

THERMAL BALANCE OF MULTILAYERED TUNABLE DIELECTRIC LOADED WAKEFIELD ACCELERATING STRUCTURE*

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Abstract

Thermal balance of a cylindrical tuneable multilayer dielectric-filled accelerating structure is considered. One ceramic layer of the structure possesses ferroelectric properties, which allow the waveguide frequency spectrum to be tuned by varying the permittivity of the ferroelectric layer. Dielectric and induction losses in ferroelectric layer and a metal shell leads to a structure warming up and increasing temperature of the ferroelectric layer. Because of a temperature sensitivity of dielectric permittivity of ferroelectric layer this effect may detune the accelerating structure. On the basis of the analysis of a thermal regime of multilayered wakefield structure the medium and pulse temperature deviations are determined. A repetition rate of electronic bunch series should be chosen to limit temperature detuning.

INTRODUCTION

The method of dielectric wakefield acceleration of electrons is one of perspective directions of creation high gradient structures of modern linear accelerators. The methods based on the concept of wakefield acceleration in structures with dielectric filling, are now one of the most perspective in sense of possibility of creation высокоградиентных accelerating structures for the future generation of linear colliders. These structures which are object of intensive studying last years, can be excited both a high current electronic bunch, and an external source of powerful microwave radiation. At wakefield acceleration method high current (as a rule, 20–80 nC), short (1–4 mm) the leading electronic bunch, moving in the vacuum channel of the dielectric wave guide concluded in spending metal cover, generates TM₀₁ mode of Vavilov-Cherenkov radiation which is used for acceleration of an electronic bunch of high energy, moving behind a leading bunch on the distance, corresponding to an accelerating phase of a wave.

In work [1] the structure analysis of wake fields and also induction losses in a metal cover was spent with reference to single-layered dielectric structure with the vacuum channel of rectangular geometry. In [2, 3] it is resulted experimental demonstration of tuneable structure with two-layer filling (a dielectric with dielectric permeability $\epsilon = 10$ and a ferroelectric material with $\epsilon = 500$), and the maximum observable shift of frequency has made 160 MHz for accelerating TM₀₁ fashions with frequency of 11.424 GHz. The analysis of losses of energy and a method of their decrease in structure is resulted in [4]. Research of possibility of creation of

tuneable waveguides is conducted in work [5] with ferroelectric layers of cylindrical geometry.

Introduction of a ferroelectric layer between dielectric ceramic plates and a metal surrounding cover in a wave guide leads to management possibility its frequency spectrum. For the appendix of an external field operating a ferroelectric material the electrode serves. The choice of parameters of the ferroelectric layer – dielectric permeability and a thickness – is defined demanded for compensation of technological and temperature shifts by controllability of base frequency of a waveguide. Last is $\delta f = 2\Delta f / f_0$, where Δf – the greatest possible deviation of base frequency from settlement frequency f_0 .

Presence located between a dielectric and a metal cover the ferroelectric layer with high value of dielectric permeability ϵ and rather big tangent of dielectric losses angle results as in increase of a share of the energy disseminated in the ferroelectric layer, and to additional induction losses in a metal cover of structure.

Last fact is caused by sharp growth tangential components of intensity of a magnetic field on a surface of a metal cover of the wave guide caused by rather high values of dielectric permeability of a ferroelectric material. As a result the contribution ferroelectrics and induction losses in the general losses of energy in system appears defining, and losses sharply accrue with growth of dielectric permeability of a ferroelectric material that limits an admissible thickness ferroelectric layer and limits possibilities of operative adjustment of frequency of accelerating structure with dielectric filling.

Total capacity of dielectric losses of energy in a ferroelectric material and a dielectric, and also the Joule losses connected with prompting of induction currents in a metal cover, can be presented as

$$w_s = \omega \epsilon \tan \delta \int_V \mathbf{E} \cdot \dot{\mathbf{E}} dV + \frac{1}{2\sigma_m \Delta} \oint_{S_m} H_\tau^2 ds,$$

where ϵ , $\tan \delta$, V are dielectric permeability, tangents of corners of dielectric losses and volumes of the dielectric and the ferroelectric material, H_τ is a tangential component of intensity of a magnetic field on border with an area S_m conductor, and depth of a skin-layer $\Delta = c / \sqrt{2\pi\omega\mu\sigma_m}$ is defined by frequency of an electromagnetic field ω and conductivity of metal σ_m , the point means complex interface.

THERMAL CALCULATION OF A MULTILAYERED WAVEGUIDE

For calculation of heat transfer in multilayered waveguide with an additional ferroelectric layer we will consider stationary distribution of temperature in the established periodic mode of gating of beams with the set period in time. We will accept following basic assumptions:

1. Heat generation doesn't depend on time and coordinate and is equal to the value in the given layer which is averaged on time.
2. The waveguide is infinitely long ($l \gg R_w$)
3. Heat conductivity of separate layers of a waveguide λ_i are constant.
4. The transient behaviour isn't considered, only the stationary mode is calculated.
5. The beam moves along an axis of a waveguide and its electromagnetic field is axisymmetric. So, the temperature field is axisymmetric too.

In this case the temperature field is described by the stationary equation of heat conductivity with a heat generation source:

$$\frac{1}{r} \frac{\partial}{\partial r} r \lambda \frac{\partial T}{\partial r} + Q = 0,$$

where r – radial coordinate, λ – heat conductivity, $W/(m \cdot K)$, T is absolute temperature, Q is volume heat generation, W/m^3 .

Internal surface of a waveguide on border with the vacuum channel of radius R_c is heat-insulated:

$$-\lambda \frac{\partial T}{\partial r} \Big|_{r=R_c} = 0.$$

The ideal contact condition is set between layers i and $i+1$ with different heat conductivity:

$$-\lambda_i \frac{\partial T_i}{\partial r} \Big|_{r=R_i} = -\lambda_{i+1} \frac{\partial T_{i+1}}{\partial r} \Big|_{r=R_i}.$$

On an external surface of a waveguide the boundary condition of 3rd type (heat exchange under Newton's law) is set:

$$-\lambda \frac{\partial T}{\partial r} \Big|_{r=R_{ex}} = \alpha (T \Big|_{r=R_{ex}} - T_{env}),$$

where α is heat transfer coefficient $W/(m^2 \cdot K)$, index «env» corresponds to ambient parameters (air in our case).

Heat transfer to environment it is carried out by free convection and radiation: $\alpha = \alpha_{conv} + \alpha_{rad}$. For a free convection on a horizontal surface of the cylinder the following formula is applied [8]: $Nu = A(Gr \cdot Pr)^n$, where

– $Nu = A(Gr \cdot Pr)^n$ where Nu is Nusselt number, R_{ex} is external radius of a metal cover of a wave guide λ_{env} – heat conductivity of air, Gr is Grashof number, Pr is Prandtl number, A and n is empirical constants. Constants A and n calculated by following correlations: for $Gr \cdot Pr < 1 \cdot 10^{-1}$ $A = 0.5$; $n = 0$, for $1 \cdot 10^{-1} < Gr \cdot Pr < 5 \cdot 10^2$ $A = 1.18$; $n = 0.125$, for

$5 \cdot 10^2 \leq Gr \cdot Pr < 2 \cdot 10^7$ $A = 0.54$; $n = 0.25$, for $2 \cdot 10^7 \leq Gr \cdot Pr$ $A = 0.135$; $n = 0.333$.

Grashof number and Prandtl number are defined by

$$Gr = \frac{g \beta_T (2R_{ex})^3 \Delta T}{\nu^2}; \quad Pr = \frac{\nu}{a} = \frac{\nu C_p \rho \mu}{\lambda_{env} R T_{env}},$$

where g is a gravitational acceleration, β_T – thermal expansion coefficient (for ideal gas $\beta_T = 1/T_{env}$), ν – kinematics viscosity, m^2/c ; $a = \lambda_{env} / (\rho C_p) = \lambda_{env} R T_{env} / (\rho \mu C_p)$ – air heat diffusivity, ρ – air density, C_p – air heat capacity under constant pressure, $J/kg \cdot K$; μ – molar mass, kg/mol ; R – gas constant, $J/mol \cdot K$; $\Delta T = T_{ex} - T_{env}$ – typical temperature drop.

For a characteristic range of differences of temperatures from 0.1 to 500 K which will be coordinated with the settlement data received more low $A = 0.54$; $n = 0.25$, whence we receive:

$$\alpha_{conv} = A \left(\frac{\lambda_{env}^3 g C_p \rho \mu \Delta T}{2 R_{ex} R T_{env}^2 \nu} \right)^{\frac{1}{4}}.$$

For an estimation of radiating factor heat transfer we will use the Stefan – Boltzman law:

$$\frac{\partial W_{изл.}}{S_{ex} \partial t} = \sigma \varepsilon (T_{ex}^4 - T_{env}^4) = \sigma \varepsilon (T_{ex}^2 + T_{env}^2) (T_{ex} + T_{env}) \Delta T,$$

whence we will receive $\alpha_{rad} = \sigma \varepsilon (T_{ex}^2 + T_{env}^2) (T_{ex} + T_{env})$.

In case of the compelled water cooling by means water current through the helicoid tube wound on outer side of a wave guide, $\alpha_f = Nu \lambda / d$, where $Nu = 0.021 Re^{0.8} Pr^{0.43} \delta$, $Re = vd/\nu$, $Pr = \nu \rho c_p / \lambda$, $\delta = (Pr(T)/Pr(T_c))^{1/4}$, d is diameter of a heat-removing tube, v is a speed of a water current on a tube, ν, ρ, c_p are a kinematical factor of viscosity, m^2/s ; density and a water thermal capacity.

The decision of the stationary equation of heat conductivity looks like:

$$u_i = u_{0i} - Q_i (r^2 - r_{0i}^2) / (2\lambda_i);$$

$$T_i = T_{i0} + \left(u_{i0} + \frac{Q_i r_{0i}^2}{2\lambda_i} \right) \ln \left(\frac{r}{r_{0i}} \right) - \frac{Q_i r^2}{4\lambda_i} + \frac{Q_i r_{i0}^2}{4\lambda_i},$$

where $u_i = r \partial T_i / \partial r$. Considering boundary conditions, for temperature gradients and absolute temperatures on borders of layers we will receive

$$u_{i0} = -\frac{1}{2\lambda_i} \sum_{j=1}^i Q_j (R_j^2 - R_{(j-1)}^2);$$

$$T_{i0} = T_{(i+1)0} - \left(u_{i0} + \frac{Q_i R_i^2}{2\lambda_i} \right) \ln \left(\frac{R_{(i+1)}}{R_i} \right) + \frac{Q_i (R_{(i+1)}^2 - R_i^2)}{4\lambda_i}.$$

On fig. 6 dependences of temperature on distance on the centre of a waveguide in the conditions of natural heat

emission from a waveguide surface are shown. Calculations are spent for different repetition rates ν at the same thickness of a metal cover $\Delta_m = 10$ mm (fig. 1).

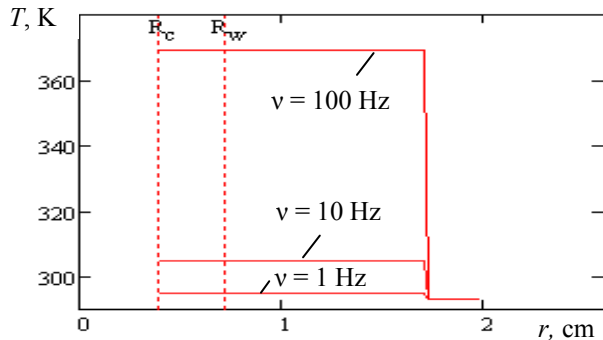


Figure 1: The dielectric waveguide with additional ferroelectric layer

From fig. 1 it is visible that distribution of temperature in dielectric and ferroelectric layers almost in regular intervals and essentially depends on factors: thickness of a metal cover of a waveguide and frequency of following of impulses series. The thermal emission in waveguide layers (especially in a ferroelectric material and on border with a metal cover) at passage of bunches considerably changes equilibrium temperature of structure. Considering that the ferroelectric material is a nonlinear material with dielectric permeability essentially depending on temperature, the obligatory preliminary analysis and the account of a thermal mode is necessary for waveguide calculation on the set of repetition rate of excitation multilayered wakefield structures.

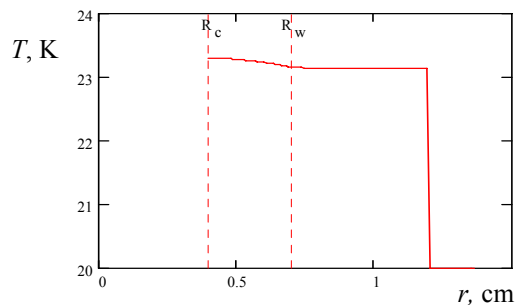


Figure 2: Dependence of temperature in cylindrical structure in the conditions of compelled heat emission

Temperature change on 10 K at repetition rate $\nu = 10$ Hz and a thickness of a metal cover $\Delta_m = 15$ mm leads to change of dielectric permeability on 5 % and to respective alteration of the basic frequency of a waveguide on 1.6%. At repetition rate $\nu = 100$ Hz and a thickness of a metal cover $\Delta_m = 10$ mm temperature change reaches 80 K that leads to change of dielectric permeability on 25% and to corresponding shift of the basic frequency of a waveguide on 4.9 %. Last value exceeds a range of adjustment of frequency of a waveguide the constant electric field enclosed to a ferroelectric material (2.92%) and can't be compensated.

The overheat of an internal part of accelerating structure in comparison with ambient temperature at repetition rate $\nu = 10$ Hz and a thickness of a metal cover $\Delta_m = 10$ mm makes 15 K. Overheat of an internal part of accelerating structure in comparison with ambient temperature at repetition rate $\nu = 100$ Hz and to a thickness of a metal cover $\Delta_m = 10$ mm makes 82 K. That is, at increase in repetition rate natural convective cooling of the waveguide appears insufficient and compulsory liquid cooling is required.

On fig. 2 dependence of temperature on distance on the centre of a waveguide in the conditions of compelled heat emission from a surface of a waveguide by means of the helicoids metal tube wound on outer side of the waveguide on which water proceeds is shown. Calculations are spent at repetition rate $\nu = 100$ Hz, a thickness of a metal cover of the waveguide $\Delta_m = 5$ mm, internal diameter of a heat-removing tube $d = 2$ mm, speeds of a current of water on a tube 1 m/s and length of cooled section of a waveguide 1 m.

The maximum overheat in relation to ambient temperature makes 3.8 K that practically doesn't render influence on dielectric properties of the ferroelectric material.

CONCLUSION

The analysis of a thermal mode multilayered wakefield structures shows that at designing wakefield accelerating structure on high current and high acceleration gradient the preliminary account of thermal balance of the waveguide is necessary for excitation. At increase in repetition rate for correct adjustment of a waveguide of natural cooling of accelerating structure insufficiently use of compulsory water cooling also is required.

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