DIAGNOSTICS FOR USR; LOW CURRENT BPMS*

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Abstract

The following paper presents the beam instrumentation foreseen for the Ultra-low energy Storage Ring (USR). The main focus of this work is on the development of beam position monitors (BPMs); a Faraday cup and a beam profile monitor will also be discussed.

INTRODUCTION

A novel electrostatic Ultra-low energy Storage Ring (USR) at the future Facility for Low-energy Antiproton and Ion Research (FLAIR), will slow down antiprotons and possibly highly charged ions to 20 keV/q. This multipurpose machine puts challenging demands on the necessary beam instrumentation. Ultra-short bunches for in-ring collision experiments on the one hand and a quasi-DC beam structure for nuclear-physics-type experiments on the other, together with variable very low beam energies, ultra-low currents and few particles, require the development of new diagnostic devices because most of the standard techniques are not suitable.

DIAGNOSTIC CHALLENGES

Table 1 presents the basic parameters of antiprotons available at the USR. The machine will be able to store and decelerate ~10^7 particles from 300 keV down to 20 keV. With a ring circumference of approximately 40 m, the revolution time of a 300 keV beam will be 5–6 μs. Due to a highly flexible lattice design [1], the beam width will vary from a few millimetres up to almost 2 cm at some positions in the ring. Also, both slow and fast beam extraction will require special attention from the diagnostics point of view.

For the standard operation of the USR, ~100-ns-long bunches are desired. For this case, a harmonic mode h = 10, corresponding to an RF frequency of 1.78 MHz and RF buckets of about 560 ns, will be chosen. The RF field will typically be applied after the beam has reached a quasi-DC state and will lead to the generation of 10 bunches with ~10^6 particles each. After deceleration, the main RF frequency will be decreased to 0.46 MHz to follow the longer revolution time, 22 μs, of 20 keV antiprotons. Such bunches of ultra-slow particles (β = 0.006–0.025), carrying a very low charge (300 fC), will require highly sensitive detection techniques.

The most challenging mode of operation will be the production of ultra-short (few ns) bunches for in-ring experiments. Initially, a 20 keV coasting beam is planned to be adiabatically captured into 50 ns buckets formed by a 20 MHz cavity operating at a high harmonic mode. With h = 436 one gets only ~$5{\cdot}10^4$ particles (8 fC) per bunch.

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Table 1: Parameters of the antiproton beams stored and decelerated in USR

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
Number of particles	~10^8 → ~10^7
Bunch length	1 ns – DC beam
Effective in-ring pbar rates	~10^{10} pps – 10^{12} pps
Average rates of extracted pbars	~10^6 pps

BEAM POSITION MONITORS

Capacitive Pick-up Design

For the non-destructive beam position determination, up to 8 capacitive pick-ups (PUs) will be installed at the USR. Their basic design has been discussed in [2], but a minor change has now been introduced. In order to avoid beam instabilities due to beam-to-ground impedance jumps, the PU should have the same diameter as the beam pipe. To increase the signal amplitude, the pipe diameter has been reduced from 250 mm to 100 mm.

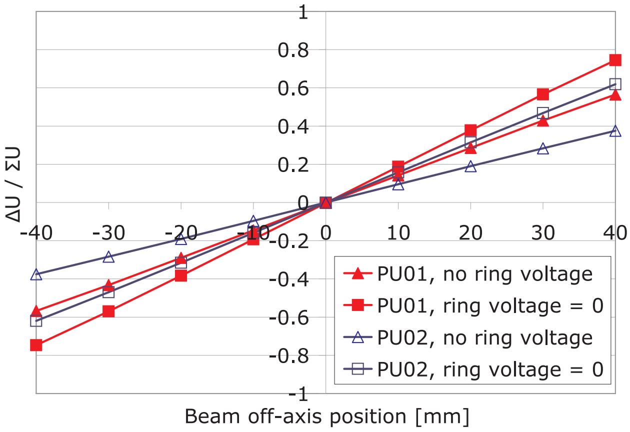

Figure 1: Response curves for two exemplary PU geometries with grounded separating rings (squares) and floating separating rings (triangles) introduced between the PU plates.

The coupling capacitance between opposite PU plates and adjacent PU units can be minimised by introducing separating rings at ground potential. With the proposed diagonal-cut design a high linearity is achieved. The guard rings, separating adjacent plates, allow for a higher sensitivity to the beam displacement as shown in Figure 1.

Signal Estimations and Analysis

The peak voltage is expected to be as low as ~100 μV. 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 voltage for x = 1 mm will be as small as only a few μV. The expected weak signals require the use of high input resistance, high gain, low noise amplifiers together with a narrowband processing system. Fig. 2 presents the estimated differential signal which includes 30 μV_{rms} noise equivalent to thermal noise at BW = 40 kHz. It is noticeable that the bunch structure is lost due to the low S/N ratio. However, the analysis of the frequency spectrum averaged over several dozens beam revolutions exhibits weak but clear peaks corresponding to the harmonics of the bunch repetition frequency. With high gain preamplifiers and a fast, high granularity ADC, the signal will be digitized and the further narrowband processing, including FFT analysis, will be performed allowing for closed-orbit measurements.

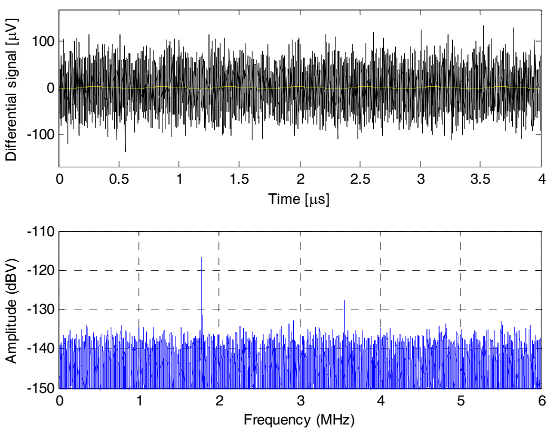

Figure 2: Top: differential signal (yellow) lost in noise (black). Bottom: its frequency spectrum for a 1 mm beam displacement averaged over 500 μs.

Resonant Amplification

With a flexible signal processing system, a resonant amplification could be added to increase the overall position sensitivity. The initial idea was to introduce coils for each plate independently as presented in Fig. 3. The behaviour of such a PU has been 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. With ohmic losses R_L in the inductance coil and no coupling capacitance C_c between the plates, a differential signal of more than 10 μV for 0.1 mm of beam displacement is expected. A shift of the resonance frequency $\omega_d = (1-R_L^2C/L)^{0.5}$ occurs, but is as low as 3 kHz for R_L = 50 Ω. However, when the coupling capacitance is considered, the resonant response is distorted, see Fig. 4. In this case, not only is the difference signal several times weaker, but also small changes in the symmetry of the setup easily affect the PU response. Several ideas on how to overcome this problem have been presented [3-4] and are presently under investigation.

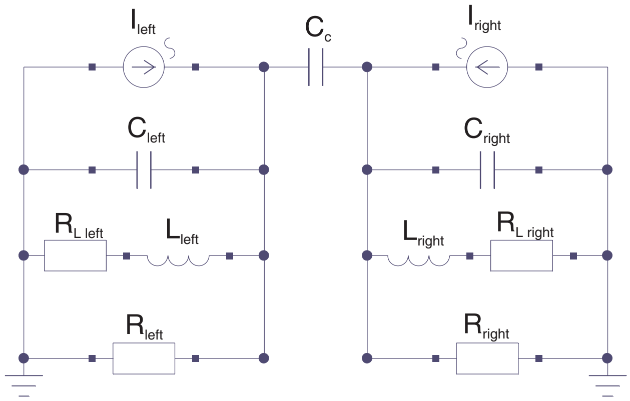

Figure 3: Equivalent circuit of the resonant capacitive PU with the image current I, plate-to-ground capacitances C, amplifier input resistors R and added inductance coils L. R_L and C_c represent coil ohmic losses and coupling capacitance respectively.

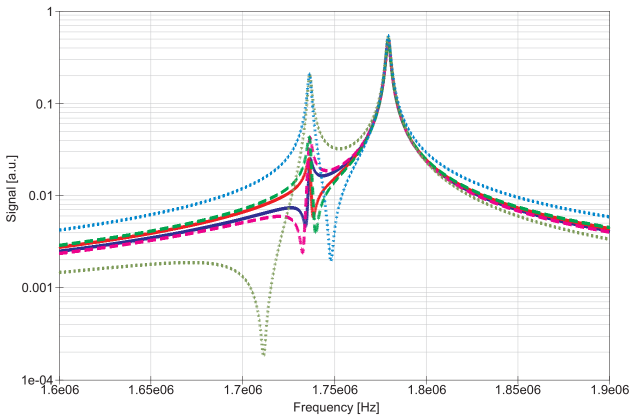

Figure 4: Resonant PU response spectra for different beam displacements (solid line: ± 1 mm, dashed line: ± 2 mm, dotted line: ± 10 mm) for two plates coupled with a parasitic capacitance.

FARADAY CUP

An electrostatic Faraday cup will be used as a simple destructive monitor for absolute beam current measurements. A limitation of this solution is, however, the interaction of antiprotons with the cup material. This can lead to the creation of not only secondary electrons but also MeV-scale charged pions and recoil ions. Such particles cannot be captured easily within the cup, and so the measured charge does not directly reflect the beam current. It will, however, be very useful for the commissioning stage with protons or ions.

The mechanical design of the Faraday cup was optimized for the USR, i.e., the aperture size was set for beams of diameters up to 2 cm and the suppressing electrode length was adjusted to increase the electron collection efficiency. Fig. 5 shows the simulation of the electric field distribution inside the Faraday cup.

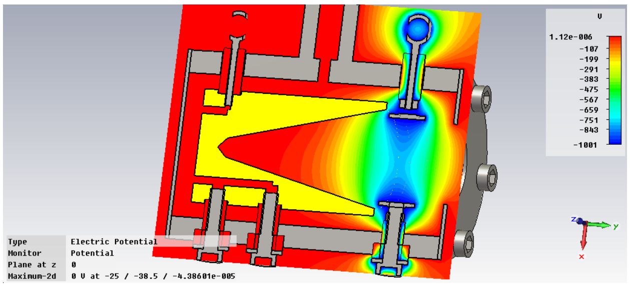

Figure 5: Simulation of the electric field distribution inside the Faraday cup.

For beam intensity measurements, a sensitive amplifier needs to be used because the expected average beam currents in the transfer lines could be as low as ~0.1 pA. For injection and fast extraction, the low currents can be measured by taking advantage of the bunched beam delivery and measuring the peak current with a fast current-to-voltage converter (transimpedance amplifier) working in the required bandwidth (50–200 kHz). For slow extraction, a sensitive solution should be applied for the weak DC currents. To overcome the difficulties with measurements for the different beam delivery schemes, a variable gain transimpedance amplifier DLPCA-200 from FEMTO was proposed. With a gain setting of 10^6–10^7 V/A, one will be able to follow the beam dynamically and get reasonably high signals. Using the highest gain of 10^{11} V/A and a limited bandwidth, it should be possible to measure intensities down to ~10^6 pps.

BEAM PROFILE MONITOR

A scintillator-based monitor will deliver information on the transversal beam profile. However, limited sensitivity and light yield decrease due to surface sputtering have been reported [5-6]; it is not clear if these results can be applied to the USR case for two reasons. First, the tests were mainly limited to plastic scintillators and other materials are still to be investigated under different irradiation conditions. And second, the thickness and other parameters of the screens were not optimized for the lowest possible beam currents. Therefore, further studies on scintillator-based monitors were undertaken using different types of screens.

The first experiments were realized at the Nuclear Physics Laboratory INFN-LNS in Catania, Italy with the invaluable help of Paolo Finocchiaro, Luigi Cosentino and Alfio Pappalardo. The tests were based on irradiation of the screens with a continuous beam of protons in the keV range with intensities down to a few fA. The scintillating materials used during the investigations included CsI:Tl, YAG:Ce and a Tb-glass-based Scintillating Fibre Optic Plate (SFOP). In order to reduce the initial beam currents of a few pA to only a few fA, pepper-pot-like attenuators were used, which produced multi-peak images, see Fig. 6. This allowed resolution testing of the screens at the same time.

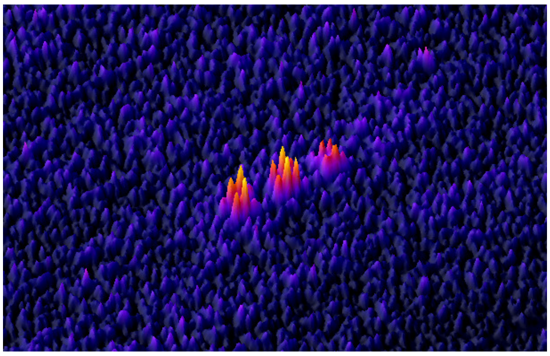

Figure 6: Intensity map of the 50 keV proton beam image taken with CsI:Tl.

The preliminary results for CsI:Tl and SFOP exhibited great sensitivity to low intensity, low energy beams such as those expected from FLAIR. For 200 keV protons, the beam was still visible at approx. 10 fA and only a few seconds of averaging. The achieved resolution was better than 0.5 mm. The YAG screen, despite its better radiation hardness, responded only in a very limited range.

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