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BEAM DIAGNOSTICS FOR THE FUTURE ULTRA-LOW ENERGY ANTIPROTON STORAGE RING AT FLAIR

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Abstract

Low energy beams are very important for many existing and future accelerator projects, but require optimisation of new diagnostic methods as most of the standard high-energy techniques no longer work. This contribution presents devices developed for the ultra-low intensity, ultra-low energy storage ring (USR) and its transfer lines at the Facility for Antiproton and Ion Research (FAIR). The monitors include a capacitive pick-up for closed-orbit measurements, a Faraday cup for femtoampere currents detection and three different beam profile monitors based on scintillating screens, secondary electron emission and least interceptive supersonic gas-jet screen. The instrumentation can find application also at other ultra-low energy storage rings and beam lines.

INTRODUCTION

The future facility for low-energy antiproton and ion research (FLAIR) [1] at FAIR [2] is an example of an accelerator complex providing beams that put challenging demands to diagnostic instrumentation. Although only 42 m in circumference, FLAIR's central machine, the ultra-low energy storage ring (USR) [3], will offer worldwide unique conditions for both in-ring studies as well as for experiments requiring extracted beams of slow and cooled antiprotons in the keV range. The beam energies that will be made available in the USR correspond to low relativistic β values and, due to the space charge limit, a low number of particles per bunch, as reported in detail in Table 1.

Table 1: General Parameters of the Antiproton ($\bar{p}$) Beams Stored and Decelerated in the USR

Beam 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	$\leq 2{\cdot}10^7$ $\bar{p}$ @ 20 keV
Bunch length	1 ns – DC beam
Effective in-ring $\bar{p}$ rates	10^{10} $\bar{p}$/s – 10^{12} $\bar{p}$/s
Average rates of extracted $\bar{p}$'s	$5{\cdot}10^5$ $\bar{p}$/s – 10^6 $\bar{p}$/s

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BEAM POSITION MEASUREMENTS

For non-destructive beam position/closed-orbit measurements, four capacitive pick-ups (PUs) will be installed in the ring [4, 5]. Their design is shown in Fig. 1. The position x of the centre-of-mass of the beam is calculated from the difference of the generated signals ΔU for opposite electrodes normalised to the sum ΣU. The diagonally cut electrodes guarantee linear response of the system to beam displacements within the required range of $\pm$40 mm. Additional separating rings between the electrodes are introduced in order to minimise parasitic coupling between the electrodes. With the rings in place, sensitivity to beam displacement increases by almost 20%, but the voltage signal measured decreases by a similiar fraction. There is therefore a trade-off between the position sensitivity and detection capabilities. The overall performance of the monitor is reported in detail in [6].

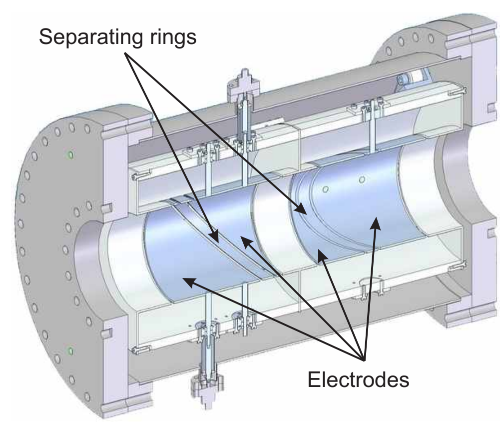

Figure 1: Cross-section view of the beam position monitor.

The scaling factors for x and y were determined with the use of pulses generated in a wire stretched inside the PU and installed on a movable platform [5]. Although the arrangement is equivalent to $\beta = 1$, it was demonstrated that the low-β values are generally not a problem in the USR as long as bunching frequencies f_{RF} are low and a narrowband signal processing is used. The chosen harmonic number h = 10 corresponds to f_{RF} less than 2 MHz at 300 keV and less than 500 kHz at 20 keV. It leads to a beam position determination error smaller than 0.02 mm, thus the low-β correction can be omitted. Should the short bunches be observed in the wide bandwidth, the low-β effect will have to be taken into account.

BEAM INTENSITY MEASUREMENTS

For measuring intensities of injected and extracted beams, a sensitive Faraday cup will be used. The monitor is shown in Fig. 2. A beam of protons or ions is stopped in a copper beam stopper optimised for efficient collection of backscattered and secondary particles. An additional suppressing electrode prevents secondary electrons from leaving the detector and the total charge can be confined in the cup. The resulting signal is transported outside the vacuum chamber by means of a custom-made UHV-compatible triaxial cable and is amplified by a variable-gain current-to-voltage converter. The latter enables the use of the system for both, the sub-μA peak currents of fast-extracted beams and sub-pA quasi-DC intensities of slowly extracted particles [7].

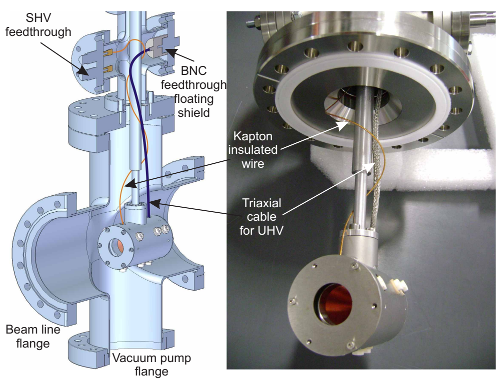

Figure 2: Cross-section view of the Faraday cup setup.

The Faraday cup was tested with an electron gun and beam currents in the femtoampere range. With a gain of 10^{12} V/A and a bandwidth of 0.1 Hz, the peak-to-peak noise was about 40 fA and further averaging over 16 seconds was applied. It was demonstrated that beam currents as low as 14.6 ± 0.9 fA can be measured in a reproducible manner. Further tests with low energy protons showed even better performance [6].

BEAM PROFILE MEASUREMENTS

Secondary Emission Monitor

For beam profile measurements in the injection and extraction lines a secondary emission monitor (SEM) was designed [8]. The detector consists of a grounded mesh and an aluminium foil on a negative potential, a chevron type microchannel plate (MCP) with a phosphor screen and a CCD camera registering the image. The primary beam passes through the mesh at 45° and ejects eV-range secondary electrons from the foil surface. These are accelerated towards the mesh placed 5 mm away by the negative voltage applied to the foil. By the time they reach the mesh, they are already highly directional and fly towards the detector located ca. 50 mm away. There, they are multiplied by the MCP and converted to visible light by the phosphor producing an image which can be registered by a CCD camera. The detailed performance of the SEM is reported in [6].

The final design of the detector is shown in Fig. 3. It was made flexible to enable the use of two configurations, the SEM and a stand-alone MCP placed directly in the beam. The latter arrangement was demonstrated to be suitable for low energy antiproton beam profile monitoring [10].

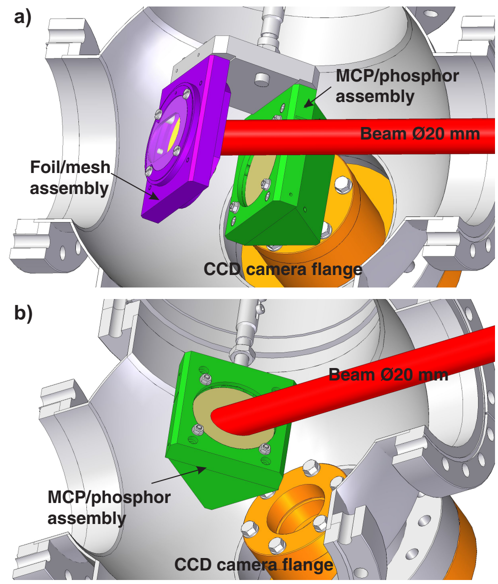

Figure 3: Two configurations of the secondary emission monitor: a) foil-based SEM, b) MCP directly in the beam.

Scintillating Screens

Should a simpler, cheaper and more robust solution be used for beam profile measurements in the injection and extraction lines, CsI:Tl screens can be used. They offer sufficiently high sensitivity to low energy, low intensity beams. It was demonstrated [9] that it is possible to measure currents even in the fA range corresponding to about 10^4 particles per second at 200 keV. For 50 keV beams, the sensitivity drops down and is about 4 times lower for CsI:Tl. Furthermore, an absolute light yield calibration technique can be applied to estimate the beam current of the impinging proton beams [9].

The bulk screen-based monitor can be prepared with additional aperture that matches the size of the beam to be transferred to/from the USR. Such a solution provides a less destructive technique for the initial tuning of the USR parameters. By making sure that most of the beam passes through the small aperture in the monitor, the number of accepted particles is maximised.

Supersonic Gas-Jet Screen

For operation in the USR ring section, however, a least-interceptive monitoring principle is needed in order to preserve beam lifetime as perturbation from interceptive screens results in beam loss. Least perturbative diagnostics is achieved by means of a beam profile monitor based on a supersonic neutral gas-jet target, whose geometry is shaped, by means of suitable collimators, in the form of a thin screen, angled at 45° with respect to the incoming beam.

Such screen then acts analogously to a secondary emission monitor: the principle of the device is illustrated in Fig. 4. When the primary beam crosses the gas it ionizes it, and the gas ions are collected through an electric field on the detector: MCP and phosphor screen in cascade. Two compensation electric fields are added upstream and downstream the monitor to correct for the kick undergone by the primary beam under the influence of the gas ions extraction field.

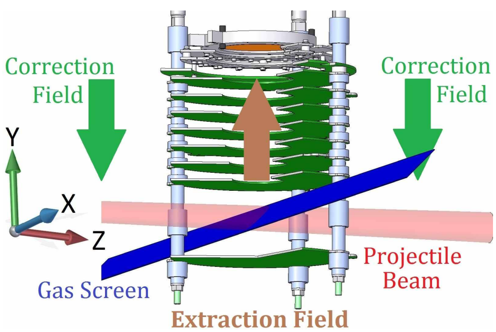

Figure 4: Supersonic gas jet based beam profile monitor setup. The projectile beam (red), traveling along the z axis, crosses the gas jet screen (blue), traveling along the x axis, and an electric field, along the y axis, extracts the ionization products towards the detector.

The monitor can be operated with residual gas pressures as low as 10^{-11} mbar, without affecting the vacuum level, and features a sub-mm space resolution. Furthermore, it can be operated with the USR beam without any supersonic jet, in the residual gas operation mode, with a spatial resolution of less than 100 μm, if the residual gas pressure exceeds 10^{-8} mbar. Finally, the design allows in principle to upgrade the monitor to an experimental station for momentum spectroscopy of molecular collisions. Design studies to implement this upgrade will be performed in the coming years.

Full theoretical and experimental characterization of the monitor in its operation as a residual gas monitor is published in [11]. Design details for gas jet target generation shaping have been published in [12].

SUMMARY AND PERSPECTIVES

Beam monitors developed for the ultra-low intensity, ultra-low energy beams at the USR were presented. The instrumentation will enable beam position, profile and intensity measurements during commissioning and operation of the USR and its transfer lines.

The Faraday cup will provide information on the proton or ion beam intensity, but can also be used to calibrate the response of the pick-ups. This way, their applicability can be extended to non-destructive proton and antiproton beam current monitoring. For non destructive acquisition of transverse profiles with sub-mm resolution instead, the use of the supersonic gas jet target based monitor is envisaged.

Although all monitors were optimized for the USR, their use stretches well beyond this particular machine and they are also suited for other low energy storage rings and beam lines.

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