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Multiple Pulse Sheath Acceleration: An Optical Approach to Spectral Control

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Introduction

Recent experimental results have shown that it is possible to produce laser-accelerated proton and ion beams with distinct quasi-monoenergetic features in the energy spectrum [1, 2]. As short-pulse ultraintense laser intensities exceed 10^{21}Wcm^{-2}, it may be possible to produce quasi-monoenergetic proton bunches with energies in the range of 100-200 MeV. This opens up the prospect of a new route to developing medical ion accelerators for oncology.

In this paper we will briefly report on some of our recent work [3]. This showed that it is theoretically possible to produce laser-accelerated proton/ion beams with distinct spectral peaks by irradiating a solid target with two laser pulses that arrive in rapid succession. No special target composition or structure is required, unlike the other schemes that have been proposed [1, 2]. This may be advantageous for certain applications.

The spectral peaks are generated by an unexpected two-stage process. Essentially the same physical processes have been observed in simulations with quite different initial conditions, and using different numerical codes. This indicates that this peak generating process is indeed physical, and is not some numerical artefact. We call this TNSA variant, MPSA (Multiple Pulse Sheath Acceleration). A study of multiple pulse was motivated by the work of Grismayer and Mora [4] who observed transient features in the spectra in the case of proton acceleration with a density gradient on the rear surface.

Simulations

Two numerical codes were used to study MPSA in 1D, one being a 1D1P Vlasov solver, and the other being a 1D3P EM PIC code. We shall primarily report on the PIC simulations, although it should be noted that the Vlasov simulations showed similar results. Since the Vlasov simulations did not include the laser absorption this shows that was is being described is essentially due to the fast electrons.

In the 1D3P EM PIC simulations we considered a 0.4μm foil consisting of H^+ and C^{4+} each at a density of $40n_{crit}$ that is initially charge neutral. Two laser pulses were incident on the

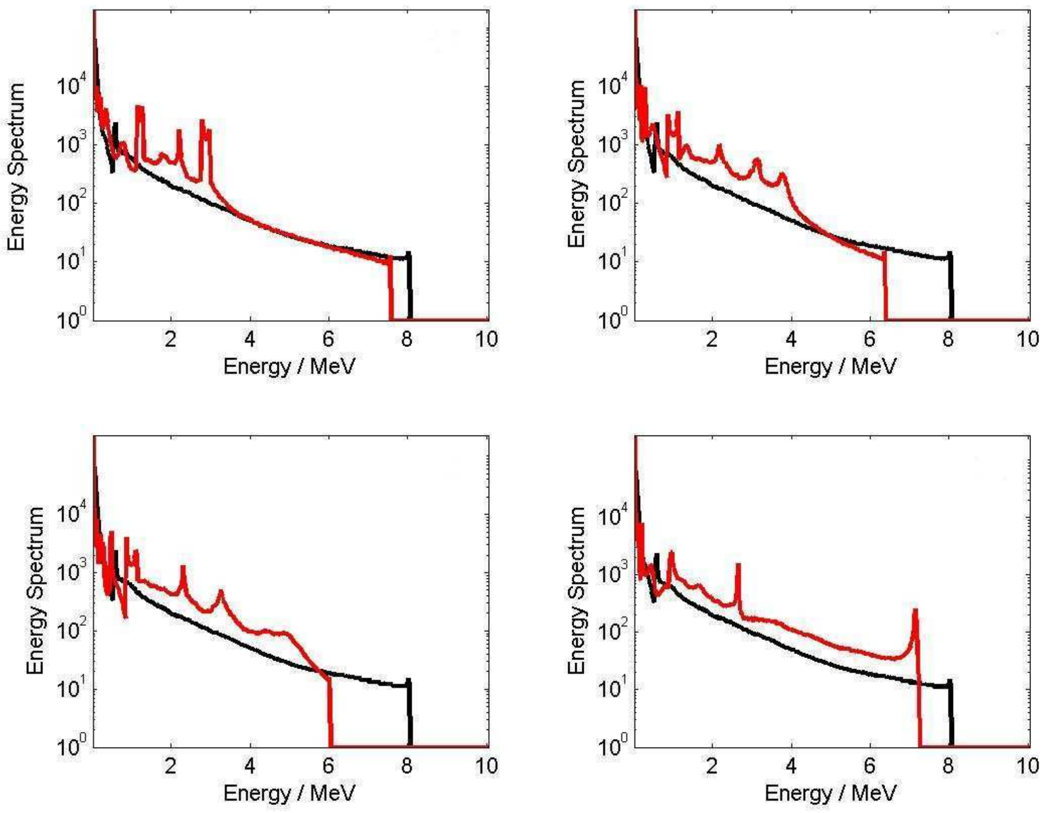

Figure 1: Proton energy spectra (red) against single pulse comparison. Set-up pulse a_0 was set to 2 (Top Left), 1.5 (Top Right), 1 (Bottom Left), 0.5 (Bottom Right).

foil with a delay between the pulses of 150fs. Each pulse was 40fs in duration and had a $\sin^2$ envelope. The second (main drive) pulse was always had $a_0 = 4$, but the intensity of the first (set-up) pulse was varied. Simulations were run up to 400fs. Proton energy spectra from four such simulations are shown in figure 1 against a comparison run (main drive pulse only).

As can be seen in figure 1, the spectra from the two pulse runs differ from those of single pulse runs in two regards. Firstly there is a reduction in the maximum proton energy. Since the first pulse generates a density gradient on the rear surface this is somewhat expected. However, it is also found that spectral peak are generated in the two pulse runs. This is somewhat unexpected and demands explanation.

Physics of Spectral Peak Formation

The spectral peaks are formed by a two stage process that to the best of the author's knowledge has not previously been observed. The first stage is caused by the increase in the fast electron temperature that the second laser pulse causes. This results in a strong spike in the electric field being formed close to the heavy ion front. In simulations without a second ion species (i.e. only protons) this occurs at the point of the steepest proton density gradient, so this process is not dependent on there being a second ion species. This spike rapidly accelerates protons in that region of the expanding proton cloud to a higher velocity than those further away from the target (although not to a higher velocity than the maximum proton velocity). The consequence of this is that these protons start to overtake the protons ahead of them. This in turn produces a peak in the proton density. The evolution of the proton phase space ($p_x - x$) is shown in figure 2 below.

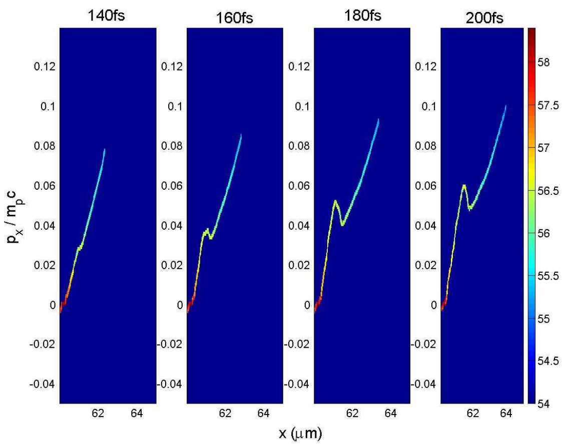

Figure 2: Proton $p_x - x$ phase space during first stage of spectral peak generation process.

As the peak in proton density is formed, the second stage begins. The creation of the peak in proton density changes the electric field once again. One expects that inside the proton cloud, i.e. not at the proton front. For the electrid field to be determined by the quasi-neutral expression, $E_x = -(k_B T_f / e n_p)\partial n_p / \partial x$ to a good approximation. A peak in the proton density would therefore create a postive going and a negative going spike in the electric field, which is indeed exactly what happens in the simulation. The positive going spike accelerations a bunch of protons to higher energy, and it is this bunch that constitutes the spectral peak. The evolution of the proton phase space is shown by figure 3 below.

Summary

In this work we have shown that it is possible to generate a laser-accelerated proton beam with spectral peaks in the energy spectrum by using two laser pulses. No special target enginnering is required. The gain in the number of protons in the peak (a factor of 2–10 depending on the circumstances) outweighs the increase in the laser energy required (at most a 25% increase in the energy budget in this set of simulations).

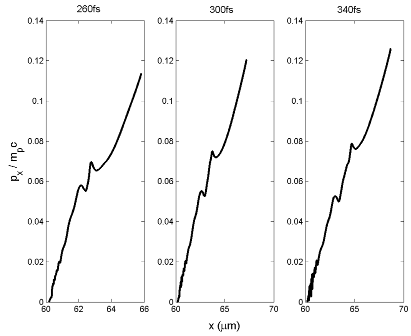

Figure 3: Proton $p_x - x$ phase space during second stage of spectral peak generation process.

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