FIBER BASED BLM SYSTEM RESEARCH AND DEVELOPMENT AT CERN

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Abstract

The application of a beam loss measurement (BLM) system based on Cherenkov light generated in optical fibers to a linear accelerator with long bunch trains is currently under investigation at CERN. In the context of the Compact Linear Collider (CLIC) study, the machine protection role of the BLM system consists of its input to the 'next cycle permit'. In between two cycles it is determined whether it is safe to commit the machine for the next cycle. A model for light production and propagation has been developed and validated with beam measurements. Monte Carlo simulations of loss scenarios established the suitability in terms of sensitivity and dynamic range. The achievable longitudinal position resolution of the system, considering that the bunch trains and the optical fiber length are comparable in size is discussed.

INTRODUCTION

Beam loss monitors (BLMs) are common devices used in lepton and hadron accelerators. They can be used as a diagnostics tool and/or as a crucial part of the machine protection system. Typically, a BLM is placed outside the vacuum chamber and observes the secondary particle shower generated when the lost particles interact with the vacuum chamber walls or beamline components. At high energy accelerators, the BLM system should detect the magnitude and location of losses and, when necessary, trigger a beam interlock system.

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 (TBMs) which cover $\sim$42 km of beamline. Losses from either beam can have severe consequences due to the high intensity drive beam and the high energy, small emittance main beam.

To monitor beam losses in the TBMs, it is estimated that a total of more than $\sim$45,500 localised monitors would be required [1]. It is therefore desirable to investigate cost effective technology choices that cover large distances along the beam line, particularly for the drive beam decelerators which would account for $\sim$41,500 of the required localized detectors. However, the BLM system based on Cherenkov fibers currently under development is in no way specific to CLIC and can be applied to any hadron machine.

MULTIMODE CHERENKOV FIBERS AS A BLM

Detection Principle

Cherenkov radiation is emitted when the velocity of a charged particle travelling through the fiber exceeds that of the phase velocity of light in the fiber. The photons are emitted along a cone with opening angle, θ_c, given by:

$$cos\theta_c = \frac{1}{n\beta} \tag{1}$$

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

The number of photons produced per unit wavelength is given by:

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

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.

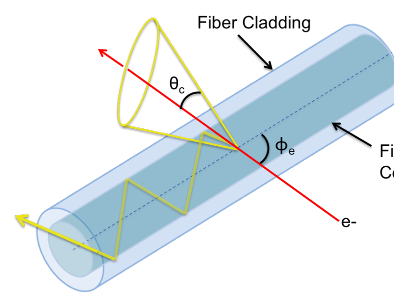

Figure 1: Schematic to illustrate the detection principle for Cherenkov beam loss monitors.

A multi-mode optical fiber will only propagate light entering the fiber within a certain 'acceptance cone'. The numerical aperture (NA) characterizes the range of angles over which the fiber can transmit light. Thus, when estimating the signal from Cherenkov fibers, one has to consider not only the probability of production of light, but the probability that it is trapped and propagates to the fiber end face. Without considering attentuation effects, the probability, $P_{e,a}$ that the photons are trapped and exit within the 'the nominal acceptance cone', is defined by [2]:

$$\mathrm{P_{e,a}} = \frac{1}{\pi} cos^{-1}\left[\frac{\beta\sqrt{n^2 - \mathrm{NA}^2} - \cos\phi_e}{\sin\phi_e\sqrt{\beta^2n^2 - 1}}\right] \tag{3}$$

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

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The photons that exit within the nominal acceptance cone exclude skew ray photons that travel larger distances in the fiber and lead to dispersion effects in the signal. The half-angle of this cone, referred to as the maximum 'acceptance angle', θ_{max}, is determined by the indices of refraction of the core and the cladding:

$$n \sin \theta_{max} = \sqrt{n_{core}^2 - n_{clad}^2} \quad (4)$$

where n is the refractive index of the material (e.g. air) into which the photons exit.

Based on the geometry considerations in [3], an analytical model to predict the number of trapped photons as a function of the velocity and incoming angle of a charged particle was developed [4]. The model has been verified experimentally using 120 GeV protons at test beam lines. Predictions were also made with the Monte Carlo transport code FLUKA [5], [6], which includes optical photon production and transport capabilities. The results were found to be in good agreement with the model and experimental data. The dependence of the detectable light yield on the incident angle of a charged particle is clearly shown in Fig. 2. Estimates of three photon yields are given: the number of trapped photons, the number of trapped photons that exit the fiber end face, and the number trapped photons that exit the fiber end face within the nominal acceptance cone.

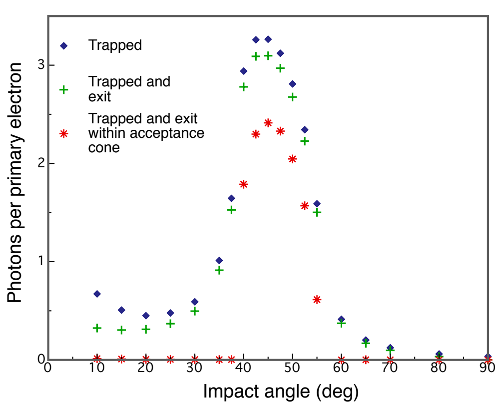

Figure 2: FLUKA estimates of the photon yields in a multimode Cherenkov fiber of diameter 365 μm fiber with NA 0.22, as a function of the angle of an incoming charged particle with β=1.

General Considerations

Multimode Cherenkov fibers have been used as beam loss monitors, or beam loss position monitors at various facilities such as Fermi@Elettra, Synchrotron Trieste [7], and FLASH, DESY [8]. The advantages of using Cherenkov fibers are that they are fast, insensitive to magnetic field and temperature fluctuations and that they cover large distances of beamline. Furthermore, as the fibers are only sensitive to charged particles, they are almost completely insensitive to the background signal from activation, which is mostly gamma radiation. The possible disadvantages of using Cherenkov fibers are that they are much less sensitive than scintillating fibers, that only a small proportion of the light is transported to the end face, and that the angular dependent response makes quantitative predictions of beam loss more complicated.

Attenuation Effects In the relevant spectral range, i.e., 200-700 nm, attenuation is mostly due to Rayleigh scattering where the corresponding attenuation coefficient is proportional to λ^{-4}. This limits the length of the Cherenkov fibers to no more than ~100 m.

Radiation Effects Whilst the fiber quartz itself is radiation hard with respect to scintillating fibers, various radiation effects in multimode fibers, such as damage to the buffer material and the radiation induced attenuation (RIA) can limit their lifetime in high radiation environments. In terms of manufacture, the RIA in fibers depends on many factors such as the OH content, the core to cladding diameter ratio, and the doping of the cladding. In general, high OH content, pure silica step-index fibers with F-doped cladding suffer less from RIA. Some of the multimode Chernekov fibers tested for use at the CMS quartz calorimeter, for example, survived in terms of the integrated light yield exposure up to 22 MGy [3], [9]. However, it should be noted that the RIA varies strongly with the wavelength. Furthermore the RIA depends not only on the total dose to which the fiber is exposed, but the dose rate and the type of radiation. Therefore careful fiber selection and specific radiation testing is necessary.

Spatial Resolution Cherenkov fiber BLMs can provide very good time and spatial resolution when used at facilities where the pulse duration is less than a few ns. The timing of the photon signal then corresponds to a longitudinal position along the beamline. For a system with fast readout electronics, it is possible to locate the longitudinal position of the loss with a resolution of less than 1 m. For example at Fermi@Elettra, using silicon photomultiplier detectors and a 250 Msamples/s ADC, a longitudinal resolution of ~50 cm is achieved [7]. For facilities where the bunches are long with respect to the length of the fiber, the situation is more complicated. The achievable longitudinal position resolution with multibunch trains is discussed in the final section.

CLIC BLM REQUIREMENTS

The following discussion focusses mainly on fiber BLMs for the CLIC drive beams. However the key beam paremeters for both the drive and main beam are listed in Table 1.

The CLIC Machine Protection System

The machine protection strategies at CLIC are based on passive protection (e.g. masks and spoilers that are able to absorb a full bunch train), a beam interlock system, the

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Table 1: CLIC Beam Parameters, Two Beam Modules

	Energy (GeV)	τ_{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

use of instrumentation and components that are 'safe by design', and a 'next cycle permit', where after every machine cycle, the permit is systematically revoked and only re-established if a predefined list of beam quality checks is passed [10]. The main role of the TBM BLM system as part of the machine protection system is to detect potentially dangerous beam instabilities and prevent subsequent injection into the main beam linac and drive beam decelerators. A possible increase in the repetition rate of the machine from 50 to 100 Hz is foreseen. The BLM response time is therefore required to be less than 10 ms.

Sensitivity and Dynamic Range Requirements

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 drive beam decelerator and main beam 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. This determines the lower limit of the dynamic range. The upper limit of 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 main beam or 1.0 % of a drive beam train impacts at an aperture restriction [10].

Radiation Levels

Conservative estimates of the radiation levels in the CLIC tunnel, which are based on the maximum permitted beam losses described in the above section and continuous operation for 180 days per year, predict that the fibers placed in the hall should withstand a dose of up to 10^5 Gy per year [1].

PREDICTIONS OF THE PHOTON YIELD IN FIBERS FROM CLIC DRIVE BEAM LOSSES

FLUKA Simulations

To investigate the use of fibers for the CLIC drive beams, Monte Carlo studies were performed to include estimates of the secondary particle distributions, i.e. the angle, velocity, and type of the shower particles at a possible detector location near each beam line.

Simulations of beam losses at 2 energies corresponding to the maximum and minimum in the drive beam were made using version 2011.2b.3 of the FLUKA code [5], [6]. The FLUKA model includes main beamline components such as the quadrupoles, Power Extraction and Transport

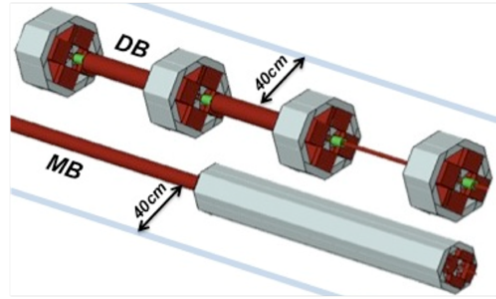

Figure 3: Representation of the two beam modules in FLUKA simulations.

Structures (PETS) and the Accelerating Structures (AS). The aperture restriction in the drive beam is modelled at the end of each PETS with a diameter of 23 m, equal to the aperture of the drive beam quadrupole.

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 defocussing 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 in the main beam and less than1% in the drive beam.

Photon Yields from Drive Beam Losses

Based on the FLUKA simulations of a drive beam bunch train lost at a single aperture, the number of trapped photons were calculated using the shower distribution data as an input for the analytical model described in [4]. The calculation assumes a 365 μm diameter fiber with NA 0.22. The number of photons travelling in the downstream and upstream directions of the fiber scaled to destructive loss limits are given in Table 2.

Similarly, the number of trapped photons produced per meter of fiber, based on FLUKA simulations of losses distributed along the aperture were calculated. The numbers, scaled to a loss of 10^{-4} of a bunch train along each 875 m drive beam decelerating sector, represent the sensitivity requirements of a photon detector and are listed in Table 3. The required dynamic range for a downstream photon de-

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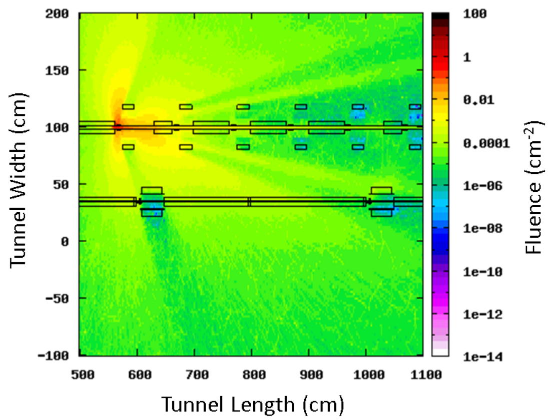

Figure 4: Spatial distribution of electron and positron fluences near the beam line resulting from a drive beam loss of 2.4 GeV, scaled to 1 lost electron.

tector is calculated by using the photon yields in Table 2 as an upper limit, and the sensitivity requirements as a lower limit, where photon pulse durations are taken into account. Assuming the full train contributes to the loss signal, the duration of the photon pulse due to a destructive loss is approximately equal to the length of the bunch train. For operational losses and a 100 m fiber, the total photon signal length at a downstream detector is 410 ns, and an upstream detector is 1080 ns. This is due to the fact that the velocity of the photons the fiber (v∼ 2/3c) is less than that of the bunch train (v∼ c).

Table 2: Number of Trapped Photons Resulting from Loss at a Single Aperture, Scaled to Dangerous Loss Limits

	N_{ph}**/train** travelling Downstream	N_{ph}**/train** travelling Upstream
DB 0.24 GeV	$4.3 \cdot 10^7$	$2.8 \cdot 10^7$
DB 2.4 GeV	$5.4 \cdot 10^8$	$3.7 \cdot 10^8$

Table 3: Estimation of Sensitivity and Dynamic Range Required for a Detector Coupled to the Fibers

	Sensitivity (N_{ph}/train)	**Dynamic Range**
DB 0.24 GeV	$2 \cdot 10^4$	$4 \cdot 10^2$
DB 2.4 GeV	$4 \cdot 10^4$	$3 \cdot 10^2$

If identical BLM systems were used for all drive beam energies the required dynamic range would be $\sim 10^4$. This is still achievable with silicon photomultipliers (SiPMs).

LONGITUDINAL RESOLUTION AND CROSS TALK, CLIC TBMS

Achievable longitudinal resolution at CLIC with multibunch trains

The achievable longitudinal resolution depends on the dispersion of the photon signal due to the fiber and the longitudinal distribution of the secondary particle shower, which for the CLIC drive beam is not considered to be a problem: for a fiber of NA = 0.22, the spread of the photon signal resulting from a 2.4 GeV loss at a single location is estimated to be < 5 ns with a rise time of < 1 ns [11]. At CLIC, the bunch trains are 156 ns and 244 ns for the main and drive beam respectively, i.e. they are comparable in length to that of the fiber. For long multibunch trains (with high frequency bunch structure) determining the achievable longitudinal position resolution is complicated. In general, it is not possible to reconstruct an arbitrary loss pattern in position and time. However, only several loss patterns can be expected:

- Single or multiple individual loss locations. Either constant losses in time (e.g. due to obstructions), or losses that vary with time (e.g. due to 'dust' particles)
- Losses building up along the train starting at a particular bunch number (e.g. due to long range or resistive wall wakefields)
- Constant losses (e.g. interaction with beam gas, combined with aperture limitations)
- Equipment failures

It is not yet certain whether the above scenarios can be distinguished from each other and with which longitudinal resolution they can be identified. Considering a uniform loss structure along a bunch train, then for single or even multiple loss locations, the location of the loss could be identified to a precision of < 1 m from the timing of the corresponding rise in the upstream photon signal (with the expected time resolution of the BLM system). For more complicated loss scenarios (e.g. a non-uniform loss structure along a train), the achievable longitudinal resolution using the timing information from both photon signals, i.e. from detectors at each end of the fiber is under investigation. Additional measurements to independently determine the loss structure along the train might be required, e.g. with the use of a fast, localized BLM (such as a diamond detector) located every ∼20 - 100 m along the beamline.

For machine protection purposes, the achievable longitudinal resolution is not an important issue, as measurements of the integrated loss signal would be sufficient to determine the onset of a dangerous loss.

Cross Talk Between Signals from Main and Drive Beams

The signal to crosstalk ratio for a beam loss monitor is the ratio of the magnitudes of the wanted to the unwanted parts of a signal. In the CLIC TBMs, a significant contribution to the unwanted part of a signal could arise from the

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neighboring beam. Whilst a detailed study of the signal induced in Cherenkov fiber BLMs due to main beam losses is currently in process, estimates of the absorbed dose near the beamline due to losses from both beams have been performed [12]. The results indicate that the dose levels on the main beam side are similar in the case of a dangerous loss from the 2.4 GeV drive beam or a dangerous loss from the 9 GeV main beam. However, the estimates of the absorbed dose on the drive beam side differ substantially for each of the loss scenarios. Therefore by comparing the signals from both the BLMs located on either side of the beamline, the origin of losses could be determined. Since a dangerous loss from either beam would never go unnoticed, the ability to distinguish losses from the main and drive beams is not necessary for machine protection purposes. However, in order to minimise the impact on machine availability from false 'veto' decisions for the next cycle permit, it is highly desirable.

SUMMARY

Cherenkov fibers have been well characterized as a beam loss monitor. The light yield for the beam losses in the drive beam is sufficient for a 365 μm diameter fiber, and the required dynamic range and sensitivity of the photon detector is achievable. Estimates of the expected, rather than maximum, radiation levels in the CLIC tunnel and specific radiation testing of fibers will indicate whether they will survive the lifetime of the accelerator or require regular replacement. Further study of the achievable longitudinal resolution for conceivable loss scenarios with long bunch trains is required to determine how suitable fibers are for CLIC compared with other technologies.

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