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NON-INVASIVE BEAM MONITORING USING LHCb VELO WITH 40 MeV PROTONS

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Abstract

In proton beam therapy, knowledge of the detailed beam properties is essential to ensure effective dose delivery to the patient. In clinical practice, currently used interceptive ionisation chambers require daily calibration and suffer from slow response time. This contribution presents a new non-invasive method for dose online monitoring. It is based on the silicon multi-strip sensor LHCb VELO (VErtex LOcator), developed originally for the LHCb experiment at CERN. The semi-circular detector geometry offers the possibility to measure beam intensity through halo measurements without interfering with the beam core. Results from initial tests using this monitor in the 40 MeV proton beamline at the University of Birmingham, UK are shown. Synchronised with an ionisation chamber and the RF cyclotron frequency, VELO was used as online monitor by measuring the intensity in the proton beam halo and using this information as basis for 3D beam profiles. Experimental results are discussed.

INTRODUCTION

Cancer is a major societal problem, and it is the main cause of death between the ages 45-65 years. In the treatment of cancer, radiotherapy (RT) plays an essential role. RT with protons and light ions, due to their unique physical and radiobiological properties, offers several advantages over photons for specific cancer types.

Proton and light ions deposit most of their energy at the end of their path in the patient's tissue. To assure the patient's safety as well as the high quality and efficacy of the cancer treatment, beam energy and energy spread, position and lateral profile of the beam as well as the beam current have to be precisely determined and recorded.

The QUASAR Group [1] at the Cockcroft Institute and University of Liverpool is developing a new stand-alone, non-invasive beam monitor based on the silicon multi-strip sensor LHCb VELO detector, developed originally for the LHCb experiment at CERN [2]. The detector offers the possibility to measure beam intensity through halo measurements without interfering with the beam core because of its semi-circular shape with a central aperture. This is advantageous compared to currently used ionisation chambers which intercept the beam, require daily calibration and have a slow response time. For the envisaged integration of VELO into a medical beamline, changes in the original design were necessary and described in [3] and [4]. The stand-alone system was recently tested at a 40 MeV proton beamline and initial results are shown.

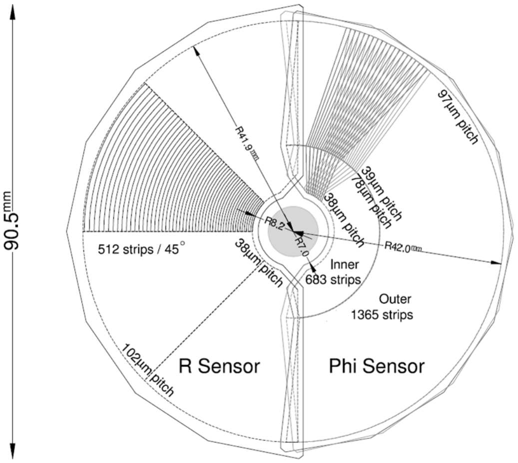

Figure 1: Sketch of the two VELO modules summarising the design of the R- and ϕ- type sensor [6].

IMPLEMENTATION OF VELO IN THE 40 MeV PROTON BEAMLINE

The development of the VELO detector into a stand-alone detector and its features are described in detail in [4]. Originally, the changes were based on the specifications of the 60 MeV proton beamline at the Clatterbridge Cancer Centre (CCC). First tests however were performed at the MC40 cyclotron beamline of the University of Birmingham. It provides proton energies from 3 to 38 MeV and currents ranging from tens of fA to µA. The facility is used for the irradiation studies of state-of-the-art detector technologies and isotope production [5]. For a brief overview, the characteristics of the VELO detector and the important adaptations are summarised in the following.

The LHCb VELO detector is a multi-strip silicon semiconductor detector that tracks vertices in a polar coordinate system (see sketch in Figure 1) [6]. 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 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.

To avoid over-heating due to the operation in air and to minimise the noise, an efficient venting and cooling system was designed and successfully implemented. Further-

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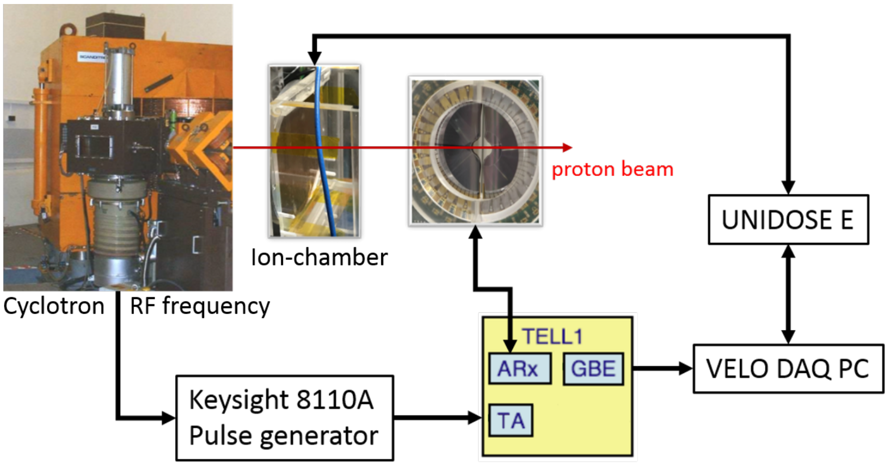

Figure 2: Synchronisation of the readout of the VELO detector and in-beam ion-chamber. A developed software trigger controls the simultaneous data acquisition of the VELO detector and the ion-chamber. The RF frequency of the cyclotron triggers the pulse generator, which injects readout triggers into the TELL1 board.

more, a remotely controlled multi-axes positioning system was built for the detector to move the detector along the beamline [7]. To precisely measure the proton beam intensity with the detector, VELO is synchronised with an in-beam ionisation chamber, which is read out by the PTW UNIDOS E electrometer. A software trigger controls the simultaneous data acquisition of the VELO detector and the ion-chamber. Additionally, VELO is synchronised with the proton bunch arrival given by the RF frequency of the MC40 cyclotron. The readout board TELL1 sends out the trigger to the front end readout out Beetle chips. Both are synchronised by a 40 MHz clock, the LHC bunch crossing frequency. A firmware update of the TELL1 board enables the acceptance of external triggers in synchronisation with the 40 MHz clock. Thus, the sinusoidal cyclotron RF frequency triggers the Keysight 8110A pulse generator which injects external triggers of up to 10 kHz into the TELL1. The full layout is shown in Fig. 2.

PRELIMINARY RESULTS

During the tests, the following settings of the cyclotron and the VELO modules were used to perform beam intensity and profile measurements: proton energies of 18 MeV with a cyclotron RF frequency 18.21 MHz and 28 MeV with a RF frequency of 22 MHz were used. Beam currents were varied from around 0.5 nA to 6 nA. Before the exit of the beam, different collimator sizes from 0 mm to 20 mm were chosen to restrict the beam size of the proton beam. The VELO detector was positioned at two points for the x- and z-axis.

To optimise the bunch arrival time on the VELO detector modules, a phase scan over one RF frequency period was performed. The pulse generator could accept frequencies up to 20 MHz. Therefore, beam current measurements were undertaken at an energy of 18 MeV with 18.21 MHz RF frequency of the cyclotron. This frequency corresponds to a 54.9 ns pulse period. During the phase scan, the delay of the pulse generator was changed in steps of 7.5 ns until a peak of the signal was found. As a check, the step size was reduced to 2.5 ns around the peak. For the scan shown in Fig. 3 across the whole detector, the delay for the highest signal output was found to be 22.5 ns.

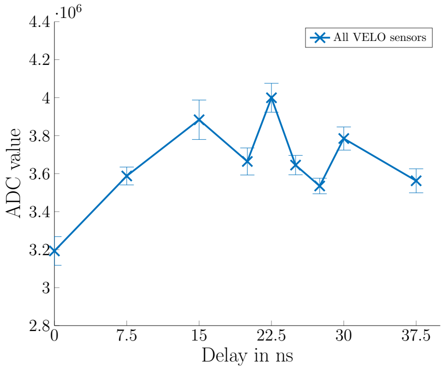

Figure 3: Phase scan of the trigger delay to optimise the readout synchronisation of the VELO detector to the proton bunch arrival. At 22.5 ns the integration of all sensors yielded the highest output.

In the following, the VELO detector modules monitored different beam currents. In Fig. 4, the output of VELO in ADC values for the different sensors is correlated to the absolute charge readings of the electrometer. The proton beam is collimated to a 7 mm diameter. The aperture of the VELO modules is 20 mm. Thus the entire beam core will pass through the aperture and only the beam halo will be detectable. The increase of the ADC values measured by the VELO detector is very linear to the charge collection of the electrometer with an average $R^2 - value$ of 0.9996. Small errors occur in the charge collection, mainly caused due to a processing delay. Therefore, the stop trigger to the electrometer from the DAQ PC is sent out later. This

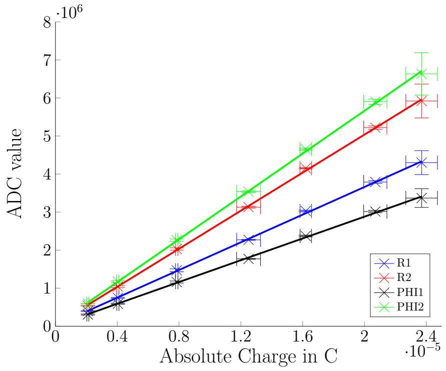

Figure 4: Beam current measurement with a 7 mm collimator. R1 and PHI1 corresponds to the R- and Phi-sensor of module 1, R2 and PHI2 to module 2.

caused it to collect more charge although the measurement of VELO was already finished. The spread of the ADC values is caused by beam current fluctuations of the cyclotron. In ideal conditions, the ADC value error is equal to or less than 1% which were attained in the first data points.

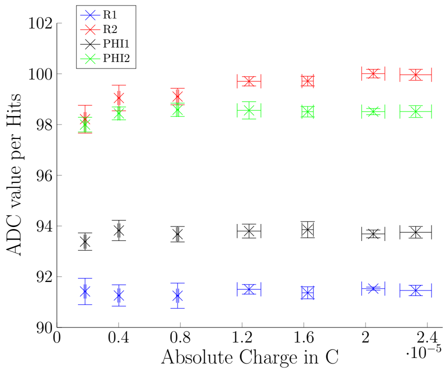

Figure 5: ADC values per recorded pixel hits for different beam currents for the 7 mm collimator. The ratio is nearly the same, since the ADC values are saturated.

Secondly, in Fig. 5 the ratio between the total ADC values and the registered hits per sensor is shown. For different beam currents, the ratio almost stays the same for all four sensors. This means that nearly every hit registered on the strips and induced by a proton will saturate the ADC value. For the four sensors the ratio was: $R1 = 91.40 \pm 0.32$, $R2 = 99.39 \pm 0.68$, $PHI1 = 93.71 \pm 0.30$ and $PHI2 = 98.44 \pm 0.29$. Further, this ratio was mapped for the two modules. To generate the hitmap, the strips of the R- and Phi sensor were overlayed to create a pixel map. The values of the two sensors are then summed up for the common pixel.

In Fig. 6, the ADC values per registered pixel hits are shown for the collimated beam with a diameter of 7 mm. It can be seen that the ADC values are nearly saturated across the entire modules, even in the outer part. Proton fluence during the operation can exceed 10^{10} protons per second which is comparatively high to the LHC environment detecting single sub-atomic particle events. Thus, only the amount of hits registered on the strips are contributing to the intensity value and therefore to the value characterising the beam current and beam profile.

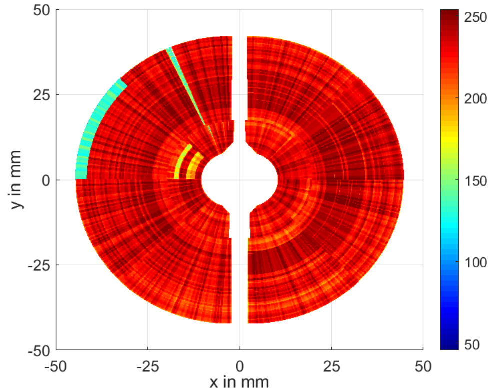

Figure 6: Hitmap of ADC values per recorded pixel hits for the 7 mm collimator at a beam current of around 1 nA. The ADC values are saturated with almost every hit. Cold spots are dead channels.

CONCLUSION AND OUTLOOK

Initial tests at the MC40 cyclotron of the University of Birmingham were performed to assess the VELO detector as a beam monitor. The integration as a stand-alone setup with all adaptations were successful. Beam currents measurements showed a very linear behaviour. Beam profiles measurements will be further assessed by complementary simulations and film measurements. Further planned measurements at the 60 MeV proton Eye therapy Clatterbridge Cancer Centre (CCC) aims to establish a halo-dose correlation data base and is used for benchmarking beam tracking simulations. In addition to the VELO detector, Medipix3, a solid state hybrid X-ray pixel detector will be used, providing complementary information about the beam properties. The aim is to combine these highly advanced sensor techniques into one comprehensive monitoring solution for proton and heavy ion beams in treatment beamlines, effectively reducing quality assurance times and allowing the treatment of more patients.

ACKNOWLEDGEMENTS

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