ОБЪЕДИНЕННЫЙ
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Дубна

97-5

E9-97-5

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THEORETICAL STUDY OF POWER RELATIVISTIC AMPLIFIERS FOR ELECTRON BEAM BUNCHING*

Submitted to the Particle Accelerator Conference (PAC-97), May 12 — 16, 1997, Vancouver, Canada

*This work was supported by the International Science Foundation (Soros), grant No.JLD100, and by the Russian Fund of Basic Research, grant No.96-02-17395

1997

1 INTRODUCTION

At present the next generation of electron-positron linear colliders with energy in the TeV range are being studied throughout the world. They will require high gradients (up to ~100 MV/m) to prevent accelerators from being too long and consuming too much power. In order to solve this problem two schemes based on the two beam accelerator (TBA) concept are being studied now [1], [2]. In a TBA the first accelerator produces a high current electron beam. The beam must be bunched along all collider length. Hereupon these bunches generate high-frequency electromagnetic power that can supply the accelerating cavities of the second accelerator, which accelerates the main beam into the TeV range of energies.

There are some schemes for generating of such high-intensity drive beam bunches. One of such scheme was tested in [3], where the Choppertron used transverse velocity modulation of a 2.5 MeV, 1 kA drive beam in a deflection cavity with a collimator for production of the longitudinal beam bunching. Another idea for generating such drive beam is to use the bunching which occurs in the free electron laser (FEL) [4]. Detailed numerical calculations were made in [5], [6] where the relevant figures of merit, the efficiency of bunching as a function of beam energy, current, and emittance were studied. The effects of wiggler errors, energy spread, beam misalignment, beam quality and space charge effects were also considered. It was shown in [5], [6] that a high degree of bunching can be rather easily achieved in a short FEL amplifier. But sensitivity of the phase stability to the variation of the beam energy during the pulse and rapid debunching upon exiting the FEL were serious problems.

In [7], [8], [9] the first direct observation of the bunching of a relativistic electron beam, produced by a high power FEL interaction, was presented. Measurements, using both electromagnetic and optical techniques, were performed at the wiggler exit, and clearly demonstrated the beam bunching.

This work is devoted to the computer simulation and comparison of the bunching of a relativistic electron beam produced by a FEL and by a travelling wave tube (TWT). The calculation results of the electron beam bunching in the FEL are also compared with the experimental results obtained in [7], [8]. With the help of rather simple model it is shown that one can obtain the electron beam bunching in the TWT at a shorter length as compared with the FEL because the space gain in the TWT is higher than in the FEL.

2 BEAM BUNCHING EQUATIONS

The following equations describe the self-consistent spatial problem of the movement of a relativistic electron beam in a microwave electromagnetic field, which can be used both for a TWT and for a FEL in the Compton regime:

$$\frac{d\gamma_j}{dZ} = -\kappa a_s \sin\psi_j \qquad (j = 1, ..., M) \tag{1}$$

$$\frac{d\theta_j}{dZ} = \frac{1}{\beta_{\parallel j}} - \frac{1}{\beta_{ph}} \tag{2}$$

$$\frac{da_s}{dZ} = \eta < \sin\psi_j > \tag{3}$$

$$\frac{d\varphi}{dZ} a_s = \eta < \cos\psi_j > . \tag{4}$$

Here M is the number of electrons (macroparticles), γ_j is the j^{th} electron energy ($E_j = m_o c^2 \gamma_j$) in units of $E_o = m_o c^2$; m_o is the electron rest mass, c is the light velocity, $Z = z\omega_o/c$ is the dimensionless longitudinal coordinate, and ω_o is the microwave frequency.

The value θ_j is the phase of the j^{th} electron relative to the electromagnetic field; φ is the phase of the microwave complex amplitude ($\hat{a} = a_s e^{i\varphi}$). $\psi_j = \varphi + \theta_j$ is the total ponderomotive phase. The brackets in the equations (3) and (4) denote an average over the bucket.

The value a_s is the dimensionless amplitude of the microwave electric field

$$a_s = \frac{eE_s}{m_o \omega_o c}, \tag{5}$$

where e is the electron charge; E_s is the amplitude of the microwave electric field.

The parameter κ is the microwave coupling coefficient. Its value depends on the type of used device.

The parameter η in equations (3) and (4) is given by [10]

$$\eta = (\frac{I_b}{I_A}) \cdot \frac{2\kappa}{N}. \tag{6}$$

The constant $I_A = m_o c^3/e \simeq 17$ kA; N is the norm of the electromagnetic wave; $\beta_{\parallel j}$ is longitudinal electron velocity and β_{ph} is the microwave phase velocity.

3 SIMULATION OF BUNCHING PROCESS IN FREE ELECTRON LASER

To obtain the system of differential equations for simulation of the bunching process in a FEL we have used the corresponding equations [10], [11] taking into account the effective frequency shift ω_p connected with the plasma wave in a beam. It is similar to the accounting of a plasma wave in the resonance condition in [7], [8]. Finally we get:

$$\frac{dw_j}{dZ} = \kappa_{1j} a_s \sin\psi_j \qquad (j = 1, ..., M), \tag{7}$$

$$\frac{d\theta_j}{dZ} = -\frac{(k_w + k_s)\cdot c}{\omega_o} + 1 + \frac{\omega_p}{\omega_o \beta_z} + \frac{1 + a_w^2 + a_w a_s \cos\psi_j}{2\gamma_o^2 (1 - w_j)^2}, \tag{8}$$

$$\frac{da_s}{dZ} = \eta_1 < \frac{\sin\psi_j}{1 - w_j} >, \tag{9}$$

$$\frac{d\varphi}{dZ} a_s = \eta_1 < \frac{\cos\psi_j}{1 - w_j} >, \tag{10}$$

where

$$\kappa_{1j} = \frac{a_w}{2\gamma_o \gamma_j} = \frac{\kappa_o}{1 - w_j}. \tag{11}$$

Here $w_j = 1 - E_j/E_o$ is the relative change of the j^{th} electron energy; $k_w = 2\pi/\lambda_w$; λ_w is the wiggler period; k_s is the axial wavenumber for the waveguide resonance mode inside the wiggler; $\gamma_o = 1/\sqrt{1 - \beta_o^2}$ is the electron beam initial energy; β_z is the longitudinal dimensionless velocity of the resonant particle, determined from the relations: $\beta_z = \sqrt{\beta_o^2 - \beta_\perp^2}$, $\beta_\perp/\beta_z = a_w/\gamma_o$; $\kappa_o = a_w/2\gamma_o^2$ and ω_p is the relativistic plasma frequency:

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_o}} \cdot \frac{1}{\gamma_z \gamma^{1/2}}; \tag{12}$$

n_e is the electron beam density and $\gamma_z = 1/\sqrt{1 - \beta_z^2}$. The parameter a_w is given by

$$a_w = \frac{e B_w \lambda_w}{2\pi m_o c^2}; \tag{13}$$

where B_w is the wiggler magnetic field amplitude. The coefficient η_1 is given by the following expression:

$$\eta_1 = \left(\frac{I_b}{I_A}\right) \cdot \frac{2\kappa_o \gamma_o}{N}. \tag{14}$$

For our simulation we used the electron beam and FEL parameters from [7], [8]:

- electron beam energy	~2.2 MeV ($\gamma_o \simeq 5.31$, $\beta_o \simeq 0.982$)
- electron current inside the wiggler I_b	~ 500 A
- electron beam radius	~0.5 cm
- wiggler period λ_w	12 cm
- wiggler field B_w	1.1 kG
- microwave frequency f_o	$3.5 \cdot 10^{10}$ Hz (H_{11} mode).

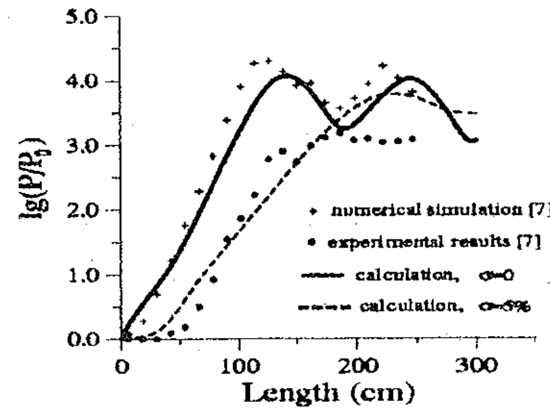

Figure 1: The FEL microwave power versus the interaction length.

In [7], [8] the initial microwave power of 10 kW was injected into the circular waveguide in the H_{11} mode. The corresponding microwave electric field amplitude $a_s \simeq 4.4 \cdot 10^{-4}$ (see formula 5). Then we obtain the following parameter values from (11), (13) and (14): $\kappa_1 \simeq 0.022$ and $\eta_1 \simeq 2.5 \cdot 10^{-4}$ (the norm of wave $N = N_{11} \simeq 24.3$ in our case).

We define the bunching parameter B in the same manner as in [7]: $B = |\langle e^{i\psi} \rangle|$.

We also simulated the initial energy spread in the electron beam with the help of 2000 electrons which had been distributed in 40 phase points from $\theta = 0$ through $\theta = 2\pi$ and in every point 50 electrons had the gaussian distribution upon the relative energy with dispersion σ.

The system of differential equations (7 - 10) was solved with the help of the Runge-Kutta method for the parameter values mentioned above.

Fig.1 shows the results of the calculations of the FEL microwave power and their comparison with the results obtained in [7], [8]. To take into account the wiggler adiabatic entrance in [7], [8], we suppose the exponential power growth to start at 48 cm from the wiggler beginning. This point corresponds to zero length in Fig.1.

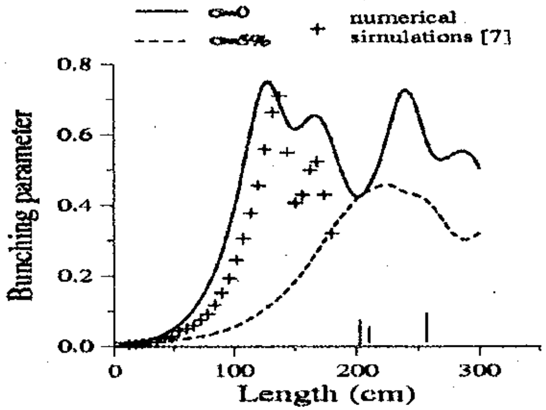

Figure 2: The FEL bunching parameter versus the interaction length.

As one can see from Fig.1, these results are in a rather good agreement. Comparing the distribution of the microwave power along the wiggler obtained experimentally in [7], [8], one can draw a conclusion that the difference observed between the maximum microwave power and the calculated one for monoenergetic beam in ~10 times may be partially caused by the initial energy spread in the electron beam.

Fig.2 shows the calculated spatial evolution of the bunching parameter B. The vertical lines in Fig.2 correspond to the time dependence measurements of the bunching parameter along the beam [7]. The regular wiggler part ends at the length approximately equal to $z \simeq 170$ cm. Our further along the wiggler calculations are not sufficiently correct. So comparing the obtained curve corresponding $\sigma = 5\%$ and the experimental results one can suppose that the low experimental bunching parameters in [7] ($B \sim 0.1$) were due to the beam energy spread influence. The maximum bunching is reached in the region of maximum micromave power values.

The electron distribution in $\{\gamma, \psi\}$ space for $B \simeq 0.75$ in the case of initially monoenergetic beam ($\sigma = 0$) is plotted in Fig.3.

The dependence of the calculated microwave power at the wiggler exit on the initial electron beam energy ($\sigma = 0$) is shown in

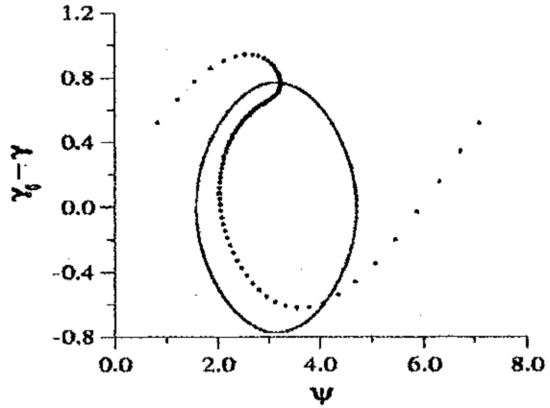

Figure 3: Phase space of a bunched beam in the FEL at z = 129.5 cm, corresponding to the maximum bunching parameter. The solid line is the calculated bucket boundary.

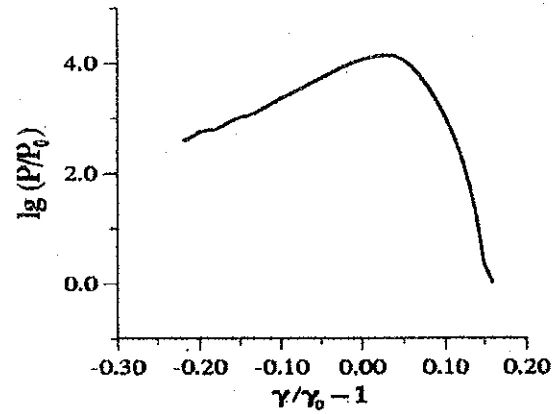

Figure 4: The dependence of the exit microwave power on the initial electron beam energy.

Fig.4. One can see from this resonance curve that it is an asymmetric one and its maximum corresponds to $\gamma_o \simeq 5.6$ for our parameter values.

4 SIMULATION OF BUNCHING PROCESS IN TRAVELLING WAVE TUBE

To simulate the electron beam bunching in a TWT amplifier based on the corrugated waveguide, we used the following system of differential equations:

$$\frac{dw_j}{dZ} = \kappa_2 a_s \sin\psi_j \qquad (j = 1, ..., M), \tag{15}$$

$$\frac{d\theta_j}{dZ} = \frac{1 - w_j}{\sqrt{(1 - w_j)^2 - \frac{1}{\gamma_o^2}}} - \frac{1}{\beta_{ph}}, \tag{16}$$

$$\frac{da_s}{dZ} = \eta_2 < \sin\psi_j >, \tag{17}$$

$$\frac{d\varphi}{dZ} a_s = \eta_2 < \cos\psi_j >, \tag{18}$$

where

$$\kappa_2 = \frac{\pi l_o}{\gamma_o d}, \tag{19}$$

l_o is the corrugation amplitude and d is the corrugation spatial period [12]. The parameter η_2 is the following:

$$\eta_2 = (\frac{I_b}{I_A}) \cdot \frac{2\kappa_2\gamma_o}{N_{01}}, \tag{20}$$

where N_{01} is the norm of E_{01} type wave in the TWT.

We chose the following electron beam and E_{01} type electromagnetic wave parameters for our simulation:

- electron beam energy ~2.2 MeV ($\gamma_o \simeq 5.31$)
- electron current inside the TWT I_b ~ 500 A

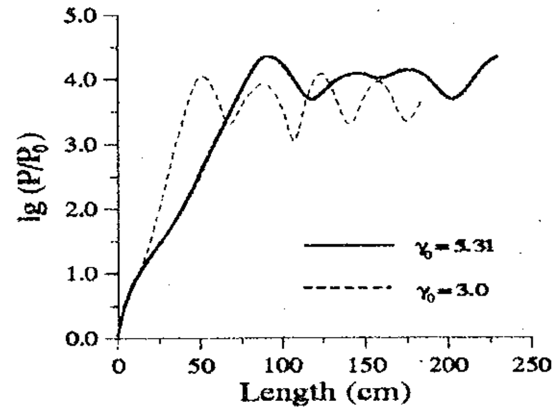

Figure 5: The TWT microwave power versus the interaction length.

- electron beam radius ~0.5 cm
- microwave frequency f_o $17 \cdot 10^9$ Hz ($\lambda \simeq 1.76$ cm)
- initial microwave power in TWT 10 kW.

The parameter d value was found from the dispersion curve of the corrugated waveguide having $l_o = 1$ mm, radius $r_o \simeq 1.8$ cm and when $\beta_{ph} \simeq 0.982$. The dispersion curve was calculated with the help of the code URMEL. In our case d was ~5.8 mm; $k_s d = \frac{2\pi}{3}$. Then we have from (19) $\kappa_2 \simeq 0.102$ and from (20) $\eta_2 \simeq 3.2 \cdot 10^{-3}$ (the norm of wave $N_{01} \simeq 10$ in our case). For the initial microwave power ~10 kW in the TWT the corresponding dimensionless amplitude of the microwave electric field $a_s \simeq 6.8 \cdot 10^{-4}$.

Fig.5 represents the calculated evolution of the microwave power as a function of the interaction length along the TWT. The two curves correspond to the initial electron beam energy 2.2 MeV and 1 MeV.

As one can see from Fig.1 and Fig.5, the bunching length of the electron beam with energy 2.2 MeV is in ~1.5 times less in the TWT than in the FEL. The plot of the electron distribution in $\{\gamma, \psi\}$ space for the maximum bunching parameter $B = 0.61$ (before the wave saturation in the TWT) is shown in Fig.6. We can see from Fig.3 and Fig.6 that the energy spread in the bunches

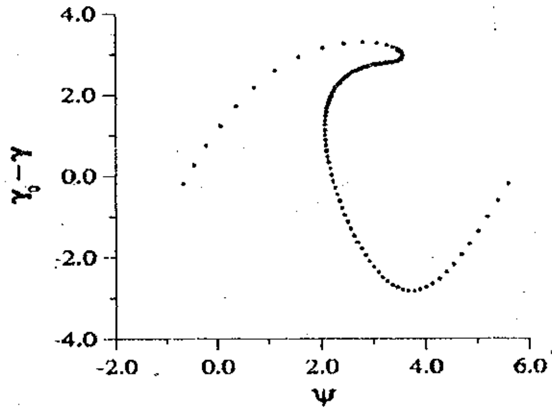

Figure 6: Phase space of a bunched beam in TWT at $z = 88.3$ cm, corresponding to the maximum bunching parameter.

is larger in the TWT than in the FEL. One can also see from Fig.5 that the bunching length in the TWT decreases essentially when the initial beam energy is diminished.

The dependence of the microwave power at the TWT exit on the energy spread (2.2 MeV) is rather weak. This dependence becomes sufficient when the initial electron beam energy decreases down to 1 MeV.

5 CONCLUSIONS

Our simulations showed that a high degree of bunching of the electron beam having the energy in the range 1 - 2 MeV can be rather easily achieved in a short travelling wave tube.

The electron beam (2.2 MeV, 500 A) bunching occurs in a TWT at the distance in ~1.5 times shorter than in a FEL. It is connected with the fact that the space gain in the TWT is much higher than that in the FEL. But the bunch energy spread is larger in the TWT than in the FEL. The bunching effect depends weakly on the initial energy spread in the TWT and greatly in the FEL.

The TWT bunching efficiency decreases with the initial electron

beam energy increase. Thus the TWT may be efficiently used for the electron beam bunching in the energy span 1 MeV through 2 MeV when the TWT length may be made of 0.5 m through 1 m.

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Received by Publishing Department
on January 14, 1997.