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Coulomb Clusters in RETRAP

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Abstract. Storage rings and Penning traps are being used to study ions in their highest charge states. Both devices must have the capability for ion cooling in order to perform high precision measurements such as mass spectrometry and laser spectroscopy. This is accomplished in storage rings in a merged beam arrangement where a cold electron beam moves at the speed of the ions. In RETRAP, a Penning trap located at Lawrence Livermore National Laboratory, a sympathetic laser/ion cooling scheme has been implemented. In a first step, singly charged beryllium ions are cooled electronically by a tuned circuit and optically by a laser. Then hot, highly charged ions are merged into the cold Be plasma. By collisions, their kinetic energy is reduced to the temperature of the Be plasma. First experiments indicate that the highly charged ions form a strongly coupled plasma with a Coulomb coupling parameter exceeding 1000.

INTRODUCTION

The development of efficient cooling schemes for ions confined in storage rings and ion traps enabled precision measurements which greatly improved our understanding of basic atomic physics, collisions and charge exchange processes as well as the behavior of strongly coupled, one component plasmas. Multi component, strongly coupled plasmas on the other hand, which are of considerable interest in an astrophysical context [1–4], have not been studied experimentally at all. The main reasons for this lack of investigations lie in the experimental and technical difficulties to produce these kind of plasmas. For example, in order to create a two component, strongly coupled plasma in a Penning trap, the mass to charge ratios of the different ion species have to match, otherwise a centrifugal separation of the plasma will take place [5–7] before the plasma becomes strongly coupled. Only a very limited number of low charge state elements fulfill this criterion ($^9Be^+$ which can be laser cooled effectively and $^{27}Al^{3+}$ are possible candidates); whereas, this difficulty can be avoided by using highly charged ions. A large variety of heavier ions with a mass to charge ratio matching $^9Be^+$ can be found. Prominent candidates include $^{45}Sc^{5+}$, $^{63}Cu^{7+}$, $^{81}Br^{9+}$, $^{180}Hf^{20+}$, $^{198}Hg^{22+}$ and $^{207}Pb^{23+}$. This short list of elements is by no means complete, many other combinations are feasible. Heavy elements in these charge states are easily produced in an electron beam ion trap (EBIT) and $^9Be^+$ can be delivered by a metal vapor vacuum arc (MEVVA) ion source.

Unfortunately the most effective cooling technique, laser cooling, cannot be applied to high charge state ions due to a lack of suitable transitions accessible with lasers. Therefore, a sympathetic cooling scheme has been implemented at RETRAP. In brief: First $^9Be^+$ is caught and confined in the trap. Then the ions are electronically cooled with a tuned circuit and optically by a laser. Highly charged ions are merged into the cold Be plasma, energy is exchanged by collisions, reducing the kinetic energy of the highly charged ions to the Be plasma temperature.

EXPERIMENTAL SETUP

The experimental setup used for the cooling experiments is shown in Fig. 1. Singly and doubly charged Be ions are produced in a MEVVA ion source. After momentum analysis in a 90° bending magnet, Be^+ is decelerated and caught in one of RETRAP's [8] Penning traps (for a description of the trap geometry see the article by D. A. Church et al. in these proceedings). A high impedance tuned circuit, consisting of the

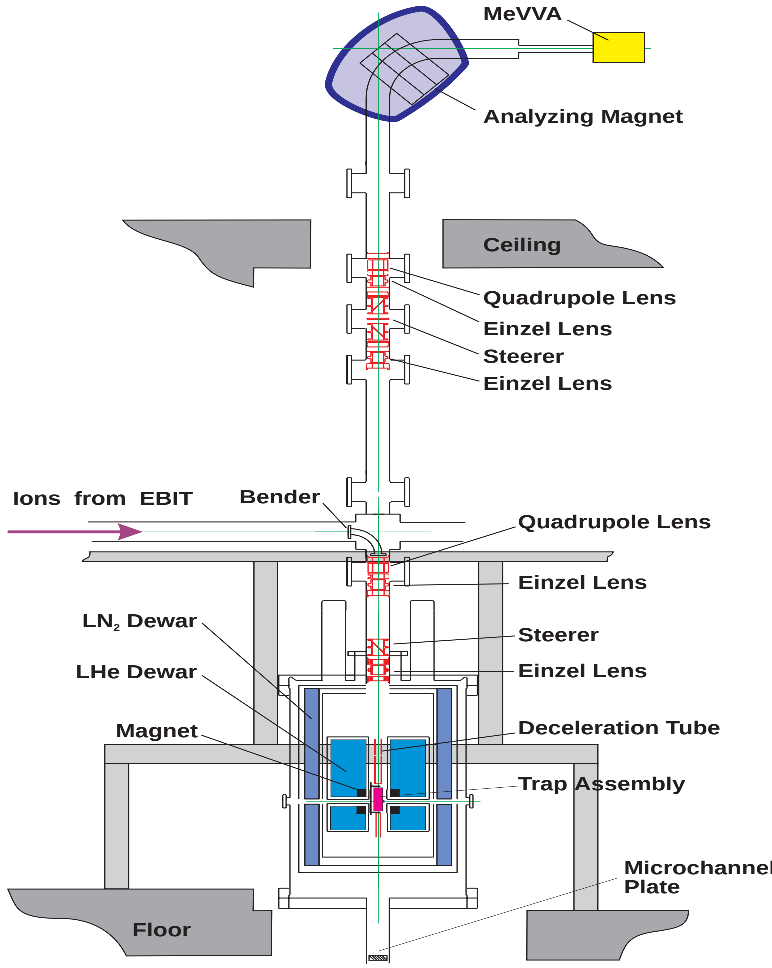

FIGURE 1. Experimental setup used for the cooling experiment. Two ion sources are being used. A Metal Vapor Vacuum Arc provides for singly and doubly charged beryllium while the highly charged ions are extracted from EBIT and transported to RETRAP. Both ion beams are momentum analyzed to select a certain charge state. Only the analyzing magnet for the Be beam is shown here. The ion energy is typically 6 $keV \cdot q$, too high for direct catching. A deceleration tube situated above the trap is used to reduce the kinetic energy of the ions to about 50 $V \cdot q$.

endcap electrode capacitance and an inductor connecting these electrodes, precools the ions with a cooling time constant of about 80 s for Be^+. A laser beam, entering the trap through holes in the ring electrode and tuned to the red side of the Be^+ $2s\,^2S_{\frac{1}{2}}(m_j = -\frac{1}{2}, m_I = -\frac{3}{2}) - 2p\,^2P_{\frac{3}{2}}(m_j = -\frac{3}{2}, m_I = -\frac{3}{2})$ transition reduces the temperature of the ion cloud below the tuned circuit temperature. Highly charged ions are produced in EBIT, extracted and a certain charge state is selected for transport to RETRAP. Here they are decelerated and caught into the trap which already confines the Be ions. Eventually, the highly charged ion-Be plasma reaches thermal equilibrium, both ion species will assume the same temperature, which is, in principle, limited only by the laser cooling force. To gain information about the number and radial distribution of trapped ions, they can be released to a microchannel plate-phosphor screen combination below RETRAP. Also, two additional holes in the ring electrode allow the detection of scattered photons. A lens, mounted in front of one of the holes, collects light emitted from the trapped ions. For light detection, a photo multiplier tube and a cryogenically cooled CCD camera are placed in the radial plane outside the vacuum vessel. The photo multiplier tube provides the time development of the photon yield, whereas the CCD camera images the plasma cloud by integration over a certain time interval (typically in the order of 10 s). In addition, the tuned circuit can be used to determine the plasma constituents. By changing the electrical field inside the trap, ions with different mass to charge ratios are tuned onto the tuned circuit resonance, thereby increasing the noise at that frequency. After background subtraction the relative amount of ions with different mass to charge ratios can be determined.

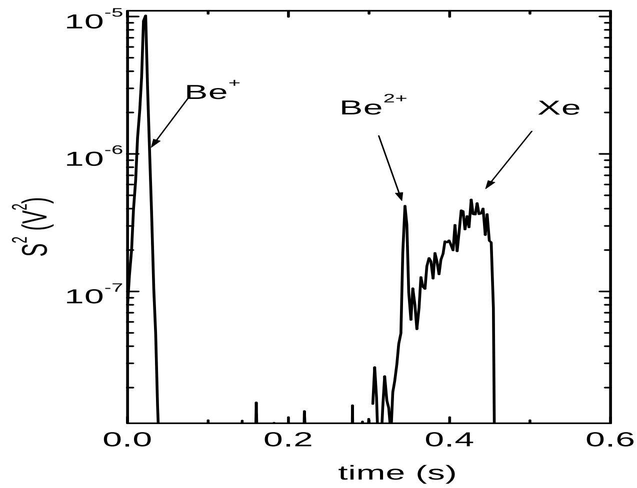

FIGURE 2. Tuned circuit signal (S^2) as a function of time, while the ring electrode potential is lowered in order to tune different ion species onto resonance. Assuming that this system has reached thermal equilibrium the relative number of ions can be determined by integrating the area under each peak. In this case the plasma consists of 98.4% Be^+, 1.2% Be^{2+} and 0.4% Xe^{44+}. The broad peak for the Xe ions is either due to a large energy spread indicating that thermal equilibrium has not been reached yet or a broad distribution of Xe charge states. In both cases a larger electrical field is necessary to tune the Xe ions onto resonance with the tuned circuit.

RESULTS

A typical tuned circuit signal is shown in Fig. 2. After the capture of Be and Xe ions the ring electrode potential is ramped in order to tune the axial oscillation frequency of different ion species to the tuned circuit resonance. After amplification a spectrum analyzer is used to measure the noise at this frequency.

Assuming that the system has reached thermal equilibrium, the tuned circuit signal can be used, after subtracting the Johnson noise, to determine the plasma composition. The measured voltage squared is given by $S^2 = \frac{NkTR}{2\tau_z}$ where N is the number of ions on resonance with the tuned circuit, $\frac{1}{2}kT$ is the thermal energy in the axial degree of freedom, R is the resistance of the tuned circuit and τ_z is the electronic cooling time constant given by $\tau_z = \frac{4mz_0^2}{\kappa^2 q^2 R}$ [9]. Here m and q are the mass and charge of the ion respectively, z_0 is the half length of the trap and κ is a constant depending on the trap geometry. Since the voltage is changed slowly compared to the characteristic frequencies of the ions the ion motion changes adiabatically. Under these conditions the action integral $\oint p_z dz = \frac{4\pi}{\omega_z}\frac{1}{2}kT$ is a constant of motion, with ω_z being the ion frequency along the magnetic field lines. Therefore the change in temperature has to be taken into account when the concentration of different ion species present in the plasma is determined. For the spectrum shown in Fig. 2, the concentrations are: 98.4% Be^+, 1.2% Be^{2+} and 0.4% Xe^{44+}. The reader should note that only Be^+ and Xe^{44+} had been injected into the trap. The doubly charged Be seems to built up during the first few seconds after the catch, possibly due to collisions with residual gas molecules. The exact process, however, is unknown. The broad Xe^{44+} signal is either due to a wide energy distribution or the presence of lower charge state Xe. Ions with larger energies can leave the harmonic region of the trap which results in a slightly lower oscillation frequency; Xe ions with $q \leq 44$ would oscillate with a lower frequency as well. A different potential has to be applied to the ring electrode in order to tune these ions onto the tuned circuit resonance.

As mentioned above, a CCD-camera is mounted onto one of RETRAP's radial ports to gain information about the spatial distribution of the Be^+ ions. The camera is placed at a 90° angle with respect to the cooling laser beam and collects a small fraction of the emitted photons. A typical image is shown in Fig. 3. At low temperatures the cloud is expected to have an ellipsoidal shape where the ratio of the two axes ($\frac{a}{b}$) is defined by the constant density of the cloud [10–13]:

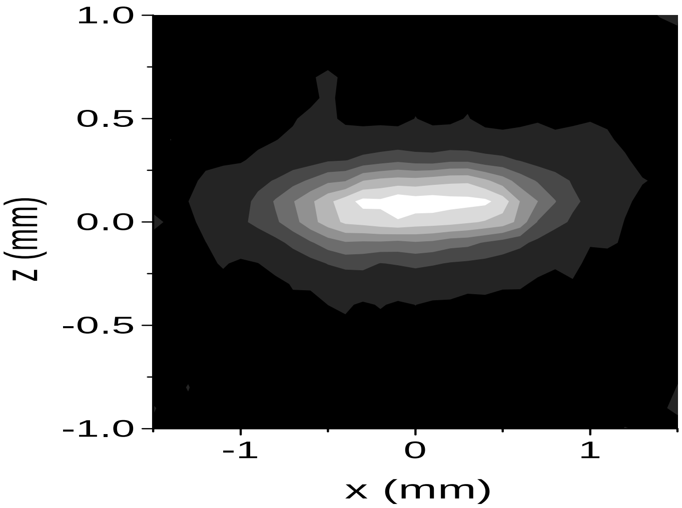

FIGURE 3. A cryogenic CCD camera is used for gaining information about the spatial distribution of the trapped Be^+ ions. The image shown here is a side view of the plasma cloud. The elliptical shape can be used to determine the Be^+ density which is constant over the full extend of the cloud. The total number can be determined by measuring the size of the plasma.

$$n = \frac{3m\omega_z^2}{4\pi q^2 \epsilon(\frac{a}{b})}. \tag{1}$$

Here $\epsilon(\frac{a}{b})$ is a function of the ratio of the axes given in [13]. In RETRAP the so obtained density for Be^+ is typically between $1 \cdot 10^9\ cm^{-3}$ and $2 \cdot 10^9\ cm^{-3}$. The total number of Be^+ lies between $1 \cdot 10^5$ and $4 \cdot 10^5$ ions. Combining the relative concentration obtained with the tuned circuit and the absolute number for Be^+ ions the number of Be^{2+} and Xe^{44+} can be calculated as well. The plasma shown in Fig. 2 contains at least 400 Xe^{44+} ions, which is in good agreement with the number of highly charged ions detected by the microchannel plate detector underneath the trap when the ions are released.

In addition, images of the plasma can be used to show the location of the highly charged ions within the Be^+ cloud. At low temperatures a centrifugal separation of ions with different mass to charge ratios is expected to occur. After laser-cooling and before the introduction of Xe^{44+} ions, the CCD image shows the appearance of a dark center in the middle of the trap. Figure 4 shows a projection of the central, radial plane. The drop of the photon yield to background level in the vicinity of $x = 0\ mm$ is clearly visible even before highly charged ions are present in the trap (solid line in Fig. 4). Composition measurements at higher temperatures revealed the presence of trapped singly and doubly charged Be ions. Be^{2+} is not visible in the laser light. At low temperatures it accumulates in the center of the trap forcing Be^+ to form an annulus around the Be^{2+} cloud. After catching and cooling Xe^{44+} the dark center increases in diameter (Fig. 4, dotted line) which can be explained by an accumulation of the highly charged ions in the very center of the trap; the two Be charge state plasmas form rings around the Xe^{44+} ions. The increase of the dark center of the trap is not observed when no Xe^{44+} is present in the trap.

The temperature of the plasma has been estimated in three different ways:

1.) When the cooling laser beam frequency is swept over the Be^+ resonance a width of 0.3 GHz has been measured indicating a temperature below 1.7 K.

2.) The observed centrifugal separation of Be^+ and Be^{2+} can be used to establish an upper temperature limit as well. O'Neil introduced a set of scaling lengths [5] l_{ij} where the l_{ij} are given by $l_{ij}^{-1} = \frac{d}{dr}[q_i|\frac{m_i}{q_i} - \frac{m_j}{q_j}|\frac{\omega^2 r^2}{2kT}]$. Here m_i, m_j, q_i, q_j are the mass and charge of the ion species i and j, ω is the density dependent rotation frequency of the plasma and r the radial extend of the plasma cloud. According to O'Neil's model complete separation takes place when the conditions $l_{ij} < \lambda_D$ are fulfilled, where λ_D is the Debye length of the plasma. The temperature dependence of λ_D and l_{ij} then gives an upper bound for the temperature of the plasma.

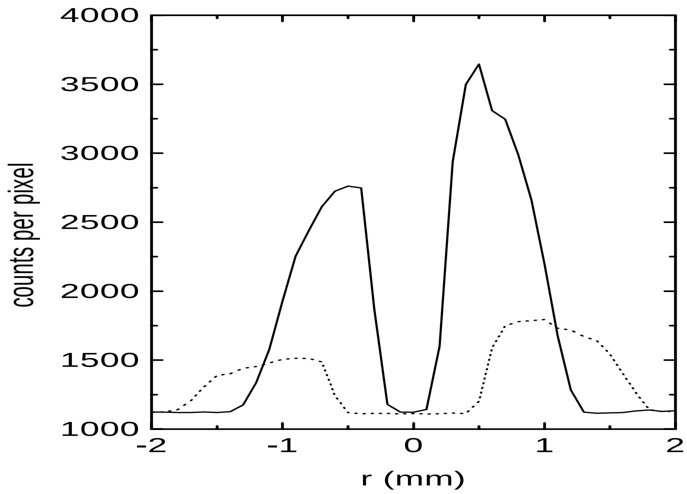

FIGURE 4. Projection of the scattered photons from the central, radial plane of the trap. Even before highly charged ions are introduced into the trap a dark center appears due to the presence of Be^{2+} (solid line). After catching and cooling highly charged ions the radius of the dark center increases (dotted line) indicating the accumulation of Xe^{44+} in the trap center. The left-right asymmetry is due to a slight misalignment of the laser beam with respect to the axis of the trap.

For typical parameters in RETRAP the temperature of the plasma should be below 0.5 K, in agreement with observed Doppler width of the cooling transition.

3.) Numerical simulations of a small number (128) of Be^+ and Be^{2+} ions show a separation only when the temperature is below 1 K [14].

Therefore we assume 1.7 K as a conservative upper temperature limit for the plasma in the following discussion.

In order to determine the Coulomb coupling parameter, , $= \frac{q^2}{akT}$ with $\frac{4\pi a^3 n}{3} = 1$, for the highly charged ion plasma the density has to be known. Unfortunately, with the present setup no direct measurement of the density is possible in RETRAP. Nevertheless, an estimate of the lower limit can be achieved with the help of equation 1, assuming that the fluid model can be applied for the highly charged ion plasma. The function $\epsilon(\frac{a}{b})$ has a maximum value of three, leading to a minimum density of $3 \cdot 10^7$ cm^{-3}, well below the Brillouin density of $3.8 \cdot 10^8$ cm^{-3} for Xe^{44+}. This lower density limit is consistent with the observed increase of the size of the dark trap center (Fig. 4). Using a density of $3 \cdot 10^7$ cm^{-3} and a temperature of 1.7 K, a Coulomb coupling parameter , $= 1370$ is calculated, indicating the formation of a strongly coupled, highly charged ion plasma and possibly the existence of an ordered structure.

CONCLUSION

The sympathetic cooling of highly charged ions with laser cooled Be^+ ions has been demonstrated for the first time. The measured Doppler broadened line width of the cooling transition, the observed centrifugal separation and numerical simulation established an upper temperature limit of 1.7 K. A rough estimate of the density leads to $n \geq 3 \cdot 10^7$ cm^{-3}. These parameters indicate the formation of a strongly coupled plasma consisting of highly charged ions with a Coulomb coupling parameter exceeding 1000. Several hundred Xe^{44+} ions could be confined and cooled in a single cycle. This number can possibly be increased by applying stacking techniques and/or improvements of the trap geometry and a more efficient deceleration scheme. A direct proof of the existence of an ordered structure was not possible at the time. An UHV compatible CCD camera is being developed in order to implement an ion projection scheme for measuring the spatial distribution of the highly charged ions.

ACKNOWLEDGEMENTS

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