PLASMON LINAC

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Abstract

A linac is proposed in which a laser first excites plasmons along the inner surface of a metallic acceleration tube. Potential of the plasmon oscillation then accelerates electron beams. It features beam size in nm range and good conversion efficiency from laser intensity to acceleration gradient; a MW laser will attain a gradient exceeding GeV/m, though the current is very small.

1 INTRODUCTION

Although acceleration based on lasers and plasmas has been successful in laboratories to attain an acceleration gradient over GeV/m[1], it has not yet been applied to design and constriction of real accelerators. This is partly because of difficulties to handle gaseous plasmas. This paper proposes use of solid-state plasmas in place of gaseous plasmas. A plasmon linac is a miniature linac which uses a hole in a metal with radius around the laser wavelength as an acceleration tube. A laser pulse excites plasmons along the inner wall of the hole. Test beams are then accelerated by the potential of the plasmons, as Fig.1 shows.

The plasmons are the energy quanta of the volume oscillations of solid-state plasmas, or collective excitation of the electron gases. Such electron gases are realized by the valence electrons of a metal, whose density exceeds \(10^{22}\) cm\(^{-3}\). Such high electron density is able to hold ultrahigh acceleration gradient. Another feature of the solid-state plasmas is that they are almost always near thermodynamic equilibrium, contrasting with gaseous plasmas which are easily driven out of equilibrium and reveal instabilities[2].

One can regard this method as a laser wakefield acceleration in a hollow channel[3], using an overdense metal plasma instead of an underdense plasma. The structure resembles that of a dielectric linac[4], which has once been studied as a rival of a linac with periodic structure. The size of this linac is much smaller than the existing ones, smaller than that of the gaseous-plasma accelerators, but larger than those of the crystal accelerators[5], and in the same order with those of photonic crystal accelerators[6].

It features beam size in nanometer range and good conversion efficiency from laser power to acceleration gradient; it attains a gradient exceeding GeV/m by a MW laser instead of a TW one, though the current is very small.

In section 2 of this paper we derive dispersion relations of the plasmons, and explicit expression of the accelerating field. We then derive the relation between the field and the laser power, integrating the Poynting vector in section 3. A numerical example is given in section 4. The last section contains discussion and conclusions.

2 DISPERSION RELATIONS OF PLASMONS

Suppose a tube with inner and outer radii \(a\) and \(\infty\), made from a medium with dielectric function \(\varepsilon_i(\omega)\). Axial symmetric components of electric and magnetic fields inside the tube \((r \leq a)\) are

\[
E_r = -\frac{ik}{K_0}A_0J_1(K_0r), \\
E_z = A_0J_0(K_0r), \\
B_\theta = -\frac{i(k^2 + k_0^2)}{\omega K_0}A_0J_1(K_0r),
\]

and those in the medium \((r > a)\) are

\[
E_r = -\frac{ik}{K_1}A_1H_1^{(1)}(K_1r), \\
E_z = A_1H_0^{(1)}(K_1r), \\
B_\theta = -\frac{i(k^2 + k_1^2)}{\omega K_1}A_1H_1^{(1)}(K_1r),
\]

where

\[
k_1^2 = \frac{\omega^2 \varepsilon_i(\omega)}{c^2} - k^2, \quad i = 0 \text{ or } 1,
\]

and \(J_n(x)\) and \(H_n^{(1)}(x)\) are Bessel function and Hankel function of the first kind, respectively[7].

Using the boundary conditions at \(r = a\), we delete \(A_0\) and \(A_1\) from these to obtain the transcendental equation

\[
\frac{\varepsilon_0(\omega)}{K_0}J_1(K_0a) - \frac{\varepsilon_1(\omega)}{K_1}H_1^{(1)}(K_1a) = 0.
\]
Inserting $\varepsilon_0(\omega) = 1$ and the dielectric function of the medium

$$\varepsilon_1(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)},$$

with $\omega_p$ and $\gamma$ being plasma frequency and relaxation constant respectively, we obtain the dispersion relation

$$K_1H_0^{(1)}(K_1a)J_1(K_0a)$$

$$- \left[1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}\right]$$

$$\times K_0H_1^{(1)}(K_1a)J_0(K_0a) = 0.$$ (5)

Figure 2 shows real part of the dispersion relations for various $k_p a$ values. Frequencies in time and space are normalized by $\omega_p$ and $k_p = \omega_p/c$. All $\omega$ values approaches $\omega_p/\sqrt{2}$, the surface plasmon-polariton frequency, with increasing $k$. Two straight lines show particle beams with velocities $v_p = c$ (relativistic electrons) and $c/2$ (for comparison). Lasers with frequencies at the crossing points are able to excite the plasmons mating with the speeds of the beams.

Equations (1) include the longitudinal and transverse electric fields. In case that the phase velocity equals the light velocity, Eq. (3) gives $K_0 = 0$ and consequently, $J_0(0) = 1$ and $E_z = A_0$. The acceleration field is therefore independent of the radial position in the tube. The transverse field contains $J_1(K_0r)$. Because $K_0r \ll 1$, we approximate it as

$$J_1(K_0r) \sim \left(\frac{K_0r}{2}\right) \left(1 - \frac{1}{\Gamma(2)}\right) = \frac{K_0r}{2},$$

to obtain

$$E_r = -\frac{ikA_0r}{2}.$$
ported that the optical transmission through subwavelength wavelength[9]. An interesting observation has been also re-
can transmit along a space whose dimension is below its 
material with negative dielectric constant such as a metal, light 
laser wavelength. It has been recently shown that in a mate-
erator tube has the cut-off frequency, the dispersion relation 
problems in the case 
k p a

This short length is due to the ohmic loss, which raises 
the temperature and destroys the accelerator structure. The 
solution is to keep the structure in a low temperature. The 
resistivity ρ is related to γ by the relation 
ρ = \frac{m^* γ}{ne^2} ,

where m* is effective mass of an electron and n is the 
electron density. The resistivity of silver at 300 K, 16.29 
×10^{-9} \ \Omega \ \text{m}, is reduced to 0.0115×10^{-9} \ \Omega \ \text{m} at 10 K[8]. 
The acceleration length and the energy gain at 10 K in-
stead increase to 6.11 mm and 273 MeV, respectively, 
with the 1MW laser. The laser intensity at the inner wall 
is 1MW/(2 \times \pi \times 227nm \times 6.11mm)=11.48×10^{9} \text{Wcm}^{-2}. 
This value can be below the damage threshold of the sil-
ver, if the laser repetition rate is moderate.

5 DISCUSSION AND CONCLUSIONS

Equations (1-2) give only the fundamental TM mode. 
Also higher TM modes and hybrid modes can, however, 
exist, though TE modes cannot[9]. Expanding the input 
laser field by the possible orthogonal modes, we could ob-
tain its coupling to the required TM mode[11]. It should 
be noted that, under certain conditions, a linear-polarized laser 
field prefers a particular mode (corresponding to the HE_{11} 
mode in optical fibers) to the TM mode. Further studies are 
required in order to solve this problem. 

The hitherto analyses suggest some interesting physical 
problems in the case k_p a < 2. In spite that a usual rf accel-
erator tube has the cut-off frequency, the dispersion relation 
has solution where the tube size is much smaller than the 
laser wavelength. It has been recently shown that in a mate-
rrial with negative dielectric constant such as a metal, light 
can transmit along a space whose dimension is below its 
wave length[9]. An interesting observation has been also re-
ported that the optical transmission through subwavelength 
holes in metal films can be enhanced by several orders of 
magnitude[10]. This phenomenon is understood as a result of 
interaction of the incident light with independent surface 
plasmon modes on either side of the film. 

Another feature of the dispersion shown in Fig.2 is in 
its negative group velocity, \frac{d ω}{d k} < 0, at k_p a < 2, in 
spite of its positive phase velocity ω/k. We have a prece-
ding example, a backward-wave tube, in which a forward-
flowing electron beam converts its energy into a backward wave[12].

This linac with a fine acceleration tube is capable of 
producing so-called nano beams. It will make a contribu-
tion to study, manufacturing and measurement in nanome-
eter range. A carbon-nanotube electron source will provide 
source beams for this linac[13].

In conclusion, we have presented an analysis of acceler-
ation using potential of plasmons excited in inner wall of 
a metal tube by a laser. It is able to attain a gradient ex-
ceeding GeV/m by, not a TW, but a MW laser to produce 
nano beams. In addition to the technical advantages, it will 
provide us some interesting problems; i.e., optical trans-
mission through the space with the subwavelength size and 
the negative group velocity. More work needs to be made 
on the interface between the accelerator structure and, both 
laser light and source beams.

6 REFERENCES

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