STUDY OF PHYSICAL PROCESSES OF ACCELERATION OF ELECTRON BUNCHES WITH EXTREMAL DENSITY BY MEANS OF STORED ENERGY IN DISK LOADED WAVEGUIDE SECTIONS

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Abstract

The physical processes of acceleration of electron bunches with extreme density in electron linacs have been considered. As a result the optimal version of a traveling wave disk loaded waveguide was chosen. The computational modeling of 20 ns beams acceleration processes was performed and theoretically the method of increasing the microwave power in section of the disk loaded waveguide (DLWG) was studied.

INTRODUCTION

Consider a non-traditional approach to the radiation of relativistic electron bunches in DLWG. The relativistic electron bunch with the charge q is moving along DLWG axis with velocity which is very close to the phase velocity of light $\beta = 1$ ($\beta = v/c$). According to P. Wilson theorem [1, 2] the energy lost by the moving bunch with the charge q is equal to the half of the multiplication of q by the induced voltage: $W = qU/2$

Assume that the voltage U increase along the distance Δx equals the result of multiplication of the current I induced by the charge q on the equivalent resistance ΔR of the DLWG length Δx: $\Delta U = I\Delta R$. According to S. Ramo theorem [3] it follows that the induced current equals: $I = qc/\Delta x$. Determine the resistance of DLWG segment with the length Δx using the DLWG series resistance R_s: $\Delta R = R_s(\Delta x)^2$, where $R_s = E^2/2P$. Here E is the electrical component strength on the electromagnetic field in DLWG and P is the power.

Using the relation for W, I and ΔR we obtain the increase of the energy being lost by the bunch at the distance Δx: $\Delta W = q\Delta U/2 = q^2 cR_s\Delta x/2$. The power of the bunch radiation equals: $P = \Delta W/\Delta t = q^2 cR_s\Delta x/(2\Delta t)$.

In our case $\Delta x/\Delta t = c$. Taking into account previous equation obtain $P = q^2c^2R_s/2 = E_q^2/2R_s$ or

$$E_q = qcR_s.$$

Note that the similar relationship was obtained in [4].

Thereby the field E_q radiated by the relativistic bunch with the charge q is determined by its charge, velocity and the series resistance of the disk loaded waveguide. The last expression is valid even for the bunch velocity v<c, i.e. in general form $E_q = qvR_s$.

MAIN EXPRESSIONS

According to our approach it could be written that DLWG with the length $l = ND$ (where N is the cells number) would have the loaded Q-factor equal: $Q_L = Q_0/\left(1 + 2Z_w\lambda\beta_{ph}\theta/\pi l r_D\right)$. The unloaded Q-factor is

$$Q_0 = \frac{\lambda}{\delta}\left[\frac{1-(a/b)^2}{(\beta_{ph}\theta/2\pi)-(\hat{t}/\lambda)} + \frac{a/b}{a/\lambda}\left(1-\frac{\hat{t}}{\lambda}\frac{2\pi}{\beta_{ph}\theta}\right) + \frac{a/b}{a/\lambda}\frac{2\pi}{\beta_{ph}\theta}\right]^{-1}.$$

The latter makes it possible to determine the DLWG series impedance and normalized value of electric field strength E on the DLWG axis using the known relations $R_s = \alpha R_{sh}$ and $E\lambda/\sqrt{P} = \lambda\sqrt{2R_s}$.

Table 1: DLWG Unloaded Q-factor. a = 20.94 mm

θ	a/b	Q_0 (equation)	Q_0 (Superfish)
π	0.4792	17809	18716
2π/3	0.4713	14017	14519
π/2	0.4707	11335	11864
π/3	0.4677	7899	8415
π/4	0.4627	5785	6211
π/8	0.4660	1882	1992
π/12	0.4100	289	293

Consider the periodic train of relativistic electrons bunches moving along the axis z with interval λ (working operational DLWG wavelength) and period T. The first bunch of the electron flow pulse radiates the field with electrical component E_q. The electromagnetic field behind the moving first bunch in some chosen cross-section will be attenuated in respect to time according $E_1(t) = E_q\exp[-\omega t/2Q_l]$. The summary field radiated by the series train of pointed bunches with charge q after completion of the transient processes is equal to $E_s = qvR_s/\left(1-\exp[(-\pi)/Q_l]\right)$. Note that we consider the ideal case when every bunch is placed in the maximum of the total decelerating field of all bunches and in the maximum of the generator accelerating field $E = E_{g0}e^{-\alpha z} - E_q(1-\exp[-\pi/Q_l])^{-1}$.

The energy obtained by every electron bunch at the exit of the accelerating section with length l equals (in voltages):

$$U = E_{g0} l \frac{1-\exp[-\alpha l]}{\alpha l} - \frac{E_q l}{1-\exp[-\pi/Q_l]}.$$

The power of the accelerated electrons beam equals:

$$P = I_0 E_{g0} l \frac{1-\exp[-\alpha l]}{\alpha l} - \frac{I_0^2 R_s \lambda l}{1-\exp[-\pi/Q_l]}.$$

The electronic efficiency of the accelerating section correspondingly equals (see Fig. 1):

$$\eta = \frac{1}{P_0}\left[I_0 E_{g0} l \frac{1-\exp[-\alpha l]}{\alpha l} - I_0^2 \frac{R_s \lambda l}{1-\exp[-\pi/Q_l]}\right].$$

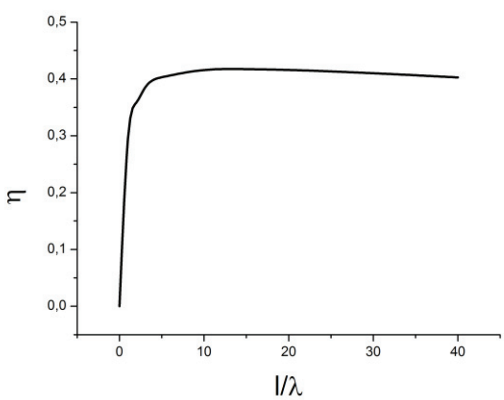

Figure 1: Dependence of DLWG electronic efficiency η from accelerating structure.

The case when the beam power is maximal and correspondingly the electronic efficiency of DLWG reaches the maximum value is of interest.

$$P_{\max} = \frac{1}{2} P_0 \frac{l}{\lambda}\left(\frac{1-\exp[-\alpha l]}{\alpha l}\right)^2 \left(1-\exp[-\pi/Q_l]\right).$$

Now consider an acceleration section of linac based on biperiodic system operating on standing wave [4]. Also we use the data of [6, 7] for structures with $\lambda/2$ period. By providing calculations we obtain a definition for a maximum value of electronic efficiency for biperiodic structure (see Fig. 1): $\eta_{\max} = 2\beta/(1+\beta)^2$.

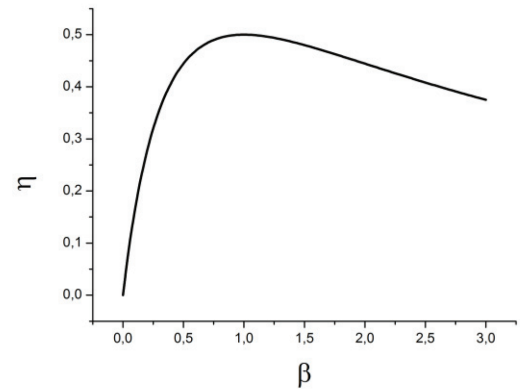

Figure 2: Dependence of biperiodic structure electronic efficiency η from coupling coefficient β.

The accelerated bunches situated in accelerating field maximum. Assume that at first the section is being filled with microwave power and after that the grouping bunches are entered into the section input. Bunches have the velocity close to that of light. The accelerating voltage acting on a single bunch when it propagates along DLWG section with length l takes the form:

$$U_1 = E_{G1} l \frac{1-\exp[-\alpha l]}{\alpha l} - q c R_s l. \qquad (1)$$

The energy (in voltage term) obtained by the charge q when it flies along l length section of CDLW will be decreased. If we increase the charge q so much that $U_1 = 0$, then the charge q after passing the section would not obtain the additional energy. Such a value of the bunch charge we consider as the limited one (LBC): $q = q_{\lim}$. With further charge increasing the bunch is decelerating by the summary field because the latter becomes negative. For $q = q_{\lim}$ (1) equals zero, therefore $q_{\lim}$ equals:

$$q_{\lim} = \frac{E_{G1}}{c R_s} \frac{1-\exp[-\alpha l]}{\alpha l} = \frac{2\sqrt{P}}{f(\lambda E_{G1}/\sqrt{P})} \frac{1-\exp[-\alpha l]}{\alpha l},$$

where f is the microwave generator frequency, i.e. the operational frequency, $\lambda E_{G1}/\sqrt{P}$ is the normalized value of the field strength in the DLWG section, the reference data for the first bunch are given in [5]. Thereby the bunch maximal energy (in volts) is expressed by the following formula:

$$U_{1\max} = \frac{1}{2} E_{G1} l \frac{1-\exp[-\alpha l]}{\alpha l}.$$

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POWER INCREASE METHOD

Consider one of several techniques for increasing the power, i.e. the technique of using DLWG sections in the traveling wave cavity (TWC) [5].

It can be proved that the power circulating in TWC could be enhanced by coefficient K that is determined by the following expression: $K = P_{TWC}/P_p = (1-\exp[-2\alpha_T\, t/T]\ )^2/(1-\exp[-2\alpha_T])$, where $\alpha_T = \alpha_{T\square} + \alpha_{T\,DLW}$, $T = l_\square / v_{gr\square} + l\ / v_{gr\,DLW}$. Computations of the maximum coefficient of the power enhancement in TWC based on DLWG for the section with parameters l=2 m, $\theta = \pi/2$, $\beta_{ph} = 1$, $a/\lambda = 0.20$, $R = t/2$ were performed. The results are presented in the Table 2.

Table 2: Maximum Power in TWC

Model	*f*, MHz	P_{max}, MW	*K*	P_{TWC}, MW
RM-1100X	9300	29.0	1.94	3.5
KIU-361	5712	77.0	3.34	16.7
MI-262	3200	245.8	7.97	71.7
TN-2094	2998	280.0	8.74	323.4
Arsenal	2797	321.8	9.01	360.4
MI-470	1885	707.9	16.24	178.6
KIU-15	1818	761.4	16.97	509.1
MIU-34	1818	761.4	11.72	421.9
TN-2104	1300	1488.9	28.04	420.6
KIU-75	991	2562.2	23.96	112.7

Consider the scene of supplying DLWG section with microwave power when the section incorporated into TWC (Fig. 2) [6]. The power increase with time from the moment of microwave generator switching on or from the moment of the pulse front arriving (if the microwave tract has the pulsed supply) could be written as $P_4 = P_1\left[1-\left(\exp\left[-\alpha_T\right]\right)^{t/T}\right]^2 / \left(1-\exp\left[-\alpha_T\right]\right)$. Here P_1 is the microwave power at the directional coupler input and P_4 is the microwave power at the input of the DLWG accelerating section. After the transient process is over the relation has the form as follows:

$$P_4 = \frac{P_1}{1-\exp\left[-\alpha_T\right]}.$$

Note that in the frequency range from 1 up to 10 GHz and when the attenuation coefficient α_{dlw} the power increase at the DLWG input may reach from 2 up to 20 times. Therefore it is possible to obtain power levels unachieved in serial microwave generator and amplifiers.

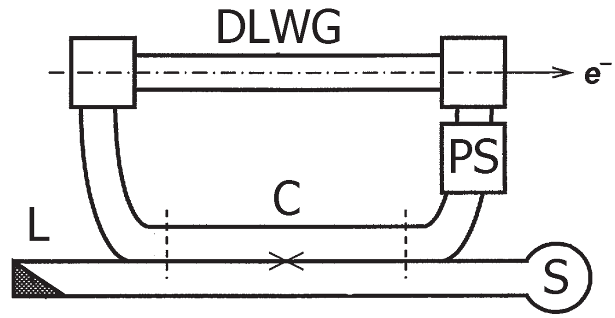

Figure 3: TWC based on DLWG. PS – phase shifter, C – directed coupler, L – loading.

CONCLUSION

Development of the linear electron accelerators with extreme parameters of accelerated beams at their output appears to be a rather complicated and even impossible problem. Authors have used the new physical approach to the determination of main linac parameters based on superposition of the field generated by the supplying microwave power source and radiation fields of the accelerated bunches. Such an approach can be used for other accelerating system which have some advantage and shortcoming and are applied in linacs. If you have any questions reach me on qstpss@gmail.com please.

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