INTERNAL TARGET EFFECTS IN THE ESR STORAGE RING WITH COOLING

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Abstract

The accurate description of beam-target effects is important for the prediction of operation conditions in terms of high luminosity and beam quality in the FAIR facility at GSI. Numerical models have been developed to evaluate beam dynamics in ion storage rings, where strong cooling in combination with a dense target is applied. First systematic benchmarking experiments were carried out at the existing ESR storage ring at GSI. The influence of the internal target on the beam parameters is demonstrated. Comparison of experimental results with simple models describing the energy loss of the beam particles in the target as well as with more sophisticated simulations with the BETACOOL code will be given.

INTRODUCTION

Nuclear physics and fundamental interaction studies in collisions of rare isotope or antiproton beams with dense targets, have a central role in the NESR and HESR storage rings of the future FAIR facility [1]. For instance, luminosities of up to 2×10^{32} $cm^{-2}s^{-1}$ are expected in experiments with a hydrogen pellet target in the HESR. In this context, it is essential not only to understand but also to predict the influence of a dense target on the stored beam and investigate the interplay between phase space cooling, intrabeam scattering (IBS) and target effects. Some experiments with gas targets in light ion storage rings have been reported before [2,3]. Here, we present the first systematic investigation of internal target effects in a storage ring for highly charged ions. The experiments were performed at GSI in the Experimental Storage Ring (ESR) [4], which is equipped with an electron cooler [5] and an internal gas-jet target [6].

EXPERIMENTAL PROCEDURE

The experiments were carried out with a stored coasting beam of bare lead ions (Pb^{82+}) with an intensity of about 10^8 particles and a kinetic energy of 400 MeV/u. The electron cooler was used (i) to reduce the phase space density of the injected beam and provide a high quality, dense stored beam for in-ring experiments and (ii) to compensate heating by the target. Four target gases (N_2, Ar, Kr, Xe) were used in the gas-jet, with densities in the range $2.5-8\times10^{12}$ atoms/cm^2 (gas-jet diameter ≈ 5 mm).

The momentum spread was determined by Schottky noise analysis from the frequency spread Δf/f according to $\Delta p/p = \eta^{-1}\,\Delta f/f$, where η is the frequency slip factor: $\eta = \gamma^{-2} - \gamma_{tr}^{-2}$, with γ_{tr} =2.78. The residual gas beam profile monitor (BPM) was used to measure non-destructively the horizontal emittance ε_x. The beam size measured with the BPM was cross-checked by beam scraping, taking into account the ratio of the beta function values at the locations of the diagnostic devices [5]. Transverse Schottky noise power spectra from a stochastic cooling pickup (measured at the central frequency in the range 0.9-1.7 GHz) were also used to measure the transverse beam emittances $\varepsilon_{x,y}$ using the fact that the area under a sideband is proportional to the $\varepsilon_{x,y}$ (see e.g. [7]). The $\varepsilon_{x,y}$ values obtained in this way were calibrated against measurements with scrapers both in the horizontal and in the vertical plane and cross-checked with the BPM in the horizontal plane. The $\varepsilon_{x,y}$ values are estimated to be accurate within 30% (essentially given by the precision of the BPM and scrapers). Obviously, for relative effects such as, for example, the time evolution of beam parameters, the achieved accuracy is much higher and benchmarking of simulations is possible.

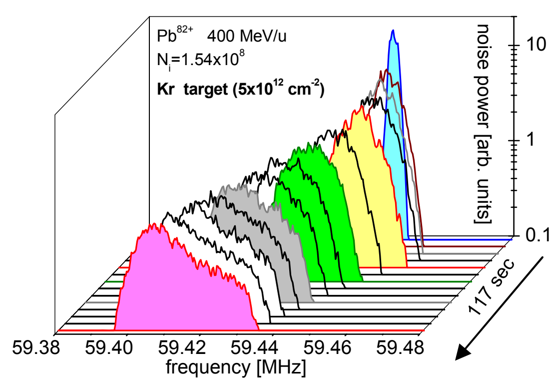

Figure 1: Longitudinal Schottky spectra recorded every 9 s during the blow-up measurement with the cooler OFF. The target is ON at t ≈ 30 s. Different colors are used to guide the eye.

Our study focussed on two main procedures. First, the time evolution of beam parameters in the presence of the target has been investigated (blow-up measurements). The energy loss and the phase space growth of the beam due to the target have been measured as a function of time within approximately 2 min. Initially, the beam was cooled down to equilibrium state. At t=0 the electron cooler is switched off. Then, after about 30 seconds delay to allow for the relaxation of the beam phase space due to IBS, the gas-jet target is switched on (t=30 s: target ON).

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Second, at fixed ion beam intensity, the beam parameters at the equilibrium between electron cooling, IBS and target effects have been measured for electron currents in the cooler in the range 10 − 800 mA. For both procedures, the corresponding measurements without target were performed, thus enabling a direct comparison in order to identify target effects.

RESULTS AND DISCUSSION

Energy Loss Due to the Internal Target

The evolution within approximately 120 s of the longitudinal Schottky noise power spectra for the 30th harmonic of the revolution frequency is shown in Fig. 1 with a time step of 9 s. After switching off the electron current in the cooler (t=0), Δp/p increases due to IBS and the signal density drops. After the target is switched ON (t ≥ 30 s), the position of the peak shifts to lower frequencies i.e. to lower energy due to energy loss and the width of the distribution increases due to energy straggling. Both target effects are clearly demonstrated in these spectra. Because of the non-zero dispersion at the target ($D_T \approx$ 1m), the beam is horizontally displaced from the closed orbit as Δp/p increases. For $\Delta f/f > 7\times10^{-4}$ most of the particles do not hit the target and the energy loss stops. This explains the steep fall on the low f side observed in the few last spectra (i.e. for t ≥ 80 s).

Table 1: Target dependence of the energy loss

Target gas atoms/cm^2	Ar 4×10^{12}	Kr 5×10^{12}	Xe 2.5×10^{12}
ξ_0	0.25 eV	0.6 eV	0.45 eV
calc. $<E_{turn}>$	3.8eV/turn	8.9eV/turn	6.4eV/turn
calc. $<E_{turn}>$ for 24% overlap	0.9eV/turn	2.1eV/turn	1.5eV/turn
meas. E_{loss}	0.6eV/turn	0.8eV/turn	0.7eV/turn

From the observed linear shift of the center of gravity with time the corresponding energy loss rate was obtained and found to be very similar for the 3 targets (Ar, Kr and Xe), namely ~0.7 eV/turn (revolution period = 506 ns). The results are given in Table 1 in comparison with the mean energy loss per turn $<E_{turn}>$ calculated by the analytical formula in [8,9]. In this model, the target dependence enters into $<E_{turn}>$ through the parameter $\xi_0 \propto$ (mass number × density in g cm^{-2}/atomic number). Qualitatively, the measured E_{loss} scales with ξ_0 as expected. The ion beam size at the target (beta function: β_T= 15.74 m) calculated from the measured r.m.s $\varepsilon_x \approx 1.5$ mm mrad (see the lower part of Fig. 2 below) was larger than the jet diameter. Thus, the overlap factor between the beam (assumed to have a Gaussian distribution) and the gas-jet (assumed to have a uniform distribution) is estimated to be about 24%. Taking this simplified overlap model into account, the agreement between experiment and calculation is reasonably good within the experimental accuracy.

Beam Blow-up Induced by the Target

The experimental results for the time evolution of Δp/p without target and with Xe target (d=2.5×10^{12} atoms/cm^2) are shown in Fig. 2 in comparison with a BETACOOL [10] simulation made under similar conditions as in the experiment. In the simulation, the Martini model is used for the IBS [11], the Parkhomchuk formula [12] for the cooling force and the gas-jet diameter was fixed to 5 mm whereas the target density $d_{sim} = 6.2\times10^{11}$ atoms/cm^2 was a fitting parameter. For the relative blow-up of Δp/p the agreement is excellent. The optimum d_{sim} is ≈ 25% of d and this is just the geometrical beam-jet overlap factor discussed above. Therefore, it is justified to say that in these experiments only the core of the beam hits the target. Hence it is not straightforward to estimate the energy straggling from the data: Between 50 and 80 s we obtain a growth rate for $(\Delta p/p)^2$ of 1.5×10^{-9} s^{-1} due to the target only (i.e. after quadratic substraction of the corresponding IBS growth rate measured without target). On the other hand, for comparison, for a beam completely immersed in the target, the energy straggling model in [9] yields a longitudinal heating rate $\Lambda_{\|}^{t} = 7.3\times10^{-11}$ s^{-1}.

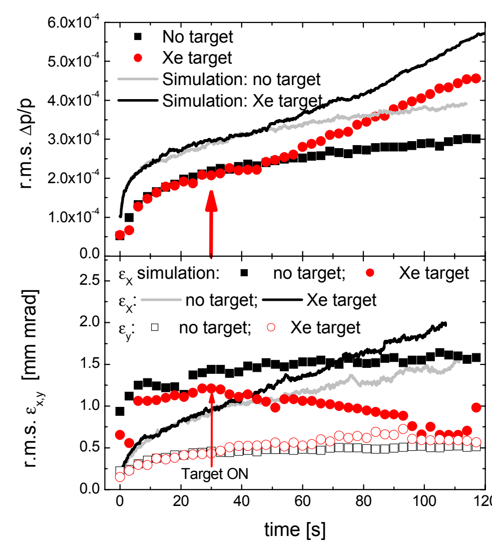

Figure 2: Evolution of Δp/p and $\varepsilon_{x,y}$ for Xe target (2.5×10^{12} atoms/cm^2) compared with BETACOOL result for an ´effective' density of 6.2×10^{11}atoms/cm^2.

The evolution of $\varepsilon_{x,y}$, which were obtained from the transverse Schottky noise analysis, is also plotted in Fig. 2. For ε_y, the BETACOOL result, which for simplicity is not shown in Fig. 2, was in qualitative agreement with experiment. For ε_x however, BETACOOL predicts a blow-up of the beam in the presence of the target, whereas the experiment shows a continuous decrease of ε_x. A possible explanation is that, as the beam is displaced horizontally in the pickup due to the finite dispersion ($D_{PU} \approx$ 6 m), the sensitivity of the plates of the pickup is reduced and the induced signal drops. Considering now the absolute magnitudes in Fig. 2 for $t < 30$ s i.e. when only the IBS acts on the pre-cooled beam, the simulation predicts systematically larger values of $\Delta p/p$ and lower values of $\varepsilon_{x,y}$ than the experiment shows. This is not very surprising since the equilibrium states are quite sensitive on the choice of the cooling force model.

Beam Parameters at Equilibrium Between Cooling, IBS and Target

The measured values of the equilibrium ε_x (from the BPM) and $\Delta p/p$ of the 400 MeV/u Pb^{82+} beam are shown in Fig. 3 as a function of the electron current (I_e) in the cooler, without target, with Kr (5×10^{12} atoms/cm^2) and with Xe target (2.5×10^{12} atoms/cm^2), respectively. The dependence of beam parameters on I_e is a result of the equilibrium between (i) cooling and IBS when the target is OFF and (ii) cooling, IBS and target effects when the target is ON, respectively. In the Kr and Xe experiments the ion beam intensity was slightly different, $N_i=1.8\times10^8$ and 1.54×10^8, respectively.

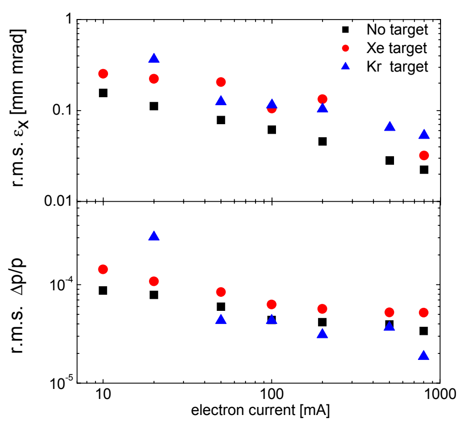

Figure 3: Equilibrium beam parameters versus the electron current in the cooler for Kr and Xe targets. No equilibrium was reached with Kr target for I_e< 20 mA.

Beam dynamics simulations with a gas-jet target were made with the BETACOOL code for the operation parameters of the ESR cooler (electron beam diameter = 5 cm, magnetic field strength = 0.1 T) and for different cooling force models, namely, the non-magnetised (NM) force model, the Parkhomchuk empirical formula (with $V_{eff,e}=1.5\times10^4$ m/s corresponding to magnetic field misalignments of $\sim5\times10^{-5}$) [12] and the magnetised (Derbenev-Skrinsky-Meshkov) model [13]. The latter predicts much stronger cooling than the two other models, such that there was no significant difference between the results with and without target, which is in obvious contradiction with the experiment. Therefore, we chose to show in Fig.4 only the comparison of the experimental results for Xe target with the NM and the Parkhomchuk models. In some cases, both in experiment and in simulations, for very low I_e the heating effect of the target could not be compensated by cooling, leading to beam blow-up and, therefore, no data points are given in Fig. 3, 4. As it can be seen in Fig. 4, the NM model is in better overall agreement with experiment: it qualitatively reproduces the dependence of ε_x and $\Delta p/p$ on I_e for the case without target and predicts an equilibrium state for all I_e when the target is ON. However, it fails to reproduce the target-induced blow-up of $\Delta p/p$ observed in the experiment.

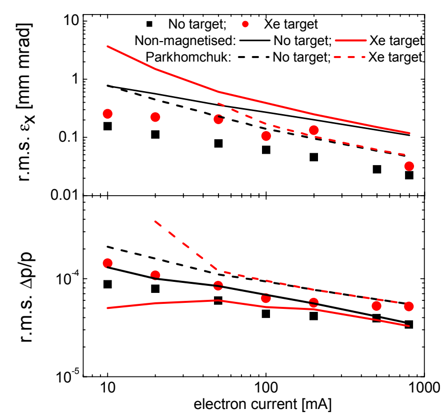

Figure 4: Same as in Fig. 3 for Xe target, compared with BETACOOL simulations using non-magnetised and Parkhomchuk electron cooling model.

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