LOWEST TEMPERATURES IN COOLED HEAVY ION BEAMS AT THE ESR

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Abstract

Heavy ion beams which are cooled in the storage ring ESR by an electron beam exhibit temperatures, both longitudinally and transversely, close to the corresponding electron temperatures. In the longitudinal phase plane the achievement of very cold ion beams is linked with a phase transition like reduction of the momentum spread. For the transverse degree of freedom indications for a similar behavior have been detected. The measured beam properties for extremely cold ion beams are determined by the stability of power supplies for the ring magnets and the electron beam acceleration voltage.

1 INTRODUCTION

Electron cooling has proven to be a very powerful tool to provide ion beams of excellent quality otherwise hardly reachable. The precision in spectroscopic investigations at storage rings is ultimately limited by the ion beam temperature. Therefore the achievement of smallest possible beam temperatures is crucial to make full use of the capabilities of cooler storage rings.

The lower temperature limit for electron cooled ion beams which is determined by the temperature of the electron beam is usually not attained as the generation of a dense ion beam is counteracted by intrabeam scattering rates growing with the phase space density of the ion beam. Until now only one experiment with a proton beam at low intensity reported the achievement of ion beams with a temperature close to that of the cooling electron beam [1]. The possibility to produce low temperature beams at low intensity is particularly interesting for experiments with radioactive beams which generally are faint. The determination of their revolution frequency with highest possible accuracy is mandatory for precision Schottky mass spectroscopy [2].

2 INTRABEAM SCATTERING DOMINATED ION BEAM TEMPERATURES

Experimental investigations of the phase space volume occupied by an ion beam with electron cooling have been performed in the storage ring ESR [3]. Electron cooling compresses the ion beam to a phase space volume which results in a heating rate by intrabeam scattering which balances the cooling rate of the electron beam. The equilibrium beam emittances and momentum spreads increase with the particle number N. Measurements for ion beam intensities exceeding 10^6 stored ions show an increase of the transverse emittance proportional to $N^{0.6}$ and a momentum spread which grows with $N^{0.3}$, typically [4].

From the dependence on the particle number it can be concluded that it is possible to achieve the highest phase space density at small particle numbers. This is a consequence of a reduction of the cooling rate for larger intensities of the ion beam. The cooling force of the electron beam decreases with increasing relative velocity between ions and electrons and larger ion beam emittances contribute larger relative velocities to the electron-ion interaction. Increase of the electron current leads to a proportional increase of the cooling power, but technical and physical limits, particularly the electron beam space charge, restrict the possibility for an increase of the cooling power.

3 SUPPRESSION OF INTRABEAM SCATTERING

The decrease of the ion beam equilibrium temperature and the related increase of the cooling rate due to reduced relative velocities between ions and electrons makes the low intensity regime most promising for high quality ion beams. The momentum spread determined by detection of Schottky noise with a high sensitivity capacitive pick up system is shown in Fig. 1 as a function of the number of stored ions for a $^{197}Au^{79+}$ beam at an energy of 360 MeV/u. The ions were cooled by an electron beam of 250 mA (electron density $n_e = 3.8 \times 10^6$ cm^{-3}) which was aligned to the ion beam direction by minimizing the transverse emittances of the cooled ion beam.

The momentum spread for particle numbers $N \geq 10^4$ shows the usual dependence indicative of an equilibrium between cooling and intrabeam scattering. For approximately $N \simeq 4000$ the momentum spread shrinks suddenly by a factor of ten most likely due to a strong suppression of intrabeam scattering. For smaller particle numbers the momentum spread remains at a constant level $\delta p/p \simeq 5 \times 10^{-7}$. This suppression of intrabeam scattering was observed for all ions with charge $q \geq 18$ [5].

For all ion species which were investigated at energies between 240 and 360 MeV/u a similar behavior was observed with two features: 1) The momentum spread drops discontinuously around a few thousand ions. 2) The lowest momentum spread is for all ion species around $\delta p/p \simeq 5 \times 10^{-7}$. The only charge dependence is related to the reduc-

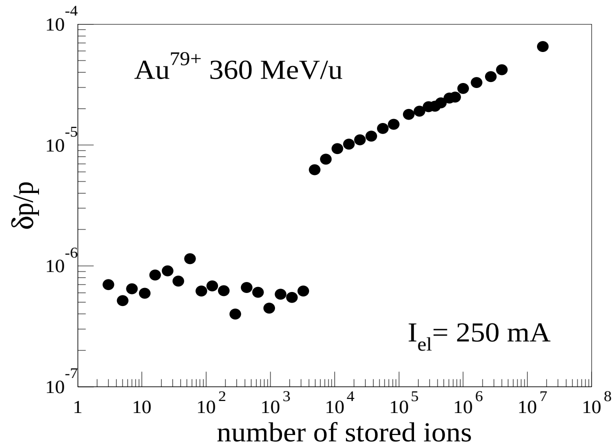

Figure 1: Momentum spread versus number of stored ions for a Au^{79+} beam at 360 MeV/u which was cooled with an electron current of 250 mA ($n_e = 3.8 \times 10^6$ cm $^{-3}$).

tion factor of the momentum spread. The ions with higher charge experience stronger intrabeam scattering and therefore show a higher momentum spread in the intrabeam scattering dominated regime, the lowest value of the momentum spread, however, is the same for all ions. The longitudinal ion beam temperature $kT_\parallel = Am_oc^2\beta^2(\delta p/p)^2_{rms}$ scales with the ion mass A and is roughly $kT_\parallel \simeq A \cdot (2 \times 10^{-5})$ eV in the low intensity regime. For light ions longitudinal beam temperatures in the sub-meV range have been achieved.

Non-destructive measurements of the transverse emittance for small particle numbers is prevented by the resolution of available detection systems. A destructive method which allows a good spatial resolution is scraping of the beam. The center of the stored beam is found when the beam is completely destroyed by a scraper moved into the beam. For different radial positions relative to this center the number of stored ions was determined from the Schottky noise power. The scraper was moved to the positions with an accuracy better than 10 μm, stopped there for a few seconds (a time which is short compared to the transverse growth rate of the cooled beam) and moved out to a position not interfering with the ions which were still circulating. The radius determined by this scraping technique corresponds to approximately a 3σ radius determined by a non-destructive method [6].

The relation between number of ions and beam radius in some cases shows a behavior similar to that for the momentum spread (Fig. 2). For higher particle numbers ($N \geq 10^4$) the usual increase by intrabeam scattering is observed with a $N^{0.3}$-growth of the beam radius [4]. For an ion intensity below $N \simeq 1000$ the beam radius shrinks much faster. The measurement of the shrinking process is hampered by the short lifetime of the stored ion beam due to radiative recombination in the cooler. The radius reduction might be instantaneous although not visible from the scraper measurement. The transverse beam temperature $kT_\perp = 1/2 \cdot m_ic^2\beta^2\gamma^2x'^2_{rms}$ (with the beam divergence $x' = x/\beta_x$) for small numbers of stored gold ions is around 0.1 eV which corresponds with the transverse electron beam temperature. The sudden shrinkage in the transverse degree of freedom could not be reproduced in all measurements so far contrary to the drop in the momentum spread which is very well reproducible. The beam position determined by scraping is likely to be subject to small fluctuations caused by the limited stability of power supplies for the storage ring magnets.

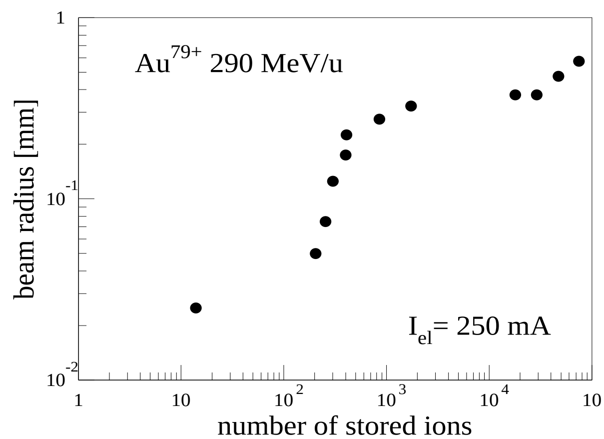

Figure 2: Beam radius determined from the scraper position as a function of the number of Au^{79+} ions (energy 290 MeV/u) which remained stored in the ring (cooled with an electron current of 250 mA, $n_e = 4.1 \times 10^6$ cm^{-3}).

Estimates of the ion beam parameters for beams of highly charged ions below the transition point to the strongly reduced longitudinal beam temperature show that the plasma parameter $\Gamma = U/kT$ with the potential energy U and the kinetic energy kT is close to unity [5]. This supports the hypothesis of a phase transition in the cold beam and of the existence of a linear ordering of the beam particles below the transition.

4 POWER SUPPLY STABILITY

Beams with a momentum spread below 10^{-6} constitute a gauge which is extremely sensitive to modulations on the output of power supplies which are relevant to the definition of the revolution frequency. Particularly the main power supplies for the ring magnets will affect the revolution frequency. In the ESR variations of the revolution frequency on a time scale of seconds are correlated with the acceleration cycle of the synchrotron SIS from which the beam is injected and which also serves other experiments during storage ring operation [7]. The limitation by the magnet power supplies is also evident from the observation that the lowest momentum spread is identical for all ion species which were stored and cooled in the ESR at energies between 240 and 360 MeV/u [5]. This is in good agreement with experiments at the transition energy ($\gamma = \gamma_t$) which evidenced a magnetic field stability $\delta B/B = 4 \times 10^{-6}$ [8]. For the standard operation mode with $\gamma_t \simeq 2.7$ this corresponds to a momentum spread $\delta p/p = \gamma_t^{-2}\ \delta B/B \simeq\ 5 \times 10^{-7}$.

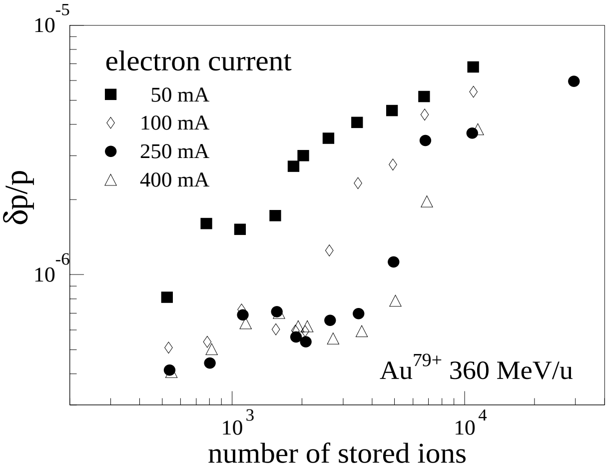

Figure 3: Momentum spread of a Au^{79+} beam at 360 MeV/u cooled by different electron currents.

Measurements for different electron currents in the cooling system confirm that interpretation. For a 360 MeV/u beam of Au^{79+} ions (Fig. 3) the lowest momentum spread is nearly the same for electron currents varying from 50 mA to 400 mA proving that the strength of cooling is not determining the lowest achievable momentum spread. The cooling power appears only in a systematic increase of the transition particle number to the cold state. Stronger cooling allows to attain the lowest momentum spread at larger particle numbers.

This measurement for the same ion species, but at the lower beam energy of 75 MeV/u reveals a significantly different behavior (Fig. 4). A distinct reduction of the momentum spread is only observed for the lowest electron current (50 mA). The minimum momentum spread increases linearly with the electron current. This is contradictory to intrabeam scattering dominated beams for which a momentum spread was observed which decreases for higher electron currents [4]. At the lower beam energy the magnetic field stability is dominating only for weak cooling. For stronger cooling the ripple on the accelerating voltage of the electron beam which amounts up to $\delta U_{rms} \simeq 3$ V for voltages around 40 kV limits the achievement of very low momentum spreads. Voltage modulations with a time constant around 0.01 s which is comparable to the longitudinal cooling time superimpose an additional energy modulation on the cooled ion beam. The usual Schottky noise analysis in frequency domain (with averaging times on the order of seconds) can not distinguish between the coherent modulation of the ion beam energy and the thermal energy spread. Thus the measured frequency spread in the Schottky noise will be increased due to the coherent energy modulation.

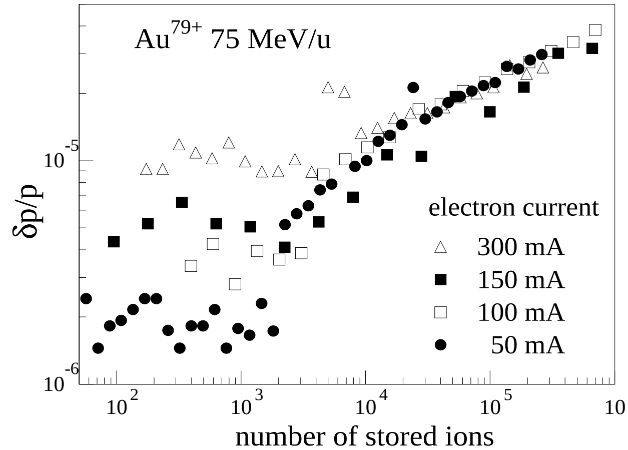

Figure 4: Momentum spread of a Au^{79+} beam at 75 MeV/u cooled by different electron currents.

For the case of limitations by magnet power supplies further improvements are very difficult as the output current fluctuations are close to the noise limit and only minor improvements can be expected. A highly stabilized high voltage power supply matched to the specific voltage range will reduce the high voltage ripple at a certain electron energy. Further progress in fast data acquisition using time domain records and subsequent off line Fourier transformation could improve the resolution in Schottky noise analysis of low intensity beams with extremely small beam temperatures.

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