STOCHASTIC COOLING SYSTEM FOR HESR: THEORETICAL AND SIMULATION STUDIES

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Abstract

The High-Energy Storage Ring (HESR) is part of the upcoming International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. The HESR dedicates to the field of high-energy antiproton physics to explore the research areas of charmonium spectroscopy, hadronic structure, and quark-gluon dynamics with high-quality beams over a broad momentum range from *1.5* to *15 GeV/c*. High momentum resolution beams are mandatory for internal target experiments which are prepared with the well-established filter method in stochastic momentum cooling. This cooling technique will also be applied for antiproton accumulation in the HESR as well as in heavy ion beam cooling experiments with internal targets. Fast beam cooling is achieved with a *(2 – 4) GHz* system. In cases when the momentum spread exceeds the filter cooling acceptance the Time-Of-Flight (TOF) method, which is easily set up when filter cooling is already available, is applied to pre-cool the beam prior to filter cooling. To compare both cooling methods the basics of the theory is presented. Beam experiments at COSY are outlined to verify these aspects of the cooling theory.

INTRODUCTION

The HESR [1] has been originally designed for storage and acceleration of up to 10^{11} antiprotons for internal target experiments with high momentum resolution up to $\approx 1 \cdot 10^{-5}$ in the momentum range *1.5 GeV/c to 15 GeV/c*. Since in the modularized start version [1] the storage rings RESR and NESR are postponed the accumulation of the beam delivered by the CR has to be accomplished in the HESR itself. The well-established stochastic stacking method [2] is however not applicable. Instead a different method using moving barriers and stochastic filter momentum cooling is established [3] to accumulate 10^{10} antiprotons within *1000 s*. Recently, the feasibility of the HESR storage ring for the application of heavy ion beams with the special emphasis on the experimental program of the SPARC collaboration at FAIR has been investigated in detail [4]. The magnetic rigidity range $5Tm \le B\rho \le 50Tm$ allows the storage of $^{132}Sn^{50+}$ and $^{238}U^{92+}$ ions in the kinetic energy range *165 MeV/u* up to ≈ *5 GeV/u*.

Both, transverse and longitudinal cooling is available at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. The highest demands are made on longitudinal cooling, especially in the high momentum resolution mode. To fulfil this goal the bandwidth of the cooling system will be *(2 – 4) GHz* with the extended option of *(2 - 6) GHz* in a later stage [5]. High sensitive pickup/kicker structures have been developed and tested at COSY [5]. The filter cooling technique [6] 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 [7] will be used.

MOMENTUM COOLING METHODS

Stochastic momentum cooling is described with the Fokker-Planck Equation (FPE) [6]

$$\frac{\partial \Psi}{\partial t} = -\frac{\partial}{\partial \delta}\left[F\Psi - D\frac{\partial \Psi}{\partial \delta} \right] \quad (1)$$

for the time evolution of the momentum distribution $\Psi(\delta,t)$ of ions with relative momentum deviation δ. The explicit expressions for the drift *F* describing cooling and diffusion *D* depend on the cooling method.

In the Filter cooling method a pickup in sum mode measures the beam current and the discrimination of particles with different momentum deviations is obtained by inserting a notch filter and a *90* degree phase shifter in the signal path before it drives a kicker in sum mode. Besides pre-amplifiers and power amplifiers a variable delay is available to adjust the signal transit time from pickup to kicker to the time-of-flight of a particle with nominal momentum. The basic system arrangement is illustrated in figure 1.

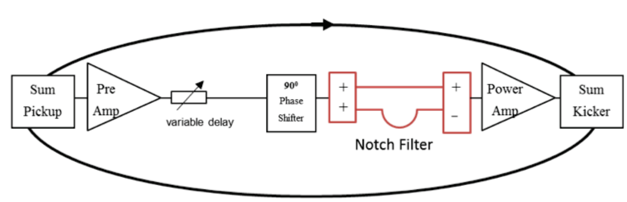

Figure 1: Basic system configuration for filter cooling.

A severe restriction in the practical cooling bandwidth comes from mixing between pickup and kicker. Large mixing from pickup to kicker will reduce the maximum momentum spread that can be cooled for a given upper cooling frequency without particle losses. Figure 2 illustrates a simulation [8] for an antiproton beam at *3.8 GeV/c* in the HESR with 10^{10} particles. The electronic gain is *110 dB*. The relative momentum spread is $5 \cdot 10^{-4}$. It shows the drift term (the energy change per second a particle receives at the kicker due to its on momentum

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deviation at the pickup) in FPE for filter method (red curve) neglecting beam feedback. Particles that are outside the cooling acceptance indicated by the arrow will be heated and will be subsequently lost.

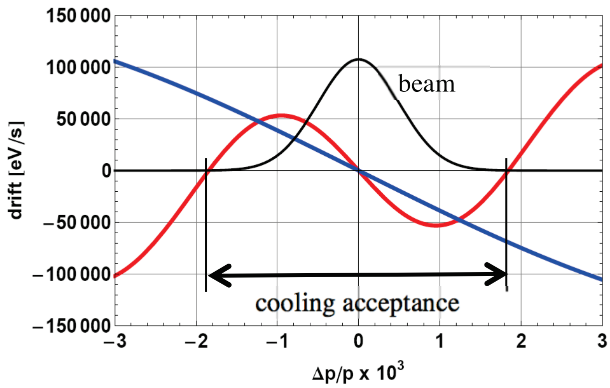

Figure 2: Drift term for filter (red) and TOF (blue) cooling for the same gain of *110 dB*. The cooling acceptance for filter cooling is indicated by an arrow. TOF cooling possesses a much larger cooling acceptance.

The advantage of the filter method is that Schottky particle noise and thermal electronic noise is substantially suppressed in the centre of the particle momentum distribution as is shown in figure 3, red curve.

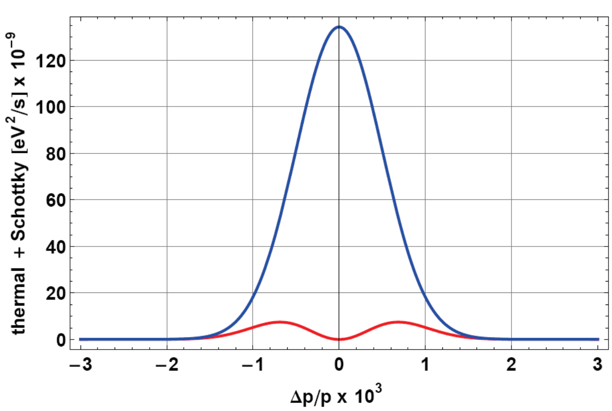

Figure 3: The diffusion term for filter cooling (red) show the suppression of thermal and Schottky noise in the center of the beam distribution. For the same gain the diffusion in TOF cooling (blue) is much larger. There is no suppression.

Strong unwanted mixing from pickup to kicker especially prevents filter cooling of antiprotons below *3.8 GeV/c*. In the low momentum range *1.5 GeV/c* up to *3.8 GeV/c* TOF cooling is therefore envisaged. TOF cooling is also applied in the heavy ion mode of the HESR at injection energy *740 MeV/u* [4]. In this method the filter in the cooling chain is opened as indicated in figure 4 and the signal transit time from pickup to kicker is adjusted with the same delay as applied for filter cooling to the time-of-flight of a particle with nominal momentum. As compared to filter cooling an additional *180* degree phase shifter is necessary to obtain cooling. Mixing from pickup to kicker can now be used to discriminate between particles of different momenta [8]. In figure 2 it is visible that the drift term for TOF cooling (blue curve) at *3.8 GeV/c* with the same electronic gain possesses a significantly larger cooling acceptance as filter cooling. However, the diffusion is much larger as is shown in figure 3. To avoid too much heating a reduced electronic gain has to be chosen in order to achieve cooling. Since thermal and Schottky noise heating is not suppressed in the center of the beam distribution the cooling time and the achievable beam equilibrium momentum value will be larger [8].

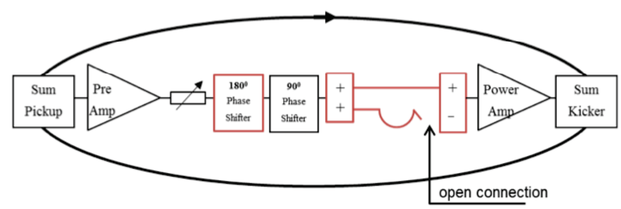

Figure 4: System configuration for TOF cooling.

A detailed analysis [8] shows that the range where the drift term either for filter or TOF cooling depends almost linearly on the relative momentum spread $\delta = \Delta p/p$ can be estimated by the expressions for

Filter cooling: *TOF cooling:*

$$|\delta| < \frac{f_0}{2|\eta + 2r\eta_{PK}| \cdot f_+} \quad \text{and} \quad |\delta| < \frac{f_0}{2|2r\eta_{PK}| \cdot f_+}.$$

The frequency slip factor from pickup to kicker is denoted by η_{PK} and for the whole ring by η. The revolution frequency is f_0. The ratio of the nominal particle travelling time from pickup to kicker to the revolution period is given by r. For filter cooling both slip factors contribute resulting in a smaller cooling acceptance as compared to TOF cooling. Increasing the upper frequency limit f_+ of the cooling system decreases the linear range and the cooling acceptance.

In recent beam experiments at COSY it could be demonstrated that TOF cooling has the larger cooling acceptance as predicted by the cooling model and that it is an appropriate technique to pre-cool the beam prior to filter cooling if the initial momentum spread exceeds the cooling acceptance of filter cooling [9].

BEAM EXPERIMENTS AT COSY

A full description of stochastic cooling has to take into account that the cooling system forms a feedback loop via the beam and has therefore to include the beam transfer function from kicker to pickup. Optimal cooling is only achieved if the system gain and phase of the feedback loop is adjusted appropriately at each harmonic in the cooling bandwidth. For filter cooling it is well-known that cooling is obtained if at each harmonic the open loop gain is adjusted as shown in figure 5 for a proton beam at

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2.4 GeV/c on COSY. The band II *(1.8 – 3) GHz* momentum cooling system is used. The measurement displays the Nyquist diagram (blue curve) of the open loop gain S at one harmonic in the cooling bandwidth. The figure also displays the magnitude of the open loop gain (yellow curve) showing the suppression of Schottky and thermal noise in the center of the distribution. The delay is adjusted for cooling. The gain is however below the optimal one where noticeable signal suppression [8] in filter cooling is observed. The cooling loop is stable since the real part of the open loop gain S is well below one.

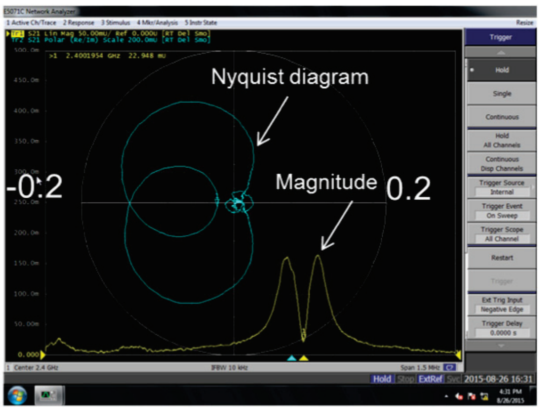

Figure 5: Nyquist diagram of the open loop gain for filter cooling (blue). The magnitude (yellow) of the open loop gain shows the suppression due to the notch filter.

The resulting momentum cooling of 10^9 protons is displayed in figure 6. The filter notch depth is *30 dB*. The initial distribution is shown in blue and the equilibrium distribution is shown in yellow after 300 s cooling.

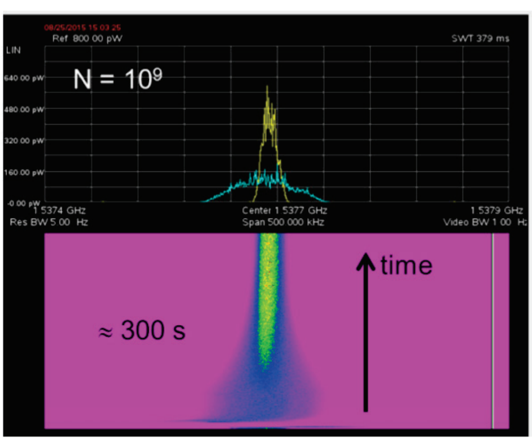

Figure 6: Filter momentum cooling.

TOF cooling has been investigated at *2.6 GeV/c* since at this slightly larger momentum the frequency slip factor is larger and thus more mixing from pickup to kicker is achieved. The open loop gain measurement is depicted in figure 7. As compared to filter cooling Schottky and thermal noise are not suppressed in the center of the distribution as shown by the magnitude of the open loop gain (yellow trace) in figure 7.

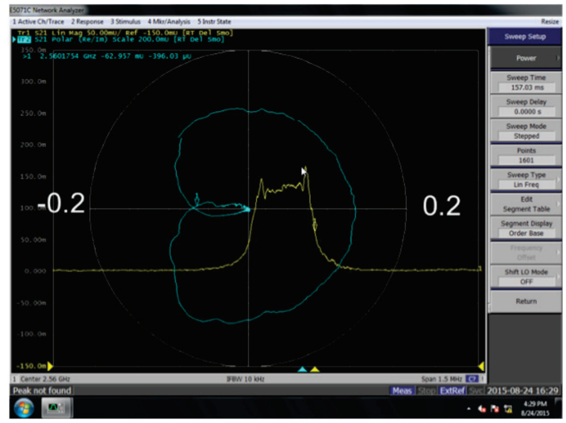

Figure 7: Nyquist diagram of the open loop gain for TOF cooling (blue). The magnitude of the open loop gain is shown in yellow.

The real part of the open loop gain now extends into the right hand plane of the Nyquist plot. The system gain must be reduced in order to stay with the open loop gain well below the critical point (1, 0) in the Nyquist plot. Heating the beam, e.g. with an internal target, leads similarly to a stable cooling loop [8].

The measurement of the open loop gain for TOF cooling at COSY, figure 7, confirms the model prediction for the HERS cooling system presented in figure 8 at harmonic number *5927*. The same beam and system parameters as for figure 2 and 3 have been used. To obtain a stable cooling loop during cooling the electronic gain was reduced from *110 dB* to *98 dB*.

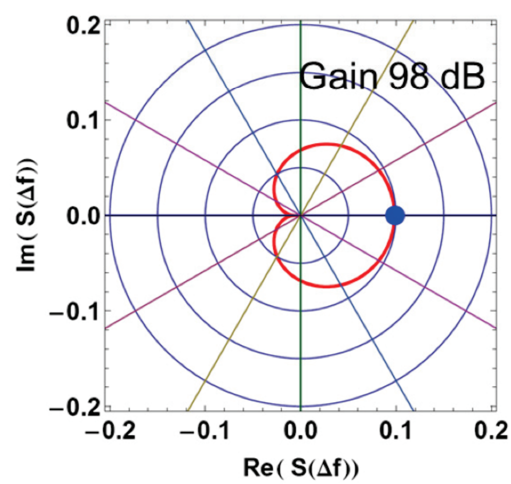

Figure 8: Simulated Nyquist plot of the open loop gain S for TOF cooling at *3.8 GeV/c* in the HESR. The gain is reduced from *110 dB* to *98 dB* to obtain stable cooling.

Beam feedback modifies the drift term F in the FPE, eq. (1), at each harmonic in the cooling bandwidth of the cooling system by the real part of $1/(1-S)$ and the diffusion term D by $1/|1-S|^2$. The impact of the beam feedback on the drift and diffusion terms is shown in figure 9.

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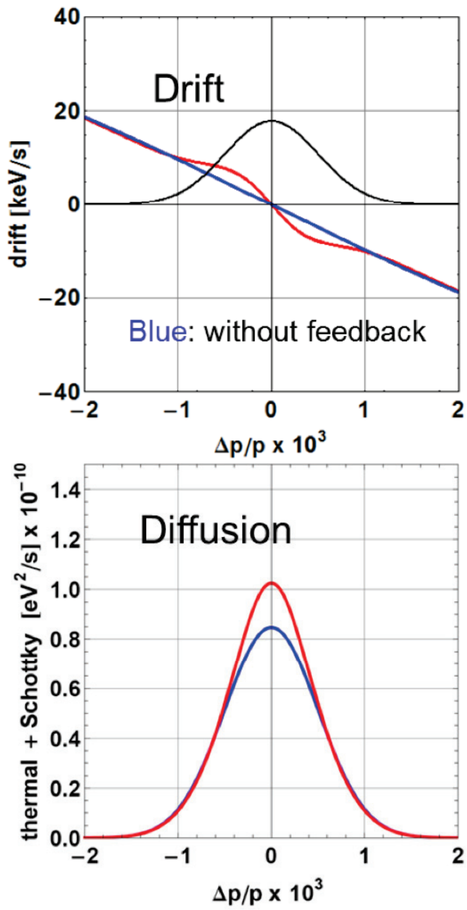

Figure 9: Drift and diffusion term in the FPE for TOF cooling with (red) and without (blue) beam feedback.

Compared to filter cooling no signal suppression is observed in TOF cooling. Instead a signal enhancement is visible which leads to an increase of the drift term in the center of the distribution which vanishes towards the edges of the beam distribution as is depicted in the upper panel of figure 9. Simultaneously, the diffusion is increased in the center of the distribution.

The initially heated beam distribution with a relative momentum spread of $1 \cdot 10^{-3}$ develops during TOF cooling with the reduced electronic gain as presented in figure 10.

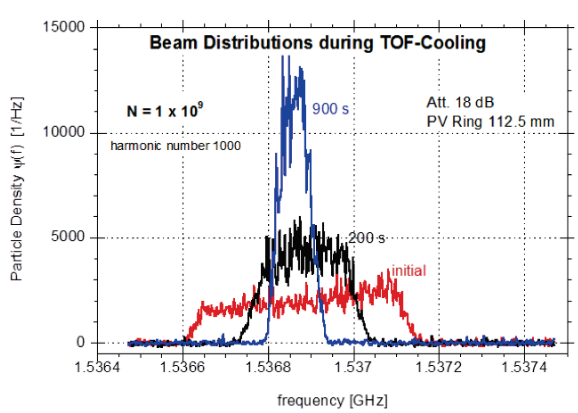

Figure 10: TOF cooling of an initially heated beam.

The experimental result in figure 10 is compared with a simulation shown in figure 11. The predictions reveal in accordance with the results shown in figure 9 that beam feedback has no significant impact on TOF cooling due to the reduced gain and the initially increased momentum spread of the beam distribution.

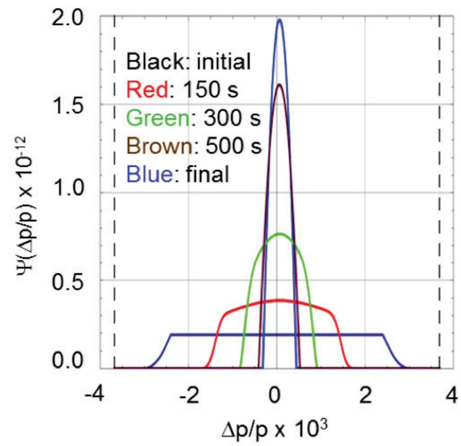

Figure 11: Simulated beam distributions during TOF cooling of an initially heated beam.

In figure 12 the rms-relative momentum spread versus time as predicted by the model is compared with the measurement results. It is visible that the model predicts fairly well the beam equilibrium value. It is also visible that the equilibrium value does not depend on the initial value of the momentum spread.

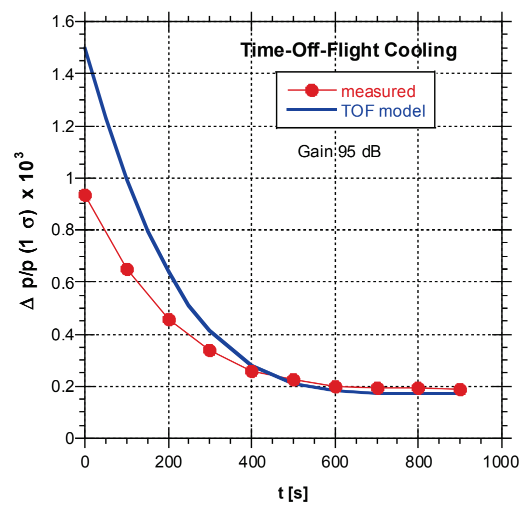

Figure 12: Model prediction of the relative momentum spread versus time during TOF cooling compared with the measurement.

The delay in TOF cooling must be adjusted very carefully in order to avoid a shift of the average momentum of the final momentum distribution. A change of the cooling system delay length by $+7.5$ *mm* results in a shifted final beam frequency distribution as shown in figure 13. This corresponds to a shift of the average final

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momentum to a larger value since the working point of the machine is above transition energy

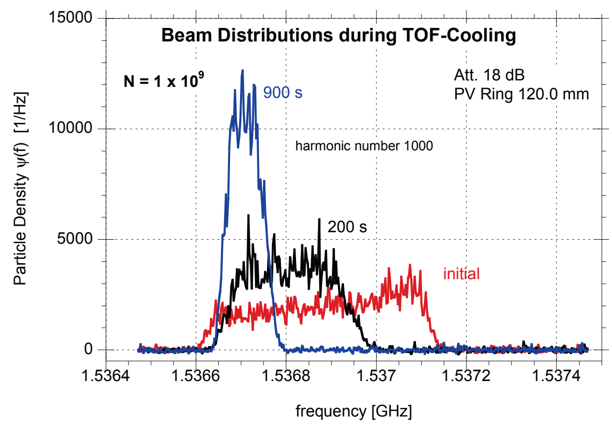

Figure 13: TOF cooling as in figure 10 but with a delay length change of *+7.5 mm*.

A simulation of TOF cooling with a delay length change of *–11 mm* is depicted in figure 14. It is visible that the shortening of the delay length for the machine working point above transition energy leads to a decrease of the average momentum in the final momentum distribution.

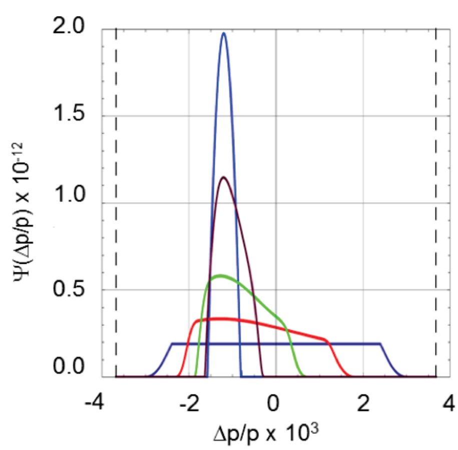

Figure 14: TOF cooling as in figure 11 but with a system delay length reduced by *-11 mm*.

Comparing the final distributions in figure 11 and 14 one notices that a delay length change only alters the final momentum. The final momentum spread does not change.

The experiments as well as the model predictions for TOF cooling demonstrate the possibility to vary the final momentum spread similarly as in filter cooling by changing the notch frequency. The mean energy loss due to an internal target with a moderate target thickness can thus be biased by a delay change prior to cooling likewise as in filter cooling by adjusting the notch frequency appropriately.

SUMMARY

Strong filter momentum cooling in the HESR for antiproton beam accumulation and internal target experiments with antiproton or ion beams is accomplished with a *(2 – 4) GHz* with the future upgrade option to extend the upper frequency limit to *6 GHz*. A detailed comparison of the theory of TOF and filter cooling including beam feedback has been worked out. The theoretical predictions are compared to the experimental cooling studies carried out at COSY. The beam cooling experiments at COSY confirm that the TOF cooling is easily established when filter cooling is already installed. The Palmer cooling method [6], which possesses a larger cooling acceptance as compared to filter cooling, cannot be implemented in the HESR due to cost and space restrictions. The TOF cooling technique thus plays a major role in the HESR for cases where the initial momentum spread exceeds the filter cooling acceptance and pre-cooling is essential prior to filter cooling.

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