INFLUENCE OF PHASE SHIFT OF ACCOMPANYING WAVE ON ELECTRON DYNAMICS IN TWO-BEAM ACCELERATOR DRIVER

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Abstract

The phase stability of the wave and steady bunching of the electrons in the driver with accompanying wave taking into account phase perturbation at RF power extraction is investigated. A special consideration of this pattern allows one to state additional requirements for the systems of power extraction. Results of numerical simulations of beam dynamics in the driver subject to the amount of phase perturbations are presented. A criterium of preservation of quasi-stationary state of the driver with high bunching extent is formulated.

INTRODUCTION

The concept of a two-beam accelerator (TBA), as a possible implementation scheme of an electron-positron collider, was proposed by A. Sessler [1]. Different TBA schemes based on induction linacs were discussed in [2–4]. A novel TBA scheme based on induction linac, one with accompanying electromagnetic wave, was proposed and studied in papers [5–8]. We consider an example of driver scheme (see Fig. 1) containing the injector, beam buncher and lengthy (possible of several hundreds meters) sequence of separate accelerating and RF-generating sections. The losses of the beam energy for the radiation are restored with the external section of induction linac. The sections alternate with transition chambers where the RF power is extracted partially.

The electron beam with the energy of 1–2 MeV produced in the injector is embedded into the buncher. It may be a traveling wave tube (TWT) operating in the amplification mode. As it was shown in [9,8] a high bunching degree could be obtained over a distance of ~ 1 m. The RF wave amplification and beam bunching in a TWT were investigated and registered experimentally [8].

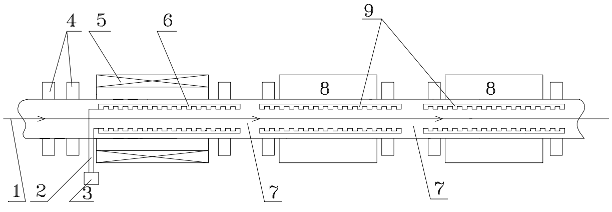

Figure 1: TBA driver scheme: 1) electron beam; 2) waveguide; 3) magnetron; 4) focusing magnetic lenses; 5) solenoid; 6) TWT – beam buncher; 7) sections of RF power extraction; 8) accelerating sections; 9) corrugated waveguide – slowing electrodynamic structure.

The scheme possesses following advantages:

1) possibility to provide phase and amplitude stability of the microwave. The phase stability can be reached at the expense of the quasi-continuity of the system;

2) as the pre-bunched beam is accelerated, there is no need of bunching at the energies of ~ 10 MeV.

According to the results of [5], the beam accompanied by synchronous wave preserves the bunching quality over hundreds of meters. If the electron bunches accompanied by the enhanced microwave are accelerated simultaneously in an external electric field, there exists a quasi-stationary state of the beam when the total power that the accelerating field puts into the beam, transforms into the RF power.

In the present paper the phase stability and the steadiness of electron bunching are under investigation taking into account influence of phase perturbation at RF power extraction.

MODEL

The modified system of equations [8] was used for the simulation of the beam dynamics taking into account phase perturbation at RF power extraction:

$$\frac{dW_j}{d\zeta} = -F\cos\psi_j + \varepsilon_0 \tag{1}$$

$$\frac{d\vartheta_j}{d\zeta} = 2\gamma_0^2(\Delta_0 + \frac{1}{\beta_{zj}} - \frac{1}{\beta_{z0}}) \tag{2}$$

$$\frac{dF}{d\zeta} = 2\pi J < \cos\psi_j > -\Gamma F \tag{3}$$

$$\frac{d\varphi}{d\zeta} = -\frac{2\pi J}{F} < \sin\psi_j > -\Phi \tag{4}$$

Here $W_j = \gamma_j/\gamma_0$ is the normalized energy of the j-th particle, $\zeta = k_0 z/2\gamma_0^2$ is the longitudinal dimensionless, $k_0 = \omega_0/c$ is the wavenumber, $\omega_0 = 2\pi f_0$ is the microwave frequency. The value ϑ_j is the phase of the j-th particle relatively to the electromagnetic field; φ – is the phase of the microwave complex amplitude ($\hat{F} = F e^{i\varphi}$), $\psi_j = \varphi + \vartheta_j$ is the total ponderomotive phase. The value $F = 2\gamma_0 e|E_z|/mc\omega_0$ is the dimensionless amplitude of the microwave longitudinal electric field. The parameter $\Delta_0 = 1/\beta_{z0} - 1/\beta_{ph}$ defines the initial detuning of the wave-particle synchronism; β_{zj} is the longitudinal dimensionless electron velocity, and β_{ph} is the microwave phase velocity the waveguide should be designed for. The brackets in Eqs. (3), (4) denote average over a bunch.

The parameter $\varepsilon_0 = 2\gamma_0 e|E_a|/mc\omega_0$ is the dimensionless value of the external electric field E_a; the parameter Γ is attenuation constant of the amplitude of the

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accompanying wave characterizing the distributed microwave losses along the driver. The phase perturbation is simulated with an imaginary additive for the Γ parameter. In corresponds to the second item of the Eq.(4) right side, $-\Phi$.

The beam-microwave interaction parameter J is proportional to the cubed Pierce parameter value: $J = \frac{2\gamma_0^3}{\pi m c^2/e} IZ$ where $Z = \frac{|E_z^2|}{2k_0^2 N}$ is the beam-wave coupling impedance (N is the wave power in the given mode).

EVALUATING CRITERUIM

The parameters of quasi-stationary state in the absence of phase perturbation are estimated from relations [8] $\psi \approx \approx \pi/2 - \varepsilon_0/F$, $\Gamma \approx 2\pi\varepsilon_0 J/F^2$, $2\gamma_0^2(1/\beta_{zj} - 1/\beta_{ph}) = -2\pi J/F^2$.

One can see from (4) that the influence of phase perturbation is to be not significant if

$$|\Phi| << 2\pi J/F. \quad (5)$$

As the range of stable phases is located in the vicinity of $\pi/2$, the $<\sin \psi_j>$ value is replaced by unity for the estimation.

SIMULATION RESULTS

Simulations were carried out for the sequence of accelerating sections of length $l_s = 50$ cm alternating with transition chambers ($l_t = 25$ cm) [5]. The RF power extracted within the bounds of the transition chambers. The starting parameters of the electron beam, acceleration fields and RF power extraction were taken closely to the conditions had been investigated in [5] (see Table 1).

Table 1. Beam and wave parameters.

Electron beam energy	~ 2.2 MeV (γ_0 ~ 5.31)
Electron current I_b	~ 500 A
Electron beam radius	~ 0.5 cm
Operating waveguide mode	E_{01}
Microwave frequency f_0	17 GHz (λ ~ 1.76 cm)
Starting microwave power in TWT	10 kW
External electric field E_a	1.5 MV/m
Attenuation constant Γ	0.112

A measure parameter of the phase perturbation is the additional phase advance of the wave in a transition chamber $\delta\varphi$ that is related to the dimensionless length of the transition chamber ζ_t by the relation $\Phi = \delta\varphi/\zeta_t$.

An estimation following criterium (5) for the given simulation parameters yields $|\delta\varphi| << 1.3$.

The simulation was carried out using the system (1–4) with particle-in-cell method (100–400 particles in bunch). In order to control computing accuracy at every step the integral of the system (1–4) was calculated:

$$\Xi = \langle W_j \rangle + \frac{F^2}{4\pi J} + \int \left(\frac{\Gamma F^2}{2\pi J} - \varepsilon_0 \right) d\zeta \cdot$$

The deviations from a constant were at the level of 10^{-6} in relative scale.

The spatial profiles of the microwave power within two fragments of driver (z = 100÷102 m and z = 175÷177 m) are shown in Figs. 2,3.

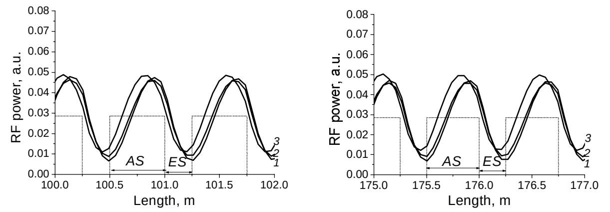

Figure 2: Spatial dependences of microwave power in two driver fragments for positive phase advance per cell: 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = 0.1\pi$; 3 – $\delta\varphi = 0.5\pi$. Locations of the accelerating sections and power extraction sections are marked as 'AS' and 'ES'.

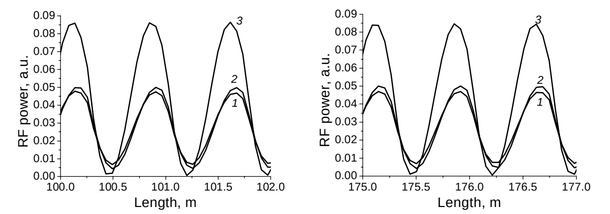

Figure 3: Spatial dependences of microwave power in two driver fragments for negative phase advance per cell: 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = -0.1\pi$; 3 – $\delta\varphi = -0.5\pi$.

As it is seen from Fig. 3, at moderate negative values $\delta\varphi < 0$ a growth of the gradient of power recovery in each accelerating-generating section is observed. It may be accounted for the partial compensation of the beam load for the wave that refines the synchronism relation.

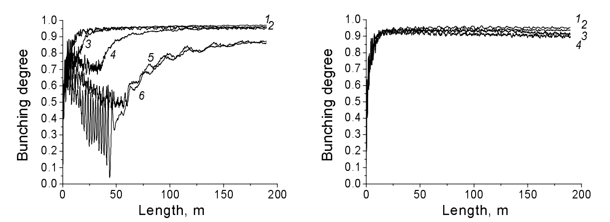

Figure 4: Spatial distributions of bunching degree. Left: 1 – $\delta\varphi$ = 0; 2 – $\delta\varphi = 0.1\pi$; 3 – $\delta\varphi = 0.4\pi$, 4 – $\delta\varphi = 0.5\pi$, 5 – $\delta\varphi = 0.7\pi$; 6 – $\delta\varphi = \pi$. Right: 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = -0.1\pi$; 3 – $\delta\varphi = -0.5\pi$, 4 – $\delta\varphi = -\pi$.

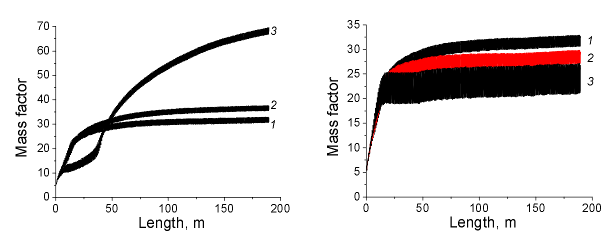

Figure 5: Spatial distributions of beam average energy. Left: 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = 0.1\pi$; 3 – $\delta\varphi = 0.5\pi$. Right: 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = -0.1\pi$; 3 – $\delta\varphi = -0.5\pi$.

Figs. 4 and 5 present simulated distributions of the bunching degree $B = |<e^{i\psi}>|$ and beam average energy at various $\delta\varphi$ values respectively.

Investigation of the bunch behaviour in the phase indicate a slight bunch intermixing due to "lagged" particles as in [5]. The effect intensifies if $\delta\varphi$ value grows. The energy spread increases while the particles, basically, remain quasi-trapped inside slowing-phase area. Phase portraits at $z \approx 200$ m for the cases of $\delta\varphi = 0$ and $\delta\varphi = 0.5\pi$ are shown in Fig. 6.

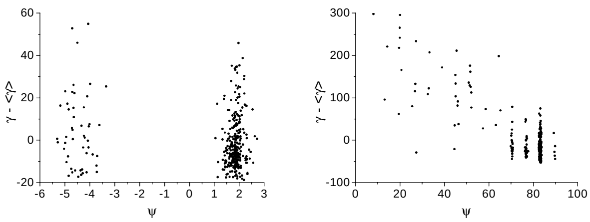

Figure 6: Phase portraits of bunches at $z \approx 200$ m for $\delta\varphi = 0$ (left) and $\delta\varphi = 0.5\pi$ (right).

The beam bunching degree remains stably high the particles keeping practically within a single-bunch separatrix at $|\delta\varphi| \leq 0.3$. It matches estimation over the criterium (5). At greater magnitudes of phase advance per cell, the bunching decays. Apparently it can arise from transition of a part of the bunch into the accelerating-phase area.

At positive phase advances per cell ($\delta\varphi > 0$) the quasi-stationary state is broken already at less magnitude. The particles fall into the accelerating-phase area faster in this case, affecting the beam bunching quality.

The analysis of the simulation results subject to the particle number N_p shows that at small values $\delta\varphi \leq 0.1\pi$ the results are practically unchanged remaining close to those for the original (non-perturbed) quasi-stationary regime. As an example, phase portraits at $z \approx 200$ m for $\delta\varphi = -0.1\pi$ in the cases of $N_p = 100$ and 200 are shown in Fig. 7.

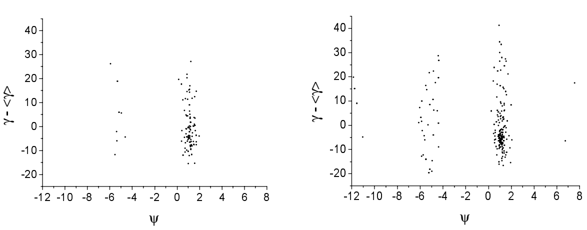

Figure 7: Phase portraits of bunches at $z \approx 200$ m for $\delta\varphi = -0.1\pi$ depending of the particle number in the simulation: $N_p = 100$ (left) and $N_p = 200$ (right).

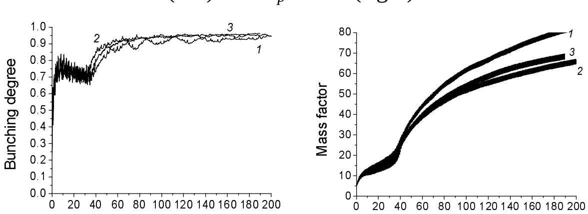

Figure 8: Spatial distributions of the bunching degree (left) and main bunch energy (right) for $\delta\varphi = 0.5\pi$ depending on the particle number in the simulation: 1 – $N_p = 100$, 2 – $N_p = 200$, 3 – $N_p = 400$.

For greater $\delta\varphi$ magnitudes the computing precision reduces, more observable dependence on N_p appears. However raising N_p up to 300–400 one obtains results stable enough. Fig. 8 presents distributions of bunching degree and main bunch depending on N_p for $\delta\varphi = 0.5\pi$.

CONCLUSIONS

Influence of phase perturbation at RF power extraction on the phase stability and the steadiness of electron bunching in the driver of two-beam accelerator with accompanying microwave has been explored by numerical simulation. A quasi-stationary state of the driver can be hold at moderate magnitudes of phase advance per cell of power extraction, of about 0.1π rad.

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