BEAM POSITION MONITOR DEVELOPMENT FOR THE USR*

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Abstract

Capacitive pick-ups for closed-orbit measurements are presently under development for an Ultra-low energy Storage Ring (USR) at the future Facility for Low-energy Antiproton and Ion Research (FLAIR). Low-intensity, low-energy antiprotons impose challenging demands on the sensitivity of the monitoring system. The non-destructive beam position monitors (BPMs) should be able to measure about 10^7 particles and give sufficient information on the beam trajectory. This contribution presents the status of the BPM project development. Main goals of the investigation include optimization of the mechanical design and preparation of a narrowband signal processing system.

INTRODUCTION

A diagonal-cut capacitive pick-up (PU) is a device of choice for beam diagnostics in hadron machines due to its highly linear response and large sensitivity. This beam position monitor (BPM) consists of four isolated and equally distributed metal plates formed to surround the beam. It provides information on beam offset by means of non-destructive measurements of electric field produced by passing bunches: by comparing the signals generated at each electrode, it is possible to determine the position of the beam centre. PU linearity, important for beams of non-negligible diameter, is assured by a diagonal cut of the plates. Their length is typically of 10-20 cm per plane, but still much less than the bunch longitudinal profile, and results in high signal strength. On the other hand, bulky dimensions might be a problem when only limited space is available. Also the capacitive coupling between the large electrodes should not be neglected and its reduction may lead to a complex mechanical design. Nevertheless, an optimised diagonal-cut PU can be a powerful tool for a variety of measurements, like beam position, Q-value or closed orbit determination [1].

The application of BPMs for low intensity, low energy beam diagnostics requires additional considerations. The signal-to-noise (S/N) ratio drops down with the decreasing beam current and becomes a dominating problem for beams with only few particles per bunch. In order to improve PU sensitivity, the signal U_S has to be amplified while the noise U_N needs to be significantly reduced. Since U_N is proportional to $\sqrt{(\Delta f)}$, where Δf is the bandwidth of the system, a narrowband signal processing is required for low intensity beam diagnostics. Further complications can be caused by low velocities. For $\beta < 0.1$, the beam can no longer be approximated by a TEM wave and deviations from a relativistic case should be taken into account. The field distribution becomes dependent on the beam displacement and the PU response may be affected [2].

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BEAM PARAMETERS

The boundary conditions of a novel electrostatic Ultra-low energy Storage Ring (USR) [3] at the future Facility for Low-energy Antiproton and Ion Research (FLAIR) [4] put challenging demands on its beam instrumentation. The USR will store and decelerate antiproton beams from 300 keV to 20 keV, corresponding to β values of only 0.025 and 0.006 respectively. At such low energies the total number of particles is restricted by space charge limitations to about $2\cdot10^7$ antiprotons. With the ring circumference of 42.6 m, their revolution frequency f_{rev} will vary from 178 kHz to 46 kHz in the given energy range. To achieve bunch lengths of the order of 100 ns required in the standard operation of the USR, an RF field $f_{RF} = h \cdot f_{rev}$ with harmonic number $h = 10$ will be applied. The resulting frequencies and related beam parameters are summarized in Table 1. Since bunches will be at least 1 m long, a diagonal-cut capacitive pick-up will be an ideal tool for beam position monitoring. However, few particles per bunch as well as low β values have to be considered when designing the BPM system.

Table 1: USR beam parameters

Energy	300 keV → 20 keV
Relativistic β	0.025 → 0.006
Revolution frequency	178 kHz → 46 kHz
Revolution time	5.6 µs → 21.8 µs
RF frequency (h = 10)	1.78 MHz → 459 kHz
Bunch repetition time (h = 10)	560 ns → 2.2 µs
RF bucket length (h = 10)	4.4 m
Charge per bunch (h = 10)	0.3 pC ($2\cdot10^6$ pbars)

MECHANICAL DESIGN

The initial proposal for the diagonal-cut capacitive pick-up for the USR was already discussed in [5], but its final design includes several important modifications.

In order to avoid distortion of the electric field in the vicinity of the monitor edges, the inner diameter of the cylindrical PU is the same as of the straight section vacuum pipe of the USR. Initially, it had been assumed to be as large as 250 mm, but this resulted in large dimensions of the vacuum vessel enclosing the BPM and in reduced signal strength. For this reason, the diameter was decreased to 100 mm. In addition, grounded guard rings were introduced at both ends and in the middle of the PU. The outer will help to minimize the effect of transition between the BPM and the vacuum chamber walls, while the inner will reduce coupling capacitance between X and Y planes. Approximate deviations from the idealized case with edge effects ignored were calculated in accordance with [6] and are presented in Figure 1. As a rule of thumb, guard rings of length equal to the beam tube diameter eliminate unwanted distortions. However, the rings length was limited to 40 mm in order to preserve space in the USR. With such a configuration, the discrepancies introduced by the boundary conditions will not be more than 2% for the image charge and scaling factor, and 0.2 mm for the centre displacement.

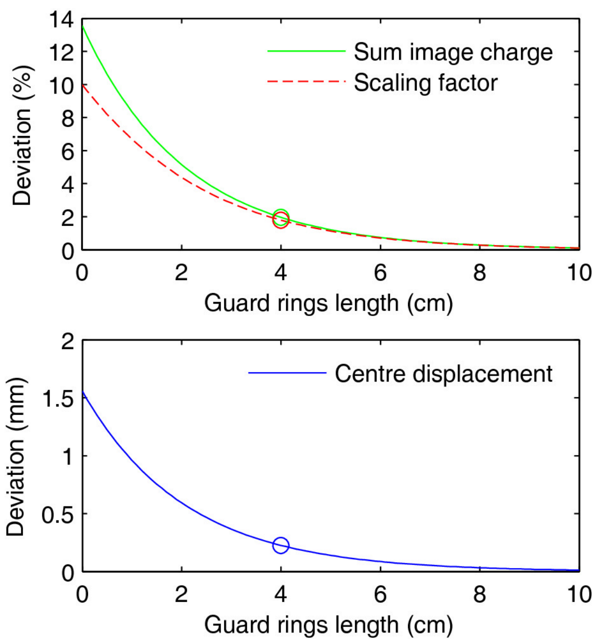

Figure 1: Discrepancies introduced by edge effects to total image charge induced on the PU plates, scaling factor and centre displacement as a function of the guard rings length for a beam tube diameter of 100 mm.

The new BPM design is presented in Figure 2. The electrodes of 100 mm length are shown in blue and green (for "left" and "right") as well as in red and yellow (for "up" and "down"). In violet are the grounded diagonal electrodes introduced to reduce cross-talk between opposite signal plates [5,7]. A version of the BPM without the separating rings will be also tested. The outer casing of 150 mm inner diameter is to ensure shielding against electromagnetic noise. It is on a separate "clean" ground and is electrically isolated from the vacuum vessel in which the monitor will be installed. The setup can be considered as a coaxial capacitor with capacitance-to-ground C:

$$C \propto \frac{L}{\ln(d_{SHIELD}/d_{PU})} \tag{1}$$

Here L is the cylinder length, d_{SHIELD} and d_{PU} are casing inner diameter and PU outer diameter respectively. In the given geometry, C can be estimated to about 20 pF. The real value will differ due to a more complex setup and will be increased by feedthroughs, connectors and the preamplifier.

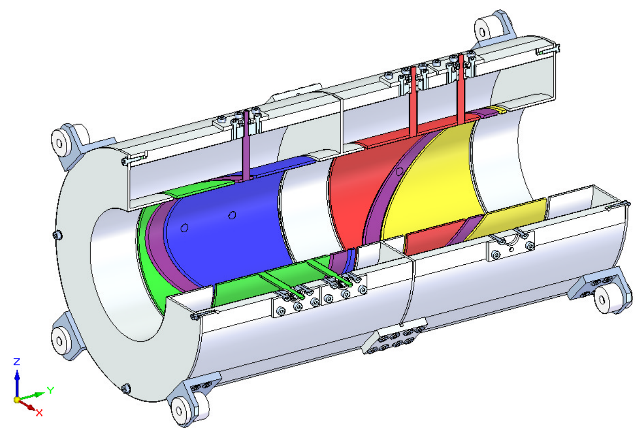

Figure 2: CAD model of the BPM.

SIGNAL PROCESSING

Signal estimation

For a BPM system equipped with a high input resistance (1 MΩ) preamplifier, the total signal U_S is a direct image of the bunch time structure and can be calculated as discussed in [8]:

$$U_S = \frac{1}{\beta c} \cdot \frac{1}{C} \cdot L \cdot I_{BEAM} \tag{2}$$

Like previously, L and C are length and capacitance-to-ground of the PU, while βc is beam velocity and I_{BEAM} is beam current. For L = 10 cm and C = 100 pF, a 300 keV antiproton beam expected in the USR will result in the average sum signal $\Sigma U = 2 \cdot U_S = 150$ µV. The difference signal ΔU for a small beam displacement x sensed by two opposite electrodes is assumed to be linear and can be estimated as:

$$\Delta U = \frac{x}{k} \cdot \Sigma U \tag{3}$$

Here k is a scaling factor. With coupling capacitance C_C between the electrodes taken into account it is:

$$k = (1 + 2 \cdot \frac{C_C}{C}) \cdot r \tag{4}$$

As can be seen, k is equal to the PU radius r when no coupling is present. For the discussed BPM, C_C was assumed to be 5 pF resulting in $k = 55$ mm. Consequently, the average ΔU signal expected for $x = 0.1$ mm is about 270 nV. This value will be compared with noise present in the system and used for S/N ratio calculations.

Noise estimation

For a beam position monitor with a high input resistance FET amplifier connected to the signal plate, the noise is determined mainly by amplifier voltage noise density $U_{N,amp}$ [9]. However, the contribution of thermal noise $U_{N,th}$ and amplifier current noise density $I_{N,amp}$ will also be considered. The total noise can be calculated as [10,11]:

$$U_N = \sqrt{(4k_B T\,\mathrm{Re}(Z) + |Z|^2 I_{N,amp}{}^2 + U_{N,amp}{}^2)\Delta f} \quad (5)$$

k_B and T are Boltzman constant and temperature, while Z is the impedance of the equivalent RC circuit:

$$Z = (\mathrm{R}^{-1} + i\omega C)^{-1} \quad (6)$$

In order to minimise the total noise, commercially available low-noise FET amplifiers SA-220F5 from NF Corporation were bought. Their parameters are summarized in Table 2. With these preamplifiers, a gain of 46 dB is achievable, while voltage, current and thermal noise densities contributing to equation (5) are 0.5 nV/√Hz, 0.2 nV/√Hz and 0.1 nV/√Hz respectively.

Table 2: SA-220F5 amplifier parameters

Frequency band	300 Hz to 100 MHz
Input impedance	1 MΩ
Input voltage noise density	0.5 nV/√Hz (0.01-1 MHz)
Input current noise density	200 fA/√Hz (100 kHz)
Voltage gain	46 dB

With equation (5), it is possible to plot the signal-to-noise ratio as a function of bandwidth Δf. Figure 3 shows the corresponding graph. It is clear that neither bunch-by-bunch (Δf = 20 MHz) nor turn-by-turn (Δf = 2 MHz) measurements are possible in the USR if resolution better than 1 mm is expected. However, closed orbit determination is still feasible with a bandwidth restricted to less than 200 kHz.

Beam position determination

Further signal processing, including filtering and position calculation, will be done in a digital manner. The signals measured by the PU will be fed into an analogue-to-digital converter (ADC) at an early stage and processed with dedicated software. Digitization will lead to a granularity of values, which might limit the accuracy.

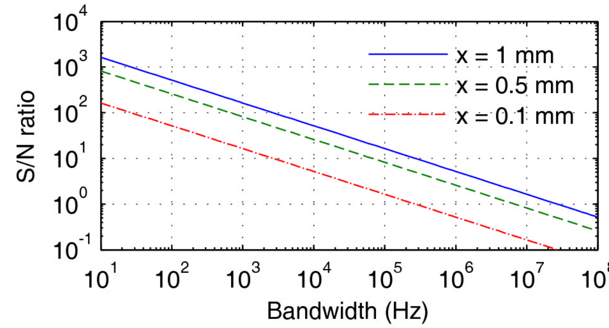

Figure 3: Signal-to-noise ratio as a function of bandwidth for different resolution requirements.

The achievable granularity for different numbers of bits and maximum input voltage settings of an ADC is summarized in Table 3. The PU signal will be amplified 200 times before digitization, which means ΔU = 54 µV for x = 0.1 mm. It should be kept in mind that this is an average signal and the peak value will be higher, yet the granularity requirements are discussed for the conservative estimation. For a bandwidth of only 100 Hz, the noise contribution will be 1.1 µV after amplification, which is much less than the granularity of the ADC configurations presented in Table 3. Therefore, it can be expected that the uncertainty of beam position determination will be dominated by analogue noise for larger Δf and by granularity for smaller Δf. This is reflected in Figure 4 presenting the beam position measurement error as a function of bandwidth for a 12-bit ADC with a 200 mV input voltage range. Figure 5 shows the S/N ratio for a digital system with a finite granularity.

Table 3: Signal granularity as a function of an ADC input voltage range (peak-to-peak)

ADC	100 mV	200 mV	400 mV	1 V
10 bit	98 µV	190 µV	390 µV	980 µV
12 bit	24 µV	48 µV	98 µV	240 µV
14 bit	6.1 µV	12 µV	24 µV	61 µV
16 bit	1.5 µV	3.0 µV	6.1 µV	15 uV

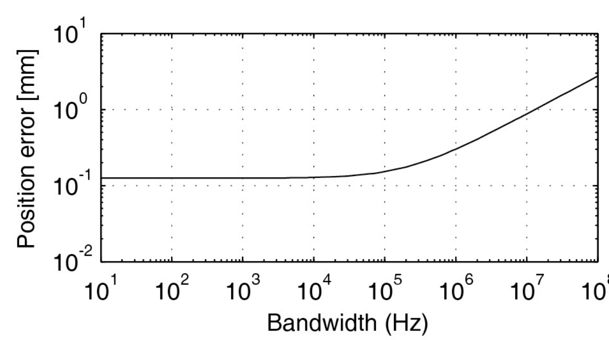

Figure 4: Beam position uncertainty as a function of bandwidth for a 12-bit ADC with a 200 mV input range.

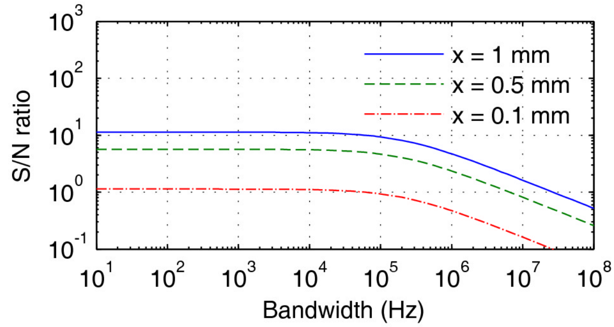

Figure 5: Signal-to-noise ratio as a function of bandwidth for different resolution requirements for a 12-bit ADC with a 200 mV input range.

The estimated uncertainty plotted in Figure 4 is for on-axis beams. However, it increases by at least 30% for off-centred beams passing a few mm from a PU electrode. This is reflected in the next plot in Figure 6.

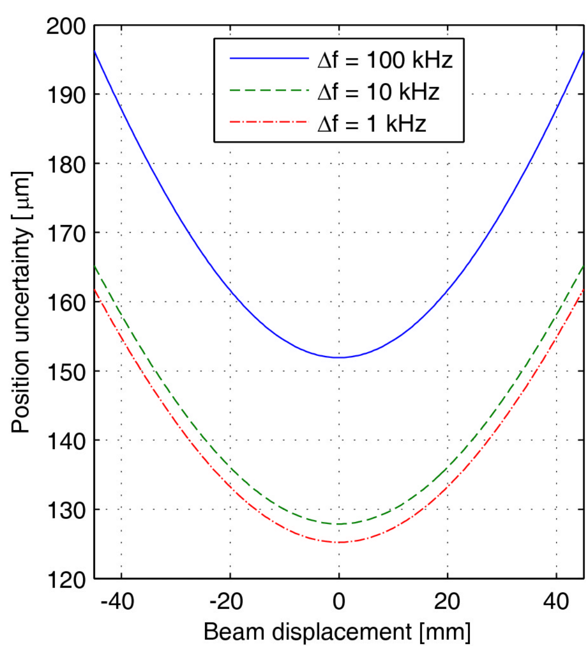

Figure 6: Calculated position read-out uncertainty.

Finally, a more realistic model of the signal expected in the USR was studied. A $\cos^2$-like bunch distribution was assumed which resulted in ΣU = 600 $\mu V_{p\text{-}p}$ and ΔU = 1 $\mu V_{p\text{-}p}$ peak-to-peak values. The noise calculated according to equation (5) was added. The signal was simulated with MATLAB [12] for a low-pass filter with the upper cut-off frequency of 10 MHz and no narrowband filtering was applied at this stage. The granularity was introduced to the signal like it would have happened with a 12-bit ADC with a 200 mV input voltage range. The sampling rate was 100 MS/s which for a 32 MSamples memory per channel means a resolution of 3.1 Hz. The results converted to values before amplification are presented in Figure 7. Although the sum signal appears to be quite clear, the difference signal for x = 0.1 mm is buried in noise as expected for a wide bandwidth Δf = 10 MHz. However, amplitude spectra taken over 1 ms, i.e. for roughly 1800 bunches which corresponds to 180 beam revolutions, exhibits visible peaks for the difference signal as can be seen in Figure 8. With further signal conditioning, it should be possible to achieve sub-mm resolution for closed-orbit measurements.

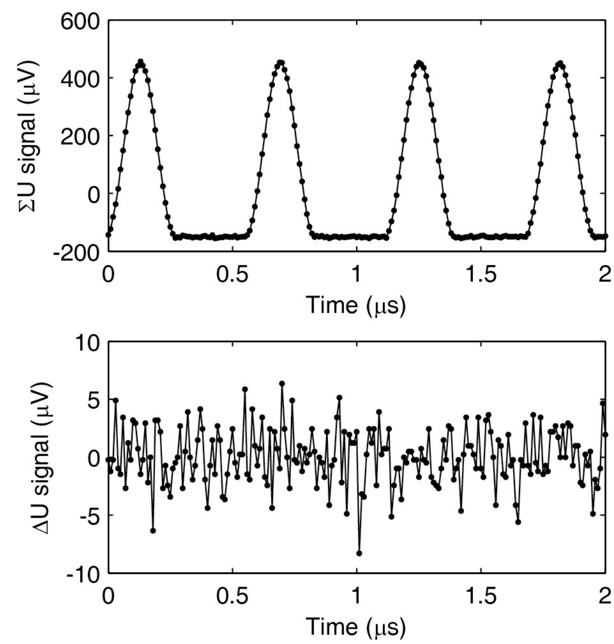

Figure 7: Sum (top) and difference (bottom) signals simulated for 0.1 mm of beam displacement with 100 MS/s sampling rate and 10 MHz bandwidth.

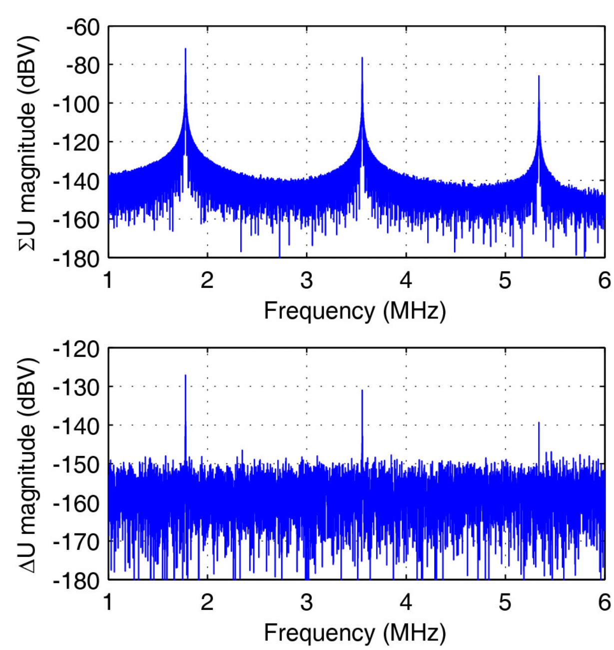

Figure 8: Sum (top) and difference (bottom) spectra for the signals shown in Figure 7 averaged over 1 ms.

Resonant amplification

With a flexible signal processing system, a resonant amplification could be added to increase the overall position sensitivity [5,10]. Should a lower S/N ratio be expected in the final BPM system, the pick-up can be built as a part of a resonant circuit with a matched inductance coil. Problems related to this solution as well as ideas how to overcome them were already discussed elsewhere [5,10,13]. In the light of the results presented in this contribution, the resonant amplification does not seem to be a necessity for the USR and will not be discussed in details.

LOW VELOCITY BEAMS

Since the USR will provide beams in the ultra-low energy regime, the influence of $\beta << 1$ on the pick-up response should not be neglected. With several assumptions discussed in [14], it is possible to estimate the PU response curve, calculated as $(\Delta U)/(\Sigma U)$, as a function of beam displacement x and harmonic number h. As can be seen in Figure 9, the approximately linear curve becomes strongly distorted for higher harmonic numbers when $\beta = 0.025$ and 0.006 is considered. Therefore, a low harmonic number should be chosen to minimise the non-relativistic effects [10]. This is the case of the standard operation of the USR for which $h = 10$ is planned to be used.

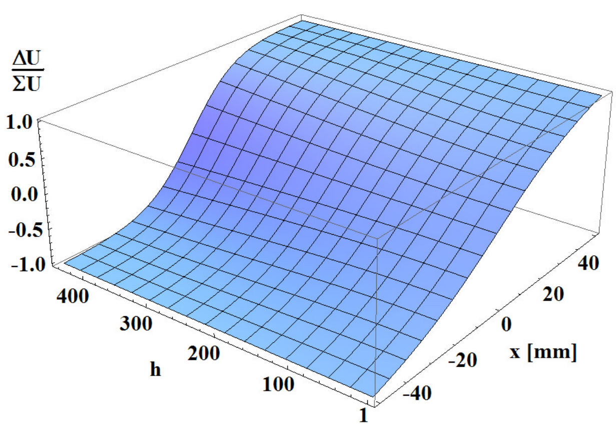

Figure 9: Theoretical response of a pick-up to the USR beams with $\beta = 0.025$ and 0.006 for a range of positions and harmonic numbers as calculated according to [11,14].

OUTLOOK

The beam position monitor is planned to be used with low energy, low intensity beams. It will be manufactured in mid 2010 and tested thereafter. It is planned to realise measurements with a "stretched wire" method in close collaboration with the Cockcroft Institute and the Daresbury Laboratory staff. Also a fully operational, flexible processing system for the close-orbit determination will be prepared in the near future.

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