ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML024

IMPLEMENTATION OF A NON-INVASIVE ONLINE BEAM MONITOR AT A 60 MeV PROTON THERAPY BEAMLINE

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Abstract

To fully exploit the advantageous dose distribution profiles of ion radiotherapy, an exact knowledge of the beam properties through online beam monitoring is essential, ensuring thus an effective dose delivery to the patient. One potential candidate for an online beam monitor is the LHCb Vertex Locator (VELO). This detector, originally developed for the LHCb experiment, has been adapted to the specific conditions of the clinical environment in a proton therapy centre. The semicircular design and position of its sensitive silicon detector offers a non-invasive way to measure the beam intensity without interfering with the beam core. In this contribution, modifications for VELO are described. The detector is synchronized with the readout of a locally-constructed Faraday Cup and the 25.7 MHz RF frequency of the cyclotron at the Clatterbridge Cancer Centre (CCC). Geant4 Monte Carlo simulations investigate the integration of the detector in the treatment line and behaviour of the beam during delivery. The capability of VELO as a beam monitor will be assessed by measuring the beam current and by monitoring the beam profile along the beamline this summer.

INTRODUCTION

Within the QUASAR Group [1] at the Cockcroft Institute and University of Liverpool, large-scale research projects are carried out by several members to maximize the healthcare benefits from cancer therapies involving medical accelerators. This includes the development of a stand-alone online beam monitor for current and future medical beamlines 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 essential to ensure patient safety as well as a high quality and efficacy of treatment.

As such, the energy, energy spread, current, position and lateral profile of the beam must be precisely determined and recorded. In clinical practice for proton therapy, currently used ionization chambers are interceptive devices, degrading both the beam profile and its energy spread. Therefore, a new non-interceptive approach of online beam monitoring is highly desirable. The semi-circular design of VELO's silicon detector offers a non-invasive way to measure the beam intensity through the beam halo without interfering with the beam core.

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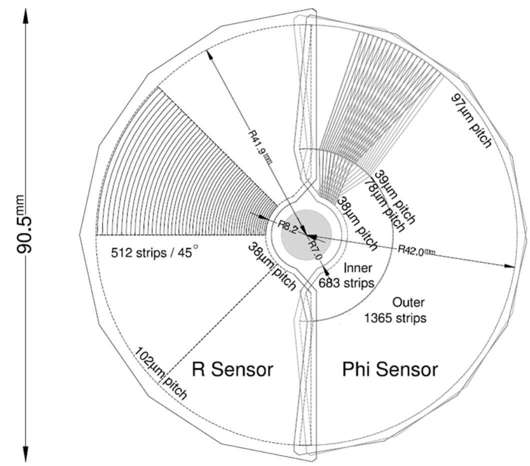

Figure 1: Sketch of the two VELO modules summarising the design of the R- and ϕ- type sensor. [3]

For the integration of VELO into the proton beamline at the Clatterbridge Cancer Centre (CCC), several modifications were implemented to assure the safe operation of the detector in air. Adaptations to synchronize the detector with a locally constructed Faraday Cup and the RF frequency of the CCC cyclotron were achieved to follow up proof-of-principle measurements in 2014 [4].

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) [3]. 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 following modification to synchronize the readout of VELO, a closer look at the VELO timing system and its configuration is needed [5]. The read-out electronics are designed to work in synchronism with the LHC bunch crossing frequency, f_{LHC} = 40 MHz. The analogue front-end readout Beetle chip consists of a preamplifier, shaper and a buffer [6]. 16 Beetle chips integrate 128 strip channels per sensor. The shape of the output pulse is shown in Figure 3. The minimum rise time (10-90%) is well below 25 ns, the remainder of the peak voltage after 25 ns is less than 30%.

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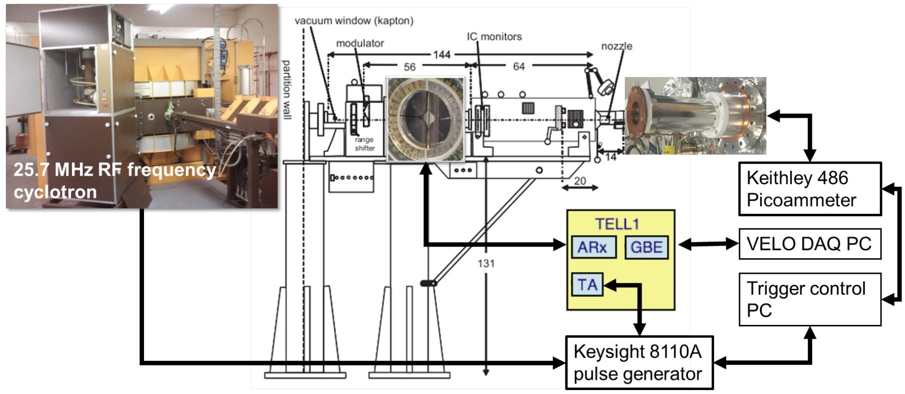

Figure 2: Synchronization of the readout of the VELO detector and the Faraday Cup optimized for the integration at the CCC proton beam line. A master trigger regulates the output of the pulse generator synchronized to the RF frequency of the cyclotron for generating VELO readout triggers and controls the picoammeter measuring the beam current by the FC.

The shaper output is sampled every 25 ns into the 160 deep sampling pipeline. The readout board TELL1 sends out the trigger to read out the specific pipeline column number (PCN) in the Beetle chip. The four analogue receivers (ARx) cards on the TELL1 accept data from the Beetle chips and digitize them at a frequency of 40 MHz. The two sampling times or clocks, in the Beetle chip and in the TELL1, have to be kept synchronous to provide an optimal readout of the silicon sensors. After digitization, 4 pre-processing FPGAs perform operations to send it to the event capturing desktop PC. For a data synchronous readout with the RF frequency of the CCC cyclotron, external triggers need to be synchronous with the clock in the TELL1 board as well as cable delays and latency settings in the Beetle chips have to be adjusted.

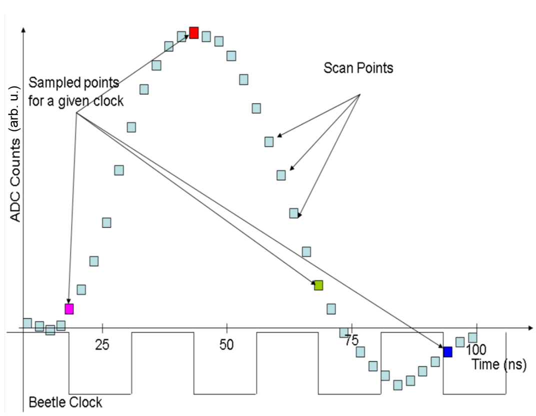

Figure 3: Sampling of the 40 MHz clock of the output pulse in the Beetle chip at different times. In the optimal case one samples at the pulse peak. [5]

IMPLEMENTATION AT THE CLATTERBRIDGE CANCER CENTER

Protons are generated by the Scanditronix MC-60 PF cyclotron with a maximum energy of 60 MeV at the Clatterbridge Cancer Centre (CCC) specialized in the treatment of ocular tumors. During normal operation, the LHCb VELO detector works under LHC vacuum conditions. For the envisaged integration of the LHCb VELO detector into a proton beamline, changes of the original design were necessary.

For the safe operation of the detector in air to avoid overheating and to minimize noise, an efficient venting and cooling system was designed and successfully implemented. Furthermore, 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 VELO detector and with the Faraday Cup, the two devices have to be synchronized to each other. Additionally, VELO needs to be matched with the proton bunch arrival given by the RF frequency of the CCC cyclotron of 25.7 MHz. The full setup is shown in Figure 2.

The clocks of the TELL1 board and Beetle chips cannot be changed directly, since non interchangeable quartz crystal oscillators are used to generate the internal frequency. However, the TELL1 can be synchronized with another clocked system (not 40 MHz) using the external readout trigger input accepting 3.3 V TTL signals with rising edge detection. The rising edge of the trigger is detected with a 120 MHz clock in phase with the 40 MHz TELL1 clock. The trigger is accepted, if the edge is within the first 0 to 8.3 ns of the 40 MHz clock and rejects all triggers which fall outside the 8.3 ns window. Therefore, an external trigger of up to 10 kHz is injected into the TELL1 with the Keysight 8110A pulse generator. The frequency is a result of the chosen output data format *non-zero-suppressed*, limiting the bandwidth frequency by carrying the full raw data information. The sinusoidal 25.7 MHz cyclotron RF frequency triggers the pulse generator and thus is in phase with the readout trigger. The trigger arrives at the Beetle chip and will read the event out of the PCN that was recorded at the specified latency in clock cycles ago. To synchronize the proton bunch arrival on the detector and Beetle chip, the L0 latency settings in the configuration file is changed to where the signal is maximum. A MATLAB script controls the output of the pulse generator and the Keithely 486 picoammeter, measuring the beam current collected by the FC. The script acts as a master

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trigger for the VELO detector and FC for a synchronized readout of both systems.

OPTIMIZATION OF A FARADAY CUP

In order to precisely monitor the absolute beam current, a FC optimised for the measurement of the 60 MeV treatment beam was also designed [8]. The Faraday Cup consists of a stainless steel DN100CF 4-way reducer vacuum vessel and aluminium beam stopper (see Figure 4). In order to preserve size and cost effectiveness the chosen beam collector diameter resulted in an impedance of 25 Ω. The impedance mismatch with the 50 Ω BNC connector cable results in reflections of the signal at transition points. To overcome a Quarter-Wave-Transformer (QWT) was designed [9]. The matching impedance is $Z_1 = \sqrt{Z_0 \cdot R_L} = \sqrt{25\,\Omega \cdot 50\,\Omega} = 35.36\,\Omega$ for $\lambda_1 = 20\,\text{cm}$. The loss of power for the full bandwidth is $\Gamma = \frac{1}{17}$.

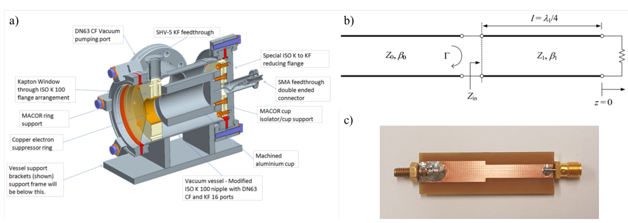

Figure 4: Optimized Faraday cup: a) Design of the FC [8] b) Quarter-Wavelength-Transformer diagram to match 25 Ω Fc with 50 Ω BNC connector c) Produced QWT. [9]

GEANT4 BEAM BEHAVIOUR STUDIES IN INTEGRATION AREA

In order to assess the integration of the VELO detector within the CCC beamline (Fig. 5a), Monte Carlo simulations were performed using the GEANT4 (GEometry ANd Tracking) toolkit. A model of the complete delivery system (Fig. 5b) was developed by the University College London (UCL) [10], facilitating an initial study into the beam propagation, extent of halo and interactions. Further collaboration to develop the code will also incorporate knowledge of the dynamics of the beam as transported from the cyclotron, along with the addition of full experimental validation for the purpose of public use.

GEANT4 simulations were run to observe the general behaviour of the beam throughout the treatment beamline, effects of the components and interactions within the designated area for implementation of the VELO online beam monitor. Given space considerations and also to allow the sensors a non-interceptive approach to the beam, it is necessary to remove the aluminium pipe (Fig. 5b). Without this tube, initial results show negligible impact to the beam profile and energy spectrum thus verifying the feasibility of integration. Transverse beam profile plots with a particular emphasis on the distribution of the primary protons are shown in Fig. 5c, revealing some divergence with a clear outward spread of protons from the core of the beam. Subsequent simulations will include the VELO sensor geometry to determine an optimal position for measurements and any resulting effects.

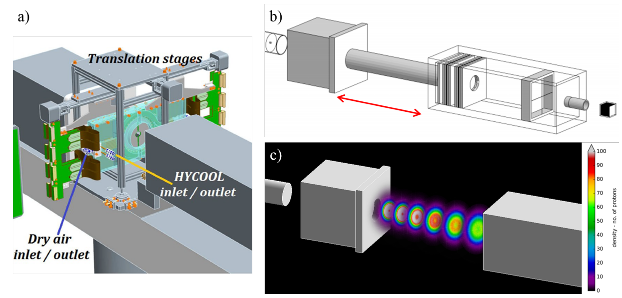

Figure 5: a) Integration area of VELO b) GEANT4 simulation of passive delivery system [10] c) Beam density profiles

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. The full setup optimized for implementation in the proton beam line at CCC is described and GEANT4 simulations inside the integration area are presented. The data acquisition of the VELO detector is synchronized to the RF frequency of the cyclotron and beam current measurements by the Faraday Cup. Additionally, improvements in the post read-out process was also achieved by using a customized VETRA [11] software version, specifically developed to automate algorithms for signal processing. The capability of VELO as a beam monitor will be assessed by measuring the beam current at different dose rates and by monitoring the beam profile supported by simulations. Furthermore, a collaboration with Amsterdam Scientific Instruments (ASI) within the Optimization of Medical Accelerators (OMA) project [12] to use the Medipix3 pixel detector is intended for complimentary particle imaging and detection measurements. These beam diagnostics studies aim to influence the design decision of future beamlines.

ACKNOWLEDGMENT

Work supported by the EU under grant agreements 215080 and 675265, as well as the Cockcroft Institute core Grant No. ST/G008248/1. The Authors would like to thank Dr. Andrzej Kacperek at the CCC and Dr. Simon Jolly from UCL and their teams for their ongoing support and are looking forward to extend the studies with the North West Cancer Research Centre under Dr. Jason Parson.

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