ORDERED ION BEAMS

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Abstract

Anomalous behavior at small particle numbers has been observed for electron cooled beams of highly charged ions. Theoretical calculations confirm that a reduction of the momentum spread indicates a linear ordering of the beam particles in a string-like structure. In the ordered state the usual heating by intrabeam scattering is suppressed. Even without cooling the cold ion beam survives more than 10^6 revolutions in the storage ring without a significant temperature increase.

1 INTRODUCTION

Cooling of ion beams to extreme phase space density will ultimately result in the generation of an ordered structure, frequently referred to as crystalline beam. The existence of such ordered structures has been demonstrated in traps for charged particles at rest. A first indication of an ordering effect in a fast electron cooled proton beam in the NAP-M ring [1] has aroused particular interest in the generation of very cold fast ion beams.

The possibility of creating a crystalline beam has mainly been studied theoretically so far. The properties of such an one-component plasma can be described by the dimensionless plasma parameter

$$\Gamma = \frac{q^2 e^2}{4\pi\epsilon_o a k T} \qquad (1)$$

which is the ratio of the Coulomb potential of two ions with charge qe at a distance a to the thermal energy kT. Already in the early theoretical investigations [2] it was pointed out that with highly charged ions the highest value for the plasma parameter can be achieved, i.e. highly charged ions give the best preconditions for the achievement of an ordered structure. Depending on the line density the beam can arrange in an one-dimensional string or for higher line density even in a two- or three-dimensional crystal [3]. For two- or three-dimensional structures it is, however, unclear whether they can survive when they experience strong shearing forces in the bending magnets or the focusing action of the quadrupole magnets of the storage ring.

Two cooling techniques are available which promise cooling down to sufficiently low ion beam temperature. Electron cooling is powerful for highly charged ions because of the q^2-dependence of the cooling force, but is limited to minimum temperatures which are determined by the electron temperature. Typical values for the electron beam temperature are $kT_\perp$ = 0.01 - 0.1 eV transversely and $kT_\| = 10^{-5} - 10^{-4}$ eV longitudinally. Much lower temperatures can be reached by laser cooling. Unfortunately laser cooling of fast ion beams is presently only available for singly charged ions. Moreover no efficient way of cooling the transverse degree of freedom has been found so far.

2 EXPERIMENTAL RESULTS FROM THE ESR

The heavy ion storage ring ESR is equipped with an electron cooling system which allows to prepare cold beams of bare ions up to uranium at energies in the range of about 10-400 MeV/u [4]. The properties of cooled highly charged ions are determined by an equilibrium between electron cooling and heating by intrabeam scattering. This results in a dependence of the phase space volume of the ion beam on the number of stored ions N. The transverse emittances increase with $N^{0.6}$ and the longitudinal momentum spread of a coasting beam with $N^{0.3}$ for the typical cooling conditions [5]. With decreasing particle number therefore the phase space density increases, approximately proportional to $N^{-0.5}$, whereas the ion beam temperature decreases towards the temperature of the electron beam.

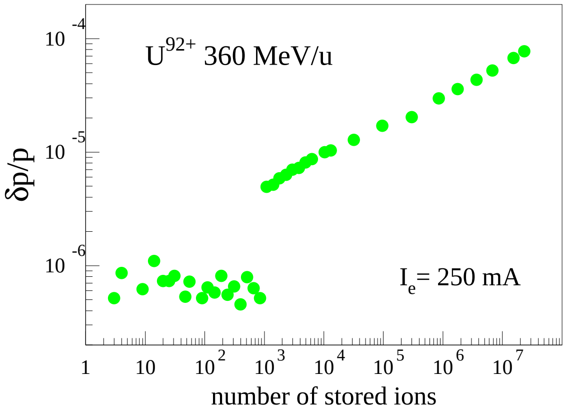

Figure 1: Momentum spread of a U^{92+} beam at 360 MeV/u cooled with an electron current of 0.25 A as a function of the number of stored ions.

A strong deviation from the continuous temperature decrease towards smaller particle numbers was observed in measurements of the momentum spread by frequency analysis of the longitudinal Schottky noise. A sudden reduction of the width of the Schottky signal around 10^3 stored ions appeared (Fig. 1). The momentum spread of a uranium beam cooled by a 0.25 A electron beam drops around 1000 stored ions from a value of $\delta p/p = 5 \times 10^{-6}$ to $\delta p/p = 5 \times 10^{-7}$ corresponding to a change of the longitudinal temperature by two orders of magnitude. A thorough analysis of the Schottky noise revealed that the measured frequency spread at low particle numbers is caused by fluctuations of the revolution frequency due to power supply ripple. The actual beam temperature is even lower.

Systematic measurements with various species of bare ions evidenced some features of the temperature reduction [6]. For constant electron current the particle number at which the transition to lower temperature occurs does not vary significantly with the ion charge. However, for stronger cooling the transition shifts to a larger particle number. The reduction factor of the momentum spread increases with the ion charge. This is mainly a consequence of the fact that lower charge states can be cooled to a smaller momentum spread in the intrabeam scattering dominated regime.

Along with the reduction of the longitudinal temperature also a reduction of the transverse temperature is expected if the ions arrange themselves in an ordered structure which is determined by Coulomb forces between the ions. For the transverse degree of freedom the determination of the beam temperature is more intricate as it requires non-destructive diagnostic devices with a spatial resolution of order 10 μm which are currently not available. An attempt to measure the beam radius near the transition point of the momentum spread by scraping the beam indicated a similar reduction of the transverse beam size [7]. The reproducibility of this technique is presently inadequate to draw definite conclusions.

3 NEW EXPERIMENTAL OBSERVATIONS FROM THE SIS

Although beam crystallization is also investigated at other existing storage rings, particularly employing laser cooling, no conclusive evidence has been available besides the observation at the ESR. After the installation of an electron cooling system at the heavy ion synchrotron SIS which was designed to serve beam accumulation at the injection energy [8] this effect can be investigated in a different environment. This allows to test whether the momentum spread reduction observed at the ESR depends on some particular property of the lattice of the ESR or of its electron cooling system.

According to ESR experience ions with the highest charge offer best conditions for the observation of an ordering effect. As the SIS electron cooling system is presently operated at the injection energy of the synchrotron only, the energy of the cooled ion beam is 11.4 MeV/u. The ions at this energy are incompletely stripped, the most abundant charge state for uranium is 73+. As it represents the highest charge state which is available with sizeable intensities the momentum spread as a function of the number of stored ions was measured with U^{73+} at 11.4 MeV/u (Fig. 2).

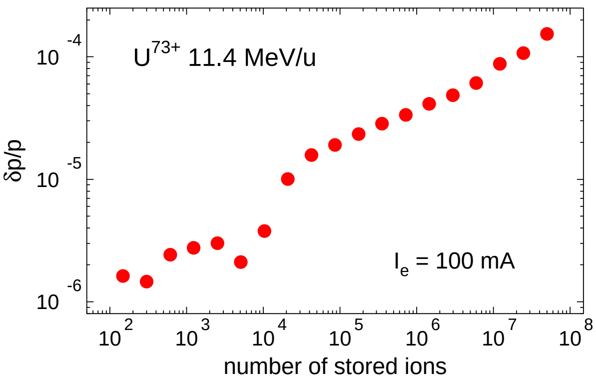

Figure 2: Momentum spread of a U^{73+} beam at 11.4 MeV/u cooled with an electron current of 0.1 A as a function of the number of stored ions.

The observation of a momentum spread reduction is well reproduced. At the SIS the momentum spread drops below 2×10^4 stored uranium ions from $\delta p/p = 1 \times 10^{-5}$ to $\delta p/p \leq 3 \times 10^{-6}$. The low momentum spread values show large fluctuations for two reasons. At the injection energy the relative value of current fluctuations in the main ring magnets are comparatively large resulting in corresponding fluctuations of the revolution frequency. Secondly cooling at the lower energy (compared to the ESR) is faster, therefore also the ripple of the high voltage power supply for the acceleration of the electron beam causes a modulation of the revolution frequency. The ion beam is effected by the variation of the electron energy.

4 CALCULATIONS OF THE REFLECTION PROBABILITY

In order to explain the momentum spread reduction we perform classical Monte-Carlo trajectory calculations of two charged particles heading at each other with constant focusing with the betatron frequencies of the ESR or of the SIS, respectively [9]. We calculate the reflection probability from thousands of such trajectory calculations with random initial conditions within the limits of the experimentally determined temperatures where the two particles either pass each other or are reflected. It is sufficient to consider the interaction of two particles only since their mutual Coulomb repulsion acts only considerably at near distance of the order of tens of micrometers. The transverse kinetic energy is distributed among the two transverse degrees of freedom according to a Boltzmann distribution in harmonic potentials with the betatron frequencies $\omega_{\beta,x,y} = 2\pi Q_{x,y} f_o$, where f_o is the revolution frequency and $Q_{x,y}$ are the horizontal and vertical tunes. The available longitudinal kinetic energy is transformed into relative velocity according to the momentum spread $\delta p/p$.

The linear string density $\lambda = a_{\mathrm{WS}}/d$ is the axial number of particles within a Wigner-Seitz radius $a_{\mathrm{WS}} = \left(3q^2e^2/4\pi\epsilon_o 2M\omega_\beta^2\right)^{1/3}$ and d is the average distance between the ions. Note that at zero temperature $\lambda = 0.709$ is the limiting value for a stable Coulomb string [10]. Here λ is of the order of 10^{-3}, thus being safely in the string region.

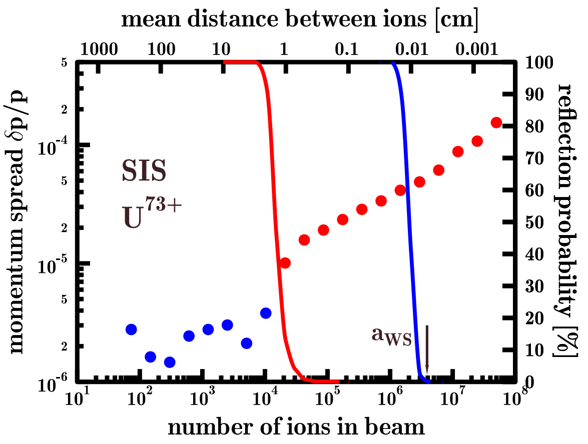

Figure 3: Measured momentum spreads (data points) with calculated reflection probabilities (line) included for the SIS experiment.

The resulting reflection probabilities are shown in Fig. 3. The left curve is calculated for the experimental temperature value of the last upper (warm) data point. It rises steeply in the vicinity of interparticle distances of 1 cm, thus indicating the transition from an ordered to a thermal state. The right curve, on the other hand is calculated for the last lower (cold) data point. It rises close to interparticle distances of the order of the Wigner-Seitz radius of $55\ \mu m$ which means that the ultracold state could survive up to such high densities provided there are no external heat mechanisms. Analyses of the ESR-data give similar results, see ref. [11].

5 ABSENCE OF HEATING

An unique property of the crystalline beam is the absence of heating. Theoretical calculations show that an ordered beam can survive more than 10^6 lattice periods without significant heat transfer [12]. This feature has been proposed as a diagnostic tool to detect a crystalline beam [13].

At the ESR a simple procedure was applied to investigate the response of the cold beam to an instantaneous switching off of cooling. A fast high voltage switch allows to stop the electron current in less than 1 ms. The electron current ($I_e = 0.25$ A) was switched on and off for equal time intervals of 6.8 s periodically, resulting in cooling down of the ions and heating by intrabeam scattering.

The Schottky noise signal was measured to determine the momentum spread for a particle number above ($N \simeq 4000$) and below ($N \simeq 600$) the transition point. The momentum spread as a function of time is shown for the two intensities in Fig. 4. The statistical quality and the time resolution in this pilot experiment were not yet optimized. However, it clearly reveals a significant difference. For both intensities heating and cooling takes a few 100 ms. For the smaller intensity the heating starts with a delay of approximately 1 s compared to the heating above the transition point. The beam continues to circulate with the small momentum spread for more than 10^6 turns without cooling.

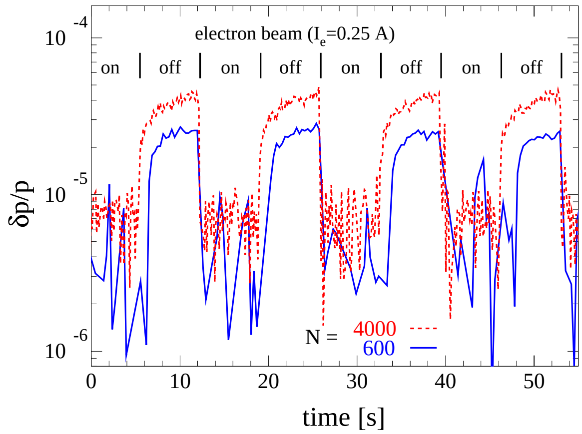

Figure 4: Momentum spread of a U^{92+} beam at 390 MeV/u above (red, dashed) and below (blue, full line) the transition point as a function of time. The electron beam is switched on and off for time intervals of 6.8 s. The low intensity cold beam heats up with a delay of about 1 s.

Above the transition point heating sets in immediately after cooling is switched off. For the ultracold beam below the transition point the beam behaves as expected for an ordered structure. It exhibits no indication for heating at the beginning of its circulation without cooling.

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