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A LOW COST BEAM POSITION MONITOR SYSTEM

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Abstract

A Beam Position Monitor (BPM) system is essential to beam diagnostics for almost all particle accelerators. However, a typical BPM system contains customized hardware and complicated processing electronics which considerably drive the cost for large facilities where hundreds of them may be used. It also limits its use in the small scale accelerator facilities. In the paper, we present a low cost BPM system which consists of a commercial available CF flange based signal pickup device, a low cost integrated circuit adjacent to the pickup to filter, sample, digitize, and broadcast the signals out of the pickup electrodes. The digital signal is transmitted out for post processing through noise-protected Wi-Fi router. We will briefly discuss the working principle and experimental progress to date.

INTRODUCTION

A Beam Position Monitor (BPM) system is essential to beam diagnostics for almost all particle accelerators. However, a typical BPM system contains customized hardware and complicated processing electronics, which considerably drive up the cost for large facilities, where hundreds of them may be used. While large-scale accelerator facilities routinely develop these systems in-house, this type of system was, until recently, out of reach for many small accelerator facilities, due to its complexity and cost. In addition, large accelerator facilities often run 24 hour shifts with demanding users, and therefore customize their electronics for their sophisticated distributed operating systems and high speed data buses, all with error handling capabilities. This level of sophistication, while enviable, is not necessary for small accelerator facilities, which typically run only a fraction of the time. The situation for simplified position and charge measurement has been remedied by the availability of a BPM electronics card from Bergoz [1], but this card does not provide a full digital system, and its cost (~$5k for an analog front end) still limits its wide usage in small-scale accelerator facilities, where only a small quantity of BPMs are needed, but where the per-unit cost to use is still prohibitive. In addition, the BPM also has become important for the new generation of medical accelerators to locate the position where the beam hits the target, in order to improve the homogeneity of the radiation dose profile. However, due to the tight space requirements and the cost sensitivity, small medical accelerators are currently out of reach for using BPMs.

Here we present a very low cost BPM system that consists of a commercially available CF flange-based signal pickup device (with a dramatic cost saving in comparison with the most commonly used button and stripline BPMs), and a very low cost integrated circuit, adjacent to the pickup, that serves to filter, sample, digitize, and broadcast the signals from the pickup electrodes. The digital signal is transmitted out for post processing through a noise-protected Wi-Fi router. The uniqueness of this approach lies in the following facts: 1) The use of an in-flange pickup device with embedded electrodes, which uses standardized double-sided CF flange fittings to adapt to any beam pipe. 2) The pickup device has an ultra-high dynamic range (tens of pC to tens of nC) and high sensitivity (tens of micron resolution), based on our recent beam measurement, which fits the needs of most beamlines. 3) The analog signal from each electrode is digitized locally, and transmitted using the WiFi protocol, which eliminates the requirement for long, expensive RF cables.

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THE ECONOMICAL PICKUP

The BPM signal pickup device is the sensor of a BPM system. It determines the BPM's sensitivity and resolution. The most commonly used BPM pickup devices are the button type (broadband response), the stripline (high signal strength), and the cavity (high resolution). Since our goal is to develop the most compact and cost-saving BPM system, we chose to use a new in-flange button-type BPM pickup from MDC Vacuum Products®, with a cost of ~$1,500 (single unit price, which may be much lower in quantity) for the CF-4-1/2" flange version, which, thanks to mass production, is at least ten times cheaper than the use of customized hardware. Figure 1 shows a picture of this pickup device. It is a double-sided flange with four embedded electrodes. Each electrode is a round disk to enhance the signal strength. The feedthrough is matched to a 50-Ω impedance. One of the pickup devices has been installed in the AWA (Argonne Wakefield Accelerator facility) 14 MeV witness beamline. In the summer of 2017, we conducted a beam test to evaluate its sensitivity and linearity. The electron bunch of the AWA witness beamline is produced by a 1.3-GHz photocathode RF-gun.

Through variation of the laser intensity, we can scan the charge while measuring the signal out of the electrodes. In order to compensate for the position jitter, we first measured the sum of the four electrode signals. Figure 2 shows the dependence of the signal strength upon the charge. An ICT (integrated current transformer) is located upstream from the BPM pickup device. The

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charge is calculated by integrating the corresponding ICT pulse, up to a unit conversion factor and a DC background subtraction. Despite the charge fluctuation due to the laser intensity jitter, the linearity between the summed signal amplitude and the beam charge is verified with a *R*-squared value of 0.98. The minimum charge that the ICT can detect is around 1 pC. At this charge level, the signal of the in-flange pickup device is still measurable. By extrapolation, the minimum measurable charge of this pickup device is around 100 *fC*. The maximum charge measured in the test was ~2 nC. By extrapolation, it should cover tens of nC, with the signal strength maintained within the allowable range for the detector.

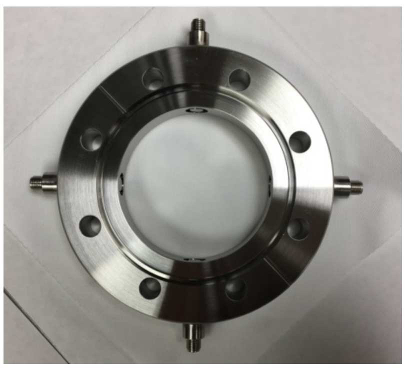

Figure 1: The in-flange simplified button-type BPM pickup device.

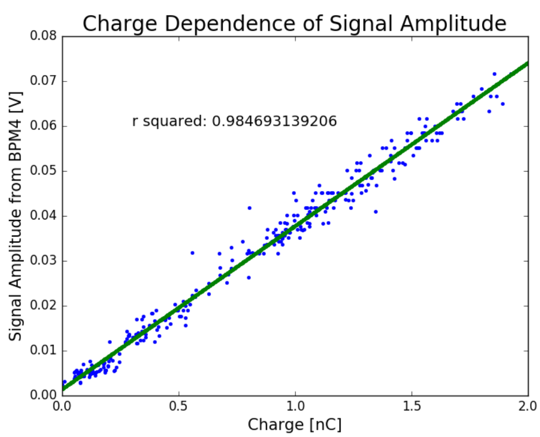

Figure 2: The combined signal strength of four electrodes of the in-flange pickup device, as a function of charge.

In the summer of 2017, we had a few hours of beam access to test the in-flange simplified button-type BPM pickup device at the AWA witness beamline. Qualitatively, the electrode that is closest to the beam centroid position picks up the largest signal amplitude, and the farthest one picks up the least. In our testing setup, we adjusted the upstream horizontal and vertical correctors to steer the beam, observed the beam position on a downstream YAG screen, and recorded the scope traces for the four BPM pickup electrodes. While keeping the beam fully inside the inner rim of the YAG screen, we evenly divided the distance across and took 13 data points on both the horizontal and vertical axes. We recorded the positions in pixels, and then converted them to centimeters using a calibration scale. For each beam position, we took 50 sets of scope traces to understand the extent of jitter in the beam position.

Figure 3 plots the difference in the signal amplitudes of the electrodes on the opposite ends against the horizontal and vertical beam positions. As expected, we observed a linear trend in the direction that the beam is steered, and a rather flat trend for the other direction. The rough resolution is around 250 micron per millivolt of signal strength, if we assume the beam trajectory is parallel from the pickup device to the YAG screen. However, this latter assumption introduces some experimental uncertainties. A more accurate way to determine the beam positions will be employed in Phase I of the project. The targetted resolution of the wireless BPM system is 100 micron.

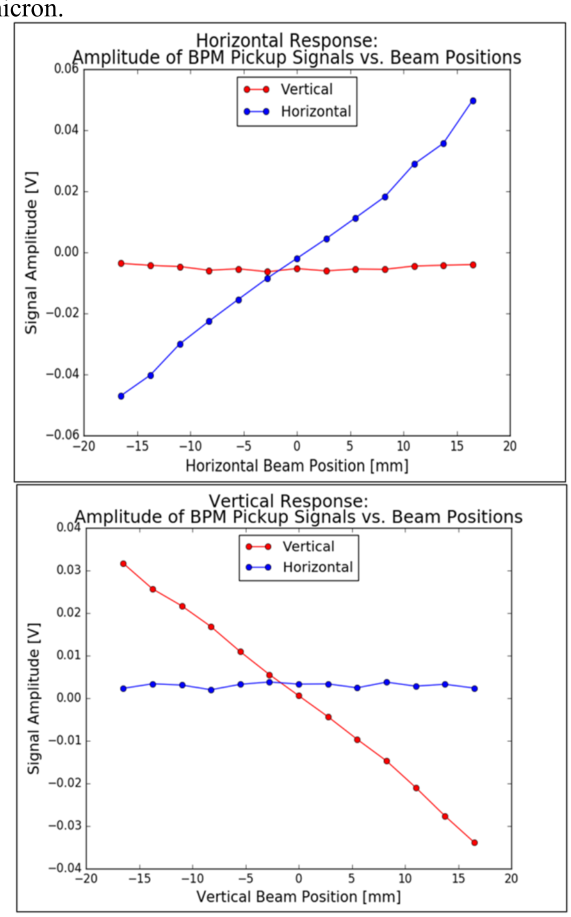

Figure 3: The difference in signal amplitudes of the opposite electrodes as a function of the horizontal (vertical) beam position.

THE SIGNAL PROCESSING FRONT END

Signals from the output of the pickups will be transmitted to the electronic front-end, which is located reasonably close to the pickup device, to minimize the need for rf cables. A fast diode-based pulse-stretching circuit will rectify and stretch the raw pulse from the ps scale to the hundreds of ns scale for easy (slow) processing.

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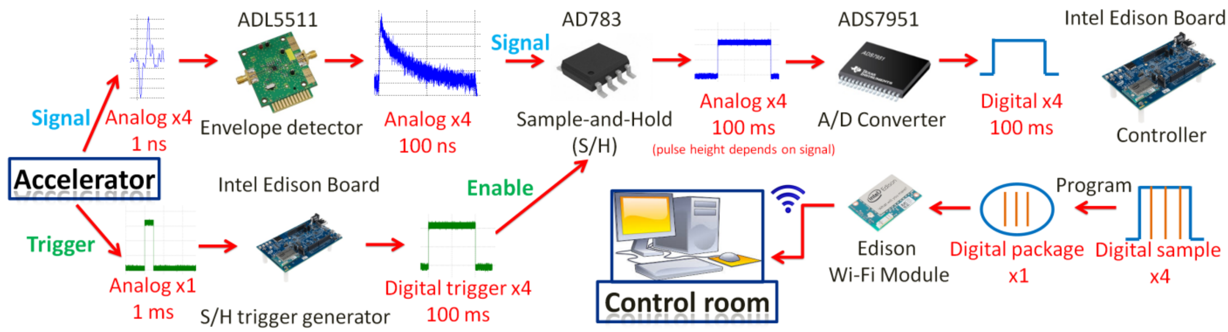

Figure 4: The mockup wireless BPM system using the COTS Intel Edison board.

The four analog signals that contain beam position and charge information are sent to an on-board sample-and-hold section of the card, so that the outputs can be held high during the ADC readout of the signal. This feature greatly reduces the speed requirements for the ADC board, from ~100 MHz to ~100 kHz, thus greatly lowering the overall cost of the system. Shortly before the next beam pulse, the control system sends out a signal to reset the S&H circuit. The digital signals will be packed and sent to readout via the WiFi protocol for further computation, in order to obtain the position and charge information using the conventional BPM algorithm. Options remain for different readout interfaces, such as Ethernet, USB, etc. Because there is no need to manipulate the RF signals, the entire circuit is frequency independent, and can be constructed on a low-cost FR-4 PC board. As an example, Fig. 4 shows our testing system in 2017. It uses the COTS (commercial off-the-shelf) Intel Edison board (~$100), which has 4 channels with integrated ADC (ADS7951) and WiFi modules. The WiFi function has only been tested in the lab environment. The WiFi transmission through a router in the tunnel will be tested in Phase I of the project.

THE TARGETED RESOLUTION

Unlike a circular machine, the AWA beamline is a single pass, low repetition rate (<10 Hz) linac. For the BPM system, only the amplitude information, at some moment of each pulse, are of interest, as long as we acquire it at the same moment for each pulse; in theory, we need to transmit one data set at the same frequency as the machine repetition rate (one set of I/Q values per pulse). In practice, more samples are obtained, to reduce the signal-to-noise ratio (SNR) using the averaging effect. The beam position is acquired from the difference of signals on opposite pickup electrodes. The signals are both intensity and position sensitive, hence the position can only be extracted by normalization to the sum of the two signals [2–4].

Horizontal position $$H = \frac{1}{S_H} \cdot \frac{\Delta_H}{\Sigma_H} + \delta_H \text{ ,} \qquad (1)$$

where S_H is the position sensitivity in the horizontal plane with unit of %/mm, Δ_H is the voltage difference of two horizontal button signals, Σ_H is their voltage summation, and δ_H is the offset correction between the electrical and mechanical center, with units of mm. Vertical position is obtained following the same approach. Both sensitivity and offset are measured in the bench calibration of the pickup device.

We expect to demonstrate a resolution of 100 micron for the prototype of this economical, wireless BPM system. The resolution is not high enough for large accelerator facilities, but it should satisfy the entry-level requirements of most small accelerator facilities. The high resolution version will be developed later of the project.

THE NEXT

We plan to finish the inegrated system in summer and have a beam test afterward.

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