HIGH ENERGY ELECTRON ACCELERATION BY HIGH PEAK POWER LASER

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Abstract

Laser wakefield acceleration (LWFA) experiment using 100TW laser is planed at JAERI-Kansai. High quality short pulse electron beams and the precise electron-laser synchronization are necessary to accelerate the electron beam by the laser. A microtron with a photocathode rf-gun was developed as a high quality electron injector. The quantum efficiency(QE) of the photocathode was measured to be 2×10^{-5}. Emittance and a pulse width of the electron beams were 6π mm-mrad and 10ps, respectively. In order to produce a short pulse electron beam, and to synchronize between the electron beam and the laser pulse, the inverse free electron laser (IFEL) is planed. A gas jet was set up and a density of the gas was measured by Mach-Zehnder interferometer. The gas densities become uniform at 1.5 mm from the nozzle at 25 atm.

1 INTRODUCTION

The laser wakefield acceleration (LWFA)[1] has a possibility of a high energy small accelerator. The gradient of the LWFA is 100 to 1000 times larger than that of the usual rf accelerators. In fact, a few hundred MeV acceleration gain and a gradient of 10 GeV/m were observed[2-5]. However, the maximum energy gain has been limited at most to 100 MeV with energy spread of 100 % because of dephasing and wavebreaking effects in highly dense plasmas where thermal plasma electrons are accelerated. The first high energy gain acceleration exceeding 200 MeV has been observed with the injection of an electron beam at an energy matched to the wakefield phase velocity in a fairly underdense plasma[4,5]. Hence the second-generation research has dealt with the injection of ultrashort electron bunches into an appropriate correct acceleration phase of laser wakefields and the optical guiding of ultraintense ultrashort laser pulses in underdense plasmas to accomplish high energy gains and high quality beam acceleration with a small energy spread. Here the conceptual designs of GeV laser wakefield accelerator are discussed from the points of view on the ultrashort pulse and high quality electron beam injection, and the optical guiding. The recent achievements of the laser acceleration research at JAERI-APR are reported.

2 DESIGN OF LWFA

Plasma waves exited by an intense laser beam interactions with plasma has a higher gradient than usual rf accelerator. The electron beam interacts with the laser wakefield in the plasma. When a Gaussian driving laser pulse with the peak power P [TW] and wavelength λ_0 [μm] is focused on the spot size r_0 [μm] the maximum axial wakefield yields

$$\left(eE_z\right)_{\max} = 8.6\times10^4 \frac{P[TW]\lambda_0^{\,2}[\mu m]}{r_0^{\,2}[\mu m]\tau_L[fs]\gamma_0},$$

where τ [fs] is a pulse duration of the laseer pulse, $\gamma_0 = (1+a_0^2/2)^{1/2}$ takes account of nonlinear relativistic effects, and $a_0 = 6.8\times\lambda_0 P^{1/2}/r_0$ is the laser strength parameter for the linear polarization[6]. Several effects limit the energy gain in a single-stage of laser-plasma accelerators; laser diffraction, electron dephasing, pump depletion and laser-plasma instabilities. For a Gaussian beam propagation of the laser pulse with the peak power P in underdense plasma, the effective acceleration length can be limited to a diffraction length. For a properly phased electron, the maximum energy gains limited by diffraction effects is given by

ΔW_{dif} [GeV] = 0.85 P [TW] λ_0 [μm] / (γ_0 τ_L [fs]).

The electrons will eventually outrun the accelerating phase and move to the decelerating phase, if the phase velocity of the plasma is constant and the electron velocity is accelerated to the speed of light. The maximum energy gain limited by dephasing effects is

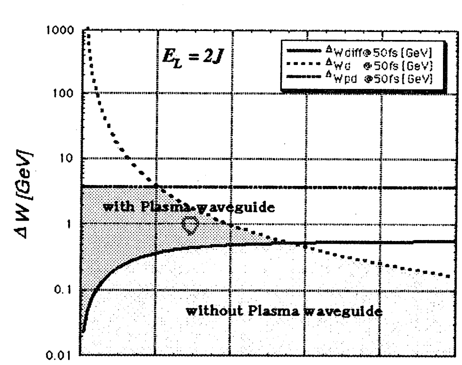

Fig.1 Energy gain of LWFA by 40TW, 50fs laser.

ΔW_d [GeV] = 0.01 P [TW] τ_L^2 [fs] / r_0^2 [μm].
The laser loses its energy when its pulse excites a plasma wave. The pump depletion length is that the length of the laser pulse loses a half of its total energy to excite plasma waves. The maximum energy gain limited by pump depletion is

ΔW_{pd} [GeV] = 0.91×10^{-3} τ_L^2 [fs] γ_0^2 / λ_0^2 [μm].
The energy gain of LWFA by the 40 TW, 50 fs laser is shown in Fig. 1. The energy gain is 1 GeV with the 3 cm plasma waveguide at the laser spot size is 30 μm. The electron beam line for the LWFA experiment is shown in Fig. 2. An electron beam injector and a plasma source for the LWFA are discussed in section 3 and 4.

3 HIGH QUALITY ELECTRON BEAM INJECTOR

It is required that femtosecond electron bunches should be injected with the energy higher than trapping threshold and femtosecond synchronization with respect to a wakefield accelerating phase space which is typically less than 100 fs in a longitudinal scale and 10 μm in a transverse size. For the purpose, we have developed an electron injection system consisting of a photocathode RF gun and a compact race-track microtron.

3.1 Photocathode RF gun

The photocathode RF gun[7,8] is prepared as a high qulity electron source. The S-band RF gun has been developed by the collaboration with BNL, KEK and Sumitomo Heavy Industries, Ltd (SHI). A copper cathode is illuminated by an UV light of 263 nm with an incident angle of 68°. This laser can generate the output pulse energy of 200 μJ at 263 nm with fluctuation of 0.5 % and the pulse width of approximately 6 ps FWHM. We have performed tests of the photocathode RF gun and the driving laser. The quantum efficiency of 2×10^{-5} and the energy of 3.5 MeV has been observed.

3.2 Microtron

We installed the photocathode RF gun as an electron source of the race-track microtron (RTM) instead of the thermionic gun. The 3.5 MeV electron beams from the photocathode RF gun enter the RTM. The electron beam is accelerated 25 times circulation and the energy of the electron beam becomes 150 MeV. The emittance of the micrtron is 6π mm-mrad at 50 pC/pulse. The emittance is enough to focus as small as 50 μm of the spot size. The 10 ps pulse width of the electron beam is measured by a streak camera.

3.3 Bunch slicing and synchronization

We apply the energy modulation technique to production of an ultrashort slice of a few 10 femtoseconds

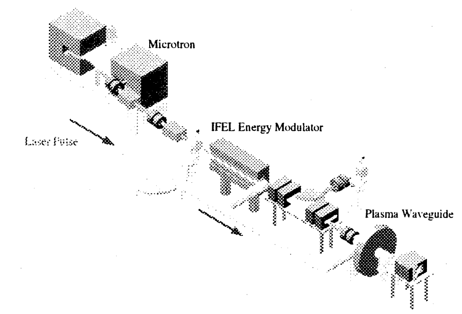

Fig.2 Electron beam line for LWFA.

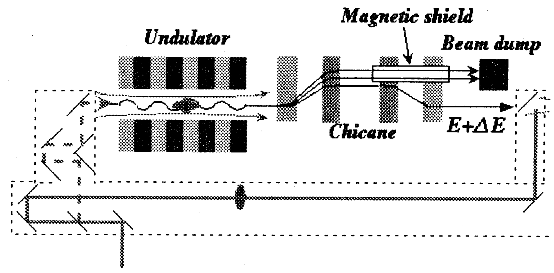

Fig.3 Setup of the bunch slice.

duration from a electron bunch of a few picoseconds duration delivered by the RTM. The mechanism of energy modulation is based on the inverse free electron laser (IFEL)[9,10], which generates the efficient energy exchange between electrons and laser fields in an undulator when the laser wavelength λ_L satisfies the resonance condition of free electron lasers, given by $\lambda_L = \lambda_u (1+K^2/2)/(2\gamma^2)$, where λ_u is the undulator period, γ is the Lorentz factor, and $K = eB_0\lambda_u/(2\pi\ m_ec) = 0.934\lambda_u[\mathrm{cm}]B_0[\mathrm{T}]$ is the deflection parameter of the undulator with the peak magnetic field of B_0. In addition to the resonance condition, when the transverse mode and the spectral bandwidth matching between the laser and the undulator spontaneous radiation can be satisfied, an amplitude of energy modulation is given by[9]

$$(\Delta E)^2 = 4\pi\alpha A_L E_L \frac{K^2/2}{1+K^2/2}\min(M_u/M_L,1)$$

where A_L is the laser pulse energy, α is the fine structure constant, E_L is the photon energy, M_u is the number of undulator periods, and M_L is the laser pulse length in optical cycles. We consider the energy modulation for the microtron beam at E = 150 MeV with an expected energy spread of 0.1 % using the undulator with λ_u = 3.3 cm, M_u = 61.5 and the maximum K value of 1.8. The resonance condition is satisfied for K = 1.5, provided by adjusting the gap. Assuming a femotosecond laser pulse with λ_L = 400 nm, the second harmonics of a 20 fs Ti:sapphire laser pulse splitted from a high peak power pump pulse, the pulse energy required to produce an energy modulation ΔE can be estimated as A_L [μJ] ΔE^2 [MeV]. The energy modulation ΔE = 15 MeV can be produced by a laser pulse with A_L = 243 μJ. The setup of the bunch slice is shown in Fig. 3. The laser pulse is separated by a beam splitter. One is for the IFEL and the other is for the

LWFA. The electron beam interacts with the laser pulse in the undulator, and the energy of electron beam is modulated. The modulated electron beams are separated in the chicane magnet. A high energy part of the electron beam is guided to the laser acceleration chamber. The expected pulse width of the modulated electron beam will be 20 fs, that is the same as that of the laser pulse. In addition to this, the perfect synchronization between the electron beam and the laser pulse.

4. PLASMA SOURCE FOR LWFA

The gas is needed for LWFA as a plasma source in vacuum. We chose two type of gas source. One is a gas jet discussed in this section, and the other is a plasma waveguide for optical guiding[11,12] discussed in another proceeding of this meeting by Dr. S. Masuda.

4.1 Gas Jet

The gas jet was set up in a vacuum chamber to test it. The orifice of the gas jet nozzle is 0.8 mm in diameter. The gas density was measured by a interferometer with 632.8nm He-Ne laser as shown in Fig. 4. The gas was Nitrogen, the backing pressure of the gas jet is 25 atm and the pulse duration of the gas was 2ms. The nozzle of the gas jet and a fringe pattern were imaged onto a charged-coupled-device (CCD) camera with an image intensifier whose gate time is 5μs. A phase shift of the interferogram is

$$\Delta\phi = \int (N_2 - N_1)\frac{\omega}{c}\,dL,$$

where $\Delta\phi$ is the phase shift in rad, N_1 is the refractive index in vacuum, N_2 is the refractive index in gas, ω is the frequency of the light and L is the interaction length. If the refractive index in gas is n_g at 1 atm and 273 K, the phase shift is

$$\frac{\Delta\phi}{2\pi} = \left(n_g - 1\right)\cdot p \cdot \frac{273}{T}\cdot\frac{L\cdot 10^{-3}}{\lambda\cdot 10^{-9}},$$

where p is the pressure in atm, T is the temperature in K, L is the interaction length in mm and λ is the wavelength in nm. The gas density is calculated from the Abel inversion of the fringe shift assuming the axisymmetry. The result at the backing pressure of 25 atm is shown in Fig. 5. It is observed that an uniform density regime is generated at 1.5 mm from the nozzle.

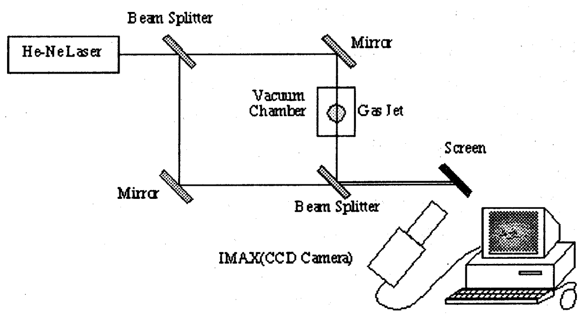

Fig.4 Schematic of Mach–Zehnder interferometer.

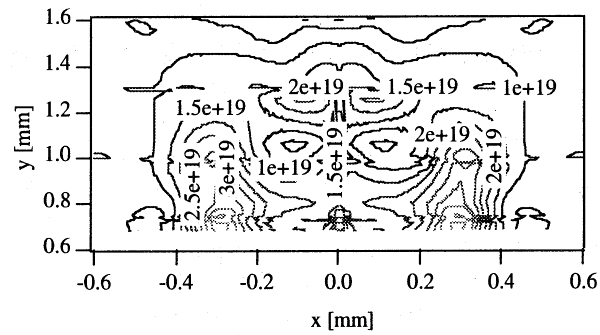

Fig.5 Contour plot of the gas density.
The nozzle is located at x=0, y=0.

5 CONCLUSION

We have developed the compact microtron with the photocathode RF gun as a high quality electron beam injector for the laser wakefield acceleration experiments. The emittance and the pulse duration of the 150 MeV electron baems were measured to be 6π mm-mrad and 10 ps, respectively. We will construct the femtosecond bunch slicing stage as a part of the laser acceleration test facility to generate a femtosecond electron pulse and to trap the electron baem in the wakefield accelerating phase. The gas jet is set up in a vacuum chamber to test it. We have succeeded to measure the density of the gas jet. The laser wakefield acceleration experiments will be demonstrated to achieve the high energy gains more than 1 GeV as well as high quality beam acceleration.

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