HIGH ENERGY-GAIN LASER WAKEFIELD ACCELERATION

K. Nakajima[1,4], M. Kando[2], H. Ahn[4], H. Dewa[4], H. Kotaki[4], F. Sakai[4],
S. Kondoh[4], H. Nakanishi[1], T. Ueda[3], M. Uesaka[3], T. Watanabe[3], and A. Ogata[1]
[1]High Energy Accelerator Research Organization (KEK), Tsukuba, Japan,
[2]Institute for Chemical Research, Kyoto University, Uji, Japan,
[3]Nuclear Engineering Research Laboratory, The University of Tokyo, Tokai, Japan,
[4]Japan Atomic Energy Research Institute, Tokai, Japan

Abstract

The laser wakefield electron acceleration up to 300 MeV has been observed in an underdense plasma driven by a 2 TW, 90 fs laser pulse synchronized with 17 MeV RF linac electron injector at 10 Hz. The electron acceleration was enhanced at a density higher than the resonant density due to gas ionization and self-channeling effects. The wakefield excitation has been confirmed by measuring the electron density oscillation of the plasma wave with the frequency domain interferometer.

1 INTRODUCTION

We report here demonstration of laser wakefield acceleration (LWA)[1] of an externally injected electron beam by a 2 TW 90 fs laser pulses in a plasma created in a gas-filled chamber. A large energy gain (∼300 MeV) was attained, partly owing to self-channeling of a laser in a plasma and partly owing to larger acceleration gradient than the prediction of a linear. Large blue shift was observed in the laser spectrum in a dense plasma, but no trace of the Raman scattering was found. These facts suggest a new mechanism of LWA using a laser power well below the critical power of the relativistic self-channeling[2], given by $P_c = 17(\omega_0^2/\omega_p^2)$ GW with ω_0 being the laser frequency and ω_p, the plasma frequency. A frequency domain interferometer certified the density oscillation in the laser wakefield[3].

2 LASER WAKEFIELD ACCELERATION

The LWA has great potential to produce ultra-high-field gradients of plasma waves excited by intense ultrashort laser pulses[1, 4]. The wakefield results from the ponderomotive force exciting the plasma wave with the frequency $\omega_p = \sqrt{4\pi e^2 n_e/m_e}$ in a plasma with an ambient electron density n_e. The maximum amplitude of an axial wakefield is achieved at the plasma wavelength $\lambda_p = \pi\sigma_z$, where σ_z is a temporal $1/e$ half-width of the pulse. Assuming Gaussian beam propagation of the laser pulse at the peak power P in an underdense plasma ($\omega_0 \gg \omega_p$), a peak amplitude of the accelerating wakefield is

$$eE_z = \sqrt{\frac{\mu_0}{\pi\epsilon_0}}\frac{P}{m_e c^2}\Big(\frac{\lambda_0}{\lambda_p}\Big)\Big(\frac{k_p\sigma_z}{2Z_R}\Big)\exp\Big(-\frac{k_p^2\sigma_z^2}{4}\Big),$$

where λ_0 is the laser wavelength, $k_p = 2\pi/\lambda_p$ and $Z_R = \pi R_0^2/\lambda_0$ is the vacuum Rayleigh length, R_0 is the spot radius at the focus. The maximum energy gain is given by $\Delta W = eE_z L_{ac}$ with the acceleration length L_{ac}.

In a homogeneous plasma, however, diffraction of the laser propagation limits the laser-plasma interaction distance to $L_{ac} \sim \pi Z_e$, where Z_e is the effective Rayleigh length. For the resonant plasma density, $n_e = 1/\pi r_e \sigma_z^2$ where r_e is the classical electron radius,

$$\Delta W_{\max}[\mathrm{MeV}] \sim 850P[\mathrm{TW}]\lambda_0[\mu\mathrm{m}]/\tau_0[\mathrm{fs}] \times (Z_e/Z_R),$$

where $\tau_0 = 2\sqrt{\ln 2}\sigma_z/c$ is the FWHM pulse duration. Note that the maximum energy gain is independent of a focal spot size of laser pulses for Gaussian propagation if $Z_e = Z_R$. Optical guiding has been proposed[5] in order to exceed this limit. Our recent experiments using intense femtosecond laser pulses report that a self-channeling has been observed under the critical power of the relativistic self-focusing[6].

3 EXPERIMENTAL SETUP

We have constructed the LWA test facility consisting of the T^3 laser system and the electron beam injector[8]. The Ti:sapphire T^3 laser system based on the chirped-pulse amplification at $\lambda_0 = 790$ nm produces output pulses compressed by a grating to 90 fs with an energy of > 200 mJ or a peak power of > 2 TW at the repetition rate of 10 Hz. We used the 2856 MHz RF linac as an electron injector to produce a 17 MeV single bunch beam with a 10 ps FWHM pulse duration containing ~ 1 nC at the repetition rate of 10 Hz.

In our experimental setup, focusing optics and the injection electron beamline were installed in the vacuum chamber filled with He gas. Laser pulses were focused with f/10 off-axis parabolic mirror with a focal length of 480 mm. The measured focal spot radius was 13 μm. An electron beam from the injector is brought to a focus in the chamber with the FWHM beam size of 0.8 mm through a beamline consisting of a triple focusing magnet and a permanent quadrupole triplet. The RF linac and the beamline are separated with a 20 μm thick titanium window from the interaction chamber to maintain ultrahigh vacuum in the electron injector. Since the multiple scattering of electrons at this window causes emittance blow-up, a collimator slit is installed at the downstream of the window to reduce the beam emittance. The beam collimation reduced an electron charge to ∼100 pC per pulse. Only the electrons injected

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to the diameter less than a half laser spot size would be trapped and accelerated by the wakefield. An electron pulse was synchronized to laser pulses with the phase locked control of the mode-locked oscillator. The phase locked loop maintains synchronization of the oscillator repetition period (79.33 MHz) with every 36th RF period of the linac (2856 MHz). A streak camera with a time resolution of 200 fs measured a timing jitter between the laser pulse and Cherenkov radiation from the electron beam. Synchronization between the two pulses was achieved within the rms jitter of 3.7 ps.

The energy of accelerated electrons was measured with the magnetic spectrometer consisting of a dipole magnet and an array of 32 scintillation detectors. Injected electrons undergoing no acceleration were swept out of the detectors by the spectrometer magnet following a permanent quadrupole doublet. The spectrometer covered the energy range of 10∼300 MeV. The energy calibration of the spectrometer was made by varying the magnetic field to measure a 17 MeV electron beam from the RF linac.

The timing between laser and electron pulses was adjusted by changing a phase delay of the reference RF to the phase locked loop so that streak images of two pulses were overlapped. After a He gas was filled in the acceleration chamber, fine adjustment of overlapping two spots of laser and electron beams was carried out within 50 μm. Two sets of pulse height data of the scintillator array were taken with pump laser pulses and without them as a background. A net pulse height proportional to the number of electrons accelerated was obtained from subtracting the data without the pump pulses from the data with them. The number of electrons was estimated to be ranged from 2 to 4 per ADC count for all detectors.

4 EXPERIMENTAL RESULTS

In the acceleration experiment the gas pressure of He was scanned from 1 Torr to 300 Torr. Figure 1 shows the pressure dependence of energy gain spectra of electrons accelerated by the laser peak power of 1.8 TW. The maximum energy gain up to 300 MeV was obtained. When the electron pulse preceded the pump laser pulse, no acceleration of electrons was observed. Accelerated electrons visibly appeared as the electron pulse was delayed. No accelerated electron was observed at a delay of 1 ns. We have tried to observe the self-trapping of plasma electrons due to wakefield, without the electron beam injection, increasing the gas pressure up to 760 Torr. No electrons with energies higher than ∼1 MeV were however observed. It implies that the ultrashort laser pulses of 100 fs do not excite the stimulated Raman instability and resultant large amplitude wakefields.

The side scattered laser light from the plasma region were imaged onto a CCD camera through a 10 nm FWHM interferential filter to measure the laser intensity distribution. Fig. 2 shows an intensity profile of the scattered light projected onto the propagation axis at various gas pressures.

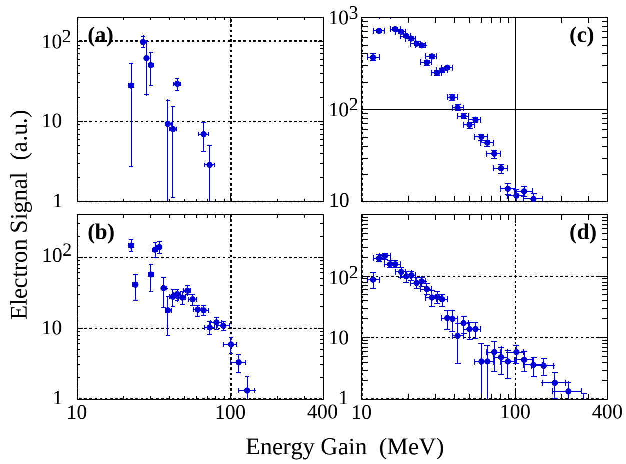

Figure 1: Energy gain spectra of accelerated electrons for a) 3.4 Torr, P=0.9 TW, b) 20 Torr, P=0.9 TW, c) 2 Torr, P=1.8 TW, and d) 20 Torr, P=1.8 TW.

The lineout width of the scattered light proportional to the laser intensity gives a good estimate of the acceleration length. The acceleration field gradient was obtained from the measured maximum energy gain and the FWHM length of the scattered light lineout equal to $2Z_e$. Figure 3 shows the peak accelerating gradient for the laser peak powers of 0.9 TW and 1.8 TW as a function of the gas pressure of He. The data indicate a good agreement with theoretical prediction based on the linear fluid model below 10 Torr, assuming the focal spot radius of 13 μm. However, they show that the acceleration occurs even at much higher pressures than a plasma wake resonance. Recent particle-in-cell simulations elucidate that a large amplitude wakefield can be excited by self-modulation at the front of a laser pulse in rapidly ionizing plasmas[2]. In Fig. 3 the acceleration gradient jumps to ∼15 GeV/m above 20 Torr for 1.8 TW. Above this pressure of 20 Torr, it was also observed that the length of the lineouted laser light turned out constant, ∼1 cm. These phenomena suggest that self-channeling accompanied by the electron density depletion may take place above 20 Torr.

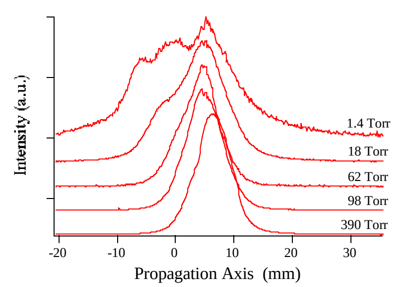

Figure 2: The lineouts of the side scattered laser light at various He gas pressures for P=2.5 TW.

The onset of self-channeling is also inferred from the spectra of the forward scattered laser light shown in Fig. 4. At the low pressure of 1 Torr, only a small blue-shift was observed as the laser intensity increases. When the pressure turned out to be as high as 20 Torr, however, a drastic blue-

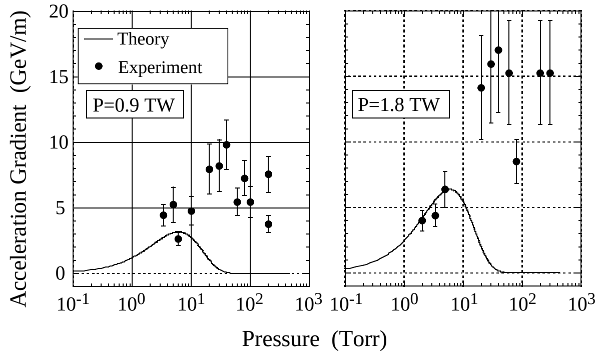

Figure 3: The peak accelerating field gradient deduced from the maximum energy gain and the acceleration length. The solid curve shows theoretical expectation for the spot radius $R_0 = 13\ \mu$m.

shifting of the laser light was induced above 0.5 TW. As the peak power increased to more than 2 TW, a whole spectrum of the incident laser pulse at 790 nm was shifted to 750 nm. It has been known that a large amount of the self-phase modulation results from a long distant self-channeling[7]. In our experiment we have not observed red-shifting nor forward Raman scattering.

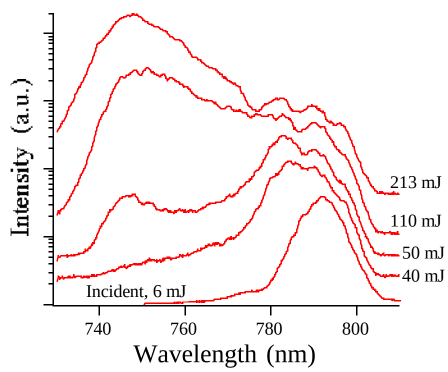

Figure 4: Forward scattered spectra measured in a He gas of a) 1 Torr and b) 22 Torr as the laser pulse energy increases.

In order to make confirmation of wakefield excitation, we measured the plasma oscillation with the frequency-domain interferometer[3]. Figure 5 shows the electron plasma wave measured at 2 Torr at the pump peak power of 1 TW. The frequency of the density oscillation is deduced to be 1.7×10^{13} rad/s from the measured period of the density oscillation, while the plasma frequency is 2.1×10^{13} rad/s assuming a fully ionized plasma at 2 Torr. A frequency decrease of the plasma wave results from nonlinear wakefield excitation. The density perturbation was $\delta n/n_e \sim 10\%$ corresponding to the longitudinal wakefield of $\sim$3 GeV/m. This measured amplitude is in good agreement with the accelerating wakefield theoretically expected.

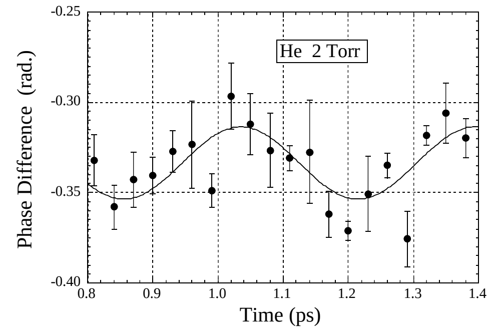

Figure 5: Measurement of the plasma density oscillation excited by a 1 TW pump power in a He gas of 2 Torr. The solid curve shows a fit of the plasma wave with oscillation period of 360 fs.

5 CONCLUSION

We have carried out electron acceleration by wakefields in a static He plasma excited by a 2 TW, 90 fs T^3 laser synchronized with the 17 MeV RF linac electron beam injector at the repetition rate of 10 Hz. We have observed high energy electrons accelerated up to 300 MeV by the wakefield of $\sim$15 GeV/m excited over a few cm long underdense plasma. Acceleration enhancement at higher pressures than the resonant pressure may be elucidated from the pulse self-modulation due to ionization and self-channeling of the laser pulse in a plasma. These effects must help to achieve an efficient electron acceleration up to the higher energy than 1 GeV. A direct measurement of the electron density oscillation by the frequency domain interferometry verified that the wakefield excitation is consistent with the results of acceleration experiments.

6 REFERENCES

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