Plasma Wakefield Acceleration and Plasma Lens Experiments at KEK and NERL Linacs

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Abstract - Two types of accelerator-oriented plasma experiments are reported; plasma wakefield acceleration experiments and plasma experiments. They are conducted at the KEK on a 500MeV linac and at the NERL (Nuclear Engineering Research Laboratory) of the University of Tokyo on a 14MeV linac.

1. Introduction

The application of plasmas to high-energy accelerators has become an exciting new area. Plasmas can support ultrahigh electric fields without breaking down and so offer the potential to accelerator particles in a compact device which is meters rather than kilometers long. Besides providing high-gradient acceleration, another roles of plasmas in accelerators are emerging, that is the use of the ultrahigh strength field available for focusing particle beams. This paper reports basic experiments on both applications of plasmas to accelerators; plasma wakefield acceleration in section 2, and plasma lens in section 3.

2. The PWFA experiments

In the plasma wakefield accelerator (PWFA), a high-intensity relativistic driving bunch excites a large amplitude plasma wave which, in turn, accelerates a low-intensity trailing bunch. One method proposed to attain the high transormer ratio, which is the ratio between the energy reached by the trailing bunch and the energy lost from the driving bunch, is to use a train of driving bunches with a triangular envelope.[1] Preparatory experiments for this bunch train method were conducted at the KEK on a 500MeV linac and at the University of Tokyo on a 14MeV linac. The KEK experiments aimed at attaining high acceleration gradient, while the Tokyo University experiments aims at examining the limit of the length of the bunch train.

<u>the KEK experiments</u> The linac provides us with a sequence of 5-6 electron 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 linac bunch frequency, 2856MHz. 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,[2,3] where an energy shift of 12MeV was caused in a low density plasma of the order of $10^{11}\mathrm{cm}^{-3}$.

The plasma chamber has a diameter of 50mm and a length of 1m with a 0.5-1kG solenoid magnetic field. Ionization is realized by a helicon wave, which is excited by a 5-10MHz and 0.5-1kW rf wave and fed through a helical antenna. The discharge pulse has a duration of 10ms and a rate of .5Hz equal to the linac beam repetition rate. Argon gas is fed through a gas-flow controller to maintain a neutral gas pressure of $4-8\times10^{-4}$torr for a plasma density of $2-8\times10^{12}\mathrm{cm}^{-3}$. Besides a standard Langmuir probe, current to a titanium end plate of the plasma chamber is used to diagnose plasma temperature and density. A PCD array combined with 488nm filter is also used to measure the transverse profile. The plasma temperature ranged 2-5eV, and the rms plasma radius was around 5mm. Combination of a bending magnet and a streak camera enables us to measure the energy spectrum of each bunch.

Fig. 1 shows the wakefields expected at the center of the each bunch, having a transverse parabolic distribution with 1mm rms radius and a longitudinal Gaussian distribution with 3mm rms length. It is assumed that the total charge of 10nC is distributed over six bunches in a Gaussian-like envelope. In resonances, all bunches are decelerated to produce the maximum amplitude of wakefield behind the bunch train.

Barycenter differences between experimental energy spectra with and without the plasma are calculated for all the bunches as a function of the plasma density. To compare the results with the theory, we have to take into account two fact. First, the bunch length is comparable to, or even longer than, the plasma wavelength. As is well known, only half of the plasma wavelength makes an accelerating field, while its neighboring halves make decelerating fields. Particles in our bunch feel both of the fields, which depends longitudinal positions inside the bunch. Second, measurements shows that a bunch has a broad energy distribution : fwhm often amounts to 50MeV even in the absence of a plasma.

The specific data processing was performed as following. In the phasespace of energy and longitudinal position, a bunch was assumed to have an experimentally-obtained energy distribution

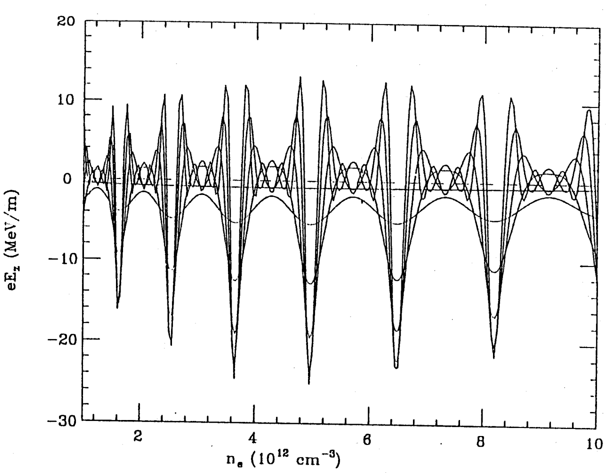

Fig. 1 Wakefields excited at the center of bunches.

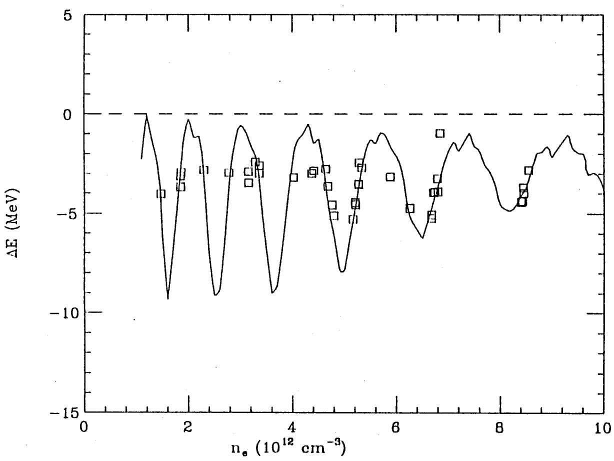

Fig. 2 Experimentally obtained energy shifts of the third bunch. The solid line shows calculated energy shifts.

and the Gaussian longitudinal distribution. We operate a wakefield, which is a function of longituginal position, onto this two-dimensional distribution. We leave the plasma density as the parameter to decide the wakefield at this stage, because our diagnostic cannot give the precise density. This operation gave an energy shift of each bunch. Then the plasma density was finely adjusted to minimize the squared sum of the differences between calculated and experimental energy shifts for six bunches, with weights proportional to the bunch intensities. Figure 2 shows an energy shift of the third bunch as a function of plasma density, together with the theoretical dependence. Comparing Figs. 2 and 1, we find the effect of the finite bunch length. First, it averages the wakefield, making the apparent field in the decelerating direction. Second, the resonance becomes broader as the plasma density becomes higher, because the plasma wavelength becomes shorter. Though the directly-observed energy shift was a few MeV, the good agreement with the experimental points and theoretical curve suggests that the energy shift inside the bunch agrees with the theory given in Fig. 1, 13MeV at the maximum in this case of the third bunch.

the NERL experiments In these experiments, a coaxial diode detector detected the plasma wakefield caused by a train of linac bunches, each of which had an identical amplitude, though the envelope had finite rise and fall times.[4] It was shown that wave amplitude cannot grow infinitely, but reaches saturation, and that the wakefield at the saturation could be 400 times higher than that caused by a single bunch.

The experimental setup was similar to that used for plasma lens experiments.[5] A 14MeV linac at the University of Tokyo can produce a bunch train, each part of which has an rms length (measured by a streak camera) less than 3mm, or 10psec. The bunch frequency is 2856MHz, the duration of the bunch train is 6μsec, and the of a bunch is about 50pC. Differential pumping technique solved the problem of multiple scattering of the beam at the foils to make boundary between the linac and the plasma.

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 chamber in synchronism with the linac bunch. The plasma pulse width was about 2msec. It was confined by using the multidipole field of permanent magnets placed around the chamber periphery. One of the features of this type of confinement is that there is no magnetic field along the beam transport. The experiments were carried out using a plasma of around $n_e = 1.01 \times 10^{11}\mathrm{cm}^{-3}$, where the plasma frequency (ω_p) is equal to the linac bunch frequency (ω_l), and $T_e = 2\mathrm{eV}$. The calculation based on the linear theory tells that the acceleration gradient caused by the wakefield of a single bunch of this linac would be approximately 4.07keV/m with 3mm bunch radius.[2] Without any damping, a bunch train of 6μsec would build up the wakefield, resulting in a gradient of 23MeV/m.

The oscillation power was measured by a KC-2 coaxial diode detector produced by Nihon Koshuha Co., with a frequency response that sharply cuts off at 3GHz. A $\pi/2$ bending magnet was placed 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. Fig. 3 shows a typical pair of envelope waveforms: those of the beam current and the power of the plasma oscillation. Note that the waveform of the plasma wave shown in Fig.3 should be compared with the square of the envelope of the oscillations.

The five main results obtained are: 1)As long as the oscillation amplitude is small, the envelope of the plasma oscillation power is almost rectangular, similar to the linac bunch train envelope (Fig. 3). 2)When the amplitude exceeds 1V, the envelope of the plasma oscillation has an irregular shape, often revealing a low frequency component. 3)The amplitude of the plasma oscillation is sensitive to the plasma density around the resonance ($\omega_p = \omega_l$). 4)The rise and fall times are, however, independent of the plasma density, when the amplitude is less than 1V. 5)No difference was observed between the energy spectra measured with and without the resonant plasma.

Results 1) and 2) show the existence of wave damping. Results 3) and 4) tell us that, once the time structure of the bunch train is given, the rise and fall times of the plasma oscillation envelope are determined only by the damping frequency (β). To the contrary, not only β but also $\Delta\omega = \omega_p - \omega_l$, the difference between the plasma frequency and the linac pulse frequency, contribute to the saturation level. Result 2) must be due to the density fluctuation. The amplitude grows large when $\Delta\omega/\omega_l \ll 1$, and becomes sensitive to $\Delta\omega$, which is, of course, a function of the plasma density. In this situation, a small density fluctuation is magnified and appears as a fluctuation of the envelope.

If the amplitude of a plasma wave envelope on an oscilloscope is less than 1V, we can derive the damping frequency of

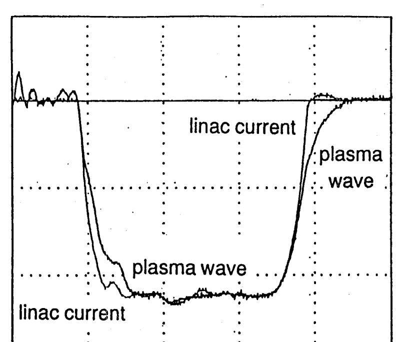

Fig. 3. Envelopes of the linac beam current and the plasma oscillation. The horizontal scale is 2μsec/div., and the vertical scale is arbitrary.

the plasma wave (β) from the fall times of the waveforms. From the curve showing the linac current envelope in Fig. 3, we have $\alpha = 1.10$MHz, where $1/\alpha$ denotes a fall time of the linac bunch envelope. Using a nonlinear least-square fit algorithm, we fit the plasma wave envelopes to curves including two frequencies, α and β, to obtain $\beta = 1.20 \pm .05$MHz. The standard deviations are calculated from 20 data. If we regard this system as a resonator, the quality factor becomes $Q = \omega_p/\beta = 2280 \sim 2484$.

Using this experimental value, we find that the steady state amplitude could amount to $\omega_p/(2\pi\beta) \sim 400$. This is quite a large magnification, which gives a gradient of 1.6MeV/m. The actual energy shift in these experiments with a 20cm long plasma is less than 320keV, which is difficult to detect using an energy analyzer with poor resolution. This is the reason for the result 5) itemized before.

3. Plasma lens experiments

The experiments were conducted in order to verify the previous results,[5] which demonstrated a plasma lens effect based on self-focusing due to shielding of the space charge of a particle beam by a quiescent plasma. The results of the present experiments have shown that (1) the observed plasma lens effect in the vertical direction agrees well with calculation based on the linear theory.[6] (2) The present results seem to reproduce the emittance reduction previously discovered.

The experiments were again conducted at the University of Tokyo on a linac, whose beam energy increases to 18MeV at the single bunch operation. The charge of a bunch was 512pC. The plasma was produced by the same method as the NERL PWFA experiments. The plasma temperature ranged from 2.5 – 4eV, as measured by a Langmuir probe. The plasma length along the beam transport was about 15cm. The transverse beam profiles were observed on three phosphor screens (Desmarquest AF995R) which were located 880mm, 1380mm and 1880mm downstream of the plasma chamber. The intensity distribution on each screen was integrated vertically and horizontally. Horizontal and vertical beam sizes were calculated from the resultant one-dimensional distribution. So-called rms beam sizes were derived from the width of the distribution to give exp(−1/2) of the peak. Fig.4 shows the vertical beam sizes at the three screens. The error bars show the deviation among 8 data.

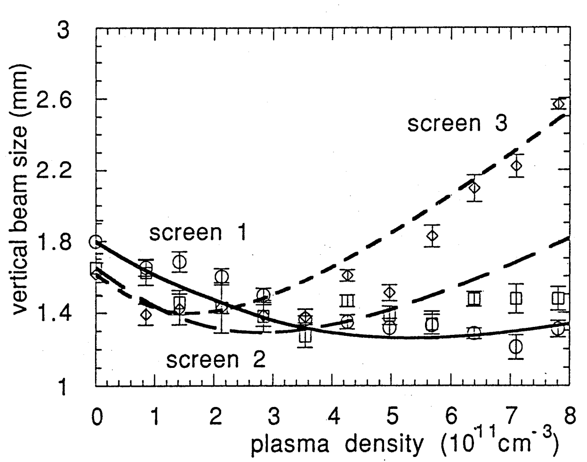

Fig. 4. Experimental and theoretical dependences of vertical beam sizes at the three screens on the plasma density.

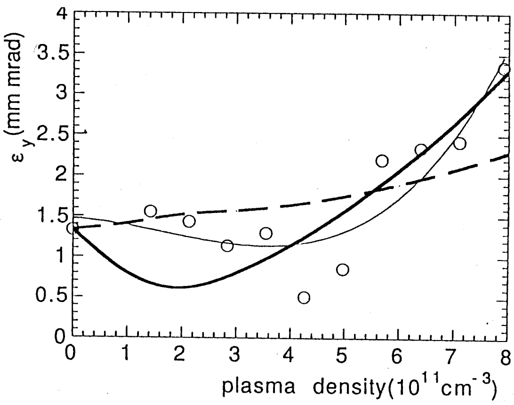

Fig. 5. Dependence of vertical emittance on plasma density. Data points and the thin solid line were calculated directly from the measured beam sizes, while the thick solid lines was calculated from the quadratic approximation of data points of Fig. 4. The dashed line was calculated based on the round-beam model.

Let us try to explain the density dependence theoretically. In the present experiments, Chen's conditions of the round-beam-limit are satisfied[6]. In these conditions, the focusing force is proportional to ζ^3, where ζ denotes longitudinal position of charges inside the bunch. Using the transfer matrix of the lens with the plasma length, and averaging the resultant size over ζ, we have the theoretical beam size at the plasma position. Bold lines in Fig. 4 gives theoretical density dependences of the vertical sizes at three screens, As the figure shows the experimental and theoretical sizes agree fairly well.

The vertical emittance were calculated in two ways from the experimental data. First was to calculate directly from a trio of beam sizes at the three screens. The results are pointed in Fig. 5, whose dependence on the plasma density were approximated by third-order polynominals and shown by thin solid lines. Second was to calculate the density dependence from the quadratic approximation of the dependence of beam sizes on the plasma density. The thick solid lines Fig. 5 show the results. Dashed lines show the theoretical dependence, which is neither constant but increases with the plasma density because of the averaging operation over ζ. The dependences of the experimentally-obtained emittance are different between two ways of data processing, but they both first decrease and then increase. The experimental emittance reduction has overcome the apparent emittance increase in certain density region.

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