DEVELOPMENT OF AN ADVANCED BARIUM ION SOURCE FOR A LASER-INDUCED-FLUORESCENCE (LIF) DIAGNOSTIC ON THE PAUL TRAP SIMULATOR EXPERIMENT (PTSX)*

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Abstract

The Paul Trap Simulator Experiment (PTSX) is a cylindrical Paul trap that simulates the nonlinear transverse dynamics of intense charged particle beam propagation through an equivalent kilometers-long magnetic alternating-gradient (AG) focusing system. Understanding the collective dynamics and instability excitations of intense charged particle beam is of great importance for a wide variety of accelerator applications. Since the optical spectrum of barium ions is better-suited to the laser-induced-fluorescence (LIF) diagnostic than that of cesium ions, a barium ion source is being developed to replace the cesium ion source. A LIF diagnostic will be able to provide *in-situ* measurement of the radial density profile and, ultimately, the velocity distribution function of the intense charged particle beam. The new barium ion source is expected to increase the ion density as well as minimize the number of neutral barium atoms which enter the PTSX vacuum chamber. The design includes an ionizer, an extractor, and a neutral gas filter. Initial test results for this new barium ion source will be presented.

INTRODUCTION

High intensity charged particle beam propagation has been an important research area in the design of present and next generation accelerators and has a multitude of applications ranging from basic scientific research in high energy and nuclear physics, to applications including spallation neutron sources, heavy ion fusion, tritium production, and nuclear waste transmutation [1]. The Paul Trap Simulator Experiment (PTSX) is a compact laboratory device that simulates the nonlinear dynamics of intense charged particle beam propagation over long distances in an alternating-gradient magnetic transport system making use of the equivalent transverse Hamiltonians between an intense charged particle beam propagating through a periodic focusing quadrupole magnetic field and a one-component nonneutral plasma trapped in an oscillating quadrupole electric field [2]. A cesium ion source has been used successfully in the initial phase of the experiment to investigate some important physical issues such as injection mismatch, beam compression, and machine imperfection effect [3, 4, 5]. However, for the *in-situ* measurement of a radial density profile and the velocity distribution function, which are critical for the detailed study of halo particle formation and beam mismatch, a LIF diagnostic has been under development. Since the atomic spectrum of barium ions is better-suited to the LIF than cesium ions, barium ions have become the preferred ion species. In this paper, the development and initial installation of a new barium ion source will be discussed, together with the characteristics of some critical parameters.

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BARIUM ION SOURCE

The new barium ion source is expected to increase the barium ion density in the PTSX vacuum chamber as well as decrease the number of neutral barium atoms that enter the PTSX vacuum chamber as compared to the previous barium source. The main components of the barium ion source will include an atomic oven, an iridium hot-plate ionizer, an extraction mesh, driven rods, and water-cooling lines shown in Fig. 1.

Experimental Setup of the Barium Ion Source

The atomic oven is a 0.5″ diameter one-end-open tube with a resistive band heater wrapped around the tube. The barium in the oven can be heated to temperatures up to 800°C. It is common to heat the oven up to high temperatures for a short while to decompose oxides and hydroxides that may come from handling materials. Lower temperatures between 400°C and 500°C are usually sufficient to produce ion densities near $10^6 \mathrm{cm}^{-3}$. The barium vapor coming out of the atomic oven will free-stream to the iridium hot plate which is held at 1000°C. Barium atoms which make contact with the hot plate will become singly-charged ions through contact ionization with approximate 86% probability. The other neutral atoms which fail to be ionized drift in all directions. In contrast, the negative dc bias voltage applied to the extraction mesh is able to extract the barium ions produced from contact ionization and send them into the 12″-long, 1.5″-diameter guiding pipe. Once in the pipe, the ions will be transversely confined by driving four 1/4″ diameter rods inside the pipe with oscillating quadruople voltages.

Adding a 12″-long guiding pipe between the main PTSX vacuum chamber and the barium ion source is a significant improvement compared to the previous barium ion source. The water-cooling lines wrapped around the long pipe reduce the pipe temperature so that neutral atoms which enter the pipe will probably adhere to the pipe wall rather than contaminate the main chamber. The driving voltages on the

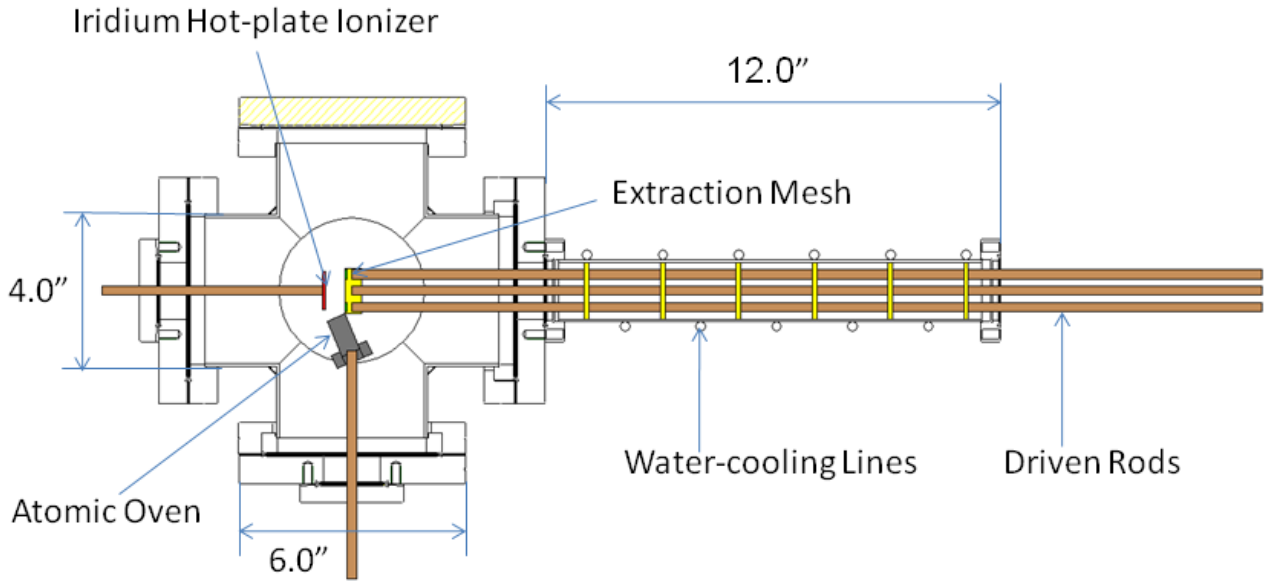

Figure 1: Schematic of the barium ion source for PTSX. The atomic oven, iridium hot-plate and extraction mesh are located in a six-way cross. The atomic oven and the ionizer are mounted on 1/4″ copper rod feedthroughs which deliver the heating current. The extraction mesh (green) is mounted on a ceramic piece (yellow) which holds the end of four driven rods. The 12″-long pipe is wrapped with water-cooling lines.

rods have the same frequency as, but 125 times smaller amplitude than, the voltages applied to the main PTSX electrodes. Figure 2 shows the use of four cylindrical copper rods to create the quadrupole focusing field in the pipe. In this way, the ions will be well-confined transversely and both the vacuum phase advance and the average focusing frequency within the four rods will be the same as in PTSX. The long guiding pipe is extended into the main PTSX vacuum chamber so that the ions can still be confined by the quadrupole field generated by the 40-cm injection electrode right after exiting the driven rods.

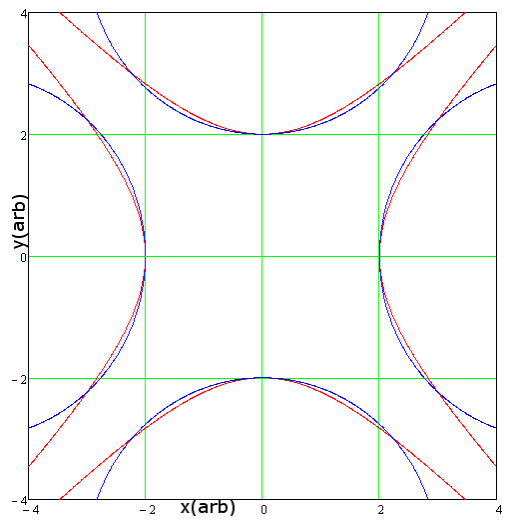

Figure 2: Four cylindrical copper rods are used to approximate the hyperbolic contours of the electric equipotentials in PTSX.

Contact Ionization of Barium

The optical transition spectrum of barium ions is presented in Fig. 3.

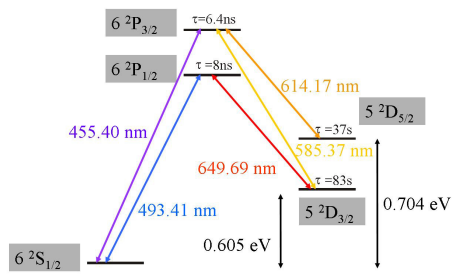

Figure 3: Diagram of the energy levels of Ba^+ with different natural life-times and transition wavelengths.

The preferred scheme for the LIF experiments is to use a 493.41 nm laser to excite the ground-state atoms and also look for 493.41 nm fluorescence light because in this case the signal light is the strongest. To get an idea of the barium ion distribution in different energy levels, the probability of contact ionization is computed using the Saha-Langmuir equation under thermal equilibrium conditions. For the barium ions, since the energy differences between metastable states and the ground state are within about 0.7 eV, the possibility of ions being excited to the metastable state should also be considered [3]. Hence, the ionization probabilities for neutral atoms to be ionized to the ground state (P_i) and the metastable state (P_i^*) are expressed as

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

$$P_i^* = \frac{g_i^* \exp\left(\frac{-\Delta E^*}{kT}\right)}{g_a \exp\left(\frac{E_i - W}{kT}\right) + g_i + \sum_* g_i^* \exp\left(\frac{-\Delta E^*}{kT}\right)}, \quad (2)$$

where W and T are the work function and temperature of the hot-plate ionizer (iridium in this case). k is the Boltzmann constant. E_i is the ionization potential of the atoms. ΔE^* is the energy difference between the ground state and the metastable state. $g_a, g_i, g_i{}^*$ are statistical weights of the atoms, the ground state ions, and the metastable state ions, respectively. The work function of several metals is presented in Table 1 [6]. Since the ionization energy of barium is very high (E_i=5.21eV), iridium, with a higher work function (W=5.4eV), is chosen as the hot plate metal to increase the ionization probability. For an ionization temperature of 1000°C, it is estimated from Eq.(1) and Eq.(2) that more than 98.7% of the barium ions produced by contact ionization are in the ground state 6 $^2S_{1/2}$, while only 0.8% are in the 5 $^2D_{3/2}$ state and only 0.5% in the 5 $^2D_{5/2}$ state. Since the typical on-axis ion density in PTSX is about $10^5 cm^{-3}$, the ion density in the edge regime of the charge bunch will be approximately $10^3 cm^{-3}$ which is only slightly above the detection limit for a LIF diagnostic [7]. Therefore, suppressing the background signal and sufficiently long integration time will be of significant importance for acquiring LIF data.

Table 1: Work Function for Various Materials

Material	Symbol	Work Function (eV)
Molybdenum	Mo	4.15
Tungsten	W	4.54
Iridium	Ir	5.40
Platinum	Pt	5.32
Rhenium	Re	4.85
Tantalum	Ta	4.12

Vacuum Conditions

When the new ion source is ready to use, the six-way cross will be attached to the main PTSX vacuum chamber. This raises a question whether the pressure in the PTSX chamber will still be low enough for meaningful experiments. The general operating pressure in the PTSX chamber is of the order of 10^{-10} – 10^{-9} Torr, while the pressure in the six-way cross is of the order of 10^{-7} – 10^{-6} Torr. When these two chambers are connected by a pipe, there would be gas flowing from the six-way cross to the PTSX chamber due to the pressure gradient. The quantity describing the capability of a pump pulling out gas molecules is the throughput $Q = P_{chamber} \times S_{pump}$, where $P_{chamber}$ is the gas pressure with the units of Torr and S_{pump} is the pumping speed with the units of ℓ/s. The gas flow from the six-way cross to the PTSX chamber is given by $Q_{pipe} = (P_{oven}\text{-}P_{chamber}) \times C$, where P_{oven} is the gas pressure inside the six-way cross, and C is the conductance of the pipe for gas flow. For the low-pressure regime, the conductance C is approximated by $C = \pi v d^3/12l$, where v, d, l are the thermal velocity of gas molecules, the diameter and length of the pipe, respectively. All the other gas sources including possible leakage and vapors escaping the chamber walls are included in another term Q_{outgas}, where Q_{outgas} is known from the pumping speed and operating pressure. In equilibrium, we have $P_{chamber} \times S_{pump} = Q_{pipe} + Q_{outgas}$. Assuming P_{oven} is 10^{-6} Torr, $P_{chamber}$ will be of the order of 10^{-8} – 10^{-7} Torr which is adequate for experiments. The conductance of the pipe is expected to be lower since it will have baffles and be water-cooled which will further decrease $P_{chamber}$.

CONCLUSIONS

A new barium ion source for an advanced laser-induced-fluorescence diagnostic system is under development with the goal of increasing the barium ion density as well as decreasing the number of neutral barium atoms that enter the PTSX vacuum chamber. An iridium hot plate is used as the ionizer to increase the ionization probabilities of barium atoms and a guiding pipe is added to improve the injected beam quality. The vacuum conditions of the PTSX chamber are expected to be good enough for experiments after the six-way cross is connected to the PTSX chamber.

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