HIGH ENERGY LASER-PLSMA ACCELERATOR DEVELOPMENTS AT JAERI-APR

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Abstract

Laser wakefield acceleration 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. One of problems of LWFA is a short acceleration length. In order to overcome the problem, the Z-pinch plasma waveguide has been developed for 1 GeV laser wakefield acceleration.

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, only a few of the injected electrons were accelerated to high energy and 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 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 shown in Fig.1.

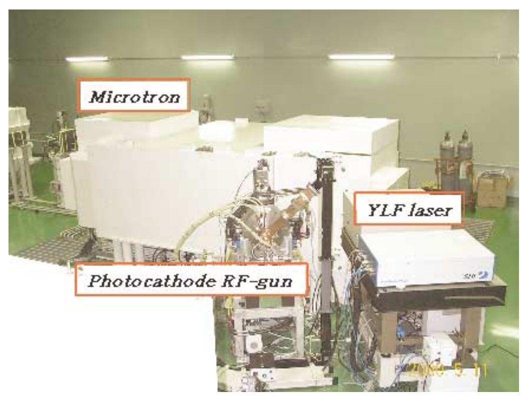

Fig.1 Microtron with photocathode RF gun

2.1 Photocathode RF gun

The photocathode RF gun[6] 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). This cavity was based on the gun developed by the BNL / SLAC / UCLA collaboration[7] and was improved for high duty operation at 60 Hz. A copper cathode is illuminated by an UV light of 263 nm with an incident angle of 68˚, delivered from a compact all solid-state Nd:YLF laser system (SHI PULRISE II). 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.

2.2 Microtron

The race-track microtron (RTM) manufactured by SHI is utilized as a booster accelerator. We installed the photocathode RF gun as an electron source of the 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

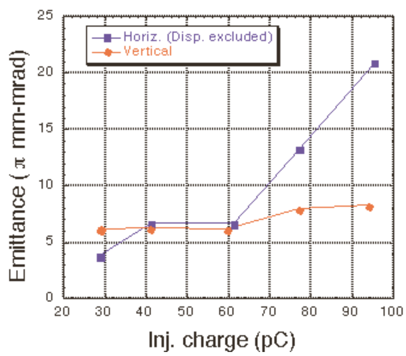

Fig. 2 Emittance of the microtron.

energy of the electron beam becomes 150 MeV. Figure 2 shows an emittance of the accelerated electron beams. The emittance 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.

2.3 Bunch slicing and synchronization

We apply the energy modulation technique to production of an ultrashort slice of a few 10 femtoseconds 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)[8,9], 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 $K = eB_0\lambda_u/(2\pi\ m_ec) = 0.934\lambda_u[cm]B_0[T]$ 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[8]

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

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.

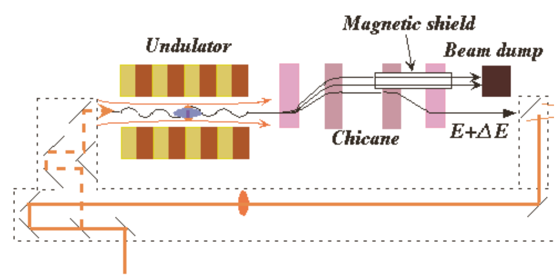

Fig.3 Setup of the bunch slice.

3. OPTICAL GUIDING IN PLASMA

The length of the laser acceleration is limited to the diffraction length of the laser. In order to increase the length, we have developed a stable cm-scale plasma channel produced by an imploding phase of fast Z-pinch discharge in a gas-filled capillary without wall ablation. A high current fast Z-pinch discharge generates strong azimuthal magnetic field, which contracts the plasma radially inward down to 100 μm in diameter. The imploding current sheet drives the converging shock wave ahead of it, producing a concave electron density profile in the radial direction just before the stagnation phase. The concave profile is approximately parabolic to out a radius of 50 μm, after which the density falls off. We succeeded in guiding a 2TW laser over 2cm in the Z pinch plasmas[10]. We have used a capillary with an inner diameter of 1 mm and a length of up to 2 cm. With this configuration, we obtained a discharge current of 4.8 kA with a rise time of 15 ns and a duration of 70 ns (FWMH). The capillary was filled with helium. A DC discharge circuit was used to preionized helium gas. A Ti:Sapphire laser pulse λ_L = 790 nm, 90 fs, was focused to $>1\times10^{17}$W/cm^2 on the front edge of the capillary with a spot size of 40 μm in diameter. The transmitted laser beam profile at the exit of the capillary was measured through a band pass filter (Δλ = 1 nm) with a CCD camera.

4 DESIGN OF GEV LWFA

The electron beam line for the LWFA experiment is shown in Fig. 4. The electron beam from the microtron is delivered through the IFEL, the chicane magnet and the plasma waveguide. The electron beam interacts with the laser wakefield in the plasma waveguide. 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

$$(eE_z)_{\max} = 8.6 \times 10^4 \frac{P[TW]\lambda_0^{\,2}[\mu m]}{r_0^{\,2}[\mu m]\tau_L[fs]\gamma_0}$$

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[11]. Several effects limit the energy gain in a single-stage of laser-plasma accelerators; laser diffraction, electron dephasing, pump depletion and laser-plasma instabilities. The maximum energy gains limited by these effects is given by

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

ΔW_d [GeV] = 0.01 P [TW] τ_L^2 [fs] / r_0^2 [μm],

ΔW_{pd} [GeV] = 0.91×10^{-3} τ_L^2 [fs] γ_0^2 / λ_0^2 [μm],

where ΔW_{diff} is the limited energy gain by the diffraction length, ΔW_d is the limited energy gain by the dephasing length and ΔW_{pd} is the limited energy gain by the pump depletion length. The energy gain of LWFA by the 40 TW, 50 fs laser is shown in Fig. 5. The energy gain is 1 GeV with the 3 cm plasma waveguide at the laser spot size is 30 μm.

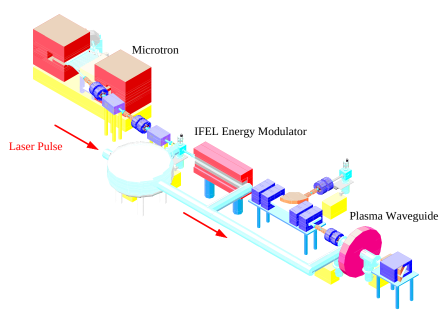

Fig.4 Electron beam line for LWFA

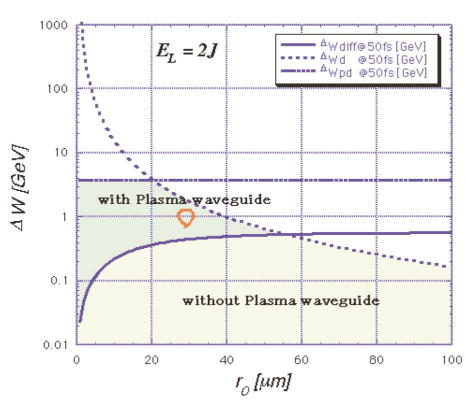

Fig.5 Energy gain of LWFA by 40TW, 50fs laser.

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. Recently commissioning of the injector system has been successfully conducted to produce a 150 MeV. The emittance and the pulse duration of the 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 optical guiding development has resulted in a cm-scale plasma waveguide using the fast Z-pinch capillary discharge. We have succeeded in demonstrating propagation of 2 TW, 90 fs laser pulses over 2 cm in the Z-pinch plasma waveguide. 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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