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FDTD ANALYSIS OF A CHERENKOV INTERACTION IN THE PRESENCE OF APPLIED FINITE MAGNETOSTATIC FIELD

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1. Introduction

The Cherenkov free-electron laser is a potential high-power and tunable source of short millimeter or submillimeter waves. It generates growing waves through the interaction between a relativistic electron beam and a slow electromagnetic wave propagated along a dielectric-loaded waveguide. In the previous paper [1], the effect of an applied magnetostatic field of arbitrary strength in a Cherenkov laser was considered on the basis of the fluid model for electron beams. On the other hand, only the case of an infinitely magnetized electron beam has been discussed on the basis of the particle model for electron beams [2]-[4]. The particle model for electron beams has an advantage that it can easily treat the nonlinear effect and stability of electron beams.The purpose of this paper is to discuss, with the aid of particle simulation [5], the nonolinear characteristics of the Cherenkov laser using a relativistic electron beam magnetized by an arbitrary finite magnetostatic field, investigating the effect of the applied magnetostatic field in detail. For the analysis of the problem, we consider a two-dimensional model for the Cherenkov laser composed of a planar relativistic electron beam and a parallel plate waveguide one plate of which is loaded with a dielectric sheet. To follow temporally the growth of an electromagnetic wave and the decrease in the kinetic energy of the electron beam in the specified model of the Cherenkov laser, a particular segment of the electron beam with the longitudinal length of one guide wavelength is picked out. In that segment, as it travels down the waveguide, the interaction between the electromagnetic wave and a group of electrons is numerically analyzed with the use of the finite-difference time-domain (FDTD) method [5]-[7].

2. Numerical Simulation via FDTD Method

The geometry of the problem is shown in Fig. 1, together with the coordinate system. The two-dimensional model of the Cherenkov laser under consideration consists of a parallel plate waveguide one conducting plate of which is loaded with a dielectric sheet of permittivity ε_r, and a planar relativistic electron beam drifting with the average velocity V_0 through it. In Fig. 1, the separation between two conducting plates is f, the thickness of a planar electron beam $d - b$, the thickness of a dielectric sheet a, and the beam-dielectric gap $b - a$. The electron beam is assumed to be magnetized in the z direction by an arbitrary finite magnetostatic field. The basic equations for the analysis are the Maxwell equations and the relativistic equation of motion for the electron. Note that the electron beam interacts with the TM waves in the Cherenkov laser. In particle simulation, we introduce the concept of superparticles [5] with large mass and charge, which are composed of a large number of actual particles. By following the motion of superparticles in an electromagnetic field, we can properly describe the collective behavior of individual particles in the field while greatly reducing the apparent number of particles involved and thus the time required for numerical simulation.

For numerical analysis of the interaction between an electromagnetic wave and the electron beam in the Cherenkov laser, we divide the two-dimensional model for the Cherenkov laser shown in Fig. 1 into many small segments, each of which is assumed to be one guide wavelength long, in the longitudinal direction. We assume that the periodic boundary conditions are approximately satisfied between adjacent segments. Then, we pick out a group of particles contained in one particular segment at the initial state, and temporally follow, with the aid of the FDTD method [5]-[7], the interaction between an electromagnetic wave and the particular group of particles, as it travels down the waveguide. As shown in Fig. 2, each segment of the two-dimensional model for the Cherenkov laser is further subdivided into N_y subsegments in the y direction and N_z subsegments in the z direction. The spatial grids subdividing a small segment in the y direction are spaced by Δy and numbered by j ($j = 0, 1, \cdots N_y$). On the other hand, those in the z direction are spaced by Δz and numbered by k ($k = 0, 1, \cdots N_z$). We assume that the surfaces of the dielectric and the electron beam coincide with one of the spatial grids in the y direction. In the beam region of one particular segment, we uniformly arrange superparticles for electrons at the initial state. Initially, we also assume that an electromagnetic wave of the lowest-order TM mode with small enough amplitude exists in the waveguide.The initial values for the velocity of superparticles and the wavelength of the electromagnetic wave are chosen in such a way that the velocity matching between the electromagnetic wave and the electron beam is satisfied. The free-space wavelength of the electromagnetic wave we picked out in the above manner is 2.42 mm, which corresponds to the frequency of 124 GHz and the guide wavelength of 2.0 mm. Then, according to the standard procedure in the FDTD method, we temporally follow the interaction between the electromagnetic wave and a group of superparticles for electrons in the particular beam segment. The values of various parameters used in numerical simulation are as follows: the thickness of the dielectric sheet is 0.5 mm, the beam-dielectric gap 0.5 mm, the beam thickness 0.125 mm, the separation between conducting plates 3 mm, the relative permittivity of a dielectric sheet 2.12, the initial average beam velocity normalized by the speed of light in vacuum 0.8275, the initial beam voltage 400 kV, and the initial beam current 1.6 A/cm.

3. Numerical Results and Discussion

In Fig. 3, we show the temporal growth of the power carried by the electromagnetic wave, changing the magnitude of the applied magnetostatic field as a parameter. First, for the case of a nonmagnetized electron beam, namely, for the case of $B_0 = 0$, the electromagnetic power exponentially grows after the initial transient state, and then discontinues at a particular point. For the case of $B_0 = 0$, the electron beam gradually spreads in the transverse direction under the influence of the growing electromagnetic wave, and finally impinges upon the surface of the dielectric sheet. At this point, the electron beam is destroyed, and we stop follwing the interaction between the electron beam and the electromagnetic wave. As the magnitude of the magnetostatic field increases and its focusing effect on the electron beam gets stronger, the electromagnetic power grows for a longer time, while the speed of growth becomes slower or the temporal growth rate becomes smaller. For the given values of various parameters, the electromagnetic power grows until it reaches saturation for the values of B_0 greater than 0.1[T], while we get almost the same growth characteristics for the values of B_0 greater than 1.0 [T] as for the case of the applied infinite magnetostatic field. From numerical simulation, we find that the saturated value of the electromagnetic power monotonously decreases as the magnitude of the magnetostatic field applied on the electron beam increases. As has been clarified above by particle simulation, the electromagnetic wave grows exponentially in the initial stage of the growth where the linear approximation holds, and the growth of the electromagnetic wave is gradually suppressed until it finally reaches saturation as the nonlinear effect of the electron beam becomes predominant. On the other hand, only the linear regime was considered in the previous paper [1] based upon the fluid model of electron beams.

In Fig. 4, we illustrate the temporal variation of the growth rate α for the electromagnetic wave. As seen from Fig. 4, the growth rate takes an approximately constant value after a short transient for small values of the applied magnetostatic field, while for large values of the applied magnetostatic field it rapidly decreases after taking an approximately constant value. The approximately constant values of the growth rate shown in Fig. 4 correspond to the linear growth rates, which are in good agreement with the results obtained from the linear analysis based upon the fluid model of electron beams [1].

4. Conclusion

With the aid of particle simulation, we discussed the nonolinear characteristics of a two-dimensional model for the Cherenkov laser using a relativistic electron beam magnetized by an arbitrary finite magnetostatic field. In the specified model of the Cherenkov laser, which is composed of a planar relativistic electron beam and a parallel plate waveguide one plate of which is loaded with a dielectric sheet, we numerically followed the growth of an electromagnetic wave and the decrease in the kinetic energy of the electron beam with the use of the finite-difference time-domain (FDTD) method. Through the numerical simulation, we clarified the nonlinear effect of the electron beam on the growth characteristics for the electromagnetic wave and the focusing effect of the applied magnetostatic field on the electron beam.

References

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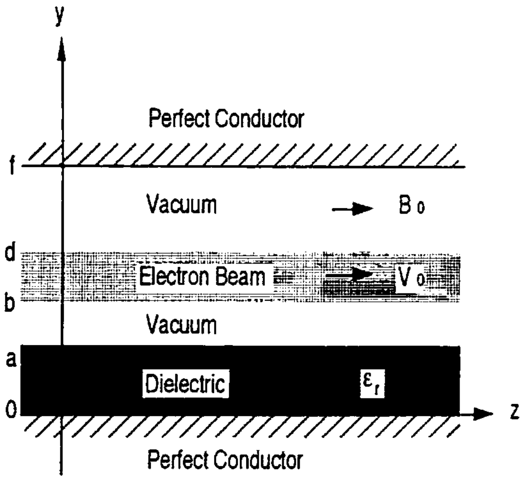

Fig. 1. Geometry of the problem.

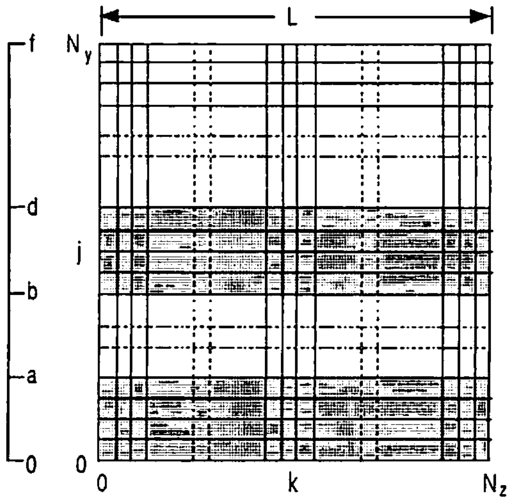

Fig. 2. Subdivision of a small segment.

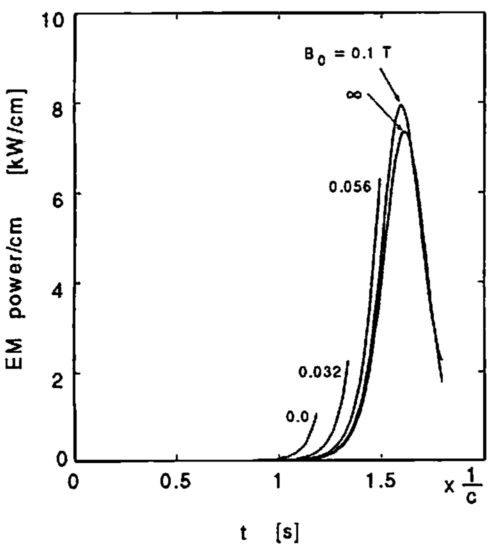

Fig. 3. Temporal growth of EM power.

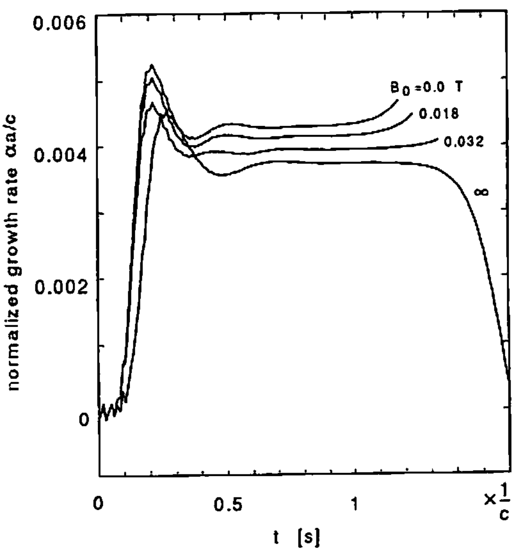

Fig. 4. Temporal variation of the growth rate.