Plasmon Linac

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Abstract

This paper proposes a new accelerator using plasmons. Size of the accelerator structure is reduced to the order of the laser wavelength. The structure is made from material whose plasma frequency is around the laser frequency. A laser pulse excites plasmons on the surface of the accelerator tube, and the electric field of the plasmon accelerates charged particle beams. This acceleration scheme is classified into a wakefield acceleration, in which the electric field of the plasmon can survive after the laser pulse passes through the structure. It does not, however, require a high power laser as other laser-plasma accelerations, because this acceleration is based not on the ponderomotive force but on a lower-order force.

1 INTRODUCTIOIN

This paper proposes a new linac using the plasmons, which can accelerate charged particles with the speed of light. It has been reported that the laser wakefield acceleration using electric field of an ionized gas successfully accelerated electron beams[1]. This technique, however, requires a special laser with energy above 1TW and pulse which nearly equal to the plasma wavelength.

In this proposal, structure of the accelerator has periodicity similar to that of the RF linac. Material with a solid-plasma frequency around the laser frequency is used in the structure. The laser propagates through the structure as TM waves to excite plasmons on the wall surface. We can regard the electric field of the plasmon as a wakefield, and the technique of the proposal as a kind of wakefield acceleration. This acceleration is, however, based not on the ponderomotive force as the laser wakefield acceleration, but on a lower-order force. Consequently, it does not require a high power laser as other laser-plasma acceleration methods.

Three dispersion relations, that of the TM mode of the laser, that of the plasmon and that of the test particles, must satisfy certain relation to realize the acceleration successfully. Section 2 discusses this problem. Section 3 calculates the acceleration gradient of this linac. Section 4 discusses this linac from practical viewpoints.

2 DISPERSION RELATIONS OF TM WAVES AND PLASMON

In order that the plasmons can accelerate particles with the speed of light c, dispersion curve of the plasmon must

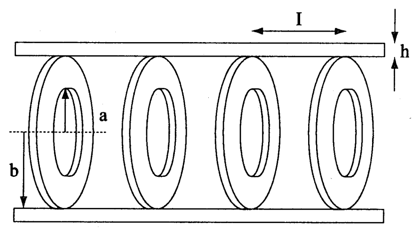

Figure 1: Disk-loaded structure.

have the point where the phase velocity equals c. Let this point be $A(\omega_1, k_1)$. The laser then must have a TM mode, whose dispersion curve has the point A on it. The disk-loaded structure shown in Fig.1 can support the TM modes, whose dispersion curves cross with that of the light, $\omega = ck$. Fig.2 shows it, which has bandgaps between TM_{00} and TM_{01} mode, etc..

The TM modes invokes charges at the intersection of the accelerator wall and the line of electric force, that are plasmons. Oscillation of the plasmons accelerate particles, if the dispersion curve of the plasmon shares the point A with the curve of speed of light and with the curve of the TM mode. It is certainly necessary to derive the dispersion of the plasmon in the disk-loaded structure. In this paper, however, we do not dare to carry out the numerical calculations. Instead, we deduce the characteristics of the dispersion curve of the periodic structure from the curve of the plasmon in a inner wall of a straight cylindrical hole dug in the homogeneous solid.

The dispersion curve of the plasmon excited on the inner surface of such a hole is found in [2]. Using Bessel functions $I_m(x), K_m(x)$, with $m = \pm1, \pm2, \pm3, ...$, we can write this dispersion function as follows:

$$\epsilon(\omega) = \frac{I'_m(kb)K_m(kb)}{I_m(kb)K'_m(kb)}, \qquad (1)$$

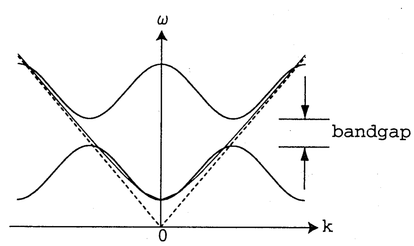

Figure 2: Dispersion curves of TM modes in the disk-loaded structure.

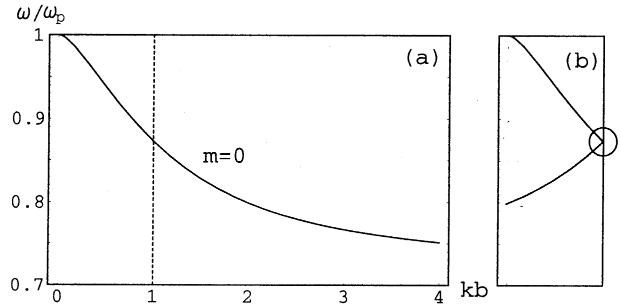

Figure 3: The dispersion curve of the plasmon.

where b is the hole radius and

$$I'_m(x) = dI_m(x)/dx, K'_m(x) = dK_m(x)/dx.$$

We approximate the dielectric function around the plasma frequency by $\epsilon(\omega) = 1 - \omega_p^2/\omega(\omega + i\gamma) \sim 1 - \omega_p^2/\omega^2$. We then have

$$\omega_m^2 = \omega_p^2 kbI_m(kb) \mid K'_m(kb) \mid . \qquad (2)$$

Eq. (2) is depicted in Fig. 3(a) for the case $m = 0$.

In general, we can obtain a dispersion curve of the periodic structure by folding the dispersion curve of the homogeneous structure at the Brillouin boundary. Let Fig. 3(a) be the dispersion of the homogeneous structure in the present case. If the hole has period $2\pi b$ in the axial direction, its dispersion curve has the Brillouin boundary at $kb = 1$. Folding the dispersion curve of the straight hole at this boundary, we can conceptually obtain the dispersion curve of the plasmon in a periodic hole, which is shown by the solid line in Fig.3(b). The original and folded lines repel each other to generate band gaps near the Brillouin boundary (in the region encircled in Fig. 3(b)). In following calculations, however, we neglect the existence of the bandgaps.

Now we are going to find the frequency ω_x at which three dispersion curves intersects. In the following, we consider only the lowest mode of the plasmons; i.e., m=0. We fix the axial period l as $b/2$. To find the ω_x, we have made the following iterations. 1) We first assume the hole radius b. 2) We then draw the dispersion line of $\omega = ck$ and find the intersection A of the dispersion curves of the plasmon and the straight line. 3) We draw the dispersion curve of the electromagnetic wave, and, if the dispersion curve of the electromagnetic wave fails to pass the intersection A, we change the value of b.

The result is shown in Fig. 4. If we inject a laser with the frequency ω_x, it transmits the tube in the TM_{01} mode and excites the plasmons. Because the phase velocity of the plasmons is c, they can accelerate the charged particles with the speed of light.

In the calculation of the dispersion relation of the laser, we used the approximate equations of the TM_{01} mode dispersions of the disk-loaded structure[3]:

$$\omega = \omega_c\sqrt{1 + \kappa\{1 - \cos\psi \exp(-\alpha h)\}}, \qquad (3)$$

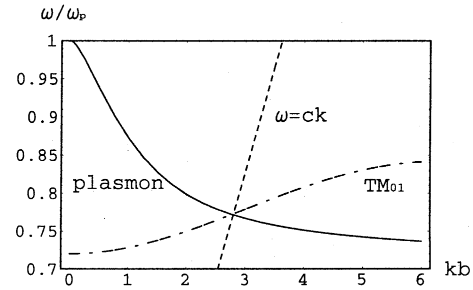

Figure 4: Three dispersion curves.

$$\alpha = \frac{2.405}{a}, \qquad (4)$$

$$\kappa = \frac{4a^3}{3\pi J_1^2(2.405)b^2 l}, \qquad (5)$$

where we put $a = l = b/2, h = b/8$ as the structure constants.

In the iteration, we started from the b value which gives $\omega_c = \omega_p/\sqrt{2}$, where $\omega_c = 2.405c/b$ is the cutoff frequency of the TM_{01} mode in a straight hole and $\omega_p/\sqrt{2}$ is the the surface-plasmon frequency. After a few trials, we have succeeded in depicting Fig. 4. For $l = b/2$, the Brillouin boundary lies at $kb = 2\pi$. Though we have neglected the effect of a bandgap on the plasmon dispersion, it must not be serious, because the intersection A exists far from the boundary.

Silver has the smallest plasma frequency in metals [4]; $\omega_p = 13.2 \times 10^{15}$ s^{-1} , while $\gamma = 68.9 \times 10^{12}$ s^{-1} [5]. The frequency at the intersection in Fig. 4 then becomes 9.96×10^{15} s^{-1}, that is the required laser frequency. The corresponding wavelength is 189 nm, which is in the ultraviolet region.

If we give the first priority to the laser wavelength in the design and set it 1 μm ($\omega = 1.88 \times 10^{15}$ s^{-1}) as an example, the required plasma frequency of the material becomes 2.49×10^{15} s^{-1}; in other words, the plasma density becomes 1.91×10^{21} cm^{-3}. No natural material has a plasma frequency in this range[4], but it is possible to attain this frequency by artificially doping impurities into the wide-gap semiconductors.

At the intersection point of the dispersion curves, the phase velocities certainly coincide, but group velocities are different. In Fig. 4, group velocities v_g of the electromagnetic wave and plasmon are $\sim$ 0.0095c and $\sim -0.0085c$, respectively. If the cavity length is L, the laser pulse length has to exceed $L/|v_g|$. Assuming $L = 1$ mm, for example, and choosing a smaller value of the two group velocities, we have the minimum pulse length as $\sim$390 ps.

3 THE ACCELERATION GRADIENT

Without plasmons, the acceleration electric field vanishes as soon as the laser pulse vanishes. Under the existence of plasmons, we can express the electric field by the equation of the forced oscillation:

$$\frac{d^2E}{dt^2} + 2\gamma\frac{dE}{dt} + \omega_p^2 E = \omega_p^2 E_0 \cos\omega_p t. \qquad (6)$$

The right-hand side expresses the laser excitation of plasmons and γ is the relaxation time.

To estimate the acceleration field of the laser in the right-hand side of Eq. (6) in the disk-loaded structure, we consider a pill-box cavity with radius b and length l. The fields of this pill-box the cavity are

$$E_z = E_0 J_0 \frac{2.405r}{b}, \quad H_\theta = \frac{E_0 J_0 2.405r}{b\zeta_0}, \qquad (7)$$

where $\zeta_0 = 376\ \Omega$ is the impedance of vacuum.

Following the standard procedure of linac design, we first derive the cavity loss using the electrical conductivity of the cavity material. In the following calculations, we assume the laser wavelength to be 1 μm ($\omega_L = 1.88 \times 10^{15}$ s^{-1}). We then have $b = 2l = 432$ nm.

The energy loss in the cavity becomes

$$P_{wall} = \frac{\zeta_m}{2}\int_s |H|^2 dS, \qquad (8)$$

where

$$\zeta_m = \sqrt{\omega\mu_0/2\sigma},$$

is the surface-resistance. If we adopt silver as the cavity material, $\zeta_m = 4.16\ \Omega$ at $\omega = 1.88 \times 10^{15}$ s^{-1}. The skin-depth

$$\delta = \sqrt{2/\omega\mu_0\sigma}, \qquad (9)$$

then becomes 3.52 nm. Modification of the right-hand side of Eq. (8) yields

$$\int_s |H_\theta|^2 dS = E_0^2\{2\int_0^b J_1^2(\frac{2.405r}{b}2\pi r dr) + 2\pi b l J_1^2(2.405)\}. \qquad (10)$$

The present parameters give $P_{wall}[\mathrm{W}] = 989 \times 10^{-15} E_0[\mathrm{V/m}]^2$. The Q value of this cavity

$$Q = \frac{l}{\delta}\frac{b}{b+l}, \qquad (11)$$

becomes 40.8. The Q value of standard RF linacs lies between 10^4 and 10^5 at ω=100 - 1000 MHz. The above Q value of our pillbox cavity is consistent with the scaling $Q \propto \omega^{\frac{1}{2}}$.

We can calculate the accumulated energy

$$W_s = \frac{\mu}{2}\int_v |H|^2 dV = \frac{\epsilon}{2}\int_V |E|^2 dV, \qquad (12)$$

using the relation

$$\int_V |H_\theta|^2 dV = \int_0^b J_1^2(\frac{2.405r}{b})2\pi r dr. \qquad (13)$$

The result is $W_s[J] = 21.3 \times 10^{-27} E_0[\mathrm{V/m}]^2$, which meets with the relation $W_s = QP_{wall}/\omega$. The necessary electric power $P = QP_{wall}$ then becomes

$$P[W] = 40.3 \times 10^{-12} E_0[\mathrm{V/m}]^2.$$

This equation tells us that the laser power of 40 MW (4 GW) is necessary to obtain the acceleration gradient with GeV/m (10 GeV/m). There is no established theory which gives the maximum-tolerable acceleration gradient in the metal cavity, though some say it is around 100 GeV/m [6].

Inserting the field of the electromagnetic wave, we have the electric field of the plasmon as the solution of Eq. (6). If the right-hand side is transient, the electric field attenuates with the time constant $1/\gamma$. If the right-hand side is stationary, the amplitude of the electric field is $\omega_p E_0/2\gamma$ times larger than the case where only the electromagnetic wave exists.

The small Q means that efficiency of this accelerator is quite poor. This must be one of the reasons why the linac whose rf is replaced by the laser has never been realized, in spite of the development of the nano-meter technique to produce fine structure. In our plasmon linac, the laser energy is used not only for generating the electromagnetic field but also for the plasmon excitation. It is necessary to reconsider the efficiency problem from this point of view.

4 DISCUSSION

Is it possible to machine this linac. If we use silver, the radius of the accelerator tube b becomes 81 nm, while if we use some other material which meets the laser wavelength 1 μm, it is 432 nm. Such sizes can be dealt with the present lithographic techniques. It is, however, impossible for it to dig holes deeper than $\sim$ 1 μm. One solution to form a longer tube is to put two surfaces together each has a gutter on it.

In summary, we have given conception of a new linac in which plasmons excited by a laser accelerate charged particles with the light velocity. There remain of course many works to be done in order to verify the feasibility of this concept, we believe that it is a promising solution to construct a miniature high-energy accelerator.

5 REFERENCES

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