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A.I. Papash, G. Karamysheva, O. Karamyshev, A. Smirnov,
MPI for Nuclear Physics, Heidelberg, Germany and
Joint Institute for Nuclear Research, Dubna, Russia (on leave)
H. Knudsen, Department of Physics and Astronomy, University of Aarhus, Denmark
M.R.F. Siggel-King, C.P. Welsch, Cockcroft Institute and
the University of Liverpool, UK

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H. Knudsen, Department of Physics and Astronomy, University of Aarhus, Denmark
M.R.F. Siggel-King, C.P. Welsch#, Cockcroft Institute and the University of Liverpool, UK

Abstract

At present, the only place in the world where experiments utilizing low-energy antiprotons can be performed is the AD at CERN. The MUSASHI trap, as part of the ASACUSA collaboration, enables access to antiproton energies of a few hundreds of eV. Whilst the MUSASHI trap enables cutting-edge research, the available beam quality and luminosity is not sufficient for collision experiments on the level of differential cross sections. A small electrostatic ring, and associated electrostatic acceleration section, has been designed and developed by the QUASAR Group. It will serve as a prototype for the future ultra-low energy storage ring (USR), to be integrated at the facility for low-energy antiproton and ion research (FLAIR). This small antiproton recycler ring will be unique due to its combination of size, electrostatic nature and energy of the circulating particles. In this contribution, the design of the ring is described and details about the injection section are given.

INTRODUCTION

Most of the physics experiments involving low-energy antiprotons utilize the Antiproton Decelerator (AD) at CERN [1]. Work is underway on a new Facility for Antiproton and Ion Research (FAIR) [2] at GSI in Germany. Within the FAIR complex, the Facility for Low Energy Antiproton and Ion Research (FLAIR) [3] will include the electrostatic Ultra-low-energy Storage Ring (USR), designed to enable a wide variety of experiments [4]. The QUASAR Group [5] is leading developments towards the USR. The time gap between now and the start of the USR provides the motivation and opportunity for a small recycling ring, which is the topic of this paper.

The ring might be placed after the MUSASHI trap at the CERN-AD and in this application would re-circulate antiprotons of energies between 3 and 30 keV. It would also be used as a prototype for the USR, enabling testing of beam diagnostics for low energy, low current beams and for development and testing of various electrostatic components. This way it would also enable progress to be made in atomic and molecular physics experiments [6] by incorporating a reaction microscope [7] into the ring.

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#Contact@quasar-group.org

Ionization studies in atomic and molecular collision experiments provide data to aid in the understanding of many-body interactions and enable theoretical descriptions to be developed. Studying ionization by antiproton impact has advantages over electron and proton impact because competing processes such as exchange and/or capture of bound electrons do not happen during antiproton impact and, therefore, interpretation of the results is less complicated. Several theoretical studies have predicted cross sectional trends in the low energy region (down to 1 keV). In order to understand the complex ionization interaction, it is necessary to obtain fully differential cross sections for the process. Such measurements are presently not possible with low-energy anti-protons due to limitations on the antiproton facilities that are available. Future facilities, such as the USR, will make such studies feasible. Adding a small recycling ring to the exit of MUSASHI trap at the CERN-AD would enable measurement of (partial) differential cross sections [8,9]. The advantage of incorporating the experiment into the ring is that the antiproton beam can be re-circulated and pass through the target many times, thus increasing the count-rate to enable partial cross section measurements of Helium and other important gasses such as Argon. The partial cross section measurements will be made by utilizing a reaction microscope of high resolution, which will be incorporated into the recycling ring. The recycling ion beam will pass through the supersonic gas jet target and the momentum vectors of the ions and electrons from the ionization events will be measured. The recycling ring has been specifically designed for a projectile beam size and divergence at the centre of the experimental chamber that will enable differential measurements. With the set-up described below, count-rates in excess of a few thousand per cycle are expected even at energies of only 3 keV, which will enable the first low-energy partial differential cross sections to be measured for helium ionization by antiproton impact.

BEAM FROM MUSASHI TRAP

As mentioned in the last section, the antiproton beam that will be injected into the ring could come for example from the MUSASHI trap. In this case, the antiprotons are first captured into the trap, then cooled, compressed by a rotating radial electric field, then extracted in ‘fast extraction mode’ as a pulse of antiprotons of 150-250 eV kinetic energy and 1-2 μs bunch length [10]. Typically around 500,000 antiprotons can be extracted from the trap after accumulation of 5 AD shots.

The recycling ring will be coupled to the trap using an injector comprised of acceleration, diagnostic and matching sections, see Fig. 1.

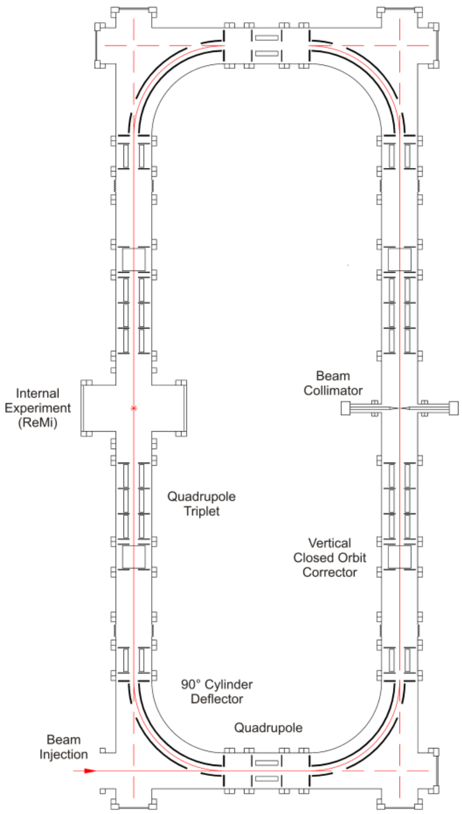

Figure 1: Scale layout drawing of the recycling ring.

The acceleration section is designed to increase the energy of the antiprotons from the trap to the desired energy of ions in the ring as well as to partly counteract beam blow up in the radial direction while the ions are passing the fringe field of the 2.5 T solenoid magnet.

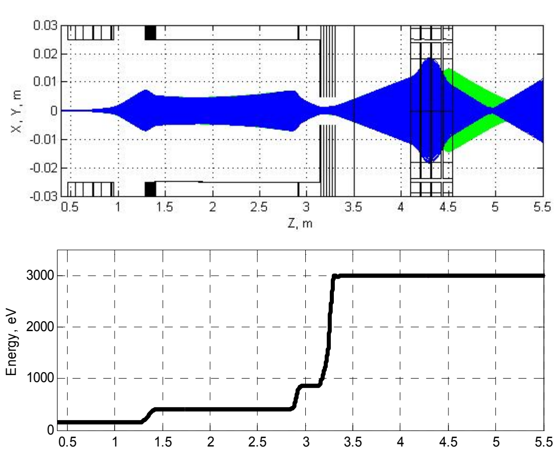

Figure 2: Injector. Top: Ion trajectories (blue–x, green–y) from inside the trap solenoid through the acceleration, diagnostic and matching sections; Bottom: The beam energy is increased stepwise in the acceleration section and at the end of the pulsed pipe.

In the matching section four electrostatic quadrupoles adjust the beam to the ring acceptance. The beam envelope and the distribution of the beam energy in the injector are shown in Fig. 2 (top) and (bottom) respectively. When the beam pulse is inside of the 1.5 m long drift tube the voltage applied to the central section of the pipe is switched to the required negative value, between -3 and -30kV. The acceleration is then realized using a series of apertures to which increasing positive voltages are applied. The choice of a pulsed electrostatic acceleration section avoids the necessity of floating the entire ring to high voltages.

RING LAYOUT

Many considerations have gone into the ring design, including the need to meet the requirements for a USR prototype, and the needs of crossed beam studies including a small beam diameter at target location. Also the overall dimensions of the setup should be kept as small as possible. The ring lattice includes four 90º deflectors of cylindrical shape which will also be used for horizontal orbit correction, electrostatic quadrupoles for beam modulation, as well as vertical correctors to align the beam along the ring axis. The mean radius of the 90º deflectors is 400 mm and the gap between the electrodes is 40 mm. The ring has a periodicity of 2. Its beta and dispersion functions for one cell are shown in Fig. 3. Two low-β inserts are located in the straight sections to reduce the beta-functions in the interaction region to $\beta_{x,y}$<10 cm.

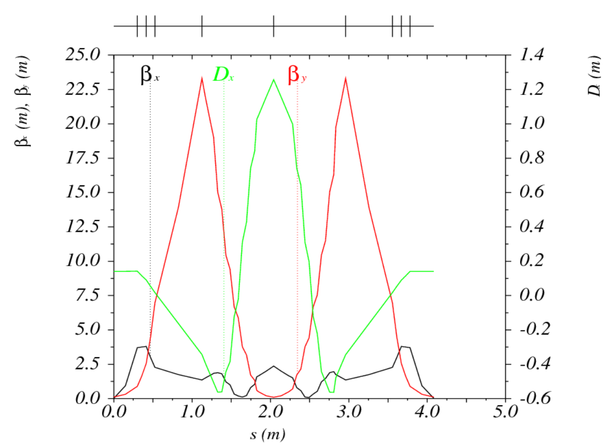

Figure 3: MAD-X simulation. Half ring is shown. At the interaction region (s=0) β_x=2 cm and β_y=11 cm.

Each focusing unit is comprised of two sets of electrostatic quadrupole triplets. These are located as close as possible to each other to provide a sharp focus in the middle of the straight section where the reaction microscope will be installed. The two quadrupoles between the 90° deflectors reduce the dispersion function significantly.

Table. 1: Summary of ring parameters

Parameter	Value
Energy range, keV	3 to 30
β (v/c)	$2.5\cdot10^{-3}$ to $7.8\cdot10^{-3}$
Circumference, m	8.165
Length of straight section, mm	1300
/ available for experiment, mm	466
Ring acceptance, π mm·mrad	15 π
Initial RMS emittance, πmm·mrad (σ)	2π
Ion rotation period, μs	3.06 to 9.55
Beta function at target (hor/ver), m	0.02 / 0.11
Dispersion at target location, m	$D_x = 0 \div 0.13$
Betatron tunes	$\nu_{x,y} = 3.315/1.76$
Chromaticity	$\xi_{x,y} = -6 / -10$
Vacuum, mbar	10^{-10}
Number of injected antiprotons	$\sim 5 \times 10^5$
Ring cycle	one bunch/500 s
Initial momentum spread ($\Delta P/P$)	$\sim 10^{-3}$
Helium target jet density, cm^{-3}	5×10^{11}
Jet diameter, mm	1
Beta function at target (hor/ver), m	0.02 / 0.11

Table 1 gives a summary of the ring, beam and target parameters. The long term beam dynamics in the ring was studied with the BETACOOL code [11]. First, the interaction between the stored antiproton beam and a Helium gas jet target was analyzed. For this purpose, multiple scattering of the ions on the target nuclei and the rest gas, intra-beam scattering of the ions, as well as beam energy loss and energy straggling due to excitation and ionization of the electrons of the Helium atoms were considered. The beam is lost on the ring aperture because of the rather low ring acceptance. Beam losses and ionization events at the target location are shown in Fig. 4 for the case of $D_x = D_x' = 0$. To estimate the number of events, experimental values of ionization cross-sections from [10] were used.

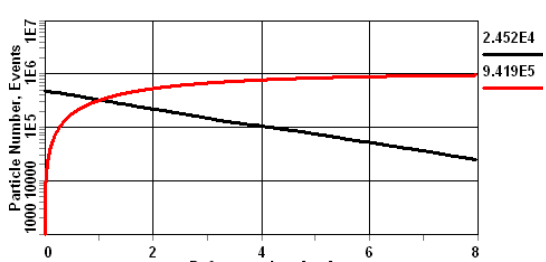

Figure 4: Beam intensity losses and integral of ionization events at E=30 keV (life time ~4s).

At 30 keV the ions may excite and ionize several atoms without being lost and the integral of ionization events might thus exceed the total number of circulating ions by a few times, see Fig. 4. In case of interaction between the antiprotons and the Helium atoms of the gas jet and an assumed density of $5\cdot10^{11}$ atoms/cm^3, our model leads to a beam life time at 30 keV of ~4 sec. The resulting energy loss will lead to a displacement of the beam core from the target, due to dispersion, but the tails will still cross the target region. At 3 keV most of the ions will be lost due to multiple scattering on the target nuclei before they can cause ionization events. In this case, we estimate that between 2,000 and 4,000 ionization events can occur during the beam life time of 100 ms. By using orbit correction the beam can be kept on the target, see Fig. 5 (left). Note that the rms momentum spread is increased from 10^{-3} to $6\cdot10^{-3}$ in 4 seconds, Fig. 5 (right).

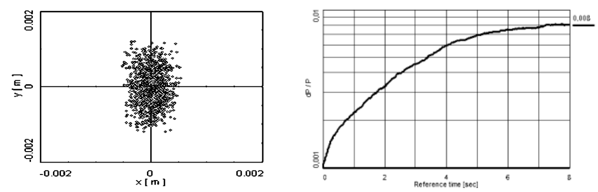

Figure 5: Antiproton beam interaction with the Helium target. E=30 keV. Left: Beam spot at target location; Right: evolution of rms momentum spread of 30 keV antiprotons.

CONCLUSION

A small recycling ring for low energy antiproton beams has been developed. The ring has been designed to be a prototype for the USR and to enable differential ionization cross section measurements by incorporating the experiment into the ring. The ring will be used to bridge the time gap before a new low-energy antiproton facility is operational and may also be used for atomic physic studies.

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