STOCHASTIC COOLING FOR THE HESR AT THE GSI-FAIR COMPLEX*

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Abstract

The High-Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt is planned as an antiproton cooler ring in the momentum range from *1.5 to 15 GeV/c*. An important and challenging feature of the new facility is the combination of phase space cooled beams with internal targets. The required beam parameters and intensities are prepared in two operation modes: the high luminosity mode (HL) and the high resolution mode (HR) with cooled antiprotons down to a relative momentum spread of only a few 10^{-5}. In addition to electron cooling transverse and longitudinal stochastic cooling are envisaged to accomplish these goals. The great benefit of the stochastic cooling system is that it can be adjusted in all phase planes independently to achieve the requested beam spot and the high momentum resolution at the internal target within reasonable cooling down times for both HESR modes even in the presence of intra-beam scattering. A detailed numerical and analytical approach to the Fokker-Planck equation for longitudinal filter cooling including an internal target has been carried out to demonstrate the stochastic cooling capability.

INTRODUCTION

The High-Energy Storage Ring (HESR) [1] of the future International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt [2] is planned as an antiproton cooler ring in the momentum range from *1.5 to 15 GeV/c*. Details of the HESR racetrack layout are presented in [3]. The circumference of the ring is *574 m* with two arcs of length *155 m* each. The long straight sections each of length *132 m* contain the electron cooler solenoid and on the opposite side the Panda experiment. The stochastic cooling tanks will be located in the straight sections. Alternatively, two diagonal signal paths are envisaged for horizontal and vertical cooling or the direct path where pickup and kicker are positioned at the beginning and end of the half-arcs, respectively. One of the systems will be used for longitudinal cooling. Two injection lines are foreseen, one coming from the RESR [2] to inject cooled anti-protons [4] with *3 GeV* kinetic energy and the other one to inject protons from SIS 18.

Using a target thickness of $4 \cdot 10^{15}$ *atoms* cm^{-2} the high luminosity mode (HL) is attained with 10^{11} antiprotons yielding a luminosity of $2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$. The HL-mode has to be prepared in the whole energy range and beam cooling is needed to particularly prevent beam heating by the beam target interaction. Much higher requirements are necessary in the high resolution mode (HR) with 10^{10} antiprotons. The same target thickness yields here a luminosity of $2 \cdot 10^{31}\ cm^{-2}\ s^{-1}$. This mode is requested up to *8.9 GeV/c* with a relative momentum spread down to nearly $1 \cdot 10^{-5}$.

The injected beam in the HESR at $p = 3.8\ GeV/c$ has the following emittance and relative momentum spread in

HR-Mode: $\varepsilon_{rms,HR} = 0.1\, mm\, mrad$ $\quad \delta_{rms,HR} = 2 \cdot 10^{-4}$ and

HL-Mode: $\varepsilon_{rms,HL} = 0.6\, mm\, mrad$ $\quad \delta_{rms,HL} = 5 \cdot 10^{-4}$.

The injected beam is then accelerated with an acceleration rate of 0.1 (GeV/c)/s to the desired momentum leading to initial beam parameters prior to cooling $\varepsilon_{rms} = \frac{\varepsilon_0\, \beta_0 \gamma_0}{\beta\gamma}$ and $\delta_{rms} = \delta_0 \cdot \frac{\beta_0 \gamma_0}{\beta\gamma} \left[\frac{\eta_0}{\gamma_0} \cdot \frac{\gamma}{\eta} \right]^{1/4}$

with the values ε_0 and δ_0 at injection for the HR- or HL mode. The normalized beam velocity is $\beta = v / c$, $\gamma^2 = 1/(1-\beta^2)$ and $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ with γ_{tr} at transition energy $E_{tr} = \gamma_{tr} E_0$. The anti-proton's rest energy is E_0.

COOLING SYSTEM AND MODELING

In general a very broad cooling bandwidth must be chosen for fast cooling. However the upper frequency of the cooling system is restricted when considering the filter cooling method [5]. In this case a proper functioning is only achieved if there is no overlap of adjacent revolution harmonics so that each band can be covered separately by the notch filter. As a reasonable compromise a (2 – 4) GHz system has been chosen that can be operated in the whole momentum range from 3.8 GeV/c up to maximum momentum. The simulations assume quarter wave pickup and kicker loops [6] which are combined in difference mode for transverse cooling. For longitudinal stochastic cooling an optical notch filter will be implemented in the signal path where the pickup and kicker loops are combined in the sum mode. The particle path length between pickup and kicker amounts 155 m and the signal path length is 98.7 m. The HESR lattice [1] that has been used throughout has an imaginary transition energy with $\gamma_{tr} = 6.5\, i$. The target-beam interaction is treated in the formalism as outlined elaborately in [7].

Transverse Cooling

The theory of transverse cooling used in this contribution is outlined in detail in [8]. The formalism has been extended to include the beam interaction with an

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internal target. The time development of the horizontal or vertical beam emittance ε during cooling and beam target interaction is governed by a first order differential equation. This equation can be solved for the rms-equilibrium emittance which yields for a low thermal noise cooling system

$$\varepsilon_{eq,rms} = \frac{1}{4\sqrt{2\pi}} \frac{f_0^2 N \beta_T \theta_{rms}^2}{|\eta| \delta_{rms} W f_C} \qquad [1]$$

under the assumption of no position and angle dispersion at the target location where the beta function is β_T . θ_{rms} is the rms value of the Gaussian small angle scattering distribution [7]. The quantity θ_{rms}^2 is proportional to the target area density N_T. The revolution frequency of a particle with nominal momentum p_0 is f_0. The center frequency of the cooling system with bandwidth W is f_C. The particle number is N, η is the frequency slip factor and δ_{rms} is the rms relative momentum spread of the (longitudinally cooled) beam. Note that eq. (1) does not depend on the initial emittance of the beam as well as pickup and kicker sensitivity. Simulations have shown [9] that an additional contribution to the equilibrium emittance due to beam heating by intra beam scattering (IBS) can be neglected here. IBS becomes only important if the beam is cooled to very low emittances. This can be avoided by a proper adjustment of the electronic gain.

Longitudinal Cooling

The time development of the momentum distribution during longitudinal filter cooling and beam target interaction is found by (numerically) solving a Fokker-Planck equation (FPE) [10] with an initial condition and a boundary condition that takes into account the acceptance limit. The FPE contains not only the coherent cooling force but also the mean energy loss in the target leading to a shift of the distribution as a whole towards lower momenta. Beam diffusion due to electronic and Schottky beam noise as well as diffusion by the target determined by δ_{loss}^2, the mean square relative momentum deviation per target traversal [7] is included. Diffusion results in a broadening of the beam distributions. The quantity δ_{loss}^2 is directly proportional to the target area density. Under the assumptions of an initial centered Gaussian beam that remains Gaussian during cooling, no thermal noise, mean energy loss compensated and no unwanted mixing one can derive a simple first order differential equation for the rms relative momentum spread from the FPE. From this equation the smallest equilibrium value

$$\delta_{eq,rms} = \frac{4}{5}\left(\frac{3}{32} \cdot \frac{N f_0^2}{|\eta| W f_C} \delta_{loss}^2\right)^{1/3} \qquad [2]$$

for the rms relative momentum spread can be found where the electronic gain is to be adjusted accordingly. Again the final equilibrium does not depend on the initial momentum spread of the beam.

COOLING SIMULATION RESULTS

Figure 1 shows longitudinal beam distributions resulting from solutions of the FPE at several times *t = 0 s (black), 20 s, 50 s, 120 s, 1000 s (blue)* for the HL-mode at $T = 3$ *GeV*. The mean square relative momentum deviation per target traversal is $\delta_{loss}^2 = 3.84 \cdot 10^{-16}$. The emittance increase due to the target beam interaction amounts to $d\varepsilon / dt = 3.6 \cdot 10^{-4}\, mm\, mrad / s$ which means

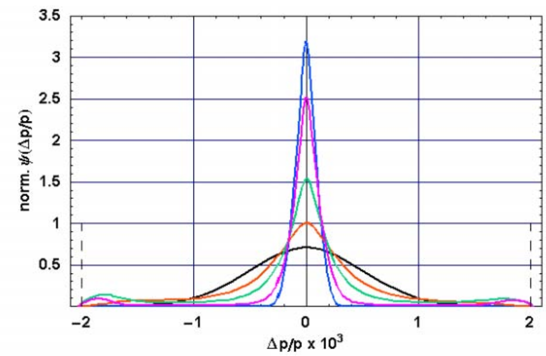

Figure 1: Beam distributions at *t = 0 s (black), 20 s, 50 s, 120 s, 1000 s (blue)* for the HL-mode at $T = 3$ *GeV*. The mean energy loss is compensated. The acceptance limit (dashed lines) is set to $\pm 2 \cdot 10^{-3}$.

that the beam emittance increases to about *1 mm mrad* within one hour without transverse cooling. It is assumed that the mean energy loss $\bar{\varepsilon} = -2.73 \cdot 10^{-2}\, eV / turn$ can be compensated by an rf-cavity. The full width at half maximum (FWHM) of the distributions are shown in figure 2. It can be seen that the FWHM attains an equilibrium value of about $2.5 \cdot 10^{-4}$ within about *100 s* (black curve). On the contrary, the FWHM values determined from the rms-values of the distributions by the relation $FWHM = 2.354 \cdot \delta_{rms}$ show up an increase during the first *100 s* and then drop down to the equilibrium value attained approximately in *600 s*. This growth is due to the tails in the distributions that evolve in the first *100 s* as can be seen in figure 1. Particles are moved towards the acceptance limit where they are lost mainly due to the

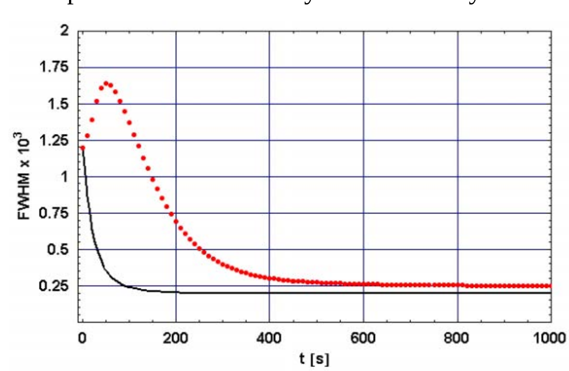

Figure 2: FWHM of the distributions versus time (black curve). The red curve are FWHM values calculated from the rms-values δ_{rms} of the distributions by the relation $FWHM = 2.354 \cdot \delta_{rms}$.

enhanced diffusion induced by bad mixing between pickup and kicker when their relative momentum spread is larger then $\pm 7 \cdot 10^{-4}$. Bad mixing plays a minor role at only slightly larger momenta as well as in the HR-mode where the initial momentum spread prior to cooling is significantly smaller. Beam loss amounts less then 30 % at $T = 3\ GeV$ in the HL-mode. Figure 2 shows that the beam distributions in equilibrium are nearly Gaussian. Here the rms-value is quite well predicted by eq. (2).

Longitudinal and transverse equilibrium values versus momentum are shown in figures 3 and 4 for both HL- and HR- mode. Figure 3 shows that the longitudinal equilibrium values are nearly constant over the displayed

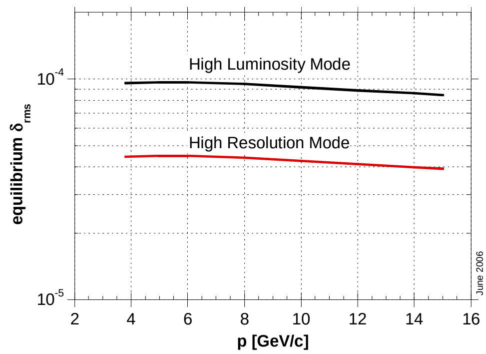

Figure 3: Longitudinal rms equilibrium values versus beam momentum for the HL- and HR-mode.

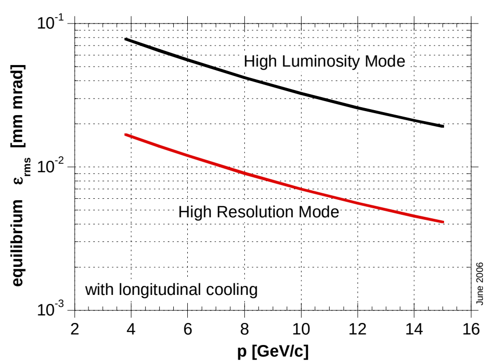

Figure 4: Transverse rms emittances versus beam momentum for the HL- and HR-mode with simultaneously longitudinal cooling.

momentum range. Stochastic cooling achieves a rms-relative momentum spread values of about $4 \cdot 10^{-5}$ in the HR-mode. In the HL-mode nearly momentum independent equilibrium values of about $1 \cdot 10^{-4}$ can be expected. The cooling down time to almost reach the longitudinal equilibrium follows from the FPE solution. These times being approximately the same for transverse cooling are shown in figure 5 demonstrating attractive values not larger than *200 s* and down to *50 s* in the HR-mode. Even in the HL-mode the cooling down time is a least *200 s* and does not exceed *800 s*. The necessary electronic power including safety margin amounts to about *300 W* for longitudinal cooling and up to about *1.5 kW* for transverse cooling. The amplifier gain is expected in the range *100 dB* up to *130 dB*.

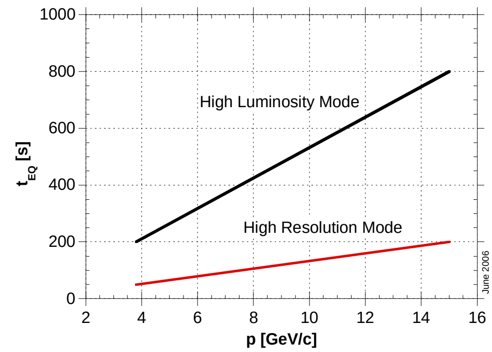

Figure 5: Cooling down times for equilibrium in HL- and HR-mode versus beam momentum.

SUMMARY AND OUTLOOK

The investigation of longitudinal filter cooling with a FPE for the HESR has demonstrated an attractive performance especially for the HR-mode where a momentum resolution of about $4 \cdot 10^{-5}$ is found. Transverse cooling can always be adjusted independently in gain to fulfil the required transverse beam dimension at the target. Further investigations to provide stochastic cooling even below kinetic energy $T = 3\ GeV$ using a cooling system with smaller bandwidth will be carried out. Such a system can serve as well as a tail pre-cooling system for the envisaged electron cooling in the HESR [11]. Barrier bucket cavity studies to compensate the mean energy loss introduced by the target are scheduled. Experimental stochastic cooling studies with internal target to test the model predictions have already started at the cooler synchrotron *COSY* [12] and will be continued this year. Hardware developments for high sensitivity pickups and kickers with large aperture have been carried out and first proto-type results are presented on this conference [13].

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