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CLIC – Note – 1087

A VERSATILE BEAM LOSS MONITORING SYSTEM FOR CLIC

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Abstract

The design of a potential CLIC beam loss monitoring (BLM) system presents multiple challenges. To successfully cover the 48km of beamline, ionisation chambers and optical fibre BLMs are under investigation. The former fulfils all CLIC requirements but would need more than 40000 monitors to protect the whole facility. For the latter, the capability of reconstructing the original loss position with a multi-bunch beam pulse and multiple loss locations still needs to be quantified. Two main sources of background for beam loss measurements are identified for CLIC. The two-beam accelerator scheme introduces so-called crosstalk, i.e. detection of losses originating in one beam line by the monitors protecting the other. Moreover, electrons emitted from the inner surface of RF cavities and boosted by the high RF gradients may produce signals in neighbouring BLMs, limiting their ability to detect real beam losses. This contribution presents the results of dedicated experiments performed in the CLIC Test Facility to quantify the position resolution of optical fibre BLMs in a multi-bunch, multi-loss scenario as well as the sensitivity limitations due to crosstalk and electron field emission.

Presented at: 7th International Particle Accelerator Conference, Bexco, Busan Korea, 8-13 May 2016

Geneva, Switzerland
8 May 2016

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The design of a potential CLIC beam loss monitoring (BLM) system presents multiple challenges. To successfully cover the 48 km of beamline, ionisation chambers and optical fibre BLMs are under investigation. The former fulfils all CLIC requirements but would need more than 40000 monitors to protect the whole facility. For the latter, the capability of reconstructing the original loss position with a multi-bunch beam pulse and multiple loss locations still needs to be quantified. Two main sources of background for beam loss measurements are identified for CLIC. The two-beam accelerator scheme introduces so-called crosstalk, i.e. detection of losses originating in one beam line by the monitors protecting the other. Moreover, electrons emitted from the inner surface of RF cavities and boosted by the high RF gradients may produce signals in neighbouring BLMs, limiting their ability to detect real beam losses. This contribution presents the results of dedicated experiments performed in the CLIC Test Facility to quantify the position resolution of optical fibre BLMs in a multi-bunch, multi-loss scenario as well as the sensitivity limitations due to crosstalk and electron field emission.

TOWARDS A CLIC BLM SYSTEM

The BLM system is a key beam instrumentation element, protecting the machine from potentially dangerous instabilities while also providing beam diagnostics by localising and characterising the beam loss. The design of a BLM system capable of performing both functions for the Compact Linear Collider (CLIC) [1] is highly challenging due to the originality in the design of the machine. Its main constituent is the Two-Beam Module (TBM), a 2 m long combination of accelerating structures (AS), quadrupoles and the Power Extraction and Transfer Structures (PETS) linking the parallel Main Beam (MB) and Drive Beam (DB) lines.

The CLIC BLM system needs to cover 48 km of beam lines and more than 45000 quadrupoles. The idea of using optical fibre BLMs (OBLMs) has been introduced as a cost-effective alternative to standard ionisation chambers. The main challenge is to achieve an adequate position resolution to distinguish losses occurring at consecutive quadrupole or cavity locations. Previous studies [2] for the case of single-location losses with long (1 μs) electron pulses have demonstrated that localisation of losses to within 2 m is achievable, easily distinguishing between different quadrupoles. In the present paper, the localisation of multi-location beam losses with multi-bunch beam is considered. Prior to the design of a CLIC BLM system, two factors that may limit the BLM sensitivity need to be thoroughly examined: the field emitted electrons from the high gradient RF cavities that can be accelerated, escape the cavity, and be detected by OBLMs; and the beam loss crosstalk between the DB and MB linacs. Both phenomena have been investigated, the field emission in a CLIC AS and the crosstalk in a prototype CLIC TBM.

MACHINE LAYOUTS

All measurements described in this paper were conducted in the different experimental areas of the CLIC Test Facility (CTF3) at CERN, an accelerator complex built to demonstrate the feasibility of CLIC technology. CALIFES (Concept d'Accélérateur Linéaire pour Faisceau d'Electron Sonde) [3] is a 26 m electron linac that aims to mimic the CLIC main beam. A beam with a total charge that can range from 0.05 - 0.6 nC per bunch and a 1.5 GHz bunching frequency is accelerated up to 200 MeV and transferred to the TBM for further acceleration by the RF power extracted from the drive beam. The CTF3 accelerator [4] is a scaled-down version of the CLIC Drive Beam accelerator, using a Delay Loop and a Combiner Ring to provide a 120 MeV beam of high current (up to 28 A) and variable lengths (0.1-1.4 μs) to the Test Beam Line (TBL) and the TBM.

The TBL is a 22.5 m long linac consisting of eight 2.8 m long FODO cells, to study the drive beam deceleration during power extraction. Each FODO cell is equipped with two quadrupoles, two PETS and two Beam Position Monitors (BPMs).

The TBM comprises two PETS and two quadrupoles on the CTF3 drive beam and four accelerating structures on the CALIFES main beam. One BPM on each side provides information on the beam entering the TBM.

THE OPTICAL FIBRE BLM SYSTEM

OBLMs are radiation detectors consisting of an optical fibre with a photosensor coupled to its end face. When high energy charged particles cross the fibre, Cherenkov photons are generated, propagate in the fibre and are detected by the photosensor [5]. In all experiments presented in this paper, pure Silica multimode fibres have been used, each one coupled to Hamamatsu Multi-Pixel Photon Counters (MPPC) [6]. A custom-made RF shielded module contains an MPPC, its readout chain and a low-pass filter for the HV power supply, as shown in Fig. 1. The type of MPPC and

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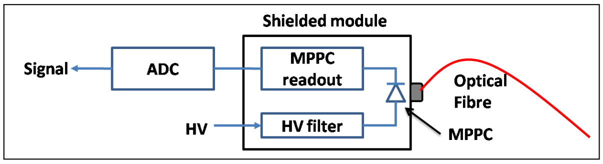

Figure 1: Schematic layout of the photosensor electronics.

readout depends on the required sensitivity: for high sensitivity an MPPC with higher gain, such as the S12572-050C, coupled to a readout containing an amplifier is selected, whereas for sufficiently large signals an MPPC with a higher number of pixels and dynamic range, such as the S12572-10C, coupled to an AC circuit based on a 50 Ω resistor and a 100 nF capacitor is sufficient.

POSITION RESOLUTION

OBLM multi-location loss resolution measurements were performed at the TBL, using a 200 μm core diameter fibre running approximately 20 cm above the decelerator. The upstream signal of the fibre has been characterised in previous studies as the one giving the best position resolution [7], and is therefore the one selected for this study. An MPPC S12572-015C was used as a photosensor in this case. In order to study losses only from the TBL, the background signal is extracted from the OBLM signal on a shot-by-shot basis. Losses at different locations were generated by changing the position of quadrupolar magnets, altering the betatron motion of the beam. However, this process did not provide beam losses at a well defined location but rather spread the losses over a certain distance. Table 1 summarizes the 3 cases that were examined along with a nominal beam transmission case. For each case 75 shots were acquired with an ~12 A, ~350 ns beam pulse. The top plot of Fig. 2 shows the rising edge of the average BLM signal for each case with respect to the time in ns. On the top horizontal axis the respective position in the TBL has been calculated from:

$$\Delta x = \frac{c\Delta t}{1 + n_Q} \quad (1)$$

as described in [2], where n_Q is the refractive index of Silica. The intensity signals from the BPMs along the TBL were also used to determine the loss location, and their corresponding mean values are presented in the lower plot of Fig. 2. In all cases the 5^{th} quadrupole was shifted with the OBLMs clearly detecting the losses generated. In the case where the 10^{th} quadrupole is also moved (case A), the OBLM signal shows a rising edge approximately 7.5 m after the first one, agreeing with the BPMs. In case B (8^{th}

Table1: TBM Optical Fibre BLM Characteristics

case	Shifted Quadrupoles	Quadrupole Distance
A	5 and 10	7.0 m
B	5 and 8	4.2 m
C	5 and 7	2.8 m

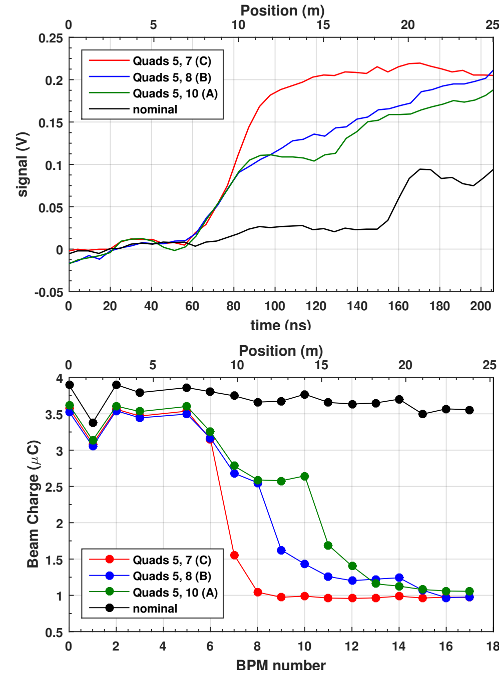

Figure 2: BLM signals (top) and BPM intensity measurements (bottom).

quadrupole deviated) and C (7^{th} quadrupole deviated) the same qualitative behaviours of BLMs and BPMs can be observed. In case B the second rising edge is barely visible, whereas in case C no distinct loss location is seen, which can be explained by the fact that the losses become more distributed. Qualitatively, however, the OBLMs can give a good indication of the loss pattern.

CROSSTALK

The understanding of the beam crosstalk is critical for the design and the operation of a CLIC BLM system. To estimate this phenomenon for OBLMs, two optical fibres were installed along the two beam lines at the TBM, separated by 15 cm transversely: one 5 m length, 200 μm core diameter covering the 3 PETS of the Drive Beam, and one 7 m length, 365 μm core diameter, covering the low current main beam. The second fibre was selected with a larger diameter to achieve greater sensitivity for the low-intensity main beam. Both upstream fibre ends were coupled to an MPPC S12572-010C, located under the main beam line. For the beam current measurement a BPM upstream of the TBM main beam was used. Two Little Ionisation Cham-

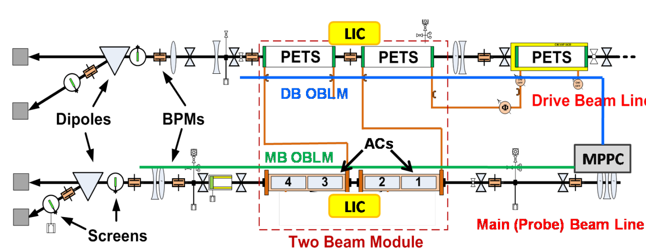

Figure 3: Layout of the BLM installation at the TBM.

ISBN 978-3-95450-147-2

bers (LICs), filled with 1.1 bar N_2 and located on the side of each beam line in the middle of the TBM were used for comparison with the OBLM data. A schematic of the layout is shown in Fig. 3.

Ten data points with 40 shots each were acquired while increasing the number of bunches for the main beam and having the drive beam off. The crosstalk of the main beam losses to the drive beam BLMs is calculated as

$$c_{MB} = \frac{Q_{DB}}{Q_{MB}} \qquad (2)$$

where Q_{DB}, Q_{MB} is the detected charge for the drive beam and the main beam respectively, estimated via

$$Q = \frac{1}{R_L}\int_{t_0}^{t_1} V(t)dt \qquad (3)$$

In Eq. (3), $R_L = 50\,\Omega$ is the measurement load, V(t) the BLM signal and $(t_0, t_1) = (1796.9, 2005.2)$ the integration limits that include only the beam loss signal. The crosstalk measured by the OBLMs (black) and the LICs (red) is shown in Fig. 4. The measured crosstalk with the OBLMs was found to be an order of magnitude larger than that of the LICs. This is attributed to the fact that the LICs are located on the side of the TBM and are relatively shielded by its elements, in comparison to the OBLMs that are located above the beam lines. Increasing the number of bunches in CALIFES (to increase the intensity) leads to a larger dispersion due to beam loading, hence higher beam losses [8]. This can therefore explain the slight increase of the OBLM crosstalk with higher beam charge. The decrease in the LIC signal is not fully understood but could be attributed to lower energies of the pulse due to beam loading or to a modification of the loss location due to the dispersion effect. Both cases would result in fewer shower particles reaching the DB LIC, therefore lower crosstalk measured. Simulations are necessary to validate these results and provide a better estimate of the crosstalk limitations for a future CLIC machine.

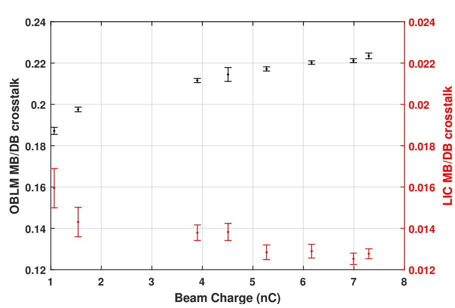

Figure 4: Crosstalk of main beam losses to drive beam BLMs, as measured by OBLMs (black) and LICs (red).

ELECTRON FIELD EMISSION

At the dogleg experiment in CTF3, a TD26 CLIC RF cavity, comprised of 26 copper cells with damping waveguides, is being tested with and without beam loading. A 550 μm core diameter optical fibre is installed 2.5 cm above the cavity, as described in [9]. The photosensor used with this fibre is an MPPC S12572-050C, coupled to a transimpedance amplifier circuit equipped with a Texas Instruments THS-3061 [10] amplifier and an $R_F = 0.5\,\mathrm{k}\Omega$ feedback resistor.

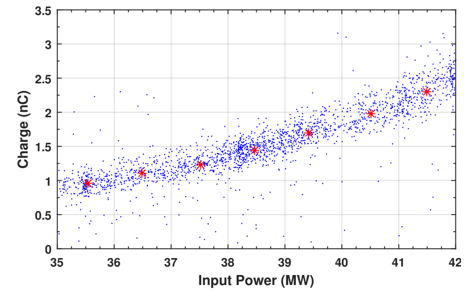

Figure 5: Field emitted electron signals (blue) and their mean values per MW (red).

In December 2015 data from 6000 pulses were acquired in an unloaded structure supplied with input RF power between 34 and 42 MW and a pulse length of 200 ns, to estimate the background created by TD26 field emitted electrons in the OBLM. Fig. 5 shows the fibre signals calculated using Eq. (3) for increasing input power in the accelerating structure (blue), with the mean values for each MW of power (red). At 42 MW, which corresponds to almost the nominal accelerating gradient (100 MV/m) of the CLIC accelerating structures, the field emitted electrons produce a signal of 2.6 nC as measured using an amplified detector. In the case of the CLIC optical fiber BLM system, foreseen to use a smaller diameter fiber (200μm) without an amplified photosensor, the corresponding background signal would drop to 7% of this value and therefore not limit the sensitivity of the BLMs. This was confirmed experimentally by the fact that electron field emission signals were not detectable in the absence of an amplifier.

CONCLUSIONS

Optical fibre beam loss monitors have been investigated as possible alternative to standard techniques for CLIC and future accelerators. A multi-location beam loss resolution of less than 5 m has been demonstrated, however studies with more distinct beam loss locations are necessary to fully quantify the resolution potential of this system. The background from RF cavity electron field emission has been shown to be very low and is therefore not considered a limiting factor for OBLM sensitivity. The beam loss crosstalk for the two beam CLIC design, however, raises serious sensitivity limiting issues. For a final CLIC OBLM system the monitor location will need to be taken into account, and estimations of the crosstalk signals for different parts of the machine will be necessary.

ACKNOWLEDGEMENT

The authors would like to warmly thank the CTF3 members and operators, for their full support during these experiments.

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ISBN 978-3-95450-147-2