NONSYNCHRONOUS ELECTRON TRANSPORTATION IN TRAVELLING WAVE OF LINAC

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Abstract

The results of theoretical and experimental research of uncaptured electrons transportation in the linac with travelling wave. Is was determined, that such particles are focusing by the accelerating wave fields. This focusing can be strong enough to overcome the influence of transverse magnetic field. The comparison of theoretical and experimental results has shown good concurrence.

INTRODUCTION

Down to the last time in all electron dynamics calculations the uncaptured particles influence was neglected, while all experimenters know about such particles existence. It was usually assumed, that their influence on accelerating particles dynamics can be neglected owing to uncaptured particles non-synchronous movement with respect to accelerating wave. However, the detailed research shows [1] that such an assumption is a mistaken one for some cases.

More faulty is an assumption about neglect of a non-synchronous electron flow because of large space charge. For ion focusing by electron beam a consideration of these particles is of general importance. This problem acquires special actuality in connection with research of the opportunity of electron transportation by a directed electromagnetic wave in space experiments, such, as sounding of the Moon surface or the Earth outer atmosphere for ecological monitoring [2].

1 THEORY

We shall consider the transverse electron motion in a direct travelling wave (TW) E_{01} field in a disk-loaded waveguide (DLW). Radial and phase electron motion in linac with TW was studied in [3], when the radial motion stability is provided by reverse wave field.

The electron transverse dynamics in DLW is described by equation [4]:

$$\frac{dp_r}{dt} = e(E_r - \beta c B_\vartheta) \qquad (1)$$

where p_r is the electron pulse transverse component, e - electron charge, E_r and B_ϑ - wave fields components.

For the electron motion analysis we'll neglect Coulomb interaction and the wave power dissipation in DLW walls ($\alpha = 0$). Also we'll assume that electrons velocity is constant ($\beta = \beta_z = const$).

Electromagnetic wave E_{01} main harmonic field components in DLW are [4]:

$$E_z = E_M J_0(k_c r) e^{j(\omega t - k_z z)}$$
$$E_r = jE_M J_1(k_c r) e^{j(\omega t - k_z z)} \qquad (2)$$

Here $k = 2\pi/\lambda$, $k = k/\beta$ph, $k_c = \sqrt{k^2 - k_z^2}$,

$J_0(x)$, $J_1(x)$ - Bessel functions, β_{ph} - wave phase velocity, λ - free space wave length.

Near the waveguide axis we have:

$$\lim_{k_c r \to 0} \frac{J_1(k_c r)}{k_c r} = \frac{1}{2} \quad ; \qquad \lim_{k_c r \to 0} J_0(k_c r) = 1$$

In this case expressions (2) will be:

$$E_z = E_M e^{j(\omega t - k_z z)}$$
$$E_r = \frac{1}{2} jE_M k_z r e^{j(\omega t - k_z z)} \qquad (3)$$
$$B_\vartheta c = \frac{1}{2} jE_M k r e^{j(\omega t - k_z z)}$$

Substituting E_r and B_ϑ form (3) into (1) and making a necessary transformations, we'll get the equation:

$$\frac{d^2\eta}{dx^2} + \frac{A}{4\pi\gamma} \cdot \frac{\beta_{ph}(1-\beta\beta_{ph})}{(\beta_{ph} - \beta)^2} \cos x = 0 \qquad (4)$$

where $\eta = r/\lambda$,
(r - electron deviation from the axis) $A = \frac{eE_M\lambda}{m_0 c^2}$,

$x = 2\pi\xi \frac{(\beta_{ph} - \beta)}{\beta\beta_{ph}} - \frac{\pi}{2}$, $\xi = z/\lambda$, (z - electron longitudinal coordinate)

m_0 is the electron rest mass, γ - relativistic factor.

The equation (4) is Matie equation of a kind:

$$\frac{d^2\eta}{dx^2} + (\delta + \varepsilon \cdot \cos x)\eta = 0 \qquad (5)$$

where $\delta = 0$, $\varepsilon = \frac{A}{4\pi\gamma} \frac{\beta_{ph}(1-\beta\cdot\beta_{ph})}{(\beta_{ph} - \beta)^2}$

The first stability region of equation (5) - interesting for practice - is defined by condition $|\varepsilon| \le 1/2$ [5], i.e.

$$\frac{A}{2\pi\gamma} \frac{\beta_{ph}(1-\beta\cdot\beta_{ph})}{(\beta_{ph} - \beta)^2} \le 1 \qquad (6)$$

For $\beta_{ph} = 1$, the inequality (6) can be simplified:

$$\frac{A}{2\pi\gamma} \frac{1}{1-\beta} \le 1 \qquad (7)$$

For weakly-relativistic electrons the condition (7) is easily fulfilled at the TW field amplitude E_r = 50...100 kV/cm, but for relativistic ones (γ>>1) it is practically impossible to fulfill this condition in DLW. For reverse TW relativistic electron beam (REB) focusing is not a problem. We'll note, that (REB) focusing by field of direct TW is possible at $\beta_{ph} < 1$ and $\beta_{ph} > 1$.

2 EXPERIMENT

A uniform DLW (a/λ =0.14, a/b = 0.35, t/λ = 0.038) with RF feed pulse power about 10 MW (f = 2798 MHz) is supposed to be used for experiments. Here the TW field amplitude $E_M \cong 80$ kV/cm. Initial beam energy W=50 keV (β=0.4; γ =1.0196). Substituting necessary values into (7), we'll get: $(A/2\pi\gamma)/(1-\beta) \cong 0.4$. So, the experimental conditions working point is in the stability region.

The maximum electron beam energy, corresponding to stability region border $(A/2\pi\gamma)/(1-\beta) = 1$ for given DLW parameters and feed power is about 500 keV.

The expression (3) can be transformed when taking into account a power dissipation:

$$E_z = E_M e^{-\alpha z} e^{j(\omega t - k_z z + \Psi_0)}$$
$$E_r = \frac{1}{2} j E_M k_z r e^{-\alpha z} e^{j(\omega t - k_z z + \Psi_0)} \qquad (8)$$
$$B_\vartheta c = \frac{1}{2} j E_M k r e^{-\alpha z} e^{j(\omega t - k_z z + \Psi_0)}$$

where α is the damping decrement, Ψ_0 - electron initial phase with respect to TW at the section input (z=0).

For equation (4) numerical integration it is more convenient to transform them in such a way :

$$\frac{d\eta}{d\xi} = \vartheta$$
$$\frac{d\vartheta}{d\xi} = \frac{A\pi}{\beta^2\gamma} \frac{\beta\beta_B - 1}{\beta_B} e^{-\alpha\lambda\xi} \cdot \sin(2\pi \frac{\beta_B - \beta}{\beta\beta_B} + \Psi_0) \qquad (9)$$

where ϑ - particle trajectory inclination corner at the point with coordinates (η, ξ).

For long linacs, as well as for electron transportation for a long distances the Earth magnetic field influences essentially on particle motion. Let's estimate the influence of external transverse magnetic field on the beam motion. This can be made by adding a supplemental term to the right part of the second equation (9):

$$M = A \frac{1}{\beta\gamma} \frac{cB_X}{E_M} \qquad (10)$$

Before making a research of electrons transverse dynamics, it is necessary to scrutinize their longitudinal motion. Since electrical field longitudinal component amplitude at section input $E_M \approx 83$ kV/cm, and the electron energy W = 50 keV, it should be expected, that electrons can not be transported in DLW for certain initial phases. Such electrons will lose energy at initial segment of section and get onto its wall. Initial phase Ψ_0 range, at which electrons are transported, can be defined by the numerical integration of the differential equation system:

$$\frac{d\gamma}{d\xi} = A \cdot sin(\varphi)$$
$$\frac{d\varphi}{d\xi} = 2\pi(\frac{1}{\beta} - \frac{1}{\beta_{ph}}) \qquad (11)$$

where φ is the electron phase with respect to TW.

The requisite initial phases are in the range from 80° to 240°. So 44 % of starting electrons will reach the DLW end. The field strength E_M = 80 kV/cm (P_0 = 10 MW) is not enough for capturing electrons into acceleration in section with β_{ph} = 1. Nevertheless, some particles can be accelerated to energy over 500 keV and leave stability region. As a result the number of particles transported to the section exit reduced to ~ 20%. RF-power decrease results in passing current increase, because the larger part of electron beam will pass initial waveguide segment and particles can not be accelerated in section to energy, appropriate to transverse stability loss.

The beam trajectory displacement compensating effect of the TW field was studied with the transverse magnetic field B_X action as an example. Under influence of field B_X =0.5 Gs at the length l=1 m axial particles displace on ~ 13 mm. TW permits to transport injected beam even at B_X = 5 Gs. Particle average displacements at the section output with (ΔR) and without (Δr) TW are given at Table 1.

Table 1: Particle average displacement

B, Gs	0.5	1.5	2.5	3.0	4.0	5.0
ΔR, mm	2.0	3.5	6.5	7.5	9.5	10.5
Δr, mm	13.4	40.1	66.8	80.1	106.8	133.5

Normalized output current v.s. magnetic induction $I(B_x)/I_{max}(B=0) = f(B_x)$ is shown in Fig.1.

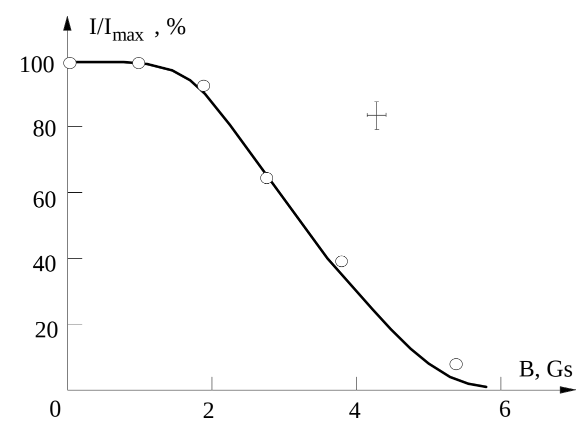

Figure 1: Normalized current at the section output dependence on normal magnetic field induction B.
——— theory; O - experiment.

Bunch emittance shape changes at section output v.s. B_X field for initial phase Ψ_0 = 180° are shown in Fig.2. With B_X value growth section acceptance reduction is also observed, that is stipulated by particles losses growth.

3 EXPERIMENTAL RESULTS

The installation for beam transportation experimental researches was constructed on the basis of electron linac U-17[6]. The installation block diagram is shown in Fig.3. Beam energy is 50 keV, output diameter is about 3 mm with angular divergence ~10^{-3}. Electron beam passes through the buncher 2 to DLW section with injection energy. RF-generator 4 with pulse power up to 20 MW exited TW in section that is used as a beam transportation chamber. Beam current is controlled at the section output and input by the induction monitors 5 and 6. Faraday cylinder 7 is placed at the section output outside of vacuum volume. It was used as indicator of accelerated current occurrence. Low-energy electron beam can not be extracted from vacuum volume and reach Faraday cylinder, therefore the current absence in it shows that the beam energy is not higher than 500 keV. Special coils 8 are used for creation a transverse magnetic field with induction up to 20 Gs.

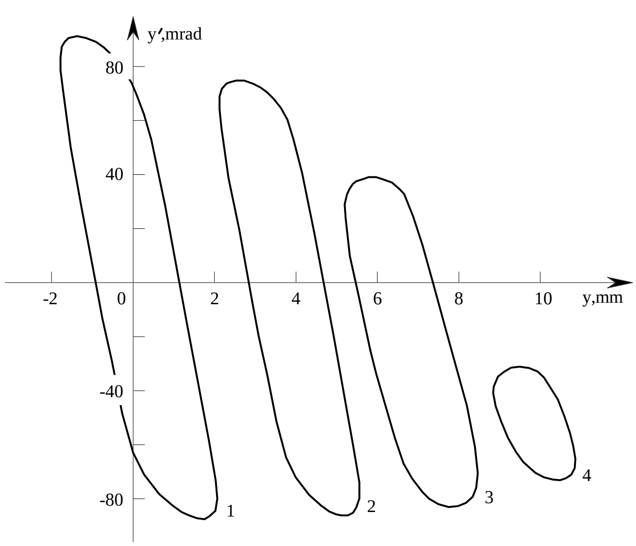

Figure 2 : Bunch emittance shape at section output.

As a result of measurements it was found out that a maximum current at section output was observed at RF-power about 2-3 MW. A further power increase resulted in passing current decrease that corresponds to theoretical results. Deviations of TW phase velocity did not influence on beam current pass, that also corresponds to theoretical results. It is necessary to note, that without RF-field a 50 keV electron beam passes in the transportation chamber not more than 1 m for initial angular divergence ~ 10^{-2}.

Calculated and experimental beam current at section output dependencies on transverse magnetic field for RF-power 10 MW are shown at Fig.1.

So theoretical and experimental researches show that electron beam (both relativistic and non-relativistic) transportation is possible in directed electromagnetic wave field with axially-symmetric or quadruple structure close to axis, along which beam passes, even at transverse magnetic field presence.

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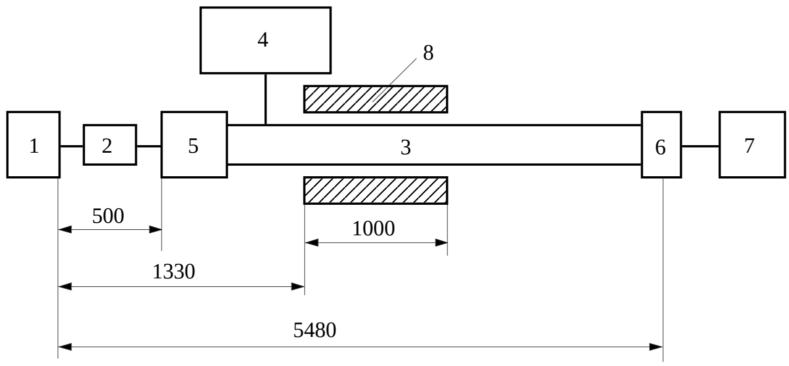

Figure 3 : Experimental installation block diagram.
1 - electron injector (50 kV); 2 - buncher; 3 - acceleration section (DLW); 4 - RF-generator; 5 and 6 - current monitors; 7 - Faraday cylinder.