ION EMISSION FROM HIGH-Z LASER PLASMAS

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Abstract

The results of systematic studies of ion emission from plasmas generated in the focus of laser beams of short wavelengths, short pulse lasers (Nd:glass, 1 *ns*, 1060 *nm*; iodine, 0.5 *ns*, 1st harm.- 1315 *nm* 2nd harm.- 675 *nm*, 3rd harm.- 483 *nm*) are presented. The corpuscular diagnostics were based on (i) Thomson parabola spectrometer to display a general view of the ion spectra, (ii) cylindrical electrostatic ion energy analyzer to determine the detailed charge-energy ion spectra (iii) ion collectors to estimate the current density of the ion fluxes far from the focus. The ion current densities about 1 *m* from the focus are typically mA/cm^2. Fairly high charge state (>50+) and simultaneously energetic (>8 *MeV*) ions were registered. The results are interpreted either in term of a two-temperature model of the expanding plasma or by an ion emission from a dual focal spot including a hot primary focus and a colder peripheral zone.

Introduction

An expanding laser plasma is an efficient source of highly charged ions [1]. It is formed by focusing a nanosecond laser beam on a target. In the plasma corona an intense collisional ionization is going on. If the plasma is left to expand the phenomenon of charge freezing sets in. Due to the fast expansion the plasma is diluted before the recombination eradicates all the highly ionized ion species. Hence, at least part of the ions has a chance to conserve the charge state acquired in the hot plasma core and carry it at a considerable distance away from the focus. There, the ions can then be either registered by various sensors of particle diagnostics, such as ion collectors and ion analyzers (Thomson or electrostatic), or after a separation of electrons they can be transformed in an ion beam and introduced in a beam line of an accelerating system. In the following we shall concentrate, in particular, on the subnanosecond pulse laser in the near infrared region.

Laser drivers

The photodissociation iodine laser PERUN [2] in the Institute of Physics of AS CR in Prague is operating at the wavelength 1.315 μm, producing pulses of $\sim$ 50 J, which are roughly 350-500 *ps* long and can be focused in a spot size (lens optics) of 80 μm . The average power density attainable on the target is thus $\sim 10^{15}$ Wcm^{-2}. Frequency conversion by DKDP crystals to 2ω and 3ω is available with about 50% efficiency. The target chamber was fitted either with an aspherical f/2 (f = 20 *cm*) lens or alternatively, with a mirror (f = 28.5 *cm*) having a 12 *mm* hole in the centre to allow access to the part of the plasma expanding directly against the laser beam. The mirror focal spot is somewhat larger ($\sim$ 100 μm) than with the lens focus.

The Nd:glass laser in the Institute of Plasma Physics and Laser Microfusion in Warsaw gives at maximum 15 *J* at 1.06 μm in 1 *ns* pulses. The spot size with lens optics is about 100 μm with a power density on the target $< 6 \times 10^{13}$ Wcm^{-2}. Besides the aspherical focusing lens a combination of a lens with an ellipsoidal mirror with a central hole was used.

The CO_2 Lumonics TEA 601 laser [3] gives 50 *J* in a 50 - 70 *ns* pulse. The power density on the target is $\sim 2 \times 10^{12}$ Wcm^{-2}. Focusing is with a parabolic mirror f = 30 *cm* with a hole of 30 *mm*.

The CO_2 TIR-1 system at Troitsk [4] delivers about 100 *J* in either 25 *ns* or 2.5 *ns* pulses. The focusing system using a parabolic mirror f = 60 *cm* with a hole of 25 *mm* achieves the power density on the target either $\sim 4 \times 10^{13}$ Wcm^{-2} or $\sim 6 \times 10^{14}$ Wcm^{-2}.

At this stage of development the potential performance of laser ion source is synonymous with the results of particle diagnostics of the expanding laser plasma. None of the near infrared lasers used has an adjoint LEBT line or an RFQ to assess directly the quality of the preaccelerated ion beam. Nevertheless, the charge-energy spectra of the expanding laser plasma allow for qualified estimates of at least some properties of the ion beam derived from such a plasma.

Results

The collector signal usually indicates several ion groups, which are separated by the time-of-flight effect. The highest charge is carried by the fastest group, to which the following table relates. It presents the results obtained with the first harmonics of the iodine PERUN system for various elements. The geometry of the measurements was either a coaxial one using a mirror (M) or the measurements were off the axis using a lens (L) focus.

Table 1. was compiled by uniting the data of IC measurements in two different distances from the focus. In the case of lens focus the IC collector was 94 *cm* from the focus, with the mirror the distance of a coaxial IC was 174 *cm*. The current densities are the peak values of the fast ion signal, recalculated in each case to the shorter distance of 94 *cm* using a quadratic law. The values for the mirror case are thus estimated fairly conservatively, [5].

Table 1

Elem.	$< z_{fast} >$	$< E_{fast} >$ [keV/u]	$j[mAcm^{-2}]$
Co (M)	22 (25)	32.7	14.2
Ni (M)	20 (26)	15.7	18.5
Cu (L)	(25)		
Ta (L)	(55)		12.8
Ta (M)	42 (48)	12.7	22.8
W (M)	45 (49)	10.9	22.8
Pt (M)	45 (50)	15.9	12.8
Au (M)	38 (49)	15.7	7.0
Pb (M)	40 (51)	15.9	8.5
Bi (M)	40 (51)	12.9	10.0

It would seem that the sharper focus for the lens case yields higher maximum charge numbers (values in parentheses second column) and that the higher currents are emitted from the larger mirror foci. In reality, the dependence of the ion current as well as of the maximum charge number on the power density and on the size of the focal spot are not trivial and are different in character. It is more likely that the differences between the mirror and lens geometry are given by the directional characteristics of the ion emission. When defocusing the dependence of the current has a sharp peak for the maximum power density, whilst the maximum charge number changes just slowly. This has implications, for instance, for the quality of the target surface, in particular, when placing several shots in the same spot and a crater is formed, [6].

The results are to be understood in the following way: the plasma is formed by a short intense pulse, in its hot core the electron temperature is exceeding 1 *keV* and the system is essentially in a thermal equilibrium. The highly charged ions are born in the core by an intense collisional ionization. During the expansion stage the electron temperature is falling fast, because also the laser power in the case of the short pulse goes down quickly. Not even the recombination heating can maintain the temperature on a steady level. The temperature is decreasing when the ions are still passing through a comparatively dense region. Owing to the temperature drop, the recombination sets in. The high charge states will thus be destroyed before the system is (due to the fast expansion) out of the thermodynamic equilibrium and the high charge states have been “frozen in”. Especially vulnerable are the high z ions. This scenario applies to the thermal ion group, which follows the fast group and is carrying charge states, which are generally lower.

The existence of the fast group is pointing to an accelerated expansion mechanism. Such a mechanism is triggered by a group of superthermal (hot) electrons which originate from a non-dissipative laser energy deposition in the plasma. A part of the primary laser energy is transformed in electrostatic plasma waves, which accelerate the plasma electrons by the mechanism of inverted Landau damping. The resulting hot electron population is guiding the fast plasma expansion contributing thus to a survival of highly charged species.

From what has been said it is clear that an ideal laser driver should provide both the fast plasma ionization to attain as high charge state as possible and also a fast expansion to conserve the charge once formed in the core by suppressing the recombination during the expansion stage. These two requirements are difficult to meet at once. The ionization rate is mainly controlled by the electron density in the vicinity of the critical surface in the plasma, i.e. the density surface where the electron plasma frequency equals the laser frequency, $\omega_L = \omega_{ec}$,

$$n_{ec} = \omega_L^2 \frac{m}{4\pi e^2} \qquad (1)$$

beyond which the laser radiation cannot penetrate (n_{ec} is the critical electron number density, e is the elementary charge and m is the electron mass). Another factor determining the maximum attainable ionization degree is the time available for the ionization process. It is either equal to the characteristic hydrodynamic build-up time τ_{hydr} of the plasma plume, which is also the residence time of an ion inside the hot plasma core

$$\tau_{hydr} = R_{spot} / C_s \ , \qquad C_s = \sqrt{\frac{< z > (n_{th} + n_h)}{M(n_{th} / T_{th} + n_h / T_h)}} \ , \qquad (2)$$

or to the laser pulse time, τ_L , which one happens to be shorter (n_{th}, n_h, $n_e = n_{th} + n_h$, and T_{th}, T_h are the number densities and temperatures of thermal and hot electron population, R_{spot} is the focal radius, M is the ion mass, C_s is the ion acoustic velocity and $< z >$ is the mean charge).

For a well tuned laser the hydrodynamic time should thus be shorter or equal to the laser pulse duration,

$$\tau_{hydr} \le \tau_L \qquad (3)$$

to use the ionization process to a full advantage [7].

Conclusion - comparison of various lasers

In the previous sections mainly the performance of the iodine laser was being assessed, in the following we shall use the same criteria for the other types of laser driver. Since the frequency conversion changes the wavelength, the iodine laser with a beam converted to higher harmonics (2ω and 3ω) will be considered as separate cases.

CO_2 drivers: The CO_2 lasers are an obvious choice for their high repetition rate and commercial availability. They also have usually a long pulse, meeting thus the criterion (3). However, owing to a long wavelengths (10.6 μm) the critical density (1) is too low and the ionization is slow. The highest attainable ionization degree is thus lower than that of the short wavelength lasers. Moreover, the focusability of the beam is usually bad, which reduces the power density on the target. Also, the pulse tends to have a fairly long "ramp", containing a non-negligible portion of the total energy, which induces low temperature phenomena on the target like digging an outsized crater and a splutter of the target material.

Nd:glass laser performance is not, in principle, different from that of iodine, it has a slightly longer pulse, which is a favourable feature, the energy is less controllable. A repetitive action is more difficult to implement, because of a heat build-up in the glass, but a future diode pumping might solve the problem.

Converted iodine 2ω, 3ω is giving about the same results as 1ω , but with less acceleration. Clearly, the fast expansion phase is missing, the hot electrons are absent. This means that in the hot plasma core, which is considerably more dense than in the case of 1ω , see (1), much higher charge states are formed, which only partially recombine during the expansion. A second maximum of very slow ions, which sometimes appears on the collector signal, is likely caused by an emission from a peripheral part of the focus, which is heated by an intense x-ray radiation of the primary plasma. A direct experimental prove of the existence of very highly ionized species in the focal spot created by the blue 3ω beam is, unfortunately, still missing, though the calculations seem to point in this direction.

An extrapolation towards still shorter wavelength points out that the use of excimer lasers (such as *KrF*) in the ultraviolet range should be given a serious thought. These lasers are technically related to CO_2 , are easy to operate in a repetitive regime and the deposition of laser energy in the plasma is very high. There are however difficulties with controlling the pulse shape, especially in the nanosecond range, but at least in a single pulse regime the ways of circumventing them are known.

A repetitive action is neither easy to implement in the case of iodine lasers. Though the sealed-off systems are known to operate with the frequency nearly 1 *Hz* at about 70 *J* of energy [8], the operation is in the free running regime and the pulse is thus far from being in the nanosecond range. There should be, in principle, no difficulties in changing the generation regime to obtain a subnanosecond pulse with the same rep rate, but this would mean to sacrifice a part of the energy. A serious obstacle is also the cost of such a would-be instrument, which might lie anywhere between 300 and 1000 k$ (US) .

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References

[1] H.Haseroth, H.Hora in "New Methods and Technologies", Chapter IV, Advances of Accelerator Physics and Technologies, Singapore, World Scientific, Singapore, Ed. E. Schopper, 466 (1993)
[2] M. Chvojka et al., Czech. J. Phys., 42, 899 (1992)
[3] R. Sherwood et al., "CERN Laser Ion Source Technical Meeting", CERN, 25th May 1994: J. Tambini, 4th WILA'95, Trest Castle, Proc. SPIE, Vol. 2762, 70 (1995)
[4] S.M. Kozikhin et al., Kurchatov Inst. Rep. IAE-5635/7, Moscow (1993)
[5] K. Roklena et al., BEAMS '96, Prague, (1996)
[6] J. Wolowski et al., "Feasability of short wavelength, short pulse laser ion source for the LHC injector", the following paper of this volume, see further citations, ibid
[7] J. Farny et al., to be published
[8] L.A. Schlie, 4th WILA'95, Trest Castle, Proc. SPIE, Vol. 2762, 28 (1995)