

Beam Diagnostics for Low Energy Antiprotons

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Advanced beam diagnostics for antiproton beams at keV beam energies are very important for the successful operation and continuous optimization of low energy storage rings and associated beam lines to the experiments. Manifold challenges arise from the low energy and intensity of the beam, its pulse structure and low repetition rate.

This paper presents a comprehensive set of beam diagnostics that has been developed to characterize low energy antiproton and ion beams (during initial machine commissioning) and subsequent facility operation. It shows results from simulations and experiments using invasive and non-invasive monitors for absolute beam current measurements; capacitive pickups for position detection; scintillating screens, secondary emission monitors and micro channel plate detectors for transverse profile monitoring, as well as an ultra-cold gas jet for minimally-invasive profile measurements and in-ring experiments. The identified limits are discussed for each technique, and options for further improvements are indicated.

KEYWORDS: Antiprotons, AD, ELENA, FLAIR, USR, beam diagnostics, profile, position, intensity, detector, measurement, SQUID, gas jet.

1. Introduction

Specialized beam diagnostics for antiproton and proton/H⁻ (during commissioning) beams at low energies are required for essentially all experiments at the Antiproton Decelerator (AD) [1] and the future Facility for Low energy Antiproton and Ion Research (FLAIR) [2]. They will be particularly important for the future Extra Low ENergy Antiproton (ELENA) ring [3] and the Ultra-low energy Storage Ring (USR) [4] and their keV beam lines to the different experiments to provide those with antiproton beams of the required quality and characteristics. It remains a big challenge for beam instrumentation to measure all key parameters of a very low intensity antiproton beam of less than $4 \cdot 10^7$ antiprotons. The boundary conditions for the USR as one example are summarized in table 1.

Low-energy particles can be easily disturbed and any intercepting solution would result in an emittance increase and, eventually, beam loss. For instance, 300 keV protons traversing an aluminum layer as thin as 500 nm undergo multiple scattering and lose more than 40 keV of their kinetic energy, whereas 20 keV protons are already fully stopped in

the same layer [5]. Furthermore, the limited number of particles in these storage rings is well below the detection limits of standard beam-current transformers used in high energy accelerators [6]. Finally, although antiprotons are main focus of research at the AD and at FLAIR, also protons or H^+ ions will be used for the initial commissioning of the machine. However, stopped antiparticles generate completely different signals than ions with an energy release that is a few orders of magnitude higher than the energy deposited by keV protons [7]. This paper gives a brief overview of beam instrumentation for very low energy antiproton and ion beams.

Table I. Antiproton beam parameters for theUSR as example case for a low energy antiproton ring.

Parameter	Value
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 μ s \rightarrow 21.8 μ s
Number of particles	$<2 \cdot 10^7$ @ 20 keV
Bunch length	1 ns – DC beam
Effective in-ring rates	$10^{10} - 10^{12}$ pps
Average extracted rates	$5 \cdot 10^5 - 10^6$ pps

2. Beam Position Measurement

Capacitive pickups are foreseen for measuring the beam position in both ELENA and the USR bunches. At low energies the induced charge is not a direct image of the beam anymore and becomes dependent on the bunch length, repetition frequency, and transverse displacement. The pickups consist of two pairs of long metal electrodes. Each pair measures the beam position only in one transverse direction and two pairs, rotated by 90° with respect to each other, are required. Cylindrical electrodes with a diagonal cut and additional separating rings to reduce parasitic coupling effects are foreseen [8]. The electrodes and rings are made of nonmagnetic stainless steel, whereas the outer shield is made of aluminum to reduce the overall weight of the monitor. The pickup signal is coupled to a high-input impedance amplifier and passed to a low-pass filter before digitization. In order to test device performance and benchmark results from simulation studies, a wire test stand was established at the Cockcroft Institute.

3. Beam Profile Measurement

Several antiproton detector technologies have been successfully tested at the AD in the past for measuring the beam profile in the ring and its transfer lines to the experiments. Candidate technologies for beam profile monitoring are screen/emulsions, secondary emission monitors and more specialized gas jet-based monitors.

3.1 Scintillating Screens

In terms of simplicity, cheapness, and effectiveness, scintillators are among the best suited instruments for beam profile monitoring. The choice of suitable scintillating materials becomes complicated if those need to be provided for both the antiproton beam and a proton/ H^+ beam during commissioning of the machine. Detection limits of various scintillating materials were investigated with low-energy, low-intensity proton beams and results were reported in detail [9]. It was shown that cesium iodide doped

with thallium (CsI:TI) and a terbiumdoped glass scintillating fiber optic plate (SFOP) are sensitive enough to be applied for proton beam diagnostics at very low energies. Their response to various beam energies and intensities is shown in Fig. 1. It was shown that a resolution of at least 0.3 mm can be achieved across the entire range.

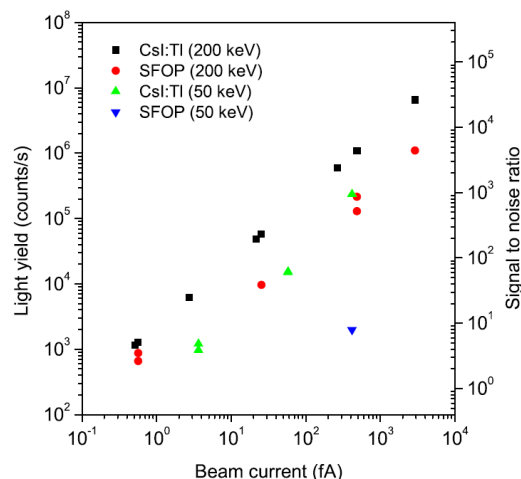


Fig. 1. Calibrated light output and signal-to-noise ratio as a function of beam current for CsI:TI and SFOP, irradiated with 200 and 50 keV proton beams [9].

3.2 Secondary Emission Monitors and Silicon Detectors

Secondary emission monitors (SEMs), as well as stand-alone micro channel plates (MCPs) have also been successfully tested in the past. In 2012 a SEM was the only on-line beam imaging monitor in a dedicated instrumentation test stand at the AEGIS experiment and the only one sensitive enough for initial low-intensity beam steering to commission also other detectors. A SEM is as an important beam imaging monitor for antiproton facilities, providing support to the delivery of beam to the experiments [10]. Two types of silicon pixel detectors with different electrode geometries were tested to study antiproton annihilations in silicon and to characterize their performance as future permanent detectors in the AEGIS experiment. The singular architecture of the MIMOTERA detector makes it a detector with essentially no dead time. This makes it an ideal detector to gather the necessary time of flight information to calculate the gravitational acceleration of antihydrogen in the AEGIS experiment. Due to its small thickness and low granularity, MIMOTERA is suitable for analyses on the deposited energy in the form of energy clusters. Its main disadvantage is a very thin active layer, which limits the detector's capability to measure absolute beam energy, and the fact that its single-channel amplifiers tend to saturate easily [11]. Data taken by a 3D silicon detector also showed a good position resolution and similar overall performance [12].

3.3 Gas Jet Monitor

Supersonic gas jets can be used to measure the beam profile with minimum perturbation of the primary beam and allow the measurement of the 2-dimensional transverse beam profile with a single unit. [13]. An example measurement is shown in Fig. 2.

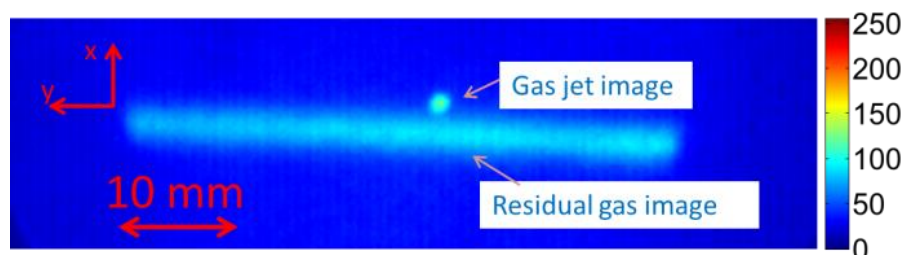


Fig. 2. Measured beam profile from gas jet in direct comparison to image obtained from residual gas at a vacuum pressure at 10^{-7} mbar.

In this type of monitor a supersonic gas jet interacts with the primary particle beam which causes some of the jet particles to be ionized. The generated ions are then accelerated by means of an external electric field and collected by an MCP-phosphor screen stack. The light emitted from the phosphor screen represents the distribution of the ions and hence the distribution of the initial particle beam to be analyzed.

In order to understand the distribution of the gas jet curtain with the smaller skimmer, a moveable gauge module has been recently installed inside the first dumping chamber. A compression gauge concept was used where the gauge is closed inside a small tube, with only a 2 mm slit open to accept the jet. The whole module is attached to a 3D translation stage outside the vacuum chamber. The measured signal is a time integration of the jet entering through the slit, and this signal gets amplified by a pico-ampere meter and then collected by a scope. These studies are ongoing and will help further improve this type of diagnostics [14]. In parallel investigations into a laser-based self-mixing system to probe the jet are also being undertaken [15].

3. Beam Intensity Measurement

Most beam intensity monitors used in particle accelerators have not been designed to measure femtoampere currents and need to be either pushed to their detection limits or replaced by other, more suitable devices. For low energy antimatter facilities, one requires a simple, easy to use solution for measuring the intensity during commissioning and a non-invasive single shot online monitor for absolute current measurement for operation with antiprotons. A sensitive Faraday Cup is a good solution for the former problem, whilst a SQUID-based cryogenic current comparator fulfils all the requirements for the latter.

4.1 Faraday Cup

A Faraday Cup for femtoampere beams was designed, built and commissioned for use at the USR [8]. Its detection limits were determined in measurements with beam at INFN-LNS. Various beam intensities were studied and it was found that DC beam currents as low as a few femtoampere can be measured by such detector.

4.2 Cryogenic Current Comparator

A Cryogenic Current Comparator (CCC) monitor optimized for the AD and ELENA rings at CERN has recently been developed and successfully commissioned, see Fig. 3 [16]. These are the first CCC beam current measurements performed in a synchrotron using both, coasting and short-bunched beams. The CCC is currently the only device able to measure non-perturbatively very low-beam intensities. A particular improvement is the possibility of absolute calibration of the experiments receiving the particle beam using data from the CCC, as well as cross-calibration of other intensity monitors for which no simple calibration method is available. A current intensity resolution of 30 nA was successfully demonstrated after low-pass filtering with a cut-off frequency at 10 Hz. The system was able to cope with a beam current signal slew-rate exceeding 8 kA/s maintaining the SQUID/FLL stability. A new cryostat mechanical design provided for an excellent decoupling of mechanical perturbations, enabling the CCC monitor to attain this performance even when the connected cryocooler unit was operating.

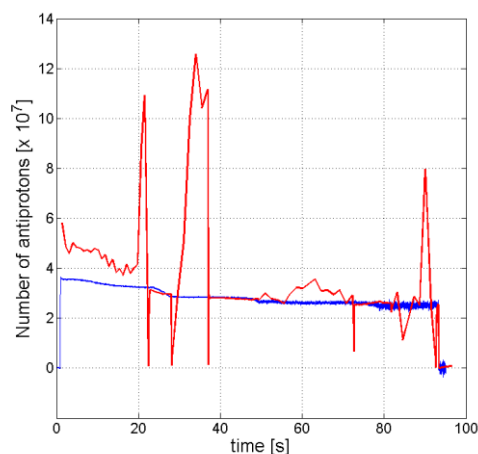


Fig. 3. Comparison between measurement with Schottky noise based monitor (large amplitude range signal) and CCC (second line).

5. Conclusion and Outlook

A full set of diagnostic instrumentation for low-energy, low-intensity charged antiproton and proton beams has been developed and tested with beams of keV energies and femtoampere range currents. Currently further investigations are being done into higher dynamic range current monitors, emittance measurement on the basis of mechanical scraper readings, phase space tomography, improvements of the CCC and gas jet setups, as well as into ultra-thin diamond and cryogenic detectors. These activities will be carried out by within a new European training network on antimatter physics that will be coordinated by the University of Liverpool/ Cockcroft Institute.

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