SIMULATION RESULTS ON COOLING TIMES AND EQUILIBRIUM PARAMETERS FOR ANTIPROTON BEAMS IN THE HESR

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Abstract

The High Energy Storage Ring HESR is part of the "International Accelerator Facility for Ion and Antiproton Beams" proposed at GSI [1]. For internal target experiments with antiproton beams in the energy range 0.8 GeV to 14.5 GeV a maximum luminosity of 5 inverse nbarn per second and a momentum resolution in the order of 10 ppm have to be attained. Electron cooling is assumed to be the most effective way to counteract beam heating due to target effects and intra-beam scattering (IBS). Equilibrium parameters and cooling times have been studied by means of three different computer codes: BETACOOL, MOCAC, and PTARGET. The results reveal that the development of fast, "magnetized" electron cooling with beam currents of up to 1 A and variable electron energies of up to 8 MeV in an extremely homogeneous longitudinal magnetic field of up to 0.5 T is crucial to achieve the required equilibrium beam parameters over the envisaged range of antiproton energies.

INTRODUCTION

A new accelerator facility is being designed at GSI for operation with heavy ion beams as well as for the production, cooling and accumulation of antiprotons [1]. The main installation for experiments with antiprotons will be the high energy storage ring HESR [2,9] that allows the storage of antiprotons in the energy rang between 0.8 and 15 GeV. Luminosities of up to 2×10^{32} $cm^{-2}s^{-1}$ are expected for experiments with an internal hydrogen target. High-energy electron cooling of antiproton beams is considered to provide antiproton beams of high quality. The required high luminosity together with a high beam quality is possible only if fast electron cooling can be applied. One has to take into account reasonable electron beam parameters of the e-cooler and beta-functions in the HESR at which the high intensity and high quality of the antiproton beam can be obtained.

The antiproton beam quality and the average luminosity in the HESR will be limited by the achievable cooling rate and by the capability to suppress heating processes by IBS and by the internal target. Obviously, strong cooling can only be achieved by so-called magnetised cooling requiring a strong longitudinal magnetic field of B = 0.5 T that guides the electron beam along the entire interaction region.

We discuss the numerical calculations to evaluate the equilibrium beam emittances and momentum spreads of high energy antiprotons in the HESR. The aim of this study is to find the optimum values of reasonable parameters of the electron cooler to provide the required luminosity and the desired beam properties during experiments, where strong electron cooling is applied. In our calculations we account for three main effects: electron cooling, beam heating by intra-beam scattering (IBS), and target effects, which influence the quality of the circulating beam.

CODES FOR CALCULATIONS

The equilibrium between electron cooling, IBS and target heating was calculated by three different codes: BETACOOL, MOCAC and PTARGET.

BETACOOL code

The BETACOOL [3] program was developed by the group of I.Meshkov (JINR, Dubna) to calculate the evolution of the ion beam parameters in rings, taking into account many different external effects. The algorithm solves for the root mean square values of the beam phase volumes in three degrees of freedom. The program structure is designed in such a way to permit including any process separately that can be described in the form of cooling or heating rates. In this code the IBS growth rates are calculated using the lattice functions of the ring, which are imported from the output file of the MAD program.

MOCAC code

The MOCAC (MOnte CArlo Code) was developed by A.Bolshakov and P.Zenkevich (ITEP, Moskow) [4]. Similar to the BETACOOL, by this code one can simulate the evolution of the beam parameters in cooler rings. The main processes considered are: the interaction of the ion beam with the electrons of the cooling system, IBS, the interaction with the internal target (only jet target), the space charge effects of the ion beam and of the electron beam. The evolution of the ion beam is calculated by direct modelling of beam dynamics with the Monte-Carlo method of so-called “big particles events”. The simulation is performed by the method of so-called “big events”, where the τ interaction time is a parameter. The IBS evolution is modeled by the binary collisions model. One has to find an optimum value of τ in order to have a stable solution and at the same time to achieve small computer times.

PTARGET code

The PTARGET (Pellet TARGET) code is developed by the group of B.Franzke at GSI to investigate beam dynamic particular in the cooler storage rings, where pellet targets will be used for nuclear experiments. Since the parameters of the ion beam are calculated from turn to turn we set up a simple model of the IBS scattering rates based on Piwinski [10]. The IBS rates are calculated depending on the actual Gaussian distribution of the particles in the beam. For electron cooling we use the interpolated expressions of the friction forces in all regions of the ion velocity [5]. In this code the Monte Carlo model is applied to evaluate the emittance and the momentum spread depending on time. The interaction of the particles with internal pellet target is considered in detail taking into account the available geometric conditions of this target given in [7]. All target effects are parameterised by two quantities: the mean square values θ_{str} and $\Delta p/p_{\text{target}}$ of the small angle scattering and relative momentum straggling per target traversal, which are calculated in accordance with equations of Hinterberger [8].

BECHMARKING OF THE CODES

The numerical calculations with the codes MOCAC, BETACOOL and PTARGET of the equilibrium beam parameters between IBS and electron cooling were performed for the Experimental Storage Ring (ESR)[6]. As an example only two types of ions (*U* and *Ni*) have been considered. Some convenient parameters of the electron cooling system, which have been used in the simulations, are given in Table 1.

In the calculation only electron cooling and IBS were employed. Electron cooling in all codes was simulated with the Derbenev-Skrinsky formulae for magnetised electron beams [5].

Fig.1 shows the dependence the equilibrium emittance and momentum as functions of the number of stored *U* ion beam. It can be seen that all codes give more or less similar results. In some cases the results differ by factors of 3.

Table 1. Electron cooling system of the ESR

Electron energy range	10-320 keV
Electron current	0.25 A
Electron beam radius	2.5 cm
Magnetic field strength	1 kGs
Length of cooling section	2.5 mm
Beta functions in cooling sections	16/6.9 m
Longitudinal electron temperature	0.2 meV
Transversal electron temperature	100 meV

In fig.1 one can see that the experimentally measured ion beam temperature increases with the particle number. In particular, the calculated slopes of the equilibrium momentum spread and of the emittances with number of stored ions are not in agreement with the experimental data. This can be well explained with strong IBS in an ion beam of high intensity. In all experiments - not only with *U* - an $N^{1/3}$ dependence of the momentum spread on the number of stored particles *N* has been observed. For the transverse emittance the results vary in the range $N^{1/3}$ to $N^{2/3}$ [6], thus indicating a high sensitivity to the actual cooling situation.

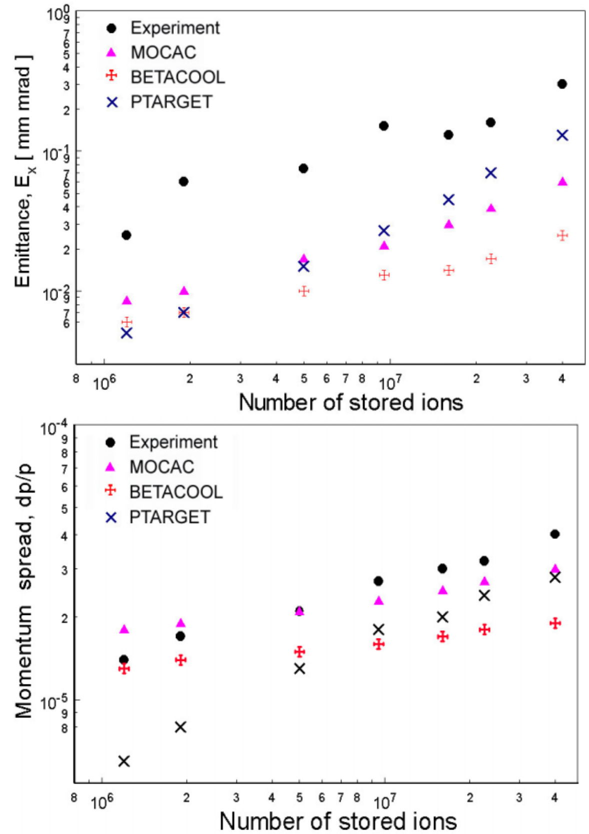

Figure 1: The equilibrium horizontal emittance and momentum spread of $^{238}U^{92+}$ ion beam at the energy of 330 MeV/u. The electron current is 250 mA.

RESULTS FOR THE HESR

We have performed numerical simulations of the equilibrium beam parameters for the HESR [9] in the antiproton energy range of 0.8-14 GeV. The beam equilibrium in our simulations is achieved by the balance of electron cooling, IBS and target heating. The main parameters of the HESR and the electron cooler entering in the calculations are summarised in Table 2. The thickness of the jet target is chosen as 5×10^{15} cm^{-2} (for PTARGET this value is effective thickness) in order to reach in the HESR an average luminosity of 2×10^{32} cm^{-2}s^{-1}. The beta-function both in horizontal and vertical planes at the target was assumed to be 1.5 m. Simulations with all mentioned codes indicate the possibility to have emittance and momentum equilibrium states at full energy range of the HESR for given electron cooling parameters.

The Fig.2,3 show the calculated results with MOCAC for both non-magnetized and magnetized electron cooling. Systematic simulations under the same cooling and target conditions were performed also with BETACOOL and PTARGET codes, but only for the magnetized electron cooling case. The obtained results

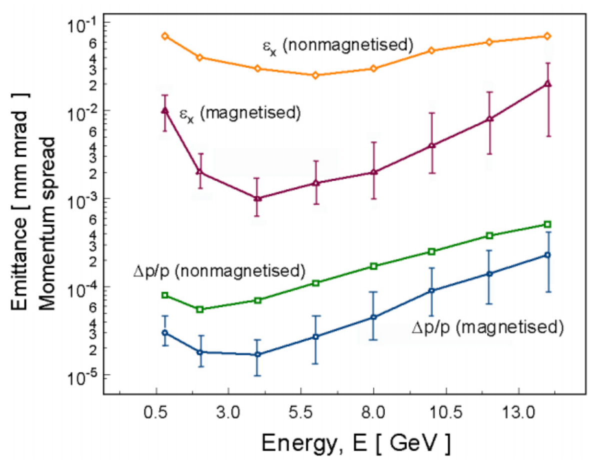

Figure 2: The calculated equilibrium horizontal emittance and momentum spread of antiprotons in the HESR.

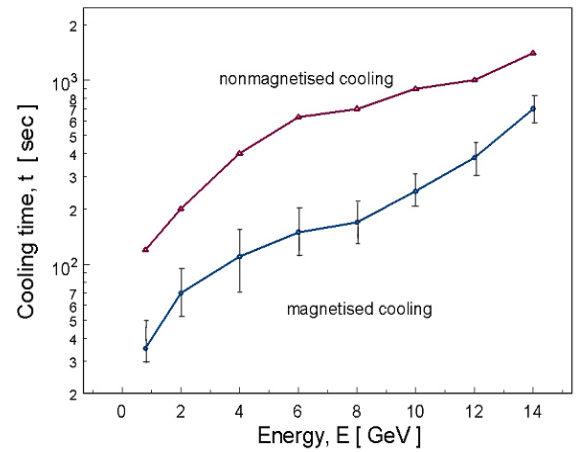

Figure 3: The cooling time needed for equilibria states of the antiproton beam in the HESR.

are not in a good agreement with each other. In Figs.2,3 one can see the error bars within which all codes predict final equilibria states. In many cases the results of the equilibria differ from each other by factors of 3-5, and similar for the cooling time (Fig.3). The maximum discrepancies occur for antiprotons at energies higher than 5 GeV. The reason for this divergence between the different programs lays, obviously, in the various numerical algorithms incorporated in these programs. Especially, in case of IBS modeling.

Table 2. Parameters of the HESR and high energy electron cooling system.

Ring parameters	
Circumference	430.4 m
Magnetic rigidity	50 Tm
Normalized emittance at energy of 3 GeV	2 mm mrad
Momentum spread at energy of 3 GeV	$\pm 4\times10^{-4}$
Number of antiprotons	5×10^{10}
Gamma-transition	19.72
Ring tunes, Q_x/Q_y	10.67/8.17
Electron cooling system	
Electron energy range	0.5-8 MeV
Electron current	1 A
Electron beam radius	3 mm
Magnetic field strength	5 kGs
Length of cooling section	30 m
Beta functions in cooling sections	190/190 m
Longitudinal electron temperature	0.2 meV
Transversal electron temperature	100 meV

CONCLUSIONS

Simulations performed by three different codes: BETACOOL, MOCAC, and PTARGET indicate the equilibrium states of antiprotons at high energy for the given parameters of the electron cooling system in the HESR. The presently available numerical models for the cooling forces, IBS and internal targets yield results, which differ from each other by a factors of 3-5. The differences are particularly pronounced for antiprotons at energies higher than 5 GeV. Further improvements of the numerical models for the electron cooling forces, IBS and targets is planned in the framework of the INTAS project 'Advanced beam dynamics for storage rings', performed in cooperation with ITEP (Moskow, Russia), JINR (Dubna, Russia), Kiev University (Kiev, Ukraine), TSL (Uppsala, Sweden), FZJ (Julich, Germany) and GSI (Darmstadt, Germany).

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