Effect of the laser pulse shape on the hole boring efficiency

V. Mironov[1], N. Zharova[1], E. d'Humières[2], R. Capdessus[2] and V.T. Tikhonchuk[2]

[1] *Institute of Applied Physics, Russian Academy of Sciences, Nizhni Novgorod 603950, Russia*

[2] *Univ. Bordeaux - CEA - CNRS, CELIA, UMR 5107, F-33405 Talence, France*

Utilization of a hollow metal cone presents a significant inconvenience for the inertial fusion reactor. A promising option is hole boring in plasma corona with an intense laser pulse. Hole boring by the ponderomotive force is a relatively slow process. Its efficiency may be enhanced if the laser pulse is split in a sequence of shorter pulses [1]. In this paper we show that the use of laser pulses with duration of a few inverse ion plasma periods allows to maintain the regime of relativistic transparency for a longer time and produce a much deeper and more stable channel compared to a single pulse of the same energy [2].

Numerical simulations of laser penetration through an overcritical plasma layer in Ref. [1] were conducted in the two-dimensional geometry for a laser beam of a circular polarization. The dimensionless vector potential of the incident wave reads: $\mathbf{a} = a_0(t)\,(\mathbf{e}_y + i\mathbf{e}_z)\,\exp[i\omega_0(x/c - t) - y^2/b^2]$. The pulse amplitude had a Gaussian shape $a_0(t) = a_m \exp(-t^2/\tau_p^2)$ with $a_m = 4$ and the beam width $b = 5\,\lambda_0$, where λ_0 is the laser wavelength. It was demonstrated in the simulations with a hydrogen plasma of a density twice the critical density, $n_{e0} = 2\,n_c$ and a length of $40\,\lambda_0$ that employing three pulses of a duration of $25\,T_0$ with the separation time of $T_{\rm delay} = 70\,T_0$, where $T_0 = \lambda_0/c$ is the laser period, one creates a longer almost straight channel compared to a single $75\,T_0$ pulse .

We studied this effect in more details by using the code PICLS [3] and another reduced PIC code [2]. We observe that the quality of the channel is improved and its length increases if a long Gaussian pulse with an amplitude a_m and duration of τ_p is replaced by two pulses of a duration $\tau_1 = \tau_p/2$ with the same amplitude. Moreover, we achieved an even stronger effect by using a flat top incident laser pulse with a steep front of a duration τ_f and the plateau duration chosen in such a way that the pulse fluence is the same as in the Gaussian pulse of the same amplitude.

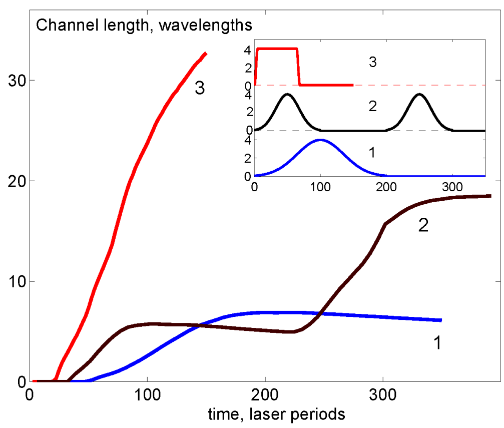

Figure 1: Temporal dynamics of the channel length $L(t)$ in a plasma. The pulse shapes are shown in the insert.

Figure 1 demonstrates the temporal dynamics of the channel length $L(t)$ in a plasma for the case of a Gaussian pulse of the duration $\tau_p = 50\,T_0$ (1), two Gaussian pulses of the duration $\tau_1 = 25\,T_0$ each with the time interval between the maxima $T_{\rm delay} = 200\,T_0$ (2) and of a flat-top pulse with the front duration $\tau_f = 5\,T_0$ (3). In all three cases the maximum amplitude is the same $a_m = 4$, the plasma density $n_{e0} = 2\,n_c$. The plasma density distributions for three cases are shown in Fig. 2. The color code presents the density in a logarithmic scale. A pulse with a steep front creates a channel of a better shape more suitable for inertial fusion applications.

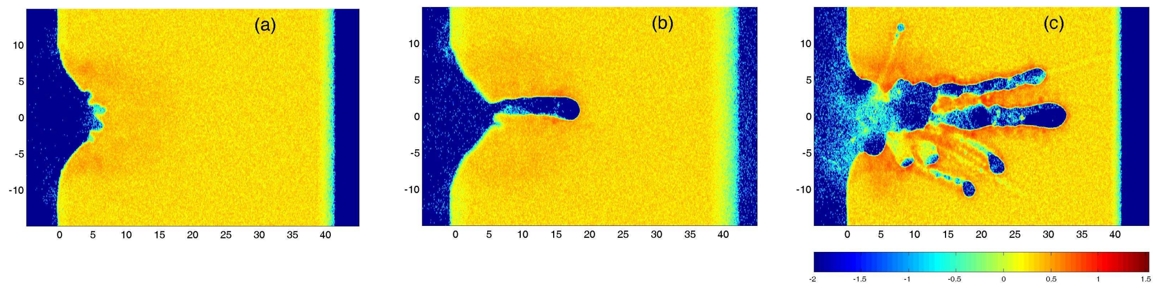

Figure 2: Spatial distribution of plasma density: (a) a single pulse $\tau_p = 50\,T_0$ at the time instant $t = 230\,T_0$; (b) two pulses $\tau_1 = 25\,T_0$ with the time delay $T_{\rm delay} = 200\,T_0$ at the time instant $t = 405\,T_0$; and (c) a flat top pulse $\tau_2 = 58.9\,T_0$, $\tau_f = 5\,T_0$ at the time instant $t = 144\,T_0$. The spatial coordinates are scaled in the vacuum wavelengths λ_0.

In order to demonstrate that the laser self-induced transparency (SIT) is indeed the dominant factor in the hole boring enhancement we have analyzed a correlation in the temporal evolution of the laser intensity and the plasma density. The laser pulse and the plasma are well separated in the ponderomotive pressure regime, while in the opposite case the laser penetrates into the plasma before the ions are accelerated, and laser field and particles are located simultaneously in the same place. The cross-correlation function

$$S_{SIT}(y,t) = n_c^{-1}\lambda_0^{-1}\int |\mathbf{a}(x,y,t)|^2 n_e(x,y,t)\,dx$$

gives a measure of how deep the laser field penetrates the plasma. The character of evolution of the cross-correlation integral in the flat-top pulse case is noticeably different. The maximum value 6×10^4 of $S_{SIT}(y=0)$ is two orders higher than that for the Gaussian pulses. That indicates a much deeper penetration of the laser pulse in plasma and its focusing in the bottom of the channel. It strongly increases the hole boring rate as the plasma is expelled in all directions at the same time.

This effect of enhanced hole boring is due to a more efficient laser plasma interaction. The combination of the parameters where the dimensionless plasma density n_e/n_c is of the order of the laser amplitude a_m corresponds to the interface between the radiation pressure acceleration (RPA) regime, where $n_e/n_c > a_m$, and the SIT regime, where $n_e/n_c < a_m$. The transition between these regimes depends on the laser pulse characteristics and the plasma density profile. For a relatively long pulse and a long density scale length, the RPA regime may be realized even in a relatively low density plasma because of formation of a higher density plasma bump in front of the laser pulse front. On the contrary, for a steep plasma profile and a steep pulse front, the ions do not have time to respond and the laser pulse may propagate deeper in the plasma.

The characteristic parameter is the ratio of the pulse front to the ion plasma period. In the case of a sharp laser pulse where $\omega_{pi}\tau_f \lesssim 1$, the ions do not have time to move. As a result, the laser pulse penetrates into plasma if its amplitude corresponds to the SIT condition. Being inside the plasma, laser field is partly trapped and it can be reflected many times from overdense plasma walls and efficiently absorbed thus transferring an additional momentum to particles. Long-living self-localized electromagnetic field also expands the channel in the lateral direction.

One may assume that the shorter are the pulses in the train (keeping the full energy constant), the deeper is the channel. However, it also depends on the time delay between the pulses. In a series of reduced PIC simulations we kept constant the amplitude of each pulse, $a_m = 4$, and the total pulse fluence and split one Gaussian pulse of a duration $\tau_p = 30T_0$ in N successive Gaussian pulses of a duration $\tau_1 = \tau_p/N$. We studied the dependence of the channel length L on two parameters: the number of pulses N and the time delay between them T_{delay}.

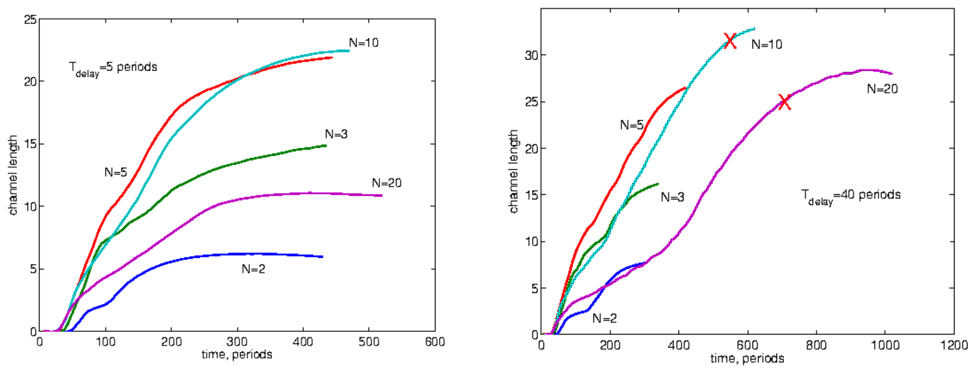

Figure 3: Temporal evolution of the channel length in function of the number N of pulses for $T_{\text{delay}} = 5T_0$ (a) and $T_{\text{delay}} = 40T_0$ (b). The pulse amplitude $a_m = 4$. Red crosses mark the moments when the layer is bored through.

The value of the channel length L was calculated as a weighted average over the plasma density distribution according to the formula

$$L(t) = b^{-1}\pi^{-1/2}\lambda_0^{-2}\int G(x,y)\exp(-y^2/b^2)\,dx\,dy$$

where the gate function $G = 1$ if $n_e(x,y) < 0.7\,n_c$ and $G = 0$ otherwise. The value of L thus depends on the density distribution. In particular, the length of the channel is reduced if its width w_p is smaller than the laser pulse width b. We found in the simulations that the laser field penetrates through the layer when its geometric length is $\sim 80\%$ of the plasma layer length. Then the actual width of the plasma channel is 20 to 30% smaller than the laser pulse width.

Figure 3 illustrates the results of this study. The dependence of the channel length on the number of pulses and the time delay is non-monotone. The channel length grows linearly with the pulse number, and it saturates for the splitting number $N \approx 5$. However, the maximum efficiency of hole boring is obtained with 10-fold pulse splitting, when the single pulse duration $\tau_1 = \tau_p/10$ is only 3 field periods. This corresponds to the value $0.2\pi \simeq 0.6$ of the parameter $\tau_1\omega_{pi}$. For the larger number of pulses the channel depth becomes smaller. However, this conclusion depends also on the time delay between pulses.

The time delay of 5 laser periods, as shown in panel a, is too small and insufficient for the pulse energy to be effectively consumed in the plasma. Increasing it to $40\,T_0$ (panel b) one certainly improves the hole boring and achieves the plasma perforation with 10 and also with 20 laser pulses. However, the channel is narrower in the latter case. In fact, the time delay of $40\,T_0$ is not optimal either. The channel depth continues increasing with T_{delay} for small number subpulses, while it saturates for higher pulse splitting. However, the channel width also increases with the time delay, and thus one needs more energy to penetrate a given plasma depth. The time of channel formation also increases with T_{delay}.

In conclusion, we have shown that a laser pulse with a steep front and a long plateau or a chain of short Gaussian pulses may significantly improve the hole boring efficiency. The numerical simulations with the reduced PIC code and in qualitative agreement with full PIC simulations. The crucial parameter is the duration of each pulse, that should verify the condition $\tau_p\omega_{pi} \approx 1$. Apart of inertial fusion, this process may find application in communications through an overdense plasma.

This work was performed within the projects HiPER #211737 and Marie Curie #230777. It had a granted access to the HPC resources of CINES, the allocation 2011-056129 made by GENCI. The support from RFBR projects #11-02-00225 and #11-02-01070 is acknowledged.

References

[1] W. Yu *et al.*, Laser and Particle Beams **27**, 109 (2009)
[2] V. Mironov *et al.*, Plasma Phys. Control. Fusion, to be published (2012)
[3] Y. Sentoku and A.J. Kemp, Journ. Comput. Phys. **227**, 6846 (2008)