25E04

Coulomb screening in laser-cooled strongly-coupled plasma
レーザー冷却強結合プラズマ中のクーロン遮蔽

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A non-intrusive probe laser induced fluorescence (LIF) system has been developed to observe laser-cooled strongly-coupled plasma. Quantitative evaluation of the spectrum shape becomes possible by using the probe-LIF system. The ion temperature is derived from the Doppler component, and the Coulomb coupling parameter Γ is determined. In this experiment, we have succeeded to control Γ over the range of 0.1 to 10. The variation of Coulomb interaction in the transitional region between the weakly coupled state and the strongly coupled state has been studied. The Γ dependence of the collisional broadening shows that the Debye screening assumption already breaks down at the transitional region.

1. Introduction

An rf trap (Paul trap) is a device that confines ions using a quadrupole rf electric field. The trapped ions are referred to as ideal one component plasma. We aim to experimentally study the influence of the correlation among the trapped ions on the nature of the strongly coupled plasma. The correlation among the ions is indicated by the Coulomb coupling parameter Γ defined as the ratio of the Coulomb interaction energy to the thermal energy of ion. Most of laboratory plasmas are characterized by $\Gamma<<1$, and called as weakly coupled plasmas. On the other side, the plasma which Γ is larger than one is called strongly coupled plasma. In the case of $\Gamma>1$, the number of existing ions into the Debye sphere is less than unity, therefore, the breakdown of the Debye screening assumption is predicted. Many elementaly processes are affected by the change of the Coulomb screening mechanism [1].

We have developed a non-intrusive probe laser induced fluorescent (LIF) method for laser-cooled ions in a linear RF trap. The undeformed LIF spectra of laser cooled plasma were observed, and the variation of the shape was systematically studied at the boundary region between the weakly and strongly coupled state. From the analysis of the line shape, the ion temperature and the change of the elementally process in the cooled plasma was clarified.

In the following sections, the experimental setup and the probe laser LIF system are explained in section 2. The results of the probe LIF measurements are discussed in section 3.

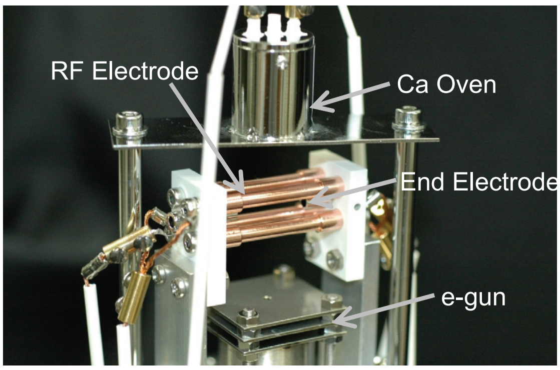

Fig. 1 Linear ion trap

2. Experiment

Figure 1 shows a linear ion trap equipped with a calcium ion source. The assembly is installed in a stainless steel chamber evacuated to less than 4×10^{-10} Torr. The linear rf trap is composed of the four cylindrical rf electrodes and the two dc end-electrodes. The ions are confined in the radial direction by the oscillating quadrupole electric field. Confinement of the ions in the axial direction is achieved by the electrostatic field generated by the end electrodes. Calcium vapor created by the Ca oven is introduced to the trap center through the gap between the rf electrodes and ionized by electron bombardment. The trapped ions are cooled using the Doppler laser cooling techniques. Once sufficient numbers of ion are loaded into the trap, the calcium oven and e-gun are turned off. Since the confinement time of the cooled ions is long enough, the number of ions is roughly constant during the measurements.

$^{40}Ca^{+}$ ions are used in this work, since all the transitions of the $^{40}Ca^{+}$ laser-cooling cycle can be

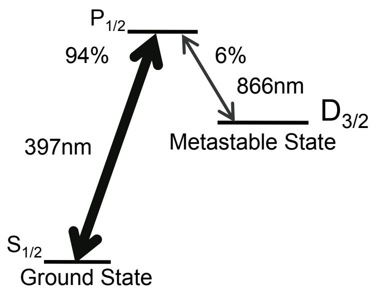

Fig. 2 Relevant energy levels of $^{40}Ca^{+}$ laser cooling

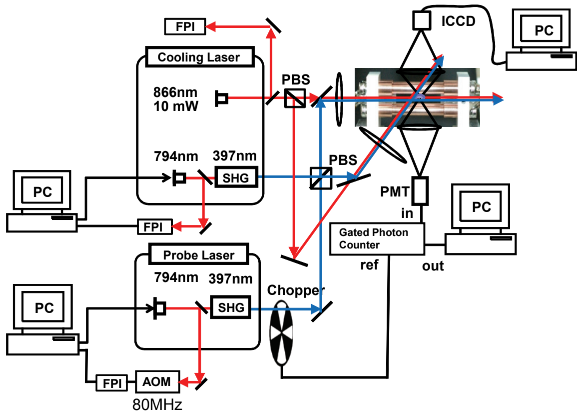

Fig. 3 Schematic diagram of the non-intrusive measurements of the laser cooled plasma.

driven by laser diodes. Figure 2 shows the relevant energy levels of $^{40}Ca^{+}$ laser cooling. The LIF emitted by the de-excitation of the $P_{1/2}$ state to the $S_{1/2}$ state is used for ion detection. A part of the ions in $P_{1/2}$ state falls into the meatastable $D_{3/2}$ state; therefore a 866-nm laser is used for repumping the ions in the $D_{3/2}$ state to the $P_{1/2}$ state.

We propose here a non-intrusive observation method for the cooled ions. Figure 3 shows the schematic diagram of the experimental setup. The second 397-nm laser is introduced for probing the LIF spectrum. The ion temperature is controlled by the cooling lasers, and the LIF spectrum is probed by sweeping the frequency of the probe laser. The power of the probe laser is weak enough to avoid deforming the LIF spectrum. Here, the probe measurements are performed with probe laser power of 15 μW. The power of the cooling laser and repumping laser lights are 500 μW and 2 mW, respectively. The probe laser was chopped at 1 kHz by an optical chopper and introduced from 0° to the trap axis. The weakly modulated LIF signal is detected by a photomultiplier tube and a gated photon counter synchronized to the chopping frequency.

3. Results and Discussion

The observed spectrum is decomposed into Gaussian component and Lorentzian component by fitting to the Voigt function. The ion temperature is calculated using the Doppler width, and then Γ is also calculated. Here, the low temperature limit approximation is adopted for the ion density calculation. We note that the Lorents width is much larger than the natural line width 23 MHz of the $S_{1/2}$-$P_{1/2}$ transition. Since the experiments are performed in the chamber evacuated to less than 4×10^{-10} Torr, the pressure broadening by the collision with background particles is negligible. The Stark broadening generated by the electric microfield is also very small (~6 mHz). Collisional broadening by ion-ion interaction is a candidate of the broadening mechanism. Figure 4 shows the dependence of Lorentz width on Γ. The natural line width is subtracted from the Lorentz width before plotting. The residual Lorentz widths are well fitted by $\Gamma^{1/2}$; therefore it is proportional to $T^{1/2}$. Since the Coulomb collision frequency based on Debye screening assuption is proportional to $T^{-3/2}$, the dependence of the collision frequency on the ion temperature is not consistent with the trend shown in Fig. 4. On the other hand, the collisional frequency based on the ion-sphere model is proportional to $T^{1/2}$ [2]. Although the experiments are performed with plasmas which are moderately coupled state, the experimental results show that the Debye screening assumption already breaks down and the ion-sphere model is appropriate for the cooled plasmas.

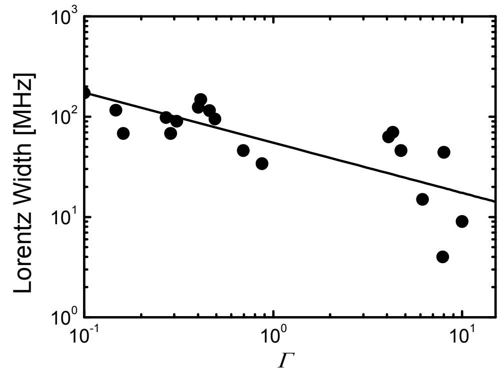

Fig. 4 The dependence of Lorentz width on Γ.

Acknowledgments

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