

THE BEAM PROFILE MONITORING SYSTEM FOR THE CERN IRRAD PROTON FACILITY*

F. Ravotti[†], B. Gkotse¹, M. Glaser, E. Matli, G. Pezzullo, CERN, 1211 Geneva 23, Switzerland
K.K. Gan, H. Kagan, S. Smith, J. D. Warner, Ohio State University, Columbus, OH 43210, USA
¹also at Université Européenne de Bretagne, Brest, France

Abstract

To perform proton irradiation experiments, CERN built during LS1 a new irradiation facility in the East Area at the Proton Synchrotron accelerator. At this facility, named IRRAD, a high-intensity 24 GeV/c proton beam is used. During beam steering and irradiation, the intensity and the transverse profile of the proton beam are monitored online with custom-made Beam Profile Monitor (BPM) devices. In this work, we present the design and the architecture of the IRRAD BPM system, some results on its performance with the proton beam, as well as its planned upgrades.

INTRODUCTION

In High Energy Physics (HEP) experiments such the one at the CERN Large Hadron Collider (LHC), devices are frequently required to withstand a certain radiation level. As a result, detector materials, equipment and electronic systems must be irradiated to assess their level of radiation tolerance. To perform these irradiations, CERN built a new irradiation facility on the T8 beam-line of the East Area at the Proton Synchrotron (PS) accelerator. At this facility, named IRRAD, a Gaussian 24 GeV/c proton beam of variable size ranging from $\sim 5 \times 5 \text{ mm}^2$ to $\sim 20 \times 20 \text{ mm}^2$ is used to irradiate experimental devices [1].

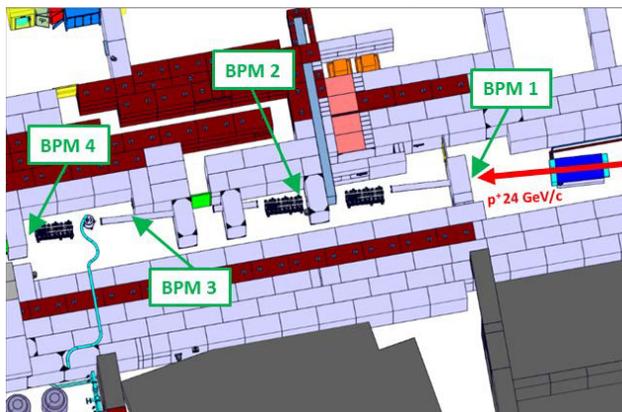


Figure 1: Position of the four BPM devices along the IRRAD facility at CERN.

The proton beam on T8 is delivered in spills with a maximum intensity of 5×10^{11} proton per spill and about 400 ms duration. Several spills per PS accelerator super cycle (CPS) are delivered to IRRAD resulting in a variable beam

intensity, depending on the number of users simultaneously served by the whole CERN accelerator complex. As a figure of merit, three spills per CPS of 30 basic periods are delivered to IRRAD, resulting in an average flux $> 8 \times 10^{13} \text{ p/cm}^2/\text{h}$ over one centimetre squared surface. During irradiations, it is thus necessary to monitor in real-time the intensity and the transverse profile of the proton beam.

The IRRAD BPM uses a 39-channels pixel detector to monitor the beam position. The pixel detector, that must withstand high-cumulated radiation levels, is constructed using thin foil copper pads positioned on a flex circuit. When protons pass through the copper pads, they induce a measurable current. To measure this current and thus determine the proton beam intensity, a new data acquisition system was designed as well as a new database and on-line display system. In its final configuration, the IRRAD facility exploits four BPM detectors located along the path of the irradiation beam as shown in Fig. 1.

The new BPM data acquisition system uses low noise integrators. The voltages from each integrator are scaled and limited before connection to a 16-bit ADC. Furthermore, an Arduino Yún collects the data from the ADC and controls its transmission over the Ethernet port to a server for further processing and storage. Finally, the live beam position and intensity data are available to the IRRAD users, as well as to the operators at the CERN Control Centre (CCC), via a dedicated web-based display.

Two BPM data acquisition systems were assembled in 2014 and were used to read out two BPM detectors during the commissioning of the new facility. Four additional BPM data acquisition systems were later installed at the beginning of the irradiation run 2015 and, since then, are operational.

In this work, we detail the design and the architecture of the IRRAD BPM system, as well as its performance and foreseen upgrades.

OPERATION PRINCIPLE AND CHOICE OF THE DETECTOR MATERIAL

The need for an on-line method to determine the position and the profile of the high-intensity proton beam of IRRAD motivated the feasibility study of an instrument based on the proton-induced Secondary Electron Emission (SEE) from thin metal foils [2]. Secondary emission of electrons from the surface of a plate occurs when a charged particle beam crosses it. The liberated charge comes mainly from delta rays escaping from the plate, with a small contribution due to the secondaries produced in the interactions of the beam particles with the plate. The total collected charge is proportional to the intensity of the impinging beam. For

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[†] e-mail address: Federico.Ravotti@cern.ch

IRRAD, the foils are required to withstand high-radiation levels (10^{17} - 10^{18} p/year are cumulated on a few square cm area) and be made of a low cost and relatively short radio-activity lifetime material. Moreover they have to be, on the one hand, thin to avoid the proton scattering but on the other hand, thick enough to allow easy handling. Finally, the material has to show a SEE yield strong enough to avoid the usage of an external bias and thus maintain the operation principle as simple as possible. Aluminium (Al) and Copper (Cu) foils have been chosen as a good compromise to satisfy these requirements. More information about the preliminary measurements leading to this choice are given in Ref. [3].

HARDWARE & SYSTEM ARCHITECTURE

Detectors

The main BPM detector element for the measurement of the proton beam profile consists in 39 separate pixels (Cu pads of 4×4 mm² spaced by 0.5 mm one to the other) covering a total area of 36 mm \times 27 mm on the beam transversal plane. These pixels are built on a six layers Kapton/Cu flex circuit as shown in Fig. 2. The Cu pads in the various internal layers are connected through vias, while a top and a bottom Cu layer act as shields. The Cu thickness is of 1.75 μ m/layer, while the Kapton one is of 120 μ m/layer for a total overall thickness of \sim 700 μ m. Fig. 3 shows one of the four BPM detector installed in its final position inside the IRRAD facility.

In addition to the main BPMs, Single-pad BPM detectors were also built for the alignment of the remote controlled tables used in IRRAD [4]. These consist in one single Cu pixel with a variable active area of 5×5 mm², 7×7 mm² or 10×10 mm². One of these BPM single-pad detectors is shown on the top of Fig. 2. The single-pad devices provide a binary signal indicating whether the samples loaded on a given irradiation system are being irradiated or outside the proton beam spot.



Figure 2: BPM pixel detector for beam profile with 39-pads (bottom) and single-pad (top).

The BPM pixel detectors are directly connected to the data acquisition (DAQ) system by a shielded, high-speed 40-channel, 50 Ω /40AVG micro-coaxial cable from Samtec [5]. The cables linking the four IRRAD BPM detectors to the DAQ systems, located outside the irradiation area, are 20 m to 35 m long.

Data Acquisition System (DAQ)

The BPM DAQ unit shown in Fig. 4 has been designed to measure detector signals in the 10pA-to-500pA range with an adjustable dynamic range. This uses commercial off the shelf, low-noise switched integrators (Burr Brown ACF2101) to amplify the detector signals. A TI ADS1115 analog-to-digital converter (16 bit, 2-3 bits noise) subsequently measures the charge integrated over the 400ms proton spills. A commercially available Arduino Yún microcontroller board, based on the ATmega32u4, finally handles the whole DAQ process, including the timing synchronization and the background noise acquisition.

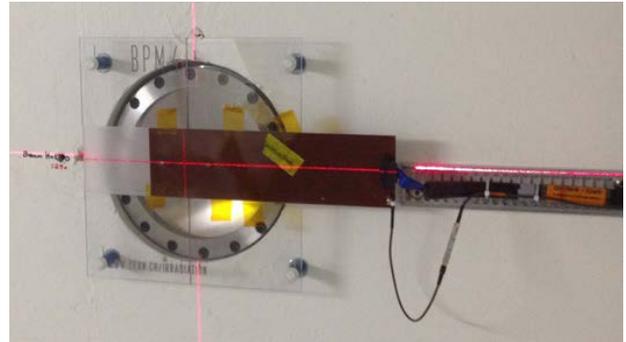


Figure 3: BPM pixel detector installed in the IRRAD.

Fifty channels can be read out in parallel by the DAQ (analog inputs): 40 channels from the main BPM pixel detector (through the Samtec cable) and other 10 auxiliary channels (LEMO connectors on the front panel visible in Fig. 3) to read out, for instance, the single-pad detectors. The DAQ unit has also three outputs. An *Analog Output* port provides the inverted output of the integrators and it is used to show the output of a selected integrator channel during operation. The *Reset Output* and the *Gate Output* are, instead, used to check in real time (with an oscilloscope) the synchronization of the timing parameters of the BPM with the signals provided by the PS accelerator [6].

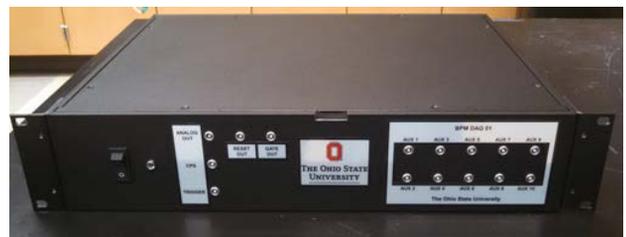


Figure 4: IRRAD BPM Data Acquisition System.

Moreover, the DAQ unit is equipped with the following digital (input) ports:

- *Trigger* (configurable NIM/TTL): this signal, directly connected to the Arduino, it is used to inform that a proton spill will occur upon its reception (beam trigger);
- *CPS* (configurable NIM/TTL): this signal can be used to inform the Arduino that, after this input signal is

received, a new super cycle of the PS accelerator (CPS) begins;

as well as with two communication ports:

- *USB 2.0* (located on the rear panel): this port is used to provide external storage media to the Arduino as well as to update the DAQ software;
- *Ethernet* (located on the rear panel): this port is used by the Arduino to access the CERN network over a wired connection.

The rest of the system architecture includes a local HP Server running a dedicated software used to collect, through Ethernet, the data from the DAQ units and to send them to a centralized ORACLE database where the spill-by-spill beam positions are archived for later analysis.

BPM Data Display

The beam profile information from the IRRAD facility is displayed in real-time on a dedicated series of CERN web pages*. These are used by the IRRAD facility operation team and users to check beam quality and the alignment of the irradiation systems, as well as by the PS accelerator operation team at CCC to setup and steer the irradiation beam over the T8 beam-line.

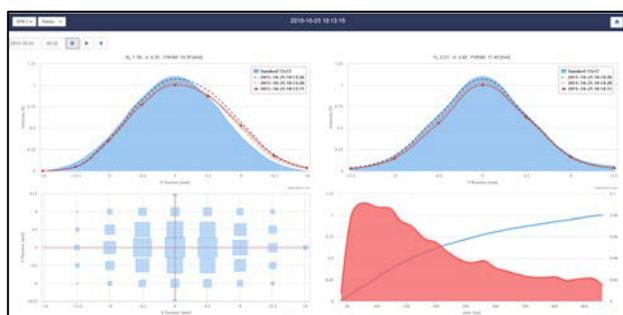


Figure 5: “main” BPM web display.

Figure 5 shows one of the user interface pages of the web-application developed to retrieve and display the beam profile information from the ORACLE database. This application performs a first level data correction (e.g. background compensation) and the analysis of the displayed data. The “main” BPM page shows, for every BPM device, the intensity over each of the 39-pads (bottom left corner) and computes the basic information about the horizontal (x) and vertical (y) Gaussian beam profiles such as the centroid (x_0, y_0) , the sigma $(\sigma_{x,y})$, and the Full Width at Half Maximum (FWHM). Moreover, this page also provides information about the longitudinal beam profile, by displaying the integrated beam-induced charge over time (bottom right corner).

The “BPM all” page shown in Fig. 6 provides instead in a combined view the footprint of the proton beam recorder simultaneously in the four locations along the IRRAD

beamline. This allows, on one hand to fully control the beam trajectory over the ~30 m long IRRAD facility, as well as to optimize the irradiation of materials and samples by choosing, case by case, the appropriate beam spot for a given irradiation experiment. Finally, by integrating the current measured with the 39-pads, or by a subset of them, it is possible to monitor during operation the total proton intensity delivered to IRRAD or the proton flux impinging on small-size samples during irradiation (bottom of Fig 6).



Figure 6: “BPM all” web display.

SYSTEM PERFORMANCE

In order to use the BPM data as an operational tool to monitor the beam conditions, it is essential that the response of the BPM detector follows linearly the variation of the beam intensity. Although the material being irradiated and crossed by the beam may affect the amplitude of the BPM signal, the BPM1 device, installed upstream IRRAD (see Fig. 1), can be used and calibrated for this purpose.

The plot in Fig. 7 shows the variation of the total current integrated by BPM1 as a function of the proton spill intensity. The reference beam intensity of each proton spill was measured using a Secondary Emission Chamber (SEC) provided by the CERN Beam Instrumentation Group [7]. The agreement of the two data series is better than +/- 7%.

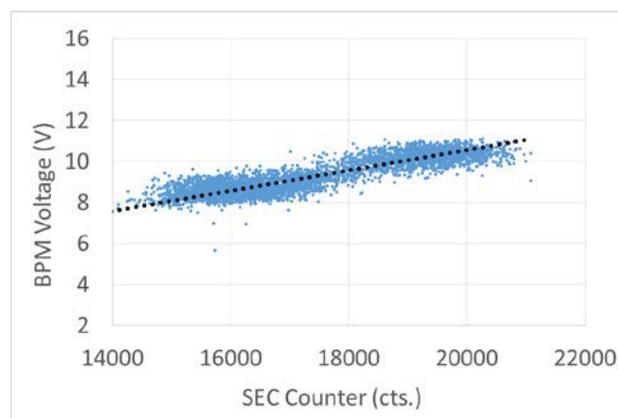


Figure 7: response of BPM1 (total current, V) compared with a SEC device (counts).

* www.cern.ch/opwt/irrad

OUTLOOK

The successful exploitation of the four main 39-pad pixelated BPM devices, installed along the IRRAD beam-line, motivated the upgrade (within the EU-funded project AIDA-2020 [8]) of the initial BPM system. The upgrade consists of new, pixelated BPM detectors with different spatial resolution and/or various total area coverage. In particular, some of these new BPM devices, called “mini-BPMs” with 9-pads and covering a smaller area of $22 \times 22 \text{ mm}^2$, will replace some of the single-pad BPMs already in use. A couple of mini BPMs installed at the front and at the back of the IRRAD remote-controlled tables will improve the precision and speed-up their alignment procedure.

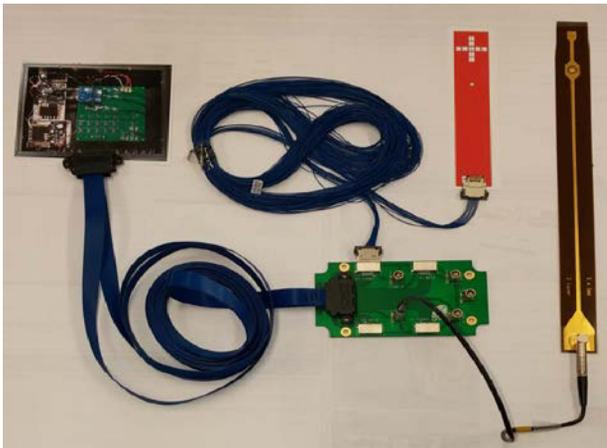


Figure 8: the mini-BPM system. Four mini-BPM devices can be connected to one DAQ unit via a channels-concentrator PCB (bottom of the picture).

For this upgrade, new DAQ units were produced while the first prototypes of mini-BPM devices were manufactured. Since the new mini-BPM uses only 9-channels per device, a channels-concentrator PCB has been developed in order to merge the signals from four mini-BPM detectors into a unique 40-channel cable such as the existent architecture, based on 50-channel readout unit, can be efficiently exploited. The four spare channels can be still used to connect single-pad BPM devices. The new connectivity for the mini-BPM devices is shown in Fig 8.

Figure 9 shows the profiles obtained with the first prototypes of mini-BPMs and visualized with a custom-made application running on a PC in the IRRAD counting room.

Another improvement ongoing for the BPM system concerns the reconstruction and analysis of the beam profile envelope. The current online algorithm computing the centroid and the sigma of the Gaussian beam (see previous section and Fig. 5), treats the experimental points as discrete variables assuming an ideal beam trajectory. Although these values are good enough for beam operation, they are often not precise enough for physics data analysis. For this reason, a new algorithm based on *Python* libraries is being developed for the on-line reconstruction of the 3D beam envelope.

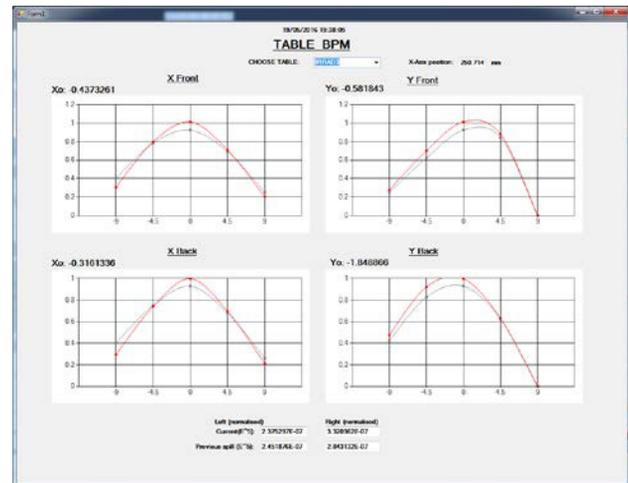


Figure 9: profiles obtained with mini-BPM mounted on an irradiation table.

First validation tests for this new algorithm, performed on the 2016 beam data, showed a precision down to $\sim 2\%$ in the determination of $\sigma_{x,y}$ and down to $\sim 4\%$ for the centroid, w.r.t. the best fit of the BPM data obtained from the least square method.

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