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High intensity ion beam generation for ionography from multi-TW picosecond laser pulse interaction with foil targets

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Abstract. It was found that maximum particle output and best possible spatial uniformity of proton beam took place for two-layer target when the front layer was the high-Z film. It was shown that the ion radiography of the convenient objects with using the two-layer targets allow to get the projecting pictures with high spatial resolution that was about one micron. Threshold spatial sensitivity of proton radiography is estimated.

At laser intensities on a target $\geq 10^{18}$ W/cm^2 high-power multi-MeV ion flow with relatively low opening angle is generated. If they put suitable object between the laser target and suitable detector, it is possible to create the projecting image of the object [1, 2].

Here we have presented some results of investigations of picosecond laser produced fast proton beam generated at rear side of the solid–state targets. There were low-Z (CH), high-Z (Cu, Au) targets and two-layer targets irradiated by laser pulse of intensity >(2-4) $\cdot$ 10^{18} W/cm^2.

The experiments have been carried out on multiterawatt laser PROGRESS-P with p-polarized 1.5 ps laser pulse at wavelength 1053 nm. Fig.1 shows the scheme of experimental setup. Laser radiation with energy on a target up to 19 J was focused on surface with f/1.4 off-axis parabola at angle of incident to the target normal of 38^0. Measurements of ion beam parameters were carried out with using “sandwiches” of RCF, track detectors CR-39, protected by 5 μm mylar filter that passed the ions with energy >300 keV.

On RCF (Fig.2) it is shown the spatial distribution of plasma particle extension in experiments with different targets. It can be seen that for CH- target the intensity of image is relatively low. As the target

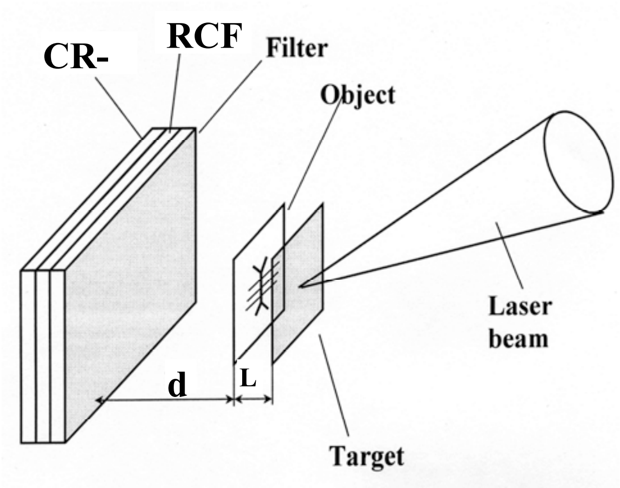
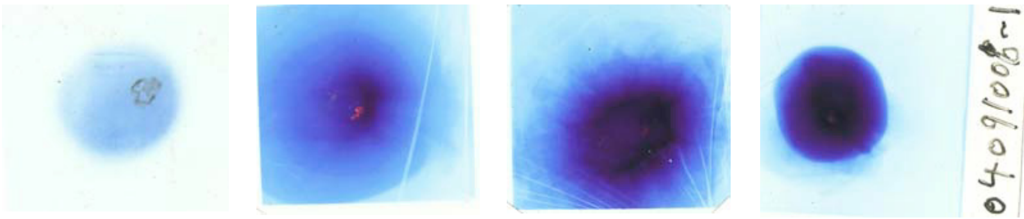


Figure 1. Scheme of experimental setup.



a) CH, 17µm b) Cu, 3µm c)Au, 3 µm d) Ta, 1.6 µm + CH, 5µm

Figure 2. The images of plasma beam with using of low-Z (a) and high-Z (b, c) targets; d)two-layer target.

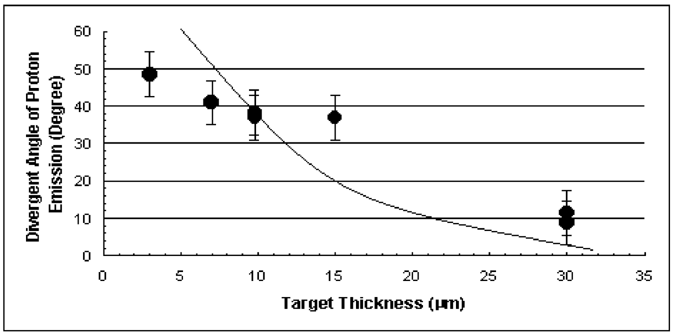


Figure 3. Ion beam divergence as function of Cu target thickness. Laser energy 10 J.

Z-number increases, the intensity of image and spatial size of the spot increases too, (see Fig.2a-c). It means that as atomic number of the target increases the absorption efficiency, i.e. hot electron conversion efficiency, increases too. The higher number of hot electrons creates higher intensity of electrostatic field that accelerates ions. However, the number of accelerated ions (protons) in heavy targets are not much and generally, these particles are close to target surfaces. We used two-layer target in order to generate on the rear surface of front high-Z layer hot electrons as many as possible and next the electrons pass through CH- media and accelerate protons.

It was found that maximum particle output and best possible spatial uniformity of particle beam took place for two-layer target when the front layer was the high-Z film (Ta, 1.6 µm) and the rear side was CH-film (see Fig.2d). Energy range of protons formed these pictures is in ~0.4-2 MeV. Lower level is related with proton stopping distance in Mylar filter and surface layer of RCF.

On Fig.3 it is shown the typical ion angle distribution as function of target thickness (experimental data are feel cycles, theory [3] – solid line).

Study of spatial distribution of the multi-MeV ion beam furnishes useful information for further research of plasma ion source for radiography. The laser produced ion radiograph of the thin biologic objects was realized for checking a possibility to get clear visible images.

It was shown that the ion radiograph of the convenient objects with using the two-layer targets allow to get the projecting pictures with high spatial resolution that was a few microns, see Fig.4. On Fig.4c we see the ant hair, which was about 2 µm in diameter. Threshold spatial sensitivity of proton radiography methods is defined by ions energy distribution and ion energy losses $d\varepsilon/dz$ in object. "Tail" of ion energy distribution function (in our experiment filter cuts off protons with an energy less than 300 keV) is given by expression

$$f_\varepsilon(\varepsilon) = dN/d\varepsilon \approx (1/\sqrt{2\varepsilon\varepsilon_0}) \exp(-\sqrt{2\varepsilon/\varepsilon_0}), \quad (1)$$

a b c d

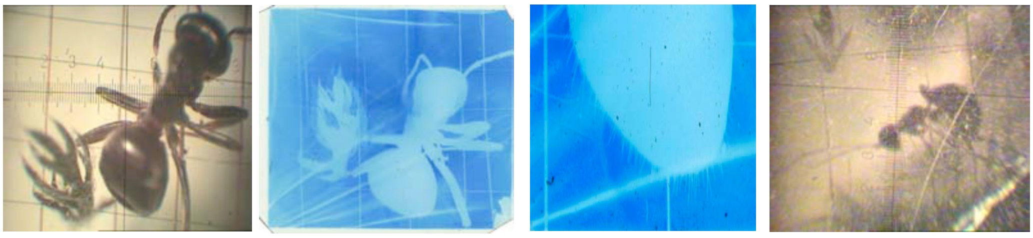


Figure 4. The images: a – optical; b – on RCF (overview); c – on RCF (bottom of the ant); d – similar picture on CR-39; thickness of the wires: vertical – Cu, 22 µm; horizontal – W, 8 µm.

where $\varepsilon_0 \approx m_e c^2(\sqrt{I + I_{18}(\lambda_L/1.2\,\mu m)^2} - 1) \approx 0.6\,\mathrm{MeV}$, I_{18}- laser intensity in terms of 10^{18} W/ñm^2. Let the object average size is δz. The initial function $f_\varepsilon(\varepsilon)$ after object passing converted in $f_\varepsilon(\varepsilon - \delta z\, d\varepsilon/dz) \approx f_\varepsilon(\varepsilon) - \delta z\,(\partial f_\varepsilon/\partial\varepsilon)(d\varepsilon/dz)$. We shall see object contrastingly if the energy fluxes (particle fluxes for a CR39) for functions $f_\varepsilon(\varepsilon)$ and $f_\varepsilon(\varepsilon - \delta z\, d\varepsilon/dz)$ differ on $\sim$20%. From matching fluxes the following understandable estimation of object threshold size is gained

$$\delta z \sim \frac{0.2 \int f_\varepsilon \varepsilon^{3/2} d\varepsilon}{\int (d\varepsilon/dz) \left| \frac{\partial f_\varepsilon}{\partial \varepsilon} \right| \varepsilon^{3/2} d\varepsilon}. \quad (2)$$

The resolving ability is better for more object absorbing ability $d\varepsilon/dz$, detector sensitivity and value of derivative $\partial f_\varepsilon/\partial\varepsilon$. For the elementary model of ion stopping (Bete-Bloch formula) $d\varepsilon/dz = \varepsilon_0^2/\varepsilon l_0(\varepsilon_0)$and protons distribution function (1) threshold size $\delta z \approx 0.3 l_0(\varepsilon_0)$, where $l_0(\varepsilon_0)$ - proton of energy ε_0 free path length in object [4]. The theoretical limit of detection polyethylene cylinder diameter in our experiment makes $\sim$1 µm and it is close to the spatial resolution of HD-820 RC film. Let us note that the image is formed by the protons, whose energy at the object output is > 300 keV. The character angle of such protons scattering is small and thus one can neglect in the influence of scattering onto the limit of the method of proton radiography resolution.

CONCLUSION

The experiments and developed theoretical model have shown that at picosecond laser pulse of intensity $\sim 4 \cdot 10^{18}$ W/cm^2 it is possible to create plasma source for proton radiograthy.

The best homogeneity and density of proton beam is equipped by two layer target where first layer of thickness 1-2 µm from high Z material (Ta) and second polymer layer is much thicker.

The possibility of getting of object image with high field of vision (10 mm) and high resolution (about 1 µm) was experimentally demonstrated.

The laminarity of proton beam permits to obtain a magnified image of object with a size smaller compare to the size of ion source. Such effect impossible to obtain in the case of X-ray source.

The theoretical estimations of spatial resolution limit of the ionography method are developed.

Acknowledgement

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