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FIRST EXPERIMENTS ON STOCHASTIC COOLING OF HEAVY ION BEAMS AT THE ESR

F. Caspers, B. Franzke*, F. Nolden*, A. Schwinn*

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*) GSI, Darmstadt, Germany

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F. Caspers, CERN, Geneva, Switzerland

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At the experimental storage ring ESR of GSI, one half of the foreseen pick-up and kicker tanks are installed, the rest will follow in 1998. First experimental tests of the stochastic precooling system have been performed since April 1997. Longitudinal Palmer cooling was successfully demonstrated. E-folding cooling times of 8.6 seconds were determined with carbon beams. No significant dependence of the cooling time on the number of particles was observed during these first tests. This may be explained by a low signal to noise ratio of the signals obtained from the pick-ups in the present configuration. With heavy ions in higher charge states faster cooling times are expected. The experiments are an important step towards the realization of experiments with radioactive fragments, e.g. in order to measure nuclear masses or half-lives of stripped exotic ions.

1 STOCHASTIC PRECOOLING OF HEAVY ION BEAMS AT THE ESR

The stochastic cooling system at the ESR [1] was built in order to provide fast cooling of newly injected beams which occupy initially such a large phase space that the well-established electron cooling would be too slow. Such beams are typically produced at the fragment separator located behind the heavy ion synchrotron SIS [2]. Beams with specific energies of several hundred MeV/u are shot on a thick target (some g/mm^2) by means of fast extraction from the synchrotron. The radioactive fragments emerging from the target occupy a large transverse and longitudinal phase space which is mainly due to the Fermi motion of nucleons inside the target nucleus. These beams are injected into the ESR where they are cooled stochastically. It was envisaged to decrease both transverse emittances from 20 π mm mrad to 2.5 π mm mrad. The maximum accepted longitudinal momentum spread of $\pm 3.5 \times 10^{-3}$ was planned to be reduced to $\pm 0.5 \times 10^{-3}$ [3]-[5].

These final values are well-suited for subsequent electron cooling. They correspond to velocities in a frame co-moving with the electrons of roughly 2×10^5 m/s (for $\beta = 0.75$), leading to electron cooling times of the order of a second for the electron densities available at the ESR.

Subsequent stacking has been a design option with considerable impact on the design of the stochastic cooling system. In order to prevent pollution of the pick-up signal by the stacked beam or heating of the stack by the kickers both pick-up and kicker tanks must be installed at locations of sufficiently large dispersion. Because of space restrictions, all tanks are installed inside the gaps of dipole and quadrupole magnets.

2 ACTUAL AND FUTURE INSTALLATIONS

Figure 1 shows the location of pick-ups and kickers in the storage ring. The basic concept has been described in [3], [4]. The experiments described in this paper were performed with the pick-up station P2 and the kicker station K2 only, the installation of P1 and K1 being delayed due to vacuum feedthrough problems. Completion of the installation is planned for August 1998.

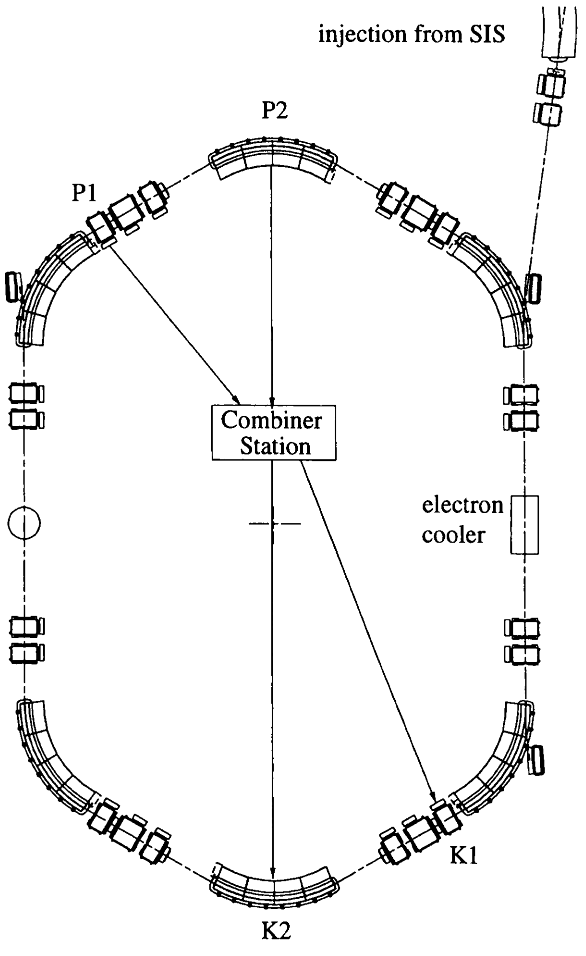

Figure 1: Location of pick-ups and kickers in the ESR

The stations P2 and K2 consist of eight identical modules (see fig 3). In such a module, four super-electrodes are arranged (Fig. 2) around the injected beam in such a geometry that the signal at the beam harmonics and betatron sidebands is maximized for the initial beam parameters. Each super-electrode consists of two quarter-wave plates connected in series. The length of these plates was adjusted experimentally to optimal performance at $\beta = 0.75$. The working band is in the range 900 MHz to 1700 MHz.

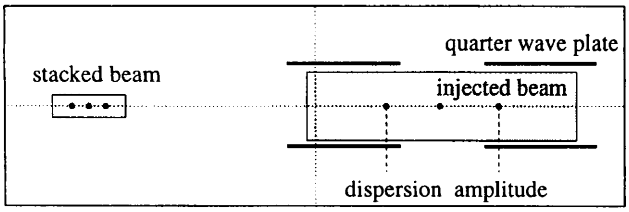

Figure 2: Arrangement of quarter-wave plates around the beam in P2 and K2. The exterior rectangle denotes the good field region with a horizontal width of 220 mm. The space occupied by the injected and stacked beams is shaded.

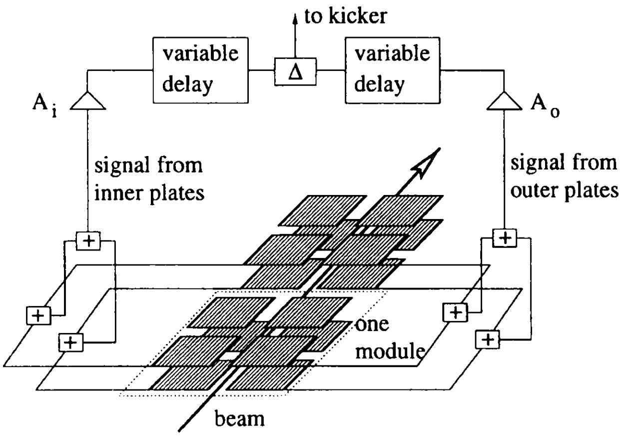

Figure 3: Schematic view of the signal processing after the pick-up P2. From eight superelectrodes in the longitudinal direction, only two are shown for simplicity

Figure 3 shows how the pick-up signals are processed in order to produce a useful correction kick. The signals from the longitudinally arranged superelectrodes and from the upper and lower halves are added in power combiners. Then the signal is preamplified in the low-noise preamplifiers A_i and A_o. Before the difference signal between the left and right parts is produced, each contribution can be delayed separately by a time which can be adjusted to a given particle velocity between pick-up and kicker. This allows the simultaneous cooling of particles at 'both ends' $\pm\delta p/p$ with an optimal phase, conceding a somewhat decreased performance for particles with $\delta p/p \approx 0$. The final signal contains information about the horizontal particle deviation from the centre of the electrode. The signal from dispersive deviations leads to the possibility of Palmer cooling, the betatron motion signal allows horizontal cooling.

The eight times four super-electrodes at the kicker K2 are powered by eight rf power amplifiers. Each power amplifier has four output gates with a maximum CW output power of 25 W. The driver amplifier limits the CW output power to 2 W in order to guarantee linear transmission of the stochastic noise at *peak* power.

3 FIRST COOLING EXPERIMENTS

So far there have been two commissioning periods, in April and in November 1997. The experiments were performed with fully stripped carbon and argon beams at a fixed energy of 392 A MeV ($\beta = 0.71$). The kicker plates were powered in phase, corresponding to longitudinal cooling. Although the line P2-K2 is actually foreseen for horizontal betatron cooling, commissioning was preferred with Palmer cooling because of the simplified diagnosis.

Calibrations were aided by the use of well-collimated, electron-cooled beams. At first, the beam was centred between the inner and outer pick-up arrays by comparison of the respective signal heights. A fine tuning of the variable delays (see Fig. 3) in steps of 200 ps followed in order to achieve optimum signal subtraction. Finally, beam transfer functions (BTFs) were measured at harmonics of the revolution frequency. The overall cable length was tuned by means of a 'trombone', a device with two sliding coaxial lines controlled by a step motor. While the beam was centred in the middle between the pick-ups, two different BTFs were always measured by alternately switching off one of the preamplifiers A_i or A_o (see Fig. 3). The phase of the BTFs could be managed to be constant (up to a difference of the order of 10 degrees), the difference between the two types of BTF being 180^0 degrees within an error of $\pm 20^0$. However, there remained a constant phase offset of several ten degrees which is produced by various rf components in front of the power amplifiers.

In order to get a reasonable model for a hot-injected beam, the momentum width of the carbon beam from the SIS was broadened artificially. Now the stochastic cooling loop was closed and cooling could be observed immediately. Figure 4 shows a waterfall diagram of the Schottky spectra measured during such an experiment.

Cooling times were derived from the Schottky spectra as follows. After subtracting the background noise floor, the square root $\sigma(t)$ of the second moment of the distribution was determined, yielding the measured points in Fig. 5. These were fitted with a shifted exponential

$$\sigma(t) = \sigma_0 + \sigma \exp\left(-\frac{t - t_0}{\tau}\right) \tag{1}$$

A fit with $\tau = 8.26$ sec is plotted, as well. The final fwhm (i.e $2.35\sigma_0$) was 1.8×10^{-4}. This is a very narrow final distribution, much better than was actually aimed at.

Deviations from an exponential cooling curve cannot be inferred, although they might have been expected from the following argument: The momentum compaction factor was $\alpha_p = 0.178$ which is equivalent to a frequency slip factor $\eta = \gamma^{-2} - \alpha_p = 0.32$. The revolution frequency was $f_0 = 1.96$ MHz. The phase error due to bad mixing is

$$\delta\phi = \Omega \, T_0 \, \eta \, \frac{\delta p}{p} \tag{2}$$

where T_0 denotes the time of flight from pick-up to kicker, and $\delta p/p$ is the relative momentum deviation from the synchronous particle. In our set-up, $T_0 = (2f_0)^{-1}$, and at mid-frequency $\Omega/2\pi = 1.3$ GHz, $\delta\phi$ amounted to 57^0 for $\delta p/p = 1.5 \times 10^{-3}$. Hence the cooling rate should have been smaller at the beginning of cooling. This is possibly counterbalanced by enhanced diffusion due to the growing spectral power density in the course of the cooling process.

No dependence of the cooling time as a function of the number of particles has been observed so far. Several explanations for this behaviour are possible. For the Carbon beams used in these tests, the signal to noise ratio of the pick-up signal is close to unity, especially at the beginning of cooling. Carbon is by no means representative for the heavy ions in high charge states the system is actually built for. Furthermore, it is probable that the constant phase offsets measured in the BTFs lead to enhanced diffusion.

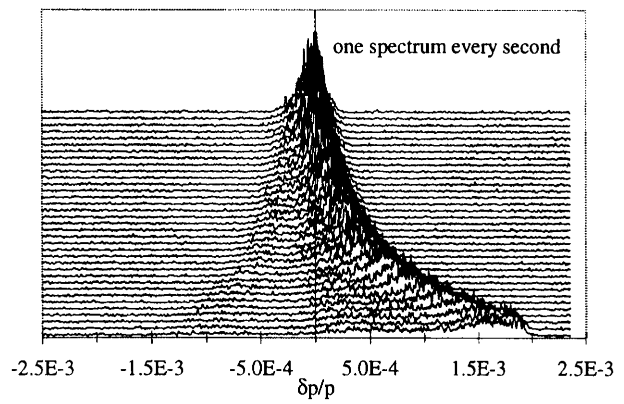

Figure 4: Waterfall diagram of Schottky spectra from stochastic cooling of a Carbon beam. Time proceeds upwards from the bottom.

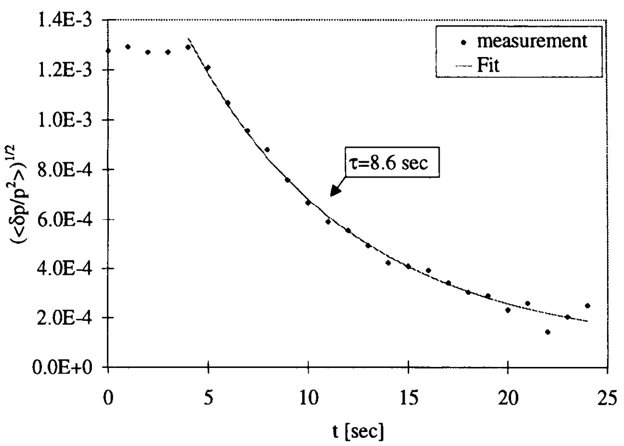

Figure 5: Development of rms momentum width

4 STOCHASTIC PRECOOLING OF A MULTI-COMPONENT BEAM

For the experiments with multi-component radioactive beams it is important to study stochastic cooling of a mixture of different ion species by the Palmer method. Palmer cooling leads to the same mean magnetic rigidity $m\beta\gamma c/qe$, independent of the ion species, but the mean values of $\beta\gamma$ will depend on m/q:

$$\frac{\delta < \beta\gamma >}{\beta\gamma} = -\frac{\delta(m/q)}{m/q} \tag{3}$$

Hence the *mean velocities* of two different species will differ by more than the *velocity spread* in each species if their relative difference in m/q is larger than the final, individual momentum spread. This is crucial if subsequent electron cooling is intended, because the electron cooling force depends strongly on *velocity* differences. Experiments should therefore match their m/q range to the desired electron cooling speed.

5 FUTURE DEVELOPMENTS

In order to achieve a quantitative understanding and reliable control of the cooling system, detailed system tests under various conditions still have to be performed. The effect of a new constant-phase corrector [6] on the cooling performance will be studied. Tests will begin with beams of $^{129}Xe^{54+}$, with a first glimpse of higher charge states.

The completion of the installation is being prepared for August 1998. Tests of horizontal cooling using the line P2-K2, of longitudinal and vertical cooling using P1-K1 as well as of a correction scheme using P1-K2 (see [3], [4]) will follow. Betatron cooling diagnosis will profit from a new rest gas ionization counter which has already successfully been used [7].

A major future step will be the stochastic cooling of exotic beams from the GSI fragment separator [8]. This would be an important step towards the realization of experiments with short-lived, cooled radioactive ions with half-lives down to a few hundred milliseconds.

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