SIMULATIONS OF PELLET TARGET EFFECTS WITH THE PROGRAM PETAG01

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Abstract

New internal targets play an important role in modern nuclear and high energy physics research. One of such targets is a pellet target which is a variant of a micro-particle internal target. This target has a number of very attractive features when it is used in a storage ring. The software package PETAG01 [1] has been developed for direct modelling the pellet target and it can be used for numerical calculations of an interaction of a circulating beam with the target in the storage ring. We present numerical calculations to study the beam dynamics of the antiprotons in the HESR storage ring, where strong cooling techniques in combination with the pellet target are planned to be applied. Some important effects due to the target in combination with electron cooling and its influence on the beam parameters are discussed.

INTRODUCTION

To provide high resolution or high luminosity conditions in a storage ring [2, 3] one should use internal targets in combination with cooling technique, which can keep equilibrium states of a beam over a long time of the nuclear experiments. To have a high luminosity in the ring (about 2×10^{32} $s^{-1}cm^{-2}$) one needs a relatively thick internal target (about 5×10^{15} cm^{-2}). For this purpose one can use the internal pellet target, which has been built up at Uppsala [4]. Keeping equilibrium states and obtaining high quality of the beam require a powerful cooling technique. Using thick internal targets in the storage ring one has to consider several factors, which influence the growth of beam phase space by multiple scattering and energy loss straggling. Depending on these factors the parameters of cooling and target systems can be defined.

A preliminary study of the beam evolution in the HESR [5] storage ring taking into account strong electron cooling in combination with thick target have been performed with BETACOOL [6], MOCAC [7] and PTAGRGET [8] codes. The results of simulations are given in Ref [8]. In all of these codes the target model is based on the internal target theory given in detail in Ref [9]. In case of using thick targets one should take into account several features, which influence the beam energy distribution. T.Ellison and H.Mayer show in Ref [10] that a thick target in combination with electron cooling causes a core of the energy distribution with long low energy tail. O. Boine-Frankenheim studied in Ref [11] a beam cooling equilibrium with an internal target interaction assuming in analytical and numerical calculations that the momentum distribution has the Landau distribution, which is induced by the interaction of the circulating beam with the pellet target. In case of the pellet target one has to consider that a great local density has a strong influence on the beam energy distribution and, as consequence, on the life time of an antiproton beam in the ring. The luminosity has a strong dependence upon the ion beam optical parameters of the storage ring at the pellet target.

In this paper our study is focused on the analysis of the particle evolution resulting from an interaction with the pellet target including electron cooling and Intra-beam-scattering (IBS) processes. Numerical simulations have been performed with the PETARGET computer code, where a new recently developed model (the PETAG01 program package) [1] for the pellet target is applied.

SIMULATION PROGRAM

The PETARGET computer program [8] was modified in terms of the new pellet target model. This model is realized by separately developed PETAG01 program package, which describes completely the real properties of the pellet target [1, 12]. In the PETARGET code the Monte Carlo method is applied to evaluate the emittance and the momentum spread depending on time. In simulations 10000 particles are generated with a Gaussian momentum distribution and density probability in the (x, x', y, y') phase space. For calculations the details of the storage ring are not taken into account, only the phase advances between the internal target and the electron cooling system, the Twiss parameters at these elements are important. The parameters of the ion beam are calculated turn by turn, where electron cooling, heating by IBS and the pellet target take place.

Pellet target model

A special computer program package PETAG01 has been developed to calculate the particle interaction with the pellet target turn by turn. The real geometry of the pellets and their moving in real time are considered in detail. In general the PETAG01 package can be implemented in any users program, where the time evolution of the beam's phase space and energy losses resulting from an interaction with the pellet target are studied.

The PETAG01 package consists of a number of subroutines, which should be called in a certain order. The structure of the program module consists of two parts. The first part supplies the geometry of the pellet target system and parameters, which should be set. In the second part the energy loss according to the Urbán model and the angle scattering according to the “Plural Scattering” model are calculated. The semidirect Monte Carlo simulation is applied to evaluate the pellets moving in the interaction region with the circulating beam. The real 2D geometry of the pellet target is modelled, i.e. transverse coordinates (x – horizontal, y - vertical) are recalculated every turn in the interaction region of the target, while the longitudinal coordinate (along beam direction) is fixed. Five independent variables characterize the circulating particle before and after the target passage, which is associated with the call routine PETAG01. These variables are namely x, θ_x, y, θ_y and the relative momentum deviation $\Delta p/p$. The call of the PETAG01 causes a variation only in three variables: θ_x, θ_y, $\Delta p/p$.

Intra-beam-scattering (IBS)

In order to save computer time, IBS is considered in a smooth focusing approximation and IBS rates are calculated only every 100 turns depending on the actual rms momentum and transverse distributions of particles in the beam. The IBS increments for a coasting beam are calculated by the equations

$$\tau_x^{-1} = F\left[\left(\frac{\gamma^2}{Q_x}+\frac{1}{2}\right)\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}} - \frac{\frac{\gamma^2}{Q_x^2}-\frac{1}{2}}{x-1}\left(1-\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}}\right)\right]; \quad (1)$$

$$\tau_y^{-1} = \frac{F}{2}\left[\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}} + \frac{1}{x-1}\left(1-\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}}\right)\right]; \quad (2)$$

$$\tau_s^{-1} = F\frac{Q_x\gamma^2\varepsilon_x}{R\sigma_s^2}\left[\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}} - \frac{1}{x-1}\left(1-\frac{\arctan(\sqrt{x-1})}{\sqrt{x-1}}\right)\right], \quad (3)$$

where the parameters F and x denote

$$F = \frac{N_i r_p^2 c L_c}{8\pi\gamma^4\beta_0^3\varepsilon_x\varepsilon_y\sigma_\delta\sigma_s}\frac{Z_i^2}{A_i}; \quad x = \frac{\gamma^2}{Q_x}\left(1+\frac{\varepsilon_x Q_x^3}{R\sigma_\delta^2}\right);$$

$$\sigma_s = \sqrt{2\pi}R; \qquad \sigma_\delta = \Delta p/p.$$

N_i is the number of particles, r_p is the proton classical radius, L_c is the Coulomb logarithm, A_i, Z_i are the mass and charge of ion, $\varepsilon_{x,y}$ is the transverse beam emittance, $Q_{x,y}$ is the betatron tune, R is the average ring radius, $\beta_0=v/c$, v is the ion velocity, c is the velocity of light.

Electron cooling

Electron cooling was simulated with the Derbenev-Skrinsky formula for magnetized electron beams [13]. Depending on the actual particle parameters x, θ_x, y, θ_y $\Delta p/p$ the cooling forces are calculated turn by turn resulting in a reduction of θ_x, θ_y, $\Delta p/p$.

RESULTS OF SIMULATIONS

Numerical simulations of the beam interaction with the pellet target in the HESR [5, 14] have been performed in the antiproton energy range 3 - 14 GeV. The initial beam parameters are $\Delta p/p_{rms} = 2\cdot10^{-5}$, $\varepsilon_{x,y,\ rms}$= 0.25 mm mrad independently of energy. The parameters of the HESR, electron cooler and pellet target entering in the calculations are summarized in Table 1.

According to simulations due to the pellet target heating the tail of the distribution is not constant in time.

Table 1. Parameters of the HESR systems.

Ring parameters	
Circumference, C, m	570
Magnetic rigidity, $B R$, Tm	50
Ring tunes, $Q_x=Q_y$	12.7
Electron cooling system	
Electron energy range, E_{kin}, MeV	0.5-5
Electron current, I_e, A	0.5
Electron beam radius, r_e, mm	10
Length of cooling section, L_{cool}, m	30
Beta functions in cooling section, β_{cool}, m	100
Longitudinal electron temper., T_{lg} ,meV	0.2
Transversal electron temper., T_{tr}, meV	100
Pellet target parameters	
Diameter of pellets, d, μm	20
Mean velocity of pellets, $\langle v_p \rangle$, *m/s*	50
Mean number of pellets per second, N_p	$5\cdot10^4$
Density of pellet material, ρ_0, g/cm^3	0.0708
Width of the pellet beam, d_w, mm	2
Vertical distance between the pellets, mm	1
Effective target density, n_t, cm^{-2}	$5\cdot10^{15}$

In Fig.1 we show the calculated evolution of the coasting beam momentum distribution at the energy of 8 GeV. One can see that more and more particles move into

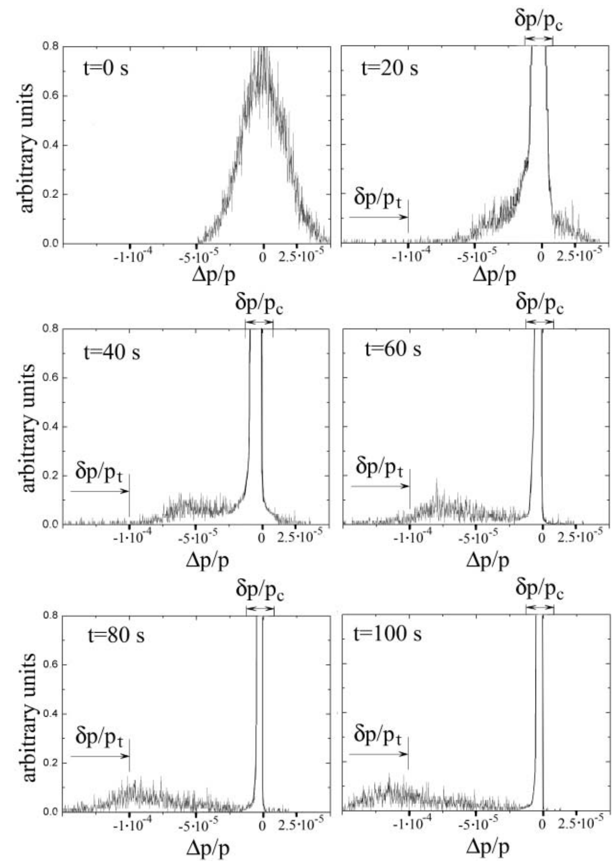

Fig.1. The evolution of the momentum distribution in the HESR at energy of 8 GeV. The effective pellet target thickness is $5\cdot10^{15}$ cm^{-2}. The electron cooling and IBS are switched on.

the momentum core with increasing time. The target interaction develops a low energy tail in the momentum distribution and together with electron cooling causes the peak of the profile, which is fixed near zero. The core of the momentum distribution is well within the narrow interval [$-10^{-5}\div10^{-5}$], where 80% of particles are concentrated after 60 s (Table 2).

Table 2. The particles concentration in the tail $\delta p/p_t$ and core $\delta p/p_c$ of the momentum distribution shown in Fig.1.

t [s]	$\delta p/p_t$<-10^{-4} [%]	$\delta p/p_c$ [-10^{-5}, 10^{-5}] [%]
0	0	45
20	0.42	61
40	0.94	75
60	2.56	80
80	6.54	79
100	11.25	78
120	14.55	75

According to numerical simulations the high resolution (better that 10^{-5}) can be reached if only the core of the momentum distribution (where 80% of particles) takes part in an interaction with the pellet target. In Fig.2 we show values of rms momentum spread and rms emittance obtained from the analysis of distributions every 5-10 s of the beam evolution in the HESR.

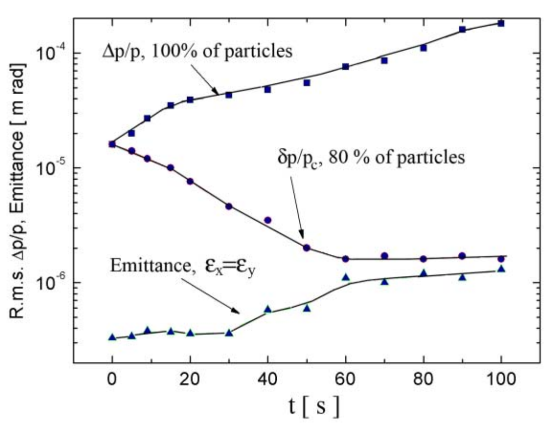

Fig.2. The time evolution of the momentum spread and emittances of the beam at energy of 8 GeV in the HESR including electron cooling and IBS.

For the planned experiments in the HESR requiring high momentum resolution the low energy tail can be separated from interaction with a target by introducing a finite dispersion function at the target. In this case one can get the particles, which will circulate on an offset orbit near the target. The value of the offset will be defined depending on the pellets spread and dispersion function. Having such a tail with so-called 'cut-off' momentum deviation the core part of the momentum distribution will pass through the pellets providing a good momentum resolution. Due to beam cooling the 'cut-off' particles are cooled back onto the target and hence they are not lost providing the required average luminosity. At the same time the high luminosity (more than 10^{32} $s^{-1}cm^{-2}$) is obtained (Fig.3).

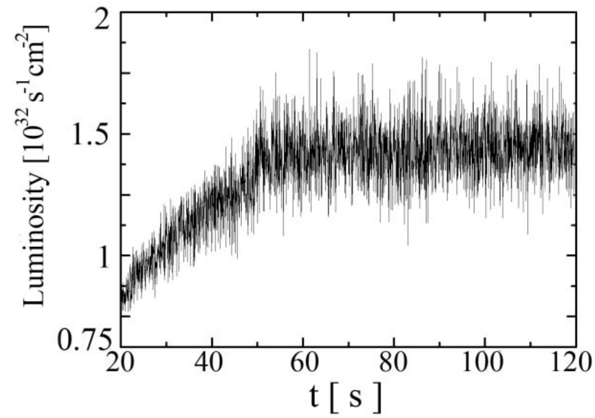

Fig. 3. The luminosity versus time calculated every 20000 turns. The effective target density n_t= $5\cdot10^{15}$ cm^{-2}, N_i=10^{11}, E_{kin}=8 GeV.

As shown in Fig.3 up to 60 s the luminosity is linearly increased with time before it becomes constant. This is because of not fitted overlapping of the circulating beam with the pellet beam in the beginning of the evolution. After 60 s most of the particles are cooled and the beam size becomes smaller and more-less constant in time that results also in a constant average luminosity at least up to 120 s.

In the transverse plane due to scattering of particles on the target the rms emittance is increased to the value of 1 mm mrad. In an angular distribution one observes also a narrow core in the middle, where the population of particles is increased with time. In Fig.4 we can see the angular distribution of particles in the horizontal plane at the times of t=0 s and t=100 s. At the time of 100 s one observes the core and the long tails with large angles. The tails are continuously increased linearly wit time forming a so-call 'halo' of the beam.

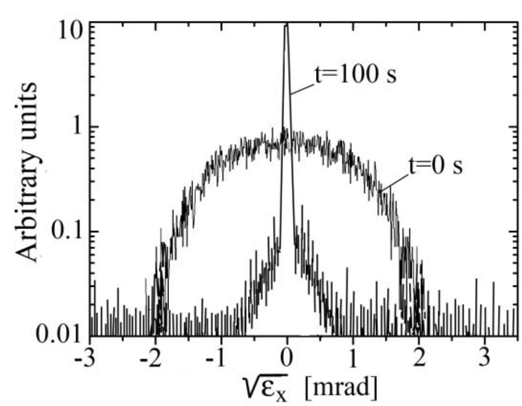

Fig.4 The normalised angular distribution of particles at E_{kin}=8 GeV.

Energy loss due to the pellet target

The analysis of calculated momentum distributions with time gives us the information about the expected particle loss if the ring has a limited momentum acceptance $\Delta p/p_{acc}$. In Fig.5 we show the comparison of the probability of loss per turn calculated numerically and analytically for all antiproton energy range of the HESR. Here the momentum acceptance $\Delta p/p_{acc}$ is assumed of $\pm 5\cdot 10^{-4}$. The plotted analytical result in Fig.5 has been obtained by the expression [11]

$$P_{long} = 1.53\cdot 10^{5}\frac{Z_i^2 Z_t}{\beta_0 A_t}\rho x\left(\frac{1}{\varepsilon_{cut}}-\frac{1}{\varepsilon_{\max}}-\frac{\beta_0^2}{\varepsilon_{\max}}\ln\left(\frac{\varepsilon_{\max}}{\varepsilon_{cut}}\right)\right), \qquad (4)$$

where A_t is the mass number of the target and ρx is the target density (in our simulation ρx=$6.7\cdot 10^{-9}$ g/cm^{-2}), ε_{max} (eV) is the maximum allowed energy transfer in a single collision with an atomic electron [15], ε_{cut} *(eV)* is the cut-off energy assuming that all particles suffering an energy loss $|\varepsilon|>|\varepsilon_{cut}|$ are lost. The value ε_{cut} is associated with the momentum acceptance $\Delta p/p_{acc}$ as

$$\varepsilon_{cut} = (\gamma_0+1)/\gamma_0 \times \Delta p/p_{acc}E_{kin}. \qquad (5)$$

E_{kin} is the kinetic energy of antiprotons.

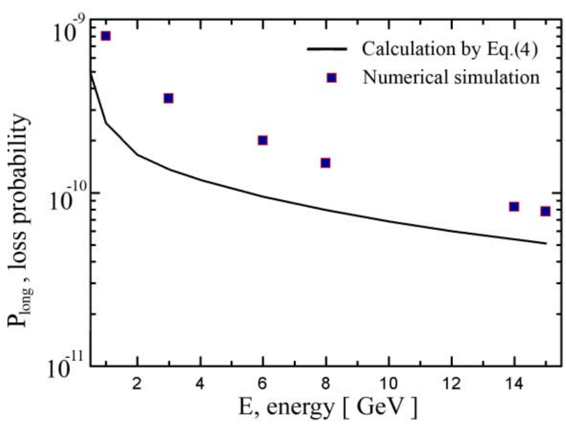

Fig.5. The probability of longitudinal beam loss per turn assuming $\Delta p/p_{acc}$=$\pm 5\cdot 10^{-4}$.

Particle loss due to angle scattering

To calculate analytically the probability of transverse beam loss per turn one can use the formula [11]

$$P_{tr} = \pi\left(\frac{2Z_t Z_i r_p}{\beta_0^2\gamma_0}\right)^2 \frac{\beta_{tg}}{\varepsilon_{acc}} n_t, \qquad (6)$$

where n_t is the target area density, β_{tg} is the beta function on the target, ε_{acc} is the acceptance. In simulations we assume that scattered particles with transverse emittance larger than ε_{acc}=10 mm mrad are lost. In Fig.6 calculated numerically and by Eq.(6) the loss probability per turn in the transverse plane of the HESR versus energy of antiprotons is shown. The beta function β_{tg} in Eq.(6) is 10m. We see that the angle scattering is rather strong and will mainly define the life time of antiprotons in the HESR.

The probability of loss per turn is received from numerical simulations by counting of particles, which overcome the maximal angle deviation that corresponds to the entered acceptance of 10 mm mrad.

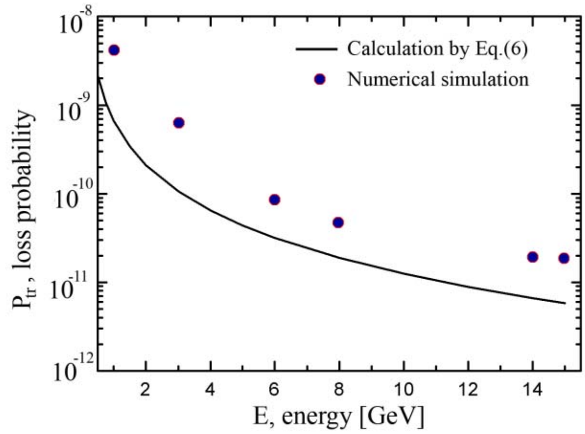

Fig.6. The probability of transverse beam loss per turn assuming the ring acceptance of 10 mm mrad.

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