AIP Review of Scientific Instruments

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Citation: Review of Scientific Instruments **63**, 2828 (1992); doi: 10.1063/1.1142819
View online: http://dx.doi.org/10.1063/1.1142819
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/63/4?ver=pdfcov
Published by the AIP Publishing

Charge state distribution of tantalum ions produced simultaneously by CO_2 and Nd:YAG laser from a laser ion source

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(Presented on 3 October 1991)

The influence of the combined interaction of a CO_2 laser (10.6 μm) and a Nd:YAG laser (1.06 μm) with a solid tantalum target has been investigated. Changing plasma parameters as temperature and density can be traced back by measurement of the charge state distribution after extraction from the expanding plasma. Analysis of the measurements for the single lasers as well as for the combined impact show an increase in plasma temperature, strongly depending on the delay between the two laser pulses. A maximum charge state rising from 11 + to 13 + can be observed.

I. INTRODUCTION

The ability of laser plasma ion sources to produce high charge states and tremendous pulsed currents has been demonstrated for quite a long time.[1-5] The search for the highest possible charge state produced in laser plasmas, however, seems to be limited by the maximum peak power of lasers available.[5] For solid state lasers this is mainly due to thermal stress in crystal or glass amplifiers, which cannot exceed a certain energy density without being damaged. Their thermal properties also limit the repetition rates of high power solid state amplifiers to less than one pulse per minute which is not usable for ion sources expected to run at about 1 Hz.

CO_2 lasers having a comparingly high output power as solid state lasers hardly achieve the same intensity (W/cm^2) in the focus because their wavelength is ten times higher and thus the focal area increases by a factor of 100.

Comparison with spectroscopic measurements show much higher charge states during the laser pulse than can be detected after extraction from the expanding plasma.[6] This can be understood from recombination processes in the expanding and cooling plasma.[7,8] A promising way to reduce this effect is to use a second laser to interact with the expanding plasma.

II. PLASMA PARAMETERS

In general, coupling between incoming laser light and a dense plasma is strongest in a thin layer near the critical electron density n_{cr} beyond which no propagation of the wave can take place:[9]

$$n_{cr}=(\epsilon_0 m_e \omega^2)/e^2, \quad (1)$$

where ω is the frequency of the laser light, ϵ_0 is the dielectric constant, m_e is the mass of the electron, and e is the elementary charge.

At intensities below 10^{14} W/cm^2 the dominant mechanism for the energy transfer from the radiation field to the plasma is via inverse bremsstrahlung, which leads to an electron temperature T_e related to laser and plasma parameters:

$$T_e=1.25\times 10^{-6}\cdot(A/\overline{Z})^{1/3}\cdot(\lambda^2\phi)^{2/3}, \quad (2)$$

where A is the mass of atoms, $\overline{Z}$ is the average charge state in the plasma, λ is the wavelength of the laser, and ϕ is the intensity in the focal spot.

Formation of charge states then takes place by multistep excitation and ionization followed by recombination in the expanding and cooling plasma. Ionization rate R for the Nd:YAG generated plasma ($n_{cr}=10^{21}$ cm^{-3}) as well as for the CO_2 laser ($n_{cr}=10^{19}$ cm^{-3}) can be described according to Ref. 10 as

$$R=2\times 10^{-6}\cdot N\cdot T_e^{1/2}/I_Z^2\cdot e^{-I_Z/T_e} \quad (\mathrm{cm}^3/\mathrm{s}), \quad (3)$$

where I_Z is the ionization energy for charge state Z, and N is the electrons in the outermost shell.

The recombination processes, however, are quite distinctive for different laser frequencies as the electron density determines the main recombination mechanism. For CO_2 laser produced plasma dielectronic ($R_{\mathrm{dielectronic}}$) and photo recombination (R_{photo}) are the most important processes,[10] leading to local thermal equilibrium between electron temperature and ionization level of ions:

$$R_{\mathrm{dielectronic}}=6\times 10^{-10}N(\overline{Z}/T_e)^{3/2}\cdot I_Z^{1/2}e^{-I_Z/T_e} \quad (\mathrm{cm}^3/\mathrm{s}) \quad (4)$$

and

$$R_{\mathrm{photo}}=2\times 10^{-13}(Z^2/T_e^{1/2}) \quad (\mathrm{cm}^3/\mathrm{s}). \quad (5)$$

Thus, for the equilibrium state when $d\overline{Z}/dt=0$ we will have

$$I_Z/T_e=56/I_Z^{1/4}\cdot\overline{Z}^{3/4}. \quad (6)$$

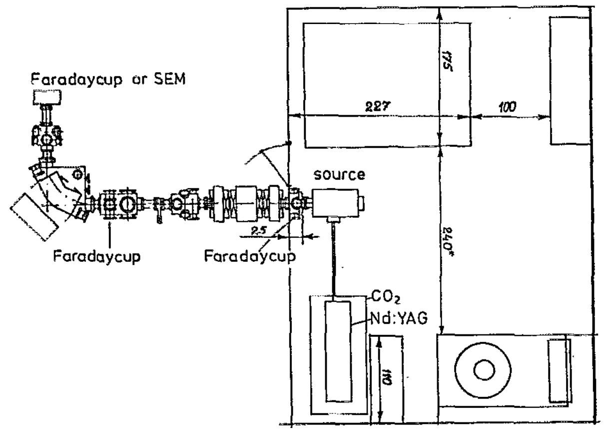

FIG. 1. Experimental setup at GSI, Darmstadt. Top view with lasers, source, time-of-flight setup, analyzing magnet and detector.

For heavy ions with observed charge states $Z = 10$–17 inside the plasma and electron temperatures $T_e = 90$–280 eV for a given $\lambda^2\phi$ [see Eq. (2)], this yields

$$I_Z/T_e = 1.5\text{–}2.4. \tag{7}$$

This must be compared to the equilibrium state for a Nd:YAG produced plasma, where three-body recombination R_{3b} becomes the dominant mechanism for equilibrium formation:

$$R_{3b} = 10^{-26} \cdot \overline{Z}^3 / T_e^{9/2} \cdot n_e \quad (\text{cm}^3/\text{s}), \tag{8}$$

as for the CO_2 case we can calculate a ratio of ionization level to electron temperature for the stationary state when $d\overline{Z}/dt = 0$:

$$e^{I_Z/T_e} = (10^7 T_e N)/(I_Z^2 \overline{Z}^2). \tag{9}$$

This, in combination with an electron temperature equal to the CO_2 case of $T_e = 90$–280 eV (the same $\lambda^2\phi$; Nd:YAG: 1.06 μm, CO_2: 10.6 μm) and observed charge states $Z = 14$–23 in the plasma, leads to

$$I_Z/T_e = 3\text{–}5. \tag{10}$$

These charge states, of course, cannot be extracted due to further recombination in the expanding plasma. The aim of the following experiment was to increase the temperature of the expanding plasma leading to reduced recombination.

III. EXPERIMENTAL SETUP

In the following experiment (Fig. 1) two lasers with comparable high intensity in the focal spot but different wavelength were combined. The Nd:YAG laser produces high charge states ($q = 11+$) which get lost by strong three-body recombination, dominant in the dense plasma and showing a strong temperature dependency [$\sim T_e^{9/2}$, cf. Eq. (8)]. A small increase in electron temperature should have a strong effect on recombination rates and on the charge states that can be extracted from the plasma.

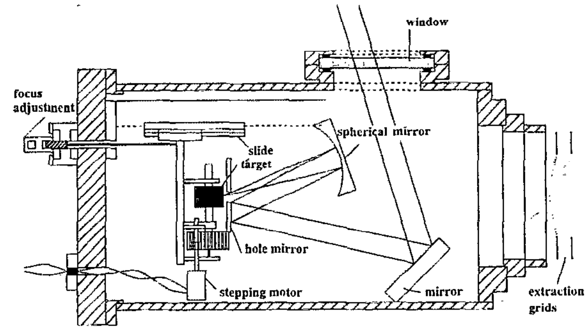

FIG. 2. Sectional drawing of the laser ion source.

Heating of the expanding plasma can be achieved by a CO_2 laser with a wavelength of 10.6 μm ($n_{cr} = 10^{19}$ cm^{-3}), which couples strongly to the expanding Nd:YAG produced plasma.

An earlier version of our laser-ion source[5] (Fig. 2) was modified to combine both laser beams in a common focal spot. For this purpose a multimirror system was inserted to prevent optical errors from chromatism, as occurring in prisms and lenses.

The expanding plasma was then extracted between two grids to peel off the electrons and accelerate the ions. They were detected by magnetic analysis and/or time-of-flight measurements with a shielded Faraday cup or a SEM.

IV. MEASUREMENTS

While the measurements of single laser impact could be achieved by scanning the magnet it was more difficult to get conclusive results with both laser beams impinging simultaneously onto the target. Looking in detail at the timing of both lasers in respect to each other, this could be traced back to a so far not overcome jitter in the laser firing. Due to this fact we used an analytical method not usual in magnetic analysis.

Instead of extracting the ions, the plasma is allowed to expand space charge neutral with its initial energy and momentum distribution.[5] The magnet, tuned for a low momentum of the ions, separates the electrons from the plasma and cuts a narrow momentum range out of every

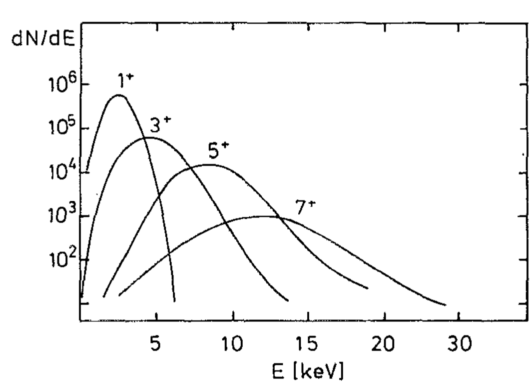

FIG. 3. Distribution of the expansion energy for different charge states.

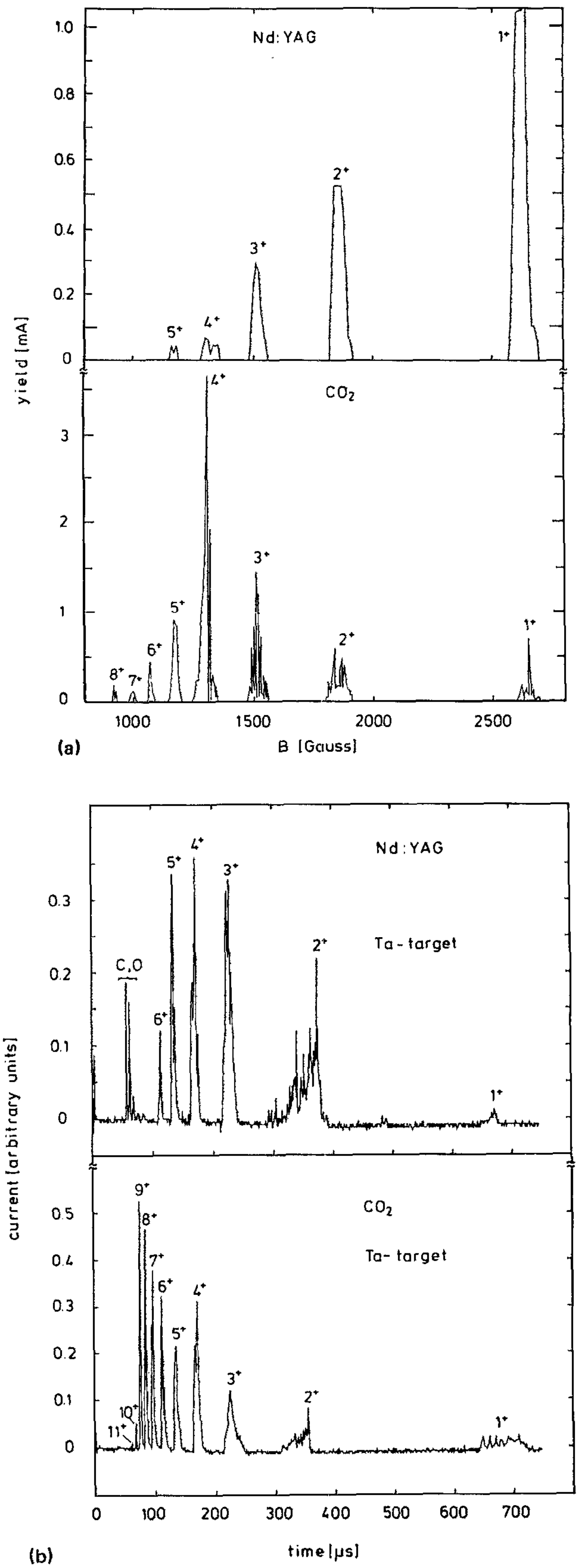

FIG. 4. Comparison of magnetic analysis with and without extraction voltage. Upper (spectrum): extraction voltage and scanning of magnet, Faraday cup; top for Nd:YAG, bottom for CO_2. Lower (spectrum): expansion of plasma and analysis by time-of-flight measurement, SEM; top for Nd:YAG, bottom for CO_2.

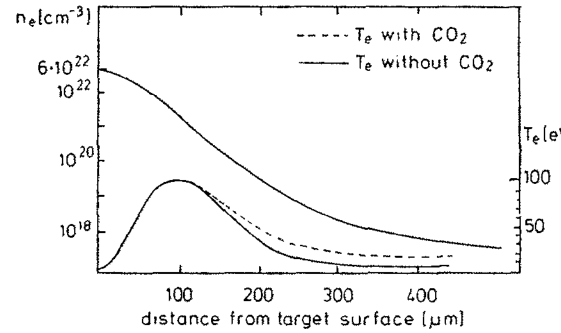

FIG. 5. Calculation of electron temperature and electron density as function of distance from the target surface for single laser (solid line) and both lasers (dashed line) impact (Ref. 10).

charge state. This, however, is only possible for laser produced plasma with its large energy spread[2,5,11] (Fig. 3).

The individual charge states are clearly identified by their time of flight. Comparison with magnetic analysis shows an excellent qualitative agreement for both methods (Fig. 4). Not yet mentioned so far is another advantage of this analytical method: information on all charge states in a single shot. This makes it possible to observe the timing of the lasers and to relate it to the achieved charge spectra.

The combined measurements can now be compared to the single laser shots. With correct timing (i.e., the Nd:YAG pulse on the rising edge of the CO_2 pulse), the maximum charge state detectable rises from $11+$ to $13+$, increasing the ionization level from 213 to 261 eV. This, however, depends strongly on the delay between the laser pulses.

V. CONCLUSION

The increase in maximum charge state for the simultaneous impact of a Nd:YAG laser and a CO_2 laser indicates a higher electron temperature in the expanding plasma plume compared to single laser impact. Calculations[10] also show a plasma temperature rising from 20 to 30 eV at the critical density for CO_2 radiation ($n_{cr} = 10^{19}\ \mathrm{cm}^{-3}$, Fig. 6), thus reducing 3b recombination by a factor of 6.

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