PARTICLE-IN-CELL SIMULATION OF STATIONARY PROCESSES IN A RELATIVISTIC CARCINOTRON

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A one-dimensional nonstationary model of relativistic carcinotrons, combines the particle-in-cell method in the description of an electron beam with a single-wave approximation in the description of the dynamics of an electromagnetic field. The influence of the intrinsic space charge of the beam is taken into account in the quasistatic approximation. A procedure is developed for computational experiment with a carcinotron in the axisymmetric approximation on the basis of the entirely electromagnetic code KARAT. The computations support the main known laws for a relativistic carcinotron. The effect the space charge has on inertial electron-beam bunching is examined. Mechanisms by which the space charge affects the carcinotron generation efficiency are demonstrated. The space charge may cause anomalously accelerated electrons in the beam and a reverse electron current to appear, increasing the impedance of the coaxial magnetically insulated diode that feeds the device. The carcinotron power and frequency are studied as functions of the strength of the guiding magnetic field. Cyclotron suppression of generation is confirmed. Calculation in combination with an electronic diode shows that generation at a higher frequency can be excited in the cyclotron "dip."

INTRODUCTION

The relativistic carcinotron proposed in the early 1970's [1, 2] continues to be an object of intensive studies. The rapid growth of the available computational capabilities heightened the interest of researchers in computer simulation of high-power electronic devices, including relativistic carcinotrons (a conventional diagram of the device is given in Fig. 1 in [13]).

The main laws governing the operation of a conventional carcinotron in the stationary generation state were studied in detail in [3] on the basis of a hydrodynamic model. At the same time, under particular conditions nonstationary modes are inherent to this device [4]. Moreover, the high-current relativistic electron beams used in modern relativistic carcinotrons as a rule are of short duration (several or tens of nanoseconds) compared to the oscillation build-up time. It is thus important to use a nonstationary treatment in the study of processes in this microwave device.

In the one-dimensional model developed in the first studies on nonstationary computer simulation of carcinotrons [5] the electron stream is described in the hydrodynamic representation. Although this approach does not provide means for describing kinetic situations (e.g., turn of particles) and prevents averaging of the time processes during the time of flight of particles through the device, it has been possible with this model to demonstrate and explain many aspects of the nonstationary behavior of a carcinotron.

Below we report the results of a nonstationary computer experiment with a relativistic carcinotron on the basis of a model that uses the particle-in-cell (PIC method), which is kinetic in nature, to describe the electron stream dynamics. In the one-dimensional model proposed here for a carcinotron the dynamics of the operating wave is described as in [5], on the basis of a nonstationary equation of waveguide excitation [6]. The entirely electromagnetic PIC code KARAT [7, 8] was used for full-scale simulation of the device, which requires that both the geometric and physical factors be taken into account.
1. ONE-DIMENSIONAL PIC MODEL OF CARCINOTRONS
(SINGLE-WAVE APPROXIMATION)

We assume that the axisymmetric electron stream interacts with the field only through one waveguide state, with a known transverse structure. Suppose that the electrons of the unperturbed beam are in Cerenkov synchronism and interact only with the (-1) spatial harmonic of the counter wave. The interaction with the other, asynchronous harmonics is ignored. Electrons do not move transversely in the beam (which is in accord with the existence of an axial magnetic field of infinite strength). The beam is tubular and has infinitely thin walls.

Description of the Excitation of an Electromagnetic Wave. Under the given conditions, motion of the beam is affected only by the longitudinal component of the electric field (-1) of the spatial harmonic of the wave, which is written as

\[ E_z(r, t) = \Re \left[ \hat{A}(z, t) \hat{E}(r, z) \exp \left[ i \left( \omega t - \int_0^z h_{-1}(z') \, dz' \right) \right] \right]. \]  

(1)

Going to the amplitude \( A = \hat{A} \sqrt{N} \), where \( N = \frac{c}{8\pi} \Re \int_S [\vec{E} \times \vec{H}^*] \, dS \) is the normal of the wave, we obtain an expression for the electric field on the beam path:

\[ E_z(z, r_0, t) = \Re \{ A(z, t) \hat{Z}(z) \exp \left[ i \left( \omega t - \int_0^z h_{-1}(z') \, dz' \right) \right] \}. \]

Here \( r_0 \) is the beam radius, \( A(z, t) \) is the complex amplitude of the wave, \( \hat{Z}(z) = \hat{E}(r_0) \sqrt{N} \) is the coupling coefficient* of the beam with the (-1) spatial harmonic of the wave (which depends on \( z \) for a carcinotron with inhomogeneous coupling), \( h_{-1} = h - h_0 \) is the longitudinal wave number (which depends on \( z \) in a device with a longitudinal inhomogeneity of the phase velocity), \( \hat{n} = \frac{2\pi}{d} \), \( h_0 \) is the longitudinal wave number of the zero spatial harmonic, and \( d \) is the corrugation period of the retarding system. The frequency \( \omega \) is given and the longitudinal wave number of the harmonic is determined from the Cerenkov synchronism condition, \( h_{-1} = \omega V_0 \), where \( V_0 \) is the initial electron velocity.

The space–time dependence \( A(z, t) \) of the amplitude is determined by the nonstationary equation of waveguide excitation [6],

\[ \frac{\partial A}{\partial t} - |V_e| \frac{\partial A}{\partial z} = |V_e| \hat{Z}(z) j_\omega(z, t) \exp \left[ i \int_0^z h_{-1}(z') \, dz' \right]. \]  

(2)

where \( V_e \) is the group velocity of the wave,

\[ j_\omega(z, t) = \frac{\omega}{\pi} \int_{-\pi}^\pi i (z, t') \exp (-i\omega t') \, dt'. \]

is the amplitude of the first Fourier harmonic of the current at the frequency \( \omega \) and \( T \) is the period of the oscillations. Using a space–time grid that is uniform in \( z \) and \( t \), we approximate Eq. (2) with a four-point difference scheme:

\[ \frac{A_i^t - A_i^{t-1}}{V_e \tau} = \frac{A_i^{t-1} - A_i^{t-1}}{2 \Delta z} + \frac{A_i^{t-1} - 2A_i^{t-1} + A_i^{t-1}}{2 (\Delta z)^2} V_e \tau = F_i^t. \]

(3)

Here \( \Delta z \) and \( \tau \) are the space and time integration steps. The superscripts and subscripts denote the numbers of the time and space layers of the grid.

*Henceforth, a coupling impedance, defined as \( Z = \frac{21}{\kappa^2 N} \), is required when describing practical cases.