J. Phys. D: Appl. Phys. **24** (1991) 2229–2231. Printed in the UK

RAPID COMMUNICATION

Energy efficiency of laser produced C- and Ta-ion sources

A Rupp and K Rohr

Universität Kaiserslautern, Fachbereich Physik, D-6750 Kaiserslautern, Federal Republic of Germany

Received 16 August 1991

Abstract. The conversion efficiency of laser energy into kinetic ion energy in a laser-produced plasma has been investigated for two quite different targets: graphite and tantalum. The laser energy (intensity) varied from several mJ to 200 mJ (10^9 to 7×10^{10} W cm^{-2}) which is appropriate to many applications of a laser produced ion source. The conversion efficiency as a function of the laser energy was directly determined by differential measurements of the charge, kinetic energy and angular emission distribution of the plasma ions in absolute units. Whilst for the Ta target a nearly constant efficiency of about 30% was observed, the graphite result shows an unexpectedly strong enhancement of the transfer efficiency of up to 80% in the laser intensity range around 1.5×10^{10} W cm^{-2}. It is assumed that the results are related to the difference in the surface roughness of the targets.

Laser produced plasmas are of growing interest as ion sources in many applications. Above all these are laser induced mass analysis techniques (LIMA), laser pulse vapour deposition (LPVD) and generation of highly charged ion beams for scattering experiments. Generally the laser intensity range of interest for these applications is from the threshold of plasma generation (10^8–10^9 W cm^{-2}) to about 10^{12} W cm^{-2}. In this range very low reflectance is observed, which is the basic requirement for an efficient energy transfer of the laser energy into particle energy of the differentially charged ions. The high absorption efficiency has been explained theoretically by assuming inverse bremsstrahlung as the dominating absorption mechanism (Johnston and Dawson 1973). Experimentally such a situation can be optimized by an appropriate choice of laser–target conditions. Absorption and reflection measurements have been carried out as a function of e.g., laser intensity, pulse duration and wavelength (Maaswinkel *et al* 1979, Ripin *et al* 1979, Nishimura *et al* 1983, Garban-Labaune *et al* 1985), angle of incidence (Shearer 1971, Mead *et al* 1983), target material (Seka *et al* 1982, Amman *et al* 1980, Garban-Labaune *et al* 1982), focal spot diameter (Bykovskii *et al* 1976, Pant *et al* 1980, Lewis *et al* 1982) and target surface structure (Donaldson *et al* 1980). The results show that the absorption can range up to more than 90%. Unfortunately, in most of these investigations the laser parameters were out of the range of interest of the above-mentioned applications and the results can only be used as a guideline for an upper limit of the kinetic ion energy blown off. The latter can be obtained indirectly if the fractions of the complementary energy distribution channels are known. By this method Boland *et al* (1968) have concluded that almost 80% or more of the incident energy is converted to kinetic energy of the ions, while Fauquignon and Floux (1970) have calculated a value of 50%.

In the present experiment we have directly measured, for the first time as far as we know, the kinetic energy contribution to the different ions without any approximations. This method affords differential measurement of the charge, energy and angular emission distribution of the plasma ions in absolute units as a function of the laser energy (intensity). By comparative measurements we have obtained for an experimental situation and laser intensities typical for many applications, the ion energy conversion efficiency for two targets which are quite different in their surface structure and atomic features: graphite and tantalum. It has been the aim of the investigation to achieve data with a reliability considerably higher than has been previously attempted.

A schema of the experiment is given in figure 1. Plasma is created by a Nd–YAG Q-switch pulse (TEM$_{00}$, $\lambda = 1.06\,\mu$m, $\tau = 14$ ns) of variable energy incident at an angle of 45° onto the target which consists of a thick flat disc of graphite and tantalum. The laser energy

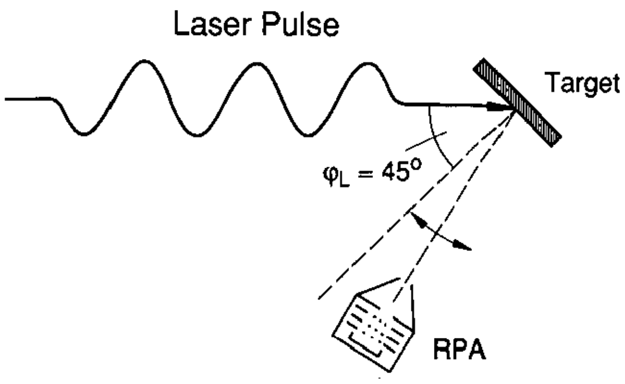

Figure 1. Schematic diagram of the experimental set-up. Ion analysis is charge and energy resolved within the plane of incidence.

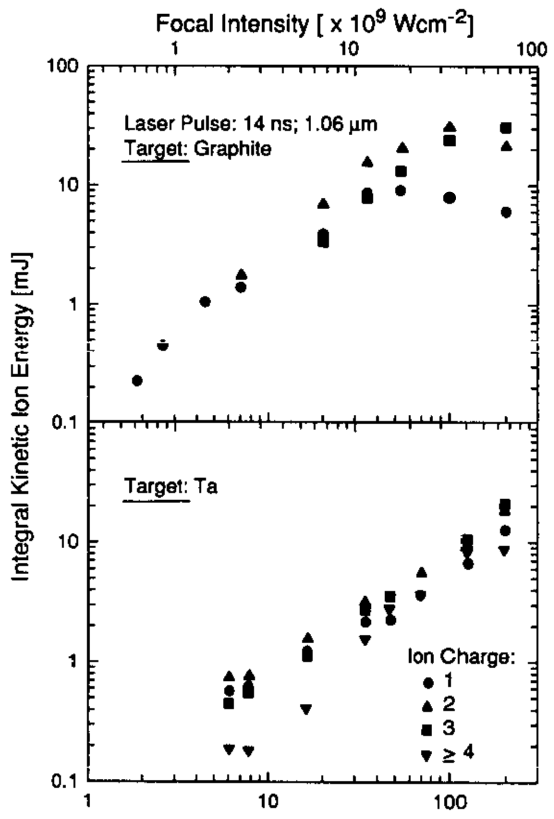

Figure 2. Integral kinetic energy of the emitted C (upper part) and Ta (lower part) ions as a function of the laser energy (intensity). Except for the C^+ ions, a continuous increase of the energy transfer, although with different gradients, is observed for the different species in the whole laser range investigated.

ranges from several mJ (threshold for plasma production) to 200 mJ. For a constant focal diameter of 140 μm (full $1/e^2$ width) this corresponds to intensities from about 10^9 to 7×10^{10} W cm^{-2}. The laser energy and pulse shape are controlled continuously. The allowed deviations in the laser energy are below 3%. The plasma expands freely into vacuum and the ions are analysed according to their charge and velocity

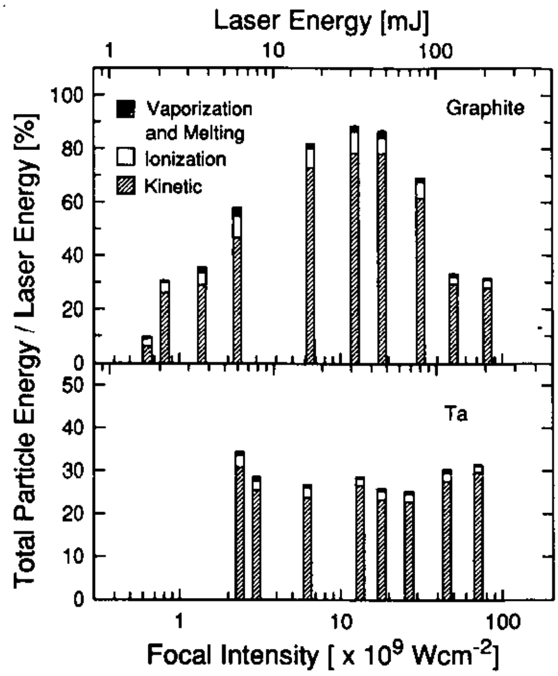

Figure 3. Energy transfer efficiency for a graphite (upper part) and a Ta target. For Ta an essentially constant efficiency of 30% for the kinetic energy transfer is observed. In contrast the graphite result exhibits a strong maximum with an efficiency of up to 80% at a laser intensity of about 1.5×10^{10} W cm^{-2}.

distributions as a function of the angle in the plane of incidence. Detection is by means of the combined time-of-flight retarding potential method. The differential spectra are multiscaled at least ten times and the observed shot-to-shot deviations for the absolute number of ions are below 15% for the larger part of the spectra with the maximum uncertainty below 40% for the highest energies and charges. Details of the experimental arrangement and the measurement procedure have been described in earlier publications (e.g. Mann and Rohr 1991).

Total kinetic ion energies are obtained by integrating the measured data over the half-space and the corresponding kinetic energy distributions. Thereby rotational symmetry was assumed for the emission cone which was confirmed to be realistic by several single spot checks.

The results for the two target materials are shown as a function of the laser energy (intensity) in the upper and lower part of figure 2. As a common feature it is observed that the integral kinetic energy of the ions generally increases with the laser energy, at least below about 50 mJ although with a different gradient. This increase is due to an enhancement of both the number of particles and of their velocity. For higher laser energies the carbon result indicates a saturation for the C^+ and C^{2+} ions. The additionally absorbed energy is increasingly transferred to the C^{3+} ions. A similar behaviour is observed in the lower part of figure 2 for the Ta-ions: the increase is strongest for the highest charges but no saturation is apparent for the lower charged ions.

The kinetic energy content per ion species in the case of tantalum is below 10% throughout the energy range investigated. The carbon result differs from this finding. This becomes apparent if, as in figure 3, the total kinetic energy conversion efficiency for the summed-up species is obtained as a function of the laser intensity (energy). Whilst for Ta the energy ratio is essentially constant ($\approx$30%), the carbon results show a continuous increase from threshold up to an unexpectedly strong maximum somewhat above 30 mJ (1.5×10^{10} W cm^{-2}). Here the kinetic energy of the ions reaches 80% of the total laser pulse energy. For still higher laser energies the ratio approaches the same value as for Ta. In both cases most of the energy of the detected ions is kinetic; vaporization, melting and ionization amount to only about 10% of the kinetic part.

Contrasting the two materials C and Ta, one would generally expect a higher absorption in the case of the high-Z target due to an increased inverse bremsstrahlung efficiency (Garban-Labaune *et al* 1982, Amman *et al* 1980). On the other hand, the higher roughness of the graphite surface compared with the nearly optically flat Ta surface reduces the reflection losses of the laser (Donaldson *et al* 1980). The two effects essentially balance each other if one looks at the nearly equal kinetic energies of the C and Ta ions in the laser energy region above 100 mJ.

The strong enhancement of the energy transfer efficiency in a limited range of the laser intensity, in the case of carbon, appears to be similarly strongly related to the roughness of the graphite target. The effect occurs despite the fact that the large angle of the laser (45°) should be unfavourable for the absorption (Shearer 1971, Mead *et al* 1983). It seems difficult, however, to explain the phenomenon without further knowledge about the actual conditions in the plasma focus in a situation like this. Investigations would be highly desirable, however, since the effect should be of considerable importance in optimizing laser-produced ion sources. Consequently, the graphite result also has a drastic influence on the energy partition of the laser energy to competing transfer channels, which in the present range of laser intensities where nonlinear processes can be neglected, are above all reflected laser light, recoil energy, plasma radiation, heat transfer and energy of the neutrals. If for the charged particles, vaporization, melting and ionization are included in the maximum in figure 3 there remains only 13% of the laser energy for all energy transfer and loss channels together. If it is assumed that laser absorption is 100% the residual energy for the competing channels is only about 4 mJ.

This work has been supported by the Deutsche Forschungsgemeinschaft under the Sonderforschungsbereich 91.

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