Plasma Wakefield Acceleration in Overdense Regime Driven by Narrow Bunches

A. Ogata, H. Nakanishi, T. Kawakubo, M. Arinaga, K. Nakajima
National Laboratory for High Energy Physics (KEK), Oho, Tsukuba, Japan
T. Kozawa, T. Ueda, T. Kobayashi
Nuclear Engineering Research Laboratory, Faculty of Engineering, The University of Tokyo, Tokai-mura, Ibaraki-ken, Japan
H. Shibata
Research Center for Nuclear Science and Technology, The University of Tokyo, Tokai-mura, Ibaraki-ken, Japan
N. Yugami, Y. Nishida
Department of Electrical and Electronic Engineering, Utsunomiya University, Utsunomiya, Japan
D. Whittum
Stanford Linear Accelerator Center, Stanford University, Stanford, California, USA
Y. Yoshida
Institute of Scientific and Industrial Research, Osaka University, Mihogaoka, Ibaraki, Japan

Abstract

Experiments of plasma wakefield acceleration driven by narrow bunches were performed in overdense regime. Acceleration gradient about 1MeV/m was observed. Energy change and focusing caused in the drive bunches were observed.

1 INTRODUCTION

Plasma wakefield acceleration is one of the methods which are proposed in order to obtain an acceleration gradient high enough for the next generation of linear colliders[1]. The concept has been first tested experimentally in 1988 at the Argonne National Laboratory (ANL)[2]. More recently, gradient of 20MeV/m has been produced by a train of bunches from the 500MeV linac at KEK[3].

The experiments reported in this paper do not aim at renewing the acceleration gradient record. They aim at accumulating basic data of this acceleration instead. A new collinear wakefield test facility was constructed for this purpose[4], which is unique in that it consists of two identical but independent linacs which are called twin-linacs, while in other wakefield accelerators one linac generates both the driving and witness beams. Beams from one linac excite wakefields in a plasma, while beams from the other linac witness the wakefields. Because these two beams are different in their energies, they are easily separated by a bending magnet. The time interval between the two beams is controllable with an accuracy of $\sim$ 1psec.

The experiments surveyed dependence of acceleration characteristics on the plasma density in the overdense regime, in which plasma density is higher than the beam density. The drive beams were narrow; in other words, the product of plasma wavenumber and the beam size was less than unity. Changes in sizes and energy casued in the drive bunches were also studied as a function of plasma density.

2 EXPERIMENTAL APPARATUS

Plasmas were produced in a chamber with .15m diameter and .36m length by pulse discharges between four lumps of LaB_6 cathodes and the chamber[5]. The cathodes were heated by a 10V-80A direct current source. The discharge pulse had a voltage of 80-120V, a current of 10-20A, a duration of 2ms and a rate of 12.5Hz equal to the linac beam repetition rate. The multi-dipole field of permanent magnets, 0.7kG at the inner surface of the air-cooled chamber, was applied to confine the plasma. Argon gas was filled the chamber at the plasma production. The plasma density was controlled both by the gas flow controller, the cathode temperature and the discharge voltage. The plasma density and temperature were measured by a Langmuir probe. The temperature was found to be 2-3eV. We adopted differential pumping in order to isolate the linacs from the test section,.

A 45^0 bending magnet at the end of the plasma chamber measured the beam energy. Beam sizes and positions were measured by using phosphor screens. The energies of the drive beams and test beams were 24.1 MeV and 16.6 MeV, respectively, and the respective charges in each bunch were 300-400 pC and 70-80 pC at the exit of the energy analyzer.

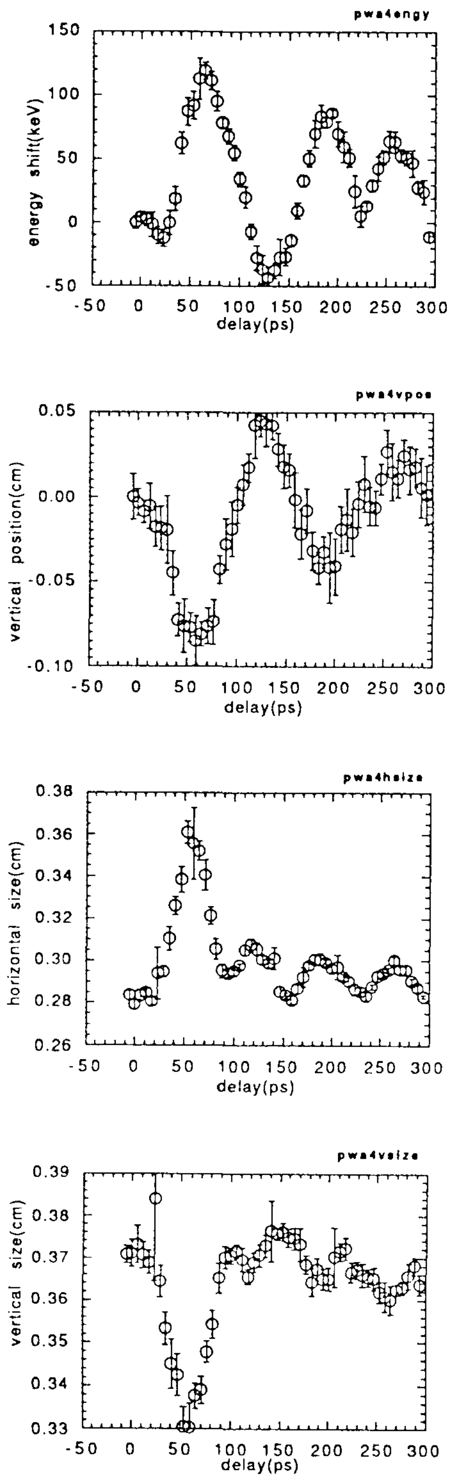

Figure 1: Each example of time dependence of (aenergy change, (b)vertical position, (c)horizontal beam size, and (d)vertical beam size of test bunches. Plasma density was $6.14 \times 10^{11}\mathrm{cm}^{-3}$.

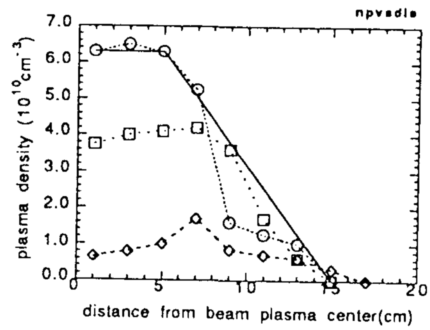

Figure 2: Plasma density distributions along the beam axis. The solid line shows trapezoidal approximation.

Vertical and horizontal beam sizes of the drive bunch were around 2mm.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Beam images on the phosphor screen at the exit of the energy analyzer were observed as a function of time delay between drive and test bunches. Position and beam sizes were derived in both horizontal and vertical directions. Examples are given in Fig. 1.

The delay dependences experimentally obtained were fit to the equation

$$f(t) = e^{-t/\tau}[a_1 \sin(\omega t + \phi_1) + a_2 \sin(2\omega t + \phi_2)]. \quad (1)$$

The $\sin 2\omega t$ term is phenomenological, included to improve the fit. Plasma frequencies and consequent plasma densities were derived from the ω values.

Plasma density distributions along the beam axis measured were shown in Fig. 2. The acceleration experiments were however performed in the density region far higher than those given in Fig. 2. The density distributions were then calculated by a similar method described in ref.[6]. This is possible because the damping characterized by τ in er.(1) can be attributed to the heterogeneity of the density distribution as following. The plasma density and the resultant plasma frequency at the ends of the plasma column are lower than those at the plasma center. The test bunches suffer from the phase difference of the plasma oscillation, which becomes more severe as the time difference becomes longer. The phase difference tends to offset the positive and negative effects of the wakefield to decrease the amplitude of the oscillation.

In this specific data processing, a trapezoidal distribution was first assumed as $n(z)$. The solid line in Fig. 2 shows the trapezoidal approximation of the distribution which were obtained experimentally and given by circles. The delay dependence of the wakefield is then calculated by the relation

$$E(t) \sim \int_0^{L_0/2} -n(z)cos(\omega_p(z)t)dz, \quad (2)$$

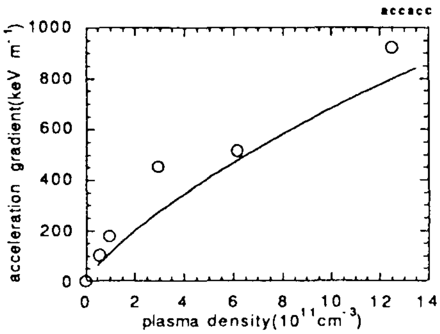

Figure 3: Dependence of acceleration gradient on plasma density. Solid line shows prediction of a linear theory.

where $\omega_p(z)$ is the plasma frequency, assumed to agree with ω in eq.(1) at the flat top of the trapezoidal distribution. The length of flat top of the trapezoid was adjusted so that its decay characteristics agree with the experimental data and the reduction of the wakefield amplitude was derived.

The acceleration gradient at the center of the distribution thus derived is given in Fig. 3. The solid line in the figure shows the prediction of linear theory,

$$E_z = \frac{8r_e mc^2 N}{a^2}\exp[-\frac{k_p^2}{\sigma_z^2}][1-\frac{4}{k_p^2a^2}+2K_2(k_pa)], \quad (3)$$

where N is the number of electrons in the drive bunch corresponding with the total charge 600pC, k_p is the plasma wavenumber, σ_z is the bunch length, 1.5mm, and a is the beam size which is assumed to be 2mm. The experimental value is larger than the theoretical.

Figure 4 shows changes caused in the drive bunches. The change in the energy can give the transformer ratio. Reduction of beam sizes shows the plasma lens effect[7], which originates in the transeverse wakefield, and, in turn, can enhance the longitudinal wakefields. No appreciable change was observed in the vertical beam position.

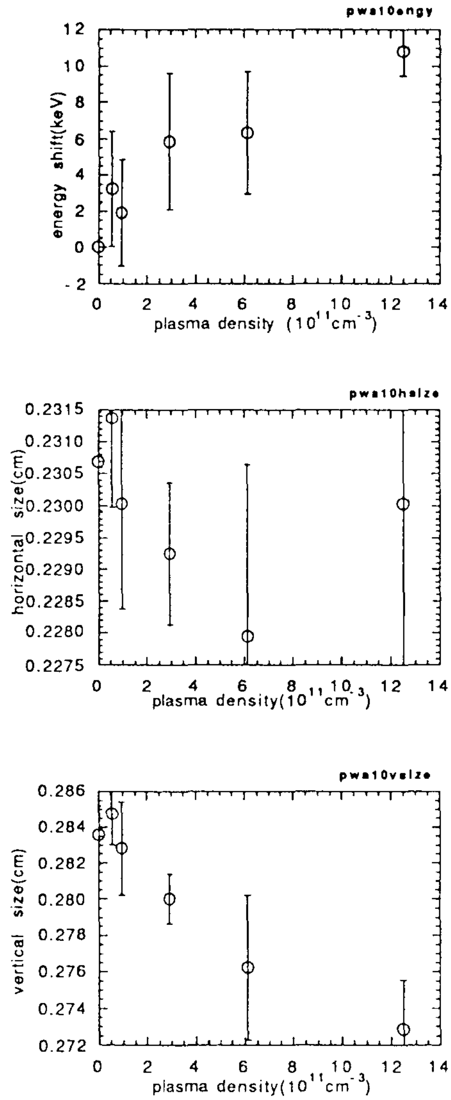

Figure 4: Change caused in energy(a) horizontal beam width(b) and vertical width(c) of the drive bunches as functions of plasma density.

4 REFERENCES

[1] P. Chen, *et al.*, **Phys. Rev. Lett., 54** (1985) 693.

[2] J. Rosenzweig, *et al.*, **Phys. Rev. Lett. 61** (1988) 98.

[3] A. Ogata, in *AIP Cof. Proc. 279; Advanced Accelerator Concepts*, Port Jefferson, New York, 1992, edited by J. Wurtele, (American Institute of Physics, New York, 1993) p.420.

[4] H. Nakanishi, *et al.*, **Nucl. Instr. Meth., A328** (1993) 596.

[5] H. Nakanishi, *et al.*, **Phys. Rev. Lett.66**(1990)1870.

[6] A. Ogata, *et al.*, **Phys. Scripta**, to be published.

[7] P. Chen, **Part. Accel. 20**(1987)171.