RESEARCH FOR AN ADVANCED ACCELERATOR AT JAERI-APRC

H. Kotaki[1)*], M. Kando[1)], S. Masuda[1)], A. Yamazaki[3)], S. Kondo[1)], S. Kanazawa[1)], T. Homma[1)], H. Kiriyama[1)], Y. Akahane[1)], M. Mori[1)], Y. Hayashi[1)], Y. Nakai[1)], N. Inoue[1)], H. Ueda[1)], Y. Yamamoto[1)], K. Tsuji[1)], K. Yamakawa[1)], K. Nakajima[1)2)4)]

1) Japan Atomic Energy Research Institute (JAERI), kyoto, Japan
2) High Energy Accelerator Research Organization (KEK), Ibaraki, Japan
3) Kyoto University, Kyoto, Japan
4) The Graduate University for Advanced Studies, Kanagawa, Japan

Abstract

Two types of optical injection schemes are investigated at Japan Atomic Energy Research Institute (JAERI) Advanced Photon Research Center (APRC). One is an optical injection scheme using a laser pulse, and the other is head-on injection scheme utilizing standing wave made of two counter-propagating laser pulses. The one pulse optical injection experimentally generates a relativistic electron beam with a charge of 5 nC, a maximum energy of 35 MeV, and a geometrical emittance of 0.3 π mm mrad. The head-on injection is analyzed theoretically and the generation of a high quality electron beam is verified by the numerical simulation. An electron beam has a small energy spread of 1%, ultrashort pulse duration less than 10 fs and normalized transverse emittance less than 1 π mm mrad.

INTRODUCTION

In order to generate a high energy and a high quality electron beam, laser-driven plasma accelerators using laser wakefields [1] have been investigated. The laser wakefield acceleration has been experimentally demonstrated and has great potential to produce ultrahigh field gradients of the order of $\sim$ 100 GeV/m [2, 3, 4, 5, 6, 7, 8]. The maximum energy gain has exceeded 100 MeV, however, the energy spread is 100% due to dephasing and wave-breaking effects in the self-modulated laser wakefield acceleration regime, where thermal plasma electrons are accelerated [9].

In order to produce an electron beam with small energy spread, electron beam injection triggered by an intense ultrashort laser has been proposed as an injector of ultrashort electron beams referred to as ”optical injection”. Presently there are three major schemes: nonlinear wave-breaking injection [10], transverse optical injection [11], and colliding pulse optical injection [12, 13]. The nonlinear wave-breaking injection [10] uses one pump laser pulse, however, the gas for the plasma source must be controlled to generate a large gradient in the gas density in a small length. The transverse optical injection [11] uses two crossing laser pulses, both of which have high intensity. The generated electron beam has a large energy spread due to the high intensity of laser pulses that trap plasma electrons. The colliding pulse optical injection [12, 13] is consisted of a pump pulse for wakefield excitation and two injection pulses that have different frequencies to produce a beat wave for trapping the electrons in plasma. The experiment may not be easy due to the difficulty of the control of the different frequency laser pulses.

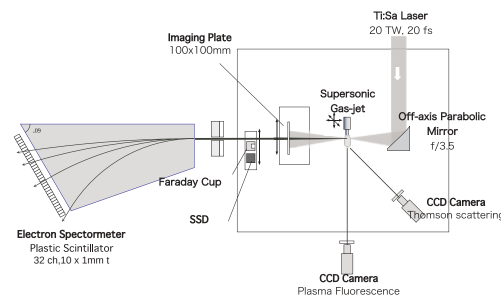

Figure 1: An experimental setup of the 1 pulse optical injection. The laser pulse is focused in gas-jet plasma.

In this paper, we present results of the one pulse optical injection experiment and a new optical injection scheme utilizing standing wave made of two counter-propagating laser pulses with the same frequency. We term this scheme ”head-on injection” that can produce a high quality relativistic electron beam.

ONE PULSE OPTICAL INJECTION

Experimental setup of the one pulse optical injection is shown in Fig. 1. The 20 TW laser pulse with the pulse width τ_L of 20 fs is focused in gas-jet plasma by an F/3.5 off-axis parabolic mirror, and plasma electrons are accelerated by a wakefield excited by the laser pulse. The wakefield is proportional to a square of the laser strength parameter $a_{0,1} = 8.6 \times 10^{-10} \lambda_0[\mu\text{m}]\sqrt{I_{0,1}[\text{W/cm}^{-3}]}$, where λ_0 is the laser wavelength and $I_{0,1}$ the laser intensity. In order to measure the accelerated electron bunch, a faraday cup and an imaging plate are set on the axis of the laser pulse propagation. The faraday cup and the imaging plate measure the charge and the spot of the accelerated electron bunch, respectively. An emittance of the electron bunch is calculated from the spot of the electron bunch. The ac-

* kotaki@apr.jaeri.go.jp

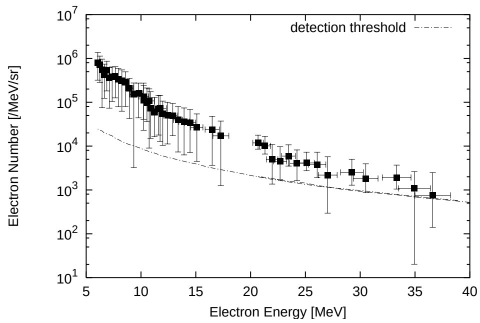

Figure 2: The energy spectrum of the 1pulse optical injection for a_0 = 3.5 at n_e = 1 × 10^{20} cm^{-3} and a laser pulse width of 23 fs.

celerated electron bunch has the charge of 5 nC and the geometrical emittance of 0.3 π mm mrad.

Figure 2 shows the energy spectrum of the electron bunch. The energy is measured by an analyzing magnet and a plastic scintillator calibrated the pulse height using a beta source (^{90}Sr-^{90}Y). The maximum energy reaches 35 MeV under the condition that the electron number is above the detection threshold.

In the short focus case like this experiment, a high charge of the electron bunch is experimentally obtained. This optical injection may become a high peak current electron source.

HEAD-ON INJECTION

The head-on injection is shown schematically in Fig. 3. The head-on injection scheme employs two short laser pulses: an intense laser pulse (pump pulse denoted by subscript 0) for plasma wake generation and injection, and a backward propagating injection pulse (subscript 1). The pump pulse generates a plasma wake with phase velocity near the speed of light. When the laser pulses collide, they generate a standing wave that injects plasma electrons into a fast plasma wake to accelerate trapped electrons.

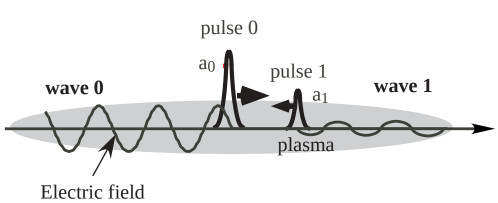

Figure 3: A schematic of the head-on injection. The laser pulse 0 and the plasma wave 0 propagate to the right, and the laser pulse 1 and the plasma wave 1 propagate to the left. The pulse 0 is a pump pulse to generate a plasma wake, and the pulse 1 is an injection pulse. The colliding pulses produce a standing wave to inject plasma electrons into the plasma wake.

In order to estimate the quality of the generated electron beam, we performed 1-D particle-in-cell simulations [14] for the head-on injection in the linear regime. The plasma length is 1 mm, and the colliding position of two laser pulses is set at the center of the plasma; i.e. the acceleration length is 0.5 mm. The simulation is carried out in such a way that no electron is accelerated only by the pump pulse.

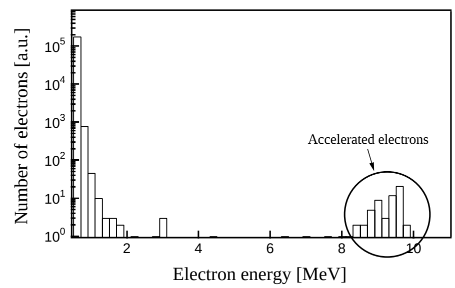

Figure 4: The energy spectrum of the head-on injection simulation for a_0 = 1.0 and a_1 = 0.4 at n_e = 7 × 10^{17} cm^{-3} and a laser pulse width of 50 fs.

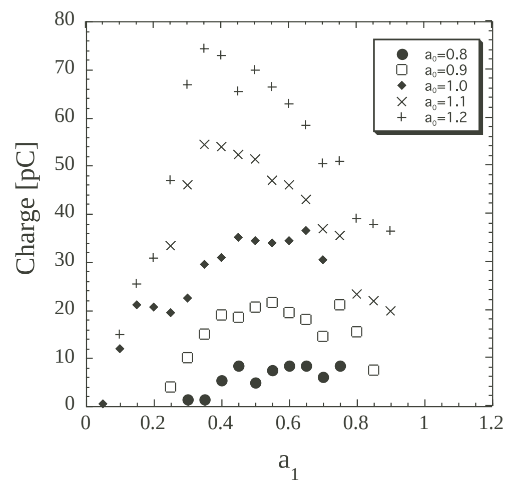

Figure 5: The charge of accelerated electrons assuming an electron beam radius of 15 μm at $n_e = 7 \times 10^{17}$ cm^{-3}.

The energy spectrum is shown in Fig. 4. Plasma electrons are trapped, and the accelerated electron beam clearly separate from background plasma electrons.

Assuming an electron beam radius of 15 μm and τ_L = 50 fs, the charge of the accelerated electron beam is shown in Fig. 5. The results show that there is an optimum standing wave field $(a_0 a_1)^{1/2} \sim 0.7$.

The pulse duration of the electron bunch is shown in Fig. 6 as a function of the elapsed time after injection. The final electron bunch length results in approximately 20% of the plasma wavelength.

Figure 7 shows the energy spread of the accelerated electron beams. The energy spread of the electron beam becomes minimum when the plasma density is near the condition of the maximum wakefield given by $\lambda_p = \pi\sigma_z$. For example, the energy spread at $n_e = 1 \times 10^{18}$ cm^{-3} and

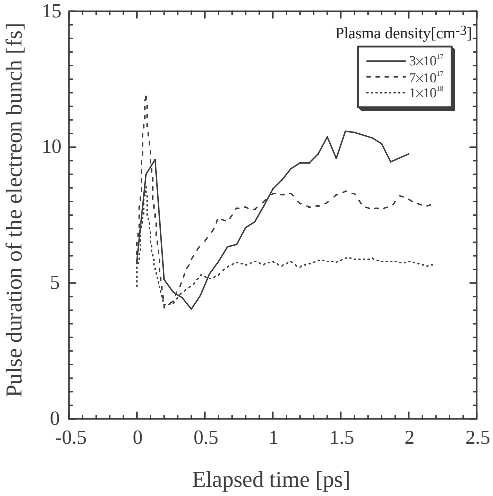

Figure 6: The change of the pulse duration of the injected electron beam for $a_0 = 1.0$ and $a_1 = 0.4$ with a laser pulse width of 50 fs.

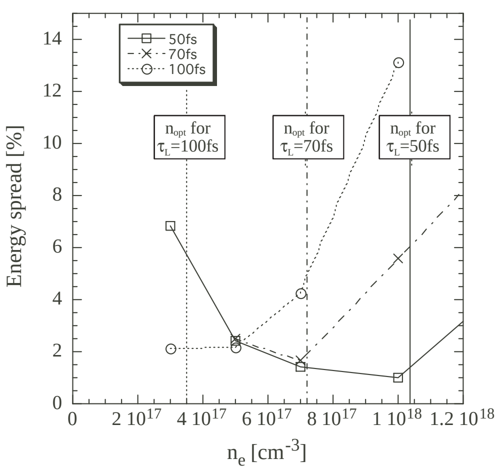

Figure 7: The energy spread defined by $\Delta\gamma/\gamma$ of the accelerated electron beam. The result shows the existence of the optimum density. The solid line, the broken line and the dotted line show the data for $\tau_L = 50$ fs, 70 fs and 100 fs, respectively. Each vertical lines show the optimum plasma density n_{opt}.

$\tau_L = 50$ fs is approximately 1%. For the low-density case, the energy spread becomes large, because the acceleration field is too small to compress the energy spread. For the high-density case, the energy spread increases due to a long injected electron bunch. The long bunch makes multiple-bunches of the accelerated electron beam and a large energy spread after acceleration. In order to generate an electron beam with low energy spread, the laser pulses should collide at the optimum plasma density given by $n_{opt}[\text{cm}^{-3}] = 3.5 \times 10^{21}/(\tau_L[\text{fs}])^2$.

These results show that the head-on injection provides a promising method to generate a high quality electron beam with ultrashort bunch and small energy spread.

CONCLUSIONS

Generation of a high quality electron beam is studied as ”optical injection”. An optical injection using a laser pulse is experimentally demonstrated at JAERI-APRC. The generated electron beam has a charge of 5 nC, a maximum energy of 35 MeV, and a geometrical emittance of 0.3 π mm mrad. On the other hand, We have thoroughly made numerical simulations and analytical calculations of a new optical injection scheme. The head-on injection scheme has the ability to produce a relativistic electron beam with a small energy spread of 1% and a short bunch length less than 10 fs. We found that the optimum conditions to generate a high quality electron beam are given by the standing wave field, $(a_0 a_1)^{1/2} \sim 0.7$, and the maximum wakefield condition at the optimum plasma density.

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