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Development of a laser ion source for production of high-intensity heavy-ion beams

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ABSTRACT

A laser ion source has been developed as a high-intensity source for the ion implanter and the single pulsed beam of the azimuthally varying field cyclotron at TIARA. Highly charged beams of C^{5+} and C^{6+} ions and low-charged beams of heavy ions such as C, Al, Ti, Cu, Au, and Pt are required for the single-pulse acceleration in the cyclotron and for the ion implanter, respectively. In the vacuum chamber of the ion source, a target holder on a three-dimensional linear-motion stage provides a fresh surface for each laser shot. A large-sized target with a maximum size of 300 mm × 135 mm is mounted on the holder for long-term operation. The ion current (ion charge flux) in the laser-produced plasma is measured by a Faraday cup and time-of-flight spectra of each charge state are measured using a 90° cylindrical electrostatic analyzer just behind the Faraday cup. Carbon-plasma-generation experiments indicate that the source produces intense high- and low-charged pulsed ion beams. At a laser energy of 483 mJ (2.3×10^{13} W/cm^2), average C^{6+} current of 13 mA and average C^{5+} current of 23 mA were obtained over the required time duration for single-pulse acceleration in the cyclotron (49 ns for C^{6+} and 80 ns for C^{5+}). Furthermore, at 45 mJ (2.1×10^{12} W/cm^2), an average C^{2+} current of 1.6 mA over 0.88 μs is obtained.

1. Introduction

The Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) ion-irradiation research facility provides beams of various ion species with a wide energy range using an azimuthally varying field (AVF) cyclotron and three electrostatic accelerators.

A 400 kV ion implanter [1], one of the electrostatic accelerators, offers a variety of low-charged direct-current (DC) beams of ions such as C, Al, Ti, Cu, Au, and Pt, mainly for material science applications. Most of these beams are produced from solid materials using a Freeman-type ion source. Plasmas are generated in the ion source by vaporizing samples of these materials in an oven or by directly introducing them to the ion-source chamber. For materials with high melting points, the beam currents are insufficient (below a few microamperes) and decrease with time. In addition, conducting experiments using multiple types of ions is difficult, because changing ion species becomes an issue owing to a long heating time (2–3 hours) required by the oven. Therefore, the development of an ion source that produces high-intensity heavy-ion beams from solid materials, allowing quick changing of the ion species, is required.

For the AVF cyclotron (K = 110) [2], a single-pulsed-beam acceleration technique has recently been developed for applications such as pulse radiolysis experiments in radiation chemistry [3], in addition to the CW beam. This technique allows the irradiation of experimental samples using a single-bunched beam with time duration of a few nanoseconds. To form a single-bunched beam, two beam kickers are installed at the low- and high-energy beam-transport lines (LEBT and HEBT, respectively). A DC beam from an ion source is pulsed with a duration of one period (49 ns for a 220-MeV $^{12}C^{5+}$ acceleration and 80 ns for a 320-MeV $^{12}C^{6+}$ acceleration) of the accelerating RF field of the cyclotron by the kicker at the LEBT. The beam is injected into the cyclotron and accelerated. At extraction from the cyclotron, the beam bunch is divided into several parts by an extraction-deflector electrode. Therefore, unneeded sub-bunches are cut by the chopper at the HEBT to form a single-bunched beam. Although high-intensity C^{5+} and C^{6+} beams, which are frequently used in experiments, are required to efficiently detect an instantaneous reaction, the beam currents from our electron-cyclotron-resonance ion source are insufficient (a few nanoamps for C^{6+} and around ten microamps for C^{5+}). Therefore, an ion source capable of producing a high-intensity pulsed beam needs to be developed.

To meet the abovementioned requirements, we are developing a laser ion source as a high-intensity heavy-ion source for the

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implanter and the cyclotron. A laser ion source can generate high-intensity ion beams from almost any solid material by irradiating a focused, high-intensity pulsed laser onto a solid target. Highly charged heavy ions can be generated, and the generation of low-charged ions is possible using a lower-energy laser [4]. Change in ion species can be made by replacing target materials or mounting multiple targets on a target holder.

In this paper, the details of the developed laser ion source and plasma-diagnostic devices as well as experimental results for carbon-plasma generation, are reported.

2. Laser ion source and diagnostic devices

To study the generation of various types of beam and investigate the behavior of the source during long-term operations, we have built equipment for generating and diagnosing laser plasma (Fig. 1). The equipment comprises an optical system on an optical bench, a laser ion source capable of mounting a large-area flat target, a drift space where the generated plasma expands, a Faraday cup for measuring the plasma-ion current, and an electrostatic analyzer for analyzing the energy and charge state of the ions in the plasma.

2.1. The optical system

The plasma-generating laser used is a Continuum Surelite I-10 Q-switched Neodymium-doped yttrium–aluminum–garnet (Nd:YAG) laser with a fundamental infrared wavelength of 1064 nm, maximum energy of approximately 480 mJ, typical pulse width of 5.4 ns, and maximum repetition rate of 10 Hz. The laser light with a diameter of 6 mm at the exit of the laser head is expanded to that with a 20 mm diameter at the entrance of the vacuum chamber of the laser ion source by a plano-concave lens ($f = -90$ mm) and a multi-element converging lens ($f = 300$ mm) so that it can be tightly focused on the target surface using a final focusing lens ($f = 150$ mm) in the chamber.

2.2. Laser ion source

The final focusing lens and a target stage are placed in the chamber of the laser ion source. Plasma of the target material is generated and heated by absorbing the focused laser on a target. The target material is ablated through this process and a crater is formed on its surface. The amount of ablated material increases with increasing energy of the laser. When the laser is irradiated multiple times at the same spot, the generated plasma becomes unstable, especially when producing highly charged ions that require high laser energy because the surface condition of the target changes with every laser irradiation. Therefore, the target holder is placed on a three-dimensional linear-motion stage to provide a fresh surface for every laser shot. A target with a maximum size of 300 mm × 135 mm is mounted on the holder. Long-term operation is enabled by scanning the irradiating position along the x (horizontal) and z (vertical) axes. For example, when irradiation is performed on the target at 1 mm intervals and 1 Hz repetition rate, the source operates for over 10 hours, which is sufficient for pulse-beam experiments at the cyclotron.

To stably generate plasma even if the target's position is shifted, the irradiation condition of the laser needs to be constant. Thus, the inclination of the target is corrected using three adjusting screws to minimize the displacement of the target at the irradiation point. The displacement distribution is measured by scanning the target with a laser-displacement sensor.

2.3. Plasma-drift space

Plasma-drift space is the region between the point of plasma generation and the Faraday cup. The plasma moves perpendicular to the target and expands with a shifted Maxwell–Boltzmann velocity distribution within this space. The ions are not extracted from the plasma in this region because the laser ion source and the drift space have the same potential (i.e., the ground potential in this study).

The drift distance is varied from 0.6 m to 1.6 m by moving the sliding table on which the Faraday cup and electrostatic analyzer are mounted. The density and pulse width of the plasma are controlled by changing this distance. The plasma density decreases in inverse proportion to the cube of the distance, whereas the pulse width increases proportionally with the distance.

2.4. Faraday cup

The ion current of the plasma is measured using the Faraday cup after traveling through the drift space. The details of the Faraday cup are shown in Fig. 2. It is composed of an outer cylindrical shield case at ground potential, a suppressor electrode, and an ion-current collector. A collimator hole in the front defines the diameter of the plasma that enters the Faraday cup. By applying a negative high voltage of maximum −5 kV to the suppressor, ions are extracted from the plasma and they enter the collector, whereas the secondary electrons that are generated in the collector are repelled. This method enables the collector to measure an accurate ion current of the plasma that enters through the hole by avoiding beam loss because of space-charge effect, which can be

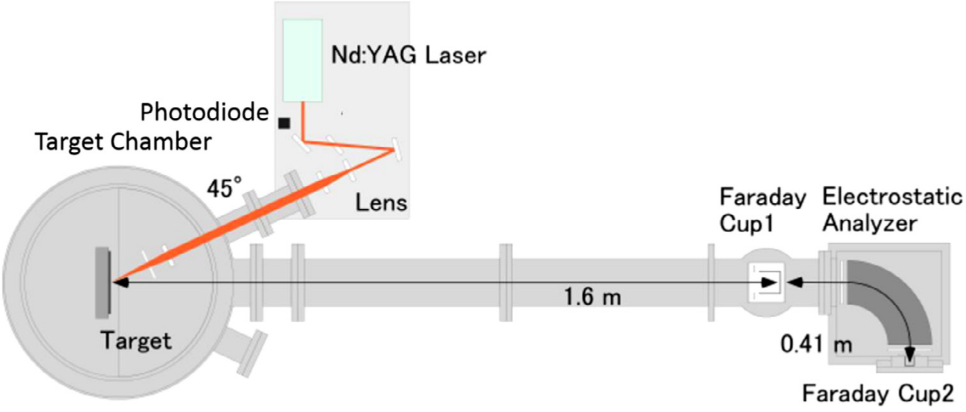

Fig. 1. Layout of the laser ion source and diagnostic device.

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