Recent Progress of Laser Wakefield Acceleration Experiments at KEK/ U. Tokyo/ JAERI

K. Nakajima, H. Nakanishi, A. Ogata, KEK, Tsukuba, Japan
H. Harano, T. Ueda, M. Uesaka, T. Watanabe, K. Yoshii, Univ. of Tokyo, Tokai, Japan
H. Dewa, T. Hosokai, M. Kando, S. Kondo, H. Kotaki, F. Sakai, JAERI, Tokai, Japan

Abstract

The laser wakefield acceleration (LWFA) experiments has been conducted by the use of 2 TW, 90 fs laser pulses synchronized with an electron beam injected from a 17 MeV RF linac. Preliminary experiments demonstrated the energy gain more than 200 MeV attributed to ionization-induced self-modulation and self-guiding of intense ultrashort laser pulses in plasmas. Measurements of the plasma density oscillation and laser-plasma interactions support the enhanced acceleration. We are also developing an RF photo-injector producing low emittance beams, a capillary plasma wave guide generating long stable wakefields and a energy measurement system with emulsion technique.

1 INTRODUCTION

The present high energy accelerators are based on the RF acceleration, in which the accelerating field is limited to approximately 100 MV/m due to electrical breakdown. The laser-plasma accelerators have been conceived to be the next-generation particle accelerators, promising ultra-high field particle acceleration[1]. It has been experimentally demonstrated that the laser wakefield acceleration (LWFA) has great potential to produce ultra high field gradients of plasma waves[2]–[5]. Recently a wakefield of the order of 10 GV/m in a plasma has been directly observed by the use of a compact terawatt laser system so called T^3 lasers[6, 7].

In a homogeneous plasma, however, diffraction of the laser propagation limits the laser-plasma interaction distance to the extent of the vacuum Rayleigh length. This deducts the advantage of ultrahigh gradient acceleration from laser-driven accelerators. It would be of importance for practical application of the laser wakefield accelerator concept to generate a high energy gain as well as high gradient acceleration. Therefore it is essential for laser wakefield acceleration to achieve a long interaction of an intense ultrashort laser pulse with an underdense plasma. We made an attempt to demonstrate laser wakefield acceleration by intense ultrashort laser pulses propagating in a plasma. This paper reports the results of LWFA experiments and developements of an RF photo-injector, a plasma guiding and a energy measurent system with emulsion.

2 LWFA EXPERIMENTS

2.1 Laser Wakefield Acceleration Test Facility

We have constructed the test facility for the LWFA experiments, consisting of a T^3 laser system and an electron beam injector[8]. The Ti:sapphire T^3 laser system produces output pulses compressed by a grating compressor to 90 fs with an energy greater than 200 mJ 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.

The setup for LWFA experiments is shown in Fig. 1. Focusing optics and magnets were installed in the acceleration chamber filled with He gas. Laser pulses were focused by a f/10 off-axis parabolic (OAP) 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 with the FWHM beam size of 0.8 mm through a triple focusing magnet and a permanent magnet quadrupole (PMQ) triplet. The beamline and the acceleration chamber were separated by a 50μm thick titanium window. An electron pulse was synchronized to laser pulses within the rms jitter of 3.7 ps by a phase locked control of a mode-locked oscillaton.

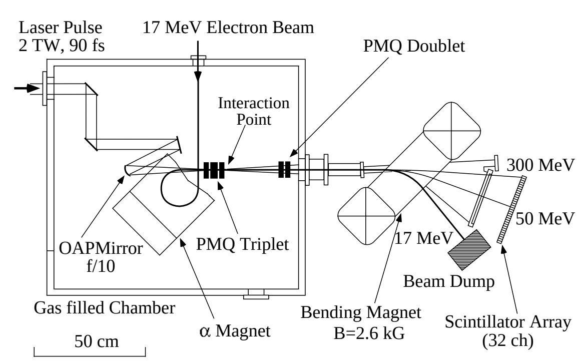

Figure 1: Schematic of the experimental setup for the laser wakefield acceleration.

2.2 Experiments

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. Fine adjustments of overlapping two spots of laser and electron beams was carried out within 50 μm. Two sets of pulse height data from the scintillator array were taken with pump laser pulses and without them as a background. The pulse height was averaged over 500 to 1000 shots to reduce fluctuations. A net pulse height proportional to the number of electrons was obtained by subtracting the data without the pump pulses from the data with them.

In the acceleration experiments the gas pressure of He was scanned from 0 Torr to 300 Torr. Figure 2 shows energy gain spectra of electrons accelerated at the laser peak power of 0.9 TW and 1.8 TW. The maximum energy gain up to 300 MeV was obtained from these data. There was no acceleration of injected electrons at 4.3 mTorr. When the electron pulse preceded the pump laser pulse, no acceleration was observed. Accelerated electrons visibly appeared as the electron pulse was delayed. We have investigated the self-trapping of plasma electrons without the electron beam injection, but could not observe any electron accelerated higher than 1 MeV.

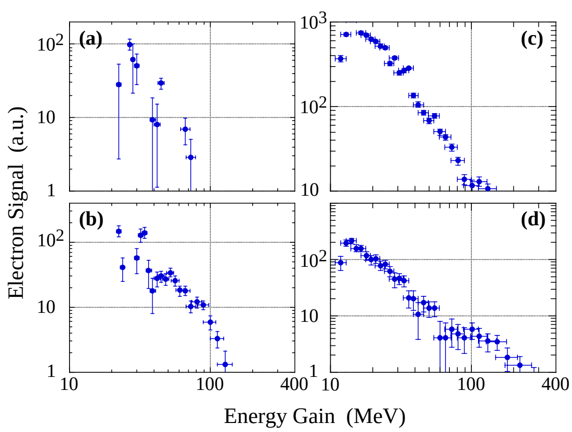

Figure 2: Energy gain spectra of accelerated electrons for a) 3.4 Torr, P=0.9 TW, b) 20 Torr, P=0.9 TW, c) 2 Torr, P=1.8 TW, and d) 20 Torr, P=1.8 TW.

In order to make confirmation of wakefield excitation by an ultrashort laser pulse in an underdense plasma, we measured the plasma wave oscillation with the frequency domain interferometer[3]. Figure 3 shows the electron plasma wave measured at 2 Torr for the pump peak power of 1 TW. The plasma electron density is deduced to be 9.6×10^{16} cm^{-3} from the measured period of the density oscillation, while the electron density is 1.4×10^{17} cm^{-3} for a fully ionized plasma at 2 Torr. The measured density perturbation was $\langle \delta n/n_e \rangle \sim 15\%$ corresponding to the longitudinal wakefield of $\sim$ 2 GeV/m. This measured amplitude is in good agreement with the accelerating wakefield of 2.2 GeV/m theoretically expected for 1 TW.

As shown in Figure 4, we found several irregular bright spots in the Thomson scattering image of the 1.8 TW pump laser in He gas plasma at 20 Torr. It indicates that strong self-focusing of the laser occurs in plasma, which would relate to the generation of ultra-high wakefield that accelerate electrons to higher energy than expected from the linear fluid plasma theory.

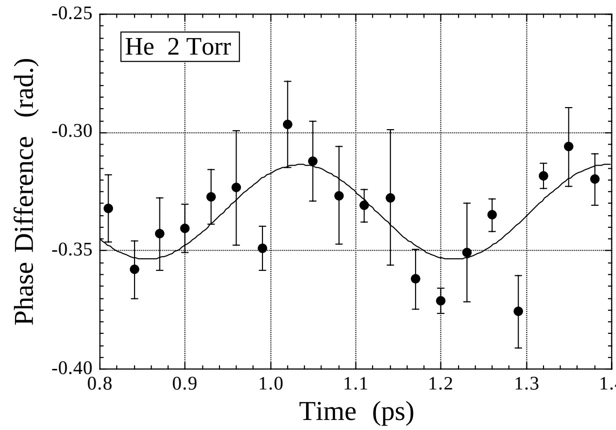

Figure 3: Measurement of the plasma density oscillation excited by a 1 TW pump power in a He gas of 2 Torr. The solid curve shows a fit of the plasma wave with oscillation period of 360 fs.

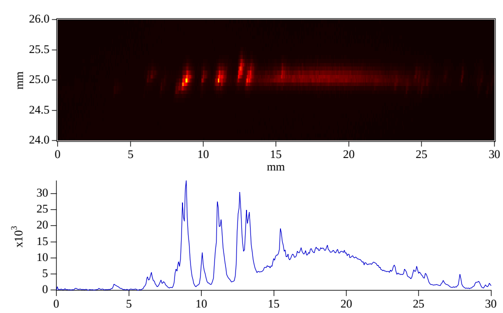

Figure 4: Thomson scattering image of the 1.8 TW pump laser in He gas plasma at 20 Torr.

3 LWFA DEVELOPEMENTS

3.1 *RF photoinjector*

An RF photoinjector generating the low emittance and short bunch beam was installed as an electron source for LWFA to increase acceleration efficiencies. It was developed by an international collaboration between BNL(Brookhaven National Laboratory), KEK and SHI (Sumitomo Heavy Industries, Ltd.) for the heavy duty operation (50Hz). The system is consisted on a 1.6 cell RF gun with the Cu cathode , a solenoidal magnet for the emittance compensation and the diagnostic system with a beam profiler and a Faraday-cup.

A prototype laser illuminating a photocathode is a laser diode pumped Nd:YLF regenerative amplifier to stable the system and make the laser system compact. The laser pulse energy is about 200 μjoule for the 4th-harmonics (263nm) at the maximum with 100Hz repetition rate. The pulse width of the 4th harmonics is about 20ps FWHM by the measurement with a femto second streak camera.

As experimental results, the relation between the maximum electron charge and laser pulse energy is shown in in Fig. 5. Quantum efficeincy is to be about $5x10^{-5}$ at the range of less than 1 nC. The normalized emittance versus the current of the solenoid magnet was measured for about 200pC electron bunch charge (in Fig. 6).

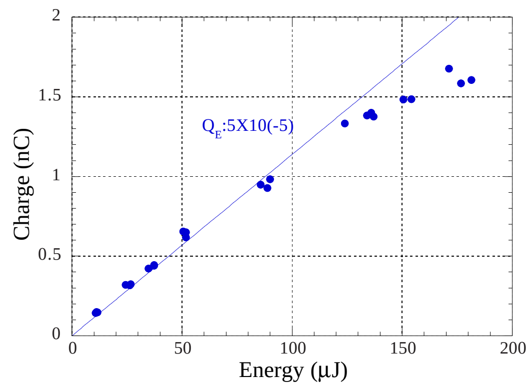

Figure 5: Emitted Charge vs. Laser Energy (263nm)

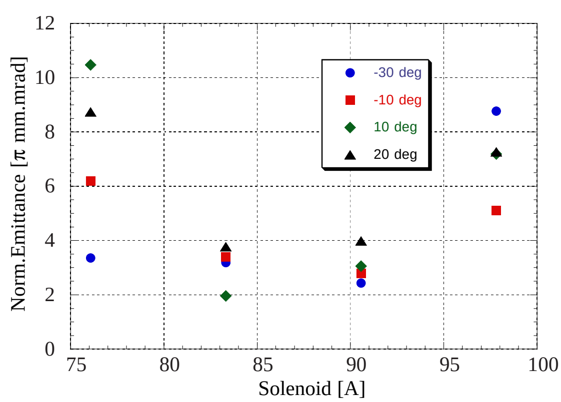

Figure 6: Horizontal emittance vs. Current of solenoid coil Linac RF phase was changed within 50 degree.

3.2 *Optical wave guiding by capillary discharge*

Propagating a laser pulse over distances larger than the vacuum diffraction length is critical issue of LWFA. Our approach is that of guiding in a preformed plasma column with concave electron density profiles. Recently it has been demonstrated by Ehrlich *et al.* that capillary discharges can guide intense optical laser pulse (up to 10^{16} W/cm^2) over length of 1cm [9].

We propose alternative scheme of capillary discharges to guide intense laser pulse over longer length. In this scheme plasma column is generated by fast Z discharges through prefilled gas in a capillary. Stably imploded Z pinch plasma columns exhibit good coaxial symmetry, and the core of the compressed column has a internal structure due to fast imploding plasma sheet and shock wave [10]. We expect that the laser pulse can be guided in the compressed core with concave electron density profiles.

Since density profiles in the core plasma strongly depend on discharge dynamics, as a first step of the study, we started out to investigate the discharge dynamics experimentally. Experiment were conducted using polyethylene capillaries of 1 mm inner diameter with length of 20 mm which was filled with 1 Torr helium gas. The discharge was driven by current of up to 2.5kA. The discharge dynamics was observed with a streak camera (HAMAMATSU C-2830) from the capillary axis direction. Results were indicate that concave luminous profiles were observed on the axis of the capillary at second implosion phase.

3.3 *Energy measurement system with emulsion*

In order to measure the energy spectrum of the accelerated electerons, we are preparing to apply the emulsion techniques. It is important to distingish the accelerated electrons by laser acceleration and other background noises for example the electrons scattered in the vacuum chamber or bremsstrahlung x-ray from the beam dump. Each energy of the electrons bent by a dipole magnet can be obtained from the position of the track in the emulsion. The angle informations help us to distinguish the tracks of the accelerated electrons and the background noises.

In the energy measurement system recentry constructed, the 15 MeV electrons from the linac are bent by the first dipole magnet by 60 degrees at the curvature radius of 15 cm, and then go into a beam dump. The magnet field prevents the electron without acceleration from going into the emulsion film. After the first dipole magnet, we install a chamber for installing the recutangular emulsion of a 40 $\times$20 mm^2. Because the position and angle resolution of the emulsion is about 1 μm and 3 mrad, energy measurements with a good resolution are expected in the next LWFA experiments.

4 REFERENCES

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