CHARACTERIZATION OF DETECTORS FOR BEAM LOSS MEASUREMENTS*

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Abstract

Silicon Photomultipliers (SiPMs) are a good candidate for use as beam loss detectors in an accelerator due to their insensitivity to magnetic fields, compactness and relatively low voltage working regime. Furthermore, when used in large numbers, they are significantly cheaper to be mass-produced than more conventional detectors, such as Ionization Chambers. To be able to evaluate the application potential of SiPMs in an accelerator, it is necessary to quantify their fundamental parameters as light detectors, as well as in combination with an optical fiber used for signal generation. In this contribution an experimental and analytical study to determine the time resolution, light sensitivity and dynamic range of a Cherenkov light detector, based on SiPMs, is presented.

INTRODUCTION

As part of a machine protection scheme, the main role of a Beam Loss Monitor (BLM) is to detect potentially dangerous beam instabilities and prevent subsequent damages to accelerator components. In addition, it should be able to localize and characterize the beam loss distribution. Depending on the position in the machine, different detector technologies often need to be applied to fulfill the requirements in terms of the spatial and time resolution, dynamic range and radiation hardness of the device. Due to the large number of monitors necessary to cover all beam modules in latest generation accelerators, it is desirable to find a solution which minimizes also the overall costs of the system.

The use of optical fibers in different configurations, allows covering larger segments of the machines with respect to more conventional BLMs, such as Ionization Chambers [1]. In the here-described study, a new BLM based on scintillating fibers and SiPMs, developed by Microsensor S.r.l. in collaboration with INFN Laboratori Nazionali del Sud, is compared to a BLM based on Cherenkov light detection by means of a standard multimodal optical fiber, connected to a SiPM. This experiment was realized at the two beam test stand, located in the CLIC Experimental area (CLEX) inside the CLIC Test Facility (CTF3). The tests were performed in proximity of an Optical Transition Radiation (OTR) screen. This choice was due to the characteristics of loss showers generated by an OTR screens: It constitutes a well defined target, both in its geometrical shape and in its location, which can thus be studied and analyzed in Monte Carlo simulations.

Extensive studies into this particular experimental setup have been performed by means of comparing results from different established simulation codes [2]. The FLUKA (*'Fluktuierende Kaskade'*) [3] software and the Geant4 (*"Geometry and tracking"*) [4] toolkit (G4) were used to create models capable to represent the interaction of the beam with the screen and the surrounding vacuum chamber and to characterize the beam losses in detail. In addition, previous studies aimed at determining the BLM requirements in terms of the detector sensitivity, resolution and dynamic range [5,6]. The above mentioned data has been used to evaluate the feasibility of a BLM system based on optical fibers and SiPMs in the CLIC environment. The main beam parameters for the CLIC Drive Beam (DB) and Main Beam (MB), are listed in the following Table 1.

Table 1: CLIC Beam Parameters

Beam line	Energy [GeV]	Time Dur. [ns]	e^-/train	Repetition Rate [Hz]
DB	2.4-0.24	243.7	$1.54 \cdot 10^{14}$	50
MB	9-1,500	156	$1.16 \cdot 10^{12}$	50

SHOWER SIMULATIONS

Simulations play a crucial role in all fields where one is interested in the behavior and response of a device even before it is physically realized. Among all numerical methods that rely on N-point evaluations in M-dimensional space to produce an approximate solution, the Monte Carlo method has an absolute estimation error that decreases with $N^{-1/2}$.

Table 2: Beam Parameters at the OTR Screen

Particle Type	Electrons
Energy	112 MeV
Repetition Rate	0.8333 Hz
Pulse duration	250 ns
Bunch Charge	1.15 nC
Bunch Frequency	12 GHz

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In the absence of exploitable special structures or other boundary conditions, all other methods have errors that decrease with $N^{-1/M}$, at best. This feature is crucial when it comes to the decision when and how to apply this method. Its full potential can only be exploited in problems involving more than two dimensions. The three dimensional problem of the beam losses generated by an OTR, is thus well suited for this simulation method.

Table 2 shows the beam parameters at the location of the OTR screen, before it hits the silicon screen. Some of these parameters were modified during the actual experiment to check the sensitivity of the detectors. When the beam hits the Silicon screen, significant beam losses occur that cross the fiber and generate a light signal which can then be detected by the sensor.

Table 3: Simulated Shower Comparison

Parameter	FLUKA	Geant4
Shower shape	conical	conical
Shower composition	Photons 82% Electrons 16% Positrons 2%	Photons 79% Electrons 18% Positrons 3%
Deposited energy (avg)	$1.3e^{-10}$ GeV/cm^3 (50 cm downstream)	$1.5e^{-10}$ GeV/cm^3 (50 cm downstream)

The simulations show a conical shaped secondary particle shower, involving mainly photons. Electrons and positrons, as charged particles, are of crucial interest for the purpose of loss detection as they can trigger scintillation and Cherenkov effects inside the fibers. Table 3 shows the composition of the simulated shower. It should be noted that of the 20 % of shower particles only high energetic particles are suitable for Cherenkov light generation, as this process requires relativistic particles.

BEAM LOSS MEASUREMENTS

Particle showers produced by the beam when hitting the silicon screen inside the OTR installation penetrate the optical fibers and generate light. This light is transported by the fiber itself and then detected by the SiPMs.

The two detectors used in the here-presented experiment were both based on SiPM technology but were based on different phenomena. One is an optical fiber connected to a SiPM to detect Cherenkov radiation, produced by relativistic charged particles passing through the fiber and is hence called a Cerenkov Light Detector (CLD). The other is a detector based on a scintillating fiber and referred to as Scintillation Light Detector (SLD) [7], producing photons by charged particles (not necessarily relativistic !) crossing the fiber, and then detected by SiPMs placed at both fiber ends. The latter solution is working in a coincidence way to reduce the SiPM dark count. This detector is also equipped with an event counting device.

All BLMs were placed downstream the OTR insertion. The beam reported in Table 1 is just the basic reference, from which some modifications were applied during the run to study the sensitivity of the detectors to different loss scenarios. A log file with all modifications and a time stamp was automatically produced.

Experimental Setup and First Measurements

The Cherenkov fiber consists of a standard multimodal plastic fiber of 400/430 µm diameter (core/cladding), 1.5 meters long, which was placed vertically and orthogonally to the beam axis due to a lack of space caused by close beam insertions. The other end of the fiber was closed with a plastic cup. The readout electronics consists of a purpose build feeding-pickup circuit and a fast amplifier (ORTEC VT120-inverter). The SiPM and the electronics were both shielded by means of lead bricks.

Two SLD were placed in two different positions to compare the behavior of the signals for different distances from the beam line. One (1) was placed directly on the beam pipe, just downstream the OTR, whilst the other (2) was placed around 30 cm downstream, on the floor. The first measurements were performed to evaluate the noise level introduced by two unavoidable sources: the long cables needed to bring the signal from the hall to the operator room (~80 m) and the environmental noise due to activation of the surrounding installation and ambient electromagnetic radiation.

This was considered as threshold level to get further signals during machine shutdown and to evaluate the component activation after the run. Fig. 1 shows the signals in case of an active beam without the OTR screen. In case of the CLD, one can see a rather noisy signal, characterized by several spikes and a maximum amplitude of about 4 V. The signal has a rise time of ~200 ns and a drop time of ~900 ns. Note that this estimation is strongly affected by the uncertainty introduced by noise.

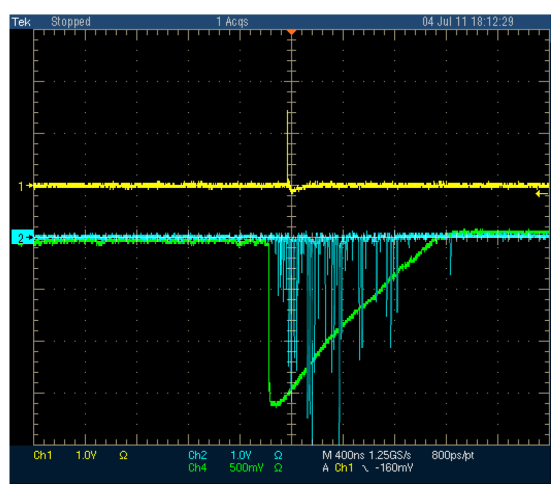

Figure 1: Signals in case of beam ON without OTR: trigger (yellow); Cherenkov fiber (blue); scintillating fiber (green). x: time 400ns/div; y: voltage.

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The SLD signal is well defined, with an amplitude of 3 V, a rise time of 2 ns and a drop time of 1,4 µs. There are several reasons for these differences: Different types of SiPMs and different electronics have direct impact on the measurement. Also, the different way in which the light is generated in the detector plays an important role when it comes to overall signal level and time response. Nevertheless, both SiPMs signals show similar behavior, with the amplitude of the CLD signal being almost twice as large as the amplitude in the SLD. One can also clearly see the very high loss level, even without the OTR screen inserted, resulting in a production of secondary charged particles energetic enough to generate a stable Cerenkov light signal.

Measurements with OTR Inserted

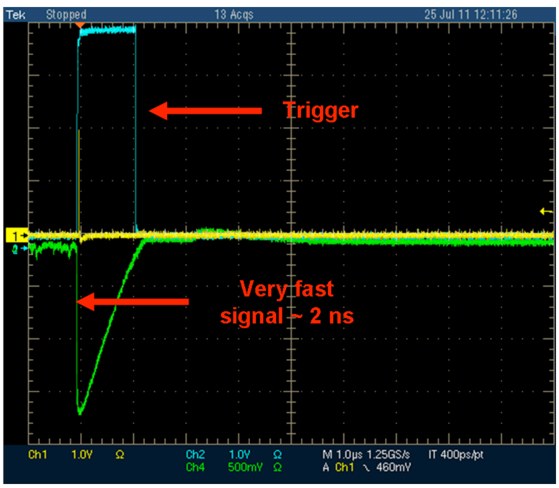

Figure 2: SLD in x: time 400ns/div; y: voltage 500mv/div.

In presence of the OTR, or rather with a higher loss level, the signals from the two BLM show drastic differences, Fig. 2. The SLD show an unmodified signal both in time and amplitude, indicating that the SiPM is working in highly saturated mode. Under such operating conditions, one can only gain information about the losses from the signal count rate. Such behavior was more or less expected for the extreme beam conditions found at CTF3. The CLD shows a maximum signal amplitude of more than 7 V, i.e. twice the amplitude of the signal in presence of the beam only. Under these conditions it is simpler to evaluate the rise time, with around 80 ns to reach 80% of the signal and a total signal time of ~600 ns. To test the sensitivity of the detectors to losses modifications two OTR screens with different materials and on different supports were used. Thereby small changes, such as a shift of a few millimeters along the beam path were realized. These were not enough to trigger any response in CLD signal, but the SLD registered a fluctuation in the count rate. The occurrence of the spikes even under these conditions suggest a damage to the detector.

Fig. 3 shows the count rate as registered by the two SLDs during the experiment. Fluctuations due to beam shifts and OTR presence can clearly be seen. It is also worth noting the higher count rate for the SLD2 as compared to SLD1, during the whole experiment, resulting from the location of the detector.

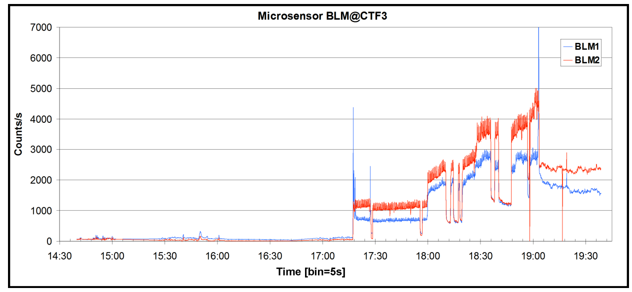

Figure 3: SLD count rates as a function of time.

CONCLUSION

First measurements with two different BLM detectors were realized at CTF3. Cherenkov light and scintillating fiber based SiPMs were used to study the beam loss in one specific location under different experimental conditions.

As expected, the noise level during the measurements was very high, even without the 'loss target'. This resulted in full detector saturation and rather long signal decay times. The CLD showed strange behavior and appeared to have been damaged during the early phase of the run. Bench tests performed after the experiment showed an increased dark noise for all SiPMs and confirm the need for either stronger shielding or larger distance between the loss location and the SiPM position. Experiments into signal deterioration in long fibers have been carried out in the meantime to investigate into different detector geometries [8].

Despite several problems in this first test, a lot was learned from this run. With a rather simple setup encouraging results were obtained to further improve the setup for a next and more detailed experimental session in near future.

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