

## Plasmon Linac

SAITO Naoko and OGATA Atsushi

Advanced Sciences of Matter, Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8530, Japan

(Received 1 May 2002 / Accepted 14 June 2002)

A linac is proposed in which a laser first excites plasmons along the inner surface of a metallic acceleration tube. The potential of the plasmon oscillation then accelerates electron beams. It features small beam size and good conversion efficiency from laser intensity to acceleration gradient.

**Keywords:** electron linac, plasma accelerator, plasmon

This paper proposes a miniature linac that uses a hole in a metal as an acceleration tube. A laser pulse excites plasmons along the inner wall of the tube, whose radius is around the laser wavelength. Test beams are then accelerated by the potential of the plasmons. One can regard this method as a laser wakefield acceleration in a hollow channel [1], though it uses an overdense metal plasma instead of an underdense gaseous plasma. The structure resembles that of a dielectric linac [2], which has once been studied as a rival of a linac with periodic structure. It features beam size in the nanometer range and good conversion efficiency from laser power to acceleration gradient; it attains a GeV/m gradient by means of a MW laser instead of a TW one, though the current is very small.

Suppose a tube with inner and outer radii  $a$  and  $\infty$ , made from a medium having dielectric function  $\epsilon_1(\omega)$ . The axial-symmetric TM components of the electric and magnetic fields inside the tube ( $r \leq a$ ) are

$$\begin{aligned} E_r &= -(ik/K_0)A_0J_1(K_0r), \\ E_z &= A_0J_0(K_0r), \\ B_\theta &= -[i(K_0^2 + k^2)/\omega K_0]A_0J_1(K_0r), \end{aligned} \quad (1)$$

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

$$\begin{aligned} E_r &= -(ik/K_1)A_1H_1^{(1)}(K_1r), \\ E_z &= A_1H_1^{(0)}(K_1r), \\ B_\theta &= -[i(K_1^2 + k^2)/\omega K_1]A_1H_1^{(1)}(K_1r), \end{aligned} \quad (2)$$

where

$$K_i^2 = \omega^2 \epsilon_i(\omega)/c^2 - k^2, \quad i = 0 \text{ or } 1, \quad (3)$$

and  $J_n(x)$  and  $H_n^{(1)}(x)$  are the Bessel function and the Hankel function of the first kind, respectively [3].

Using the boundary conditions at  $r = a$ , we delete  $A_0$  and  $A_1$  from these to obtain the transcendental equation  $(\epsilon_0/K_0)[J_1(K_0a)/J_0(K_0a)] - (\epsilon_1/K_1)[H_1^{(1)}(K_1a)/H_0^{(1)}(K_0a)] = 0$ . Inserting  $\epsilon_0 = 1$  and the dielectric function of the medium

$$\epsilon_1 = 1 - [\omega_p^2/\omega(\omega + i\gamma)], \quad (4)$$

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

$$\begin{aligned} K_1H_0^{(1)}(K_1a)J_1(K_0a) - [1 - \omega_p^2/\omega(\omega + i\gamma)] \\ \times K_1H_0^{(1)}(K_1a)J_1(K_0a) = 0. \end{aligned} \quad (5)$$

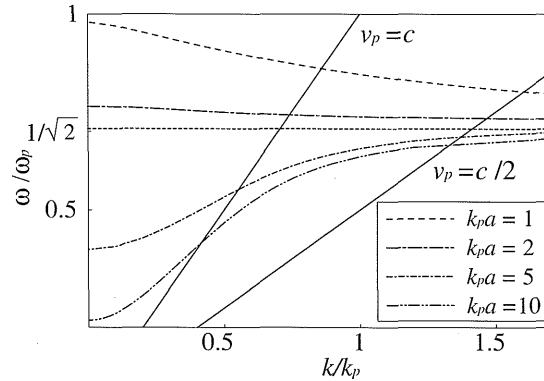


Fig. 1 Real part of the dispersions of the plasmons inside the vacuum tube. Two straight lines give those of particle beams with  $v_p = c$  and  $c/2$ .

Figure 1 shows the 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 approach  $\omega_p/\sqrt{2}$ , 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

author's e-mail: ogata@sci.hiroshima-u.ac.jp

frequencies at the crossing points are able to excite the plasmons mating with the speeds of the beams.

Equations (2) include the longitudinal electric field. In the 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.

Integration of the Poynting vector gives the laser power transmitting along the tube;

$$P = \frac{1}{2} \left[ \int_a^\infty \int_0^{2\pi} E_r H_\theta r dr d\theta + \int_0^a \int_0^{2\pi} E_r H_\theta r dr d\theta \right]. \quad (6)$$

Using the boundary conditions of the field components, and by inserting  $E_z$  in eq. (2), we find that the accelerating field  $E_z$  inside the tube is proportional to the square root of the laser power  $P$ ;

$$E_z(0) = \alpha k_p P^{1/2}. \quad (7)$$

The  $k_p a$  dependency of the coefficient  $\alpha$  of the above equation is numerically calculated and given in Fig. 2 for two phase velocities,  $v_p = c$  and  $c/2$ .

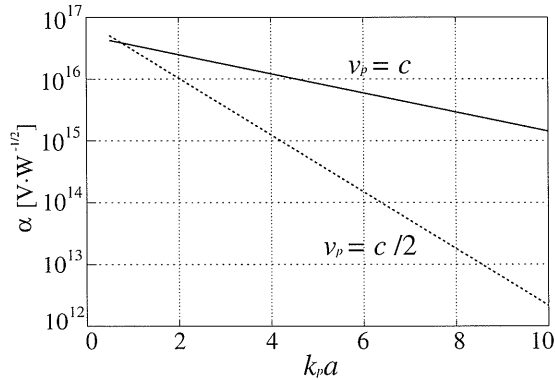


Fig. 2 Conversion coefficient between  $r k_p P$  and the acceleration field  $E_z(0)$ , as a function of  $k_p a$  for two phase velocities,  $v_p = c$  and  $c/2$ .

Use of silver ( $\omega_p = 13.2 \times 10^{15} \text{ s}^{-1}$  and  $\gamma = 68.9 \times 10^{12} \text{ s}^{-1}$ ) under the design conditions  $k_p a = 10$  and  $v_p = c$  gives  $a = 227 \text{ nm}$  and the laser wavelength as  $344 \text{ nm}$ . According to Fig. 2, a laser with a power of  $1 \text{ MW}$  attains an acceleration gradient of  $45.0 \text{ GeV} \cdot \text{m}^{-1}$ . The acceleration length  $\sim c/\gamma$  is, however, only  $4.32 \mu\text{m}$ , giving an energy gain of  $194 \text{ keV}$ .

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 at a low temperature. The resistivity  $\rho$  is in proportion to  $\gamma$ . That of silver at  $300 \text{ K}$ ,  $16.29 \times 10^{-9} \Omega \cdot \text{m}$ , is reduced to  $0.0115 \times 10^{-9} \Omega \cdot \text{m}$  at  $10 \text{ K}$  [4]. The acceleration length

and the energy gain at  $10 \text{ K}$  instead increase to  $6.11 \text{ mm}$  and  $273 \text{ MeV}$ , respectively, with the  $1 \text{ MW}$  laser. The laser intensity at the inner wall is  $1 \text{ MW}/(2 \times \pi \times 227 \text{ nm} \times 6.11 \text{ mm}) = 11.48 \times 10^9 \text{ W} \cdot \text{cm}^{-2}$ . This value can be below the damage threshold of silver, if the laser repetition rate is moderate.

Equations (1-2) give only the fundamental TM mode. Also higher TM modes and hybrid modes can, however, exist as well, though TE modes cannot [5]. Expanding the input laser field by the possible orthogonal modes, we could obtain its coupling to the required TM mode [6]. It should be noted that, under certain conditions, a linear-polarized laser field prefers a particular mode (corresponding to the  $\text{HE}_{11}$  mode in optical fibers) to the TM mode. Further studies are required in order to solve this problem.

The above analyses suggest some interesting physical problems in the case  $k_p a < 2$ . The dispersion relation has a solution in which the tube diameter is much smaller than the laser wavelength, contrary to that of a usual waveguide. This property is going to be applied to light transmission through nanostructures [5]. Another feature of the dispersion relation regards its negative group velocity,  $\partial\omega/\partial k < 0$ , in spite of its positive phase velocity  $\omega/k$ . We have a preceding example, a backward-wave tube, in which a forward-flowing electron beam converts its energy into a backward rf wave [7].

This linac with a fine acceleration tube is capable of producing so-called nano beams. It can contribute to further investigation, manufacture and measurement in the nanometer range. A carbon-nanotube electron source will provide the source beams for this linac [8].

- [1] T.C. Cuiou, T. Katsouleas and W.B. Mori, *Phys. Plasmas* **3**, 1700 (1996).
- [2] S. Frankel, *J. Appl. Phys.* **18**, 650 (1947).
- [3] C.A. Pfeiffer, E.N. Economou and K.L. Ngai, *Phys. Rev.* **B10**, 3038 (1974); J.A. Stratton, *Electromagnetic Theory* (McGraw-Hill, 1941).
- [4] D.R. Lide and F.P.R. Frederikse, eds., *CRC Handbook of Chemistry and Physics*, 75th ed. (1994-1995), CRC Press, p12-40.
- [5] J. Takahara and T. Kobayashi, in S. Kawata, M. Ohtsu and M. Irie, eds., *Near Field Nano Optics* (Springer, in press).
- [6] A.W. Snyder, *IEEE Trans. Microw. Theory Tech.* **MIT-17**, 1138 (1969).
- [7] Y. Carmel *et al.*, *Phys. Rev. Lett.* **69**, 1652 (1992).
- [8] Y. Saito and S. Uemura, *Carbon* **38**, 169 (2000).