ANALYSIS OF DYNAMICS OF INTENSIVE ELECTRON BEAM IN DISK-LOADED WAVEGUIDE WITH VARIABLE PHASE VELOCITY

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Abstract

The results of electron dynamics numeral simulation in an unhomogeneous disk-loaded waveguide, which is used in the S-band linac, with average power of an accelerated beam of 10 kW, are presented. Taking into account the self-fields of beam radiation, two approaches are considered: the first method is an estimative based on the power diffusion equation; the second one is based on self-consistent equations of field excitation and particles motion. The self-consistent approach showed the presence of substantial phase slipping of particles in the homogeneous part of the rf structure, conditioned by the reactive beam loading.

INTRODUCTION

The low-energy rf linac for technology applications for which we study beam dynamics consists of the elements showed in Fig. 1.

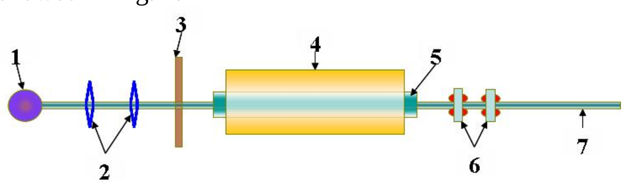

Figure 1: A linac outline: electron gun (1), magnetic lenses (2), magnetic screen (3), solenoid (4), accelerating section (5), quadrupole lenses (6), beamline (7).

The accelerating section is a piece-wise unhomogeneous disk-loaded waveguide, which consists of a buncher conjugated with a homogeneous constant-impedance accelerating part of this section. The buncher includes 15 cells with variable phase velocity, β, as shown in Tab.1.

Table 1: Structure Parameters

Cell Number	Iris Radius, cm	Length, cm	β
1 – 6	2.165	0 – 10.3	0.6998
7	2.165	10.3 – 12.3	0.7494
8	2.11	12.3 – 14.6	0.8494
9 – 13	2.035	14.6 – 26.6	0.8994
14	2.035	26.6 – 29.1	0.9244
15	1.715	29.1 – 31.7	0.9741
16 – 101	1.5	31.7 – 263.5	1

The regular accelerating part consists of 86 cells with phase velocity equals to the velocity of light, *c*. Phase advance per cell is π/2 at the operating frequency 2797 MHz. A 80 kV diode electron gun provides beam current up to 1.5 A per pulse. The focusing system includes 2 lenses, a solenoid and one quadrupole duplet.

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THE POWER DIFFUSION TECHNIQUE

The equation of power diffusion often used to calculate fields induced by an ultrarelativistic beam [1,2] has the form

$$\frac{dP_r}{dz} + 2\alpha P_r = IE_r \qquad (1)$$

where α is the attenuation constant, P_r is the power induced by a beam, I is the beam current averaged over an RF period, E_r is the longitudinal component of the induced electric field.

To use the well-known code PARMELA that calculates motion of particles at given fields it is required to make some assumptions, which ensue from the power diffusion approximation: i) the beam is a sequence of point bunches; ii) beam particles move synchronously with the induced wave at the maximum of decelerating field. By using $P_r = E_r^2 / R_{ser}(z)$ (where R_{ser} is the serial impedance) the induced field can be found from Eq.(1). The total accelerating field of a fundamental space harmonic is given by

$$E_{tot}(z,t_0) = E_0(z)\cos\varphi(z,t_0) - E_r(z), \qquad (2)$$

where $E_0(z)$ is the field from an rf source; t_0 is the entry time of a particle into a accelerating section. The phase of a particle with respect to wave phase is defined as

$$\varphi(z,t_0) = \omega t_\Lambda(z,t_0) - \int_0^z dz' \,\omega / v_{ph}(z'), \qquad (3)$$

where v_{ph} is the wave phase velocity, $t_\Lambda(z,t_0)$ is the particle Lagrangian time, ω is the angular frequency.

To analyze phase motion of a beam, we use the phase of the first Fourier harmonic of current, $\psi(z)$, which is defined from the following expression:

$$I_\omega e^{i\psi(z)} = \frac{I}{N}\sum_{n=1}^{N} e^{i\omega t_\Lambda(z,t_{0,n})}, \qquad (4)$$

where N is the number of particles in a bunch.

The codes, POISSON/SUPERFISH is used to calculate the characteristics of the optical system. The thermionic gun with current of 1.5 A is simulated by EGUN code.

The distribution of accelerating field is plotted in Fig.2, for both the field loaded by a current of 1 A and unloaded one. It is obvious that the field induced by the beam makes considerable contribution into the total field in the acceleration part of the section.

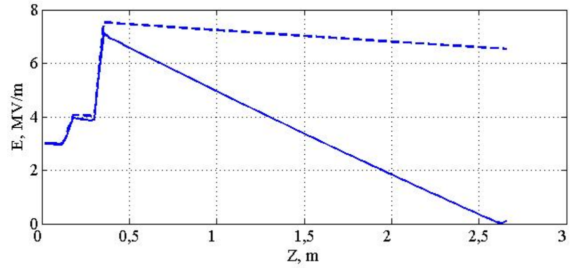


Figure 2: Distribution of the total field along the structure: current is 1A (solid line), no load (dashed line).

The result of the bunching is shown in Fig. 3. The rms phase extent (for 70 % of particles) equals 60 degrees. There is an appreciable amount of low-energy particles (lower than 300 keV) which have not been captured by a traveling wave.

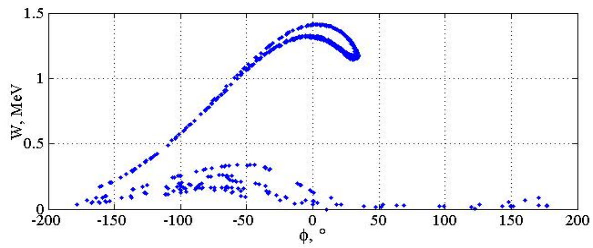


Figure 3: The phase–energy distribution of particles at the buncher exit (z_1=31.7 cm).

The phase of the first Fourier harmonic of the beam current with respect to the travelling wave phase will be further referred to as the phase of a bunch. The dependence of the phase of a bunch on longitudinal coordinates is shown in Fig. 4.

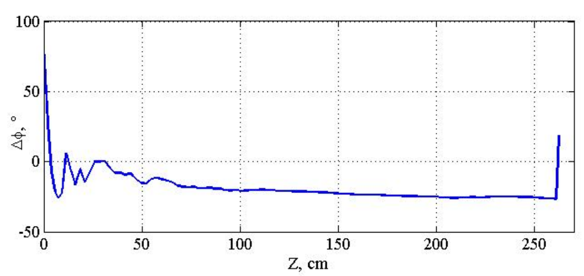


Figure 4: The bunch phase versus longitudinal coordinate.

As is evident from this dependence there are the phase oscillations of bunches in the buncher part of the section (z from 0 to 31.7 cm) that show particle bunching. Considerable phase slipping is observed in initial cells of uniform accelerating part of the section (z from 31.7 to 111.7 cm) conditioned by accelerating up to ultra relativistic velocities. Actually the bunch phase remains constant and is equal to approximately -23 degrees in the second part of the accelerating structure (z from 111.7 to 263.5 cm).

According to the equation of power diffusion the bunch phase should be zero. Thus, the law of conservation of power balance is violated and for more appropriate simulation of acceleration we need the method taking into account self-consistent variation both of the amplitude and the phase of the first Fourier harmonic of beam current along accelerator.

THE SELF-CONSISTENT DYNAMICS

In this section we use the self-consistent technique that incorporates PARMELA to simulate bunching and acceleration [3]. This technique is based on unsteady theory of excitation of resonators and inhomogeneous traveling wave accelerating structures. According to this approach an electric field of traveling wave is written as

$$\vec{E}(t,\vec{r}) = \left|C(t,z)\right| \vec{E}_0(\vec{r}) \exp\left(i\left[\int_0^z \frac{\omega}{v_{ph}(z)}dz - \omega t + \varphi(t,z)\right]\right). \quad (5)$$

Here the slowly varying amplitude $\left|C(t,z)\right|$ and the phase $\varphi(t,z)$ obey excitation equations:

$$\frac{\partial|C|}{\partial z} + \alpha|C| - \frac{1}{2R_s}\frac{dR_s}{dz}|C| + \frac{1}{v_g}\frac{\partial|C|}{\partial t} = \frac{IR_s}{2}\frac{1}{N}\sum_{n=1}^{N}\cos\left(\omega t_\Lambda(z,t_{0,n}) - \int_0^z \frac{\omega}{v_{ph}(z)}dz - \varphi(t,z)\right) \quad (6)$$

$$\frac{\partial\varphi}{\partial z} + \frac{1}{v_g(z)}\frac{\partial\varphi}{\partial t} = \frac{IR_s}{2|C|}\frac{1}{N}\sum_{n=1}^{N}\sin\left(\omega t_\Lambda(z,t_{0,n}) - \int_0^z \frac{\omega}{v_{ph}(z)}dz - \varphi(t,z)\right) \quad (7)$$

where v_g is group velocity.

To calculate the eigen-fields $\vec{E}_0(\vec{r})$ and electrodynamic characteristics of axially-symmetrical rf structures (R_s, v_g) we use the SUPERFISH code. A motion of charged particles at each integration time step is simulated by the PARMELA code. Let us consider steady-state acceleration characteristics. The distribution of the fundamental space harmonic of the total field along the structure axis is presented in Fig. 5. One can see that the beam loaded field decreases less than the field, which was calculated by the power diffusion technique. This difference is caused by two factors: i) insufficiently in-phase superposition of fields induced by the particles of bunches of finite phase width; ii) phase slipping of the first Fourier harmonic with respect to the accelerating wave phase [4], as shown in Fig. 6.

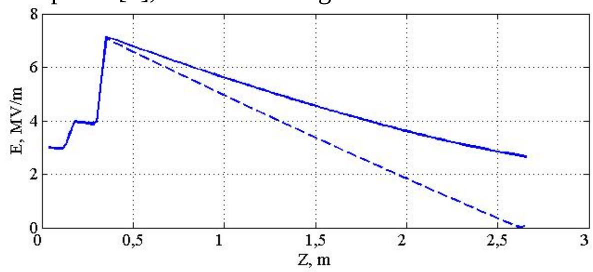


Figure 5: The distribution of the total field along the rf structure: solid) self–consistent approach; dashed) power diffusion method.

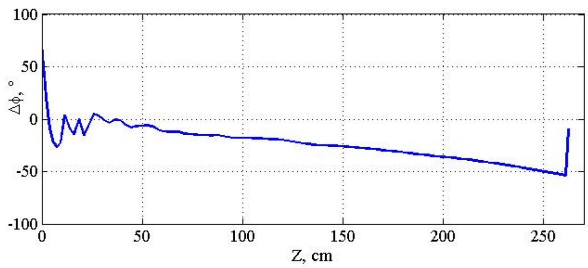
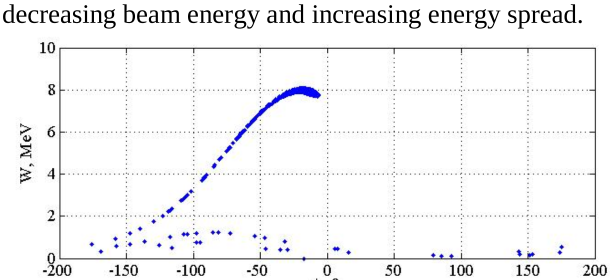


Figure 6: The bunch phase versus longitudinal coordinate.

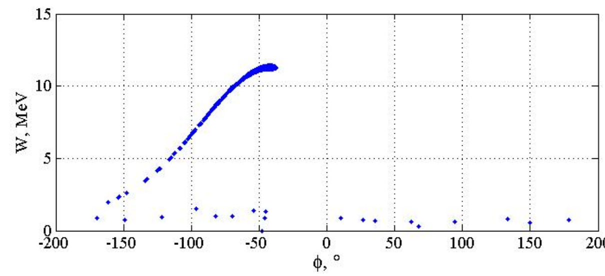
From Fig.6 one can see that in spite of ultrarelativistic particle velocity in the accelerating part of the section (z from 111.7 to 263.5 cm) there is strong shift of the bunch phase, which approximates to 40 degrees in absolute value. It can be treated as changing of the phase velocity of accelerating wave due to reactive beam loading, which is described by the Eq. (7). This equation shows that derivation of the wave phase is inverse to the wave amplitude. Therefore, the less is the amplitude the more phase slipping might be observed.

It should be noted that the phase–energy distribution of particles at the buncher exit (z_1=31.7 cm) is almost the same as the distribution obtained by the power diffusion technique (Fig.3), because beam loading could be neglected in the buncher.

The next Figs.7 (a, b) demonstrate the strong phase motion of the bunch in the accelerating part of the section due to the reactive beam loading. One can see, that the head of the bunch located near the wave crest (the cross-section z_2=147.6 cm, Fig. 7a) is accelerating and significantly slipping off crest (Fig.7b), that results in decreasing beam energy and increasing energy spread.



a)



b)

Figure 7: The phase–energy distribution of particles in: a) the middle of the accelerating part (z_1=147.6 cm); b) the section exit (z_2=263.5 cm).

Finally, it should be noted that energy spread of the accelerated beam, which is obtained by solving the self-consistent problem, is 7% for 70% of the bunch particles. That is 2% more than the value of the energy spread calculated by the diffusion technique.

CONCLUSION

The numerical simulation of steady-state dynamics of an intensive electron beam in the disk-loaded waveguide consisting of the buncher with variable phase velocity conjugated with the acceleration part of the section having constant phase velocity was carried out. We considered two approaches based on: i) the equation of power diffusion; ii) the self-consistent unsteady-state equations of field excitation and particle motion. It has been shown that for estimation of acceleration parameters the diffusion technique can be used, if the value of reactive current loading is not significant. The simulation of a self-consistent problem has shown that there is considerable phase slipping of ultrarelativistic particles in homogeneous part of the accelerating structure. That is caused by variation of wave phase velocity due to reactive beam loading. The disadvantage of the accelerating structure integrated with the buncher is the impossibility of external phasing. Therefore the optimization of self-consistent longitudinal beam dynamics in such type of structures is required.

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