Generation of proton beams from a hydrocarbon target irradiated by an ultra-intense femtosecond laser pulse

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Introduction

Extreme Light Infrastructure (ELI) is a currently implemented large-scale European project that uses cutting-edge laser technologies to build multi-PW lasers generating femtosecond pulses of ultra-relativistic intensities ~ 10^{22} – 10^{23} W/cm^2 [1]. The ELI lasers will have a potential to produce intense ion beams of sub-GeV and GeV ion energies demanded for research in various branches of science and technology as well as for medical applications such as the hadron cancer therapy [2-3]. However, the studies of ion acceleration in the ultra-relativistic intensity regime are in a very initial stage and properties of the ion acceleration process in this regime are not sufficiently well understood.

This paper presents selected results of two-dimensional (2D) particle-in-cell (PIC) simulations of ion acceleration performed for thin polystyrene (CH) targets (the areal targets density ranging from $\sigma_t = 0.06\ mg/cm^2$ to $\sigma_t = 0.8\ mg/cm^2$) irradiated by a 130fs, 800nm laser pulse of intensity from the range 10^{21} - 10^{23} W/cm^2 predicted for the ELI lasers. A special attention is paid to the effect of the laser pulse intensity and polarization as well as the target thickness on characteristics of the generated proton beam.

Results and discussion

Figure 1 presents a 2D spatial distribution of charge density of protons (a, c) and carbon ions (b, d). The target was irradiated by the linearly-LP and circularly-CP polarized laser pulse of the intensity equal to 10^{23} W/cm^2 for CP and 2*10^{23} W/cm^2 for LP (the laser energy fluencies was approximately the same for both types of polarization). The presented situation corresponds to the final stage of ion acceleration (the simulation time is equal to 0.4 ps). It can be observed that protons move with the relativistic velocities in the form of high-density proton (plasma) block. For this reason a velocity dispersion of the accelerated protons is small. It is worth mentioning that a fairly large part of carbon ions move with the velocities close to the proton velocities. Furthermore, it is clearly visible that the parameters of ion beams generated from the target do not depend significantly on the laser beam polarization. The weak influence of laser polarization on the acceleration process could be explained by the dominance of the RPA (radiation pressure acceleration) mechanism [2,3]. In this mechanism the mean ion energy depends on the laser energy fluency and the target areal density. These parameters were identical for the considered cases.

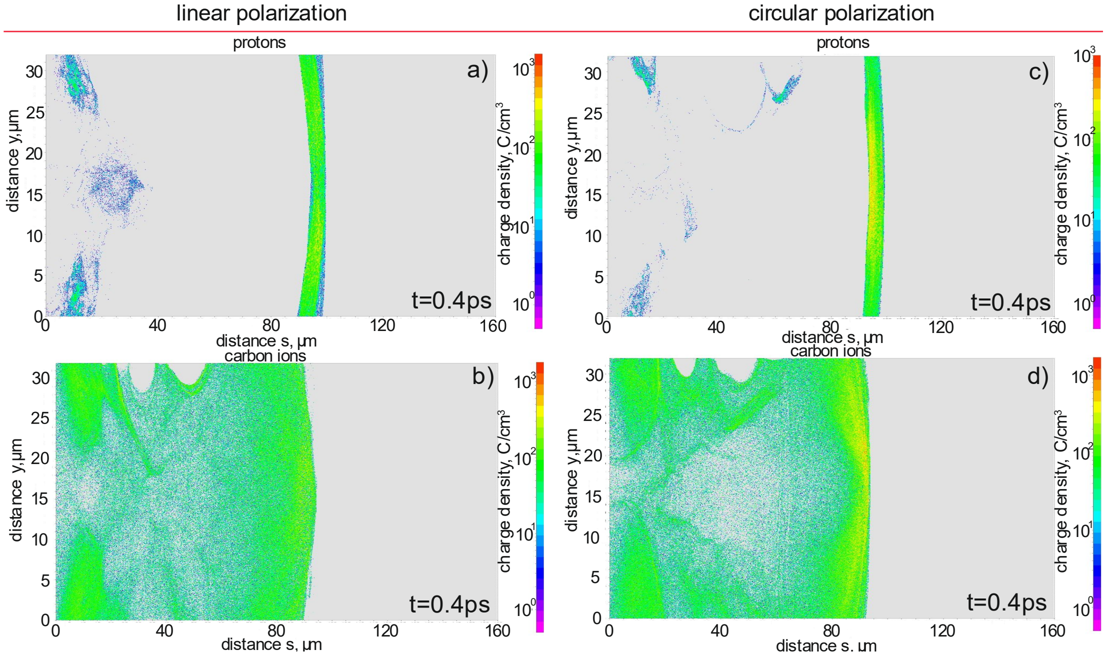

Figure 1. 2D spatial distributions of charge density of protons (a, c), carbon ions (b, d) . The target was irradiated by the linearly-LP (a, b) or circularly-CP (c,d) polarized laser pulses of intensity equal to 10^{23} W/cm^2 for CP and 2*10^{23} W/cm^2 for LP. t=0.4ps. σ_t =0.06mg/cm^2.

The mean energy of protons for both types of polarization as a function the laser beam intensity (a) and the areal target density (b) are shown in figure 2 (the laser energy fluency is the same for both types of polarizations and the laser intensities on the plot correspond to the circular polarization). The mean energy of protons is approximately proportional to the laser intensities and inversely proportional to the thickness of the target. Furthermore, it is clearly visible that the influence of laser polarization on the proton energies are weak as it was stated above. For the highest intensity of laser pulse the mean energy of protons approaches 1.8 GeV and in this case the proton energy spectrum widths are ranging from 0.2 to 0.3 (in the mean energy unit).

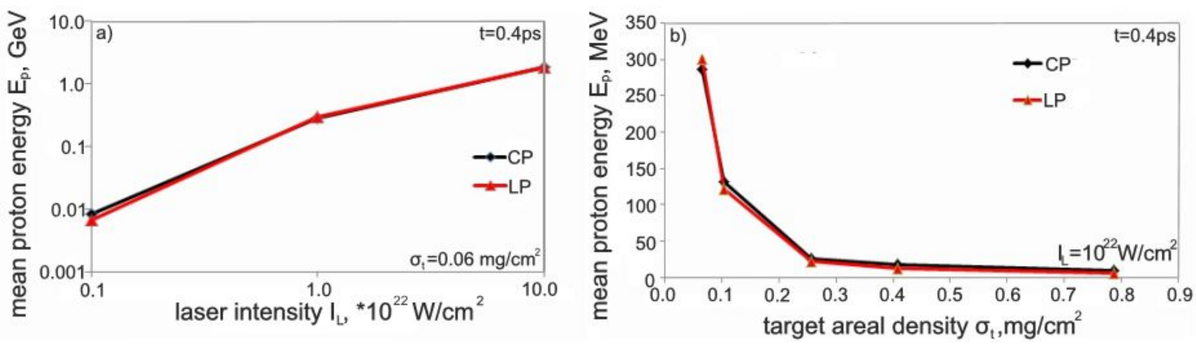

Figure 2. The quantitative values of the mean energy for protons as a function of the laser beam intensity and the areal targets density. t=0.4ps.

Fig. 3 presents the temporal distribution of intensity of the proton beam driven by the laser pulse of linear or circular polarization recorded 40 μm behind the target rear surface. For both types of polarizations, the proton pulses of duration about 11 fs and peak intensity of $8x10^{21}$ W/cm^2 are produced. These proton pulses are by several orders of magnitude shorter and their intensities are much higher than those produced in conventional RF-driven accelerators.

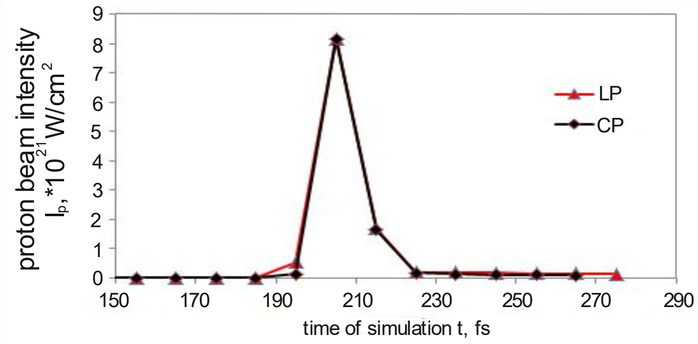

Figure 3. The temporal distribution of intensity of the proton beam driven by the laser pulse of linear or circular polarization. The distributions were recorded 40 μm behind the rear surface of the target. I_L=10^{23} W/cm^2 for CP and I_L=2*10^{23} W/cm^2 for LP, σ_t =0.06mg/cm^2.

Due to the inhomogeneous distribution of the charge in the plasma, the electric current which the total net value $J = (J_p + J_C)- J_e$ can be fairly high, is generated (J_e, J_p and J_C are the electron current, the proton current and the carbon ion current, respectively). Figure 4 presents temporal run of the of the total current at the distance of 40 um from the target rear surface. It can be seen that at the time several times longer than the laser pulse duration the total current is dominated by fast electrons (the current is negative) and reaches the value of several MA. This strong flux of fast electrons escaping from the target is a generator of an intense electromagnetic emission (usually in the THz domain of frequency) and moreover it is the cause of the creation of a net positive charge of the target (an electric neutrality of the target is disturbed by the loss of negative charge carried by the fast electron flux). The neutralization current flowing through the target and the target holder can be a source of a strong electromagnetic pulse (EMP), usually in the GHz domain, which propagates into the interaction chamber and may be harmful for diagnostic equipment and other electronic devices [4]. The problem of EMP generated in the laser-target interaction is especially important for big laser facilities like ELI and is currently a hot topic intensely studied. Our simulations show briefly what way the fundamental source of EMP is created in the sub-ps time scale. More detailed analysis of this issue will be done in other our papers.

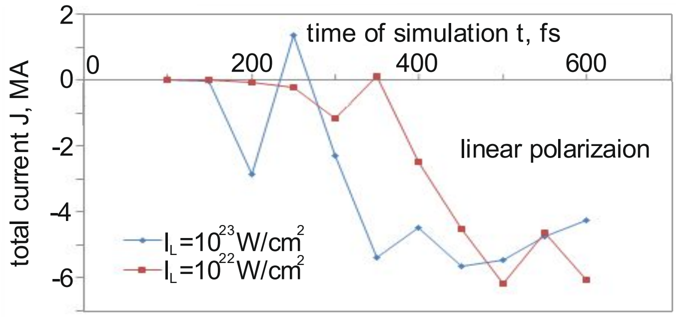

Figure 4. The temporal run of net total current recorded at the distance of 40 μm from the target rear surface. σ_t =0.06mg/cm^2, linear polarization.

Conclusions

In conclusion, it has been found that for the ultra-relativistic laser intensities parameters of the generated proton beam weakly depend on the laser beam polarization and a dominant mechanism of proton/ion acceleration is RPA. At laser intensity ~ 10^{23} W/cm^2 ,a quasi-monoenergetic proton beam of the mean proton energy ~ 2 GeV, beam intensity >10^{21} W/cm^2 and duration < 20 fs is produced. Such proton beam parameters are much higher than those attainable in conventional accelerators and can open the door for new areas of research in nuclear physics, high energy-density physics or materials research.

Acknowledgments

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References

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