# OBSERVATION OF ULTRACOLD HEAVY ION BEAMS WITH MICROMETER SIZE BY SCRAPING

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### *Abstract*

A method to measure the horizontal beam size of electron cooled ion beams with micrometer resolution has been developed. It exploits small variations of the beam momentum for micrometer displacement in a dispersive section of the storage ring. The method has been applied to low intensity beams which are supposed to undergo a phase transition to an ordered state. The measurements evidenced that the low intensity beam does not only collapse to small momentum spread, but also shrinks abruptly in the transverse degree of freedom. This confirms the hypothesis that a one-dimensional ordered structure is formed.

## INTRODUCTION

Experiments with a large variety of electron cooled bare heavy ion beams in the ESR storage ring have evidenced a pronounced reduction of the momentum spread when the number of stored ions is reduced to less than a few thousand [1]. The momentum spread of the cold low intensity beam drops abruptly below $10^{-6}$. The measurement of such small momentum spreads is achieved routinely by Schottky noise analysis. Detection of the frequency spread in the $10^{-7}$-range is readily available by spectral analysis of the beam noise detected by a capacitive pick-up. The main limitation for the frequency analysis originates from variations of the revolution frequency caused by ripple on the power supplies of the bending magnets of the storage ring. The high sensitivity of Schottky noise analysis for cooled ion beams even allows detection of single highly charged ions.

The non-destructive Schottky noise technique for the determination of the longitudinal momentum spread has no counterpart of similar resolution and sensitivity in the transverse degree of freedom. Detectors like residual gas ionization beam profile monitors or detectors for particles, which have interacted with the residual gas and captured or lost an electron, can resolve transverse structures down to 0.1 mm. For the lowest intensities beam sizes below 0.1 mm are expected, particularly if a reduction of the transverse emittance occurs similar to the longitudinal momentum spread reduction. Indications of a discontinuous reduction of the transverse beam size were observed by scraping of the beam [2].

## BEAM SCRAPING

The beam size determination by way of moving a scraper into the circulating ion beam is limited by the accuracy and reproducibility of the position of the scraper. The scrapers installed in the ESR storage ring are based on stepping motors which are connected to a high precision spindle, thus transforming the rotation of the stepping motor into a linear motion. This method allows a minimum step size of 5 $\mu$m which determines the resolution and reproducibility. For the investigation of extremely cold ion beams, even better resolution is preferable.

A higher resolution for the horizontal beam size is achieved by moving the beam center with respect to the scraper instead of relying on the reproducibility of the scraper position. A well defined transverse motion of the beam can be achieved by a change of the longitudinal beam momentum, which, in a dispersive section of the storage ring, also results in a horizontal displacement of the beam. As, during variations of the electron beam velocity, the ion beam is not perfectly cooled, it is preferable to move the scraper to a parking position which is separated from the ion beam during velocity changes. After shifting the ion beam to the new velocity the scraper is moved to a position which is defined by a fixed mechanical end block and no longer by the movable parts of the positioning system. Thus the scraper can reproducibly be positioned and the distance between beam center and scraper can be varied by energy changes.

The horizontal displacement $dx_s = D(z_s)/(dp/p)$ for a change of the relative momentum $(dp/p)$ depends on the dispersion $D(z_s)$ at the scraper location $z_s$. The velocity of the electron cooled ion beam is determined by the velocity of the electron beam. A change $\Delta U$ of the accelerating voltage $U$ of the electron beam causes a momentum change $\Delta p/p = (\gamma/(\gamma+1))\Delta U/U$ with the relativistic $\gamma$ factor. The momentum change results in a change of the horizontal position $\Delta x_s$ at the scraper. The accelerating voltage can be changed in a smallest step of $\Delta U_{min} = 1.2$ V which corresponds to the lowest significant bit of the DAC providing the reference value for the accelerating voltage. The ion optical dispersion function has a value of about 1 m at the location of the scraper. For a typical accelerating voltage of 220 kV the smallest voltage step corresponds to a horizontal displacement per minimum step of about 3 $\mu$m which determines the horizontal resolution. The precise value of the displacement and consequently the dispersion at the scraper location is calibrated each time before a measurement, since the dispersion can vary due to higher order magnetic field contributions depending on the magnetic rigidity of the beam. Independent variations of quadrupole magnet groups in the ESR allow variations of the dispersion at the scraper location. This option has not been employed for the achievement of even better horizontal resolution.

Another experimental difficulty arises from the fact that cooled beams exhibit a distribution which is due to an equilibrium between electron cooling and intrabeam scattering. Scraping of a fraction of the distribution creates an artificial distribution with sharp edges which will be redistributed by intrabeam scattering and cooling. Therefore, if the scraper is kept at a position which is used to scrape the beam, the scraper causes permanent losses due to particles which are scattered out of the central part of the distribution. Increased transverse oscillation amplitudes will cause the scattered particles to hit the scraper and, consequently, to be lost. With no scraper in their orbit, these particles will be be cooled back and a new distribution of smaller intensity and smaller emittance will be formed. In order to minimize the slow losses, the scraper must be moved to such a distance from the beam that the beam can circulate without interference. As the time constant for transverse heating is on the order of seconds or longer, scraper movements with the standard stepping motor drive are fast enough to scrape the beam in a reproducible way.

## BEAM SIZE OF ULTRACOLD HEAVY ION BEAMS

The measurements of the beam size of cooled heavy ion beams by the scraping technique were subdivided into two regimes. At higher ion beam intensities the beam size is on the order of millimeters. Therefore, the standard accuracy of scraper positioning was sufficient to resolve the beam size. By moving the scraper closer and closer to the central orbit the beam size was probed. When the beam size was reduced to about 1 mm, further scraping was performed by shifting the beam position relative to the scraper.

In the second regime the scraper end position was fixed by a mechanical block and the ion beam position was changed by stepping the electron energy and consequently the energy of the ion beam. Initially, the minimum energy, at which all cooled stored ions were lost after moving the scraper from an outer position towards the beam center against its end block, was determined with the resolution given by the minimum voltage step of the electron beam high voltage power supply. For this minimum energy the scraper in its end position is exactly on the central orbit. After a new beam injection the beam was cooled to an energy slightly below the energy for full beam loss. Then the energy of the circulating beam was increased by increasing the energy of the electron beam in steps, thus the ion beam center was approaching the end position of the scraper. After each change of the accelerating voltage of the electron beam to a new value, which was closer to the scraper than the previous one, the scraper was moved to its end position close to beam center, thus scraping off the outer fraction of the transverse distribution. After a few seconds the scraper was retracted to an outer parking position, no longer affecting the beam.

The surviving fraction of the beam was cooled back to a new equilibrium distribution. For the equilibrated beam the Schottky noise signal at a higher harmonic of the revolution frequency was recorded. The noise power of the Schottky signal is proportional to the beam intensity and the frequency width of the noise signal is converted into the corresponding momentum spread according to $\delta p/p = \eta^{-1}\delta f/f$ with the frequency slip factor $\eta$. Starting from a scraper position which corresponds to a distance of about 2 mm from the scraper edge to the beam center, the noise power and the momentum spread are shown in Fig. 1 as a function of the distance to the scraper.

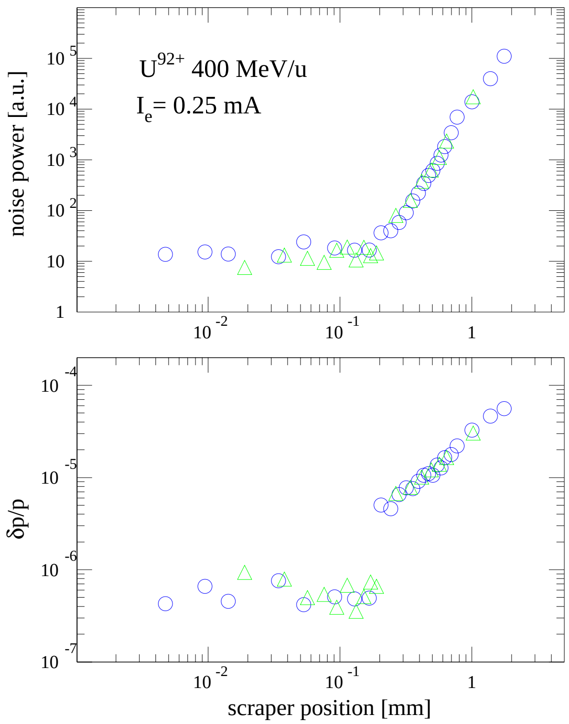

Figure 1: Schottky noise power and momentum spread derived from the width of the Schottky signal as a function of the distance between beam center and scraper for a cooled beam of bare uranium with an energy of 400 MeV/u. The distance of the ion beam center to the scraper was controlled by energy variations with the electron beam.

For this measurement a beam of bare uranium at an energy of 400 MeV/u was cooled by an electron current of 0.25 A. The Schottky noise was detected at the $31^{st}$ harmonic of the revolution frequency. The continuous decrease of the noise power and the momentum spread ceased at a scraper position of about 0.2 mm. The momentum width dropped abruptly from $5 \times 10^{-6}$ to $5 \times 10^{-7}$. Concurrently the noise power stayed on a constant value and did not change with smaller distance between beam and scraper. The whole surviving beam was lost after a final step with the beam energy corresponding to a distance change of 4 $\mu$m. The whole procedure was well reproducible, as evidenced by the comparison of two independent measurements. The two measurements in Fig. 1 were performed with two fillings of the ring and repetition of the successive reduction of beam intensity. The main uncertainty at small beam size comes from the determination of the beam center which is measured with the uncertainty of the minimum voltage step of the electron beam acceleration voltage. Position variations due to power supply ripple are negligible because of the small value of the dispersion function at the scraper position. Supplementary methods of finer energy variations, e.g. small changes of the electron current varying the electron beam's space charge or the use of an additional voltage, for finer control of the potential difference between gun and cooling section, will reduce the uncertainty in beam center definition and further increase the resolution.

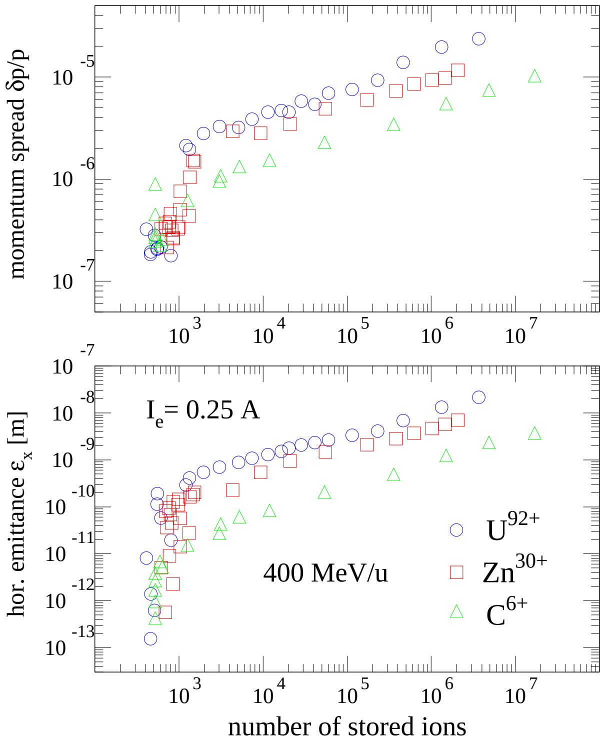

Figure 2: Momentum spread and horizontal emittance ($1\sigma$-values) as a function of the number of stored ions for three species of bare ions stored and cooled at an energy of 400 MeV/u. The simultaneous reduction of the longitudinal momentum spread and of the horizontal emittance occurs for all species around one thousand stored ions.

The obvious conclusion is that the beam shrinks at the transition point of the momentum spread to a correspondingly small horizontal size. This is clearly evidenced when the momentum spread and the horizontal emittance is plotted as a function of the number of stored ions (Fig. 2). The number of ions was determined from the integrated noise power of the Schottky signal. The Schottky noise power was calibrated at higher beam intensity by comparing the noise power to the current reading from the standard current transformer which measures the circulating ion current non-destructively. This method assumes that the noise power is proportional to the beam intensity. This is generally true, but small deviations have been found close to the transition point of the momentum spread, likely to be caused by collective effects in the Schottky noise [1]. The emittance was estimated by the known fact that the beam radius determined by scraping corresponds to a $3\sigma$-value, and with the beta-function at the scraper position obtained by ion optical calculations.

By the conventional scraper method which employs the movement of the scraper, the vertical beam size has been probed, additionally. Indications have been found that the vertical beam size also drops suddenly at the transition point [3]. However, the higher resolution method employing energy changes of the beam is not applicable to the vertical degree of freedom.

## CONCLUSIONS FROM SCRAPER MEASUREMENTS

The scraper measurements provide information on the beam parameters in the transverse degree of freedom. For higher beam intensities, with particle numbers exceeding a few thousand, they exhibit a continuous increase of the momentum spread and transverse emittances with intensity which is attributed to an equilibrium between cooling and intrabeam scattering. For lower beam intensities the scraper measurements have confirmed that a sudden reduction occurs not only in the longitudinal, but also in the transverse degree of freedom. It is suggested by these observations that the beam turns into an ordered state which can be imagined as a linear string of ions with extremely small transverse extension. The ions are confined to their longitudinal position by the Coulomb potential of their nearest neighbors [4]. Estimates of the beam temperature at small particle number result in rather low values which, due to the limited resolution of the detection method, constitute only an upper limit. Values of the order of meV, both for the longitudinal and the transverse temperature, have been found if the particle number is reduced below one thousand [5]. For the lighter carbon ion longitudinal and transverse temperatures of about 0.1 meV have been estimated in the low intensity limit. The surprisingly low transverse ion beam temperature, which is significantly smaller than the transverse electron temperature, is attributed to the effect of magnetized cooling.

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