STOCHASTIC COOLING DEVELOPMENTS FOR THE HESR AT FAIR*

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Abstract

Numerical and analytical studies of stochastic filter cooling to provide the beam quality requirements in the HESR at FAIR with a normal-conducting (NC) ring lattice have been carried out. The NC-ring lattice offers the possibility to vary the value of transition gamma in a wide range at all required energies while the horizontal and vertical tune can be kept fixed. Stochastic cooling profits from this lattice property since for a given system bandwidth and target thickness the frequency slip factor can be adjusted to achieve the smallest equilibrium momentum spread. Additionally, the dispersion and its derivative with arc length can be adjusted to zero. Experimental stochastic cooling studies with an internal cluster target to test the model predictions for longitudinal cooling using the filter method were carried out at the cooler synchrotron COSY. The routinely operating longitudinal stochastic cooling system with an optical notch filter has been used in the frequency range 1.0 to 1.8 GHz.

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. The circumference of the ring is 575 m with two arcs of length 155.5 m each. The long straight sections each of length 132 m contain the electron cooler and on the opposite side the Panda experiment. The stochastic cooling tanks will be located in the long straights. Two injection lines are foreseen, one coming from the RESR [2] to inject cooled antiprotons [3] with 3 GeV kinetic energy and the other one to inject protons from SIS 18. An overview on the HESR ring is given in figure 1.

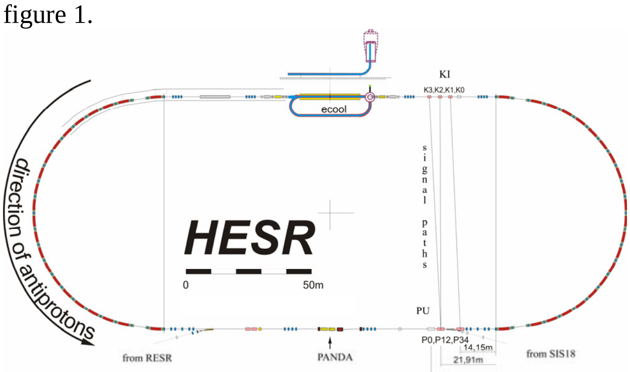

Figure 1: Layout of the HESR ring including the signal paths for transverse and longitudinal cooling.

Two operational modes will be available for the users. A pellet target with a thickness of $4 \cdot 10^{15}$ atoms cm^{-2} provides the high luminosity mode (HL) 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 $2 \cdot 10^{31}$ cm^{-2} s^{-1}. This mode is requested up to 8.9 GeV/c with a rms-relative momentum spread down to about $4 \cdot 10^{-5}$. In the HR-Mode the injected antiproton beam covers the emittance $\varepsilon_{\mathrm{rms,HR}} = 0.1\,\mathrm{mm\,mrad}$ and a relative momentum spread $\delta_{\mathrm{rms,HR}} = 2 \cdot 10^{-4}$. Larger initial phase space values are present in the HL-Mode with $\varepsilon_{\mathrm{rms,HL}} = 0.6\,\mathrm{mm\,mrad}$ and $\delta_{\mathrm{rms,HL}} = 5 \cdot 10^{-4}$.

Both, transverse and longitudinal cooling is foreseen at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. Due to the already small initial beam emittances a proper adjustment of the electronic gain is necessary to prevent beam blow up due to intra beam scattering (IBS). The highest demands are made on longitudinal cooling, especially in the HR-mode. To fulfil this goal the bandwidth of the cooling system will be increased from (2 – 4) GHz to (2 – 6) GHz in the final stage. High sensitive pickup/kicker structures are being developed [4]. The filter cooling technique [5] is applied for longitudinal cooling.

LATTICE PROPERTIES

The normal conducting HESR [6] lattice offers the possibility to vary the value of transition gamma between $6 \le \gamma_{\mathrm{tr}} \le 30$ at all required energies while the horizontal and vertical tune can be kept at 7.6. In addition, the dispersion and its derivative with arc length can be adjusted to zero. The resulting frequency slip factor $\eta = 1/\gamma^2 - 1/\gamma_{\mathrm{tr}}^2$ is sufficient small to reduce unwanted mixing from pickup to kicker. For all energies the signal paths contain enough time reserve for electronic equipment and delay adjustment to match the particle travelling time. An overview on momentum equilibrium values for N stored antiprotons with revolution frequency f_0 is found from

$$\delta_{eq,rms} = \frac{4}{5}\left(\frac{3}{16}\cdot\frac{N\,f_0^2}{|\eta|Wf_C}\delta_{loss}^2\right)^{1/3} . \qquad (1)$$

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The bandwidth W of the stochastic cooling system is centered at frequency f_C. The mean square relative momentum deviation per target traversal, δ^2_{loss}, describing the beam-target interaction is directly proportional to the target area density [7]. The formula assumes that the mean energy loss in the target is compensated e.g. with a barrier bucket cavity [8] and that there is no mixing from pickup to kicker [9]. As an example figure 2 shows that an equilibrium relative momentum spread $\delta_{rms} = 5.4 \cdot 10^{-5}$ should be achieved in the HR-mode for a (2 - 6) GHz cooling system if the lattice is tuned to $\gamma_{tr} = 6$ at kinetic energy T = 8 GeV. The equilibrium value increases to $\delta_{rms} = 7.5 \cdot 10^{-5}$ if the upper frequency limit of the cooling system is restricted to 4 GHz (horizontal line in figure 2).

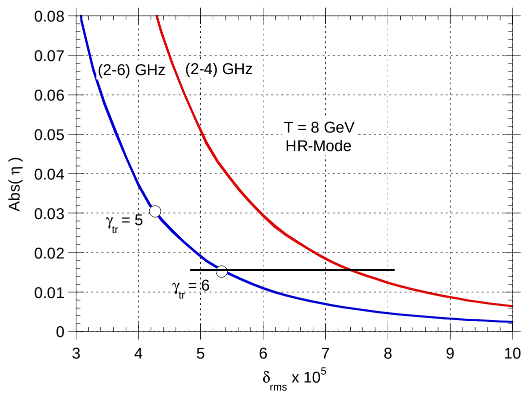

Figure 2: Required $|\eta|$ for a given relative momentum spread in the HR-mode at *T = 8 GeV* for (2 - 4) GHz and (2 -6) GHz. The smallest value of γ_{tr} is 6.

COOLING SIMULATION RESULTS

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) [9] with an initial condition and a boundary condition that takes into account the momentum acceptance $(\Delta p / p)_{acc} = \pm 2.5 \cdot 10^{-3}$. 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 from δ^2_{loss} is included. To first order, diffusion induced by the target results in a broadening of the beam distributions. Details of the beam-target interaction are outlined in [7]. The simulations in [9] clearly show that in the HESR case the strong mean energy loss can not be compensated by the stochastic cooling system alone. A promising compensation mechanism seems to be cooling by the time of flight (TOF) method [10]. However the equilibrium values are larger due to the absence of the notch filter [9]. Recently a HESR prototype barrier bucket cavity came into operation in COSY and was applied for a mean energy loss compensation [8]. Additionally stochastic filter cooling was utilized to cool the beam longitudinally in the presence of a pellet-target. In table 1 and 2 the momentum cooling performance for a (2 – 6) GHz system is summarized for three energies. The tables include approximate numbers for the cooling down times t_{eq} to equilibrium.

Table 1: High Resolution Mode

T [GeV]	γ_{tr}	$\delta_{rms} \cdot 10^5$	t_{eq} [s]	G_A [dB]
3	13	5.4	60	109
8	6	5.4	150	116
15	6	3.9	150	119

Table 2: High Luminosity Mode

T [GeV]	γ_{tr}	$\delta_{rms} \cdot 10^5$	t_{eq} [s]	G_A [dB]
3	6	13.6	600	95
8	6	11.7	600	103
15	6	8.8	600	105

The Schottky particle power and the thermal noise power after filtering at the kicker entrance amounts up to 10 W each. In the HL-Mode at T = 3 GeV a transition value of 6 has been chosen in order to reduce particle losses of about 14 % with a $\gamma_{tr} = 13$ lattice down to less than 1 %. Larger particles losses may occur if the initial beam momentum as delivered by the RESR is increased.

STOCHASTIC COOLING EXPERIMENTS

In order to gain confidence in the stochastic momentum cooling predictions with internal targets cooling experiments [9] have been carried out at COSY with the present cooling system. The experiments were carried out at beam momentum 3.2 GeV/c with about 10^{10} stored protons. The frequency slip factor was measured with the result η = -0.1, i.e. the machine was operated above transition. Longitudinal cooling was carried out with band I ranging from 1 to 1.8 GHz. The measured particle distributions in the frequency range of the harmonic number 1500 were converted to momentum distributions using the relation $\Delta f / f_0 = \eta \cdot \Delta p / p_0$. The frequency distributions were measured every 2.5 min or 5 min in flat top with a duration of about 30 min.

First of all the target beam interaction was investigated in order to determine the mean energy loss per turn ε and the mean square relative momentum deviation per turn δ^2_{loss}. In figure 3 the measured center of the frequency distributions is shown from which the revolution frequency of the protons can derived by dividing the values by the harmonic number 1500. The initial revolution frequency is $f_0 \approx 1.568\,\mathrm{MHz}$. The measured data (black symbols) in figure 3 show the expected behavior that the beam distributions are shifted linearly towards lower energies due to the beam target interaction. This corresponds to a linear increase in frequency due to the negative frequency slip factor. From the slope of the data (black symbols) in figure 3 the mean energy loss per turn was determined to $\varepsilon = -1.8\,\mathrm{meV/turn}$. The relative momentum spread in figure 4 (black symbols) shows only

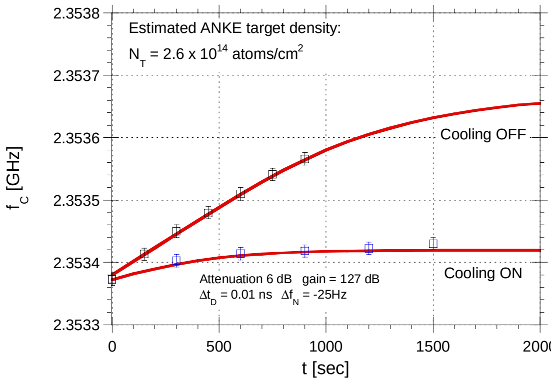

Figure 3: The measured center frequency at harmonic 1500 (blue symbols: cooling ON, black symbols: cooling OFF) in comparison with the model predictions (red curves).

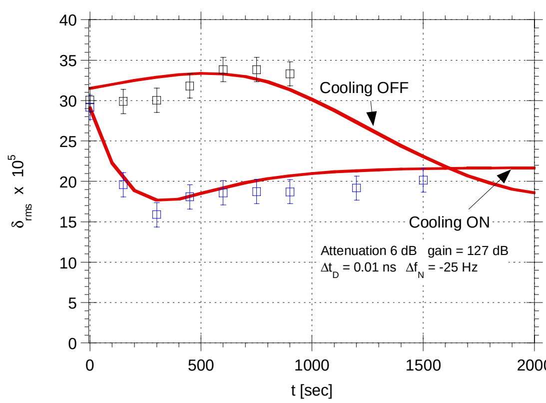

Figure 4: The measured relative momentum spread at harmonic 1500 (blue symbols: cooling ON, black symbols: cooling OFF) in comparison with model predictions (red curves).

a small increase from which the mean square relative momentum deviation per turn $\delta^2_{\mathrm{loss}} = 2\cdot 10^{-17}\,/\,\mathrm{turn}$ was derived. From the mean energy loss a target thickness $N_T \approx 3\cdot 10^{14}\, atoms/cm^2$ was deduced. The values for ε and δ^2_{loss} have been then used in the FPE with cooling switched off to determine the beam distributions versus time when only the target-beam interaction is present. A Gaussian initial distribution in the calculations was assumed. The results are shown in figure 3 and 4 as red curves. The model starts to deviate from the linear behavior at about 600 s which is due to particle losses when the shifted distributions reach the momentum acceptance of the machine. This becomes clearly visible in figure 5 for t = 900 s. Stochastic cooling with internal target has then been applied for different gain settings. The filter was set 25 Hz below the frequency at harmonic one. The cooling effect is clearly visible in figures 3 and 4. The mean energy loss is almost compensated for the present target thickness which is about one order of magnitude smaller as the one expected from the pellet-target in the HESR (figure 3).

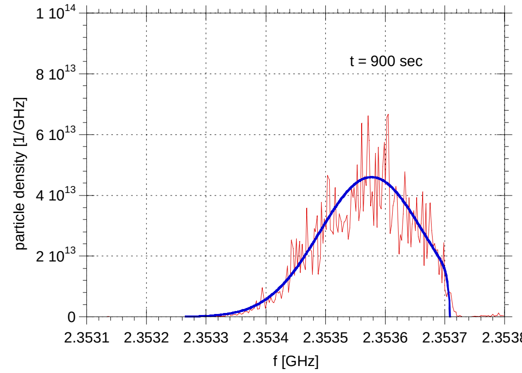

Figure 5: Measured frequency distribution (red) at harmonic number 1500 for t = 900 s and prediction (blue curve). The sharp cut-off at about 2.3537 GHz corresponds to the acceptance limit at $\delta_{\mathrm{acc}} = -1.4\cdot 10^{-3}$.

The momentum spread drops down initially and increases until an equilibrium value with $\delta_{\mathrm{rms}} = 2.2\cdot 10^{-4}$ between target-beam interaction and cooling is attained after about 1000 s. Again the cooling effect is clearly visible when the data with cooling on and off are compared.

Albeit the FPE model predicts the data quite well the future work will deal with a refinement of the target-beam interaction simulation and to include the beam dynamics in a barrier bucket in the cooling model. Recently, successful tests at COSY to compensate the strong mean energy loss due to the beam-pellet target interaction and stochastic cooling were performed. The data analysis and simulations are currently under development.

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