

# ANOMALOUS PENETRATION OF ULTRAHIGH INTENSE SHORT PULSE LASER AND PULSE EXPANSION OF REFLECTED LASER

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## 1. Introduction

Recent developments of laser technology have made it possible to generate ultrahigh intense subpicosecond pulses, and experiments are now being carried out to explore new regimes of relativistic laser-plasma interactions [1-3]. When the plasma is irradiated by such intense lasers, electrons oscillating in the field of the laser wave are strongly relativistic. It was predicted that the ultrahigh intense laser would be able to propagate into a sufficiently overdense plasma by the relativistic electron mass correction and hence decreasing the effective electron plasma frequency [4-6]. Recently, it was reported that an s-polarized wave interacting with a sharp-boundary plasma has excited an electromagnetic nonlinear pulse with relativistic amplitude propagating into the overdense plasma [7], and the transition between an opacity and a transparency regime for the propagation of the ultrahigh intense laser into overdense plasmas has been discussed [8]. The recession velocity was found to be significantly reduced due to the relaxation-oscillation of the penetration that was coupled with the electron density oscillation at the laser front. The intensity threshold for the penetration was also found to depend on both plasma density and ion dynamics that was characterized by the ion acoustic speed [9].

In this paper, we present the interactions between ultrahigh intense ( $> 2 \times 10^{18} [\text{W}/\text{cm}^2\text{-}\mu\text{m}^2]$ ) short pulse (16 ~ 133 [fsec]) lasers and slightly overdense (twice a critical density) plasmas with the use of a 1-1/2 dimensional electromagnetic, relativistic both for electron and ion, particle-in-cell code, EMPAC. The Gaussian laser pulse is launched from the right boundary and ramped up to a given amplitude over a given period, and the plasma is a thick slab with a constant density and sharp boundary edges. Simulations are performed with immobile ions to inhibit plasma expansions into vacuum and to investigate relativistic electron dynamics.

## 2. Pulse expansion

The ultrahigh intense short pulse laser can penetrate into the overdense plasma due to the relativistic effect, but it is completely reflected after propagating to a certain extent except a portion of the absorbed energy. As a typical result, the x-t diagram of the electromagnetic field

intensity and the incident and reflected pulse shapes are shown in Fig. 1 for  $I_L \lambda_L^2 = 2 \times 10^{19}$  [W/cm<sup>2</sup>-μm<sup>2</sup>] and HWHM (Half Width at Half Maximum) =  $2.5 \lambda_L$ , where  $I_L$  is the peak laser intensity and  $\lambda_L$  is the wavelength in microns. The leading portion of the pulse is immediately reflected by the plasma because the temporal intensity is not enough to accelerate electrons to the relativistic velocity and to trigger on the anomalous penetration. The trailing portion of the pulse, however, can penetrate into the plasma and propagate until the reflection at the recession front, where a discontinuity between the perturbed and unperturbed plasma exists, acting as a mirror. Thus the shape of the pulse is changed and the pulse length of the reflected laser is expanded more than that of the incident laser by a modulation due to the anomalous penetration. Longer the duration and higher the intensity, the pulse penetrates deeper into the plasma from the boundary, but the laser is finally reflected back when no energy is supplied at the recession front to sustain the permeation. Pulse expansion factors are shown in Fig. 2 for various laser intensities and pulse durations. Deeper anomalous penetration causes longer traveling time and leads to more pulse modulation and expansion.

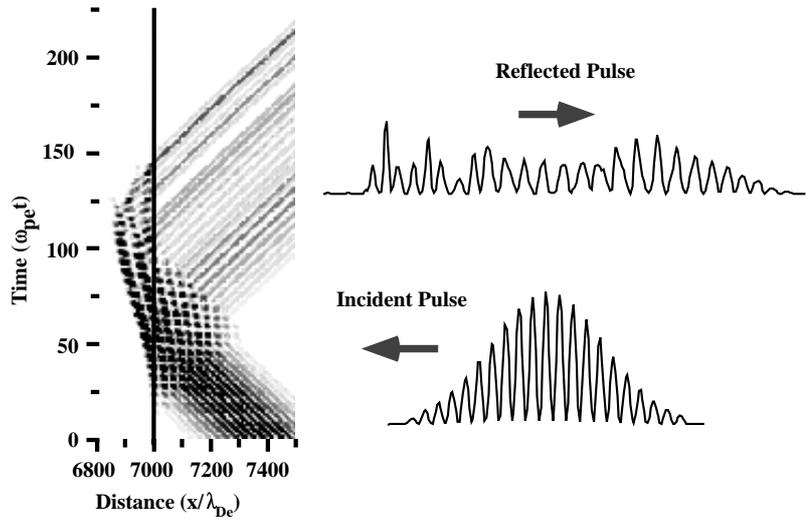


FIG.1. The x-t diagram of the electromagnetic field intensity and the incident and reflected pulse shapes for  $I_L \lambda_L^2 = 2 \times 10^{19}$  [W/cm<sup>2</sup>-μm<sup>2</sup>], HWHM =  $2.5 \lambda_L$ ,  $n_0 = 2n_c$  and plasma exists  $x/\lambda_{De} < 7000$ .

The frequency of the reflected laser can be calculated by the matching condition of the Doppler shift formula coupling with the relativistic dispersion relations[10] as follows:

$$\frac{\omega_r}{\omega_L} = \frac{\frac{u_f}{c} - \frac{v_{prop}}{c}}{\frac{u_f}{c}} \cdot \frac{\frac{u_b}{c}}{\frac{u_b}{c} + \frac{v_{prop}}{c}} \quad (1)$$

$$\frac{u_f}{c} = 1 / \sqrt{1 - \frac{n_0}{n_c \gamma}} \quad (2)$$

$$\frac{u_b}{c} = \frac{\omega_r}{\omega_L} / \sqrt{\left(\frac{\omega_r}{\omega_L}\right)^2 - \frac{n_0}{n_c \gamma}} \quad (3)$$

where  $v_{\text{prop}}$  is the propagation velocity of the front,  $c$  is the light speed in vacuum,  $n_0$  is the plasma density,  $n_c$  is the critical density, and  $\gamma$  is the Lorentz factor.  $u_f$ ,  $u_b$ ,  $\omega_L$  and  $\omega_r$  are the phase velocities of the forward and backward laser in the plasma, the frequencies of the incident and reflected laser, respectively. Ignoring the oscillation in the longitudinal field, the simple estimation for  $\gamma$  is obtained as follows [11]:

$$\gamma = \sqrt{1 + \frac{I_L \lambda_L^2}{1.37 \times 10^{18}}} \quad (4)$$

As  $v_{\text{prop}}$  is evaluated with the x-t diagram of the electromagnetic field intensity for different laser intensities, the predicted frequency of the reflected laser with Eqs. (1)-(4) is shown in Fig. 3 and is in good agreement with the simulation result.

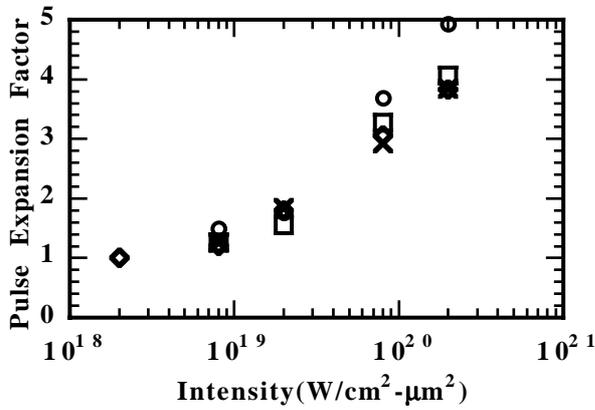


FIG.2. The pulse expansion factor as a function of the laser intensity. Circle, square, diamond and cross indicate HWHM=1.25 $\lambda_L$ , 2.5, 5 and 10, respectively.

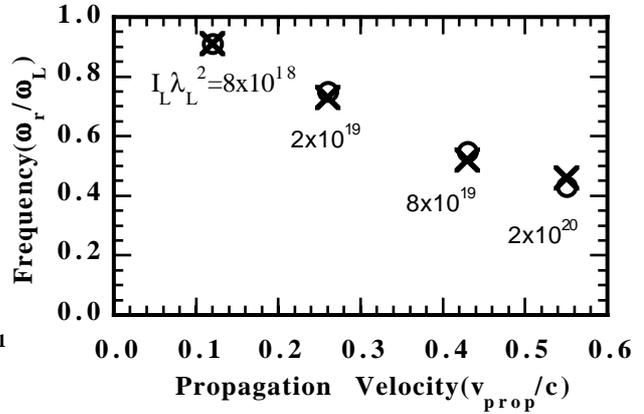


FIG.3. The frequency of the reflected pulse as a function of the propagation velocity which depends on the laser intensity. Circle and cross indicate the predicted value and simulation result, respectively.

### 3. Soliton-like propagation

The anomalously penetrating pulse shows soliton-like behaviors in the plasma after the incident laser has vanished. The partial x-t diagram of the electromagnetic field intensity is shown in Fig. 4 for  $I_L \lambda_L^2 = 8 \times 10^{19}$  [W/cm²-μm²] and HWHM = 5 $\lambda_L$ . As one wavepacket collides with another and then overtakes it, the individual reflected wavepackets seem to propagate independently like a soliton.

The wavepacket can accelerate electrons and the local effective Lorentz factor increases, hence this leads to an increase of the local refraction index. The wavepacket is trapped by the plasma which has a larger refraction index more than that of surroundings, and accelerates electrons much more. These processes construct a positive feedback and compensate for an

energy absorption by the plasma, keeping the wavepacket stable as a soliton. It is noted that the average electron density is unchanged with the initial value due to immobile ions and electrons do not affect the refraction index in our simulations. It was observed in the simulation results that the local effective plasma frequency along the trajectory of the solitons was smaller than the value of surroundings.

Unfortunately, characteristics of soliton, such as a relation between an amplitude and a speed, are not obvious, and need more researches and open to discuss.

We would like to thank participants of CECAM workshop on The Interaction of Short Ultra-intense Laser Pulses with Plasmas, Lyon, France, September 16-20 (1996) and September 29-October 3 (1997) for fruitful discussions.

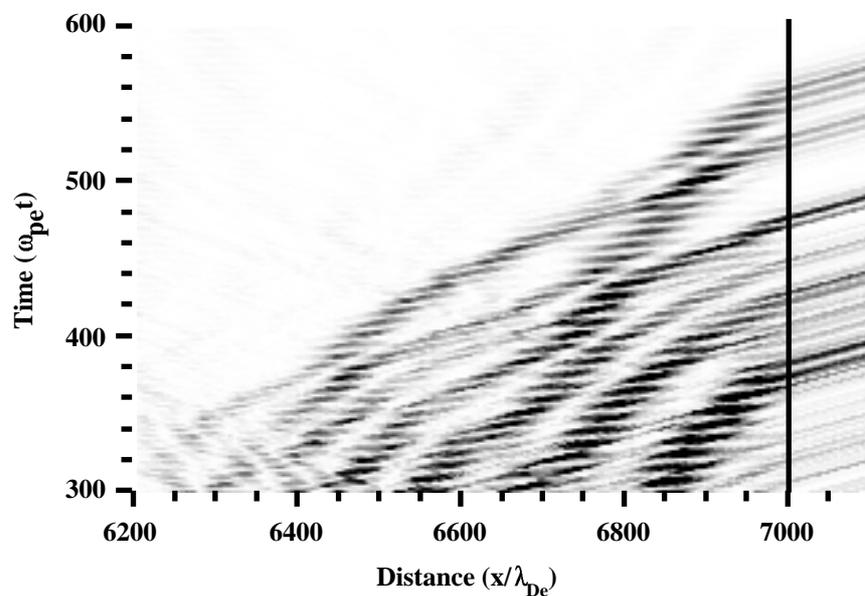


FIG. 4. The partial x-t diagram of the electromagnetic field intensity for  $I_L \lambda_L^2 = 8 \times 10^{19}$  [W/cm<sup>2</sup>-μm<sup>2</sup>] and HWHM =  $5\lambda_L$ .

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