STOCHASTIC COOLING FOR THE HESR AT FAIR

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Abstract

The High-Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt is planned as an anti-proton 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 with beam intensities up to 10^{11} anti-protons, and the high resolution mode with 10^{10} anti-protons cooled down to a relative momentum spread of only a few 10^{-5}. Consequently, powerful phase space cooling is needed, taking advantage of high-energy electron cooling and high-bandwidth transverse and longitudinal stochastic cooling. 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. 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. Experimental stochastic cooling studies with the internal ANKE target to test the model predictions for longitudinal cooling were carried out at the cooler synchrotron COSY. The routinely operating longitudinal stochastic cooling system applies the optical notch filter method in the frequency band I from 1-1.8 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 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 long straights and in one arc. Two injection lines are foreseen, one coming from the RESR [2] to inject cooled anti-protons [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. 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 rms-relative momentum spread down to about $4 \cdot 10^{-5}$.

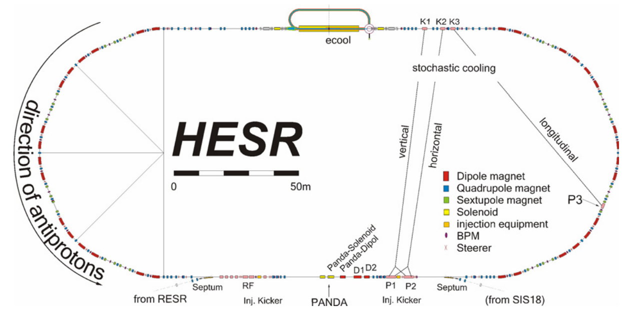

Figure 1: Layout of the HESR ring including the signal paths for transverse and longitudinal cooling.

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 experiment momentum.

COOLING SYSTEMS

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 [4]. 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 [5]. For longitudinal stochastic cooling an optical notch filter will be implemented in the signal path. In figure 1 the cooling signal paths are shown. Cooling simulations applying a linear notch filter have been already presented in [6]. In this contribution the model utilizes a more realistic non-linear notch filter. The HESR optics [1] that has been used throughout has an imaginary transition energy with $\gamma_{tr} = 6.0\,i$. 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 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

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

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 almost 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

$$\delta_{eq,rms} = \frac{4}{5}\left(\frac{3}{16} \cdot \frac{N f_0^2}{|\eta| W f_C} \delta_{loss}^2 \right)^{1/3} \quad [2]$$

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 2 shows longitudinal beam distributions resulting from solutions of the FPE at several times *t = 0 s (black), 50 s, 100 s, 150 s, 2000 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 with time due to the target beam interaction amounts to $d\varepsilon / dt = 3.6 \cdot 10^{-4}\ mm\,mrad / s$ resulting in a beam

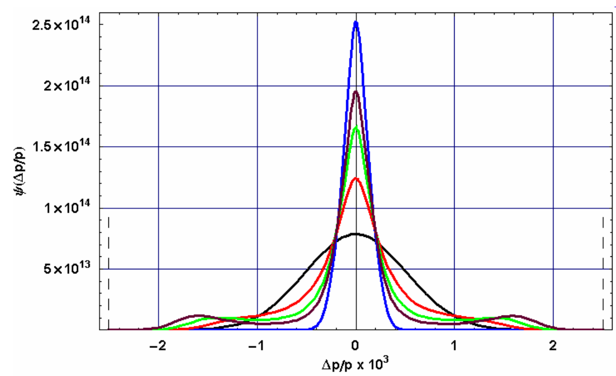

Figure 2: Beam distributions at t = 0 s (black), 50 s, 100 s, 150 s, 2000 s (blue) for the HL-mode at $T = 3\ GeV$. The mean energy loss is assumed to be compensated. The acceptance limit (dashed lines) is ± 2.5 · 10^{-3}.

emittance of about *1 mm mrad* within one hour when transverse cooling is off. It is assumed that the strong mean energy loss $\bar{\varepsilon} = -2.73 \cdot 10^{-2}\ eV / turn$ can be compensated by an rf-barrier bucket cavity or by TOF cooling as explained below. In figure 3 the rms relative momentum spread (red dots) versus time is shown.

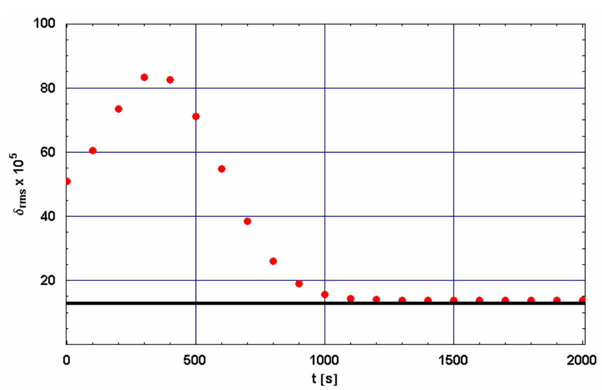

Figure 3: Rms-relative momentum spread (red dots) during cooling with an internal target at T = 3 GeV for the HL-mode. Horizontal line: eq. (2)

The rms values of the distributions exhibit an increase during the first 400 s and then drop down to the equilibrium value, $\delta_{rms} = 1.4 \cdot 10^{-4}$, which is attained in nearly 1200 s. This growth is due to the tails in the distributions that evolve in the first 400 s as can be seen in figure 2. Particles are moved towards the acceptance limit where they are lost mainly due to the enhanced diffusion induced by the unwanted mixing between pickup and kicker when their relative momentum spread is larger then $\pm 7 \cdot 10^{-4}$. A short period of the larger acceptance TOF cooling prior to filter cooling can avoid these losses. Bad mixing plays a minor role at only slightly larger beam momenta as well as in the HR-mode where the initial momentum spread prior to cooling is significantly smaller. The beam loss amounts about 20% at $T = 3\ GeV$ in the HL-mode. Figure 3 shows that the beam distributions in equilibrium are nearly Gaussian. Here the rms-value is quite well predicted by the formula given in eq. (2). Table 1 and 2 summarize for two beam energies the expected equilibrium values and cooling down times in the HR- and HL-mode, respectively. The necessary electronic gain lies in the range 95 dB to 110 dB. The particle power ranges up to 15 W.

Table 1: HR-Mode Stochastic Cooling

p [GeV/c]:	**3.8**	**8.9**	**14.9**
rms rel. momentum spread δ_{rms}:	$7 \cdot 10^{-5}$	$6 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
rms transverse emittance ε_{rms} [mm mrad]:	$2 \cdot 10^{-2}$	$7 \cdot 10^{-3}$	$4 \cdot 10^{-3}$
cooling down time [s]:	≈100	≈200	≈250

Table 2: HL-Mode Stochastic Cooling

p [GeV/c]:	**3.8**	**8.9**	**14.9**
rms rel. momentum spread δ_{rms}:	$1.3 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
rms transverse emittance ε_{rms} [mm mrad]:	$8 \cdot 10^{-2}$	$4 \cdot 10^{-2}$	$2 \cdot 10^{-2}$
cooling down time [s]:	≈500	≈800	≈1000

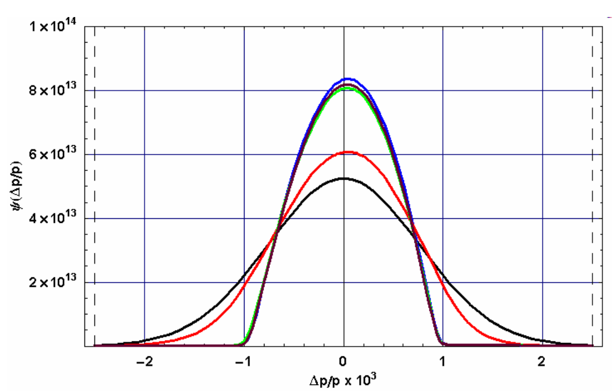

Figure 4: TOF momentum cooling at T = 3 GeV for the HL-mode. The mean energy loss due to the target-beam interaction is compensated. The initial distribution (black) is cooled down to a stable equilibrium without tails in about 300 s (brown curve).

All simulation and experimental results show that the dominant process due to the target-beam interaction is the mean energy loss in the target. The stochastic cooling predictions were deduced under the assumption that the mean energy loss can be compensated by a suitable method. An interesting and promising method to accomplish this goal is the time of flight discrimination cooling method (TOF cooling). Here the notch filter in the cooling chain is replaced by a ninety degree broadband phase shifter. This method prefers a high bandwidth and a low electronic gain. An example using the (2 - 4) GHz system is shown in figure 4. After proper adjusting the electron gain (98 dB) and the system delay ($\Delta T_D = -0.195\,ns$) the initial beam distribution with even a 50% larger initial momentum spread in the HL-mode at $T = 3\ GeV$ is cooled down to a stable equilibrium beam momentum spread within 300 s. No particle losses occur and the mean energy loss is compensated as can be seen in figure 4. The corresponding rms-relative momentum spread during TOF cooling shows an exponentional decrease and attains an equilibrium value $\delta_{rms} = 4.5 \cdot 10^{-4}$ after 300 s. The value is larger as compared to that in figure 3 due to the absence of the notch filter which strongly suppresses the particle and thermal noise in the center of the distributions. Consequently the particle power is larger and amounts up to 30 W. The TOF cooling method also helps to prevent the development of low momentum tails in the beam distribution. By adjusting the system delay it is also possible to accelerate or decelerate the beam in flat top if a small energy change should be necessary.

STOCHASTIC COOLING EXPERIMENTS

In order to gain confidence in the stochastic momentum cooling predictions with internal targets cooling experiments [10] have been carried out at COSY with the present cooling system [11]. The cooling experiments were carried out at beam momentum 3.2 GeV/c with about 10^{10} stored protons. The frequency slip factor was measured and resulted in $\eta = -0.1$, i.e. the machine was operated above transition. Longitudinal cooling was carried out with band I ranging from 1 to 1.8 GHz. Particle distributions were measured in the frequency range of the harmonic number 1500 with the band II system (1.8 – 3) GHz and can be 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.

Beam Target Interaction

First 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} . The results are shown in the figures 5 and 6. In figure 5 the measured center of the frequency distributions are shown from which the revolution frequency of the protons can derived by dividing the values by the harmonic number 1500. At time zero this gives $f_0 \approx 1.568\,MHz$.

The measured data (black symbols) in figure 5 show the expected behavior that the beam distributions are shifted linearly towards lower energies due to the beam target interaction.

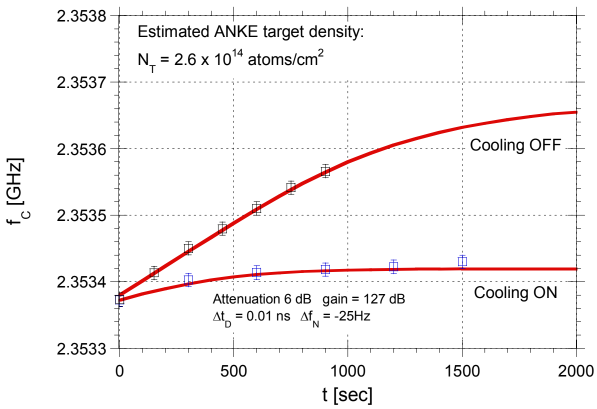

Figure 5: The measured center frequency at harmonic 1500 (blue symbols: cooling ON, black symbols: cooling OFF) in comparison with the model predictions (red curves).

Due to the negative frequency slip factor this corresponds to a linear increase in frequency. Thus the revolution frequency of the protons increases with increasing energy loss. From the slope of the data (black symbols) in figure 5 the mean energy loss per turn was determined to $\delta^2_{loss} = 2 \cdot 10^{-17} / turn$. The relative momentum spread in figure 6 (black symbols) shows only a small increase. From the linear increase of δ^2_{rms} the mean square relative momentum deviation per turn $\delta^2_{loss} = 2 \cdot 10^{-17} / turn$ was derived.

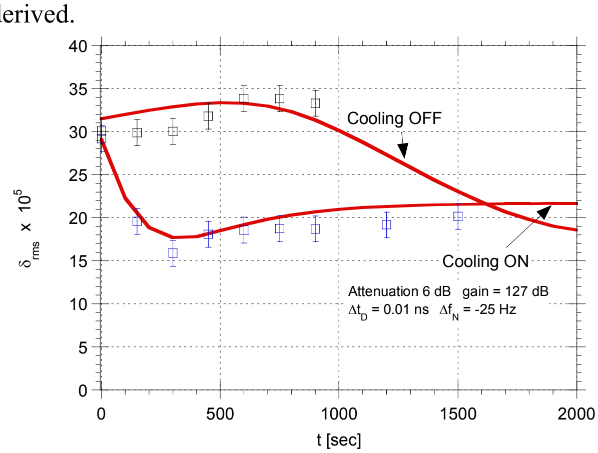

Figure 6: The measured relative momentum spread at harmonic 1500 (blue symbols: cooling ON, black symbols: cooling OFF) in comparison with the model predictions (red curves). The linear increase of the squared momentum spread determines the mean square relative momentum deviation per turn when cooling is switched off.

The indicated error bars result from three consecutive measurements and reflect the uncertainties due to the finite frequency resolution of the spectrum analyzer. The values for ε and δ^2_{loss} have been then used in the FPE when cooling is switched off to determine the beam distributions versus time. A Gaussian initial distribution in the calculations was assumed. The results are shown in figure 5 and 6 as red curves. As can be seen the model deviates 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 when the measured frequency distributions are compared with the distributions predicted by the model as is depicted in figure 7 for $t = 900\ s$.

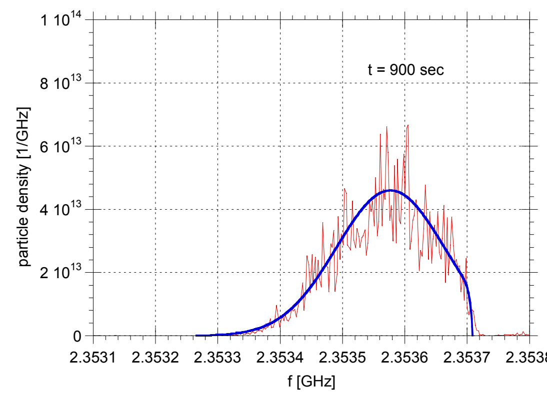

Figure 7: Measured frequency distributions (red) at harmonic number 1500 for $t = 900\ s$ in comparison with the model prediction (blue curve). The sharp cut-off at about 2.3537 GHz corresponds to the acceptance limit.

The measurement as well as the model prediction show a cut off in the distributions at about 2.3537 GHz which corresponds to the negative relative momentum acceptance limit $\delta_{acc} = -1.4 \cdot 10^{-3}$. It is seen that this value is reached after about 600 s. Particle losses are increasing then with time as indicated by the increase in the slope at the high frequency side of the distributions. Measured and predicted distributions agree remarkable well. The measured mean energy loss yielded a target thickness $N_T \approx 3 \cdot 10^{14}\ atoms / cm^2$.

Momentum Cooling with Internal Target

After determining the parameters of the beam target interaction stochastic cooling was switched on. The system delay was adjusted for cooling by means of BTF measurements and the notch filter was set 25 Hz below the center frequency of the distribution at harmonic one. In momentum space this means that the filter was set above the mean momentum of the protons. Measurements for different attenuations of the electronic gain of the cooling system were then carried out. As an example the figures 5 and 6 show the results for the attenuation set to 6 dB which corresponds to a model gain and an additional delay of 127 dB and $\Delta T_D = 0.01\, ns$, respectively. Figure 5 shows the center frequency measured at harmonic number 1500 (blue data points) in comparison with the model prediction. The figure clearly shows the cooling effect. The ANKE target thickness is more than an order of magnitude smaller as compared to the HESR case. The mean energy loss is nearly compensated by cooling. The time development of the relative moment spread during cooling and ANKE target on (blue data points) is fairly well predicted by the model as shown in figure 6. Initially the momentum spread drops down and increases until an equilibrium value $\delta_{rms} = 2.2 \cdot 10^{-4}$ 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.

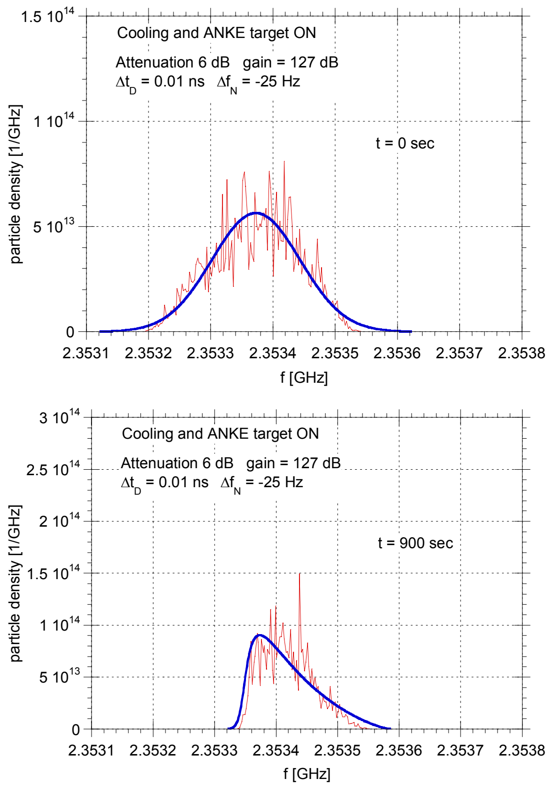

Figure 8: Measured beam distributions (red) during cooling in comparison with model predictions (blue). Initially a Gaussian distribution has been assumed with values for the center frequency and variance determined from the measured initial distribution.

Figure 8 presents a comparison of the measured distribution with the model prediction at $t = 0\ s$ and $t = 600\ s$. Initially a Gaussian distribution has been assumed with values for the center frequency and variance determined from the measured initial distribution. The particle distributions are normalized to the number of protons in the ring. The Fokker-Planck solutions present the absolute beam distributions. There are no scaling factors to adjust the solutions to the measured distributions. A more detailed discussion of the cooling experiment can be found in [10].

SUMMARY AND OUTLOOK

The stochastic filter cooling model developed for the investigation of stochastic cooling at the HESR receives a remarkable good agreement with the experimental results at COSY when the internal ANKE target is in operation. The beam target interaction is well described by the model through the quantities mean energy loss and mean square relative momentum deviation per turn. Both quantities can be measured. Once the main parameters are known the model can be employed to predict the cooling properties under different conditions, e.g. if the target thickness is increased, different beam energy, etc.. The good agreement of the model with the experimental results at COSY gives a save confidence that the model will also fairly well predict the cooling properties in the case of the planned HESR at the FAIR facility. However more investigation are needed concerning the undesired mixing that is here much more severe as at COSY. The available equilibrium values for the HESR are close to the desired beam quality. Beam heating due to the internal target can be compensated with stochastic cooling in the whole momentum range. The promising TOF cooling method will be further investigated in theory as well as in experiment especially including the feedback via the beam. Also other methods to compensate the mean energy loss have to be studied. A further method to compensate the mean energy loss by a barrier bucket cavity will be investigated theoretically and will be soon tested at COSY. The stochastic cooling model will be further developed to include the characteristics of the newly designed pickup and kicker structures [12] as well.

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