EXTERNALLY CONTROLLED INJECTION OF ELECTRONS BY A LASER PULSE IN A LASER WAKEFIELD ELECTRON ACCELERATOR*

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Abstract

Spatiotemporally localized injection of electrons is a key element for development of plasma-wave electron accelerator. Here we report the demonstration of two different schemes for electron injection in a self-modulated laser wakefield accelerator (SM-LWFA) by using a laser pulse. In the first scheme, by implementing a copropagating laser pulse with proper timing, we are able to control the growth of Raman forward scattering (RFS) and the prepulse also plays the role of injecting hot electrons into the fast plasma wave driven by the pump pulse. In the second scheme, by using a transient density ramp we achieve self-injection of electrons in a SM-LWFA with spatial localization. The transient density ramp is produced by a prepulse propagating transversely to drill a density depression channel via ionization and expansion.

INTRODUCTION

The recent advance in laser technology offers new possibilities for efficient compact accelerators, advanced fusion concepts, and new generation of radiation sources. The laser wakefield acceleration (LWFA) of charged particles in a plasma has the potential of becoming the next generation particle accelerator because of its huge acceleration gradient and compact size compared to the conventional radio frequency linac. Production of high-quality electron beams has been reported in several experiments recently [1]. Nevertheless, for applications there are still many problems that have to be resolved. The way to a practical laser-plasma accelerator relies on the development of three key elements: efficient excitation of the plasma wave, spatiotemporally localized electron injection, and the extension of acceleration distance.

The requirement of spatiotemporally localized electron injection calls for a suitable electron injector. An ideal and robust laser accelerator injector should satisfy the following conditions: (a) trapped electron bunch duration much less than the plasma wave period, (b) femtosecond synchronization with the accelerating structure, (c) simplicity of operation and reasonable tolerance on alignment, (d) good emittance, (e) efficient coupling to the accelerator, and (f) precise reproducible phasing and uniform electron acceleration. In this proceeding, we present the experimental demonstration of two different schemes for externally controlled injection of electrons in a SM-LWFA by using a laser pulse [2-3].

A 55-fs, 810-nm, 10-Hz, and 10-TW Ti:sapphire laser system at *IAMS* [4] based on chirped-pulse amplification was used for these experiments. The output beam is split into two, each going through an energy tuner and a pulse compressor. With this double-compressor configuration, the pulse duration, chirp, energy, beam size, and delay of these two laser beams can be controlled independently with a combined maximal energy of 550 mJ. A 1-mm-long helium gas jet of 2×10^{19}-cm^{-3} atom density was used for the results shown below. The detailed descriptions of the experimental setups were presented in Ref. [2-3].

CONTROLLED SEEDING OF RFS AND INJECTION OF ELECTRONS

RFS instability must grow from an initial seed of density perturbation, which may have several origins. The first possibility is the wakefield driven by ionization-induced ponderomotive force and ionization steepening of the laser pulse. The second possibility is Raman backward scattering instability (RBS), which saturates and produces a notch in a localized region of the laser pulse, and the resulting sharp intensity gradient then drives a wakefield. The third possibility is the wakefield driven by the rising edge of the laser pulse. In the proposed cross-modulated laser wakefield accelerator (XM-LWFA), by introducing a prepulse to resonantly drive a seed plasma wave in advance, the plasma wave amplitude driven by the main pulse through RFS can be increased. All these mechanisms suggest that RFS can be controlled by regulating its seed.

In this experiment, two laser pulses propagate collinearly and are focused with an off-axis parabolic (OAP) mirror to a focal spot of 8.5 μm diameter in full width at half maximum (FWHM) with 80% energy enclosed. The prepulse is 60 mJ and 55 fs, and the positively chirped main pulse is 280 mJ and 250 fs. This corresponds to a peak intensity of 8×10^{17} W/cm^2 for both pulses. The prepulse duration was chosen to match resonant excitation of wakefield as close as possible and the main pulse duration and chirp were chosen to enhance the RFS [2].

The results shown in Fig. 1(a) lead to several conclusions. Firstly, RFS satellite energy is suppressed by preionization when the prepulse arrives 50 ps before the main pulse. Secondly, the RFS satellite energy of the main pulse becomes larger with decreasing pulse separation, reaching a maximum when both pulses overlap and stays approximately the same as the case of using the main pulse only when the prepulse arrives later than the main pulse. This observation supports that RFS

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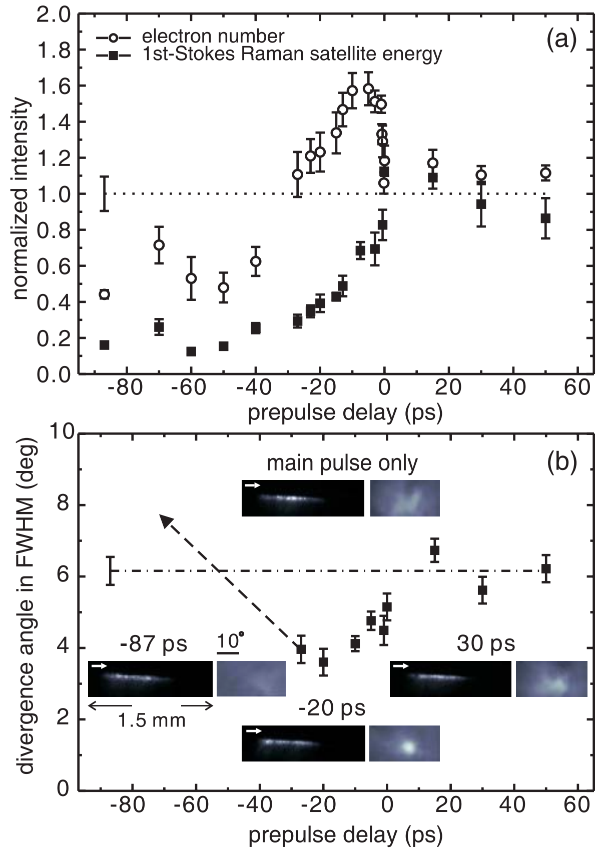

Figure 1: (a) The first-Stokes RFS intensity and the number of accelerated electrons as a function of prepulse timing. The dotted line is the case of using only the main pulse and the number of electrons above 200 keV is 10^9. (b) The beam divergence angle of the electron beam as a function of prepulse timing. The dash-dotted line is the case of using only the main pulse. The data earlier than -40 ps are not shown because the beam profile exceeds the field of view. Inset: electron beam profiles and side scattering images for different prepulse timing.

of the main pulse is seeded by the plasma wave driven by the prepulse, and the dependence on pulse separation shows the decay rate of the seed plasma wave. Thirdly, the RFS satellite energy and the number of electrons show a similar variation with the prepulse delay. This identifies that the observed electron beam is indeed accelerated by a RFS-generated plasma wave.

Furthermore, Fig. 1(a) shows enhancement of electron injection relative to that for using the main pulse only when the prepulse is within 30 ps before the main pulse. When the separation between the two pulses is decreased, the prepulse can seed the main pulse with a fast plasma wave of larger amplitude but with a smaller number of hot electrons, and vice versa. The trade-off between the two effects results in a peak of electron number at a prepulse delay of -10 ps. The hot electrons produced by the prepulse is believed to come from the decay of the slow plasma wave excited by RBS. Similarly, RBS occurring in the main pulse may also contribute to the injection of hot electrons, leading to the small but finite electron number at a prepulse delay of < - 50 ps.

Fig. 1(b) shows that the electron beam divergence is at minimum for a prepulse delay of -20 ps. When the separation between the two pulses is decreased, the main pulse can catch up with the hot electrons produced by the prepulse to trap those moving in the near-forward directions, leading to a larger electron beam divergence. As the separation becomes larger, electrons with larger transverse momentum will have escaped from the laser channel by the time the main pulse catches up, resulting in a smaller beam divergence. As the separation becomes even larger, the main pulse takes even longer time to catch up and therefore the acceleration distance after injection decreases. This leads to lower longitudinal momentum and thus increased electron beam divergence.

CONTROLLED INJECTION BY A SHARP DENSITY RAMP

As proposed in Ref. [5], by creating a sharp downward density ramp, electrons can be injected into the plasma wakefield. When a plasma wave is generated across a sharp downward density ramp, electrons near the boundary move backward to the high density region and then oscillate to the low density region. Since the plasma wavelength is longer in the low density region, these electrons are dephased with respect to the background plasma-wave electrons and thus become trapped. For significant injection, the scale length of density ramp should be less than a few times plasma-wave wavelength (λ_p). For an electron density of 10^{19} cm^{-3}, λ_p is about 10 μm. A density ramp of this length scale cannot be produced by mechanical shaping of the gas nozzle. Here we report the production of a sharp density ramp in a gas jet with optical machining and the resulting injection of electrons when a pump pulse traverses through it.

In this experiment, one laser pulse is used as the pump pulse for driving a plasma wave through RFS, and the other is used as the prepulse for gas jet drilling. The pump pulse is focused by an f/8 OAP mirror to a focal spot of 8.5 μm diameter in FWHM with 80% energy enclosed. The 210-mJ, 260-fs pump pulse is negatively chirped, with its duration optimized for maximum RFS satellite energy. Perpendicular to the pump pulse, the 55-fs, 7-mJ prepulse is focused with an f/4 OAP mirror to a focal spot of 4 μm diameter in FWHM with 54% energy enclosed. The prepulse ionizes a transverse plasma column and, 4 ns later after expansion of this plasma column, a density depression channel is formed in the neutral gas. By positioning this channel in the path of the pump pulse, the pump pulse driving a plasma wave is forced to go through sharp density ramps.

The number of self-trapped electrons without the prepulse is 6.8 x 10^8. As shown in Fig. 2(a), with the prepulse the electron number increases by 25% in the region within ±25 μm, while the RFS satellite energy stays the same or reduced. Both signals drop to about 70% at ±60 μm, at which the pump beam hits the vertical boundary of the density depression channel. As the

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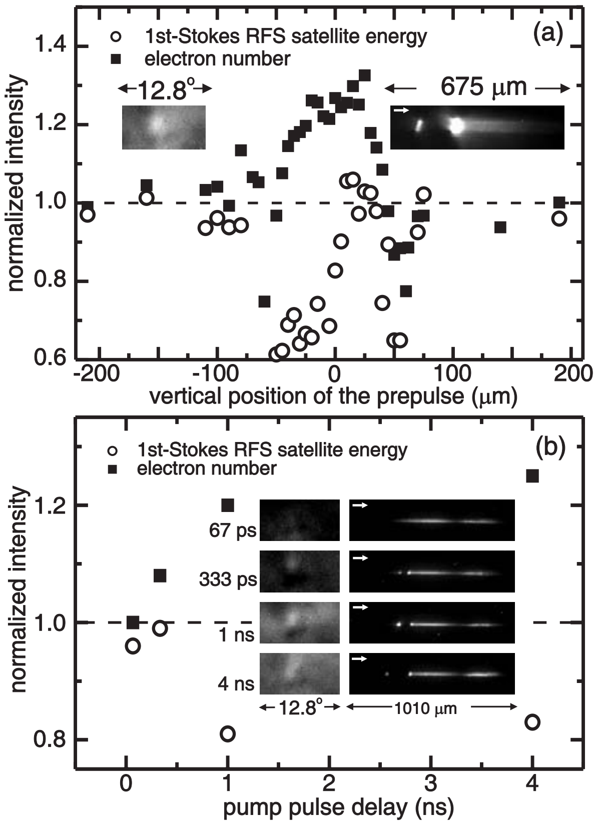

Figure 2: The first-Stokes RFS intensity and number of accelerated electrons as a function of vertical position of the prepulse at 4 ns pump pulse delay, (a), and as a function of pump pulse delay for zero vertical position of the prepulse, (b). The dashed line is the case without the prepulse and the number of self-trapped electrons is 6.8×10^8. Insets: left images shows the profile of electron beam from ramp injection and right images shows the side scattering image of the pump pulse.

prepulse is moved further away from the pump pulse, both the electron number and RFS satellite energy return to the same levels as without the prepulse.

Since RFS satellite energy is a measure of the plasma wave amplitude, the data show that the increase of electron number within ±25 μm is due to enhanced electron injection rather than enhanced self-trapping. The vertical spatial extent of the region where the electron number increases correlates well with the observation of density depression zone in the side scattering image of Thomson scattering from plasma electrons. This correlation identifies that the additional electrons are injected by the density ramps. We can further identify that it is the downward density ramp that injects electrons, not the upward density ramp, since the simulations in Ref. [5] show that no injection for the latter. In addition, no dependence of electron number on the polarization of the two pulses is observed. The relative temporal position of the pulses and the polarization independence rule out all other optical injection mechanisms proposed before.

Since the density profile encountered by the pump pulse is a combination of the preformed plasma and the residual neutral gas, the density ramp should become sharper with time as the preformed plasma expands outward and dissipates on nanosecond time scale. As shown in Fig. 2(b), the fraction of ramp-injected electrons increases from 0% at a pulse separation of 67 ps to 25% at 4 ns, which verifies the prediction of Ref. [5] that a sharper density ramp enhances electron injection. In contrast, the RFS satellite energy drops, which can be understood from the shortening of the interaction length for RFS by the density depression channel. In addition, no difference in the propagation of the pump pulse between these cases was shown in the side scattering images. These observations strongly support our interpretations.

CONCLUSION

In summary, we report the demonstration of two different schemes for externally controlled injection of electrons in a SM-LWFA by using a laser pulse. In the first scheme that uses an ionizing prepulse to control the seeding of RFS and the injection of hot electrons, we demonstrate the concepts of XM-LWFA and laser-injection laser acceleration (LILAC). In the second scheme that uses a laser-produced transient density ramp to induce self-injection of electrons, we demonstrate injection of electrons with spatial localization. If a temporally localized plasma wakefield produced by two optimally separated collinear pump pulses can be used in conjunction with the ramp injection scheme, it should lead to single-bucket injection, thereby producing a high quality and stable electron bunch.

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