ION KINETICS IN THE ULTRA-LOW ENERGY ELECTROSTATIC STORAGE RING (USR)

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Abstract

The Ultra-low energy Storage Ring (USR) at the Facility for Low-energy Antiproton and Ion Research (FLAIR) will provide cooled beams of antiprotons in the energy range between 300 keV down to 20 keV and possibly less. A large variety of the envisaged experiments including in-ring collision experiments with a reaction microscope require a comprehensive study of the long term beam dynamics processes in the ring.

Detailed investigations into the ion kinetics under consideration of the effects from electron cooling and multiple scattering of the beam on a supersonic gas jet target have been carried out using the BETACOOL code.

The life time, equilibrium momentum spread and equilibrium lateral spread during collisions with this internal gas jet target were estimated. The results from simulations were benchmarked against experimental data of beam losses in the ELISA storage ring. In addition, the results from experiments at the TSR ring where a 93 keV/u beam CF^+ ions has been shrunk to extremely small dimensions have been reproduced.

Based on these simulations, conditions for stable ring operation with extremely low emittance beam are presented. Finally, results from studies into the interaction of ions with a gas jet target at very low energies are summarized.

INTRODUCTION

The next-generation antiproton facility at GSI, the Facility for Antiproton and Ion Research (FAIR), will not only provide future users with antiprotons in the high energy range, but it is also intended to include a dedicated research program for ultra-low energy antiproton research, realized with the FLAIR project [1]. Low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the femto- and sub-femtosecond time regime [2]. Within the FLAIR Facility the Ultra-low energy Storage Ring (USR) operates in the variable energy range from 300 keV down to 20 keV and possibly to even lower energies [3,4]. The USR will enable, for the first time, access to kinematically complete antiproton-induced rearrangement and fragmentation measurements. The USR, presently being developed in the QUASAR group [5], is comprised of electrostatic ion optics elements and studies into the long term beam dynamics and ion kinetics are of crucial importance for the performance of the envisaged experiments.

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BENCHMARKING OF EXPERIMENT

For benchmarking purposes, the ELISA electrostatic ring, successfully in operation since the late 90s and dedicated to atomic physics studies [6], has been chosen. In the original ring design spherical deflectors had been used to provide equal focusing in both the horizontal and vertical plane but were later on substituted by cylinder deflectors [7]. Systematic experimental studies showed strong limitations on the maximum storable beam current and reduced beam life time at higher beam intensities. The nature of these effects was not fully understood [8].

We studied transition processes, i.e. growth rates of beam emittance and momentum spread, as well as equilibrium conditions in ELISA by simulating the rms parameters of the evolution of the ion distribution function with time. For this purpose the BETACOOL code was applied [9,10]. In this study, the beam parameters summarized in table 1 were used. BETACOOL allows choosing and switching between different effects and in this particular investigation only heating processes were used: Intra-Beam Scattering (IBS), small angle multiple scattering of the circulating ions on the residual gas atoms, energy straggling and ion losses on the ring acceptance. It was found that beam losses caused by single large angle scattering are negligible at a vacuum level $2 \cdot 10^{-11}$ Torr, even at such a low beam energy. The limited life time of O^- ions due to the electron detachment by collision with the residual gas

Table 1: BETACOOL beam parameters of ELISA.

Ion	O^{16}	Mg^{24}
Charge	–1	+1
Ion energy, keV	22	18.4
Initial beam intensities	$5 \cdot 10^5 \div 1.6 \cdot 10^7$	$2.7 \cdot 10^7$
Ring circumference, m	7.616	7.616
Initial hor/vert ε, π mm mrad (σ)	1 / 1	0.7/0.35
Initial full ε, π mm mrad (3σ)	6 / 6	4 /2
Ring acceptance ESD-cyl, π mm mrad	10	10
Ring acceptance ESD-sph, π mm mrad	6	6
Initial RMS momentum spread, $\Delta p/p$	10^{-3}	10^{-4}
Equilibrium momentum spread, $\Delta p/p$	$4 \cdot 10^{-3}$	
Electron detachment life time of O^-, sec	26	--
Life time of O^- at 22 keV, sec	~ 12	

as measured by S.P. Møller [8] has been included in the program as an input parameter.

The measured rates of beam intensity decay of a 22 keV O^- beam were reproduced with good accuracy, see Fig. 1. This gave rise to the conclusion that the main reasons for beam size growth in a keV storage rings are multiple scattering on the residual gas and Coulomb repulsion of the ions from each other at high intensities, i.e. IBS. As a consequence, the beam is then lost on the ring aperture because of a rather small ring acceptance. The rate of beam losses increases at higher intensities because IBS adds to vacuum losses.

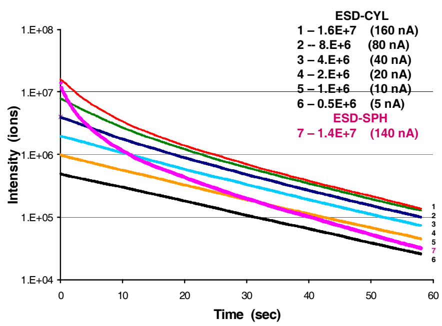


Figure 1: Simulation of beam current decay in ELISA. The intensity of the 22 keV O^- beam was varied over a wide range, reflecting earlier measurements.

The IBS effect is clearly seen in Fig. 1 as an excessive drop of beam current during the first few seconds when the beam intensity is still high. The long term slope of this loss curve is determined by the ring acceptance and the rate of multiple scattering which is inversely proportional to the vacuum level in the ring. The slope of the decay curve also depends on the life time due to electron detachment for negative ions or electron stripping for positive ions.

An exception is seen in the pink curve, representing the decay of the beam intensity in ELISA with spherical deflectors. In this case, significantly higher loss rates are caused by the significantly reduced ring acceptance. IBS is also much stronger when the beam density is high and thus in particular in regions where the beam is strongly focused. The IBS rates for ELISA with spherical deflectors are significantly higher than with cylindrical electrodes because of the double focusing effect of the first and the resulting small beam size in both planes.

The measured equilibrium profile of an 18.6 keV Mg^+ beam (FWHM=3.43 mm) was compared to BETACOOL simulations made under the assumption that the transverse beam size is mainly defined by losses on the optical elements of the ring structure, see Fig. 2. The resulting rms width is equal σ=1.5 mm and corresponds to a ring acceptance of A≈8π mm·mrad.

The ring acceptance was then varied as an input parameter in BETACOOL. Assuming a ring acceptance of ~50 π mm·mrad, an rms beam size of σ=3 mm would result, i.e. twice as large as what was measured in the experiment. Also, if the acceptance would be that large the life time of the O^- beam in ring should be 24 s which contradicts a measured life time of τ~12 s. The fast decay in ELISA with spherical deflectors can be explained by a small acceptance of nonlinear nature [11].

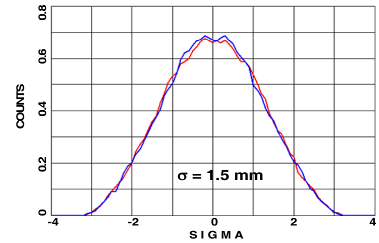


Figure 2: Profile of the Mg^+ beam corresponds to the ELISA ring acceptance of A≈8π mm·mrad.

USR OPERATION WITH TARGET

The BETACOOL code was used to optimize parameters of the USR electron cooling system during operation with internal gas jet target. The beam parameters summarized in table 2 were used. During deceleration and cooling modes of the USR operation the four fold symmetry ring lattice provides smooth beta-functions in all four achromatic straight sections. At this regime the electron cooling cannot suppress beam heating caused by multiple scattering of low energy antiprotons with high density helium gas jet target. As a consequence the beam life time will be very low. One can operate with low density target at four fold symmetry standard mode but in expense of reduced luminosity of the experiment.

At high target density (n_{tgt}~5×10^{11} cm^{-3}) the two fold asymmetric lattice with low beta functions at target location will be more suitable. Request to reduce the

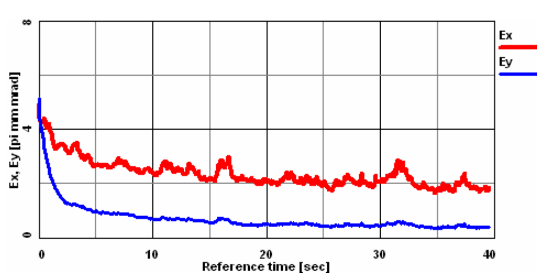
Table 2. Beam parameters for USR with internal target

Ring circumference, m	42.598
Antiproton energy, keV	20
Vacuum pressure (hydrogen), Torr	10^{-11}
Number of achromatic straight sections	4
Length of achromatic straight sections, m	4
Particle number	2×10^7
Initial emittance, π mm·mrad	5
Acceptance, π mm·mrad	40
Initial momentum spread	10^{-3}
Helium target density, cm^{-3}	5×10^{11}
Target length, cm	0.1
Beta function at target (hor/ver), m	0.7 / 0.06
Dispersion at target point, m	0
Cross section of He ionization, barn	5×10^7
Length of electron cooler, m	2
Magnetic field at cooler, G	100
Beta functions at cooler (hor/ver), m	7.3 / 15.6
Dispersion at cooler, m	0
Electron beam radius, cm	2
Electron beam current, mA	0.1
Electron temperature (tran/long), eV	4 / 0.5
Electron energy shift (dp/p units)	-2×10^{-3}

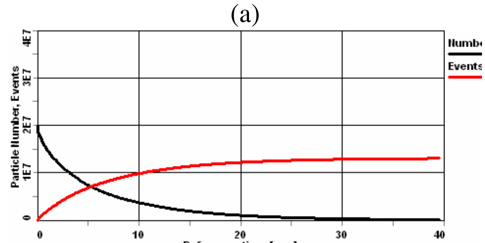
beam size at target to ~1 mm will cause the growth of the maximum value of beta-functions in other locations of the ring up to 80 m. So, the USR acceptance will be limited during low beta mode of operation. Another side effect of low beta lattice is an increase of the intra-beam scattering heating rate up to the level comparable to the heating rate from the target itself.

We've found equilibrium conditions when e-cooling suppresses beam heating caused by multiple scattering of ions at high density internal target as well as scattering due to IBS (Fig.3). The beam emittance is reduced in equilibrium to ~2 π mm·mrad (Fig.3a). Maximum relative transferable energy during impact between incident antiprotons and electrons of helium atom will not exceed $2\cdot 10^{-3}$ of ion kinetic energy. Thus the maximum energy lost in one ionization event should not exceed the longitudinal acceptance of the USR ring. Also we do not have valuable experimental data of the ratio between ionization and excitation events of He atoms by incident antiproton beam. Due to the lack of the experimental data at ultra-low energy range we assume that each ionization event should lead to the loss of the incident ion i.e. particle number is reduced during USR operation with internal target. We have used experimental cross-sections of He atoms ionization by low energy antiprotons in order to estimate integral of ionization events [12]. Under this assumption the integral of the ionization events (red curve in fig.3b) can not exceed number of beam ions (black curve in fig. 3b). The luminosity will be decreased in proportion with reduced particle number.

The beam transverse distribution in equilibrium is Gaussian. The longitudinal momentum spread (Fig.4.a) is Non-symmetric due to the large influence of the space charge of the electron beam (Fig.4.b). The space charge effect is the main limit of the electron current for coolers in low energy storage rings.

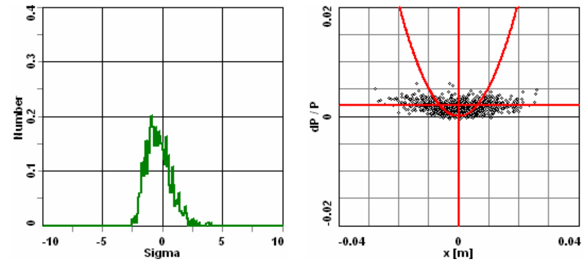


(a)



(b)

Figure 3. The beam evolution during USR operation with internal target: a) horizontal (red) and vertical (blue) emittances; b) decay of particle number (black) and integral of ionization events (red).



(a) (b)

Figure 4. Beam distribution after 40 sec of cooling process. a) longitudinal profile, b) particle distribution at cooler section and space charge parabola of the electron beam.

SUMMARY

It was shown how the beam behaviour in keV electrostatic storage rings can be described, what processes lead to beam degradation and how the electron cooling will counteract the beam scattering on target. Experimental data from ELISA served as a benchmark and was reproduced with very good agreement in BETACOOL. The results from these studies were used to estimate the event rates of envisaged future collision studies between low energy antiprotons and gas targets in an Ultra-low energy Storage Ring.

REFERENCES

[1] C.P. Welsch, et al., "FLAIR – A Facility for Low-Energy Antiproton and Ion Research at GSI", Hyperfine Interactions, **172** (1-3) 71-80 (2007)

[2] C.P. Welsch, et al., "Exploring Sub-Femtosecond Correlated Dynamics with an Ultra-low Energy Electrostatic Storage Ring", AIP Conf. Proc. **796** (2005) p. 266-271

[3] C.P. Welsch, et al., "An ultra-low-energy storage ring at FLAIR", NIM A **546** (2005) 405–417

[4] A. Papash, C.P. Welsch, "An Update of the USR Lattice: Towards a true multi-user experimental facility", Proc. Part. Acc. Conf., Vancouver (2009)

[5] http://www.quasar-group.org

[6] S.P. Møller, Design and First Operation of the Electrostatic Storage ring ELISA. Proc. EPAC (1998)

[7] S.P. Møller, "Operational experience with the electrostatic storage ring ELISA". Proc. PAC (1999)

[8] S.P. Møller et al., Intensity Limitations of the Storage Ring ELISA. Proc. EPAC (2000)

[9] A. Sidorin. BETACOOL program for simulation of beam dynamics in storage rings. Nucl. Instr. Meth. A **558** (2006)

[10] BETACOOL guide. http://betacool.jinr.ru

[11] A.I. Papash, C.P. Welsch, Simulations of space charge effects in low energy electrostatic storage rings. Proc. IPAC (2010)

[12] H. Knudsen, *private communication* (2009)