FAST STOCHASTIC COOLING OF HEAVY IONS AT THE ESR STORAGE RING

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Abstract

Since the completion of the installation of pick-up and kicker tanks in the ESR, stochastic cooling in all phase space dimensions has been demonstrated with rather short cooling times. New RF components were added. The system is now ready for experiments with secondary beams. The momentum sensitivity of the pick-up electrodes was measured. The ability of the Palmer cooling system to cool beams with a maximum momentum spread of ± 0.7 % was demonstrated. After injecting an uncooled primary argon beam from the SIS synchrotron, e-folding cooling times of 0.86 s in the longitudinal phase plane and 1.6 s in the horizontal plane were measured with $5 \cdot 10^6$ injected particles. These values are close to theoretical expectations. In a first experiment with uranium, the shortest cooling times have been below 0.5 s in both the longitudinal and vertical phase planes. The system cools the complete injected beam without beam loss. An experiment with beam accumulation following stochastic precooling was performed successfully. The resulting equilibrium phase space densities are high enough to be followed by fast electron cooling of the stack.

1 HARDWARE STATUS

After first momentum cooling experiments using the signal path between the northern and southern dipoles [1], the pick-up tank in the north-west corner inside quadrupole E01QS2F and the kicker tank in the south-east corner (quadrupole E02QS2F) were added. The path between these serves for momentum and vertical betatron cooling, whereas the older one between the dipoles is finally used for horizontal betatron cooling, as originally intended [2].

Each of the 4×8 pick-up superelectrodes at E01QS2F has been equipped with a low-noise preamplifier ahead of the signal combiner, in order to increase the Schottky signal-to-noise ratio and facilitate system diagnosis. All preamplifiers can be turned on and off separately via their power supply. A similar installation is planned for the horizontal pick-ups in late 2000. In addition to the coaxial lines with variable length (needed for exact synchronization between beam and signal) phase shifters have been inserted in each path of the cooling system which impose a *frequency-independent* shift in the phase of the transmission function. These devices were developed in a collaboration with the Fachhochschule Dieburg [3]. The fast cooling rates reported below would not have been reached without this installation.

Some modules inside the longitudinal kicker still suffer from too large reflection due to unreliable contacts in their signal path. They have therefore been turned off. The reason for this failure is still unclear and will be investigated during the next shutdown period.

2 COMMISSIONING EXPERIMENTS

2.1 General procedure

As in previous experiments [1], commissioning was performed at a specific energy of 391 MeV/u. Cooling in all three phase space planes was observed. The narrowing of the Schottky bands around harmonics of the revolution frequency is used for the diagnostis of momentum cooling. Vertical and horizontal betatron cooling are verified by the decreasing Schottky power of betatron sidebands. As well, horizontal betatron cooling is shown by measurement of the horizontal beam width using a residual gas ionization monitor.

The beam position at the pick-ups and the kickers can be centered by appropriate orbit corrections. The Schottky signal is used for diagnosis of the beam position at the pick-ups, the position at the kickers is optimized by measurement of beam transfer functions (BTF's).

2.2 Sensitivity measurements

An electron-cooled argon beam was used to test the sensitivity of the superelectrodes as a function of the beam orbit. Beam momentum was controlled by changing the energy of the electron beam. Each of the superelectrodes at the pick-up equipped with separately switchable preamplifiers was measured. By using a bolometric measurement technique the frequency-integrated sensitivity was determined. In relative units of power, the dependence of the signal from the horizontal beam position is roughly the one expected from an electrostatic pick-up model [4]. Fig. 1 shows the measured power from all superelectrodes. The points show the measured power, the solid curve is the result of a fit to the data using an appropriately scaled electrostatic pick-up model with background noise. An absolute determination of the sensitivity still has to be performed.

Four superelectrodes are used inside the Palmer pick-up electrodes to derive the horizontal position [2]. There are eight of these quadruplets inside the Palmer pick-up at E01QS2F. The signal from each of them was measured as a function of momentum. No significant departure from their average sensitivity was observed.

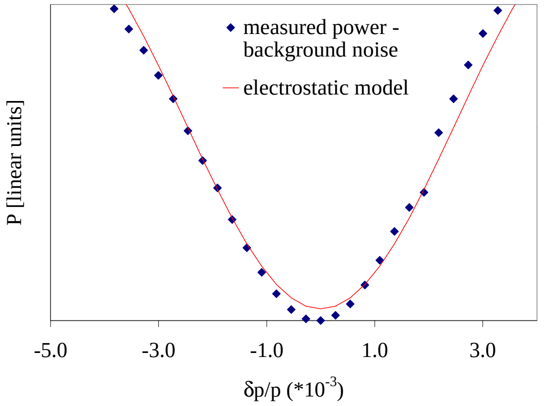

Figure 1: Sensitivity measurements of Palmer pick-up

2.3 Cooling with large initial momentum deviation

Momentum cooling of a beam consisting initially of two distinct components separated by the largest foreseen momentum deviation $\delta p/p = 0.7\%$ has been reported in [4]. In order to overcome the synchronization problem between pick-up and kicker at the large $\delta p/p$, the lengths of the transmission lines for signals from particles with large positive or negative $\delta p/p$ were initially different and only gradually made equal in the course of the cooling process as part of an automatized cooling cycle.

2.4 Cooling experiments with an argon beam

In order to approach the situation of a beam of secondary particles from the fragment separator, a beam with a maximum momentum width $\delta p/p = \pm 0.15\%$ was injected from the SIS synchrotron. Due to coupling between the phase subspaces [2], beam loss caused by the stochastic cooling system can be avoided only if all subsystems are turned on simultaneously. In spite of the rather low ionic charge of the $^{36}\mathrm{Ar}^{18+}$ beam, short cooling times in the longitudinal ($\tau_{\|}$) and horizontal (τ_x) betatron phase planes were measured. The momentum width was determined from the second moment of the Schottky power density at the 30^{th} harmonic. The horizontal width was determined from measurements with the ESR rest gas ionization monitor (Fig. 2). Both the rms relative momentum width $\sigma_{\|}$ and the rms horizontal beam width σ_x in the northern dipole decrease approximately exponentially versus time (Fig. 3):

$$\sigma(t) = (\sigma(0) - \sigma^{\mathrm{eq}})\, e^{-t/\tau} + \sigma^{\mathrm{eq}}$$

Table 1 shows the cooling times $\tau_{\|}$ and τ_x as well as the equilibrium widths $\sigma_{\|}^{\mathrm{eq}}$ and σ_x^{eq} for two different beam intensities N. In both cases the initial width $\sigma_{\|}(0)$ was $8 \cdot 10^{-4}$ and the width $\sigma_x(0)$ was 9 mm. The rms emittance is $< 2 \cdot 10^{-6}$ m initially and about $1 \cdot 10^{-7}$ m finally. The final longitudinal and horizontal emittances are smaller than what is needed for fast electron cooling following the stochastic precooling.

Table 1: Measured cooling parameters for an argon beam

N	$\tau_{\|}$ [s]	τ_x [s]	$\sigma_{\|}^{\mathrm{eq}}$	σ_x^{eq} [mm]
$6 \cdot 10^7$	1.06	4.6	$1.0 \cdot 10^{-4}$	1.5
$6 \cdot 10^6$	0.86	1.6	$0.5 \cdot 10^{-4}$	1.6

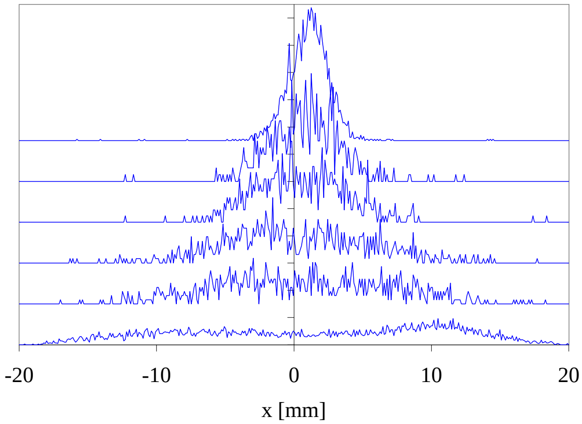

Figure 2: Cooling of an argon beam: horizontal beam profiles recorded every 2 seconds

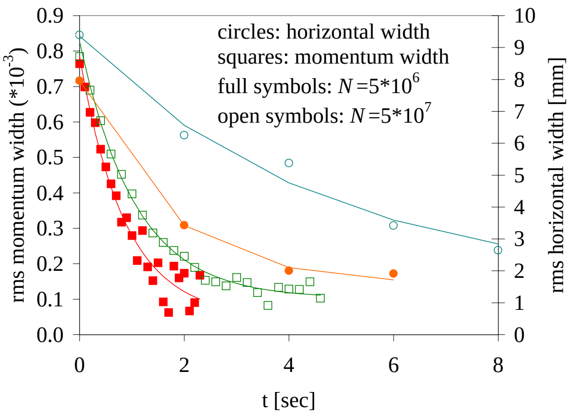

Figure 3: Cooling of an argon beam: $\sigma_{\|}(t)$ and $\sigma_x(t)$ with fitted exponentials

2.5 First experiments with uranium beams

As the Schottky power density is proportional to the square of the charge state, the fastest cooling rates are expected if the Schottky signal to noise ratio is at its optimum value, i.e. for fully stripped uranium ions. Indeed, the fastest cooling rates have been reached with a $^{238}\mathrm{U}^{92+}$ beam. Cooling times in all three phase space dimensions were measured during a first commissioning run.

The vertical and horizontal cooling times were evaluated by determining the power of betatron sidebands inside the cooling band as a function of time. The sideband power would be proportional to emittance only if there was no signal suppression by feedback through the beam. Therefore the derived values have an uncertain systematic error and should be confirmed by independent measurements. After background noise subtraction, the integrated power of both sidebands around the 663^{rd} harmonic of the revolution frequency was determined and fitted to an exponential. The cooling times derived from the two sidebands agree within the limits of accuracy. Fig. 4 displays the decreasing betatron sideband power.

Table 2: Measured cooling times for uranium beams

N	$\tau_\parallel$ [s]	$\sigma_\parallel^{\mathrm{eq}}$	τ_x [s]	τ_y [s]
$3 \cdot 10^6$	0.40	$7.6 \cdot 10^{-5}$	> 2.5	≈ 0.49
$7 \cdot 10^5$	0.41	$6.2 \cdot 10^{-5}$	> 5	≈ 0.33

Table 2.5 shows the measured cooling times. The longitudinal and vertical cooling rates are rather fast. The horizontal cooling rate is much slower. Because the longitudinal kicker is located in a dispersive region, horizontal cooling has to compensate the horizontal blow-up due to the longitudinal kicks. Furthermore, non-optimum parameter settings cannot be excluded as another possible explanation. The measured cooling times below one second are of the same order of magnitude as was expected theoretically [5] under the assumption of limited available RF power.

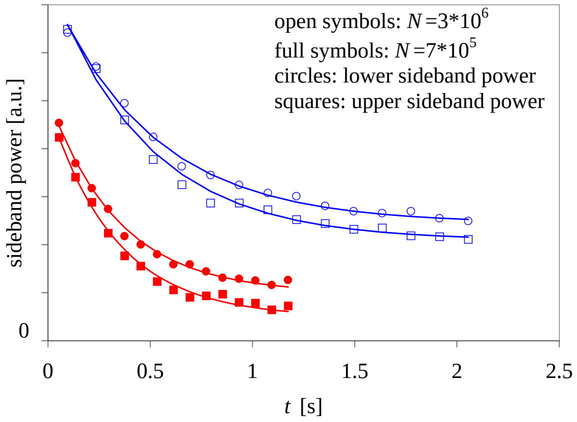

Figure 4: Cooling of a uranium beam: decreasing vertical betatron sideband power

2.6 *Beam accumulation following stochastic precooling*

Again with a uranium beam, an experiment with beam accumulation following stochastic precooling was successfully performed. Stochastic precooling was applied for 4s. Then the beam was transferred by RF to a relative momentum offset 1.8 % below injection, where it was was stabilized by electron cooling. The injected beam intensity was $N = 7 \cdot 10^6$. Fig. 5 displays the number of stored ions as a function of time. Even at a stored beam of 1.4 mA corresponding to $4.8 \cdot 10^7$ particles no beam loss due to the signal from stacked beam at the pick-ups of the stochastic cooling system was observed. During this experiment the total stacking rate was limited by the fact that the SIS synchrotron was requested by different users in a time-sharing mode.

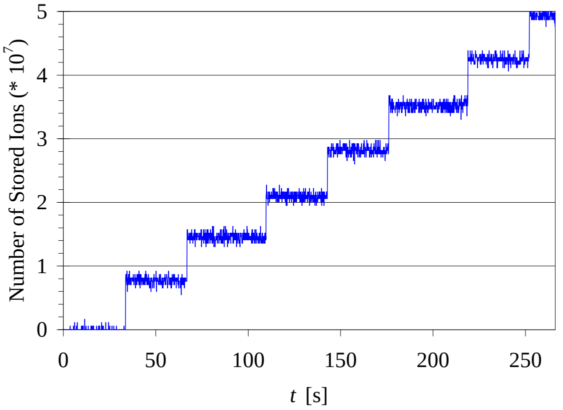

Figure 5: Stacking of a uranium beam: beam current as a function of time

3 CONCLUSIONS AND OUTLOOK

Except for the path in which horizontal heating by longitudinal kicks is compensated in the same revolution by a suitable correction kick at the horizontal kicker [2], all parts of the system have been commissioned successfully. Both the measured cooling times and the equilibrium phase space densities satisfy the requirements. On the other hand, further improvements of the system performance will be investigated, especially for highly charged ions.

It is now planned to use the system for the stochastic precooling of secondary fragment beams, optionally followed by RF stacking and accumulation. A first experiment with a secondary thallium beam is scheduled for August.

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