THE DIRECT TRANSFORMATION OF POTENTIAL ENERGY OF ELECTRIC FIELD INTO KINETIC ENERGY OF CHARGED PARTICLES OR ELECTROMAGNETIC RADIATION

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The research results on energy transformation based on parameter interaction of charged particles bunch with alternate electromagnetic field created by itself in resonant conditions in the presence of external electrostatic field are considered. It was shown how the oscillations of kinetic energy of electrons bunches and potential energy of electrostatic field are excited and the synchronism between the oscillation frequency in beam and that in potential electric field, accompanied with field energy transfer into kinetic energy of charged particles or microwave electromagnetic radiation, is automatically maintained[1,2].

Let us consider two-gap resonator formed by two coaxial cylinders which axis coincides with OZ axis(Fig.1). Let us mark the points near axis intersection by B and C. In G-region between cylinders the electric field with definite energy and given field polarity is created. Let C_1 be capacity of G-region. The charged particles beam emitted in point A passes through the system. The interaction of beam with field is localized around entry AB region and exit CD region of the device. BC region is drift space where the beam is screened from external fields. If electron beam is interpreted as infinite sequence of RL branches, each of them together with the capacity of adjacent region forms successive branch RLC (C - equivalent capacity comprising C_1 capacity and that between beam and A and B holes' boundaries, we will have the problem about dissipation of preliminary accumulated energy at C_1 capacity in closed oscillation circuit RLC. The system as a whole is the system with distributed parameters. Only the working region AB with confined beam element is presented by the circuit with concentrated parameters. And the current excited in this element may be considered relatively to the whole beam as current source localized on this element. The capacities of the circuit may be considered as given.

In oscillation circuit RLC as results of beam grouping the resistance R and beam inductance L are reactive parameters. And the energy of electric field W_e and magnetic field W_m will be equal to $W_e= q^2/2C$ and $W_m= LJ^2/2$, where q - the charge on C_1 capacity, J - the current in beam equivalent inductance. The intrinsic oscillation in the circuit without losses with C and L constants are excited with frequency $\omega_0 = 1/\sqrt{LC}$. And the full energy $W=W_e + W_m$ in RLC circuit remains invariable, only its periodical transformation from electric into magnetic energy with the frequency $2\omega_0$ takes place. The change of RL parameters is accompanied by the work of external forces and leads to the change of the system full energy. If the grouping frequency coincides with RLC- circuit frequency (in this case the changes are due to intrinsic oscillations), the work is done over system at an period average and hence full energy and oscillation amplitude will increase monotonously. The necessary condition in this case is superposition of the regions of RLC-circuit formed by beam and the line with distributed parameters. The regions of interaction of beam and excited wave must be combined. The grouped electrons excite electromagnetic oscillations with the subsequent establishment of stationary regime. The swing of the oscillation is caused by the interaction of the beam with wave formed as results of acceleration and breaking of the beam. The energy losses are compensated by power supply source. The swing of the oscillation is possible while changing R and L of the beam by leaps (grouping) according any periodical law with period $T_n=nT_0/2$ or frequency $\omega_n=\omega_0/2n$ (n - integer number, T_0 - the period of intrinsic oscillations of the circuit). The most effective swing is at n=1 when the pumping frequency ω_n is equal to transformation frequency of W_e into W_m in the system. The increasing of oscillations is possible not only at exact fulfilling of relations but in some finite ranges of ω_n values near ω_0 (in non-stability zones). In this case there is parameter resonance mechanism and its effectiveness depends on relation between the character of parameter changing of the grouping in beam zone and space structure of waves generated in the system. The wave excited in system causes the emission of electrons on the cathode (7), thus the grouping on the stage of electron emission is implemented.

The beam grouping is done both at the electron emission stage and during their movement in ABCD space. Let us consider the emission stage.

The potential displacement field V_0 and MW field $V_1\sin\omega t$ are applied to the cathode. Thus in the AB gap the full voltage is equal to $V(t)=V_0+V_1\sin\omega t$. If ABCD system with BC drift space has size equal to the wavelength λ, the bunch with the size 0.5λ is formed in the field as results of oscillations RLC circuit. During this the displacement voltage is much more than MW component $V_1\sin\omega t$. MW component modulates cathode emission and the electron current coincides on phase with voltage at AB gap. The grouping beam consumes energy in positive half-period of MW component. The second stage of grouping begins from the movement moment and beam acceleration in AB gap in V_0. The consumption of energy during acceleration leads to the voltage change in RLC contour and in the line with distributed parameters. In the first approximation we take that this change occurs on harmonic law $U_l= U_{0l}\cos(\omega t+\phi)$, where ϕ is phase delay relatively U_1. The AB gap from power supply source (6) will be charged and its voltage will change according $U_J=U_0\cos\omega t$. In feeding line the voltage changes the same but with ϕ phase shift. During the entrance of the bunch into CD in accelerating phase additional acceleration takes place (implementation scheme - accelerator), and in braking phase - the energy transferred to the bunch in AB returns to the ABCD system (implementation scheme - generator). In last case the electrons oscillate having ordered movement due to phase grouping. During this the current in RLC resonance contour increases till the level determined by concordance of bunch energy parameters and excited wave and is limited by system perveance. During the experimental studies of the accumulation of oscillating electrons under 300 kV potential the electron current growth is observed in comparison with initial cathode current.

So the oscillations of electron bunch kinetic energy and electric field potential energy are excited and the synchronism between the oscillation frequency in beam and that in potential electric field, accompanied with field energy transfer into kinetic energy of charged particles or electromagnetic radiation, is automatically maintained.

Let us consider the structure of fields originating in ABCD. The electromagnetic field in resonator may be presented in the form

$$\vec{E} = \sum_{j\rangle 1}^{\infty} \alpha_j \vec{E}_j , \tag{1}$$

where $\vec{E}_j$ - nonzero solutions of homogenious Maxwell equations describing the electric field structure on the frequency ω_j .

The value α_j is proportional to the function

$$A_j(\omega) = \frac{1}{\omega^2 - \omega_j^2} , \tag{2}$$

where ω - the frequency of electromagnetic oscillations in resonator. At small losses in resonator ω_j values have small imaginory part and as it is seen from (1) and (2) while approaching ω to Rω_j the field amplitude in resonator sharply increases. That α_j coefficient corresponding to given ω_j becomes many times bigger than others and field structure $\vec{E}$ practically coincides with corresponding $\vec{E}_j$. It is of interest to consider the structure of $\vec{E}_j$ functions. Let is see the $\vec{E}$ field structure having longitudinal (parallel to Z axis) component. In this field the electron bunch takes acceleration in the movement direction along Z axis.

The structure of several oscillations of TE types(i.e. without longitudinal components of magnetic field) were calculated with the use of “AZIMUTH”[3] software. If electron bunch is in accelerating field AB it is necessary for it to be in drift tube during T time for symmetric type to reach accelerating field CD and T/2 time for anti-symmetric type to reach deceleration field, here T-oscillations period. The intrinsic system frequencies and non-loaded Q-s have the following values:

f_1=471 MHz (λ=0,63 m), f_2=1371 MHz (λ=0,218 m), f_3=2121 MHz (λ=0,141m); Q_1=12674, Q_2=22077, Q_3=25455.

Let us note some peculiarities of considered electric field. In drift tube Z-th component of electric field is practically absent. The whole electric field is concentrated in AB and CD regions. In close vicinity of drift tube ends there are peaks of the field due to the presence of the boundaries with small curvature radius. At decreasing the drift tube diameter the field peaks are approaching to the beam. Z-th components of electric fields in AB and CD are directed to one side for symmetric type of oscillations with drift about T, where T is period.

E_r component in drift tube is practically absent too. E_r peaks near drift tube ends are also due to the presence of the boundaries with small curvature radius. E_r longitudinal distribution in G space is close to field distribution in the coaxial line segment. On the Z axis E_r component is equal to zero. Near the axis there is field directed along r which is capable to focus or defocus the electron beam moving along the axis.

Let us note that for symmetric relatively the drift tube center points on one end (AB) there is accelerating and defocusing force, at the other end (CD) there is accelerating and focusing force from the electric field. After the time t=T/2, the forces direction reversed. The amplitudes of these fields depend on the size of “congruent” oscillating electron bunch. The physical picture of origination of resonances of the second and third oscillations types on the frequencies f_2=1371 MHz and f_3=2121 MHz as in the case of first type f_1=471 MHz is close to the resonance in coaxial line with TEM wave. In E_r component distribution of the second and third type of oscillations near Z axis the negative peaks amplitudes are much bigger than in the first type of oscillations. It means that the electron bunch coming in the moment $t=t_0$ into the region near Z=0 in accelerating field E_Z is exposed in more extent to focusing field $|E_r|$ than defocusing one $-|E_r|$, in comparison with the first type of oscillations.During the study of energy exchange proccesses of electron bunch and electromagnetic field the disc model was used, which gives good coincidence with experimental data. The beam is approximated by system of discs moving as a whole and the questions of the changing of radial dimensions of beam are not considered. For each particle-disc at each time-step the following equations are solved:

$$\frac{d\vec{P}(z,t)}{dz} = qE(z,t), \tag{3}$$

where $\vec{P}$ - the disc momentum with charge q, z - coordinate along movement axis, t - time, E - electric field on the axis.

Let us consider the case of grouping during passing the electron beam “in-flight”. In time $t=t_0$ the system of discs flies into ABCD. The disc length is $l_c= v_0TN$ where v_0 - the initial disc speed corresponding to the energy 300 keV, T - period of oscillations corresponding 471 MHz frequency and N - number of oscillation periods. The charge of each disc was chosen so that the disc system movement corresponded to 100 A current.

On Fig. 2 the plots of the density change of electron disc system along Z axis for various time moments are presented. The coordinates corresponding to the middle points of AB and CD gaps of resonator are shown by dashed lines.

It is seen that the disc density in the system changes with time and it is related to the interaction with vortex electric field, which being excited under the action of electron bunch modulates it by speed. As it is from Fig. 2, there is grouping during disc movement. So at Z=0.24 m disc system density is 0,078 $\bullet 10^{-5}$ Coul /m, and at Z=0,33 m it is $\approx$ 0,115 $\bullet 10^{-5}$ Coul /m, i.e. the density change is $\approx$ 32%. In conclusion authors would like to express deep gratitude to participants of JINR HEPL seminar for discussions and to academician A.M. Baldin for support.

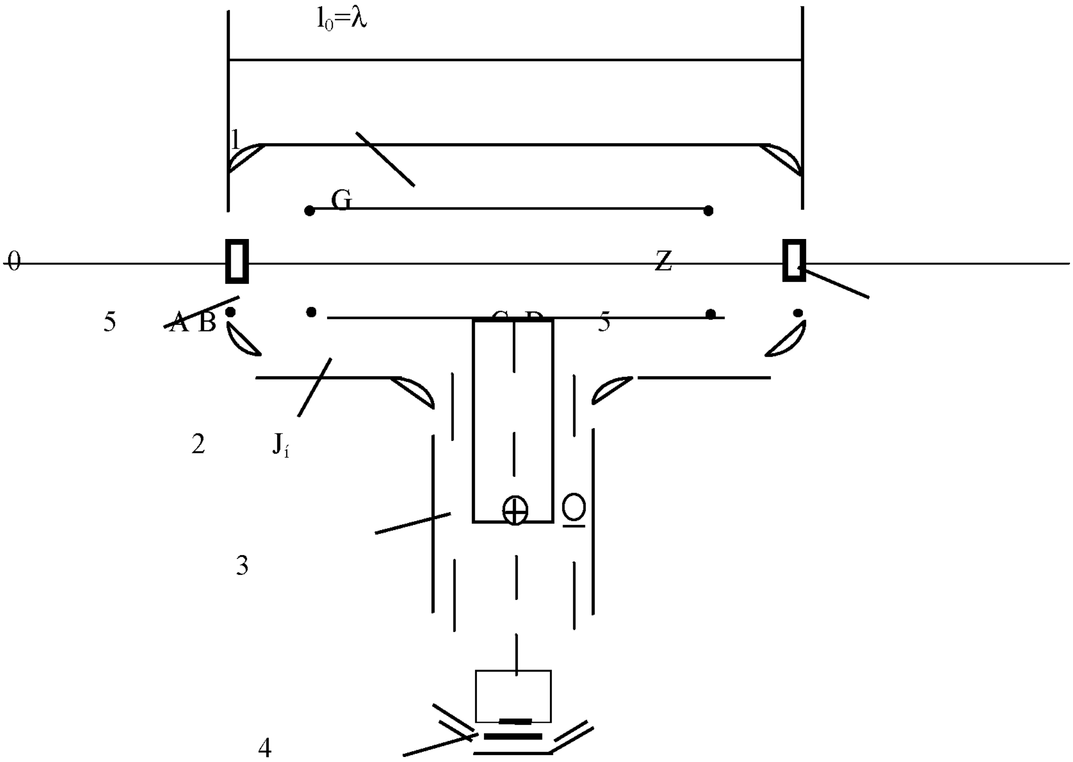

Fig.1. Two gap resonator with interaction regions AB and CD, drift tube - 1; outer screen of resonator - 2; coaxial delay line - 3; electrostatic field source - 4; electron source, cathodes - 5

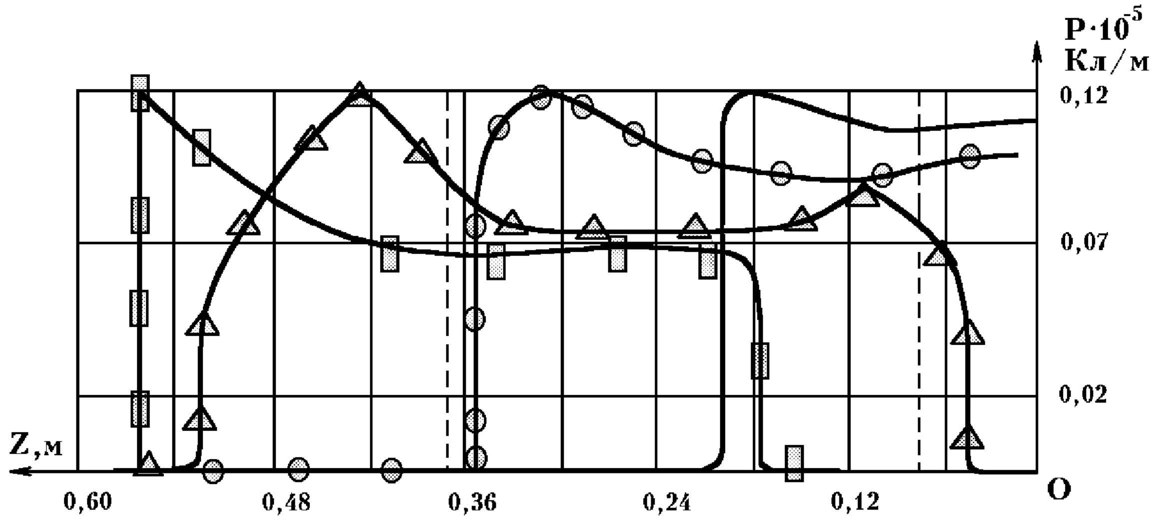

Fig.2. Dependences of the change of electron disc density - grouping for various time moments during the movement of disc along Z-axis in rotational electric field. The middles of the gaps AB and CD of ABCD system are shown by dashed lines.

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