INTERPRETATION OF CHARGE SPECTRA OF IONS IN AN EXPANDING LASER PLASMA

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Abstract

Model calculations of ion composition of the expanding laser plasma generated on a high-Z target by a subnanosecond laser pulse in a near infrared region *(1)* a simplified model using a semianalytic approach and *(2)* a full hydrodynamic model are compared. The key fact respected in both the models is the presence of high charge states in a far expansion region. The simplified model, however, renders an unrealistically low value of the collector current. This feature corrected in the full hydrodynamic model is thought to be a consequence of an inconsistency in the treatment of the initial expansion stage. In both the models, however, a discrepancy persists in rendering the ion spectra.

1. Introduction

Experiments with laser ion sources for large colliders in particle physics or for ion implantation motivated the need for a deeper understanding of source physics. The underlying principle is a fast expansion of the laser plasma formed by a nanosecond laser pulse focused on a target leading to the phenomenon of charge freezing. The freezing of high charge states can be modelled hydrodynamically. The expansion stage means a conversion of the plasma thermal energy in the kinetic energy by an adiabatic process leading to a drop in the plasma temperature. A low temperature enhances three-body recombination (proportional to $\sim n_e z^3 T_e^{9/2}$). The recombination heating may partially compensate the electron temperature drop and reduce the recombination rate. However, when considering a sub-nanosecond laser pulse in a NIR region (such as iodine lasers working on the first harmonics $\lambda = 1.315 \mu m$) a simple hydrodynamic model combined with an ion balance during the expansion stage is predicting a substantial neutralization of the high charge species very near (typically cm) from the target. Consequently, the ion placed far from the target diagnostics should record no high charge states (exceeding 20+). Contrary to these findings the experimental evidence points to the occurrence of high charge species in the far expansion zone. When working with the high Z elements, a typical charge number corresponds to Ni-like ions, such as $Ta^{45+}, Au^{51+}, Pb^{54+}, Bi^{55+}$, e.t.c. This discrepancy was resolved in terms of accelerated expansion guided by a fast electron group. The fast electron population is formed in the laser plasma by non-dissipative energy deposition processes during the heating stage. There are several mechanisms converting the transverse

light wave of the heating beam in a family of longitudinal electrostatic plasma waves, which then, in turn, accelerate the electrons by the mechanism of Landau damping. Although in the fusion experiments the fast electrons are not desirable, because they are causing target pre-heat, the expansion is accelerated by their presence and the recombination is suppressed giving a chance to the high ion charge states to survive. To illustrate the above mechanism results of two models will be presented. The first is a semi-analytic one, describing the formation stage of the plasma by a simple analytical description of the two-temperature plasma followed by a detailed ion balance during the expansion stage. The second is a full computational model with the hot electron population included. Both the models seem to account for the presence of the high ion charge states in the large distances from the target, the full hydrodynamic model, however, gives, in addition, also correct values of the collector current densities.

2. Modelling the plasma expansion

The plasma expansion proceeds in two stages. The first stage is lasting while the laser pulse is on and it describes the development of plasma plume (corona) above the target surface. This expansion stage is essentially isothermal. The size of the forming plasma plume is given by the diameter of the laser spot. Inside the plasma an intense ionization is going on by electronic collisions. The residential time of an ion in the ionizing environment of the hot plasma plume is given by the spot size divided by the ion acoustic velocity. The time available for the ionization is thus given either by this residential time or by the laser pulse duration, whichever is shorter. The second stage starts after extinguishing of the laser pulse and it corresponds to a nearly adiabatic expansion, since the only heating comes from the recombination. It is during this stage, when the charge freezing occurs.

The spatial distribution of plasma parameters at the end of the isothermal expansion can be regarded as the initial condition for the adiabatic stage. The plasma is divided in separate slabs, which are then left to fly apart with the initial density, velocity and temperature given by their position within the initial plasma profile. However, since we are in the first place interested in the ion densities evolution it is necessary to evaluate the distribution of ion species in each of the slabs. This is done by solving a set of local balance equation for ionic species densities n_z

$$
\begin{aligned}
dn_z/dt \quad = \quad & n_{th}[n_{z-1}(S_{g,z-1} + S_{ex,z-1}) + n_{z+1}(\alpha_{r,z+1} + \alpha_{3b,z+1}) - \\
& n_z(S_{g,z} + S_{ex,z} + \alpha_{r,z} + \alpha_{3b,z})], 0 \leq z \leq z_{max}
\end{aligned}
\tag{1}
$$

The production terms included describe the ionization from the ground state $S_{g,z}$ and the ionization via high excited states $S_{ex,z}$, n_{th} is the majority thermal electron group density, T_{th} its temperature. As the processes lowering the ion charge the radiative $\alpha_{r,z}$ and three-body $\alpha_{3b,z}$ recombination were taken into account.

Integrating these equation for the given parameters n_{th} and T_{th} we obtain the time dependent ion distribution, which yield supplementary initial conditions for modelling the charge species evolution during the "adiabatic" expansion stage of the laser-produced plasma. In this second stage of expansion, essentially the same system of balance equation for the ion species is solved inside each flying plasma slab, the temperature, however, now follows the adiabatic law with

the recombination heating included

$$\frac{dn_z}{dr} = n_{th}\{[\alpha_{rad}(z+1, T_{th}) + \alpha_{3b}(z+1, T_{th})]\, n_{z+1} -$$
$$- [\alpha_{rad}(z, T_{th}) + \alpha_{3b}(z, T_{th})]\, n_z\}/v_r, \tag{2}$$
$$\frac{dT_{th}}{dr} = -\frac{2T_{th}}{r} + \frac{2}{3v_r}\sum_z [E_{rec}(z, T_{th}) + \frac{3T_{th}}{2}]\alpha_{3b}(z, T_{th})\, n_z. \tag{3}$$

r is the coordinate of the flying slab and v_r is the velocity of its free and isotropic spherical expansion, E_{rec} is the recombination heating rate. The collector signal in the distance r_{coll} is reconstructed by considering the contributions of the slabs arriving with the time delay r_{coll}/v_r at a collector.

3. Examples

As an example of the method just described collector signal will be calculated using a specific approximation for the first (isothermal) stage of the expansion. An analysis for the *planar* case of the two-temperature plasma density profile [1] gives

$$n_e = n_{th} + n_h \quad n_{th} = n_{th0}exp(e\Phi/T_{th}) \quad n_h = n_{h0}exp(e\Phi/T_h) \tag{4}$$

Φ is the plasma potential (e is the elementary charge), which is tied to the densities n_{th}, n_h and temperatures T_{th}, T_h by an implicit relation, n_e is the total electron density. Applying the procedure described above the results shown in Figs. 1, 2 are obtained. The collector current density Fig. 1, which experimentally should lie in the $mAcm^{-2}$ region is rendered, however, too low by this simplified model. We suspect that the discrepancy is caused by the application of the planar analytic approximation of the first isothermal expansion stage as given by (4) to the subsequent spherical adiabatic expansion. On the other hand, the high charge states are present in the calculated ion spectra, even if the high charge state is somewhat exaggerated as against the experimental finding, Fig. 2.

To correct the above mentioned discrepancy, a full hydrodynamic code was run to calculate the collector spectra. This code, in difference to the approximate procedure described above, treats also the first heating stage of the plasma formation (isothermal expansion) numerically. The adiabatic expansion is essentially treated as in the approximate model. The results are shown in Fig. 3, 4. It is seen that the resulting collector current density is for the case of full hydrodynamic treatment described realistically Fig. 3. The charge spectrum, however, still deviates from the experimental one.

Reference

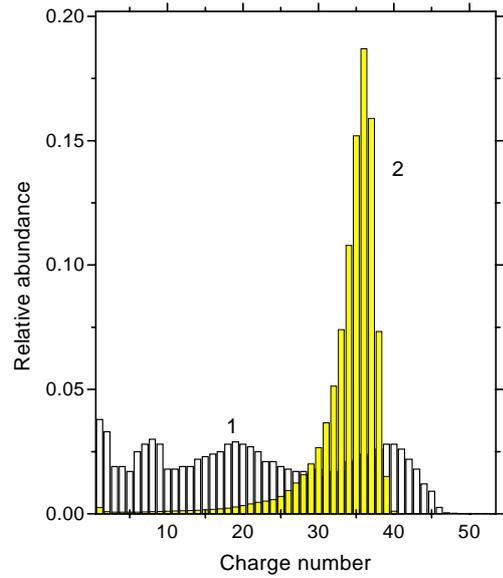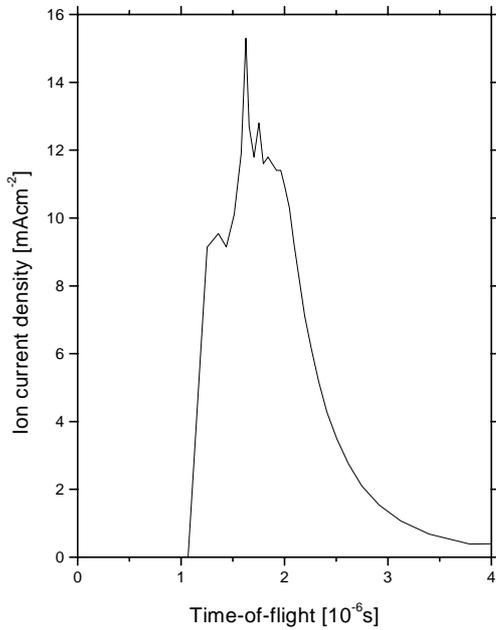[1] L.M. Wickens and J.E. Allen: "Free expansion of a plasma with two electron temperatures." J. Plasma Physics P1 **22**, 167-185, 1979.
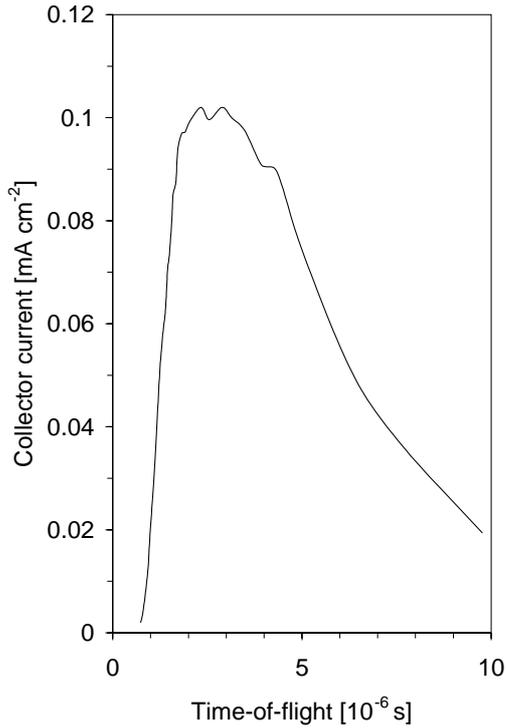
Fig. 1. A typical form of the collector signal calculated for $\lambda = 1.315\ \mu$m. Ta target, parameters: distance from the target 145 cm, T_{th} =880 eV, $T_h =$

Fig. 2. Percentage abundance of Ta-ions (ion charge spectrum). $E_L(1\omega)$ = 29.5 J. 1-experiment, 2-theory

Fig. 3. Collector signal calculated from the full hydrodynamic model. Ta target, parameters: distance from the target 174 cm, hot electrons at 8.5keV taking **25%** of the absorbed laser energy. $E_L(1\omega)$ = 19.1 J, focal spot 100 μm, pulse length 500ps.
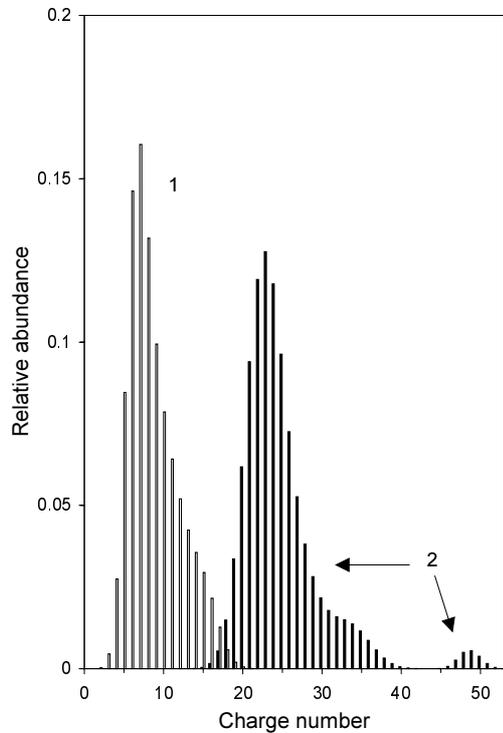
Fig. 4. Ion spectra for the parameters of Fig. 3, hydrodynamic model: 1-without the hot electrons, 2-with hot electrons.