Silicon Photomultipliers for Beam Loss Monitoring

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Fibre optics for Beam Loss Monitoring

Motivation

Machine protection is an important consideration for many present day and future accelerator facilities. Beam loss from beams with high energy and intensity pose a risk for both machine operation and may lead to increased radiation exposure to humans

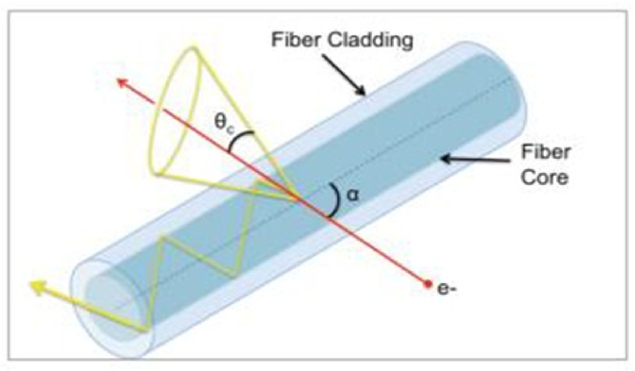
Beam Loss Monitors (BLMs) are online detectors designed to prevent any further beam loss once it has become too high.

(multi mode) Fibre optic BLMs have been under consideration over the past several years as they could potentially be a **cheaper alternative to standard BLM technology** which would be placed along the beam line making them a **compact** detector which can **cover large sections** of the accelerator at a time

The disadvantages of a fibre based BLM would be

- Attenuation due to Rayleigh scattering (effectively limiting length of a fibre to < 100m)
- Lower sensitivity compared to standard technology
- Angular dependence of the signal detected from a fibre.
- Signal change due to radiation induced attenuation not fully understood in an accelerator environment

Working Principle



The detection principle is **based on the production of Cherenkov photons**, which occurs when charged particles of sufficient velocity traverse the fibre.

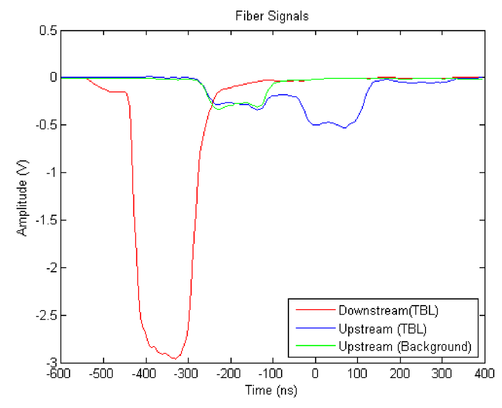
The photons are emitted along a cone with an opening angle defined by the velocity of the particles and the refractive index of the fibre core.

Depending on the angle of incidence of the photons with respect to the fibre cladding, they either exit the fibre or propagate to the fibre ends where they are detected.

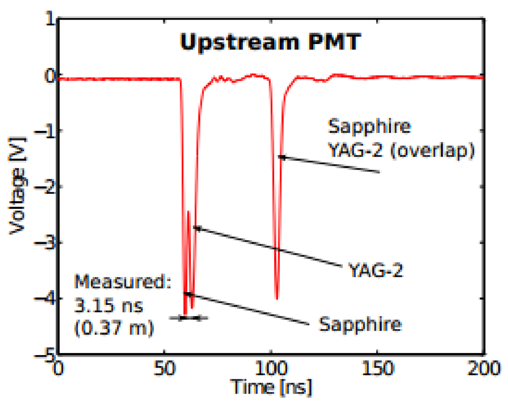
The response of the detector is proportional to the probability that a photon is produced, trapped and exits the end face within the 'nominal exit cone'.

Installations

This technology has been installed at many electron accelerators. The plots below show 2 examples



Left: Signal readout using optical fibres installed at the CLIC test facility CTF3 [1]. Light was detected using silicon photomultipliers



Left: Signal readout using optical fibres installed at the Thomx machine [2]. Light was detected using standard photomultipliers

Silicon Photomultipliers

Silicon photomultipliers consist of a segmented array of avalanche photodiodes (APD) operated in Geiger mode with the output of each cell summed together to give the final output of the device. These devices can be referred to as SiPM or multi-pixel photon counter (MPPC).

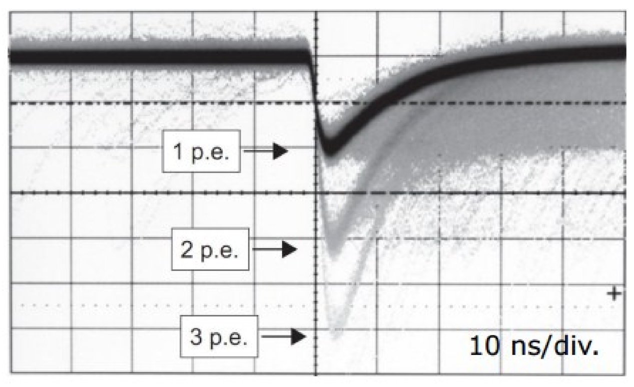
Advantages

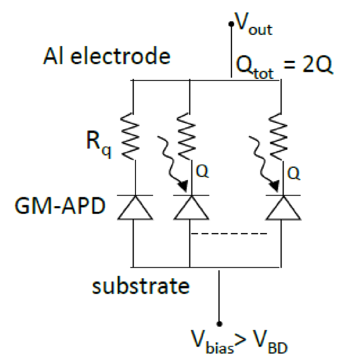
- Insensitive to magnetic fields
- Similar gain ($10^5/10^6$) to standard photomultiplier tubes
- Low operational voltages (40-100V)
- Single photon detection resolution

Negatives

- Thermally generated signals produce the same output as a true event
- **Afterpulsing** (AP) and **crosstalk** effects (CT) (see far right)
- Dynamic range limited by the number of cells
- ~20 ns dead time after detection as a cell recovers.

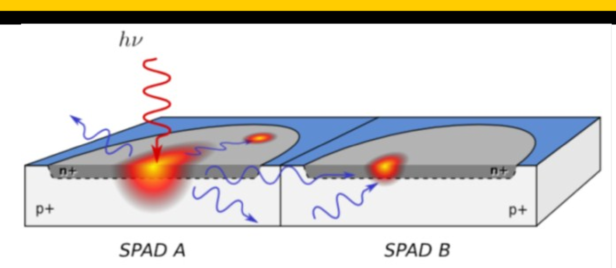
  This can cause non-linearity can occur if Nphoton >> Npixel





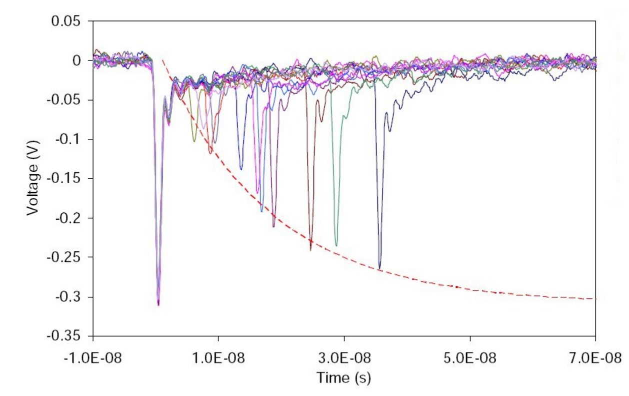
Top Left: Scope output from Hamamatsu SiPM [3] The darker band with lowest peak signal is the response of a single cell being triggered.
The output characterised by a fast rise time and a slower recovery time.
The higher signals are from multiple cells being simultaneously fired.

Top Right: Equivalent circuit of an SiPM.
Each cell is treated as a photodiode in series with a quenching resistor.
The output of each cell is connected to a common output.



Above: Illustration [4] demonstrating optical crosstalk. Photons migrate to neighbouring cells
Optical trenches are introduced to reduce transportation but reduces the fill factor and so also the QE

Below: Demonstration of afterpulsing after the main triggered pulse. [5]



SiPMs are available from many varieties and vendors offering devices with different pitch sizes, architecture and total number of cells

Considerations for Beam Loss Monitoring

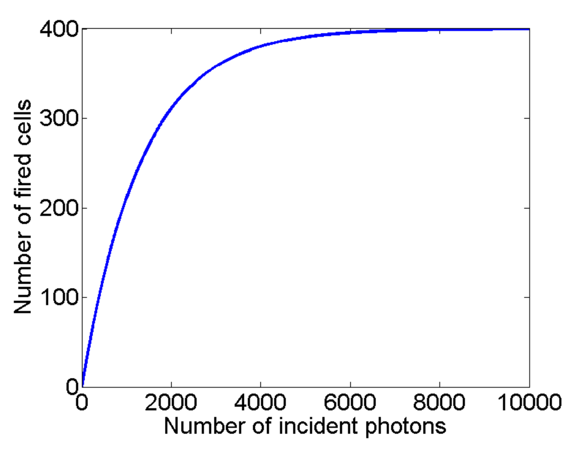
SiPMs have been considered for many different high energy physics and medical applications. Silicon photomultipliers for use in BLMs offer many questions of SiPMs which have not been considered before.
Different loss scenarios will produce different signals to reach the end of a fibre.
Several things need to be considered such as the dynamic range, saturation and the SiPM response to different light pulse lengths

Saturation and dynamic range

The dynamic range of an SiPM is limited to the number of pixels that can be fired.
However due limited photon detection efficiency (PDE) the number of photons required to trigger all the pixels is much higher than the number of pixels on the device.

The number of fired pixels in terms of the total number of pixels available (Ntotal) and the PDE and as a function of the number of incoming photons (Nphoton) is given as:

$$N_{fired} = N_{total}\left[1-\exp\left(-\frac{N_{photon} * PDE}{N_{total}}\right)\right]$$



Right: The result of the above equation for the case where PDE is 30% and the total number of pixels is 400.
It takes a high number of photons to saturate the detector.
For a low number of photons the curve is linear but not so for higher numbers, this makes it difficult to tell the number incident photons for a given signal output. This would mean for BLM purposes that we would require an SIPM with a number of cells much higher than the expected input to avoid non-linearity . Dynamic range required ~ 10^6

Effects from the fibre

The fibre can sometime have a big effect on what is trying to be detected
Ideally the detection process should be as fast as possible but intermodal dispersion can cause a pulse of finite length to spread over distance. It has been found that for a 100 m fibre that for a short light pulse the resolution after transmission down the fibre the resolution is still well within a resolution which translates to a position to within 1m [6]. However this is for an ideal case and the detector should be as fast as possible to locate losses from a beam line.

Ideal SiPM

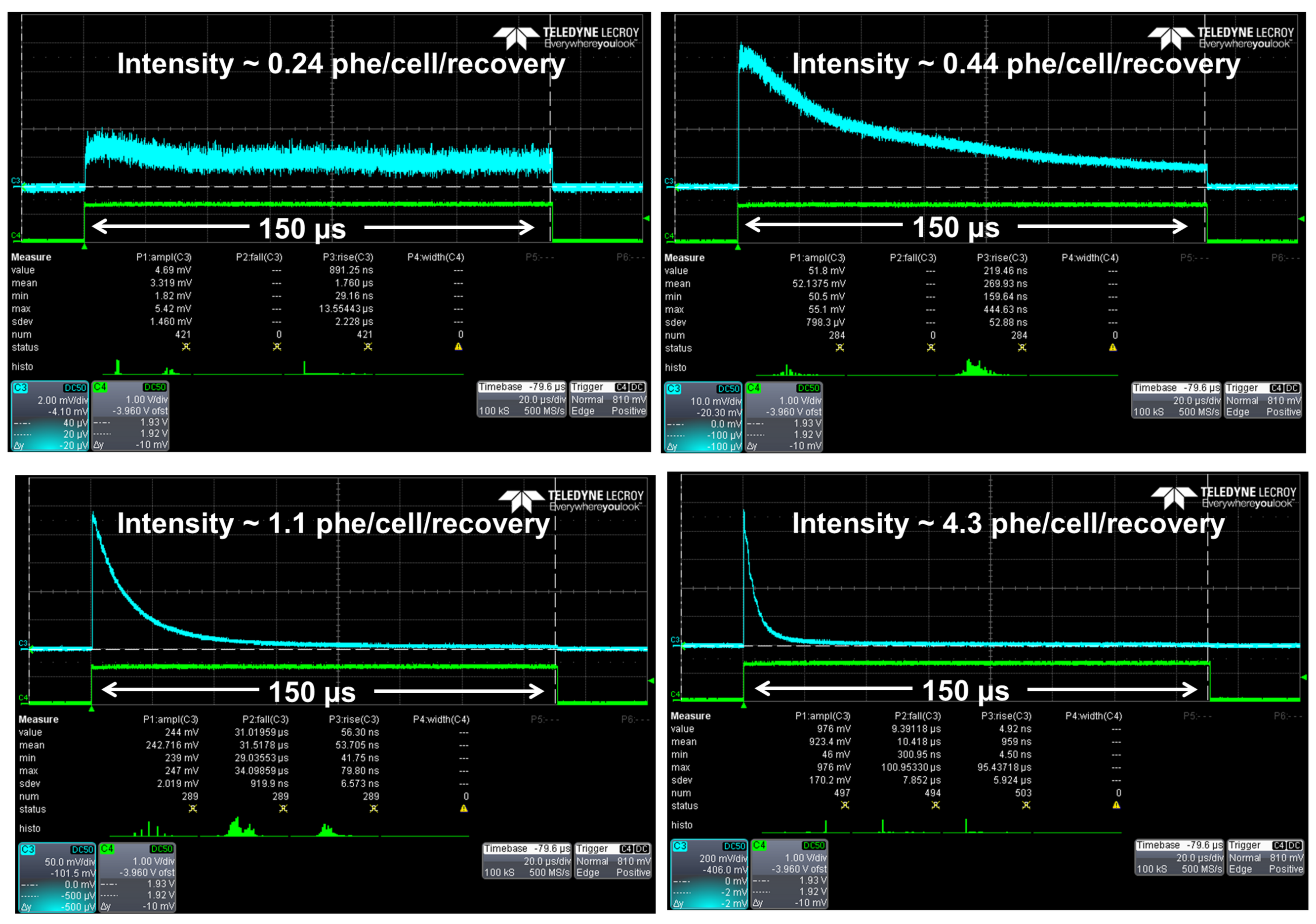
The ideal SiPM for beam loss monitoring purposes would have a large number of pixels and small cell size (faster recovery) whilst also having low CT and AP.
SiPMs for BLMs are a challenging application but improvements to performance should allow them to be used whilst allowing them to be used for light pulses not previously considered.

Response due to long pulse

Experiments have been carried out with a **Hamamatsu S10362-33-050C** with 50 µm cell size and 3x3 mm^2 area (below blue trace). An LED (below green trace) with wavelength 440 nm and variable intensity and pulse width was made to be incident on the active area and the response of the detector for a pulse width of 150 um and different intensities of light. SiPMs are typically used for short light pulses making this an interesting investigation

The output can be separated into three regions:

1) The initial rise and decay– All pixels are available and detection governed by Binomial distribution
2) Plateau- fluctuations in recovery time and retriggering produce a plateau with height less than the initial pulse height
3) Final decay after the light has been turned off– small signal (cannot be seen in the scope trace) due to CT and AP is present which decays to zero



Output shows a strong dependence on light intensity and needs to be investigated further

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Work supported by STFC Cockroft Core Grant No.ST/G008248/1

[1] L.Devlin et al, WEPC43, IBIC 2013 Oxford [2] I.Chaikovska et al, THPME086, IPAC 14, Dresden [3] D.Di Giovenale et al, Nucl.Instrum.Meth A 665, 33–39, 2011 [4] A. Lacaita et al. IEEE TED, 1993 [5] M Danilov Nucl.Instrum.Meth. A604 (2009) 183-189 [6] M Panniello et al, BIW12 VA, USA