INITIAL DENSITY PROFILE MEASUREMENTS USING A LASER-INDUCED FLUORESCENCE DIAGNOSTIC IN THE PAUL TRAP SIMULATOR EXPERIMENT *

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Abstract

Installation of a laser-induced fluorescence (LIF) diagnostic system has been completed and initial measurements of the beam density profile have been performed on the Paul Trap Simulator Experiment (PTSX). The PTSX device is a linear Paul trap that simulates the collective processes and nonlinear transverse dynamics of an intense charged particle beam propagating through a periodic focusing quadrupole magnetic configuration. Although there are several visible transition lines for the laser excitation of barium ions, the transition from the metastable state has been considered first, mainly because a stable, operating, broadband, and high-power laser system is available for experiments in this region of the red spectrum. The LIF system is composed of a dye laser, fiber optic cables, a line generator, which uses a Powell lens, collection optics, and a CCD camera system. Single-pass mode operation of the PTSX device is employed for the initial tests of the LIF system to make optimum use of the metastable ions. By minimizing the background light level, it is expected that adequate signal-to-noise ratio can be obtained to re-construct the radial density profile of the beam ions.

INTRODUCTION

Understanding the physics of high-intensity beams is important because of the wide variety of accelerator applications, including high energy physics, heavy ion fusion, ion-beam-driven high energy density physics, nuclear waste transmutation, and spallation neutron sources to mention a few examples [1]. To address the many important issues in high-intensity beams experimentally, the Paul Trap Simulator Experiment (PTSX) device was built at the Princeton Plasma Physics Laboratory (PPPL) in 2002, and demonstrated quiescent beam propagation over equivalent distances of tens of kilometers [2]. The PTSX device is a compact laboratory facility that investigates intense beam dynamics by taking advantage of the similarity between the dynamics of an intense beam propagating through a periodic focusing quadrupole magnetic field, and a one-component nonneutral plasma trapped in an oscillating quadrupole electric field [3]. Currently, three diagnostic systems are installed on PTSX, which include: a Faraday cup, capacitive pick-ups, and a laser-induced fluorescence (LIF) diagnostic. The LIF diagnostic is expected to be very useful for the in-situ measurement of the transverse beam density profile, velocity distribution measurements, and halo particle detection. Because the atomic spectrum of barium ions is amenable to the present LIF experimental setup, barium ions have been chosen as the preferred ion species. In this paper, the installation of the barium ion source and the LIF system are summarized, together with the initial test results.

BARIUM ION SOURCE

Barium ions are produced at a hot metal surface by contact ionization. Traditionally, rhenium and tungsten have been used for the hot metal plate to produce both ions by contact ionization, and electrons by thermionic emission. Because electrons are not required for the PTSX device, platinum is a more favorable choice for the hot metal plate because of its higher work function than rhenium and tungsten. Platinum's work function is 5.65 eV, and its melting point is 1768 °C.

The design of the barium ion source is based on the compact metal-ion source developed for heavy ion beam probes used for plasma diagnostics [4]. The ion source is composed of a beam material oven and a metal ionizer. The oven is a tantalum tube with 0.5" in diameter and 4" in length. The radial tube size is adequate to make the beam RMS-matched to the externally applied focusing field for the nominal operating conditions of PTSX. The length of the tantalum tube is chosen in such a way that heat conduction and radiation processes sustain the proper temperature distribution along the tube. Normally, the tantalum tube is maintained higher than 400 °C to decompose any barium oxide layer. The ionizer consists of a stack of platinum meshes which are woven from 0.1 mm platinum wires and have 62.7% open area. The platinum meshes are inserted into the open end of the oven tube, and the vapor of the beam material is ionized on the hot platinum wire surfaces as it passes through the tube. Two tungsten heaters are wrapped around the tube and the ionizer, respectively. Each heater has its own heat shield to increase the thermal efficiency and is connected to a high-current power supply through thick copper rods [Fig. 1(left)]. The temperature of the oven and the ionizer are controlled by adjusting the currents of the power supplies and monitored by two independent K-type thermocouples attached to these components. To minimize oxidization, barium is loaded into the oven inside an argon-filled tent. About 6 g of barium allowed 2-3 months of operations in the initial experiments.

The ionizer is surrounded by a Pierce electrode, fol-

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lowed by an acceleration grid and a deceleration grid to extract the desired ion current and adjust the final ion kinetic energy. The Pierce electrode is made of copper and has a 67.5° opening angle to produce laminar flow of the beam ions. For the acceleration and deceleration grids, 85% transparent electroformed copper meshes have been used [Fig. 1(right)]. However, due to the reaction with barium vapors, the lifetime of the copper mesh can be limited. Hence, nickel mesh is also being considered for future experiments. The entire assembly of oven, ionizer, heater, and grids is surrounded by a large stainless steel can to prevent the neutral barium from contaminating the electrodes and to reduce visible radiation from the hot ion source.

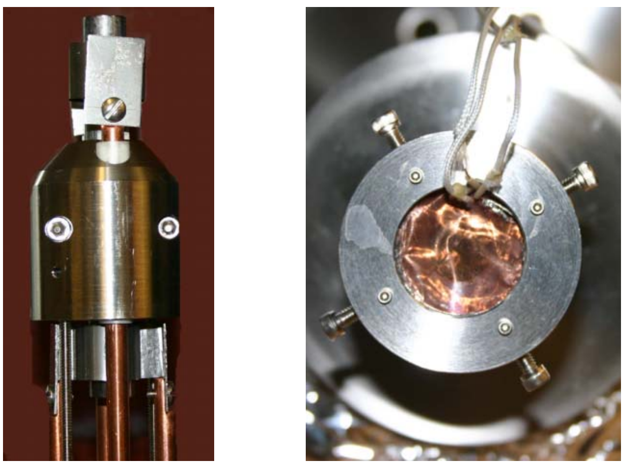

Figure 1: Assembly of tantalum oven tube, platinum mesh ionizer, tungsten heaters, and copper rods (left). Assembly of Pierce electrode, acceleration grid, and deceleration grid on top of the aluminum can (right).

Initial results show that the barium ion beam current can be kept stable for more than 3 hours with an oven temperature of $400\ ^\circ\mathrm{C}$ and an ionizer temperature of $1000\ ^\circ\mathrm{C}$ (Fig. 2). The radial profile of trapped barium ions measured by

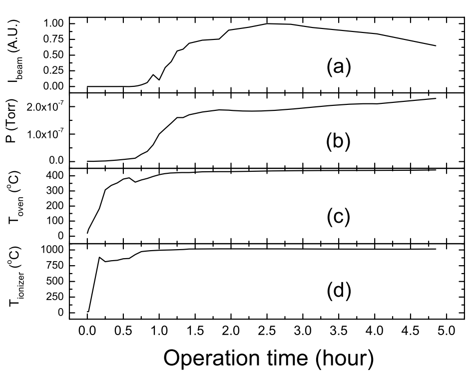

Figure 2: Time evolution of: (a) the beam current generated by the barium ion source; (b) pressure; and (c) and (d) temperatures of the oven and the ionizer.

the Faraday cup is nearly Gaussian, and corresponds to the normalized beam intensity $\hat{s} = \omega_p^2(0)/2\omega_q^2 = 0.28$ (Fig. 3). Here, $\omega_p(0)$ is the on-axis plasma frequency, and ω_q is the average transverse focusing frequency. For an ion-

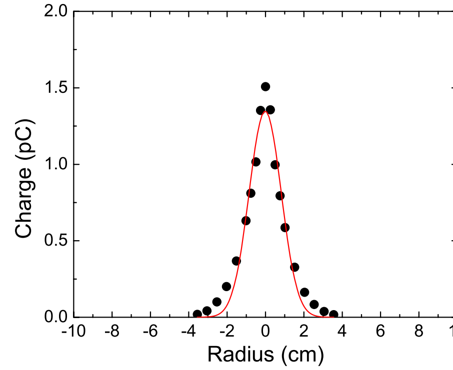

Figure 3: Radial profiles of the trapped barium ions in the PTSX device. The red curve is a Gaussian fit to the measured signals.

izer temperature of $1000\ ^\circ\mathrm{C}$, it is estimated from the Saha-Langmuir equations that the fraction of barium ions produced by the hot platinum surface will be 98.7% in the ground state ($6^2\mathrm{S}_{1/2}$), 0.8% in the $5^2\mathrm{D}_{3/2}$ metastable state, and 0.5% in the $5^2\mathrm{D}_{5/2}$ metastable state.

LASER-INDUCED FLUORESCENCE DIAGNOSTIC

For the initial test of the LIF system, single-pass mode operation of the PTSX device is employed to make optimum use of the metastable ions. Since there is a continuous supply of metastable ions into the detection volume, we can write down rate equations for the populations of the metastable state (n_1), excited state (n_2), and ground state (n_3) with source-sink terms according to

$$\frac{dn_1}{dt} = -n_1 B_{12}\rho_\nu(\nu_0) + n_2 B_{21}\rho_\nu(\nu_0) + A_{21}n_2 + \frac{(n_1^0 - n_1)}{\tau}, \quad (1)$$

$$\frac{dn_2}{dt} = +n_1 B_{12}\rho_\nu(\nu_0) - n_2 B_{21}\rho_\nu(\nu_0) - A_{21}n_2 - A_{23}n_2 + \frac{(n_2^0 - n_2)}{\tau}, \quad (2)$$

$$\frac{dn_3}{dt} = +A_{23}n_2 + \frac{(n_3^0 - n_3)}{\tau}. \quad (3)$$

Here, A_{ij} and B_{ij} are the Einstein coefficients, n_i^0 is the initial population of each state, $\rho_\nu(\nu_0)$ is the spectral energy density of the laser around the resonance frequency ν_0, and τ is the characteristic ion transit time through the detection volume. Steady-state solution of rate equations (Fig. 4) indicates that when the ion flux into the detection volume is high, then the LIF intensity I_{LIF} is strongly dependent on the incident laser power and on the initial metastable density. Although there are several visible tran-

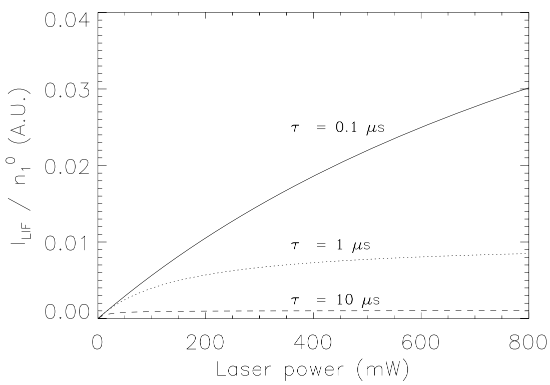

Figure 4: Dependence of LIF intensity I_{LIF} on laser power and characteristic ion transit time τ.

sition lines for the laser excitation of barium ions, the transition from the $5^2\mathrm{D}_{3/2}$ metastable state has been considered first, mainly because a stable, operating, broadband, and high-power laser system is available for experiments in this region of the red spectrum. Ions excited from the metastable state $5^2\mathrm{D}_{3/2}$ to the excited state $6^2\mathrm{P}_{1/2}$ decay to the ground state $6^2\mathrm{S}_{1/2}$ almost immediately (8 ns), emitting blue-green light (493.41 nm). Because the typical ion density in PTSX is about $10^5\ \mathrm{cm}^{-3}$, the metastable ion density will be about $10^2 \sim 10^3\ \mathrm{cm}^{-3}$, which is slightly above the detection limit for typical LIF diagnostics. Hence, suppression of background signals and sufficiently long integration times are essential for meaningful data. The laser system and collection optics for the LIF diagnostic in the PTSX device are described in detail elsewhere [5], and only a brief discussion of the noise reduction method is presented here.

The major source of background light is the glowing red-hot barium ion source, which is operated at around $1000\ ^\circ\mathrm{C}$. To reduce the scattered light from the ion source, a carbon coating (Aquadag) is applied to the inside of the electrodes. For the collection optics, the focal length of the lens and the length of the extension tube have been adjusted so that the CCD camera is focused mostly onto the dark viewing dump. A 1 nm bandpass filter is also placed in front of the lens. A portion of the incoming laser light reaching the detection system through reflection at the windows and electrodes can also be a problem. To avoid this stray light, an anti-reflection coating is applied to the entrance window, and a laser collimator with a precise rotation stage is adopted. Because of the long integration time ($\sim$3 sec) and high gain to detect the small LIF signal, the CCD camera itself generates noise as well. This noise includes thermally-induced dark current, readout noise, intensifier noise, and hot pixels. To improve the signal-to-noise ratio, an image is obtained by averaging over 100 repeated measurements. Finally, by subtracting the background image without a barium ion beam from the image with a barium ion beam, we obtain an image of the fluorescence light in which the intensity is proportional to the local ion density.

Initial measurements using a Pulnix CCD camera with a separate non-inverting image intensifier show that the signal-to-noise ratio is not adequate to re-construct the radial density profile (Fig. 5). To deal with this problem, the Princeton Instruments ICCD-MAX intensified CCD camera with 16-bit A/D converter and thermoelectric cooler is being installed on PTSX for future experiments.

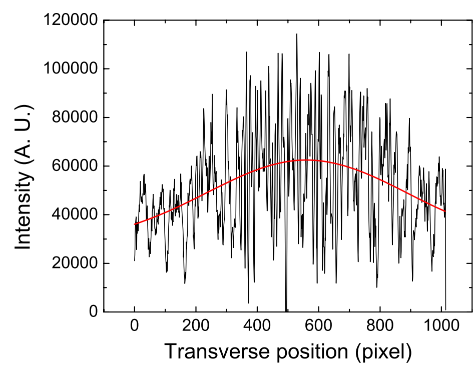

Figure 5: Transverse LIF intensity profile extracted from the 2D CCD image. The red curve is a Gaussian fit to the measured signals.

CONCLUSIONS

A new compact barium ion source has been installed for laser-induced fluorescence measurement in the PTSX device. Because the density of the metastable ions is very low, technical issues such as suppressing the background light, and data acquisition with long integration times turn out to be critical. With the addition of a new CCD camera system which is being installed, and by optimizing the laser power, it is expected that an adequate signal-to-noise ratio can be obtained to re-construct the radial density profile of the beam ions for the study of beam mismatch and halo particle production.

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