PARAMETERS OF TWO-CHANNEL FIVE-ZONE DIELECTRIC STRUCTURE FOR EXPERIMENTS ON WAKEFIELD ACCELERATION IN KIPT

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The computations results of the parameters of a two-channel five-zone rectangular dielectric structure for the experimental test of basic principles of using such structures for wakefield acceleration are presented. The structure consists of two adjacent vacuum channels (one for the drive bunches, the other for the accelerated bunch) bordered by dielectric slabs. The entire structure is placed in a rectangular waveguide. In the work is also investigated the tolerances for parameters of the structure that affect the value of the transformer ratio and the accelerating gradient.

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INTRODUCTION

Transformer ratio (**T**) is one basic parameters of wakefield accelerator providing maximal energy of accelerated particles, collinear units have the value of **T** <2 [1]. Multi-zone dielectric structures [2, 3] make it possible to obtain a high transformer ratio, significantly greater than 2.

For the purpose of experimental test of the basic principles of using of multi-zone dielectric structures for wake acceleration, a two-channel five-zone rectangular dielectric structure [4] is designed in KIPT. Parameters of the reference dielectric wakefield accelerator (DWA) are presented below. The very significant practical importance for the realization of DWA has a sensibility of designed DWA to tolerances (Δε, errors in geometric dimensions, in an energy of drive bunches etc.). In what follows, the results of a few tolerance studies are presented.

1. REFERENCE DEVICE

The two-channel five-zone dielectric structure represents the metal rectangular waveguide having the cross sizes $w\times 2d$ ($2d$ is the height and w is full width of the waveguide) with three dielectric slabs (dielectric permittivity is equal to ε), two of which cover opposite walls of a waveguide (Fig. 1). Drive electron bunches pass through a wide vacuum channel of width w_{dr} and excite the wakefield representing superposition of eigenmodes of a waveguide. Witness electron bunch pass through a narrow vacuum channel of width of w_{dr} and accelerates by the excited wakefield.

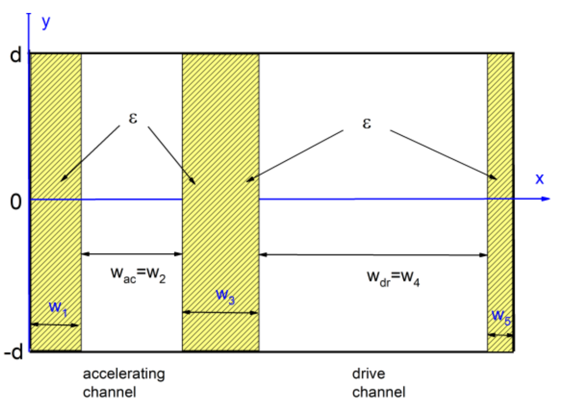

Fig. 1. Cross-section of the two-channel five-zone dielectric structure

1.1. BASIC EQUATIONS

For the finding of eigen frequencies ω_{nm} of the investigated device we use the general theory of multi-zone rectangular dielectric waveguides excited by particle bunches [2, 4]. Frequencies of eigen modes are defined from matrix equations for the LSM waves

$$\left(\frac{k_x^1}{\varepsilon_1}\sin k_x^1 w_1, \cos k_x^1 w_1\right)\left(\prod_{i=2}^{5} S_i\right)\begin{pmatrix}\cos k_x^5 w_5\\ \frac{k_x^5}{\varepsilon_5}\sin k_x^5 w_5\end{pmatrix}=0 \qquad (1)$$

and for LSE waves

$$\left(\cos k_x^1 w_1, -\frac{\mu_1}{k_x^1}\sin k_x^1 w_1\right)\left(\prod_{i=2}^{5} T_i\right)\begin{pmatrix}\frac{\mu_5}{k_x^5}\sin k_x^5 w_5\\ -\cos k_x^5 w_5\end{pmatrix}=0, \qquad (2)$$

where the transition matrix S_i and T_i are

$$S_i \equiv \begin{pmatrix}\cos k_x^i w_i & -\frac{\varepsilon_i}{k_x^i}\sin k_x^i w_i\\ \frac{k_x^i}{\varepsilon_i}\sin k_x^i w_i & \cos k_x^i w_i\end{pmatrix},$$

$$T_i \equiv \begin{pmatrix}\cos k_x^i w_i & -\frac{\mu_i}{k_x^i}\sin k_x^i w_i\\ \frac{k_x^i}{\mu_i}\sin k_x^i w_i & \cos k_x^i w_i\end{pmatrix}$$

and $(k_x^i)^2 = (\beta_0^2\varepsilon_i\mu_i - 1)k_{zmn}^2 - k_{yn}^2$, $k_{yn} = \pi n/(2d)$, $k_{zmn} = \omega_{mn}/\mathrm{v}_0$, $\beta_0 = \mathrm{v}_0/c$, v_0 is the bunch velocity, n is integer, ε_i and μ_i are dielectric and magnetic permeability of *i-th* zone.

Amplitudes of eigen modes are defined from matrix excitations equations for the LSM waves

$$\frac{\partial}{\partial x}\frac{1}{\varepsilon}\frac{\partial}{\partial x}(\varepsilon E_x) + \frac{\partial^2 E_x}{\partial y^2} - (\beta_0^2\varepsilon\mu - 1)\frac{\partial^2 E_x}{\partial s^2} = 4\pi\frac{\partial}{\partial x}\left(\frac{\rho}{\varepsilon}\right), \qquad (3)$$

and for LSE waves

$$\frac{\partial}{\partial x}\frac{1}{\mu}\frac{\partial}{\partial x}(\mu H_x) + \frac{\partial^2 H_x}{\partial y^2} - (\beta_0^2\varepsilon\mu - 1)\frac{\partial^2 H_x}{\partial s^2} = -4\pi\frac{\partial j_z}{\partial y}, \qquad (4)$$

where ρ and j_z charge density and axial current density of particle bunch. Explicit form of solutions of the equations (3), (4) is given in the paper [4].

1.2. DETERMINATION OF DIELECTRIC CONSTANT

Before to design the reference accelerator structure we determined exact value of dielectric permeability of the material that we planned to fabricate slabs from. Dielectric constant was found by measuring of frequency shift $df=f-f_0$ of wave E_{010} – in cylindrical resonator (diameter is D=81.5 mm, length is 40.4 mm) when inserting a dielectric rode: rode diameters are d=5 mm *and* d=7 mm. Then dielectric constant can be found from approximate expression:

$$\varepsilon = 1 + 0.54(d / D)^2 df \; / \; f_0 . \qquad (5)$$

More exact value can be found from direct CST [5] computations of frequency shift.

The results of the CST computation together with analytic approximations (see eq.(5)) of frequency shift are shown in Fig. 2.

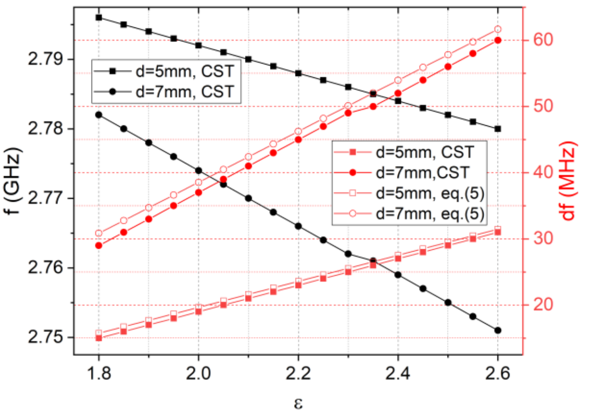

Fig. 2. Frequency f (black symbols) of loaded cylindrical resonator and the shift df=f-f₀ (red symbols) of the principal mode frequency f₀ versus dielectric constant ε for rode diameters d=5 mm and d=7 mm

Having measured the experimental shift df=20 MHz if d=5 mm we have obtained for our sample of Teflon ε=2.05.

1.3. PARAMETERS OF THE REFERENCE UNIT

For the designing of the reference two-channel five-zone DWA we choose metal waveguide R_{13} with dimensions 108×85 mm. In our planned experiments we will use electron beam from accelerator Almaz-2M, providing the electron energy of 4.5 MeV and bunch repetition rate (BRR) 2803 MHz. Having used the equations (1), (2) the dimensions of slabs, witness and drive channels were computed for the operation frequency 5606.5 GHz (it is second harmonic of BRR). They are given in the Table.

Transverse profiles (across slabs) of axial electric field E_z for the first six LSM_{m1} modes of the reference unit are shown in Fig. 3. Operation mode is LSM_{31}, it has symmetric profile in witness channel and ratio of the E_z in witness channel to the E_z in drive channel is ~10, that is appreciably exceed the similar value in collinear devices.

2. TOLERANCES

2.1. FREQUENCY SHIFT

In this subsection we study the operation frequency change when the dielectric constant ε deviates from the found in subsection 2.2 ε=2.05 or thickness of dielectric slabs varies from the values given in Table.

Parameters of the two-channel five-zone DWA device

Dielectric constant of slabs(Teflon)	2.05
Waveguide (R_{13}) dimensions $w \times 2d$, mm	180x85
Bunch energy (“Almaz-2M”), MeV	4.5
Bunch repetition rate, MHz	2803
Operation frequency of the DWA, MHz	5606.5
Slab 1 width, mm	9.28
Slab 2 width, mm	14.69
Slab 3 width, mm	5.41
Witness channel width, mm	21.44
Drive channel width, mm	129.18
Bunch charge, nC	0.32
Bunch diameter, mm	10
Bunch length, mm	17

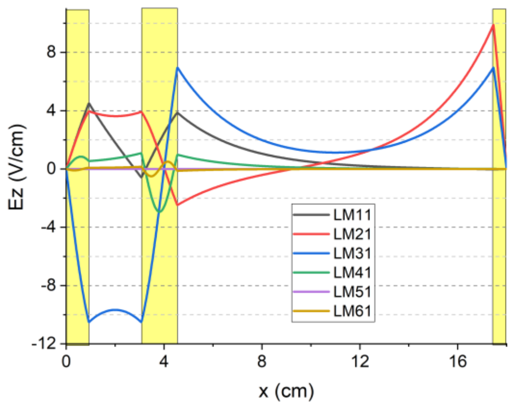

Fig. 3. Transverse profiles of LSM_{m1} modes excited by single drive bunch

In Fig. 4 is shown axial profile of the **T** in the reference unit. **T**~8 is reached at the drive bunch head distance of 5.3 cm.

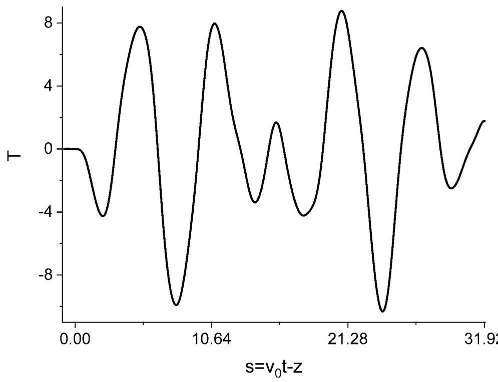

Fig. 4. Axial profile of the transformer ratio. The DWA structure is excited by single drive bunch

In Fig. 5 is shown frequency shift of operation mode when changing ε. Black line and symbols are computed shift, red line is linear approximation. On the interval

ε=1.95…2.15 the frequency shift Δ*f* changes from +200 to -170 MHz. As seen from the inset in Fig. 5 within the interval 2.045…2.055 computed values of the frequency shift are less than 10 MHz and coincide with the linear approximation.

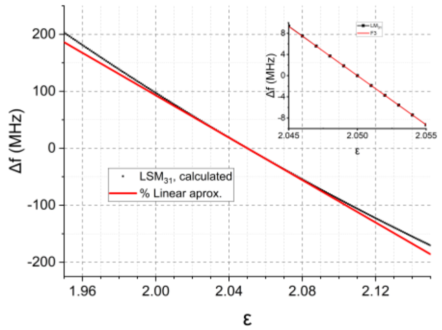

Fig. 5. Frequency shift of the operation mode LSM_{31} versus dielectric permittivity: black symbols is computed shift, red line is linear approximation

Frequency shift of the LSM_{31} mode when changing the width of each dielectric slab is given in Fig.6. When changing each slab from +0.25 to -0.25 mm the frequency shifts from +130 to -70 MHz. It should be noted the nonlinear dependence *Δf(Δw)*. Also in order to support the frequency shift less than 10 MHz we should fabricate slabs with accuracy ±0.05 mm.

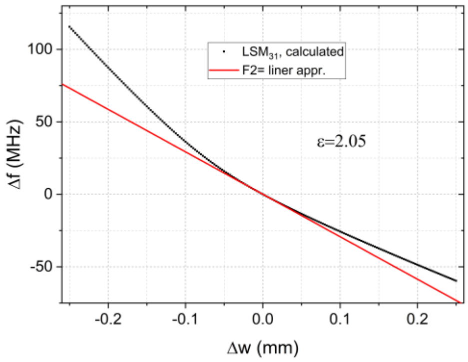

Fig. 6. Frequency shift of the LSM_{31} mode when changing the width of dielectric slabs. Each slab changes by the same value. Black line is computed shift, red line is linear approximation

2.2. AMPLITUDES OF EIGEN WAKE MODES AT SINGLE BUNCH EXCITATION CASE

At first glance, it intuitively seems the amplitudes of eigen modes at single bunch excitation regime don't may to change significantly when changing eigen frequency of slow down structure, and correspondently at deviation of dielectric permittivity or slab width from those of the reference device. The computations confirm this assumption for the *LSE* modes. There is negligible deviation the E_z of *LSE* modes from the optimal one for reference DWA unit.

In Fig. 7 are shown the amplitudes of *LSM* modes when changing the dielectric constant. In given interval ε=1.95…2.15 greatest deviations are for LSM_{31} and LSM_{21} modes, anyway they are small. So at single bunch regime errors in finding ε are nonfatal.

In Fig. 8 are shown the amplitudes of LSM modes when changing a width of dielectric slabs. In given case the width of each slab changes equally. Transverse locations of slab centers are fixed. Also positions drive and witness bunches are fixed, but in general case (excluding the reference unit $w=0$) are not centered in channels. There are significant deviations the E_z amplitudes of LSM_{31} and LSM_{21} eigen modes, especially if we fabricated slabs more thin. Great decreasing of wakefield amplitudes is related with breakdown of transverse profiles of LSM_{31} and LSM_{21} modes (see Fig. 3). It can be diminished (but not eliminated) if drive and witness to centre. So it should manufacture slabs with tolerances ±0.1 mm in order obtain reference wakefield.

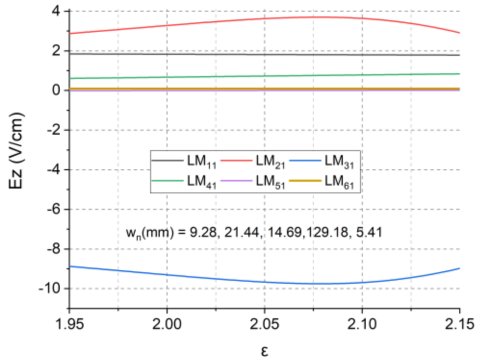

Fig. 7. Amplitudes of the first six LSM modes versus dielectric permittivity at the center of witness channel for single bunch excitation case

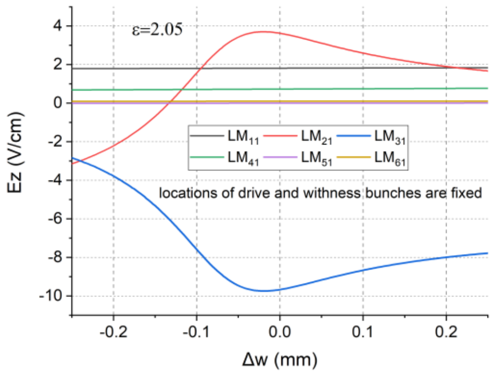

Fig. 8. Amplitudes of the first six LSM modes versus dielectric slab width at the center of witness channel for single bunch excitation case. Each slab changes by the same value

2.3. AMPLITUDES OF WAKEFIELDS AT BUNCH TRAIN EXCITATION CASE

Coherent summation of wakefields from N_b drive bunches spaced with period of L_m is if |phase shift $|\Delta k_z L_m N_b|<\pi$, or in linear section of dispersion $|\Delta f_{coh}|<v_0/2L_m N_b$, where Δf_{coh} is frequency shift from the resonance frequency of the reference device, v_0 is bunch electron velocity. At exact resonance the $E_z \propto N_b$. In our case L_m=10.6 cm, $v_0 \approx c$. If we use N_b=101, then $|\Delta f_{coh}|<15$ MHz for the resonant operation mode LSM_{31}. In the interval ends $2|\Delta f_{coh}|$ the wakefield from N_b will be suppressed. It is confirmed with direct calculations of wakefields when changing ε or the width of dielectric slabs w_n.

One can see in Fig. 9 at $2.04<\varepsilon<2.06$ all bunches of the train put into the wakefield of LSM_{31} mode. In exact resonance the amplitude of LSM_{31} is by 100 times greater than for single-bunch regime. No coherent summation of rest *LSM* and *LSE* modes.

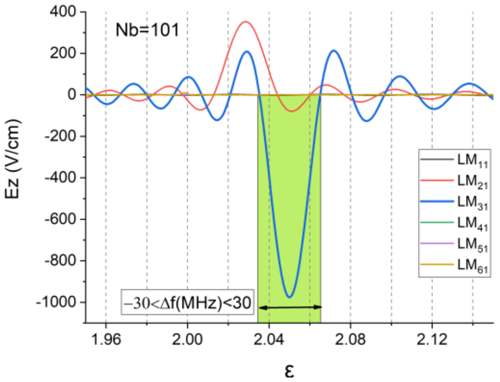

Fig. 9. Amplitudes of the first six LSM modes versus dielectric constant of slabs at the center of witness channel for bunch excitation case

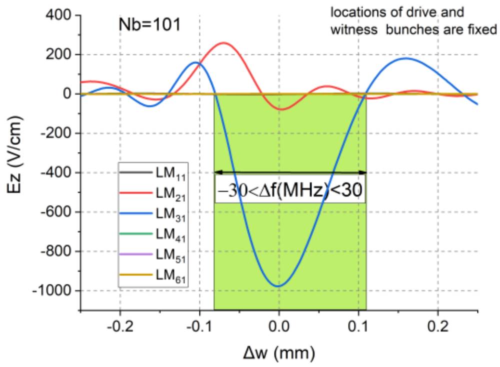

Fig. 10. Amplitudes of the first six LSM modes versus dielectric slabs width at the center of witness channel for bunch excitation case. Each slab changes by the same value

From Fig. 6 follows that $2|\Delta f_{coh}| < 30$ is reached if $-0.085 < \Delta w(\mathrm{mm}) < 0.11$. Thus, inside this interval there should be nonzero summations of wakefield of LSM_{31} mode from 101 bunches. Direct computations in Fig. 10 confirm this estimation. Also no coherent summation of rest *LSM* and *LSE* modes.

CONCLUSIONS

The 5-zone 2-channel dielectric accelerator unit is designed for wakefield experiments in KIPT. It is based on rectangular metal waveguide R_{13} with transverse dimension 180x55 mm. As dielectric material was chosen Teflon with ε=2.05.

Dimensions of dielectric slabs and their positions are computed supposing double repetition rate of bunches (2803 MHz). At this was required high **T**>>2. Designed unit gives possibility provide **T**≈8.

Tolerances on deviation dielectric permittivity and width of dielectric slabs are analyzed. The most rigid requirements are for slab width, especially they gain when exciting by long train of N_b bunches. For example if we use N_b=101 then errors in fabrication of slab must be < 0.1 mm.

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ПАРАМЕТРЫ ДВУХКАНАЛЬНОЙ ПЯТИЗОННОЙ ДИЭЛЕКТРИЧЕСКОЙ СТРУКТУРЫ ДЛЯ ЭКСПЕРИМЕНТОВ ПО КИЛЬВАТЕРНОМУ УСКОРЕНИЮ В ХФТИ

Д.Ю. Залеский, Г.В. Сотников

Представлены параметры двухканальной пятизонной прямоугольной диэлектрической структуры с целью экспериментальной проверки основных принципов использования таких структур для кильватерного ускорения. Пятизонная двухканальная диэлектрическая структура состоит из двух соседних вакуумных каналов (один для ведущего сгустка, другой для ускоряемых сгустков), окруженных диэлектрическими пластинами. Вся структура помещена в прямоугольный волновод. Также исследуются допуски на параметры структуры, которые влияют на величину коэффициента трансформации и ускоряющего градиента.

ПАРАМЕТРИ ДВОКАНАЛЬНОЇ П’ЯТИЗОННОЇ ДІЕЛЕКТРИЧНОЇ СТРУКТУРИ ДЛЯ ЕКСПЕРИМЕНТІВ З КІЛЬВАТЕРНОГО ПРИСКОРЕННЯ В ХФТІ

Д.Ю. Залеський, Г.В. Сотніков

Представлено параметри двоканальної п’ятизонної прямокутної діелектричної структури з метою експериментальної перевірки основних принципів використання таких структур для кільватерного прискорення. П’ятизонна двоканальна діелектрична структура складається із двох сусідніх вакуумних каналів (один для ведучого згустка, інший для згустків, що прискорюються), оточених діелектричними пластинами. Уся структура поміщена в прямокутний хвилевід. Також досліджено допустимі відхилення параметрів структури, які впливають на величину коефіцієнта трансформації та прискорюючого градієнта.