ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPWC01

OPTICAL BEAM LOSS MONITOR FOR RF CAVITY CHARACTERISATION*

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Abstract

Beam Loss Monitors (BLMs) based on optical fibres have been under development for many years as an alternative solution to commonly used methods, such as ionisation chambers. Optical BLMs (oBLMs) maintain standard BLM functionality but can also be used for machine and personal protection. They can be implemented over the entire beam line providing excellent position and time resolution, while being insensitive to radiation induced damage. This contribution describes how oBLMs can also assist in the characterisation of RF cavities during commissioning and operation. It first presents the design principle of highly compact monitors and the underpinning theory for particle loss detection, before discussing data obtained in experimental tests at the electron accelerator CLARA. It then shows how a 4-channel oBLM can be applied for efficient cavity monitoring. Finally, the results are put into a broader context underlying the application potential in accelerators and light sources.

INTRODUCTION

Optical fibre-based beam loss monitors (oBLMs) have been developed as a comprehensive low-cost solution for beam loss detection in an accelerator [1]. An oBLM system consists of one or more fibres running along a beamline with fast photodetectors at the end of the fibre. The front end readout electronics convert the light signals to electrical pulses followed by high-speed analogue-to-digital converters. The operating principle of an oBLM is based on Cherenkov radiation emitted as a result of a charged particle crossing the fibre. This charged particle originates from beam losses which occur when the charged particle beam impinges on any obstacles along the accelerator, including the beampipe itself. For electrons, the threshold energy to produce Cherenkov radiation in a quartz fibre is 175 keV. The oBLM system is completely insensitive to magnetic fields, so it can be installed inside a magnet, or close to it, without any restrictions. When compared with standard beam loss monitoring methods, an oBLM can monitor the entire beamline and localise the losses with a resolution of up to 10 cm instead of detecting losses only at specific locations. Moreover, on-line oBLM systems can be integrated with the machine and personnel protection systems of an accelerator reducing the probability of losses not being detected early and thus ensuring safer operation.

CLARA (Compact Linear Accelerator for Research and Applications) is a Free-Electron-Laser (FEL) test facility under construction at Daresbury Laboratory [2]. CLARA is based on a 250 MeV electron linac capable of producing short, high-brightness electron bunches. The CLARA front end, on which the oBLM system has been installed, consists of a 2.5 cell RF photocathode gun, and a 2 m S-band (2998.5 MHz) accelerating structure.

For the CLARA front end, in the area marked in Fig. 1 by red lines, four oBLM units have been installed, using two different types of fibres: 600 µm and 400 µm core. Two types of different core fibres provide different sensitivities to ensure the detection of a range of beam loss intensities. Combining four sensors instead of one, oBLMs can collect more information on losses and on their origin, including the estimation of the deviation from the ‘golden orbit’. Additionally, four oBLMs allow the reliability of each oBLM system to be cross-checked. Moreover, this configuration allows the potential of localising the losses regarding the symmetry of the beampipe to be thoroughly explored. As can be seen from the marked locations on Fig. 1, fibres are installed in the locations of south, north, west and east of the pipe. The photodetectors installed at the fibre ends are silicon photomultipliers (SiPMs), which are an array of avalanche photodiodes operating in Geiger mode. SiPMs are insensitive to magnetic fields, unlike standard photomultiplier technology and so they do not require additional shielding. This allows for compact installation behind the gun without impeding other systems. Each SiPM, four in total connected to each fibre end, is biased from a custom made power supply to just above the Geiger-breakdown voltage of 70 V, and the charge produced in each SiPM is collected by a transimpedance amplifier and converted to a voltage signal [3].

LINAC CONDITIONING: LOADED AND UNLOADED RF STRUCTURE

Imperfections on the RF cavity surface can cause the field emission of electrons [4]. A travelling RF wave can accelerate these electrons up to energies of tens of MeV, depending on the available distance for the electrons to travel, the accelerating gradient and the RF phase. When colliding with the

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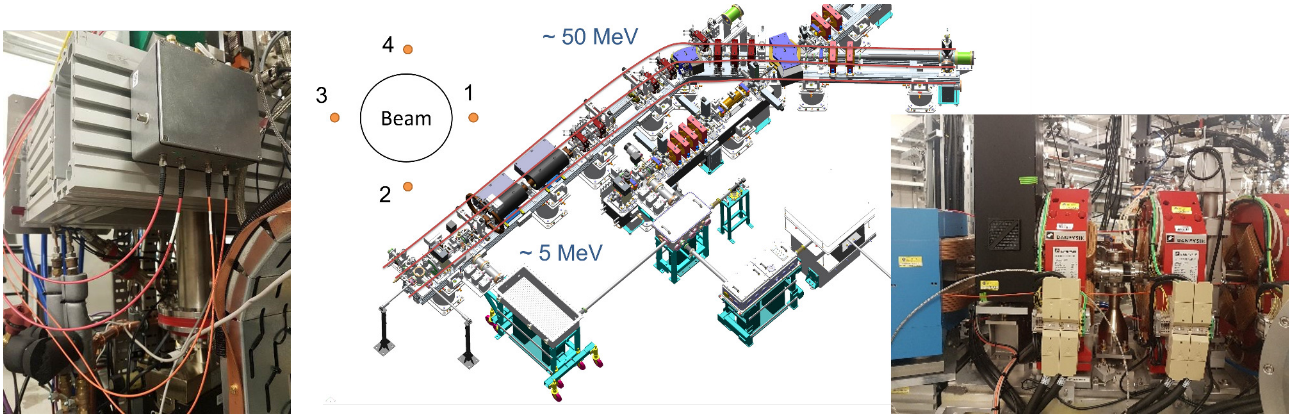

Figure 1: Fibres of oBLM (red line) on CLARA front end to VELA spectrometer line [2]. The inner picture demonstrates the location of four fibres with respect to the beampipe. oBLMs are located at the front end of the beamline therefore the sensors are located upstream. The inner photographs show the oBLM box (left corner) and the fibre locations along the beamline (right corner).

wall, these high energy electrons cause secondary showers, which can be detected by the oBLMs. With sufficiently high fields at certain locations of the cavity, electric breakdown or sparks can appear, caused by field emission. The current due to field emission has been shown to be proportional to the electric field on the surface of the cavity. As a beam propagates through the RF cavity, its field changes due to the charges that are induced on the wall of the cavity [4]. To compensate for this, high output power is applied to the accelerating structure. The unloaded effects can be studied when RF power is provided into the structure without the beam present. Conditioning of RF cavities – gradually ramping the input power and RF pulse length – is a necessary procedure to ensure that the design specifications have been met. During this procedure, breakdowns must be monitored in order to ensure that no damage to the cavity or the klystron occurs. During the breakdown, the input power can be reflected off the RF cavity which can lead to the damage of the klystron and windows. This can be monitored by observing spikes in vacuum activity or in the power reflected back from the cavity. We have measured the response of the oBLM sensors (see Fig. 2) to the RF input parameters and vacuum activity in CLARA. The Inverted Magnetron Gauge (IMG) that is located close to the linac provides the pressure readings which are then returned to the control system for monitoring. The data from IMG are shown by green lines, demonstrating vacuum activity. The input power, which is sent to the RF cavity, is shown by an orange line. The oBLM sensor is installed along the whole structure in four positions, and data has been taken during conditioning of the CLARA Phase 1 linac. The breakdown and oBLM measurements are presented for the unloaded case. The data presented in Fig. 2 shows the charge measured by the silicon photomultipliers, which detects the Cherenkov light propagating in the fibre, according to:

$$Q = \frac{1}{R_L}\int_{t_0}^{t_1}(V_{mes} - V_{off})dt, \tag{1}$$

where $R_L = 50\,\Omega$ is the load, V_{mes} is the measured amplitude within the integration interval (t_0, t_1) and V_{off} is the offset mean value of the oBLM sensor without any activity in the accelerator.

The measured total collected charge is plotted together with other measurements from the control system to cross-check the oBLMs signals. The cavity input power and the collected signal from the oBLM sensors show a correlation, in which the increase in the input power changes proportionally with the absolute signal. As the accelerating gradient of a cavity depends on the input power, an increase in power causes a greater number of primary particles to arise due to field emission in the structure. Along with this, the increase in gradient can cause some of the dark current to gain higher energy. Both of these effects lead to larger particle showers, which are then detected by the oBLMs. The rapid increase in the signal of the oBLMs demonstrates the increasing electron field emission and can be used as an indicator of potential breakdown (see Fig. 2 a). Another source of evidence for breakdown is spikes in vacuum activity. A higher level of dark current, which leads to sparking, breaks the vacuum, leading to increased pressure, which can be picked up by the oBLM system, see the spike in pressure and oBLM signal in Fig. 2 b). Currently, the reflected power from the cavity is being used to monitor the RF breakdown. Moreover, any obstacle introduced into the beamline should lead to a change in the oBLM signal, which is demonstrated in Fig. 2 c). At the moment, our sensors are digitised through an oscilloscope before being recorded in our control system with the other measured signals, meaning that the measurements are not fully synchronised. Direct digitisation of the oBLM signals will soon be integrated into the control system, allowing single beam loss events to be captured at rates of up to 100 Hz, meaning that it may be possible to isolate individual beam loss events at high repetition rates.

Figure 3 shows the signal obtained during the dark current studies during conditioning of the RF photo-injector gun. The response of the oBLM signal to variations in the RF

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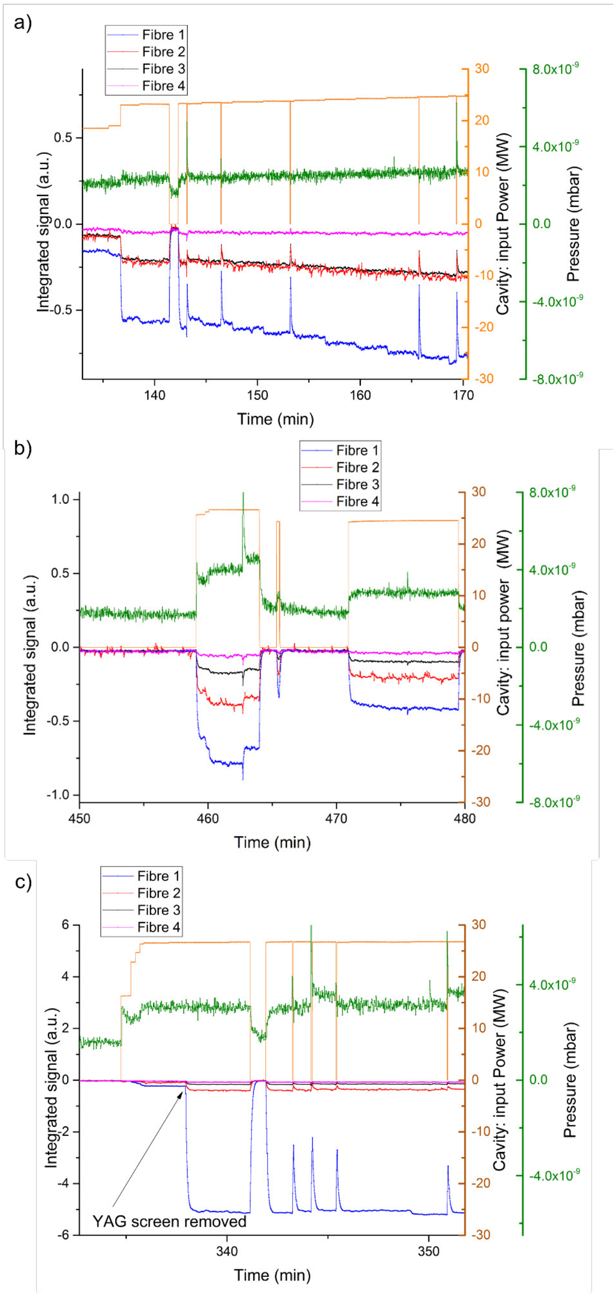

Figure 2: Integrated oBLMs signals (see Eq. 1) from all 4 fibres is presented by blue, red, black and purple lines for the detectors 1, 2, 3 and 4 respectively (see Fig. 1 for the location of the fibres) together with input power (orange line) and measured by IMG pressure (green line). The integrated oBLM signals follow the shape of the cavity input power, see graph a). From graph b) it can be seen that oBLM signals can detect the pressure spikes. Graph c) shows the change of the amplitude of the integrated signals when the obstacle is introduced into the beamline. The collected signal has increased by an order of the magnitude.

pulse length has been measured. An RF pulse of 10 MW power was sent to the cavity, and the pulse width was varied from 3.0 µs to 2.0 µs. The increase in field emission with the RF pulse length can be seen clearly. Figure 4 shows the correlation of the oBLM signal with the signal from the Wall Current Monitor.

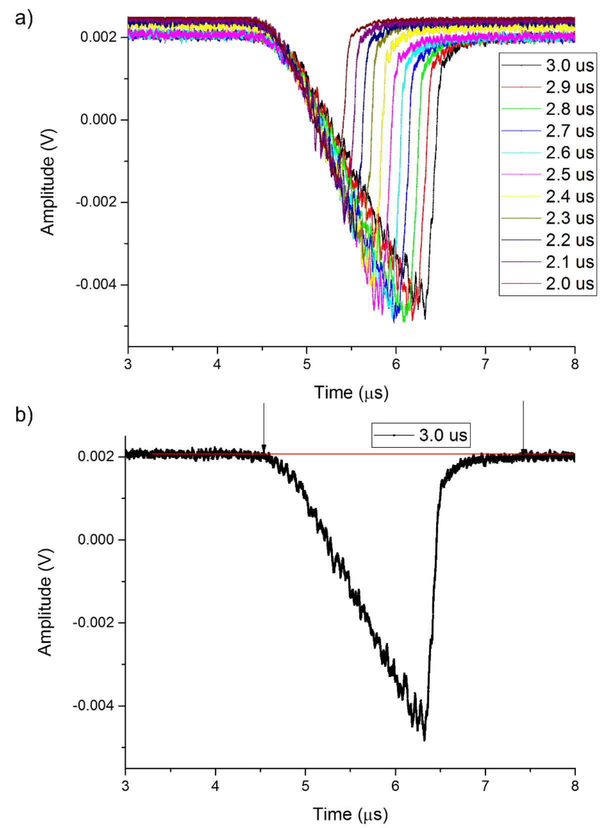

Figure 3: oBLMs signals from one channel for different RF pulses length is presented by different colours on top graph. The RF pulse was varied within 3.0 µs to 2.0 µs. From graph a) it can be seen that the oBLMs signal follows the shape of the pulse and its length can be reconstructed from the oBLM signal. Graph b) shows the oBLM signal which was obtain for 3.0 µs pulse.

CONCLUSION

The oBLM has proven itself as a useful tool which can be used during the conditioning of the RF structures by detecting dark current. This contribution has demonstrated that an oBLM can function as a cavity monitor to monitor the dark current appearing within the linacs and can, as such, provide further information into the sources of RF breakdown. Measurements presented in this contribution were obtained parasitically during the commissioning stage. As we have qualitatively demonstrated the potential of the oBLM systems, a comprehensive and quantitative study in the localisation of the main sources of dark current is planned. The oBLM as a beam loss monitor will also be tested during laser-induced beam commissioning.

Ensuring that losses are kept to a minimum is a crucial part of effective machine operation and the advances we

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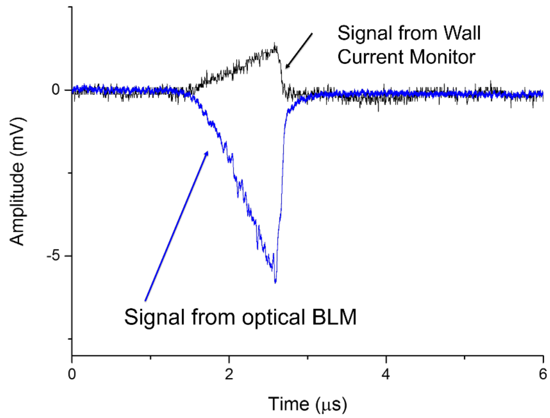

Figure 4: Graph demonstrates measurements which were taken by oBLM (blue signal) and by the Wall Current Monitor (black signal), and their correlation is clear.

have made in this area will ensure that any future UK FEL will benefit from the coverage of the accelerator we are able to deliver and at a cheaper price compared to standard technology. When applied to an FEL, an oBLM system could be particularly advantageous in undulator regions, since the system is not sensitive to magnetic fields and synchrotron radiation and should be able to provide the information about the properties of the propagating beam and intra-beam dynamics.

ACKNOWLEDGEMENT

The authors would like to thank the CLARA team for the opportunity to perform studies at the accelerator, with special thanks to Deepa Angal-Kalinin for supporting the idea of testing oBLMs on CLARA. Many thanks to Steve Buckley for helping to ensure the smooth process of oBLMs installation and ASTEC Drawing department for providing high-resolution pictures of CLARA, and to Chris Edmonds, Bruno Muratori and the CLARA team for fruitful discussions over the subject.

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