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TESTS OF A LASER ION SOURCE AT THE HEIDELBERG ELECTRON BEAM ION TRAP

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A laser ion source (LIS) has been designed and successfully tested for loading the Heidelberg electron beam ion trap (H-EBIT) with ions of practically all solid-state elements. A pulsed YAG:Nd^{3+} laser (30 mJ, 8 ns) is used to produce plasma from a solid target. Lowly charged ions are extracted from the plasma and accelerated by a short high-voltage pulse, generating a pulsed ion beam with energy of up to 6 keV per charge. The ion beam is transported into the EBIT, decelerated and captured within it by switching the trapping electrode potentials. The electron beam further ionizes the trapped ions to the desired highly charged states. The experimental setup is described together with the source parameters measured for different target materials. X-ray spectra of up to He-like highly charged ions (Cu, Mo, Pb, Al, and Ge) produced in the EBIT after injection from the LIS have been measured. The reliability and convenience of this method allows the use of the LIS to produce highly charged ions of both insulating and conducting solid elements with an EBIT as needed for different experiments.

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1. Introduction

The electron beam ion trap (EBIT) [1] has become one of the premier tools used in the study of highly charged ions. The Heidelberg EBIT [2,3] has been designed as a combination of ion trap and ion source, employing a magnetically compressed beam of electrons to both confine and ionize the desired species within the trap. The resulting highly charged ions can then be observed through x-ray, UV, and visible spectroscopy, or extracted as an ion beam and delivered to an external experimental station for cold target recoil ion momentum spectroscopy (COLTRIMS) [4,5].

The number of elements, which can be loaded into an EBIT, and consequently studied, has always been restricted by the available atom or ion sources. Since working with solid elements usually requires the use of ovens, which can cause numerous difficulties in the ultra-high vacuum environment of an EBIT, gases are typically leaked into the trap to serve as the source. Spark- or arc-type sources, such as the metal vapor vacuum arc (MEVVA) [6], require frequent maintenance and are limited to conducting materials. Another, more flexible method is to use a laser to produce a plasma by the ablation of a solid target.

A laser ion source (LIS) has many properties, which makes it suitable for loading an EBIT. Most notable is the versatility of producing ions from a variety of atomic species, since almost any solid material can be used as a target. In addition, the plasma can be oriented along an extraction axis and the plasma generation times are short, which may be necessary for both fast injection into and extraction from the trap. Finally, a LIS does not require any carrier gas, which can act as a contaminant to the required ultra-high vacuum. For these reasons, a LIS has been designed and constructed for the production and injection of ions into the H-EBIT [7,8].

The principle of the LIS operation is based on plasma generation from a powerful laser beam focused on a target [9]. The subsequent expansion of the plasma into vacuum and the pulsed extraction of ions from the plasma in the acceleration gap formed by two grid electrodes produce a beam of ions. A schematic diagram of such an ion source is shown in figure 1. The target material is explosively evaporated when the laser beam intensity exceeds the necessary ablation threshold that is typically on the order of 10^8 to 10^9 W/cm^2, depending on target material. A dense, hot plasma is formed close to the target surface, growing until the plasma density becomes too great for the laser to penetrate. The plasma then starts to expand into the vacuum where recombination processes occur, due to the high electron density, before the ion charge state distribution is frozen from the subsequent fast decrease in the plasma density. The plasma expands preferentially in a direction normal to the target with a typical velocity of about 10^6 cm/s, with greater velocities for more highly charged ions.

A copious number of ions (up to 10^{14} particles per 1 J of laser energy) can be generated in such a process. With a delay of around 5 μsec, a pulsed, positive voltage of a few kV is applied to the first grid electrode, which is separated by a distance of 3 mm from the second, grounded grid. Those ions that are between the two grids at the moment of the voltage application are accelerated and extracted from the expanding plasma to the trap through an aperture in the EBIT electron collector. Here, the ions are captured longitudinally by means of modulating the trap drift tube voltages and confined radially by the space charge of the electron beam.

2. Experimental Setup

A pulsed YAG:Nd^{3+} laser (Ultra CFR, Big Sky Laser Technologies Inc.) is used. It is capable of generating 8 ns, 30 mJ pulses at a wavelength of 532 nm with a repetition rate of up to 20 Hz. The laser beam is expanded to a diameter of 11 mm by a telescopic lens arrangement and is deflected by a dielectric mirror through a window into the vacuum chamber. A lens with a focal length of 20 cm, combined with a second dielectric mirror, then focuses the beam onto the target surface at an angle of 23°. The beam is focused to a spot with a diameter of less than 50 μm, yielding a power density of up to 10^{10} W/cm^2, well above the ablation threshold value for any target material.

The side view of the LIS design is shown in figure 2 with the LIS positioned in the trap beamline. The target unit consists of small (∅8×1 mm) interchangeable disks attached to a special holder that can be rotated by a stepper motor at a maximum frequency of 20 Hz. The holder can be placed, in less than 50 ms, such that the extraction of highly charged ions from the EBIT to an external experimental facility becomes possible. The target holder is held by a linear manipulator and can be completely removed from the main chamber to a second high-vacuum chamber for target replacement without breaking the ultra-high vacuum of around 10^{-10} Torr. The holder can be rotated in small, controlled steps to change the ablation spot position from laser shot to laser shot, thus minimizing any changes in the beam parameters due to target surface damage.

The LIS extraction system consists of two 4-mesh/1-mm stainless steel grids with an overall transmission of 80 %, mounted at a distance of 10 cm from the target and 120 cm from the middle of the trap. An Einzel lens is mounted after the extraction system to help focus the ion beam into the EBIT. Both the extraction system and the Einzel lens are designed to operate with voltages of up to 35 kV. The entire source is contained in an ultra-high vacuum chamber having a total length of only 32 cm.

At the beam intensities mentioned above, most of the extracted ions are of charge state +1 and +2 for the tested target materials. Off-line measurements of the LIS ion beam allowed the number of extracted ions per laser beam pulse and the duration and energy of the extracted ion pulses to be determined. It was found that the typical number of ions per pulse is around 10^{10} and that the maximum energy of the particles is close to the value from the applied extraction pulse voltage. The delay between the laser firing and the extraction pulse was adjusted empirically to maximize the ion yield.

A typical time-of-flight spectrum for the Cu target is shown in figure 3. Here, the power density was about 10^9 W/cm^2 and the detector (channeltron) was located at a 50 cm distance from the target. Though most of the Cu ions were found to have a charge state of +2, singly and triply charged ions were also clearly extracted. Using the extraction grids as charge collectors, the plasma pulse duration was estimated to be around 10 μs in the extraction gap, giving a mean plasma velocity of 1.6×10^6 cm/s for the Cu targets. Shot-to-shot variations of the ion yield were observed at the level of ± 10 %.

3. Results of Injection into the EBIT

During the experiments of loading the ions from the LIS, the EBIT was used for x-ray diagnostics of the trapped highly charged ions and for studying the dielectronic recombination resonance (DRR) processes of the ions. No extraction of the ions from the trap was performed during these runs. The LIS was equipped with a set of interchangeable targets, holding Cu, Mo, Pb, Al, and Ge. X rays were detected with a high-purity Ge detector mounted at one of the two radial access ports on the trap chamber. During the DRR experiments, the potential of the trap drift tubes was varied slowly in the desired range, allowing the modulation of the electron beam energy. The intensity of the characteristic x-ray radiation emitted by the trapped ions was detected as a function of the electron beam energy. The trap was emptied periodically (typically once per 10 s) by raising the potential of the central drift tube to push the ions over the potential barriers of the outer drift tubes. At the end of this dumping period, the trapping potentials were reset to their initial values.

After forming the pulsed ion beam from the LIS, the ions were transmitted through the EBIT electron collector into the drift tube assembly that was biased at a voltage of up to 10 kV. If the delay between the ion extraction and the end of the dumping cycle is chosen properly, raising the drift tube trapping potential results in the confinement of substantial amounts of the ions produced by the LIS. In the closed trap, the ions were held for a time period of a few tens of seconds or more per cycle, allowing the desired experiments to be performed over many capture–breed–measure–dump cycles.

For all of the targets used, a noticeable increase of the characteristic x-ray radiation from the corresponding ions was detected after injection. As an example, figure 4 shows the dependence of the Ge K_α-line on the electron beam energy as obtained with the injection of Ge ions into the EBIT. The electron beam energy was varied in a range from 6 to 12 keV during the experiment.

The application of a LIS to load the H-EBIT has been successfully shown. In the specific case of the DRR experiments, the trap and LIS worked without any interruption for more than 5 days. No significant changes in the number of trapped ions were observed, confirming the long-term stability of the LIS operation. In addition, no changes in the residual gas pressure were observed.

4. Summary

A laser ion source has been designed and constructed for loading ions into the Heidelberg EBIT. Off-line measurements were done to characterize the LIS operation. The numbers of the extracted and accelerated ions were defined for a variety of target materials, as well as other important parameters of the source. The LIS was used to successfully inject Cu, Mo, Pb, Al and Ge ions into the trap and the characteristic x rays of the corresponding highly charged ions were detected from the EBIT. The LIS has demonstrated long-term stability of operation and is capable of providing enough ions to the EBIT to perform the desired experiments.

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Figure captions

Fig. 1. The different elements of a laser ion source necessary to its operation.

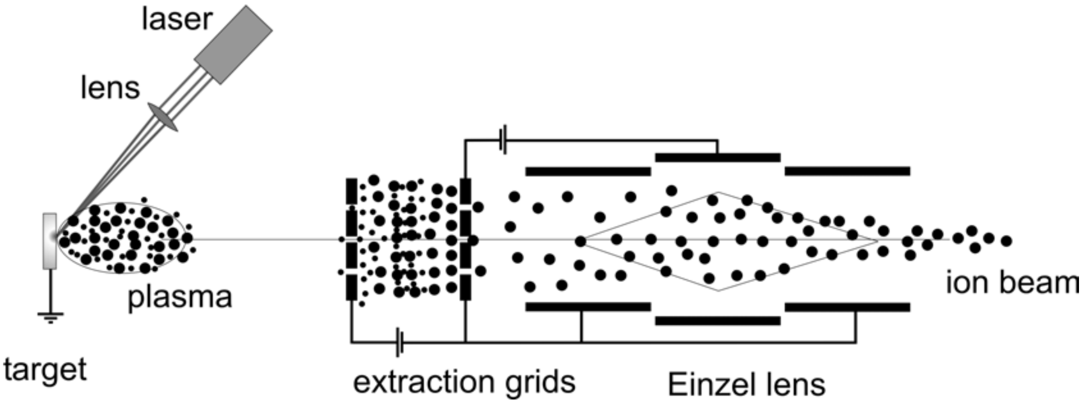

Fig. 2. Side view of the Heidelberg laser ion source.

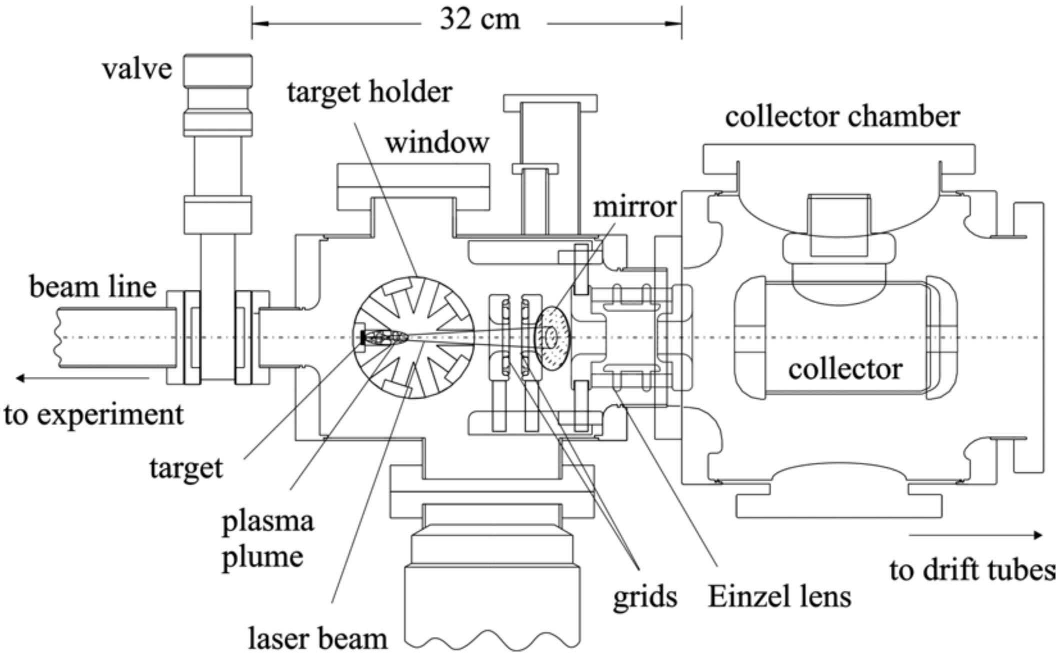

Fig. 3. The ion current from the laser ion source with a Cu target as measured off-line b a channeltron detector placed 50 cm from the target.

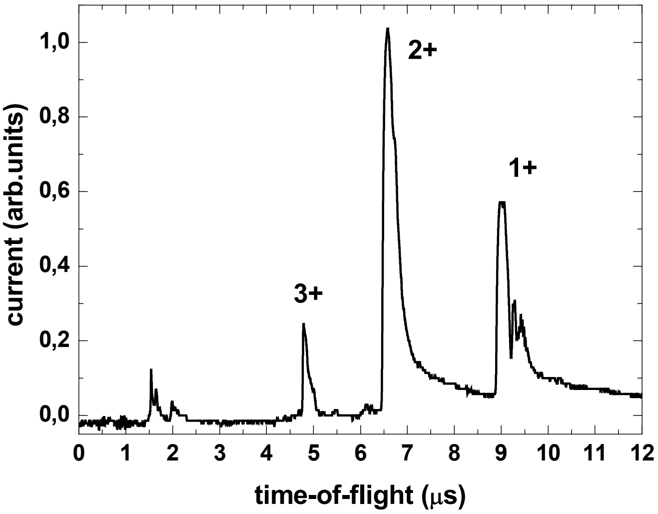

Fig. 4. The K_α-line projection of trapped Ge ions injected from the laser ion source into the Heidelberg EBIT.