PLASMA WAKEFIELD ACCELERATION DRIVEN BY MULTIPLE BUNCHES

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Abstract

Electron acceleration by plasma wakefields driven by multiple bunches were experimentally studied. It is expected that a wakefield driven by each bunch builds up to result in a large acceleration gradient. However, the build-up of wakefields was not ideal, due to the peaked plasma-density distribution in a small plasma chamber. The amplitude of the wakefield observed was larger than calculated.

1 INTRODUCTION

Plasma wakefield acceleration is one of the methods which are proposed to attain high acceleration gradient[1]. It drives plasma waves using a particle beam called a "drive" beam. Potential of the waves accelerates a "test" beam following the drive beam.

One of drawbacks of this acceleration is that the energy gain of the test beam is limited below twice of the energy of the drive beam. One way to overcome this limit is use of the drive beam consisting of multiple bunches. Calculations show that, if the separation of the bunches is in synchronism with the plasma wavelength, amplitude of the wakefields builds up[2].

This paper reports plasma wakefield acceleration experiments using multiple bunches. Mainstream of the wakefield acceleration at the present is not in the use of particle beams but in the use of laser beams. Note that the use of multiple laser pulses is also proposed in the laser wakefield acceleration in order to build up wakefields[3]. The present experiments give information useful also to the laser wakefield acceleration.

2 EXPERIMENTAL SETUPS

Two linacs were used, one of which gave drive beams while the other gave test beams[4]. Their energies were 24.1MeV and 16.6MeV, respectively. Time interval between the two beams was controllable with accuracy of 1ps. A bending magnet merged trajectories of two linac beams into one, before they enter into a plasma chamber.

The beam energy was analyzed by a bending magnet at the end of the plasma chamber with sensitivity of 51keV/mm. Beam sizes and positions were measured by three phosphor screens at the entrance and exit of the plasma chamber, and at the exit of the energy analyz er. Typical bunch distribution of a drive beam is showin in Fig. 1. Total charge of a drive beam was 300-400pC, which was shared by seven bunches. Bunch spacing was $1/2856\mathrm{MHz}$ or 350ps. A test beam consisted of a single bunch with charge of 70-100pC. In the following data analyses, total charge of a drive beam is assumed to be 350pC.

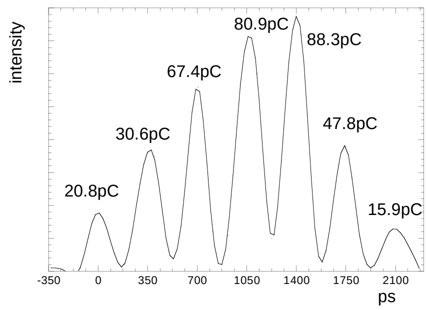

Figure 1: Bunch distribution in a drive beam. Total charge is 352pC. Bunch spacing is 350ps.

Horizontal [vertical] rms beam sizes of drive bunches were 2.33mm [1.43mm] and 1.76mm [1.10mm], at the entrance and exit of the plasma chamber, respectively. Corresponding horizontal [vertical] sizes of a test bunch were 2.05mm [1.12mm] and 1.32mm [1.68mm], respectively. Horizontal [vertical] distances between drive and test beams were 1.46mm [0.45mm] and 2.39mm [.04mm], at the entrance and exit of the plasma chamber.

The air-cooled plasma chamber was 15cm in diamter and 36cm in length. Differential pumping technique isolated the linacs from the plasma chamber. Argon plasmas were created by pulse discharges at four $\mathrm{LaB_6}$ cathodes. The discharge pulses had a voltage of 80-120V, a current of 10-20A, duration of 2ms and a rate of 6.25Hz equal to the linac repetition. A multi-dipole field of permanent magnet, 0.7kG at the inner surface of the chamber, confined the plasmas.

The plasma density was controlled by the gas flow rate, the cathode temperature and the discharge voltage. The plasma density and temperature were measured by a Langmuir probe. The electron temperature was found to be 2-5eV. Typical axial distributions of the plasma densities are shown in Fig. 2.

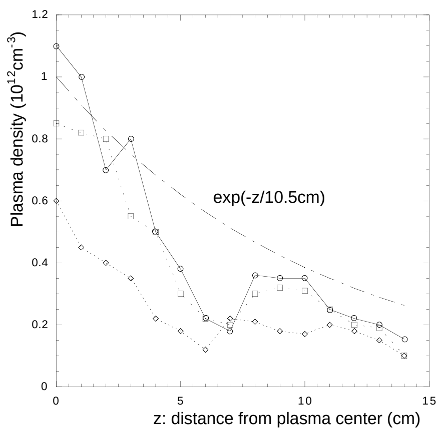

Figure 2: Plasma density distributions in a plasma chamber and their approximation used in the analyses.

Buld up of wakefields is possible under the condition $n\omega_{rf} = \omega_p$, where n is an integer, ω_{rf} is the bunch frequency, and ω_p is the plasma frequency. In the present experiments, the cases of $n = 1, 2, 3$ were tried, corresponding to the plasma densities $n_p = 1.0 \times 10^{11}\mathrm{cm}^{-3}, 4.1 \times 10^{11}\mathrm{cm}^{-3}, 9.1 \times 10^{11}\mathrm{cm}^{-3}$, respectively. The Broken line of figure 3 shows an ideal build-up, which figure gives energy shifts of a test beam as a function of time delay from the first drive bunch. The amplitude of acceleration gradient $|E_z|$ is assumed to follow the relation $|E_z| = m_e\omega_p c(n_b/n_p)$, where n_b is the electron density inside the drive bunch.

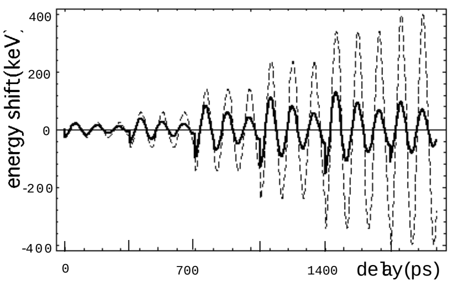

Figure 3: Calculated energy shift of a test bunch at $n_p = 9.1 \times 10^{11}\mathrm{cm}^{-3}$. Dashed curve: in a homogeneous plasma. Solid curve: in the plasma density distribution shown by the dot-dash curve in Fig.2.

3 RESULTS AND DISCUSSION

Raw Data

Horizontal and vertical shifts, and, horizontal and vertical sizes of test bunches were measured downstream of the energy analyzing magnet as a function of the time delay. Two sets of results are shown in Figs. 4, in which upper and lower figures correspond to $n_p = 1.0 \times 10^{11}\mathrm{cm}^{-3}$ and $9.1 \times 10^{11}\mathrm{cm}^{-3}$, respectively. The following data analyses are mainly made on the data in the lower figure at $n_p = 9.1 \times 10^{11}\mathrm{cm}^{-3}$.

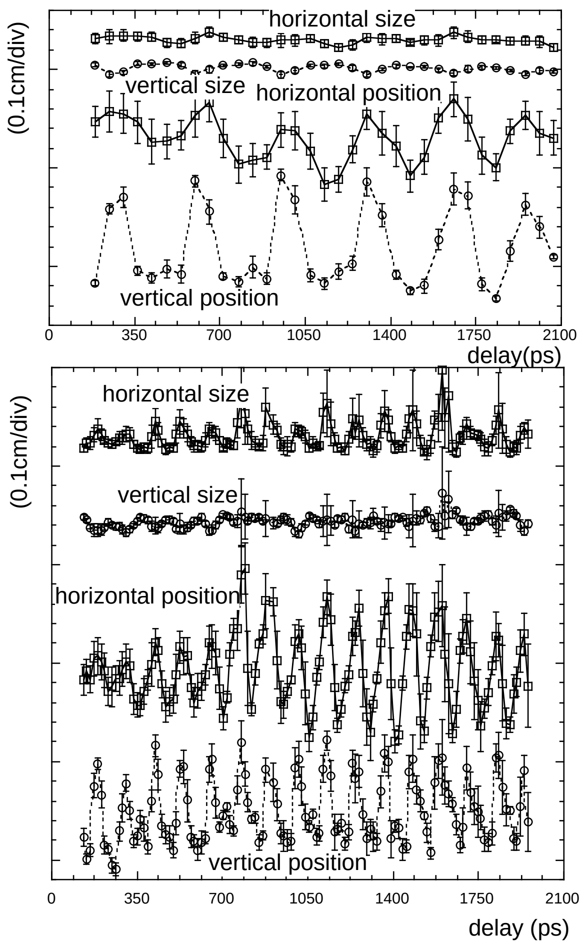

Figure 4: Delay dependence of horizontal and vertical shifts, and, horizontal and vertical sizes of test bunches at the energy analyzer. Plasma densities are $1.0 \times 10^{11}\mathrm{cm}^{-3}$ and $9.1 \times 10^{11}\mathrm{cm}^{-3}$ in the upper and lower figures, respectively. Injection timing of a drive bunch is every 350ps, with the first one at 0ps.

Horizontal Shifts

Because the drive and test beams were not colinear, not only the energy change of the test bunch but also the transverse wakefields of the drive bunches contribute to the horizontal beam shifts of the test bunch at the exit of the energy-analyzer, although only the latter contributes to the vertical shift. The radial dependence of the transverse wakefield is given in ref.[5]. From the measured distance between the test and drive beams, and the vertical beam shifts, we can deduce the contribution of the transverse wakefield to the horizontal shift. This estimate tells that 51.6% of the horizontal shift of Fig.4 is due to the transverse wakefield. Subtracting these contributions, we obtain the energy shifts caused purely by the longitudinal wakefield, which is shown by the dash curve with circles in Fig.5.

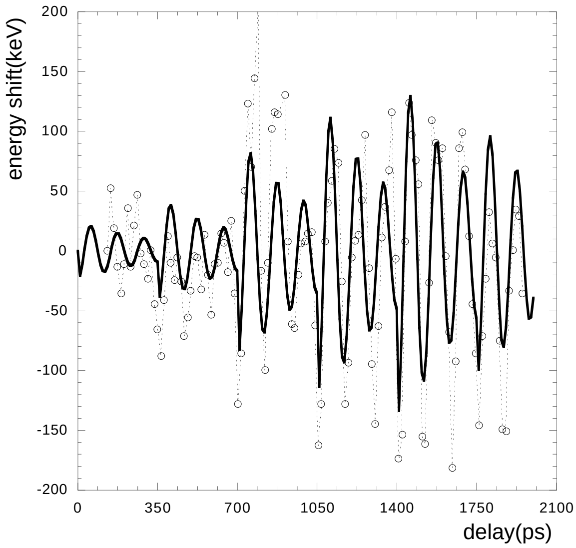

Figure 5: Delay dependence of experimental (circles with the dash lines) and theoretical (the thick solid curve) energy shift.

Time Decay of Wakefield

The wakefield buildup seems far from ideal in the experimental data in Fig.5, in which wakefield makes considerable decay during a bunch interval. The plasma density distribution shown in Fig.2 explains this fact. The plasma density and the resultant plasma frequency at the both ends of the plasma column is lower than those at the plasma center. The phase difference of the oscillation tends to offset the positive and negative effect of the wakefield to decrease its amplitude[6], which becomes more severe as the time delay of the test bunch becomes larger.

The plasma oscillation caused by a drive bunch at position z and time $t+\tau$ is proportional to $\cos[k_p(z)z - \omega_p(z)(t+\tau)] = -\cos[\omega_p(\tau)]$. Energy change of a test bunch at the delay τ then becomes

$$E(\tau) \propto 2\int_0^L n_p(z)\cos[\omega_p(z)\tau]dz, \qquad (1)$$

where k_p is the plasma wave number, and L is the half of the plasma-column length. Let us approximate the density distribution by an exponential function shown in Fig.2. as $n_p(z) \sim \exp(-z/d)$, with d=10.5cm at $n_p = 9.1 \times 10^{11}\mathrm{cm}^{-3}$. According to numerical calculation using the present parameters, we can approximate the delay dependence of the energy shift of a test bunch as

$$W(\tau) \sim 0.55 \times 2LE_0\exp(-c\tau/d)\cos[\omega_{p0}\tau], \qquad (2)$$

where E_0 and ω_{p0} are the wakefield amplitude and the plasma frequency at the plasma center, The delay dependence of the energy gain thus calculated is shown by a solid line in Fig. 3. The same curve is reproduced in Fig.5. The experimental data agree fairly well with this calculation.

Wake Amplitude and Its Density Dependence

The derivation of the amplitude of the longitudinal wakefield used to obtain Fig.3 could make over-estimate. A more exact expression giving the amplitude is[5]

$$|E_z| = -\frac{8r_e mc^2 N}{\sigma_x\sigma_y}\exp[-\frac{k_p^2\sigma_z^2}{2}] [1 - \frac{4}{k_p^2\sigma_x\sigma_y} + 2K_2(k_p\sqrt{\sigma_x\sigma_y})], \qquad (3)$$

on the drive-beam axis. It gives 94.2keV/m at $n_p = 9.1 \times 10^{11}\mathrm{cm}^{-3}$ with the charge of 100pC in a drive beam. The drive-beam charge is accumulated to $\sim$ 100pC at 700ps delay in Fig.5, where the energy gain is $\sim$ 150keV. Equation 2 converts it to the acceleration gradient of 750keV/m. Observed gradient is five times larger than the calculated. This discrepancy is even larger in a less-dense plasma. Figure 4 suggests $E_z \sim$ 200keV/m at $n_p = 1.0 \times 10^{11}\mathrm{cm}^{-3}$ with 100pC, under the assumption that $\sim$ 50% of the horizontal shift is due to the energy change. Equation 3 gives only 17.4keV/m. The ratio then becomes more than 10.

The discrepancy was not large in the previous experiments[6] in a similar plasma-density range. The difference is in that the beam-sizes of drive bunches are larger or the electron densities inside them are smaller in the present experiments. Delay dependence of the vertical positions in Fig.4 suggests that the wakefield is strongly nonlinear, and it is more distinct in a less-dense plasma. This nonlinearity must contribute to the large wakefield amplitude in the present experiments.

Remarks

There still remain some observations which should be referred.

No build-up were observed in Fig.4in the vertical positions and both horizontal and vertical sizes by the multiple drive bunches. This means that growth of the transverse wakefield has already saturated in a small delay range. The diameter of the plasma chamber was only 15cm, so the diameter of the plasma column was not large enough compared with the plasma wavelength, 3.5cm at $n_p = 9.1 \times 10^{11}\mathrm{cm}^{-3}$ and 10.5cm at $1.0 \times 10^{11}\mathrm{cm}^{-3}$. Speculation taking account of the transverse boundary conditions must give an explanation.

Another observation is that the phases of vertical and horizontal sizes in Fig.4 is opposite. This contradicts with the theory that the plasma-lens effect is isotropic.

4 REFERENCES

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