A normalized mathematical model for describing the motion of electrons in a relativistic peniotron with smoothly varying magnetostatic field, which provides a state of exact gyroresonance along the entire length of the device, is constructed. The results of computer calculations of the energetics of this device are presented and an example of an effective choice of its parameter corresponding to high electronic efficiency of a one-velocity flow are presented.

The peniotron as a weakly relativistic device with a uniform magnetostatic field was proposed in [1, 2]. It was subsequently studied in detail theoretically and experimentally (for example, in [3-6]). A substantially relativistic peniotron differs from its weakly relativistic prototype by the elevated energy of the electrons. Like the weakly relativistic peniotron, the highly relativistic peniotron is capable of functioning with a uniform magnetic field. But, in the weakly relativistic peniotron the extraction of energy from the electrons, for all practical purposes, does not change the gyrofrequency of the particles or the Doppler frequency of the wave, whereas in the strongly relativistic device both the gyrofrequency and the Doppler frequency change appreciably in proportion to the change in the energy and the longitudinal velocity of the particles, which in the case of a uniform magnetic field destroys the gyroresonance state and limits the electronic efficiency. The efficiency of other gyrosonance devices with a uniform magnetic field, in particular, the strongly relativistic gyrotron and cyclotron antiresonance maser (CARM), is also limited for the same physical reasons.

For this reason, the theoretical electronic efficiency of the relativistic peniotron with a uniform magnetic field can be approximated of the same order of magnitude as the efficiency of a gyrotron or CARM, i.e., for reasonable electric-field intensities of the wave and acceptable dimensions of the interaction space, it must fall in the range 20-30%.

We shall study below a relativistic peniotron with a specially configured induction of the guiding magnetic field, which provides conditions for precise through resonance, i.e., resonance along the entire length of the interaction space. Under these conditions, the changes in the relativistic gyrofrequency and Doppler frequency are compensated, and prolonged deceleration of the particles becomes possible. In this case, the relativistic factor is in principle combined with high electronic efficiency. A similar situation is solved theoretically in a tube based on the anomalous Doppler effect, but its technical indicators are reduced by the strong nonuniformity in the growth of the efficiency along the axis of the device, owing to the rectilinearity of the electronic trajectories at the input. In contrast to this, the peniotron is powered not by a rectilinear, but rather a spiral electron flow (a single rotating tube). For this reason, the particles give up their energy to the wave approximately uniformly along the entire working channel and the device is more suitable for practical implementation.

A model diagram of the interaction space is shown in Fig. 1. The tubular electronic flow, rotating as a whole, enters the circular waveguide, which maintains one of the modes of the rotating structure. At first the electrons move with a constant radius coaxially with the field, with almost no exchange of energy with it. But, then, because of the transverse drift of the guiding centers of the rotators the coaxiality is destroyed, which gives rise to significant energy exchange and decreases the radius of the electronic spirals. The direction of drift depends on the time at which the particles enter the field, but since the trajectories of different particles are congruent, it may be assumed that all electrons operate under identical conditions. For this reason, it is sufficient to study the behavior of one electron. For simplicity, we shall neglect the spread in the velocities of electrons and the

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space charge, and we shall assume that the longitudinal distribution of the amplitude of the wave is uniform.

The procedure for constructing the averaged equations of spiral motion of relativistic electrons in a resonant electromagnetic and smoothly nonuniform magnetostatic fields is described in [7, 8]. We shall employ this procedure here.

We shall use the Hertz function of a rotating TE mode

$$\Pi(\rho, \varphi) = I_m(k_\rho V 1 - \frac{\beta_p^2}{R}) \exp(-im\varphi)$$  \hspace{1cm} (1)

and the axisymmetric magnetostatic field

$$B_\rho = -0.5pB_0(z), \quad B_z = B_0(z),$$  \hspace{1cm} (2)

where $\rho, \varphi, z$ are cylindrical coordinates, $J$ is the Bessel function with the indicated index and argument, $k$ is the wave number, $\beta_p$ is the phase velocity of the wave normalized to the speed of light, $j = (-1)$, and $m$ is the number of azimuthal variations of the high frequency field. Then the working harmonic of the Hertz function assumes the form

$$\Pi_n = J_n \left( kr \sqrt{1 - \frac{\beta_p^2}{R}} \right) J_{m-n} \left( kR \sqrt{1 - \frac{\beta_p^2}{R}} \right) e^{(m-n)\rho},$$  \hspace{1cm} (3)

and the average quasipotential corresponding to it assumes the form

$$V = \frac{\eta Fs}{\Gamma kn} kr \sqrt{1 - \frac{\beta_p^2}{R}} \frac{n!}{k} J_n \left( kr \sqrt{1 - \frac{\beta_p^2}{R}} \right) J_{m-n} \left( kR \sqrt{1 - \frac{\beta_p^2}{R}} \right) \cos \theta,$$  \hspace{1cm} (4)

where $\eta$ is the absolute magnitude of the specific charge of the electron at rest; $F$, amplitude of the wave; $s = 1 - \beta_0^2 \beta_p^2$; $\beta_0$, longitudinal velocity of the particle normalized to the speed of light; $\Gamma$, initial nonrelativistic gyrofrequency; $n$, order of the gyroresonance; $\delta$, instantaneous induction of the magnetostatic field normalized to its initial value; $r$ and $R$, adiabatic variables used for describing the evolution of the radius of the electron orbit $r_1 = r/\delta$ and the radial coordinate of its guiding center $R_1 = R/\delta$; and $\theta$, generalized slow phase of the resonance forces of the rotating field acting on the electron on the spiral trajectory.

From the averaged quasipotential we transform directly to the equations of average motion:

$$\dot{t} = -\frac{n\Gamma\delta}{s \omega \gamma} \frac{\eta Fs}{\Gamma kn} kr \sqrt{1 - \frac{\beta_p^2}{R}} \frac{n!}{k} J_n \left( kr \sqrt{1 - \frac{\beta_p^2}{R}} \right) \times$$

$$\times J_{m-n} \left( kR \sqrt{1 - \frac{\beta_p^2}{R}} \right) \sin \theta,$$

$$\dot{R} = \frac{\eta Fs \sqrt{1 - \frac{\beta_p^2}{R}}}{n \Gamma \sqrt{\delta}} kr \sqrt{1 - \frac{\beta_p^2}{R}} \frac{n!}{k} J_n \left( kr \sqrt{1 - \frac{\beta_p^2}{R}} \right) \times$$

$$\times \frac{m-n}{kR} \sqrt{1 - \frac{\beta_p^2}{R}} J_{m-n} \left( kR \sqrt{1 - \frac{\beta_p^2}{R}} \right) \sin \theta,$$

$$\dot{\theta} = s \omega - \frac{n\Gamma\delta}{\gamma} \frac{\eta Fs}{\Gamma kn} \frac{\delta}{k \dot{\rho}} \left[ kr \sqrt{1 - \frac{\beta_p^2}{R}} \frac{n!}{k} J_n \left( kr \sqrt{1 - \frac{\beta_p^2}{R}} \right) \right]$$

$$\times J_{m-n} \left( kR \sqrt{1 - \frac{\beta_p^2}{R}} \right) \cos \theta,$$  \hspace{1cm} (5)