NON-DESTRUCTIVE BEAM PROFILE MEASUREMENTS WITH AN IONISATION PROFILE MONITOR (IPM) BASED ON TIMEPIX3&4 HYBRID PIXEL DETECTORS (HPDs)

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Abstract

Beam Gas Ionisation (BGI) monitors have been operating in the CERN Proton Synchrotron for 3 years now, and they were installed in the CERN Super Proton Synchrotron this year. An overview of the operating principal of the instruments is presented, followed by an update on their development. The mechanical design has been simplified and the Timepix3 devices are now mounted individually for easier assembly and maintenance. Reliability and availability have been improved with a new radiation-hard readout, using the GBTx [1] and bPOL12 [2] devices. Performance has been improved with a SoC Back-End exploiting the capabilities of both the FPGA and the Processing System. We have worked to improve the calibration of the instruments, equalization can now be performed in-situ and we have a procedure to calibrate the response between the four detectors. This paper also presents some example results from the instruments and describes our plans for future developments.

BGI OVERVIEW

A schematic cross section is shown in Figure 1 and an overview of the instrument design is shown in Figure 2 (field cage removed for clarity).

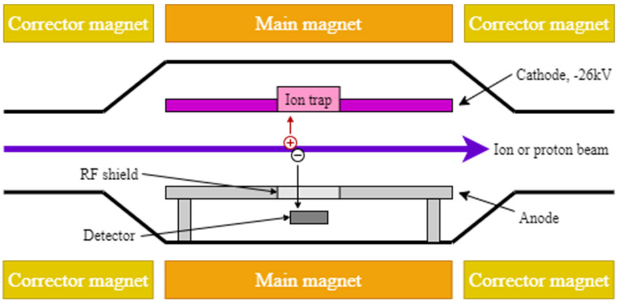

Figure 1:BGI schematic.

Rest gas ionisation electrons are accelerated by an electric drift field towards an electron imaging detector located beneath a 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 -26 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 [3]. The instrument is mounted on a rectangular vacuum flange with a ConFLat type seal [4].

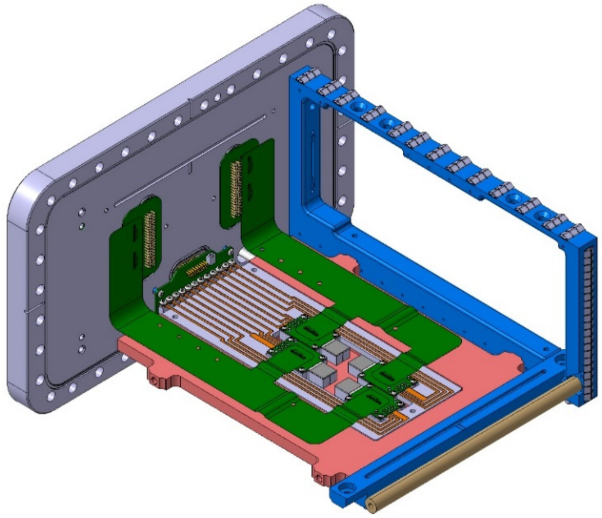

Figure 2: BGI viewed without field cage.

OPERATIONAL EXPERIENCE

During 2023/4 the PS-BGIs were compared with the wire-scanners. Data was collected from LHC-type beams at flat top with both PS-BGIs, without gas injection. An example of the good agreement with the wire-scanner is shown in Figure 3 and, as discussed in [5], the agreement in terms of normalized emittance is within 1 statistical sigma.

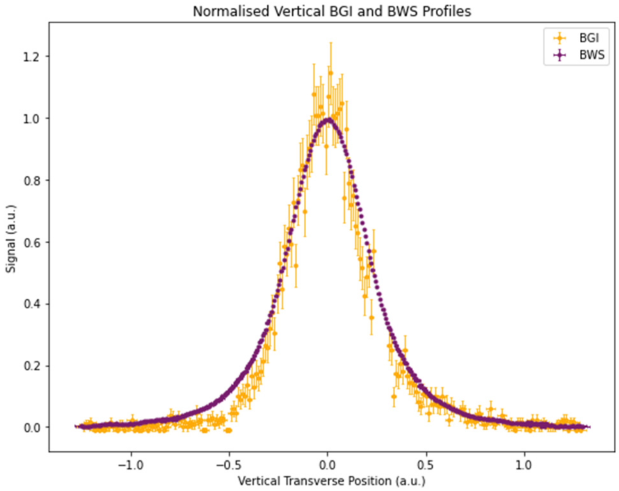

Figure 3: BGI – Wire-scanner comparison.

Despite this success, the operational adoption of the PS-BGIs has been slow, mostly because the instrument remains difficult to use. Outstanding issues include:

- Beam loss saturates the readout chain, causing subsequent profiles to be lost.

- Vertical instrument has an insufficiently strong electric field to give good profiles at flat-bottom (beam momentum 2 GeV/c), when the beam is close to the detector.
- Noisy pixels appear from time to time, severely distorting the profile.

MAIN DEVELOPMENTS

Radiation-hard Front-End and SOC Back-End

The first BGIs used an FPGA based Front-End in the tunnel and an FPGA based Back-End in the surface building.

The radiation dose received by the Front-End (FE) electronics is between 10 and 60 Gy/year, leading to premature failures. This has been addressed by replacing the FE electronics by a fully radiation hard system. This uses the GBTx and VTRx optical transceiver chipset [1] from CERN as well as the bPOL12 switched-mode regulator [2]. The DataOut signals from each Timepix3 device are sampled at 320 MHz, giving a maximum event bandwidth of 213 Mevents/s from the four Timepix3 devices combined.

The Back-End electronics have been replaced with a board using the Xilinx MPSoC. The FPGA is used to deserialize the data coming from the Timepix3 and store it as events in a RAM buffer. This data is then transferred by DMA to the Processing System where the profiles are reconstructed in software. This firmware/software split allows us to share the data processing tasks appropriately and create a system capable of sustaining a high readout rate. A schematic of the readout chain is depicted in Figure 4.

Detector Orientation

In the recently installed SPS BGIs, the detectors are orientated so the readout columns are perpendicular to the beam. This means that the ionisation electrons are spread evenly over many columns, eliminating the readout bottleneck at the end of each column. The detectors are also spaced to create a small overlap between them, which permits the use of sensors with a guard ring, and makes detector-to-detector normalisation easier, see Figure 5.

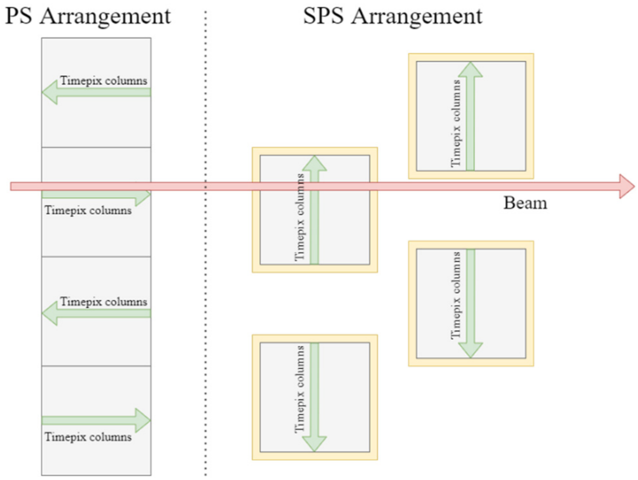

Figure 5: Timepix3 column orientation for the PS-BGI (left) and SPS-BGI (right) instruments.

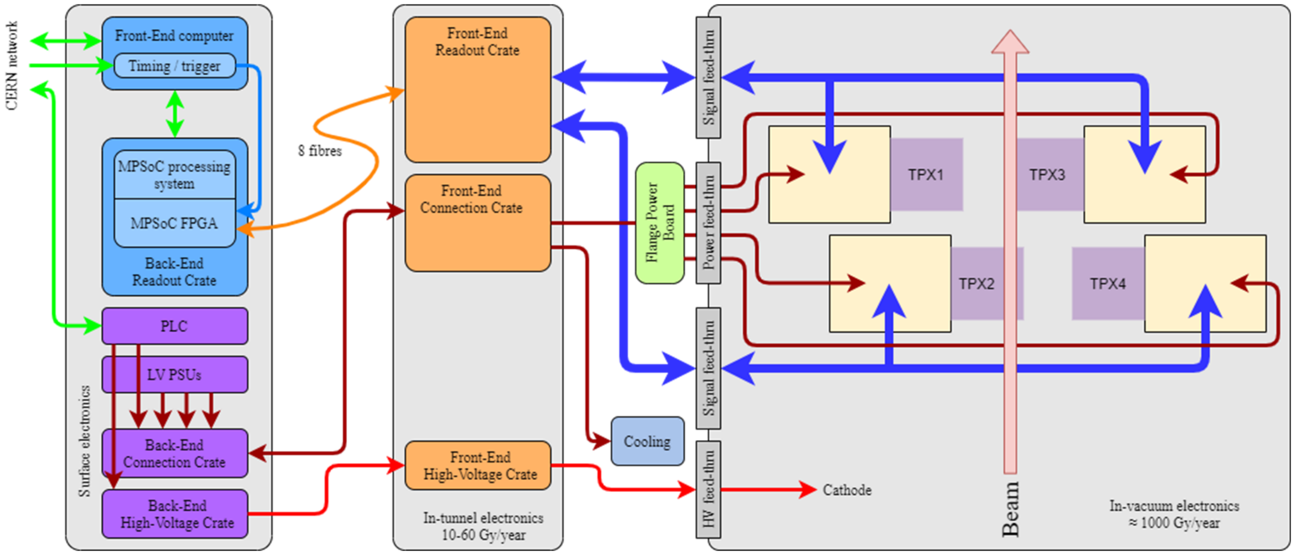

Figure 4: Readout chain schematic.

Improved Electron Detection Efficiency

The detection efficiency of the ≈10keV ionisation electrons is limited by the entrance window of the silicon sensor, into which a significant fraction of the 10keV is deposited before the electron reaches the depletion volume. Reducing the Timepix3 detection threshold helps, but increases the noise. Increasing the cathode voltage imparts more energy to the electrons and so improves their detection efficiency. The SPS instruments have been designed for a cathode voltage of up to -30 kV. The sensors used in the SPS instruments also have a much thinner entrance window (implantation thickness), just 200 nm rather than the 1 µm of the sensors used in the PS.

Automated Detector Equalisation

The detectors can now be equalised after installation in the instrument. This is done by adjusting the pixels DACs until all pixels respond similarly to the noise floor. The few pixels that cannot be equalised by this method are then masked. See [6].

Automatic Pixel Masking

One of the obstacles to straightforward operational use of the BGI, is that new noisy pixels appear quite frequently, perhaps caused by beam loss in the sensor/detector. These then create spikes in the profile, distorting calculated values of the beam position and width, and even overloading the readout bandwidth. To address this, we are implementing some code to take an acquisition during the 170ms between the cycle starting and the beam arriving. Any pixels with more than a few hits during this time are labelled as noisy and marked for masking. There are several steps to generating a new mask, so this is done offline and the new mask only loaded later. The noisy pixel mask is added to a mask of the pixels that are shadowed by the RF shield (see Figure 1:BGI schematic., or that have failed the equalisation process. This mask is then processed so that every column contains the same number of masked pixels (to maintain equal weighing of each detector column), and the extra masked pixels are distributed evenly across the detector super-pixels. During a subsequent non-acquisition cycle the new mask is loaded to the detectors.

Modular Detector Design

The first installed BGI had all four Timepix3 detectors glued and bonded to a common ceramic PCB. This had the disadvantage that if any detector failed or was improperly bonded, then the whole assembly had to be re-worked or replaced. In addition, the ceramic PCB provided some resistance to heat transfer from the Timepix3, and there were further thermal interfaces between the PCB and the cold head.

Subsequently we have designed a small module (see Figure 6) with a single Timepix3 and a small ceramic PCB carrying a connector and decoupling capacitors. These modules can be assembled and tested individually and then four of them are selected to be used for the instrument assembly. If problems are found with a module during the instrument's final tests, it is relatively straightforward to swap it for another. The Timepix3 is bonded with Staystik AIN 672 directly to the aluminium module base, which is then screwed to the cold head.

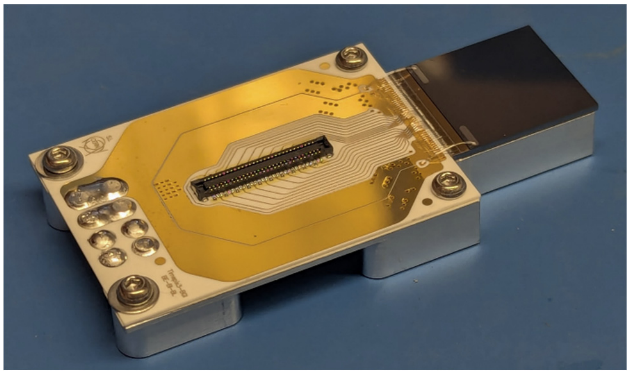

Figure 6: BGI detector module.

Standardization of Software

FESA (Front End Software Architecture, the CERN standard for real-time distributed control) is now used to handle all changes to instrument settings. These changes are logged and access control can be easily implemented.

The MPSoC currently runs a custom Petalinux build incorporating device drivers for DMA transfers to/from buffers in the FPGA. The registers in the FPGA are handled through UIO. In the future it is planned that there will be a dedicated “Front-End Computer OS” and that this will include support for SoCs. Eventually it should be possible to run FESA on the MPSoC and eliminate the Front-End computer.

Mechanical Improvements

The SPS BGI was redesigned based on the experience gained from the design, build and installation of the PS BGI. There were numerous improvements:

- The horizontal and vertical instruments are identical, so only one spare is needed.
- The number of different fasteners was reduced.
- The high-voltage feedthrough was moved to the side of the instrument, where it directly contacted the cathode.
- The instrument was designed for a -30kV cathode voltage, up from -20kV for the PS design.
- The support arms are covered by finger stock gaskets to provide good RF contact to the vacuum tank.
- The cathode is made from ceramic with a conductive coating which is thinner than the RF skin-depth. This makes the cathode transparent to the beam.
- These last two points, plus a coated ceramic rod between the support arms minimised the RF impedance of the instrument.

NEXT STEPS

High Luminosity (HL) LHC-BGI

Horizontal and Vertical BGIs are planned for the LHC. Several options for the design are being explored, using either Timepix3 or Timepix4. One elegant solution (see Figure 7) uses parts from the 4D Photon project [7] for the vacuum feedthrough and Timepix4 support.

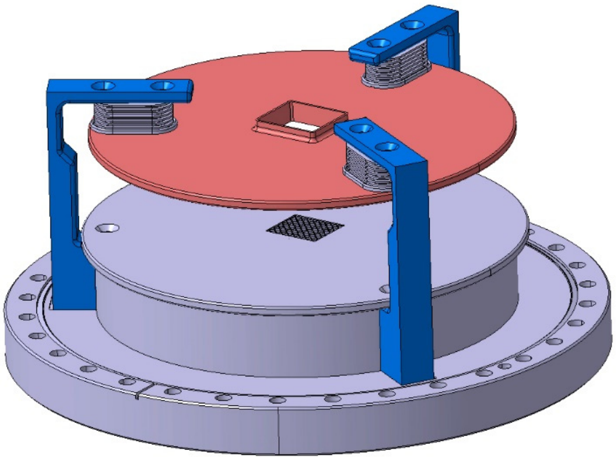

Figure 7: LHC-BGI Timepix4 concept.

However, before we can go very far with the design of the HL-LHC-BGI, we need to understand a problem that we are facing in the SPS-BGI. This is that beams with strong high frequency components (large intensity and shorter bunches) cause the Timepix3 to go into reset. We have largely ruled out beam loss and Single Event Upsets as the cause of the problem, but it is not yet clear if the problem relates to the power supply for the Timepix3, or the Timepix3 itself.

PS-BGI Improvements

One of the issues with the vertical instrument in the Proton Synchrotron is that there is insufficient electric field to impart enough energy to the electrons for them to be detected. This is largely because the beam is not far enough from the detector. When the beam is steered away from the detector then good profiles can be obtained. Fixing this issue requires that the cathode voltage be increased from the current value of -26 kV to -30 kV or more. This will require some mechanical design to achieve the necessary isolation gaps. An alternative solution is to replace the sensors with units featuring a thinner entrance window, thus permitting greater sensitivity to lower energy electrons.

Timepix4

We plan to add support for Timepix4 with essentially the same readout chain as we are using now. The main change will be to use VTTx+ devices [4] to couple the Timepix4 DataOut electrical signals to optical fibres. This readout chain will be used with a long baseline Timepix4 telescope, as well as a fast Beam Loss Monitor and potentially the HL-LHC-BGI.

Electron Beam Test Stand

To help us test and characterize the Timepix3 and Timepix4 modules, we are building a test stand with an electron gun which can deliver between 5 and 60 keV. This will deliver electrons of known energy to the Timepix3 and allow us to direct the electrons to particular locations on the chip. Currently the instrument tests are done with a Strontium 90 source, so this facility will allow much more precise testing to be done. It will be particularly useful for calibrating the sensitivity between chips.

CONCLUSION

Much work has been done over the past few years to improve the BGIs and make them more suited for operational use. They are now installed in the SPS as well as the PS. Our next task is to help the operators to get the best from the instruments and for the engineering team to identify the features and improvements that are most needed. We look forward to these capable and flexible instruments finally fulfilling their potential.

ACKNOWLEDGEMENTS

The BGI would not exist without the many years of hard work that Swann Levasseur and Hampus Sandberg put into its development.

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