PLASMA WAKEFIELD ACCELERATOR EXPERIMENTS IN KEK

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ABSTRACT

A plasma wakefield experiment will start using an existing linac with a relativistic beam, which is separated into several bunches by the rf field. The preceding bunches generate the wakefield in a plasma to accelerate or decelerate the following bunches. The linear theory predicts for this experiment an accelerating gradient of approximately $80 MeV/m$.

1. Introduction

Suppose we have two successive linac bunches with identical energy and current. Is it possible to double the energy of the second bunch sacrificing the energy of the first one? The plasma wakefield accelerator will realize it. It uses the first driving bunch to generate a high velocity electrostatic wave in a plasma. The field of the wave then accelerates the second trailing bunch.[1] The energy increase of the trailing bunch could be more than the energy of the driving bunch under some optimized conditions.

The plasma accelerator experiment has been successfully performed at the ANL using the dedicated test linac.[2] We report here another project which uses an existing linac with a relativistic beam. It is the positron linac, the injector of the Photon Factory (PF) and the TRISTAN Accumulation Ring of the National Laboratory for High Energy Physics (KEK).

The positron linac generates and accelerates electrons up to $200 MeV$. They bombard a target to generate positrons. The positrons are then accelerated to $250 MeV$ in this linac. It is also possible to accelerate pure electrons or electrons mixed with a traceable amount of positrons. It affords a current 2 or 3 order of magnitude larger than the main electron linac of KEK does. The rf field separates the beam into several bunches.

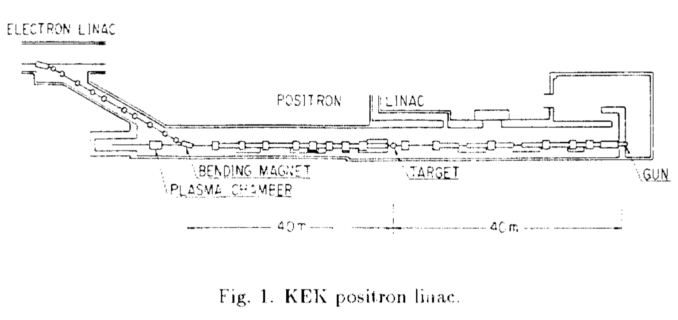

Fig. 1. KEK positron linac.

The experiment has several features. First, both the driving and the trailing bunches are ultrarelativistic. Second, we can observe the multiple effect of several bunches. Third, we can use not only electron bunches but also positron bunches; the condition to accelerate the electrons decelerates the positrons, and *vice versa*. Fourth, the large beam current will cause the nonlinear effect.

The plasma has just been prepared and tested at the laboratory separated from the linac. The acceleration experiment will start from coming May.

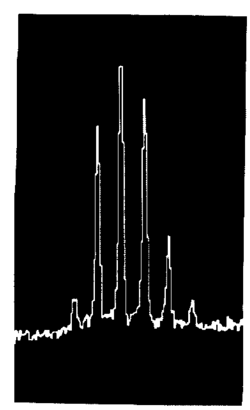

Fig. 2. Bunch current distribution of the positron linac derived from a streak picture.

2. Linac

Fig. 1 shows the PF linac.[3] In usual operations, the $250 MeV$ positrons are bent and injected into the main linac vaccum tube, and finally accelerated up to $2.5 GeV$. In the plasma wakefield experiments, the target will be removed and the bending magnet will be disconnected so that the $450 MeV$ electron beam is introduced into the plasma chamber located at the end of the straight section. In some cases, the $450 MeV$ electron beam containing a traceable amount of $250 MeV$ positrons will also be used.

Usually the beam has 5 to 6 bunches, as shown in the streak picture of Fig. 2. The number of bunches are contrllable between 2 and 15. The separation of the bunches is $350 psec$ or $10.5 cm$, inverse of the rf frequency, $2856 MHz$. The peak current is about $10 A$.

3. Plasma

A simple model says that the half of the wavelength of the longitudinal electric field of the plasma wave contributes to accelerate the trailing bunch, and that the half of the wavelength of the transverse field contributes to focus the trailing bunch, as shown in Fig. 3[1]. These conditions demand the wavelength of the plasma wave, a quarter of which should be longer than the length of the trailing bunch.

The total bunch length of $9mm$ thus specifies the maximum plasma frequency to be $8.3GHz$ ($52.3GHz$ in angular frequency). The maximum electron dendity of the plasma thus becomes $2.58 \times 10^{12} cm^{-3}$. The phase velocity of the plasma wave equals the light velocity c.

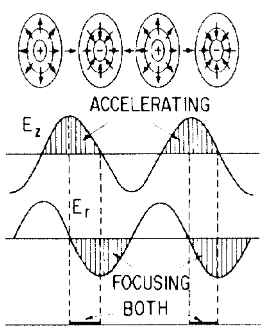

Fig. 3. Electric fields of plasma wave.

It is essential that the plasma wave caused by the driving bunch does not damp but survive till the trailing beam arrives. Because the phase velocitry is c, we can neglect the Landau damping. Let us estimate the collisional damping. The dispersion of the wave along the magnetic field is given by[4].

$$\omega^2 = {\omega_p}^2/\gamma + \beta k^2(\epsilon + 2)/(\gamma\delta),$$

where

$$\gamma = 1 + i\gamma_1 = 1 + i\nu_{ei}/\omega,$$

$$\delta = 1 + i\delta_1 = 1 + i(\nu_{ei} + \nu_{ee})/\omega,$$

$$\epsilon = 1 + i\epsilon_1 = 1 + 5i(\nu_{ei} + \nu_{ee})/(3\omega),$$

β is the square of the themal velocity, and γ_1, δ_1 and ϵ_1 are much smaller than unity. Rewriting k, we have

$$k = k_0(1 + ik_1) = k_0 + ik_i,$$

where k_i gives the the damped wave number. Its substitution into the original dispersion relation yields

$$\omega^2 = \omega_p^2 + 3\beta k_0^2, (\gamma_1 + \delta_1)\omega^2 = \delta_1\omega_p^2 + \beta k_0^2(\epsilon_1 + 6k_1),$$

or

$$k_i = \nu_{ei}\omega_p/(6\beta k_0).$$

After a bit of modifications, we have the practical relation

$$k_i = 2.15 \times 10^{-11} n_e/T_e^{5/2},$$

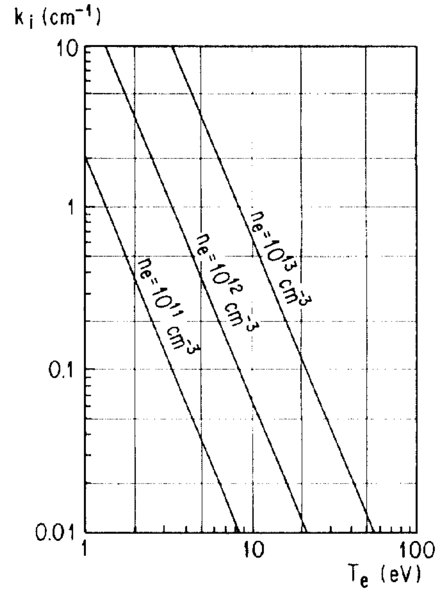

Fig. 4. Dependence of k_i on density and temperature.

where we have approximated $\ln \Lambda = 10$. Fig. 4 gives the dependence of k_i on the density and temperature. Because the bunch separation is $10.5cm$, k_i should be smaller than $0.1cm^{-1}$.

We thus require a plasma with the electron density $10^{11} - 10^{13} cm^{-3}$ and the electron temperature $2 - 20eV$. The plasma presently tested is contained in a chamber of Fig. 5, $300mm$ in diameter and $1000mm$ in length. It is similar to the one used in the crossfield accelerator experiments.[5] An argon plasma is produced by pulse discharges between multifilaments and the chamber. The pulse has a duration of $5msec$ and maximum rate of $25Hz$, which equals the beam rate of the linac, with discharge voltages $100-130V$ and currents $20-30A$. The multidipole field of permanent magnets (Tokin Ferrinet cores), $1kG$ at the inner surface of the chamber, confines the plasma. The chamber is water-cooled. The vacuum system is independent of the linac, using $0.1mm$ thick aluminum foils at the inlet and outlet of the beam.

The electron density is controlled both by the gas pressure and by the discharge current. Typical plasma parameters are a maximum electron density $1 \times 10^{12} cm^{-3}$, an electron temperature $3eV$, and a neutral gas pressure of $1 \times 10^{-4} torr$ under a base pressure of $1 \times 10^{-7} torr$. The consideration on the collisional damping suggests the necessity of heating. The electron cyclotron resonance heating will be tried using a microwave oven. A Langmuir probe measures the density and the temperature.

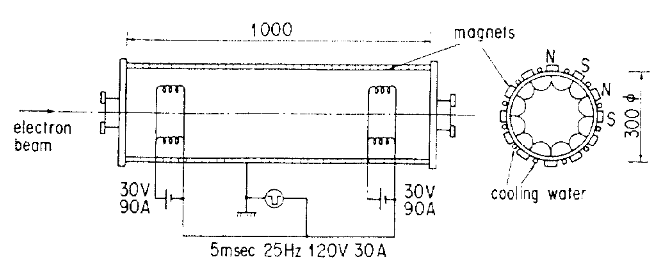

Fig. 5. Plasma chamber.

4. Energy Measurement

Combination of an energy analyzer and a streak camera enables the bunch energy measurement, as shown in Fig. 6. The bunches fly in the air for about $300mm$ behind the energy analyzer to produce Cerenkov radiation. Only the rdiation is reflected by mirrors and introduced into the streak camera. The streak picture is two dimensional; one dimension for horizontal bunch positions which are in proportion to the bunch energy, the other dimension for time to identify the bunches. The picture intensity gives the bunch current.

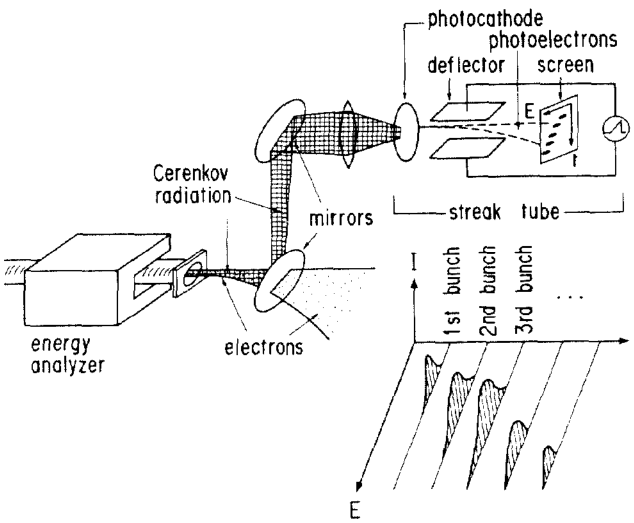

Fig. 6. Measurement of bunch energies using a streak camera.

5. Accelerating Gradient

Accelerating gradient is estimated based on the linear two-dimensional model.[6] Fig. 7 gives a result. Each bunch is assumed to have parabolic distribution in both directions, with sizes $8.5mm$ longitudinally and $1.4mm$ transversely. Another assumption is that the total charge of $25nC$ is Gaussian-distributed in five bunches. The positive sign in the figure shows deceleration.

The resonance occurs when the relation $kf = \nu$ is satisfied, where f is the rf frequency, ν is the plasma frequency and k is an integer, which corresponds to the electron density $n_e = 10^{11}k^2$ in the parameters of our experiment. In a resonance, all bunches are decelerated. The maximum field, $85MV/m$, is felt by the last bunch when the density is $8\times10^{12}cm^{-3}$. Among resonances, there exist density regions where some bunches are accelerated and some are decelerated. It is fatally impossible to accelerate all bunches, because the driving bunches have to be decelerated to accelerate the trailing bunches.

However, we can attain the acceleration using positrons. It is possible in our linac to mix a small amount of positrons in electron bunches. The positrons are accelerated under the condition where electrons are decelerated.

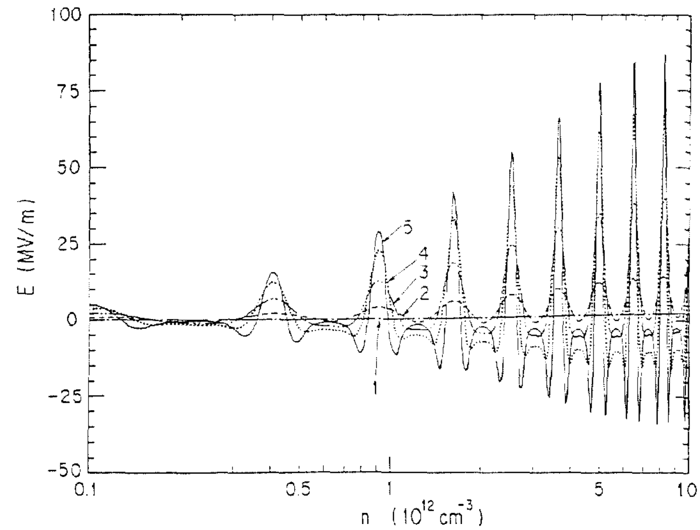

Fig. 7. Accelerating gradients received by bunches as a function of the electron density. The numerals denote the order of bunches.

6. Wakefield Caused by the Structure

The linac accelerating tube is $80m$ long in this experiment; $40m$ from the electron source to the electron- positron converter, and further $40m$ from the converter to the plasma chamber. The bunches generate the wakefield in the vacuum duct structure even in the absence of a plasma. Its density is much smaller than the plasma's, but the 80m travelling distance is so long that the wakefield unnegligibly modifies the energy of the following bunches.

The natural energy spectra of the linac bunches are precisely measured. In this preliminary experiment, the bunches are accelerated only in the section before the converter, up to $200MeV$. They travel another $40m$ without acceleration. Their energy spectra are analyzed at the end of the straight section. It is found that the vacuum duct structure gives 13.5% dispersion on the final energy, corresponding to the gradient of $325keV/m$. The accelerating gradient of the plasma must be 80 times larger than this value if we want a distinct result.

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