OPTICAL BUNCHING OF RELATIVISTIC ELECTRONS FOR INJECTION INTO A GeV PLASMA BEATWAVE ACCELERATOR

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Abstract

A proposed GeV plasma beatwave accelerator (PBWA) requires a high power 1 μm laser running on two frequencies. The vacuum interaction between such a laser and a relativistic electron beam is one mechanism whereby the electrons can be bunched such that when injected into the PBWA they occupy only small regions of phase situated at the peaks of the accelerating field. This is exactly what is required to obtain a high quality beam from the accelerator. We outline the details of this scheme.

1 INTRODUCTION

In another publication [1], we describe a mechanism whereby a two-frequency laser beam modulates the axial momentum of a copropagating relativistic electron beam via the vacuum interaction between the two. The momentum modulated electrons can subsequently be bunched by a drift space or a magnetic compression device. The resulting beam is ideally suited for injection into a plasma beatwave accelerator (PBWA) [2] where the plasma wave is driven by the same two-frequency laser that was used to bunch the injected particles. Because the bunching is driven by the same pump that drives the plasma wave, the periodicity of the plasma wave and the injected electron bunches would be identical. Hence, the injected electrons would occupy small regions of phase situated at the peaks of the accelerating field, and a nearly monoenergetic beam would emerge from the plasma.

In Ref. [1], we presented an example of the above process wherein a 2.5 TW CO_2 laser modulates the momentum of a 16 MeV electron beam. A chicane compressor was proposed as the bunching element since a drift space would have been too long in light of space charge effects. However, this example was chosen only because it reflects the realities of the PBWA experiments that are likely to be carried out in the next few years. In fact, the technique of optical bunching described in Ref. [1] would lend itself better to the proposed GeV PBWA [3] which employs a 14 TW 1 μm laser. In this case, the perturbation to the axial momentum of the electrons is sufficiently large so that a short drift space suffices to compress the electrons. This simplifies experimental realization of the scheme.

2 OPTICAL BUNCHING

The mechanism of optical bunching described in Ref. [1] works as follows.

Any real laser beam contains an axial electric field. This field becomes smaller as the Rayleigh length becomes larger. This relationship is exactly balanced in the sense that the work done on a particle by the axial field does not change when the Rayleigh length is changed. In other words, the instantaneous force can only be increased by losing interaction length, and can only be decreased by gaining interaction length. If the interaction between the laser and the particle takes place over many Rayleigh lengths, it follows that the axial fields can never be dismissed simply by focusing the laser more gradually.

The effect of the laser's axial electric field on a copropagating electron beam is profound. Without this field, all the forces on the electrons would vary rapidly at the optical frequency and would average to zero when integrated over all time. With the axial field, however, a slowly varying force arises which allows for the possibility of making a net change to the momentum of the electron even after an infinite interaction time. The slowly varying force arises because of the phasing between the transverse and axial electric fields. These two conspire such that an electron is always pushed slowly away from best focus. In the case of a single frequency laser, this repulsion would integrate to zero since it would be the same on either side of the optical waist. In the case of a dual frequency laser, however, a slowly varying interference pattern is introduced which causes the impulse delivered on either side of the waist to be different. A net energy change can then occur.

In order for the above mechanism to work, a number of requirements must be met. Let the Lorentz factor of the electons be γ. The average wavenumber of the two laser lines is k, and the wavenumber difference is Δk. The radius of the laser waist is w_0, while the Rayleigh length is z_0. The peak normalized vector potential of the laser is a_0.

It is required, first of all, that the electron be highly relativistic ($\gamma >> 1$). This assures that the velocity, and hence the rate of slippage through the optical cycles, remains approximately constant. In order that forces varying at the optical frequency be dismissed from consideration, it is required that the electron slip through many optical cycles for each cycle of the beat envelope. That is,

$$\Delta k / k << 1 \quad (1)$$

Similarly, the electron must slip through many optical cycles while passing through the focal region. The exact expression of this requirement turns out to be subtle, depending on the geometric mean of k and Δk:

$$\gamma^2 << z_0 \sqrt{k \Delta k} / 2 \quad (2)$$

At the same time, the electrons must slip through only a small fraction of the beat envelope while passing through the focal region. That is,

$$\gamma^2 >> z_0 \Delta k / 8\pi \quad (3)$$

Finally, the intensity of the laser must not be too high. This prevents electrons from being lost radially during their transverse quiver motion. We have,

$$a_0 << k w_0 / \gamma \quad (4)$$

If all these requirements are met, it is shown in Ref. [1] that the energy of a constant stream of electrons is sinusoidally modulated by the laser. In mks units, the normalized energy perturbation is expressed as

$$\delta\gamma = -\frac{1}{8\gamma}\left(\frac{e}{mc^2}\right)^2 \eta P \frac{\Delta k}{k} \sin(\Delta k z) \quad (5)$$

where η = 377 Ω is the impedance of free space and P is the average power in the beat pattern. The modulated beam will reach a longitudinal waist after propagating a distance given by

$$L = \frac{4\pi}{\eta P}\left(\frac{mc^2}{e}\right)^2 \gamma^4 \frac{k}{\Delta k^2} \quad (6)$$

provided space charge forces are negligible.

3 APPLICATION TO THE GEV PBWA

The design of the GeV PBWA proposed in Ref. [3] is summarized as follows. A large amplitdue plasma wave is driven by a Nd:glass laser running on the 1.05 μm and 1.06 μm lines. The laser achieves 14 TW in 4 ps via chirped pulse amplification, and is focused into a gas jet to a 100 μm radius spot where a plasma is formed via multiphoton ionization. A photoinjector driven RF linac generates a beam of 10 MeV electrons which are injected into the plasma wave and accelerated. The emittance of the 10 MeV electron beam is given as 0.5π mm-mrad, but this is a conservative estimate. We assume here that the intrinsic uncorrelated energy spread on the electron beam is much less than 1%. This is not unusual for a photoinjector driven RF linac.

For these parameters, $\Delta k/k$ is about 0.01, so the condition (1) is easily met. The remaining conditions depend on the f-number of the laser beam which has yet to be specified for the vacuum interaction. Suppose w_0 = 50 μm (z_0 = 8 mm). Then the conditions (2) and (3) become

$$z_0 \Delta k / 8\pi << \gamma^2 << z_0 \sqrt{k \Delta k} / 2 \quad \Leftrightarrow \quad 18 << 441 << 2325$$

which is acceptable. In fact, in Ref. [1] it was found numerically that the upper bound on γ^2 is really higher than equation (2) suggests. Condition (4) requires that a_0<<15. For the spot size being considered, a_0=0.4 so this requirement is easily met.

Assuming all the available laser power is used for the vacuum interaction, equation (5) gives the depth of modulation of the electron energy ($\delta\gamma/\gamma$) as 5.4%. This is well beyond the intrinsic energy spread on the beam. According to equation (6), a beam thus modulated will reach a longitudinal waist after propagating a distance L = 22 cm. Assuming no space charge, the maximum compression ratio should approach the limit for a beam with a sinusoidally correlated velocity disribution. This limit is approximately seven [4].

Once a compressing electron bunch is generated, it must be properly injected into the plasma wave. Both the laser and the electrons must be refocused a distance L from the vacuum interaction. Given the size of typical electron lenses, it might be desirable to increase L either by using a stiffer electron beam or less laser power for the vacuum interaction. This might also be desirable from the standpoint that a small L corresponds to a large energy spread which will lead to chromatic aberration in the final electron lens.

One possible injection scheme is shown in Fig. 1. Here, a single laser beam is split into two parts. The first part is focused by an off-axis parabola (OAP) through a small hole in a second OAP. The second OAP focuses the second part of the laser beam into the plasma. Not shown are two quadropole triplets. The first, located between the two OAP's, focuses the electrons into the hole of the second OAP where the vacuum interaction with the laser modulates the electron momentum. The second is beyond the second OAP and focuses the electron beam into the plasma where the acceleration process occurs.

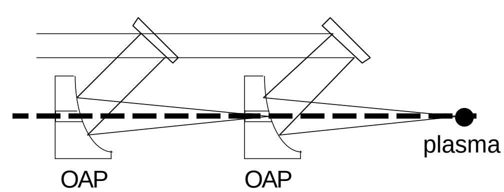

Figure 1: Schematic of the GeV Experiment. The dotted line represents the electron beam while the solid lines represent the laser.

We note here that an aperture placed some distance from the vacuum interaction will eliminate the noncompressing ("negatively chirped") portions of the modulated electron beam [1].

The laser power required for the vacuum interaction is determined from the distance between the second OAP and the plasma. That is, the power is selected to bring the electrons to a longitudinal waist after propagating that distance. This distance must be rather long since Ref. [3] calls for a very gradual focus of the laser into the plasma. In particular, a distance of at least one meter would be needed in order to make the laser reasonably large on the second OAP. A distance of one meter corresponds to 3 TW of laser power on the first OAP, which would perturb the energy of the electrons by 1%.

The only remaining questions are how much charge can the electron bunches carry, and is a 1% energy spread sufficiently small so that the electrons can be tightly focused into the plasma. These questions are addressed via numerical calculation.

4 NUMERICAL CALCULATIONS

The effects of space charge and chromatic aberration are examined using the computer code TRACE3D. The model commences at the first OAP where it is assumed the electrons have already been perturbed by the laser. The electrons are initialized at a 50 μm waist with an emittance of 0.5π mm-mrad. The longitudinal phase space is approximated by a line segment drawn from (90°,9.875 MeV) to (-90°,10.125 MeV), where 360 degrees of phase corresponds to 111 μm. These electrons are propagated through a 50 cm long drift space, followed by a quadropole triplet, followed by a 47 cm long drift space. The effective length of each quadropole in the triplet is 3 cm, and each pair is separated by 2 cm. The field gradient in the outer quadropoles is 0.927 kG/cm, while the gradient in the inner quadropole is 1.700 kG/cm.

When the beam current is zero, the electrons will of course compress to zero pulse length. When the initial current is 10 A, the longitudinal waist is about 20° wide and occurs at the end of the second drift space, where we assume the plasma is located. The energy spread there is reduced to about 30 keV. Transversely, chromatic aberration in the triplet increases the horizontal emittance to 1.09π mm-mrad, while the vertical emittance increases to 0.65π mm-mrad. Because of this, the beam size at the plasma is about 100 μm x 200 μm, somewhat larger than desired (the electrons should stay inside the laser). However, as mentioned above, the initial emittance of the beam might actually be much better than the 0.5π mm-mrad assumed in this calculation, in which case the final spot size could be made smaller. In addition, the longitudinal bunching guarantees not only that electrons will see the peak accelerating field, but also that they will see the focusing fields of the plasma wave. Chromatic aberration, then, does not appear to be a major problem.

5 CONCLUSIONS

We have presented a practical scheme whereby electrons can be injected into a GeV plasma beatwave accelerator such that they are confined to within 20° of phase from the peak accelerating field of the plasma wave. The average current of the injected beam is 10 A, while the peak current after bunching is 90 A. These numbers might be improved by considering more sophisticated electron optics. If an achromatic focusing system is devised, a larger energy perturbation could be applied to the electrons in which case they would more readily overcome space charge repulsion as they compress. Considering a lower emittance electron beam might also be helpful.

6 ACKNOWLEDGEMENTS

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[4] T. Katsouleas, private communication. Actually, it was found numerically in Ref. [1] that a compression ratio of 10 is attainable, suggesting that the velocity perturbation contains harmonics favorable to compression.