INVESTIGATION OF THE HIGH-Z LASER-PRODUCED PLASMA WITH THE USE OF ION DIAGNOSTICS FOR OPTIMIZATION OF THE LASER INTERACTION WITH THE HOHLRAUM-TYPE TARGETS (preliminary studies)

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Abstract. This paper presents the program of the Research Contract Proposal No. 11535/RBF. entitled: "Investigation of the high-Z laser-produced plasma with the use of ion diagnostics for optimization of the laser interaction with the hohlraum-type targets" included to the Research Project: "Elements of Power Plant Design for Inertial Fusion Energy" co-ordinated by the IAEA. We also report the preliminary experiments performed at the IPPLM in the frame of this proposal. The Au plasma was produced with the use of terawatt Nd:glass CPA laser system delivering up to 1 J energy in 1.2 ps or 0.5 ns pulses at the wavelength of 1.053 μm. Properties of ion streams emitted the plasma were studied with the use of ion diagnostic methods: an electrostatic ion energy analyzer and ion collectors. The charge state, the ion energy, the ion current density together with its angular distribution were the basic parameters of our interest. The results obtained demonstrate the that the interaction of the laser pulses in the 1 ps and sub-ns range with the Au target provides favourable conditions for the generation of a large amount of Au ions in high charge states. The thermal and fast ions driven be hot electrons were investigated.

1. Introduction

1.1. General

The investigation of high-Z laser produced plasma is interesting for many reasons (e.g.: the laser beam energy is efficiently converted to X-ray energy, radiation transport of energy is substantial, multiply-charged ions are generated and emitted from the plasma [1, 2]). The knowledge of physics of high-Z plasmas produced by a high-power laser is very important for optimization of indirect laser fusion, particularly for the determination of conditions for efficient interaction of laser beams with the inner surface of the hohlraum. Characteristics of X-rays generated by laser beams striking the hohlraum are determined by parameters of high-Z plasma produced as a result of this interaction. Most of up to date studies of such plasma have concerned X-rays generation and emission from the plasma. Combined measurements using several diagnostic methods are essential for quantitative analysis of the indirect illumination of thermonuclear capsule. The precise ion diagnostics offer the alternative methods of studying the physics of high-Z plasma emitting the X-rays from the inner shell of hohlraum.

The main goal of this project is to investigate the physical properties of high-Z plasma generated by laser beams inside the hohlraum with the use of ion diagnostic methods supplemented by X-ray diagnostics. In this project we would like to determine the characteristics of this plasma in dependence on laser pulse parameters (intensity, pulse duration, wavelengths, energy), illumination geometry (focus position, target tilt angle) and target material.

We want to use the results of these measurements to analysis of the following physical phenomena important for efficient compression of the thermonuclear capsule due to heating by the X-rays emitted from the high-Z laser-produced plasma: non-thermal processes influencing the energy distribution of electrons and multi-charged ions, production of cold plasma by X-rays in the target regions outside the focus as well as recombination processes in the plasma.

Experiments will be performed at the IPPLM with the use of lasers and measuring equipment available in the Institute and the additional measurements will be accomplished within the co-operation with the PALS Research Centre in Prague (Czech Rep.) with the use of high power and high energy PALS laser system [3].

In this paper we report on the preliminary studies, particularly observations of the ion emission from Au plasmas produced at nearly the same level of Nd: glass laser energies ≤ 1 J but at two considerably different duration of the laser pulses, i.e., 1.2-ps and 0.5-ns. Streams of multi-charge ions produced by high power ~1 μm laser pulses were investigated many times with the use of ~1 ns pulses at higher energies (>10 J e.g. [1, 2, 4, 5]), whereas in the case of ~1 ps, except of our recent studies (e.g. [6, 7]), the investigations were carried out only in a few experiments with the use of solid targets of low atomic number [8 – 11].

1.2. Work plan

The work planned within the frame of this research project are as follows:

• Preparation and testing the research system existing in the IPPLM consisting of experimental chamber, diagnostic apparatus (particularly ion collectors, electrostatic ion energy analyzer and additionally X-ray detectors) a Nd:glass laser system operating at wavelength λ_L = 1.053 μm with energy up to 1 J in a 1.2-ps pulse and in a 0.5-ns pulse.

• Preliminary investigations of parameters of heavy-ion fluxes emitted from laser-produced plasma at various experimental conditions, performed at the IPPLM, with participation of scientific workers from the Inst. of Phys. ASCR in Prague:

- measurements of the characteristics of ion streams emitted from plasma and complementary measurement of the X-ray emission,
- identification of the ion species emitted from plasma,
- determination of the hot plasma parameters (electron temperature, average charge state of ions and angular distributions).

• Analysis of results of preliminary investigations in relation to the physics of fusion targets.

• The second phase of the common experiment at the IPPLM - investigations of the influence of experimental conditions (particularly the laser intensity and illumination geometry) on the high-Z laser produced plasma.

• Completion of the common experiment at the PALS RC in Prague with the use of iodine PALS laser system with output energy > 0.5 kJ in a 0.4 ns pulse at the fundamental wavelengths (1.315 μm) or 3^{rd} harmonic (0.438 μm).

• Investigations of the influence of the laser wavelengths and intensity as well as the focusing conditions on properties of high-Z plasma with the use of ion and X-ray diagnostics.

• Analysis of all results of experimental studies in relation to the physics of the fusion targets.

• Summary of the possibilities of the ion diagnostic methods' applications to optimization of the laser-high-Z target interactions in the hohlraum fusion target.

2. Methods of investigations

The investigations of expanding plasma properties in dependence on laser beam parameters are done by means of corpuscular diagnostics [12]: ion collectors (IC), cylindrical ion energy analyzer (IEA) with the windowless electron multiplier (WEM) and Thomson mass pectrometer (TP) with multi-chanel plate (MCP) as well as X-ray diagnostics: semiconductor detectors, fast photodiodes and spectrometers.

Ion collectors of different construction are used: the ring collector (inner diameter = 3.8 cm, outer diameter = 5.0 cm) and standard circular collectors (diameter = 1.5 cm). The first one makes the measurements close to the IEA beam axis possible. The IEA have a bending radius of 10 cm, the deflection angle is 90^0 and the gap between the cylindrical electrodes of the analysing capacitor is 0.5 cm. A windowless electron multiplier (WEM) is used as an ion detector behind the IEA. Calibration of our WEM was performed by using beams of Ta ions generated by the Kansas State University Cryogenic Electron Beam Ion Source (KSU-CRYEBIS) [13]. For the measurement of X-rays a p-i-n Si photodiode filtered with various Be and Al foils as well as a crystal spectrometer are used.

In the case of the IEA, using measured voltage amplitude of ions (for a given charge state) reaching the WEM and simple formulas, one can obtain the velocity or energy distribution of each ion species existing in the plasma. By integration of any of the distributions, the total number of ions of various charge states, was calculated. With the use of these values, the total number of ions, the average charge state of the plasma and abundance of ion species were determined.

From recorded voltage amplitude of IC signal (or the time derivative of the ion charge recorded for a given time of flight) the velocity, and energy distributions of the ion charge can be obtained; and by integrating them it is possible to calculate the total charge (or the total number of ions) and the total energy carried by the ions as well as the mean ion energy. For the absolute measurements of the ion flux characteristics the influence of secondary electron emission effect on the IC signal was studied in [13]. The measurement of an angular distribution of ion emission helps to explain some aspects of physical processes taking place in the plasma and also makes obtaining quantitative data on the total charge, energy carried out by ions and so on, possible.

Taking into account the maximum charge state of ions, $<z>$, from the IEA measurements and the mean ion energy, $<E_i>$, from the ion collector measurements, one can estimate the electron temperature, T_{e0}, and the average charge state, $<z_0>$, in the region of interaction of laser radiation with the plasma. T_{e0} is determined from relation [14, 15]: $<E_i> = C (<z_0> + 1) T_{e0}$. The factor C depends on the model of plasma expansion (C = 3.33 ÷ 5, for isothermal expansion C = 4). The mean ion charge $<z_0>$ in the hot region of plasma is calculated with the use of Busquet formula [16] or formula [17]: $<z_0> = B\{ T_{e0} (keV) / [1 + (B/Z)^2 T_{e0} (keV)]\}^{1/2}$, where: Z is the atomic number of the target material, B - the constant dependent on the kind of target material. Values of constant B for selected target materials are: $C_C = 35$, $C_{SiO2} = 37$, $C_{Al} = 40$, $C_{Cu} = 45$, C_{Ta} - 47, $C_{Au} = 50$.

The Thomson parabola mass spectrograph (TP) is capable of recording the velocity distribution of all ion species in a single shot [12]. The processing of the experimental results obtained with the use of TP is similar to that of IEA.

Following the model of isothermal expansion of plasma, one can sufficiently accurately describe the ion velocity distribution by relation [18, 19, 20]: $d(N)/dv \sim \exp(-v/c_T)$, where N is the number of ions with velocity v, $c_T = (<z_0>T_{e0}/m_i)^{1/2}$ - ion sound velocity corresponding to the electron temperature T_{e0} of plasma with charge state ions $<z_0>$ and ion mass m_i

The temperature of the hot electrons can be estimated following the formula given in [21]: $T_{e,h} \approx \langle E_f \rangle / 1.25 \langle z_f \rangle$, (where $\langle E_f \rangle$ and $\langle z_f \rangle$ - the mean energy and the mean charge state of fast ions, respectively) on the assumption that the fast ions appear as a result of ion acceleration in the electrostatic potential being created by the hot electrons.

3. Preliminary experiments

3.1. Experimental details

The preliminary experiments were performed at the IPPLM with the use of terawatt all-Nd:glass CPA laser system [22]. Thick gold foil targets were irradiated by normally incident laser pulses (λ = 1.053 μm) of energy up to 1 J and 1.2-ps or 0.5-ns in duration. The laser beams were focused with the use of parabolic mirror (27-cm focal length) having a hole in the centre to make measurement of ions escaping from the plasma perpendicularly to the target possible. The maximum intensity of the focused laser beams were 8×10^{16} and 2×10^{14} W/cm^2 for 1.2 ps and 0.5 ns laser pulses, respectively.
The ion fluxes were analysed with the use of three ion collectors): the ring collector (IC1) placed at 0° and two standard collectors (IC2 and IC3) placed at 26°, and 34° with respect to the target normal at distances of 110, 35, and 35 cm from the target, respectively. The electrostatic ion energy analyser (IEA) was placed at a distance of 190 cm from the focus and at an angle of 0° with respect to the target normal co-axially with the ring collector. The focus position (FP) was changed within the range from –1.4 mm front o to 0.8 mm with respect to the target surface. The scheme of the experimental arrangement is presented in *Fig. 1.*

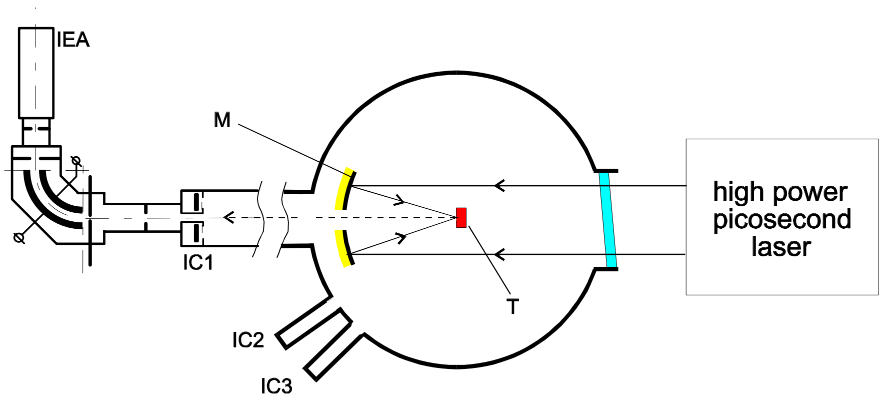

Fig. 1. Scheme of the experimental arrangement. IEA – electrostatic ion-energy analyzer; IC1, IC2, IC3 – ion collectors; T – target; M – parabolic mirror.

3.2. Results of measurements

In our experiments with high-Z targets, we observed the occurrence of at least two ion groups on the charge-integrated and time-resolved signal from an ion collector, placed far from the target. Simultaneously, the ion spectra were measured by IEA.
The ion charge Q_i, the average ion kinetic energy $\langle E_i \rangle$, the maximum ion current density j_{max} and the maximum recorded charge state z_{max} of Au were measured as a function of laser pulse energy and focus position with respect to the target surface. Angular distributions of ion emission were measured with the use of 3 ion collectors.
An example of the IC1 collector signal and the IEA spectrum of ions recorded in the same laser shot at 1 ps laser pulse duration is given in *Fig. 2*. The shapes of IC signal and IEA

spectrum for 0.5-ns pulse are similar. IC signals usually show more than one group of ions, the existence of which corresponds to the different mechanisms of generation.

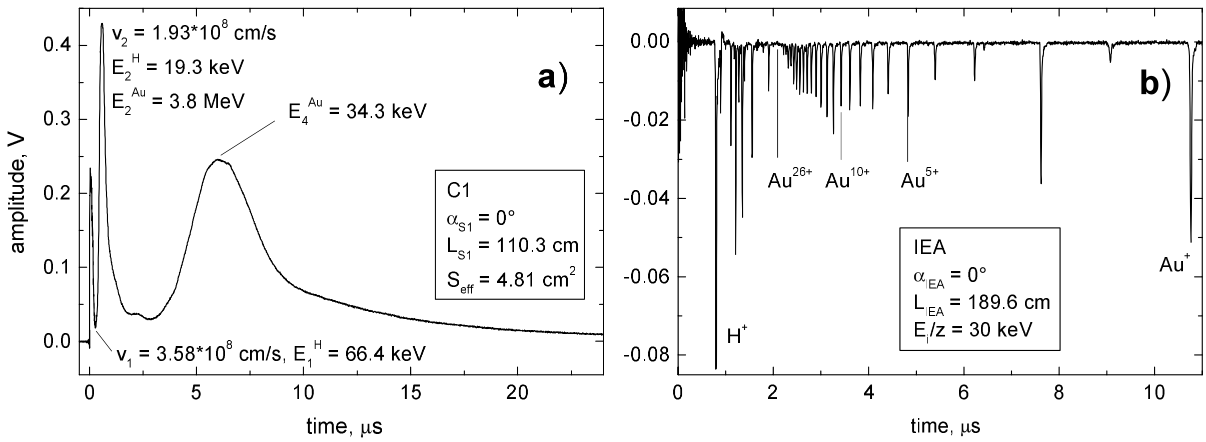

Fig. 2. Ion collector signal and spectrum of Au ions recorded with the use of IEA for the same laser shot at 1 ps laser pulse duration. The shapes of IC signal and IEA spectrum for 0.5-ns pulse are similar.

The ion charges carried by thermal and fast ion groups (relative values) as well as average fast ions energy as a function of laser energy are presented in *Fig. 3.* The charge carried by fast ion group is about 10 times higher for ps pulses than for sub ns pulses over the whole laser energy range.

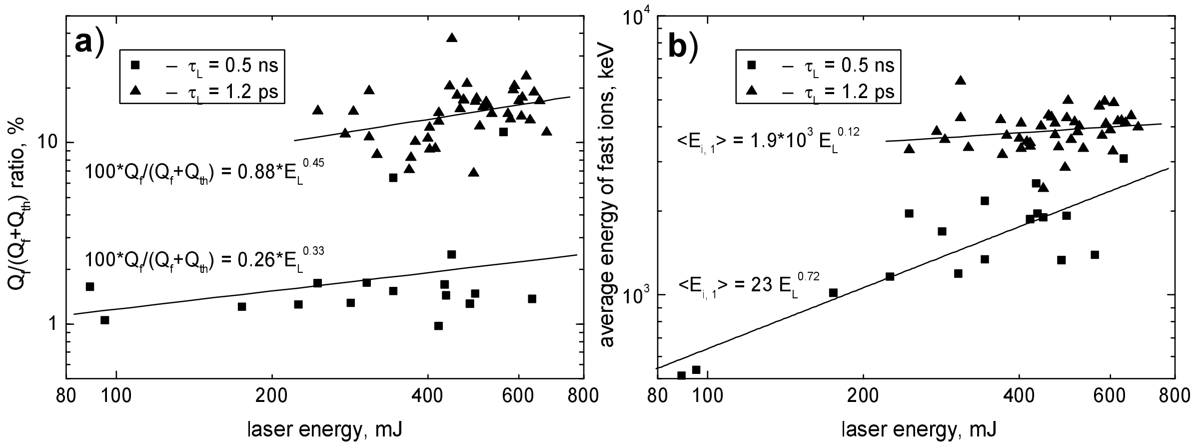

Fig. 3. Dependence of the relative values of ion charge carried by thermal and fast ions (a) as well as average fast ion energy (b) on the laser energy for 1.2-ps and 0.5-ns laser pulses and for FP = 0.

Taking into account that apart of light contaminant ions the fastest part of the IC signal contains Au ions, it is seen that the average fast Au ions energy is more than 2 times higher for ps pulse than that for sub-ns pulses and for ps pulses it is nearly constant at $\langle E_{i,f}\rangle \approx 4$ Mev. For sub-ns pulses $\langle E_{i,f}\rangle \propto E_L^{0.72}$ and reaches the highest value of $\langle E_{i,f}\rangle = 2.5$ Mev for Au ions (velocity 2.5×10^8 cm/s) at $E_L \approx 600$ mJ.

Dependence of maximum fast and thermal ion current densities on the laser energy are shown in *Fig. 4.* The current density depends on laser energy most strongly for ps pulses than for sub-ns pulses. Over the whole laser energy range the maximum ion current densities of fast ion groups ($j_{max,\ f}$ and $j_{max,\ th}$ respectively) are up to one order of magnitude higher for ps pulses than for sub-ns ones. For ps pulses j_{max} attains the value about 3 mA/cm^2 at a distance of 100 cm from the target.

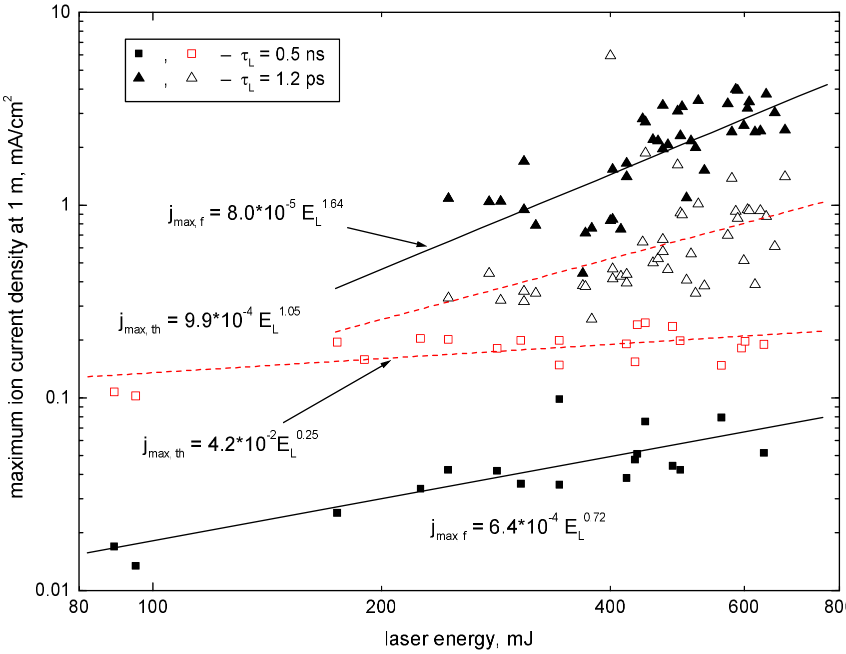

Fig. 4. Dependence the maximum thermal and fast ion current densities on the laser energy for 1.2-ps and 0.5-ns laser pulses and for FP = 0.

The dependence of the maximum ion current density and average energy of fast ions on the focus position are shown in *Fig. 5*. The maximum fast ion current densities have minima for sub-ns pulses and for ps pulses at FP = -0.3 mm. Average ion energy of the fast ion groups have maxima for both the laser pulses. Also, average ion energy of the thermal ion group (not shown in the diagram) has maximum for sub-ns pulses while it is nearly constant for ps pulses.

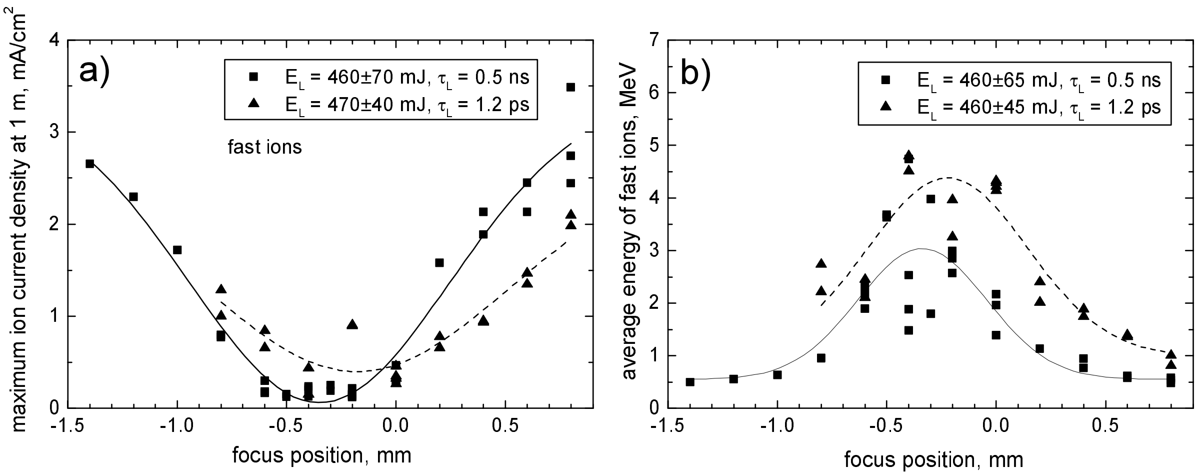

Fig. 5. Dependence of the maximum fast ion current density (a) and average energy of fast ions (b) on the focus position with respect to the target surface for 1.2-ps and 0.5-ns laser pulses.

Angular distributions of ion charge Q_i emitted from plasma are shown in *Fig. 6*. These distributions follow a smooth $Q_0\cos^x\alpha$-dependence for the whole range of focus positions in the case of ps pulses, and of the focal waist in the case of sub-ns pulses. The preferred direction of plasma expansion is along the target normal for ps pulses. In the vicinity of the waist the distributions show a two-lob structure for the case of sub-ns pulses and the privileged direction is not longer along the target normal.

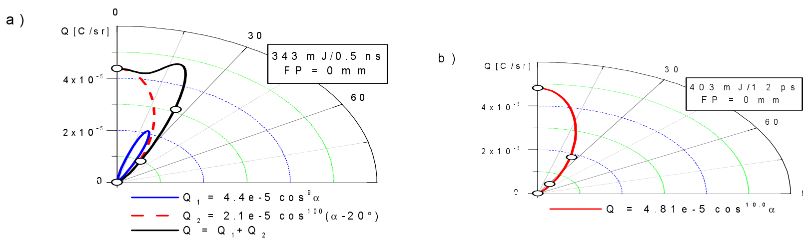

Fig. 6. Angular distributions of ion charge emission from Au plasma generated with the use of 1.2-ps and 0.5-ns laser pulse.

In *Fig. 7* the typical ion velocity distributions for expanding plasma calculated on the basis of ion collector signals are presented.

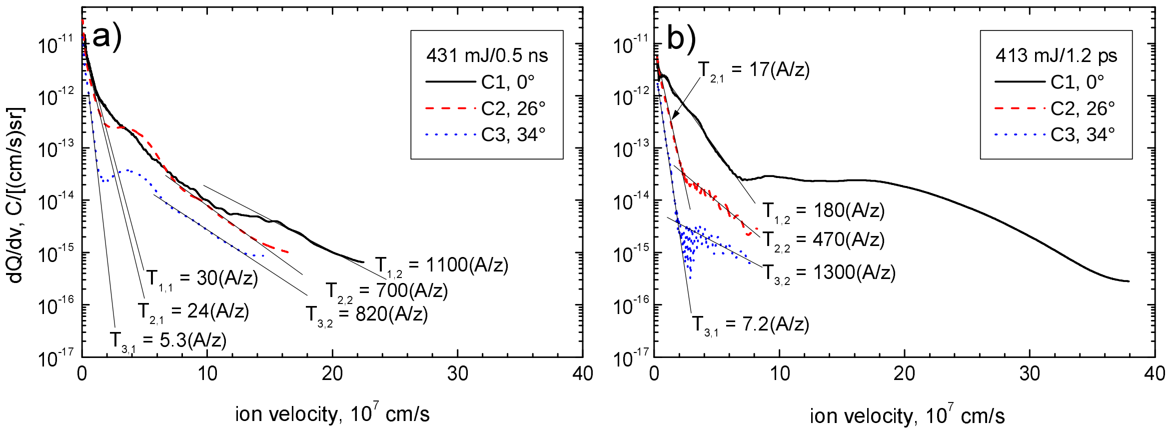

Fig. 7. Ion velocity distributions for expanding plasma calculated on the basis of ion collector signals for 1.2-ps (a) and 0.5-ns (b) laser pulses and for FP = 0 ([T] = eV).

3. Summary

The obtained experimental results show that the interaction of the radiation of 1-µm wavelength laser pulses in the picosecond and subnanosecond range provides favourable conditions for the generation of a large amount of Au ions with high charge states up to 26+ at a laser energy of about 0.5 J and at an optimum focus position. The faster ion group in collector signal, if analyzed by the IEA is found to be composed of the highly charged ions and light contamination ions (H, C and O). The highest registered energies of Au ions attained values of several MeV.

It is believed that an essential role in the motion of fast ions is played by nonthermal processes in the plasma, which can generate suprathermal (hot) electrons. Escaping from the plasma hot electrons generate electric field, which accelerates a group of fast ions. In principal, the emission of the highly charged ions can be severely restricted by the recombination in the zone of the dense plasma. It seems, on the basis of obtained experimental results and our previous studies (e.g. [1, 2, 4]) that due to the velocity of the fast group of highly charged

ions, their residential time in the dense recombination region is not long enough for a complete destruction of the high charge states to occur.
The fast ion group is not the only one, which besides the thermal group appears on the ion collector signal. There is also a slow group of ions, following the thermal one. The average charge state of this group is also a low one. We interpret this group as coming from a peripheral region of the laser focus, where a secondary plasma is created by the X-ray radiation of hot plasma.
It result from this experiment and from our previous investigations (e.g. [1, 2, 4]) that for the investigation of high Z plasma (e.g. Au) ion diagnostic methods, particularly ion collectors as well as the electrostatic ion analyzer are indispensable tools.

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