DESIGN AND FIRST OPERATION OF A SILICON-BASED NON–INVASIVE BEAM MONITOR

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Abstract

Non–invasive, highly accurate and reliable beam monitors are a desired aim of any beam diagnostics design. Knowledge of beam parameters is essential in fundamental research, industrial or medical applications with varying demands. It's also extremely critical in the optimization of ion beams used for cancer treatment. Ocular tumour treatment at the Clatterbridge Cancer Centre (CCC) uses a 60 MeV proton beam. Disturbances introduced to a beam by intercepting devices risk affecting its energy and deteriorating the energy spread, thereby limiting the effectiveness of the treatment. The advantageous semi-circular structure of the LHCb Vertex Locator (VELO) detector has been investigated in the QUASAR Group as an interesting option for a non-invasive online beam monitor. The method relies on beam 'halo' measurements without disturbing the part of the beam used for treatment. This contribution discusses the measurement method, setup design and integration within the CCC treatment beam line and outlines the preliminary experimental results of the performance of the monitor.

INTRODUCTION

A multi-strip silicon LHCb VELO detector [1] has been investigated at the Cockcroft Institute / University of Liverpool as a core module of a non-invasive beam current monitor. The first tests of the prototype, using proton beam at the CCC, were performed in April 2014. This had been preceded by investigations in beam 'halo propagation and beam dynamics studies of the whole treatment line based on dataset from the quadrupole variation scans performed in October 2012 [2].

The first feasibility tests were performed at the treatment beam line in 2010 and demonstrated possible use of the VELO detector as a non–intrusive beam monitor [3]. These consisted of data taken at several points along the propagation direction of the beam, starting from the brass collimator, see Fig. 1. Thus, a new method was proposed to relate the proton 'halo' region hit rate measured by the VELO detector with the absolute beam current provided by a Faraday cup (FC), despite the fact the architecture of the VELO sensors has been specifically dedicated to track particles in the LHCb experiment at CERN. Here, a rough indication of the dose delivered to the patient can be estimated.

The FC design was optimised using the FLUKA Monte Carlo code [5] to maximise the charge collection efficiency for a 60 MeV proton beam.

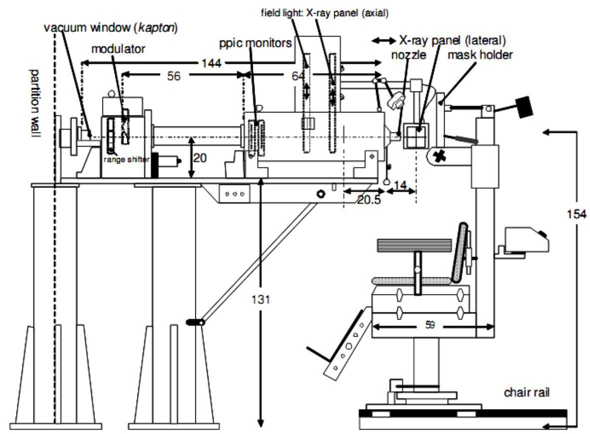

Figure 1: A layout of the treatment beam line at the Clatterbridge Cancer Centre [4]. The integration region is located between the modulator and the PPIC monitors.

LHCB VELO DETECTOR

The head-on collisions in the LHCb experiment produce showers of particles which paths are tracked by the LHCb VELO detector. The traces are resolved in a polar coordinate system defined by a hybrid of two semi-circular n+ - in – n silicon sensors, see Fig. 2. Each sensor consists of 2048 diode strips providing the position of the hits in r – and φ-coordinates. At the same time both the geometrical arrangement of the sensors and the hybrids are optimised to support the ghost hit recognition algorithms, and at the same time keeping the overall strip capacitance and its occupancy at a very low level. Detailed information on the design of the detector can be found in references [6]-[7].

The design of the central part of the sensor lets the LHC beam pass without any interference with the detector. Therefore, the data collection is limited only to the product of the collisions.

Sixteen Beetle chips located at the circumference of each of the sensors read out the signal of the consecutive events and store them in a pipeline until the readout trigger is present. Here, the nominal sampling rate of the detector is around 1.5 times higher than the RF frequency of the Scanditronix MC-60 cyclotron at CCC, where fc=25.7 MHz.

VELO INTEGRATION AT CCC

Integration of the VELO detector with the treatment beam line at the CCC required the design of a dedicated stand to enable its operation in ambient air at temperatures below 0°C.

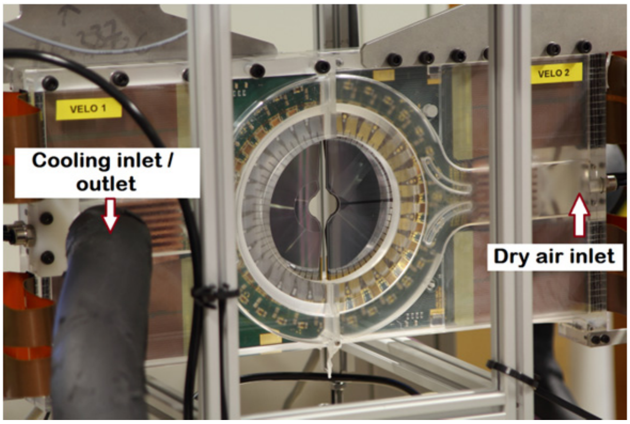

Figure 2: The LHCb VELO detector integration with the beam line at the CCC. The free drift space is housing a motorised stand with two VELO detector modules covering 2π azimuthal angle. Dry air shrouds provide the mechanical support for the detector and constitute a border between its electronics embedded in dry air and ambient atmosphere.

The area designated for the integration is pictured in Fig. 1 between the modulator box and PPIC monitors. Therefore, a motorized stand was designed and manufactured to enable precise positioning of the detector modules in both the beam propagation direction (z) and the perpendicular axes. Three MacLennan stepper motors drive translation stages of the system with 5 µm resolution in both axes [8]. These are controlled by a dedicated LabVIEW interface for driving all three axes in both an independent or coupled manner. The movement range along the z axis allows setting the position from 0 to 16 cm, and 0 to 9.4 cm in the perpendicular direction. This allows for precise proton 'halo' maps determination in the designated region.

The DAQ system of the detector consists of the repeater cards, which amplify the analogue signal from the detector, and send it for digitisation and analysis on the TELL1 cards, see Fig. 3. The Low Voltage cards (LV) distribute power to the repeater boards and the VELO hybrids. It has been estimated that the powered hybrids produce approx. 50W of heat load [9] that has to be dissipated to keep the silicon sensors in the temperature range between -7°C and 0°C. This ensures lower leakage currents and prevents excessive radiation damage to the sensors. Ultimately, to keep the detector dry and mitigate any risk of damage to the electronics, due to vapour condensation, purpose-built dry air shrouds were introduced to the set up to support the above and to provide a rigid mechanical base for the detectors, see Fig. 6. EKOM DK50 2V S/M compressor [10] provides dry air at the rate of approx. 80 l/min at a pressure of 3 bars and the dew point below -20°C.

The Thermo-Pyrolytic-Graphite central base of the hybrid couples directly to the cooling element. An ATC K3 chiller [12], with a cooling capacity of 3200 W, keeps the fully powered detector at a temperature of 0°C in its centre.

The LHCb VELO electronics has been also simplified for the purpose of the 'halo' studies. However, this came at price of a few drawbacks as the repeater boards are not equipped with the Experiment Control System cards, which manage some of the interlocks or timing of the experiment.

Four 33 cm long Kapton cables connect the VELO hybrids to the dummy cards. Flexible ribbon cables, fitted between the dummy cards and the repeater boards, constitute coupling between the moving part and fixed repeater board and transport both power and signals between them. The ribbon cables are 4 times longer than in normal operation and measure 40 cm. These modifications however didn't show any significant rise in the noise level with regard to the original set up.

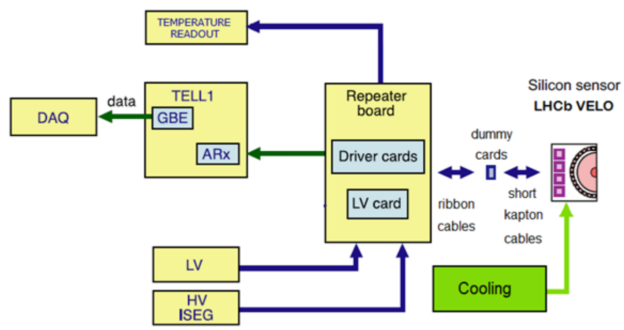

Figure 3: LHCb VELO electronics consist of two main active elements: the repeater boards (signal amplification) and TELL1 boards (digitisation and analysis).

An ISEG EHS 82 05P-F-XXX PS supplies the reverse bias voltage to the silicon sensors with a ripple of 5 mVp-p at the maximum load of -500V [11]. The full depletion voltage during the experiment was sufficient for the operation at only -100 V.

A dedicated alignment system was built to match the detector z axis with the centre of the beam. Two cross–shaped targets, placed at both ends of the stand, marked the centre of the silicon sensors. A cylindrical boss fitted on the beam pipe houses a laser simulating the beam centre in the beam propagation direction to ultimately find the alignment of the system with the geometrical treatment iso-centre.

TESTS AND FIRST MEASUREMENTS

In order to precisely monitor the absolute beam current, the FC design has been optimised for the measurement of 60 MeV protons. Initial FC impedance was matched to a 50 Ω SMA CF-based flange and the signal cable. This allowed resolving the bunch time and repetition frequency on the oscilloscope avoiding any signal reflections. The design has been however altered to reduce the size of the device. As such, the final impedance of the cup is approximately half of the anticipated value. Tests performed on the FC prior to the final experiment

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demonstrated that the response to the test signal: width t = 4.1 ns, repetition rate f = 12.85 MHz, peak current I = 1.0 μA; allows resolving the beam structure in time and frequency domain, Fig. 4.

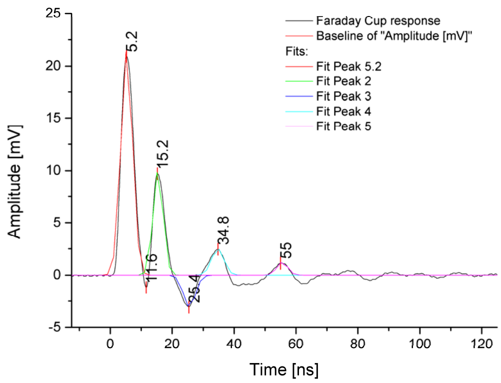

Figure 4: Response of the FC to the test pulse depicting the main signal peak at 5.2 ns and signal reflected from the end of the beam stopper detected 10 ns after the main pulse.

A Keithley 486 Picoammeter [13] was used to read the beam currents form the FC, which were in the range of 0.12 - 0.90 nA. A dedicated LabVIEW interface was used to control the unit and log the current readings to a file. The bunch time and frequency readout were measured using a FEMTO DHCPA-100 low noise amplifier [14] coupled to a 200 GS/s TEKTRONIX oscilloscope.

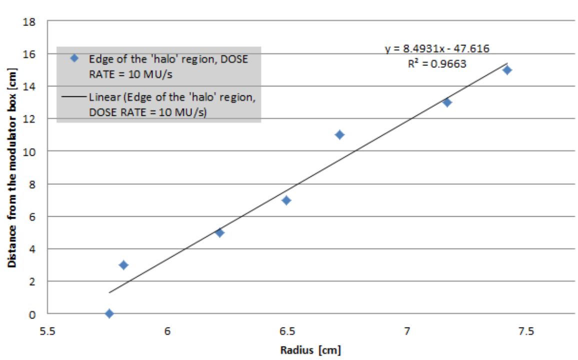

Figure 5: Beam 'halo' dimensions as a function of detector position in the beam propagation direction

Proton beam 'halo' maps were measured by the VELO detector for three different dose rate outputs of the accelerator, e.g. 10 Monitor Units (MU)/s, 30 MU/s and 60 MU/s. These were chosen accordingly to the range used in clinical practice. Mean beam currents and current uncertainties were estimated for every dataset. The measuring points were in the range 0.0 – 5.0 cm in steps of 1.0 cm in the direction perpendicular to the beam propagation and in the range between 0.0 – 15.0 cm in steps of 2 cm in the longitudinal direction.

The LHCb VELO detector was programmed to collect events during 4000 trigger events for each of the sensors. Integrated signal information is being used to find the correlation between the 'halo' and the absolute beam current, whilst data from R-side only can be used to find the extent of the 'halo' region. Fig. 5 presents the distance along the radius of beam, where the signal strength falls below threshold of 3ADC counts (noise level not greater than 2.5ADCs). The results are preliminary approximation of the tail region and therefore the estimated uncertainty should be thought of at least 0.2 cm. The radius of the tail region as a function of dose rate doesn't change more than 0.2 cm, however the intensity rises from the mean of 25 ADCs for 10 MU/s to 125 ADCs for 60 MU/s, see Fig. 6 for reference, see Fig. 6.

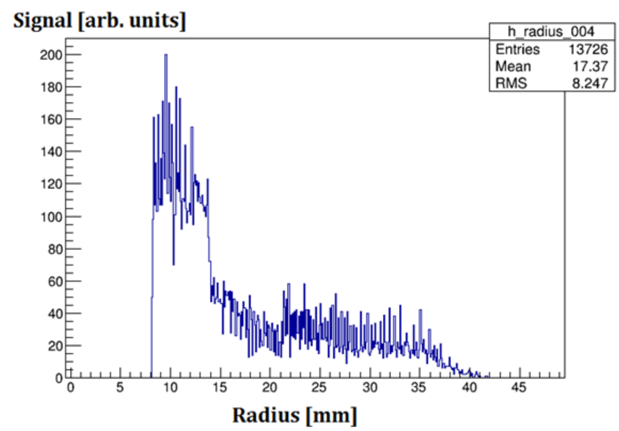

Figure 6: Beam and 'halo' image on R-sensor for the detector modules at x = y = 0.0 cm and at the distance z = 15 cm from the initial longitudinal position. Dose rate = 10 MU/s (approx. 0.9 Gy/s).

Advanced data studies are being carried out to investigate the correlation between the absolute beam current value and the beam halo region intensities and shape.

SUMMARY

A stand-alone test stand was designed to allow for the integration of the LHCb VELO detector into the treatment beam line at the Clatterbridge Cancer Centre. The detector has been tested as an option for a new online, non–intrusive beam monitor, based on proton beam 'halo' detection. The design required safe operation of the detector in air, a remotely controlled multi-axes positioning system, as well as integration of an efficient cooling system to avoid over-heating and minimize the noise. The system was tested with the proton beam at the CCC in April 2014.

Two independent data sets were collected to relate the absolute beam current measured with the Faraday cup to the beam tail region integrated by the LHCb VELO detector. Studies are being carried out to determine the sensitivity and reliability of signal cross-correlation. Thereby, halo–current mappings are expected to give access to an online dose monitoring during treatment.

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