# Cooling Scenario for the HESR Complex

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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 stochastic cooling. Both cooling techniques are envisaged here theoretically, including the effect of beam-target interaction and intra-beam scattering to find especially for stochastic cooling the best system parameters.

**Keywords:** FAIR, electron cooling, stochastic cooling
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## 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 anti-proton cooler ring in the momentum range from 1.5 to 15 GeV/c. The basic racetrack layout of the HESR is shown in figure 1. 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. Two diagonal signal paths are foreseen for horizontal and vertical cooling. One of the systems will be used for longitudinal cooling. Two injection lines are envisaged, one coming from the RESR [2] to inject cooled anti-protons with 3 GeV kinetic energy and the other one to inject protons from SIS 18.

An important feature of the new facility is the combination of phase space cooled beams with internal targets. The desired beam quality and intensity is prepared in two operation modes: the *high luminosity mode* (*HL*) with a luminosity of $2 \cdot 10^{32}$ cm$^{-2}$ s$^{-1}$. The HL-mode is attained with $10^{11}$ anti-protons and a target thickness of $4 \cdot 10^{15}$ atoms cm$^{-2}$. The HL-mode has to be prepared in the whole energy range of the HESR 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 a luminosity of $2 \cdot 10^{31}$ cm$^{-2}$ s$^{-1}$ that can be attained with $10^{10}$ anti-protons and a target thickness of $4 \cdot 10^{15}$ atoms cm$^{-2}$. In this mode that is requested up to 8.9 GeV/c

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an anti-proton beam with a relative momentum spread down to $1 \cdot 10^{-5}$ has to be furnished.

To accomplish these goals this contribution discusses a possible scenario from a theoretical point of view in which electron cooling is applied in the HR-mode while a high bandwidth stochastic cooling system is utilized to provide the HL-mode over the entire momentum range of the HESR. The challenging and tough tasks in designing a 2 MeV electron cooler system at the cooler synchrotron COSY as an intermediate energy step towards the future high-energy magnetized cooler concept at the HESR is outlined in [3].

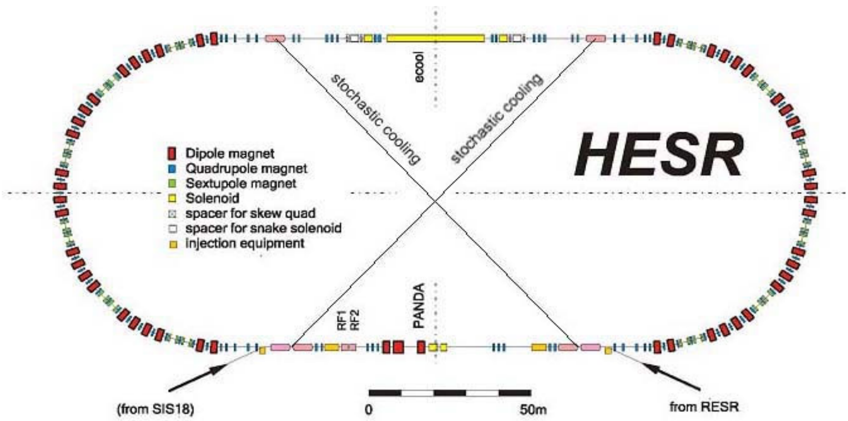


**FIGURE 1.** Basic layout of the HESR showing the electron cooler location and the signal paths for the stochastic cooling system. The PANDA experiment is located on the opposite side to the electron cooler.

## COOLING MODELS

Stochastic and electron cooling simulations has been carried out with the computer code BETACOOL [4]. In collaboration with the Joint Institute for Nuclear Research at Dubna, JINR, stochastic cooling simulation has been now added in the program. Transverse stochastic cooling [5] is applied in accordance with the theory that was published in [6]. The longitudinal Filter cooling technique [5] has been chosen for stochastic momentum cooling in the HESR. A revised theory that was originally outlined in [7] has been prepared and integrated in the program. The transfer functions of quarter wave loop pickups and kickers are implemented in the model. These functions are discussed in detail in [8, 9] and can be expressed analytically. The stochastic cooling model calculations allow to optimize the electronic gain to achieve the desired beam parameters in the HR- or HL-mode in the presence of an internal target and intra beam scattering. The number of pickup and kicker loop pairs can be optimized with respect to the available electronic power and space for the pickup and kicker tanks installations. The model also allows to optimize the system parameters with respect to the desired equilibrium beam parameters with analytical formulas.

All cooling simulations include intra-beam scattering (IBS) according to the Martini model [4]. The HESR lattice [10] 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 in detail in [11, 12].

Electron cooling simulations utilize the cooling force formula as evolved by V.V Parkhomchuk. The time development of tails which arise during electron cooling is accounted for by choosing the model beam option in BETACOOL [4]. The main electron cooler parameters as adopted in the HESR technical report [1] are listed in table 1.

**TABLE 1.** Electron Cooler Parameters

| | | |
|---|---|---|
| Beta function at cooler (h/v): | 100 | m |
| Cooling section length: | 30 | m |
| Electron beam radius: | 5 | mm |
| Electron beam current: | 1 | A |
| Electron beam density: | $2.7 \cdot 10^{8}$ | $cm^{-3}$ |
| Field homogeneity: | $1 \cdot 10^{-5}$ | |
| Transverse electron temperature: | 0.1 | eV |

During stochastic cooling the time development of the rms-emittances and the rms relative momentum spread of a nearly DC-beam is determined for a 2 GHz bandwidth system operating in the frequency range (2 – 4) GHz. The mixing from pickup to kicker is adjusted so that it plays no significant role. The basic parameters of the stochastic cooling system are summarized in table 2.

**TABLE 2.** Main Stochastic Cooling System Parameters

| | | |
|---|---|---|
| Beta function at pickup and kicker (h/v): | 75 | m |
| Number of PU and KI loop pairs: | 64 | |
| Electrode length, gap height and width: | 2.5 | cm |
| PU/KI length: | ≈ 3 | m |
| Impedance: | 50 | Ω |
| Cooled structures and eq. amp. temperature: | 80 | K |

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. Including safety margins the necessary electronic power is less than 500 W per plane. It should be pointed out that, due to band overlap, the longitudinal filter cooling method is only feasible for momenta above 3.8 GeV/c.

## HIGH RESOLUTION MODE

In general, the cooled anti-proton beam is injected at 3.8 GeV/c from the RESR. The beam is then electron cooled and accelerated to the desired experiment energy. Figure 2 shows a result of an electron cooling simulation for the HR-mode at p = 3.8 GeV/c (T = 3 GeV). The initital rms-emittance is 0.092 mm mrad in both planes and the relative rms-momentum spread is $1.5 \cdot 10^{-4}$. It is shown that the relative rms-momentum spread attains an equilibrium value of about $3.5 \cdot 10^{-5}$ after 10 s of cooling. At the same time the emittances reach an equilibrium. Note the effect of IBS. Initially, both emittances and momentum spread are decreasing during cooling. At about 5 s IBS becomes visible and leads to a minimal value for the relative momentum spread which slightly increases to the final value while the emittances attain an equilibrium. The horizontal equilibrium emittance, 0.0024 mm mrad, is larger than the vertical one, 0.00063 mm mrad, due to the fact that the mean horizontal beta function in the HESR lattice is smaller than the vertical one [1, 10]. The target is switched on at 22 s and has no visible effect on the equilibrium values. This means that IBS is the dominant mechanism at these low emittances.

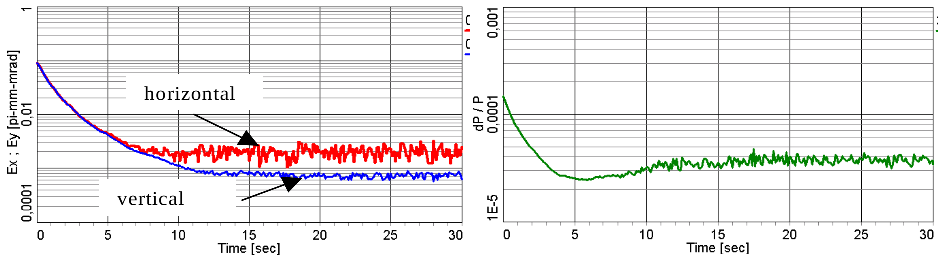


**Figure 2.** Time development of the rms-emittances (left figure) and relative rms-momentum spread (right figure) at T = 3 GeV. The equilibrium values are IBS dominated. A stable equilibrium relative momentum spread of about $3.5 \cdot 10^{-5}$ after 15 s of cooling is achieved.

The result of electron cooling at T = 8 GeV is drawn in figure 3. The beam is pre-cooled with electron cooling at injection energy. It is assumed that adiabatic shrinking of phase space during acceleration can be applied. The target is switched on at the experiment energy. A stable equilibrium relative rms-momentum spread of about $3 \cdot 10^{-5}$ is found in this simulation.

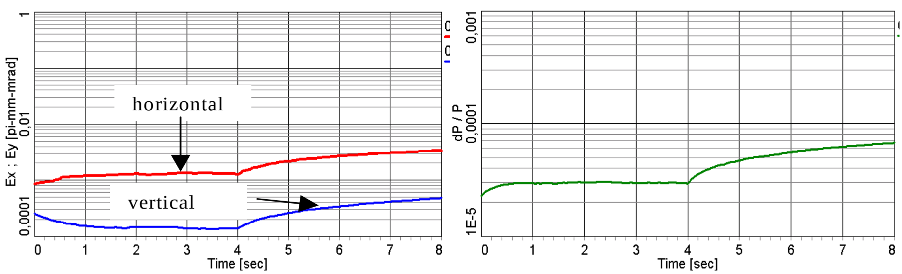


**Figure 3.** Time development of the rms-emittances (left figure) and relative rms-momentum spread (right figure) at T = 8 GeV. The equilibrium values are IBS dominated. A stable equilibrium relative momentum spread of about $3.0 \cdot 10^{-5}$ is achieved with electron cooling on. Beam heating is visible when electron cooling is switched off after 4 s.

In all cases above the final emittances attain tremendously small equilibrium values resulting in a beam that can be expected to be highly sensitive to perturbations. Moreover, to attain the necessary beam-target overlap with a Pellet target the beam emittance should be 1 mm mrad if the beta function at the target point is 1 m. Since electron cooling acts always on all phase planes simultaneously one possibility to circumvent such small emittances could be transverse beam heating. However simulations have shown that switching on a transverse noise source may lead to a significant beam loss due to an increasing transverse beam emittance.

## HIGH LUMINOSITY MODE

Simultaneously transverse and longitudinal stochastic cooling of a DC-beam at injection momentum 3.8 GeV/c with an internal target is shown in figure 4.

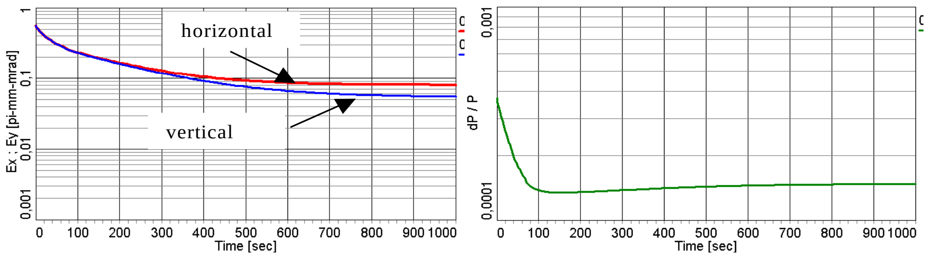


**Figure 4.** Time development of the rms-emittances (left figure) and relative rms-momentum spread (right figure) at T = 3 GeV. A stable equilibrium equilibrium momentum spread is attained after about 150 s. The rms-emittances becomes stable after about 800 s. The momentum acceptance of the machine is set to infinity.

The electronic gains have been adjusted independently to achieve the smallest equilibrium values. The figure demonstrates that target-beam heating can be significantly suppressed by stochastic cooling. The effect of IBS is also here visible however it is less pronounced as in case of electron cooling. Nevertheless it leads to slightly different final horizontal and vertical emittances. Transverse cooling is slower than the longitudinal one because of the reduction in momentum spread during transverse cooling. The wanted mixing from kicker to pickup is thereby reduced.

In the frame of this work detailed studies of small angle and energy straggling [11, 12] in the HESR energy range have shown that the dominant beam heating mechanism above 8.9 GeV/c due to an internal target is caused mainly by energy loss straggling. The emittance increase within a typical experiment run of one hour is less than a factor of two. Consequently it seems to be sufficient only to cool the longitudinal phase space above 8.9 GeV/c.

Table 3 lists the equilibrium relative momentum spreads that can be achieved for three different energies. Two cases have been studied. First, the momentum acceptance of the machine was assumed to be infinity, $\delta_{Cut} = \infty$, as in figure 4. In the second case the more realistic acceptance $\delta_{Cut} = 2 \cdot 10^{-3}$ was assumed. The simulation clearly demonstrates the sufficient damping of the target-beam interaction and IBS with stochastic cooling.

The table lists also the normalized gains $\sqrt{n_P n_K} G_A$ where $n_P$, $n_K$, $G_A$, denote the number of pickup and kicker loop pairs and the electron gain, respectively. Given the number of pickup loop pairs for a good signal-to-noise ratio at the pickup output the normalized gain allows to determine the number of kicker loop pairs if the power is limited. The table also contains the normalized gain expressed in the technical unit *dB*. $\delta_{rms,eq}$ denotes the equilibrium rms-momentum spread that is reached in approximately $t_{eq}$ seconds.

**TABLE 3.** Stochastic Cooling for the HL-Mode

| | | 3.9 GeV/c | 8.9 GeV/c | 14.9 GeV/c |
|---|---|---|---|---|
| Initial relative momentum spread: | $\delta_{rms,Ini} \cdot 10^4$: | 3.8 | 2.5 | 1.8 |
| $\delta_{Cut} = \infty$ | $\delta_{rms,eq} \cdot 10^4$: | 1.3 | 1.6 | 1.8 |
| | $t_{eq}$ [s]: | ≈ 150 | ≈ 150 | - |
| | $\sqrt{n_P n_K} G_A$ : | $0.64 \cdot 10^7$ | $2.0 \cdot 10^7$ | $3.6 \cdot 10^7$ |
| | *dB:* | 136 | 146 | 151 |
| $\delta_{Cut} = 2 \cdot 10^{-3}$ | $\delta_{rms,eq} \cdot 10^4$: | 1.0 | 0.94 | 0.9 |
| | $t_{eq}$ [s]: | ≈ 250 | ≈ 400 | ≈ 500 |
| | $\sqrt{n_P n_K} G_A$ : | $0.36 \cdot 10^7$ | $0.9 \cdot 10^7$ | $1 \cdot 10^7$ |
| | *dB:* | 131 | 139 | 140 |

# SUMMARY AND OUTLOOK

A possible cooling scenario has been discussed with respect to the desired high resolution and high luminosity modes at the future facility HESR. With electron cooling the HR-mode can be nearly fulfilled with respect to the desired momentum resolution. Further investigations however are needed to achieve the necessary beam-target overlap when a pellet target is used. In case of stochastic cooling it seems feasible to accomplish the HL-mode for kinetic energies above 3 GeV. A stochastic cooling system operating in the frequency range 2 to 4 GHz with a moderate power level seems to be sufficient. Since an emittance increase due to the beam-target interaction is less important above 8 GeV only longitudinal cooling is necessary in this energy range.

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