THEORETICAL STUDY OF PLASMOIDS ACCELERATION IN ELECTROMAGNETIC POTENTIAL HF WELLS

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Abstract

Some analytical and computational study results of charged or neutral plasma bunches acceleration by means of high-frequency potential wells are presented. The computational study was performed by means of a 2.5-D kinetic model taking into account the plasmoids self field. The problems of holding of both ellipsoidal and thoroidal bunches, purely electron as well as partly neutralized by ions, were considered for the case of cylindrical field E_{omn}. The investigation results confirm the basic theoretical assumptions and give the possibility to propose values of achievable acceleration gradient and current of particles for various conditions.

1. Introduction

Some types of electromagnetic waves can restrict charged particles motion in 1, 2 or 3 dimensions (RF wells, quasipotential or ponderomotive wells). This phenomenon has important applications in radiospectroscopy.

The works [1-3] (see also references in [2,3]) are devoted to basic principles of various RF wells and to some perspectives of their uses. In the works [4,5] some properties of the 3-D RF wells which are formed by cylindrical axially-symmetric electromagnetic E-waves are studied. Various schemes of laser collective accelerators are proposed.

It must be noted that this method of plasmoids acceleration by means of RF wells differs from the known method of plasma beat wave acceleration (Tajima, Dawson, 1979): isolated by the HF field plasmoids are used instead of a continuous plasma fiber; relatively high plasma density $n \gtrsim 0.3\, n_c$ is used instead of $n \gtrsim 0.01\, n_c$ ($n_c = \omega^2 m\varepsilon_0/e^2$ is the so called critical density, m and e - electron mass and charge); the plasmoids (bunches) repetition rate is much higher, it corresponds to the mean frequency $(\omega_1+\omega_2)/2$ of the two waves instead of $\omega_1-\omega_2$; an outer rigid hologram resonator is used instead of using the plasma resonance.

2. Theoretical and experimental prerequisites.

The method of plasmoids acceleration by means of RF wells was studied in our work for the case of cylindrical axially symmetric electromagnetic standing waves $E_{omn}(\varphi,r,z)$, in particular, E_{011} :

$$\begin{aligned} E_z &= \hat{E} J_0(k_r r)\sin k_z z \sin\phi \,, \\ E_r &= -(k_z/k_r)\hat{E} J_1(k_r r)\cos k_z z \sin\phi, \\ B_\varphi &= (k/ck_r)\hat{E} J_1(k_r r)\cos k_z z \cos\phi \,, \\ k_z^2 + k_r^2 &= (\omega/c)^2 = k^2 \,, \quad \phi = \omega t + \alpha \,, \end{aligned} \tag{1}$$

or of corresponding oppositely running swift waves, or similar slow waves in a periodical waveguide. The latter case may be useful for preliminary experimental proof of the acceleration principle and for collective acceleration of heavy ions (proposal of prof. A.M. Sessler).

The standing waves (1) form a chain of RF wells for charged particles, electrons in the first turn, along the z-axis near the points where

$\sin k_z z = 0$. The form of these wells is ellipsoid-like. Besides of these wells there exist also thoroid-like wells, which correspond to the higher zeros of the Bessel function $J_1(k_r r)$. They also may be used for acceleration.

The known theoretical and experimental investigations ([2,3] and references therein) correspond to the case of weak field:

$$q = e\hat{E}\lambda/2\pi mc^2 \ll 1 \qquad (2)$$

mc^2 being the electron energy, $\lambda = 2\pi c/\omega$ – the field wavelength. The restriction (2) gives the possibility to prove the existence of RF wells in general case [2,3], and to find their properties, in particular their depth $G = q^2mc^2/4$. But the corresponding simple theory leads to the conclusion [2,3] about the low effectiveness of RF wells, i.e. low ratio of effective field (gradient of the quasipotential) to the field amplitude $\hat{E}$.

Experiments with RF wells ([2,3] and references therein) were also made with weak fields. It was caused by low RF powers available and by electrical breakdown.

The treatment of the HF trapping effect as a slightly nonlinear variant of alternating gradient focusing leads to the assumption [4] of high effectiveness of RF wells at high fields,

$$q \gtrsim 1 \ . \qquad (3)$$

Besides of the field amplitude the plasma density is an important parameter. According to the known experiments [2,3] in weak fields (2) the 1-particle theory of HF wells is adequate up to the subcritical densities

$$n \gtrsim n_c/2 \ , \qquad (4)$$

if the electron temperature of the plasma reaches $T_e \sim 10$ keV. Relatively high density (4) is needed for collective acceleration of ions by means of plasmoids in HF wells.

The conditions (3) and (4) exclude purely analytical investigation. These considerations justified elaboration of the computer program simulating self-consistent particles in a RF well.

3. Some results of computer simulation.

For numerical experiments the 2.5-dimensional (axially symmetric geometry) model based on full Maxwell's equation system and macroparticles relativistic motion equations solving was developed.

The results appear as the graphs of particles density, 2-dimensional fields $\vec{E}$, $\vec{B}$, charge and current densities ρ , $\vec{j}$ in the rz-plane. The borders of the graphs correspond to the resonator walls and z-axis.

The obtained results have confirmed the possibility of trapping of dense ($n \gtrsim n_c/3$) electron and electron-ion bunches in strong fields (3) in the RF well (1) at time intervals at least of several tens of HF periods . Typical pictures of a plasmoid in the well are shown on figs. 1 and 2. The HF oscillations of a plasmoid resemble the motion of a butterfly.

The computational experiments show that the superfluous charge in the well is lost after several HF oscillations independently of the initial form of its distribution (in case of $T_e = 0$). The loss of the superfluous electrons takes place mainly in the r-direction if $r_{max} < z_{max}$ and in the z-direction in the opposite case. We suppose that the use of a longitudinal magnetic field will minimize these losses.

The conserved charge varies approximately $\sim q^2$, i.e. it is proportional to the well depth (at given values of k_r , k_z), if $q < q_{max}$; but if $q > q_{max}$ the charge quickly decreases with q . The value of q_{max} varies from 0.6 at $z_{max}/r_{max} = 0.5$ to 0.8 at $z_{max}/r_{max} = 2$, which is close to the value $q_{max} = 0.9$ for the corresponding Mathieu equation which describes the linearized motion.

The field of trapped electrons reaches $\sim 0.1\ \hat{E}$.

Conclusion

We have shown that the axially symmetric RF well of the E_{011} field can effectively hold dense plasmoids. Their density may reach $\sim 0.3\, n_c$. The effective field may reach ~ 0.1 of the field amplitude. These results may be used for projecting of various 2-frequency accelerators with accelerating gradient $\sim$ 100 kV/λ, λ being the HF well wavelength, e.g. 10 MV/m at λ = 1 cm or 10 GV/m at λ = 10 μm.

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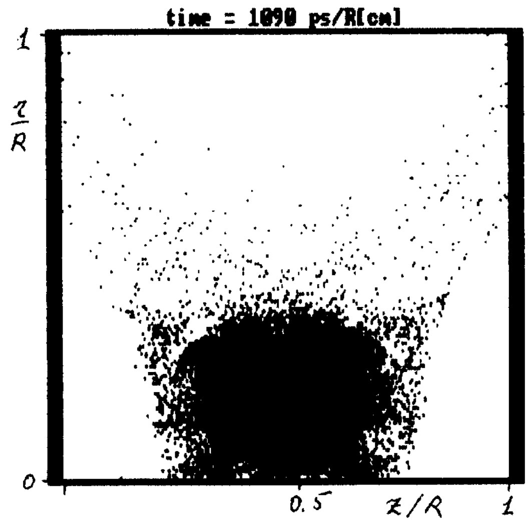

fig. 1

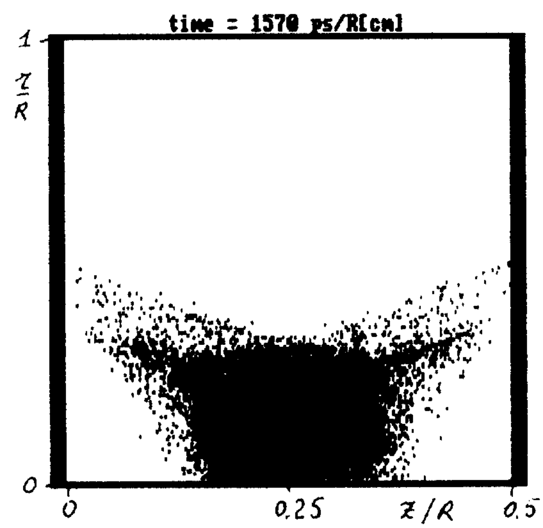

fig. 2