FEASIBILITY STUDY OF AN OPTICAL FIBRE SENSOR FOR BEAM LOSS DETECTION BASED ON A SPAD ARRAY*

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Abstract

This contribution describes an optical fibre sensor based on the use of a silicon photomultiplier (SiPM) composed of an array of Single Photon Avalanche Detectors (SPADs). This sensor will be used for the detection and localization of particle losses in accelerators by exploiting the Cerenkov Effect in optical fibres. As compared to conventional vacuum photomultipliers, the SPAD array allows for maximizing the geometrical efficiency of Cerenkov photon detection. The array can be directly integrated into the fibre end while retaining the same quantum efficiency (20%) in the wavelength range of interest. The SiPM is intrinsically very fast due to its small depletion region and extremely short Geiger-type discharge, which is in the order of a few hundreds of picoseconds. Therefore, the combined use of optical fibres and SiPMs seems a promising option for a modern Cherenkov detector featuring subnanosecond timing, insensitive to magnetic fields, capable of single photon detection and allowing for the possibility of realization in the form of a smart structure. We present the layout and operating principle of the detector, its characteristics, and outline possible fields of application.

INTRODUCTION

Beam loss monitor systems are designed for measuring beam losses around an accelerator or a storage ring [1]. Particles showers penetrate the optical fibre and generate Cerenkov radiation. Using two parallel sensors along the most critical parts of the accelerator such as collimators, scrapers and aperture limitations the losses can be detected and localized. To couple the highest number of photons into the fibres, the geometrical features of the sensor have to be optimized. For this purpose a simulation code was developed, to achieve the best collection efficiency with the optical fibres available commercially in the range between 450-550 nm. The Numerical Aperture (NA) of these fibres is chosen considering the meridional and skew rays contribute to the coupling efficiency and the attenuation curves in the specific range of wavelengths where the SiPMs have their highest photosensitivity.

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CERENKOV RADIATION IN OPTICAL FIBRES

A charged particle passing through an optical fibre of large enough radius ($a \gg \lambda$) produces Cerenkov radiation inside the fibre if its velocity exceeds the phase velocity of light in the medium. Cerenkov photons are immediately generated and the number of photons N_{ph} per wavelength interval λ and distance L is given by [2]:

$$\frac{d^2 N_{ph}}{d\lambda\, dL} = 2\pi\alpha z^2 \frac{\sin^2\theta}{\lambda^2} \qquad (1)$$

where $\alpha = 1/137$ is the fine structure constant, θ is the Cerenkov cone semi-angle, λ the wavelength and L the path length of the particle with charge z in the fibre.

Cerenkov light is emitted on the surface of a cone with an angular opening semi-angle given by:

$$\cos\theta = \frac{1}{n\beta} \qquad (2)$$

where $\beta = v/c$ and n the refractive index of the fiber.

From Eq. (1), the intensity of Cerenkov light increases inversely to the cube of the wavelength as it is plotted in Fig. 1, consequently the blue color dominates in the visible spectrum.

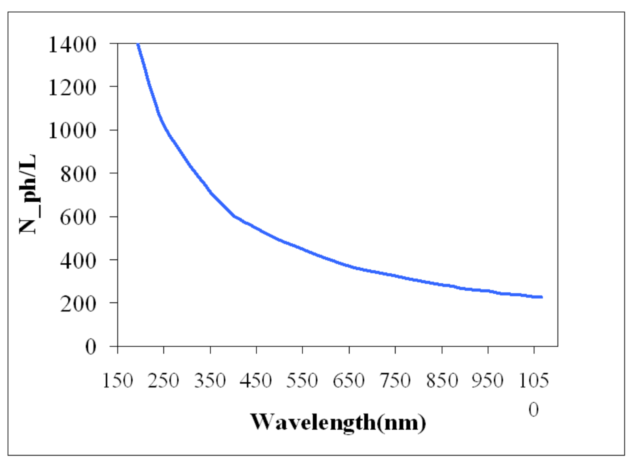

Figure 1: Number of photons produced per incident electron and per unit length L between 193 – 1064 nm.

When we consider the Cerenkov propagation inside a fibre we have to consider the probability of survival of the created photons (Collection Efficiency, CE) in the waveguide: this is determined by NA of the fibre and by the direction of the Cerenkov photons. In Fig. 2 we can see CE as a function of the incidence angle of the charged particle with respect to the fiber axis and the impact parameter, i.e. the shortest distance between the charged particle trajectory and fiber axis. To calculate CE we considered the contribution of both meridional and skew rays and of the fibre cleaving angle in a C++ code written for the purpose.

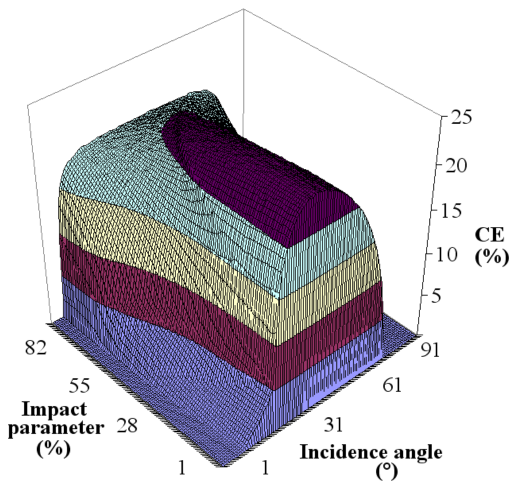

Figure 2: Collection efficiency of Cerenkov photons inside a pure silica optical fibre with NA=0.63.

The collection efficiency increases with the numerical aperture of the fiber as we can see in Fig. 3.

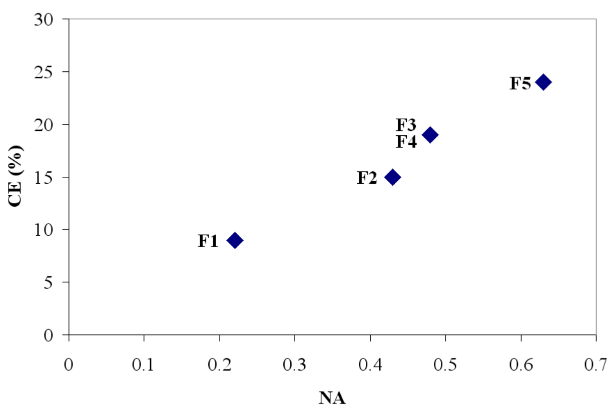

Figure 3: Collection efficiency of Cerenkov photons as a function of the Numerical Aperture (NA) of the optical fibres listed in Table 1. The collection efficiency is independent of the value of the fibre core diameter as it can be seen from the points F3 and F4.

The propagation of Cerenkov light in the fibre depends on the particle shower geometry as well as on the particle and fibre properties. For electrons the threshold energy to emit Cerenkov light in quartz fibre (n=1.46) is about 175 keV and the semi angle of the Cerenkov light is about 46°.

BEAM LOSS DETECTION SYSTEM

The proposed sensor is based on two parallel fibres with high numerical apertures as shown in Fig. 4. Both fibres are connected to two SiPMs with the same features.

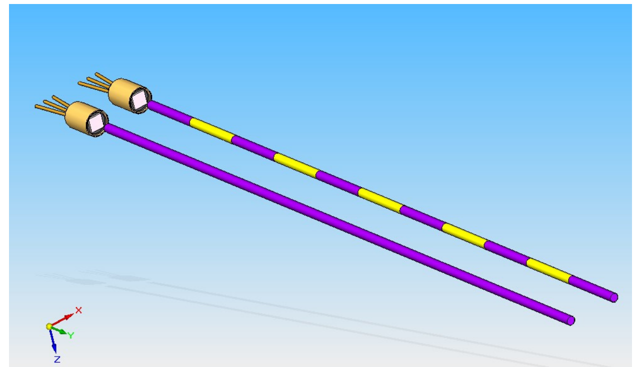

Figure 4: Sketch of the complete arrangement of the optical fibre sensor.

The first fibre, F1 (shown in violet), is used as reference arm. Its geometrical features are chosen to maximize the Cerenkov photons produced in the range between 450-550 nm, in which range the detector has a high Photon Detection Efficiency (PDE) of 15-20%.

The second arm of the sensor will be realized by splicing two fibres with different properties, F1 and F2, respectively indicated in violet and yellow, so that the fibre F2 will have much higher attenuation of F1. In this way the number of Cerenkov photons detected on the composite arm will be smaller than the number of the reference arm F1, with the difference depending on the number of large attenuation sections encountered by the travelling photons. By counting the number of fibres in the second arm it will then be possible to localize losses.

The advantages of this optical fibre sensor with respect to the traditional delay line configuration are:

- The resolution of the sensor depending mainly on the length of the spliced fibres of the second arm. It is therefore possible to achieve resolution of down to a few centimetres, much finer than the resolutions achieved by usual delay line sensors, which are limited by the detector time resolution to about 1 meter. Such finer resolution is particularly relevant when there is the need to monitor losses in narrow spaces as in CLIC Experimental area (CLEX) where the distance between the main beam and the drive beam is about 75 cm. Here this optical sensor, placed perpendicular to the accelerator pipes in a region where losses have been spotted, would allow detecting which pipe the losses came from.
- Each signal is read independently and absolute position calculated from the intensity ratio in the two branches, therefore, there is no overlap of signals and it becomes possible to detect multiple signals without using clock triggers.
- The active surface of the SiPM has the same dimensions of the fibre listed in Table 1 and this reduces the coupling losses between fibres and SiPM.

Optical Properties of Fibres

In this paper we considered multimode step index fibres with a total diameter of 1 mm for simple coupling with a

SiPM of the same dimension. The properties of these fibres are listed in the table below.

Table 1: Properties of optical fibres used in this paper for calculating the collection efficiency.

Fibres	NA	Core Diam. (μm)	Core material
F1	0.22	200	Pure Quartz
F2	0.43	200	Pure Silica
F3	0.48	200	Pure Silica
F4	0.48	400	Pure Silica
F5	0.63	486	PMMA

SILICON PHOTOMULTIPLIER

The Cerenkov light is detected with Silicon Photomultipliers at the end of the fibres. In the last few years, a new kind of planar semiconductor device has come out, namely the SiPM with promising features that could even replace traditional photomultiplier tubes. It is based on a Geiger mode SPAD elementary cell and it consists of an array of *n* independent identical microcells whose outputs are connected together as we can see in Fig. 5. The final output is thus the analog superposition of *n* ideally binary signals. This scheme along with the sensitivity of each individual cell to single photons appears to result in a perfect photosensor capable of detecting and counting single photons in a light pulse.

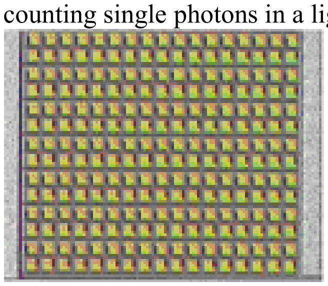

Figure 5: Magnification of a SiPM (courtesy of ST-Microelectronics, Catania).

Every SPAD cell is a p-n junction operating in Geiger mode at a low voltage (≈30 V) and fabricated in silicon planar technology. The junction is biased slightly above the breakdown by an overvoltage around 10% of the breakdown voltage itself, and it remains quiescent until a photon is absorbed in the depletion volume. This gives rise to the development of an avalanche current pulse, which needs a dedicated circuit to quench it, whose total charge is independent of the number of initial photocarriers. The quenching circuit is a passive one (a large-value resistor), which allows to keep the overall circuitry very simple. Such a resistor, in the form of a transparent polysilicon square frame, was integrated on top of the cell's cathode. The cell is square-shaped, with a 50/30 μm side-over-active-area ratio and a resulting 36% fill factor (the active area also includes the polysilicon frame) [3, 4].

It is deposited an antireflective coating layer and reduced the quasi-neutral region thickness above the thin junction depletion layer, in order to enhance the spectral response in the blue and near-ultraviolet wavelength ranges. The expected consequences are low leakage currents, low noise, and good PDE as it can be seen in Fig. 6.

The dimensions of these detectors make their coupling with optical fibres easier without influencing the final coupling efficiency.

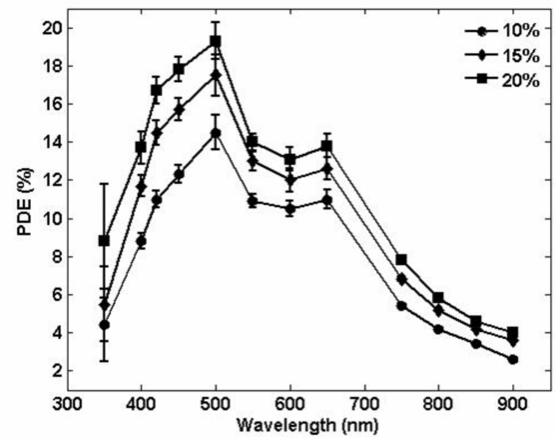

Figure 6: Photon detection efficiency of a SiPM as a function of wavelength (courtesy of ST-Microelectronics, Catania).

CONCLUSIONS

The properties of Cerenkov light emitted inside fibres combined with the lightguide conditions and the performances of SiPMs can be used for detecting and localizing losses in harsh environments such as accelerators. The optical fibre radiation hardness to very high radiation levels, the fast response of the SiPM associated to the sensor and the compact detector dimensions make it a good candidate for beam loss monitoring. To improve the collection efficiency in the range of 450-550 nm high aperture numerical fibres with core diameters between 200 μm and 500 μm are explored.

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