論文の内容の要旨

論文題目　　Control of Laser Plasma Based Accelerators up to 1 GeV
(GeV 級レーザープラズマ加速器の解析と制御)

氏名　　中村　啓

1. Introduction

Laser plasma based accelerators (LWFA) have demonstrated their capability of sustaining accelerating gradients up to several hundred GV/m, which makes them attractive as compact particle accelerators or radiation sources. Furthermore, the intrinsically laser-synchronized electron beams are naturally short in time duration because the characteristic scale length of the accelerating structure is the plasma wavelength, which is typically ~10 μm (~30 fs). The LWFA offers ways to realize many kinds of femto-second pump-probe experiments, which may be of benefit to ultra-fast sciences.

One of the main goals in the present LWFA research is to increase the energy with improved stability and tunability. The energy is a key parameter when applications such as light sources are considered. In 2004, a breakthrough was reported with the generation of high quality 100 MeV class electron beams from an LWFA, while the conventional light sources consist of accelerators that provide up to several GeV. The stability and tunability are of great interest for all kind of applications. For example, recently reported from University of Tokyo was beam generation with higher quality and stability by using an external magnetic field for conditioning the interaction.

In the LOASIS Program at Lawrence Berkeley National Laboratory (LBNL), to pursue those frontiers, a new kind of LWFA was designed. Instead of a gas jet target, a hydrogen-filled capillary discharge waveguide, which was developed at the University of Oxford. With the goal of GeV-class e-beam generation, a 50 TW class 10Hz Ti:Sapphire laser amplifier was developed at the LOASIS Facility. Critical to the GeV-class capillary discharge guided (CDG) LWFA was the development of a diagnostic for the e-beam, namely an electron spectrometer (ESM). One of the objectives of this dissertation was to develop an ESM specialized to the operation of a CDG-LWFA to realize a GeV-class LWFA. The developed ESM has served as the main diagnostics for the development of the GeV LWFA, and successfully measured GeV class e-beams. The other objective of this dissertation was to control CDG-LWFAs. Thousands of shots with a broad range of laser and plasma parameters were statistically analyzed to shed light on its complicated trapping and acceleration processes.

2. Broadband Electron Spectrometer

An LWFA can provide electrons with a wide range of energy. When the CDG-LWFA experiments were designed, the decision was made to develop a magnet-based spectrometer with as large a momentum acceptance as possible. In addition, sufficient momentum resolution and angular acceptance and the capability of high repetition rate (rep-rate) operation were needed. Furthermore, the laser guiding performance was critical for the operation of a CDG-LWFA, therefore simultaneous measurements of laser output mode and electron beam properties became essential. Those requirements made the spectrometer design quite challenging. Proposed and developed in this work was a collimator-free broadband high rep-rate electron magnetic spectrometer that resolved up to 1.1 GeV. The collimator-free scheme allowed us to diagnose an output laser mode with resolution of a few μm, and gave a sufficient geometrical acceptance. Detailed calculations of the magnet-optics were required to evaluate the electron beam properties.

The electron spectrometer utilized a round pole magnet, with an effective radius of 195 mm and a peak field strength of 1.25 T. The magnet deflected the electrons vertically downward onto two scintillating screens, LANEX Fast back (LANEX-FB), mounted on the exit flanges of the vacuum chamber. Four synchronously triggered 12-bit charge-coupled device (CCD) cameras imaged a 75 cm long (bottom) and 45 cm long (forward) screens, allowing simultaneous single shot measurement of electrons from 0.01 to 0.14 GeV (bottom) and 0.17 to 1.1 GeV (forward). The schematic is shown in Fig. 1 (a) with representative trajectories and magnetic field by the gradation map. The electron beam divergence and energy spread were calculated from the spectral data, assuming an axisymmetric electron beam profile, and by using the imaging properties of the magnetic spectrometer which were calculated using the arbitrary order beam physics code COSY INFINITY and the measured magnetic field map. The electron beam divergence was determined from the e-beam size in the horizontal plane, taking into account the transverse defocusing properties of the magnet. Under the assumption of an axisymmetric beam, the intrinsic resolution of the spectrometer at a specific monoenergetic energy can then be calculated for a given beam divergence. The real energy spread of the electron beam is then calculated by deconvolving the effect of finite divergence from the measured e-beam profile. The momentum resolution for 1 and 2 mrad e-beam is shown in Fig. 1 (b). Momentum resolution of less than 5% was achieved over the whole range.

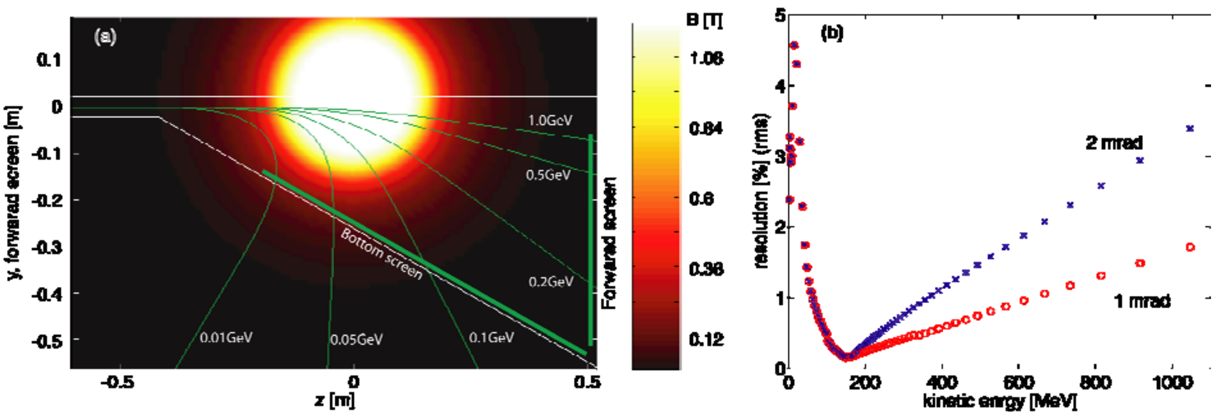

Fig. 1: (a) Schematic of the ESM with trajectories and B-field, (b) Momentum resolution.

Due to the finite angular acceptance of the system, the spectrometer had an intrinsic error bar in the determination of the absolute energy value. Shown in Fig. 2 (a) is the calculated error as a function of the incident electron energy for electrons propagating along the axis (0 degree) or at angles of +/- 4 mrad and +/- 8 mrad in the vertical plane. For example, one can see that if a 1 GeV electron beam enters the spectrometer with an incident angle of –4 mrad, it would be measured with 7% error, namely 1.07 GeV. To evaluate the error bar, the angular fluctuation of the beam was statistically analyzed from the position of the beam in the horizontal plane and found to be typically ~3.7 mrad in rms.

The scintillating screens have been used as the relativistic electron detector. Although simulation and experiments suggested little energy dependence of the light yield above a few MeV, it has never been explored with GeV e-beams. At Advanced Light Source (ALS) in LBNL, experiments were carried out to explore energy dependence of the LANEX-FB screen up to 1.2 GeV. Shown in Fig.2 (b) is the result of the calibration/energy dependence study experiments. One can see that the charge-CCD count ratio showed a slight dependence on the electron energy. By this calibration, the ESM provided the function of charge detector as well.

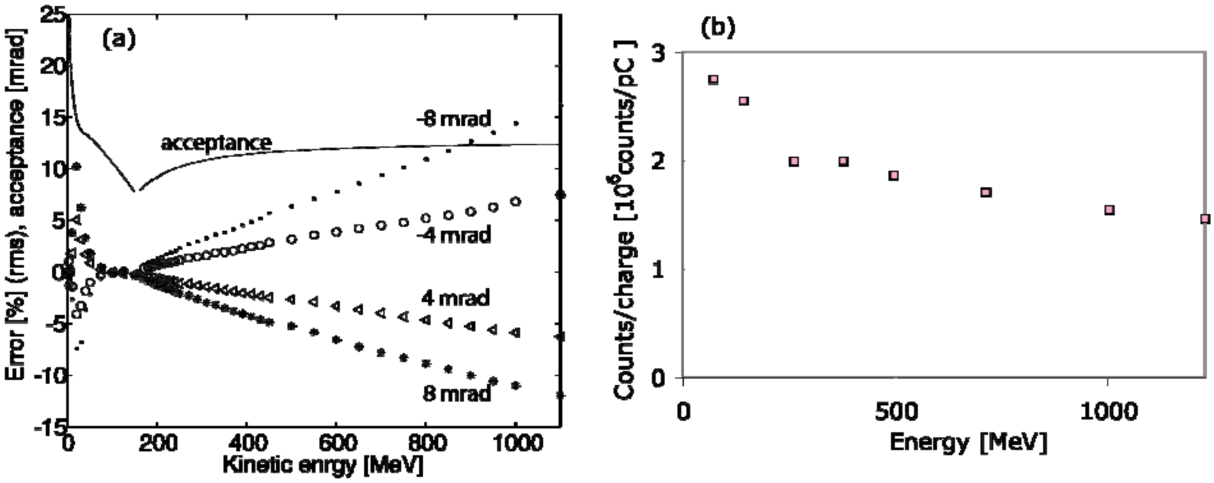

Fig. 2: (a) Error in the determination of energy, (b) Energy dependence of LANEX-FB.

3. Capillary Discharge Guided LWFA

The relativistic electron beam generation via CDG-LWFA was studied experimentally by making use of 33 mm long capillaries with diameters of 190, 225, and 310 μm (see Fig. 3 (a) for setup). Laser guiding was optimized by adjusting the initial gas density and the delay between onset of the discharge current and arrival of the laser pulse (discharge delay t_{dsc}). The laser beam transmission was found to be ~90 % for low power operation (Laser peak power P < 1 TW), and became lower when the intensity was sufficiently high for wakefield generation. The parameters of the generated electron beams were found to be sensitive and exhibited a complicated interdependence on input laser and plasma parameters. Developed in this dissertation was software for statistical analysis. By taking advantage of the high rep-rate system, data sets containing several thousands shots were taken and sorted into sets with similar parameters, allowing a statistical evaluation of the overall performance.

Electron beams with energies of 1 GeV were obtained in a 310 μm diameter capillary for P ~ 42 TW and a density of ~ 4.3×10^{18} /cm^3. The single shot e-beam spectrum with the space-integrated energy profile are shown in Figs. 3 (b) and (c). The energy spread was found to be 2.6% (2.0% resolution) rms. In order to understand a mechanism for the generation of GeV-class e-beam, statistical analysis including the guiding performance was carried out on the 310 μm diameter capillary operation. High energy beams were generated just above the threshold density for self injection, which provided the longest dephasing length possible, and kept the amount of injected electron small. The longitudinal laser pulse modulation, especially pulse compression, was critical for the generation of e-beams with the energy above the dephasing limited gain of 440 MeV. If large amount of electrons are injected into the plasma wakefield, the accelerated electron beam affects to wakefield, eventually leading to the larger energy spread (the beam loading effect). The pulse compression of down to ~20 fs, and the wake energy of ~120 mJ would be sufficient enough to provide a high quality GeV e-beam. From the analysis, the mean peak e-beam energy was found to be ~670 MeV with the standard deviation of ~190 MeV. Statistically, the probability of observing e-beams above 860 MeV (1σ) was ~16%, and above 1000 MeV (~1.7σ) was 4.5%. This unstable nature of this capillary was probably due to (a) a greater difference between the spot size of the input laser beam and the matched spot size of the plasma channel, (b) weaker transverse variation of the plasma density leading to a reduction in transverse wavebreaking, and (c) the significance of small variations in the laser plasma parameters for this high power regime.

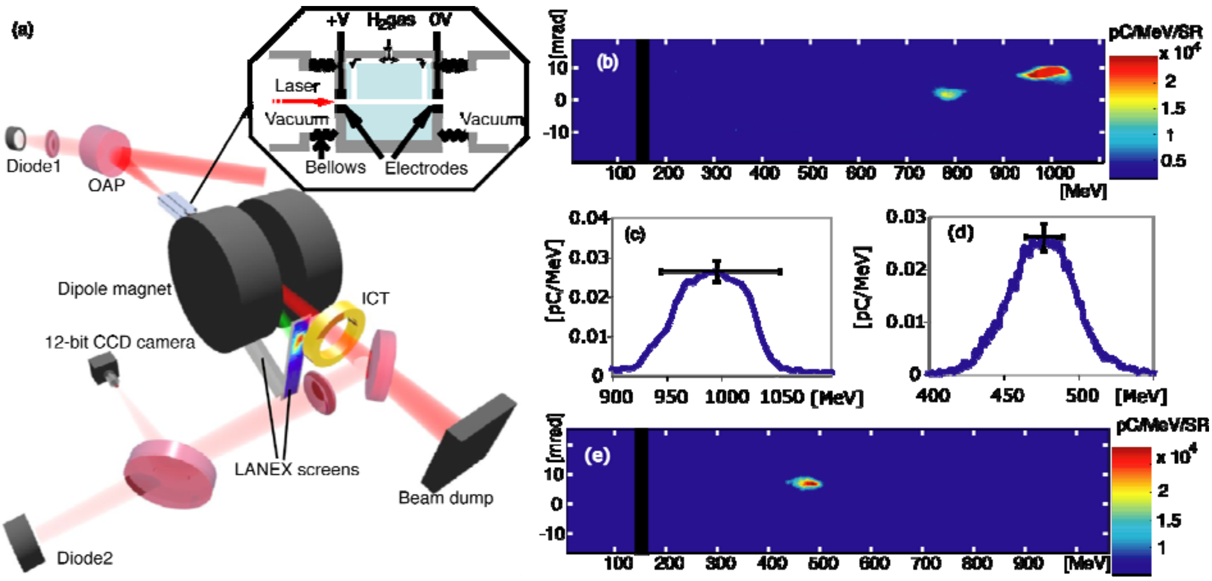

Fig.3: (a) Setup, (b) GeV single shot spectrum, (c) GeV space integrated profile, (d) half GeV space integrated profile, (e) Half GeV single shot spectrum.

Stable 0.5 GeV e-beam generation was found from the 225 μm diameter capillary with ~12 TW ~80 fs lasers and a density of ~3.5x10^{18}/cm^3. Shown in Figs. 3 (e) and (d) are a typical single shot e-beam spectrum and the space-integrated energy profile of (e). In the vicinity of this regime, the results were analyzed against the discharge delay and laser intensity, in terms of the normalized vector potential, a_0. The performance exhibited a complicated interdependence on input laser and discharge delay. Shown in Fig. 4 are the discharge delay and intensity dependence of the peak energy, and energy spread. With the right discharge delay, 140 < t_{dsc} < 155 ns, the high energy (~480 MeV), and low energy spread (~4%) e-beams were observed, while the later discharge delay, all the parameter became opposite. In case of high intensity input, excessive self injection seemed to lead to the larger energy spread, probably due to the beam loading effect. This analysis suggested that the control of the laser input energy and discharge delay was critical for the stable generation of high quality e-beams from the CDG-LWFA. With a 10 ns window of the discharge delay (142 <t_{dsc} [ns] < 152), and +/- 5% window of the input energy (0.82 < E_{in} [J] < 0.9), resultant self injection probability was 77%, the peak energy was 481 MeV with the standard deviation of 28 MeV.

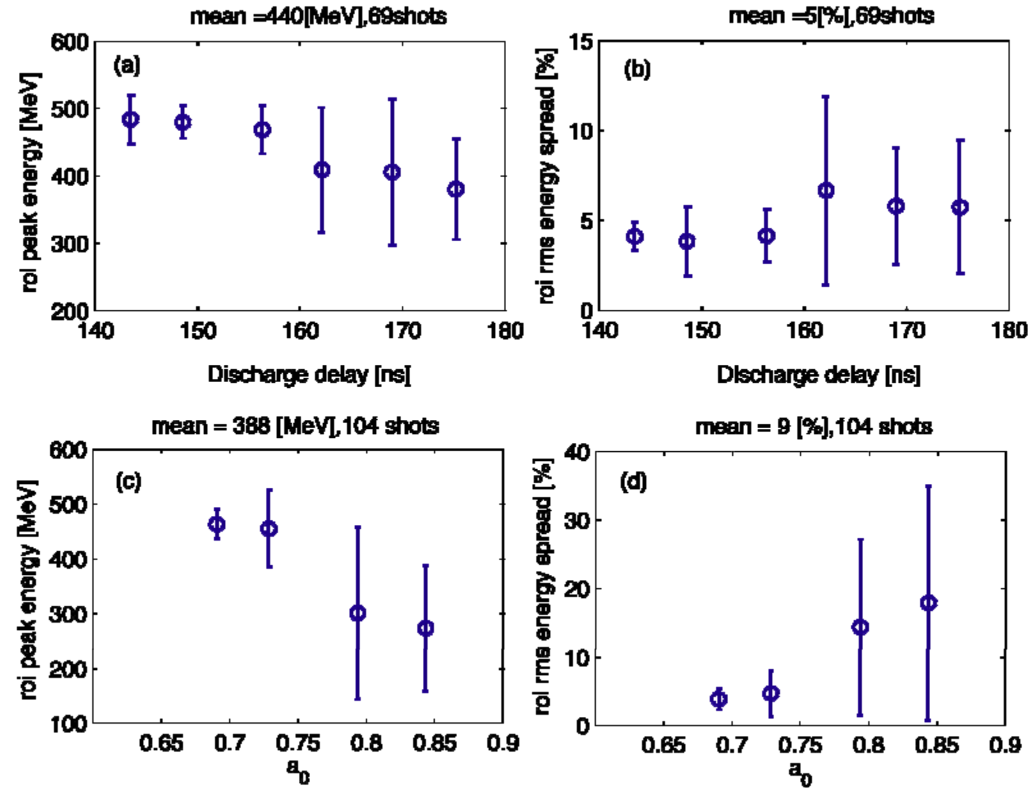

Fig.4: Discharge delay (a,b) and intensity (c,d) dependence in the vicinity of the stable 0.5 GeV generation regime. (a,c) Peak e-beam energy, (b,d) energy spread.

4. Conclusions

A broadband single-shot electron spectrometer was developed for the CDG-LWFA at LBNL. The experiments have shown its suitability and capability as a diagnostic for such a unique accelerator. The production of high quality e-beams up to 1 GeV from a centimeter-scale accelerator was demonstrated. This is the highest beam energy yet reported for a LWFA. Also demonstrated was the stable generation of high quality 0.5 GeV e-beams. The statistical analysis on the performance of CDG-LWFA was carried out. The analysis suggested the generation of high energy beams was from unstable regime, cause of which was probably due to a mismatch between the input spot and channel profile, reduced transverse wavebreaking via larger diameter, and the significance of small variations in the laser plasma parameters for this high power regime. For the stable 0.5 GeV generation, analysis showed that the control of the discharge delay and laser input energy was critical for the stable operation. The change of < 10 ns in the discharge delay, and of < 10% in the input energy significantly affected performance.

There are several diagnostics that could be employed in the future to gain a better understanding of the CDG-LWFA, and perhaps improve performance. The longitudinal laser pulse modulation during the propagation may be critical for the generation of high energy e-beam. A technique that provides information of the temporal profile, such as an auto-correlator, could give a better understanding of the laser pulse evolution during the propagation. The change in the discharge delay induces small amount of fluctuation in the plasma density, and the change in the transverse plasma profile. Therefore, transverse interferometry should be investigated. For applications of LWFA e-beams, a diagnostic for the longitudinal structure of e-beam would be essential. There are many techniques to provide such information, such as a transition radiation measurement.

Although additional diagnostics, further modeling and study with particle-in-cell simulations are required to understand the detailed physics of injection and acceleration of a CDG-LWFA, this dissertation provides information for future optimization, and suggest the direction for next generation LWFA.