Satellite meeting to LCWS14
"Multi-bunch dielectric wake-field accelerator"
October 08, 2014

INVESTIGATIONS OF MULTI-BUNCH DIELECTRIC WAKE-FIELD ACCELERATION CONCEPT

I.N. Onishchenko

National Scientific Center
«Kharkov Institute of Physics and Technology»
Kharkov, Ukraine

OUTLINE

- MOTIVATION and BACKGROUND
- Objective and structure of the Project ANL-T2-247-UA / STCU P522 «Multi-bunch Dielectric Wakefield Accelerator» (MB DWFA)
- Experimental facilities
- Theory and Simulation
- Experimental investigation of the MB DWFA concept:

  "Multi-bunch" "Multi-mode" and "Resonator" aproaches for wakefield enhancing in structures of round and rectangular geometry with Teflon, quartz, alumina, zirconia

  Wakefield excitation and electron acceleration at frequency detuning

  Plasma-dielectric structure: excitation/acceleration and focusing/defocusing
- Testing of the dielectric materials and components under beam irradiation
- CONCLUSIONS

ANL-T2-247-UA / STCU P522:

«Multi-bunch Dielectric Wakefield Accelerator»

NIS Institute – **NSC “KIPT”** (Project manager Prof. **I. Onishchenko**)

Support institute: **DonIPE** (Prof. **T. Konstantinova**)

Partner–**DoE**/Global Initiatives for Proliferation Program (Director **Regina Carter**)

Technical Monitor/Collaborator - **Argonne National Laboratory**
(HEP AWA, Prof. **Wei Gai**)

U.S. Industry Partner - **Euclid TechLabs**, LLC (Dr. **Alexej Kanarejkin**)

Andrew Castiglioni*, GIPP Program Manager, Argonne National Laboratory*

BACKGROUND

FOUNDATION of the multi-bunch dielectric wakefield accelerator– **MB DWFA**:

1. Wakefield in dielectric (Cherenkov radiation) excited by charged particles can be enhanced by using a regular sequence of relativistic electron bunches (**multi-bunch operation**).

I.N. Onishchenko, V.A. Kiselev, A.K. Berezin et al, 1995

2. Interference of many transversal modes can enlarge wakefield picked amplitude (**multi-mode regime**).

T.B. Zhang, J.L. Hirshfield, T.C. Marshall, B.Hafizi, 1997

J.G. Power, Wei Gai, Paul Schoessow, 1999

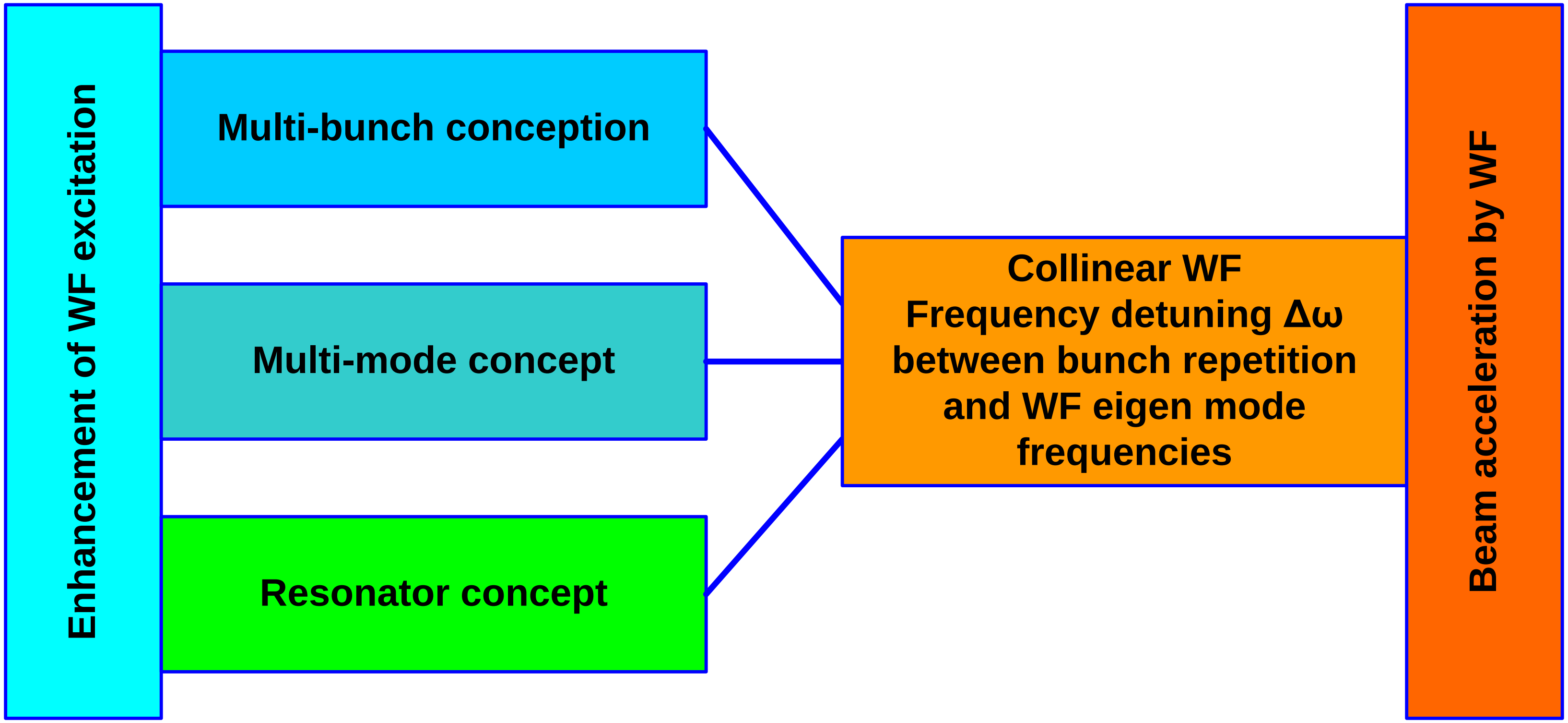
3. Resonant accumulation of wakefield in a cavity from many bunches + multi-mode regime (**resonator concept**).

T.C. Marshall, J.-M. Fang, J.L. Hirshfield, S.J. Park, 2001.

OBJECTIVE of the Project

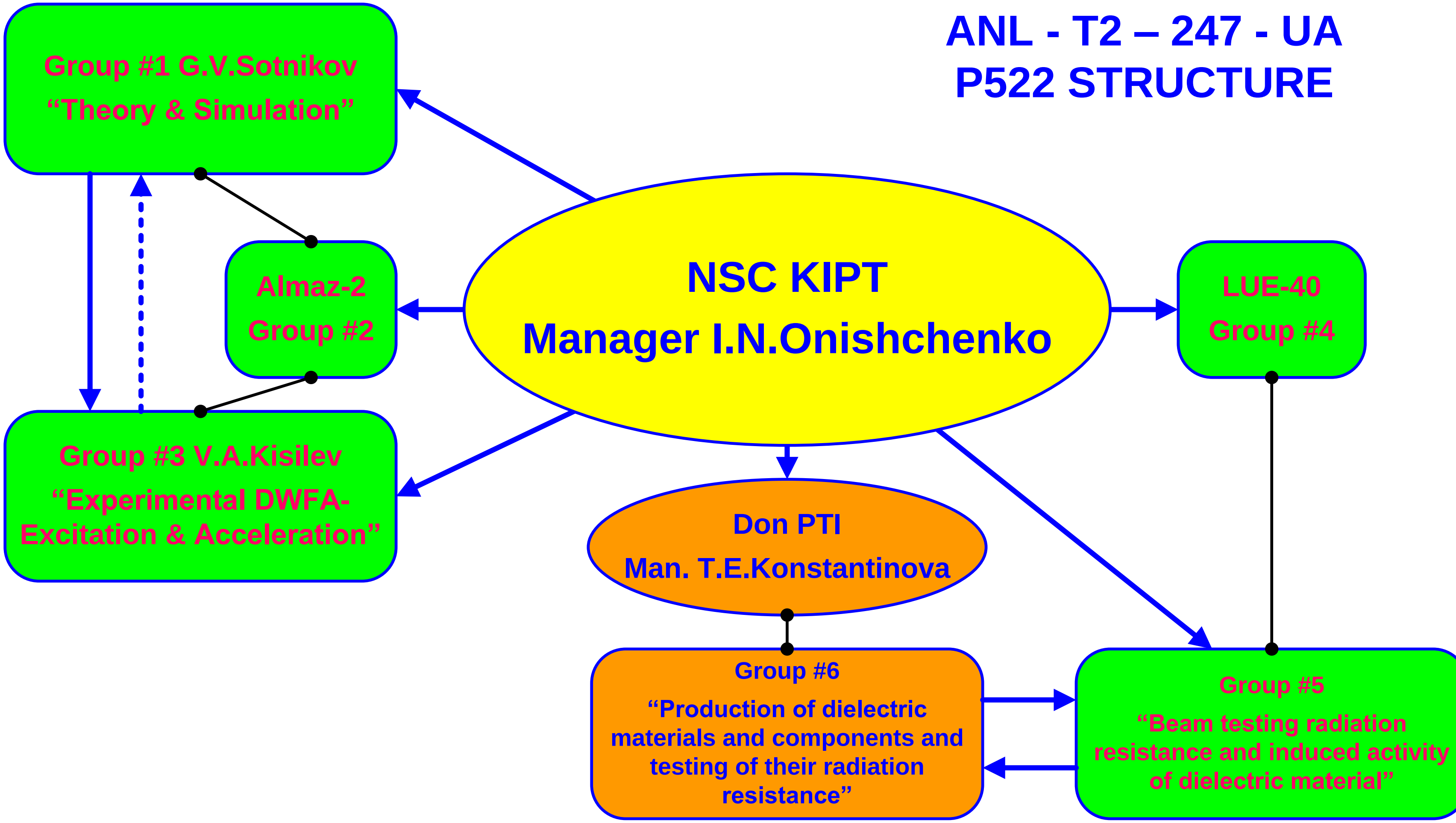
- The primary objective of the Project is the development, construction and investigation of a dielectric wakefield accelerator, based on multi-bunch, multi-mode, and resonator concepts of wakefield excitation enhancement in dielectric lined structure, and demonstration of particles wakefield acceleration by means of detuning between the bunch repetition frequency and the frequency of excited principal mode.
- The additional objective is the investigation of the change of dielectric materials and components properties under irradiation by the relativistic electron beam.

Scientific problems to be solved in ANL - T2 – 247 – UA/STCU P522 “Multibunch Dielectric Wakefield Accelerator”



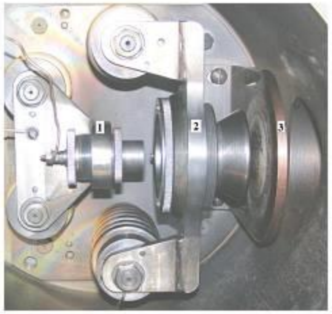
Beam testing of dielectrics relating to radiation resistance (ε and $tg\delta$). Induced activity

ANL - T2 – 247 - UA
P522 STRUCTURE



1. Experimental facilities for R&D of multi-bunch dielectric wakefield accelerator

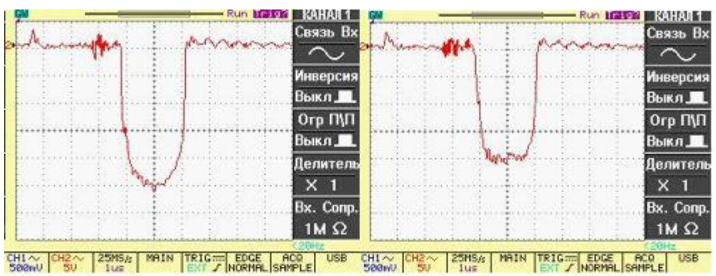
1.1 Updating electron linac to produce 3-6·10^3 bunches of energy 4.5MeV and charge 0.32nC, rms length 1.7cm, rms radius 0.5cm of each bunch



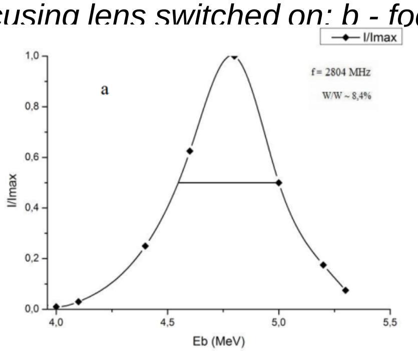
a b

a - electron gun: 1-unit of electron beam heater of the cathode, 2-cathode unit, 3-anode; b - electron gun chamber

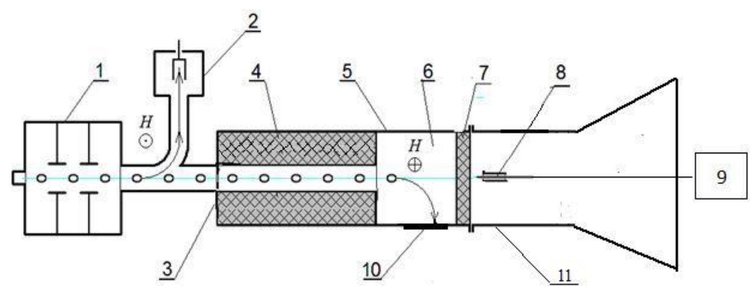
Restored klystron KIU-12M



Oscillograms of electron beam current on accelerator exit: a –focusing lens switched on; b - focusing lens switched off

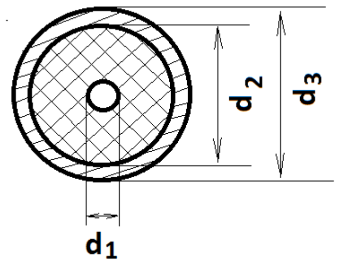


Electron energy spectrum at of the master oscillator frequency f=2804 MHz;

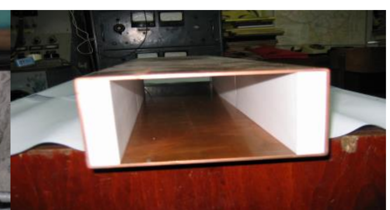


1 - accelerator "Almaz-2M", 2 - magnetic analyzer, 3 - diaphragm, 4 – dielectric structure, 5 - waveguide, 6 - traversal magnetic field, 7 – vacuum teflon plug, 8 - microwave probe, 9 - oscilloscope, 10 - metal collector, 11 - waveguide with a horn

The cross-sectional dimensions of the beam can be changed by means of aperture diameter. This will allows to carry out the planned experiments with dielectric structures with different sizes of transit channels for bunches of relativistic electrons.



Dielectric waveguide of circular cross-section; d_1=21.1 mm; d_2=85 mm; d_3=89 mm



Rectangular copper waveguide has cross-section size 85×180mm2 and length 75cm; along the narrow/wide sides dielectric was placed

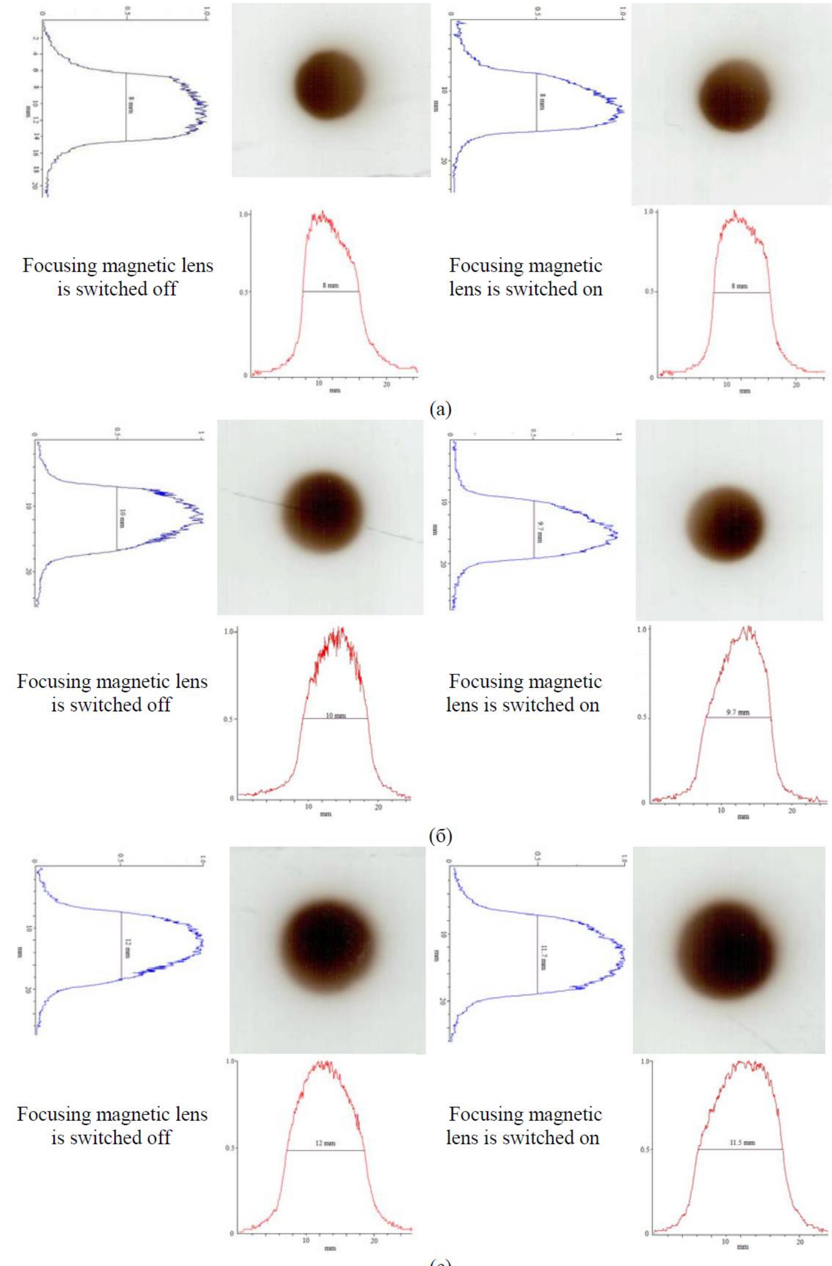


Fig.1.1.4. Imprints on glass plate of the bunches passing through the diaphragms of different diameter (a) - 8 mm, (b) - 10 mm, and (c) - 12 mm and current density distribution with and without magnetic focusing lens operating.

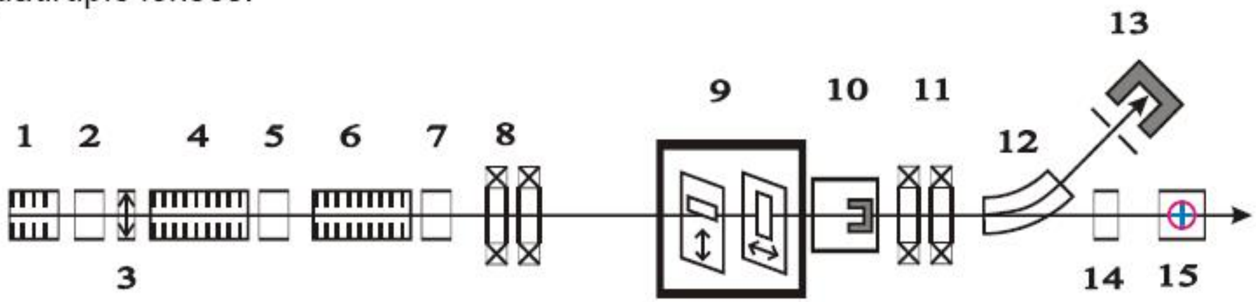
1.2 Arrangement of installation at electron linac on energy 100MeV for beam testing of dielectric patterns

LUE-40

Main parameters of the beam :

- energy of electrons up to 95 MeV;
- width of energy spectrum for 70% particles 2- 3 %;
- length of beam pulse 1.5 μs;
- pulse repetition rate up to 50 Hz;
- pulse current up to 70 mA;
- average current up to 6 mkA;
- minimum beam size at the output 3 mm

The following beam parameters were measured: electron energy spectrum, change of electron energy during the current pulse, pulsedcurrent, position of beam and spatial distributing of electrons in the transversal plane. To form the spatial distributing of electrons on a target in the transporting channel there were set 4 quadruple lenses.



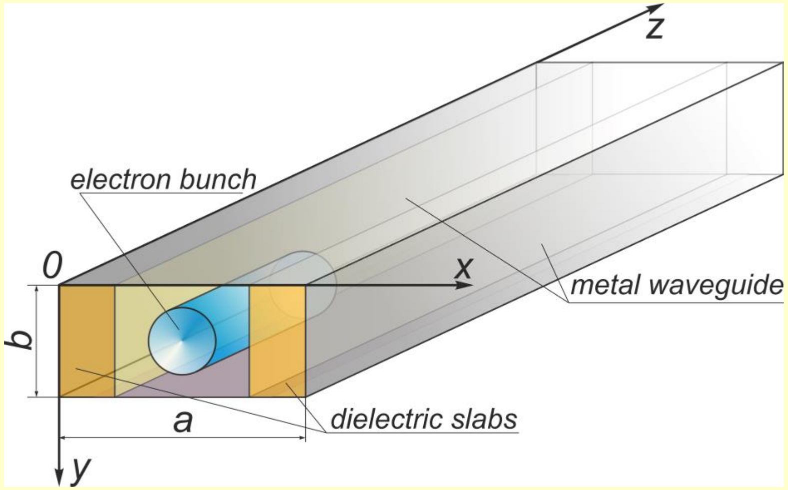
The scheme of the layout of accelerator elements: 1 electrons injector; 2,14 beam current monitor; 3 movable collimator; 4, 6 accelerating sections; 5,7 induction sensors of current, compatible with the beam position sensor; 8 duplet of the quadruple lenses; 9 block of the slotted collimators; 10 movable Faraday cup, 11 duplet of the quadruple lenses; 12 magnet analyzer, 13 Faraday cup; 15 indicator of position and focusing of beam.

Beamline between acceleration structure and exit of the linac LUE-40

Beam current monitor and indicator of position and focusing of beam

2. Theoretical investigation and simulation of dielectric wakefield excitation by a sequence of relativistic electron driver-bunches and acceleration of witness-bunches of the same sequence

2.1 Electrodynamics of cylindrical and rectangular waveguide lined with dielectric



Schematic view of a rectangular dielectric waveguide.

Electron bunches of linac "Almaz-2M" (energy 4.5 MeV, charge 0.32 nC, bunch repetition frequency 2.8 GHz) passing through the **rectangular structure**, excite the wakefield representing superposition of the structure eigenmodes.

The purpose of numerical calculations was the determination of the slab thickness to provide **the coincidence excited eigen mode frequence with the bunch repetition frequence $\omega_0=\omega_{rep}$**

As a dielectric material for the slabs teflon (ε =2.1), cordierite (ε =4.6), alumina (ε =9.0), quartz (ε =3.8), and zirconia (ε =23) were taken.

Parameters of Teflon dielectric waveguide (ε =2.1)

Waveguide	R32 (72.14 x 34.04 mm)		R26 (86.36 x 43.18 mm)	
Frequency of a resonant mode	5.61 GHz		5.61 GHz	
Sizes of slabs (mm)	27.5 x 34.04	10.97 x 72.14	14.16 x 86.36	8.27 x 86.36
Type of resonant mode	LSE_{11}	LSM_{21}	LSE_{11}	LSM_{21}
Mode composition of a total field from a single bunch	Multimode	Single-mode	Multimode	Single-mode
Accelerating gradient	~ 130 eV/cm	~ 230 eV/cm	~ 170 eV/cm	~ 130 eV/cm
Amplitude of a resonant mode	~ 65 eV/cm	~ 190 eV/cm	~ 35 eV/cm	~ 125 eV/cm

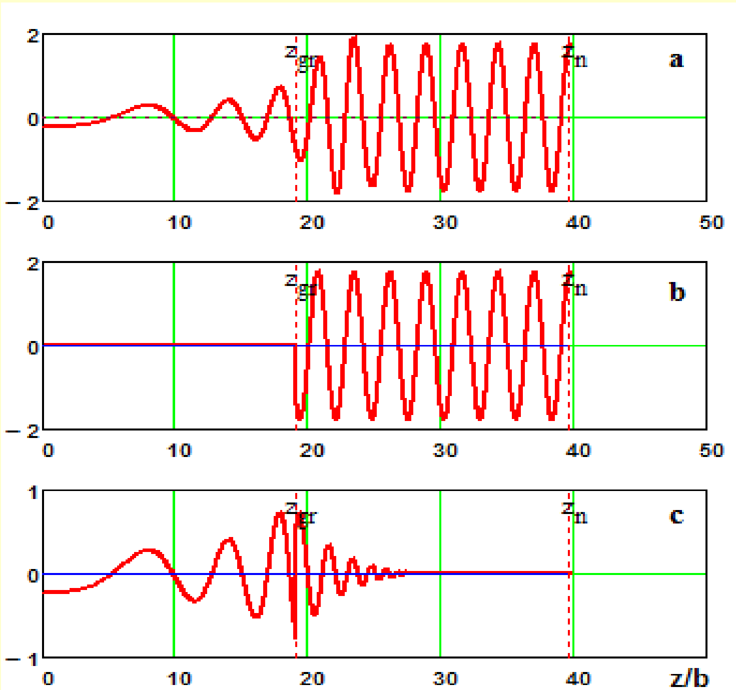
Parameters of a Alumina dielectric waveguide (ε =9.0)

Waveguide	R32 (72.14 x 34.04 mm)		R26 (86.36 x 43.18 mm)	
Frequency of a resonant mode	2.805 GHz		2.805 GHz	
Sizes of slabs (mm)	8.94 x 72.14	10.29 x 72.14	8.35 x 86.36	10.24 x 86.36
Type of resonant mode	LSE_{11}	LSM_{21}	LSE_{11}	LSM_{21}
Mode composition of a total field from a single bunch	Multimode	Multimode	Multimode	Multimode
Accelerating gradient	~ 170 eV/cm	~ 150 eV/cm	~ 110 eV/cm	~ 100 eV/cm
Amplitude of a resonant mode	~ 35 eV/cm	~ 55 eV/cm	~ 21 eV/cm	~ 48 eV/cm

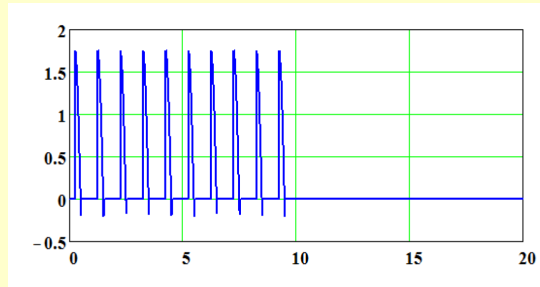
Calculations of wakefield eigen frequencies excited by bunches at Cherenkov resonance in Alumina dielectric waveguide of a **cylindrical geometry** was carried out too. For planned experiments two options of dielectric tubes are proposed: 1) external diameter the dielectric tube is 90 mm, an inside diameter is 74.18 mm; 2) outer diameter the dielectric tube is 86.5 mm, inside diameter is 70.44 mm. The accelerating gradient in the first case is equal to 42 eV/cm, in the second case is 46 eV/cm. The main contribution to the total field is given by the 1st and 2nd radial modes.

2.2 Wakefield excitation in dielectric waveguide and resonator by a sequence of relativistic electron bunches

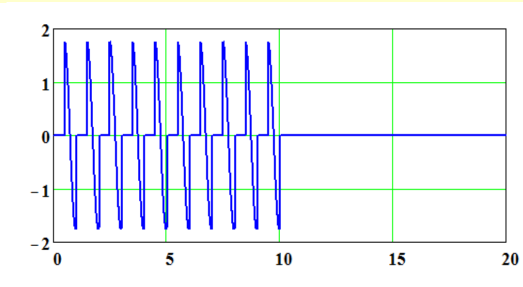
Dielectric semi-infinite waveguide



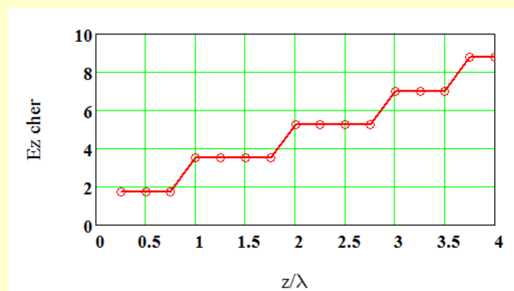
The structure of the principal mode of longitudinal wakefield excited by a thin ring bunch in a semi-infinite cylindrical dielectric waveguide: a)- total field E_z, b)- Cherenkov radiation field E_z^{cher}, c)- transition radiation E_z^{trans}. Observation time $tc/b=40$, $t_0=0$, $\gamma= 9.806$, $\varepsilon=2.1$



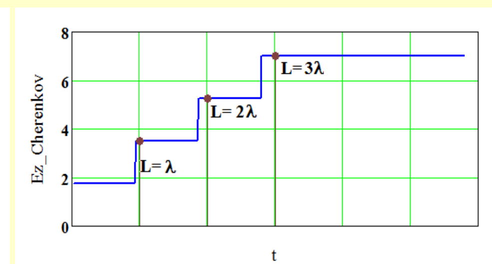
Dependence of Cherenkov wakefield on time at exit for waveguide length $L=\lambda/4$. Number of bunches is N=10.



Dependence of Cherenkov wakefield on time at exit for waveguide length $L=\lambda/2$. Number of bunches is N=10.

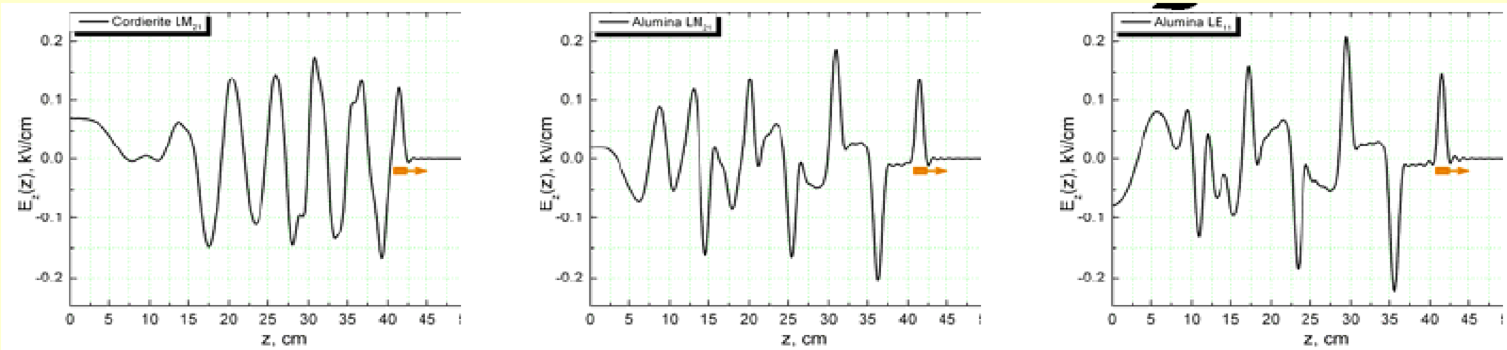


Dependence of Cherenkov wakefield amplitude at exit on waveguide length

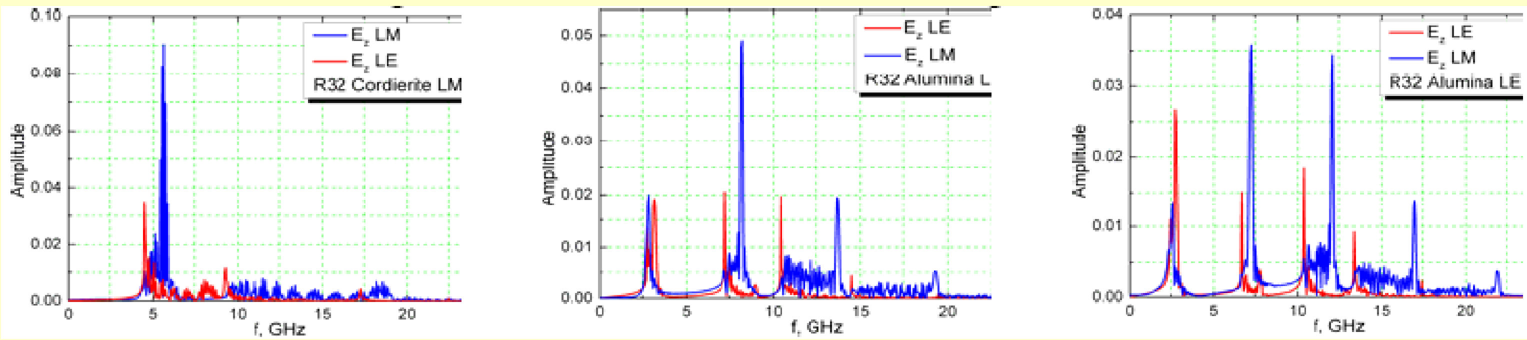


Dependence Cherenkov wakefield at exit on time for fixed length of dielectric waveguide

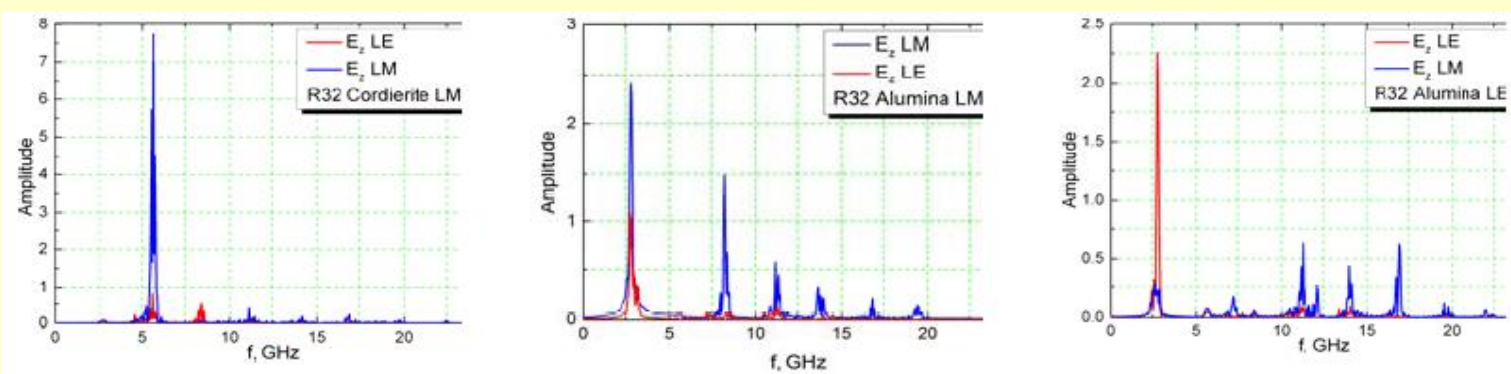
1. Waveform of a longitudinal electric field excited in the rectangular dielectric **resonator** by a single bunch 0.32nC (orange rectangle) for 3 different cross sizes (i.e. operation modes are LSM21, LSM21, LSE11)



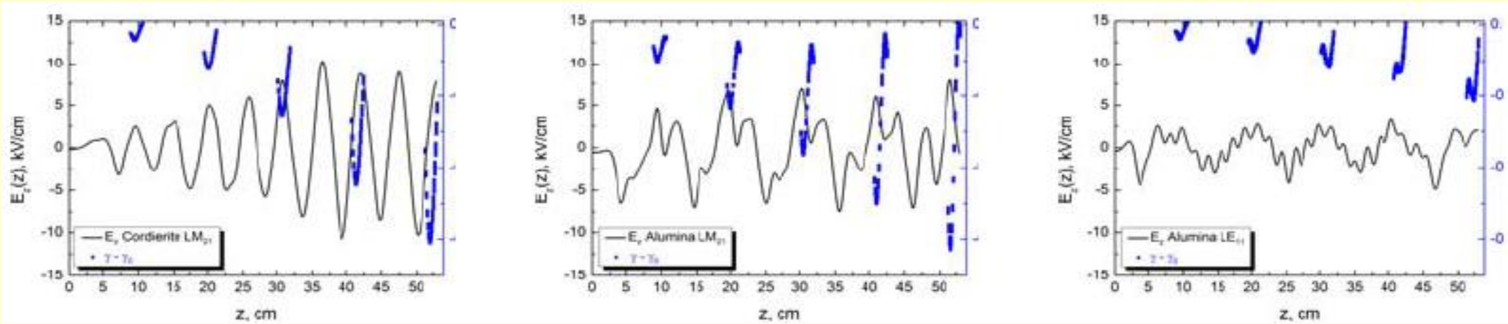
2. Spectra of a longitudinal electric field excited in the resonator by a single bunch



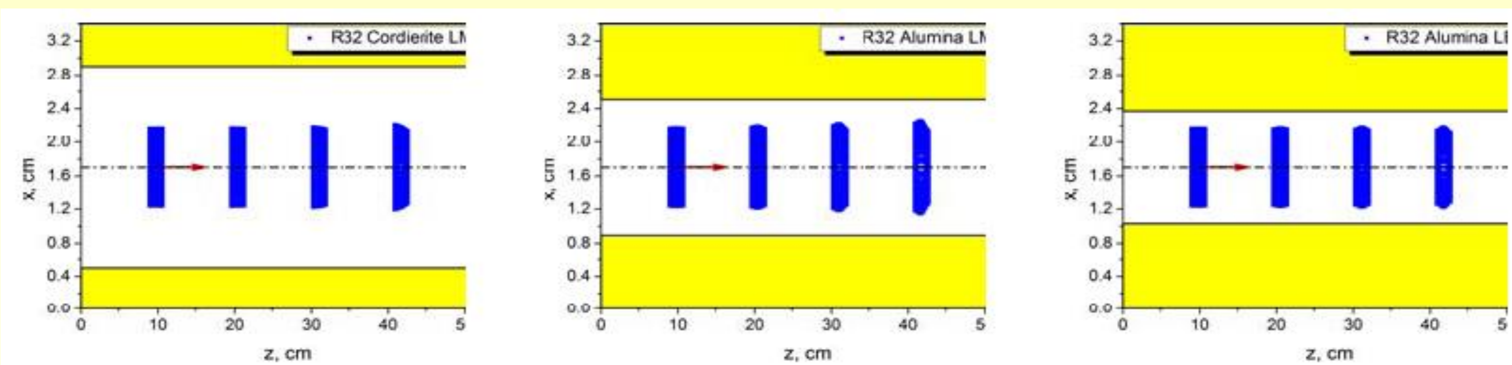
3. Spectra of a longitudinal electric field on axis at the resonator exit excited by a sequence of 10 bunches



4. Axial distribution of a longitudinal component of an electric field after injection of the 10th bunch into the resonator (black solid line), and also the phase planes "energy-longitudinal coordinate" of bunches (blue dots).



5. Transversal dynamics of particles of a sequence of bunches



2.3 Wakefield excitation and electron acceleration at detuning bunch repetition frequency and eigen principal mode of wakefieldfield

Detuning for acceleration.

Single mode

Parameters of the dielectric waveguide and the chain of electron bunches:

$b = 4.325\,cm$ *is radius of the metal tube,*

$a = 1.44\,cm$ *is radius of the vacuum channel,*

$\varepsilon = 2.1$ *is dielectric constant,*

$r_b / a = 0.5$ *is radius of the bunches,*

$\gamma_0 = 9.806$ *is relativistic factor,*

$Q_b = 0.32 \cdot 10^{-9} C$ *is charge of bunch,*

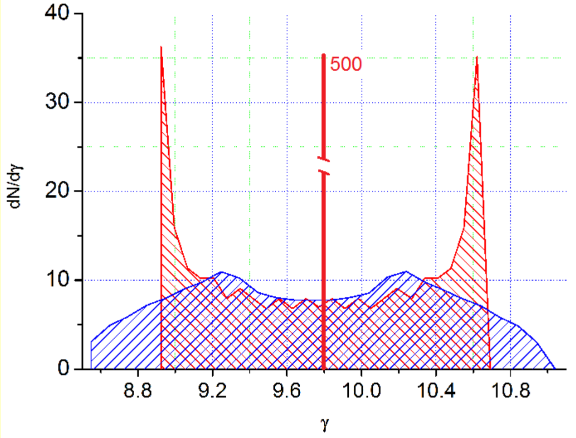
$\omega_b = \omega_1 + \alpha$ *is bunch repetition frequency,*

$\omega_1 = 1.7618 \cdot 10^{10}$ *is frequency o f fundamental wave,*

$\alpha = (\omega_1 - \omega_b) / \omega_b$ *is detuning of bunch repetition,*

$\tau_b = \omega_1 t_b = \pi / 3$ *is duration of single bunch,*

N *is the number of the relativistic electron bunches in the chain,*



Energy spectra for infinitely thin ring bunches (red) and rectangularly extended ones (blue) at detuning α=0.002, N=500

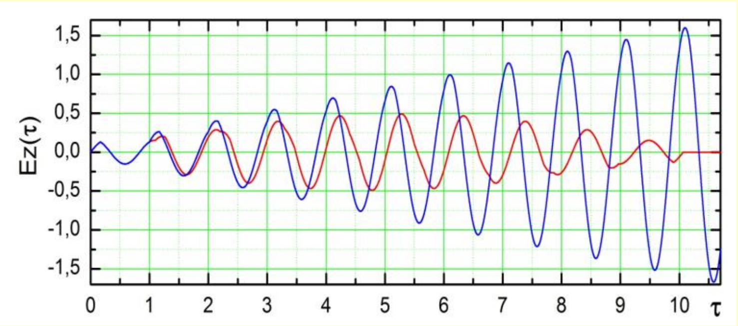


Fig.1. E_z component of normalized wakefield excited by sequence of $N = 10$ rectangular bunches of duration $\tau_b = \pi / 3$ upon $\tau = \omega_1 (t - z / v_0)$, $\alpha = 0$ (blue line) and $\alpha = 0.1$ (red line)

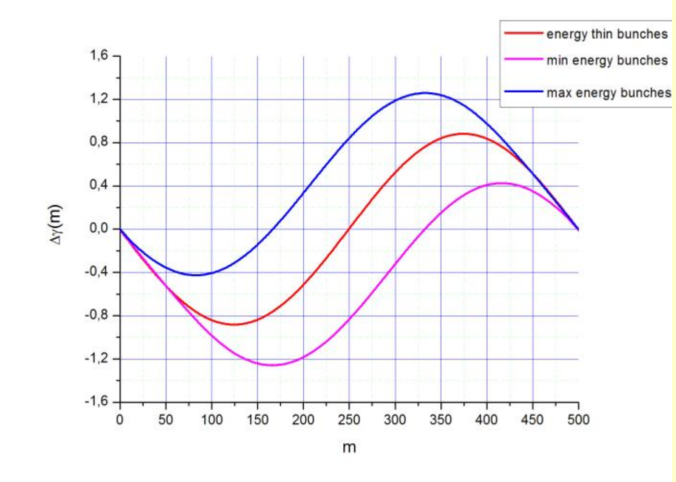
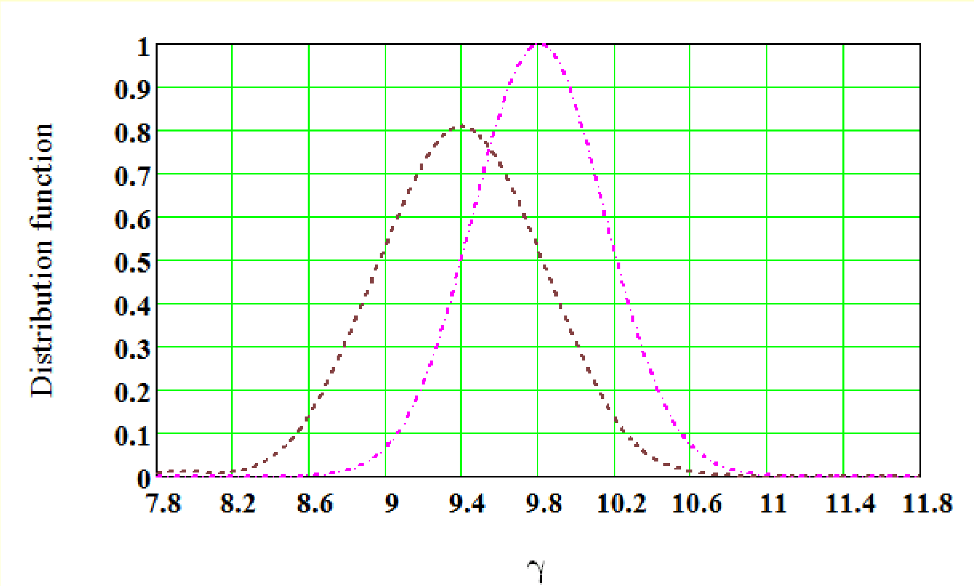


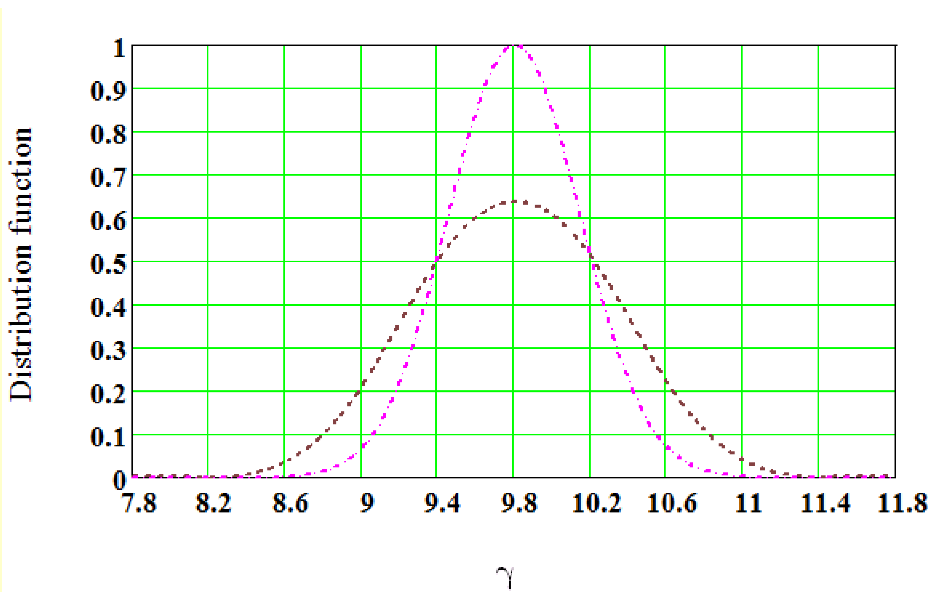
Fig.3. Dependences of energy first particle (magenta line), last particle (blue line) of rectangular bunches upon bunch number. Red curve corresponds case of infinitely thin ring bunches, $\alpha = 0.002$, $N = 500$

Energy spectrum of interacted bunches for initial spectrum of finite energy halfwidth



Initial distribution function with energy halfwidth ***$\Delta\gamma/\gamma$=0.1*** *(red line) and distribution function of interacted bunches at detuning*

$\delta\omega = (\omega_{m,n}-\omega_{rep})=0$ *(black line)*

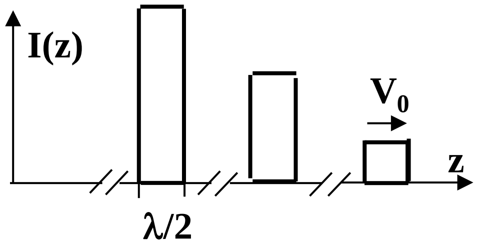


Initial distribution function with energy halfwidth ***$\Delta\gamma/\gamma$=0.1*** *(red line) and distribution function of interacted bunches at detuning*

$\delta\omega = (\omega_{m,n}-\omega_{rep})= 0.001\omega_{m,n}$ *(black line)*

2.5 Accelerating gradient of excited wakefield, electron energy spectrum and transformer ratio for parameters of experimental facility

Transformation ratio in resonator concept



Waveguide- for **R=2N**:

1) $Q_N = Q_1(2N-1)$

2) $\Delta z_b = \lambda/2$

3) $\omega_0/\omega_{rep} = n + 1/2,\quad n = 1, 2, \ldots$

Resonator - for **R=2N**:

Additional condition:

4) synchronization of bunch repetition frequency and forward+backward transit time of wakefield trains in resonator of length L $\quad 2\pi/\omega_{rep} = 2L/V_g$

$$
\begin{aligned}
E_z(z,t) = {} & E_1\{0.5\{\theta[V_0(t-T(N-1))-\Delta z_b-z]-\theta[V_0(t-T(N-1))-z]\}\sin\{k[V_0(t-T(N-1))-z]\}+\\
& +\{\theta\left[V_g(t-T(N-1))+L\left(1-V_g/V_0\right)-z\right]-\theta[V_0(t-T(N-1))-z]\}(N-1)\sin\{k[V_0(t-T(N-1))-z]\}+\\
& +\{\theta[V_0(t-T(N-1))-\Delta z_b-z]-\theta\left[V_g(t-T(N-1))-z\right]\}N\sin\{k[V_0(t-T(N-1))-z]\}\},\quad T = 2L/V_g
\end{aligned}
$$

1-st term is the decelerating field inside of Nth bunch, 2-nd (3-rd) term is the wakefield train after N-1 (after N) bunches.

Summarizing all coherent wakefield trains, excited by N injected bunches, leads to the total wakefield

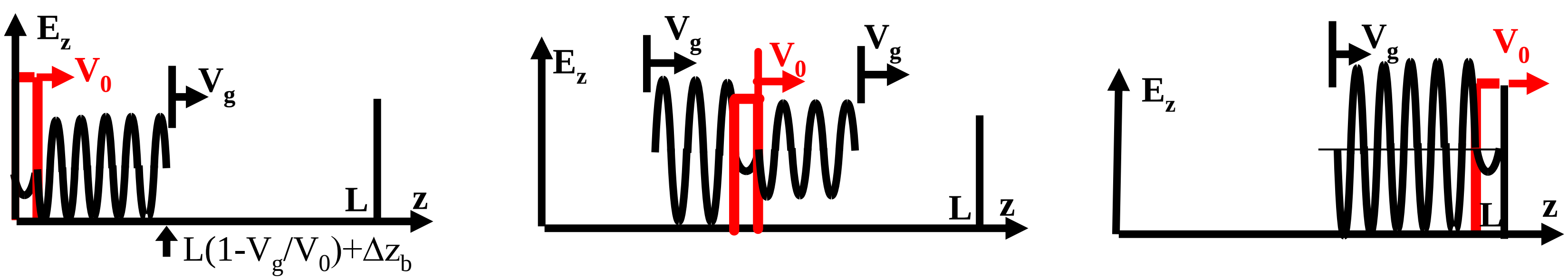
$$E_{acc} = E_N = E_z\Big|_{z=V_0(t-T(N-1))-3\lambda/4} = NE_1.$$

E_1 is wakefield after 1-st bunch.

$$E_{dec} = E_z\Big|_{z=V_0(t-T(N-1))-\lambda/4} = E_1/2,$$

Decelerating field is the same for each subsequent bunch.

$$R = \frac{E_{acc}}{E_{dec}} = 2N$$



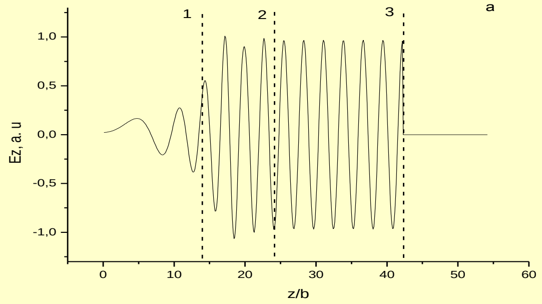
3. Experimental investigation of the conceptual multi-bunch dielectric wakefield accelerator

3.1 Research of the wakefield enhancement due to the summation of coherent wakefields driven by a regular sequence of electron bunches

Multi-bunch issue

- Statement of the problem

Phys. Rev. E 65, 066501(2002)



1. Single bunch excitation:

The length of the Cherenkov radiation train behind the bunch is $l=L(1- v_g/v_0)$, where L is distance from the waveguide entrance to the exciting bunch propagating inside of the waveguide, v_g is group velocity of wakefield wave, v_0 is velocity of the bunch. At the exit of waveguide of the length L_0 the duration of observed wakefield pulse will be $\tau=l/v_g=L_0/v_0(v_0/v_g-1)$.

2. Resonant sequence of bunches excitation:

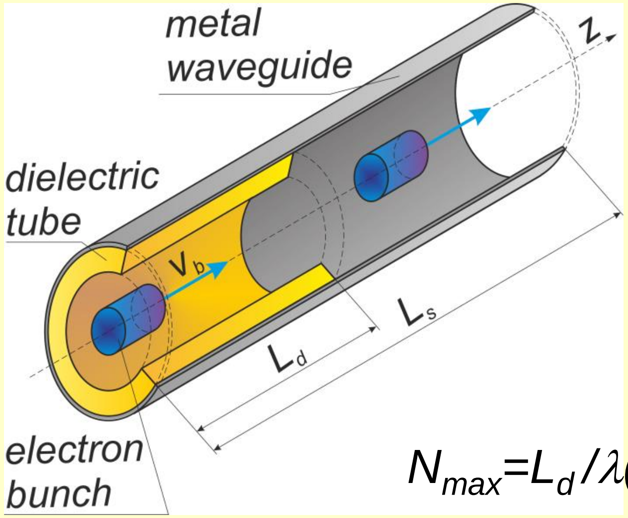
Due to the removal of the excited field from the waveguide exit with group velocity v_g. maximal number of bunches, wakefields summation of which leads to the total wakefield increase is restricted by

$$N_{max}=L_0/\lambda(v_0/v_g1) \qquad (1)$$

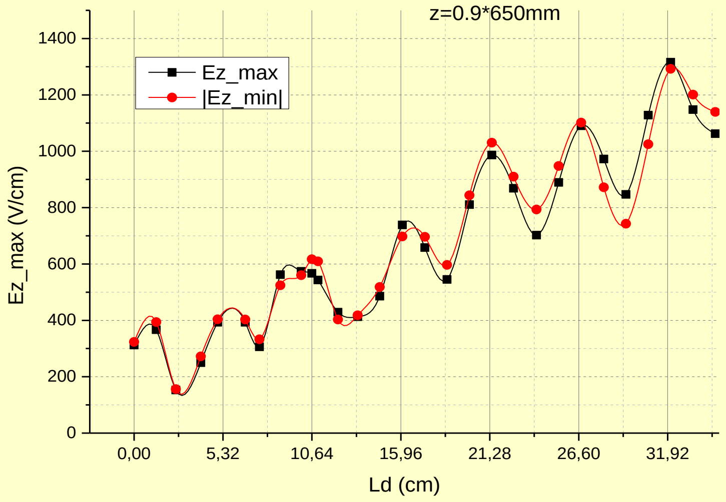
3. Number of bunches change is equivalent to dielectric waveguide length change:

According to (1) varying the length of the dielectric waveguide L_0 allows to observe wakefied at the waveguide exit from various N_{max}=1,2,3…Thus, instead of varying the the length of a resonant sequence of bunches (i.e. N) that is difficult to realize in the experiments, we vary the length of dielectric waveguide (i.e.L_0) and can “feel” separate/each bunch.

SIMULATION



$N_{max}=L_d/\lambda(v_0/v_g-1)$



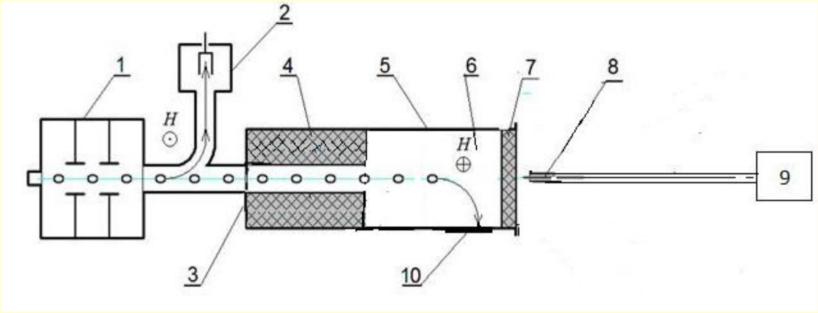
General view of the dielectric structure, excited by sequence of electron bunches.

Dependence of maxima and minima of the longitudinal electric field on L_d in point $z=0.9L_s$

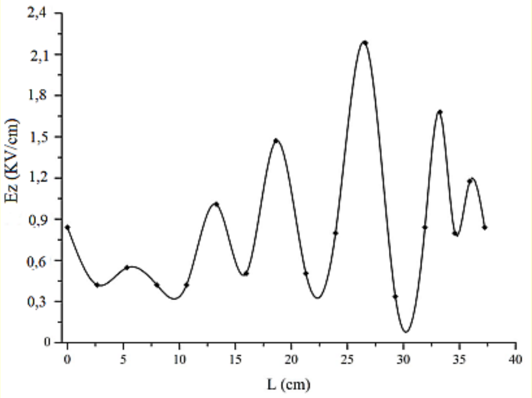
Into a metal cylindrical waveguide of length L_s the dielectric part of length L_d is inserted (yellow color). Electron bunches (blue color) propagate along a cylinder axis from left to right.

Markers show calculated points, between calculated points spline interpolation is carried out. Vertical grid lines are drawn by each half length of the lowest resonant wave.

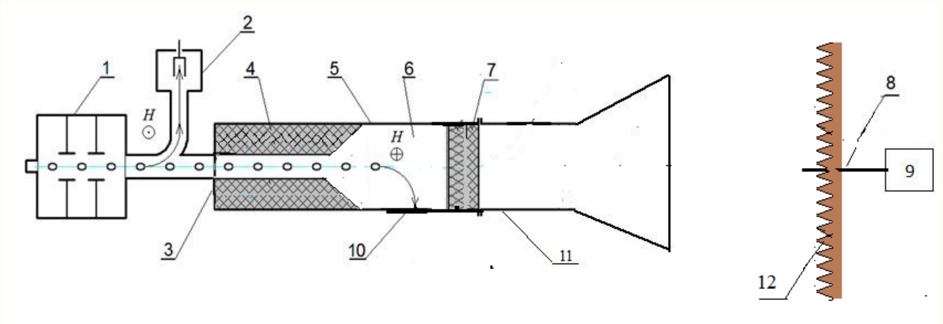
EXPERIMENT (cylindrical waveguide)



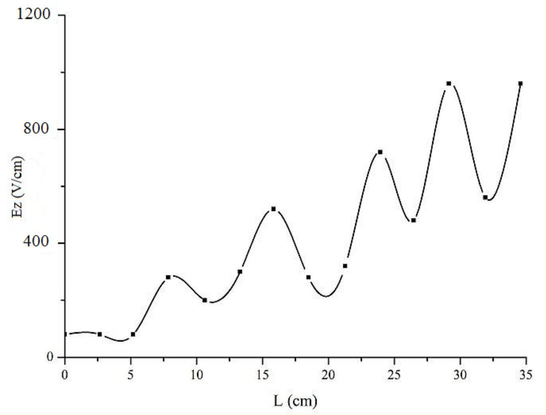
1-accelerator "Almaz-2M", 2-magnetic analyzer, 3-diaphragm, 4-dielectric structure, 5–waveguide, 6-transverse magnetic field, 7-Teflon vacuum plug, 8-microwave probe, 9-oscilloscope, 10-glass plate



Amplitude of E_z of excited wakefield on the dielectric part length L_d

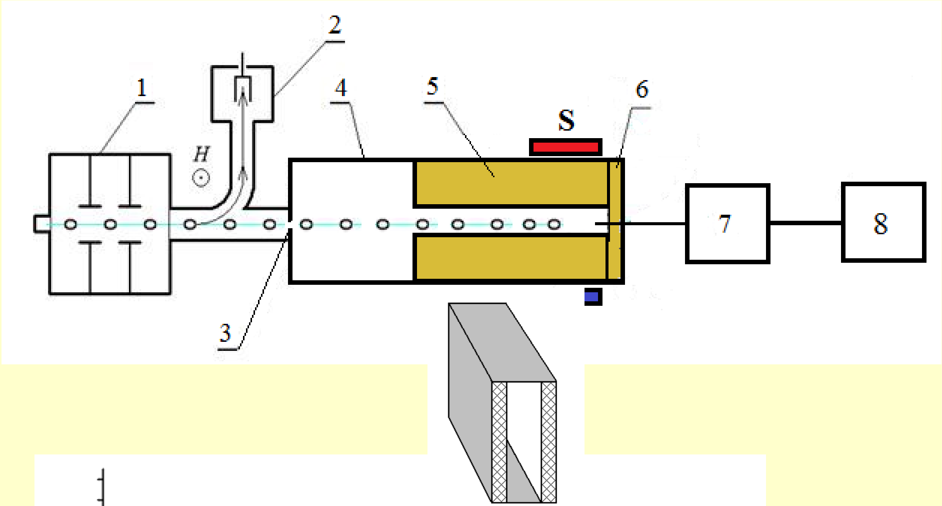


Scheme of the installation for “matched” dielectric waveguide: 1-accelerator "Almaz-2M", 2-magnetic analyzer, 3-diaphragm, 4-dielectric, 5-waveguide, 6-transverse magnetic field, 7-vacuum dielectric plug, 8-RF-probe, 9-oscilloscope, 10-glass plate, 11-additional waveguide with horn, 12-ferrite absorber

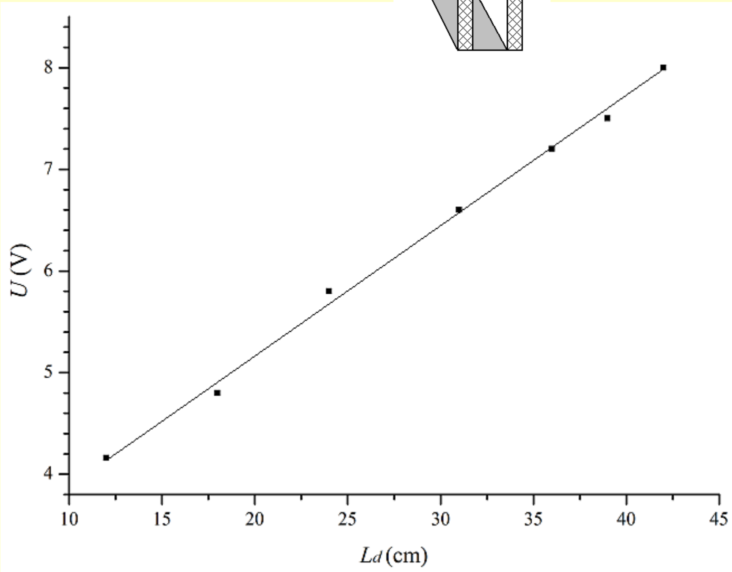


Amplitude of E_z of excited wakefield on the dielectric part length L_d for “matched” dielectric waveguide

EXPERIMENT (rectangular waveguide)



1 - Accelerator "Almaz-2M", 2 - magnetic analyzer, 3 - diaphragm, 4 – waveguide, 5 - insulator, 6 - dielectric plug, 7 - wavemeter VMT-10, 8 – oscilloscope

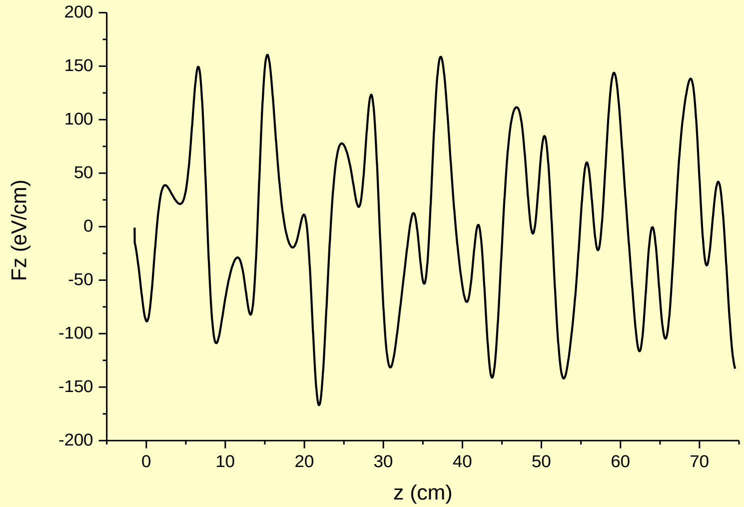


Dependence of wakefield amplitude on interaction length of bunches with rectangular dielectric waveguide

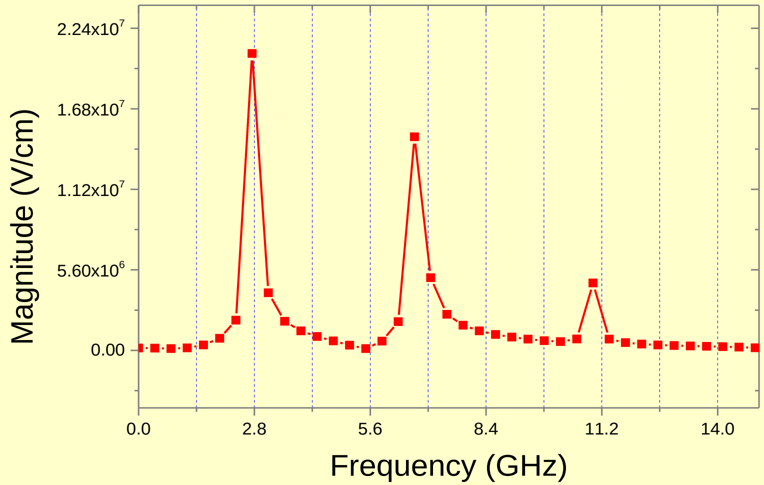
3.2 Research of the wakefield enhancement due to the summation of many equidistant transversal modes of wakefield, excited in a rectangular dielectric structure

Multi-mode concept

- Theoretically determined frequencies of transversal modes excited by a single bunch in an infinite waveguide were theoretically obtained.



(a)



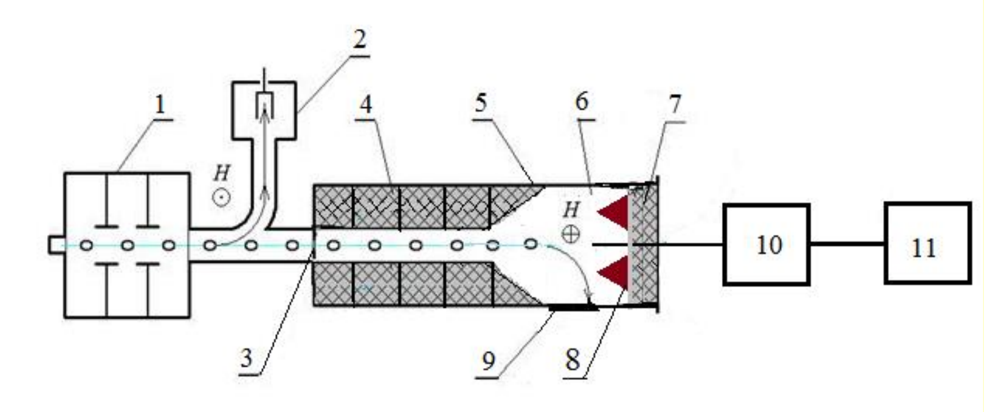
(b)

(a) - waveform of the longitudinal component E_z of the total wakefield on the axis;

(b) - frequency spectrum of the excited waves E_{0m}, obtained by FFT from corresponding waveform.

- In such a system the following modes are excited: E_{01} (2.8029 GHz), E_{02} (6.7568 GHz), E_{03} (10.9712 GHz), E_{04} (15.2378 GHz), and E_{05} (19.6228 GHz). Although these modes are not equidistant, the summation of their fields allows increasing the amplitude of the excited wakefield by about 30%.

Experimental setup (cylindrical waveguide)



1 - Accelerator "Almaz-2M", 2 - magnetic analyzer, 3 - diaphragm, 4 – a set of dielectric tubes, 5 - waveguide 6 - transverse magnetic field, 7 - dielectric plug, 8 - ferrite absorber, 9 - metal collector, 10 - wavemeter VMT-10, 11 - oscilloscope

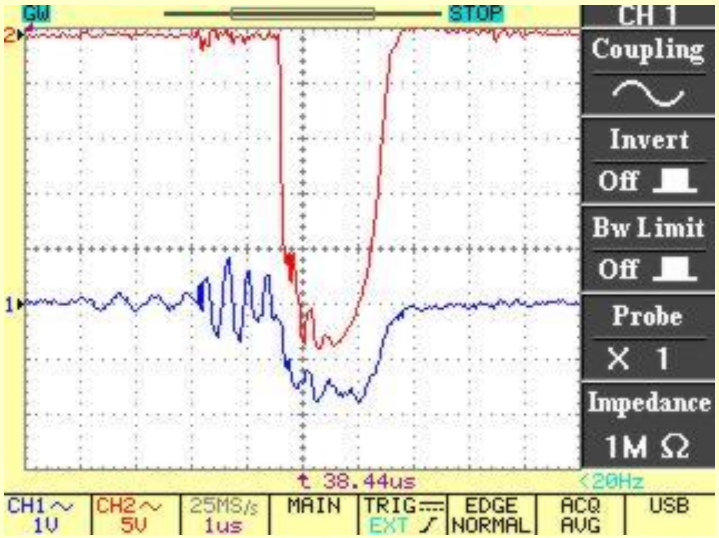
E-beam: 4.5 MeV, 0.8-1A, 2μs.
N = 6·10^3 bunches,each 0.26C, 60 ps, rep. period 360 ps

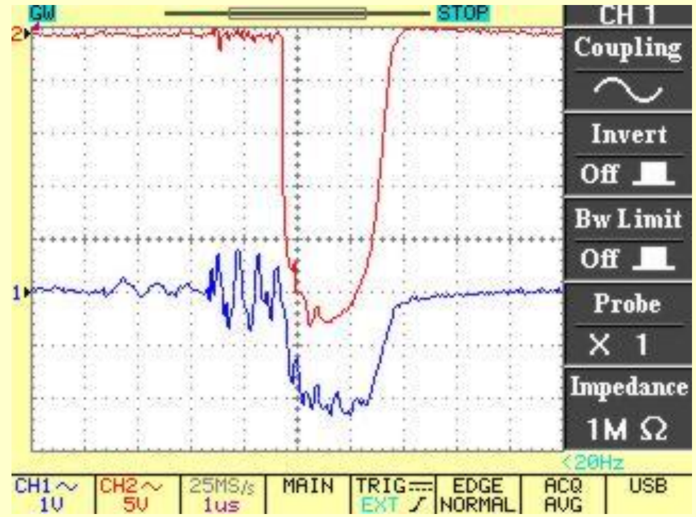
Teflon (ε=2.04, tgδ=4·10-4),
Ld = λ/4 ÷ 3.5λ, step λ/4

For investigatiing waveform and frequency spectra of excited wakefield there were used oscilloscope GD-840S (200 MHz band), the oscilloscope TDS6154 (15GHz band), fast Fourier transform (FFT) or "direct" calculation of the Fourier integral, wavemeter TDC-10, below cutoff waveguides, filtering dielectric plugs of different thickness on the waveguide output.

Experimental results (cylindrical waveguide)

Ratio of microwave signals *of the total wakefield and principal mode wakefield was experimentally measured using mode filtering with the wavemeter*.



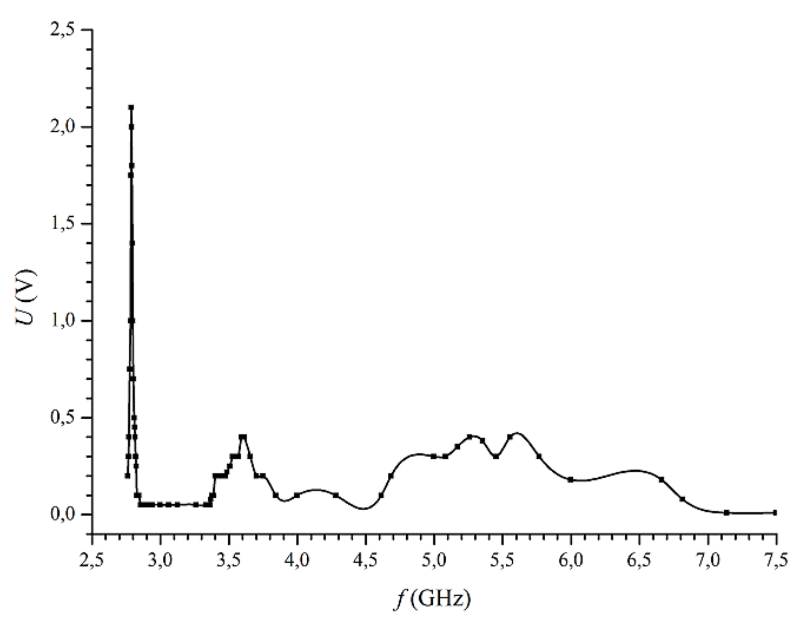


Beam current waveforms (top) and microwave signals (bottom): a) total signal; b) principal mode. Dielectric waveguide length L=3λ

Taking into account that the sensitivity of the wavemeter detector 1.4 times higher than the total field signal detector, from these oscillograms we obtain, that the amplitude of the total field signal exceeds the amplitude of the principal mode signal of about 10%.

Experimental spectrum for a short diel.waveguide $L_d=\lambda$

- For determining the frequency spectrum of the excited radial modes it is needed to use a single bunch moving in a long dielectric waveguide (see theoretical spectrum above) .
- Due to the complexity of obtaining a single bunch at used accelerator "Almaz -2M", instead of “a single bunch” scenario we proposed and used the other one – scenario with a short length of a dielectric waveguide excited by a long sequence of bunches so that their wakefield trains do not overlap. Excited spectra are evaluated for one period of total wavefield waveform. Above it is justified the compliance of excited spectra for these two approaches. Note that transition radiation is delayed and can be separated from Cherenkov wakefield (it is analyzed below).

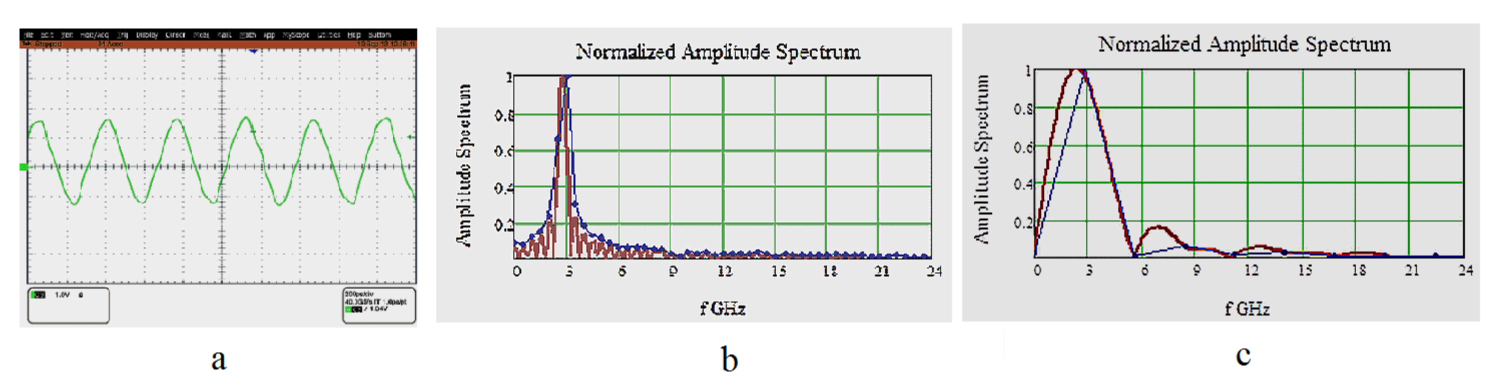


Visible prevailing large amplitude of the microwave signal at bunch repetition frequency 2.805 GHz. 2^{nd} radial mode frequency 6.75 GHz is not stood out. Absence of multiple bunch repetition frequency.
Wideband spectrum in the frequency range 4.5 - 6 GHz is caused by the field jumps due to non-multiple frequencies of radial modes to the bunch repetition frequency.
Contribution of the transition radiation arisen at the input boundary and asymmetric mode excited due to misalignment and the azimuthal asymmetry of bunches is significant too.

To determine transition radiation spectrum the sequence of bunches was carried through the waveguide without dielectric part, but with metal diaphragm at the entrance. Peaks of radiation at frequencies 3.6 GHz and 5.2 GHz were detected, that allows to estimate the contribution of transition radiation to the excited spectrum.

Mode filtering by a dielectric plate of varied thickness (e.g. d=5cm)

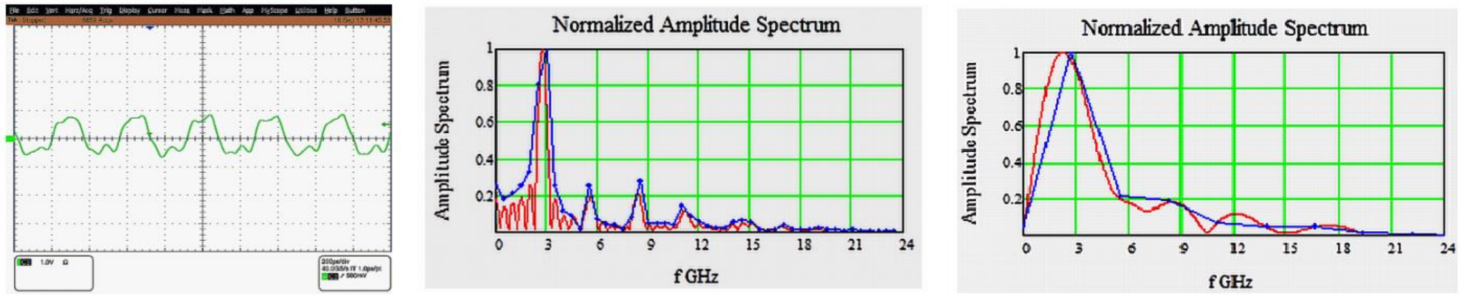
Another method for determining the wakefield frequency spectra excited in the dielectric waveguide was frequency **filtering of radiation by Teflon vacuum plug of various thicknesses**. Waveform of microwave radiation signal was taken by microwave probe, located behind the Teflon plug, and applied to the oscilloscope TDS6154. Taking into account that the maximum passage of the plug observed at its thickness equal to half-length of the incident wave , it is possible by changing the thickness of the plug to pass through it the chosen frequencies excited in the dielectric waveguide



a b c

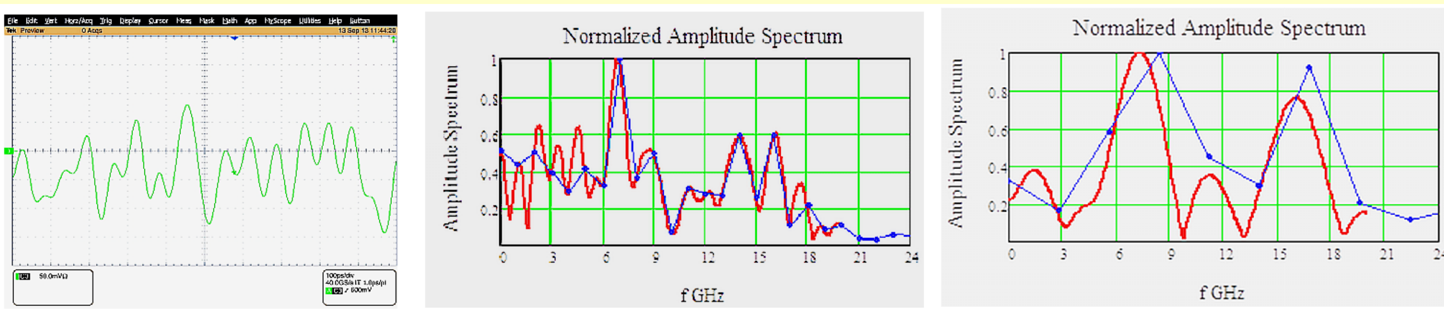
- Figures show:
- (a) the oscillogram of microwave radiation excited in the dielectric waveguide of length $L_d=3\lambda$ at the thickness of the dielectric plug 5 cm, close to a half-wavelength of the principal mode (λ=10.6 cm), for which principal mode passes the plug with minimal reflection, but radiation of shorter wavelengths pass worse.
- (b) normalized spectra obtained using FFT (blue) and with the help of "direct" calculation of the Fourier integral (red) of the whole waveform presented in (a).
- (c) normalized spectra for a sample of length equal to the length of one period of $L=\lambda$ from the whole waveform.
- It is evident that for the whole length of the waveform (b) only the first mode of the excited wakefield stands out, the other modes do not appear, "spilling" over the nearest frequencies that are multiple to the bunch repetition frequency. For the length of the waveform sample equal to the length of one period (c) the second mode at a frequency of 6.7 GHz stands out clearly.

Mode filtering by a dielectric plate of varied thickness (e.g. d=3.6; 2.6 cm)



a b c

- When the thickness of the plug is decreased to **d=3.6 cm** the amplitude of the microwave radiation with a frequency 2.805GHz is reduced due to the increase of the reflection coefficient. At oscillogram the waveform distortions are observed (a) due to the passage through the dielectric plug of higher frequency modes.
- In this case the spectra obtained from the experimental whole length waveform by FFT and "direct" calculation of the Fourier integral (b) show that in addition to the principal mode the oscillations at frequencies that are multiple to the bunch repetition frequency with much smaller amplitude appear.
- Spectra (c) obtained by FFT and "direct" calculation of the Fourier integral for the waveform sample of the length equal to the length of one period, taken from the whole waveform (a) show the frequencies of the second and even the third radial modes.



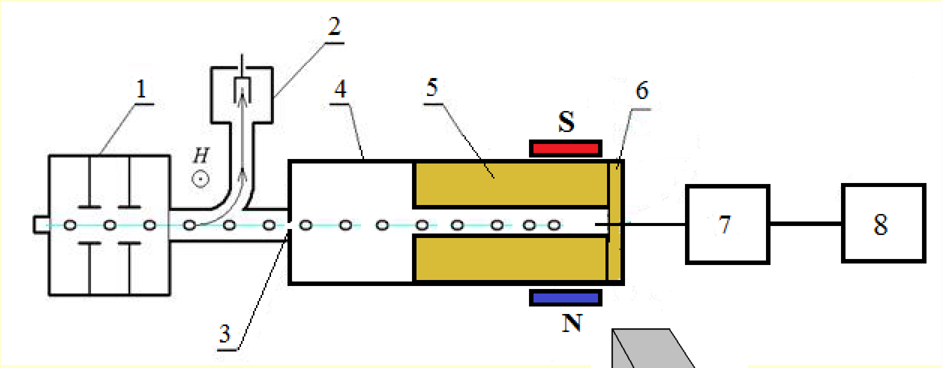
a b c

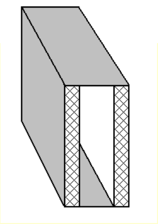
- For **d=2.6 cm** at the oscillogram and corresponding obtained spectra (Fig.a, b, c) there is an absence of the principal mode (due to its maximum reflectance) and the presence of the higher order modes.

Experimental setup (rectangular waveguide)

Multi-mode excitation:

<more number of excited modes; more equidistant modes>





1 - Accelerator "Almaz-2M", 2 - magnetic analyzer, 3 - diaphragm, 4 – waveguide, 5 - insulator, 6 - dielectric plug, 7 - wavemeter VMT-10, 8 – oscilloscope

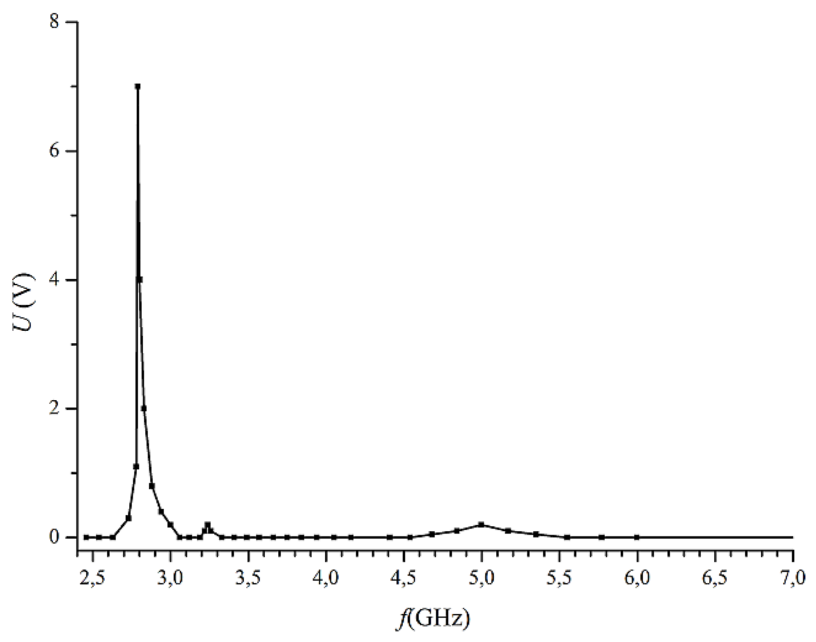
Rectangular dielectric waveguide is a segment of a standard cooper rectangular waveguide R26 of inner cross-section 45×90 mm^2 with dielectric plates made from quartz (ε = 3.8, tgδ = 2·10^{-4}) located along the broad walls of the waveguide

E-beam: 4.5 MeV, 0.8-1A, 2μs.
N = 6·10^3 bunches, each 0.26C, 60 ps, rep. period 360 ps

In the rectangular dielectric waveguide electron bunches excite wakefield, which can be represented by a set of LSM and LSE waves. Each of the families of LSE and LSM waves composed of even and odd modes. Electron bunches excite even modes $LSM_{2n,1}$ and odd modes $LSE_{2n-1,1}$ comprising component E_z on the axis.

The thickness of plates was chosen such (15.3 mm), so that the working mode LSM_{21} was excited at Cherenkov resonance frequency (2.802 GHz), close to the bunch repetition frequency (2.805 GHz). Besides LSM_{41} (7.978 GHz, LSM_{61} (13.381 GHz), LSM_{81} (18.925 GHz) и LSE_{11} (3.24 GHz), LSE_{31} (8.922 GHz), LSE_{51} (14.724 GHz), LSE_{71} (20.611 GHz) are also excited . These frequencies except LSE_{11}, are more equidistant than in the cylindrical case. For summation *LSM*-modes are dominated, as amplitudes of LSE- modes are significantly less.

Frequency spectrum
in a multi-mode rectangular dielectric waveguide



Frequency spectrum, excited in a multi-mode rectangular dielectric waveguide by a sequence of 6000 relativistic electron bunches, measured by wavemeter VMT-10, when the microwave probe is located at dielectric exit

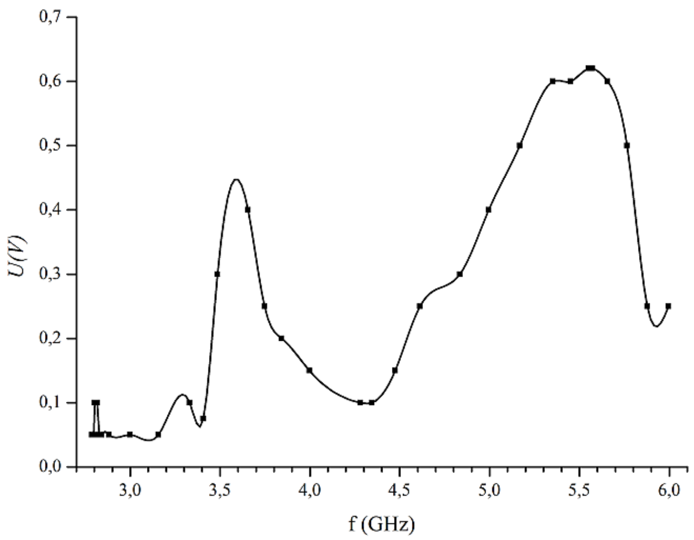
Large amplitude at the frequency of the principal mode is explained by the below cutoff vacuum rectangular waveguide after dielectric part which becomes a resonator for the excited principal mode .

Experimental setup (rectangular waveguide)

Single-mode excitation:

The dielectric waveguide is designed so (plate thickness 4.7mm), that the Cherenkov resonance of bunches with the working mode $LSM_{2,1}$ occurs at a frequency of **5.765 GHz** equal to **double bunch repetition frequency**. Possible frequencies excited in such waveguide: $LSM_{2n,1}$ (5.765; 21.327; 39.815; 58.765 GHz) and $LSE_{2n-1,1}$ (10.641; 29.026; 48.127; 67.721 GHz).The working mode is $LSM_{2,1}$ .This waveguide can be considered as a single-mode one, since the second mode ($LSM_{4,1}$) is 60 times smaller in amplitude compared to the working mode, not to mention the rest of the modes with even smaller amplitudes.

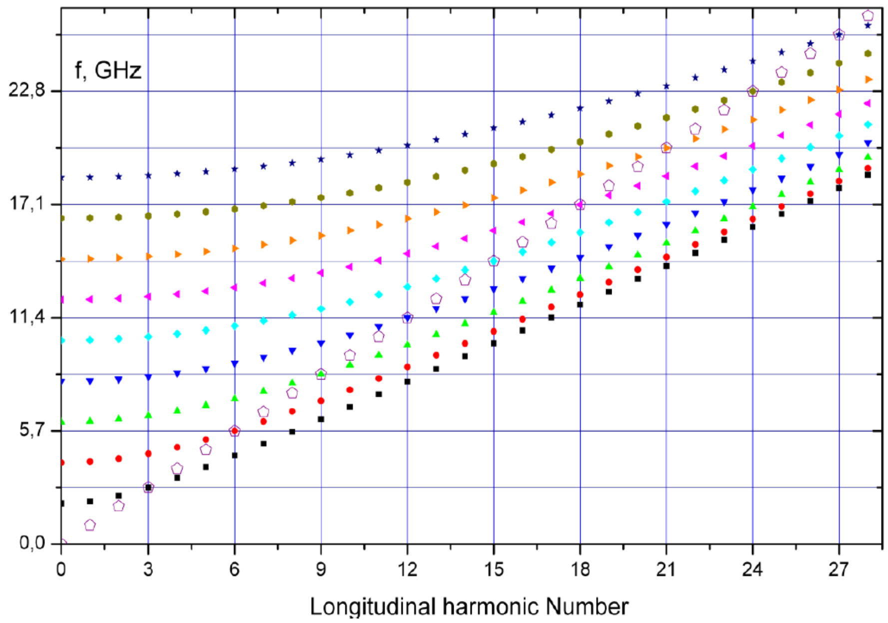
The amplitude of the working mode is smaller (U = 0.6 V) compared to the case of multimode rectangular dielectric waveguide, that can be explained by decrease in the coupling coefficient of bunches with the excited wave for larger cross-section of the transit channel ($14.4\times35.6 mm^2$)



In accordance with the theory the frequency equal to bunch repetition frequency 2.805 GHz is absent, but the frequency 5.6GHz equal to double bunch repetition frequency is clearly observed. Wide continuous spectrum and its selected part around 3.65 GHz are caused by the emergence of the field jumps of transversal modes whose frequencies non-multiple to bunch repetition frequency. In addition, a significant contribution is given by the transition radiation produced at the input boundary and asymmetric mode excited due to misalignment and the azimuthal asymmetry of bunches

3.3 Experimental study of the wakefield enhancement by using a resonator

Basic approach to resonator concept



Eigen frequencies of the cylindrical resonator with the above-mentioned parameters and Cherenkov bunch frequencies (circles)

Coincidence of bunch repetition frequency ω_m with Cherenkov radiation frequency ω_0 ($\omega_m = \omega_0$) and, simultaneously, with the fundamental eigen frequency of the resonator ω_{r1}, i.e. $\omega_m = \omega_0 = \omega_{r1}$ should be provided for operating multibunch, multimode, and resonator concepts.

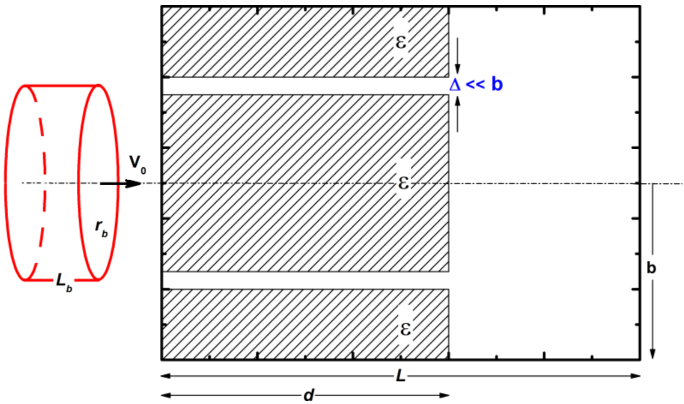
$$L = Na\sqrt{\beta_0^2\varepsilon - 1}, \quad \beta_0 = v_0 / c$$

$$a = v_0 / 2f\sqrt{\beta_0^2\varepsilon - 1}$$

where N is number of longitudinal harmonics of the resonator, being in Cerenkov resonance with the beam at bunch repetition frequency, longitudinal harmonics with l = Nm are automatically equidistant, and multiple to the radial modes frequencies. It provides peaking of the sinusoidal total field at the summation of modes fields and the increase in the amplitude of the total wakefield.

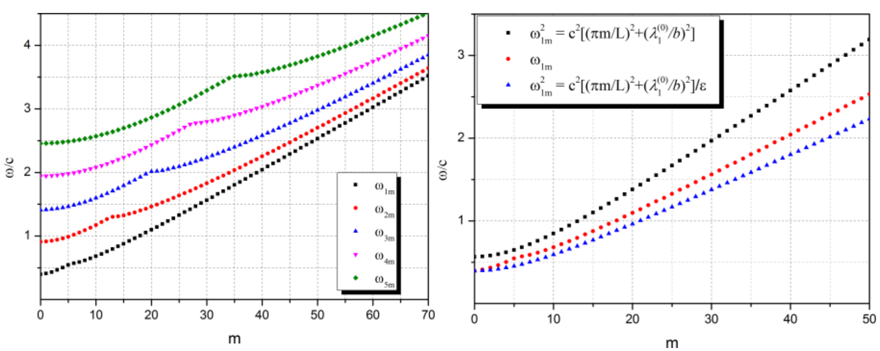
For bunches of energy 4 MeV, bunch repetition frequency of 2.805GHz, ε = 2.1, N =3, the resonator should be of sizes: L = 15.68 cm and a = 5.05 cm

Theory of "compound" resonator

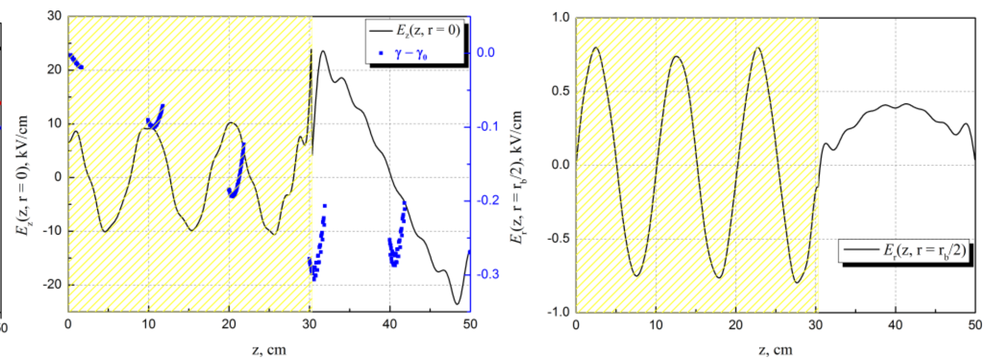


Scheme of the "compound" resonator , excited by a sequence of electron bunches

Analytical and numerical researches of wakefield excitation by a sequence of bunches in "compound" resonator (dielectric+vacuum parts, each of integer number of own wave half-lengths). For such choice of lengths of vacuum and dielectric areas the radial component of resonant mode E_r =0 at z=0, z=d, z=L, i.e. for this mode dielectric and vacuum parts are uncoupled resonators.

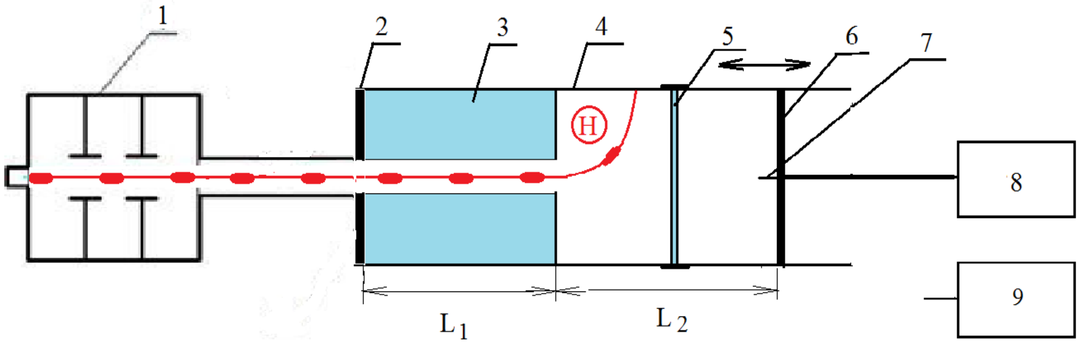


*(a) - eigen frequencies of the first five transverse modes; (b) - eigen frequencies of the first mode for the following cases: "compound" resonator $d=3\lambda d$, $L-d= \lambda v/2$ **(red)**, the vacuum resonator (**black**), the resonator wholly filled with dielectric **(blue)**. The index **m** means number of longitudinal harmonics.*

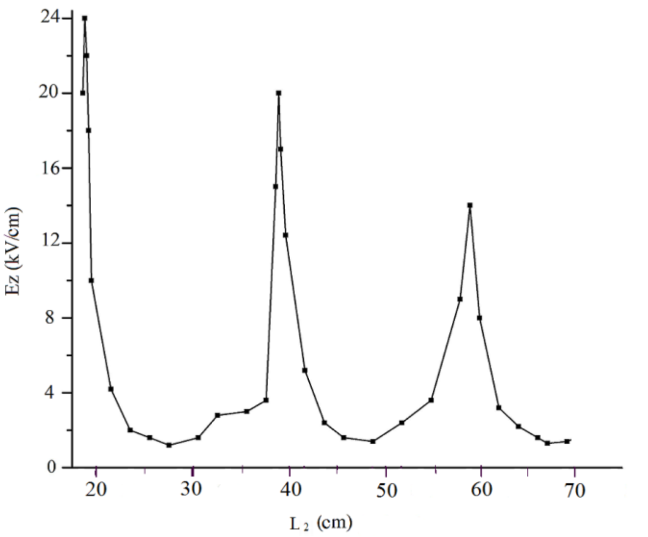


Axial distribution of a) longitudinal and b) radial components of wakefield after injection of the 300th bunch in the resonator at z=0 (left) and phase planes "energy-longitudinal coordinate" of bunches (right).

*Experimental setup for resonator concept investigation (compound-resonator of **cylindrical** geometry)*



1 - linac "Almaz-2M", 2 - metal diaphragm, 3-dielectric, 4 – cylindric copper waveguide, 5 - vacuum dielectric plug, 6 - short circuited plunger, 7 - microwave probe, 8 – wave-meter VCT-10, 9 - oscilloscope TDS6154.
Length L1=λd, 2λd, 3λd,…(λd =10,634см is the length of the excited wave in the dielectric) with dielectric insert (3) from Teflon (ε = 2.045; tgδ = 2·10-4) with the transit channel of diameter 21 mm for the passage of bunches.
Length L2=λv/2, (λv=39см is wavelength in the empty part) is the space between the dielectric insert and a movable short-circuited plunger (6).
To deflect bunches by magnetic field on the waveguide wall is provided between the end of the vacuum dielectric insert (3) and vacuum teflon plug (5).
The sequence of bunches produced by the linac "Almaz-2M" (1). Electron energy is 4.5 MeV, the pulsed current 0.8 A, pulse duration 2 μs. Each pulse is a sequence of N=6·103 electron bunches with charge of 0.26 nC, diameter of 1 cm and duration of 60 ps each. The bunch repetition frequency ωм/2π=2.805GHz

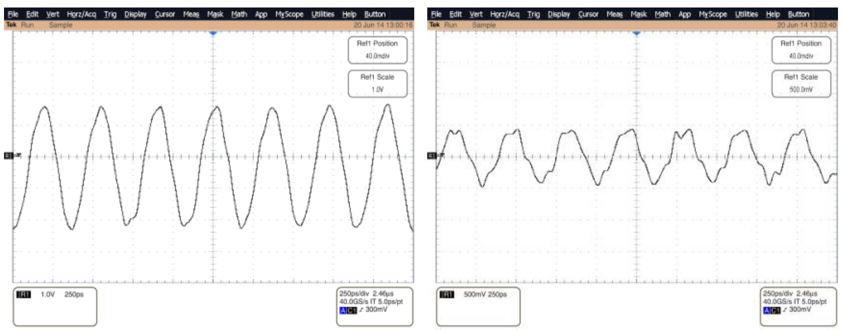


Amplitude of E_{zv} component of the wakefield in the empty part of the compound-resonator in dependence on the position of the plunger relatively to the end of the dielectric part (i.e. on L_2).

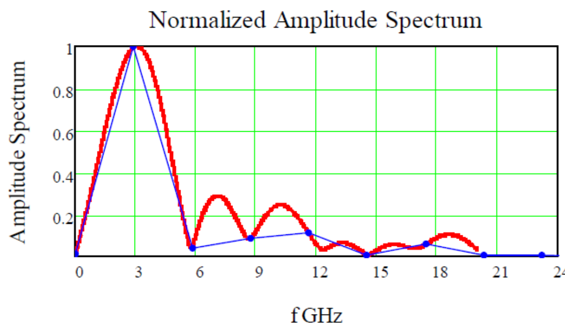
The longitudinal component of the excited field measured at the end of empty part exit of the compound-resonator is equal E_{zv} = 24 kV/cm and, correspondingly in the channel of the dielectric part E_{zd} = E_{zv}/ε = 11.8 kV/cm

Experimental setup for resonator concept investigation (cntd)
*(**cylindrical** geometry)*

In the compound-resonator mainly one mode, the frequency of which coincides with the frequency of bunch repetition frequency of the resonator and ω0 = ωm = ωr1 =2π·2.805, is excited. Wakefield excitation in the compound-resonator by a long sequence of bunches with a repetition frequency of ωm and frequency filtering in the compound-resonator with eigen frequency ωr1 lead to the excitation in the compound resonator of only the fundamental radial mode with frequency ω0 = ωm = ωr1



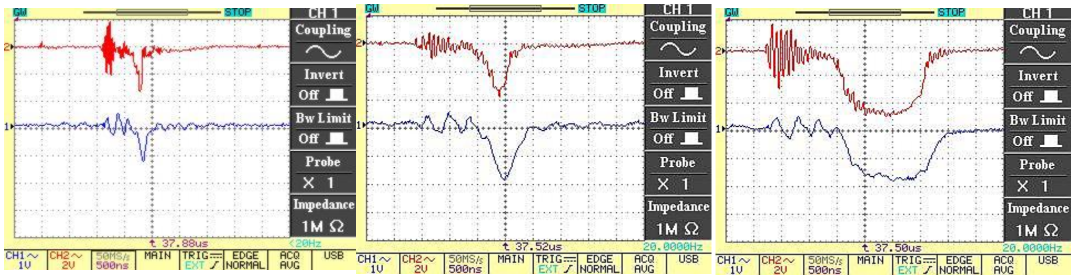
Oscillograms of wakefield excited by a sequence of 6·103 bunches in the compound-resonator (a: - L1=3λd, L2 = λv(ωr1); b: - L1=3λd, L2 = 10λv(ωr2)), obtained using an oscilloscope TDS 6154



Fourier spectrum of the waveform (b): FFT (blue) and direct calculation of one period (red).

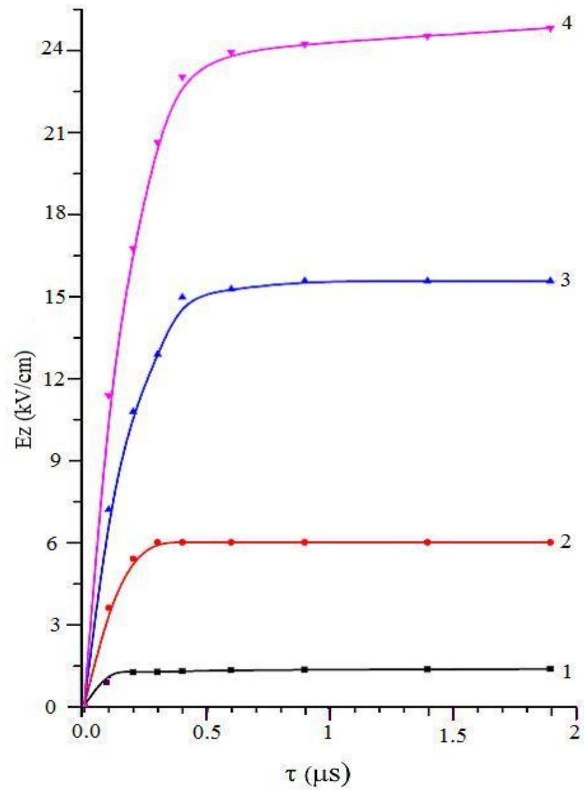
It is clearly visible the frequencies of the 2nd and 3rd modes, which distort the monochromatic signal.

Dependence of the wakefield amplitude on the number of injected bunches for different Q-factors of the compound-resonator



a) *b)* *c)*

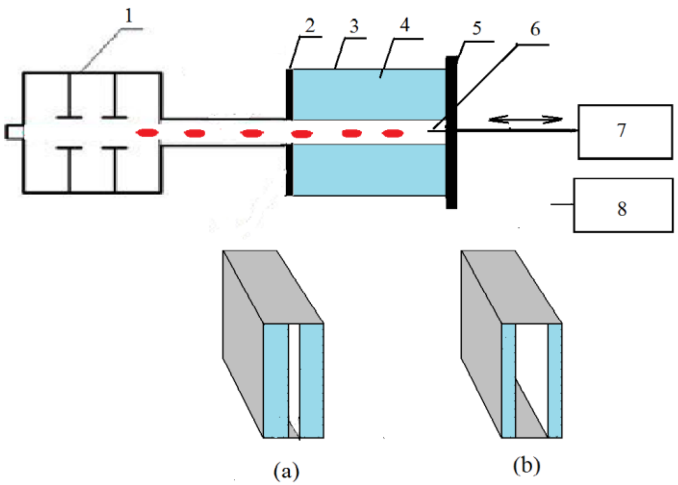
Oscillograms of the beam current (top) and the envelope of the microwave signal of wakefields (bottom) for 3 half-width durations of the current pulse (i.e. sequence of bunches): a)-0.1μs (300 bunches), b)-0.3μs (900 bunches), c)-1.4μs (4200 bunches).



Dependence of the wakefield amplitude on the duration of bunch sequence for different Q-factors of the compound-resonator: 1-Q_1=65, 2- Q_2=268, 3-Q_3=539, 4-Q_4=676.

With increasing the sequence duration the total field increases and saturates, remaining constant for large duration sequences. With the growth of the Q-factor increases the number of bunches of the sequence that contribute to the increase in the total wakefield excited by a long sequence of $6{\cdot}10^3$ bunches. By achieved saturation amplitude such sequence is almost equivalent to the sequence of an infinite number of bunches. Note the qualitative agreement of the experimental results with the theoretical model: $N^*=Q/\pi$.

*Experimental setup for resonator concept investigation (**rectangular** cross-section)*



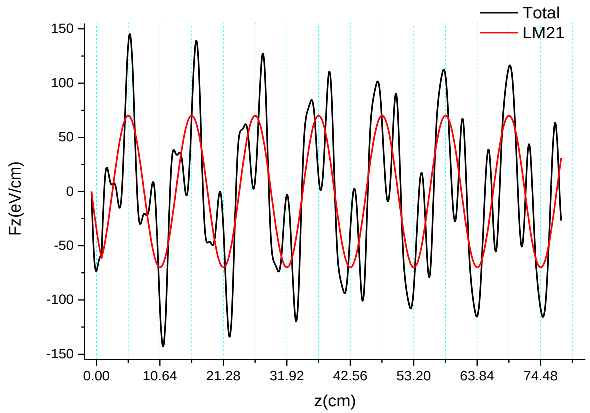
Scheme of the experimental setup with a rectangular dielectric resonator:
1 - lnac "Almaz-2M", 2 - metal diaphragm, 3 - copper waveguide, 4- quartz plates, 5 - vacuum metal cap, 6 -microwave probe 7 - wavemeter VMT-10, 8 - oscilloscope TDS6154.

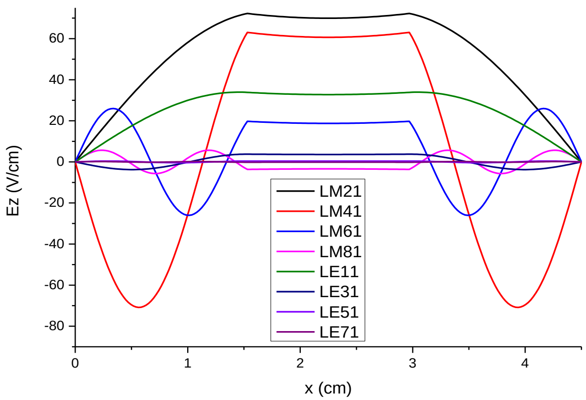
(a) - multimode waveguide with thick (15.3mm) quartz plates, at the frequency $\omega_0 = \omega_m$
(b) - single-mode waveguide with thin quartz plates at the doubled frequency $\omega_0 = 2\omega_m$.

Resonator is made on the basis of a standard rectangular waveguide R26 (cross-section $45\times90mm^2$) with quartz plates ($\varepsilon = 3.8$; $tg\delta=4\cdot10^{-4}$) of
(a)-thickness 15.3mm and length 3λ, λ=10.64cm is the wavelength of the principal mode with $\omega_0=\omega_m$;
(b)- thickness 4.7mm and length 6λ, λ=5.32cm is the wavelength of the principal mode with $\omega_0=2\omega_m$.

Theoretically calculated :
(a)- Frequencies of LSM modes, $LM_{2n,1}$:
2.802; 7.978; 13.381; 18.925 GHz
Frequencies of LSE modes, $LE_{2n-1,}$:
3.244; 8.922; 14.754; 20.611 GHz
(b)- Frequencies of LSM modes, $LM_{2n,1}$:
5.5765; 21.327; 39.815; 58.765 GHz
Frequencies of LSE modes, $LE_{2n-1,}$:
10.041; 29.026; 48.127; 67.221 GHz

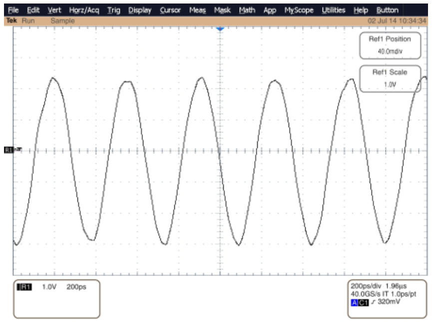
(a) – multi-mode waveguide at bunch repetition frequency $\omega_0=\omega_m$ (theory)

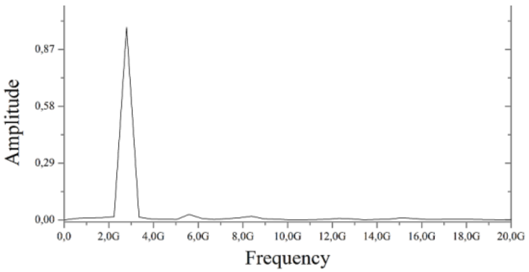




Longitudinal component of wavefield excited by a single bunch: waveform upon z of the total field of LSM+LSE modes and resonant mode LSM_{21} on the axis (left); transversal topography of each accounted LSM and LSE modes (right)

Excitation of multimode quartz dielectric resonator (experiment)

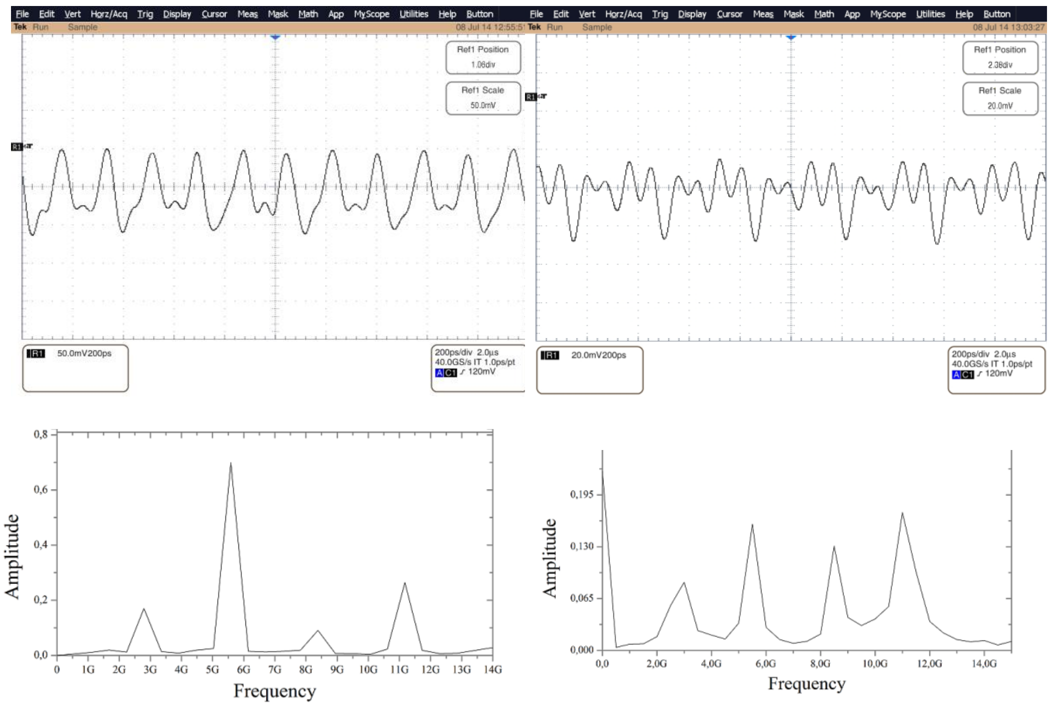




Oscillogram of the total microwave signal on with oscilloscope TDS 6154 (left) and the corresponding frequency spectrum (right).

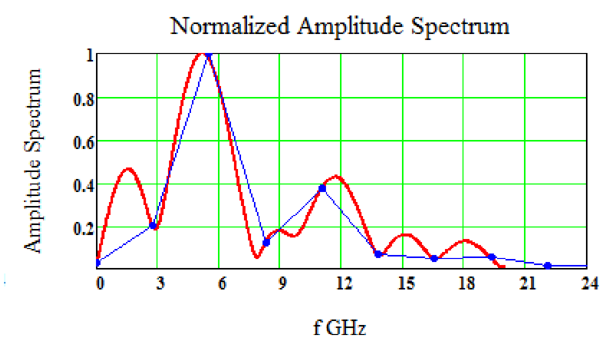
Wakefield E_{zd} =5.4 kV/cm of the principal mode LSM_{21} at frequency 2.805 GHz was observed

(a) – multi-mode waveguide (cntd)



a) b)

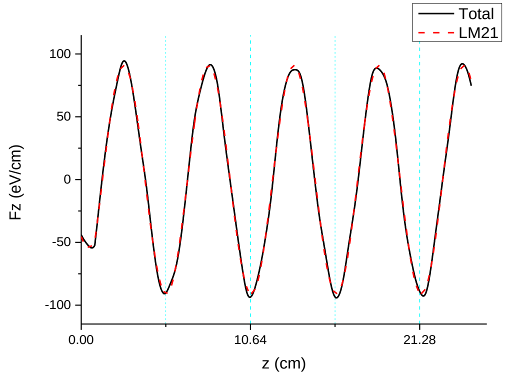
For detection of higher frequencies at the installation with rectangular resonator as well, as in the case of a cylindrical resonator, after vacuum dielectric plug the empty rectangular part without dielectric filling and with a movable short-circuited plunger was attached to form the resonator that can be tuned to the other transverse modes frequencies.

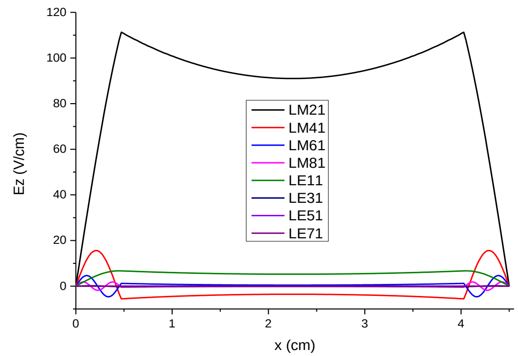


Oscillograms of the wakefield signals and their FFT spectra for two plunger positions: a)-L_2=19cm, b)-L_2=18cm

Fourier spectra of the waveform (a) : by FFT (blue) and by direct calculation over the pulse of one principal mode period (red)

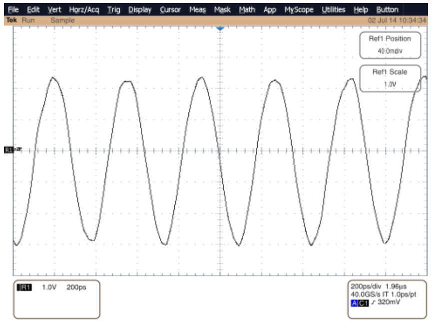
(b) – single-mode waveguide at double frenquency $\omega_0=2\omega_m$ (theory)





Longitudinal component of wavefield excited by a single bunch: waveform upon z of the total field of LSM+LSE modes and resonant mode LSM_{21} on the axis (left); transversal topography of each accounted LSM and LSE modes (right)

Excitation of single-mode quartz dielectric resonator (experiment)



Oscillogram of the longitudinal field E_z of LSM_{21} mode of frequency 5.576 GHz excited in the dielectric resonator of length L=6λ by a sequence of bunches with bunch repetition frequency of 2.805 GHz

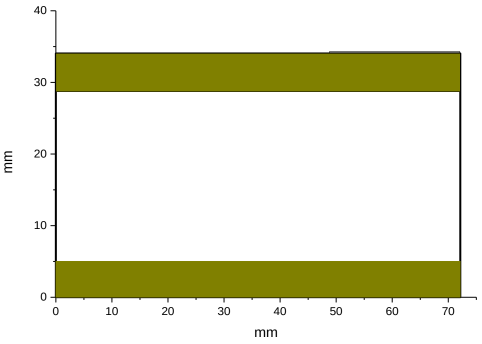
Excitation of monochromatic wakefield of amplitude E_{zd} =2.8 kV/cm was measured

Multimode zirconia ($\varepsilon = 23$) rectangular resonator at frequency $\omega_0 = \omega_m$

For large values of permittivity ε while maintaining the size of the channel for the bunch passage dielectric resonator can be made on the basis of copper rectangular waveguide with a smaller cross-section. When using plates of zirconia ceramics (ZrO2-4 wt% MgO, ε = 23; tgδ≅10-3) it was taken a standard rectangular waveguide R32 of smaller cross-section 34×72mm^2 (instead of R26 (45 × 90mm^2)) with zirconia plates of thickness 5.3 mm, providing a coincidence of Cherenkov excitation frequency with bunch repetition frequency $\omega_0=\omega_m=2\pi\cdot 2805$ MHz. The length of the plates and, therefore, of the resonator is chosen equal to 3λ, λ=10.64cm is wavelength of the principal mode with frequency ω_0.

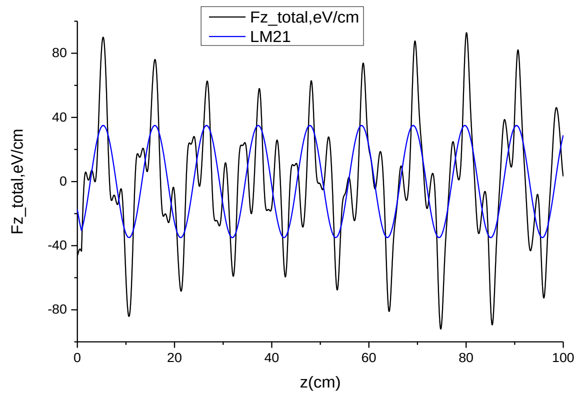
Theoretically calculated electrodynamics of dielectric waveguide for such resonator and the dynamics of its excitation by a single bunch for experimental parameters are the followings:

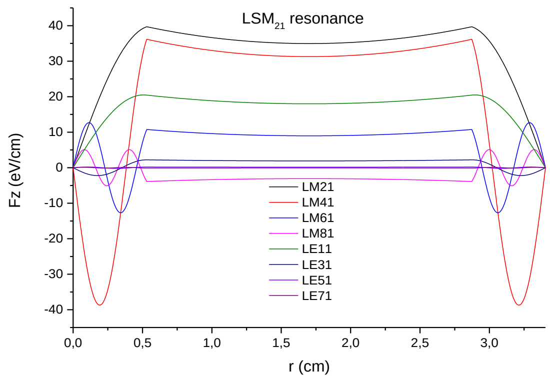
Waveguide	R32			
Dimensions	34.04 x 72.14mm			
Operating frequency	***2.8047 GHz***			
Beam energy	4.5 MeV			
Dielectric constant	23.0			
Dimensions of plates	5.305 x 72.14mm			
	(placed along wide walls of waveguide)			
Chanel dimensions	23.43 x 72.14mm			
Operating mode	LSM_{21}			
Frequencies of LSM modes, $LM_{2n,1}$ GHz	2.8047	8.354	14.003	19.774
Frequencies of LSE modes, $LE_{2n-1,}$ GHz	3.1740	9.101	15.110	21.130



Cross-section of a multimode zirconia waveguide

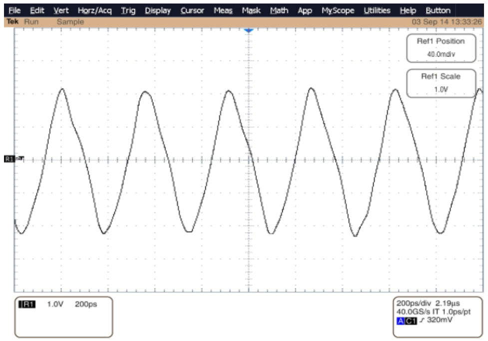
Multimode zirconia rectangular waveguide (theory)

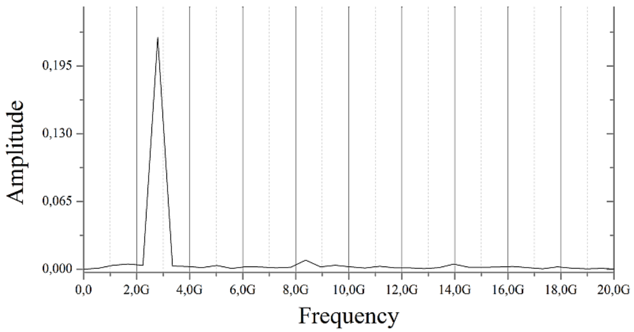




Longitudinal component of wavefield excited by a single bunch: waveform upon z of the total field of LSM+LSE modes and resonant mode LSM_{21} on the axis (left); transversal topography of each accounted LSM and LSE modes (right)

Excitation of multimode zirconia rectangular resonator (experiment)



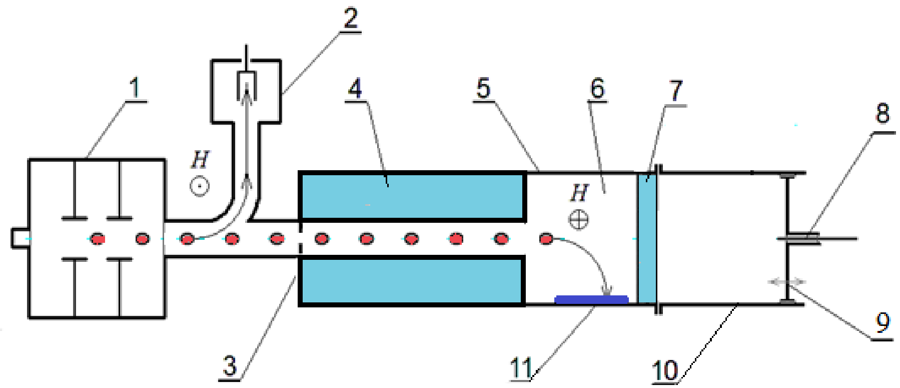


Oscillogram of the total microwave signal on with oscilloscope TDS 6154 (left) and the corresponding FFT frequency spectrum (right).

The amplitude of the excited wakefield signal is 1V that accordingly to the calibration of the microwave probe corresponds to wakefield amplitude 0.2kV/cm.

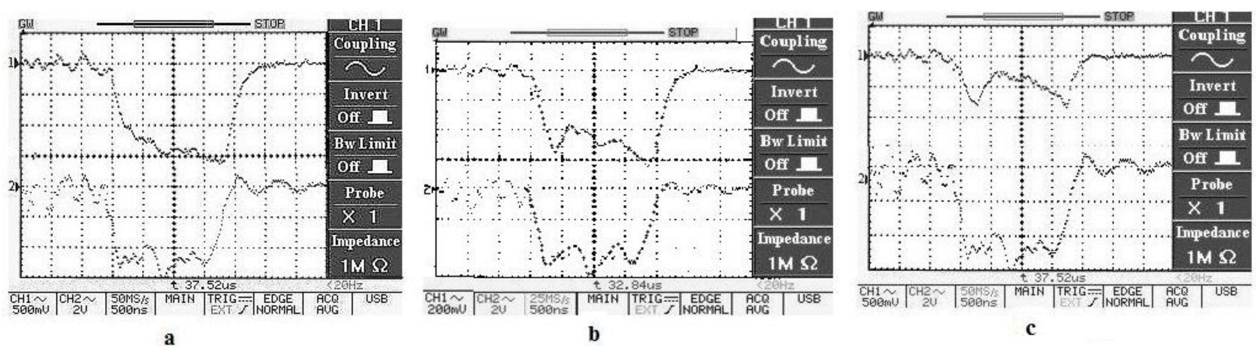
3.4 Research of the injection problem concluded to displacing rear tail of the bunch sequence into accelerating phase of the wakefield by means of detuning master oscillator frequency of the klystron

Acceleration of electrons by excited wakefield

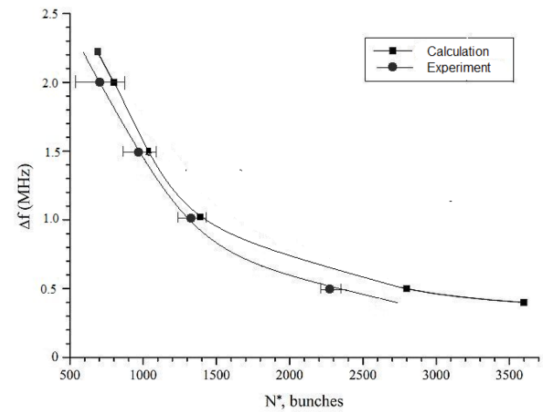


Experimental setup. 1 - accelerator "Almaz-2M", 2 - magnetic analyzer, 3 - entrance aperture, 4 - Teflon tube; 5 - metal waveguide; 6 - transverse magnetic field; 7 - vacuum dielectric plug; 8 - microwave probe; 9- plunger; 10- additional waveguide; 11 - glass plate,

Due to detuning $\Delta f=f_m-f_0$ the number of bunches N^*, enhancing wakefield, after which subsequent bunches fall into the accelerating phase of excited wakefield, can be calculated from the condition of the phase shift of the N^{*th} bunch on π, i.e. from the expression $N^*=f_m/2\Delta f$.



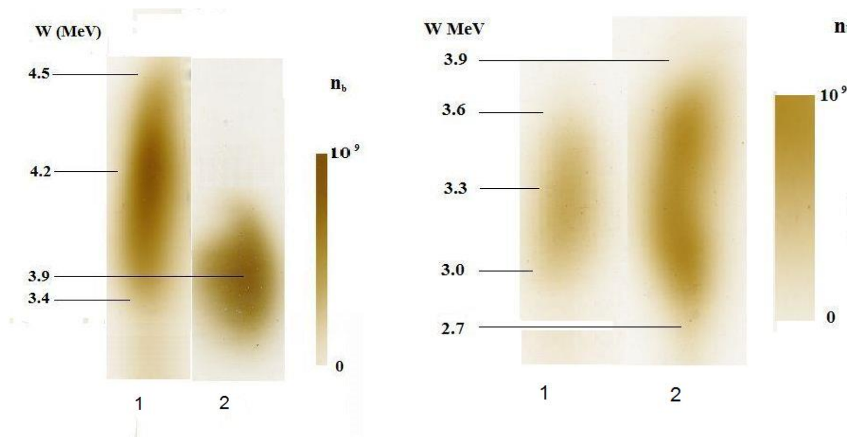
Waveforms of wakefield signal (upper) and current of deflected beam (below): a – Δf = 0; b – Δf = 1.0 MHz; c – Δf = 1.5 MHz



The oscillations are explained by the beating of the wakefield amplitude caused by alternating wakefield excitation during energy loss of a part of bunch sequence and wakefield decrease during energy gain of a subsequent part of bunch sequence.

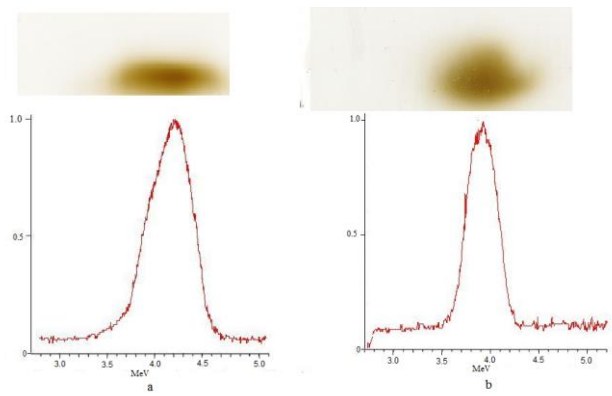
Dependence of the number of bunches, enhancing wakefield, upon detuning $\Delta f=f_m-f_0$

Energy spectra of bunches obtained with magnetic field and glass plate



a *b*

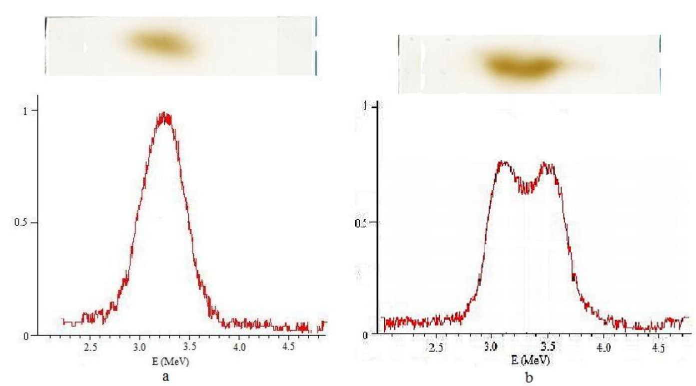
Prints of the bunch electrons, deflected by transverse magnetic field, on glass plates: a) - Δf=0; б) - $\Delta f=f_m-f_0$=2.5 MHz (1 – initial beam, 2 – beam interacted with dielectric resonator)



Density distribution of the beam darkening at prints on the glass plate at detuning Δf = 0 (1 – initial beam, 2 – beam interacted with dielectric resonator

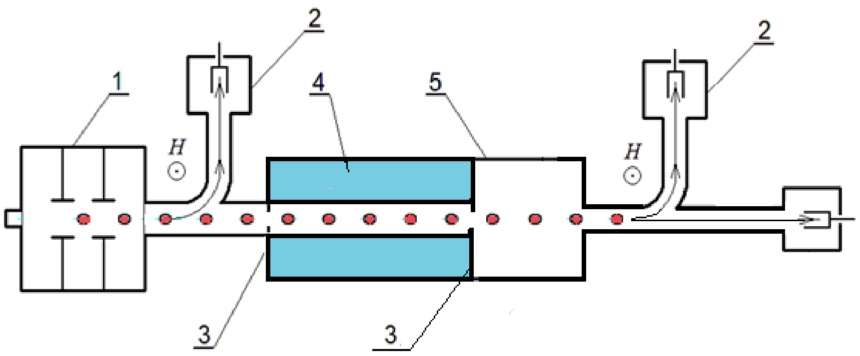
1.In resonant case Δf=0, energy spectrum is shifted as a whole one to the smaller energy region, i.e. all bunches lose their energy to excite the wakefield. Energy loss is about 400 keV).

2.At detuning Δf=2.5 MHz the part of bunch sequence, being shifted, is occurred in the accelerating phase of the wakefield excited by previous bunches of the same sequence, gain energy from wakefield. In this case, in the energy spectra electrons lost (-150keV) and electrons gained energy (+ 150 keV) are observed.

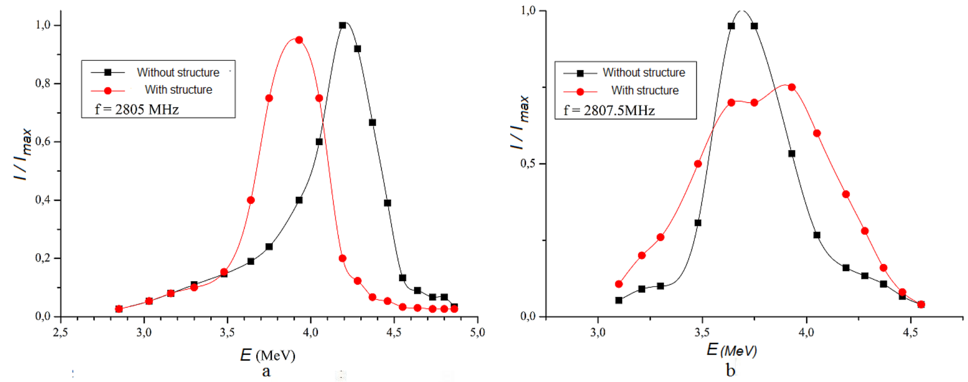


Density distribution of the beam darkening at prints on the glass plate at detuning $\Delta f = f_m - f_0$ = 2.5 MHz (1 – initial beam, 2 – beam interacted with dielectric resonator

Energy spectra of bunches obtained with magnetic analyzer



Experimental setup. 1 - accelerator "Almaz-2M", 2 - magnetic analyzers, 3 –entrance and exit diaphragms, 4 – Teflon tube; 5 – metallic waveguide

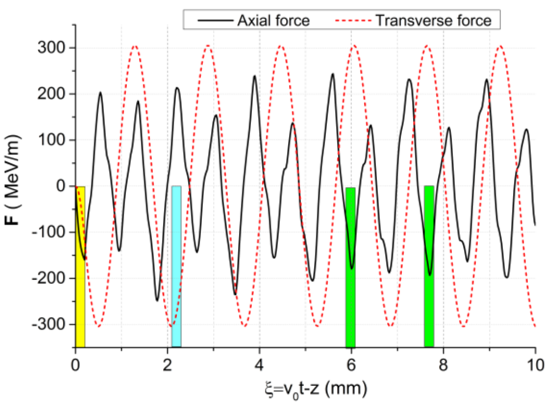


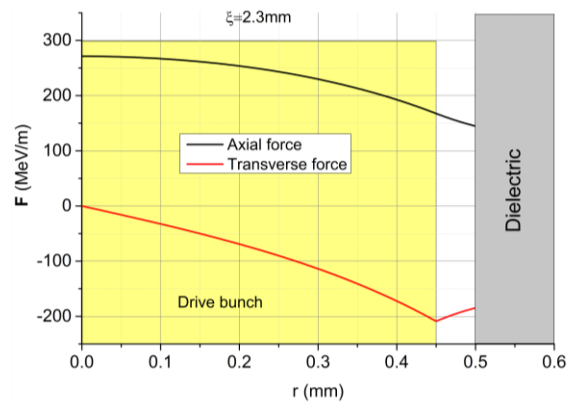
Electron energy spectra of bunches passed through the cavity without dielectrics, i.e initial spectra (black curves) and filled with dielectric (red curves): a - . Δf = 0; b - Δf = f_m - f_0 = 2.5 MHz

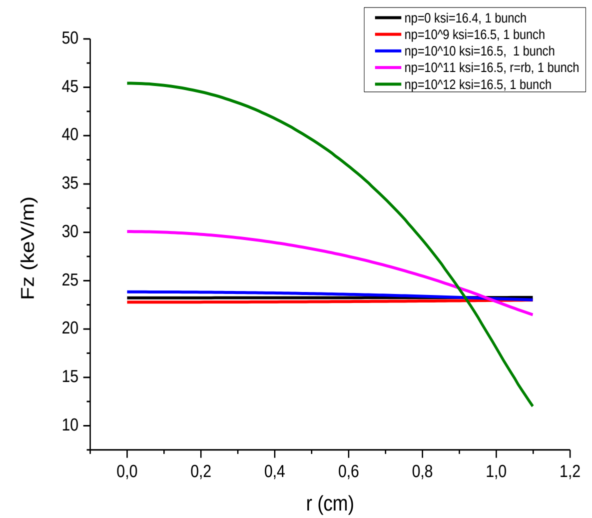
Results are close to those for the method of magnetic field and glass plate:
1.In resonant case Δf=0, energy spectrum is shifted as a whole to the smal energy region, evidencing energy loss of about 400 keV for exciting the wakefield.
2.At detuning Δf=2.5 MHz the are observed energy loss on wakefield excitation (-150keV) and accelerated electrons, which gain additional energy (+150 keV).

3.5 Experimental study of the bunches transportation through the narrow transit channel filled with plasma

Theory







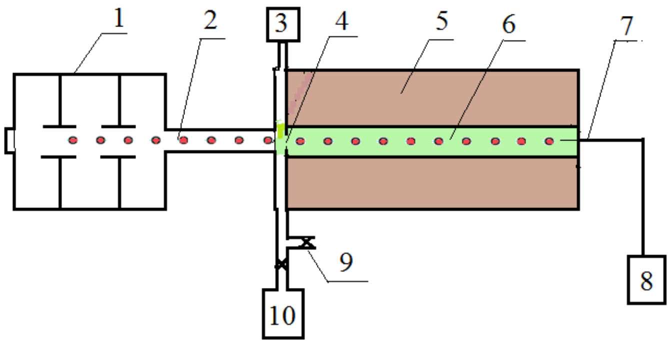
Axial and transverse profiles of the axial force (black line) and axial profile of transverse force (red line) at plasma density $n_p = 3n_b$: a) r=0.45mm, drive bunch (yellow rectangle) moves from right to left. Cyan rectangle shows possible location of electron witness bunch and green rectangles show possible location of positron witness bunch; b) $\xi \equiv v_0 \tau = v_0 t - z = 2.3$mm

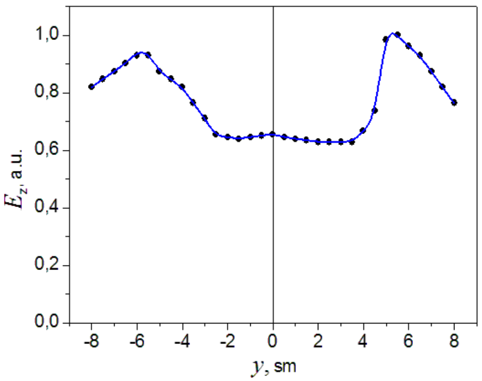
Radial topography of the total longitudinal wakefield excited by a single bunch in dielectric+plasma waveguide at various plasma density. Plasma filling concludes to excitation of plasma wakefield and depression of dielectric wakefield. Total wakefield increases with plasma density growth.

From axial dependence of the longitudinal force follows that we can ensure acceleration of the witness bunch with simultaneous radial focusing by placing it at some distance from the drive bunch head. The radial force almost harmoniously depends on the axial coordinate with the period of approximately 0.16 cm, i.e. plasma wave makes the main contribution into the radial force. Its contribution into the axial force is small. The axial force is predominantly determined by the eigen mode (wavelength is 0.1cm) of the dielectric waveguide.

3.5 Experimental study of the bunches transportation through the narrow transit channel filled with plasma (cntd)

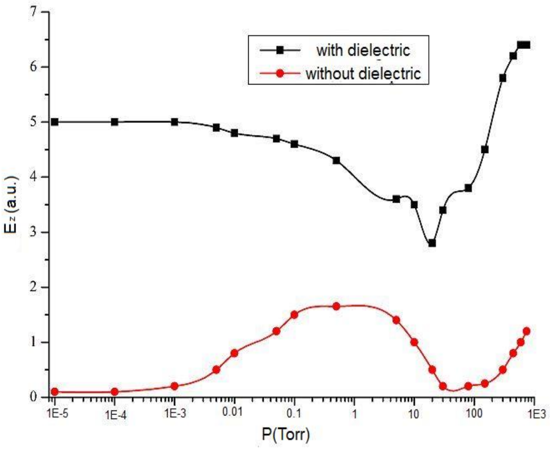
Experiment





Transversal distribution of longitudinal component Ez of dielectric wakefield at plasma absent

Experimental setup: 1 - accelerator "Almaz-2M; 2 - sequence of bunches; 3 – pressure gauge; 4 - entrance aperture; 5 - dielectric resonator; 6 – plasma; 7 - microwave probe; 8 -oscilloscope; 9 - gas valve; 10 - vacuum pump



Dependence of the total longitudinal wakefield (black) and plasma wakefield (red) both excited by a sequence of bunches with repetition rate fm in dielectric+plasma resonator upon gas pressure.

Plasma wakefield is excited at gas pressure about 1Torr caused probably by beam-plasma discharge. When plasma density increases the total field decreases due to emergence of detuning between dielectric field frequency and bunch repetition frequency.

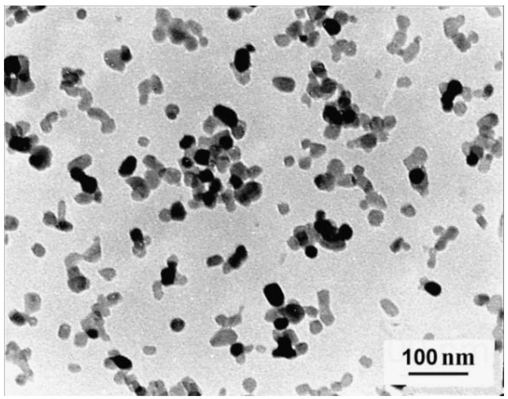
4. Beam testing of the dielectric materials and components

4.1 Study of the mechanical and electrical properties of microwave ZrO_2-Y_2O_3;ZrO_2-MgO ceramics and ceramic composite before and after irradiation. Revelation of their properties change under beam irradiation

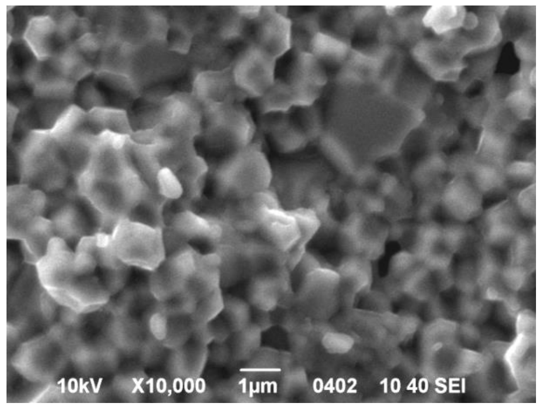
Obtaining of ZrO_2-Y_2O_3 and ZrO_2-MgO ceramics and ceramic composites from nanopowders for composing dielectric structures and for beam testing

ZrO_2-Y_2O_3 system

Powder



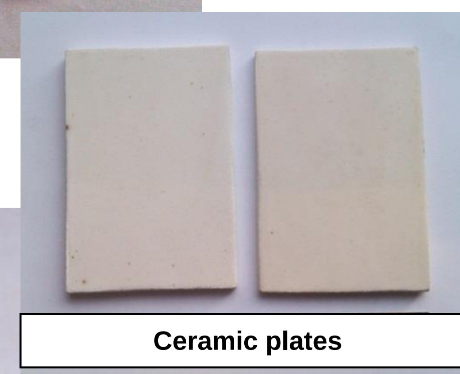
Ceramics



Samples

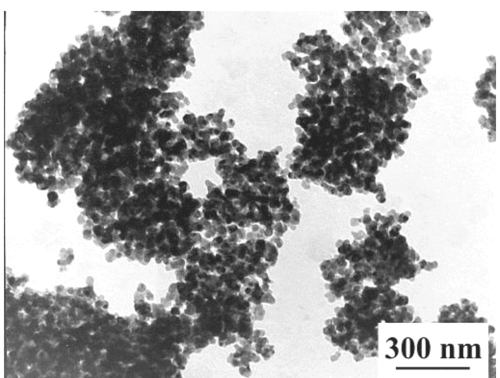
Properties

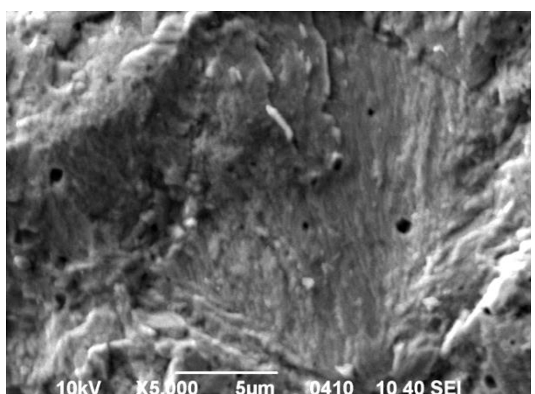
H_V = 12-13 GPa
ρ = 6,0 g/cm^3
ε_1= 22.6

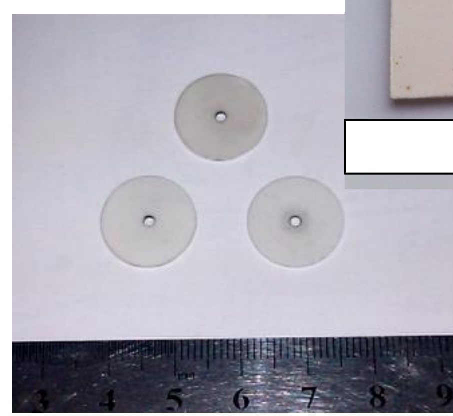


Ceramic plates

ZrO_2-MgO system







H_V = 10,8 GPa
ρ = 5,6 g/cm^3
ε_1= 22.8

Measurement of dielectric properties of ceramic materials

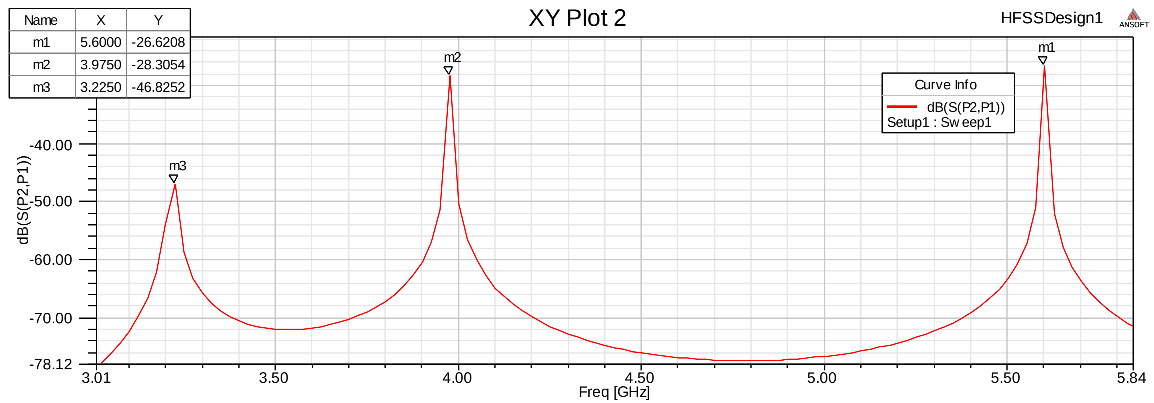
ZrO_2-Y_2O_3, ZrO_2-MgO, Al_2O_3, glass-ceramics, flan, rogers 3010

Fabrication of resonators

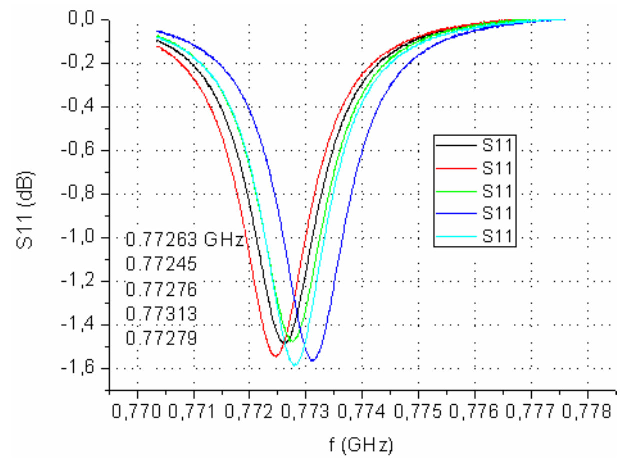
Cylindrical resonator with partial loading

Open-ended coaxial resonator

Measurement of resonance frequency and data fitting



Resonator frequency response of filled with Teflon and pellet of ZrO_2-4 wt% MgO ceramics.



Data scattering (~ 0.15 %) of coaxial resonator reflection coefficient for resonator loaded with dielectric sample ZrO_2-4 wt% MgO (ε = 23.0, H = 0.87 mm).

4.2 Experiments on various dielectric samples irradiation by a segence of electron bunches produced at 100MeV electrin linac “LUE-40”. Study of the induced radioactivity of the used samples

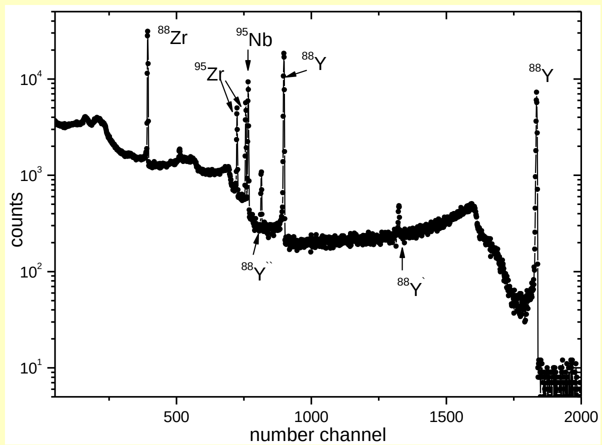
The samples of nanoceramics of ZrO_2+4%MgO and ZrO_2+8%Y_2O_3 have been irradiated with high energy electrons (up to 100 MeV)

Gamma-spectrum of ceramic samples after irradiation

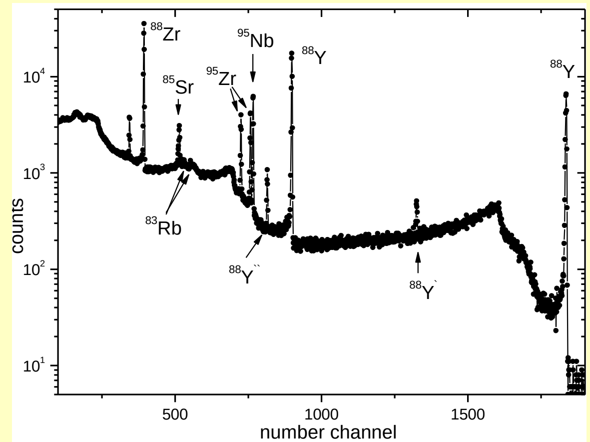
$2 \cdot 10^{16}$ e

ZrO_2+8%Y_2O_3

43 MeV

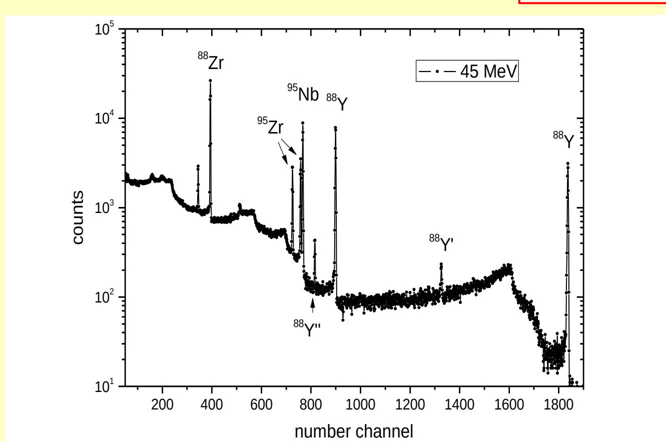


96 MeV

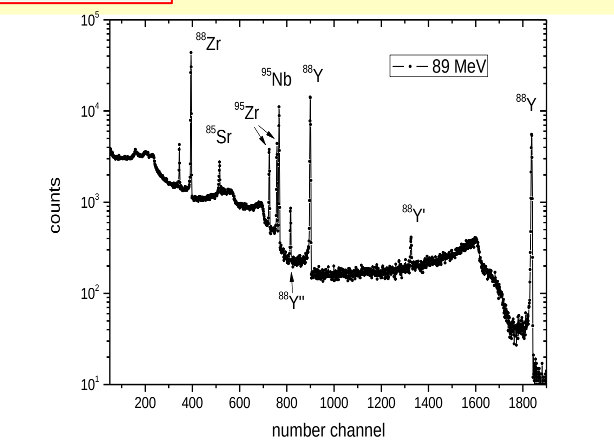


ZrO_2+4%MgO

45 MeV

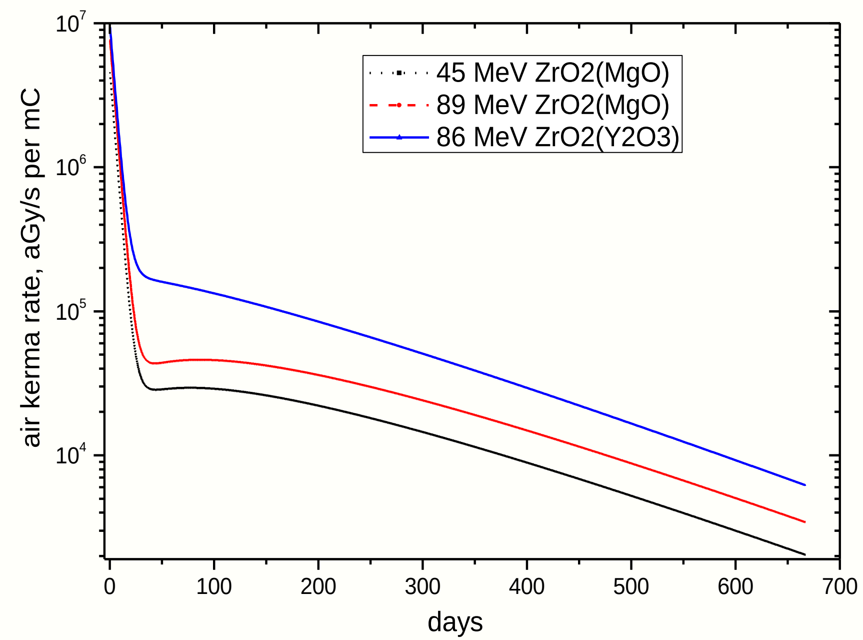


89 MeV

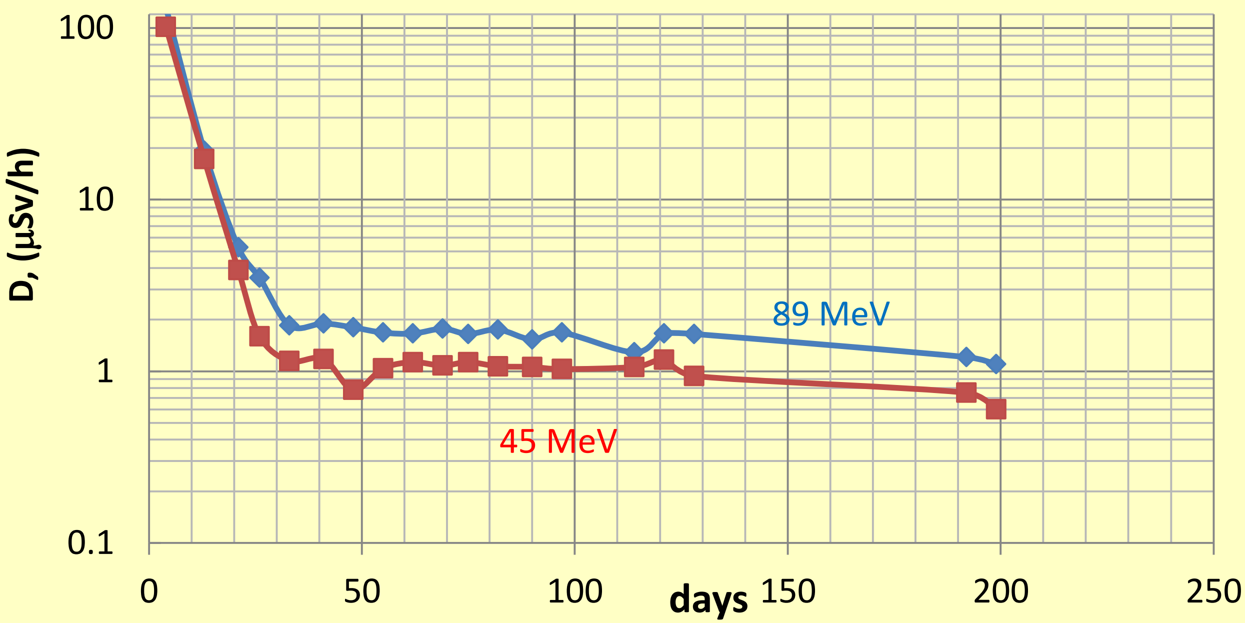


The use of nanoceramics ZrO_2, alloyed with MgO, results in diminishing of its activity as compared to nanoceramics, alloyed with Y_2O_3 for considerable time (more than 20-30 days) of the radiation cooling in 6-8 times !!!

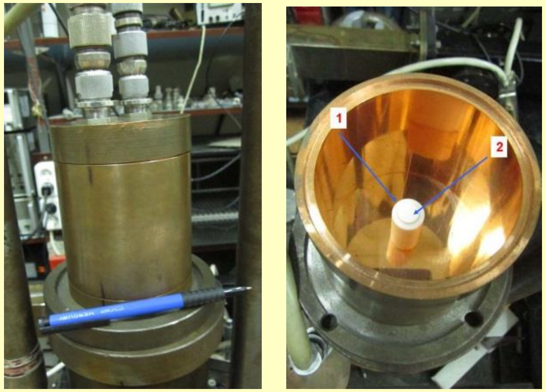
The activity of irradiated samples vs. time

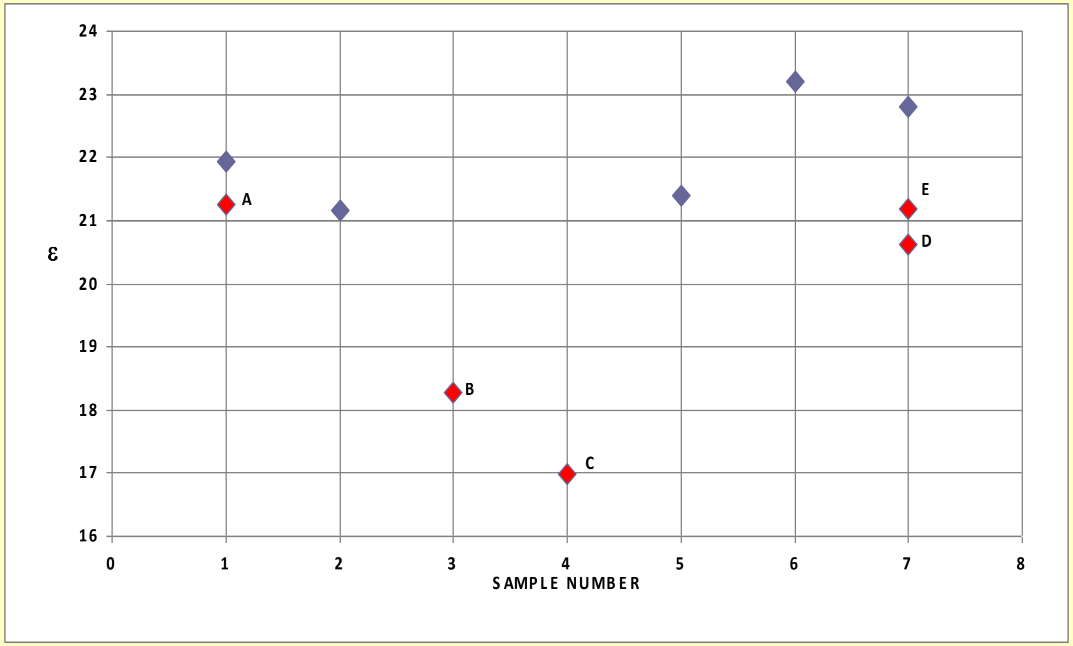


ZrO_2+4%MgO



CHANGE of PERMITTIVITY ε under BEAM IRRADIATION





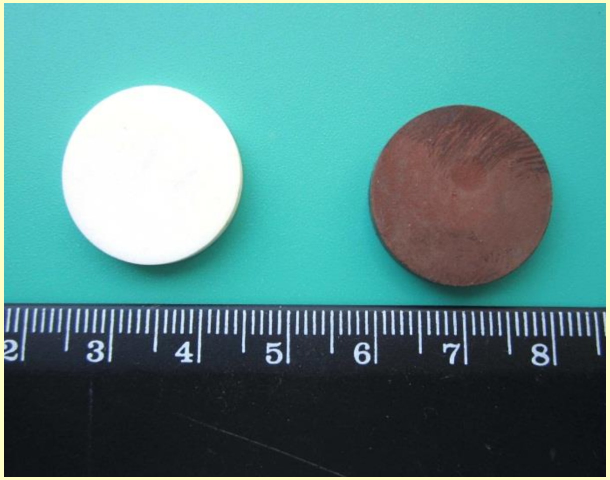
Exterior view of the RF cavity and

Dielectric sample (2) placed on Teflon holder (1) inside the RF cavity

Permittivity of all irradiated Zr samples, at least, does not exceed the permittivity of the non-irradiated samples. Because of the low accuracy of measurements (error to 10%) the obtained data do not allow to conclude about the influence of irradiation by the electrons with energy 40 -90 MeV and total charge of about 30 μA hour ($\approx 7 \cdot 10^{17}$ electrons) on the value of permittivity. Yet there is a number of parameters, which in principle can influence on the permittivity: dependence of the permittivity on temperature, the uneven of electron beam density distribution over the sample, and the uneven of temperature distribution over the sample during the irradiation.

Blue points are the non-irradiated samples, red points are the radiation-exposed standards.
***A** – 39 MeV, 20 μA·hours;*
***B** – 89 MeV, 31 μA·hours;*
***C** – 40 MeV, 31 μA·hours;*
***D** – 40 MeV, 14.5 μA· hour;*
***E –** after "cooling" once more irradiated 40 MeV, 20 μA·hours*

Improvement of measurement accuracy



Samples of ceramic for realizing the method of permittivity measurement with the complete filling RF cavity. Sample of ceramics before the spattering (on the left) and after the copper spattering (on the right).

Proposed variant is the resonance method with the whole filling of the resonator with dielectric. In this case the permittivity and loss tangent can be found by using exact analytical expressions.

Preliminary we have experimentally found that loss tangent has not exceed 10^{-3} so the Q-factor of the resonator with copper walls should be about $6{\cdot}10^{2}$. To exclude the errors related to the gaps between the dielectric and metal, it is planned to coat the dielectric sample with metallic layer by the sputter method.

Presently, the new samples of zirconia nanoceramic have been made for making the resonators, and the method of sputtering the copper/silver coverage is worked off. The basic sizes of dielectric disks are stand up to accuracy 10 microns.

According to calculations, at the resonator of diameter 20 mm, height 3 mm and Zr ceramics permittivity 21, the frequency of E_{010} mode is about 2500 MHz. At the change of permittivity of Zr ceramics from 21 to 20 the eigenfrequency is changed by 40 MHz. For the method with the partial filling of the resonator this frequency change is only 60 kHz

Conclusions

- Experimental facilities for R&D of multi-bunch dielectric wakefield accelerator were constructed including: upgrade of 4.5MeV electron linac to produce (3-6)·10^3 bunches each of charge 0.32nC, rms length 1.7cm, rms radius 0.5cm for dielectric wakefield invesigations; and arrangement of installation at 100MeV electron linac of the main parameters of the beam - energy 95MeV; pulse current 70mA; pulse duration 1.5μs; beam size 3 mm, for investigations of radiation influence on dielectric properties.

- Theoretically and in experiments multi-bunch concept for the dielectric wakefield acceleration was studied. Varying the length of the dielectric waveguide $L_0 = \lambda, 2\lambda, 3\lambda\ldots$ allows to observe wakefied at the waveguide exit from any number of bunches N=1,2,3…Thus, instead of varying the the length of a resonant sequence of bunches (i.e. N) that is difficult to realize in the experiments, we vary the length of dielectric waveguide (i.e. L_0) and can "feel" each bunch. It was proved the coherent summation of the wakefield of bunches till saturation occurs due to the field energy moving away with group velocity.

Conclusions (cntd. 1)

- Multi-mode concept for dielectric wakefield acceleration was investigated theoretically and experimentally in waveguide case. For wakefield excitation in a short waveguide L=λ, only for the waveform duration equal to one period (one bunch or one period of a long waveform of the several bunches) in the spectrum obtained with the help of "direct" calculation of the Fourier integral, the second radial mode is manifested. At that the spectral analysis by FFT does not register the frequency the second radial mode. In experiment one bunch excites a lot of transversal modes that gives “picking” of the total field waveform with enhanced amplitude. At the same time for a sequence of bunches only principal transversal mode frequency equal to bunch repetition frequency is observed in the spectrum.

- The resonator concept was investigated at resonant conditions of coincidence of bunch repetition frequency with Cherenkov modes frequencies and simultaneously with corresponding resonator frequencies. It was shown that number of bunches, enhancing total wakefield, increases essentially compare to the waveguide case and is limited only by Q-factor. However summation of transversal Cherenkov modes does not enhance total wakefield because they are not enough equidistant to be in resonance and are slightly excited.

Conclusions (cntd. 2)

- Electron acceleration by excited wakefield when introduce detuning of bunch repetition frequency with excited wakefield mode $\Delta f = f_m - f_0$. In resonant case $\Delta f = 0$, energy spectrum is shifted as a whole one to the smaller energy region, i.e. all bunches lose their energy to excite the wakefield. Energy loss is about 400 keV). At detuning $\Delta f = 2.5$ MHz the part of bunch sequence, being shifted, is occurred in the accelerating phase of the wakefield excited by previous bunches of the same sequence, gain energy from wakefield. In this case, in the energy spectra electrons lost (-150keV) and electrons gained energy (+ 150 keV) are observed.

- Basing on ZrO_2-Y_2O_3 system and ZrO_2-MgO system <u>zirconia nanopowders and ceramics for beam testing</u> and dielectric properties measurements were produced for investigations of their radiation resistance. The samples of nanoceramics of ZrO_2+4%MgO and ZrO_2+8%Y_2O_3 were irradiated with high energy electrons (up to 100 MeV). Gamma-spectrum of zirconia samples after irradiation were measured. Induced radioactivity of irradiated samples was registered and its radiation decay was measured. Diagnostic installations with fabricated resonators of several types were developed for measuring permittivity and loss tangent of irradiated zirconia samples. The dose of beam irradiation that changes perceptibly zirconia properties was measured.

THANK YOU

for your attention

Further development

- Further R&D of problems emerged in wakefield acceleration
  (for the bunch train: wakefield enhancing, focusing driver/witness bunches, transformation ratio)

- Metallization of ceramic structures of dielectric wakefield accelerator
  (KIPT invented filtered vacuum arc technology)

- Studies of dielectric structure charging
  (suitable capabilities of the KIPT linacs)

Publications on Project ANL-T2-247-UA / STCU P522

«Multi-bunch Dielectric Wakefield Accelerator»

1. К. Галайдич, І. Онищенко І., Г. Сотніков. Чисельне моделювання динаміки електронних згустків та кільватерного поля у трьохзонному діелектричному резонаторі. Тези доповідей міжнародної конференції студентів і молодіх науковців з теоретичної та експериментальної фізики **ЕВРИКА-2013, Львів, Україна 15-17 травня 2013р**. P.J4.
2. R.R. Kniazev, G.V. Sotnikov. Quasistatic field influence on bunches focusing by wakefields in the plasma-dielectric waveguide. Proceedings of **IPAC2013, Shanghai, China 12-17 Sept., 2013.** TUPEA055. P. 1256-1258 (http://accelconf.web.cern.ch /AccelConf/IPAC2013 /papers/tupea055.pdf).
3. I.N. Onishchenko, V.A. Kiselev, A.F. Linnik, G.V. Sotnikov. Concept of dielectric wakefield accelerator driven by a long sequence of electron bunches. Proceedings of **IPAC2013, Shanghai, China 12--17 Sept., 2013**. TUPEA056. P. 1259--1261 (http://accelconf.web.cern.ch /AccelConf/IPAC2013 /papers/tupea056.pdf).
4. G.V. Sotnikov, K.V. Galaydych, V.A. Kiselev, P.I Markov, I.N. Onishchenko. Optimization of rectangular dielectric structures for the planned wakefield acceleration experiments in KIPT. Proceedings of **IPAC2013, Shanghai, China 12--17 Sept., 2013**. TUPEA057. P. 1262--1264 (http://accelconf.web.cern.ch /AccelConf/IPAC2013 /papers/tupea057.pdf).

5. Р.Р. Князев, О.В. Мануйленко, П.И Марков, Т.К. Маршалл, И.Н. Онищенко, G.V. Sotnikov. Фокусировка электронных и позитронных сгустков в плазменно-диэлектрическом кильватерном ускорителе. Вопросы Атомной Науки и Техники. Серия ''Плазменная электроника и новые методы ускорения''. 2013. No. 4(86). С.84-89.
6. K.V. Galaydych, V.A. Kiselev, P.I Markov, I.N. Onishchenko, G.V. Sotnikov. Optimization of rectangular dielectric structures for the planned wakefield acceleration experiments in KIPT. Problems of Atom Science and Technology. Series ''Nuclear Physics Investigations''. 2013. No. 6(88). C.35-38.
7. G.V. Sotnikov, R.R. Kniaziev, O.V Manuilenko, P.I. Markov, I.N. Onishchenko. Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerators. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2014. V.740, P. 124-129.
8. К. Галайдич, І. Онищенко, Г. Сотніков. Збудження електромагнітного поля електронними згустками у частково заповненому діелектричному циліндричному резонаторі. Міжнародна наукова конференція студентів і молодих науковців з теоретичної та експериментальної фізики **Еврика–2014, 15-17 травня, 2014: тез. доповідей. – Львів, Україна, 2014**. С.15.
9. R.R. Kniaziev, G.V. Sotnikov. Transverse dynamics of accelerated bunches in a plasma-dielectric wakefields. Proc. of the **41st IEEE International Conference on Plasma Science and the 20th International Conference on High-Power Particle Beams**, May 25-29, 2014, Marriott Wardman Park, Washington DC.

10. K.V. Galaydych, R.R. Kniaziev, V.A. Kiselev, P.I Markov, I.N. Onishchenko, G.V. Sotnikov. Spectra of a wakefield excited by an electron bunch train in a short section of a dielectric waveguide. Proc. of **9th International Workshop "Strong Microwaves and Terahertz waves: sources and applications". Nizhny Novgorod, Russia, July 24--30, 2014**. P.73—74.
11. G.V. Sotnikov, K.V. Galaydych, R.R. Kniaziev, P.I. Markov, and I.N. Onishchenko. Radiation of a Wakefield Excited by an Electron Bunch Train in a Section of Dielectric Waveguide. **16th Advanced Accelerator Concepts Workshop, 13-18 July 2010, San Jose, California, USA**;; AIP Conf. Proceedings. (will be published).
12. P.I. Markov, V.A. Kiselev, R.R. Kniaziev, I.N. Onishchenko, G.V. Sotnikov. Study of wakefields in longitudinally and transversely inhomogeneous rectangular dielectric resonators. Problems of Atom Science and Technology. Series Plasma Physics''. 2014 (to be published).
13. K.V. Galaydych, G.V. Sotnikov, I.N. Onishchenko. Electromagnetic field excitation by an electron bunches in a partially filled cylindrical dielectric resonator. Problems of Atom Science and Technology. Series Plasma Physics''. 2014 (to be published).
14. . V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky. Wakefield Excitation and Electron Acceleration at Detuning Bunch Repetition Frequency and Frequency of Eigen Principal Mode of Wakefield // Problems of Atomic Science and Technology. 2013, №6, p.80-83.
15. V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky. Excitation of Wake Fields in a Semi-infinite Dielectric Waveguide by Nonresonance Sequence of Bunches // Problems of Atomic Science and Technology. 2014, №3, p.102-106.

16. V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky. Wakefield Excitation by Sequences of Relativistic Electron Bunches in Dielecric Cavity at Detuning between Bunch Repetition Frequency and Frequency of Eigen Principal Mode// to be published.
17. V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky. Influence of the finite Q-factor on excitation of wakefield oscillations in dielectric cavity by sequence of relativistic electron bunches in the presence of detuning between the resonant frequency and repetition bunches frequency // to be published.
18. V.I.Maslov, I.N.Onishchenko. Transformation Ratio at Wakefield Excitation in Dielectric Resonator by Shaped Sequence of Electron Bunches with Linear Growth of Current. Problems of Atomic Science and Technology. Problems of Atomic Science and Technology N4 (86), 2013. P. 69-72.
19. V.I.Maslov, I.N.Onishchenko. Transformation Ratio at Wakefield Acceleration in Dielectric Resonator. Problems of Atomic Science and Technology. Ser. Nuclear Physics Investigations. 2014. N3 (91). P. 99-101
20. V.I.Maslov, I.N.Onishchenko. Transformation Ratio at Wakefield Excitation in Dielectric Resonator by Sequence of Rectangular Electron Bunches with Linear Growth of Charge. Problems of Atomic Science and Technology. Ser. Nuclear Physics Investigations. 2014. N3 (91). P. 95-98.
21. V.I.Maslov, I.N.Onishchenko. To the transformation ratio in resonator concept of dielectric wakefield accelerator driven by a tailored sequence of electron bunches. Proc. of the 9th Int. Workshop “Strong Microwaves and Terahertz Waves: Sources and Applications”. Nizhny Novgorod. 24-30 July 2014. 2p.

XII International Workshop "Plasma Electronics and New Acceleration Methods" 26-30 August, 2013, Kharkov, Ukraine.
Oral report "Wakefield Excitation and Electron Acceleration at Detuning Bunch Repetition Frequency and Frequency of Eigen Principal Mode of Wakefield", *V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky*

XXIII International Workshop on Charged Particle Accelerators, September 08-14, 2013, Ukraine, Alushta, the Crimea
1.Oral Report "Excitation of Wake Fields in a Semi-infinite Dielectric Waveguide by Nonresonance Sequence of Bunches", *V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky*.
2.Oral Report Transformation Ratio at Wakefield Excitation in Dielectric Resonator by Sequence of Homogeneous Electron Bunches with Linear Growth of Charge" *V.I.Maslov, I.N.Onishchenko*

International Conference and School on Plasma Physics and Controlled Fusion, September 15-18, 2014, Kharkov, Ukraine.
1.Oral report "Wakefield Excitation by Sequences of Relativistic Electron Bunches in Dielecric Cavity at Detuning between Bunch Repetition Frequency and Frequency of Eigen Principal Mode", *V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky*
2. Poster report "Influence of the finite Q-factor on excitation of wakefield oscillations in dielectric cavity by sequence of relativistic electron bunches in the presence of detuning between the resonant frequency and repetition bunches frequency", *V.A.Balakirev, I.N.Onishchenko, A.P.Tolstoluzhsky*

XII Conf. Phys. of High Energy, Nuclear Physics and Accelerators. Kharkov. Ukraine. 17-21 March 2014.
Transformation Ratio at Wakefield Acceleration in Dielectric Resonator. *V.I.Maslov, I.N.Onishchenko*