# STOCHASTIC COOLING FOR THE HESR AT THE FAIR FACILITY

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*Abstract*

An important and challenging feature of the new High-Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt is the combination of phase space cooled beams with internal targets. Detailed numerical and analytical studies of stochastic filter and Time-Of-Flight cooling to provide the beam quality requirements in the momentum range from 1.5 to 15 GeV/c with a normal-conducting (NC) ring lattice have been carried out. Experimental stochastic cooling studies to test the model predictions for longitudinal cooling were performed at the cooler synchrotron COSY with an internal pellet target similar to the one which will be used at the HESR. A barrier bucket cavity has been installed to compensate the mean energy loss induced by the internal target-beam interaction. 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 the GSI in Darmstadt [2] will be built as an antiproton cooler ring in the momentum range from 1.5 to 15 GeV/c. The circumference of the ring, figure 1, is 575 m with two arcs of length 155.5 m each.

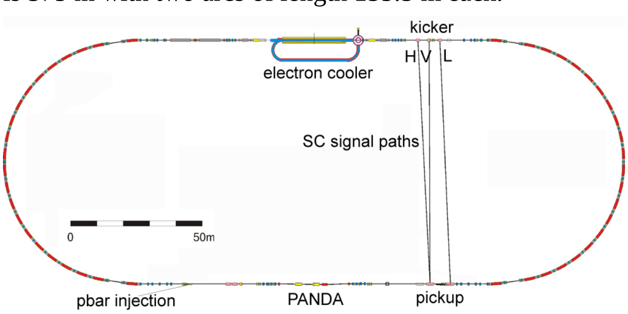


Figure 1: Layout of the HESR ring.

The long straight sections each of length 132 m contain the electron cooler and on the opposite side the Panda experiment. Cooled antiprotons [3] with 3 GeV kinetic energy are injected from the RESR [2]. The stochastic cooling tanks will be located in the long straights. One common pickup [4] is used for horizontal (H) and vertical (V) phase space cooling. A separate path is envisaged for momentum cooling (L).

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 compensate beam heating by the beam-target interaction. Much higher requirements have to be fulfilled 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 an rms-relative momentum spread down to about $4 \cdot 10^{-5}$.

Both, transverse and longitudinal cooling are foreseen at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. The already small initial beam emittances require a proper adjustment of the electronic gain to prevent beam blow up due to intra beam scattering. 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 and tested at COSY [4]. The filter cooling technique [5] is applied for longitudinal cooling in the momentum range above 3.8 GeV/c. Below 3.8 GeV/c the Time-Of-Flight momentum (TOF-) cooling technique [6] will be used.

## MOMENTUM EQUILIBRIUM VALUES

Stochastic cooling profits from the normal conducting HESR [7] lattice since it offers the possibility to vary the value of transition gamma between $6 \le \gamma_{tr} \le 30$ at all required energies while the horizontal and vertical tune can be kept at 7.6. In addition, the dispersion and its derivative can be adjusted to zero. The resulting frequency slip factor $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ is sufficient small to reduce unwanted mixing from pickup to kicker [8] in the case of filter cooling. 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 for filter cooling from

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

The bandwidth $W$ of the stochastic cooling system is centered at frequency $f_C$. The mean square relative momentum deviation per target traversal, $\delta_{loss}^2$, describing the beam-target interaction is directly proportional to the target area density. The formula assumes that the mean energy loss in the target is compensated e.g. with a barrier bucket cavity [4] and that there is no mixing from pickup to kicker [8]. Momentum equilibrium values with TOF cooling can be found from a similar equation

$$\delta_{eq,rms} \approx 0.283 \left( \frac{f_0^2 \ln \dfrac{2f_C+W}{2f_C-W}}{r^2 |\eta_{PK}|^2 W f_C} \cdot \frac{N f_0^2}{|\eta| W f_C} \delta_{loss}^2 \right)^{1/5} \quad (2)$$

in which the ratio from signal path length from pickup to kicker $s_{PK}$, to ring length *C*, is denoted by $r = s_{PK} / C$. The frequency slip factor from pickup to kicker is $\eta_{PK}$ and for the HESR $\eta_{PK} = \eta$.

## MOMENTUM COOLING RESULTS

The time development of the momentum distribution during longitudinal cooling and beam target interaction is found by numerically solving a Fokker-Planck equation (FPE) [8] 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 includes the complete cooling system, i.e., pickup and kicker characteristics, filters, amplifiers and contains not only the coherent cooling force but also the mean energy loss in the target leading to a strong shift (drift) 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 $\delta_{loss}^2$ are included. Details of the beam-target interaction are outlined in [9]. The simulations clearly showed that in the HESR the strong mean energy loss can not be compensated by the stochastic cooling system alone. A promising compensation mechanism seems to be the application of a barrier bucket cavity.

A large bandwidth and a high center frequency of the cooling system are necessary to reach small equilibrium values, eq. (1). However, the upper frequency is limited by unwanted Schottky band overlap for filter cooling. For both HESR operational modes a good compromise from a technical and theoretical point of view are the choice of a (2 – 4) GHz system. Additionally, the NC-lattice flexibility allows adjusting an optimum value for the frequency slip factor $\eta$. It is then possible to apply filter cooling for both operational modes of the HESR above 3.8 GeV/c. A future extension of the upper frequency limit to 6 GHz is worthwhile to further decrease the final beam momentum spread and to reduce the cooling down time to equilibrium. Strong unwanted mixing from pickup to kicker especially prevents filter cooling below 3.8 GeV/c in the HL-mode. In the low momentum range 1.5 GeV/c up to 3.8 GeV/c TOF cooling is envisaged. In this method the filter in the cooling chain is removed and the signal transit time from pickup to kicker is adjusted to the time-of-flight of a particle with nominal momentum. Furthermore a broadband 90 degree phase shifter is included in the cooling path. Mixing from pickup to kicker can now be used to discriminate between particles of different momenta. This method attains a larger cooling acceptance which is especially preferable for the HL-mode. Larger initial momenta can thus be cooled without particles losses. The main disadvantage of this method is however that due to the absence of the notch filter strong particle noise diffusion occurs in the distribution centre. The ensuing broadening is further enhanced by the slow phase change inherent to the TOF method. Consequently, equilibrium values according to eq. (2) are larger than those required specifically in the HR-mode. Another feature of TOF is that cooling is initially faster due to the positive beam feedback in the centre of the distribution. However a controlled reduction in gain is necessary to avoid instabilities in the cooling loop [10].

Table 1 and 2 summarize the momentum cooling performance for a (2 – 6) GHz system (Filter cooling) and a (2 – 4) GHz system (TOF cooling) for three energies. The tables include approximate numbers for the cooling down times $t_{eq}$ to equilibrium and the expected gain *G*. For $T > 5\ GeV$ optimal cooling is achieved with a lattice tuned to $\gamma_{tr} = 6$. Below 5 GeV a value of $\gamma_{tr} = 13$ leads to the smallest equilibrium values. However, in the HL-mode with filter cooling 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. In all cases of TOF cooling a lattice with $\gamma_{tr} = 6$ was chosen.

Table 1: Filter Cooling at three Kinetic Energies

| | 3 GeV | | 8 GeV | | 15 GeV | |
|---|---|---|---|---|---|---|
| | **HR** | **HL** | **HR** | **HL** | **HR** | **HL** |
| $\delta_{rms} \cdot 10^5$: | 5.1 | 14 | 5.4 | 12 | 3.9 | 9 |
| $t_{eq}$ [s]: | ≈60 | ≈600 | ≈150 | ≈600 | ≈150 | ≈600 |
| G [dB]: | 109 | 95 | 116 | 103 | 119 | 105 |

Table 2: TOF Cooling at three Kinetic Energies

| | 0.8 GeV | | 1.3 GeV | | 2.0 GeV | |
|---|---|---|---|---|---|---|
| | **HR** | **HL** | **HR** | **HL** | **HR** | **HL** |
| $\delta_{rms} \cdot 10^5$: | 11 | 19 | 14 | 23 | 20 | 32 |
| $t_{eq}$ [s]: | ≈10 | ≈200 | ≈150 | ≈500 | ≈250 | ≈800 |
| G [dB]: | 95 | 88 | 95 | 87 | 94 | 86 |

The Schottky particle power and the thermal noise power after filtering at the kicker entrance amounts up to 10 W each. For TOF cooling at the lowest energy, 0.8 GeV, pre-cooling of the momentum distribution at injection energy 3 GeV is necessary to avoid a too large initial momentum spread.

## BARRIER BUCKET SIMUALTIONS

It has been already demonstrated at COSY [4] with a 2.6 GeV/c proton beam that the mean energy loss induced by an internal pellet target similar to that coming into operation at HESR could be compensated and that the beam distribution could be cooled, figure 2.

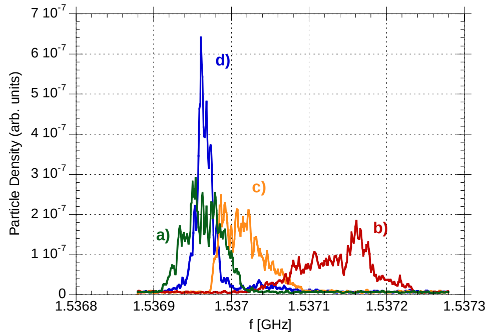


Figure 2: Schottky spectra of a COSY proton beam measured at the 1000th harmonic: a) initial distribution; b) final distribution after 160 sec only pellet-target, the energy loss led to a shift to higher frequencies since COSY was operated above transition; c) final distribution with longitudinal stochastic cooling only and d) final distribution with cooling and barrier bucket. The mean energy loss is compensated. Data are taken from ref. [4].

The mean energy loss was measured and yielded a target thickness of $N_T \approx 3 \cdot 10^{15}\ atoms / cm^2$. The synchrotron motion of particles in a barrier bucket has been investigated with a numerical tracking code including the beam-target interaction and stochastic momentum cooling. The measured barrier voltage equivalent to the potential displayed in figure 3 was included in the code.

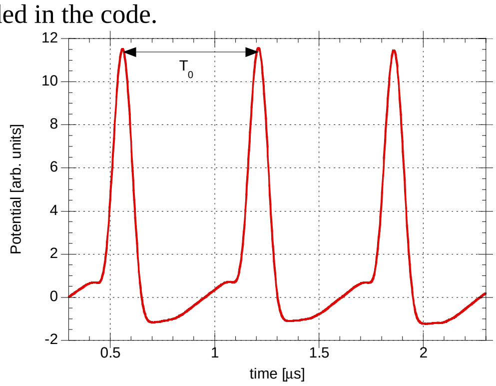


Figure 3: Potential of the synchrotron motion in the barrier bucket. The valley in the potential is due to a small bank of the voltage between the sinusoidal boundaries [4]. Here a large fraction of the particles can be captured if the momentum spread is sufficiently cooled down.

As a first result of the theoretical investigations figure 4 represents beam spectra at the initial time, after 60 s and 160 s during stochastic cooling and beam-target interaction. The calculated spectra correspond to the measured distributions in figure 2 and show the cooling effect when the target is on. The mean energy is kept constant by the barrier bucket and the beam distribution is cooled. Some particles losses are visible due to a slightly too small barrier voltage, similarly as observed in the experimental data [4].

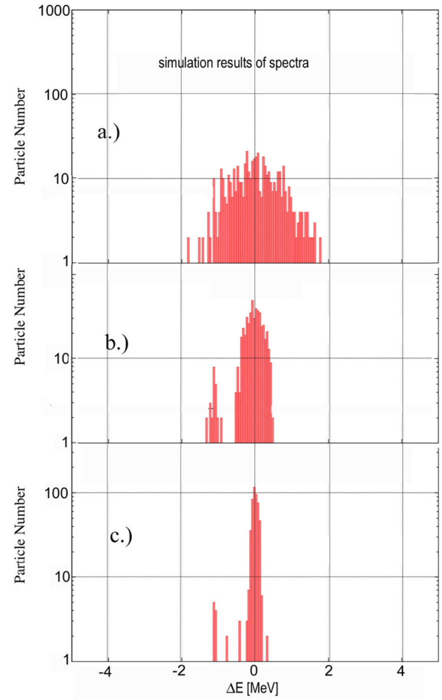


Figure 4: Predicted beam spectra at initial time (a.)), after 60 s (b.)) and after 160 s (c.)). Stochastic cooling and target are switched on.

The forthcoming experiments and theoretical investigations at COSY are dedicated specifically to TOF cooling. A barrier bucket operation and target will be included.

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