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Laser ablation system for the injection of neutral materials into an electron beam ion trap

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We have designed and implemented a laser ablation system to inject neutral material into the EBIT-I and SuperEBIT high-energy electron beam ion trap at the Lawrence Livermore National Laboratory. A laser-generated vapor created from a solid material target was scrubbed of ions prior to injection into the trap in the form of a collimated beam. We used a Q-switched Nd:YAG laser with a pulse duration of 15.7 ns full width at half maximum and intensities at the target controllable from 0.035 to 0.46 GW/cm^2. Compared with other injection methods, this pulsed system adds new flexibility including the ability to vary fill trap in both time and quantity and without changing trap or beam parameters. Moreover, it allows us to inject materials that are not readily injected by the standard metal vapor vacuum arc (MeVVA) method. Performance comparisons between the laser ablation system and MeVVA method are presented.
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I. INTRODUCTION

Lawrence Livermore National Laboratory's electron beam ion traps, EBIT-I and SuperEBIT, in operation since the mid-1980s,[1] have been employed for investigating the radiation emitted by a large range of ion species with high-resolution spectroscopy across several wavelength bands. Results have been used in a variety of fields, including in the analysis of spectra measured from celestial sources,[2] x-ray laser, inertial confinement fusion, and tokamak research,[3–5] and in stringent tests of quantum electrodynamics.[6]

In summary, EBIT-I consists of an electron gun for creating the electron beam, an electrostatic trap where the beam-target plasma interaction takes place, a collector where the beam terminates, and an injection system for introducing the target material into the trap. In the past, the two most widely used injection systems have been the metallic vapor vacuum arc[7] (MeVVA) and the gas injector. The MeVVA uses an electrical discharge to create singly and doubly charged ions that are electrostatically transferred to the trap through rapid switching of the trap electrodes. The MeVVA has the advantage of being able to inject the material in relatively short bursts with high timing precision at the beginning of the plasma cycle. However, it can only inject materials that can be machined into a cathode and are electrically conductive, thus limiting the material to metals or metal alloys. The gas injector uses differential pumping to ballistically inject a collimated stream of neutral material into the trap. Once the neutrals intersect the electron beam, they are ionized and trapped. The gas injector not only injects elements occurring naturally as a gas, e.g., Ar, N_2, and Xe, but also compound materials that have a high vapor pressure, such as metallo-organics, e.g., $Fe(CO)_5$,[8,9] and materials whose vapor pressure can be raised by heating, e.g., Ti and K.[10,11] The gas injector greatly increases the range of elements and the amount of material that can be injected; however, the constant stream of neutrals reduces the average ion charge present in the trap, and may limit the ability to isolate a specific charge state. We have also fielded a pulsed gas injector system to control the amount and timing of the injected gas. However, this method requires a high gas pressure, so the range of material it can inject is limited.[12]

The most recent injection system implemented at our EBIT facility is a laser ablation system. It combines several of the advantages of the other injection systems. The system makes it possible to inject neutral material, including radioisotopes, with timing precision and in controlled amounts. It is highly repeatable, requires little maintenance, and has a rapid turnover rate for changing the target material. Here, we give an overview of the laser ablation system and compare its injection performance to the MeVVA.

II. EXPERIMENTAL SETUP

The experimental arrangement is shown in Fig. 1 and consists of a commercially available Q-switched Nd:YAG (yttrium aluminum garnet) laser, conditioning optics, target chamber operated in the 10^{-7}–10^{-8} torr range, spatial filters, and the SuperEBIT high-energy electron beam ion trap operated at $\sim 10^{-12}$ torr. We used a flash lamp pumped Q-switched Nd:YAG laser/amplifier model NY82-10 manufactured by Continuum. Pulse energy was measured to be 1.4 J with a pulse duration of 15.7 ns full width at half maximum (FWHM) and a $1/e^2$ beam diameter of 11.6 mm. The laser output was linearly polarized and highly multimode. Pulse energy was adjusted using a half wave plate in combination with a thin film polarizer optimized at a 57° angle of incidence (AOI) and provided continuous adjustability from 0.11–1.1 J at the target. A dielectric turning mirror reflected the beam through an antireflection coated optical window

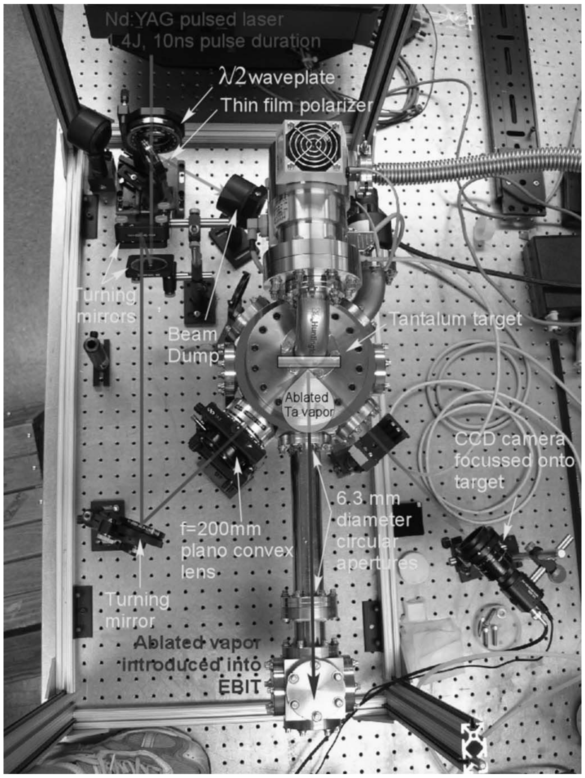

FIG. 1. (Color online) Layout showing laser beam path, optics train, target chamber, target position, collimating apertures, and vapor path from target to EBIT-I.

into a vacuum chamber and onto the target at 45° AOI. Lastly, a $f=200$ mm planoconvex lens was positioned 148 mm from the target to produce an elliptical spot of semiminor axis=2.0 mm and semimajor axis=2.8 mm at the target. This larger spot size was selected to reduce alignment sensitivity between the target and the 10.0×0.5 mm^2 rectangular entrance aperture to EBIT-I. Intensities at the target were experimentally optimized for material delivery to the EBIT and were adjustable from 0.035–0.46 GW/cm^2. Intensities above 0.35 GW/cm^2 produced excess material. In the absence of EBIT-I's residual magnetic field, target intensities of 0.06 GW/cm^2 produced a mass equivalent of 3.0×10^9 atoms/pulse of tantalum measured just after the 6.3 mm diameter far field aperture.

To characterize the spatial distribution of the vaporized material, a deposition profile was obtained by positioning a series of microscope slides inside the vacuum chamber in front of the target and allowed the ablated material to sputter onto the slides. $1/e^2$ (approximately 85.6%) of the vaporized material was measured to be within a 23.5° half cone angle to the target surface normal. The expanding plasma was collimated by 6.3 mm diameter circular near and far field apertures placed along the axial path defined by the ablated target and the electron beam in the interior of the ion trap. Electrons and ions were scrubbed due to interactions between the charged particles in the expanding vapor and the EBIT's residual external magnetic field. Only neutrals within the distribution and traveling along the axial path were able to gain entrance to the ion trap. Some fraction of the neutrals transited the magnetically compressed beam of electrons became ionized and trapped. Nonionized particles transited through and exited the trap on the opposite side plating themselves onto a stop shield.

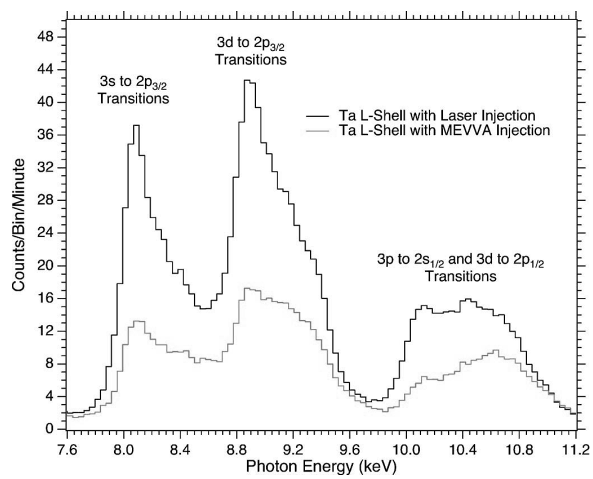

FIG. 2. (Color online) Ta L-shell spectrum in the Ge detector. The upper black curve shows the average spectrum from sixteen 10 min observations of Ta injected into the trap via the laser system. The lower red curve shows the average spectrum from sixteen 10 min observations of Ta injected via the MeVVA. The difference in spectral shape is attributed to a somewhat lower charge balance attained during laser injection because of an increased gas load.

The spatial distribution of the vapor plume was centered about the target surface normal. Over a period of 5000–10 000 laser fires, the target normal gradually walked towards the incident laser beam due to surface erosion. A corresponding reduction of material introduced into the EBIT was observed. This was mitigated by translating the target to ablate a fresh surface approximately every 1000 laser fires. Material impurities on the target surface were removed within the first few laser fires and were not considered to be an experimental issue. For the materials we have injected, no impurities from targets have been observed in the trap.

III. EXPERIMENTAL RESULTS AND PERFORMANCE COMPARISON

We quantified the comparison of the laser and MeVVA injection by looking at the total flux of tantalum L-shell radiation in an ORTEC High Purity Ge IGLET-X detector. The electron beam was run at an energy of 85 keV and the electron beam current was 160 mA. For the comparison, we used a 12 s timing cycle with material injected at the beginning of the cycle and then dumped every 12 s. We tuned the injection of the Ta MeVVA so that a maximum of L-shell x rays were counted and then took sixteen 10 min spectra to get an average count rate and to look for timing variations due to MeVVA misfires. For the test case, we used a laser intensity of 0.30 GW/cm^2 at the target, two laser shots temporally spaced 100 ms apart and with a repetition rate of 12 s. As in

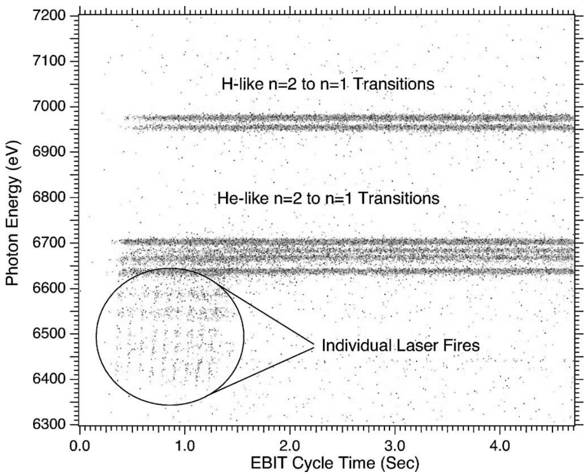

FIG. 3. (Color online) Fe He-like and H-like *K*-shell x-ray spectrum: plot showing x-ray energy vs timing. The laser was fired in bursts of ten shots 100 ms apart and with a rep rate of 7 s for a duration of 6 h with each laser fire evident in the form of x rays from low charge states, reaching from neutral *K*-alpha radiation to the He-like transitions. This also illustrates temporal flexibility in that the laser system can inject material into the trap at any time.

the case of the MeVVA we took an average of 16 spectra. The laser settings used represented optimized conditions determined by varying both laser intensity and number of pulses.

Figure 2 shows the average spectra from the 16 MeVVA and laser experiments normalized to counts/min. The laser had an average count rate of 1450 counts/min whereas the MeVVA had a count rate of almost half that at 740 counts/minute in the Ta *L* shell. The laser also showed greater repeatability on a 10 min spectrum than the MeVVA. The standard deviation for the total number of counts was 25% for the MeVVA and 13% for the laser. At intensity settings above 0.45 GW/cm^2 we saw a significant reduction in count rate. We believe this to be a result of increased ionization caused by excess power.

On subsequent tests we experimented with multiple ($\geqslant$10) laser fires per cycle time at lower laser intensities. This proved optimal in that it maximized the filling of the trap while minimizing residual gas load on SuperEBIT. Figure 3 shows the results of a 6 h run in which the laser was fired in bursts of ten shots spaced 100 ms apart at a repetition rate of 7 s to inject Fe into the trap. One can see the individual laser fires as the neutrals are ionized through to He-like ions. We also found that periodic injections could be made well into the cycle. With the new injection system, this can be accomplished without dumping ions already in the trap or changing the electrostatic parameters.

IV. SUMMARY

We have successfully demonstrated the use of a laser ablation system to vaporize and inject uncharged material into SuperEBIT. To date we have injected: Ta, Bi, Fe, Ni, and Au. When compared to the MeVVA injection system, laser ablation has been demonstrated to match or exceed MeVVA injected material quantities, especially, if several repeated low-power injections are employed. This system also has the ability to vary fill trap in both time and quantity and without changing trap or beam parameters. In addition, this laser ablation system now allows the investigation of materials otherwise impossible to inject into EBIT using traditional schemes.

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