# Beam-Driven and Laser-Driven Plasma Wakefield Acceleration Experiments

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Abstract

Two types of wakefield acceleration experiments are described. One of which is by the beam-driven plasma wakefield using two linacs and the other is by the laser-driven plasma wakefield using the peak power of about 30TW and the pulse width of 1ps produced by the Nd:glass laser system.

## I. INTRODUCTION

A relativistic plasma wave is useful to accelerate particle beams. The maximum amplitude of its longitudinal field is related to the plasma density $n_p$ as $E=n_p{}^{1/2}$ V/cm. This gives impressive values of between 1-100GeV/m for the plasma densities in the range of $10^{14}$-$10^{18}$ cm$^{-3}$. Recently, the plasma wave excited by the beat-wave scheme has attained the energy gain of 20MeV over a 1cm-long plasma, or 2GeV/m acceleration gradient [1]. However, the acceleration length of this scheme is limited to around 1cm because of dephasing between the particle and the plasma wave. It has another technical difficulty that the plasma density must be controlled exactly to the resonant value. Plasma wakefield acceleration schemes are free from such constraints. The wakefield can be excited either by a particle beam or by a short laser pulse. We have tried both schemes experimentally.

Beam-Driven plasma wakefield acceleration experiment was conducted using a collinear wakefield test facility [2]. This facility consists of two identical but independent linacs which are called twin-linacs. Beams from one linac excite wakefields in a plasma, while beams from the other linac witness the wakefields. The time interval between the two beams is controllable with an accuracy of ~1ps.

Laser driven plasma wakefield acceleration experiment has been conducted using intense, short laser pulse with peak power of 30TW and pulse width of 1ps delivered by the Nd:glass laser system GMII in Osaka University [3]. This laser achieves $10^{17}$-$10^{18}$W/cm$^2$ intensity, strong enough to create a fully-ionized plasma on an ultra fast time scale by the tunneling ionization process. In a plasma with appropriate density, a large amplitude of wakefield is generated behind the laser pulse propagation through the plasma due to the ponderomotive force. The phase velocity of the plasma wave is highly relativistic so that the wakefield can accelerate charged particles trapped by the plasma oscillation.

## II BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION

### *A. Experimental apparatus*

A schematic diagram of the twin linacs is shown in Fig.1. The part depicted by thick lines has been newly constructed. Because the two beams have different energies, the beam lines were joined at one dipole magnet BM3, i.e., the two lines merge at BM3. The configuration of the transport in this system is designed so as to transport the entire drive beam into the test region without loss due to energy dispersion. It is also possible to introduce witness beams with good energy resolution by inserting a vertical slit at the position of the quadrupole magnet. Since argon gas is quite harmful to the ion pumps, nitrogen was adopted as a working gas in the plasma chamber.

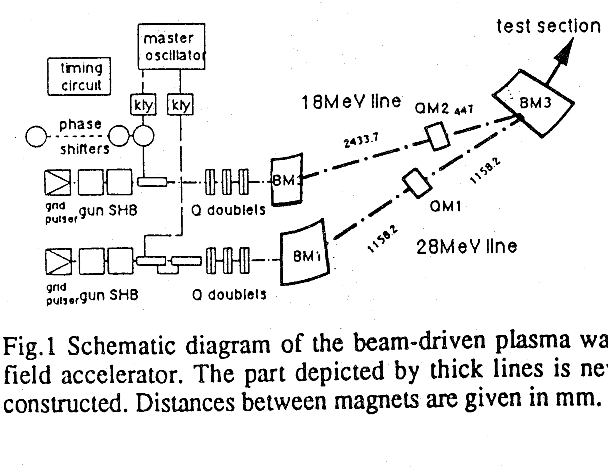


Fig.1 Schematic diagram of the beam-driven plasma wakefield accelerator. The part depicted by thick lines is newly constructed. Distances between magnets are given in mm.

Plasmas are produced in a chamber with 0.3m in diameter and 1m in length by pulse discharges between four lumps of $LaB_6$ cathodes and the chamber. The base pressure of the chamber is typically $10^{-6}$ torr. The plasma density was controlled both by the gas flow controller and the discharge current. The plasma density and temperature are measured by a Langmuir probe. Five phosphor screens measured transverse profiles, whose positions are given in Fig.2.

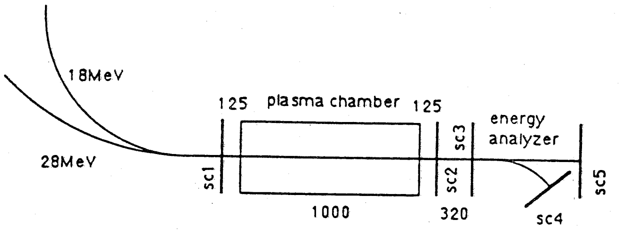


Fig.2 Positioning of phosphor screens.

*B. Experimental results*

The beam energies of drive beams and test beams were 26.76 MeV and 15.98 MeV, respectively, and the respective charges in each bunch were 300 pC and 15-30 pC.

Beam images on SC5 were observed as a function of time delay between drive and test bunches. A remarkable observation is a periodical, horizontal split of the test bunch, which is shown in Fig.3

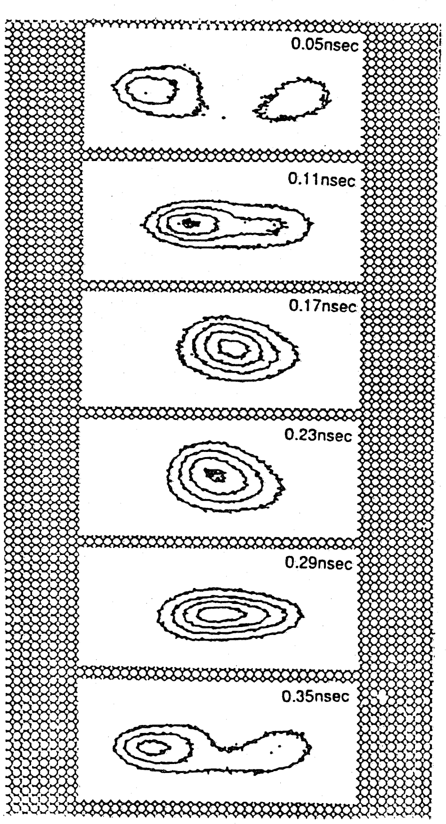


Fig.3 Typical images on SC5

Such an effect would be expected given the incomplete overlap of the two beams. The horizontal distribution is assumed to be sum of two Gaussian distributions. Delay dependence of the centroids of the two components obtained by the least square fit is given in Fig.4. As for the vertical distribution, the mean and the standard deviation are calculated, which are given in Fig. 5 as position and spread.

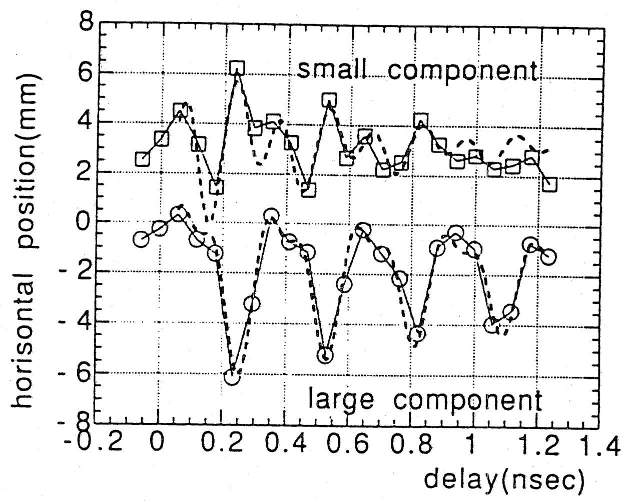


Fig.4 Delay dependence of the horizontal centroids shift of two components

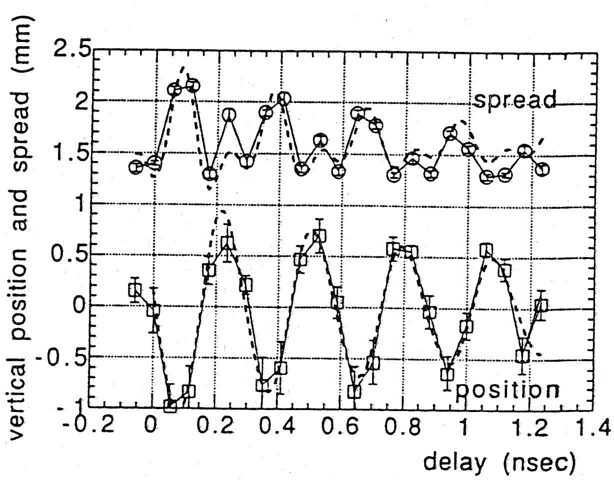


Fig.5 Delay dependence of the vertical position and spread.

The delay dependences were fit to the equation

$$f(t) = e^{-t/\tau} \left( a_1 \sin(\omega t+\phi_1) + a_2 \sin(2\omega t+\phi_2) \right)$$

The sin($2\omega t$) term is phenomenological, included to improve the fit. The following is a discussion of the parameters in this equation.

(1) $\omega$ gives the plasma frequency. The plasma density derived from the $\omega$ value of the delay dependence of the vertical position is $1.46*10^{11}cm^{-3}$. This is quite consistent with the value given by the Langmuir prove, $1.5*10^{11}cm^{-3}$.

(2) $\tau$ gives the damping time of the oscillation. The same curve gives 3.69nsec. This is very fast.

(3) The vertical position is varied only by the transverse wakefield, while the horizontal positions are varied both by

the transverse and longitudinal wakefields. Panofski-Wentzel theorem tells there should be $\pi/2$ difference between these two wakefields. Let us consider only the $\sin(\omega t+\phi_1)$ term. The vertical position of Fig.5 is approximated as $\sin(21.96t-0.249)$, where t is in nsec. The small component of Fig.4 is approximated as $\sin(21.15t-1.22) = \sin(21.96t-0.249-0.97)$ while the large component is $\sin(22.47t-0.85) = \sin(21.96t-0.249-0.60)$. The coefficients of t are regarded as the same values. Using the equality $a_T\sin(\omega t+\phi_1) + a_L \cos(\omega t+\phi_1) = (a_L{}^2+a_T{}^2)^{1/2} \sin(\omega t+\phi_1+\psi)$, $\tan\psi=a_L/a_T$, we can derive the ratio between longitudinal and transverse wakes $a_L/a_T$ from the $\psi$ values. The small component gives $a_L/a_T=\tan(-0.97)=-1.45$ while the large component gives -0.684.
(4) We can derive amplitudes of longitudinal wakefields from $a_L$ and $a_l$ values, which are around 100keV, consistent with the predictions of linear theory.

## III. LASER-DRIVEN PLASMA WAKEFIELD ACCELERATION

### A. Theoretical predictions

Assuming the Gaussian beam optics and taking the linear model with an unmagnetizxed, cold plasma of classical electrons and immobile ions, the 1ps, 30TW laser pulse at wavelength $\lambda_0 = 1.052\mu m$ should be able to produce the maximum energy gain of 45MeV. The minimum threshold kinetic energy to be trapped by the plasma wake is about 40keV for excitation of a $10^{18} W/cm^3$ intensity. The present experiments utilizes the ability of tunneling ionization of a short pulse laser. This phenomenon on an ultra fast time scale (<10fs) is distinct when the intensity is greater than $10^{15} W/cm^2$.

### B. Experimental apparatus

The chamber is filled with $H_2$ or He gas beforehand with static pressure to mate with the optimum plasma density for acceleration when completely ionized. It is also possible to feed the gas pulsively in synchronous with the laser pulse.

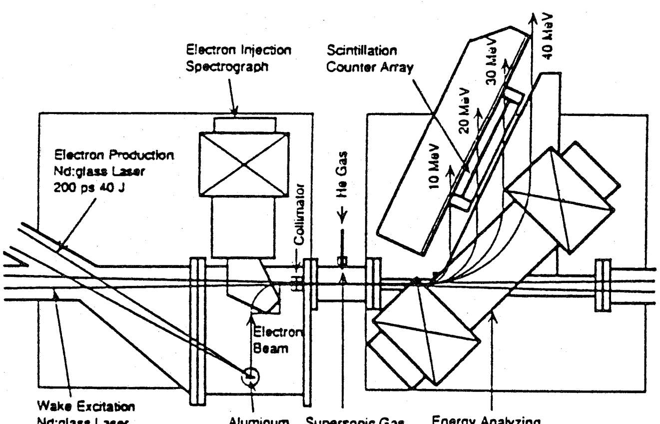


Fig.6 Experimental layout for electron acceleration caused by laser-driven plasma wakefield

Two 1.052μm Nd:glass laser beams are injected into the chamber as shown in Fig.6. One bombards a solid target to produce test electrons whose energy ranges to the order of MeV. The other with 1ps duration and 30TW peak power with a focal spot size of ~100μm ionizes the gas and excites wakefield in the resultant plasma in synchronism with the first laser. The energy change of the test electrons caused by the wakefield is measured by an energy analyzer.

The repetition rate of the laser system is less than once per hour. The pair of gratings, a focusing lens and the setups of Fig.6 are contained in the chamber and evacuated to $\sim 10^{-5}$ torr. The laser power and the time structure can be measured at the exit of the plasma chamber by a calorimeter and a streak camera with 0.6ps time resolution, respectively.

The test electrons with energy satisfying the trapping condition are produced by irradiation a solid target by the 40J, 200ps laser. The electron production may be explained by the Raman instability or resonance absorption of the laser radiation. In order to inject electrons emitted from the target into the laser wakefield at the waist of the laser beam, a dipole magnet is used to select the electron energy in the range of 0.2~3MeV. This spectrograph is placed between the target and the image point of electrons, as shown in Fig.6. The time delay between two laser beams are adjusted by the optical path lengths of two laser pulsed. It takes account of the time-of-flight of the electrons, which amounts to 1.8ns for electrons of 1.5MeV/c.

The acceleration occurs at the waist of the laser beam characterized by a Rayleigh length of 25mm in the plasma chamber. The spectrometer covers the energy range of 10~45 MeV at the dipole field of 4.3kG. The electron detector is an array of 32 scintillation counters each of which is assembled with a 1cm wide scintillator and 1/2-in. H3165 photo multiplier. Shields of lead blocks and plates were necessary to reject background noise. The pulse heights of the detector array are measured by the fast multi-channel CAMAC ADCs gated in coincidence with the laser pulse. The energy resolution of the spectrometer is 1.3MeV per channel.

## IV. CONCLUSION

In the beam-driven plasma wakefield acceleration experiments, beam images were observed as a function of time delay between drive and test bunches at the end of an energy analyzer. A periodic, horizontal split of the test bunch is observed. The plasma oscillation decayed with a very short time constant; a few nsec. A $2\omega_p$ component also appeared in the oscillation.

The laser-driven plasma wakefield acceleration experiments have been conducting.

## V. REFERENCES


[1] C. Clayton, 1993 IEEE Particle Accelerator Conference, paper #L2.
[2] A. Ogata et al., 1993 IEEE Particle Accelerator Conference, paper #Pa124.
[3] K. Nakajima et al., 1993 IEEE Particle Accelerator Conference, paper #L3.