LIMITATIONS TO THE OBSERVATION OF BEAM ORDERING

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Abstract

The observation of beam ordering for low intensity cooled ion beams depends on various parameters. Experimental observations concerning the influence of fluctuations of beam energy and magnetic field on the lowest measured momentum spread detected by Schottky noise analysis are reported. Further measurements illustrate the limits due to the sensitivity of the Schottky noise detection system and the resolution of transverse beam size measurements.

INTRODUCTION

Experiments with electron cooled heavy ion beams have evidenced a linear ordering of the ions at low beam intensity. The main criterion was a discontinuous reduction of the momentum spread of the ion beam when the particle number was reduced to a few thousand [1], [2], [3]. Later, a similar reduction of the transverse emittance for these low intensity beams measured by destructive beam scraping confirmed the transition from a gaseous to a liquid-like state with longitudinal ordering [4]. The beam quality in the high intensity gaseous state is determined by an equilibrium between intrabeam scattering and cooling. For the low intensity ordered beam intrabeam scattering is suppressed and the beam temperature is dependent on the ability to provide most powerful cooling in order to achieve lowest beam temperature. The detection of this low beam temperature requires highest stability of all technical systems and diagnostics systems with exceptional resolution for the beam parameters, longitudinal momentum spread and transverse emittance. Therefore the observation of the transition to the ordered state depends on various technical parameters which influence the lowest achievable and detectable beam temperature. In addition a significant increase of beam temperature in the intrabeam scattering dominated regime, which means a large heating rate, is required to distinguish the two regimes. As a consequence, the strongest reduction of the beam temperature was observed for highly charged ions, as for these the intrabeam scattering rate is highest.

INFLUENCE OF INTRABEAM SCATTERING

The transition from the gaseous to the ordered beam state is most pronounced, if the intrabeam scattering rate and therefore also the beam temperature is high. The highest intrabeam scattering rate is achieved, if the ion beam is cooled in full six-dimensional phase space under optimum cooling conditions. An intentional reduction of the cooling rate of the electron cooling system can be easily achieved by a misalignment between the ion and the electron beam in the cooling section. Normally the ion and electron beam are aligned parallel to each other with an angular error of less than 0.1 mrad. The increase of the transverse ion beam emittance caused by the misalignment results in a reduced intrabeam scattering rate. Consequently, the longitudinal momentum spread can be reduced, if the reduction of the longitudinal heating rate outbalances the reduction of the cooling rate due to the misalignment.

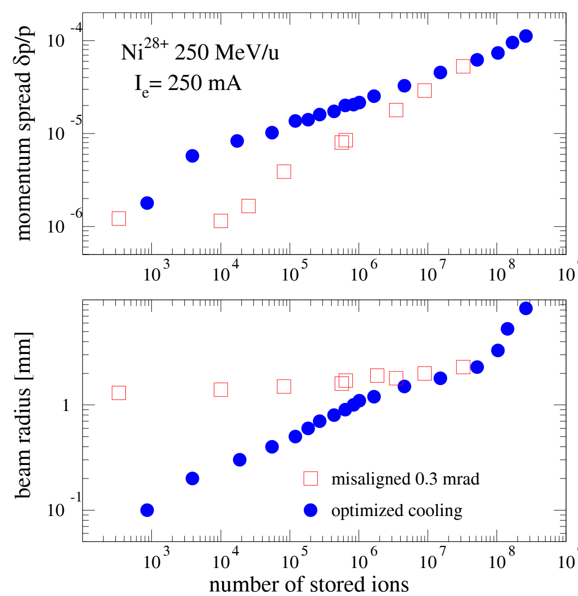

Figure 1: Measurement of the momentum spread and the beam radius of an ion beam ($^{58}Ni^{28+}$ 250 MeV/u) with perfect alignment of ion and electron beam and with an intentional misalignment of the electron beam by 0.3 mrad. At low intensity the ion beam radius is determined by the misalignment angle, whereas an even smaller momentum spread can be achieved with the misaligned electron beam.

The method of intentional misalignment can also be useful if a reduced longitudinal momentum spread at the expense of an increased transverse emittance is beneficial for the experiment. Therefore, with misaligned beams, already at higher ion beam intensity the momentum spread can be as small as the one in the low intensity ordered state (Fig. 1). Even if there is a transition to the ordered state, it cannot be observed in the usual way as a reduction of the momentum spread. In the transverse degree of freedom the ion beam emittance is limited by the misalignment angle to a minimum value.

The introduction of a misalignment is one way to increase the transverse emittance intentionally and reduce the momentum spread. The dependence of the momentum spread on the number of stored ions can be modified, if there is additional transverse heating of the ion beam. The heating can originate from external source like rf noise or the use of an internal target. Strong transverse heating occurs, if the ion beam is cooled to the transverse space charge limit, which is particularly relevant for low energy beams [5].

STABILITY OF THE REVOLUTION FREQUENCY

The measurement of the momentum spread by detection of longitudinal Schottky noise requires highest stability of the revolution frequency, as the longitudinal momentum spread is proportional to the width of the frequency distribution. Any variation of the revolution frequency during the time interval of the frequency analysis will broaden the Schottky signal and therefore limit the measurement of smallest frequency spreads. The main frequency uncertainties come from current variations of the dipole power converter. Any change of the current δI_p causes a change of the bending field strength δB_{dip} and consequently a change of the revolution frequency $\delta f_{rev} = \frac{1}{\gamma_t^2}\frac{\delta B_{dip}}{B_{dip}} f_{rev}$. Already for the very first observations of the momentum spread reduction this was identified as the limiting parameter for the determination of the lowest longitudinal beam temperature. The longitudinal beam temperature is proportional to the square of the measured frequency spread and to the ion mass $kT_{\parallel} = m_i c^2 \beta^2 (\frac{\delta p}{p})^2_{rms}$ and $\delta p/p = \eta^{-1}\delta f/f$ with the frequency slip factor η. For a frequency spread which is determined by the dipole power converter stability the lowest temperatures occur for the lightest ions. Therefore conclusions about limiting temperatures due the electron beam must be determined with light ions.

Current variations of power converters depend on the current level. The best relative stability will usually be achieved at high output current, but the relative stability of the output current depends on the electronic circuits and cannot necessarily be described by a simple analytic dependence on the output current. Generally lower output current will have less relative stability. The corresponding frequency uncertainty can be larger than the smallest frequency spread of the beam in the intrabeam scattering dominated regime. In this case the observation of the discontinuous momentum spread reduction is complicated or even ruled out.

The momentum spread of bare krypton ions at different energies as a function of the number of stored ions is shown in Fig. 2 for similar electron density ($n_e \simeq 6 \times 10^6$ cm^{-3}), i.e. similar cooling rate. The variation of the momentum spread in the intrabeam scattering dominate regime is weak, but the minimum momentum spread at lowest particle numbers varies almost linearly with beam momentum and the corresponding bending field strength of the storage ring dipole magnets. Other magnetic elements of the ring can also effect the orbit length, but their influence is much weaker. According to their influence on the orbit length relative to the dipole magnet field, the specification of the power converters for other ring magnets must be defined.

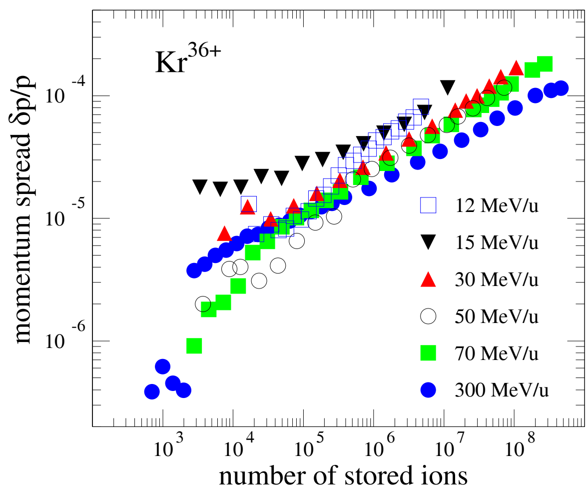

Figure 2: Momentum spread of a beam of bare krypton ions at various energies for an electron density $n_e = 6 \times 10^6$ cm^{-3}. The stability of the magnetic field of the ring dipole magnets determines the minimum momentum spread at low intensity.

STABILITY OF ELECTRON BEAM ENERGY

The revolution frequency of the ion beam is proportional to the ion velocity. At non-relativistic beam energies any variation of the beam velocity will cause proportional frequency variations. The electron beam drags the ion beam to the electron velocity. The drag force and consequently the response of the ion beam to any change of the electron velocity depends on the cooling force, which is a function of the relative velocity between ions and electrons. Any temporal variations of the electron velocity will result in ion velocity variations. The coupling of the ion beam to the electron beam, to first order, is proportional to the electron density in the beam frame. Electron energy variations are mainly caused by variations of accelerating voltage of the electron beam. Another source of velocity variations can be changes of the space charge compensation, which has to be controlled precisely in experiments with very cold beams.

For variations of the accelerating voltage of the electron beam the situation is similar as for the power converters of the ring bending magnets. The difference is that the coupling to the ion beam is not directly proportional, but depends on the cooling force. The influence of electron energy variations is most pronounced for the lowest beam energies, when energy changes result in proportional velocity changes and when space charge effects are largest.

An example of the influence of the stability of the electron beam energy is shown in Fig. 3. A bare gold beam at 75 MeV/u was cooled by electron currents in the range from 50 to 300 mA. The momentum spread as a function of the number of stored ions shows the usual dependency with $\delta p/p \propto N^{0.3}$ in the intrabeam scattering dominated regime above 10^4 stored ions. There is only a weak indication that for higher electron current smaller momentum spreads can be achieved. In the low intensity regime the behavior is more obvious. Smaller electron currents result in smaller momentum spreads. The variations of the electron beam accelerating voltage couple most strongly to the ion beam when the electron current is highest. The momentum spread at low intensity is about proportional to the electron current. For the linear regime of the cooling force this behavior is expected. The typical variations of the accelerating voltage of the ESR electron cooler of $\delta V/V \leq 2\times10^{-5}$ agree with the assumption of a cooling force which is proportional to the relative velocity caused by voltage fluctuations.

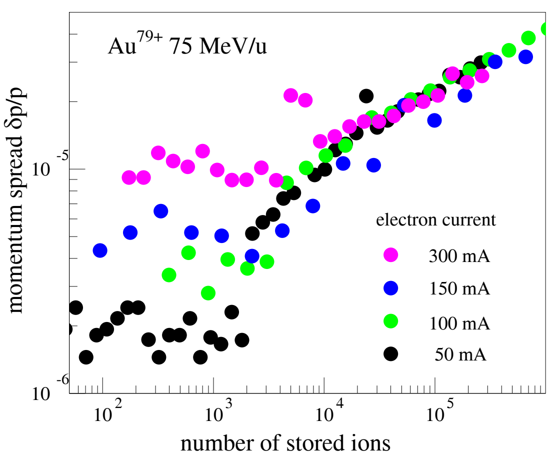

Figure 3: Momentum spread of a bare gold beam at 75 MeV/u cooled with different electron currents. At low intensity the momentum spread depends on the electron current due to the stability of the electron energy.

The main aspect with respect to the observation of ordering is the fact the the momentum spread reduction is only evidenced for small electron currents (50 and 100 mA). At higher electron currents the energy variations caused by fluctuations of the accelerating voltage of the electron beam smear out the momentum spread reduction. Therefore, in the situation of an insufficient stability of the accelerating voltage it can be beneficial to cool with reduced electron current in order to achieve minimum variations of the revolution frequency and consequently smallest frequency spread in the Schottky signal.

If the electron energy is stable enough, it has been observed that higher electron currents result in an increase of the transition particle number [1], [3]. Consequently, it depends on the energy stability of the electron beam, whether higher electron current, i.e. higher cooling rate, improves or decreases the possibility of the observation of ordering.

Temporal variations of the revolution frequency can be overcome if the sampling time of the frequency analysis system is shorter than the time constant of the fluctuations. Schottky analysis at higher frequencies gives higher frequency resolution or allows a reduction of the sampling time.

DETECTION LIMIT OF THE SCHOTTKY NOISE

The reduction of the momentum spread which evidences the linear ordering occurs at low intensity, for the ESR storage ring typically around one thousand stored ions. No significant dependence of the transition particle number on the ion species has been observed [1]. This is attributed to the charge dependence of the cooling force in the linear cooling force regime, which is relevant for well cooled beams with small emittance and momentum spread. The q^2-dependence of the Schottky noise power provides high sensitivity and good signal to noise ratio for highly charged ions. For cooled beams with a momentum spread below 10^{-6} single ions are routinely detected with the standard ESR Schottky noise detection system, which was designed for versatile use rather than for a specific application or certain beam parameters [6]. Bare uranium ions (charge 92) induce a Schottky signal which corresponds to nearly 10^4 singly charged ions of the same frequency spread. With increased frequency spread the signal to noise ratio drops inversely proportionally to the frequency width of the Schottky signal. Therefore it is quite obvious, that a measurement of the Schottky noise signal of protons at low intensity is limited to more than 10^4 stored protons. By connecting the Schottky pick-up to a resonant circuit the signal to noise ratio at the resonant frequency can be increased by an order of magnitude, thus lowering the detection limit to some 10^3 protons.

The measurement shown in Fig. 4 evidences that the lowest momentum spread (2σ) achieved in these experiments is 2×10^{-6}. Although the protons have an energy of 400 MeV like the heavy ions which showed an ordering effect, their magnetic rigidity is more than a factor of two lower. At the lower magnetic field level the stability of the bending field is reduced. The rigidity of the proton beam is the same as for bare gold beam at the energy of 75 MeV/u shown in Fig. 2. In both cases the frequency spread ($\delta f/f \simeq 1 \times 10^{-6}$) is a mark of the bending field stability, which for a bending field of 0.50 T in the ESR is about $\delta B/B = \gamma_t^{-2}\delta f/f = 6 \times 10^{-6}$. The rms momentum spread of 1×10^{-6} corresponds for protons to a longitudinal proton temperature of 0.5 meV. An improvement of the field stability will allow to test the temperature of the electron beam, for which a lowest value of about 0.2 meV was determined in experiments with bare carbon ions at two times higher magnetic field strength [4].

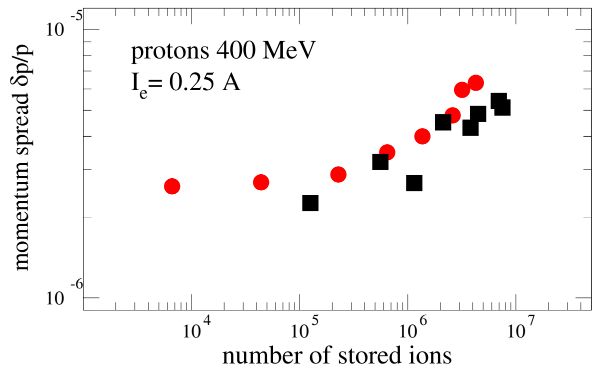

Figure 4: Momentum spread of protons at 400 MeV cooled with an electron current of 0.25 A. The black data points were measured with the standard set-up of the Schottky pick-up at 59.3 MHz, for the red data points the Schottky pick-up was connected to a resonant circuit (29.7 MHz) to increase the signal to noise ratio.

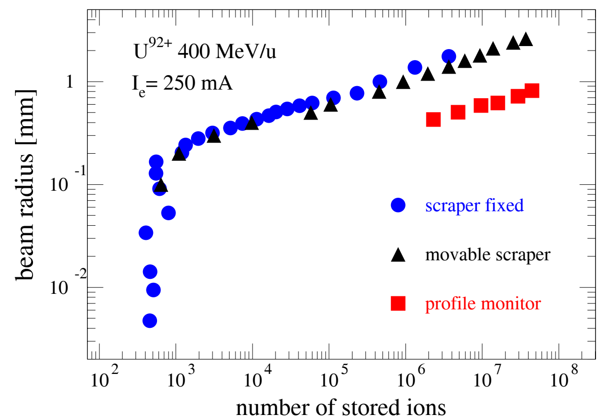

Figure 5: Beam radius measurement of a cooled beam (U^{92+}, 400 MeV/u) with a residual gas ionization profile monitor (1σ-value), a movable scraper and the method of shifting the ion beam towards the scraper by energy variation of the electron beam.

DISCONTINUOUS REDUCTION OF THE TRANSVERSE BEAM SIZE

For ordered beams with low transverse temperatures, typically in the range of meV, a beam radius of the order of μm is expected. Non-destructive transverse diagnostics with suitable resolution and sufficient sensitivity to detect the low intensity ordered beam parameters are not available. The only method which was useful so far for quantitative measurements of the transverse emittance of low intensity ordered beams is destructive beam scraping. Such scrapers have to be calibrated against non-destructive detection systems at higher intensity in order to allow quantitative measurements of the transverse width of the distribution. Positioning scrapers with μm precision is a difficult task. An alternative method for horizontal beam radius measurements has been developed. The ion beam center is shifted relative to a scraper which has a fixed inner end position and which is only moved into the beam for about a second and moved out afterwards [7]. The scraper is located in a section with small dispersion ($D \leq 1$ m) and the beam momentum is changed with changes of the energy of the cooling electron beam. Thus the resolution does not depend on the positioning accuracy of the scraper and with tiny changes of the electron energy the ion beam position can be changed in the μm range. A small value of the dispersion at the scraper is favorable, as it increases the resolution for the beam size determination and minimizes the influence of the momentum spread on the measurement of the horizontal beam size. The ion optical β-function at the scraper location should be large to achieve good resolution.

The detection of a reduction of the transverse beam size is strongly dependent on the resolution as shown in Fig. 5. The standard profile monitor which is based on ionization of the residual gas has a resolution limit of about 0.5 mm (1σ) which does not allow a profile measurement below 10^6 stored ions. By comparison of the beam size measurement with profile monitor and scraper, it can be concluded that the scraper cuts the beam at about 3σ of the distribution. With a movable scraper a resolution of about 100 μm (3σ) is achieved routinely, with high precision positioning it can be reduced to about 20 μm. With the scraper method based on small energy changes a resolution better than 5 μm (3σ) has been achieved, which clearly evidenced the discontinuous beam radius reduction when the beam transits to the ordered state. With optimized parameters a resolution down to 1 μm is feasible.

Such scraper measurement which extend over several minutes require an extraordinary stability of the beam orbit and of the beam center at the scraper, particularly. Nevertheless, at the ESR it has been found that these measurements can be well reproduced at the μm level [4].

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