BEAM DIAGNOSTICS FOR THE USR*

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Abstract

The novel electrostatic Ultra-low energy Storage Ring (USR), planned to be installed at the future Facility for Low-energy Antiproton and Ion Research (FLAIR), will slow down antiprotons and possibly highly charged ions down to 20 keV/q. This multipurpose machine puts challenging demands on the necessary beam instrumentation. Ultra-short bunches (1–2 ns) on the one hand and a quasi-DC beam structure on the other, together with a variable very low beam energies (20–300 keV/q), ultra-low currents (down to 1 nA or even less in transfer lines) and few particles ($\leq 2{\cdot}10^7$), require the development of new diagnostic devices as most of the standard techniques are not suitable. Several solutions, like resonant capacitive pick-ups, beam profile monitors, Faraday cups or cryogenic current comparators, are under consideration. This paper presents the beam instrumentation foreseen for the USR.

INTRODUCTION

The electrostatic Ultra-low energy Storage Ring (USR) will be a multi-purpose machine installed at the Facility for Low-energy Antiproton and Ion Research (FLAIR) in Darmstadt, Germany [1]. Providing electron-cooled antiprotons and possibly highly charged ions for both in-ring experiments and effective injection into traps, it will enable the investigation of a large number of fundamental physics questions [2]. The low beam energies and high beam quality to be assured by this accelerator will, however, require the development of new instrumentation as most of the known diagnostic solutions will no longer work.

BEAM DIAGNOSTIC CHALLENGES

Table 1 presents the basic parameters of antiprotons stored and decelerated in the USR. The machine will be able to accept a 300 keV beam consisting of up to $2{\cdot}10^7$ particles. With the ring circumference of 42.6 m, the revolution time t_{rev} of such a beam will be equal to 5.6 μs. Due to a highly flexible lattice design, the beam width will vary from a few millimetres up to 2 cm before the electron cooling at some points of the ring. Also, both slow and fast beam extraction modes will require special attention from the diagnostic point of view. For the standard operation of the USR, $\sim$100-ns-long bunches might be of the main interest. For 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 and will lead to the generation of 10 bunches not longer than $\approx$150 ns with $2{\cdot}10^6$ particles each. After the deceleration stage, the main RF frequency will have to be decreased to 458 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. Such packages of ultra-slow particles (β = 0.006–0.025) carrying a very low charge (300 fC) will require highly sensitive detection techniques. Nevertheless, the most challenging mode of operation of the USR will be the production of ultra-short (1–2 ns) bunches for in-ring experiments [3]. 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 $h \approx$ 430 one gets only $\leq 5{\cdot}10^4$ particles (8 fC) per bunch.

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

Energy	300 keV $\rightarrow$ 20 keV
Relativistic $\beta = v/c$	0.025 $\rightarrow$ 0.006
Revolution frequency	178 kHz $\rightarrow$ 46 kHz
Revolution time	5.6 μs $\rightarrow$ 21.8 μs
Number of particles	$\leq 2{\cdot}10^7$
Bunch length	1 ns – DC beam
Effective in-ring $\bar{p}$ rates	10^{10} pps – 10^{12} pps
Average rates of extracted $\bar{p}$'s	$5{\cdot}10^5$ pps – 10^6 pps

FORESEEN DEVICES

A wide range of diagnostic devices has been investigated for the USR. They are foreseen for different stages of the machine development and most of them can be used for the monitoring of more than just one beam parameter.

Beam Transformer

Ultra-low currents (down to 1 nA) expected in the ring are below the sensitivity of standard beam transformers which makes the non-destructive intensity monitoring more complicated. However, FFT-based spectral analysis of the Schottky signals can provide sufficient information not only on the beam intensity but also on momentum spread and mean momentum. Such a solution, based

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on a ferrite loaded transformer used as a Schottky pick-up, was successfully developed for the CERN Antiproton Decelerator (AD) [4] and could now be adapted for the USR.

An interesting option is a SQUID-based cryogenic current comparator (CCC) for absolute, non-destructive in-ring measurements of the beam intensity [5]. However, an extensive R&D is required as there is still place for optimization, e.g., a fractional turn loop sensing coil may enhance the CCC sensitivity above that of a SQUID [6].

Faraday Cup

An electrostatic Faraday cup is considered 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 which will lead to the creation of not only secondary electrons but also MeV-scale charged pions and recoil ions. Such particles cannot be easily captured within the cup and so the charge would escape from it in a variety of ways. Nevertheless, it still can be used for the commissioning stage with protons or H^- ions.

The mechanical design of the Faraday cup has been optimized for the USR, i.e., the aperture has been prepared for the beams of diameter up to 2 cm and the suppressing electrode length has been adjusted to increase the electron collection efficiency. Fig. 1 shows the simulation of secondary electrons emitted from the inner surfaces due to proton impact. For the intensity measurements, a sensitive amplifier needs to be applied because the expected average beam currents in the transfer lines will be as low as ~100 fA. For the injection and fast extraction stages, the problem can be resolved by taking the advantage of the bunched beam delivery and measuring the peak current with a fast current-to-voltage converter working in the required bandwidth.

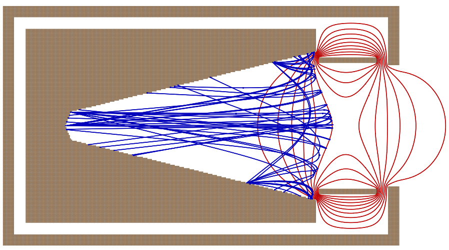

Figure 1: Simulation of secondary electrons (blue lines) emitted from different points of the Faraday cup due to proton impact (equipotential lines of the suppressing electrode are shown in red).

Scintillating Screen

A simple scintillator-based device would deliver sufficient information on the beam profile. However, a limited sensitivity and the light yield decrease due to the surface sputtering were reported [7, 8]. Although the results might be valid for the performed experiments, it is not clear if they can be applied to the USR case. First, mainly plastic scintillators were tested and other materials are still to be investigated under different irradiation conditions. Second, thickness and other parameters of the screens were not optimized for the lowest possible beam currents as scintillators were just used for the particular beam intensities. Therefore, further studies on this topic have been launched and an ultra-thin CsI:Tl scintillator is currently being tested in collaboration with INFN-LNS in Catania, Italy. Preliminary results with ultra-low intensity, very-low energy proton beams are promising.

Secondary Electron Emission Monitor

A possible problem of limited sensitivity can be solved with the use of a foil-based secondary electron emission (SEE) monitor equipped with a microchannel plate (MCP) and a phosphor screen. In this case, the accelerating field is introduced and its influence on the primary beam should not be neglected. In Fig. 2, trajectories of particles at different energies are presented. The grounded grid electrode is placed parallel to the y-axis at x = 0 mm, whereas the SEE foil on -5 kV potential is located at x = 5 mm. The primary beam enters the monitor in the lower-left corner and travels towards the upper-right corner. Its deviation from the primary path can be observed for a low energy range.

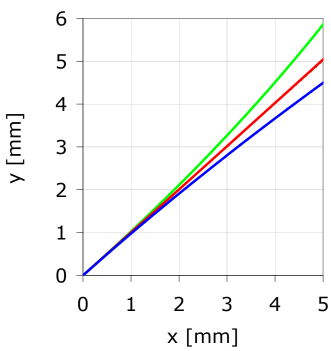

Figure 2: Disturbance of different primary beams in the presence of the SEE monitor: 20 keV antiprotons (green), 300 keV antiprotons (red) and 20 keV protons (blue).

Furthermore, instead of a thin foil, a micro-wire chamber could be used for the less perturbing profile measurements. Although more complex, such a solution, intercepting only 1% of the beam, has been successfully tested with 25 keV – 5.3 MeV antiprotons at the CERN AD [9].

Curtain-Shaped Supersonic Gas Jet Monitor

For the lowest beam perturbation, an ionization beam profile monitor relying on a supersonic gas-jet shaped into an extended thin curtain is proposed for the operation under ultra-high vacuum [10]. Existing in-ring monitoring techniques, such as residual gas monitors, can take up to about 100 ms to make meaningful measurements because of the low residual gas pressure. The proposed monitor allows injection of the additional gas (in order to increase the ionization rate) together with its efficient evacuation (to keep the required vacuum level in the ring) due to the high directionality of the supersonic jet. Furthermore, it allows simultaneous determination of both transverse profiles and beam imaging.

The proposed beam profile monitor relies on a neutral gas-jet, shaped into a thin curtain crossing the beam. In its simplest configuration, shown in Fig. 3, the gas curtain flows perpendicularly to the projectiles propagation axis, and the curtain plane forms with the same axis an angle $\alpha = 45°$. When the projectile beam crosses the gas-jet, ionisation interactions occur and gas ions are created in the region of the curtain. These ions are accelerated by an electric extraction field of 5 kV/m towards an amplification stage with an MCP and hence detected via a phosphor screen and a CCD camera. The magnitude of the extraction field is such as to project the ions on the imaging system in a nearly straight line, making negligible the contribution of initial velocity spread. After having crossed the beam in the interaction chamber, the gas-jet flows into the dumping chamber, where a differential pumping stage dumps the 10^{-5} mbar jet down to 10^{-10} mbar, preventing it from affecting the vacuum in the ring.

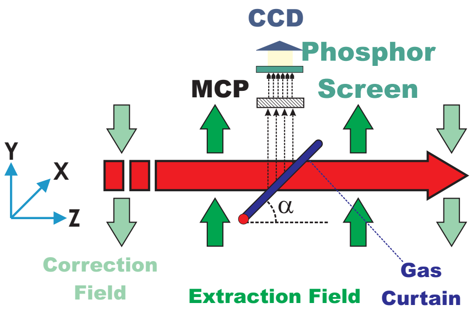

Figure 3: Gas curtain monitor working principle.

Resonant Capacitive Pick-Up

Capacitive pick-ups (PU) are foreseen for the nondestrucitve beam position monitoring. Due to a low number of particles and a low signal-to-noise ratio, a tuned resonant circuit is under investigation. Different PU geometries have been studied and a great improvement of sensitivity to the beam displacement has been achieved by separating electrodes by a ring on ground potential. However, preliminary studies of equivalent circuits showed that a coupling (parasitic) capacitance between two separate electrodes cannot be neglected as it results in a loss of information on the beam position. Even for a small value of this coupling capacitance (a few pF) not only is the difference signal smaller by three orders of magnitude as compared to the uncoupled electrodes, but also the frequency spectrum is distorted, see Fig. 4. The problem can be solved by creating just one resonant circuit directly measuring the difference signal from two electrodes.

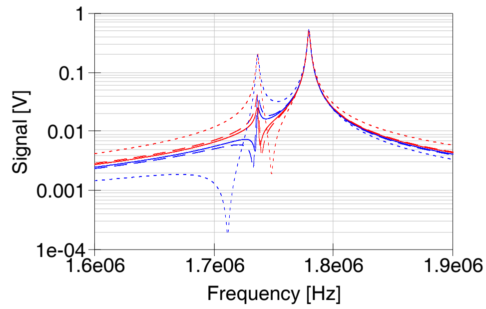

Figure 4: Resulting spectra for different beam displacements (solid line: ± 1 mm, dashed line: ± 2 mm, dotted line: ± 10 mm) for two resonant pick-up electrodes coupled with a parasitic capacitance.

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