Direct Observation of Plasma Wakefield Caused by a Train of LINAC Bunches

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abstract

Plasma wakefield caused by a train of $14MeV$ linac bunches was detected by a coaxial diode detector. The pulse period was $350psec$ while the duration of the pulse train was $6\mu sec$. The time evolution of the plasma wave was explained by a simple linear model. Damping time of the plasma wave was derived from the experiments.

1. Introduction

A plasma wakefield accelerator(PWFA) is one of the plasma-based-type accelerators that show promise to produce ultra-high accelerating gradients. In the PWFA, a high-intensity relativistic driving bunch excites a large amplitude plasma wave which, in turn, accelerates a low-intensity trailing bunch.[1] The PWFA has to attain a high transformer ratio in order to be a real accelerator, which is the ratio between the energy reached by the trailing bunch and the energy lost from the driving bunch. One method proposed to attain the high ratio is to shape the longitudinal distribution of the particles inside the driving bunch as triangular.[2] Because this idea is technically difficult to realize, an alternative method is proposed, which uses a train of driving pulses with a triangular envelope.[3,4]

This paper reports preparatory experiments for this pulse-train method. A train of identical pulses are introduced into a plasma, and the resultant high-frequency plasma wave was detected by a coaxial diode detector. Time evolution of the plasma wave was compared with the calculation taking account of the damping of the wave.

The next section describes computer simulation based on the linear theory. Experimental setup is then given in section 3. Experimental results are reported in section 4. The last section contains discussion.

2. Calculation

The wakefield E caused by an impulsive bunch with charge σ is expressed by the following equation:

$$\ddot{E} + 2\omega_d \dot{E} + \omega_p^2 = 4\pi\sigma\dot{\delta}. \tag{2.1}$$

Its solution is given by

$$E(t) = 4\pi\sigma \exp(-\omega_d t)[\cos\omega_0 t - (\omega_d/\omega_0)\sin\omega_0 t], \tag{2.2}$$

where $\omega_0 = (\omega_p^2 - \omega_d^2)^{1/2}$. The wakefield caused by a train of identical impulsive bunches is just superposition of $E(t)$;

$$f(t) = E(t) + E(t-\tau) + E(t-2\tau) + ..., \tag{2.3}$$

where $E(t-n\tau) = 0$ if $t < n\tau$, and $\tau = 2\pi/\omega_l$ is the period of the linac bunches.

Fig. 1 shows the calculated time evolution of the plasma wave in the case $\omega_p = \omega_l$, where the resonant condition is satisfied. If $\omega_d = 0$, the wave amplitude grows up to infinity. However, if ω_d has finite value, the wave saturates. As ω_d becomes large, both the saturation level and the time to reach there become small. Fig. 2 shows the calculated evolution of the plasma wave in the case $\omega_p \neq \omega_l$. If $\omega_d = 0$, a steady beat-wave appears. However, if ω_d has finite value, the wave amplitude reaches a certain constant level. The level becomes small as the difference $\omega_p - \omega_l$ becomes large, and also as ω_d becomes large. The beat-wave character appears transiently. The length of the transience is inverse-proportional to ω_d.

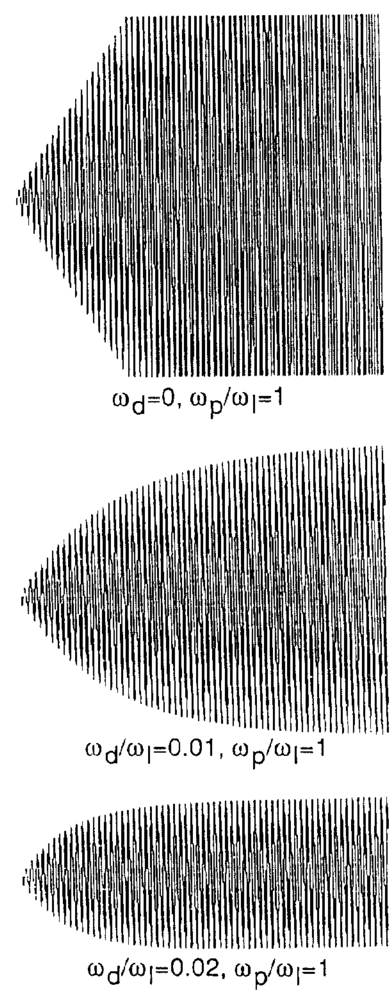

Fig. 1. Evolution of the plasma wave in the case $\omega_p = \omega_l$. Response to first 64 linac pulses is shown.

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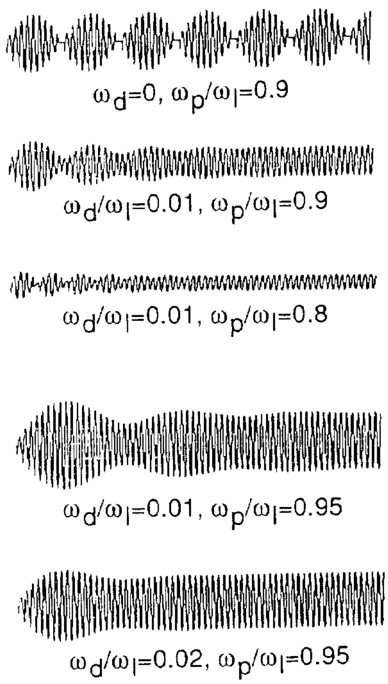

Fig. 2. Evolution of the plasma wave in the case $\omega_p \neq \omega_l$. Response to first 64 linac pulses is shown.

Let us observe these figures microscopically. Fig. 3(a) shows the wakefield caused by the first several linac pulses in the case $\omega_p = \omega_l$ and $\omega_d = 0$. Each linac pulse gives negative jump in the waveform. It means that the energy of the bunch is decelerated to raise the plasma wakefield. The amount of the deceleration grows with time. Using the energy analyzer, we could observe the increasing negative energy shift of the linac bunches. The figure tells that we could accelerate the test bunch, if it were injected in the timing when the amplitude is positive. Fig. 3(b)-(c) show another case, where ω_p does not coincide with ω_l and ω_d has finite value. Fig. 3(b) shows response to the first several pulses and (c) shows the steady state. The beam energy, which is given by the vertical position after each negative jump in the figure, fluctuates at first, and approaches a constant value, half of the wakefield caused by a single bunch.

Aside from this microscopic behavior, the time evolution of the envelope of the plasma wave can be described by the equation where an approximation is applied to regard the pulse train as cosine wave whose frquency is equal to the pulse frequency. We will use this approximation to discuss the time evolution of the envelope.

3. Experimental Setup

The setup of the experiments is similar to the one used for the plasma lens experiments.[5] The experiments were conducted at the Tokyo University $14MeV$ linac.[6] It produces a pulse train each of which has rms length (measured by a streak camera) less than $3mm$. The pulse frequency is $2.85GHz$, or the pulse period is $350psec$, the duration of the pulse train is $6\mu sec$, and the repetition rate of the train is $6.25Hz$. The charge of a pulse in the present experiments was about $50pC$. The averaged electron density inside the bunch was about $1.2 \times 10^9 cm^{-3}$, assuming the bunch radius to be $3mm$. The acceleration gradient caused by wakefield of a single bunch of this linac would be approximately $400eV/m$ according to the one-dimensional linear theory.[1] Without any damping, the pulse train of $6\mu sec$ would result in the gradient of $2.3MeV/m$, as shown in Fig. 3.

We usually separate the plasma chamber from the linac duct using metal foils in order to avoid any vacuum problems. An obstacle in this case is multiple scattering of the beam caused by the foils and gas along the beam transport, which decreases the charge density and the resultant plasma wakefield. Differential pumping solved this problem by enabling separation without having to use any hard boundaries. Four turbomolecular pumps are used, three of which are placed between the linac main duct and the plasma chamber. Ducts with low conductance, $16mm$ in diameter and $1233mm$ in total length, connected the linac and the plasma. An automatic gate valve closes the line whenever the pressure of this section exceeds a prescribed value.

An argon plasma was produced in the chamber, $147mm$ in inner diameter and $360mm$ in length, by a discharge between the LaB_6 cathodes and the plasma chamber in synchronism with the linac pulse. The plasma pulse width was about $2msec$. It was confined by the multidipole field of permanent magnets placed around the chamber periphery. The magnetic field had its maximum value $700G$ at the chamber wall. One of the features of this confinement is that there is no magnetic field along the beam transport. The argon plasma density ranged from $.5 - 15 \times 10^{10} cm^{-3}$ and the temperature from $2.5 - 4eV$, as measured by a Langmuir probe. It shows that the plasma length along the beam transport is about $15cm$ in the case $n_e = 1.3 \times 10^{11} cm^{-3}$, which increases to $20cm$ at $n_e = .75 \times 10^{11} cm^{-3}$. The electron density was controlled either by the discharge current or by the gas flow. The experiments were carried out using a plasma around $n_e = 1.01 \times 10^{11} cm^{-3}$, where the plasma frequency ω_p is equal to the linac pulse frequency ω_l.

The power of the oscillation is measured by a KC-2 coaxial diode detector produced by Nihon Koshuha Co., whose frequency response cuts off sharply at $3GHz$. As shown in Fig. 4(a), the diode is connected at the end of the semi-rigid cable, in the plasma

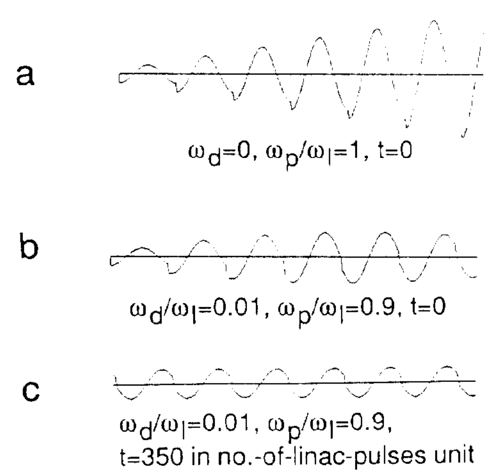

Fig. 3. Evolution of the plasma wave in a magnified time scale.

side. The dc component of the signal is short-circuited to the ground by a BNC-T connector to protect the detector. A $\pi/2$ bending magnet was settled downstream of the plasma as an energy analyser. The half width of the linac beam energy measured by this method was approximately 5% or $700keV$.

4. Experimental Results

Four main results obtained are: 1)The envelope of the plasma oscillation power is rectangular, similar to the linac pulse train envelope. 2)Its amplitude is sensitive to the plasma density around the resonance; $\omega_p = \omega_l$. 3)Its risetime and falltime are, however, independent of the plasma density. 4)No difference is observed between the energy spectra measured with and without the resonant plasma. Fig. 4(b) shows a typical pair of envelope waveforms: those of the beam current and the power of the plasma oscillation. Note that the oscillation power of Fig.4(b) should be compared with the square of the envelope of the oscillations shown in Figs.1-3.

The result 1) shows the existence of the wave damping. The results 2) and 3) are consistent with the previous analysis, which tells us that, once a time structure of the pulse train is given, the risetime and falltime of the plasma oscillation envelope are determined only by the damping frequency ω_d. To the contrary, not only ω_d but also $\omega_p - \omega_l$, the difference between the plasma frequency and the linac pulse frequency, contribute the saturation level. The result 4) is obtained, because the energy change caused by the plasma wakefield is smaller than $100eV$ as is shown in Fig. 3(c), much smaller than the fwhm of the linac beam energy, $350keV$.

Comparing two waveforms in Fig. 4(b), we can derive the damping frequency ω_d. The following equation

$$\ddot{E} + 2\omega_d\dot{E} + \omega_p^2 = 4\pi\sigma\cos\omega_l t[1 - \exp(-\alpha t)], \qquad (4.1)$$

gives the macroscopic response of the wakefield when the linac pulse envelope has finite risetime $2\pi/\alpha$. Similar equation gives the response to finite fall time. From Fig. 4(b), we have $2\pi/\alpha = 260nsec$. Fitting the data to the above equation, we have $2\pi/\omega_d = 600 \pm 150nsec$ for risetime, $2\pi/\omega_d = 375 \pm 25nsec$ for falltime, and $Q = \omega_p/\omega_d = 1071 \sim 1714$. (Remember that the Fig. 4(b) gives amplitude of the square of the oscillation amplitude.)

5. Discussion

We cannot find any mechanism which brings the damping of the plasma wave in the present experiments. Landau damping is negligibly small, because the phase velocity of the plasma wave is equal to the velocity of the linac beams; *i.e.*, the light velocity. To the contrary, certain calculation of the collisional damping[7] gives the very short damping time; less than $100nsec$. Our previous

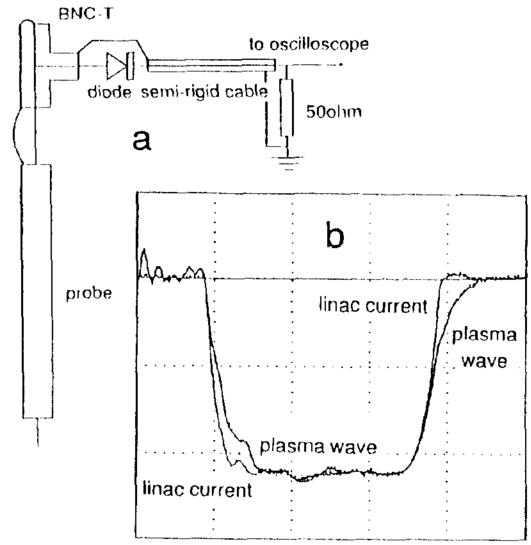

Fig. 4. (a)Setup of the plasma oscillation detection. (b)Envelopes of the linac beam current and the plasma oscillation. Horizontal scale:$2\mu sec/div$. Vertical scale:arbitrary.

experience tells us that the collisional damping should not be serious.[8] We guess that the small chamber, the length of which is less than twice of the plasma wavelength, has caused some boundary effect.

In conclusion, the present experiments show that a Langmuir probe combined to a coaxial diode detector gives qualitative information on the plasma wakefield. They tell us that we have take into account the damping of the plasma wave. Because of this damping, the pulse train with identical amplitude cannot grow the wakefield. It requires the pulse train with increasing amplitude to obtain a high transformer ratio.

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