Near-Saturation Single-Photon Avalanche Diode Afterpulse and Sensitivity Correction Scheme for the LHC Longitudinal Density Monitor

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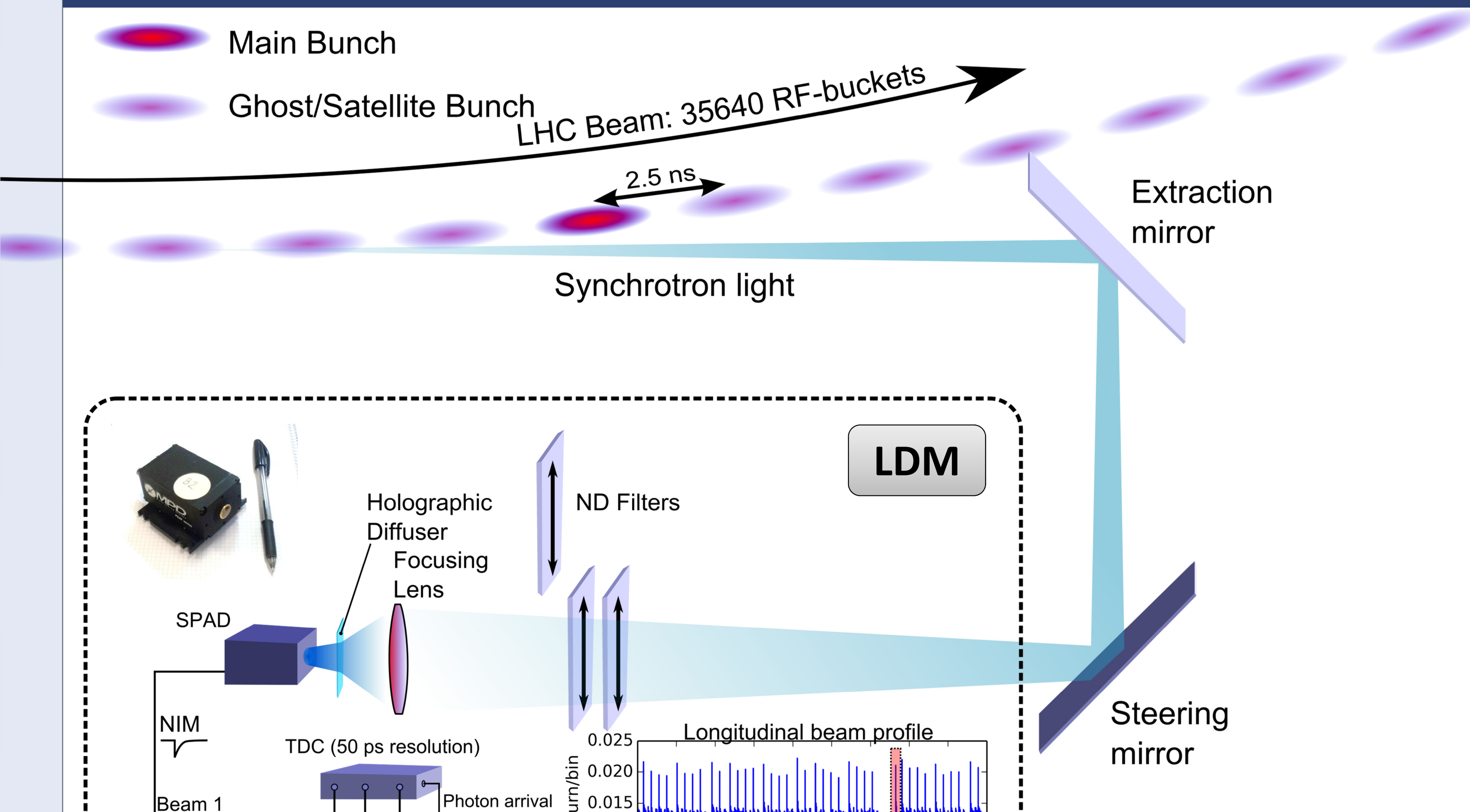
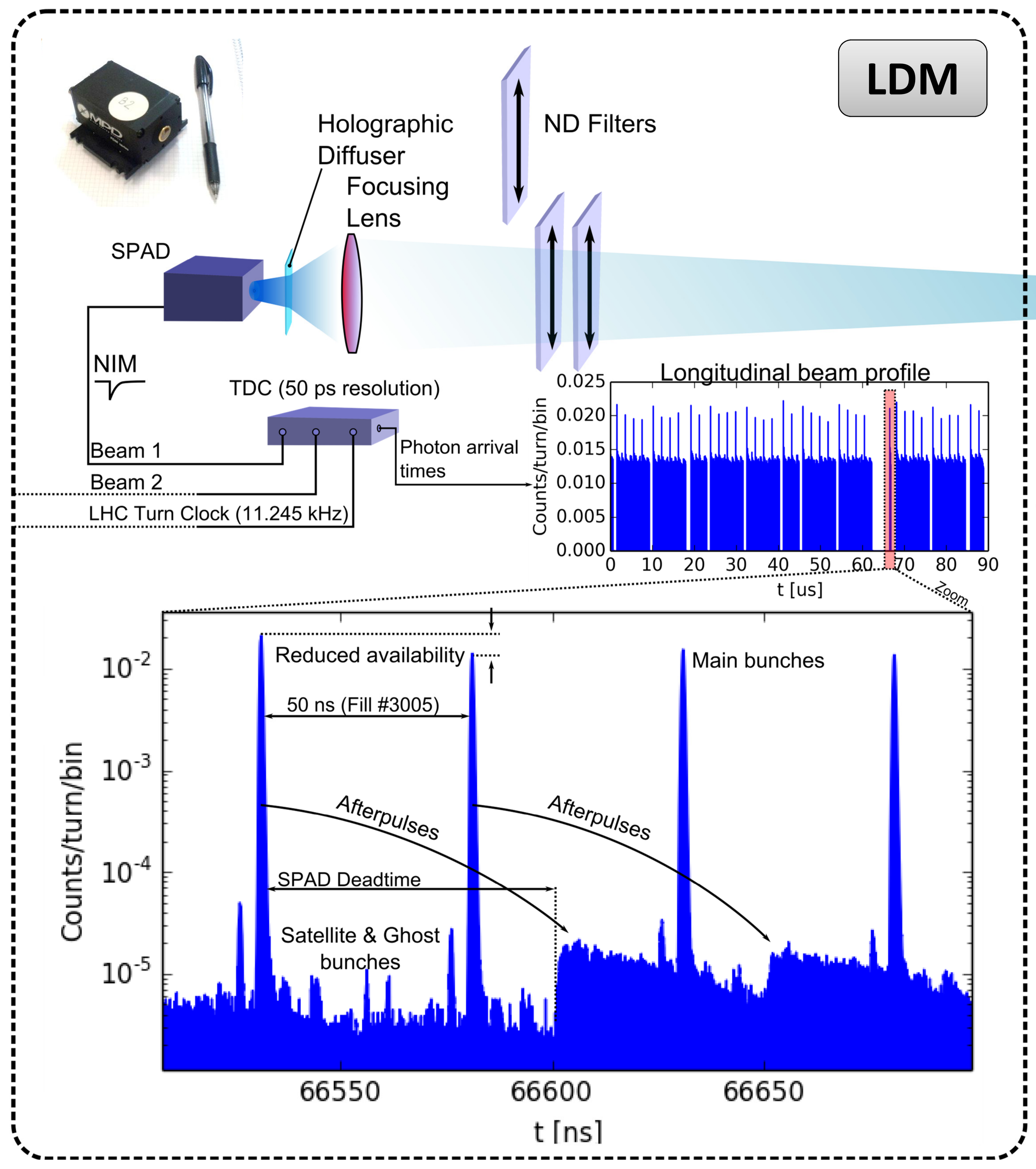
ABSTRACT

Single-Photon Avalanche Diodes (SPADs) monitor the longitudinal density of the LHC beams by measuring the temporal distribution of synchrotron radiation. The relative population of nominally empty RF buckets (satellites or ghosts) with respect to filled bunches is a key figure for the luminosity calibration of the LHC experiments. Since afterpulsing from a main bunch avalanche can be as high as, or higher than, the signal from satellites or ghosts, an accurate correction algorithm is needed. Furthermore, to reduce the integration time, the amount of light sent to the SPAD is enough so that pile-up effects and afterpulsing cannot be neglected. The SPAD sensitivity has also been found to vary at the end of the active quenching phase. We present a method to characterize and correct for SPAD deadtime, afterpulsing and sensitivity variation near saturation, together with laboratory benchmarking.

LDM OVERVIEW





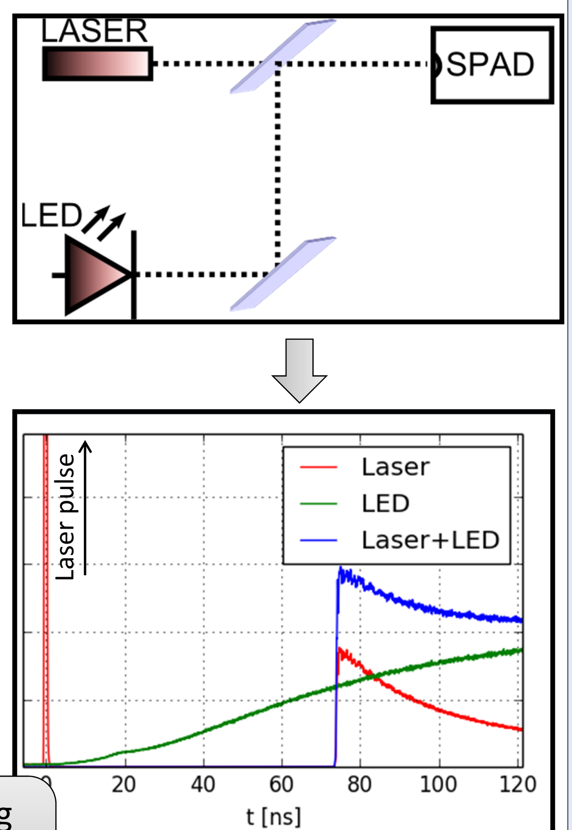
Aim: The filtering strength is adjusted to maximize the signal from ghosts that are within one deadtime of a main bunch. The SPAD operates near saturation, where deadtime and pile-up effects must be taken into account. Afterpulse-induced signal from main bunches are as high - or higher - than the amplitude of the ghost bunches. The aim of this work is to improve the correction algorithm of the LDM raw data by modelling and removing afterpulses from raw data.

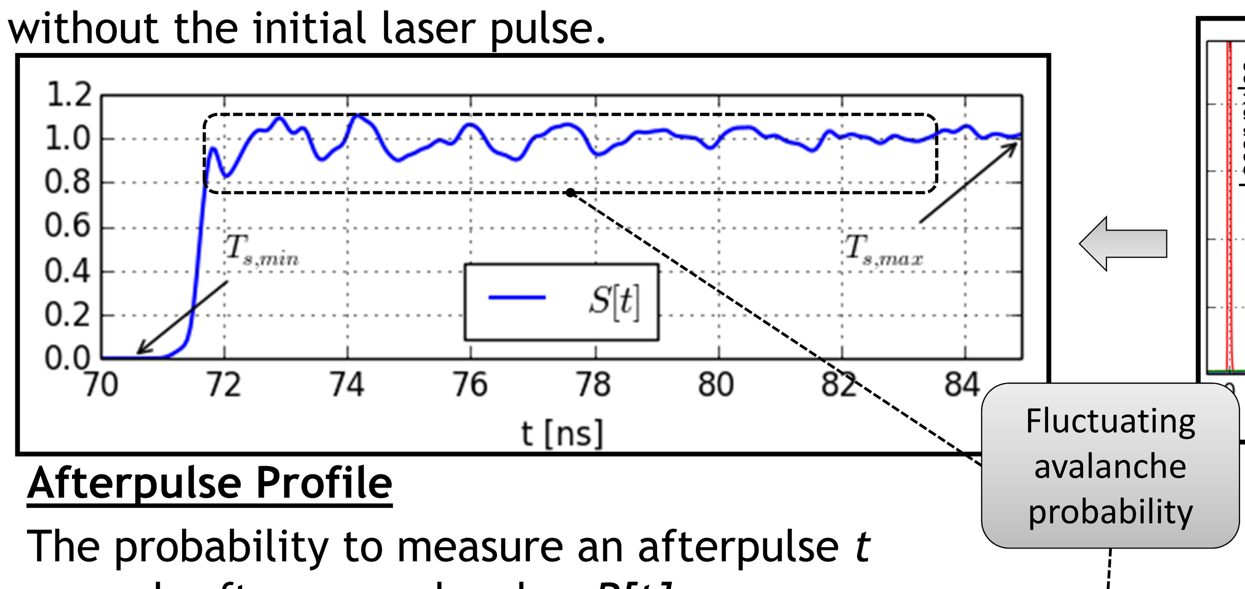
LDM Purpose: To measure the population of nominally filled RF-buckets ("Main bunches") and nominally empty RF-buckets ("Ghost/Satellite bunches). The dynamic range is in the order of 1:10⁵ [1].

DETECTOR CHARACTERIZATION

Relative Sensitivity

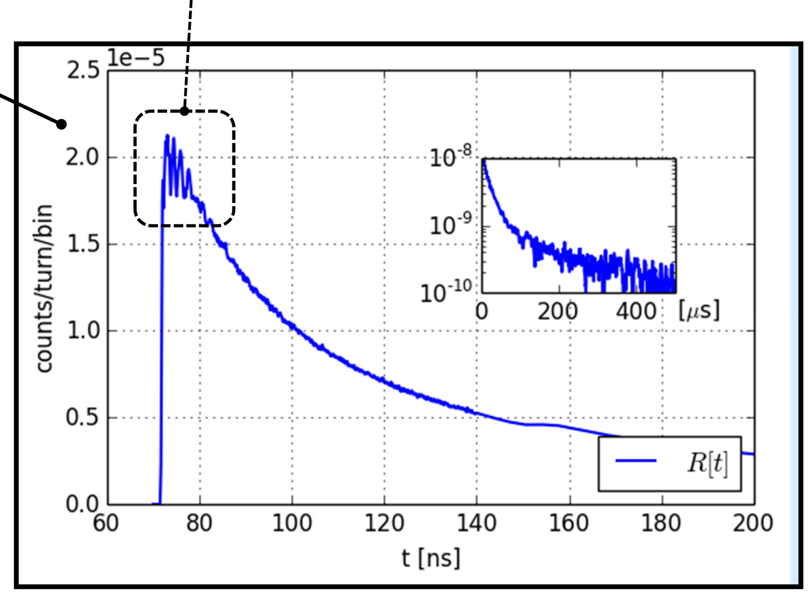
As voltage is restored to the sensor at the end of the deadtime [2], the probability for a photon to cause an avalanche was found to fluctuate during several ns. The relative probability, *S[t]*, was measured by exposing the SPAD to a picosecond laser pulse at $t = 0$, followed by an LED pulse at the end of the deadtime. $S[t]$ was measured by comparing the SPAD response to the LED pulse with and without the initial laser pulse.





Afterpulse Profile

The probability to measure an afterpulse t seconds after an avalanche, *R[t]*, was characterized using a single pulse from a picosecond laser. Afterpulses were seen several hundred μs after the primary avalanche.



SPAD Characteristics	
Photon detection efficiency @ 550 nm	49%
Deadtime, τ	≈72 ns
Afterpulse probability	4%
Dark count rate	300 Hz
Timing resolution (FWHM)	50 ps
Sensor diameter	50 µm

CORRECTION ALGORITHM

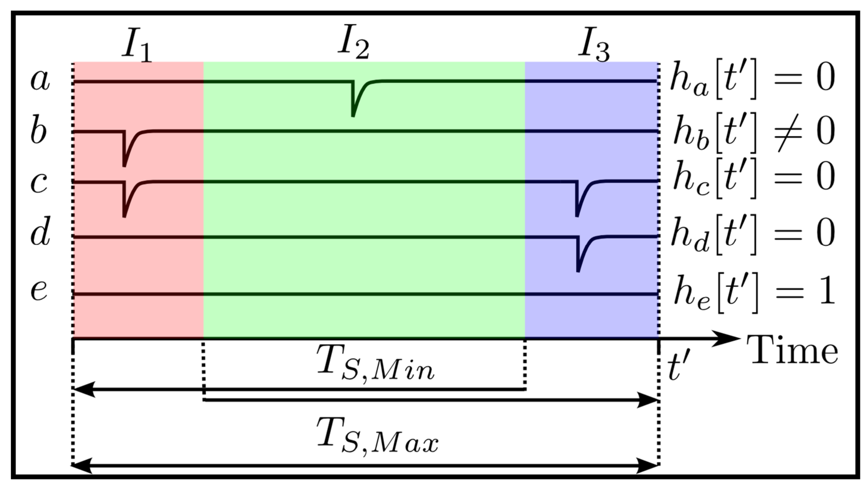
Average sensitivity: The photon rate, $\gamma[t]$, can be expressed in terms of the measured avalanche rate, $a[t]$, the afterpulsing rate, $r_m[t]$, the average SPAD sensitivity, $h[t]$, and a constant background rate b:

$$\gamma[t] = -\ln 1 - \frac{1-(1-a[t])e^{r_m[t]}}{h[t]} - b$$

To estimate the average sensitivity in time bin t', histogram events in the interval $[t' - T_{S,Max}, t' - 1]$ need to be taken into account (for earlier events, $S[t']$ is restored to 1). In a single turn, 5 avalanche configurations (**a-e**) are possible:

By evaluating the resulting sensitivity at t' in the individual cases **a-e**, as well as the probability of each case, $p_a - p_e$, the resulting average sensitivity at t' can be expressed as the weighted sum:

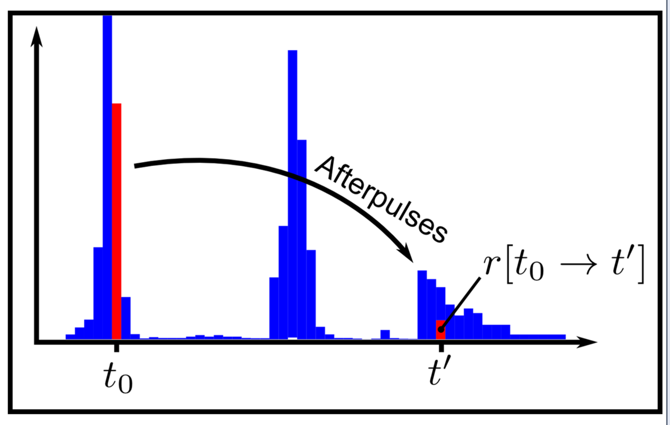
$$h[t'] = \sum_{a-e} p_i \times h_i[t']$$



Afterpulses: The afterpulse contribution at t' from avalanches in bin t_0 are estimated using $R[t]$, $S[t]$ and $h[t]$:

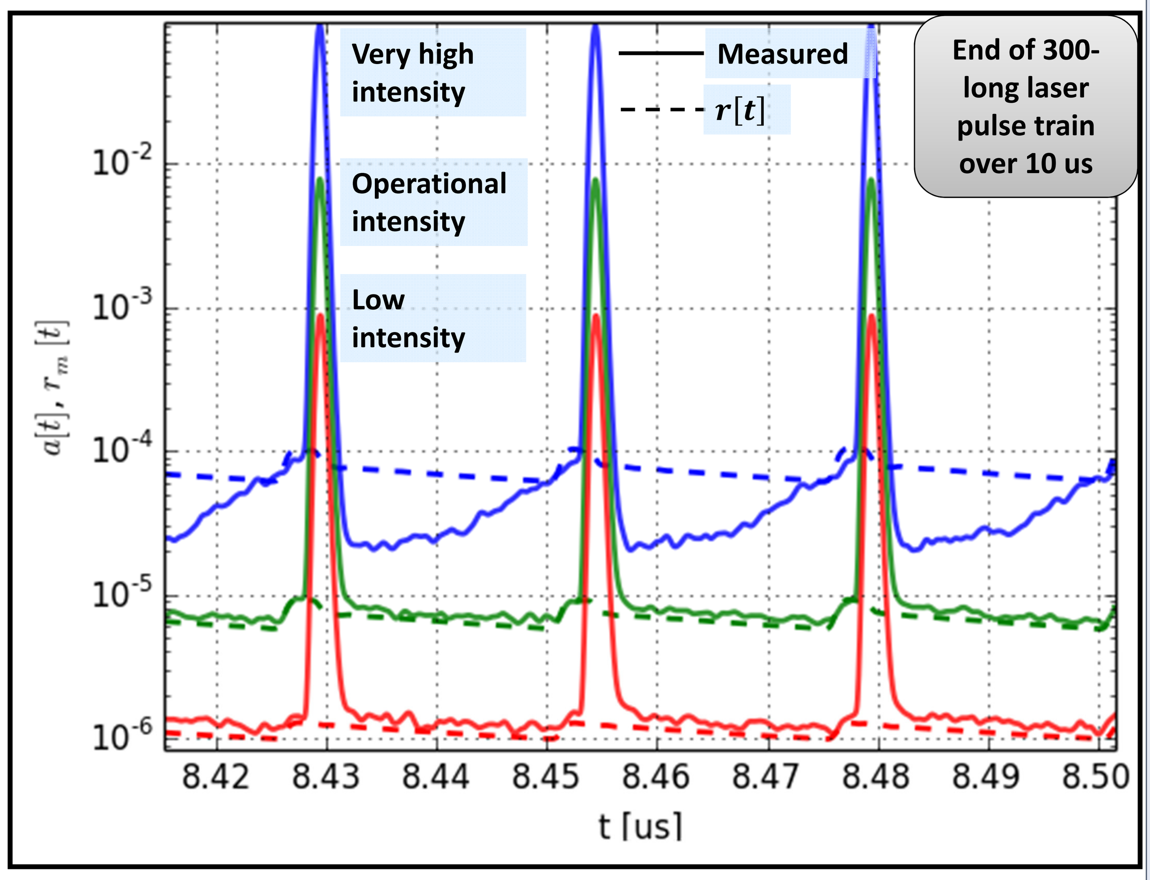
$$r[t_0 \to t'] = a[t_0]R[t'-t_0] \prod_{t_1=t_0+1}^{t'-1} \left(1 - \frac{S[t_1 - t_0]a[t_1]}{h[t_1]}\right)$$

Integration over all t_0 gives the total afterpulse rate at t' (see paper for details).

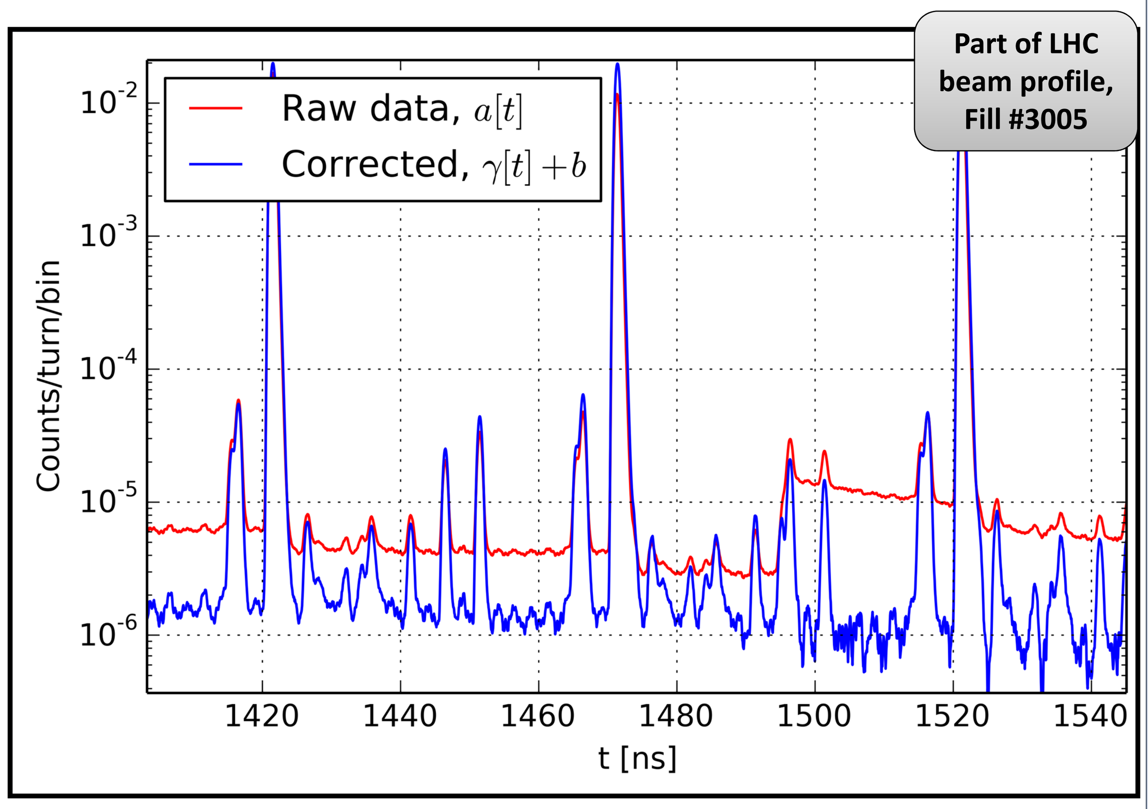


RESULTS

Afterpulse model: By simulating LHC conditions using laser pulses of different intensities at 25ns spacing, the predictive accuracy of the afterpulse model was verified up to operational intensities. It was discovered that the model breaks down at very high intensities due to an unaccounted feature of the SPAD quenching cycle: during the end of the deadtime, when the bias voltage is above breakdown, avalanches can occur, but the output is still inactive.



LHC Data: The figure shows raw data from Beam 2 during fill #3005 in 2012, and corrected data (photon + background rate). The raw data shows a "baseline" variation between main bunches by more than one order of magnitude, caused by afterpulsing. Corrected, the baseline is flattened and the satellite/ghost bunch structure is resolved.



CONCLUSIONS

A correction algorithm for removing afterpulse signal and compensating for varying detector sensitivity and the end of the deadtime has been successfully verified in laboratory and benchmarked on LHC data from Run 1. The window where unregistered can occur was confirmed to be close to 75 ns, i.e. a multiple of a typical main bunch spacing in LHC. To minimize the impact of this effect, the deadtime of the SPADs has been adjusted for Run 2.

REFERENCES & CONTACT

[1] A. Jeff et.al, "Longitudinal density monitor for the LHC", Phys. Rev. ST-AB, p. 032803 (2012) 15(3)

[2] F. Zappa et.al, "Monolithic Active-Quenching and Active-Reset Circuit for Single-Photon Avalanche Detectors", IEEE Journal of solid-state circuits, p.~1298 (2003) 3(7)

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