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Measurements of Temperature Dynamics of Ions Trapped Inside an Electron Beam Ion Trap and Evidence for Ionisation Heating

F. J. Currell[1,2], H. Kuramoto[2], S. Ohtani[2], C. Scullion[1], E. J. Sokell[3] and H. Watanabe[2]

[1] Department of Physics, The Queen's University of Belfast, BT7 1NN, U.K.
[2] Cold Trapped Ions Project, ICORP, JST, Tokyo 182-0024, Japan
[3] Department of Physics, University College Dublin, Belfield, Dublin 4, Ireland

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Abstract

A technique is described whereby measurements of ions extracted from an electron beam ion trap can be used to deduce their temperature dynamics. The measured temperature dynamics shows the expected trend as a function of charge and also gives evidence for Landau-Spitzer heating, ionization heating and evaporative cooling.

1. Introduction

Ensembles of highly charged ions (HCIs) with a low energy spread are of fundamental interest for ultrahigh precision spectroscopic measurements [1] and the study of low energy HCI-matter interactions [2]. Furthermore, a high enough density of cold HCIs would lead to the formation of an HCI Coulomb-crystal, which should open up fascinating new areas of research. Recently a new phase transition has been identified [3] specific to HCIs trapped by a negatively charged beam. This phase transition occurs when the ion temperature falls below a certain critical temperature and results in a sudden contraction of the ion cloud.

One device frequently used to produce and study highly charged ions is the electron beam ion trap (EBIT). Closely related to the production and use of cold HCIs with EBITs is the determination of their temperature as a machine diagnostic. Furthermore, the time dependence of the temperature evolution gives information about plasma physics processes in general and more specifically about the machine physics of EBITs. There have been various measurements of the equilibrium temperature of ensembles of trapped HCIs [4] in EBITs. These measurements have generally relied on determining the spatial location of the ions by imaging radiation they emit. Until recently [5], there were no measurements of the time evolution of the temperature. Hence an important piece of machine physics has remained unstudied. This paper discusses these measurements, and their extension to a wider range of charge states.

2. Background theory

An alternative to imaging radiation is to use the axial escape rate of ions from the trap to determine their temperature. A useful parameter in considering axial escape is the quotient of the potential ions of species i must overcome ($q_i V_t$) to escape axially and their characteristic temperature kT_i. Here q_i is the charge of species i, V_t is the lowest axial trap depth the ions must overcome to leave the trap. The parameter governing the escape rate is

$$\omega_i = \frac{q_i V_t}{kT_i}. \tag{1}$$

In the rare collision limit we are concerned with, once an ion gains sufficient energy to leave the trap it can be considered to do so immediately. In this case, the escape rate is not determined by the number of ions with sufficient axial velocity to escape but by the rate of velocity diffusion replenishing such ions. The escape rate is then given by [6]

$$\frac{dN_i^{ESC}}{dt} = -\frac{3}{\sqrt{2}} N_i \nu_i \frac{e^{-\omega_i}}{\omega_i}, \tag{2}$$

where N_i is the number of ions of species i trapped and N_i^{ESC} is the number which escape. When all the ions have a mass m, ν_i is given by

$$\nu_i = q_i^2 \sum_j \frac{4}{3}\sqrt{\frac{2p}{m}} \frac{q_j^2}{(4\pi\varepsilon_0)^2} \frac{\ln(\Lambda_{ij}) n_j}{(kT_j)^{3/2}}, \tag{3}$$

where n_j is the number density of species j and $\Lambda_{i,j}$ is the ion-ion Coulomb logarithm for species i and j. The summation in equation 3 runs over all trapped ion species. It should be noted that this summation has a dependence on species i only through the Coulomb logarithm $\Lambda_{i,j}$ and hence the dependence is extremely weak.

It is important to take account of the different detection sensitivity factors for escaping ions and for ions deliberately dumped from the trap. Denoting the detected escape rate for species i measured at some time t after the last dumping of the trap inventory as $E_i(t)$ and the measured number due to a dump occurring a time t after the previous dump as $D_i(t)$ the ratio of these two types of detection then becomes

$$R_i(t) = \frac{E_i(t)}{D_i(t)} = -\frac{3}{\sqrt{2}} S \nu_i \frac{e^{-\omega_i}}{\omega_i}, \tag{4}$$

where S is the ratio of detection sensitivities. The ratio of two such ratios, one for each of the highest two charge states (h and $h-1$) can then be used to determine their average temperature [5],

$$P(t) = \frac{R_{h-1}(t)}{R_h(t)} \approx \frac{h-1}{h} e^{V_{dt}/\overline{kT}}, \quad \overline{kT}(t) \approx \frac{V_{dt}}{\ln\left(\dfrac{h}{h-1} P(t)\right)}. \tag{5}$$

In fact, $\overline{kT}(t)$ is a temperature which lies between that of the

*e-mail f.j.currell@qub.ac.uk

h^{th} and $h-1^{th}$ charge states and is a good approximation to the temperature of the h^{th} charge state provided that $2\Delta kT/\overline{kT} \ll 1$ as will be discussed at greater length in an article under preparation [5]. It is possible to define a factor $\gamma(t)$, which combines the summation of Eq. (3) and the ratio of sensitivity factors of Eq. (4) to be

$$\gamma(t) = \frac{V_{dt}}{(h-0.5)\overline{kT}(t)} \frac{R_{h-1}(t) + R_h(t)}{2} \frac{1}{e^{-(h-0.5)V_{dt}/\overline{kT}(t)}}. \tag{6}$$

This factor can be used to create a relationship between the R_i and the temperatures of the trapped ions.

$$R_i(t) = \gamma(t) \frac{q_i kT(t;q_i)}{V_{dt}} \mathrm{Exp}\left[-\frac{q_i V_{dt}}{kT(t;q_i)}\right]. \tag{7}$$

All the variables in Eq. (7) can be determined directly experimentally, except for the characteristic temperatures $kT(t;q_i)$ of the various species. These characteristic temperatures can be represented at any time t by a smooth function. Hence the above set of equations represent a numerical model for relating measured sets of data $\{E_i(t)\}$ and $\{D_i(t)\}$ to the full temperature dynamics of a range of charge states.

3. Experimental method and results

Using a technique described previously [7], the dynamics of charge creation and escape in an electron beam ion trap (EBIT) was measured. A high energy (20 keV), high current (60 mA) electron beam was magnetically compressed using a 4 T axial magnetic field. This electron beam was used to sequentially ionize neutral argon continuously injected into the trap. At certain times the whole inventory of trapped ions was extracted through a "dumping" process whereby the potential of the central drift tube was raised past the potentials of the two end drift tubes. Since the potential of the final drift tube was always kept below that of the first drift tube, all ions leaving the trap headed towards the electron collector. A significant portion then enters the ion extraction/transport line [8] to be charge-analyzed using a 90° analyzing magnet and then detected with a position sensitive detector. Periodically the current of the analyzing magnet was changed to facilitate detection of a wide range of charge states. The detection events were correlated with the analyzing magnet current and the time through a sequence of dumps designed to poll the trap inventory at different times. All detection events were stored in list-mode for subsequent analysis.

The resultant list-mode file was analyzed to yield two separate data sets $\{E_i(t)\}$ and $\{D_i(t)\}$. These were then used as input to a numerical fitting procedure described by Eqs (4–7). The temperature function was modeled at time t by $kT(t;q_i) = a(t) + b(t)q_i + c(t)q_i^2$. This was found to be the lowest order polynomial able to account for the measurements. Figure 1 shows the result of such a fit for data collected after a confinement time of 300 ms.

From several similar fits, the time dependence of the temperatures of the trapped Ar^{q+} ions ($q = 13-18$) was deduced. A portion of the resulting temperature dynamics is shown in Fig. 2.

As is expected [9], the temperature increases as a function of charge although the difference between neighboring charge states decreases for the higher charge states. Furthermore, the temperature increases as a function of confinement time due to Landau-Spitzer heating. Although not shown in Fig. 2, the profiles for 300 ms and 400 ms are the same as that for 350 ms within the error bars. The temperature-profile has stopped changing as a function of time because the system has reached equilibrium. This equilibrium occurs when the cooling due to escape balances the heating. Extrapolation of the temperature-profile to $t = 0$ ms does not produce zero temperature as would be expected for Landau-Spitzer heating alone. This is contrary to previous predictions [9] but can be well accounted for in terms of ionization heating [5].

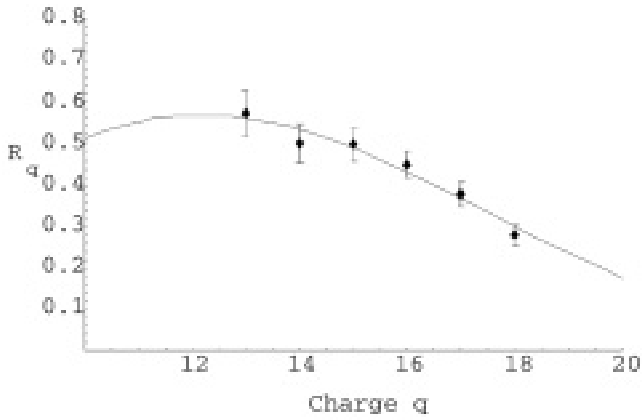

Fig. 1. Fit to data collected after 300 ms confinement time as described in the text. The error bars were determined from the Poisson statistics derived from the measured data.

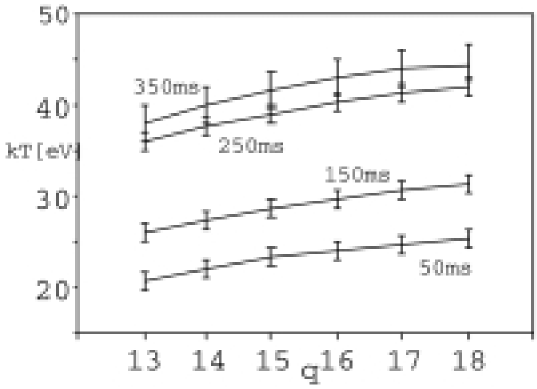

Fig. 2. Snapshots of the temperature dependence of trapped ions taken after the confinement times indicated. Error bars were determined from the statistical uncertainty in the fit used to model the measurements.

4. Conclusion

We have outlined a procedure for determination of ion temperatures in an EBIT from measurements of extracted ion yields. The measurements broadly confirm existing predictions of EBIT behavior but point to the requirement that ionization heat is included.

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