DEVELOPMENT OF LASER-INDUCED FLUORESCENCE DIAGNOSTIC FOR THE PAUL TRAP SIMULATOR EXPERIMENT *

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Abstract

The Paul Trap Simulator Experiment (PTSX) is a cylindrical Paul trap whose purpose is to simulate the nonlinear dynamics of intense charged particle beam propagation in alternating-gradient magnetic transport systems. For the in-situ measurement of the transverse ion density profile in the PTSX device, which is essential for the study of beam mismatch and halo particle production, a laser-induced fluorescence diagnostic system is being developed. Instead of cesium, which has been used in the initial phase of the PTSX experiments, barium has been selected as the preferred ion for the laser-induced fluorescence diagnostic. The installation of the barium ion source and the characterization of the tunable dye laser system are discussed. The design of the collection optics with an intensified CCD camera system is also discussed. Finally, initial test results using the laser-induced fluorescence diagnostic are presented.

INTRODUCTION

Intense charged particle beam propagation is an active research area and has a wide range of application ranging from basic scientific research in high energy and nuclear physics, to applications such as spallation neutron sources, ion-beam-driven high energy density physics, and nuclear waste transmutation, to mention a few [1]. The Paul Trap Simulator Experiment (PTSX) is a compact laboratory facility that investigates intense beam dynamics by taking advantage of the similarity between an intense beam propagating through a periodic focusing quadrupole magnetic field and a one-component nonneutral plasma trapped in an oscillating quadrupole electric field [2]. The PTSX device is described in detail elsewhere [3], and initial experiments with a cesium ion source and a simple Faraday cup diagnostic have been very successful [4]. However, for the in-situ measurement of the transverse ion density profile in the PTSX device, which is essential for the study of beam mismatch and halo particle production, a laser-induced fluorescence (LIF) diagnostic system is begin developed [5]. Because the optical transition of barium ions is more relevant to LIF than cesium ions, barium ions have been chosen as the preferred ion species. In this paper, the development of the barium ion source and the installation of the LIF system are summarized, together with initial test results.

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BARIUM ION SOURCE

Barium ions are produced at the hot metal surface by contact ionization. The available optical transition lines of barium ion are presented in Fig. 1.

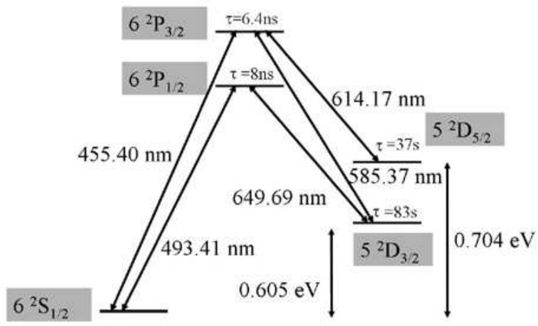

Figure 1: Energy level diagram of Ba^+ with transition wavelengths and natural lifetimes.

Although there are several transition lines for laser excitation, the $5^2\mathrm{D}_{3/2}$ to $6^2\mathrm{P}_{1/2}$ transition is selected mainly because there exists a commercially available, stable, broadband, high-power laser system in this red spectrum region. 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). It is expected that the ionization efficiency for the metastable ions is equal to or less than the estimate made from the Saha-Langmuir equation,

$$P_i^* = \frac{g_i^* \exp\left(\frac{-\Delta E^*}{kT}\right)}{g_a \exp\left(\frac{E_i - W}{kT}\right) + g_i + \sum_* g_i^* \exp\left(\frac{-\Delta E^*}{kT}\right)}. \quad (1)$$

Here, W and T are the work function and temperature of the metal, respectively, E_i is the ionization potential of the atom, and ΔE^* is energy difference between the ground and metastable states. The quantities g_a, g_i, and g_i^* are statistical weights of the atoms, ground state ions, and metastable ions, respectively. Because of its higher work function, platinum is a more favorable choice for the hot metal plate than rhenium, which is widely used in many experiments where electrons are also present. For $T = 1000\ ^\circ\mathrm{C}$, it is estimated that only 0.8% of the barium ions produced by the hot plate are in the $5^2\mathrm{D}_{3/2}$ metastable state. Because the typical ion density in PTSX is about 10^5 particles/cm^3, the metastable ion density will be about

$10^2 \sim 10^3$ particles/cm^3, which is slighlty above the detection limit of typical LIF diagnostics. Hence, suppression of background signals and sufficiently long integration times are essential for meaningful data.

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 [6]. The ion source is composed of a beam material reservoir and metal ionizer. The reservoir is a tantalum container, and the ionizer is a bundle of fine platinum wires. The wire bundle is inserted into the open end of the supporting pipe, and the vapor of the beam material is ionized on the hot platinum wire surface as it passes through the pipe. The temperature of the reservoir and the ionizer are controlled by adjusting the currents of two independent power supplies attached to these components. Initial bench-test results show that the ion beam current can be increased up to 2 $\mu\mathrm{A}$ and can be kept stable for more than 5 hours at currents of 0.5 $\mu\mathrm{A}$.

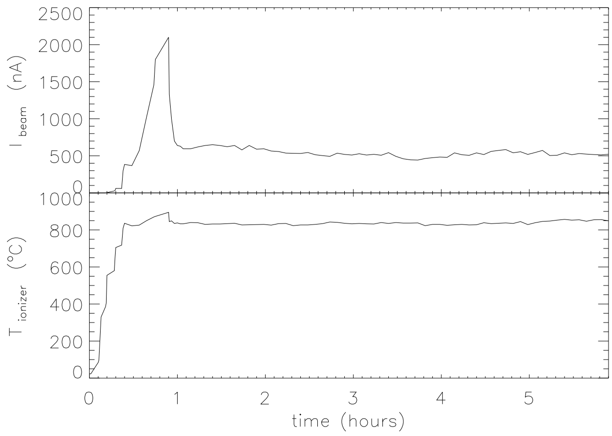

Figure 2: Time evolution of the the beam current generated by the ion source, and temperature of the ionizer.

LASER-INDUCED FLUORESCENCE DIAGNOSTIC SETUP

The laser used in this research is a Coherent 899-21 ring dye laser that is optically pumped by an argon ion laser [7]. DCM dye is used with EPH solvent, giving output powers of up to 800 mW at around 650 nm, appropriate for matching the $5^2\mathrm{D}_{3/2}$ to $6^2\mathrm{P}_{1/2}$ transition. A Burleigh wavemeter is used to measure the output wavelength, and the spectral characteristics are monitored with a Fabry-Perot cavity. An optical isolator is inserted in the beam path before coupling to a single-mode fiber, which carries the laser beam across the laboratory to the PTSX apparatus. The three-plate birefringent filter allows broadband operation over approximately 2 GHz, which is nearly matched to the Doppler width of the transition.

At the fiber output, a commercial laser beam line generator has been installed to increase the detection volume and fully utilize the available metastable barium ions. The line generator, which uses a Powell lens, transforms the

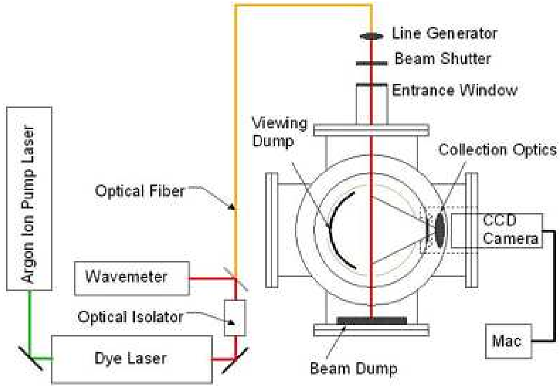

Figure 3: Schematic diagram of the experimental setup.

collimated laser beam into a line with a uniform output intensity. A Powell lens with 10° fan angle and 0.8 mm linewidth can result in a width of the detection volume corresponding to $\sim$ 7 cm.

Since the PTSX device manipulates the plasma using a load-trap-dump cycle, there is a need for the laser beam to be synchronized with the trapping cycle. A beam shutter and shutter controller are employed for this purpose.

To suppress the stray light, i.e., the part of the incoming laser light reaching the detection system through reflection at windows and the vacuum vessel walls, an anti-reflection coating is applied to the entrance window , and a stack of razor blades has been installed at the beam exit. In addition, the line generator and beam shutter are enclosed by a light-tight aluminum box so that no background room light enters into the entrance window.

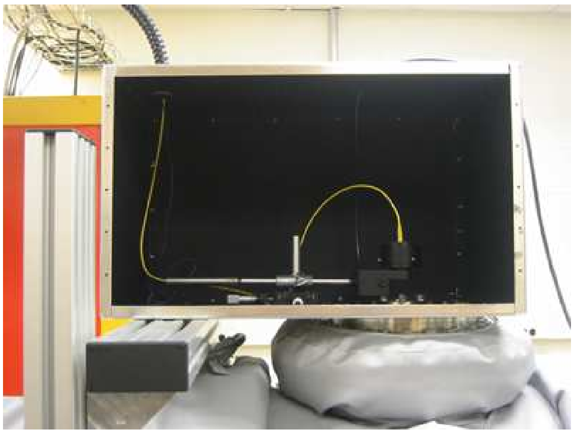

Figure 4: Assembly of the optical fiber, line generator, beam shutter, and x-y translation stage, which is enclosed by a light-tight aluminum box.

A Pulnix CCD camera with inverting image intensifier captures the fluorescence image digitally and the transverse density profile can be determined from the intensity of the recorded image with suitable calibration and averaging techniques. The fluorescence light passes through the 1-inch OD hole in the electrode, a glass vacuum window, an interference filter tuned to the wavelength of the $6^2P_{1/2}$ to $6^2S_{1/2}$ transition, and a 9 mm fixed-focal-length C-mount lens directed towards to the CCD camera. A custom-made reentrant viewport has also been installed so that the overall detection system has a wide field of view and covers the entire transverse dimension of the plasma column.

The background of the observation path has been made to appear black by installing a so-called viewing dump. In order not to affect the performance of the electrodes, carbon particles (Aquadag) are applied as a coating. This coating reduces the scattered light by two orders-of-magnitude.

To estimate the background light level, preliminary measurements have been made with the present cesium ion source. The integration time of the CCD camera is set to 8 ms, and the 10-bit A/D converter provides 1024 gray scale levels with 1008(H) $\times$ 1018(V) pixel resolution. This measurement shows that a glowing red-hot ion source can be a major source of background light. To deal with this problem, a radiation shielding structure is being developed for the new barium ion source design, and a narrower bandpass filer will be adopted.

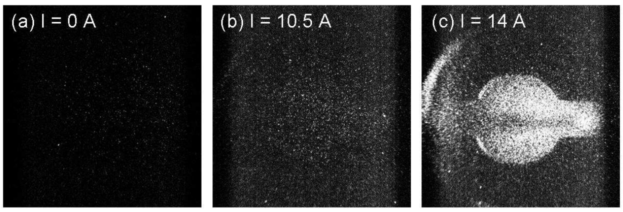

Figure 5: Images of the background light level for various heater currents for the cesium ion source: (a) I = 0 A, (b) I = 10.5 A (normal operating condition), (c) I = 14 A (maximum current available).

SIGNAL-TO-NOISE RATIO ESTIMATE

The fluorescent signal is estimated from the equation

$$S \approx n_2 A_{23} V \frac{\Omega}{4\pi} \eta_T \eta_Q \tau N_\tau, \qquad (2)$$

where, S is the collected number of photoelectrons, the density of excited state n_2 is evaluated numerically including the net flux of ions into the detection volume, A_{23} is the spontaneous transition rate, V is the volume from which the signal is collected (assuming a volume element of 2.54 mm $\times$ 0.8 mm $\times$ 70 mm), and Ω is the solid angle subtended by the aperture stop in the collection optics. The transmission efficiency of the collection optics (glass, filter, and lens) η_T is assumed to be 35 $\%$, and the quantum efficiency of the intensifier η_Q is 15 $\%$ for 493.41 nm. The duration of the laser pulse $\tau = 2$ ms is matched to the time required for depleting all of the metastable ions in the trap, and the number of pulses is $N_\tau = 100$. Since the background emission from collisional transitions can be neglected in PTSX, the signal-to-noise ratio is simplified as $S/N = \sqrt{S}$, assuming the noise N is given by photon statistics in the signal. For the typical operating parameters of PTSX, the signal-to-noise ratio is estimated to be about 20, which is adequate.

Since the plasma column is relatively uniform axially, adding the fluorescent signals along the axial direction and dividing by the width of the detection volume will give the average florescent signal for a given radial position.

CONCLUSIONS

A laser-induced fluorescence diagnostic system is under development for the nondestructive measurement of the transverse ion density profile in the PTSX device. The accompanying barium ion source is also being developed with the goal of maximizing the metastable ion fraction and minimizing the visible radiation. Since the density of the metastable ions which will eventually emit fluorescent light is very low, technical issues such as suppressing stray light and data acquisition with long integration times must be resolved to obtain meaningful data for the study of beam mismatch and halo particle production.

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