DEVELOPMENT OF AN IONIZATION PROFILE MONITOR BASED ON A PIXEL DETECTOR FOR THE CERN PROTON SYNCHROTRON

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Abstract

The transverse emittance measurement in the CERN Proton Synchrotron (CPS) is currently performed using fast rotational wire scanners. These scanners cannot provide continuous bunch-by-bunch measurements and the expected future increase of the beam brightness will lead to an accelerated sublimation of the wire. A novel Ionization Profile Monitor (IPM) is currently under development to cope with these challenges. The readout of this device will be based on a hybrid silicon pixel detector with a Timepix3 readout chip. Pixel detectors are sensitive to single electrons therefore eliminating the need for traditional Multi-Channel Plates, which suffer from aging phenomena. The early digitization of the signal will reduce the susceptibility of the readout system to electromagnetic interference, while the time resolution of the Timepix3 allows for bunch-by-bunch measurements. Due to the small length of the detector a new simplified ion trap has been designed. The guiding field will be provided by a new self-compensating magnet. It is foreseen to test a prototype version of the device with beam in 2016.

INTRODUCTION

A fast non-destructive transverse profile monitor is currently under development for the CERN Proton Synchrotron (CPS) which is based on the ionization of rest gas molecules by high energy beam particles. The transverse beam profile is inferred from the distribution of ionization electrons which is measured by accelerating the electrons onto an imaging detector consisting of a pixelated p-on-n silicon sensor bonded to a Timepix3 readout chip. The fast sampling and readout speed of the Timepix3 will facilitate bunch-by-bunch measurement of the beam profile. A 0.2 T magnetic field parallel to the electric field will maintain the transverse position of the ionization electrons during the passage of the electrons to the imaging detector. The main elements of the design are shown in Fig. 1. Initial studies of the electron rates for various types of beams expected in the PS together with proposed modes of data acquisition are presented in [1]. Here the final design of the prototype device is presented.

HYBRID PIXEL DETECTOR

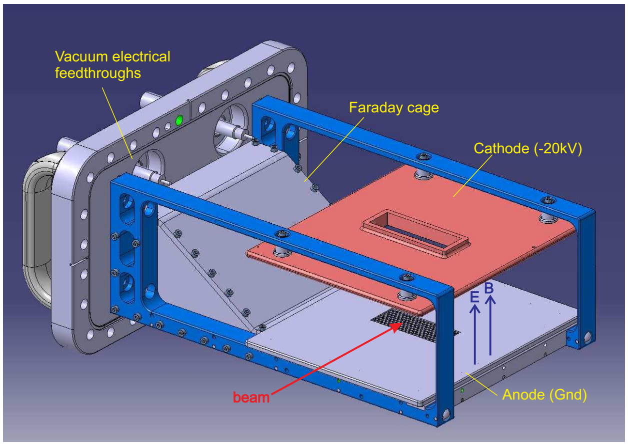

Figure 1: Design of the new non-destructive transverse beam profile monitor for the CPS. Ionization electrons are accelerated by a 270 kV/m electric field towards the pixel detector, which is located at the ground electrode just beneath a honeycomb shield. To suppress any beam induced electromagnetic effects the pixel detector and readout electronics are located in a Faraday cage.

Ionization profile monitors typically amplify the ionization signal electrons or ions by means of Micro Channel Plates (MCPs). Charge from the MCP is then either readout optically by means of a phosphor screen and camera [2, 3] or directly using arrays of narrow anodes [4, 5]. A common problem for MCP based systems is the inhomogeneous degradation of the MCP gain and limited lifetime. In recent years hybrid pixel detectors, which consist of a pixelated silicon sensor bump bonded to a pixelated readout chip, have become widely used in many high energy physics and medical imaging applications. By removing the metalization usually applied to the surface of a silicon sensor, hybrid pixel detectors become sensitive to single electrons with an energy of at least 3.6 keV. As an imaging detector for IPMs hybrid pixel detectors offer a number of advantages, namely: trigger-less readout, high spatial and time resolution, early digitization, radiation hardness and removing the requirement for additional amplification stages.

The imaging detector for the CPS IPM is based on the Timepix3 hybrid pixel detector readout chip, which has been developed in the framework of the Medipix3 collaboration [6, 7]. Timepix3 consists of a pixel matrix of 256×256 square pixels with a pitch of 55 µm, covering an area of $14 \times 14\,\mathrm{mm}^2$. The trigger-less readout allows for a sustained hit-rate of up to 40 Mhits/cm^2/s and has a minimum time resolution of 1.562 ns. To detect electrons the Timepix3 will

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be bump bonded to a 100 µm thick p-on-n silicon sensor. The metalization layer on the backside of the sensor is removed and the depth of the n+ layer is minimized in order to improve the detection efficiency of the ionization electrons.

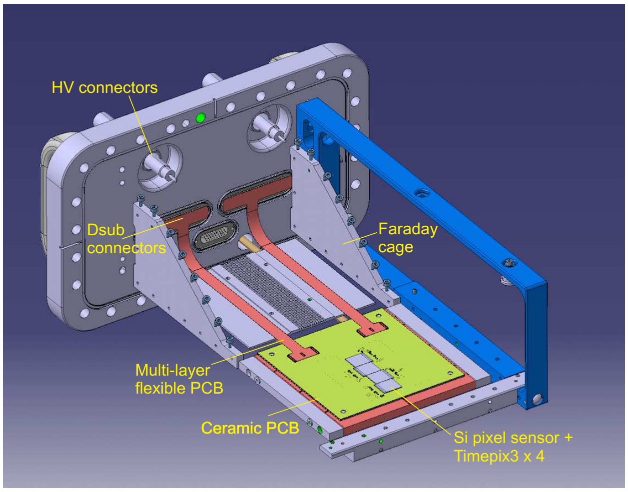

Figure 2: Hybrid pixel detector imaging system based on the Timepix3 readout chip.

The design for the CPS IPM Timepix3 based imaging detector is shown in Fig. 2. The imaging detector, covering a total area of 5.6 cm × 1.4 cm, will consist of four hybrid pixel detectors aligned transverse to the direction of the beam. The environment in which the pixel detector must operate is very challenging: it must operate inside the CPS ultra-high vacuum (10^{-9} mbar), in a 10 kGy/yr radiation area and be tolerant to electromagnetic interference caused by the beam. Furthermore, the system must be sufficiently robust to run reliably for the duration of the annual injector program. To ensure compatibility with the ultra high vacuum environment a complete readout system for the Timepix3 has been designed which is optimized for low out-gassing characteristics. The pixel detectors themselves are mounted on a 300 µm thick ceramic PCB. Multi-layer flexible PCBs provide the link between the ceramic PCB and sub-D connectors on the electrical feedthrough. A Faraday cage is used to shield all elements of the readout electronics from electromagnetic interference from the beam. The radiation tolerance of the Timepix3 chip is expected to be high; the Medipix3 hybrid pixel detector is based on the same 130 nm CMOS technology as the Timepix3 and has been measured to be operating well after 4.6 MGy [8].

The readout architecture for the IPM imaging detector is shown in Fig. 3. A front-end readout board, mounted on the air side of the vacuum feed-through, provides the power and control signals for the Timepix3 chips. It is also responsible for transmitting the 32×640 MB/s data outputs of the 4 × Timepix3 chips via radiation hard optical transceivers to the back-end readout electronics located in a non-radiation environment. The data acquisition and bunch-by-bunch reconstruction will be done by an FPGA based system. Synchronization to the CPS bunch structure will follow the procedure developed for the CPS trajectory measurement system [9].

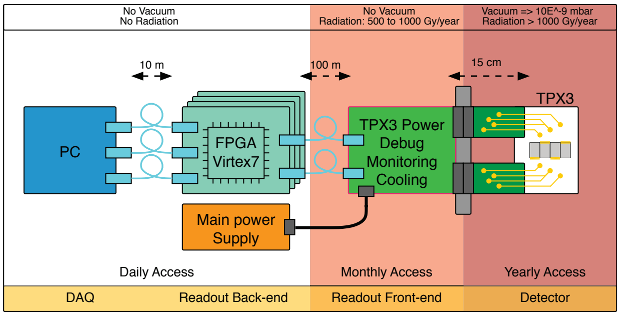

Figure 3: Readout architecture for the hybrid pixel detector.

Cooling

The silicon sensors will be exposed to radiation levels of several tens of kGy per year. A cooling system has been designed to cool the sensors to below 0°C. This serves two purposes: firstly, to remove the 12 W of heat produced by the Timepix3 chips and secondly, to improve the radiation hardness of the sensors. Operating the sensors at 0°C rather than room temperature will reduce the radiation induced increase in leakage current by two orders of magnitude and increase the reverse annealing time constant from one to fifteen years [10].

In the first design cooling was performed with Peltier elements, which on further investigation were found to be unsuitable due the presence of Bismuth which upon interaction with neutrons transmutates to Polonium. The final design is based on liquid cooling a copper plate that is soldered to the Ceramic PCB holding the hybrid pixel detectors. The ceramic PCB has a very good thermal conductivity (24 W/mK, about 50 times more than a standard PCB) and thermal simulations show that the coolant temperature needed to keep the copper plate below 0°C is between −2°C and −8°C.

FIELD CAGE DESIGN

The IPM field cage, shown in Fig. 1, is required to:

- provide an electric field to accelerate ionization electrons onto the hybrid pixel detector, with sufficient homogeneity as to not distort the original transverse position of the ionization electron.
- shield the pixel detector from electrons produced by the interaction of the ionization ions with the cathode.
- provide a path for the beam mirror current.
- shield the readout electronics from electromagnetic interference from the beam.

The field cage is made of two flat parallel electrodes: an upper cathode held at a potential of −20 kV and a lower anode which is grounded. The hybrid pixel detectors are located at the anode below a honeycomb shield which protects the chips from electromagnetic interference from the beam, while also providing high transparency for the passage of the ionization electrons.

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Ion Trap

The ionization process produces ions in addition to the electrons used to measure the beam profile. The ions will accelerate towards the cathode and impact the electrode surface with sufficient kinetic energy to cause the emission of secondary electrons. These electrons the transverse position of which are distorted compared to the original ionization electron, will accelerate back towards the anode and can be a potentially significant source of background electrons for the imaging detector system. The problem of background electrons for the Timepix3 pixel detector is particularly acute since the sustained readout rate is limited to 40 Mhits/cm^2/s.

In order to remove these background electrons, a wire mesh is typically located just below the cathode with a slightly higher potential than the cathode itself. Secondary electrons emitted from the cathode are stopped by the potential barrier between the cathode and the wire mesh and are thus unable to reach the detector. However, the wire grid itself can also be a source of background electrons due to either electron emission caused by beam induced heating of the wire or emission of secondary electrons due to the impact of the ion on the wire grid. To remove these additional sources of background electrons a simplified scheme has been devised which dispenses with the wire grid. In this *ion trap* scheme a slit is created in the cathode directly above and with dimensions similar to the imaging detector plane. The slit allows ions to pass through the cathode and to be directed by electric fields lines onto the back of the cathode where the secondary electrons will find no path back to the pixel detector. The wire grid and ion trap schemes are illustrated in Fig. 4. Simulations of the ionization electron trajectories in the presence of the ion trap demonstrate negligible distortion of the transverse beam profile.

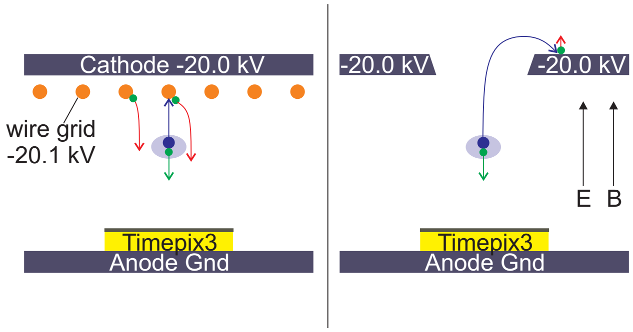

Figure 4: Schemes to prevent ion induced secondary electrons from reaching the pixel detector. Left: A wire grid based scheme forms a potential barrier for electrons between the cathode and wire grid, but the grid itself is a source of background electrons. Right: Ion trap scheme to prevent secondary electrons reaching the pixel detector, which does not require a wire grid structure.

Side Electrodes

Side electrodes are typically used to increase the uniformity of the electric field and therefore decrease the distortion of the transverse beam profile. Simulations have been performed to optimize the number and shape of the side electrodes in the presence of the 0.2 T magnetic field. Fig. 5 shows the standard deviation of an electron distribution on the imaging detection surface for point sources at different transverse distances from the beam center for the case of a field cage with 0 and 3 side electrodes. The simulation shows that at up-to ±28 mm from the center of the beam there is negligible difference between the 0 and 3 side electrode designs. Based upon this simulation no side electrodes are included in the field cage design, which simplifies both the construction and assembly of the field cage.

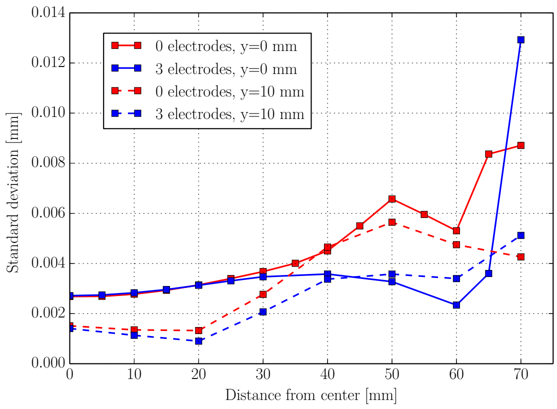

Figure 5: Simulation of the effect of side electrodes on the trajectory of electrons. Initial electrons are a point source produced in the middle between the two electrodes (y=0 mm) and 10 mm higher.

Simulation of Beam Space Charge Effect

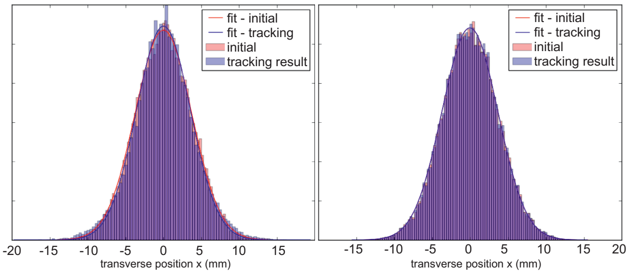

Figure 6: Initial and reconstructed beam profiles without magnetic field (left) and with a 0.2 T magnetic field (right).

The magnetic field should be strong enough to ensure that the electron gyration radius is much smaller than the beam size. The gyroradius depends on the initial velocity of the electron; which is determined by the ionization process and the kick given to the electron by the space charge of the beam. A simulation of the beam space charge effect on the reconstructed beam profile has been performed. The simulated reconstructed profile for a standard 25 ns LHC beam in the PS (1.33×10^{11} protons per bunch, extraction energy =

25 GeV, beam width: $\sigma_x = 3.7$mm, $\sigma_y = 1.4$mm) is shown in Fig. 6 for an IPM with no magnetic field and a 0.2 T magnetic field. Without the magnetic field the systematic error on the reconstructed beam profile width is 2.6%; while the error with the 0.2 T magnetic field is 0.03%. Details of this simulation will be the subject of a forthcoming publication.

MAGNET

A novel magnet is designed to provide a 0.2 T magnetic field in the detector region (x=50 mm long, y=84 mm gap, z=50 mm width) with a field homogeneity of less than 1×10^{-3}. The magnet design is illustrated in Fig. 7.The magnet provides the field for the detector and the canceling field that brings the beam particles back in orbit. Both functions are integrated into a single magnet and ensures that the integrated magnetic field along the beam axis is equal to zero. Lattice correctors installed around the accelerator ring will compensate the 0.5 mm shift of the beam in the transverse plane. The magnet fits within the available space of the available straight section of 850 mm. The design allows direct access to the detector and the magnet can be removed from its position directly.

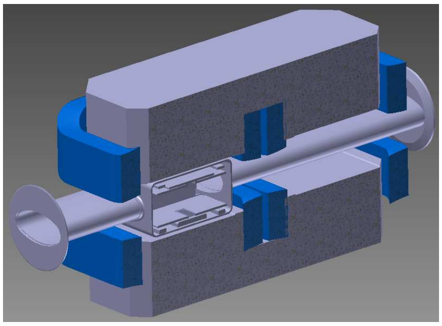

Figure 7: A single magnet provides both the field for the IPM and the corrector field.

CONCLUSIONS

The new Ionization Profile Monitor for the CERN Proton Synchrotron will use, for the first time in an IPM, a hybrid silicon pixel detector as the imaging detector for the ionization electrons. The application of this technology to the ultra-high vacuum, high radiation, and electromagnetic environment of the CPS is very challenging but offers the prospect of fast bunch-by-bunch measurement in a compact design, without the need for additional electron amplification stages. Detailed simulations of the IPM field cage have been used to develop a field cage design without side electrodes and an ion trap that dispenses with the need for a wire grid. A prototype version of the design will be tested in the CPS in 2016.

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