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NON-INVASIVE BEAM DIAGNOSTICS FOR A 60 MeV PROTON BEAM

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Abstract

Hadron therapy has proven to be a very sophisticated and precise technique in cancer treatment. A particular advantage of hadron therapy is the precise dose distribution, which can be limited exactly to the tumour volume, thus decreasing the dose in the nearby organs. Work on detectors for quality assurance of the proton beam at the Clatterbridge Centre for Oncology (CCO) has been started in the QUASAR Group. As a core element, the LHCb VELO (VErtex LOcator) detector is being adopted as a non–invasive beam current and beam position monitor. The mechanical design for integrating this detector in the treatment beam line has been finalized and will be presented in this contribution. In addition, a Faraday Cup has been designed and optimized in FLUKA simulations for the 60 MeV proton beam available at CCO. In this contribution results from the Faraday Cup design optimisation will be presented together with a description of the VELO detector setup.

INTRODUCTION

A non-invasive beam current monitor based on the multi-strip silicon LHCb VELO detector is being developed at the Cockcroft Institute/University of Liverpool and first tests at the treatment beam line at CCO are planned in the near future. Whilst having been originally designed to track vertices in the LHCb experiment at CERN [1] , the flexible VELO architecture allows for different applications.

First feasibility tests were performed at the treatment beam line in 2010 and demonstrated the possibility of non–intrusive beam monitoring [2]. These initial measurements consisted of data taken at several points along the propagation direction of the beam, starting from the brass collimator, see Fig. 1. 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) and thereby get an indication of the dose delivered to the patient. The FC design was optimised using the FLUKA code [3] to maximise the charge collection efficiency for a 60 MeV proton beam.

LHCb VELO DETECTOR SETUP AND INTEGRATION AT CCO

The LHCb VELO detector tracks vertices in a polar coordinate system. The active area of the detector consists of two semi-circular silicon sensors, each equipped with 2048 strip diodes. 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. A stereo angle is then introduced to the stripes to support ghost hit recognition, see Fig. 2.

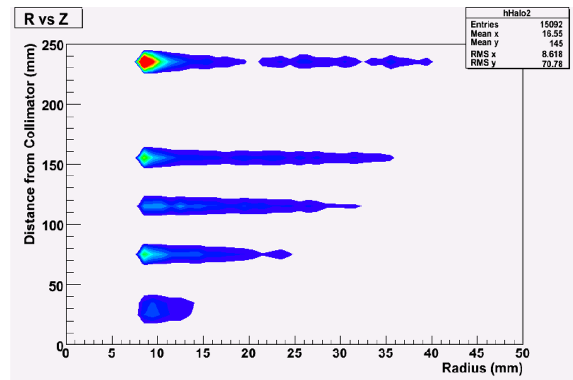

Figure 1: Proton beam divergence at CCO imaged with the LHCb VELO detector at 5 different location form the collimator. [2]

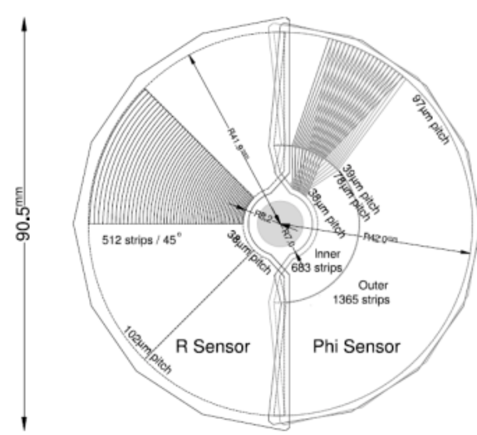

Figure 2: Illustration of the LHCb VELO sensor architecture; note the split into an r/phi sensor, from [4].

A central aperture of 0.8 cm radius enables the main LHC beam to pass through the detector without causing interference with the detector, thereby limiting data recording to reaction products that leave the experiment zone with larger angles then the primary beam.

The readout electronics was designed to work in synchronism with the LHC bunch crossing frequency, f_{LHC}=*40 MHz*. This means that the detector sampling rate is around 1.5 times higher than the RF frequency of the

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Scanditronix MC-60 cyclotron at CCO, where f_c=*25.7 MHz* requiring the development of a dedicated software to readout and analyse the experimental data.

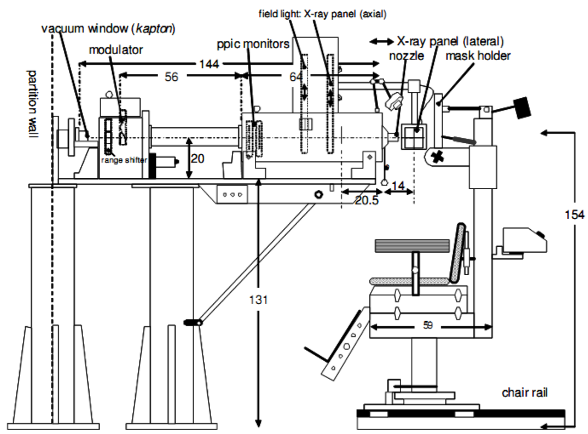

Figure 3: Illustration of the treatment beam line at the Clatterbridge Centre for Oncology, from [5].

The LHCb VELO detector was designed to be operated in vacuum. However, experimental constraints at CCO require its operation in air: In first tests it is planned to integrate the detector directly in a free space region within the treatment beam line between the modulator and integrated parallel-plate ionisation chambers, see Fig. 3. It shall be noted that the sensor readout electronics produces a heat load of 40 W. Therefore, it was essential to couple the electronics board with a purpose-built cooling system through a Thermo-Pyrolytic-Graphite central base. It should be noted that this cooling down process may, however, lead to water condensation on the detector elements and thus a major challenge during the design of a dedicated support structure was the integration of an efficient cooling system together with a precision detector positioning system.

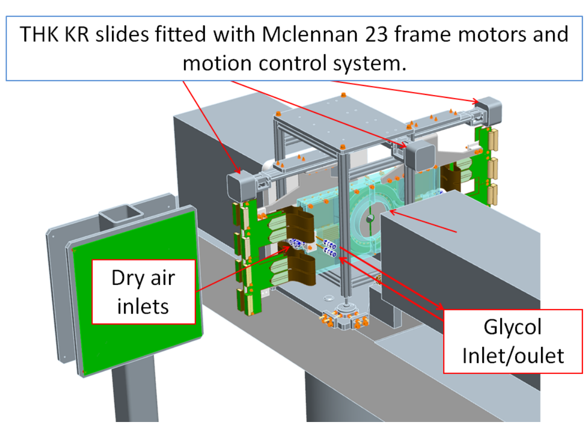

Figure 4: Sketch of the LHCb VELO test stand at CCO.

Two orthogonal translation stages, equipped with McLenan stepper motors, provide detector positioning with a resolution of 5 µm along two axes, parallel and perpendicular to the beam direction. A chiller enables the whole detector to be cooled down to-7°C, reducing noise and efficiently keeping the overall heat load down. Two perspex envelopes enclose the detector hybrids, forming dry air shrouds around the cooler elements, see Fig. 4. The required air dryer flow rate will be determined experimentally, but is expected to be lower than the nominal flow rate of up to 45 l/min at a pressure of 8 bars.

An ISEG EHS 82 05P-F-XXX voltage supply will bias semicondutor junction region in the sensors by applying a depletion potential of up to -500 V. This power supply provides a stable voltage of only 5 $mV_{p\text{-}p}$ ripple at maximum load, see [6]. The unit is equipped with both, positive and negative polarisation channels and a total number of four channels of each type. This will allow the use of both, p–on-n and n-on-n type sensor hybrids in the experiment.

FARADAY CUP OPTIMISATION

In order to precisely monitor the absolute beam current, a FC optimised for the measurement of the 60 MeV treatment beam was also designed. It was important to optimize both, the beam stopper material and the geometrical arrangement to maximise the charge collection efficiency. These studies were performed with the FLUKA Monte Carlo code. Investigations into suitable materials and geometrises focused on the minimisation of the proton-induced flux of various charged particles liberated from the surface of the beam stopper after impact of the 60 MeV proton beam.

Proton interactions with matter, such as inelastic proton collisions with the Fermi electron gas inside the metal, as well as elastic collisions with the nuclei, initiate processes that lead to the generation of secondary particles [7,8]. These influence the overall charge collection efficiency and hence the performance monitor. Simulation studies showed that secondary electrons and protons escaping from the metal surface directly can cause significant measurement accuracy deterioration.

Over 50% of the proton–induced electrons emitted from the metal surface are in the low energy region below 50 eV, with a local maximum in the energy region between 2–20 eV. This characteristic spectrum is material dependent, but does not depend on the projectile energy. This effect is believed to be driven by cascade processes of high energy ionising δ–electrons. This situation changes for emitted electrons of energies higher than 50 eV. In this case the electron yield becomes impact energy-dependent; the abovementioned high-energy electron spectrum can then extend up to some hundreds of keV and is believed to be triggered by inelastic proton collisions with electrons in the material, leading to direct kinetic energy transfer. Moreover, molecular processes also contribute to the high–energy electrons resulting from electron loss caused by the projectile. This leads to electron emission at energies centred around the energy corresponding to the velocity of the impinging particle [7].

FLUKA simulations gave good agreement with theoretical predictions and it was found that graphite showed the lowest proton-induced charged particle currents, see Table 1. It was decided, however, to choose Aluminium as material for the beam stopper since it can be much easier machined than graphite. The ion-induced particle currents as a function of the target material proved to be independent of the geometry of the beam stopper within the estimated current errors. The following three target shapes were considered: flat, conical and spherical. Due to the low beam power of only $P=0.3\ W$ no special requirements with regard to local heating/cooling were found to be necessary [9]. This way it was possible to optimize and further simplify the FC geometry and a flat shape was chosen to minimize the overall manufacturing cost.

Table 1. Charged particles currents from the FC as a function of the beam stopper material.

Material	$I_{protons}$ **[nA]**	$I_{electrons}$ **[nA]**
Copper	$2.97 \cdot 10^{-5}$	$5.45 \cdot 10^{-4}$
Aluminium	$2.54 \cdot 10^{-5}$	$3.22 \cdot 10^{-4}$
Graphite	$2.54 \cdot 10^{-5}$	$3.38 \cdot 10^{-5}$

The FC was impedance matched to a 50 Ω SMA KF-based flange and a signal cable. The beam stopper is mounted directly on an end flange and isolated by a Macor layer; see Fig. 5.

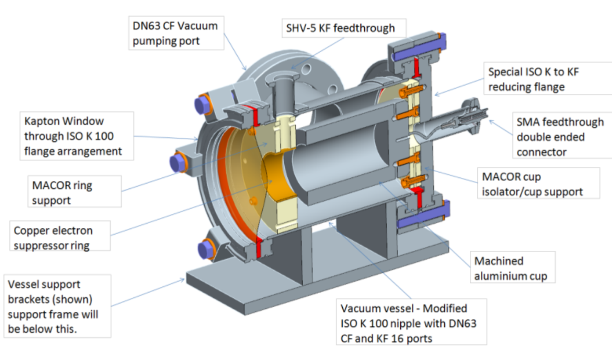

Figure 5: Overview of the optimized CCO Faraday cup design.

SUMMARY

A test stand was designed to allow for the integration of the LHCb VELO detector into the treatment beam line at the Clatterbridge Centre for Oncology. There, the detector will be used as a new online, non–intrusive beam monitor, based on proton beam 'halo' detection. Particular challenges were to guarantee the possibility of moving the detector remotely, as well as to include an efficient cooling system to avoid over-heating and minimizing noise. This system is presently being assembled and will allow installation of the apparatus in a free space region in proximity of the patient.

An Aluminium based Faraday cup was also designed and optimised for the characteristics of the proton beam at CCO and will be used to precisely determine the absolute beam current. The LHCb VELO readings will then be related to the current readings and studies will be carried out to determine the sensitivity and reliability of signal cross correlation. Thereby, halo signal-dose mappings shall be determined to allow for a true online monitoring system during patient treatment. The shape of the FC beam stopper has been optimized in numerical simulations with FLUKA. The stopper will be built from Aluminium since it showed lower proton-induced particles emission than copper and it can be machined much easier than graphite. The readout electronics for the FC will be proposed shortly and custom made software is being developed to read out and analyse the VELO and FC data simultaneously.

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