Wave guided laser wake-field acceleration in splash plasma channels

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Abstract. A transient plasma micro optics (plasma channel and focusing plasma optics-TPMO) in the LWFA provides controllable electron self-injections that result in production of higher quality bunches. In recent study of the TPMO, the deep, straight and short-lived plasma channels [splash plasma channel] were produced by picosecond and sub-picosecond laser pulses in the ponderomotive force dominant regime. Various techniques were used to characterize those channels in argon gas jets irradiated by moderate intensity, \(\sim 10^{15-16}\) W/cm\(^2\), laser pulses with their durations from sub-picoseconds.

1. Introduction

We study laser wake-field acceleration (LWFA) for generation of stable ultra-short electron bunches with a low beam divergence and a high charge. Such acceleration is a basis for high-temporal and high-spatial resolution imaging systems as well as the first stage of the ultra-high energy multistage acceleration technique. Using of plasma channels in the wake field acceleration has been shown to provide a controllable self-injection that result in the production of higher quality stable-electron beams. Moreover, the longer guiding of the laser pulses in a plasma channel leads to a higher energy of accelerated electrons. We have demonstrated the process of the formation of short-lived, deep, straight, and controllable plasma channels (splash plasma channel) produced by picosecond and sub-picosecond laser pulses in the ponderomotive force dominant regime. Various techniques were used to characterize those channels in argon gas jets irradiated by moderate intensity, \(\sim 10^{15-16}\) W/cm\(^2\), laser pulses with their durations from sub-picoseconds.
2. Experimental Setup

The experiment was performed at JLITE-X 800nm Ti: Sappier CPA laser system at the JAEA-KPSI (Kansai Photon Science Institute, Japan Atomic Energy Agency) [3, 4]. An outline of the experimental setup is given in Fig. 1. A laser pulse with a diameter 30 mm is focused to the position of the ~100 μm front edge of the slit gas jet height of 1.5 mm form nozzle exit with f/5.9 off-axis parabolic mirror. In order to study the effects of the TPMO formation by the laser pulse, we controlled the nanosecond order laser pre-pulse by tuning the Pockels cell behind the regenerative amplifier of the laser system [4]. We also controlled the pulse durations from 300 fs to ~6 ps by turning the distance of the grating pair in the pulse compressor, to observe the effect of pulse duration. The focal spot size was 16 μm in full width at 1/e² of maximum with 186 μm Rayleigh length. The maximum laser intensity on the target was estimated to be 3.5×10¹⁵ W/cm². We used an argon gas jet target, which was provided through a supersonic nozzle by a pulse valve (Smartshell Co.Ltd). The stagnation pressure of the pulse valve was 2.00 MPa. The neutral gas density is estimated to be 1.5×10¹⁹ cm⁻³.

To observe the formation process of a TPMO, we used time-resolved interferometer. The wavelength of the probe laser was 400 nm, which was produced with a 2 mm-thickness BBO (barium metaborate) crystal. The interferograms were taken by a CCD camera.

![Fig. 1. Experimental setup](image)

3. Experimental results

Fig.2 (a), (b) (left) show interferograms taken during the propagation of a CPA pulse of 300 fs through the gas jets. Laser pulse comes from the left side. The corresponding electron density distributions are also shown in Fig.2 (a), (b) (right). Time delay between main pulse and probing pulse, which is about 9 ps, was chosen to illustrate the most important stages of channel formation and relaxation. The electron density distribution was calculated from the phase shift. An IDEA code was used to obtain a phase shift map. A fast Fourier transform technique was used to retrieve the plasma-imposed phase shift. The phase-shift map is processed then with an Abel inversion algorism [5].

The maximum channel length was 600 μm. It was three times the Raleigh length. The channel diameter is about 15 μm. The maximal electron density was 4.9x10¹⁹ cm⁻³ and the minimum electron density was 1.0x10¹⁸ cm⁻³. The minimum electron density in the channel is almost 50 times as lower as the maximal.
4. PIC simulation of LWFA in a splash channel

To understand usability of the channels for the laser wake-field acceleration, we perform 2D particle-in-cell (PIC) simulations which included the optical field ionization of plasma. We use the variable particle weight approach [7-9] to calculate the plasma ionization.

PIC simulations are performed for a linearly polarized laser pulse propagating in Ar under 1/2 of the normal pressure or \( N_0 = 1.5 \times 10^{19} \text{ cm}^{-3} \), and for the laser, intensity \( I = 3 \times 10^{19} \text{ W/cm}^2 \), \( \lambda = 0.8 \text{ \textmu m} \), and 40 fs FHWM duration. The \( s \)-polarized laser pulse is numerically focused in diameter \( D = 16 \text{ \textmu m} \) with the focal length, \( f = 150 \text{ \textmu m} \). The initial density profile is chosen to emulate the density profile from the experiment with 6 ps laser pulse (see chapter 3). While the channel diameter is kept constant \( D = 37 \text{ \textmu m} \), the channel depth is a parameter. In the PIC simulation we use the code FPLaser2D [10] exploiting the moving window technique. We use a 320 \( \text{\textmu m} \times 150 \text{\textmu m} \) window and the spatial resolution \( \lambda / 10 \); the kinetic cell is 2 times as large as the PIC one.

Electron density distribution for two channels with different depth is shown in Fig. 3 a, b. One can see that the ionization of higher density plasma periphery results in an essential narrowing of the splash channel. Therefore, the initial plasma structure cannot completely determine the electron self-injection and to provide the controllable self-injection at the long pulse guiding ionization effect have to be taken into account. Nevertheless finally, the electron acceleration can be controlled by the splash channel structure.

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**Fig. 2. Plasma channel**

((a)The pulse energy 90 mJ and pulse duration 300 fs , (b)The pulse energy 90 mJ and pulse duration 6 ps)

**Fig. 3 Spatial distribution of electron density distribution in plasma channels with the different depths:**

(a) Maximum electron density is \( 3 \times 10^{19} \text{ cm}^{-3} \) and minimum density is \( 0.5 \times 10^{18} \text{ cm}^{-3} \).

(b) Maximum electron density is \( 3 \times 10^{19} \text{ cm}^{-3} \) and minimum density is \( 2.0 \times 10^{18} \text{ cm}^{-3} \).
Fig. 4 Spatial distribution of accelerated electron momenta in two plasma channels: (a) minimal electron density is $0.5 \times 10^{18}$ cm$^{-3}$; (b) minimal electron density is $2.0 \times 10^{18}$ cm$^{-3}$.

In Fig. 4 spatial distribution of momenta of accelerated electrons for two different plasma channels are given. One can see that in the shallower channel the maximal energy of electrons is expectedly lower than that in the deepest channel. The geometrical emittance and energy spread are also poor in the shallow channel. That means the formation of splash channel may result in the quality of the electron beams and their total charge. The energy spread also depends on the channel depth: it decreases from 30% for the shallow splash channel down to 8% for the deep channel.

5. Conclusion

We have analysed experimentally and numerically the process of formation of short-lived plasma channels (splash channels), produced by picosecond order laser pulses in argon gas jets and its result in the laser wake field acceleration. The quantitative measurements of splash-plasma channel parameters have been performed with the use of the picosecond time-resolved interferometry. In the present experiments we could produce a splash channel with its length $\sim 600 \mu$m, which is 3 times longer than the Rayleigh length. We anticipate that far longer channels with their lengths of the order of several mm can be created by this technique. The results of the calculation have confirmed the advantage of the channel-guided LWFA in the generation of the high quality, repeatable electron beams.

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