PHASE STABILITY IN TWO-BEAM ACCELERATOR DRIVER WITH ACCOMPANYING WAVE

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Beam-wave dynamics in two-beam accelerator driver with accompanying wave is studied with numerical simulations. Special attention is paid to the problems of phase stability and tolerances for microwave extraction facilities.

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1. INTRODUCTION

A. Sessler proposed the concept of a two-beam accelerator (TBA) [1], as a possible implementation scheme of an electron-positron collider. A novel scheme of the TBA driver based on an induction linac, the driver with accompanying electromagnetic wave, was proposed and studied in [2,3]. (References for other TBA schemes based on induction linacs can be found in the bibliography therein.)

According to the results of [2], there exists a quasi-stationary state of a beam over hundreds of meters when the total power that the external accelerating field puts into the beam, transforms into the microwave power.

In the present article, the phase stability and the steadiness of electron bunching are under investigation taking into account the influence of possible phase perturbations at microwave extraction. Tolerances for microwave extraction facilities are estimated.

2. MODEL

The modified system of equations [3] was used for the beam dynamics simulation taking into account phase perturbation at microwave power extraction:

$$\frac{dW_j}{d\zeta} = -F\cos\psi_j + \varepsilon_0; \quad (1)$$

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

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

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

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 coordinate, $k_0 = \omega_0/c$ 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 relative 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 phase. The value $F = 2\gamma_0 e|E_z|/mc\omega_0$ is the dimensionless amplitude of the longitudinal microwave 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 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 the attenuation constant characterizing the microwave loss distributed along the driver. The phase perturbation is simulated by the second term $-\Phi$ in the right hand side of Eq.(4).

The beam-microwave interaction parameter J is proportional to the cube of Pierce parameter value: $J = \frac{2\gamma_0^3}{\pi mc^2/e} IZ$, where $Z = \frac{|\tilde{E}_z^2|}{2k_0^2 N}$ is the beam-wave coupling impedance ($\tilde{E}_z^2$ is the effective amplitude of the longitudinal electric field of the microwave, and N is the wave power in the given mode).

3. STABILITY OF QUASI-STATIONARY STATE

Since the equilibrium phase of quasi-stationary state is located in the vicinity of $\psi = \pi/2$ [3], one can see from Eq.(4) that the influence of phase perturbation is to be not significant under the condition

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

To study the influence of phase perturbation we considered the set of accelerating sections each with length of $l_s = 50$ cm being alternated by transition chambers ($l_t = 25$ cm) [2]. The microwave power was extracted only within the transition chambers. The starting parameters of the electron beam, accelerating fields, and microwave extraction have been chosen to be close to the conditions studied in [3]. Electron beam energy was taken to be ~ 2.2 MeV (γ_0 ~ 5.31), electron current I_b ~ 500 A, electron beam radius r_b ~ 0.5 cm, operating waveguide mode – E_{01}, microwave frequency $f_0 = 17$ GHz (λ ~ 1.76 cm), starting microwave power in TWT P_0 ~10 kW, external electric field $E_a = 1.5$ MV/m, attenuation constant $\Gamma = 0.112$.

The phase perturbation in the transition section results in the additional microwave phase advance $\delta\varphi$ connected with the dimensionless length of the transition chamber ζ_t by the relation $\Phi = \delta\varphi/\zeta_t$. Estimation according to the criterion (5) for the chosen simulation parameters yields $|\delta\varphi| << 1.3$.

The simulations have been performed by means of the macroparticle code (100…400 macroparticles per bunch) using Eqs.(1)-(4). In Fig.1, the calculated spatial profiles of the microwave power within a fragment of the driver (z = 175…177 m) are shown.

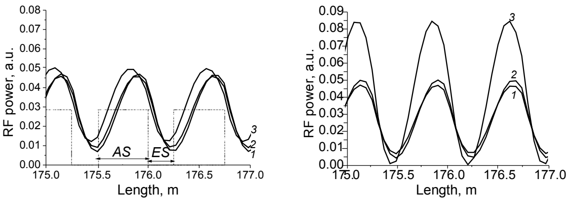

Fig.1. Spatial dependences of microwave power in a driver fragment for different phase advances per cell: (left) 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = 0.1\pi$; 3 – $\delta\varphi = 0.5\pi$; (right) 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = -0.1\pi$; 3 – $\delta\varphi = -0.5\pi$. Positions of accelerating sections (AS) and power extraction sections (ES) are shown symbolically

It is seen from Fig.1 that the power distributions preserve at $|\delta\varphi| = 0.1\pi$. But already at $|\delta\varphi| = 0.5\pi$ the distributions change significantly that means the decay of the quasi-stationary state.

Fig.2 presents the simulated distributions of the bunching degree $B = |\langle e^{i\psi}\rangle|$ and the bunch average energy at various $\delta\varphi$ values.

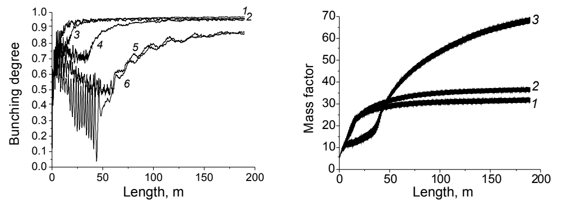

Fig.2. Spatial dependences of bunching degree (left) and of bunch average energy (right) for different phase advances per cell: (left) 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = 0.1\pi$; 3 - $\delta\varphi = 0.4\pi$, 4 – $\delta\varphi = 0.5\pi$, 5 – $\delta\varphi = 0.7\pi$; 6 – $\delta\varphi = \pi$; (right) 1 – $\delta\varphi = 0$; 2 – $\delta\varphi = 0.1\pi$; 3 – $\delta\varphi = 0.5\pi$

On can see the beam bunching degree remains high stably until $|\delta\varphi| < 0.3\pi$. At greater magnitudes of phase advance per cell, a dip of the bunching degree occurs. It apparently should be connected with transition of some part of the bunch into the accelerating-phase area. The stable character of the beam energy are broken down approximately at $|\delta\varphi| = 0.3\pi$.

Study of the bunch behavior in the phase space shows that the particles are actually trapped within the single-bunch separatrix at $|\delta\varphi| \leq 0.3$. Phase portraits at $z \approx 200$ m for the cases of $\delta\varphi = 0$ and $\delta\varphi = 0.5\pi$ are shown in Fig.3.

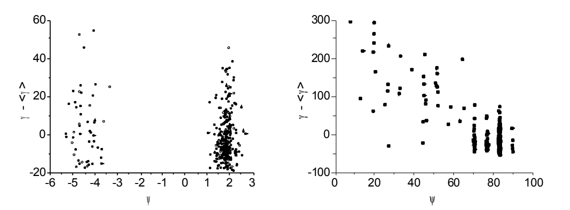

Fig.3. Phase portraits of bunches at $z \approx 200$ m for $\delta\varphi = 0$ (left) and $\delta\varphi = 0.5\pi$ (right)

The critical value $|\delta\varphi| \approx 0.3\pi$ matches the estimation according the criterion (5).

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 independent on N_p remaining close to those for the original (non-perturbed) quasi-stationary regime. For greater $\delta\varphi$ magnitudes the accuracy of the results reduces, and a greater dependence on N_p appears. But increase of N_p up to 300…400 leads to sufficiently stable results.

4. RANDOM PHASE PERTURBATIONS AND TOLERANCES OF AMPLITUDE AND PHASE ERRORS

The errors of RF field amplitude and phase in accelerating structures of linear colliders, both from pulse to pulse and over the accelerator length, are exposed to rigid limitations because such errors lead to the beam fluctuations.

An analysis of influence of random perturbation of RF field amplitude and phase at the entrance of accelerating sections of a linear collider designed under traditional scheme where separated sections were powered with independent sources has been carried out in [4]. By an example of the NLC project for the energy of 1 TeV it was shown that in order to reduce the error in the final beam energy to the level of 0.1%, the RF amplitude and phase jitters in every accelerating unit should be not greater than 2% and 3°, respectively.

In contrast to the traditional scheme of accelerating structure powering, the sections of the main linac (accelerating up to TeV energies) in the TBA are powered from the driver where a high-current beam over large length of the collider is used for the microwave generation [1]. So, both random errors in every separate extraction facility and random perturbations from the preceding sections correlated over the electron beams contribute to the random perturbations in the amplitude and phase of the microwave extracted from the driver.

In the studied scheme of the driver with accompanying electromagnetic wave, the microwave is extracted regularly over the whole length for the powering the accelerating structures of the main linac. Correspondingly tolerances of the phase and amplitude jitter arising from the conditions of the main beam acceleration should be satisfied in the facilities of power extraction.

To study the influence of phase perturbation we considered the same example of driver that in Section 3. The Φ value was set as a random quantity (relatively to the number transition chamber) with normal (Gaussian) distribution around the average $\langle\delta\varphi\rangle = 0$ with the dispersion $\sigma_{\delta\varphi}$. The beam dynamics was simulated at various values of $\sigma_{\delta\varphi}$ for different seeds of random sequences of $\delta\varphi$ values in the microwave extraction sections.

As a consequence of Eq.(3), the extracted power (per unit length) within the extraction sections is coupled with the dimensionless power of the accompanying wave $W \sim F^2$ by the relation $U = 2\,GW$.

As a measuring function of instabilities, the deviations of the phase and amplitude from the non-perturbed distributions (i.e. the case of $\langle\delta\varphi\rangle = \sigma_{\delta\varphi} = 0$) were considered. The non-perturbed distribution of the dimensionless power W_0 of the accompanying wave coincides with the curves 1 in Fig.1.

To find the general characteristics of the instability we realized large enough number of seeds of the values of the phase advance over an extraction cell at various values of $\sigma_{\delta\varphi}$. The results of simulation were then averaged over the seeds.

Fig.4 presents the results of statistical data manipulation (over 100 seeds) for obtained spatial dependencies of the power of the accompanying wave and by the example of $\sigma_{\delta\varphi}\approx 0.3°$. The similar results have been obtained for power of the extracted wave *U*.

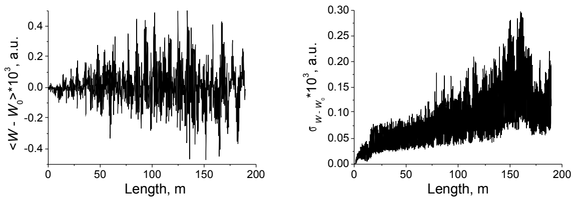

Fig.4. Statistical characteristics of the spatial dependence of the deviation of the accompanying microwave power from the non-perturbed regime at $\sigma_{\delta\varphi} \approx 0.3°$. The averages over 100 random seeds of the phase advance at the extraction cell are shown: (left) averaged value (central tendency); (right) dispersion

In Fig.5 the results of statistical data manipulation for the phase of the accompanying wave are shown (the deviation from the non-perturbed distribution φ_0 is considered).

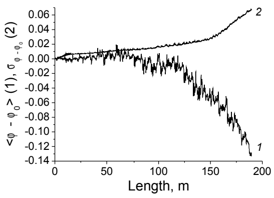

Fig.5. Statistical characteristics of the spatial dependence of the deviation of the extracted microwave phase from the non-perturbed regime at $\sigma_{\delta\varphi} \approx 0.3°$. The averages over 100 random seeds of the phase advance at the extraction cell are shown. Curve 1 – averaged value, curve 2 – dispersion

One can see from Fig.4 that the wave power deviation are of order of 0.0001 in the dimensionless units while the power itself amounts to hundredth parts of unity in the same units (0.01…0.05, Fig.1). For the extracted wave, deviations were found to be about 10^{-6} with respect to the level of ~ $3{\cdot}10^{-4}$. Thus, the relative deviations of the power of both the accompanying and the extracted waves amount to tenth part percent. It gets into the amplitude tolerance of 2% for the example [4] with a reserve. At the same time, according to the Fig.5, the phase instability scales to 0.1 rad. It is comparable with the tolerance of 3° for the example [4]. The accumulative nature of the power and phase deviations results from correlated contributions of perturbations in separate cells.

5. 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.

As a result of the performed numerical simulation the following conclusion should be drawn: under typical range of the phase advance per cell at the level of several tenth parts of a degree, the phase and amplitude instabilities are of small scale enough that is acceptable for the transmission of the power to the main linac of the collider.

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ФАЗОВАЯ СТАБИЛЬНОСТЬ В ДРАЙВЕРЕ ДВУХПУЧКОВОГО УСКОРИТЕЛЯ С СОПРОВОЖДАЮЩЕЙ ВОЛНОЙ

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В численном моделировании исследуется динамика взаимодействия электронного пучка и волны в драйвере двухпучкового ускорителя с сопровождающей электромагнитной волной. Особое внимание уделено вопросам фазовой стабильности и допусков для систем вывода мощности.

ФАЗОВА СТАБІЛЬНІСТЬ У ДРАЙВЕРІ ДВОПУЧКОВОГО ПРИСКОРЮВАЧА З СУПРОВІДНОЮ ХВИЛЕЮ

А.В. Єлжов, Е.А. Перельштейн

У чисельному моделюванні досліджується динаміка взаємодії електронного пучка і хвилі в драйвері двопучкового прискорювача з супровідною електромагнітною хвилею. Особлива увага приділена питанням фазової стабільності і допусків для систем виводу потужності.