EXPERIMENTAL PROGRESS IN FAST COOLING IN THE ESR

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Abstract

The storage ring ESR is equipped with systems for stochastic cooling and electron cooling. As the ESR is preferentially operated with highly charged ions, the cooling times are in the range of seconds down to some ten milliseconds for cold ion beams in equilibrium with intrabeam scattering. For low beam intensity ordering effects were observed with momentum spreads below 10^{-6} and emittances below 10^{-12} m. Recent experiments studied electron cooling of an ion beam above transition energy and the use of electron cooling as a pre-cooling method for laser cooling of C^{3+} ions.

INTRODUCTION

The main feature of the heavy ion storage ring ESR at GSI is the availability of powerful beam cooling which was incorporated in the initial design [1]. Two aspects governed the design considerations for the cooling systems. Firstly, high beam quality should be achieved for precision spectroscopy of stored ion beams for atomic and nuclear physics experiments. Secondly, cooling times for injected hot secondary beams on the order of seconds should be provided to allow experiments with short-lived rare isotope beams. The secondary beams are produced in the fragment separator FRS [2] by projectile fragmentation of primary heavy ion beams which are accelerated in the heavy ion synchrotron SIS [3] to energies in the range 500 to 1000 MeV/u. The typical injection energy into ESR is 400 MeV/u, because of the availability of both stochastic and electron cooling at this energy. As the final beam quality of stored cooled beams is determined by an equilibrium with heating processes in the storage ring, like intrabeam scattering or interaction with an internal target, the requirement of high beam quality corresponds to the achievement of maximum cooling rates.

STATUS OF THE COOLING SYSTEMS

Electron Cooling

The electron cooling system of the ESR [4] has been continuously operated from the initial commissioning phase of the ESR up to date. The maximum electron energy for cooling of the ion beam has been raised to a present maximum value of 230 keV. Higher energies are expected to be available, but the lack of urgent need to increase the beam energy and the increased risk of a damage of the high voltage system have to be considered. At the typical injection energy of the ion beam of 400 MeV/u the magnetic guiding system is operated at 0.1 T and electron currents range from 0.1 to 1.0 A.

One of features of the ESR is deceleration of highly charged ions for the reduction of Doppler effects which limit the experimental resolution. In this context the energy at which electron cooling is applied is reduced to 3 MeV/u, corresponding to an electron energy of 1.7 keV. At the lower beam energies the magnetic field is reduced, to a minimum value of 0.015 T, because of the increased influence on the ion orbit at lower beam momentum. The electron density increases with decreasing beam velocity, as a consequence at the lowest energies electron currents around 0.1 A provide sufficient cooling power.

Stochastic Cooling

The stochastic cooling system of the ESR [5] was installed in 1996 and has been optimized during recent years. It is mainly used for fragment beams, which are injected with so large emittance and momentum spread that the cooling time with electron cooling is increased to several 10 seconds, even with electron currents up to 1 A. Stochastic cooling is only used, if fast cooling after injection is mandatory. Recently stochastic cooling was also employed to cool the ion beam, if the electron cooler was operated as an electron target for recombination experiments providing electrons with a velocity detuned with respect to the ion velocity.

Because of space constraints, the pick-up and kicker electrodes are installed in the main dipole and quadrupole magnets of the ESR. All electrodes are installed in the outer part of the ring acceptance at dispersive locations, where the ions circulate, immediately after injection, with positive momentum offset to the central orbit. A stack of pre-cooled particles can be accumulated on an inner orbit. One set of electrodes is located in two quadrupole magnets on opposite sides of the ring. By proper processing, the signals from the upper and lower halves of the electrodes are added for longitudinal cooling or subtracted for vertical cooling. The horizontal cooling is performed employing electrodes inside the central dipole magnets of the bending section.

The signals from two sets of four electrodes encompassing the beam are combined to constitute a superelectrode. Variable delays allow matching of the travel time between pick-up and kicker to the beam energy in the range 400 to 550 MeV/u. At present the system is optimized for a beam energy of 400 MeV/u. A total rf power in the frequency band 0.9-1.7 GHz of 2 kW is available.

COOLING OF HIGHLY CHARGED IONS

The ESR storage ring is predominantly used with the heaviest ions in the bare charge state or with only few bound electrons. The ion species range from bare carbon

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ions up to bare uranium ions. For these ions several systematic cooling studies have been performed. The heaviest ions provide favorable conditions for cooling because of the high electric charge. The cooling force in electron cooling increases roughly with the square of the ion charge q^2 and the cooling rate scales with A/q^2 , A being the mass number of the ion. Small deviation of this scaling have been found experimentally [6] and can be attributed to plasma physics screening effects. The high ion charge results in strong Schottky signals which are the basis of stochastic cooling. An increase of the signal to noise ratio reduces the cooling time for stochastic cooling, too. Therefore fast cooling of highly charged ions is significantly favored by the large value of the ion charge.

RESULTS OF STOCHASTIC COOLING

Cooling Time

The behavior of the stochastic cooling system was studied with respect to system optimization and to the influence of the ion charge on the cooling time. At present the delay times in the electronic circuits are optimized for a beam energy close to 400 MeV/u. In previous measurements with an Ar^{18+} beam cooling times of 1.6 s for the transverse degree of freedom and 0.9 s for the longitudinal degree of freedom could be demonstrated for 6×10^6 ions [7]. The result of a recent measurement of the reduction of the momentum spread with U^{92+} is shown Fig. 1. The minimum longitudinal cooling time is reduced to 0.3 s, a reduction of a factor of 3 compared to the previous value for the Ar^{18+} beam.

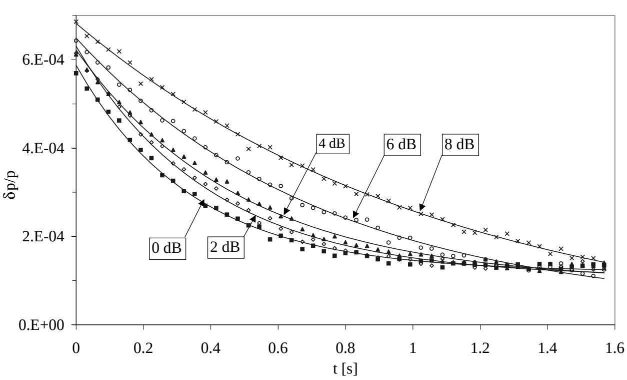

Figure 1: Momentum spread as a function of time for the stochastic cooling of 7.6×10^6 U^{92+} ions. The gain in the system was changed with a variable attenuator in the signal path.

Stochastic pre-cooling

The stochastic cooling system of the ESR acts on particles which circulate on an outer orbit, i.e. particle with an positive momentum offset to the central orbit. This applies to particles immediately after injection, as the partial aperture injection kicker is placed on the ring outside. This allows a mode of beam accumulation with stochastic pre-cooling on the injection orbit, stacking to an inner orbit with the rf system and accumulation on the inner orbit by application of electron cooling [7]. This method is particularly suited for radioactive ions which can be accumulated for internal experiments in the ESR.

Another pre-cooling method is applied in mass measurements of radioactive ions with lifetimes on the order of seconds. Electron cooling is powerful for cold beams, but rather slow (some ten seconds) for hot ion beams with the typical energy of the radioactive beams (300-400 MeV/u). The stochastic cooling system and the electron cooling system act on the beam circulating on the injection orbit. As the noise and diffusion generated by the stochastic cooling system does not allow the lowest temperatures achievable with electron cooling, the stochastic cooling system is switched off as soon as the ion beam has been cooled down to beam parameters which allow further electron cooling with cooling times below a second. The stochastic cooling system reduces the initial momentum spread from $1 - 2 \times 10^{-3}$ to a few times 10^{-4}, electron cooling brings the final momentum spread below 10^{-5}. The total cooling time for hot fragment beams is reduced to about 5 s.

Equilibrium Beam Parameters

From experiments it is known that the emittance and momentum spread for electron cooled heavy ion beams are limited by intrabeam scattering [8]. The cooling rate of stochastic cooling for a cold beam is inferior to the electron cooling rate. Therefore stochastic cooling results in larger equilibrium values. A comparison of the cooling methods was performed by measurement of the equilibrium beam parameters. The momentum spread of a U^{91+} beam at 400 MeV/u was determined from Schottky noise spectra, the emittance was measured with a non-destructive beam profile monitor based on the position sensitive detection of residual gas ionization products (Fig. 2). The intensity of the ion beam was varied and the gain of the stochastic cooling system was optimized to the beam intensity. For comparison the equilibrium values were measured applying electron cooling with electron currents of 25 and 250 mA, the latter being a typical electron current to provide high beam quality for experiments.

For an estimate of the corresponding cooling rates the intrabeam scattering rates for the experimental conditions were calculated numerically with the approximation by Martini [9]. For stochastic cooling the calculated horizontal heating rates vary between 0.5 and 1.3 s^{-1}, the longitudinal heating rates are slightly higher in the range 0.9 to 2.2 s^{-1}. This is in reasonable agreement with the directly measured cooling rates for U^{92+} detecting the reduction of the beam emittance after injection. Electron cooling results in heating rates of 1.4 to 3.3 s^{-1} horizontally and 2.0 to 6.0 s^{-1} longitudinally for the ion beam cooled with an electron current of 25 mA. The heating rates estimated for the higher electron current of 250 mA are in the range 7 to

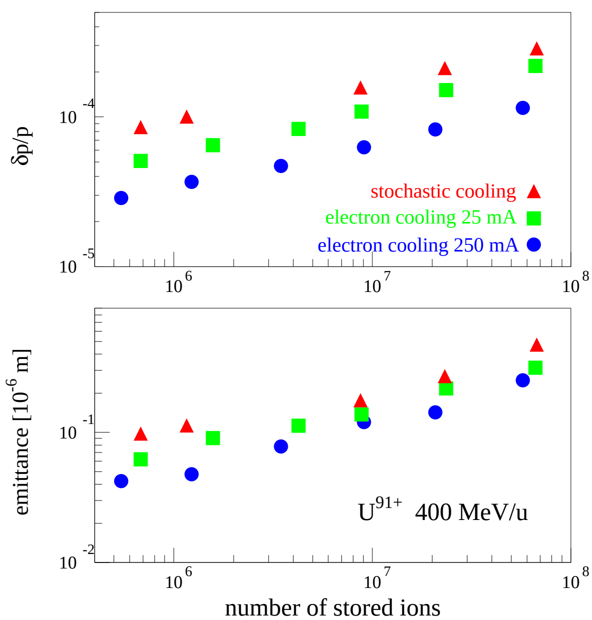

Figure 2: Momentum spread and transverse emittance (2σ-values) of a U^{91+} beam. Stochastic cooling was optimized for the beam intensity, electron cooling with two electron currents (25 and 250 mA) was measured in comparison.

10 s^{-1} horizontally and 18 to 58 s^{-1} longitudinally. The measurements show that the longitudinal cooling rates are higher than the transverse ones. For stochastic cooling the two degrees are decoupled due to application of two basically distinct cooling circuits with independent parameters. Electron cooling forces in the magnetized cooling regime are known to be higher in the longitudinal than in the transverse degree of freedom, in both degrees of freedom, however, they scale with the electron current.

RESULTS OF ELECTRON COOLING

Cooling Times

The cooling time for electron cooling is strongly dependent on the properties of the ion beam. At large relative velocities between ions and electrons the cooling time increases with the third power of the relative velocity, towards small velocities the cooling time approaches a constant minimum value in the linear cooling regime. It is impossible to give a general value of the cooling time. For heavy ions at an energy of 300-400 MeV/u with highest charges, which should be cooled fastest, the cooling time for the typical electron current of 0.25 A applied in the ESR ranges from the order 10 s for the injected beam with an emittance of about 1×10^{-5} m and a momentum spread of about 1×10^{-3} down to the order 0.01 s, when the beam is cooled to equilibrium. The lower values are mainly derived from the beam parameters in equilibrium with intrabeam scattering. Direct observation of the cooling times is limited by the temporal resolution of the non-destructive diagnostics.

Equilibrium Beam Parameters

The equilibrium beam parameters of electron cooled beams have thoroughly been studied with non-destructive [8] and with destructive diagnostics [10]. These studies included beams at the typical injection energy of 400 MeV/u down to the minimum energy which can be achieved by decelerating the beam in the ESR [11]. The observations can be summarized as follows. The beam is always cooled to an equilibrium with intrabeam scattering which is dependent on the beam energy and the ion species. Lower energies result in larger emittance and momentum spread, but the normalized emittance for comparable cooling conditions (electron density) is nearly constant. As the intrabeam scattering rate roughly scales with q^4/A^2, but the electron cooling rate scales with q^2/A, the equilibrium values for heavier bare ions are slightly higher. Higher electron currents with correspondingly increased cooling rates result in smaller equilibrium values. In one degree of freedom however the equilibrium values vary only weakly with the cubic root of the electron beam density and of the ratio q^2/A. This is a rough general rule, as the cooling rate can be easily affected by imperfections like the quality of the electron beam, which can be intensity dependent, or angular misalignment between ion and electron beam.

Ultra-cold Ion Beams

Measurements with cooled beams in the regime of maximum cooling rate have evidenced an outstanding feature. For ion numbers below a few thousand the ion beam enters into an ordered state [12]. This phenomenon was observed first by a reduction of the momentum spread by up to one order. This occurs when the ion beam is cooled to the equilibrium with intrabeam scattering and then the ion beam intensity is reduced. More recent experiments have also confirmed a simultaneous discontinuous reduction of the horizontal beam emittance (Fig. 3) for the same intensity (below a thousand ions).

The measurements at low intensity have two peculiarities. Firstly, the beam intensity cannot be measured with the standard beam transformer, as the electric current is too low. Therefore the Schottky noise power is calibrated at higher intensity and is used at low intensity for the determination of the particle number. Secondly, the non destructive residual gas ionization profile monitor is limited by the detector resolution. A high precision method to vary the beam position by energy variation of the electron cooled ion beam relative to a beam scraper allows a limitation of the horizontal beam radius to 3 μm [13]. Thus the emittance can be measured down to values of about 10^{-13} m. Together with the high resolution of the Schottky noise analysis which detects frequency spreads as low as 10^{-7} an exceptional lower value of the ion beam temperature could be confirmed. For U^{92+} beam with less than one thousand ions at an energy of 400 MeV/u minimum beam temperatures of 1 meV horizontally and of 5 meV longitudinally could be evidenced [4]. These low values of the ion temper-

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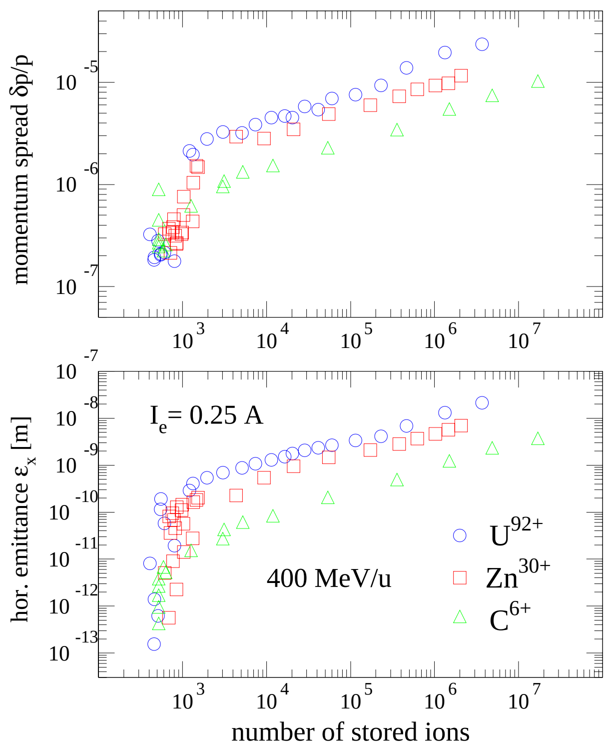

Figure 3: Momentum spread and horizontal emittance (1σ-values) as a function of the number of stored ions for three species of bare ions stored and cooled at an energy of 400 MeV/u. The momentum spread is determined from Schottky noise, the emittance is determined by probing the beam with a scraper.

ature have to be compared to the electron temperature. The transverse electron temperature is determined by the cathode temperature of 0.1 eV, the longitudinal temperature of the accelerated electrons is much lower, from various experimental results it is expected to be around 0.1 meV. Consequently, the lowest ion temperatures, both transversely and longitudinally, are limited by the longitudinal electron temperature. The very low values of the ion temperature in all degrees of freedom must be attributed to the effect of magnetized cooling.

Electron Cooling above Transition Energy

The ion optical lattice of the ESR is flexible, thus the focussing properties can be chosen in a wide range. A special mode allows a reduction of the transition energy to $\gamma_t = 1.37$. Tuning the beam energy to the transition energy of the lattice, the isochronous circulation of fragment beams is useful in mass measurements of short-lived radioactive ions [14]. When the beam energy exceeds 344 MeV/u, the particles circulate in the ring above transition energy. No rf manipulation is required, as the ions are injected into the ESR above transition energy. The isochronous mode allows studies of cooled ion beams above transition energy.

First experiments with an electron cooled beam above transition energy employed a beam of bare krypton ions injected at an energy of 380 MeV/u. As a reference the cooling was studied in the standard ion optical mode before. Applying an electron current of 0.25 A, the reduction of momentum spread and emittance could be measured. Differences in the cooling time for the two ion optical settings have to expected, as the beam can be injected with slightly different parameters and as the overlap between ion and electron beam can also be different. Nevertheless, the time for cooling the injected beam to equilibrium was for both ion optical settings about 10 s.

In the isochronous mode the energy of the electron beam was varied, the corresponding changes of the ion revolution frequency were monitored by Schottky noise detection. By comparison of the ratio of relative frequency change to relative momentum change the momentum slip factor $\eta = \gamma^{-2} - \gamma_t^{-2} = (df/f)/(dp/p)$ was measured. The relative momentum change $dp/p = (\gamma/(\gamma+1))dE/E$ is known from the change of the electron energy dE. The measured value $\eta = -0.019$ was a well defined quantity only in the vicinity of the injection orbit. For larger momentum deviations the η-value varied considerably, it even changed from negative to positive value.

The measured η-value around the orbit of the cooled beam allows the determination of the momentum spread from frequency spectra. The measured frequency spreads and the horizontal beam emittances are shown in Fig. 4 as a function of the number of stored ions. The small absolute value of η results in a strong compression of the frequency spread. At low beam intensities the main contribution to the frequency spread originates from fluctuations of the dipole field due to power supply ripple. The current ripple $\delta I/I$ of the main dipole power supply causes a frequency spread $\delta f/f = \gamma_t^{-2} \cdot \delta I/I$. The known current ripple $\delta I/I = 1 \times 10^{-6}$ agrees well with the lowest measured frequency spread $\delta f/f = 5 \times 10^{-7}$ for ion numbers below 5×10^6.

The strong increase of the momentum spread with intensity at higher intensities is attributed to the onset of microwave instabilities heating the beam. The unstable behavior of high intensity beams above transition energy could be monitored in different ways. Strong longitudinal self bunching for ion numbers exceeding 10^7 was probed by beam position pick-ups. For intensities in the 10^8 range the Schottky spectra exhibited a strong low energy tail [10]. A corresponding distribution was also observed in the beam profile monitor which is located in a section with large dispersion. The observed linear dependence of the momentum spread agrees well with the Keil-Schnell limit. The instabilities did not cause a significant beam loss.

Electron Cooling as a Pre-Cooling for Laser Cooling

Experiments to study laser cooling of relativistic ion beams in the ESR have been proposed. These experiments

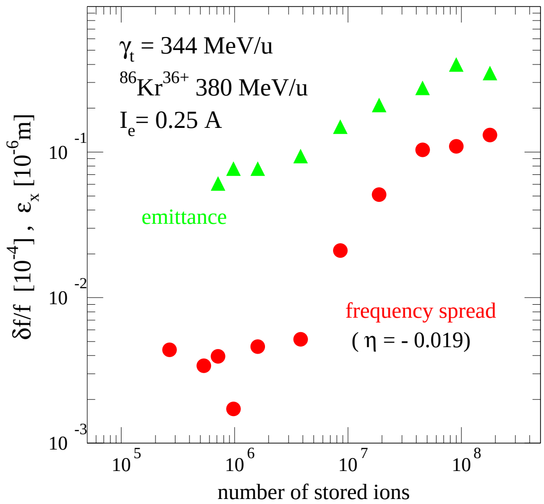

Figure 4: Frequency spread and horizontal emittance (2σ-values) of an ion beam stored above transition energy as a function of the particle number. The bare krypton beam at an energy of 380 MeV/u was cooled by an electron current of 0.25 A.

require C^{3+} at an energy of 122 MeV/u. The ion energy shifts the frequency of a frequency doubled counter-propagating Ar-ion laser to a value which is matched to the closed $2S_{1/2} - 2P_{3/2}$ transition in the Li-like charge state. The momentum spread and emittance of the ion beam must be reduced to smallest values in order to be matched to the narrow bandwidth and small transverse size of the intense laser beam. This can be achieved by employing electron cooling as pre-cooling before laser cooling is applied. The cooling time for the low charged ion of about 10 s is still short compared the measured lifetime in the residual gas of 360 s. The incompletely stripped ion is subject to losses due to ionization in the residual gas.

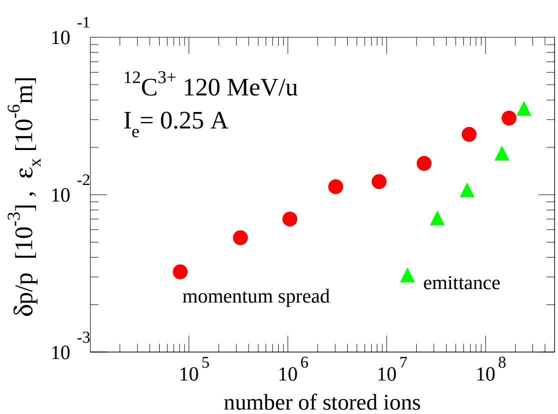

Figure 5: Momentum spread (in permille) and horizontal emittance (in 10^{-6} m) of C^{3+} at 120 MeV/u cooled with an electron current of 0.25 A.

The low cooling rate for the low charge state by electron cooling is acceptable as the intrabeam scattering rate is even more reduced. Rather low equilibrium values can be achieved compared to highly charged ions (Fig. 5). The emittance of the electron cooled C^{3+} beam increases almost linearly with the ion beam intensity, whereas the momentum spread grows proportionally to $N^{0.3}$, as previously observed for many ion species [8]. The linear dependence of the emittance on the ion beam intensity indicates an influence of the ion beam's space charge. The measured values correspond to a space charge tune shift $\Delta Q_x \simeq -0.005$. The emittance measurement at lower beam intensities was limited by the resolution of the beam profile monitor. The detection limit for the cooled ion beam by Schottky noise analysis was around 10^3 stored ions. Values of the momentum spread below 10^{-5} and of the emittance below 10^{-8} m provided excellent initial beam parameters for the first laser cooling experiments performed in the ESR [15].

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