# Like a string of beads

## Coulomb order for cooled ions observed in the ESR

**Highly charged ions circulating in storage rings have opened up new and previously unimaginable perspectives in atomic and nuclear physics. Examples are the precision spectroscopy of hydrogen-like heavy ions, as well as the mass measurements and the investigations into the decay properties of radioactive nuclides, which belong to the highlights of recent research at the Experimental Storage Ring (ESR). Another interesting phenomenon has recently been observed at the ESR: the transition of cooled ion beams to a Coulomb-ordered state. In this state, the ions circulate like a string of beads without the possibility of passing each other.**

The key to all these experiments is a technique developed thirty years ago by G. I. Budker in Novosibirsk, which allows the beam quality of ions circulating in a storage ring to be strongly improved—the technique of electron cooling. As the ion beam from the synchrotron (SIS) is transferred to the ESR, it exhibits a longitudinal momentum spread of several parts per thousand ($\partial p_L/p_L \approx 10^{-3}$), which is completely insufficient for the performance of precision experiments.

In order to force the orbiting ions into a uniform velocity, one superimposes a parallel electron beam with a well-defined energy over a distance of about two meters. Again and again the ions circulating in the storage ring interact with the constantly renewed electron beam and thereby attain the velocity of the electrons within fractions of a second.

Depending on the particle number in the ring, the longitudinal momentum spread can thereby be reduced, by three to four orders of magnitude. At the same time, the beam diameter and its divergence are drastically diminished.

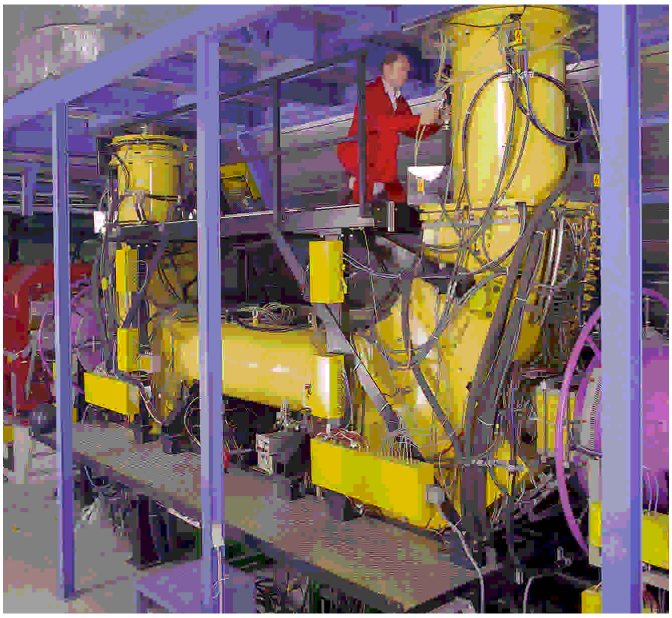
In the reference system of the ion beam, this process corresponds to a decrease of the disordered motion of the individual beam particles, which can be formally parameterised by a reduction of the beam temperature. For this reason, one speaks of cooling the ion beam by the electrons. As a result of electron cooling, an ion beam with low momentum spread and divergence is circulating in the ultra-high vacuum of the storage ring for up to several hours.

Already during the planning phase of the ESR, the interesting question came up whether by electron cooling the disordered motion of the individual ions could be reduced in such a way that the electrostatic repulsion becomes dominant, eventually leading to an ordered motion of the ions in the beam. Such ion systems, in which the charged particles are ordered in one or even more dimensions by the Coulomb interaction are called Coulomb crystals. At the beginning of the nineties, such systems were observed in ion traps for the first time and investigated in detail [1].

So far the question remained unresolved whether also the fast rotating ions in a storage ring can form ordered structures. Convincing experimental and theoretical evidence for this phenomenon was recently found at the ESR —at least in one dimension. For sufficiently small particle densities, the cooled ions circulating in the ESR arrange themselves like beads on a string [2].

First evidence for the transition from disordered to a somewhat ordered motion of the cooled ions in the ESR resulted from systematic measurements of the momentum spread as function of the particle number in the ring, which can also be expressed in terms of the average particle distance. Figure 1 shows the respective measurements for $^{86}Kr^{36+}$ and $^{132}Xe^{54+}$ at 240 AMeV—this corresponds to ion velocities of 60 % of the velocity of light—as well as

*Electron cooler in the Experimental Storage Ring (ESR). For very low particle numbers, a transition of the cooled ion beams to a Coulomb-ordered state was observed.*



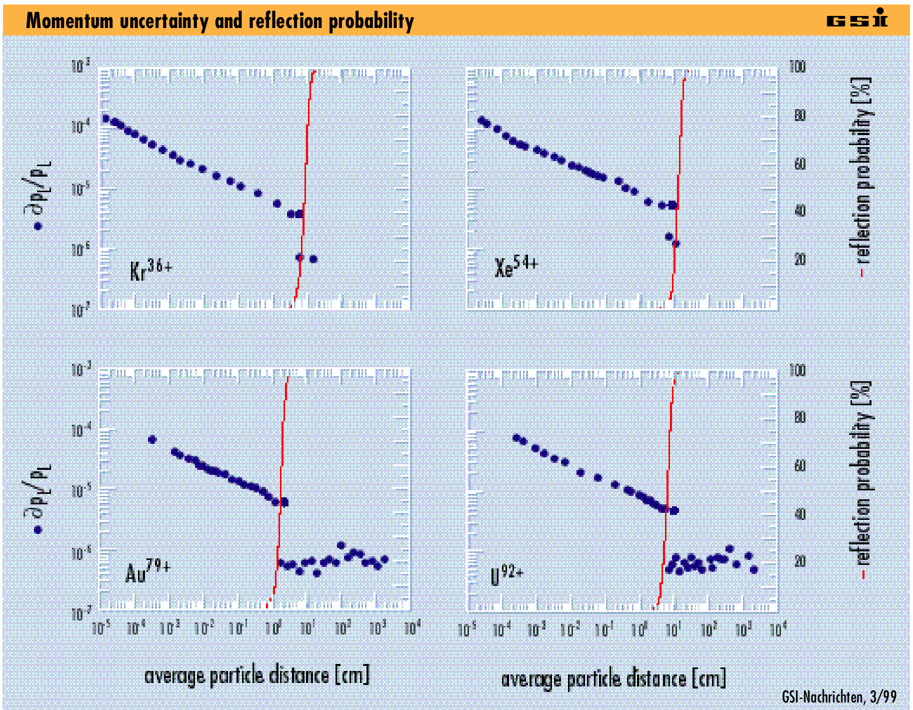



*Fig. 1: In a double logarithmic presentation of the longitudinal momentum spread $\partial p_L/p_L$ versus average particle distance, $\partial p_L/p_L$ initially shows a linear decrease, which is then followed by a sharp drop by a factor of ten (see blue points and scaling on the left hand side). The sharp drop coincides with the calculated rise of the reflection probability of two neighbouring ions from 0% to 100 % (red line and scale on the right hand side). In this Coulomb-ordered phase, the ions can no longer overtake each other.*

for $^{197}Au^{79+}$ and $^{238}U^{92+}$ at 360 AMeV —corresponding to ion velocities of some 70 % of the velocity of light. For small average particle distances, the longitudinal momentum spread decreases inversely proportional to the particle distance, and then shows a sharp drop by one order of magnitude (from $\partial p_L/p_L \simeq 5\times10^{-6}$ to $5\times10^{-7}$) at ion distances of a few cm up to roughly 10 cm. For even larger particle distances, $\partial p_L/p_L$ remains constant at $5\times10^{-7}$. Due to ring instabilities, this is presently the lowest possible value for the longitudinal momentum spread that can be reached in the ESR. In addition to the sudden drop of $\partial p_L/p_L$, the beam diameter shrinks to approximately 60 micrometers.

## Drastic change in beam properties

How can the sharp decline of the longitudinal momentum spread and in the beam diameter be accounted for? In order to understand this phenomenon, one has to take a closer look at the mutual interactions of the ions circulating in the ring and on the compensating influence of the electron cooling on these effects. In an uncooled beam, e.g. directly after injection into the ESR, the ions exhibit a broad longitudinal and transversal momentum distribution. The faster ions overtake the slower ones and can thereby scatter off each other. Due to the repulsive electrostatic interaction, this intrabeam scattering leads to a spatial expansion and momentum broadening of the beam. The electron cooling counteracts these effects by adjusting the ion velocity with each revolution to that of the electron beam. The smaller the particle number in the ring, i.e. the larger the average distance of the ions, the better the electron cooling can compensate for the beam heating by ion-ion scattering. Above a certain particle distance, the intrabeam scattering suddenly breaks down.

It had been speculated for some time that this sudden breakdown of the intrabeam scattering is caused by the transition of the beam from a disordered to an ordered phase, where the ions can no longer pass each other but instead are reflected by each other. This interpretation was recently confirmed by Monte Carlo calculations for the beam trajectories of two neighbouring ions circulating in the ring. Due to the large particle distances of several centimeters, it is sufficient to consider at the interaction of two ions only. In the transverse directions, the ions are focused by betatron oscillations with the betatron frequency of the ESR of typically 10 MHz. In longitudinal direction, their motion can be described by the velocity distribution given by the longitudinal momentum spread. For the ion beams under consideration, one finds at the distances where the drop of $\partial p_L/p_L$ occurs, the average collision time of two neighbouring ions to be in the millisecond range. Between two collisions the ions therefore perform more than thousand betatron oscillations. This already hints at a very small intrabeam scattering.

In the Monte Carlo simulations one can in addition obtain the probability for a reflection of the two ions by each other, i.e. a collision process in which the two particles are scattered on the 180 degrees. The essential parameters to be considered for these simulations are the longitudinal and transversal beam temperature, the charge and mass of the ion, the betatron frequency, and the average particle distance.

## No passing for ions

By comparison of the theoretical results thus obtained with the experimental data, one finds that in all cases the calculated probability of reflection rises steeply in direct proximity of the observed drop of the longitudinal momentum uncertainty (Fig.1). This strongly supports the above interpretation in terms of a transition of the beam into a kind of string order, in which the ions are circulating in the ring without passing each other.

By an observer rotating with the beam, the situation might be described by the picture of a thinly occupied string of beads. The beads are statistically distributed along the circumference of the string. Assuming an average distance of 10 cm, one finds 10 particles per meter with an uncertainty of ±3. Due to the fast betatron oscillations within the 10 MHz range, the beads appear to be smeared to disks in the transverse beam direction. With relative velocities of a racing car, they move towards or apart from each other, and with a frequency of some hundred Hz, they undergo reflecting collisions with their neighbours.

In summary, experimental and theoretical evidence was found for a Coulomb-ordered beam structure in a high-energy storage ring for the first time. Compared to the crystalline beam structures observed in ion traps, the one dimensional string order found at the ESR represents, however, only a weak degree of order. It may be compared to the weak order phenomena found in liquids rather than to a solid state lattice. Higher degrees of order for the ESR beams will probably not be feasible, due to the machine limitations concerning the achievable momentum spread and also due to the high circulation velocity of the ions that would lead to considerable shearing forces in the bending sections of the ESR and thus destroy the ordered structures. ■


**REFERENCES**

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# New high-current injector under commissioning

Commissioning of the new high-current injector started in October 1999, following nine months of installation work in the UNILAC tunnel. The high-current injector allows intense pulses of low charge-state ions to be accelerated up to the 1.4 AMeV stripper energy of the UNILAC. To produce the required ion intensities, e.g. 10 mA $Ar^{1+}$ or 15 mA $U^{4+}$, special ion sources (CHORDIS, MUCIS, and MEVVA) are employed. Alternatively, a second injector with a Penning source can be used that provides lower intensities, e.g. 1 mA $U^{1+}$, but at a higher duty cycle of up to 20 %.

The ions are electrostatically pre-accelerated and then injected into the new rf-accelerator that has replaced the old Wideröe section of the UNILAC. It consists of a 36 MHz RFQ structure with maximum acceleration voltage of 8 MV, followed by two 36 MHz IH structures, each with an acceleration voltage of some 40 MV. With these structures, the stripper energy of 1.4 AMeV can be attained for all ions up to $U^{4+}$.

Commissioning of the new injector was very successful so far. For lighter ions, e.g. $Ar^{1+}$, the specifications are almost fulfilled. For heavier ions, about half of the specified currents could be achieved so far. Already in November, the new injector could be employed for first experiments, using an $Ar^{1+}$ beam. In February 2000, a uranium beam from the new injector is on schedule with intensities up to $5\times10^9$ particles per synchrotron cycle. Ultimately, some $2\times10^{10}$ uranium ions per cycle can be provided with the new facility. This drastic gain in intensity will open up new perspectives for the investigation of exotic nuclei far off stability and for plasma research with intense ion pulses. ■