RECTANGULAR DIELECTRIC STRUCTURES FOR THE WAKEFIELD ACCELERATION EXPERIMENTS IN KIPT

K.V. Galaydych[1]*, V.A. Kiselev*[1]*, P.I. Markov*[1]*,*
A.M. Naboka[2]*, I.N. Onishchenko*[1]*, G.V. Sotnikov*[1]
[1]*National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;*
[2]*Institute of Electrophysics and Radiation Technologies NAC of Ukraine, Kharkov*
E-mail: sotnikov@kipt.kharkov.ua

At the Kharkov Institute of Physics and Technology is planned experimental test of the basic principles of the multi-bunch multi-mode dielectric wakefield accelerator. For this purpose we carried out a series of calculations of wakefield excitation and dynamics of the drive and witness bunches in rectangular structures with a dielectric substrate. For optimization two rectangular vacuum waveguides of R32 (72.14×34.04 mm) and R26 (86.36×43.18 mm) which were filled with the dielectric covering two any opposite metal walls of a waveguide were chosen. As possible dielectric Alumina, Cordierite, or Teflon were tested. It was supposed that the structure will be energized by train of electron bunches (bunch repetition frequency is 2.805 GHz) of 4.5 MeV energy, average current is 1 A. As the candidate for operating mode the LSM-wave or the LSE-wave, with frequency to equal the bunch repetition frequency or its doubled frequency were tested. The gradient of an accelerating field, small transverse deflection (or divergence) of drive and witness bunches were the main criteria of optimization. As a result of optimization we propose some dielectric structures for future wakefield experiments in KIPT.

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INTRODUCTION

Acceleration of charged particles by wake fields excited by a bunch or a bunch train in dielectric structures belongs to the perspective two-beam accelerator methods. Theoretical and experimental studies have shown that the acceleration gradient can be significantly higher than in the conventional accelerators, therefore dielectric structures can be used in future multi-TeV colliders.

Among carried out researches the studies of rectangular dielectric structures occupy a special place [1 - 12]. This is due to their following advantages:

- ease of manufacture;
- easy control the operation frequency by adjusting the metal walls of the waveguide, free from dielectric;
- for a given frequency, and the accelerating voltage they can store more energy than the cylindrical configuration, this property reduces the beam loading;
- additional internal focusing - the structure of transverse forces acting on the electron beam is similar to the quadrupole focusing;
- the possibility of multi-mode excitation, leading to a significant increase in the amplitude of the wakefield.

With purpose of verifying main advantages of rectangular dielectric structures for wakefield acceleration we planned a series of experiments. For these experiments we need dielectric structures with required properties (operation frequency, accelerating gradient, bunch stability) and parameters which fit existing in KIPT experimental facility. We have carried out a lot of computations, and here we propose possible candidates.

RESULTS OF COMPUTATIONS

The rectangular dielectric waveguide represents the metal waveguide having the cross sizes $a \times b$ with two dielectric slabs (dielectric permittivity is equal to ε), covering opposite walls of a waveguide (Fig. 1).

Slabs can be placed along the narrow side *b* or along the wide side *a* of a waveguide. Electron bunches, passing through a slow-wave structure, excite the wakefield representing superposition of eigenmodes of a waveguide.

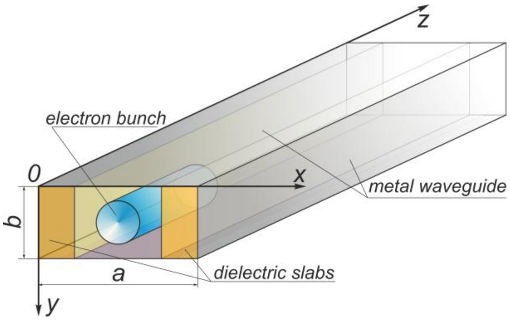

Fig. 1. Schematic view of a rectangular dielectric waveguide. Yellow bricks show dielectric slabs, blue cylinder shows electron bunch

Frequencies of these modes are defined by the transverse dimensions of a waveguide and dielectric slabs, dielectric permittivity of slabs and energy of bunch electrons. The purpose of numerical calculations was the determination of thickness of dielectric slabs in case of the fixed other parameters of a waveguide and a bunch.

The parameters of bunches in numerical calculations were chosen corresponding to the experimental installation "Almaz-2": repetition frequency is 2.805 GHz, electrons energy is 4.5 MeV, a bunch charge is 0.32 nC, bunch length is 1.7 cm, bunch diameter is 1 cm.

As possible waveguides in which dielectric slabs can be placed, two metal waveguides the R32 waveguide with sizes of $a = 72.14$ mm, $b = 34.04$ mm and R26 waveguide with sizes of $a = 86.36$ mm, $b = 43.18$ mm were considered. As a dielectric material for the slabs the Teflon ($\varepsilon = 2.1$), the Cordierite ($\varepsilon = 4.6$) and Alumina ($\varepsilon = 9.0$) were analyzed.

For numerical calculations of eigen frequencies of dielectric waveguides and excited wakefields the theory of excitation of multizone dielectric waveguides was used [7, 9]. According to this theory the total expression for a wakefield is represented as superposition of LSM and LSE eigenmodes [13]. Their eigen frequencies are determined from the appropriate dispersion equations. For the given frequency of bunches repetition the thickness of dielectric slabs can be selected so that LSM mode or LSE mode was a resonant one. Each of these modes contains the longitudinal component of an electric field necessary for acceleration of a test bunch. The choice of one or another mode depends on value of an accelerating field and on stability of accelerated particles in the selected type of a wave. In the Tables 1 - 3 presented below the results of optimization only on the maximum accelerating field are provided. One more restriction which was considered in the case of these calculations: the cross size of the vacuum channel can't be less than 1 cm – the diameter of bunches which is supposed to be used in the experiment. Along with the accelerating gradient, we calculated the other important characteristics of the accelerator structures – ratio of shunt impedance to Q-factor R/Q, the group velocity of the resonance wavelength and power of the resonant mode. Also the mode composition of the total field excited by a single bunch was investigated (Tables 1 - 3).

Parameters of Teflon Dielectric Waveguide ($\varepsilon = 2.1$) **Table 1**

Waveguide	**R32 ($a \times b$ =72.14×34.04 mm)**		**R26 ($a \times b$ =86.36×43.18 mm)**	
Frequency of the resonant mode (GHz)	5.61		5.61	
Sizes of slabs (mm)	27.5×34.04	10.97×72.14	14.16×86.36	8.27×86.36
Type of resonant mode	LSE_{11}	LSM_{21}	LSE_{11}	LSM_{21}
Mode composition of a total field	Multimode	Single-mode	Multimode	Single-mode
Accelerating gradient (keV/m)	~ 13	~ 23	~ 17	~ 13
Amplitude of a resonant mode (keV/m)	~ 6.5	~ 19	~ 3.5	~ 12.5
R/Q of resonant mode (kOhm/m)	0.737	2.002	0.467	1.473
Group velocity β_g of resonant mode	0.53	0.493	0.641	0.575
Power of resonant mode (point bunch) (W)	~373	~1089	~198	~ 687

Parameters of a Cordierite Dielectric Waveguide ($\varepsilon = 4.6$) **Table 2**

Waveguide	**R32 ($a \times b$ =72.14×34.04 mm)**		**R26 ($a \times b$ =86.36×43.18 mm)**	
Frequency of the resonant mode (GHz)	5.61		2.805	
Sizes of slabs (mm)	7.57×72.14	4.99×72.14	15.65×86.36	13.16×86.36
Type of resonant mode	LSE_{11}	LSM_{21}	LSE_{11}	LSM_{21}
Mode composition of a total field	Multimode	Single-mode	Multimode	Multimode
Accelerating gradient (keV/m)	~ 17	~ 13.5	~ 18	~ 16
Amplitude of a resonant mode (keV/m)	~ 3	~ 13	~ 3.55	~ 6.6
R/Q of resonant mode (kOhm/m)	0.29	1.052	0.426	0.546
Group velocity β_g of resonant mode	0.465	0.37	0.322	0.228
Power of resonant mode (point bunch) (W)	~167	~761	~178	~ 333

Parameters of a Alumina Dielectric Waveguide ($\varepsilon = 9.0$) **Table 3**

Waveguide	**R32 ($a \times b$ =72.14×34.04 mm)**		**R26 ($a \times b$ =86.36×43.18 mm)**	
Frequency of the resonant mode (GHz)	2.805		2.805	
Sizes of slabs (mm)	10.29×72.14	8.94×72.14	10.24×86.36	8.35×86.36
Type of resonant mode	LSE_{11}	LSM_{21}	LSE_{11}	LSM_{21}
Mode composition of a total field	Multimode	Multimode	Multimode	Multimode
Accelerating gradient (keV/m)	~ 17	~ 15	~ 11	~ 10
Amplitude of a resonant mode (keV/m)	~ 3.5	~ 5.5	~ 2.1	~ 4.8
R/Q of resonant mode (kOhm/m)	0.285	0.255	0.211	0.263
Group velocity β_g of resonant mode	0.215	0.121	0.265	0.147
Power of resonant mode (point bunch) (W)	~177	~284	~107	~ 241

TEFLON AS MATERIAL OF SLABS

If we demand that the frequency of a resonant mode must be equal to the bunch repetition rate, then we find that there is no such thickness of dielectric slabs which would provide the given resonance frequency of LSM mode or a LSE mode in a rectangular waveguide of R32 or R26 dimension type. The solution is absent for any orientation of slabs: along narrow or along wide wall of any of the selected waveguides. If the frequency of a resonant mode is equal to the double frequency of the bunch repetition, i.e. 5.61 GHz, the solutions for both waveguides of R32 and R26 dimension types are possible. Possible options for a choice of thickness of slabs are given in the Table 1.

CORDIERITE AS MATERIAL OF SLABS

In case of Cordierite choice as material of dielectric slabs the solution of the dispersion equations for determination of thickness of slabs already has frequencies, resonant to the frequency of bunch repetition, 2.805 GHz. These solutions exist both for R32 waveguide, and for R26 waveguides. But a longitudinal field excited in R32 dielectric waveguide is significantly lower, than in the R26 waveguide. For a waveguide of R32 dimension type it is more preferable to work at the twice frequency of 5.61 GHz. Possible options of filling of waveguides of R32 and R26 dimension types by the Cordierite are given in Table 2.

As calculations showed, the orientation of dielectric slabs along a wide wall of a metal waveguide is more preferable to both types of waveguides because amplitude of an excited wakefield in these cases is higher.

ALUMINA AS MATERIAL OF SLABS

Large value of dielectric permittivity of Alumina ceramics allows to use it for filling of waveguides R32 and R26 in order to obtain the given period of the wakefield corresponding the bunch repetition rate of

2.805 GHz. Moreover in this case the slabs can be oriented either along wide or narrow sides of the waveguide. However orientation along the wide sides of the waveguide is more preferable because amplitude of a wakefield in this case is much higher. In case of orientation of slabs along the narrow side the excited fields fall down from a dielectric surface quicker and width of the vacuum channel is larger therefore coupling of a bunch with a wave is worse and field amplitude is lower, than in the case of orientation of slabs along the wide side. Aggregate results of choice of possible thickness of dielectric slabs from Alumina are given in Table 3.

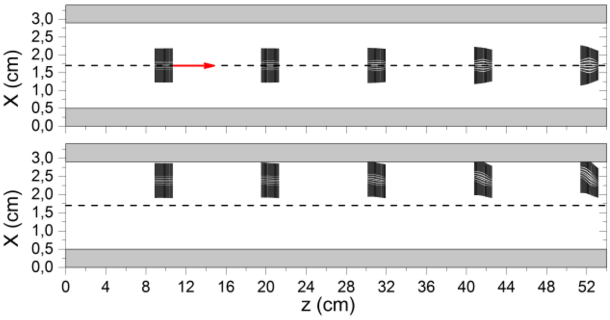

Fig. 2. Positions of drive bunch electrons after injection 10-th bunch of the train: top picture corresponds to on-axis bunch injection; bottom picture corresponds off-axis injection, offset is 6.8 mm. Drive bunch charge is increased by 10 times in comparison with Tables 1, 2 and equal to 3.2 nC. Grey rectangles show dielectric slabs

From the data provided in the Tables 1-3 follows that when using Alumina for dielectric slabs the wakefield excited by a single electron bunch has multimode character in both types of waveguides. If to make slabs from Cordierite, the total field has also multimode character with the exception of a case when the R32 waveguide is used and excitation happens on fundamental mode LSM_{21} with frequency, equal to the double frequency of the bunch repetition. Wakefield excited in waveguides R32 and R26 with slabs made from Teflon, has the single-mode character in case of resonance excitation of LSM_{21} mode and multimode character if the dielectric waveguide is excited on frequency of LSE_{11} mode. It is necessary to note to the general tendency: when transition from Teflon to Alumina, i.e. from a material with smaller value of dielectric permittivity to a material with greater one, the amplitude of a longitudinal electric field decreases.

Above selection of possible variants of filling of waveguides R32 and R26 with dielectric was made by criterion of amplitude of an accelerating field. By such optimization it was supposed that width of the vacuum channel where the drive and the accelerated bunches are transported, can't be less than their transverse size. The accounting of transverse dynamics can eliminate some of options proposed in Tables 1 - 3. The computation of a transverse dynamics of bunches have been started. For numerical simulations we elaborated a code based expansion on eigen waves [10, 14, 15]. One example of these calculations is presented in Fig. 2. Cordierite dielectric structure under this investigation was the same as in Table 2, third column (R32, resonance mode is LSM_{21}). From this figure follows that bunch train of 100 bunches having charge of 0.32 nC will be stable in cordierite dielectric unit even if bunches are strongly displaced from z-axis.

Spectra of the axial electric field component that is excited by a single electron bunch and their sequence in the dielectric resonators are shown on Fig. 3. Corresponding longitudinal distributions are shown on Fig. 4.

Sequence of bunches excites the equidistant spectrum of fields in the dielectric resonator by means of resonant amplification of resonant mode and modes with frequencies close to multiples of the resonant frequency. Bunch train suppresses non–resonant modes as shown in Fig. 3.

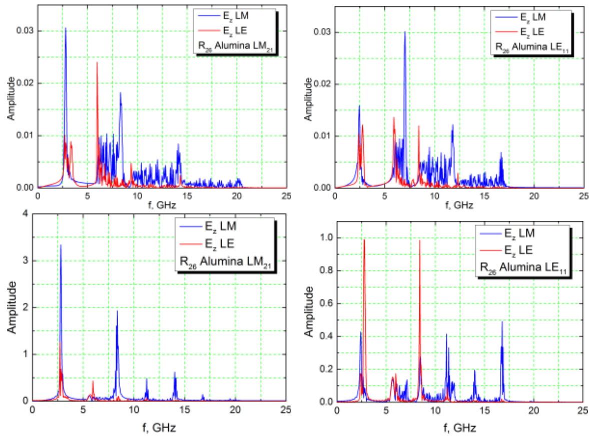

Fig. 3. The spectra of the longitudinal electric field excited in resonator by single bunch and sequence of the 10 bunches with charge 3.2 nC. The transverse dimensions of the resonators are given in Table 1, 2. Graphs at the left correspond to the R_{26} waveguide, operation mode is LSM_{21}, at the right – R_{26} waveguide, operation mode is LSE_{11}

Due to the excitation of the resonator eigenmodes the total wakefield forms. Axial distribution of longitudinal electric field that excited by single bunch is shown in Fig. 4.

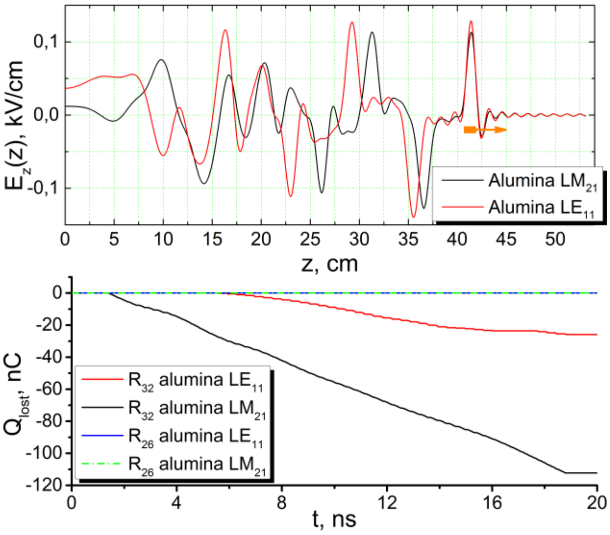

Fig. 4. (At the top) Longitudinal distribution of axial electric field in the dielectric resonator, excited by a single electron bunch (orange rectangle). Electron bunch moves from left to right. The transverse dimensions of the resonators are given in Table 1, 2. Other parameters are the same as for the Fig. 3. (At the bottom) The total lost charge of 50 bunches sequence as a function of time; a charge of single bunch is 6.4 nC

Inhomogeneity and multiwave amplitude envelope structure of the excited electromagnetic field is due to the excitation of a large number of eigenmodes by a single bunch.

There is an undesirable effect of subsidence particles of the bunch on the dielectric surface under the excitation of dielectric resonators by an electron bunches. As a consequence of that can be violated the dielectric quality and the vacuum conditions in the transport channel. Fig. 4 shows the dependence of the total lost charge as a function of time at excitation of dielectric resonators by sequence of 50 bunches with a charge of 6.4 nC. It is seen from Fig. 4 that, in general, taking into account the transverse dynamics of particles electron bunches is required. In resonators based on R_{26} waveguide subsidence particles is absent, because the width of a vacuum channel in this resonator more than in resonator based on R_{32} waveguide.

When comparing the results of numerical analysis of excitation dielectric resonators based on R_{26} and R_{32} waveguides, in which as a material of dielectric slabs the Alumina ($\varepsilon = 9.0$) was used, the next conclusions can be done. Wakefield that excited in both types of resonators by sequence of an electron bunches have a multimode structure. All the bunches of sequence make improvements in the wakefield amplitude. When using resonators based on R_{26} waveguide bunch particles losses on dielectric surface are negligible small (with the same number of driving bunches).

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ПРЯМОУГОЛЬНЫЕ ДИЭЛЕКТРИЧЕСКИЕ СТРУКТУРЫ ДЛЯ ЭКСПЕРИМЕНТОВ ПО КИЛЬВАТЕРНОМУ УСКОРЕНИЮ В ХФТИ

К.В. Галайдыч, В.А. Киселев, П.И. Марков, А.М. Набока, И.Н. Онищенко, Г.В. Сотников

В ХФТИ запланирована экспериментальная проверка основных принципов многосгусткового и многомодового кильватерного ускорителя. Для этого проведена серия расчетов возбуждения кильватерных полей и динамики ведущего и ускоряемого сгустков в прямоугольных вакуумных волноводах R32 (72,14×34,04 мм) и R26 (86,36×43,18 мм), которые заполнялись диэлектриком, нанесенным на две противоположные металлические стенки волновода. В качестве материала диэлектрика тестировались Alumina, Cordierite и Teflon. Ускорительная структура возбуждалась последовательностью электронных сгустков с частотой следования 2,805 ГГц, энергией 4,5 МэВ и средним током 1 А. В качестве рабочих мод тестировались LSM- и LSE-волны с частотой, равной частоте следования сгустков или ее удвоенной частоте. Основными критериями оптимизации были градиент ускоряющего поля, малая величина поперечного отклонения ведущего и ускоряемого сгустков. В результате оптимизации нами было предложено несколько диэлектрических структур для будущих кильватерных экспериментов.

ПРЯМОКУТНІ ДІЕЛЕКТРИЧНІ СТРУКТУРИ ДЛЯ ЕКСПЕРИМЕНТІВ ПО КІЛЬВАТЕРНОМУ ПРИСКОРЕННЮ У ХФТІ

К.В. Галайдич, В.А. Кисільов, П.І. Марков, О.М. Набока, І.М. Оніщенко, Г.В. Сотніков

У ХФТІ запланована експериментальна перевірка основних принципів багатозгусткового й багатомодового кільватерного прискорювача. Для цього виконана серія розрахунків збудження кільватерних полів і динаміки провідного згустка та згустка, що прискорюється в прямокутних вакуумних хвилеводах R32 (72,14×34,04 мм) та R26 (86,36×43,18 мм), які заповнювалися діелектриком, що нанесен на дві протилежні металеві стінки хвилеводу. У якості матеріалу діелектрика тестувалися Alumina, Cordierite та Teflon. Прискорювальна структура збуджувалася послідовністю електронних згустків з частотою проходження 2,805 ГГц з енергією 4,5 МеВ і середнім струмом 1 А. У якості робочих мод тестувалися LSM- та LSE-хвилі із частотою, що дорівнює частоті проходження згустків або подвоєній до неї частоті. Основними критеріями оптимізації були градієнт прискорювального поля, мала величина поперечного відхилення провідного згустка та згустка, що прискорюється. У результаті оптимізації нами було запропоновано кілька діелектричних структур для майбутніх кільватерних експериментів.