INTERNAL TARGET EFFECTS IN THE ESR STORAGE RING WITH COOLING

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Abstract

The accurate description of internal target effects is important for the prediction of operation conditions which are required for future experiments in the storage rings of the FAIR facility at GSI. A number of codes such as PTARGET, MOCAC, PETAG01 and BETACOOL have been developed to evaluate the beam dynamics in the storage ring, where an internal target in combination with an electron cooling is applied. The systematic benchmarking experiments were carried out at the ESR storage ring at GSI. The 'zero' dispersion mode (dispersion at target position is only 0.09 m) was applied to evaluate the influence of the dispersion function on the small beam parameters when the internal target is on. The influence of the internal target on the beam parameters is demonstrated. Comparison of the experimental results with the Bethe-Bloch formula describing the energy loss of the beam particles in the target as well as with simulations with the BETACOOL code will be given.

INTRODUCTION

Nuclear physics and fundamental interaction studies in collisions of rare isotope or antiproton beams with internal targets, play an important role in the NESR and HESR storage rings of the future FAIR facility [1]. High luminosities of up to 2×10^{32} $cm^{-2}s^{-1}$ are required for experiments with a hydrogen pellet target in the HESR. Therefore, an understanding of the process of beam-target interaction is crucial for prediction of the target effects which effect on the parameters of the stored beam. Investigations of the interplay between electron cooling, intrabeam scattering (IBS) and target effect is essential for the prediction of equilibrium beam parameters. Some experiments with gas targets in light ion storage rings have been reported before [2,3]. Recently the first systematic investigation of internal target effects in a storage ring for highly charged ions was performed at GSI [4]. The blow-up measurement was performed in 'zero' dispersion mode (the dispersion function at the target position was about 0.09 m) in the recent experiment. This experiment was performed in the Experimental Storage Ring (ESR) [5], which is equipped with an electron cooler [6] and an internal gas-jet target at GSI [7].

EXPERIMENTAL PROCEDURE

The experiment was carried out with a stored coasting beam of bare nickel ions (Ni^{28+}) with an intensity of a few times 10^7 particles and a kinetic energy of 400 MeV/u. The electron cooler was used to increase the phase space density of the injected beam and provide a high quality, dense stored beam for experiment and to compensate heating by the target. Two target gases (Ar and Kr) were used in the gas-jet, with thickness of about 6×10^{12} atoms/cm^2 for both gases (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 horizontal emittance ε_x was non-destructively measured with the residual gas beam profile monitor (BPM). 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 (see [6]). Transverse Schottky noise power spectra from a stochastic cooling pickup (measured at the central frequency 1.3 GHz of the system) were used to measure the transverse beam emittances $\varepsilon_{x,y}$ due to the fact that the area under a sideband is proportional to the $\varepsilon_{x,y}$ [8]. The transverse emittance $\varepsilon_{x,y}$ 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%. This accuracy is essentially given by the precision of the BPM and scrapers. Obviously, for relative effects such as the time evolution of beam parameters, the accuracy is much higher and benchmarking of simulations is possible.

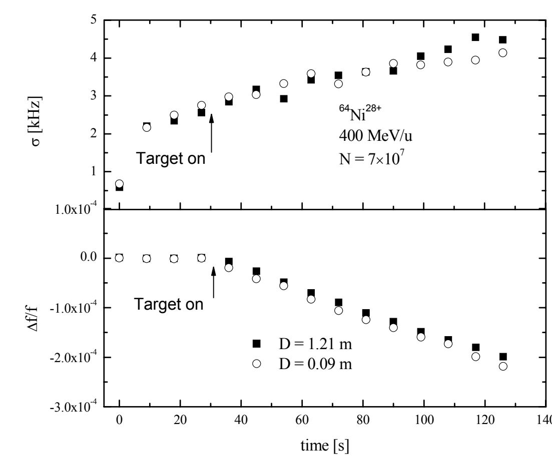

Figure 1: Relative change of the mean frequency Δf/f caused by the energy loss due to the internal target (Kr-target 6×10^{12} atoms/cm^2). The change of the width of distribution σ with the time.

There are two main procedures in our study. Firstly, the blow-up measurements were performed to investigate 'pure' target effects. A possible influence of dispersion function, particularly, at the pick-up position, on the horizontal emittance decrease was investigated (see [4]). The blow-up measurements were performed at the 'zero'

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dispersion mode ($D_T \approx 0.09$ m) obtained by ion optical tuning of the ESR storage ring. Similar measurements were performed when the dispersion function at the target position D_T was 1.21 m. The measurements were performed over 2 min which corresponds to previous measurements. The beam was cooled down to the equilibrium state and at t=0 the electron cooler was 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 was switched on (t=30 s: target ON). Secondly, at fixed ion beam intensity, the beam parameters at equilibrium between electron cooling, IBS and target effects were measured for electron currents in the cooler in the range 20 − 800 mA. In order to identify target effects the corresponding measurements without target were performed, thus enabling a direct comparison.

RESULTS AND DISCUSSION

Energy Loss Due to the Internal Target

The relative change of the mean frequency due to energy loss in the Kr target (6×10^{12} atoms/cm^2) and the growth of the distribution width σ due to energy straggling are shown in Fig. 1. After switching off the electron current in the cooler (t=0), Δf/f remains constant up to the moment when the target is switched on. 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 graphs. Because of the non-zero dispersion at the target ($D_T \approx 1.21$ m), the beam is horizontally displaced from the closed orbit as Δp/p increases. The situation similar to the previous experiments is observed. As can be seen from Fig.1, there is no great difference between measurements when the dispersion function at the target position is different ($D_T \approx 1.21$ m and $D_T \approx 0.09$m).

Table 1: Dispersion dependence of the energy loss

Target gas atoms/cm^2	**Kr** 6×10^{12}	**Kr** 6×10^{12}
D_T	1.21 m	0.09 m
ξ_0	0.06 eV	0.06 eV
calc. $<E_{turn}>$	1.2 eV/turn	1.2 eV/turn
calc. $<E_{turn}>$ for 66% overlap	0.9 eV/turn	0.9 eV/turn
meas. E_{loss}	0.16 eV/turn	0.15 eV/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 two dispersion values D_T at the target position, namely ~1.2 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 [9,10]. The measured values are almost the same for two cases ($D_T \approx 1.21$ m and $D_T \approx 0.09$m). The calculated values are larger than the measured ones by factor of 6. The target dependence enters into $<E_{turn}>$ through the parameter $\xi_0 \propto$ (mass number × density in g cm^{-2}/atomic number) in accordance with the Bethe-Bloch formula. The ion beam size at the target (beta function: β_T= 15.7 m) calculated from the measured r.m.s $\varepsilon_x \approx 0.1$ mm mrad (see the lower part of Fig. 2 below) was less 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 66%. 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 and $\varepsilon_{x,y}$ without target and with Kr target (d=6×10^{12} atoms/cm^2) are shown in Fig. 2 in comparison with a BETACOOL [11] simulation made under similar conditions as in the experiment. In the simulation, the Martini model is used for the IBS [12], the Parkhomchuk formula [13] for the cooling force and the gas-jet diameter was fixed to 5 mm whereas the target density d_{sim} = 4.36×10^{12} atoms/cm^2 was chosen as a fitting parameter. For the relative blow-up of Δp/p the agreement is very good. The optimum d_{sim} is ≈ 66% of d and this is just the geometrical beam-jet overlap factor discussed above. This means the beam is immersed into the target completely but there is no complete overlap. Hence the target thickness should be reduced in the BETACOOL simulations due to geometrical factors.

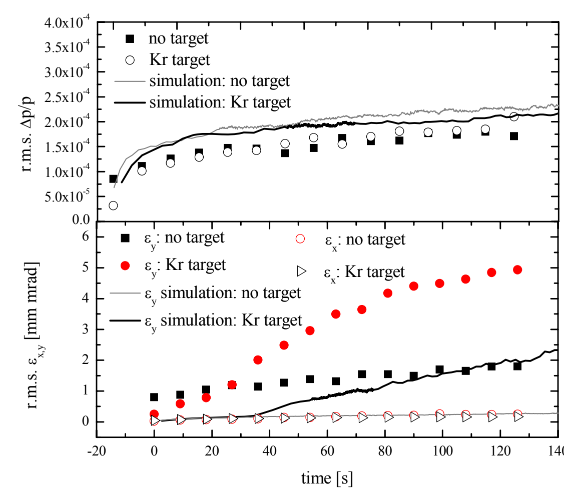

Figure 2: Evolution of Δp/p and $\varepsilon_{x,y}$ for Kr target (6×10^{12} atoms/cm^2) compared with BETACOOL result for an ´effective' density of 4.36×10^{12}atoms/cm^2.

The evolution of $\varepsilon_{x,y}$, which were obtained from the transverse Schottky noise analysis, is also plotted in Fig. 2 for the ‘zero’ dispersion mode. For ε_y, the BETACOOL result, which for simplicity is not shown in

Fig. 2, was in qualitative agreement with the experiment. A decrease of ε_x (noise power signal) was measured in previous experiments in the ESR storage ring (see e.g. [4]). It was suggested that a possible reason for ε_x decrease is the shift of the beam from the sensitive volume of the pick-up due to the dispersion function at the target position. This fact causes the reduction of the noise power signal which was measured. In the recent experiments the value of the dispersion function at the target position was reduced from 1.2 m to 0.09 m. A rather small growth of ε_x is observed instead of an ε_x decrease in the recent blow-up measurements. Therefore, the suggestion about an influence of the dispersion function is assumed to be valid. Obviously, it is difficult to estimate an increase of $\Delta p/p$ due to the target heating in Fig. 2. The relatively large growth of ε_y is also observed in the experiment. 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 ε_x than the experiment shows. The simulations for ε_x were excluded from the Fig.2 for simplicity. The measurements show a great target effect in the vertical plane as shown in Fig. 2. In fact, the results obtained from simulations with BETACOOL code are similar to the measured ones but they have smaller magnitudes in comparison with measured values in the vertical plane. Calibration by means of beam scraping was not performed for the mode with $D_T \approx 0.09$ m. The measurements of ε_y can not be cross-checked with beam profile measurements. Probably, because of this fact, the values of vertical emittance, which were obtained from transverse Schottky spectra analysis, are too large in comparison with horizontal ones. The calibration of ε_x measurements was performed by means of cross-checking values obtained from transverse Schottky spectra and measured by the BPM. The discrepancy in magnitudes between simulations and measurements is not very surprising since the equilibrium states are quite sensitive to 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 Ni^{28+} beam are shown in Fig. 3 as a function of the electron current (I_e) in the cooler, without target, with Kr (6×10^{12} atoms/cm^2). The dependence of beam parameters on I_e is a result of the equilibrium between electron cooling and IBS when the target is off and electron cooling, IBS and target effects when the target is on, respectively.

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 two cooling force models, namely, the non-magnetised (NM) force model and the Parkhomchuk formula (with $V_{eff,e}=1.5\times10^4$ m/s corresponding to magnetic field errors of $\sim5\times10^{-5}$). In some cases, 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. As it can be seen in Fig. 3, the NM model is in better overall agreement with the experiment: it qualitatively reproduces the dependence of ε_x and $\Delta p/p$ on I_e for the case without target. However, it fails to reproduce the target-induced blow-up of $\Delta p/p$ observed in the experiment.

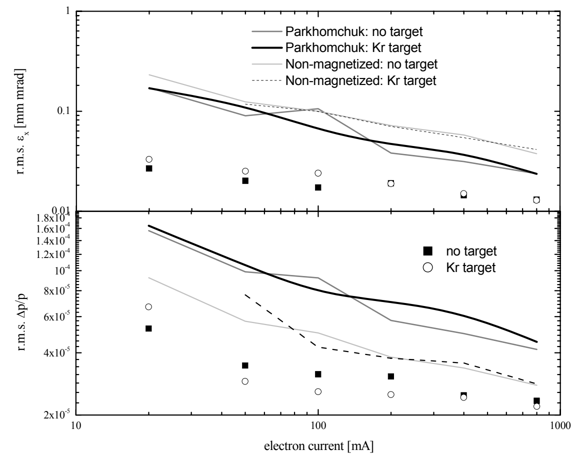

Figure 3: Equilibrium beam parameters compared with BETACOOL simulations using the non-magnetised and Parkhomchuk electron cooling model.

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