Controlling the fast electron divergence in a solid target with multiple laser pulses

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Controlling the divergence of laser-driven fast electrons is compulsory to meet the ignition requirements in the fast ignition inertial fusion scheme. It was shown recently that using two consecutive laser pulses one can improve the electron beam collimation. In this paper we propose an extension of this method by using a sequence of several laser pulses with a gradually increasing intensity. Profiling the laser pulse intensity opens a possibility to transfer to the electron beam a larger energy while keeping its divergence under control. We present numerical simulations performed with a radiation hydrodynamic code coupled to a reduced kinetic module. Simulation with a sequence of three laser pulses shows that the proposed method allows to improve the efficiency of the double pulse scheme at least by a factor of 2. This promises to provide an efficient energy transport in a dense matter by a collimated beam of fast electrons, which is relevant for many applications such as fast ignition inertial fusion and ion beam sources.

I. INTRODUCTION

In the last decades the experiments all over the world are showing that, despite the initial optimistic predictions, the laser-driven fast electron beam is characterized by a large divergence which makes impossible to meet the fast ignition requirements. The electron beam divergence can be controlled both by acting on the electron generation mechanism (target manufacturing technique [2]) or by controlling the electron transport (artificial confinement of the beam). Recently a two consecutive laser pulses scheme has been proposed by Robinson et al. [3] to optimize electron transport and collimation in a solid target. In this scheme two collinear laser pulses, with a given intensity ratio I_2/I_1, are used to generate energetic electron beams. The resistive azimuthal magnetic field generated by the first electron beam can guide the electron beam generated by the second pulse. This scheme has been successfully tested, in a experiment, two years later [4]. Experimental results confirmed the validity of the scheme showing that the best time delay is of the order of the laser pulse duration. Moreover, the limits of the scheme have been demonstrated as the collimation was observed only for a special combination of the laser pulses intensities (I_2/I_1). Indeed, a more detailed analysis shows that the electrons can be collimated in a very limited range of laser intensities and pulse durations. As we discuss in the following, exceeding intensities of 10^{20} W/cm^2 for the second laser pulse, or remaining under intensities of 10^{18} W/cm^2 for the first laser pulse, strongly reduce the efficiency of the scheme. In this paper we propose an extension of the double pulses scheme by using a sequence of several pulses with adjusted intensity profile and delay times. An example is proposed of splitting the second (main) pulse in two pulses with the same amount of energy. Such a "triple pulses scheme" allows to increase the total delivered laser energy by keeping the single intensity per pulse below 10^{20} W/cm^2 and stretching the duration of the whole process within the limits imposed by fast ignition requirements.

II. FAST ELECTRON BEAM DIVERGENCE

It is an experimental evidence that the laser-driven fast electron beam divergence increases with the laser intensity. Green et al. [5] have collected the results from many experiments obtaining a scaling law of the total beam divergence (half-angle in degrees) as a function of the laser intensity (with $\lambda = 1\mu$m) $\theta_{1/2}(I_L) = 15 + 13\log(I_L^{18})$. where I_L^{18} is the laser intensity in the units of 10^18 W/cm^2. The fast electron beam collimation due to the self-genereted resistive magnetic field was studied in Ref. [7]. It was shown that this "natural collimation" is less favourable at high divergence angles, and fast-electron energies. It is inefficient at intensities in excess of 10^{19} W/cm^2. In addition as the laser intensity increases the resistive magnetic field changes its sign acting to hollow rather then to collimate the electron beam [8]. Indeed the positive (defocusing) and the negative (focusing) components of the azimuthal magnetic field are in competition depending on the value of the beam current density and the target resistivity. The beam divergence is limited by the collimating magnetic field only at relatively low laser intensities.

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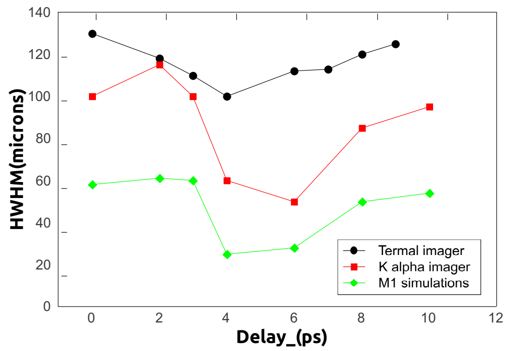

FIG. 1. Dependence of the HWHM of the Cu K_α (red diamonds) and thermal emission images (dot) from the rear target surface on the time delay compared with (green diamonds) numerical simulations.

III. DOUBLE PULSES SCHEME

In the "double pulses scheme" [3], the laser pulse is split in two pulses with a given intensity ratio (typically $I_2/I_1 \in [10 : 100]$). The first pulse (with a moderate intensity I_1) creates an electron beam which starts to propagate inside the target. The return current generates an azimuthal magnetic field which collimates the electrons produced by the second laser pulse (with intensity I_2) arriving on the target with a given time delay. This scheme has been tested at the Rutherford Appleton Laboratory and the main results of the experiment are summarized in Ref. [4]. Figure 1 shows the Half Width at Half Maximum (HWHM) of the main electron beam transverse size as a function of the time delay between the two pulses as was obtained in the experiment and in the hybrid kinetic simulations. These simulations show a qualitative agreement with the electron beam HWHM measured from the images of the thermal radiation and the copper K_α emission.

A. Numerical simulations

The fast electron propagation through the target has been modelled with the radiation hydrodynamic code CHIC coupled to the kinetic module M1 [11]. This fast kinetic model, describes the collisional transport of energetic particles while taking into account the self generated magnetic field. Derived from the Vlasov-Fokker-Planck equation, it involves an angular closure in the phase space leading to a set of hyperbolic equations for the moments of the distribution function evolving in time, space and energy. This method is suitable for the computation of the fast electron transport on the hydrodynamic time scales. It provides an alternative to prohibitive full kinetic simulations with large, complex and time consuming codes.

Simulations have been performed in a cylindrical geometry (where z is the beam propagation axis and r is the radial direction in the target surface plane). The target is a 96 μm thick (along the z direction) aluminium cylinder of radius of 96 μm. The simulations were conducted with 4 μm resolution. Initial conditions have been calculated assuming Beg (Eq. (1), Ref. [12]) and Wilks (Eq. (2), Ref. [1]) scaling laws for the estimate of the fast electron mean energy as a function of the laser intensity and the Solodow scaling law (Eq. (3), Ref. [13]) to account for the laser-electron conversion efficiency ξ as a function of the laser intensity:

$$T_b = \alpha_b \left(\lambda^2 I_L^{18}\right)^{1/3}; \ \alpha_b = 215. \quad (1)$$

$$T_w = \alpha_w(\sqrt{1 + \lambda^2 I_L^{18}/2.8} - 1); \ \alpha_w = 511. \quad (2)$$

$$\xi = \alpha_s(\lambda^2 I_L^{18})^{1/4}; \ \alpha_s = 0.108 \quad (3)$$

where T_b and T_w are in keV, and the laser intensity I_L is in 10^{18}W/cm^2.

B. Parametric analysis of the beam guiding

In this section we present the results of numerical simulations performed to study the double pulse scheme [3], its stability and possible modifications. In particular, it is shown that equally sharing the amount of energy of the second (main) pulse in two consecutive pulses, one can improve the efficiency of beam guiding. Collecting all the energy in a single pulses (the second one in the double pulse scheme) is convenient in terms of the laser-electron conversion efficiency, which increases with the intensity [10]. However, it is not so from the point of view of guiding. By increasing the laser intensity one reduces the collimating magnetic field [7] and increases the total electron beam divergence [5]. The triple pulse scheme overcomes these problems and opens the way for a more efficient beam guiding.

1. *Double pulses scheme*

Here we present several examples which are important for understanding the physics of beam guiding. The first example concerns the time dependence of the maximum magnetic field B_θ. The simulations have shown that for laser intensities in the range of 10^{19-20} W/cm^2 the time of maximum magnetic field depends only on the laser pulse duration and the electron beam size w_e as $t_{best} = s(w_e)w_t + 0.7$ where w_t is the pulse time HWHM in pico-second and $s(w_e) = 0.157w_e + 0.9$ is a dimensionless parameter related to the electron beam size in microns. Assuming w_e=17 μm, and $w_t = 1$ ps (these are the conditions in Ref. [4]) we obtain $s = 3.6$ and then $t_{best} = 4.3$ ps. The same calculation by assuming w_e=10 μm, and $w_t = 0.4$ ps gives $s = 2.5$ and a shorter $t_{best} = 1.7$ ps. Finally t_{best} can be reduced both by reducing the pulse duration (i.e w_t) and the electron beam size (i.e s). The beam size dependence of t_{best} can be understood also by solving the equation $\partial B_\theta(t)/\partial t = 0$ in the "rigid model" approximation (see Appendix **??**). In conclusion, both, numerical simulations and experimental results suggest that the best time delay between the consecutive pulses is defined as $\Delta_t \simeq t_{best}$ with an uncertainly of about 1 ps. Delays shorter (the magnetic field is still not at its maximum) or longer (the magnetic field is decreasing due to the diffusion) than t_{best} reduces the efficiency of the double pulses scheme. Figure 2 (left panel) shows the maximum B_θ as a function of time in the double pulses scheme at various time delays between the first and the second pulses. The continuous and the dotted blue lines represent respectively the maximum magnetic field and the main laser beam temporal profile alone (i.e without the first pulse). The azure line represents (up to 10 ps) the maximum magnetic field of the first pulse which is amplified by the injection of the second pulse at different time delays, the green line $\Delta t = 3$ ps, redline $\Delta t = 4$ ps, azure line $\Delta t = 8$ ps. At the best condition the magnetic field propagates along the beam axis "driving" the electrons inside the target. The main problem

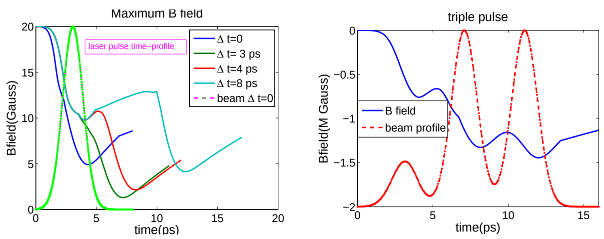

FIG. 2. [a] Temporal evolution of the maximum magnetic field at various time delays between the first and the second laser pulse ($\Delta t = 0$ ps represent the second pulse alone). The azure line represents (up to 10 ps) the maximum magnetic field of the first pulse which is amplified by the injection of the second pulse at different time delays, green line $\Delta t = 3$ ps, redline $\Delta t = 4$ ps, azure line $\Delta t = 8$ ps. The diffusion time of the magnetic field depends only on the beam radius and on the target resistivity $\tau_{B_\theta} \sim w_e^2/\eta$. [b] Temporal evolution of the maximum magnetic field (continuous line) and of the laser pulse intensity (dotted line) for the time delay $\Delta t = 4$ ps for the triple pulses scheme.

of the electron guiding is that the electron beam divergence increases with the laser intensity. Consequently the "natural collimation" becomes less and less efficient, as it traps in the guiding channel only a small paraxial part of the beam. Double pulses scheme overcomes this problem but still it is limited to laser intensities smaller then 10^{20} W/cm^2. Ref. [3] shows that this limitation is due to the interplay between the strength of the resistive magnetic field generated by the first electron beam and the momentum of the incoming electrons of the second beam. According to [7], the guiding imposes a condition on the radial extension R and on the absolute value of the negative magnetic field B_θ generated by the return current of the first electron beam. Assuming [3] $\eta = 0.5$, $w_t^1 = 0.25$ and $\xi = 0.2$ (see Eq. (3)) this condition write::

$$I_1^{18} > 0.1 I_2^{3/4} \tag{4}$$

According to this condition one may increase the intensity of the first laser beam and consequently reduce the intensity of the second one by keeping the total energy constant. Since a part of electrons produced by the first laser pulse will be lost (all the electrons produced before that the magnetic field attains its maximum value) this solution is not favourable. The second possibility is to reduce the intensity of the second beam by stretching it in time. As the laser beam intensity is defined by the required electron energy, this stretching can be achieved by splitting the second laser pulse in a sequence of pulses separated by the appropriate time delays.

According to Eq. (4) and assuming $I_2 = 10^{20}$ W/cm^2 we get $I_1 > 3 \times 10^{18}$ W/cm^2. Let us now split the second pulse into two equal pulses having a twice lower intensity. This will relax the condition (**??**) by a factor of $2^{3/4}$; in addition the intensity reduction induces a reduction of the electron beam divergence (from $\theta_{1/2} \simeq 20°$ to $\theta_{1/2} \simeq 15°$) again by a factor $2^{3/4}$ (according to Eq. (**??**)).Thus by reducing the intensity by a factor 2 one can achieve a significant relaxation of the condition (**??**) by a factor larger then 2 (see in the following). This simple example is confirmed by numerical simulations.

2. *Triple pulses scheme*

We limit ourselves here by splitting the second pulse into two pulses of equal intensities. As shown in Figure. 2 (right panel) in the triple pulses scheme the third laser pulse is injected when the magnetic field due to the first two pulses achieves its maximum. In this case simulations show that the delay times shorter then t_{best} are preferable. This is explained by the fact that the magnetic field of the second beam starts to follow the electron beam along the propagation direction moving away from the front target surface. In the following, three configurations are compared: (A) Double pulses configuration, (B) Triple pulses configuration and (C) Single pulse configuration. We choose configuration A such that the collimation condition (**??**) is not satisfied $I_2 \sim 10^{20}$ W/cm^2. Consequently the configuration B is obtained by equally sharing the energy in the second and third pulses $I_2 \sim I_3 \sim 5 \times 10^{19}$ W/cm^2. The laser parameters for configurations A and B are chosen according to the typical values of the Vulcan laser at the Rutherford Appleton Laboratory which has been used to test the double pulses scheme [4]. The total available energy is E_L =190 J, the pulse duration w_t =1 ps HWHM the laser pulses are focused on a 96 μm thick aluminium target within a focal spot of w_L=3.5 μm radius. The laser and electron beam parameters for the configurations A and B are listed in Table I. Figure 3 shows the distribution of the electron beam density for the single pulse (case C) at t=6 ps, for the double pulse scheme (case A) at t=10 ps and for the

(A) two pulses configuration									
	E_L	w_t	w_L	n_L	I_L	E_e	T_e	ξ	$\theta_{1/2}$
	[J]	[ps]	[μm]	[/]	[W/cm^2]	[J]	[MeV]	[/]	[deg]
I beam	15	1	3.5	0.6	$5 \cdot 10^{18}$	1	0.4	0.15	12
II beam	175	1	3.5	0.6	10^{20}	40	2.5	0.34	21

(B) three pulses configuration									
	E_L	w_t	w_L	$_L$	I_L	E_e	T_e	ξ	$\theta_{1/2}$
	[J]	[ps]	[μm]	[/]	[W/cm^2]	[J]	[MeV]	[/]	[deg]
I beam	15	1	3.5	0.6	$8 \cdot 10^{18}$	1	0.4	0.15	12
II beam	87	1	3.5	0.6	$5 \cdot 10^{19}$	18	1.7	0.29	17
III beam	87	1	3.5	0.6	$5 \cdot 10^{19}$	18	1.7	0.29	17

TABLE I. Comparison between double (case A) and triple (case B) pulses scheme.

triple pulses scheme (case B) at t=13 ps. As the double pulses parameters do not fulfil the collimation condition the beam strongly diverges in the case A. It would be possible assuming a lower intensity for the second pulse to obtain a good electron beam collimation but the electron energy will be lower. The triple pulses scheme allows to guide the electrons with the required energy.

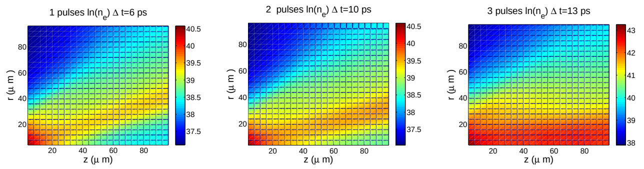

FIG. 3. Distribution of the electron beam density at the end of the process for the double pulse scheme at t=10 ps (case A center) and for the triple pulses scheme at t=13 ps (case B right). In the left panel is shown the case C with the energy E= 40 J. Other parameters are shown in Table 1.

Figure 4 shows the distribution of the resistive magnetic field at two time instants for the case A (t= 6,10 ps) and for the case B (t= 6,14 ps). A comparison of these figures shows that the three pulses scheme is more efficient. Indeed as shown in Fig. **??** the K_α signal is better confined along the propagation axis and the negative part of the resistive magnetic field can collimate the electrons. In contrast, the positive part (that hollows the beam) is much less important. This is not the case in the double pulse scheme where the competition between the negative and the positive part of the resistive magnetic field leads to a significant modification of the beam spatial distribution with a smaller number of guided electrons. The negative component of the magnetic field pushes electrons towards higher beam current density regions despite the positive component which does the opposite. The combination of these two processes leads to a macroscopic electron beam "filamentation".

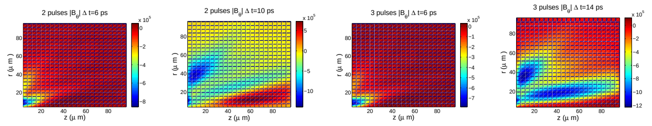

FIG. 4. from left to right distribution of the resistive magnetic field for the case A (t=6,10 ps) and for the case B (t=6,14 ps)

IV. CONCLUSIONS AND PROSPECTIVES

Simulations show that the multiple pulses scheme is more flexible, allows to overcome several limitations already observed in the experiments. In particular, by increasing the number of pulses (and then the duration of the process) one can reduce the single pulse intensity while keeping the total delivered energy constant and the total duration of the process within the fast ignition limits. The presented example of three consecutive pulses shows that the efficiency of the double pulse scheme can be increased at least by a factor of 2. Moreover putting together many laser pulses gives a possibility to increase the total amount of delivered energy while keeping the average energy constant. This method is promising to achieving an efficient energy transport in a dense matter by a collimated beam of fast electrons, which is relevant for many applications such as fast ignition inertial fusion and ion beam sources.

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