INVESTIGATIONS INTO THE BEAM LIFE TIME IN LOW ENERGY STORAGE RINGS

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Abstract

In low energy storage rings, beam life time critically depends on the residual gas pressure, scattering effects caused by in-ring experiments and the available machine acceptance. A comprehensive simulation study into these effects has been realized with a focus on the long term beam dynamics in a small antiproton recycler ring with an internal target, the cooling process of a beam of CF^+ ions at 93 keV/u in the TSR storage ring at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany as well as intra-beam scattering and target effects in the ultra-low energy storage ring (USR) at the future Facility for Low energy Antiproton and Ion Research (FLAIR). This was done by using the computer code BETACOOL in combination with the OPERA-3D and MAD-X programs. In this contribution, the results from these studies are presented and compared to available experimental data. Based on these simulations, criteria for stable ring operation are then presented.

INTRODUCTION

Electrostatic storage rings are typically operated at energies of a few tens of keV and have proven to open up many new research avenues for atomic and molecular physics [1]. In combination with the latest generation of in-ring spectrometers, so-called reaction microscopes, they are the ideal tool to study high precision effects by multiple crossing of the stored particle beam and various gas jet targets [2].

The beam parameters in some of the existing electrostatic storage rings, namely ELISA in Arhus, Denmark and at KEK and Tokyo University, Japan were measured in the past with high precision. [3-5]. Interestingly, strong limitations on beam intensity were found and a reduced beam life time was observed at higher currents [6]. The attempts to explain the nature of these effects were made, but no comprehensive model had yet been presented [7]. Therefore, additional studies were initiated to improve the knowledge of the nature of these beam losses and the physics processes that dominate at such low beam energies.

BENCHMARKING OF EXPERIMENTS

Initially, the beam behaviour in the ELISA ring was studied based on the inclusion of non-linear field terms in the electric field distribution around the electrostatic ion optical elements [8]. A computer model of the whole ring was created and ions were tracked individually through the relaxation electric field maps of the bending and focusing elements. In this study it was found that strong sextupole field components reduce the ring acceptance to less than 30π mm·mrad.

In order to identify the driving forces responsible for pushing the ions out of the acceptance of the storage ring, transition processes and equilibrium conditions were studied based by applying stochastic (kinetic) differential equations to the periodic motion under the assumption that diffusion processes, i.e. beam heating, as well as friction processes, i.e. beam cooling, leading to a growth or reduction of the beam phase space are small compared to the electro-magnetic forces from external bending and focusing elements. This study replies on the use of the well established BETACOOL code [9] with a main focus on the long term beam dynamics, i.e. the description of processes that are long compared to the ion revolution period in the ring. It is furthermore assumed that the betatron motion in the storage ring is stable. In a next step, the emittance growth rates and the evolution of the momentum spread were determined by simulating the rms parameters of the evolution of the ion distribution function with time [10]. In this simulation, the effects from non-linear fields in the ion optics were taken into account by adjustment of the ring acceptance.

In order to benchmark the results from simulations earlier measurements at ELISA with coasting O^- and Mg^+ ions were chosen [11], limiting the study initially to heating processes 'only' and assuming a ring acceptance of A≈10π mm·mrad. With these parameters, the measured rates of beam intensity decay for a 22 keV beam of O^- ions have been reproduced with good accuracy [12]. This allowed to conclude that the main reasons for beam size growth in the keV energy regime are multiple scattering of the ions on the atoms and molecules of the residual gas, as well as Intra-Beam Scattering (IBS) at higher intensities. As a consequence of such fast beam growth, the ions are then lost quickly on the ring aperture since the acceptance is rather small. It should be pointed out that the rate of beam losses increases at higher intensities since IBS then adds to the vacuum losses. The fast momentum spread growth of a high intensity Mg^+ beam can be explained by this higher IBS rate [12].

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OPERATION WITH INTERNAL TARGET

The kinetics of an ultra-low energy antiproton beam, circulating in a small electrostatic recycler storage ring was studied next with a focus on understanding the interaction between the stored beam and an internal supersonic gas jet target, see Fig. 1 [13]. The energy range of the ion circulating in this ring is between 3 and 30 keV. Low-β inserts are included in the middle of each long straight sections of the racetrack ring lattice to provide a sharp beam focus in the centre of the reaction chamber [14]. In addition to multiple scattering of the circulating antiprotons on the nuclei of the residual gas atoms, IBS and beam losses on the ring aperture, small angle multiple scattering of the stored ions on the nuclei of the helium gas jet target had to included. Also, effects from mean energy losses and fluctuations in energy loss due to excitation and ionization gas jet Helium atoms had to be included [15].

The ring performance at different initial conditions was compared and both low ($5{\cdot}10^5$) and high (10^7) currents, and different beam energies, 3keV and 30 keV, were considered. In the centre of the straight section of the ring a low β value of β_{tgt}=10 cm is realized. In combination with a rather small ring acceptance of $A_y=15\pi$ mm·mrad the 2σ beam spot size at the target location might then be reduced to only 2 mm in diameter, see Fig. 2.

The decay of a high intensity 3 keV beam is shown together with the integral number of ionization events in Fig. 3. The blue curve (1) represents the beam decay when the target is switched off. In this case the life time is around $\tau_{1/2}$ ~1.5 s. In presence of the target the life time reduces to $\tau_{1/2}$ ~0.15 s due to multiple scattering of the stored ions on the atoms of the internal gas jet, see black curve (3). In total, more than $2.5{\cdot}10^4$ ionization events can be detected during the first 200 ms of beam storage, see red curve (2). In other words, more than 99.7% of all stored ions will be lost on the ring aperture corresponding to an average count rate of 1.2 ionization events per revolution, assuming that every ionization event leads to the loss of the respective antiproton. The life time of a 30 keV antiproton beam was found to be about $\tau_{1/2}$=15 s without the target and $\tau_{1/2}$=1.8 s with the target.

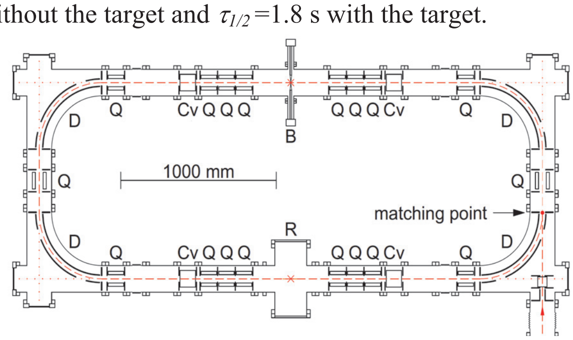

Figure 1: Cross-sectional drawing of the recycler ring; horizontal cut including the mean path of the ion beam (dashed red line). Four 90° bending ES deflectors (D), four ESQ triplets (QQQ) and six ES single quads (Q) form ring lattice. Beam crosses gas jet in the reaction chamber (R).

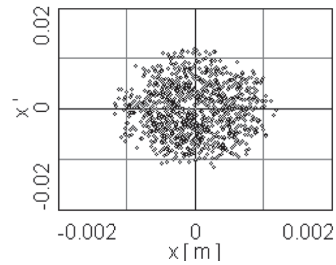

Figure 2: Antiproton beam interaction with a Helium target of density $n_{tgt}=5{\cdot}10^{11}$ cm^{-3}. The phase space area occupied by the beam corresponds to the ring acceptance, $A_x=15\ \pi$ mm·mrad.

In this case up to $3.6{\cdot}10^6$ ionization events might be detected during the first two seconds with an average count rate of ~5 events per revolution.

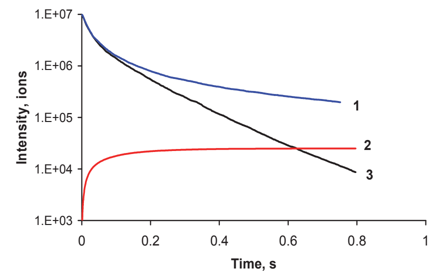

Figure 3: Beam decay of 3 keV H^- ions. The blue curve corresponds to the beam intensity when the target is switched off (1), whilst the black curve shows the intensity with the target on (3). The integral number of ionization events is presented by the red curve (2). The initial intensity is $N_o=10^7$ ions, the density of the Helium gas jet target is $5{\cdot}10^{11}$ cm^{-3}.

BEAM SHRINKING

Cold electron beams at an energy range of 150 eV down to 10 eV and possibly even less are a key element of the next generation of electrostatic storage rings where electron cooling of keV ion beams needs to be achieved.

Experiments with electron cooling of CF+ ions (A=31) at the Test Storage Ring (TSR) have been reported in [16], in which a low-intensity beam of 93 keV/A CF^+ ions has been shrunk to an ultra-small size using a cold beam of 53 eV electrons produced by a cryogenically cooled GaAs photophoto-cathode.

The transverse and longitudinal temperatures of the photo-electrons in the electron target were estimated as $kT_\perp$=0.5 meV and $kT_{||}$=0.03meV, respectively. A cooling time of less than τ_{cool}< 2 s and an equilibrium beam size of around $0.2^x0.04$ mm^2 (r.m.s.) have been measured.

All parameters of the TSR ring lattice and the electron target have been used as input data for BETACOOL and results from earlier measurements were reproduced with good accuracy. Electron cooling was added to the heating processes and a life time of 4 s caused by recombination of the CF^+ ions was taken into account [17]. After a few seconds of beam cooling the emittance of the low intensity beam collapsed shrunk 1,000 times from an initial value of 1π mm·mrad to an equilibrium at no more than $10^{-3}\pi$ mm·mrad (r.m.s.), see Fig. 4.

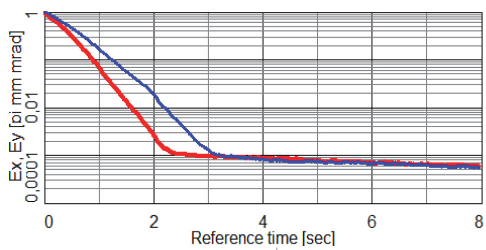

Figure 4: Kinetics of 93 keV/A CF^{+} ions in the TSR ring; beam cooling by a factor of 1,000, reaching equilibrium after 2-3 seconds.

COMPENSATION OF IBS AND INTERNAL TARGET EFFECTS

The transition processes and equilibrium conditions of stored ions under the combined action of electron cooling and IBS, multiple scattering of the stored ions on the residual gas and an internal gas jet target have been studied on example of the ultra-low energy storage ring (USR) [12]. The ring can be operated in a 4-fold symmetry mode, but for experiments with an internal target where the beam must be focused to a 1 mm² spot, a special two-fold symmetry *low-β* mode, combined with achromatic conditions in the straight sections, needs to be applied, see [18] for full details.

The reachable cooling rates and equilibrium conditions in the USR have been compared for the cases of using a thermo cathode and a cryogenic photo cathode electron gun. The evolution of the r.m.s. emittance for a beam with $N_0=2\cdot10^7$ ions is shown in Fig. 5. (1) corrsponds to a 20 keV antiproton beam, cooled down by a thermo cathode gun, whereas (2) represents the photo cathode gun. (3) and (4) correspond to the same cathodes, but a beam energy of 300 keV. Such a high intensity beam at 20 keV might be focused to a 1 mm² beam spot, but only at the cost of significantly increased IBS rates. In this case the equilibrium between friction and heating processes is reached at much higher beam emittance, blue curve in Fig. 6, as compared to equilibrium emittance for the standard 4-fold symmetry mode, red curve. The increase in IBS growth rate during *low β* operation is the main reason for a shift in the equilibrium parameters.

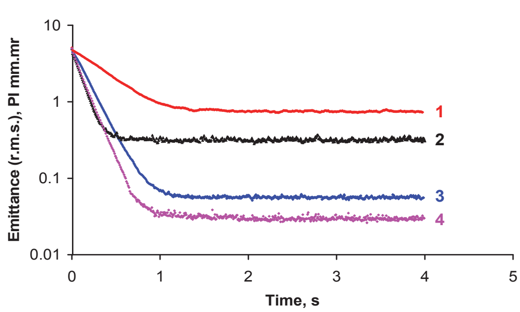

Figure 5: Evolution of beam emittance for a high intensity antiproton beam in the case of the 4-fold symmetry lattice. Plot (1) and (3) illustrate the beam at 20 and 300 keV, cooled down by thermo cathode electron gun, whereas (2) and (4) show 20 and 300 keV ions cooled down by a photo-cathode.

Almost 10^7 ionization events with an average count rate of 20 events per revolution might be accumulated in the first 8 s of interaction between the stored antiproton beam and the internal Helium gas jet target, if $n_{tgt}= 5\cdot10^{11}$ cm^{-3}. The beam life time in this case is τ_{life}=12 s.

In case no internal experiments are carried out, the best operation conditions and highest beam intensity in the USR can be achieved if the ring is set to an operating mode with a flat ring lattice as this will reduce the IBS rate significantly.

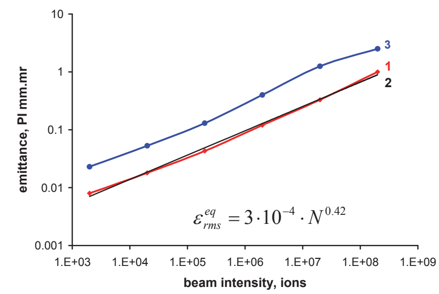

Figure 6: Dependence of the equilibrium beam emittance on the injected beam current: (1) ring is tuned to a 4-fold symmetry mode; (2) Line fit by a power series $\varepsilon_{rms}^{eq} = 3\cdot10^{-4}\cdot N^{0.42}$ and (3) *low β* mode operation with internal target.

SUMMARY

Based on ion kinetics and long term beam dynamics studies a consistent explanation of some of the effects observed so far in electrostatic storage rings was provided. It was shown that multiple scattering of the stored ions on the atoms and molecules of the residual gas, together with IBS at higher beam intensities lead to a fast growth in beam emittance. In combination with a significant reduction of the ring acceptance because of non linear fields in electrostatic ion optical elements, experimental data was reproduced in simulations.

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