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STOCHASTIC COOLING AT THE ESR

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Stochastic precooling at the ESR storage ring of GSI will be used mainly for experiments with stored radioactive fragment beams. They arrive from the fragment separator with momentum spreads and emittances for which electron cooling is too slow. The installation of components at the ESR is now complete and first commissioning experiments have been performed. Both longitudinal and transverse stochastic cooling have been demonstrated. The paper gives a short account of the system architecture, and of the response of quarter-wave plates and superelectrodes at intermediate energies. The preparation of fragment beams suitable for subsequent electron cooling is discussed for the case that a mixture of different ion species is present in the cooler ring. Results of commissioning and future prospects are presented.

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Abstract

Stochastic precooling at the ESR storage ring of GSI will be used mainly for experiments with stored radioactive fragment beams. They arrive from the fragment separator with momentum spreads and emittances for which electron cooling is too slow. The installation of components at the ESR is now complete and first commissioning experiments have been performed. Both longitudinal and transverse stochastic cooling have been demonstrated. The paper gives a short account of the system architecture, and of the response of quarter-wave plates and superelectrodes at intermediate energies. The preparation of fragment beams suitable for subsequent electron cooling is discussed for the case that a mixture of different ion species is present in the cooler ring. Results of commissioning and future prospects are presented.

1 Purpose of the Stochastic Precooling System

The purpose of the stochastic precooling system [1] at the Experimental Storage Ring of GSI is the cooling of freshly injected beams occupying a large phase space prior to subsequent electron cooling. Such beams arise typically as nuclear fragment beams from the GSI fragment separator.

As of 1999, nuclear fragment beams have been used for Schottky Mass Spectrometry [2], but attempts to perform nuclear spectroscopy experiments have suffered from insufficient luminosity. After the GSI intensity upgrade, beam intensities of some 10^{10} heavy ions like lead are expected from the heavy ion synchrotron SIS. Projectile-near fragments can be produced with efficiencies of up to 10^{-4}, such that some 10^6 fragment ions are expected for each SIS shot. However, cooling of primary beams with intensities of up to 10^8 particles is intended, as well. According to the ESR injection acceptance, the

ESR stochastic cooling system has to cope with momentum deviations of up to $\delta p/p = \pm 0.35\%$ and transverse emittances of up to $\mathcal{E}_{x,y} = 20\pi$mm mrad. The optimum cooling energy was chosen to be 477 A MeV, corresponding to $\beta = 0.75$ and an electron cooling voltage of 262 kV. In order to achieve *electron cooling* times of the order of a second, the final momentum spread after stochastic cooling should be better than $\delta p/p = \pm 0.1\%$ with emittances of $\mathcal{E}_{x,y} = 2.5\pi$mm mrad. *Stochastic cooling* times of the order of a second are expected for 10^8 particles [3].

These cooling times are achievable with a stochastic cooling bandwidth of a few hundred MHz. The band 0.9 GHz–1.7 GHz was chosen as it can be covered using a single layout for the pick-up and kicker devices. Furthermore, a design for semiconductor (GaAs-) power amplifiers had been developed [4] for the same band. This design could be used without additional development costs.

2 Response of Pick-ups and Kickers for $\beta < 1$

The pick-up and kicker design is based on quarter-wave plates [5]. The construction of these devices is presented in some detail in [3]. It was designed using estimates of the sensitivity which have originally been developed for highly relativistic beams. Here, a correction for finite β will be discussed. If (at $\beta = 1$) the device is used as a longitudinal pick-up, the interaction with the beam can be estimated to take place only at the ends of the plate. If the effective interaction time is very short compared with the length of the device, one gets two very short pulses for each interaction:

$$u_{\text{simple quarter-wave}}(t) = \sigma(x)\left[\delta(t) - \delta(t - 2t_e)\right] \tag{1}$$

Here, $\sigma(x)$ describes the geometric sensitivity for a particle in the mid-plane between the upper and lower plates, if the device is used as a horizontal pick-up; x is the horizontal position relative to the center of the device. In the limit $\beta \to 1$ an electrostatic approximation for the calculation of sensitivities can be used. A theoretical justification can be found in [5]. For two quarter-wave loops in the sum mode one gets [6]:

$$\sigma(x) = \frac{2}{\pi}\arctan\left[\frac{\sinh(\pi w/h)}{\cosh(\pi x/h)}\right] \tag{2}$$

where w is the width of each plate and h the vertical distance between the plates. t_e is an effective travelling time that depends on the length L of the pick-up, as well as on the particle and signal transmission velocities v_{p} and v_{S}:

$$t_e = \frac{L}{2}\left(\frac{1}{v_{\text{p}}} + \frac{1}{v_{\text{S}}}\right) \tag{3}$$

The frequency response is then given by the Fourier transform of eq. (1):

$$\tilde{u}_{\text{simple quarter-wave}}(\Omega) = 2i\sigma(x)e^{-i\Omega t_e}\sin(\Omega t_e) \tag{4}$$

At the ESR stochastic cooling systems the signal from two subsequent pick-ups is coherently superposed after inserting a suitable delay of $\approx 2t_e$. Such a device is usually called a superelectrode. Then eq. (1) must be replaced by

$$u_{\text{simple superelectrode}}(t) = \sigma(x)\left[\delta(t) - \delta(t-2t_e) + \delta(t-4t_e) - \delta(t-6t_e)\right] \tag{5}$$

The sensitivity gain is twofold at midband (instead of $\sqrt{2}$ if power combination was used), but the length of the signal train becomes longer, as well, reducing the effective bandwidth with the frequency response

$$\tilde{u}_{\text{simple superelectrode}}(\Omega) = 4i\sigma(x)e^{-3i\Omega t_e}\sin(\Omega t_e)\cos(2\Omega t_e) \tag{6}$$

With particle velocities substantially below c, a more realistic model is appropriate that takes into account finite interaction times at each end of the plates. After replacing the delta functions in eq. (1) by a well-behaved finite interaction model $f(\tau)$, one can write the new pulse structure using convolutions (denoted by $*$) with the delta functions. Then the new frequency response becomes (with the Fourier transform $\tilde{f}$ of f):

$$u_{\text{better}}(t) = u_{\text{simple}}(t) * f(t) \iff \tilde{u}_{\text{better}}(\Omega) = \tilde{u}_{\text{simple}}(\Omega)\tilde{f}(\Omega) \tag{7}$$

The effective interaction time depends mainly on the effective field length at the pick-up. We estimate the duration of the interaction from the well-known [7] electric field of a free particle with velocity βc. The field component in the laboratory frame $E_\perp(t)$ perpendicular to the direction of motion at a distance d can be written as $E_\perp(t) = E_0\left[1 + (t/\Delta t_{\text{pulse}})^2\right]^{-3/2}$. The duration of this pulse is of the order $\Delta t_{\text{pulse}} = d/(\beta\gamma c)$. The Fourier transform of $E_\perp(t)$ can be expressed using the modified Bessel function K_1: $\tilde{E}_\perp(\Omega) = 2E_0\Omega\left(\Delta t_{\text{pulse}}\right)^2 K_1\left(\Omega\Delta t_{\text{pulse}}\right)$. In the asymptotic limit $\beta \to 1$ the response becomes frequency-independent: $\tilde{E}_\perp \approx 2E_0\Delta t_{\text{pulse}}$. This corresponds to δ-functions in the time domain. Therefore $\tilde{E}_\perp(\Omega) = f(\Omega)\lim_{\beta\to 1}\tilde{E}_\perp(\Omega)$ with the finite-energy correction

$$\tilde{f}(\Omega) = \Omega\Delta t_{\text{pulse}}K_1\left(\Omega\Delta t_{\text{pulse}}\right) \tag{8}$$

This result for a free particle can serve as a first estimate of the electric field inside our pick-up. In the case of the pick-ups installed inside quadrupole magnets in the ESR, d is 25 mm at $x = 0$, leading to a maximum value of $\Delta t_{\text{pulse}} = 83$ps at the lowest velocity $\beta = 0.71$. This number should be compared to $2t_e$, the pulse distance of the quarter wave plates. As $\Omega t_e = \pi/2$ at midband, we get $2t_e = 385$ps, or $\Delta t_{\text{pulse}}/(2t_e) \approx 0.2$. Hence the sensitivity should be degraded in comparison to the extremely relativistic case. At the

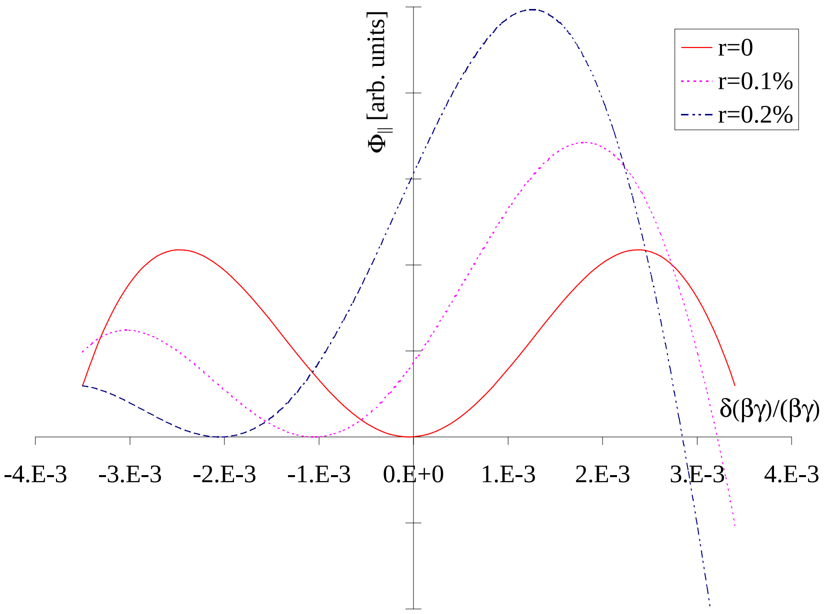

Fig. 1. Cooling Potentials at different values of the relative rigidity difference r derived from eq. (10).

upper end 1.7 GHz of the useful ESR band, this leads to $\Omega\Delta t_{\text{pulse}} = 0.88$. The function $f'(z) = zK_1(z)$ decreases monotonically, showing an approximately linear behaviour in the interval of interest $0.3 \leq z \leq 0.9$, with $f'(z) \approx 1.05 - 0.45z$, with a maximum error of 0.004 in this interval, which is probably better than the physical accuracy of the underlying free particle field approximation. The value $f'(0.88) \approx 0.65$ shows that for the worst case (large distance d, lowest β, highest frequency) a reduction of the sensitivity by about one-third may be realistic.

3 Palmer Cooling of Fragment Mixtures

This subject has been discussed in [8]. Here we discuss Palmer cooling of fragment mixtures in the presence of undesired mixing. For the momentum dependence of Palmer cooling, we assume a linear pick-up response and a constant kicker response. If an ion species with a rigidity difference $r = \delta(m/q)/(m/q)$ relative to a reference species is present, the pick-up signal will be proportional to $\delta(\beta\gamma)/(\beta\gamma)+r$. The synchronization error due to undesired mixing between pick-up and kicker is due to a timing error relative to the reference particle

$$\frac{\delta T}{T_{p\to k}} = -\eta\,\frac{\delta(\beta\gamma)}{\beta\gamma} + \alpha_p r \tag{9}$$

with the momentum compaction α_p and the frequency slip factor $\eta = \gamma^{-2} - \alpha_p$. The longitudinal drift (or roughly, cooling force) will scale as

$$F_{||} \propto \left(\frac{\delta(\beta\gamma)}{\beta\gamma} + r \right) \sum_m |f_m|^2 \cos \left[m\omega_0 T_{p\to k} \left(\eta \, \frac{\delta(\beta\gamma)}{\beta\gamma} - \alpha_p r \right) \right] \tag{10}$$

if the system is tuned to the reference particle. The sum is over the harmonics of the revolution frequency $\omega_0/2\pi$ of the reference particle which are inside the useful bandwidth. The f_m take into account the frequency response of pick-ups and kickers which are assumed to be equal. For the ESR case the response of superelectrodes (eq. (6) with the correction eq. (8)) can be inserted. If the undesired mixing is not obstructive (i.e. if the sum in eq. (10) has the right sign), cooling will proceed towards an equilibrium momentum $\delta(\beta\gamma)/(\beta\gamma) = -r$. Off-velocities where subsequent electron cooling is too slow should generally be avoided. A restriction to simultaneous cooling of fragments with $|r| \leq 10^{-3}$ should therefore be recommended.

Undesired mixing can significantly affect the depth of the corresponding potential well. This is illustrated in fig. (1) where the potentials $\Phi_{||}$ derived from the forces according to eq. (10) are displayed for different values of r. For increasing r, the potential well becomes more and more shallow in the direction of large negative momenta.

4 Commissioning of the Completed Installation

The installation of pick-up and kicker stations is complete. Commissioning was performed with beams at 391 A MeV, corresponding to $\beta = 0.71$, as in previous commissioning runs [3].

Simultaneous Palmer cooling of a beam containing particles at both extreme momentum deviations $\delta p/p = \pm 0.35\%$ could be demonstrated. In order to achieve this goal, cables of different lengths [1] can be switched under remote control. A waterfall diagram of such a cooling cycle is shown in fig. 2. E-folding cooling times of about 8 seconds at 9.5×10^7 particles were measured. After closing the cooling loop for a long time, beam loss due to horizontal betatron blow-up is observed. This was expected because of the dispersion at the location of the longitudinal kicker.

Vertical betatron cooling has been demonstrated using the same line. The effect of cooling was inferred from the reduction of power in the Schottky sidebands after finally switching off cooling. A quantitative analysis has not yet been performed. Conclusive evidence for horizontal betatron cooling has also been achieved. The beam loss mentioned above vanishes with the horizontal system turned on.

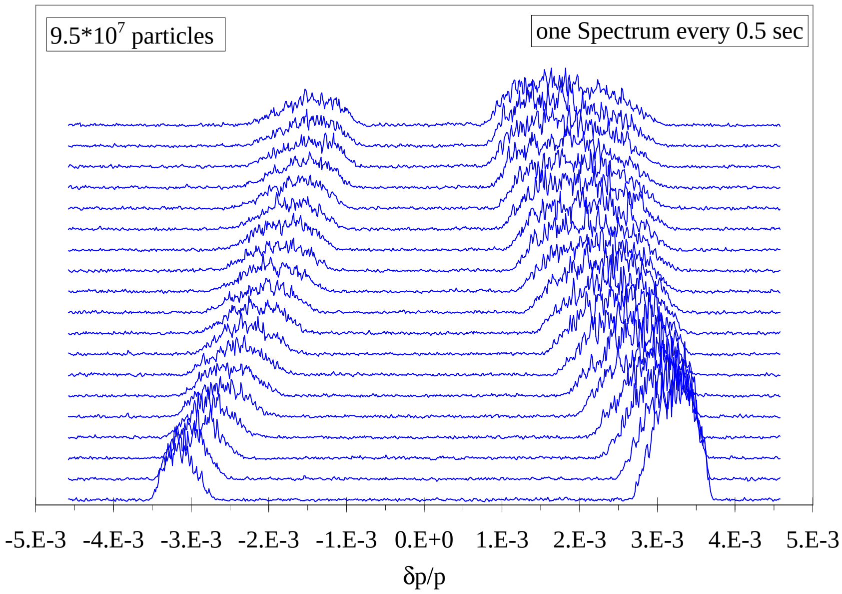

Fig. 2. Waterfall diagram of longitudinal Schottky spectra of a carbon beam showing cooling of an artificially produced double-peaked distribution with large initial off-momentum (see text).

In the forthcoming months commisioning will be continued with the aim of offering a new experimental feature at the ESR to the scientists.

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