NON-INVASIVE ONLINE BEAM MONITOR USING LHCb VELO

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Abstract

Online beam monitoring is essential for ion beam therapy to assure effective delivery of the beam and maintain patient safety for cancer treatment. One candidate for such a monitoring device is the LHCb Vertex Locator (VELO) detector. It is a position sensitive silicon detector with an advantageous semi-circular design which enables approaching the core of the beam without interfering with it. In this contribution, tests using an Infra-Red laser to calibrate the detector and obtain information about its dynamic range, spatial and time resolution will be discussed. Initial results from using the detector at the 60 MeV proton therapy beamline at the Clatterbridge Cancer Centre (CCC), UK are also presented.

INTRODUCTION

The QUASAR Group [1] at the Cockcroft Institute and University of Liverpool is currently developing a stand-alone online beam monitor for medical accelerators using the LHCb VELO detector technology that has been used for tracking vertices originating from collisions at the LHCb experiment at CERN [2]. Online beam monitoring in medical accelerators is an essential part of ensuring patient safety whilst also maintaining a high quality and efficacy of cancer treatment.

As such, the energy, energy spread, current, position and lateral profile of the beam must be precisely determined and recorded. The semi-circular design of VELO enables approaching the core of the beam, however, without interfering with it. This offers advantages in comparison to clinically used ionization chambers that degrade the beam quality.

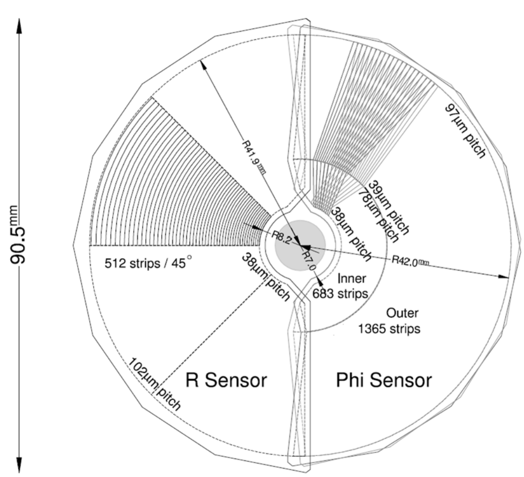

Figure 1: Sketch of the two VELO modules summarising the design of the R- and ϕ-type sensor [3].

An integration of VELO into the proton beam line at the Clatterbridge Cancer Centre for Oncology (CCC) was achieved in 2014 [3]. In this paper, the preparations for additional measurements at CCC will be discussed. For testing purposes, an Infra-Red Laser Diode was used to assess the dynamic range, spatial and time resolution of VELO.

LHCb VELO DETECTOR

The LHCb VELO detector is a multi-strip silicon semiconductor detector that tracks vertices in a polar coordinate system (see sketch in Figure 1) [4]. The active area of the detector consists of two semi-circular silicon sensors each equipped with 2048 strip diodes, the R-sensor and the ϕ-sensor. The R-sensor is divided into four 45° wide sectors, whilst the ϕ-sensor is divided into an inner- and outer-region with radially oriented strips. The radius of the active area ranges from 8.17 mm to 42.00 mm.

The silicon layer structure is $n^+ - in - n$ with a total thickness of 300 µm.

For the signal read-out, a trigger is sent to sixteen Beetle chips that are surrounding the sensor and storing the read-out events. Further, the DAQ system of the detector consists of repeater cards and TELL1 cards that will amplify the analogue signal and digitize it for later analysis. The read-out electronics are designed to work in synchronism with the LHC bunch crossing frequency, $f_{\mathrm{LHC}} = 40\,\mathrm{MHz}$ resulting in the capture of an read-out event every 25 ns.

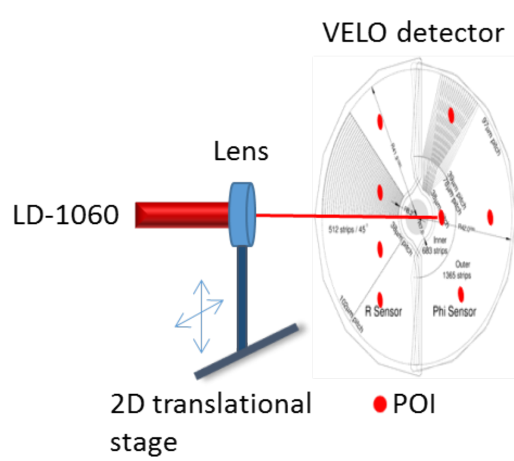

Figure 2: Setup of the LD-1060 to measure the output of the R-sensor and the ϕ-sensor for different peak-to-peak voltages. The red dots indicate the points of interest (POI, not true to scale).

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For the envisaged integration of the LHCb VELO detector into a proton beam line, changes of the original design were carried out [5]. For the safe operation of the detector in air to avoid over-heating and to minimize the noise, an efficient venting and cooling system to keep the silicon sensors in the temperature range between -7°C and 0°C was designed and successfully implemented. Furthermore, a remotely controlled multi-axes positioning system was built for the detector.

Test with an Infra-Red Laser Diode

In the following, results from first test measurements are presented, where an InGaAs/GaAlAs/GaAs Laser Diode (LD-1060) with a peak wavelength of 1060 nm was used. Other characteristics are presented in Table 1. The setup is described as follows (see Figure 2). The laser lens (f=10 mm) was mounted on a 2D translational stage in front of the VELO detector. The position accuracy of the stage is ± 0.25 mm enabling the movement of the LD-1060 to the points of interest for the R-sensor and the ϕ-sensor, also indicated in Figure 2.

Table 1: LD-1060 Specifications

Pulse frequency	1 MHz
Peak-to-Peak Voltage	1 V-1.5 V
Offset	0.5 V
Duty cycle	10 %

The location of the POIs (four per sensor type) were chosen to scan the different design of the sensor types of VELO described previously. For the R-sensor, these points were placed in the four different regions for different radii to get an overview of the effect of different areas within the sensor. Similar considerations were made for the ϕ-sensor however, only one point was located within the significantly smaller area of the inner region and the other three were located in the outer region.

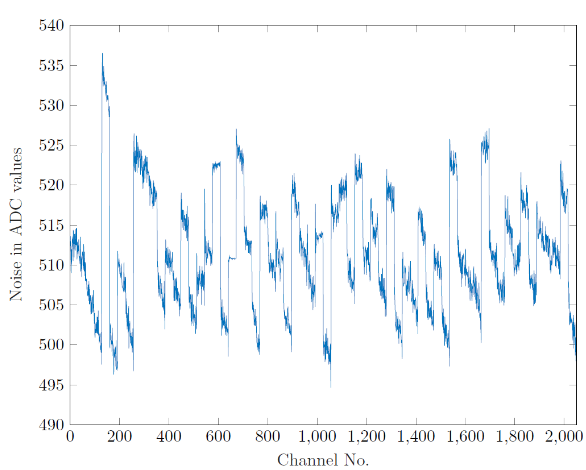

Figure 3: Example of the noise (mean of 4000 events in ADC values) per Channel of the R-type sensor.

In the first step, background measurements were taken to characterise a noise cut-off threshold for later measurements with the LD-1060. The electronics digitize the analogue signal (ADC) in the read-out process. For the measurement, 4000 events are captured and the mean ADC value is calculated for each channel. As an example, the noise in ADC values of the R-Sensor is shown in Figure 3. The noise differs significantly between each channels, so the threshold is set for the individual channel.

Secondly, the LD-1060 was used to evaluate the output of the VELO detector. In Figure 4 the output of 4000 events for each sector of the R-sensor is shown.

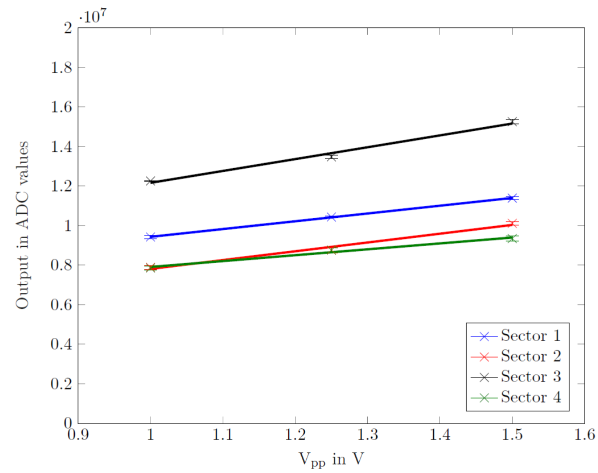

Figure 4: Output as the sum of 4000 events of VELO for three different Peak-to-peak voltages for the R-type sensor.

The different output values correlate to the channel architecture of the VELO R-sensor (Fig. 1). The pitch between the channels increases with increasing radius, hence more channels were able to register a signal when the radius is small. The analysis yielded the radii of the signal peak for Sector 1: 20.3 mm; Sector 2: 17.9 mm; Sector 3: 12.6 mm and Sector 4: 22.8 mm. The output of the ϕ-sensor is presented in Figure 5. The standard deviation of the output is 1%. In comparison with the previous measurement of the R-sensor, the ϕ-sensor has only two different sectors.

Similar to the results of the output measurement of the R-sensor, the output is highly dependent on the spot location of the laser. Also, the pitch of the radially oriented strips increases with increasing radius.

The test showed various aspects of the VELO detector that have to be considered. The noise of each sensor was examined and a noise-cut off threshold was determined to extract the absolute signal of the LD-1060. The signal showed a good linearity across the sensor.

INITIAL EXPERIMENTAL RESULTS

First measurements with a 60 MeV proton beam were done at CCC in 2014 [4]. The increase of the proton beam intensity was measured by the VELO detector and by a Faraday Cup (FC) that was optimised for the measurement [6]. The amplitude expressed as ADC values per event for each

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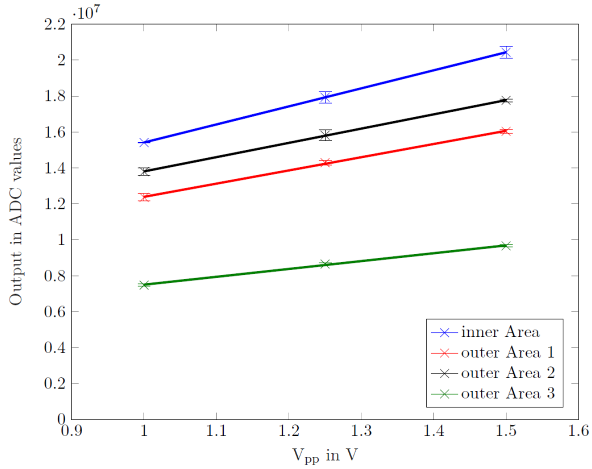

Figure 5: Output as the sum of 4000 events of the VELO for three different Peak-to-peak voltages for the ϕ-type sensor.

sensor of VELO were related to the measured beam intensity by the FC. The sensitivity of response, expressed as a slope of a linear fit to the experimental points, for both R- and ϕ-sensors, demonstrates similar amplitude increase per the readout event. In Figures 6 and 7 the results for the R-sensor

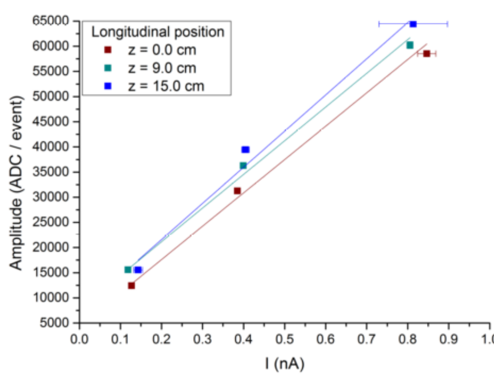

Figure 6: Average increase of the integrated ADC values in the R-sensor per readout event versus the proton beam intensity measured by the FC [4].

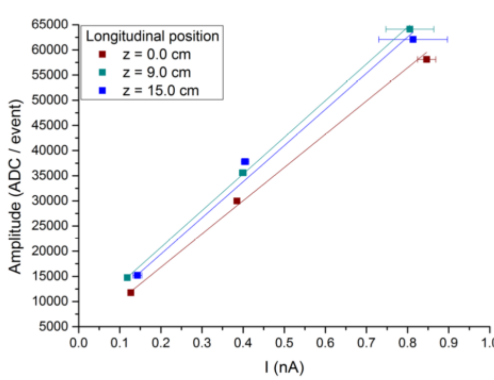

Figure 7: Average increase of the integrated ADC values in the ϕ-sensor No. 76 per readout event versus the proton beam intensity measured by the FC [4].

and ϕ-sensor are presented. The detector monitored the signal at three longitudinal positions z in the beam propagation direction with the origin at a distance of 6.9 cm from the beam modulator box wall.

Testing the detector as non invasive beam monitor, this experiment showed a good linearity between the integrated signal and the delivered dose. This indicates the viability of the detector for estimation of the beam current. Moreover, the signal can also be correlated to position, allowing information of the beam profile to be obtained.

CONCLUSION AND OUTLOOK

The beneficial sensor design of the LHCb VELO detector with a central semi-circular aperture enables the core of the beam to potentially pass through with minor distortions to its profile or energy.

Measurements to assess the noise level of the detector and a simple test to show the linearity of the detector of the signal output generated by an IR-laser were performed successfully. Moreover, improvements in the post read-out process are currently in development to achieve automated algorithms for the signal processing. These preparations help to understand the performance of the sensor for further implementations at the CCC in the near future, including the use of the existing Faraday Cup. On this basis, the capability of the technology to measure the dose, profile, position and potentially even emittance (using a 2nd detector set) online, will be assessed further. Simulation studies into beam and halo propagation will additionally support these studies.

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