OPTIMISATION STUDIES OF A RESONANT CAPACITIVE PICK-UP FOR BEAM POSITION MONITORING OF LOW INTENSITY, LOW VELOCITY ANTIPROTON BEAMS AT FLAIR*

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Abstract

The Ultra-low energy Storage Ring (USR) at the future Facility for Low-energy Antiproton and Ion Research (FLAIR) at GSI, Germany will decelerate antiproton beams of very low intensities from 300 keV down to 20 keV. Such beams can be easily disturbed by standard monitoring devices and the development of new sensitive diagnostic techniques is required. To overcome the limitations related to a very low number of particles, a low signal-to-noise ratio and ultra-low kinetic energies, a resonant capacitive pick-up has been proposed as a beam position monitor. In the planned solution, the signal gain will be realised by the use of a specially designed resonant circuit optimized to meet the requirements of the USR. The current overall design studies of the resonant capacitive pick-up, including simulations of the beam displacement sensitivity and linearity for different pick-up geometries and the equivalent resonant circuit characterisation, will be discussed.

INTRODUCTION

The novel Ultra-low energy Storage Ring (USR) is currently being developed for the future Facility for Low-energy Antiproton and Ion Research (FLAIR) [1]. It will be able to accept, store and decelerate a 300 keV beam of $\leq 2 \cdot 10^7$ antiprotons down to 20 keV.

For the standard operation of the USR, $\sim$100-ns-long bunches might be of the main interest. With the ring circumference of 42.6 m, the revolution time t_{rev} of the 300 keV antiproton beam will be equal to 5.6 μs. In this case, a harmonic mode h = 10, corresponding to the RF frequency f_{RF} = 1.78 MHz and RF buckets of about 560 ns, might be chosen. The RF field will typically be applied after the beam has reached a quasi-DC state which will lead to the generation of 10 bunches not longer than $\approx$150 ns. After the deceleration stage, the main RF frequency will have to be decreased to 459 kHz to follow the longer revolution time t_{rev} = 21.8 μs of 20 keV antiprotons resulting in bunches being not more than $\approx$550 ns long. Therefore, the standard operation of the USR will include $\approx$1.1 m long bunches of ultra-slow particles (β = 0.006–0.025) carrying a very low charge (300 fC) with the repetition rates in the range of $\sim$0.4–2 MHz.

In addition, a production of ultra-short (1–2 ns) bunches for in-ring experiments is also foreseen for the USR [2]. Initially, a 20 keV coasting beam is planned to be adiabatically captured into 50 ns stationary buckets formed by a 20 MHz cavity operating at a high harmonic mode. With h = 436 one gets only $\leq 5 \cdot 10^4$ particles (8 fC) per bunch. The final bunch length will depend on the initial RF voltage applied to capture the circulating beam. The desired ultra-short bunches of 1–2 ns duration, corresponding to $\approx$2 mm only, will then be formed by an additional double drift buncher with a voltage of $\approx$300 V.

Accurate beam position measurements, necessary for the successful operation of the USR, will require devices suitable for the proposed beam distributions. For the standard mode (h = 10) with the bunch repetition frequencies of the order of 1 MHz and the bunches much longer than the space available for a beam monitor, a capacitive diagonal-cut pick-up (PU) is a favourable solution. It offers a high linearity which is a huge advantage when the beam diameter can reach up 2 cm in some parts of the USR before electron cooling. However, this relatively simple device will not be suitable for the ultra-short, very slow bunches intended for the in-ring experiments. In this case, other monitors extracting information from electromagnetic fields of moving charged particles might also fail to measure the beam displacement. Figure 1 shows the transverse electric field calculated at a distance of 125 mm from the beam for 20 keV antiproton cos^2-like bunches formed with h equal to 10, 75, 200 and 436. For the highest h, the modulation of the signal is practically lost, thus none of the beam position pick-ups will work.

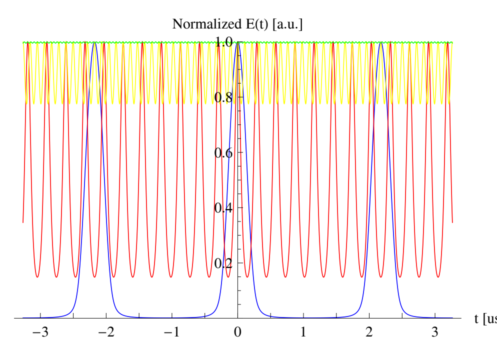

Figure 1: Normalized transverse electric field at a distance of 125 mm from the 20 keV cos^2-like bunches formed with h = 10 (460 kHz, blue curve), 75 (3.5 MHz, red curve), 200 (9.2 MHz, yellow curve), and 436 (20 MHz, green curve).

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CAPACITIVE PICK-UP DESIGN AND SIGNAL ESTIMATIONS

As already mentioned, a diagonal-cut capacitive pick-up will be used for the beam position measurements. The whole monitor will consist of two units, each l = 100 mm long and able to monitor the displacement in one axis. In order to avoid beam-to-ground impedance jumps and so the beam instabilities, the PU should have the same diameter as the beam tube, thus the radius r = 125 mm has been assumed. The coupling capacitance between opposite PU plates and adjoining PU units can be minimised by introducing guard rings on ground potential [3]. Figure 2 shows the simulations performed for different PU geometries. In all cases, not only is high linearity achieved, but also the guard ring separating two plates results in a greater sensitivity to the beam displacement.

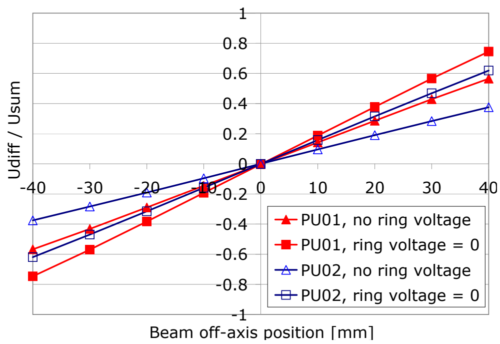

Figure 2: Response curves for two exemplary PU geometries with (squares) and without (triangles) ground voltage set to a guard ring introduced between PU plates.

For the 300 keV bunches at f_{RF} = 1.78 MHz consisting of $2 \cdot 10^6$ particles each and the foreseen PU length l = 100 mm, radius r = 125 mm and plate-to-ground capacitance $C \approx$ 100 pF, the expected peak voltage can be as low as ∼100 μV [4]. If the coupling capacitance between two plates is ignored, one can assume a simple linear response $\Delta U/\Sigma U = x/r$, where ΔU is the differential signal between two opposite plates, ΣU is the sum signal and x is the beam displacement. In this case, the differential signal for x = 0.1 mm will be as small as 150 nV and a low-noise amplifier will be required. Nevertheless, even with the equivalent amplifier input noise lowered to 0.6 nV/$\sqrt{\text{Hz}}$ (e.g., see [5]), a 20 MHz bandwidth system necessary for the USR bunch structure observation will result in the signal-to-noise ratio $S/N \approx$ 0.3 for 0.5 mm of beam displacement. Smaller bandwidth of 2 MHz could at least allow for the bunch-by-bunch observation, but in this case $S/N \approx$ 0.9 is still quite low. If a resolution better than 0.5 mm is to be achieved, a further bandwidth reduction will be required. Therefore, it has been proposed to build the pick-up as a part of a resonant circuit well tuned to the repetition frequency. Due to the bandwidth restriction, it will not be possible to measure the individual bunch properties, but a much higher sensitivity can be expected.

EQUIVALENT CIRCUIT STUDIES

An equivalent circuit of a capacitive PU plate with an external inductance coil introduced to create a resonant solution is shown in Fig. 3. The image current I flowing from the pick-up into the circuit can be estimated for a point charge moving inside the PU; then the total bunch signal can be calculated by summing up the weighted contributions. Although cos^2-like bunches with the full width at the baseline T = 150 ns and f_{RF} = 1.78 MHz have been assumed for the purpose of this study, the differences in the signals from arbitrary charge distributions for low β values can be neglected [6]. Figure 4 shows the calculated image current. A sine function of the same amplitude of ≈500 nA has been used for the resonant circuit analysis.

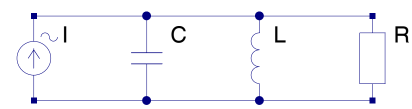

Figure 3: Equivalent circuit of the resonant capacitive PU plate with the image current I, plate-to-ground capacitance C, added inductance coil L and amplifier input resistor R.

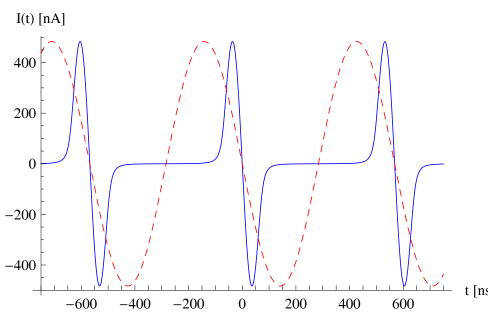

Figure 4: Image current flowing from the pick-up into an external circuit (blue curve) and a sine function with the same amplitude and repetition frequency (dashed red curve). The signal is generated on a PU plate of l = 100 mm and r = 125 mm by cos^2-like bunches with β = 0.025 and T = 150 ns.

The behaviour of two PU plates has been compared and studied in terms of the detectable voltage difference for I_{peak} = 500 nA, C = 100 pF, R = 1 MΩ, $\omega_0 = 2\pi f_{RF}$ and $L = 1/(\omega_0^2 C)$ = 80 μH. Signals from the off-centre beam has been estimated according to [7]. In the first assumption, ohmic losses $R_L << R$ in the inductance coil and the coupling capacitance C_c between the plates were ignored which resulted in the peak voltage of 0.5 V and the differential signal of 4 mV for 0.1 mm of beam displacement. However, damping and a shift of the resonance frequency $\omega_d = \omega_0\sqrt{1 - R_L^2 C/L}$ occurs when R_L is taken into account. With R_L = 50 Ω, the change in the resonance frequency Δf is smaller than 3 kHz, but the peak voltage and the differential signal for x = 0.1 mm decrease to about 8 mV and 50 μV respectively. When the coupling capacitance is considered, the differential voltage at f_{RF} = 1.78 MHz may drop down even by three orders of magnitude for C_c as low as 2 pF and no R_L included; with R_L = 50 Ω, the same signal is decreased only by a factor of 2. In both cases, the effect is due to the resonant response distortion. Figure 5 shows the behaviour of the system for C_c = 10 pF and R_L = 50 Ω. As can be seen, the signal from each plate is maximized at the desired frequency, but the maximum of the differential signal, still about 50 μV, is shifted to f = 1.62 MHz. Therefore, a careful selection of the inductance and the frequency is necessary. One can also consider a different setup with one inductance coil only connecting two plates for the direct measurement of the differential signal. In this case, the signal is not increased above the previous value of 50 μV, but the required inductance $L \approx 130$ μH is higher.

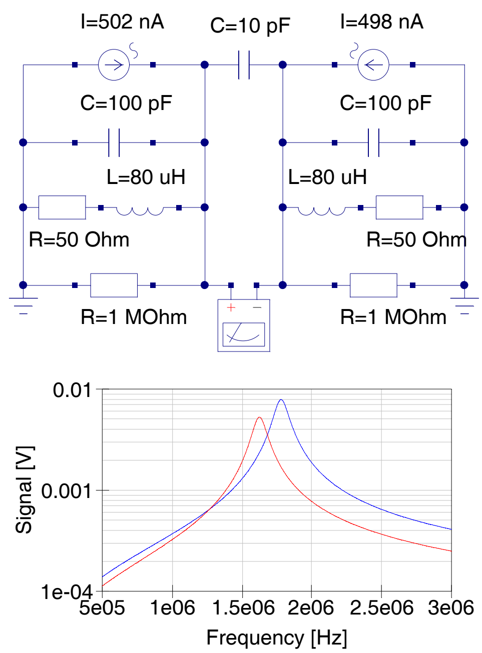

Figure 5: Equivalent circuit of two plates of the resonant capacitive PU and the resulting signal: peak voltage (blue curve) and differential voltage scaled by a factor of 100 for the picture clarity (red curve).

LOW-β EFFECT

The influence of the low β value on the pick-up response should be discussed as well. The sensitivity of the beam position monitor for a logarithmic ratio processing and small beam displacements can be expressed by a relativistic component multiplied by $(1 - G)$, where the correction factor for a non-relativistic beam is approximately [8]:

$$G \approx 0.139 \left(\frac{2\pi f_{RF} r}{\gamma\beta c}\right)^2 - 0.0145 \left(\frac{2\pi f_{RF} r}{\gamma\beta c}\right)^3 \quad (1)$$

Figure 6 shows the pick-up sensitivity deviation from the relativistic case for 300 keV and 20 keV beams. As can be noted, the correction factor increases with the increasing harmonic mode, but for the considered standard operation of the USR it should still be as low as 0.5%.

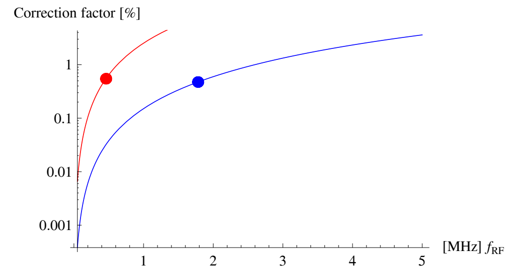

Figure 6: Correction factor calculated for 300 keV (blue) and 20 keV (red) bunches as a function of their repetition frequency (dots correspond to harmonic mode $h = 10$).

CONCLUSIONS

The studies of the foreseen capacitive pick-up design were presented. The diagonal-cut plates assure high linearity of the monitor, whereas grounded rings provide its greater sensitivity. Due to a very low number of particles and a low signal-to-noise ratio, a narrowband system is required and it has been decided to adopt a resonant circuit solution. Although the values of the considered circuit parameters were only estimated, the study provided an insight into the behaviour of the proposed system and the differential signal at least several times stronger is expected. Finally, it was shown that the sensitivity of the PU is strongly dependent on a harmonic mode h and not the β value itself.

REFERENCES

[1] C.P. Welsch and J. Ullrich, “FLAIR – a Facility for Low-energy Antiproton and Ion Research”, Hyperfine Interact. 172, 71-80 (2006).

[2] A. Papash, C.P. Welsch, “On the Possibility of Realizing Shortest Bunches in Low-energy Storage Rings”, Phys. Part. Nucl. Lett. 6(3), 216-226 (2009).

[3] P. Kowina et al., “Optimisation of ’Shoe-Box Type’ Beam Position Monitors Using the Finite Element Methods”, DIPAC’05 Proc., Lyon, France, 114-116 (2005).

[4] H. Koziol, “Beam Diagnostics for Accelerators”, CERN Accelerator School, Loutraki, Greece (2004).

[5] M. LeGras et al., “The Closed-orbit Measurement System for the CERN Antiproton Decelerator”, DIPAC’99 Proc., Chester, UK (1999).

[6] P. Strehl, “Beam Instrumentation and Diagnostics”, Springer (2006).

[7] R.E. Shafer, “Beam Position Monitoring”, AIP Conf. Proc. 212, 26-58 (1990).

[8] R.E. Shafer, “Beam Position Monitor Sensitivity for Low-β Beams”, AIP Conf. Proc. 319, 303-308 (1994).