EXPERIMENTAL RESULTS FROM TEST MEASUREMENTS WITH THE USR BEAM POSITION MONITORING SYSTEM*

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Abstract

A diagonal-cut capacitive pick-up (PU) was optimised for monitoring slow ($v < 0.025c$), long (≈1 m) bunches consisting of only about 10^6 antiprotons at the future Ultra-low energy Storage Ring (USR). Ultra-low noise FET amplifiers are used to enable detection of the weak signals generated in the PU plates. The amplified signals are then digitized by a 16-bit, 200 MS/s ADC and processed in a digital manner. This contribution presents the beam monitoring system as it was tested with a stretched-wire method and compares the measurements with preliminary results of 3D electromagnetic simulations.

INTRODUCTION

The design of the diagonal-cut capacitive pick-up (PU) developed for the Ultra-low energy Storage Ring (USR) [1] was already introduced in details [2] and will be described only briefly here. This beam position monitor (BPM) consists of four isolated and equally distributed metal plates formed to surround the beam, see Fig. 1. It provides information on the beam position by means of non-destructive measurements of the electric field produced by bunches of charged particles circulating in the storage ring. By comparing the signals induced in each electrode, it is possible to determine the position of the beam centre.

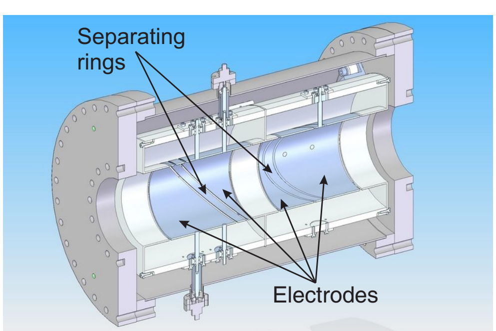

Figure 1: Cross-section view of the beam position monitor.

The pick-up was designed to monitor slow ($v < 0.025c$), long (≈1 m) bunches consisting of only about 10^6 antiprotons. The diagonal cut of the electrodes was introduced in order to assure a linear response of the PU over a wide range of beam positions. The total length of the BPM is approximately 40 cm, thus still much less than the bunch length, and results in high signal strength.

In order to align, test and characterise the BPM, a stretched-wire technique was employed [3]. The method enables the investigation of the PU position sensitivity without a beam in a fully controlled environment. It was therefore a preferred testing procedure at the prototyping stage.

PRINCIPLE OF THE MEASUREMENTS

The position sensitivity S of the PU is its response to changes in the beam position [4]. The displacement x of the centre-of-mass of the beam with respect to the centre of the vacuum tube can be expressed as the difference of the electrodes signals ΔU normalised to their sum ΣU:

$$x = \frac{1}{S}\frac{\Delta U}{\Sigma U} + \delta \qquad (1)$$

The pick-up offset δ represents the misalignment of the electrical centre with respect to the geometrical centre of the PU. Also the inverse of S, called a scaling factor $k \equiv 1/S$, is often used to characterise the BPM response.

The position sensitivity can be derived with the use of pulses generated in a wire stretched inside the BPM and installed on a movable platform. Such a signal-carrying wire represents the beam and is also detected by the PU electrodes. By having a full control of its location within the PU aperture, one can determine the response of the BPM to different positions of the signal carrier, being it either a wire or a particle beam.

Naturally, Eq. 1 is only an approximation, thus the response of the PU might not be linear for larger displacements x and it may also vary with the bunch frequency. The BPM for the USR was designed such as to avoid this problem and only a fixed scaling factor k should be needed to determine the beam offset. Nevertheless, a full 2D position map of the PU response was experimentally verified.

EXPERIMENTAL SETUP

The PU was installed in a UHV vacuum vessel custom-made for the USR and the whole assembly was mounted vertically on a test stand, see Fig. 2. Two manual translation stages with 100 mm movement range were stacked

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in an XY configuration and then fixed on top of the setup in order to move the wire within the PU aperture. An insulated 32 AWG wire with an outer diameter of 0.5 mm was used as a signal carrier. It was stretched with an added weight which was freely dipped in a dense fluid to damp any potential swing motion of the wire caused by its movement to a new position. One end of the wire was connected to a signal generator, while the other to an oscilloscope to observe the signal delivered to the pick-up.

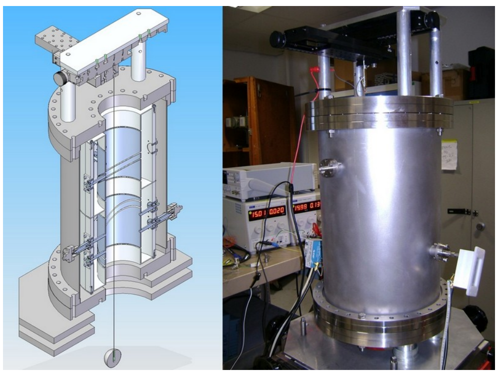

Figure 2: Stretched-wire test setup.

It was important to properly align the wire and the BPM. While the alignment of the wire was determined by gravity, the PU vessel was installed on three levelling screws enabling the adjustment of its position with respect to the wire. Also additional components were manufactured to define the main axes of the BPM and to match them with the axes of the translation stages. The X and Y faces of the alignment tools were used to verify if the wire had been set perpendicular to the main axes and to position it coaxially with the PU, see Fig. 3.

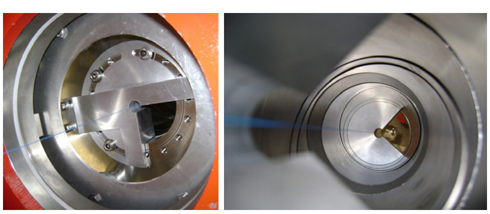

Figure 3: BPM with the alignment components.

SIGNAL PROCESSING

Sine-wave signals with frequencies of 459 kHz and 1.78 MHz were generated in the wire so that the response of the pick-up to the USR bunch frequencies could be tested.

The signals generated in the electrodes were fed to the low-noise, high-input impedance amplifiers installed directly on the vacuum feedthroughs. Two sets of amplifiers were tested during the measurements: 1 MΩ input impedance, 0.5 nV/$\sqrt{\text{Hz}}$ noise density, 46 dB (200x) gain SA-220F5 commercial units from NF Corporation and 5 MΩ, 0.9 nV/$\sqrt{\text{Hz}}$, 54 dB (500x) custom-made units [5].

The signals were then filtered by 2.5 MHz low pass filters and digitized by GaGe Razor CompuScope CS1642, a commercial digitizer equipped with 4 channels in a single-slot PCI with 200 MS/s sampling per channel and 128 MB of on-board acquisition memory. Further signal processing, such as narrowband filtering, averaging and peak-to-peak calculation, was realised in the digital domain.

A LabVIEW application was prepared to control the digitizer as well as to display, analyse and save the signals from the PU electrodes, see Fig. 4.

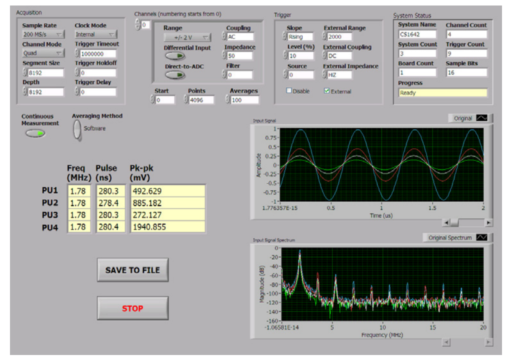

Figure 4: LabVIEW application as prepared for the tests.

MEASUREMENT RESULTS

The BPM was tested in different configurations. At first, it was examined with the separating rings included in the diagonal gaps between the electrodes. The rings were either grounded or left floating and both cases were investigated. Later, the rings were removed and the measurements were repeated.

The response of the BPM in terms of $\Delta U/\Sigma U$ was recorded as a function of the beam displacement along the main BPM axes. The points plotted in the graphs followed the linear approximation as shown in Fig. 5 for the X-axis example. The resulting scaling factors k for X and Y were the same within 0.15% and they were independent from the chosen frequencies.

The presence of the separating rings and their electrical connections had a significant impact on the results. The highest position sensitivity was observed for the grounded rings and it was about 20% and 40% higher than for the floating rings and no rings at all, respectively. On the other hand, the absolute voltage measured with the grounded rings was smaller by about 25% and even 80% as compared to the floating rings and no rings setups. This can be explained by an increased capacitance C introduced by the rings and the fact that the measured signal $U \propto 1/C$ [4]. There is therefore a trade-off between the PU electrodes decoupling and the detection sensitivity.

In addition, the position sensitivity assumed in [2] and plotted in Fig. 5 (green curve) was too high which can be explained by the underestimated coupling capacitance C_C.

With the derived scaling factors k_X and k_Y, 2D posi-

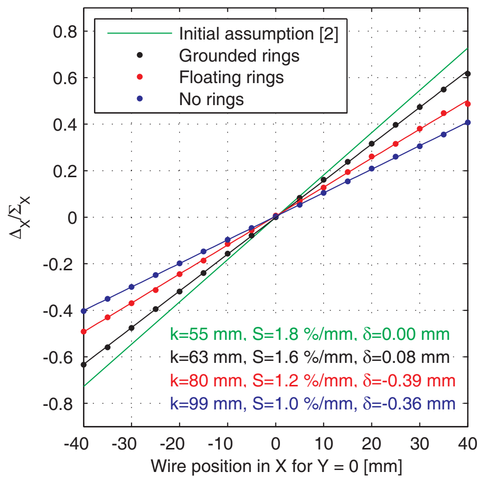

Figure 5: BPM response to wire displacements in X-axis.

tion maps were created, as shown in Fig. 6. The wire was manually swept within the BPM aperture with 5 mm steps. For each XY-coordinates of the wire, $\Delta U/\Sigma U$ was measured and used to reconstruct the wire position according to Eq. 1. The position determination was accurate within 0.5 mm or better for displacements smaller than 20 mm from the BPM axes, but reached up to 1.5 mm for positions close to the electrodes. However, such large discrepancies manifested mainly in the bottom-right quarter of the 2D map and could be due to the wire positioning inaccuracy.

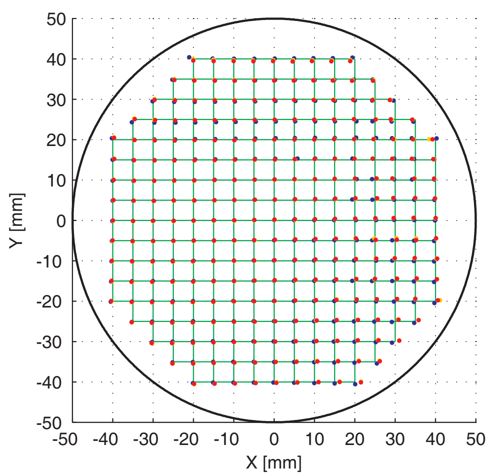

Figure 6: 2D map of the PU response to different wire positions for grounded rings (red), floating rings (orange) and no rings (blue).

SIMULATIONS

A 3D model of the PU was created in CST Particle Studio [6] to benchmark it against the measurements and use for possible optimisation in the future. The PU material was defined as a perfect electric conductor (PEC), but no separating rings have been introduced yet. A beam with $\beta = 1$ and 0.025, and a Gaussian pulse with $\sigma = 1$ m was modelled. Discrete ports with 1 MΩ impedance were used to record the output voltages and the simulations were performed using the wakefield solver.

As can be seen in Fig. 7, the results from the simulations for $\beta = 1$ agree well, within an uncertainty of 2.5%, with the measurements. The preliminary results for $\beta = 0.025$ differ by 10%, but this can be due to a different response of the diagonal-cut BPM to low velocity beams. Further investigation is still required and more detailed simulations are planned.

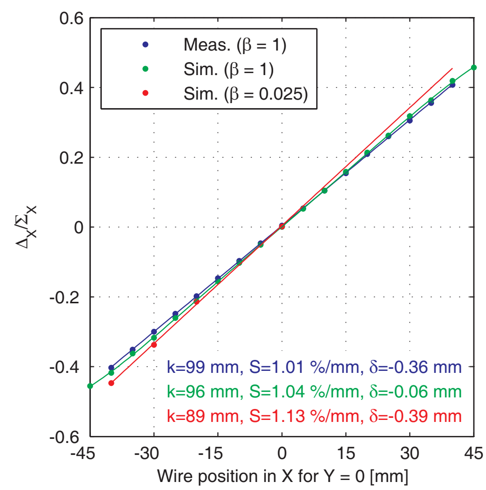

Figure 7: Simulations ($\beta = 1$ and 0.025) compared with the wire measurements for the BPM with no separating rings.

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