KEK PLASMA WAKEFIELD ACCELERATOR EXPERIMENTS

A. Enomoto, H. Kobayashi, K. Nakajima, H. Nakanishi, Y. Nishida*,
A. Ogata, S. Ohsawa, T. Oogoe, Y. Suetsugu, and T. Urano

National Laboratory for High Energy Physics, Tsukuba, 305 Japan
**Utsunomiya University, Utsunomiya, 321 Japan*

The KEK plasma wakefield accelerator experiments use a train of several 500MeV electron bunches with total charge of 5-10nC. A plasma with density of $10^{11}-10^{13}cm^{-3}$ is produced by pulse discharges between cathodes and a chamber, .3m in diameter and 1m in length with a multidipole confinement field. The experiments proved that the field of the plasma wave excited by preceding bunches accelerates or decelerates trailing bunches. The resonant condition between the buncher radio frequency and the plasma frequency causes barycenter shift more than 12MeV in the energy distribution of a trailing bunch. This amount of energy shift is much larger than predicted by the linear theory.

1. Introduction

A plasma wakefield accelerator(PWFA) is one of plasma-based accelerators promising ultra-high accelerating gradients. In the PWFA, a high-intensity relativistic driving beam excites a large amplitude plasma wave which in turn accelerates a low-intensity trailing beam.[1]

Our experiments on the PWFA were conceived by the use of a high-intensity electron beam for the positron production in the KEK PF linac.[2] The linac provides us with a sequence of multiple bunches which generate wakefields in a plasma to accelerate or decelerate trailing bunches. Analyzing the energy of each bunch, we can observe the energy transfer between the bunches without a test beam. The theory tells us that the plasma wakefields are enhanced at certain plasma frequencies which are resonant with the frequency of spacing of the linac bunches. Because the plasma frequency is determined by the plasma density, we can probe the resonance by controlling the plasma density.

The preliminary results are described in previous papers,[3-5] where an energy shift of 4MeV was caused in a low density plasma of the order of $10^{12}cm^{-3}$ by a 250MeV electron beam. The present paper reports a more remarkable energy shift, approximately 12MeV, in a denser plasma, up to $10^{12}cm^{-3}$, caused by a higher energy beam, 500MeV with a higher density. In section 2, the experimental setup is described. In section 3, experimental results and their analysis are given. Section 4 contains discussion.

2. Experimental Setup

The experiments have been performed at KEK using a high current electron linac for positron production.[2] A 4ns beam pulse emitted by a triode gun is compressed to less than 2ns in a subharmonic buncher. The 2856MHz rf buncher then separate the 2ns pulse into a train of more than 6 bunches with 350ps spacing. They are then accelerated up to 500MeV. Bunches with total charge of 5-10nC are focused on a plasma by a quadrupole triplet at the end of the linac. Radius and length of the maximum bunch are 1-1.5mm and 3mm, respectively. It was found that the preceding bunches cause to decelerate the followings even in the absence of a plasma, exciting wakefields in the linac structure. The difference of the barycenter energy between the first and the last bunches amounts to 15MeV without a plasma.

The plasma is produced in a chamber with .3m in diameter and 1m in length by pulse discharges between 4 lumps of LaB_6 cathodes and the chamber. The cathodes are heated by a 10V-80A direct current source. The discharge pulse has a voltage of 80-100V, a current of 10-20A, a duration of 2ms and a rate of .5Hz equal to the linac beam repetition rate. The multidipole field of the permanent magnets, 1kG at the inner surface of the water-cooled chamber, is applied to confine the plasma. Both beam windows of the plasma chamber are made of 50μm thich titanium foils. Identical foils are used at the windows of the linac duct and the spectrometer magnets to separate the vacuum from the plasma chamber. The base pressure of the chamber is typically 10^{-6}torr by using a 300l/s turbomolecular pump. Argon gas is fed through a gas-flow controller to maintain a neutral gas pressure of 4×10^{-4}torr for a plasma density of $10^{12}cm^{-3}$. The plasma density can be controlled both by the gas pressure and the discharge current.

The plasma electron density and temperature are measured by a Langmuir probe. The plasma density was measured to be radially homogeneous, extending over 20cm. Though we have no measurement of the longitudinal distribution, the measurement on a similar confinement device tells that it is also fairly homogeneous.[6]

Combination of a bending magnet and a streak camera enables us to measure the energy spectrum of each bunch. The energy aperture of the magnet is only 15MeV, so it is necessary to sweep the analyzing field to obtain the spectra of all bunches. Bunches analyzed in the bending magnet travel in air over a length of about .5m to a mirror, radiating Cherenkov radiation.

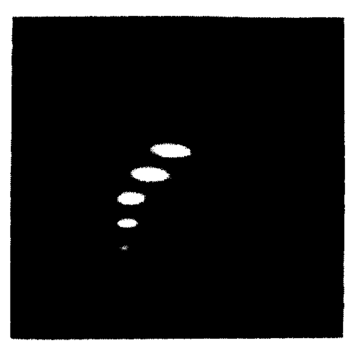

Fig. 1. A typical streak picture.

The mirror reflects only the radiation, transmitting the electron beam. The reflected radiation is finally focused on the slit of the streak camera. A Dove prism in front of the slit rotates the image so that the energy dispersion axis is perpendicular to the time axis of the camera.

A typical streak picture is shown in Fig. 1. It contains three-dimensional information; the horizontal dimension gives the convolution of the energy spread and the horizontal beam size, the vertical dimension shows the time structure of the bunches, and the picture intensity indicates the number of electrons. Digitizing the streak picture, we can calculate a mean and a standard deviation of energy of each bunch. Because of the high energy of the beam, effects of multiple scattering on titanium windows are negligible in the transverse spread of the streak picture.

3. Experimental Results

First we summarize the previous results,[5] which well agree with the linear theory. The theory tells that the resonant excitaion of plasma wakefields driven by a train of bunches occurs when the plasma frequency coincides with a multiple of the radio frequency of the buncher; *i.e.*, $\omega_p/2\pi = kf_{rf}$, where k is an integer. Fig. 2 shows the wakefields expected at the center of the each bunch, having a transeverse parabolic distribution with 1.5mm rms radius and a longitudinal Gaussian distribution with 3mm rms length. It is assumed that the total charge of 7nC is distributed over six bunches in a Gaussian-like envelope. The figure illustrates the energy gain of each bunch accelerated or decelerated in a 1m long plasma column as a function of electron density ranging $(2-12)\times 10^{11}\mathrm{cm}^{-3}$. In resonances, all bunches are decelerated to produce the maximum amplitude of wakefield behind the bunch train. As a matter of course, the latter bunches exibit the higher energy gains.

The energy spectra of 4th and 5th out of 6 bunches were measured as a function of the plasma density around $4\times 10^{11}\mathrm{cm}^{-3}$ using a 250MeV, 7nC electron beam in the previous experiments. We found the deceleration of approximately 3MeV and 4MeV in the 4th and 5th bunches, respectively. These values agree with the calculation given in Fig. 2. The 6th bunch was too weak to be energy-analyzed.

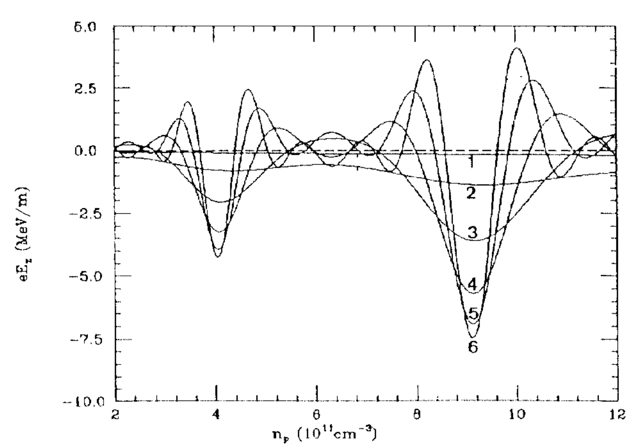

Fig. 2. The expected longitudinal wakefield at the barycenter of each bunch. The numerals denote the order of bunches.

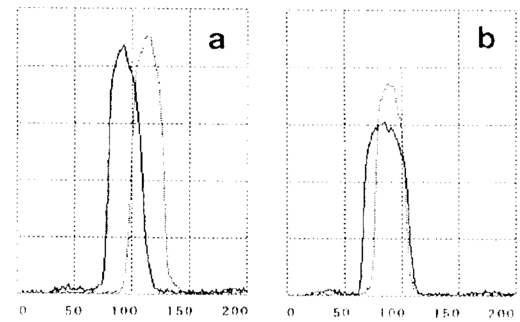

Fig. 3. Typical energy spectra, .547MeV/channel. (a) those of the bunch with the maximum intensity. Solid line: in the presence of a plasma with a resonant density, dotted: in the absence of a plasma. (b) those of the bunch just after the one with the maximum intensity. Solid line: in the presence of a plasma with resonant density, dotted: in a plasma with density off the resonance.

In the present experiments, we have tried combination of a wider plasma density region (up to $10^{12}\mathrm{cm}^{-3}$) and a beam with a higher energy (500MeV). The higher energy mainly contributed to the improvement of the beam size, decreasing multiple scattering of electrons at the beam windows. The reduction in the beam size contributes to increase the electron density inside the bunch. The higher energy also increased the Cherenkov radiation intensity to improve the signal-to-noise ratio of the streak camera measurement.

We meet a new aspect in a higher beam density region. The following data are afforded by a beam with a total charge of 7.5nC, an rms radius σ_r = 1mm, and an rms bunch length σ_z = 3mm. Note that the radius is reduced to 2/3 from the previous experiments, owing to both the multiple scattering reduction at the windows and the improved operation of focusing magnets. We find that the bunch with the maximum intensity is strongly decelerated at the resonant plasma densities in this condition. Little deceleration, less than 2MeV, is found at the resonances in the bunch following just after this maximum one. Instead, the energy spectra of this bunch get broad. The energy changes of the following weak bunches are contrarily negligible.

Fig. 3(a) shows energy spectra of the bunch with the maximum intensity. The difference of the mean energy between those given by the solid and dotted lines is approximately 12MeV, where the solid line gives the energy spectrum in the presence of a plasma with the density of $9\times 10^{11}\mathrm{cm}^{-3}$, the second resonant density given in Fig. 2, while the dotted gives the spectrum in the absence of a plasma. The observed energy shift is much greater than predicted by the linear theory given in Fig. 2, the 3rd or 4th bunch of which has the maximum intensity; it is derived from the figure that the energy shift of the 3rd bunch at the second resonance should be about 5MeV taking account of the density increase of in the present experiments.

The nature of the resonance is still valid, as shown in Fig. 4. This observed resonance is, however, sharper than the theoretical prediction given in the curve numbered 3 or 4 of Fig. 2. In Fig. 4, the curve numbered 6 in Fig. 2 is re-scaled and depicted, which funnily fits the experiments, in spite that it should have no physical meaning.

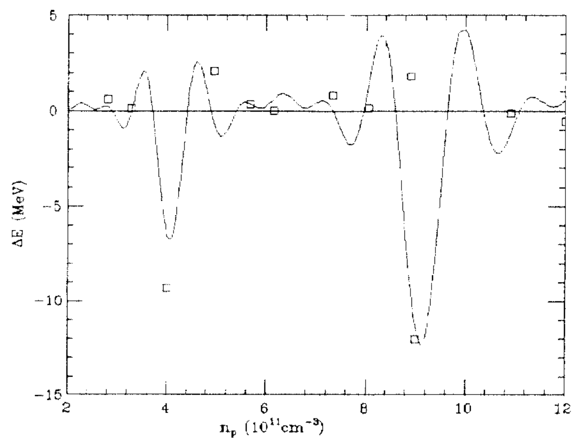

Fig. 4. Observed centroid energy shifts of the maximum bunch as a function of the plasma density.

Fig. 3(b) shows energy spectra of the bunch following just after the maximum. The spectrum at the resonant plasma density is 40% broader than that off the resonance. The spectrum without a plasma has similar distribution as the one given by the dotted line in Fig. 3(b). Fig. 5 shows the rms energy width of this bunch as a function of the plasma density, where the resonances are clear but broader than in Fig. 4. We cannot tell whether this is due to the energy broadening or due to the defocusing of the wakefield. As shown in Fig. 3(a), no significant change was found in the width of the spectrum of the maximum bunch at the resonant plasma density.

4. Discussion

One explanation of the anomalous deceleration of the maximum bunch is introduction of a nonlinear mechanism. The perturbed electron density is given by[7]

$$n_1 = k_p N exp[-(k_p \sigma_z)^2/2]/(2\pi\sigma_r^2),$$

where $k_p = c/\omega_p$, and N is the number of particles in the bunch. Inserting our values and assuming that the maximum bunch has the charge of 2nC, we have $n_1 = 3.04 \times 10^{11}\mathrm{cm}^{-3}$, or $n_1/n_o = .3$ at the second resonance. We are certainly in the region where the linear theory is not applicable.

The nonlinear effect also gives an explanation to the fact that the tail bunches do not exhibit energy change at the resonances; the phase difference is probable between the plasma wave and the bunch spacing, if the plasma wave does not remain sinusoidal. It seems to correspond to the phenomenon of the spectrum broadening shown in Fig. 5. Another plausible explanation is the possibility that the tail bunches are off-centered before they enter the plasma. The vertical offsets of tail bunches more than 1mm are often observed in this linac,[8] which is brought about by a transverse wake field inherent in the linac structure. If the offset is greater than the driving bunch beam size, its effect on the trailing bunches cannot be strong enough to cause the energy shift.

Only the deceleration is remarkable at the resonant density of a plasma, as long as the bunch spacings are fixed, and the envelope of the bunch train is Gausian, as in the experiments reported here. We can, however, make acceleration possible, controlling the envelope.[9] It is known that a train of M bunches with linearly ramping intensities, given by the nth bunch intensity $N_n/N_1 = 2n - 1$, can produce maximum transformer ratio $2M$, if the frequency of the bunch spacing is resonant with the plasma frequency. A traceable amout of test bunch can be accelerated, benefitted by this transformer ratio, even if its distance between the last of driving bunches is also determined by the buncher radio frequency. We can modify the cathode grid pulser of the KEK linac to produce such a bunch train envelope.

In summary, we observed about 12MeV energy shift in an electron bunch travelling through a 1m long plasma column. This shift amount is more than the prediction of linear model. We are planning to ascertain the reproducibility and cause in detail in the nearest future.

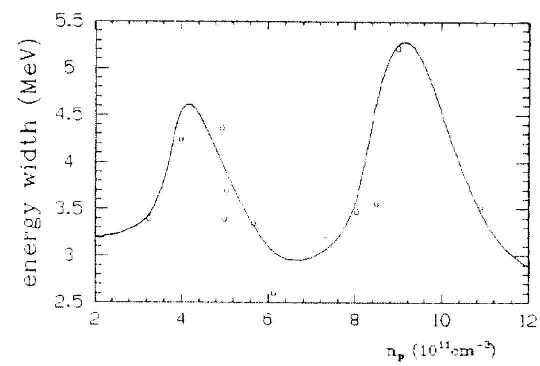

Fig. 5. RMS energy width of the bunch following just after the maximum as a function of the plasma density.

REFERENCES

1. P. Chen *et al.*, "Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma", Phys. Rev. Lett. 54(1985)693.

2. A. Enomoto *et al.*, "Focusing System of the KEK Positron Generator", Nucl. Instr. and Meth. A281(1989)1.

3. A. Ogata *et al.*, "Experiment of the Plasma Wake-Field Accelerator at the KEK LINAC", Proc. 1989 IEEE Particle Accelerator Conf., Chicago (IEEE 1989) p618.

4. H. Nakanishi *et al.*, "First Results of KEK Plasma Wakefield Accelerator Experiment", Particle Accelerators 32(1990)203

5. K. Nakajima *et al.*, "Plasma Wake-Field Accelerator Experiments in KEK", Nucl. Instr. and Meth. (to be published).

6. Y. Nishida *et al.*, "High Energy Electron Production by $V_p \times B$ Acceleration in Microwave-Plasma Interaction Experiments", IEEE Trans. Plasma Sci. PS-15(1987)243.

7. J. B. Rosenzweig, "Nonlinear Plasma and Beam Physics in Plasma Wake-Fields", FERMILAB-Conf-90/40 (1990).

8. Y. Ogawa *et al.*, "Direct Observation of the Multi-Bunch Instability Caused by a Transverse Wake Field", KEK Preprint 90-35 (1990).

9. K. Nakajima, "Plasma Wake-Field Accelerator Driven by a Train of Multiple Bunches", Particle Accelerators 32(1990)209.