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Study of the energy spectra of multiply charged Ti ions from a laser plasma

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***Abstract*.** **Experimental data are presented concerning the generation and investigation of multiply charged Ti ions from the plasma produced by the second harmonic radiation of a neodymium laser (with an energy under 14 J and a pulse duration of 2.5 ns). A group of ions with charge states ranging from +16 to +20 was recorded with an electrostatic energy mass analyser and a collector was employed to measure the ion current of this group, which was found to be equal to $\sim$1 mA cm^{-2} for an ion pulse duration of $\sim$0.8 μs.**

Keywords: *laser plasma, multiply charged ions, ion injector, energy spectrum, ion current.*

1. Introduction

The rapid progress of acceleration technology during the past decade has opened up the prospect of employing charged particle beams in inertial confinement fusion. To this end, the existing projects propose the use of both light ions (deuterium nuclei, carbon ions) and the multiply charged ions of heavy elements (from xenon to uranium). For the feeding of the storage rings of heavy-ion accelerators, of special interest is the development of a source of multiply charged ions (an injector) from the laser plasma driven by radiation with different wavelengths (from 0.3 to 10 μm) and target-irradiation power densities (from 10^{12} to 10^{16} W cm^{-2}) [1 – 3]. In this connection it was necessary to carry out experiments to optimise the conversion of laser radiation energy to the energy of multiply charged ions, i.e. to study the dependence of their energy spectra on the laser radiation flux at the target, to measure the density and duration of the current pulse of multiply charged ions, and also to perform numerical simulations of the laser plasma at the expansion stage, which allow determining the charge-state plasma composition under laser irradiation of the target.

In this work we investigated the possibilities for the generation of multiply charged ions from the laser plasma of a Ti target. The choice of target material is determined by the parameters of an accelerator, in which the ion charge-to-mass ratio (Z/A) should lie in the 0.25 – 0.35 range, i.e. the charge state of the Ti ions should be about +20 [4]. To obtain such ions, it is necessary to heat the plasma to a temperature of $\sim$1.5 keV (provided that inverse bremsstrahlung is the main absorption mechanism). Considerable difficulties in these experiments arise in the measurements of the absolute number of ions in the plasma. In particular, it is an intricate task to calibrate the seconda-ry-emission multiplier (SEM) in the sort of ions and their energy, as well as to calibrate the ion collector to determine the absolute coefficient of secondary electron emission from a plate surface for each sort of ions in relation to their energy [5].

To overcome these difficulties, in this work we calculated a collector in which there occurs plasma 'breakage' with subsequent recording of the ion current and suppression of the secondary emission flux. The intensity and potential of the electric field on the collector axis calculated for a voltage of -3000 V at the high-voltage electrode are plotted in Fig. 1. The transverse section of the ion collector is schematically shown in Fig. 2. In the calculation, account was taken of the space charge of the ion beam extracted from the plasma and the ion energy in the expanding laser plasma.

The high-temperature plasma was produced by using the 'Kamerton' one-channel high-power laser facility (General Physics Institute, Russian Academy of Sciences). The facility generated 1.055-μm, 100-J, 2.5-ns laser pulses for a beam diameter of 72 mm, which can be converted to 50-J second harmonic pulses [6].

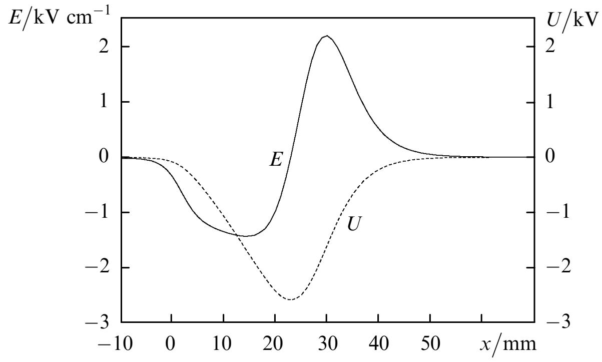

Figure 1. Intensity E and potential U of the electric field calculated on the collector axis.

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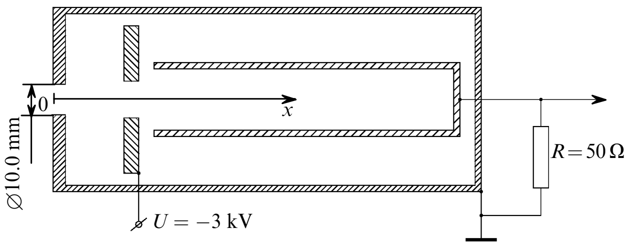

Figure 2. Scheme of the ion collector (transverse section).

One of the features of a laser plasma produced in vacuum is a strong angular dependence of ion expansion on the charge. The higher the ion charge, the smaller the solid angle in which the ions expand. That is why we selected an axially symmetric arrangement of plasma irradiation and expansion. The second harmonic of the laser radiation was focused onto the target surface with a spherical mirror having a central opening to allow a free ion expansion along the axis of the facility. A time-of-flight technique was employed to analyse the energy and charge state of the expanding plasma ions with the aid of a cylindrical electrostatic analyser. The analyser was located at a distance of about 320 cm from the target surface. The ions were recorded downstream from the analyser employing a VEU-1 secondary-emission multiplier with subsequent feeding of the current to a TDS-740 Tektronix digital storage oscilloscope with an input resistance of 50 Ω. The total ion current was measured with a Faraday cylinder with a voltage up to −3 kV at the negative electrode, which is employed for plasma breakage and impedes the arrival of secondary electrons from the collector (Fig. 2). The experimental scheme is shown in Fig. 3.

The laser radiation intensity at the target surface was determined by measuring the intensity distribution of the second harmonic of laser radiation in the focal plane. The measurements were performed with a microscope and a CCD array. The diameter d of the focal spot at the target was ~ 10 μm (Fig. 4). This distribution differs from the Gaussian distribution due to an opening 25 mm in diameter located at the centre of the spherical focusing mirror. For an energy of 20 J and a wavelength of 0.527 μm, the radiation intensity amounted to 6×10^{15} W cm^{-2} at the target surface.

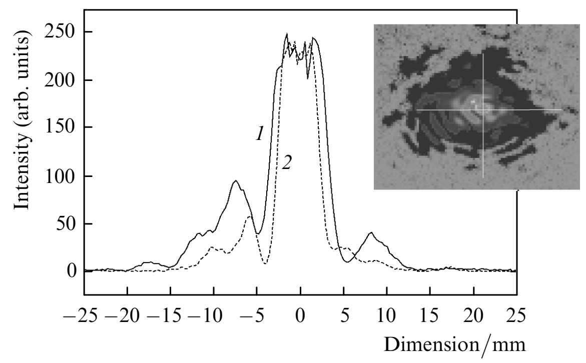

Figure 4. Diameter of the focal spot at the target surface in the horizontal (*1*) and vertical (*2*) planes; the inset shows the focal spot at the target surface.

The laser plasma temperature and hence the charge states of plasma ions depend primarily on laser radiation intensity at the target surface. To elucidate this dependence, we selected laser radiation energies of 3, 6.5, and 14 J. The energy spectra of Ti ions were investigated in the course of these experiments. The ion signal from the electrostatic analyser measured for a 3-J laser pulse and an acceleration potential of 2000 V is shown in Fig. 5. One can see that the majority of ions have charges from +15 to +19.

For known parameters of laser radiation in the focal plane we performed a theoretical calculation of the charge-state composition and energy distribution of Ti ions at a distance from the target equal to the distance from the recording instruments (Fig. 6). The calculations were carried out using a two-temperature hydrodynamic model taking into account ionisation of the residual vacuum by X-ray and ultraviolet plasma radiation. In the calculations, the total laser pulse energy was divided into two halves. One half energy was contained in the central spot 10 μm in diameter and the second half in the remaining part. The enveloping curve is the sum of the currents of ions of all charge states under the assumption that the secondary emission coefficient depends only slightly on the ion charge. A comparison of the collector current measured at a distance of 320 cm from the target with the calculated current (Fig. 7) allows a conclusion about the feasibility of a rather good prediction of the ion current density away from the target. A collector signal of the plasma ion current is given in Fig. 8.

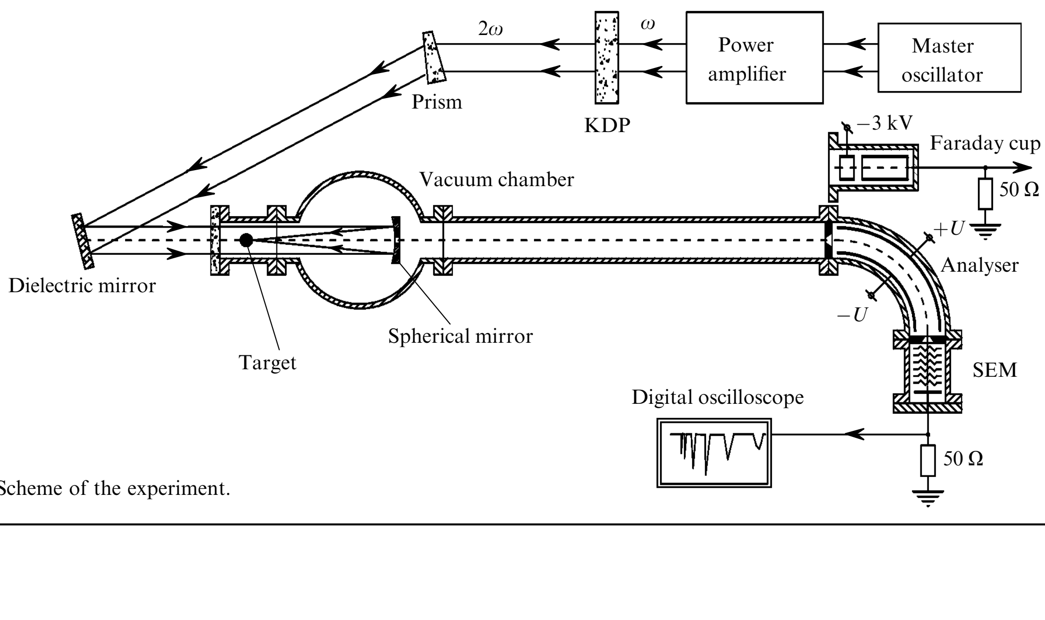

Figure 3. Scheme of the experiment.

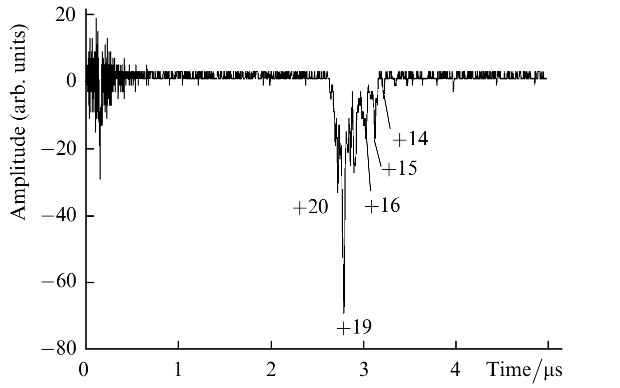

Figure 5. Ion signal from the electrostatic analyser for a laser pulse energy of 3 J and an accelerating potential of 2000 V.

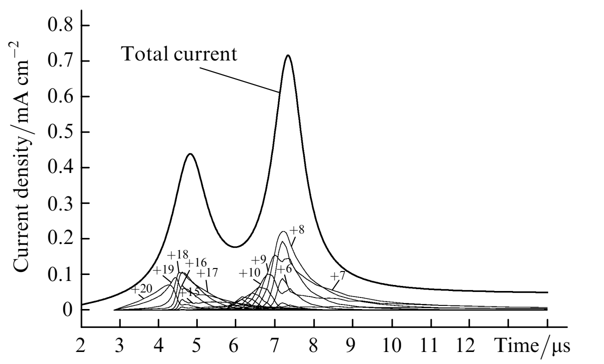

Figure 6. Theoretical calculation of the charge-state composition and energy spectrum of Ti ions.

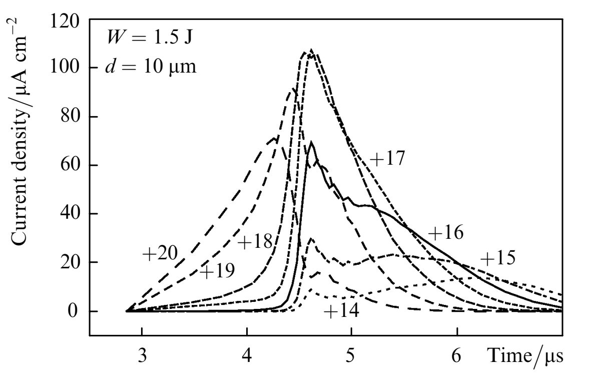

Figure 7. Comparison of the collector current measured at a distance of 320 cm from the target and the calculated current.

From the measured signals from the electrostatic analyser, we constructed the energy distributions (energy spectra) of Ti ions of different charge state for different energies of laser radiation. For instance, Fig. 9 presents the energy spectra of Ti ions for $W = 14$ J. One can see that the plasma analysed consists primarily of ions with charge states ranging from +16 to +20, i.e., a rather narrow energy spectrum is observed, and the total current density of the group of multiply charged ions is equal to about 1 mA cm^{-2} for an ion pulse duration of $\sim$0.8 μs (the number of ions is $\sim 10^9$, the ion beam aperture is $\sim$5 cm).

These data also imply that the plasma produced by the second harmonic radiation of a Nd laser can generate He-like Ti ions capable of travelling over long distances ($\sim$320 cm) from the target with retention of their charge

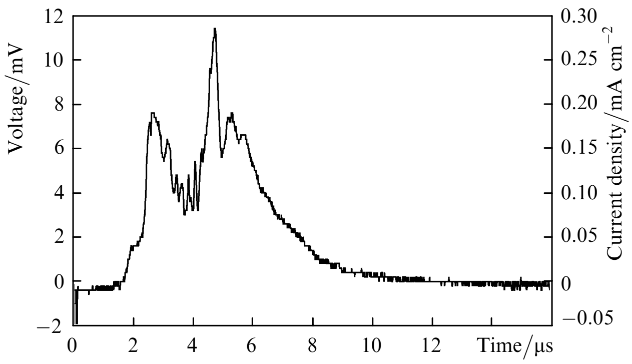

Figure 8. Collector signal of the ion current.

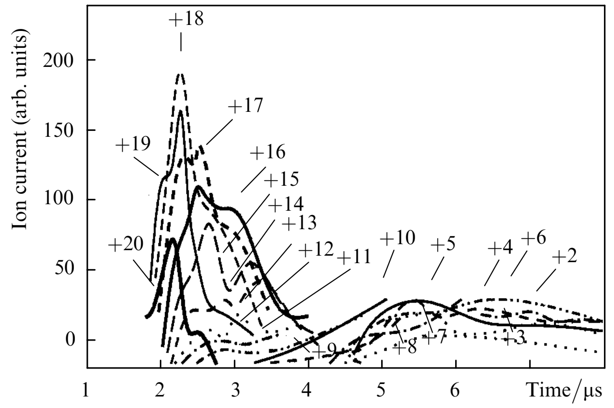

Figure 9. Energy spectra of Ti ions for $W = 14$ J.

state. The currents produced by these ions are close in value to those required of an ion injector. In the future, the development of a laser-driven particle injector operating with a repetition rate of 1 Hz and furnishing the generation of ion currents with a density of several mA per square centimetre and an ion charge state of $+3 - +5$ is quite feasible with the use of modern solid-state lasers.

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References

1. Laska L., Jungwirth K., Kralikova B., Krasa J., Pfeifer M., Rohlena K., Skala J., Ulschmied J., Badziak J., Parys P., Wolowski J., Woryna E., Gammino S., Torrisi L., Boody F., Hora H. *Plasma Phys. Control. Fusion*, **45**, 585 (2003).
2. Gammino S., Torrisi L., Ciavola G., Ando L., Wolowski J., Laska L., Krasa J., Picciotto A. *Nucl. Instr. Meth. Phys. Res. B*, **209**, 345 (2003).
3. Satov Yu., Sharkov B., Haseroth H., Smakovski Yu., Makarov K., Kondrashev S., Roerich V., Stepanov A., Kugler H., Scrivens R., Camut O., Shumshurov A., Balabaev A., Charushin A. *J. Rus. Las. Res.*, **25** (3), 205 (2004).
4. Koshkarev D.G., Sharkov B.Yu., Alexeev N.N. Project ITEP-TWAC. GSI-97-08 Annual report.
5. Woryna E., Parys P., Wolovski J., Krasa J., Laska L., Rohlena K., Stockli M.P., Winecki S., Walch B. *Rev. Sci. Instr.*, **69** (2), 1045 (1998).
6. Kil'pio A.V., Kochiev D.G., Malyutin A.A., Pashinin P.P., Suchkov Yu.A., Shashkov E.V. *Tr. Inst. Obshchei Fiz. Akad. Nauk*, **36**, 202 (1992).