REQUIREMENTS OF A BEAM LOSS MONITORING SYSTEM FOR THE CLIC TWO BEAM MODULES

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Abstract

The Compact Linear Collider (CLIC) study investigates the feasibility of a high-energy electron-positron linear collider optimized for a centre of mass energy of 3 TeV. To achieve the high accelerating gradients, the RF power is produced by a novel two-beam acceleration method in which a decelerating drive beam supplies energy to the main accelerating beam. The linacs are arranged in modular structures referred to as the two beam modules which cover 42 km of beamline. Beam losses from either beam can have severe consequences due to the high intensity drive beam and the high energy, small emittance main beam. This paper presents recent developments towards the design of a Cherenkov fiber BLM system and discusses its ability to distinguish losses originating from either beam.

INTRODUCTION

As part of CLIC machine protection scheme, the main role of the two beam module BLM system is to detect potentially dangerous beam instabilities and prevent subsequent injection into the Main Beam linac (MB) and Drive Beam decelerators (DB). In addition, it should be able to localize and characterize the beam loss distribution. The main beam parameters for the two beam modules are listed in Table 1. Studies based on Monte Carlo simulations have been performed to determine BLM requirements in terms of detector sensitivity, resolution and dynamic range. These have been described previously in [1] and in the CLIC Conceptual Design Report. To date, the focus has been on whether ionization chambers would meet the requirements for a CLIC BLM system. However, due to the large number of monitors necessary to cover the two beam modules, it is desirable to find a less expensive solution. Cherenkov fibers are cheap, radiation hard compared with scintillating fibers, can cover large areas, and provide reasonable position and time resolution. Various feasibility studies [2], [3] have been performed for Cherenkov fibers as part of a BLM system, and they have been successfully implemented at, for example FLASH, DESY [4] and Sincrotrone Trieste [5]. Therefore to investigate the used of fibers at CLIC, previously performed Monte Carlo studies have been updated to include estimates of the secondary particle distributions (angular, velocity, type) of the shower particles at a possible detector location near each beam line.

Table 1: CLIC Beam Parameters, Two beam modules

	Energy (GeV)	$\tau_{\mathbf{train}}$ **(ns)**	**e$^-$/train**	**Rep Rate (Hz)**
DB	2.4 - 0.24	243.7	$1.53 \cdot 10^{14}$	50
MB	9 -1500	156	$1.16 \cdot 10^{12}$	50

ESTIMATING THE CHERENKOV SIGNAL

Cherenkov radiation is emitted when a charged particle with a velocity greater than the velocity of light in the medium (fiber) passes though a fiber with radius r $\gg \lambda$. The number of photons produced per unit wavelength is given by:

$$\frac{d^2N_{ph}}{d\lambda dL} = \frac{2\pi\alpha z^2 \cdot sin^2\theta}{\lambda^2} \tag{1}$$

where α is the fine structure constant, λ the wavelength of the light produced, and L the path length of the charged particle traversing the fiber. The wavefronts expand along the surface of a cone. The Cherenkov cone semi-angle, θ, is given by:

$$cos\theta = \frac{1}{n\beta} \tag{2}$$

where β = *v/c* and *n* is the refractive index of the fiber. The numerical aperture (NA) characterizes the range of angles over which the fiber can transmit light. The collection efficiency (CE), i.e. the number of photons that propagate in the waveguide over the total produced, depends on the NA of the fiber and the direction of the Cherenkov photons [6]:

$$\text{CE} \propto cos^{-1}\left[\frac{\beta\sqrt{n^2 - \text{NA}} - cos\phi_e}{sin\phi_e\sqrt{\beta^2 n^2 - 1}}\right] \tag{3}$$

where ϕ_e is the angle between the direction of propagation of the charged particle and the fiber axis. Fig. 1 shows the

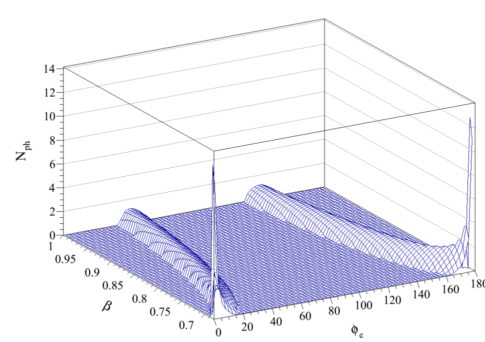

Figure 1: Number of the transmitted photons as function of β and ϕ_e, for a fiber diameter 0.365mm and NA 0.22.

calculated number of transmitted photons (C.E.$\times N_{ph}$) in the range λ = 300 to 700 nm for an electron (or positron) crossing a fiber of NA 0.22 and diameter 0.365 mm, as a function of β and ϕ_e.

Simulations

Simulations of beam losses at four energies corresponding to the maximum and minimum in each beam line were made using version 2011.2b.3 of the FLUKA code [7], [8]. The FLUKA model includes main beamline components such as the quadrupoles, Power Extraction and Transport Structures (PETS) and the Accelerating Structures (AS). The layout of the modules are represented in accordance with their energy dependent position in the MB. The aperture restriction in the DB is modelled at the end of each PETS with a diameter of 23 mm, equal to the aperture of the DB quadrupole. In the MB, the decreasing aperture of the 24 cells within the AS is modelled in fewer but thicker steps, with a final diameter of 4.7 mm. The vacuum chamber within in the MB quadrupole is modelled with a diameter of 10 mm.

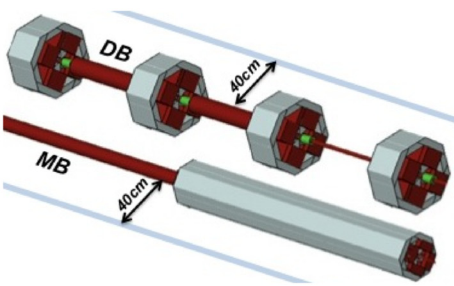

Figure 2: Representation of Two Beam Modules in FLUKA simulations. The blue areas indicate the location of the boundaries used for scoring the shower particles.

For each energy, two loss scenarios were considered: a loss at a single aperture restriction immediately upstream of a quadrupole, and losses distributed at several points along the aperture before each quadrupole. For the first scenario, the impact was represented in the horizontal plane, and the loss angle determined by the maximum grazing angle possible between a defocusing and focusing quadrupole. For the second scenario the losses were represented by electrons travelling in the direction of the beam, generated in a circular distribution just inside the aperture. For each loss scenario the secondary shower particles crossing two boundaries were recorded. The boundaries were placed parallel to each beam, at a horizontal distance of 40 cm from the beamline. The charged particles above the Cherenkov production threshold were binned according to their velocity, particle type and crossing angle. In the following calculations only electrons and positrons in the secondary particle shower were considered. Whilst other charged shower particles are produced (e.g. protons for beam losses at higher energies), they account for less than 5% of the particle shower.

Cherenkov signal

Fig. 3 shows an example of the distribution of electrons and positrons crossing a boundary parallel to the beamline for the case of 2.4 GeV electrons impacting a single DB aperture. The results are normalized to one lost electron and scaled for a boundary height of 0.365 mm to match the diameter of a typical Cherenkov fiber used in BLM. The number of transmitted Cherenkov photons is calculated by multiplying the central value from each bin by the corresponding values in Fig. 1. The result is displayed in Fig. 4. It is clear from this example that not all the secondary particles above the Cherenkov production threshold energy crossing the fiber will result in a detectable signal.

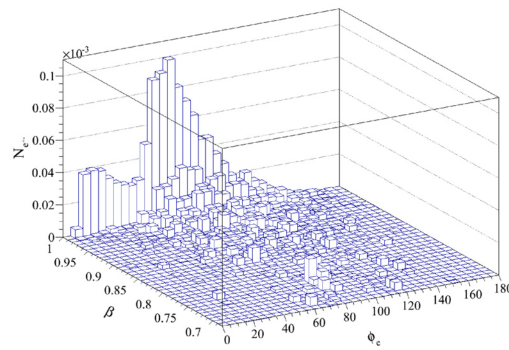

Figure 3: Distribution of electrons and positrons crossing a boundary representative of the fiber axis as a function of β and ϕ_e normalized to one lost electron, for 2.4 GeV losses at a single aperture in the DB.

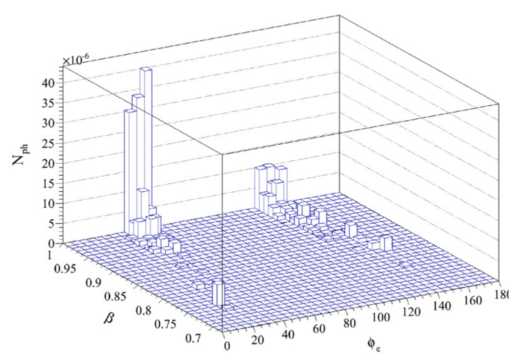

Figure 4: Distribution of transmitted photons as a function of β and ϕ_e normalized to one lost electron, for 2.4 GeV losses as a single aperture in the DB.

The above calculations were performed for each loss scenario and loss energy.

SYSTEM SENSITIVITY AND DYNAMIC RANGE

Ideally the system sensitivity should allow for the detection of standard losses during operation. It is considered that a loss of 10^{-3} of the full intensity of the beam along each DB decelerator and MB linac would result in luminosity losses due to beam loading variations. To prevent the onset of such losses, the BLM system should be able to detect losses at 10 % of this level. The number of transmitted photons produced per meter of fiber, based on FLUKA simulations of losses distributed along the aperture, scaled to a loss of 10^{-4} of a bunch train along each 875 m DB decelerating sector and each 20 km MB linac were calculated. The sensitivity requirements for the photodetector are expressed as the number of photons arriving at the photodetector per bunch train for a 100 m fiber.

The upper limit of the dynamic range is determined by the requirement of the BLM system to detect the onset of dangerous losses. Beam losses become destructive when 0.01 % of a MB or 1.0 % of a DB train impacts at an aperture restriction [9]. The number of transmitted photons for the destructive losses of a DB and MB bunch train, based on FLUKA simulations of beam loss at a single aperture, were calculated. Using the arrival rate at the detector of these photons as an upper limit and the sensitivity requirements as a lower limit, the required dynamic range is estimated and listed in Table 2.

Table 2: Estimation of sensitivity and dynamic range required for a detector coupled to the fibers. *For a 100 m fiber, the photon pulse duration is 410 ns and 323 ns for the DB and MB respectively

	Sensitivity (N_{ph}/train)*	**Dynamic Range**
DB 0.24 GeV	$7 \cdot 10^3$	$5 \cdot 10^3$
DB 2.4 GeV	$2 \cdot 10^5$	$2 \cdot 10^3$
MB 9 GeV	$1 \cdot 10^2$	$1 \cdot 10^3$
MB 1500 GeV	$7 \cdot 10^3$	$5 \cdot 10^2$

TEMPORAL AND SPATIAL RESOLUTION

The machine protection strategy is based on a 'next pulse inhibit', which requires a BLM response time of 8 ms. This time resolution is easily achievable as it is much greater than the light propagation time in the fiber and rise time in photomultiplier electronics.

However, sufficient spatial resolution to distinguish between losses from two successive quadrupoles on the same beamline is desirable. The minimum distance between quadrupoles is 1 m, corresponding to several ns in terms of photon arrival time at a detector. Whilst the time resolution of some photodetectors might be sufficient, a sensor based on two parallel fibers has been conceived to provide improved position resolution [2]. The method involves comparing intensity between the two signals. A standard fiber provides a reference signal and a second fiber with a higher attenuation coefficient provides a comparison signal allowing a position resolution to the order of several cm.

The 'signal to cross-talk ratio' for a beam loss monitor is the ratio of the power of the wanted signal to the power of the unwanted signal. In the CLIC two beam modules a significant contribution to the unwanted signal could arise from the neighboring beam. Considering dangerous loss scenarios, and comparing the estimated number of propagated photons produced in a fiber from the near and far beams, it appears there could be problems distinguishing a MB loss signal from cross-talk. In terms of machine protection, this would not be a problem since a dangerous loss would never go unnoticed.

CONCLUSIONS

A method has been developed to determine the Cherenkov signal from a secondary particle shower in the CLIC two beam modules. The study has indicated that in terms of sensitivity and dynamic range, Cherenkov fibers seem to be a good candidate for a BLM technology choice. Further studies verifying the dynamic range and sensitivity requirements will enable an appropriate choice of photon counting device. Concerning cross-talk, the difference in time structures between the pulses from the MB and DB could be utilized to distinguish between losses from each beam by using a photodetector with adequate time resolution. Installations of fibers at the CLIC Test Facility (CTF3) experimental hall are planned to complement these studies and further investigate the feasibility of Cherenkov fibers as a CLIC BLM system.

REFERENCES

[1] M. Sapinski, B. Dehning, E.B. Holzer, M. Jonker, S. Mallows, T. Otto, C.P. Welsch "Requirements of CLIC Beam Loss Monitoring System", IPAC'10, Kyoto, July 2010, p. 2869

[2] A. Intermite, M. Putignano, C.P. Welsch "Feasibility Study of and Optical Fibre Sensor for Beam Loss Detection Based on a SPAD Array", DIPAC'09, Basel, May 2009, p. 228

[3] X.M. Marechal, T.Itoga, Y. Asano, "Fiber Beam Loss Monitor for the Spring-8 X-FEL: A numerical Studay of is Design and Performance", IPAC'10, Kyoto, July 2010, p. 2833

[4] F. Wulf, M. Koerfer, "Local beam loss and beam profile monitoring with optical fibers", Proc. DIPAC '09, Basel, May 2009, WEOA01, p. 228

[5] L. Froehlich, "Machine protection for FLASH and the European XFEL." DIPAC'11, Hamburg, May 2011

[6] S.H. Law, S.C. Fleming, N. Suchowerska, D.R. Mckenzie, Appl, Opt. 45 (2006) 9151

[7] G. Battistoni, et al., "The FLUKA code: Description and Benchmarking", AIP Conference Proceeding 896, 31-49, (2007)

[8] A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, "FLUKA: a multi-particle transport code", CERN-2005-10

[9] M. Jonker, E.B. Holzer, S. Mallows, D. Manglunki, G. Morpurgo, T. Otto, M. Sapinski, "The CLIC Machine Protection", IPAC'10, Kyoto, July 2010, p. 2860