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SINGLE PHOTON DETECTOR TESTS FOR THE LHC SYNCHROTRON LIGHT DIAGNOSTICS

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A synchrotron light detector using a Single-Photon Avalanche Detector (SPAD) is planned for the LHC longitudinal diagnostics monitor, an application which requires high count rate, low noise and good time resolution. SPAD detectors have been developed at Milan Polytechnic with active quenching circuits. Initial tests of these detectors and currently available commercial time-to-digital data acquisition equipment were made at the ESRF. We present the results of those tests, an estimation of the performance that can be expected for the LHC case and an analysis of the difficulties, constraints and potential of this type of detector.

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A synchrotron light detector using a Single-Photon Avalanche Detector (SPAD) is planned for the LHC longitudinal diagnostics monitor, an application which requires high count rate, low noise and good time resolution. SPAD detectors have been developed at Milan Polytechnic with active quenching circuits. Initial tests of these detectors and currently available commercial time-to-digital data acquisition equipment were made at the ESRF. We present the results of those tests, an estimation of the performance that can be expected for the LHC case and an analysis of the difficulties, constraints and potential of this type of detector.

THE SPAD MODULE

The advantages of using SPADs[1,2] as opposed to other detectors such as photomultiplier tubes, is that they exhibit high count rates, low timing jitter <50ps, and low dark noise <100 counts per second[3,4].

A thorough experimental characterisation of SPAD devices with active area diameters of 8, 20 and 50 µm was carried out, in order to carefully ascertain the performance of the detectors. All the main parameters, i.e. photon detection efficiency (PDE), dark counting rate (DCR) and timing resolution were measured as a function of excess bias voltage and operating temperature.

The best compromise between PDE and DCR was found by operating the SPAD at an excess bias voltage of 5 V. At room temperature, devices with 8 and 20 µm diameter size met the specifications, while devices with 50 µm size showed too high a DCR (about 2 kc/s for the best devices). On the other hand, a larger active area is a definite advantage in the foreseen experiments, since it makes it possible to relax the optical alignment requirements without sacrificing the photon collection efficiency. Furthermore, fibre pigtailing may be routinely made on these devices. We therefore decided to exploit a 50 µm SPAD device, even though moderate cooling is required to meet specifications. When operated at 5V excess bias voltage the selected device shows: peak detection efficiency 48% at a wavelength of 530 nm (> 30% all over the visible range); 44 ps FWHM time resolution; dark counting rate of 80 c/s with device cooled at –15 °C.

Integrated Active Quenching and Reset Circuit (i-AQC)

The SPTM employs a fully integrated active quenching and active reset circuit (i-AQC), which is the first monolithic circuit of this kind [5]. This circuit had been previously developed at Politecnico di Milano and is covered by US and European patents[6]. After the detection of a photon, the dead time is given by the sum of the quenching delay plus an adjustable hold-off time plus the reset time. The dead time was set to 125ns, corresponding to a saturated photon counting rate of 8 Mc/s. The i-AQC power dissipation is quite low (30 mW at 2Mc/s, 170 mW at 8 Mc/s).

In order to achieve the required time resolution, a patented timing board including a linear network that feeds a fast comparator must be connected to the high voltage terminal of the SPAD [7,8,9]. The purpose of the timing board is to extract the avalanche current pulse at a very low threshold level, corresponding to an avalanche current of a few hundreds µA. The time resolution improves by reducing the threshold voltage of the comparator. By lowering the threshold to 10 mV, the SPTM can achieve a time resolution of about 40 ps FWHM. The TCSPC card used in these measurements was a Becker and Hickl SPC600 photon counting card [10].

In various applications, it is necessary or at least advantageous to operate the SPAD under the control of a gate command [1]. In this case, the SPAD is turned on only in a time window centred on the optical pulses of interest. A standard TTL gate signal can be provided to the SPTM. The minimum duration of the gate-on TTL signal is 20 ns, corresponding to an effective minimum gate-on duration of 10 ns.

Performance evaluation

Preliminary tests of the performance of the SPTM with the selected SPAD sample were carried out on the bench at Politecnico di Milano. The operating temperature of the SPAD was set at –15°C and the dark counting rate was checked to be 80 c/s at +5V excess bias voltage.

Photon detection efficiency (PDE) of the SPTM has a peak of 48% around 530 nm and it stays well above 30% in all the visible range.

Time resolution measurements were performed in a conventional time-correlated single photon counting (TCSPC) setup by using an ultra fast laser diode (Antel MPL-820 laser module) emitting 10 ps FWHM optical pulses at 820 nm wavelength. The unit has a prompt peak with a full-width at half maximum of 44 ps and a clean exponential diffusion tail with 300 ps lifetime. The overall duration of the diffusion tail is less than 2.5 ns. A signal-to-background ratio (SBR) higher than 10^4 is clearly demonstrated.

EXPERIMENT AND RESULTS

The operating mode of the ESRF was 2x1/3 fill, there were two frequency sources available for synchronisation of the light, the orbit revolution frequency of the synchrotron 355 kHz and the RF frequency of 352.2MHz. The RF frequency was too high for the synchronisation input of the TCSPC card allowing only the orbit revolution frequency to be used for data collection. The bunches of light in each batch were separated in time by 2.84 ns.

The synchrotron radiation was filtered by using a mirror before entering the optical inspection laboratory. The remaining beam still had a broad spectrum, which was filtered by using either one bandpass filter centered at a wavelength of 650nm with 35nm bandwidth, or a combination of two identical ones. The latter configuration would reduce the bandwidth of transmission to between 31 and 20nm, depending on the angle of inclination of one of the filters (fig.1).

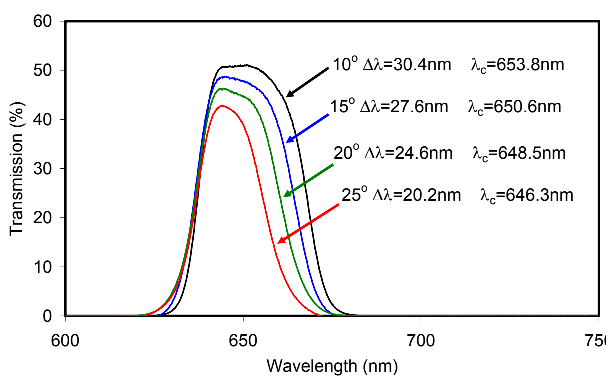

Figure 1: Transmission spectra of two bandpass filters in series, one placed at normal incidence and the other at 10°, 15°, 20° or 25° to the normal.

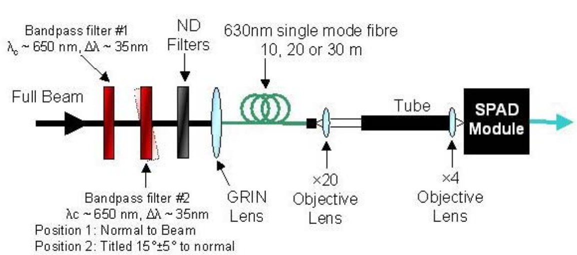

Figure 2: Optical arrangement employed to couple the synchrotron beam into the 4.3µm core fibre (single mode at a wavelength of 630nm) and optically image the photons onto the 50µm diameter SPAD.

Free Running Measurements

The SPAD module was initially operated in free running mode, which simply allows the SPAD to operate continuously. Figure 3 shows the results obtained by measuring the dynamic of the rising edge of one batch. The figure also shows the dark counts obtained from the SPAD during the same measurement time. One can see on the left part of the diagram before the arrival of the pulses, it is evident that there is background radiation, much higher than the intrinsic dark counts of the detector, which could not be filtered in the current experimental conditions.

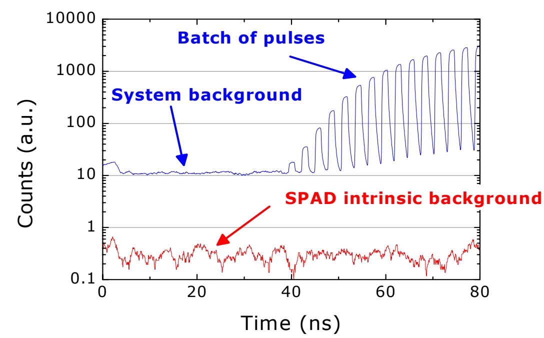

Figure 3: System background between batches of pulses compared to dark noise from SPAD module collected over 10 minutes.

Further experiments were carried out to study the effect of the optical fibre dispersion on the timing resolution. The resolution worsens of approximately 10ps for every 1m of fibre added to the experiment. The temporal profile is increased by ~8ps per metre of fibre for a 35nm bandpass. This means for a 10nm bandpass, we can expect a FWHM of approximately 135ps for the necessary 30m of optical fibre in the LHC, using the same detection system and the same central wavelength.

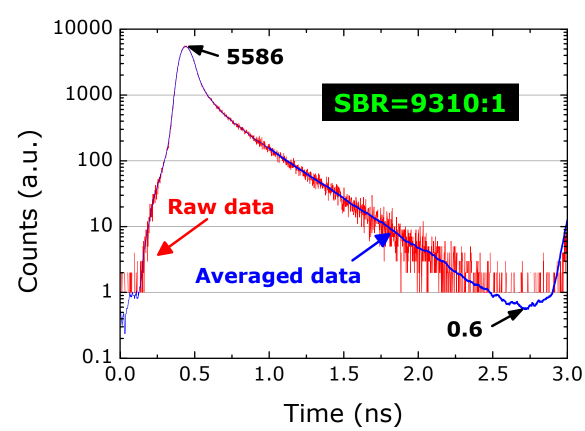

Figure 4: Histogram taken using the setup in Figure 2 employing two BP filters and 10m of Single mode fibre

In terms of signal-to-background ratio (SBR), as mentioned before, our experiments were limited by the scattered background light coming from the synchrotron radiation. Nevertheless we managed to obtain a SBR of approximately 9000:1 as shown in Figure 4.

CONCLUSIONS AND SUMMARY

The timing jitter of the system is lower than that required for the LHC system, but the use of fibres can cause a significant deterioration in the timing resolution. The choice of detection wavelength and spectral detection band will be critical in the final system. From this feasibility study, it can be inferred that a 30m length of single-mode fibre (necessary in the LHC experiment) can be used but only if spectral filtering is employed to limit the bandwidth to approximately 10-20nm.

The signal-to-background ratio at ~2.5ns after the main peak was demonstrated at 9300:1. However, this was affected by background light signal from the synchrotron. We estimate the possible SBR in the LHC experiment – which will have a spatial filter arrangement in place – to be well in excess of 10,000:1. Provided that the background light is spatially filtered, further improvement in the SBR may be achieved by choosing a shorter wavelength (e.g., 450 – 500 nm instead of 650 nm), as it is well known that the diffusion tail that affects the time resolution curve of a SPAD detector is wavelength dependent [7]. Its decay time gets shorter while reducing the excitation wavelength. Figure 5 shows the time resolution curve of the SPAD module measured with a Ti: Sapphire laser providing excitation pulses with a wavelength of 440 nm and a repetition rate of 76 MHz. The slow exponential diffusion tail is not present, since all photons with 440 nm wavelength are absorbed within the depletion layer.

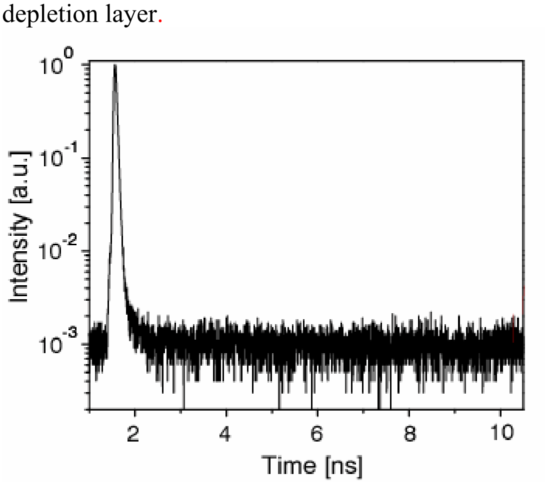

Figure 5: Time resolution curve of the SPAD module as measured at 440 nm excitation wavelength. The diffusion tail is barely visible. Note that the background counts are due to stray light in the experimental set up.

In order to perform the requirements of the Longitudinal density monitor for the LHC, the final detector will have to operate as a sustained counting rate of over 1 Mc/s, which will require attention to the selection of the final devices and optimization of the associated quench and cooling circuits.

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