EXTREMELY COOLED ION BEAMS IN THE ESR WITH EVIDENCE OF ORDERING

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Abstract

Experiments with electron-cooled highly charged ions in the storage ring ESR have evidenced an unusual behavior for small particles numbers. The momentum spread drops suddenly by a factor of three to ten, depending on the ion charge, when the ion number decreases below a few thousands. The transition particle number increases with the intensity of the electron beam which determines the cooling rate. Destructive measurements of the beam radius suggest a similar reduction of the transverse emittance near the transition point of the momentum spread. The assumption that the momentum spread reduction is connected with a suppression of intrabeam scattering could be confirmed by direct observation of the longitudinal heating of a cooled beam above and below the transition point. A possible explanation is, that the ions are circulating in a longitudinally ordered structure, where the ions are confined by their neighbors to a fixed longitudinal position relative to each other.

1 INTRODUCTION

Beam cooling is a standard method in the preparation of beams with high phase space density. Unlike stochastic cooling which is well suited for hot beams at relativistic energies, electron cooling is most powerful for low energy beams which have either been precoooled or which occupy a moderate phase space volume. Strongest cooling by electrons is achieved for highly charged ions because of the q^2/A-dependence of the cooling rate with the ion charge and mass number q, A. Because of the high cooling rate it was speculated that an electron-cooled heavy ion beam might even undergo a phase transition to an ordered structure [1]. The relevant plasma parameter $\Gamma = U/k_B T$ is highest for highly charged ions because of the q^2-dependence of the Coulomb-potential U. This idea was supported by the observation of an unexpected behavior of the Schottky noise of an electron-cooled proton beam in the cooler storage ring NAP-M [2]. A number of theoretical considerations investigated the optimum conditions for the achievement of an ordered structure in a storage ring for fast charged particles and tried to formulate constraints for the formation of such an ordered structure [3].

2 STORAGE RING AND ELECTRON COOLING SYSTEM

The heavy ion storage ring ESR [4] which has a maximum magnetic rigidity of 10 Tm has been designed for large longitudinal and transverse acceptances ($A_x = 450\,\pi$ mm mrad, $A_y = 150\,\pi$ mm mrad, $\Delta p/p = \pm\,2$ %). Horizontal and vertical tune are $Q_x = 2.29, Q_y = 2.27$, respectively.

In one straight section an electron cooling system is installed which has cooled heavy ions up to energies of 400 MeV/u [5]. The 5 cm diameter electron beam with a current of typically a few hundred mA is merged with the ion beam over a length of 2.5 m. For an electron density $n_e = 1 \times 10^6$ cm^{-3}, which corresponds to an electron current of about 60 mA at ion energies around 300 MeV/u, the ring averaged longitudinal cooling rate for a cooled beam of highly charged ions is approximately 10 s^{-1} [6]. Transverse cooling rates are typically a factor of two to five smaller. The cooling rate is expected to increase roughly proportional to the electron density.

3 EQUILIBRIUM BETWEEN ELECTRON COOLING AND INTRABEAM SCATTERING

The beam properties of the cooled ion beam are not only determined by the rate of cooling, but also by all kinds of heating mechanisms which counteract cooling. For dense ion beams of moderate intensity the dominant heating process is intrabeam scattering [5]. The heating rate due to intrabeam scattering is proportional to the ion number and is inversely proportional to the six-dimensional phase space volume of the ion beam. The dependence of the heating rate on the ion charge and mass with a proportionality to q^4/A^2 even exceeds the increase of the cooling rate for highly charged ions. Thus an increase of the phase space volume with particle number and with the ion charge is expected.

Systematic measurements of emittances and momentum spread of coasting beams of bare ions have been performed. For a constant cooling current of 0.25 A at ion energies around 300 MeV/u the emittance and the momentum spread of coasting cooled ion beams in the ESR exhibited the expected increase of the phase space volume with the number of stored ions N and with the charge of the ion (Fig. 1). The increase, however, is slightly stronger than expected from the dependence of the heating rate which grows inversely proportional to the phase space volume. This can be explained by a weak dependence of the cooling rate on the properties of the ion beam, which is comprehensible by a reduction of the cooling rate when the relative velocities between ions and electrons are outside the range of the linear part of the cooling force. The observed

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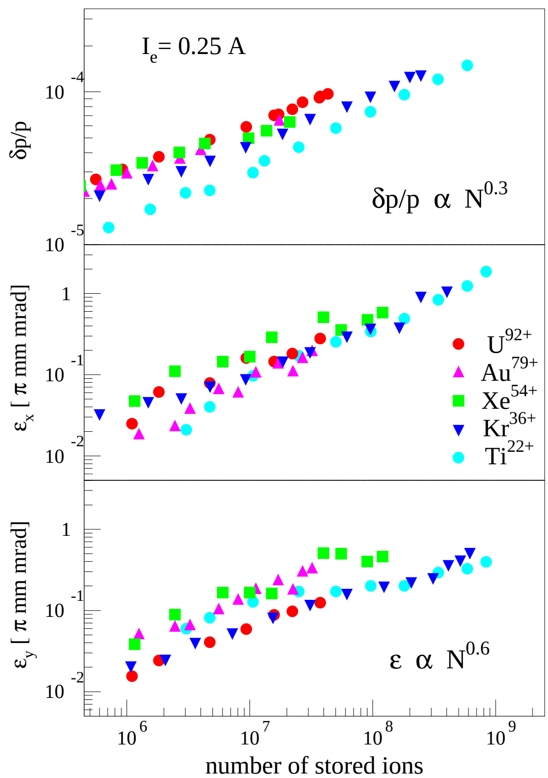

Figure 1: Equilibrium values of beam emittance and momentum spread for coasting beams of various bare ions cooled with an electron current of 0.25 A.

increase of the transverse emittance proportional to $N^{0.6}$ and of the momentum spread proportional to $N^{0.3}$ results in a reduction of the phase space density proportional to $N^{-0.5}$. Thus it can be concluded that due to a reduction of the cooling rate for high intensity ion beams associated with the increased relative ion motion the achievable phase space density of the ion beam is highest at small particle numbers. This is the regime which is most favorable for studies of ordering effects.

4 LONGITUDINAL SCHOTTKY NOISE AT LOW INTENSITY

At low intensity a direct determination of the beam intensity with the current transformer is ruled out due to the insufficient sensitivity. In order to extend momentum spread measurements to smallest intensities which are still observable with Schottky noise analysis the known lifetime of the ion beam was employed. The lifetime was determined with an accuracy better than 10 % either with a current transformer used at intensities above some 10 μA or by detection of those ions which are lost due to recombination. Radiative electron capture from the electron beam is the dominant loss mechanism for bare ions stored with energies of a few hundred MeV/u in a vacuum better than 1×10^{-10} mbar and thus determines the lifetime of electron-cooled beams.

The Schottky noise at the 31st harmonic of the revolution frequency of an uranium beam cooled with a 0.25 A electron beam was measured over the whole storage time of a beam of initially 1.3×10^4 ions. The Schottky signal at the end of the measurement comes from only a few remaining ions. Due to the narrow frequency distribution and the high spectral density even detection of single ions is easily achievable. The integrated noise power and the momentum spread derived from the width δf of the frequency distribution according to $\delta p/p = \eta^{-1}\delta f/f$ with the momentum slip factor $\eta = \gamma^{-2} - \gamma_t^{-2}$ is shown in Fig. 2. The noise power is proportional to the beam intensity although one could suspect a noise suppression which is frequently found in longitudinally cold ion beams [7]. Also at other harmonics no coherence in the Schottky noise could be detected.

The prominent feature of this measurement is a reduction of the momentum spread by a factor of ten when the particle number reaches about 1000 stored ions. This corresponds to a reduction of the longitudinal beam temperature by two orders of magnitude.

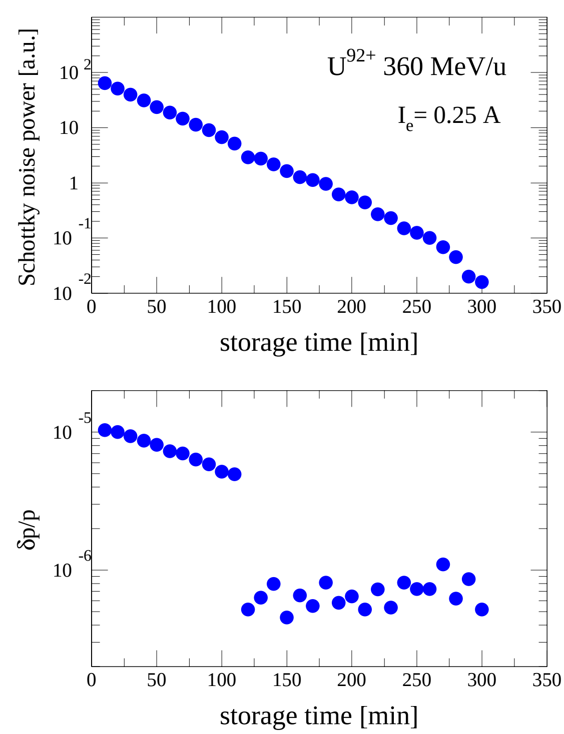

Figure 2: Noise power and momentum spread of an uranium beam obtained from analysis of the Schottky noise at the 31st harmonic of the revolution frequency.

In other measurements around the transition point to smaller momentum spread a reduction of the noise power by a factor of two to three was observed close to the transition point. For intensities which are not in the vicinity of the transition point the noise power always has the value which is expected for normal Schottky noise without collective effects. Therefore it can be concluded that apart from the vicinity of the transition point the longitudinal Schottky signal can be employed, after proper calibration, for the determination of the ion beam intensity.

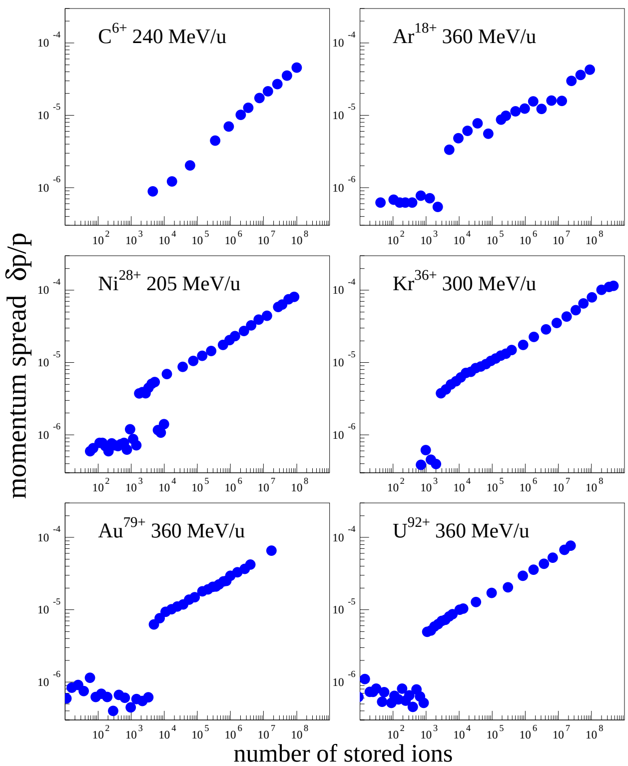

Figure 3: Reduction of the momentum spread for coasting beams of various bare ions cooled with an electron current of 0.25 A.

The dependence of the momentum spread reduction on the ion charge was examined for a wide variety of bare heavy ions from C^{6+} to U^{92+} with beam energies between 200 and 360 MeV/u (Fig. 3). The electron current in all measurements was 0.25 A. These measurements can be summarized as follows [8]. The transition particle number for all ions is around a few thousand stored ions and does not show a significant dependence on the charge of the ion. For ions with low charge ($q < 18$) no reduction of the momentum spread is observed. The momentum spread for large particle numbers is dominated by intrabeam scattering ($N^{0.3}$-dependence) and therefore the higher charged ions have for a certain particle number a larger value of the momentum spread. The minimum momentum spread for all ions is around $\delta p/p = 5 \times 10^{-7}$. This value is not determined by the beam temperature. The measured frequency width of the Schottky signal, which is obtained after averaging over several seconds, is at small particle numbers due to the stability of the main ring magnets ($\delta B/B \simeq 2 \times 10^{-6}$). From the minimum momentum spread an upper limit of the longitudinal beam temperature $k_B T_\parallel = m_i c^2 \beta^2 (\delta p/p)^2_{rms}$ of about 4 meV for the heavier species and less than 1 meV for the lighter ones can be estimated. Fast Fourier spectral analysis of the Schottky noise (with averaging times of some ten milliseconds) has indicated that the actual beam temperature is about another order of magnitude smaller which is in agreement with a longitudinal temperature of the electron beam below 0.1 meV.

The observed momentum spread reduction has been studied in Monte-Carlo simulations of the particle motion for the measured beam temperatures and the given storage ring parameters [9]. The calculations suggest that the ions are longitudinally confined by their neighbors to their position along the beam orbit and that the reflection probability from the neighbor ions steeply rises from zero to one around the transition point.

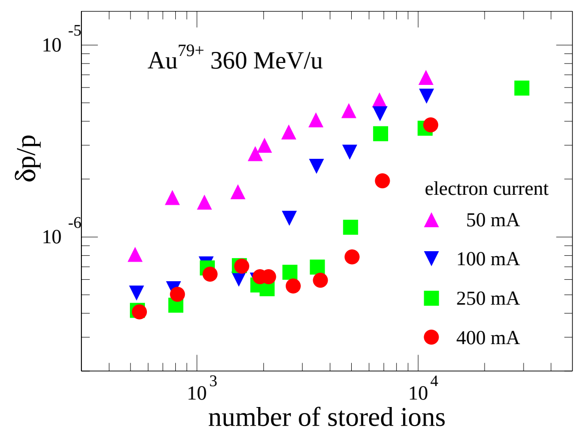

Figure 4: Momentum spread of a bare gold beam cooled with various electron currents as a function of the number of stored ions.

The influence of the cooling rate on the momentum spread reduction is shown in Fig. 4, which shows the momentum spread as a function of the number of stored ions for four electron currents. A clear correlation between the transition point to smaller momentum spread and the electron current is observed. Only for the lowest current (50 mA) the momentum spread at low intensity is slightly increased due to insufficient cooling. The measured minimum momentum spread is for all electron currents limited by the magnet power supply stability.

For a lower ion beam energy of 75 MeV/u it has been observed that the minimum momentum spread increases with the electron current [10]. This can be explained by a contribution of two effects. The cooling rate at lower energy is higher, the stability of the electron beam energy is lower due to a larger relative value of the variation of the accelerating voltage. This results in a modulation of the ion energy which increases proportional to the electron current. If this modulation of the ion beam energy is of similar value as the energy (or momentum) spread due to the beam temperature a reduction of the momentum spread at the transition point will be covered by the energy modulation originating from the ripple of the accelerating voltage of the electron beam.

5 EMITTANCE AT LOW ION BEAM INTENSITY

The emittance determination of the cooled beam is limited by the resolution of the detector which measures the transverse beam profile either by detection of ions which have changed their charge by electron capture or by a residual gas ionization beam profile monitor [11]. Both techniques are non-destructive, but have a resolution not better than 1 mm which results in a lower limit of about 0.01 π mm mrad for the emittance measurement (compare Fig. 1).

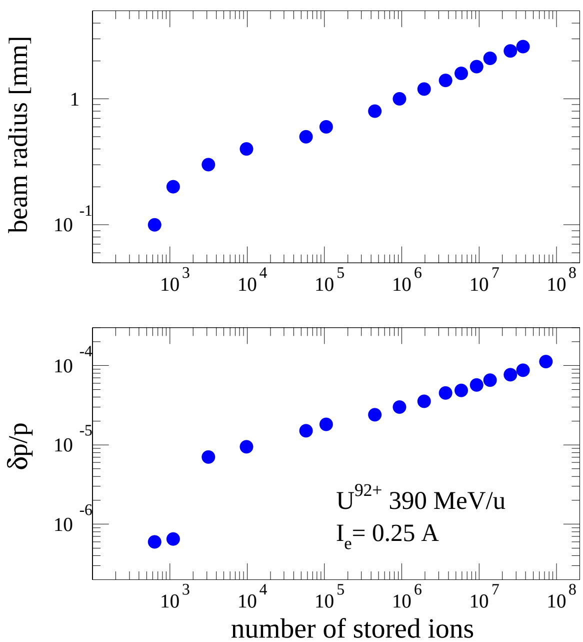

Figure 5: Beam radius from scraper measurements and momentum spread of a bare uranium beam cooled with an electron current of 0.25 A as a function of the number of stored ions.

Smaller beam emittances can presently only be detected by the destructive method of beam scraping. A beam scraper is moved from one side for a few seconds horizontally into the beam, moved out again and the surviving number of ions is determined, for higher intensities with the current transformer, for lower intensities with the calibrated Schottky noise power. This procedure is possible since the time scale for diffusion of particles to the outer part of the emittance is longer than the typical time of placing the scraper in the beam path. The scraper position, where the beam is lost completely, marks the center of the ion beam. The measured beam radius is determined from the difference of the actual scraper position and the beam center. This beam radius which is about three times the rms radius is plotted in Fig. 5 together with the momentum spread of the beam versus the number of ions surviving after scraping. The scraper measurements confirm that the ion beam emittance decreases continuously down to ion numbers of a few thousand with a dependence which resembles the $N^{0.6}$-dependence of the emittance measured non-destructively for higher intensities. In this scraper measurement, similar to others with different ions, an indication that the transverse beam size also changes discontinuously around a thousand ions is observed. A more precise measurement of the beam radius with the scraper is shown in Fig. 6. For lowest beam intensities the scraper, which can be positioned in stepping increments of 5 μm was moved in steps of 25 μm. Below a radius of 3 mm the beam radius seems to collapse to less than 50 μm. This corresponds to an emittance of less than $7 \times 10^{-5}\pi$ mm mrad or a ring averaged horizontal beam temperature below 0.2 eV. This surprisingly low ion beam temperature, which is around the transverse electron temperature (0.1 eV) is plausible for strong magnetized electron cooling.

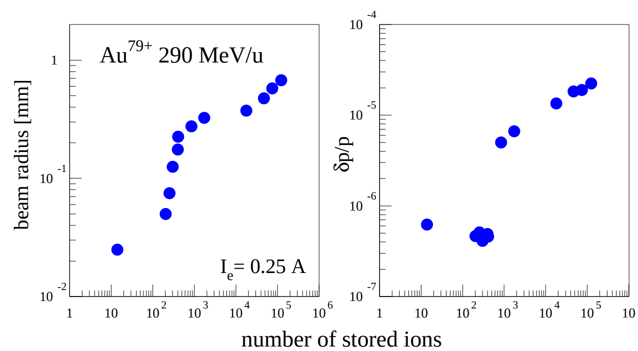

Figure 6: Beam radius from scraper measurements and momentum spread of a bare gold beam cooled with an electron current of 0.25 A as a function of the number of stored ions.

6 ABSENCE OF HEATING

Following the experience from traps it was proposed that a crystalline beam will be resistant against heating [13]. Assuming that the sudden reduction of the beam temperature indicates a phase transition from a gaseous to an ordered state of the beam, a change of the beam behavior with respect to heating is expected. This can be detected by observation of the beam temperature when cooling is interrupted. Longitudinal Schottky noise analysis offers sufficient resolution of the beam distribution and its temporal evolution. Moreover, heating due to intrabeam scattering will mainly act on the colder longitudinal degree of freedom. The momentum spread of cooled beams above and below the transition point (particle numbers N= 19000, 600) is shown in Fig. 7. At the time t = 0.8 s cooling is stopped by setting the electron current to zero. The beam in the intrabeam scattering dominated regime immediately blows up, whereas for the ultracold beam the growth of the momentum spread starts with a delay of about 0.5 s. At t= 6.8 s cooling starts again and the momentum spread shrinks within a few 100 ms for both intensities to the old value. At t = 12.8 s the cycle starts again with stopping the electron beam and again the blow up of the colder beam shows a delay. The cold beam survives for about 10^6 revolutions without a temperature increase by intrabeam scattering. This demonstrates the suppression of heating by intrabeam scattering which is expected for a cold beam which is governed by Coulomb interaction between the ions resulting in an ordered structure.

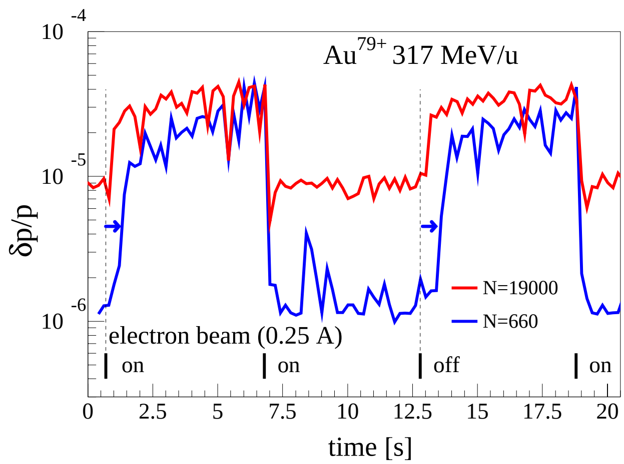

Figure 7: Momentum spread for the cold ion beam above ($N = 19000$) and below ($N = 600$) the transition point to small momentum spread when cooling is switched off and on periodically for time intervals of 6 seconds. The delay of heating for the ultracold beam is indicated by the little arrow.

7 APPLICATIONS AND OUTLOOK

The method of Schottky mass spectrometry is based on the measurement of the revolution frequency of radioactive nuclei with unknown mass and the comparison with the revolution frequency of cocirculating nuclei with a known mass [14]. The mass resolution is inversely proportional to the frequency width of the Schottky line. Therefore it is favorable to perform the measurements at particle numbers below the transition point to small momentum spread. A mass resolution $M/\delta M$ of up to 1×10^6 has been achieved for low intensity beams. The increased spectral density of the Schottky signal at low intensity facilitates detection of single ions and also changes of the ion beam intensity due to loss or creation of a single ion. Consequently lifetime measurements of radioactive nuclei and their isomeric states even for lowest intensities by Schottky noise detection are feasible.

The momentum spread reduction was until recently observed only for electron-cooled highly charged ions at the ESR. Measurements at the synchrotron SIS [15] and at the storage ring CRYRING [16] have evidenced the same phenomenon of a sudden momentum spread reduction for partially stripped highly charged ions which are electron-cooled at energies around 10 MeV/u. The variety of experimental conditions and accelerator and beam parameters now available may allow further insights into the creation of ordered beam structures.

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