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Highly collimated, high-current heavy ion beams from the subnanosecond laser-plasma interaction

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Abstract

Production of heavy ion fluxes at the interaction of 70 J, 0.438 μm subnanosecond laser pulse with a massive planar target has been investigated using the time-of-flight method and three-frame interferometry. It is found that after proper optimization of high-Z (Cu or Ta) target irradiation, a highly collimated, energetic (0.1 – 1 MeV) heavy ion beam of the ion current > 100A and the ion current density > 1A/cm^2 at 1m from the target can be produced with an energy conversion efficiency nearly 10%.

Generation and study of ion beams from high-intensity laser-plasma interaction is rapidly developing into a frontier area stimulated by a variety of potential applications including accelerator technology, ion implantation, nuclear medicine or high energy-density physics. Some of these applications require collimated high-current beams of heavy ions. Up to now, the highest currents (i_i) and current densities (j_i) of heavy ions in the far expansion zone (~ 1m) were produced with the use of long (subns and ns) laser pulses interacting with massive targets [1, 2]. However, the angular divergence (Θ_i) of ion fluxes generated in the long-pulse experiments was relatively large (tens of degrees or more), which makes them difficult to use for applications. Moreover, the large angular divergence was one of the reasons, which limited the heavy ion current and current density in the far expansion zone to the values not exceeding a few A and 100mA/cm^2 at 1m from the target, respectively.

This contribution presents results of the experiment on heavy ion beam generation with 3ω beam of the PALS iodine laser in Prague. Characteristics of plasma produced by the interaction of 70-J, 0.3-ns laser pulse with solid targets (Cu, Ta, Al or CH) were measured with the use of the time-of-flight method, three-frame interferometry and X-ray diagnostics. It is shown the after a careful optimisation of the conditions of irradiation of a high-Z target by a subns laser pulse, a highly collimated ($\Theta_i \leq 10°$) energetic (0.1 – 1 MeV) heavy ion beam of $i_i > 100$A and $j_i > 1$A/cm^2 at 1 m from the target can be generated with a high efficiency approaching ~ 10%

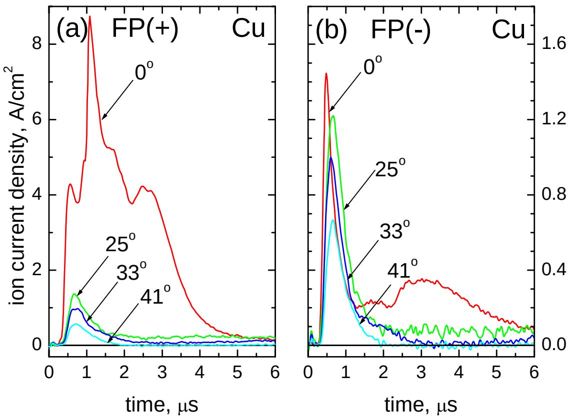

Fig.1. Ion collector signals from Cu target for different laser focus positions FP. E_L=(69±2)J, d_L=500µm, L_{IC}=50cm.

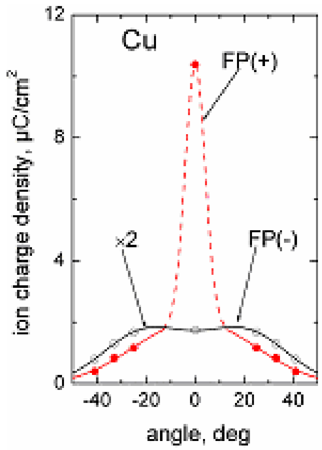

Fig.2. Angular distributions of the ion charge density for ions of velocities in the range (0.2-2)x10^{8}cm/s. E_L=(69±2)J, d_L=500µm, L_{IC}=50cm.

Fig.1 presents the ion collector signals (recalculated to the ion current density) produced at the interaction of large aperture (defocused) laser beam (d_L = 500µm, FWHM) with the Cu target for the two cases: when the laser focal plane is placed behind the target surface – marked as the case FP (+) – and when the focal plane is in front of the target surface – marked as FP(–). As it results from our previous measurements, performed at similar laser intensities with the use of the electrostatic ion-energy analyzer [3], the recorded ion flux is dominated by Cu ions of the maximum charge state z_{max} ~ 20 – 25. The IC signals also contain contaminant ions (mostly protons), which are situated on the leading edges of the signals. In turn, Fig.2 shows angular distributions of the ion charge density (calculated from the above IC signals) for ions of velocities in the range (0.2 – 2) × 10^8 cm/s. This range of velocities corresponds to the minimum, maximum and mean energies of Cu ions equal approximately 13keV, 1.3 MeV and 100keV respectively.

The most striking phenomenon revealed by Figs. 1 and 2 is the generation of a highly collimated ion jet of very high ion current when the laser beam interacts with the Cu target at FP(+) (the laser focus behind the target surface). Generation of the ion (plasma) jet for this case was also observed using the interferometric measurements, as shown in Fig. 3. Similar results were obtained for Ta targets, in which case the distribution was as peaked as for Cu.

The generation of highly collimated ion jets was observed only under specific conditions of the laser-target interaction, and particularly when: (a) the laser beam diameter on the target, d_L, was sufficiently large, (b) high-Z (Cu or Ta) target was used (we did not observe distinct ion jets from Al and plastic targets for the laser beam diameters applied in the experiment, i.e. of $d_L \leq 800\mu m$.), (c) the laser focus was behind the target surface (for laser intensities on the target ~ $10^{14} W/cm^2$ or higher). Requirement (a) can be understood if we realize that for relatively long (subns or longer) laser pulses, the main part of the pulse interacts not with a solid but with pre-plasma produced by the pulse leading edge [1]. For the case of the large-aperture beam, (i.e. of $d_L \geq 500\mu m$), the thickness of the overdense pre-plasma L_{pre}^{od} (i.e. of the density higher than the critical density n_{cr}) is remarkably smaller than d_L, so the critical plasma surface is relatively flat. However, when d_L decreases, the ratio d_L / L_{pre}^{od} decreases, too, and the critical surface curvature increases. The laser beam interaction with such a strongly curved critical surface prevents generation of highly collimated plasma (ion) beam.

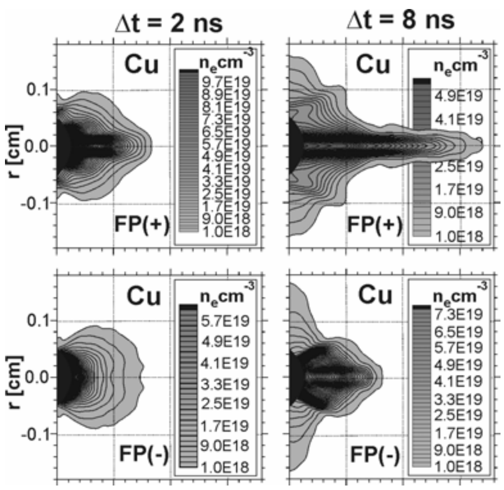

Fig.3. Sequences of electron isodensitograms for Cu target and different laser focus positions FP. $E_L=(69\pm2)J$, $d_L=500\mu m$.

An explanation of the influence of the target atomic number on the ion (plasma) beam collimation is more complex. One of plausible mechanisms favorable to the beam collimation is a radiative cooling of plasma during the beam formation [4] which is more intense for the high-z plasma.

The influence of the laser focus position FP on the ion beam collimation can be explained taking into account the essentially different conditions for the interaction of the laser beam with the underdense preplasma (produced by the laser pulse leading edge) at FP(+) and FP(–). As the laser intensity threshold for the preplasma generation is ~ $10^9 – 10^{10}$W/cm^2, at the laser pulse peak intensity ≥ 10^{14}W/cm^2 the preplasma starts to be formed at least ~ 1 ns before the time corresponding to the peak intensity. Thus, the main part of the laser pulse interacts with the underdense preplasma of the thickness L_{pre} at least several hundreds μm. For our experiment, the laser intensity in the focal plane reaches ~ 7x10^{15}W/cm^2. For the laser beam diameter on the target equal d_L= 500μm, the target surface is shifted from the focal plane about 0.9 mm, which is comparable to L_{pre}. When the focal plane is placed in front of the target surface (the case FP(–)), the laser beam hits the preplasma at the peak laser intensity > 10^{15}W/cm^2. This intensity and the laser power (~ 3 x 10^{11}W) are both well above the thresholds for laser beam ponderomotive self-focusing in plasma [5]. Due to self-focusing, the laser beam intensity in the vicinity of the beam axis considerably increases. This results in the significant increase in radial components of both ponderomotive and termokinetic forces in the plasma, which prevents the expanding plasma (ion) flux collimation along the axis. In the case of FP(+) the laser beam intensity in the preplasma is several tens times smaller than in the case of FP(–) and self-focusing is insignificant. Thus, the conditions for quasi-planar acceleration of plasma in the case FP(+) should be much better than at FP(–).

In conclusion, it has been shown that after proper optimization of the conditions of irradiation of a high-Z target by a short-wavelength, 70 J, subns laser pulse, a highly collimated ($\Theta_i \leq 10^o$) energetic (0.1 – 1 MeV) heavy ion beam of j_i > 1 A/cm^2 and i_i >100 A at 1 m from the target can be generated with a high energy conversion efficiency approaching ~ 10%. Radiative cooling of the expanding high-z plasma acts in favour of the ion beam collimation, while laser beam self-focusing in the plasma seems to be the main effect, which hinders it. To our knowledge the measured heavy ion currents and current densities are the highest among the ones achieved up to now in laser-plasma experiments.

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