FIRST RESULTS FROM THE OPERATION OF A REST GAS IONISATION PROFILE MONITOR BASED ON A HYBRID PIXEL DETECTOR

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Abstract

A novel rest gas ionisation profile monitor which aims to provide continuous non-destructive bunch-by-bunch measurement of the transverse emittance is currently under development for the CERN Proton Synchrotron (CPS). The instrument consists of an electric drift field to transport ionisation electrons onto a measurement plane, a self-compensating magnet to maintain the transverse position of the ionisation electrons and an imaging detector to measure the transverse position of the ionisation electrons. Uniquely for this type of instrument the imaging detector consists of an array of pixelated silicon sensors which are read-out using Timepix3 readout chips. This so-called hybrid pixel detector is sensitive to single ionisation electrons and therefore removes the need for electron amplification with Multi-Channel Plates which typically suffer from aging phenomena and distorts the measured profile. The use of a pixel detector also offers the promise to significantly improve the time and spatial resolution of the position measurement compared to existing instruments. An ambitious program has been undertaken to develop a pixel based imaging detector that is compatible with operation directly inside the beam pipe vacuum together with the necessary radiation hard control and data acquisition electronics. A prototype version of the instrument was recently installed in the CPS and first results from the operation of this novel instrument will be presented.

INSTRUMENT DESIGN & REALISATION

An overview of the instrument design is shown in Fig. 1. Rest gas ionisation electrons are accelerated by an electric drift field towards an electron imaging detector located beneath a honeycomb structured radio-frequency shield. A magnetic field parallel to the electric field, formed by a self-compensating 0.2 T dipole magnet, helps to maintain the transverse position of the ionisation electrons during transport to the measurement plane. The electric drift field is formed by a single -11 kV cathode, without side-electrodes. The cathode includes an ion trap that prevents ion induced secondary electrons from re-entering the vacuum chamber and reaching the imaging detector [1]. The instrument is mounted on a rectangular vacuum flange with a ConFLat-type seal [2].

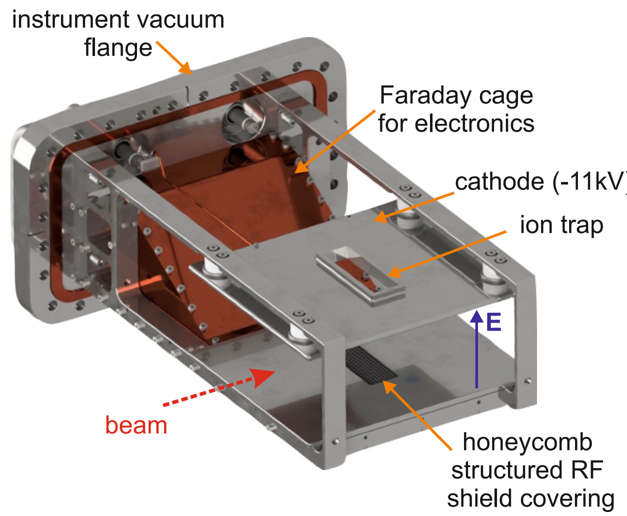

Figure 1: Rest gas ionisation profile monitor for the CERN PS.

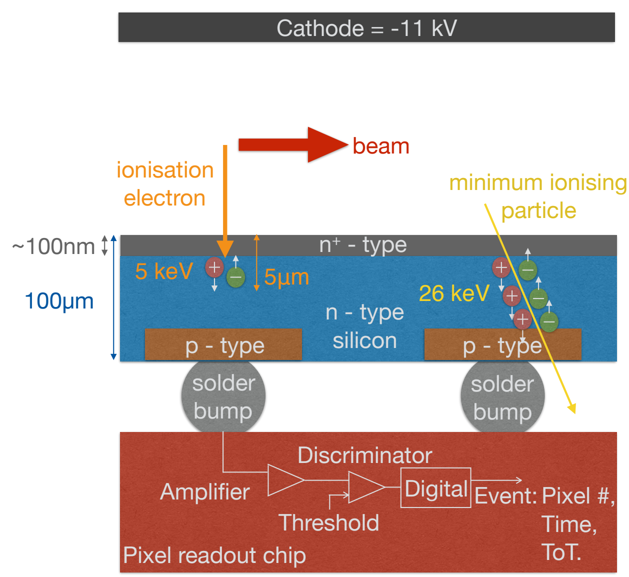

Figure 2: Detection of rest gas ionisation electrons with a hybrid pixel detector.

Detection of Rest Gas Ionisation Electrons With a Hybrid Pixel Detector

The ionisation electron imaging detector consists of four 14 × 14 mm hybrid pixel detectors mounted side-by-side creating a measurement plane 56 mm wide (transverse to the beam direction) and 14 mm long (in the direction of the

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beam). Each hybrid pixel detector consists of a pixelated p-on-n silicon sensor bonded to a Timepix3 readout chip. Figure 2 illustrates the method by which ionisation electrons are detected in the hybrid pixel detector. Electrons produced by protons ionising the rest gas in the center of the beam vacuum chamber reach the surface of the detector with an energy of 5.5 keV due to the 11 kV voltage applied to the cathode. The aluminum metalization layer typically deposited on the front face of silicon sensors has been removed from the sensors used in the pixel detector to allow these low energy electrons to reach the silicon. The 5.5 keV electrons are completely stopped in the first 5μm of the sensor and the energy they deposit in the depletion layer of the silicon produces electron-hole pairs which can be collected by each pixel's electrodes. Charge from each of the 65,536 55 μm $\times$ 55 μm silicon sensor pixels is amplified and digitized by a Timepix3 readout chip directly bonded to the silicon sensor [3]. If the charge exceeds a pre-defined threshold an event is created consisting of: 1) the pixel location, 2) the time of the event relative to an external trigger and 3) the time that the signal remains above threshold. The time resolution for each event is 1.625 ns. Events are readout from each chip on 8 parallel links at a combined speed of up-to to 5.12 Gbps.

Since the pixel detector is located directly inside the ultra high vacuum environment of the beam pipe the total out gassing rate must be less than than 5.0×10^{-6} mbar.l.s^{-1} after 10 hours of pumping. The in-vacuum pixel detector electronics developed to meet this requirement are shown in Fig. 3 [4]. The four hybrid pixel detectors are mounted on a carrier board consisting of two metal layers and a 114.3 x 114.3 x 0.389 mm^3 ceramic substrate. The Timepix3 power and data signals are connected via wire bonds to pads on the top layer of the carrier board from which the signals are routed to two micro-connectors on the board. A flexible printed circuit board consisting of two metal layers and a 50μm thick Liquid Crystal Polymer (LCP) substrate is used to transmit the signals from the micro-connectors to the front-end read-out electronics via a 182-pin electrical vacuum feedthrough. The four Timepix3 chips generate 12 W of heat that needs to be actively removed to ensure continuous operation of the chips inside the vacuum. Active cooling is provided by a continuous flow of de-mineralized, room temperature water flowing through a stainless steel pipe that is brazed to a copper plate holding the ceramic carrier. A radio frequency shield, consisting of a stainless steel honeycomb structure with 0.125" cell size, is located immediately above the pixel detector to minimize interference between the Timepix3 chips and the electromagnetic field of the beam. The honeycomb is part of a Faraday cage that shields the Timepix3 chips and the electrical signals on the carrier board and flex cables.

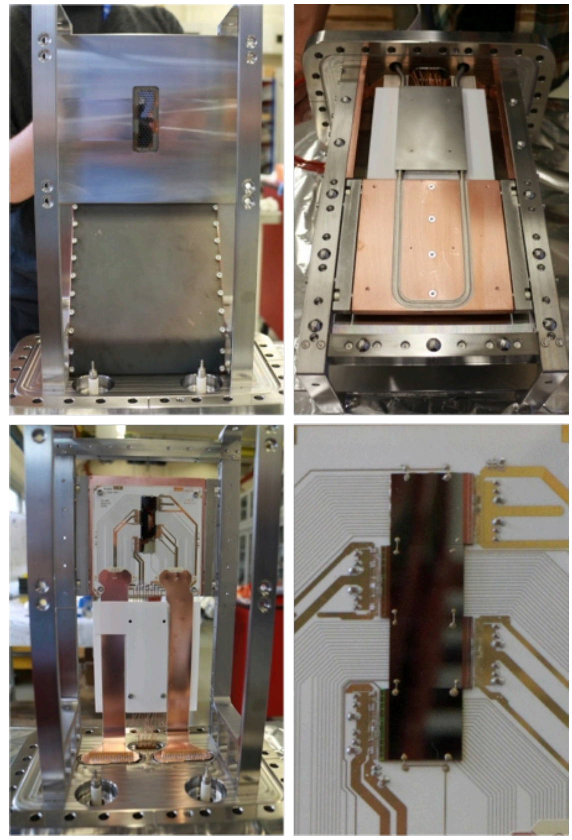

Figure 3: Ionisation profile monitor installed in the CPS. The beam passes horizontally from left to right. Top left: Cathode removed to reveal pixel detector beneath honeycomb RF-shield. Faraday cage cover is carbon coated to minimize the creation of secondary electrons. Top right: Copper cooling plate with stainless steel pipe for cooling water. Bottom left: Pixel detector mounted on ceramic carrier board, flexible cables connecting carrier to the electrical vacuum feedthrough. Bottom right: The four hybrid pixel detectors mounted on the ceramic carrier board.

Data Acquisition, Slow Control and Monitoring

The front-end electronics are located in a radiation environment close to the accelerator beam pipe, requiring a complete radiation tolerant data acquisition and control system for the pixel detector to be implemented. This is responsible for: sending commands to and reading data from the four Timepix3 chips, serializing data onto an optical link, and forwarding the acquisition triggers to the chips. The front-end is based on a multipurpose radiation hard FPGA board developed by the CERN Beam Instrumentation group that uses the GigaBit Transceiver (GBT) and Versatile Link components developed by CERN for upgrades to existing LHC experiments [5]. Single mode optical fibers connect the front-end electronics to the back-end electronics located 200 m away in a non-radiation environment. The back-end functionality includes: buffering data from the front-end, managing external timing and trigger signals, and providing a standard Ethernet interface to a computer. The first version of this back-end electronics is based on a commercial off-the-shelf Xilinx VC707 FPGA development board.

A Programmable Logic Controller (PLC) based control system has been developed for the slow control and monitoring of: the cathode high voltage, pixel detector bias voltage,

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front-end power supplies, detector cooling and temperature monitoring. The PLC will turn off the pixel detector power supplies if it detects the loss of the cooling circuit and prevents the power supplies exceeding pre-defined current and voltage limits.

Installation in the CERN PS

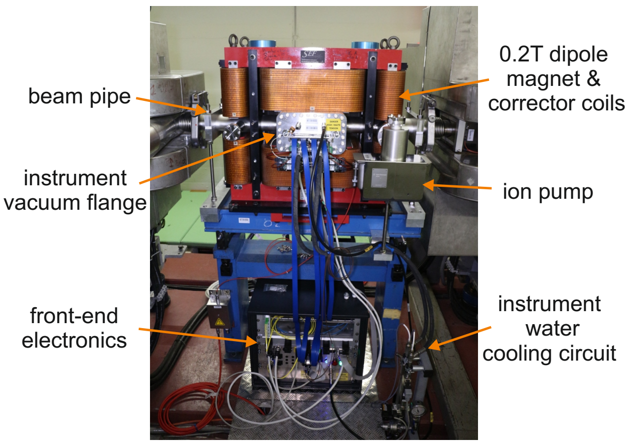

Figure 4: Pixel detector based rest gas ionisation profile monitor installed in the CERN PS.

Before installation in the CERN PS out-gassing tests were performed to qualify the instrument for operation in an ultra-high vacuum environment. RF measurements were also made to ensure that there was no significant contribution to longitudinal beam impedance [6]. The vacuum chamber, instrument, front-end electronics, cooling circuit and self-correcting dipole magnet were installed in PS straight section number 88 during the 2016/17 winter shutdown. The complete installation is shown in Fig. 4. After a 24 hour vacuum pump down down the pressure in the vicinity of the instrument reached 1×10^{-8} mbar and has reached a steady-state pressure of 2×10^{-10} mbar.

RESULTS

Operation During the Acceleration Cycle

Before attempting to detect rest gas ionisation electrons tests were made to verify the operation of the chips inside the beam pipe vacuum during an acceleration cycle. After configuring the pixel matrix registers, which included setting the threshold voltage for each pixel, images as shown in Fig. 5 of single inelastic hadronic interaction were acquired. This confirmed successful operation of the the detector under vacuum.

Detection of Rest Gas Ionisation Electrons

The pixel detector is sensitive to ionisation electrons and any other charged particle that deposits energy in the silicon sensor. The latter may come from beam loss in the vicinity of the pixel detectors and are typically high energy minimum ionising particles. The expected energy deposited in

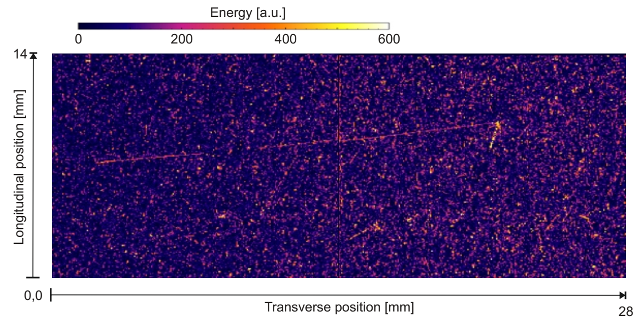

Figure 5: Inelastic hadronic interaction observed in the pixel detector during an acceleration cycle. Heavily ionising tracks - indicated by the higher deposited energy - originate from a common vertex, together with with a less heavily ionising track that crosses two hybrid pixel detectors.

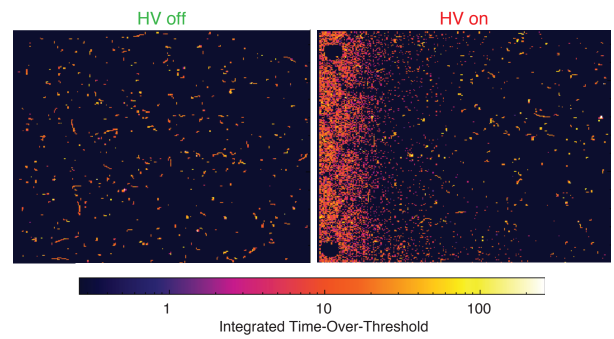

Figure 6: Integrated energy measured on one pixel detector with cathode high voltage OFF (left) and ON (right).

the pixel detector for 1) a 5.5 keV rest gas ionisation electron and 2) a minimum ionising particle is shown in Fig. 2. The ionisation electron will be stopped in less than 5μm, however, not all of the 5.5 keV kinetic energy will create charge carriers since some energy will be deposited in the quasi-conductive heavily doped n+ top layer the depth of which is not well known. A high energy minimum ionising particle (MIP) will travel completely through the 100μm deep silicon sensor and deposit 26 keV - almost five times more energy than the ionisation electron. Images observed on one of the four pixel detectors are shown in Fig. 6 for acquisitions taken without and with high voltage applied to the cathode. The images were recorded with the dipole magnet at 0.1 T, during a 100 ms period with an intensity of 6×10^{12} protons. Without high voltage applied to the cathode the image contains short tracks consistent with MIP activity, however, with high voltage applied to the cathode an image is observed on the left side of the detector consistent with the expected position of the proton beam. Ionisation electrons do not have sufficient energy to pass through the honeycomb RF shield nor the circular glue deposits used to attach the bias wire to the non-metalized sensor. These regions therefore show-up as shadows in the image with high voltage applied to the cathode. The single pixel energy distribution is shown in Fig. 7 for acquisitions with and without high voltage. Without high voltage the energy deposited in a single pixel is consistent with a Landau distribution with

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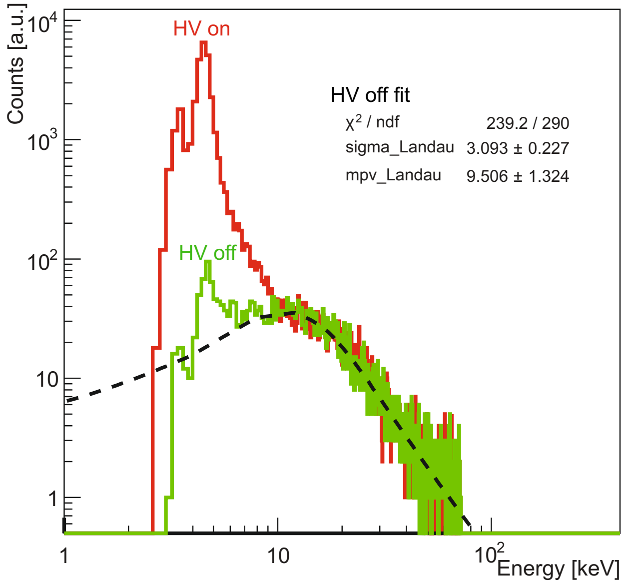

Figure 7: Distribution for energy deposited in a single pixel detector for acquisitions with and without high voltage applied to the cathode.

a most probable value of 9.5 keV, which is consistent with the expected 26 keV deposited by MIPs shared amongst a number of pixels depending upon the incidence angle of the particle track. With the high voltage applied to the cathode there is a significant peak at 4.5 keV consistent with a 5.5 keV ionisation electron. A smaller peak is also visible at 3.5 keV the origin of which is still to be determined but could be due to charge sharing between neighboring pixels.

Beam Profile Measurement

An image acquired by two of the four pixel detectors is shown in Fig. 8. This is consistent with the expected transverse position of the beam. The counts in each pixel column are integrated to produce the beam profile shown in Fig. 9. The pixel data is currently not corrected for the inhomogeneity of the honeycomb shadow, but nonetheless the measured transverse beam profile is consistent with a Gaussian beam profile of width 1.22 ± 0.01 mm. The expected beam size at the location of the ionisation profile monitor from wire scanner measurements is 1.20±0.01 mm, in very good agreement with the value measured by the ionisation profile monitor.

CONCLUSIONS AND OUTLOOK

An ionisation profile monitor that uses a pixel detector to measure ionisation electrons has been installed directly in the PS beam pipe vacuum and operated successfully during the acceleration cycle. Rest gas ionisation electrons have been detected with the pixel detector and a first beam profile has been measured, in good agreement with wire scanner measurements. Future efforts will be directed towards exploiting the unique characteristics of the pixel detector technology to improve the accuracy of the beam profile measurement and to minimize the number of turns needed to measure the profile of a single bunch.

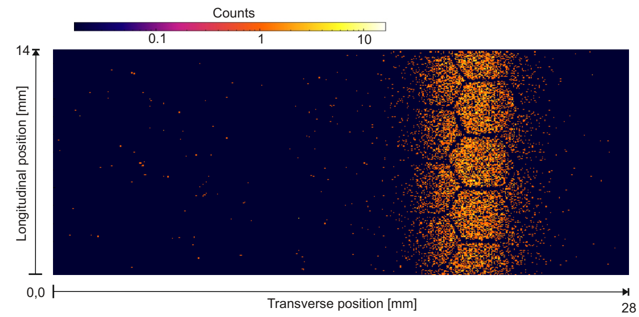

Figure 8: Pixel detector image of an LHC cycle in the CPS acquired during a 10 ms window at extraction energy. Dipole magnetic field at 0.2 T and cathode high voltage set at -13 kV.

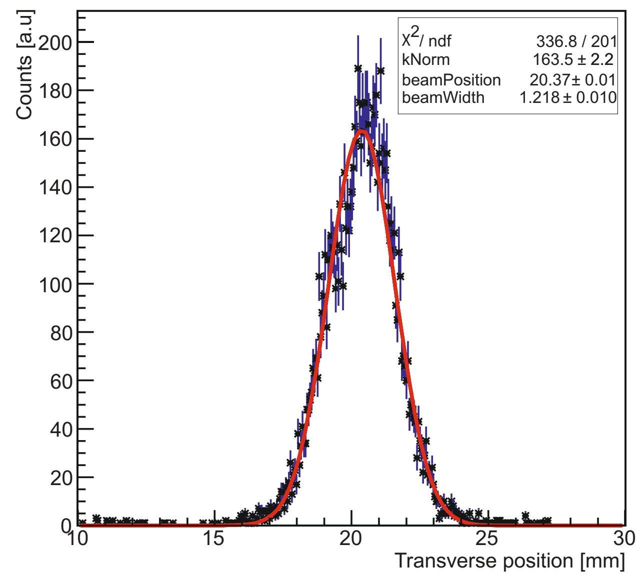

Figure 9: Horizontal beam profile obtained from the image shown in Fig. 8.

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REFERENCES

[1] D. Bodart *et al.*, "Development of an Ionization Profile Monitor based on a Pixel Detector for the CERN Proton Synchrotron", in *Proc. IBIC15*, Melbourne, Australia, paper TUPB059.

[2] A. Miarnau, G. Schneider, R. Veness, "Development and test of a rectangular CERN ConFlat-type flange", *Elsevier Vacuum* 121 (2015) 202-206.

[3] T. Poikela *et al.*, "Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout", 2014 *JINST* 9 C05013.

[4] S. Levasseur *et al.*, "Development of a Rest Gas Ionisation Profile Monitor for the CERN Proton Synchrotron Based on a Timepix3 Pixel Detector", in *Proc. TWEPP2016*, Karlsruhe, Germany.

ISBN 978-3-95450-192-2

[5] M. Barros Marin, "The Giga Bit Transceiver based Expandable Front-End (GEFE) – a new radiation tolerant acquisition system for beam instrumentation", in *Proc. TWEPP2015*, Lisbon, Portugal.

[6] N. Nasr Esfahani *et al.*, "Evaluation of Longitudinal Beam Impedance in the Beam Gas Ionization Monitor of the CERN-PS Accelerator", in *Proc. IPAC2017*, Copenhagen, Denmark, `doi.org/10.18429/JACoW-IPAC2017-WEPIK095`