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Beam instrumentation for the Ultra-low energy Storage Ring (USR)

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Abstract The electrostatic Ultra-low energy Storage Ring (USR) at the future Facility for Low energy Antiproton and Ion Research (FLAIR) will make available antiprotons from 300 keV down to 20 keV beam energy. This multipurpose machine puts challenging demands on the beam instrumentation due to the varied bunch structure (ultra-short bunches of 1–2 ns up to a quasi-DC beam structure on the other), together with variable very low beam energies, ultra-low currents of down to 1 nA (or even less in the transfer lines which means less than 2×10^7 particles). Thus, the development of new diagnostic devices is required as most of the standard techniques are not suitable. Within the QUASAR Group, the necessary beam instrumentation for the commissioning phase and standard operation of the USR, as well as advanced techniques such as a gas curtain-jet beam profile monitor, have been developed and prototypes of all devices have been built up. This paper presents the design of all beam diagnostics devices for the USR and summarizes the results from first measurements.

Keywords Antiprotons · Beam · Diagnostics · Instrumentation · Low energy · Storage ring

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1 Introduction

Cooled antiproton beams at very low energies (KeV range) provide an ideal tool to investigate the dynamics of correlated quantum systems [1]. Such beams can only be provided by beyond state-of-the-art low energy storage ring technologies and put stringent demands on the beam diagnostics system. The beam energies that will be made available in the USR correspond to low relativistic β values and a very limited number of particles per bunch, as reported in detail in Table 1. Under these conditions, preservation of the beam lifetime and improving of the detection resolution are the most crucial requests which cause standard techniques, such interceptive foils, to be strongly improved or simply not suitable [2]. These parameters necessitated the development of a new set of high performance instruments for the USR. Prototypes of all the beam diagnostics have been built up, including a more sophisticated technique based on a curtain gas jet to monitor the beam profile which will have applications beyond the USR as a diagnostics tool for accelerators.

2 Beam profile monitors

2.1 Scintillating screen for keV ion beams

Scintillators are amongst the best suited devices for beam profile monitoring in terms of simplicity, cost and effectiveness even though they are not as sensitive as devices equipped with micro channel plates (MCPs) and other amplification stages. Surprisingly, their ultimate detection limits have not been investigated in detail. To satisfy the USR requirements, their detection limits in the low energy regime were studied [3]. Three different scintillating screens were chosen for testing in the keV range between 50 and 200 keV. The tests were performed in close collaboration with INFN-LNS (Italy) and included a 1 mm thick Caesium Iodide doped with Thallium (CsI:Tl) and a 2 mm thick Terbium-doped glass Scintillating Fibre Optic Plate (SFOP). The intensity of the beams was varied by inserting pepper pot grids into the beam path. The tests showed that CsI:Tl and the SFOP are sensitive enough for proton beam profile monitoring in the ultra-low energy, ultra-low intensity regime. It was possible to measure currents even in the subfemtoampere range, corresponding to about 5×10^3 particles per second, for 200 keV beams. For 50 keV beams, however, the sensitivity of both screens drops down and is about four times lower for CsI:Tl and approximately two orders of magnitude lower for the SFOP [3].

2.2 The curtain-jet beam profile monitor

For transverse beam profile monitoring applications, where low beam perturbation and bi-dimensional imaging are required, a device based on a neutral gas-jet target, shaped into a thin curtain, is being developed and tested [4].

In Fig. 1 a sketch of the working principle of the monitor is shown. The thin curtain-shaped jet of neutral atoms is used as target for the incoming beam, which ionizes the gas; the created ions are extracted by an electrostatic field and imaged on a position sensitive detector; an MCP and a phosphor screen.

Table 1 Summary of 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 ($2{\cdot}10^6$ pbars)

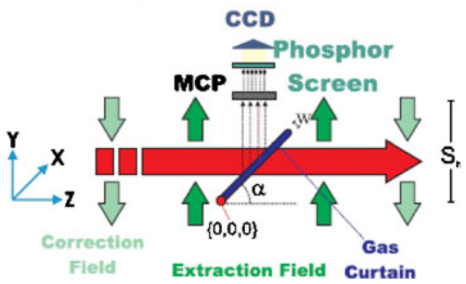


Fig. 1 Curtain jet beam profile monitor operation principle

The creation of the gas-curtain was first studied by means of simulation using the Gas Dynamic Tool (GDT) software developed by the CFD group, Russia. In addition, the GDT code was augmented with purpose-written C^{++} analysis tools, to automate and optimize the simulations and perform the post-processing evaluations. To explore the geometry of the nozzle/skimmer system for the curtain characteristics responsible for monitor resolution in terms of its density, thickness and width, five geometric parameters were varied, as shown in Fig. 2a: these included the skimmer aperture angles (α and β); the width of the skimmer slit (SW); the depth of the skimmer structure (SD) and the nozzle-skimmer distance (dns). In addition, the homogeneity of the curtain density and its confinement, which are related to the accuracy and the pumping efficiency respectively, will be investigated.

Based on the simulations, several geometrical configurations gave optimized conditions for the nozzle/skimmer system, which increases by a factor 2 the resolution and a factor 13 the accuracy, as compared with conventional systems using a collimated pencil jet made using a circular orifice, followed by a conical skimmer and collimators [4]. This novel monitor is presently being commissioned for the USR and also has potential for uses in other applications.

2.3 The secondary emission monitor (SEM)

A secondary emission monitor is being developed to measure the profile of the beam. In Fig. 3 a diagram of a model of the SEM device is shown [5]. The working principle is based on the production of secondary electrons by the collision of beam particles against a foil, or metallic plate, in this case made of aluminum.

The emitted electrons are accelerated by a high voltage mesh grid towards the detector. The spatial resolution of the system depends strongly on the voltage applied to the aluminum foil, which has a maximum limit imposed by the thermionic emission of electrons and the breakdown [6]. These phenomena can deeply affect

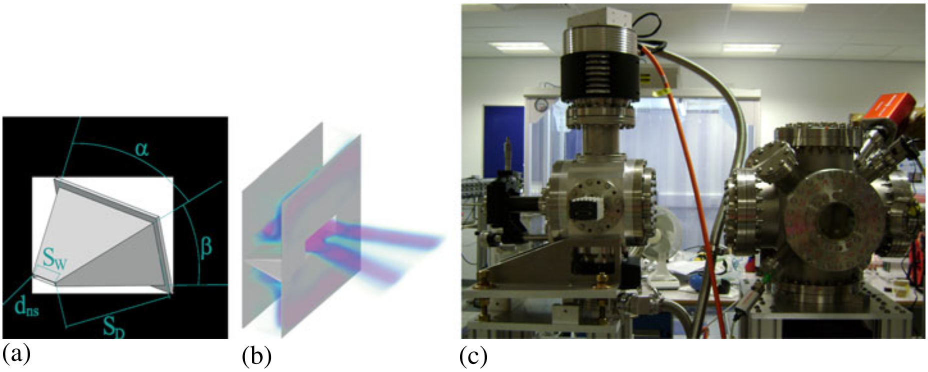
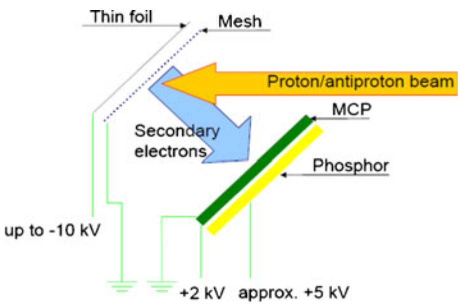


Fig. 2 **a** Geometric Variables of the skimmer; **b** the nozzle/skimmer system; **c** the experimental setup at the Cockcroft Institute

Fig. 3 Diagram of the SEM under study. It is usually made of robust materials, which can guarantee a very good hardness to deterioration induced by the beam



the signal quality by adding white noise and, in case of breakdown, damaging the foil. Furthermore, the secondary emission is very sensitive to the roughness of the plate surface and the nature of the combination target/beam [7], which means that the average number of secondary electrons emitted per event depends on many characteristics of the projectile/surface combination [8].

The detector of choice is a position sensitive MCP assembly, combined with a fluorescent screen and a monochromatic Charge Couple Device (CCD) camera. The Monte Carlo code FLUKA was adopted to evaluate the characteristics of the particle showers resulting from the secondary emission. Based on theoretical evaluations of proton beams, a shower of mainly low energy electrons and a few percent of other charged particles, such as for example backscattered protons, is expected. Figure 4a shows a 2-dimensional slice of a particle shower induced by a 300 KeV proton beam of 2 cm diameter. The color palette indicates the particle track density. It can be seen that the 300 keV protons do not penetrate through the target. At the MCP surface the density of particle tracks is around 100 corresponding to the detection of one particle for every 5000 primary particles. Figure 4b shows the expected electron energy spectrum, with the changes introduced by the electric field. Since FLUKA cannot take into account the applied electric field which affects the electron trajectories and energies, a different code needs to be adopted for future studies.

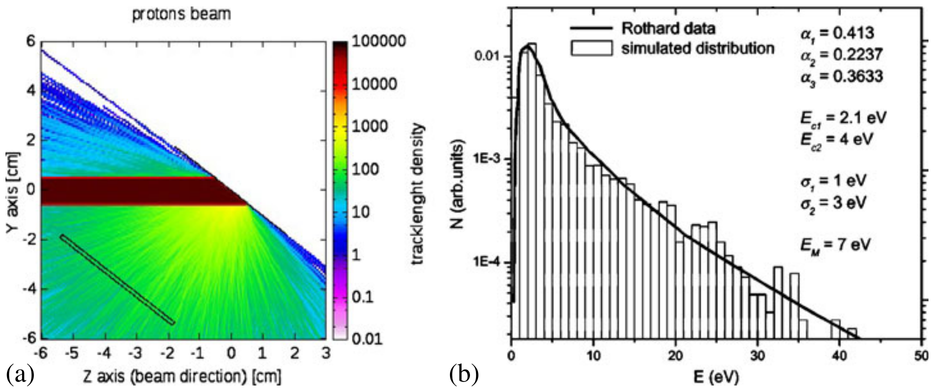
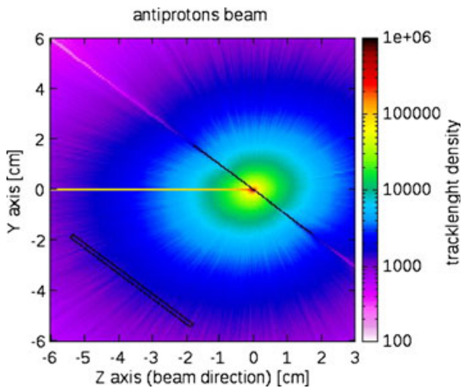


Fig. 4 **a** Particle shower generated by a 300 KeV proton beam. The proton beam is shown by the dark brown horizontal bar; the colors indicate the relative density of ejected particles; the position of the MCP detector is shown by the thin rectangular black box in the lower left side of the figure. **b** Simulation of electrons energy spectrum compared to experimental data [8, 9]

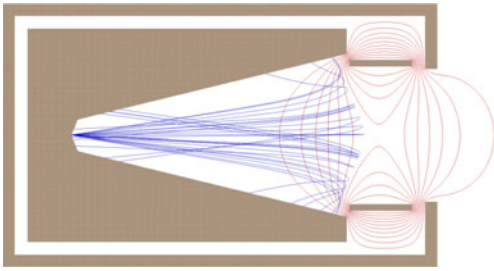
Fig. 5 Particle shower generated by the antiproton beam

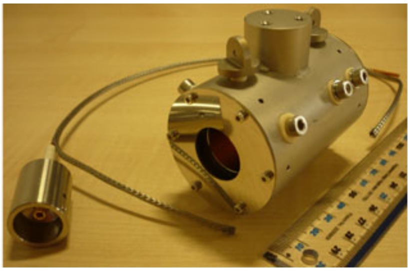


The geometry of the detector has been optimized to allow the MCP to detect the particles which are within 44° of the aperture angle, or 7% of surface coverage, relative to the solid angle centered in the hitting point. Furthermore, the number of electrons which reach the effective detector region accounts for more than 99% of all particles, the rest being photons and backscattered protons.

In the case of an antiproton beam, there are more kinds of particles involved in the event, which are generated by the annihilation phenomenon. The beam used for the antiproton beam simulations is more collimated to achieve a point like source, as this significantly simplifies the simulation with regard to the number of particles reaching the detector surface.

Figure 5 shows a shower induced by the antiprotons on the same system adopted for protons. The large cloud of particles produced is made not only of electrons but many different ionizing particles. As a consequence, the target thickness becomes relevant to the amount of secondary electrons produced and the energy distribution is influenced by the antiproton annihilation process. Further simulation studies,





(a) (b)

Fig. 6 The Faraday Cup beam intensity monitor. **a** A cross section through the centre of the cup showing the equipotential lines (*red*) and the trajectories of the charged particles (*blue lines*). **b** Prototype under test at the Cockcroft Institute

including the influence of the electric field and the foil surface roughness, are underway for an overall SEM optimization for an application with antiproton beams.

3 Beam current monitor

An electrostatic Faraday Cup has been studied and optimized [10] for beam intensity measurements for the USR and its transfer lines. This type of device is a commonly used destructive monitor for absolute beam current measurements, which is reliable and relatively simple.

A conductive beam stopper electrode (usually copper) is introduced in the beam path and the total charge carried by the particles is collected and measured by means of an ammeter (Fig. 6).

In order to evaluate the trapping of the emitted secondary particles and optimize the design, the cup was modeled and studied in terms of electric field distribution and electron collection efficiency using Simion and CST Studio package, for protons and antiprotons. In the case of a proton beam, only a few eV secondary electrons are emitted by the surface of the beam stopper and they are confined by means of the electric field applied at the entrance of the monitor. Since their energy is lower than the main beam energy, this field is not able to deflect the beam particles before reaching the cup. In the case of an antiproton beam, however, the use of the Faraday cup is strongly affected by the annihilation of antiprotons, which generates charged particles and recoil ions with energies hundreds of times higher than the main beam, i.e. in the MeV range. These particles will escape the device and falsify the current measurement. Despite this limitation, the Faraday Cup will be very useful for the USR commissioning stage, when protons and H^- ions will be used.

4 Beam position monitor (BPM)

A diagonal-cut capacitive pick-up (PU) BPM is often used for beam diagnostics in hadron accelerators, providing a highly linear signal together with a large sensitivity. Information on the beam position is obtained by means of non-destructive measurements of induced electric field current produced by passing bunches. In order

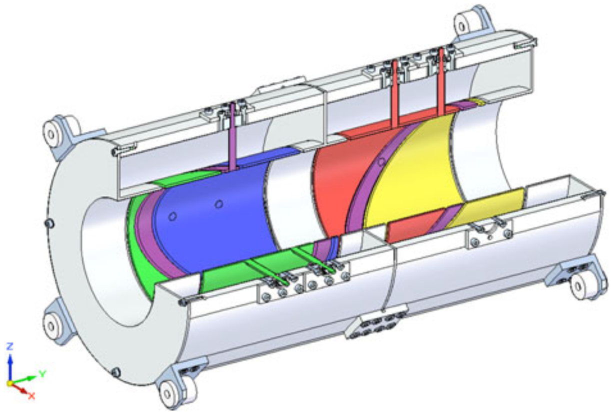


Fig. 7 CAD model of the USR beam position monitor

to evaluate the suitability of this type of device to meet the requirements of the USR, a prototype has been optimized and built [11]. A drawing of the PU is shown in Fig. 7; it consists of four isolated metal pick-up electrodes, shaped to surround the beam. Information on the beam position is obtained by means of a comparison between the signals generated at the electrodes. Linearity is important for beams of non-negligible diameter, and it is improved by a diagonal cut of the plates. To avoid distortion of the electric field in proximity of the monitor edges, the inner diameter of the cylindrical PU is the same as the USR vacuum chamber. To reduce the effect of the transition between the BPM and the vacuum chamber walls, and to reduce coupling capacitance, guard rings were introduced at both ends and in the middle of the PU. Moreover, grounded diagonal electrodes were introduced to reduce cross-talk between opposite signal plates.

To improve PU sensitivity to match the USR resolution requests, the signal has to be amplified while the noise needs to be significantly reduced. Since the latter is proportional to the bandwidth of the system, narrowband signal processing is required for low intensity beam diagnostics. In order to minimise the total noise, commercially available low-noise FET amplifiers SA-220F5 were used. The signal measured by the PU is then digitized further and analysed by dedicated software. The digitisation process inevitably limits the accuracy and introduces granularity. Even with these limitations, it is expected to be able to achieve sub-mm resolution for closed-orbit measurements. The device is currently under test using an experimental technique which emulates the passage of a beam using a current pulse running on a wire stretched along the beam axis.

5 Conclusion

The USR puts stringent requirements on its beam diagnostics system due to the low energy beam, the low current and varying time structure of the beam, from ns pulses to quasi-DC beams. Prototypes of all required diagnostics devices have been developed that satisfy the challenging requests of the USR. These devices were tested in either laboratory measurements or—in most cases—with beam and gave promising results. These monitors will overcome the limitations of present instrumentation and will assure that all important beam parameters can be monitored during both the machine commissioning phase and later operation.

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