GSI-Preprint-96-45
Oktober 1996

ANOMALOUS TEMPERATURE REDUCTION OF ELECTRON COOLED HEAVY ION BEAMS IN THE STORAGE RING ESR

M. Steck, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, H. Reich,
B. Schlitt, T. Winkler

Gesellschaft für Schwerionenforschung mbH
Planckstraße1 • D-64291 Darmstadt • Germany
Postfach 110552 • D-64220 Darmstadt • Germany

Anomalous Temperature Reduction of Electron Cooled Heavy Ion Beams in the Storage Ring ESR

M. Steck, K. Beckert, H. Eickhoff, B. Franzke,
F. Nolden, H. Reich, B. Schlitt, T. Winkler
Gesellschaft für Schwerionenforschung,
Planckstr. 1, D-64291 Darmstadt

October 15, 1996

Abstract

Experiments with low intensity beams of electron cooled highly charged ions in the storage ring ESR have been performed. The momentum spread which was analyzed by Schottky noise detection shows a considerable reduction when the number of stored ions is reduced below several thousands. This indicates that intrabeam scattering which determines the momentum spread for higher beam intensities is strongly suppressed. Estimates of the plasma parameter Γ support the idea of a phase transition from a gaseous phase to a liquid like phase.

PACS numbers: 29.20.Dh, 29.27.Fh

Clear evidence of a crystallization of ion clouds by laser cooling is a recent achievement in ion traps [1]. A storage ring can be considered as a large circular trap for fast charged particle beams and therefore provides similar experimental possibilities as traps do for ions at rest [2]. It was pointed out during the construction phase of the new generation of cooler storage rings [3] that highly charged heavy ions offer the best preconditions to study ordering effects in fast ion beams [4]. Even before, a first indication of such an ordering effect was reported from the NAP-M storage for electron cooled proton beams [5]. Ordered ion beams are of interest for high precision spectroscopy and for experiments requiring high brilliance beams.

The storage ring ESR [6] in combination with the heavy ion synchrotron SIS [7] now opens the field for experimental studies of electron cooling of highly charged ions [8] for a wide range of ion species at variable energy. The properties of the cooled ion beams in the ESR are normally studied following a general procedure. The ions are injected with velocities $\beta \simeq 0.6 - 0.7$ and cooled with a velocity matched cold electron beam of 0.25 A (electron density $n_e^* \simeq 4 \times 10^6$ cm^{-3}). After injection the hot ion beams are cooled sufficiently long (a few minutes) to erase any memory of the initial particle distribution and to establish a balance between cooling and the inevitable heating by intrabeam scattering (IBS). Finally an equilibrium state is reached where the heating rate by Coulomb scattering between the individual particles in the dense ion beam is balanced by the cooling rate of the electron beam. The typical longitudinal cooling rate amounts to $(q^x/A) \cdot 3$ s^{-1} with q, A the charge and mass number of the ion and $1.7 \leq x \leq 2.0$ [9]. The final temperature of the ion beam is determined by an equilibrium between this heating and cooling rather than by the temperature of the electron beam. This equilibrium is sensitive to the alignment of ion and electron beam in the cooling section. A standard optimization procedure uses the achievement of minimized transverse emittances as an indication for optimum alignment.

For minimized transverse emittances a rather general behavior in the IBS dominated regime is found. The dependence of the ion beam temperature, commonly represented by the longitudinal momentum spread and the transverse emittance of the ion beam, on the number of stored ions N is quite universal for all ion species. The momentum spread shows a $N^{0.3}$- dependence, whereas the horizontal and vertical emittances agree within a factor of two and increase with $N^{0.6}$, typically [10]. A rather faint increase with the ion charge is attributed to the fact that both IBS and electron cooling depend on the ion charge and mass and that in equilibrium these dependencies nearly cancel [9]. The momentum spreads which are for highly charged ions on the order $\delta p/p \simeq 10^{-5} - 10^{-4}$ in the IBS dominated regime contrast with the observation that for ion beams with an intensity $N \simeq 10^3$ the momentum spread $\delta p/p$ is reduced below 10^{-6}. Extrapolating from the IBS regime such low momentum spreads could only be expected for much smaller intensity ($N \leq 10^1$).

The standard beam diagnostics of the storage ring are well suited for the detection of large beam intensities, but for low intensity ion beams the sensitivity of the diagnostics is limited by the finite resolution or by electronic noise. For ion currents exceeding a few μA the standard current transformer can be used to determine the stored ion intensity with an accuracy of 1 μA, but for even smaller intensities it is not sensitive enough. The most powerful tool for low intensity ion beams is Schottky noise detection which provides the longitudinal momentum distribution from a spectral analysis of a harmonic of the revolution frequency. After careful calibration versus the current transformer at higher ion currents also the ion beam intensity can be determined from the integrated noise power in one Schottky band. The validity of this interpretation for very cold beams has to be checked since the spectra can be dominated by collective beam behavior [12]. Transverse beam emittances of low intensity beams can only be examined by the destructive method of beam scraping as the resolution of non-destructive detection methods is presently limited to 1 mm, typically. Beam scraping, however, allows to trace the beam radius down to 0.1 mm imposing an upper limit for the transverse beam temperature.

The objective of the current experiments was the investigation of the beam properties at small numbers of stored ions in the regime when IBS heating decreases due to the large interparticle spacing. A typical experiment was performed with Au^{79+} ions at 360 MeV/u ($\gamma = 1.386$) cooled with an electron current of 0.25 A. The lifetime of the cooled beam was determined by radiative electron capture in the cooling section. The measurement with the current transformer resulted in a lifetime $\tau = 1520$ s. This lifetime was also confirmed by observation of recombined ions. The ions which have captured an electron can be detected in the dispersive ring section downstream the electron cooler where different charge states are spatially separated.

To study the longitudinal momentum spread towards a smaller number of stored ions an initial intensity of $N = 10^6$ ions ($I_i = 24$ μA) was injected and cooled. This intensity is still high enough to be readily detected with the beam current transformer. The Schottky noise at the 35^{th} harmonic of the revolution frequency was averaged every 10 minutes over a 30 s time interval. The integral noise power in this harmonic and the momentum spread calculated from the frequency spread via the relation $\delta p/p = \eta^{-1}\delta f/f$ with $\eta = \gamma^{-2} - \gamma_t^{-2}$ and a transition energy $\gamma_t = 2.6$ of the storage ring setting are shown in Fig. 1. The decrease of the Schottky noise power with a time constant $\tau = 1430$ s agrees well with the known beam lifetime, the noise power at the end of the measurement (t = 330 min.) corresponds to 3 ± 1 particles. Therefore collective effects in the Schottky noise are ruled out. The integrated noise power in this harmonic of the revolution frequency is proportional to the number of stored ions and the frequency distribution represents the longitudinal momentum distribution.

The momentum spread first decreases proportional to $N^{0.3}$ as expected for the IBS dominated regime. After 2.5 h of storage time, however, it exhibits a strong discontinuity with a reduction of the momentum spread by a factor of about ten. Thereafter the momentum spread stays on a constant level for particle numbers $N \leq 4000$. This constant level of $\delta p/p \simeq 5 \times 10^{-7}$ is known to be caused by the stability of the magnet power supplies rather than by the ion beam temperature. The measured revolution frequency is dependent on the bending field in the dipole magnets of the storage ring. The field stability $\delta B/B = 4 \times 10^{-6}$ which was measured independently is equivalent to a momentum spread $\delta p/p = \eta^{-1}\gamma_t^{-2} \cdot \delta B/B$ which is in full agreement with the typical value from the Schottky noise analysis. Experiments with short averaging times have evidenced that the actual momentum spread is smaller, typically $\delta p/p \simeq 2 \times 10^{-7}$. Therefore the spectra measured with long record times (tens of seconds) rather give an upper limit of the longitudinal beam temperature.

The importance of strong cooling for the observation of a momentum spread reduction is exemplified in Fig. 2. The Schottky noise power and the momentum spread as a function of the number of stored ions are shown for various electron currents. All measurements were performed on a single fill of the storage ring. The data points for a certain ion beam intensity were measured successively varying the electron current. After some storage time which determined the remaining beam intensity the next set of data points at lower ion beam intensity was measured. A momentum spread close to the minimum value $\delta p/p \simeq 5 \times 10^{-7}$ can only be attained for electron currents exceeding 100 mA. For higher electron currents the transition from high to low momentum spread occurs for a larger number of stored particles. The Schottky noise power is nearly independent of the cooling strength. Only close to the transition particle number ($N \simeq 10^3 - 10^4$) for a certain electron current the integrated power is reduced by a factor of 2 - 3 indicating weak collective effects in the beam noise.

For many other species of bare ions which were stored and cooled under comparable conditions (electron current 0.25 A) the momentum spread as a function of ion beam intensity has been investigated. The measured momentum spreads as a function of the stored particle number are summarized in Fig. 3. Significant discontinuities were evidenced for all ions heavier than Ar. The transition to the colder state was observed at particle numbers of a few thousands, but no dependence of the critical intensity on the ion species could be concluded from these measurements. For lighter ions no effect of momentum spread reduction was observed. The reduction of the momentum spread at the transition point is largest for the heavier ions. This is a consequence of the constant lower value in the regime of low intensities and stronger IBS for highly charged ions in the high intensity regime. The constant lower level of the momentum spread $\delta p/p \simeq 5 \times 10^{-7}$ for all ions confirms the explanation that the magnetic field stability determines this lower limit.

For a few ion species the transverse beam size of the cooled beam was probed destructively with a beam scraper [9]. The scraper was moved close to the beam for a few seconds and the remaining intensity of the stored beam was measured. By comparison with measurements of position sensitive particles detectors [11] which at higher beam intensity monitor the beam size non-destructively the scraper method was calibrated. The scraper measurements fairly resembled the increase of the beam emittance with $N^{0.6}$ observed in the IBS dominated regime with the particle detectors. For a few thousand ions, however, the resolution of the scraper technique was inadequate to determine the beam size. Close to the transition point of the longitudinal momentum spread the accuracy in scraper positioning limits the detection of a possible discontinuity in the transverse beam size which would also indicate a similar discontinuous reduction of the transverse ion beam temperature. Only an upper limit of the rms beam radius at the scraper position of 30 μm can be derived for particle numbers below a few thousands.

The measured momentum spreads and emittances can be interpreted in terms of beam temperatures observed from the reference frame of a particle moving with the ion velocity. The longitudinal beam temperature which represents the incoherent part of the longitudinal kinetic energy

$$kT_{\parallel} = m_i c^2 \beta^2 (\delta p/p)^2_{\mathrm{rms}} \tag{1}$$

can be determined directly from the measured momentum spread with $(\delta\ p/p)_{\mathrm{rms}} = (8 \times \ \ln 2)^{-1/2} \cdot \delta p/p$. The transverse beam temperature

$$kT_{\perp} = 1/2 \cdot m_i c^2 \beta^2 \gamma^2 (x'^2_{\mathrm{rms}} + y'^2_{\mathrm{rms}}) \tag{2}$$

can be calculated from the transverse beam divergences x'_{rms} and y'_{rms} with the usual relativistic notations β, γ and the rest mass of the ion $m_i c^2$. The transverse emittance is conserved along the storage ring circumference, whereas the transverse temperature is not constant. Due to the focusing structure the transverse temperature in one degree of freedom varies and usually only the ring averaged transverse temperature is considered.

Using the Au^{79+} beam for a case study the following beam temperatures close to the transition point can be estimated. The measured momentum spreads of $\delta p/p = 6 \times 10^{-6}$ above the transition point and $\delta p/p = 5 \times 10^{-7}$ in the low intensity regime result in longitudinal beam temperatures of $kT_{\parallel} = 0.5$ eV and $kT_{\parallel} = 4 \times 10^{-3}$ eV, respectively. As some measurements with short record times for the Schottky spectra have indicated the actual beam temperature in the low intensity regime should be smaller than 1 meV ($T_{\parallel} \leq 10$ K).

The transverse temperature for a rms beam size of 30 μm at the scraper is calculated with the beam envelope function at the scraper $\beta_x^{sc} = 16$ m and $\beta_y^{sc} = 3.6$ m and the ring averaged values $\beta_x^{av} = 19$ m and $\beta_y^{av} = 14$ m resulting in an upper limit for the beam temperature $kT_{\perp} = 1.5$ eV. Even more than for the longitudinal temperature this value mainly reflects the limited resolution, from the intensity dependence of the transverse temperature values of order 0.1 eV are realistic.

In plasma physics the properties of an one-component plasma can be described by the ratio of potential energy U to thermal energy kT. The plasma parameter $\Gamma = U/kT = q^2e^2/4\pi\epsilon_o a kT$ with the average particle distance a characterizes the state of the plasma. For a finite one-dimensional plasma a phase transition from gas to liquid is expected for $\Gamma \simeq 1$. Three dimensional ordering requires a much higher plasma parameter $\Gamma = 178$ [2].

The analysis of the potential energy of the ion beam shows a similar anisotropy as for the temperatures which is mainly due to the focusing structure of the storage ring and its consequence for the transverse ion motion.

The focusing structure limits the transverse ion motion for a certain emittance, whereas the longitudinal position in the storage ring is boundless. Therefore a longitudinal potential energy $U_\parallel = q^2e^2N/4\pi\epsilon_o C\gamma$ can be defined for N particles equally spaced along the ring circumference C. The transverse potential energy $U_\perp = q^2e^2/4\pi\epsilon_o a_\perp$ refers to the potential energy between two ions approaching each other to the average beam radius $a_\perp$.

Calculations of the potential energy for the experimental values of the gold beam of 4000 ions result in a longitudinal potential energy $U_\parallel = 2.4\times 10^{-4}$ eV and a transverse potential energy $U_\perp = 0.3$ eV. The longitudinal potential energy is rather small, but the transverse potential energy which determines the potential energy of the ions at the nearest distance during a Coulomb collision is comparable to both the longitudinal and transverse thermal energy of the ion beam at the transition point. This implies the intuitive picture that the ions can not pass each other in longitudinal direction as the potential energy which has to be overcome during their closest encounter is too high.

For other ion species the plasma parameter scales roughly with q^2/A which for heavy ions shows that for constant beam parameters a similar behavior can be expected, only for light ions the potential energy might be too low for the observation of a transition. This agrees with the experimental results for different ion species.

The current experiments with electron cooled heavy ions have clearly evidenced a discontinuous reduction of the longitudinal ion beam temperature by up to two orders of magnitude. This behavior is reminiscent of effects observed in traps with laser cooled ions which undergo a phase transition to an ordered structure [1]. Estimates of the plasma parameter show that it is close to unity which is an indication that the beam temperature is sufficiently low for a phase transition from a gaseous to a liquid state of the beam. However, higher resolution for the determination of both the longitudinal and the transverse beam temperature is required for conclusive results on such a phase transition in the cold ion beam.

Another open question is the influence of the focusing structure on the formation of an ordered structure. For future experiments the storage ring ESR offers the opportunity to operate the storage ring at a variable working point.

References

[1] F. Diedrich, E. Peik, J. M. Chen, W. Quint, and H. Walther, Phys. Rev. Lett. **59**, 2935 (1987).

[2] D. Habs and R. Grimm, Annu. Rev. Nucl. Sci. **45**, 391 (1995).

[3] R. E. Pollock, Nucl. Instrum. Methods A **287**, 313 (1990).

[4] J. P. Schiffer and P. Kienle, Z. Phys. A **321**, 181 (1985).

[5] E. N. Dementev, N. S. Dikansky, A. S. Medvedko, V. V. Parkhomchuk, and D. V. Pestrikov, Sov. Phys. Tech. Phys. **25** (8), 1001 (1980).

[6] B. Franzke, Nucl. Instrum. Methods B **24**, 18 (1987).

[7] K. Blasche, B. Franzke, *Proceedings of the 4th European Particle Accelerator Conference, London, 1994*, edited by V. Suller and Ch. Petit-Jean-Genaz (World Scientific, Singapore, 1994), p. 133.

[8] M. Steck, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, and P. Spädtke, *Proceedings of 1993 Particle Accelerator Conference, Washington D.C., 1993*, 1738.

[9] M. Steck, K. Beckert, F. Bosch, H. Eickhoff, B. Franzke, O. Klepper, R. Moshammer, F. Nolden, H. Reich, B. Schlitt, P. Spädtke, and T. Winkler, Proceedings of the Eloisatron Workshop, Erice, 1995.

[10] M. Steck, K. Beckert, F. Bosch, H. Eickhoff, B. Franzke, O. Klepper, R. Moshammer, F. Nolden, P. Spädtke, and T. Winkler, *Proceedings of the 4th European Particle Accelerator Conference, London, 1994*, edited by V. Suller and Ch. Petit-Jean-Genaz (World Scientific, Singapore, 1994), p. 1197.

[11] O. Klepper, F. Bosch, H. W. Daues, H. Eickhoff, B. Franczak, B. Franzke, H. Geissel, O. Gustafsson, M. Jung, W. König, C. Kozhuharov, A. Magel, G. Münzenberg, H. Stelzer, J. Szerypo, and M. Wagner, Nucl. Instrum. Methods B **70**, 427 (1992).

[12] V. V. Parkhomchuk and D. V. Pestrikov, Sov. Phys. Tech. Phys. **25(7)**, 818 (1980).

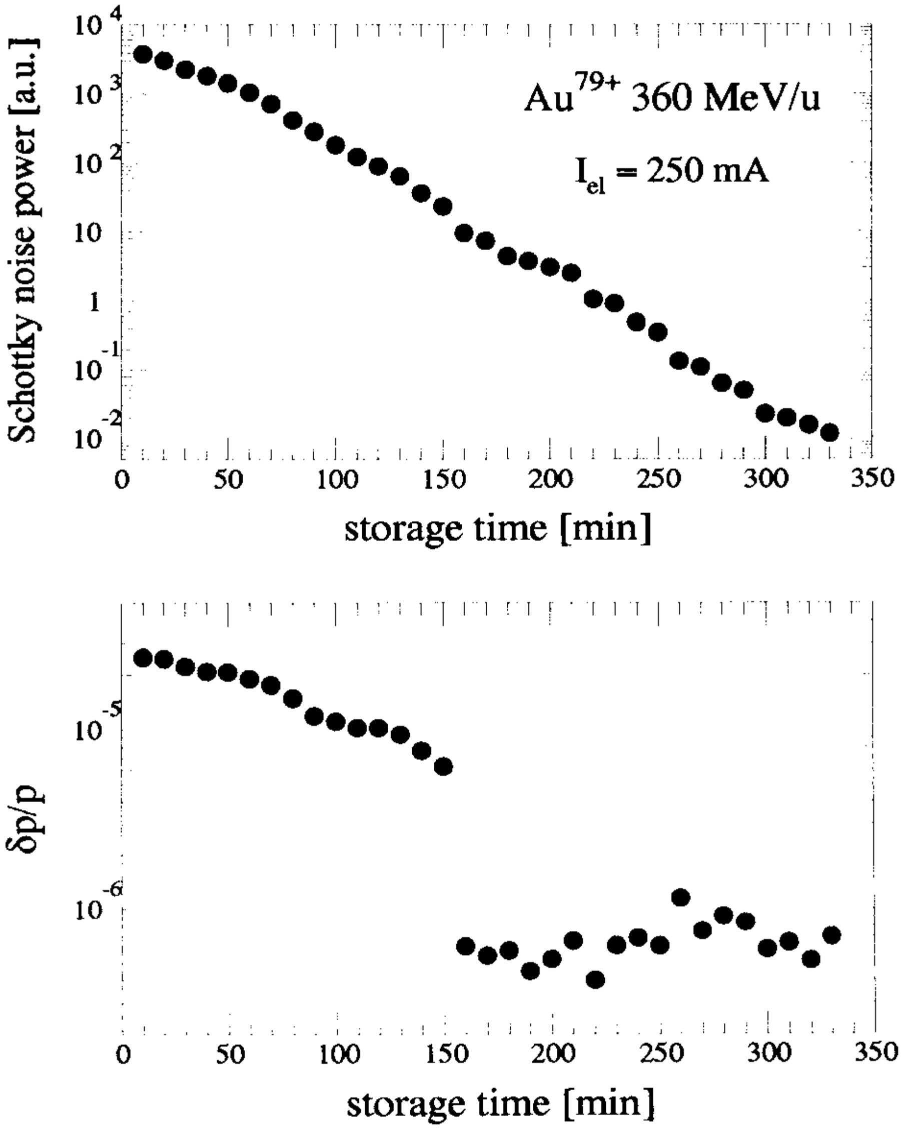

Figure 1: Schottky noise power and momentum spread (FWHM) during decrease of beam intensity due to radiative recombination in the electron cooler.

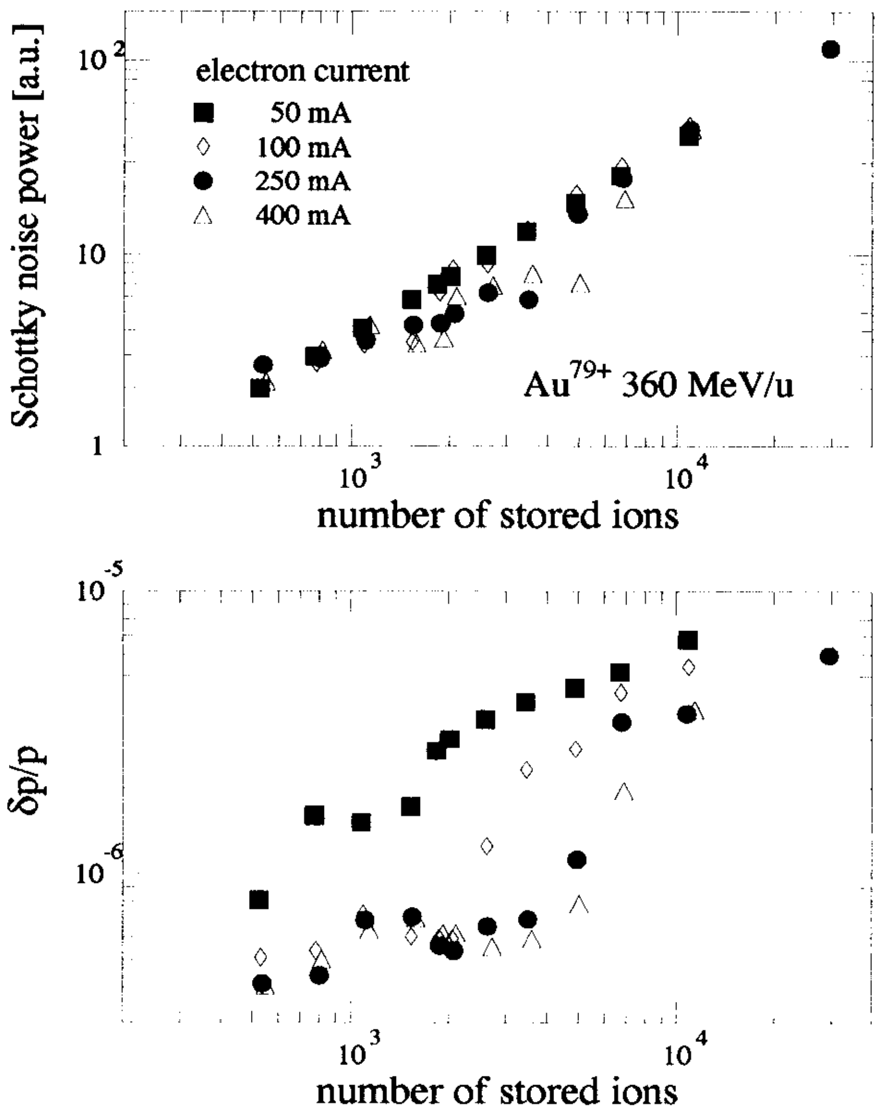

Figure 2: Schottky noise power and momentum spread as a function of the stored ion beam intensity for various electron currents.

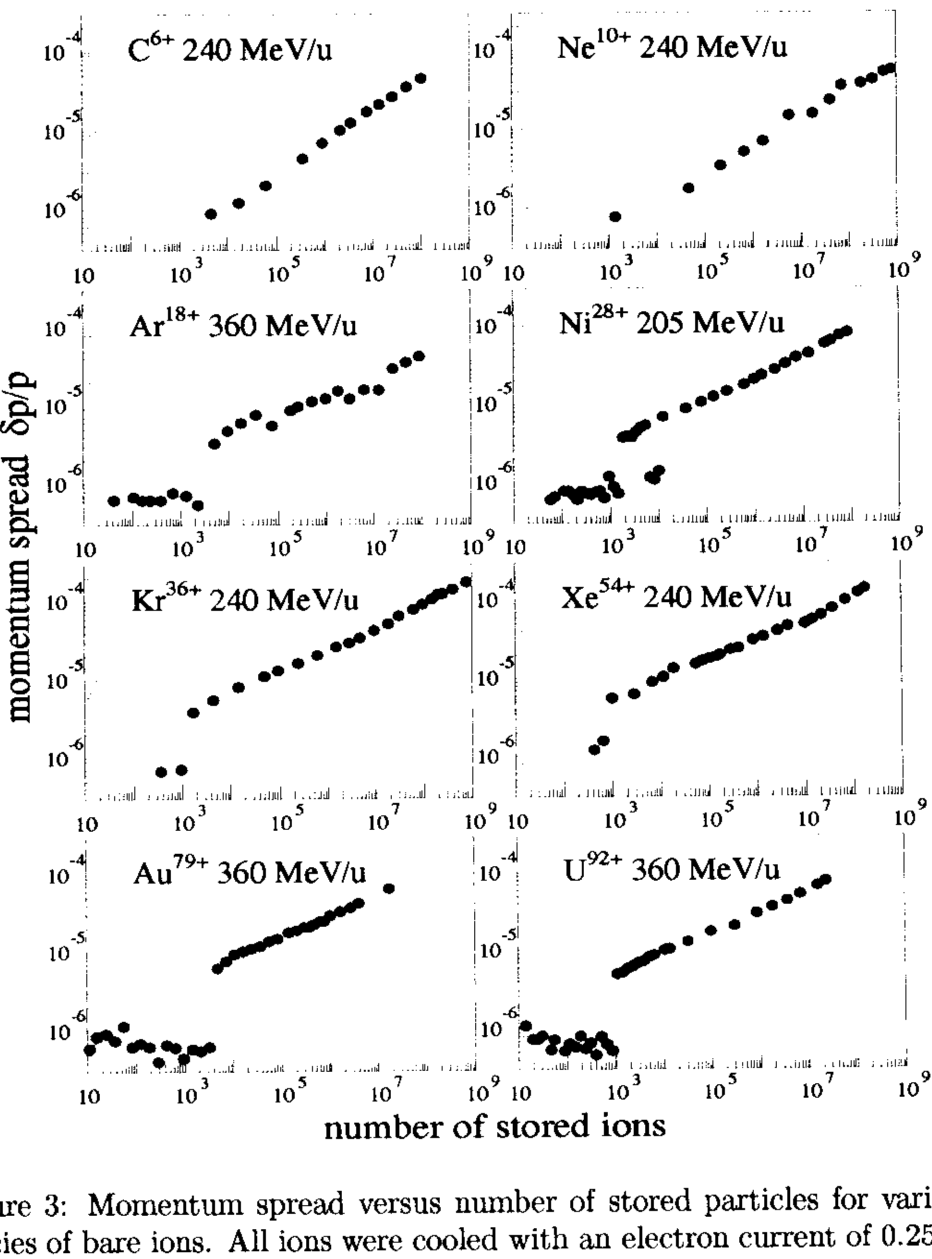

Figure 3: Momentum spread versus number of stored particles for various species of bare ions. All ions were cooled with an electron current of 0.25 A.