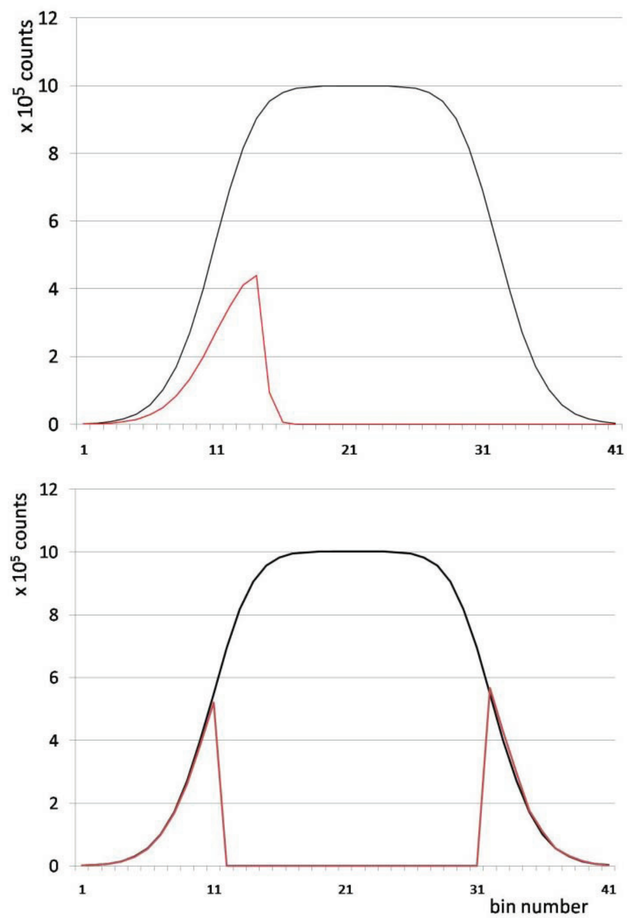

Figure 2. APD signal after correction compared to the true bunch shape, from simulation. Arrival rate is 90 photons per bunch per turn, bin width 50ps, integration time 10s. Top, the detector is saturated and correction is unable to restore the true profile. Bottom, the detector is gated off in the central part of the bunch; the corrected signal then accurately portrays the tails.

Electrical gating

The performance of one APD in gated mode was tested. At low repetition frequency, the gate operates well, with pulses arriving when the detector is gated OFF being completely hidden. However, when tested with a faster gate repetition rate such as would be needed for this application, the detector did not perform as expected. If the gate is switched on immediately after a light pulse is received, a count will be generated as the gate is switched on. This could be because the incident light causes the generation of electron-hole pairs in the APD even if the voltage is below breakdown; if the operating voltage is restored before these have recombined, an avalanche will occur. When the gate-on signal followed the laser pulse by some 10ns, a false avalanche occurred in nearly 100% of cases, and the detector was therefore unable to detect any real photons in the gate, which was shorter than the deadtime of the detector.

Optical gating

Due to the problems encountered with the fast gating of the detector, gating of the light itself is being considered. This can be achieved by use of an electro-optic (EO) deflector. A suitable optical gate can be made by placing the deflector and the APD on opposite sides of a converging lens, such that collimated synchrotron light entering the deflector reaches the APD regardless of deflection. A small mask is placed on one side of the lens to block the central line. This arrangement avoids the need for a pulse generator; instead requiring only a sinusoidal voltage at half the bunch repetition frequency, synchronized so that the light hits the masked line whenever a bunch is passing. The necessary switching speed can be achieved and since EO deflectors are essentially achromatic this setup should produce a very high extinction ratio across the whole spectrum.

CONCLUSION

It is feasible to produce a longitudinal profile of the LHC beam by using APDs to count photons of synchrotron light.

A single APD can measure the average bunch length in the required 1ms integration, but not the individual bunch lengths. This could be possible using an array of APDs.

In parallel to this, a second APD will be installed after an optical gate, to measure the bunch tails and ghost bunches with a longer integration time.

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