

STOCHASTIC COOLING DEVELOPMENTS FOR HESR AT FAIR

H. Stockhorst, R. Maier, D. Prasuhn, R. Stassen, Forschungszentrum Juelich GmbH, Germany,
C. Dimopoulou, A. Dolinskii, T. Katayama, Yu. A. Litvinov, M. Steck, T. Stöhlker,
GSI Darmstadt, Germany

Abstract

The option of heavy ion stochastic momentum cooling is investigated under the constraint of the present concept of the HESR. The simulations include the beam-target interaction due to a Hydrogen and Xenon target at injection energy 740 MeV/u and at 2 GeV/u . The capability of momentum Filter cooling is envisaged and at lower energies where the revolution harmonics begin to overlap the possibility of TOF cooling is examined.

INTRODUCTION

The High-Energy Storage Ring (HESR) [1] of the future International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt is designed as an antiproton cooler ring in the momentum range from 1.5 to 15 GeV/c . The major tasks are antiproton beam accumulation by means of moving barrier buckets and stochastic cooling in order to provide dense phase space cooled beams for the PANDA internal target experiment.

Since the new storage rings, NESR and RESR are postponed in the modularized start version of the FAIR project, proposals were tabled to prove the feasibility of the HESR storage ring for the application of heavy ion beams with special emphasis on the experimental program of the SPARC collaboration at FAIR. The study of the dynamics of highly relativistic ion-atom collisions requires internal targets and cooled ion beams. Stable or radioactive ions stochastically pre-cooled in the collector ring CR will be extracted from the CR and injected into the HESR at 740 MeV/u . The magnetic rigidity range up to 50 Tm allows the storage of $^{132}\text{Sn}^{50+}$ and $^{238}\text{U}^{92+}$ ions in the kinetic energy range 740 MeV/u to 4 GeV/u . In this study a bare $^{238}\text{U}^{92+}$ beam with $N = 10^8$ ions is injected with an initial relative momentum spread $\delta_{rms} = 1 \cdot 10^{-4}$ and a horizontal as well as vertical emittance $\epsilon_{rms} = 0.125 \text{ mm mrad}$. Adiabatic phase space damping with a dilution of 25 % is applied when the ion beam is accelerated to higher energies. The lattice has been optimized for internal target experiments and stochastic antiproton cooling with $\gamma_r = 6.23$.

The application of the new 2 MeV electron cooling system, presently under construction for COSY [2], to heavy ion cooling has been complementary studied in detailed separate contributions [3, 4].

MOMENTUM COOLING MODEL

In the HESR a (2 - 4) GHz cooling system is foreseen to cool the transverse and longitudinal phase space [5]. For momentum cooling with internal target operation a

Fokker-Planck equation (FPE) for the particle energy or momentum distribution $\Psi(E, t)$

$$\frac{\partial}{\partial t} \Psi(E, t) = \frac{\partial}{\partial E} \left[-F(E, t) \Psi(E, t) + D(E, t) \frac{\partial}{\partial E} \Psi(E, t) \right]$$

is solved numerically. The drift term $F(E, t)$ includes the cooling action. It contains the pickup and kicker response as well as the electronic transfer function (filters, phase shifters) of the cooling system from pickup to kicker. The mean energy loss of the ions introduced by the target contributes an additional drift term. Schottky particle noise and thermal noise of the cooling system add to an incoherent heating of the beam. These effects appear in the diffusion term $D(E, t)$ in the FPE. The Schottky noise diffusion term depends on the instantaneous beam distribution. The beam-target interaction implies a further diffusion due to the mean squared momentum deviation per target traversal. The contribution of intra beam scattering shares in the diffusion term. In the HESR the Filter [6] and Time-of-Flight (TOF) [7] cooling techniques will be applied. Both methods are routinely operated at COSY [8]. The present investigation does not include feedback via the beam [9] since the beam target interaction and IBS are expected to influence cooling much stronger.

SIMULATION RESULTS

Momentum cooling of a $^{238}\text{U}^{92+}$ beam with $N = 10^8$ ions with a kinetic energy 740 MeV/u and 2 GeV/u interacting with either an internal Hydrogen or a Xenon target is investigated. To achieve high luminosities in the experiments, targets of large densities are envisaged. However, the choice of the target thickness also strongly depends on the ion beam life time. The ion beam-target interaction can lead to severe particle losses due to charge exchange reactions. As has been shown [3] the particle life time is expected in the order of minutes for an uranium beam at 2 GeV/u interacting with a ^{134}Xe ($Z = 54$) target with a thickness of $1 \cdot 10^{14} \text{ p/cm}^2$ while at 740 MeV/u the life time will be in the order of several tens seconds. In this case the target density used in the present study is decreased to $1 \cdot 10^{13} \text{ p/cm}^2$ to achieve a beam life time that is larger than the cooling down time. The effect of a Hydrogen target with a thickness of $4 \cdot 10^{15} \text{ p/cm}^2$ as used for the PANDA experiment is treated at 740 MeV/u . The simulation shows that the major contribution to a beam quality dilution stems from the strong mean energy loss of the ions in the target. In addition intra beam scattering results in a strong beam diffusion that significantly determines the achievable beam equilibrium momentum spread.

Beam Target Interaction

Besides charge exchange reactions the ion beam target interactions [10] result in a mean energy loss and energy loss straggling that limits the beam life time and requires therefore strong phase space cooling.

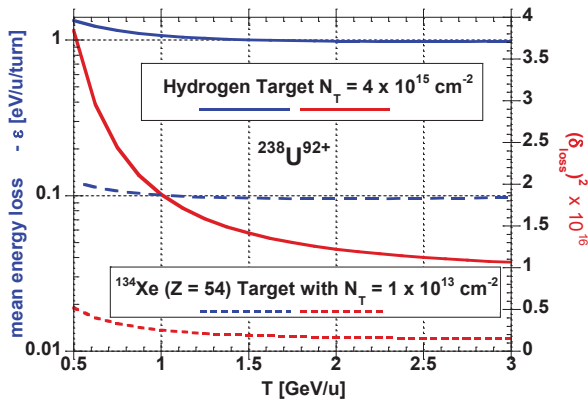


Figure 1: Mean energy loss (eV/u/turn) and mean square momentum deviation per turn for a uranium beam interacting with a Xenon target (dotted curves) with $1 \cdot 10^{13} \text{ p/cm}^2$ or an hydrogen target with $4 \cdot 10^{15} \text{ p/cm}^2$.

In addition multiple small Coulomb angle scattering in the target can lead to an emittance blow-up of the beam. To keep the emittance increase per turn small the target is located at the PANDA position with almost zero dispersion and a betatron function in both planes with $\approx 1 \text{ m}$ amplitude to guarantee a good beam target overlap. For the case of a different target location see [3]. Figure 1 shows the mean energy loss per turn and the mean squared momentum deviation per turn for a ^{134}Xe ($Z = 54$) and for a Hydrogen target. The mean energy loss per nucleon and turn ε in the target contributes to the FPE with a constant drift term which to first order scales as $F_T \propto \varepsilon \propto Z^2 Z_T N_T / A$ where Z is the projectile charge number, Z_T the target charge number, N_T the areal target thickness and A the mass number of the projectile. The target diffusion D_T is proportional to the mean squared relative momentum deviation per target traversal δ_{loss}^2 and results in a widening of the beam distribution. The diffusion term scales as $D_T \propto Z^2 Z_T N_T / A^2$. In both cases the emittance increase per turn amounts less than $4 \cdot 10^{-9} \text{ mm mrad/turn}$ and is thus negligible.

Intra Beam Scattering

Intra beam scattering (IBS) due to the Coulomb interaction of the ions in the beam becomes an important issue specifically for heavy ions since the rates are proportional to Z^4/A^2 . The calculations apply the Martini model as outlined in [11]. The HESR lattice is utilized with $\gamma_{tr} = 6.23$ and $Q_x = Q_y = 7.2$. The optimized beta function at the PANDA location is $\beta_x = \beta_y = 1 \text{ m}$. The dispersion in the long straights is zero for optimal target operation and stochastic cooling application. Figure 2

shows the growth rate $1/\tau_p = (d\sigma_p^2/dt)/\sigma_p^2$ for the relative momentum spread σ_p for the two kinetic energies of the uranium ions. It is assumed that the initial emittance as indicated in the figures is kept constant. The figure indicates that the emittance growth rates are rather small.

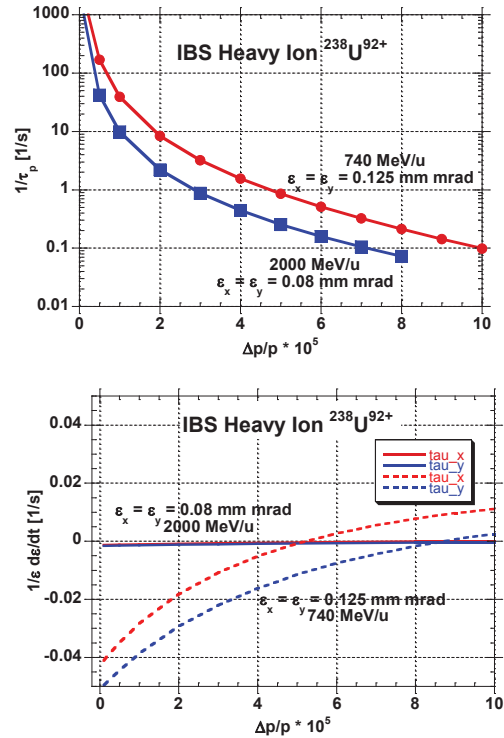


Figure 2: IBS rates. Upper figure: Momentum growth rate at indicated energies and emittances of the ion beam. Lower figure: Horizontal (τ_x) and vertical (τ_y) emittance growth rates.

Momentum Cooling Results

Stochastic momentum cooling in the HESR applies the Filter technique for fast antiproton cooling at higher energies [12]. However at lower energies severe problems result from the unwanted mixing from pickup to kicker determined by both, the frequency slip factor from pickup to kicker and that for the whole ring. In addition strong beam target and IBS effects complicate stochastic cooling. Figure 3 clearly demonstrates the restricted cooling acceptance of the cooling force for Filter cooling at 740 MeV/u due to unwanted mixing. Particle loss due to heating is unavoidable. A practicable solution would be to make use of the larger cooling acceptance in TOF cooling as is visible in Figure 3. However, due to the absence of the notch filter, particle and thermal noise diffusion now contribute also in the beam core leading to larger final momentum spreads. As compared to the Filter method TOF cooling requires a smaller system gain [8, 9]. The energy distributions of a uranium ion beam interacting with a hydrogen target with the density $4 \cdot 10^{15} \text{ p/cm}^2$ are depicted in Figure 4 during cooling at $t = 0$ (black), 0.4 s (red), and at $t = 3 \text{ s}$ (blue) when an equilibrium is reached.

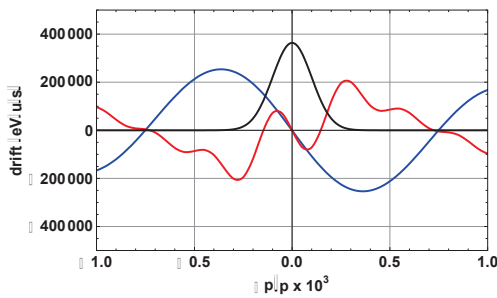


Figure 3: Cooling drift terms for the Filter (red) and TOF (blue) method at 740 MeV/u for the same electronic gain in comparison with the initial uranium beam distribution. The larger cooling acceptance of TOF cooling is visible.

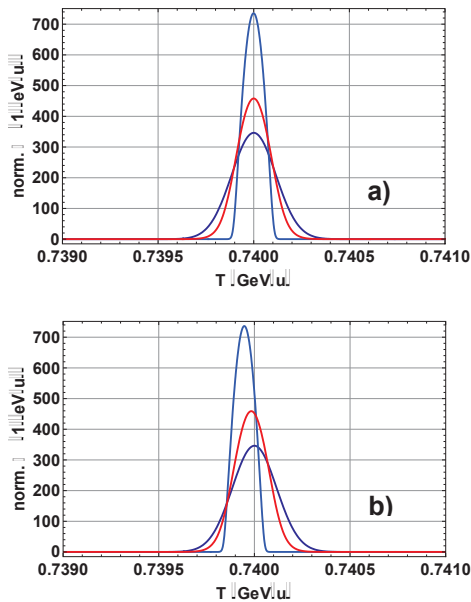


Figure 4: Uranium energy distributions during cooling at $t = 0$ s (black), 0.4 s (red) and final equilibrium at $t = 3$ s. Hydrogen target thickness $4 \cdot 10^{15} p/cm^2$. Mean energy loss compensated with BB cavity (a). The mean energy loss is compensated with stochastic cooling alone if the target thickness is reduced to $4 \cdot 10^{14} p/cm^2$ (b).

It turned out that in this case the strong mean energy loss could not be compensated by stochastic cooling alone, figure 4a. It is therefore necessary to compensate it by the HESR barrier bucket cavity [5] with a peak voltage of about ± 2 kV. The final relative momentum spread attains $\delta_{rms} = 4 \cdot 10^{-5}$ after 3 s. If the target thickness is reduced by a factor of ten the mean energy loss in the target can be compensated by stochastic cooling alone as depicted in Figure 4b. The beam center energy is slightly shifted downwards.

Inspecting Figure 1 one observes that a hydrogen target of thickness $4 \cdot 10^{14} p/cm^2$ yields almost the same beam target interaction as the Xenon target with $1 \cdot 10^{13} p/cm^2$. One can therefore expect the same cooling results as shown in Figure 4 in that case. The beam equilibrium

value is almost the same because it is predominantly determined by IBS alone. Stochastic ion beam cooling becomes more relaxed at higher energies. Albeit the mean energy loss gives still a major contribution in the beam target interaction the diffusion due to IBS scattering rates and mean squared momentum deviation in the target drop significantly as is visible in Figures 2 and 3. Moreover, due to the smaller initial momentum spread and the smaller frequency slip factors fast Filter momentum cooling is now applicable leading to the results compiled in table 1 for a $^{238}\text{U}^{92+}$ beam with $N = 10^8$ ions. Schottky and thermal noise power at the kicker entrance are less than 30 W. Including a safety factor 4 to 10 due to the statistical nature of the cooling signals the required electronic power does not exceed the power of 500 W as foreseen for momentum cooling in the HESR [5].

Table 1: Beam Equilibrium and Cooling Down Time

T [MeV/u]	Target/density [p/cm^2]	$\Delta p/p_{rms}$, equilibrium	cooling down time t_{EQ} [s]	cooling method
740	$\text{H}_2/4 \cdot 10^{15}$ $\text{Xe}/1 \cdot 10^{13}$	$4 \cdot 10^{-5}$	3	TOF
2000	$\text{H}_2/4 \cdot 10^{15}$ $\text{Xe}/1 \cdot 10^{14}$	$2 \cdot 10^{-5}$	2	Filter
3000	$\text{H}_2/4 \cdot 10^{15}$ $\text{Xe}/1 \cdot 10^{14}$	$3 \cdot 10^{-5}$	5	Filter

CONCLUSION

Stochastic momentum cooling of a bare $^{238}\text{U}^{92+}$ beam interacting with a Xenon or Hydrogen target has been investigated under the constraint of the present HESR design concept. The results are promising in view of an extension to employ the HESR also for a heavy ion research program of FAIR in its modularized start version. Furthermore, a combined electron and stochastic cooling could be a future option from which both anti-proton and ion research at the HESR can benefit.

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