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Recent Results of Laser-Plasma Electron Beam Acceleration Experiments at JAERI-APRC

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Recently there is a great interest growing in advanced accelerator technologies based on laser and plasma acceleration mechanisms, which have attractive potential for applications to a wide range of sciences. In the past decade great advances of ultraintense ultrashort pulse lasers have brought about tremendous experimental and theoretical progress in development of laser plasma particle accelerator concepts. In particular it is known that ultrarelativistic laser-plasma interactions can generate extreme high gradient accelerating fields of the order of 1 TeV/m to accelerate ultrahigh current electron beams well collimated with small emittance and femtosecond buch length up to 1 GeV in a 1 mm plasma. In the relativistic highly nonlinear regime, relativistic electron beams can be accelerated by complex mechanisms based not only on wakefields and also on direct ponderomotive fields. We report the recent results of electron beam acceleration experiments made by using 20 TW, 20 fs laser pulses at JAERI-APRC. The experiments result in ultrahigh current relativistic electron beam acceleration of the order of Mega Ampere with energy spectrum characterized by a power law up to 40 MeV rather than a Maxwellian distribution. We focus on the acceleration mechanism of ultrahigh current electron beams in plasma and their applications to femtosecond X-ray beam generation and coherent Terahertz radiation.

I. INTRODUCTION

Recently there is a great interest growing in advanced accelerator technologies based on laser and plasma acceleration mechanisms, which have an attractive potential for applications to a wide range of sciences. A novel particle acceleration concept was proposed by Tajima and Dawson[1], which utilizes plasma waves excited by intense laser beam interactions with plasmas for particle acceleration, known as laser-plasma accelerators. Recently there has been a great experimental progress on the laser wakefield acceleration (LWFA) of electrons since the first ultrahigh gradient acceleration experiments[2]. Recent experiments have successfully demonstrated that the self-modulated LWFA mechanism is capable of generating ultrahigh accelerating gradient of the order of 1 TeV/m and of accelerating electrons up to the high energy beyond 200 MeV[3, 4]. These capabilities make it possible to realize a table-top accelerator and high energy frontier accelerators in a reasonable size and cost.

Plasmas provide some advantages as an accelerating medium in laser-driven accelerators. Plasmas can sustain ultrahigh electric fields, and can optically guide the laser beam and the particle beam as well under appropriate conditions. For a nonrelativistic plasma wave, the acceleration gradient $E_0[\mathrm{eV/cm}] = m_e c\omega_p \simeq 0.96 n_e^{1/2}[\mathrm{cm}^{-3}]$, where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency and n_e is the ambient electron plasma density. It means that the plasma density of $n_e = 10^{20}$ cm^{-3} can sustain the acceleration gradient of 1 TeV/m.

In the past decade the worldwide experiments of laser-plasma particle acceleration have boosted their frontier of particle beam energy and intensity. The experimental results indicate a rapid increase of electron energies accelerated by laser-driven plasma-based concepts, whose rate is three to four orders of magnitude over the past ten years in coincidence with increase of the laser ponderomotive energy. From the practical point of view for particle accelerator applications, it is crucial that an ultrashort particle bunch with energy higher than the trapping threshold should be injected with respect to the correct acceleration phase of the wakefield to produce a high quality beam with small momentum spread and good pulse-to-pulse energy stability. There are several electron injection schemes referred to as optical injection, which is triggered by an intense ultrashort laser pulses[5–8]. Nowadays experimental efforts are focused on generation of high quality electron beams with a small energy spread and a low emittance.

The electron acceleration experiments were carried out with 100 TW, 20fs laser pulses at the Advanced Photon Research Center, Japan Atomic Energy Research Institute(JAERI-APRC). Here we report results of charge and energy distribution measurements for electrons accelerated by the interaction of an ultrashort laser pulse tightly focused into an underdense plasma. Discussions focus on acceleration mechanism of ultrahigh current electron beams and their applications.

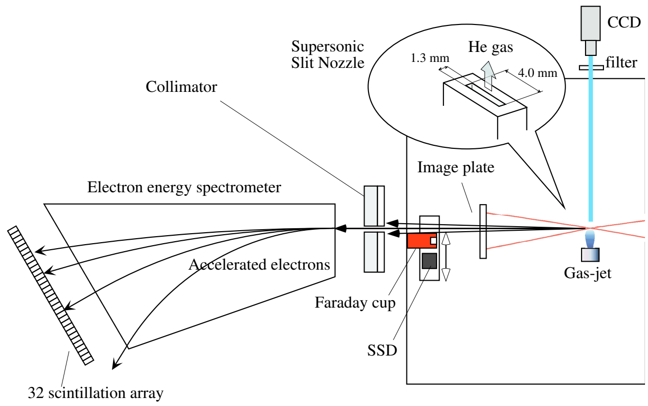

FIG. 1: A schematic of the experimental setup.

II. ELECTRON ACCELERATION EXPERIMENTS

A 100-TW Ti:Sapphire chirped pulse amplification laser system of the wavelength $\lambda_L = 800$nm operated at 10 Hz repetition rate at JAERI-APRC[9] was used for electron acceleration experiments with a super sonic gas jet. In this experiment laser pulses with a typical peak power of 20 TW and 23 fs FWHM duration were focused onto a gas target with an off-axis parabolic mirror with a focal length of 178 mm (f/3.5). The experimental setup is shown in Fig. 1.

A typical pulse energy delivered from the laser system was 420 mJ on a focal spot of 10 μm at the 1/e^2 intensity containing 50 % of the total pulse energy, generating the peak focused intensity of $I = 2.3 \times 10^{19}$ W/cm^2. The intensity I is often described by the normalized vector potential a_0 defined as $a_0 \equiv eA_0/m_ec^2$ with a vector potential A_0, given by $a_0 \cong 0.85 \times 10^{-9}\lambda_L[\mu\text{m}]I^{1/2}[\text{W/cm}^2]$. In this experiment, the highest focused intensity was $a_0 \simeq 3.3$.

The contrast ratio of the laser system was typically 10^{-6} on the nanosecond scale. A specially designed pulsed valve with a shock-wave-free nozzle was operated at a repetition rate of 0.5–5 Hz to form a flat-top-profile helium gas plume in a vacuum chamber. The nozzle has a rectangular shape of 1.3 × 4 mm. The plasma density was varied from 1×10^{19} to 1.4 $\times10^{20}$ cm^{-3} (minimum $\lambda_p/c\tau = 0.4$) in fully ionized helium by changing the stagnation pressure of the pulsed valve. The position of the gas-jet was aligned in such a way that the electron signal becomes its maximum by adjusting movable stages equipped with the gas-jet. The laser was focused at a point 1 mm from the entrance edge of the slit.

Energetic electrons were monitored with a lithium-doped silicon semiconductor detector (SSD) with amplifiers, which was contained in a shielding box of which an electron detection window was covered with a 20 μm thick titanium foil to avoid exposure from the strong laser light and plasma fluorescence. The electron spatial profile was taken with a stack of four image plates (Fuji Film, BAS-SR) with shielding substrates to filter low energy electrons. The image plates were placed at 180 mm from the focus on the laser axis. The electron charge was measured with a Faraday cup consisting of 20 × 20 mm copper, of which signals were taken with a CAMAC charge-sensitive ADC module. The electron energy spectrum was obtained with a magnetic spectrometer composed of a dipole magnet and a 32-channel plastic scintillation array coupled with photomultipliers. In order to increase energy resolution, a collimator placed in front of the dipole magnet to limit an angular acceptance within ±10 mrad was made of a stack of polyethylene and lead to reduce the amount of bremsstrahlung X-rays hitting the plastic scintillation array. Lead shielding blocks were also placed around the scintillation detectors to reduce the background X-rays. A CCD camera with a gate time of 4 ms observed light emissions from the focus point along both the laser propagation and polarization directions through two kinds of band-pass filters; a blue-pass filter to measure plasma recombination fluorescence and a red-pass filter to measure wavelengths greater than 726 nm, while the laser bandwidth was 100 nm centered at 800 nm.

The electron charge of accelerated electrons was 5 nC (3 $\times10^{10}$) per shot measured with the Faraday cup. As the solid angle of the Faraday cup covers only 0.012 sr, the total amount of the charge of accelerated electrons is inferred to be extremely as high as 50nC, which means that a 20% of the laser pulse energy was converted to the energetic electrons. Assuming that this electron bunch length is on the order of the plasma wavelength, the peak current of the beam may exceed 0.5 MA, which is much larger than the Alfvén limit[10]: $I_A = 1.7 \times 10^4\beta\gamma \simeq 170$ kA for $\gamma = 10$, where $\gamma m_e c^2$ is the electron

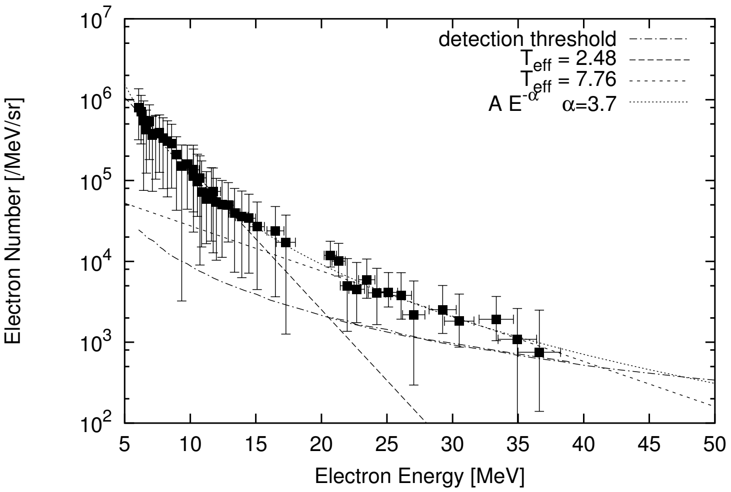

FIG. 2: Energy spectrum obtained at a plasma density $n_e \simeq 1.4 \times 10^{20}$ cm^{-3} and a laser intensity $I \simeq 2.3 \times 10^{19}$ W/cm^2. The dashed line shows the detection threshold that corresponds to the energy deposited by a relativistic electron entering each detector. By changing the magnetic field strength and shielding in front of the detectors, it was confirmed that these signals were produced by high energy electrons. The Maxwellian fitting curves are plotted for the effective temperatures, 2.5 MeV and 7.8 MeV, respectively. The power law fit $AE^{-\alpha}$ is also shown in the dotted line.

beam energy and $\beta = (\gamma^2 - 1)^{1/2}/\gamma$. Since the numerical simulation indicated production of an electron bunch with ~ 0.3 fs duration[11], it is inferred that the peak current of the accelerated electron bunch was 17 MA, which is four orders of magnitude larger than that of the conventional accelerator beams. The electron spot radius (r_1) at L=180 mm downstream from the focus was 30 mm on the image plate. Assuming that the electron beam spot, r_0, at the focus is the same as that of the laser and collimated at the focus, geometrical emittance, ε, can be calculated by $\varepsilon = (r_0/L)\sqrt{r_1^2 - r_0^2}$. Thus, the emittance is estimated to be 0.5 π mm-mrad where no space charge effects are included in this calculation.

The averaged energy spectrum at the initial plasma density, $n_e = 1.4 \times 10^{20}$ cm^{-3}, is shown in Fig. 2. Assuming that the accelerated electron energy spectrum $N(E)$ is a Maxwellian distribution characterized by an effective temperature T_{eff} as $N(E) \propto \exp(-E/T_{eff})$, the measured spectrum is fitted to two Maxwellian distributions with $T_{eff} = 2.5$ MeV for lower energies than 12 MeV and with $T_{eff} = 8$ MeV for higher energies than 22 MeV. The another analysis of the electron spectrum was tried to explore the acceleration mechanism. Assuming that the spectrum can be characterized by a power law, where the number of electrons N with energy between E and $E + dE$ is given by $N(E)dE \propto E^{-\alpha}$, all data are well fitted to the power law for $\alpha \simeq 3.7$ over the whole measured energy range of $5 < E < 37$ MeV. This means that the acceleration mechanism for this experiment is different from the self-modulated wakefield acceleration due to a long laser pulse, of which energy spectra are dominantly characterized by the Maxwellian distribution of electrons accelerated due to both the laser field and the pure wake field[12].

The maximum energy of the accelerated electrons is determined to be about 40 MeV from the detection threshold for a single electron. For the acceleration length much longer than the detuning legth $L_d \simeq \gamma_p^2 \lambda_p \simeq 35\mu$m, where $\gamma_p \simeq 3.5$ is the Lorentz factor corresponding to a phase velocity of the plasma wave and $\lambda_p \simeq 3\mu$m is the plasma wavelength at the electron density $n_e \simeq 1.4{\times}10^{20}$ cm^{-3}, an estimate of the maximum energy gain is given by $\gamma_{max} = 4\gamma_p^2 E_{max}/E_0$, where E_{max} is the maximum wakefield amplitude. Assuming $E_{max} \simeq E_{wb}$, where $E_{wb}/E_0 = \sqrt{2(\gamma_p - 1)}$ is a nonlinear wave breaking field, the maximum energy results in 56 MeV that leads to a reasonable agreement with the measurement.

III. APPLICATIONS OF LASER-ACCELERATED ELECTRON BEAMS

The intense ultrashort pulse laser and plasma interactions produce high-brightness radiations with a wide range of spectrum and femtoseconds duration, which are useful for many applications in a number of scientific fields. An ultrashort pulse electron beam accelerated by wakefields can generate a well-collimated Multi-keV X-ray beam with femosecond duration through relativistic Larmor radiation or nonlinear Thomson scattering[13] and the betatron oscillation of electrons in plasma. It is known that Terahertz radiation can be generated by transition radiation from laser wakefield accelerated electron bunches[14].

Femtosecond X-ray beams with a wide range of the spectrum ranging from the soft X-ray to the hard X-ray are generated by Compton (Thomson) scattering of an intense laser pulse colliding with an ultrashort bunch electron beam accelerated by laser wakefields. A generated X-ray flux is expected to be extremely high when laser-accelerated electron beams with an ultrahigh peak current of the order of Mega Ampere interact with a Multi-TW laser pulse. The peak flux of generated X-rays are given by $F[\text{photons/s}] \simeq 6.3 \times 10^{-2} I_b[\text{A}] I[\text{W/cm}^2] \lambda[\mu\text{m}] \tau_L[\text{fs}]$, where I_b is the electron beam current and τ_L the laser pulse duration. As an example, assuming that a counter-propagating 20 fs laser pulse focused on a laser accelerated electron beam with the peak current of 1 MA at the intensity of 10^{20} W/cm^2, the peak X-ray flux is expected to be 10^{28} photons/s.

As an another attractive application of laser-plasma accelerated electron bunch with high charge, coherent transition radiation from electron beam accelerated by laser wake fields at a plasma-vacuum boundary generates Terahertz radiation over wavelengths longer than the electron bunch length. The total coherent radiated energy over all angles and frequencies is given by $W_{tot}[\text{J}] \simeq 3.6 \times 10^{-2} (Q[[\text{nC}])^2 \ln(\gamma)/\lambda_{min}[\mu\text{m}]$, where Q is the bunch charge and λ_{min} is the minimum wavelength for which the bunch radiates coherently, approximately the rms bunch length σ_z[15]. As an example, $Q = 5$ nC, $\gamma = 10$, and $\lambda_{min} = 10\mu$m give $W_{tot} \simeq 200$ mJ, which is several orders of magnitude larger than that of the state-of-the-art THz radiation sources, such as laser-triggered semiconductor THz sources.

IV. CONCLUSIONS

We measured accelerated electrons produced in the interaction of the presently shortest, 23 fs, relativistically intense, 20 TW, tightly focused laser pulses with underdense He plasma to produce the peak intensity of 2.3×10^{19} W/cm^2 ($a_0 \approx 3.3$). A 5 nC total charge of accelerated electrons with emittance 0.5 π mm-mrad has been observed at high plasma density of 10^{20} cm^{-3}. The measured electron energy spectrum extending up to the maximum energy of 40 MeV, which are fitted to a power law given by $E^{-3.7}$. With the numerical simulation result of the accelerated electron bunch with 10 fs duration, it is inferred that the peak current is 0.5 MA, which is three magnitude larger than that of the conventional accelerator beams. Laser-plasma accelerated femtosecond Mega Ampere electron beams opens fruitful applications for a number of scientific fields as ultraintense femtosecond radiation sources over a broad spectrum ranging from hard X-ray to Terahertz radiation.

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