J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 309–312

Velocity Distributions and Density Profiles of Buffer-Gas Cooled One Component Plasma in Toroidal RF Ion Trap

ARAMAKI Mitsutoshi*, SAKAWA Youichi, SHOJI Tatsuo and HAYASAKA Kazuhiro[1]
Department of Energy Engineering and Science, Nagoya University, Nagoya 464-8603, Japan
[1]Communications Research Laboratory, Kobe 651-2492, Japan

(Received: 5 December 2000 / Accepted: 3 September 2001)

Abstract

Velocity and spatial distributions of calcium (Ca^+) ions confined in a toroidal RF trap have been measured by using laser-induced fluorescence method. Ca^+ ion temperature in the toroidal direction decreases from over 2000 K to about 500 K by collisions with He atoms when He pressure is increased from 5×10^{-7} Torr to 5×10^{-5} Torr. The ion density, estimated from the fluorescence intensity of the trapped ions, is roughly estimated as 10^5 cm^{-3}. The Coulomb coupling parameter Γ, defined by the ratio of Coulomb energy to kinetic energy of ions, is about 10^{-4}. Ca^+ ion temperature in poroidal cross-section is estimated from the measured density profile. The velocity distributions and density profiles of the cooled ions are not deviated from those obtained from Boltzmann statistics.

Keywords:

toroidal RF ion trap, buffer-gas cooling, velocity distribution, density profile

1. Introduction

Several types of ion trap have been used for precise spectroscopical diagnostics of ions [1] because they can confine ions in a small space for long time. They are also used to study one-component plasma physics such as crystallization [2,3], nonlinear phenomena [4], and statistical property [5] of ion or electron cloud. The aim of our experiment is to study the statistical property of ion cloud confined in a toroidal RF ion trap [6]. In this paper, Ca^+ ion cloud is cooled by He buffer-gas cooling method, and He gas pressure P_{He} dependence of Doppler spectra and density profile are measured by using laser-induced fluorescence (LIF) method. Since the toroidal ion cloud are irradiated tangentially by excitation lasers (397 nm and 866 nm) of Ca^+, ion temperatures T_t in toroidal direction and T_p in the poroidal cross-section are estimated from Doppler spectra and density profile, respectively. We also measure the P_{He} dependence of ion confinement time τ from the decay curve of the LIF signal.

2. Experimental

Figure 1 shows the top view of the experimental setup. The toroidal RF ion trap, placed in a high-vacuum chamber, is used to confine Ca^+ ions. Table 1 shows dimensions of the toroidal RF ion trap and experimental parameters. Ca vapor is introduced into the ion trap from the oven placed under the ion trap, and ionized by electron-beam bombardment. Velocity distributions and density profiles of the Ca^+ ion cloud are measured by using LIF method. Electronic energy levels of Ca^+ are shown in Fig. 2. To pump up the energy levels of Ca^+ to $^2P_{1/2}$, 397 nm ($^2S_{1/2}$ – $^2P_{1/2}$ transition) and 866 nm ($^2D_{3/2}$ – $^2P_{1/2}$ transition) light obtained by diode lasers are collinearly overlapped and focused tangentially to the

**Corresponding author's e-mail: aramaki@nuee.nagoya-u.ac.jp*

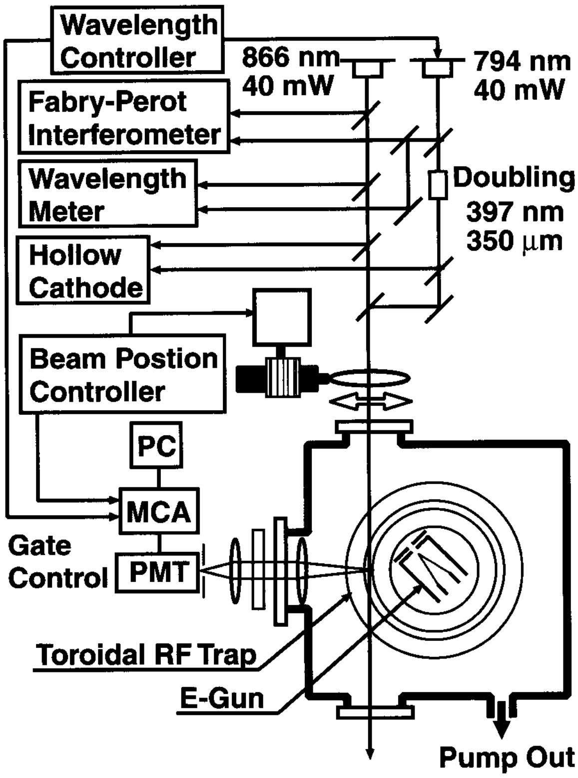

Fig. 1 Experimental setup of the laser-induced fluorescence measurement system.

Table 1 Dimensions of the toroidal RF ion trap and experimental parameters.

Main radius	R	=	40 mm
Minor radius	r_0	=	4.5 mm
RF voltage	V_{RF}	=	250 V
RF frequency	Ω	=	2 MHz
DC voltage	V_{DC}	=	0 V
Base pressure	P_B	$\ll$	4×10^{-9} Torr
He pressure	P_{He}	=	$10^{-7} \sim 10^{-5}$ Torr

toroidal ion cloud. The 397 nm UV light is obtained by frequency doubling of 794 nm light of the diode laser. The emission of $^2S_{1/2} - {}^2P_{1/2}$ (397 nm) transition is used for the detection of Ca^+ ion fluorescence. To measure the radial Ca^+ ion density profile, the beam focusing positionis swept radially in a poroidal cross section with a fixed laser frequency. The Doppler broadening of $^2S_{1/2} - {}^2P_{1/2}$ radiation is observed by detuning the UV laser frequency around the resonance frequency at the center of the ion cloud. Temperature of Ca^+ ion is estimated from the density profile and the Doppler broadening.

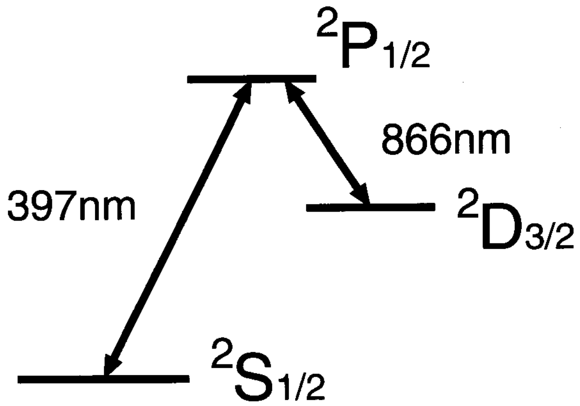

Fig. 2 Electronic energy levels of Ca^+.

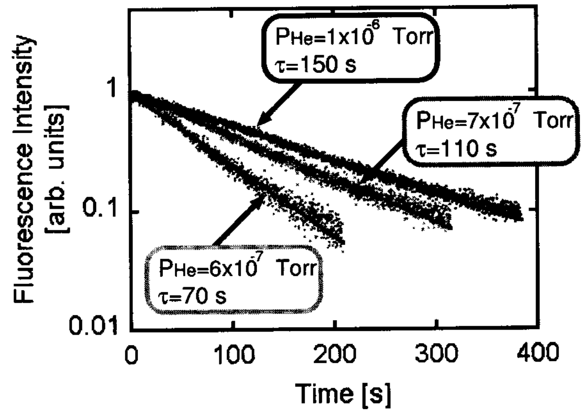

Fig. 3 He gas pressure dependence of the decay of fluorescence intensity of Ca^+.

The 397 nm radiation from Ca^+ ion is collected by optical lens, and detected by photomultiplier tube (PMT). The number of photon pulse-signal from the PMT is counted by the multi channel analyzer (MCA) and stored in the computer (PC).

3. Results and Discussion

He buffer-gas is introduced into the vacuum chamber at room temperature. Figure 3 shows P_{He} dependence of 397 nm fluorescence decay after the electron beam is turned off. The ion confinement time τ deduced from Fig. 3 is 70, 110, and 150 s for $P_{He} = 6 \times 10^{-7}$, 7×10^{-7}, and 1×10^{-6} Torr, respectively. These confinement time are more than two-orders of magnitude longer than that of non-cooled Ar^+ ion [6]. The buffer-gas cooling of Ca^+ ions elongates τ.

Figure 4 shows the P_{He} dependence of Doppler spectra of Ca^+ ion cloud. The frequency of the UV laser is swept ±3 GHz from the $^2S_{1/2} - {}^2P_{1/2}$ resonance frequency. These Doppler broadening spectra agree with Gaussian profiles. The ion temperature T_t in the toroidal direction is obtained from the Doppler spectrum since the probing lasers are focused tangentially to the toroidal ion cloud. T_t is estimated as 2600, 1200, and 550 K for $P_{He} = 6 \times 10^{-7}$, 2×10^{-6}, and 3×10^{-5} Torr, respectively. We roughly estimate the ion density n as 10^5 cm^{-3} from the measured number of photon by using rate equation [7]. Here, we considered only the photons of $^2S_{1/2} - {}^2P_{1/2}$ transition, since the high-intensity 866 nm laser repumps the ions in the metastable $^2D_3/2$ state to the $^2P_{1/2}$ state. Table 2 shows parameters of the photon counting system. Here, V is observation volume, Q is product of total transmittancy of optical system and quantum efficiency of PMT, $d\Omega$ is solid angle of optical system, and A is Einstein A coefficient. The Coulomb coupling parameter Γ, estimated from these experimental results, is about 10^{-4}. In order to obtain the larger value of Γ for strongly-coupled plasma studies, it is necessaryto cool the ions by the laser-cooling technique.

Figure 5 shows the P_{He} dependence of density profile of the Ca^+ ion cloud in the poroidal cross-section. The full width at half maximum of UV laser spectrum is much narrower than that of the Doppler spectrum of Ca^+ ion. The increase in the fluorescence intensity by increasing P_{He} is mainly caused by the decrease in T_t by He buffer-gas cooling. The ion density profile in the RF potential can be calculated from the differential equation derived from Poisson equation and Boltzmann distribution of ions [8,9],

$$n'' - \frac{(n')^2}{n} + \frac{n'}{r} - \frac{e^2 n^2}{\varepsilon_0 k_B T_p} + \frac{n e^2 V_{RF}^2}{m r_0^4 \Omega^2 k_B T_p} = 0, \quad (1)$$

where e is elementary charge, ε_0 is permittivity in vacuum, k_B is Boltzmann constant, m is Ca^+ ion mass, and T_p is ion temperature in the cross section of ion cloud. The measured density profiles (Fig. 5) are Gaussian type, because the fourth term on the left-hand side of Eq. (1) is much smaller than the fifth term in this experiment. T_p and full width at half maximum D of the density profile are estimated by curve-fitting the density profile with Gaussian distribution as (1800 K, 0.9 mm), (1600 K, 0.8 mm), and (1400 K, 0.7 mm) for $P_{He} = 5 \times 10^{-7}$, 2×10^{-6}, and 4×10^{-6} Torr, respectively. Both T_p and D decrease by increasing P_{He} due to He buffer-gas cooling. Note that T_p has weaker dependence on P_{He} than that of T_t. This weaker P_{He} dependence of T_p may be explained in terms of the ion heating by the radial RF field in the poroidal cross-section. In order to evaluate the dependences of T_t and T_p on P_{He} quantitatively, precise treatment of non-adiabatic process of ion heating inactual RF trap configuration is needed.

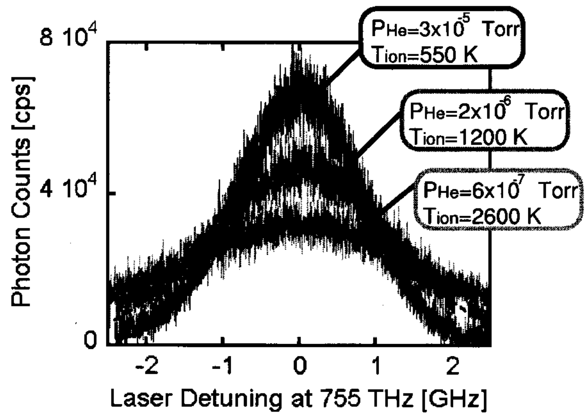

Fig. 4 Helium gas pressure dependence of the Doppler spectrum of the Ca^+ ion cloud.

Table 2 Parameters of the photon counting system.

V	=	0.65×10^{-11} m^3
Q	=	0.1
$d\Omega$	=	0.13 sr
A	=	1.4×10^8 s^{-1}

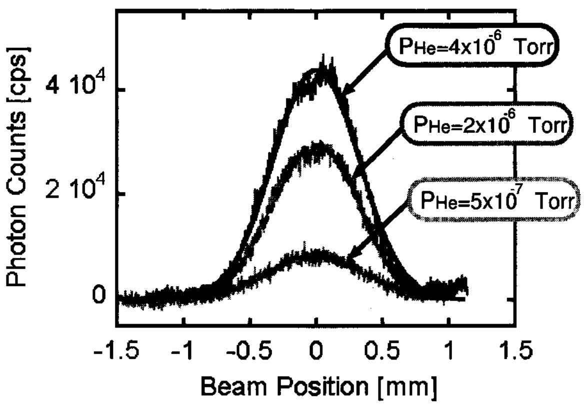

Fig. 5 Helium gas pressure dependence of density profile of the Ca^+ ion cloud in the poroidal cross-section.

4. Conclusion

Ca^+ ions are trapped in a toroidal RF trap. The velocity and spatial distributions of the ion cloud have been measured by using the LIF method. The Ca^+ ions are cooled by collisions with He atoms of the buffer gas. We have estimated the ion density as 10^5 cm^{-3} from the measured number of photon by using rate equation. The estimated Γ from these experimental results is about 10^{-4}. The velocity distribution and density profile of ions cooled by He-buffer gas agree with those of Maxwellian. The deviation from the Boltzmann statistics is hardly observed in this temperature region.

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