UPDATE ON BEAM LOSS MONITORING AT CTF3 FOR CLIC*

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Abstract

The primary role of the beam loss monitoring (BLM) system for the compact linear collider (CLIC) study is to work within the machine protection system. Due to the size of the CLIC facility, a BLM that covers large distances along the beam line is highly desirable, in particular for the CLIC drive beam decelerators, which would alternatively require some ~40,000 localised monitors. Therefore, an optical fibre BLM system is currently under investigation which can cover large sections of beam line at a time. A multimode fibre has been installed along the Test Beam Line at the CLIC test facility (CTF3) where the detection principle is based on the production of Cherenkov photons within the fibre resulting from beam loss and their subsequent transport along the fibre where they are then detected at the fibre ends using silicon photomultipliers. Several additional monitors including ACEMs, PEP-II and diamond detectors have also been installed. In this contribution the first results from the BLMs are presented, comparisons of the signals from each BLM are made and the possible achievable longitudinal resolution from the fibre BLM signal considering various loss patterns is discussed.

INTRODUCTION

CLIC [1] is a proposed lepton collider capable of reaching a centre of mass energy of 3 TeV. CLIC will use a novel two beam acceleration method in which a drive beam (DB) is decelerated to transfer RF power through power extraction and transfer structures (PETS) to a main beam (MB).

Strategies for the CLIC machine protection system are described in [2]. Working within a machine protection system, a BLM will detect particles lost from the beam which could occur due to several reasons such as poor beam alignment, scattering with residual gas etc.

CTF3 located at CERN is designed to test the charge multiplication process using a delay loop and combiner ring that will be used at CLIC to generate a high charge DB required to transfer RF power to the MB. The beam is transferred to the CLEX hall where it is directed down one of two beam lines. The first is the two beam test stand (TBTS) where a PETS tank transfers RF power to accelerate a probe beam in the CALIFES linear accelerator and the second is the test beam line (TBL) which is used to measure the stability of a decelerated beam. The TBL consists of 16 modules each containing a quadrupole, a beam position monitor and a PETS tank. Table 1 below shows the comparison of TBL with the CLIC drive beam.

Table 1: Comparison of Parameters of TBL at CTF3 and the Future Drive Beam Decelerator at CLIC

Parameter	TBL	CLIC
Number of PETS	16	1492
Length of PETS (m)	0.80	0.21
Initial average current (A)	28	101
Initial Energy (MeV)	150	2400
Mean energy extracted (%)	~54	84
Number of FODO cells	8	524
Pulse length (ns)	140	240
Bunch Spacing (GHz)	12	12

The baseline technology for the CLIC BLM system is based on ionisation chambers. However, due to cost considerations an alternative choice of technology based on optical fibres is currently under investigation [3, 4]. The advantage of an optical fibre BLM is that it can cover large distances of beam line (it is limited to ~100 m, due to attenuation effects).

This type of BLM technology has been shown to work at Free Electron Laser facilities such as FERMI@ELETTRA [5]. However due to the beam pulses at CTF3 and CLIC it is not clear whether the longitudinal position resolution for various loss scenarios makes optical fibres a suitable choice to locate the origin of a beam loss.

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

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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'. This is dependent on the angle of the charged particle with respect to the fibre axis and its velocity.

A multimode fibre has been installed along TBL at CTF3 to test this technology under multi bunch beam conditions. Along with the fibre, three localised detectors are installed, namely: Aluminium Cathode Electron Multipliers (ACEM), Cherenkov crystal PEP-II radiator detectors and diamond detectors. Such localised detectors are used as an independent measure of beam losses detected by the fibre BLM.

DETECTOR INSTALLATION

Optical Fibre BLMs

The fibres installed at CTF3 are made from Heraeus preform and have a core and cladding thickness of 200 µm and 220 µm respectively. For the measurements presented in this paper, a 28 m fibre was installed parallel to TBL attached to a rope 28 cm above the beam line. A fibre of 25 m is attached to the downstream end of the fibre and a 75 m fibre attached to the upstream end of the fibre using fibre couplers (measured to give approximately 80% transmission). These fibres are used to take the signal produced in the fibre parallel to the TBL to the photon detectors located outside the accelerator hall, where they are situated to protect them from potential radiation damage.. Two additional fibres run alongside the downstream and upstream read-out fibres to subtract the background signals not generated along the TBL.

The photon detectors used at the fibre end are avalanche photodiodes (APD) operated in Geiger mode and referred to as a silicon photomultiplier (SiPM) or multi-pixel photon counter (MPPC). An SiPM is a segmented array of APDs with the output of each cell summed together to give the final output of the device. SiPMs are small robust devices that are insensitive to magnetic fields and compared to photomultiplier tubes they have a similar gain ($10^5/10^6$) and reduced operational voltages (50-100V). The SiPM currently being used is a Hamamatsu S10362-33-050C [6]. It is biased with a voltage of 71.6 V and is housed in a light tight box to protect the device from ambient lighting. The charge produced by the SiPM is converted to a voltage before exiting the box and sent to a LeCroy 104MXi-A 10 Gs/s oscilloscope with 1 GHz bandwidth.

Localised Detectors

Three detectors (ACEM, PEP-II and diamond) were installed downstream of the 8th quadrupole of TBL in order to perform direct comparison of their response. Furthermore, six extra ACEM detectors were installed immediately after the 3rd, 4th, 7th, 11th, 12th, 15th and 16th quadrupoles in the FODO lattice. A configuration with one localised detectors in consecutive quadrupoles was chosen to potentially study the fraction of beam losses on the horizontal/vertical plane. To avoid saturation the detectors were placed 40 cm below the beam line.

The ACEM detectors are photomultiplier tubes with the cathode replaced with a thin aluminium foil making it sensitive to charged particles rather than photons. The rise time of an ACEM detector is typically < 10ns but this is not fast enough to measure losses from individual bunch trains bust sufficient to measure some loss structure over the train. ACEM detectors also require shielding to protect from magnetic fields.

PEP-II detectors are small Cherenkov detectors made from fused silica, 8 mm diameter and 10 mm long, coupled to a photomultiplier tube. These detectors were borrowed from the PEP-II experiment in Stanford [7]. PEP-II detectors also require shielding for the PMT tube.

Diamond detectors work like a solid state ionization chamber. Diamond is a radiation hard material and with a band gap of 5.5 eV, diamond is classed as a large band gap semiconductor. This large band gap coupled with a large thermal conductivity of 22 W/(cm.K) allows for the operation of diamond detectors at room temperature with low noise even in the presence of high intensity radiation. The diamond detector used in these experiments was a polycrystalline diamond detector bought from CIVIDEC[8] as used at the LHC for beam loss monitoring purposes [9].

These detectors are powered by a high voltage power source. The ACEMs and PEP-II are biased negatively with operational voltages in the range of -600 to -700 V and -500 to -600 V, respectively. The diamond detector is positively biased with an operational voltage in the range of 500 to 600 V.

All three localised detectors were read out with a 250 MHz ADC

MEASUREMENTS

Various data samples were taken using the detector setup described above during stable beam operation of TBL on the 15th May 2013. The beam conditions during data acquisition were a beam current of 16 A and a pulse length of 150 ns. The fibre used for downstream background subtraction was damaged before measurements had taken place; hence no measurement of this signal was possible. Figure 1 represents an average of 25 pulse samples for the three localised detectors situated downstream of the eighth quadrupole in the lattice. The diamond detector produces a positive output since it was biased by a positive voltage and likewise the ACEM and PEP-II detectors were biased negatively which show a negative signal output. A clear difference in the time response between the detectors is observed. The PEP-II and the diamond detector are fast enough to follow the 150 ns beam pulse, providing also some information of the substructure of the beam losses within the bunch train. However, a small delay and widening of the signal is observed for the ACEM detector, which somewhat averages the structures observed on the other two cases. Note also the presence of a small pre-pulse starting at -400 ns for the ACEM detector. This effect is still under investigation.

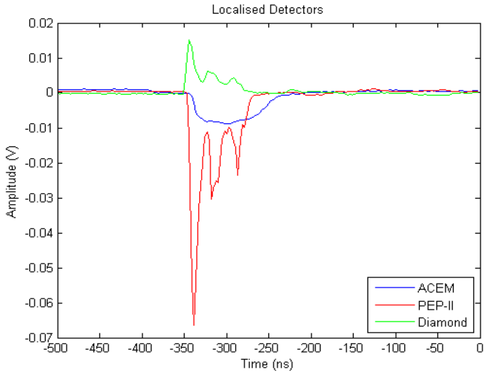

Figure 1: Average of 25 samples from the localised detectors.

Figure 3 shows the average for the same 25 samples on the signals observed by the working optical fibres. The blue (green) line corresponds to the upstream TBL signal (background) fibre. The signal observed between -250 ns and -150 ns is a background contribution, as both the TBL signal and background fibre detect an identical pulse. The plateau observed immediately after is attributed to the positioning of the fibre at certain points along TBL. Due to space limitations with the support system used, the ends of the 28 m fibre were not parallel to the beam line. As a result of the angular dependent response of the fibre and the fact that the ends were orientated at a more sensitive angle to the loss shower, a higher signal is detected in these regions which generate a higher signal than other angles. This means a disproportionally higher signal is detected in these regions which can be seen in Fig 2. The red line corresponds to the signal downstream fibre, which shows significantly higher amplitude compared to the upstream fibres. This is due to the fact that more particles are produced from losses in the downstream direction producing more photons and a higher signal. Moreover, the read out fibre connected to the downstream end of the TBL fibre is 50 m shorter than the corresponding upstream fibre, hence the signals travelling towards the downstream end are less affected by attenuation. There is a small rising edge and plateau observed between -530 and -430 ns in the downstream fibre, this is attributed to the background contribution. The time shift between the start of the upstream and downstream signals comes from the different time of flight of photons travelling to opposite ends of the fibre.

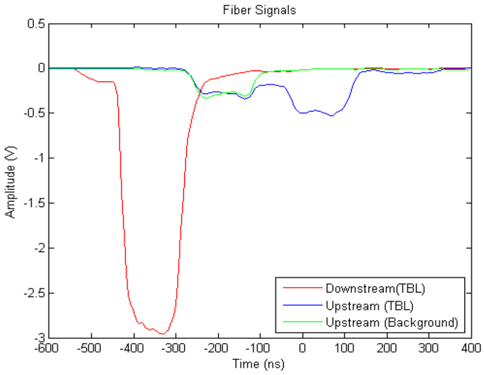

Figure 2: Average of 25 samples from the optical fibres.

FIBRE SIGNAL DECONVOLUTION

Fibre based BLM systems can provide information on loss location with a good position resolution when used at machines with pulse duration shorter than a few ns [5]. However, in CLIC-like conditions, the length of the beam pulse is in the same order of magnitude than the length of the foreseen optical fibres, making disentangling the origin of the beam loss complicated. In this section, an analysis technique based on a method proposed in [10] is presented. The signals observed from a fibre can be expressed as the following convolution:

$$S_{fiber} = \int S_{bunch}(t)\cdot f(t-\tau)d\tau . \tag{1}$$

S_{bunch} represents the contribution from losses produced by a single bunch to the total signal observed in the fibre, S_{fibre}. The time evolution of beam losses throughout the beam pulse, $f\ (t-\tau)$, is assumed to be provided by the signal response in the installed PEP-II and diamond detectors.

Transforming equation (1) to the frequency domain, the single bunch contribution can be expressed as:

$$S_{bunch}(\omega) = \frac{S_{fiber}(\omega)}{f(\omega)} . \qquad (2)$$

The frequency domain does not contain any information about the origin of the loss; however it may provide an insight on the periodicity of beam losses. Beam losses are expected to occur at every quadrupole. Assuming that the signal is produced in the fibre at the same location and simultaneously with the beam loss it is easy to obtain, using the speed of light in the fibre as 2/3 c and a beam travelling at c, that S_{bunch} should have a significant contribution around 425 MHz. Equivalently, if losses happen only on alternate quadrupoles the frequency contribution should be 213 MHz. This second case is interesting as the beam size in the TBL is significantly higher in the horizontal plane. Hence, losses at every defocusing quadrupole are more likely to occur [11].

Figure 3 shows the resulting power spectrum for S_{bunch} for a single data sample. The signal of the upstream fibre, with a correction using the corresponding background signal, is used for the calculation of S_{fibre} (ω) via fast Fourier transform (FFT). Two other FFTs are applied to calculate *f(w)* as seen by the Diamond and PEP-II detectors. There are large differences in the spectrums obtained for the two localised detectors, as two clear peaks are observed around 300 and 420 MHz only in the case of the diamond detector. The common feature to the two power spectrums is a peak at 200 MHz. For an analysis over 20 pulses, a common peak at a frequency ranging from 200 to 230 MHz was observed. A peak on the spectrum on this range may indicate the detection of losses in non-consecutive quadrupoles. Several factors, such as the effect of noise and the systematic differences encountered between the two localised detectors, require further investigations

CONCLUSION

Multiple types of beam loss monitors have been installed and tested at CTF3. Three localised detectors, ACEM, PEP-II and Diamond, have been installed at a single location at the TBL as well as an optical fibre along TBL. It was shown that using data obtained during stable conditions of CTF3 that there is a suggestion that losses occur at every other quadrupole using the fibre BLM. However, an optimization of the localised detectors needs to be made to improve the analysis technique.

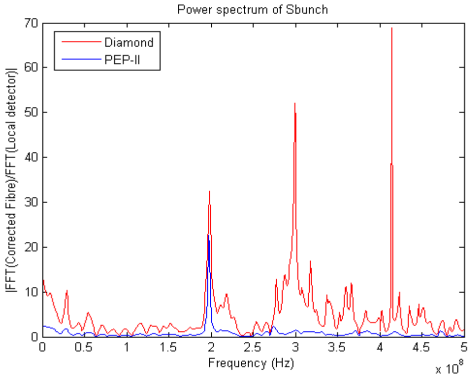

Figure 3: Power spectrum of the S_{bunch}. The red (blue) line assumes the diamond (PEP-II) detector as time evolution.

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