STOCHASTIC PRECOOLING OF HEAVY FRAGMENTS IN THE ESR

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Introduction

In the new accelerator complex at GSI [1], exotic nuclei will be produced and separated in a fragment separator [2] downstream the synchrotron SIS. Beams of these nuclei are expected to have low phase space densities. In the cooler ring ESR [3], therefore, stochastic cooling will be applied prior to rf-stacking and, e.g., electron cooling.

We present some special features of the stochastic cooling system which are due to the high charge states, the existence of a stack, and the fairly large frequency dispersion. These include Palmer cooling with adjustable cable lengths for high and low momentum signals in order to reduce unwanted mixing, and compensation of horizontal heating due to momentum kicks by suitable transverse kicks. Also, a method of cleaning the horizontal pick-up signal from momentum information is discussed.

Design Performance

The main purpose of the stochastic cooling system in the ESR is to precool beams of heavy fragments at a fixed kinetic energy of 500 MeV/u. After stochastic precooling, the beam will be rf-stacked. The momentum width of the injected beam will be reduced from $\pm 0.35\%$ to $\pm 0.1\%$. Both transverse emittances will decrease from 20π mm mrad to 2.5π mm mrad. For the layout of the system we assumed that the injected beam currents vary between 10^5 and 10^8 particles. All sorts of fragments can be cooled, but optimum performance is only reached at the highest charge states. In general, the ratio of currents in the stack and on the injection orbit will not be larger than 10. Cooling times of the order of a second are intended for high currents of the highest charged particles. To achieve that aim, a step by step realization is envisaged.

Boundary Conditions from the Given Storage Ring Design

Our technical concept is governed by three major constraints: First, due to the existence of a stack, it is necessary to position pick-up and kicker modules at locations where the dispersion function D is large enough such that the electrodes are sufficiently 'blind' for the stack. Because of space restrictions one has to install the pick-up and kicker electrode arrays inside the vacuum chamber of magnets. Then, each kick changing the relative momentum deviation by an amount $\Delta p/p_0$ changes the amplitude x of horizontal betatron motion by an amount $D_{\text{kicker}}\Delta p/p_0$ [4]. This effect may lead to considerable diffusion in horizontal betatron space which is proportional to $D^2_{\text{kicker}}/\beta_{\text{kicker}}$, where β_{kicker} is the horizontal betatron function at the kicker. The effect does not only apply to the electrodes designed as momentum kickers. Particles with large momentum deviation in a horizontal kicker at a location of high dispersion will be subject to momentum kicks, and hence, to both momentum diffusion and additional horizontal emittance diffusion. Second, within the framework of ion optical design of the ESR, the dispersion η of the particle revolution frequency f is fairly large in our machine at the operational energy of 500 MeV/u:

$$\eta = \frac{\delta f/f_0}{\delta p/p_0} = 0.246$$

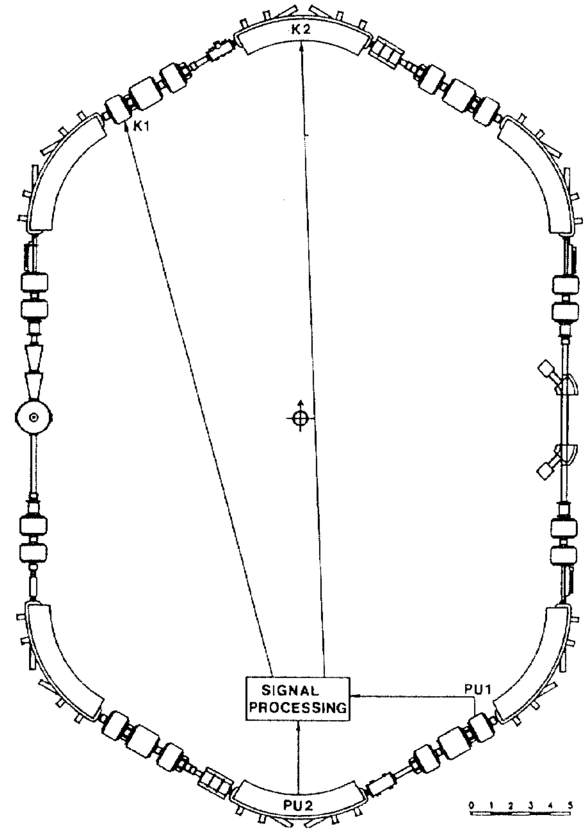

Figure 1: Positions of pick-ups and kickers in the ESR

This number is important for the question of 'mixing' [4]: Because of the large spread in revolution frequencies, the 'samples' seen by the cooling systems rearrange very quickly, which leads to enhanced cooling. On the other hand, with cooling at high harmonics of the revolution frequency, the synchronism of signals and particles between pick-up and kicker may be lost. The time lag between a particle and a signal along a line which is adjusted to the design momentum is to first order given by

$$\delta T = -\eta_{\text{P}\to\text{K}} T_0 \frac{\delta p}{p_0}$$

T_0 is the signal time required for the particle with design momentum. The local time dispersion between pick-up and kicker can be expressed by

$$\eta_{\text{P}\to\text{K}} = \frac{1}{\gamma^2} - \frac{< D >_{\text{dipoles}}\, \vartheta}{\beta c T_0}$$

where $< D >_{\text{dipoles}}$ is the average dispersion in the dipoles between pick-up and kicker, ϑ is the respective bending angle, and β and γ are the usual relativistic factors. The equivalent phase errors $\Omega\delta T$ at cooling frequency $\Omega/2\pi$ can be so large that even the sign of the kicker voltage is reversed. A method of reducing the phase error is explained below.

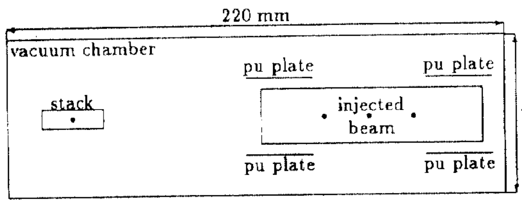

Figure 2: Simplified cross section of vacuum chamber in a dipole magnet (Explanations in the text)

Third, in the presence of high charge states Q, the (Schottky) signal to (thermal) noise ratio is enlarged with respect to protons by a factor of Q^2. At equal numbers of stored particles, this leads to an enhancement by 39 dB for beams of fully stripped uranium! Therefore it is not urgent to use notch filters in order to improve the signal, even not at low intensities.

Adjustable Delays

Our choice of the frequency band 0.9 - 1.6 GHz has the following implications: Because of Schottky overlap in this band, one has to use the Palmer method for longitudinal cooling. The momentum signal is deduced from the horizontal deviation from the closed orbit of the design particle by means of two pairs of electrodes. From each vertical pair one uses the sum signal and then takes the difference of the two sum signals. At this point it is possible to get rid of the phase errors mentioned above. Instead of taking the difference directly, one delays the signals from the left and right pairs by an opposite amount of time T_D in order to restore synchronism of signals and particles with large momentum deviations. This compensation scheme was invented by L. Thorndahl and has been successfully applied at CERN. Denote the sensitivity of the left pair of pick-ups by S_{hi} and the one of the right pair by S_{lo}, respectively. For example, a particle with large positive momentum deviation would produce a large signal on the 'hi' momentum plates and a small signal on the 'lo' momentum plates. Then the cooling process may be characterized by the quantity

$$\begin{aligned} S_{eff} &= S_{lo}(\delta p/p_0)\exp\left(-i\Omega\left(\delta T + T_D\right)\right) \\ &- S_{hi}(\delta p/p_0)\exp\left(-i\Omega\left(\delta T - T_D\right)\right) \end{aligned}$$

The cooling efficiency is proportional to the real part of S_{eff}. The delay T_D is optimized for relative momentum deviations

$$\frac{\delta p}{p_0} = \pm\frac{T_D}{\eta_{P\to K}T_0}$$

Momentum diffusion is proportional to the absolute square of S_{eff} which is non-zero at $\delta p/p_0 = 0$ for $T_D \neq 0$ even if the beam center passes through the symmetry axis of the electrode array. Therefore, as an unwanted by-product, an unbiased Schottky contribution from particles near the center of the momentum distribution emerges, which is continuously minimized by decreasing the signal delay according to the progress of cooling.

A practical advantage of the chosen frequency band is the reduction of R&D expenses, because the CERN design [5] of semiconductor power amplifiers in this band is available.

Choice of Locations for Pick-ups and Kickers

In the ion optical mode used for injection the dispersion vanishes on the way between the entrances and exits of the long straight sections. Therefore the following locations for pick-up and kicker modules have been chosen (see fig. 1):

location	D [m]	β_x [m]	β_z [m]	μ_x [degrees]	μ_z [degrees]
P1	3.99	1.6	17.3	0	0
P2	5.76	39.5	4.3	65	66
K1	3.99	1.6	17.3	414	432
K2	5.76	39.5	4.3	479	498

Table 1: Ion optical parameters at pick-up and kicker locations

line	η	T_0 [ns]	δT [ps]
P1→P2	0.114	46	18
P1→K1	0.246	238	205
P2→K2	0.246	238	205
P1→K2	0.224	284	223

Table 2: Time delays for various signal lines (at 500 MeV/u and $\delta p/p_0$ = -0.35 %)

1. Horizontal and vertical pick-ups inside the first focusing quadrupole of the south-eastern triplet (named P1)
2. Horizontal pick-ups inside of the southern dipole (named P2)
3. Vertical and momentum kickers inside the first focusing quadrupole of the north-western triplet (named K1)
4. Horizontal kickers inside the nothern dipole (named K2).

Table 1 shows the essential optical parameters at these locations. D is the dispersion function, $\beta_{x,z}$ are the horizontal and vertical beta functions, and $\mu_{x,z}$ are the corresponding betatron phase advance angles with respect to P1. The quantities refer to the centers of the corresponding elements.

The lines between these locations may be qualified as follows:

1. The line between P2 and K2 is suited for horizontal betatron cooling although the signal will contain about 50 % of momentum information at the beginning of cooling. A 'purification' concept is presented below.
2. The line between P1 and K1 is suited for momentum cooling by the Palmer method although there will be emittance blow-up by the momentum kicks due to both the low horizontal beta function and the fairly large dispersion at K1. An idea how to reduce this heating is discussed below.
3. The line between P1 and K1 is suited for vertical cooling.

Table 2 shows the quantities relevant for the adjustable delays for various lines. Adjustable delays up to 200 ps are sufficient for our purposes. Note that without these, the phase errors $\Omega\delta T$ would cover a range between 72^0 and 128^0 in our frequency band at maximum momentum deviation and for the line from P1 to K2.

Generation of the Transverse Cooling Signal

The excellent signal to noise ratio in heavy ion Schottky signals allows for a signal purification scheme with the aim of preparing from the available resources a kicker signal at K2 which contains a better ratio of the transverse to the momentum contributions. From table 1 it follows that it should be possible to subtract from the P2 signal a suitable fraction of the P1 signal in order to get rid of the momentum information in the P2 signal. This is favourable at high currents of ions in a sufficiently high charge state. Unwanted diffusion in both transverse and momentum phase space is considerably diminished this way. Table 2 shows that the line P1 to P2 is almost isochronous so that the goodness of signal subtraction is practically independent of momentum.

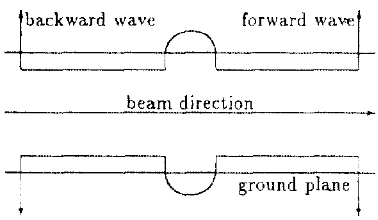

Figure 3: Model of superelectrode used as pick-up

Reduction of Transverse Diffusion Caused by Momentum Kicks

Diffusion in transverse phase space due to momentum kicks at K1 is reduced by applying a proportional correction kick at the horizontal kicker K2. This is possible as the horizontal betatron phase advance between K1 and K2 is close enough to 90^0. The benefits of controlled correlations between the K1 and K2 voltages do not necessarily depend on a good signal to noise ratio. The method would even make sense if the K1 voltage was of purely thermal origin.

Hardware Realization

Figure 2 shows a cross section through the vacuum chamber around the pick-up P2 with the limits of the injected beam and the stack. The dots indicate the centers of the stacked beam and the injected beam particles at $\pm 0.35\%$ and zero momentum deviations, each with zero one-particle emittance. The need for rf-stacking forbids the use of vertical electrodes. Cross-talk from the stack to the pick-up's and from the kickers to the stack will be insignificant because of the moderate intensity in the stack.

Similar to the AC ring at CERN, we shall superpose the signal of two subsequent loop electrodes coherently in superelectrodes (see fig. 3). Along the line sketched in [6] it can be shown that the voltage response of such a device is ideally proportional to

$$-2 \sin \alpha \cos 2\alpha = \sin \alpha - \sin 3\alpha$$

where α measures the deviation from midband frequency Ω_m:

$$\alpha = \frac{\pi}{2} \frac{\Omega}{\Omega_m}$$

(The equivalent response of one single loop would be $\propto \sin \alpha$). Over the chosen frequency band, the power efficiency of superelectrodes used as kickers is superior by 2.0 dB to the one of two usual loop electrodes fed with the same power. The signal to noise ratio of pick-ups is enhanced by an equal amount (which is of minor importance in our application). This outweighs the fact that the effective system bandwidth is decreased due to the dominance of the midband frequencies. Each pick-up/kicker station consists of eight modules each of which contains two pairs of superelectrodes as shown in fig. 2.

Fig. 4 shows how the signals from P1 and P2 are processed in order to get the appropriate signals for K1 and K2. From each pick-up, there are two lines, one for the 'lo' momentum plates and one for the 'hi' ones, to a signal processing box which is situated in the direct neighborhood of P2. The processing network contains three equal subsystems each of which is built up in the following way: The delays of the low momentum signals are made equal and opposite to those of the high momentum ones. Their gradual variation is realized by using dc-controlled capacitor diode arrays. The signals are then subtracted in 180^0 hybrids. Each of the subsystems is equipped with dc-controlled variable attenuators (pin-diodes) that balance the relative weight of the delayed pick-up signals at the kickers.

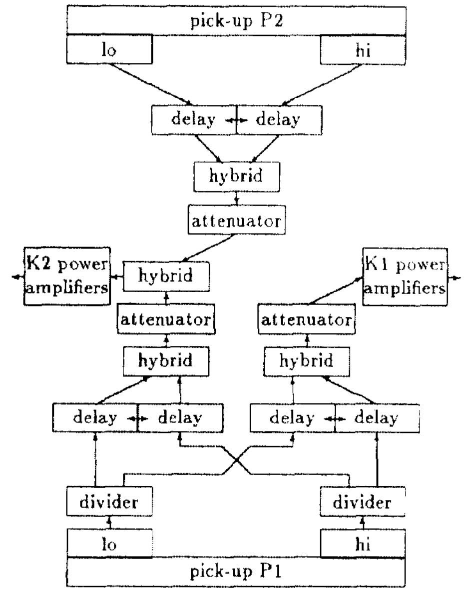

Figure 4: Block diagram of signal processing

From a theoretical point of view, the line from P1 to K2 serves two different purposes:

1. The signal from P1 is used to subtract the momentum deviation information from the mixed information of the P2 signal if the Schottky signal to thermal noise ratio is sufficiently large.

2. It contains an appropriate fraction of the momentum kick at K1, thus making it possible to reduce the emittance blow-up due to the momentum kick.

The optimum adjustment of the attenuator in the P1-K2 line should therefore depend on both adjustments of the attenuators in the two other lines, a situation that promises interesting experimental tests.

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