WAKEFIELD EXCITATION IN PLASMA FILLED DIELECTRIC STRUCTURE BY A TRAIN OF ELECTRON BUNCHES

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Abstract

Essential increase of wakefield intensity at excitation by a long train of relativistic electron bunches when the rectangular dielectric structure is filled with plasma was experimentally observed. The first portion of the bunches ionizes gas so that plasma frequency is equal to bunch repetition frequency and to the frequency of principal eigen mode of the dielectric structure. Excitation enhancement at such resonant conditions is being studied taking into account the improvement of bunch train propagation in the transit channel and electrodynamics change of the dielectric structure at filling with plasma.

INTRODUCTION

Many works [1-7] are devoted to the investigation of wakefield method of charged particles acceleration using dielectric structures both of cylindrical and rectangular geometry. In this presentation with the purpose to increase coupling of electron bunches with excited wakefield, it is proposed to use plasma filling the vacuum transit channel for electron bunches. At plasma assistance the excited wakefield in the channel from superficial, which sages on the axis, becomes volumetric on [5] so that the excitation efficiency increases. Besides development of wakefield method of acceleration in dielectric structures for increase of acceleration rate requires using dielectric with a great permittivity and small size bunches. It forces to reduce the transit channel size that makes difficult the passage of bunches through the channel. Angular dispersion caused by the excited wakefield leads electrons to hit on the internal dielectric walls and to no passing of bunches. Plasma in the channel compensates arising electrostatic field of deposited electrons, that provides good transportation of bunches through the channel.

Results of the experimental research of the excited wakefield and energy loss of electron bunches in dielectric structure are presented for rectangular geometry with the vacuum channel, at filling it with plasma, and the same for cylindrical geometry.

EXPERIMENTAL INSTALLATION

The scheme of the experimental installation is shown in Fig. 1. As a dielectric structure with great permittivity ε the standard copper waveguide R32 by cross-section 72.14×34.04 mm^2 was used. In it along two wide walls dielectric plates made from high-frequency ceramics with ε=9 were located. The thickness 8.8 mm of plates was chosen from the condition of coincidence of the frequency ω_0, determined by Cherenkov resonance, i.e. crossing of the beam mode and the principal mode of the considered structure, with bunch repetition frequency ω_m. Thus the width of the transit channel for bunches appeared equal to 16.4 mm. The length of dielectric plates was taken equal to 270 mm. The electron bunches with energy 4.5 MeV and charge 0.16 nC each were produced by the linear resonant accelerator. Amount of bunches N=6000, frequency of bunch repetition $\omega_m=2\pi\cdot 2805$ MHz. Bunch size: length σ_z=17 mm and radius σ_r=5 mm.

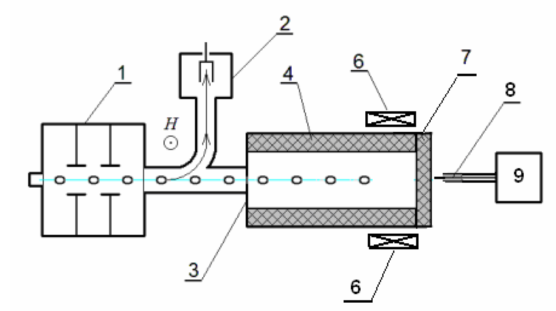

Figure 1: Scheme of the installation: 1-electron accelerator, 2-magnetic analyzers, 3-diaphragm, 4-dielectric plates, 5-rectangular copper waveguide, 6-deflecting magnets, 7-Teflon seal, 8-RF-probe, 9-oscillograph

Measurements of excited field amplitude were carried out by means of the RF- probe, beam current was measured by Faraday cylinder, and electron energy spectrum was estimated by using magnetic analyzer located on accelerator exit and electron path length in the glass plate.

Experiments were carried out with vacuum and plasma filled transit channel in dielectric structure. In the first case electron bunches through the aperture in metal diaphragm passed through dielectric structure, which exit end has been closed by Teflon seal of thickness 10 mm for maintenance of vacuum. To avoid electrons hitting on the seal, at exit electron bunches were deflected by transverse magnetic field to waveguide wall.

In the second case electron bunches through the Ti-foil of thickness 50 microns were injected in dielectric structure, which transit channel was filled with air at atmospheric pressure. In this case Teflon seal at exit of structure was absent. Estimation of electron energy at exit of the accelerator and after passage of bunches through structure were carried out by measuring the path length of electrons in glass plate, which was determined by depth of darkening of glass plates.

EXPERIMENTAL RESULTS

Waveguide-Dielectric Structure of Rectangular Section (ε=9) with the Vacuum Transit Channel

Measurement of E_z component of the excited field at structure exit, performed by means of the RF-probe, showed that the signal 0.36V was observed even in the absent of dielectric. With dielectric plates inserting it was decreased up to 0.13V. To explain it the decrease of passed bunches current was measured by means of Faraday cup. It appeared, that without dielectric current passed through the waveguide fully, while at presence of dielectric plates only 10% of the current passed. It evidenced practically full interception of the current due to electrons hit on dielectric plate's walls and building up an electrostatic charge on them that locked bunches to pass and therefore stopped wakefield excitation.

It is necessary to note, that in contrast to this experiment, our earlier experiment [7] with dielectric plates made from Teflon (ε=2.1) and a waveguide with greater cross-section 85×180 mm^2 and hence wider transit channel 41.6 mm, showed considerable growth of excited field amplitude at presence of dielectric plates. For this dielectric structure the measurement of the passed current by Faraday cup have shown that whole current passed through the structure. That is the width of the transit channel was big enough in order t electron bunches did not hit internal wall of dielectric plates.

Dielectric Structure of Rectangular Cross-Section (ε=9) with Plasma Filled Transit Channel

Earlier we have shown [8], that at output of the relativistic electron beam from linear resonant accelerator into atmosphere plasma is produced, with which electron beam effectively interacts. At that the area of resonant plasma formation, in which plasma frequency is close to frequency of bunch repetition ($\omega_p = \omega_M$), is of length nearby 15 cm. Acting analogically, we carried out research of wakefield excitation in waveguide-dielectric structure of rectangular cross-section in conditions when the transit channel was with air at atmospheric pressure which was ionized by passing bunches of relativistic electrons.

Measurements of amplitude E_z-component of excited field (Fig.2) showed that at presence of plasma in the transit channel of dielectric structure the amplitude of the excited field signal increases in 20 times in comparison with the amplitude in vacuum case.

Oscillograms presented in Fig. 2 for vacuum (2a - sensitivity 50 mV/div) and plasma (2b - sensitivity 200 mV/div) cases, were obtained by the same HF-probe. At presence of plasma the signal was in addition decreased by means of attenuator by 20 dB.

The increase of excited field amplitude at presence of plasma gives the basis to assume, that the formed plasma, firstly, compensates the accumulated electrostatic charge on dielectric plates and promotes good passage of electron bunches through the structure and, secondly, changes topography of excited fields and increases coupling of bunches with the field.

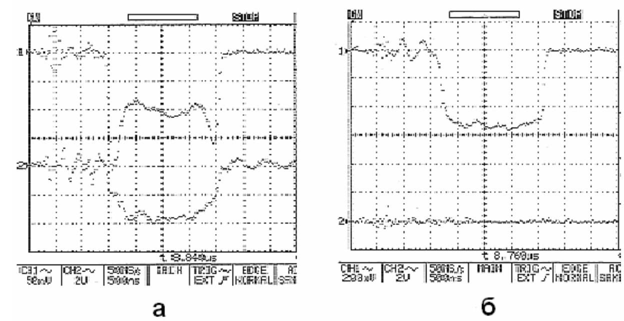

Figure 2: a) - oscillogram of signal of E_z - component of excited field (top) and beam current (bottom) without plasma filling; b) - oscillogram of signal of E_z - component of excited field (top) at presence of plasma.

Distribution of E_z-component of excited field over the axis *x* and *y* is presented in Fig. 3. It is visible, that plasma filling leads to volumetric character of the excited field over the cross-section in the direction across plates. In the direction along plates two maxima of field amplitude are observed not on the axis of system, but they are symmetric to the axis on distance of 2-3 cm from the axis. Such kind of transversal topography of wakefield allows increasing transformation rate to value above 2 in collinear two-beam scheme of particle acceleration.

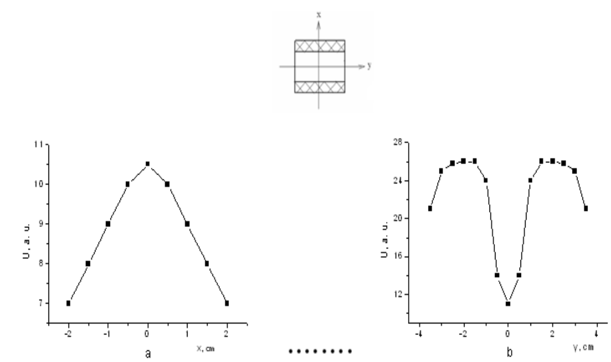

Figure 3: Distribution of E_z-component of excited field over axis *y* (a) and on an axis *x* (b). Top picture is the cross-section of the structure.

Measuring of beam current by Faraday cup showed that for injected beam current I_b=0.5A, the current passed through the structure was 0.25A in case of plasma filling, and it was only 0.05A in vacuum case.

The discrepancy between increase of value of the passed current and growth of E_z- component amplitude of excited field that was observed at plasma presence can be explained by that at plasma presence in the transit channel bunches excite wakefield along whole length of dielectric plates, but in vacuum case excitation length is considerably reduced because of beam interception.

Effective wakefield excitation in such structure is accompanied by corresponding considerable energy losses of electron bunches. In Fig. 4a the darkening of the glass plate caused by its irradiation with relativistic electron bunches are shown: (1) - at entrance and (2) - at exit of dielectric structure. In Fig. 4b there are presented curves of changing of darkness density of glass plate along beam propagation, by which the extrapolated path length of electrons was determined, that gives the possibility to determine energy of electrons.

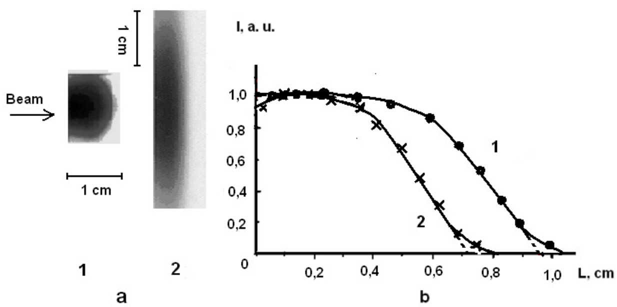

Figure 4: a) - change of darkness density of glass plate, caused by irradiation with relativistic electron bunches (1) – at entrance and (2) - at exit of dielectric structure; b)- distribution of darkness density along thickness of a glass plate in direction of beam propagation.

Estimated by such method energy loss of electron bunches, passed through the dielectric structure, make ≈ 30%. Besides it is visible from the figure, that the size of bunches increases up to the sizes of the transit channel that does not exclude non-full passage of bunches through the channel and decrease of the current twice.

Plasma-Dielectric Structure of Cylindrical Cross-Section (ε =2.1)

In this section results of experiments with the dielectric structure of round cross-section are presented. The structure represented a copper pipe in diameter of 90 mm and length of 20 cm, filled with dielectric (Teflon ε=2.1) with hole in diameter of 2 cm as a transit channel for electron bunches that was filled by air at atmospheric pressure. The sizes of structure have been calculated from a condition that eigen frequency of the principal mode ω_0 coincided with frequency of bunch repetition ω_m and simultaneously on this frequency Cherenkov resonance of the beam with the principal mode was satisfied.

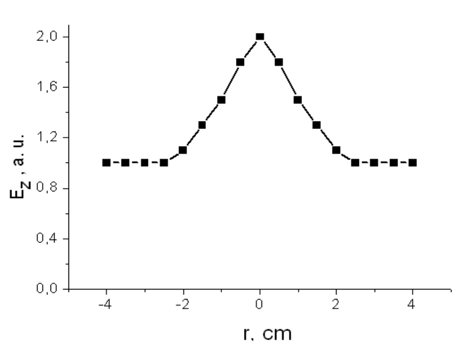

Figure 5: Distribution of E_z-component amplitude of excited field over radius.

For the vacuum case in considered structure field sagging on the axis of the transit channel takes place [2]. Plasma filling of the transit channel changes transverse topography of the field that can be used for increase in wakefield excitation efficiency. Measurements of E_z-component of excited field showed that its amplitude is 2.5 times more than amplitude in the vacuum case. Transversal distribution of E_z-component of excited field is shown in Fig. 5. It is visible that the excited field is volumetric with maximum on the transit channel axis.

CONCLUSIONS

At plasma producing in the transit channel of dielectric structure of rectangular cross-section by a sequence of electron bunches via gas ionization the amplitude of excited wakefield considerably increases, that is explained by plasma compensation of the electrostatic charge, build up at electron bunch touching the inner walls of dielectric plates.

Presence of plasma in the transit channel of dielectric structure allows to avoid sagging of excited field on axis of the structure that can increase efficiency of wakefield excitation.

Possibility of increasing wakefield excitation efficiency at coincidence eigen frequency of the principal mode of dielectric structure with frequency of bunch repetition and simultaneously with plasma frequency (double resonance) deserves further research.

REFERENCES

[1] W. Gai, P. Schoessow, B. Cole, R. Konecny, J. Norem, J. Rosenzweig, and J. Simpson, Phys. Rev. Lett. 61, 2756 (1988).
[2] I.N. Onishchenko, V.A. Kiseljob, A.K. Berezin, G.V. Sotnikov, V.V. Uskov, A.F. Linnik, Ya. B. Fainberg, Proc. 1995 Particle Acceleration Conf. pp. 782-783 (IEEE, 1996).
[3] T.-B. Zhang, J.L. Hirshfield, T.C. Marshall, and B. Hafizi, Phys. Rev. E56, 4647 (1997).
[4] T.-B. Zhang, J.L. Hirshfield, T.C. Marshall, IEEE Trans. Plasma Sci. 26, 787 (1998).
[5] J.G. Power, W. Gai, P. Schoessow, Phys. Rev. E60, 6061 (1999).
[6] V.A. Kiselev, A.F. Linnik, T.S. Marshall, I.N. Onischenko, N.I. Onischenko, G.V. Sotnikov, V.V. Uskov, Proc. VI Int. Workshop “Strong microwaves in Plasmas ”, N. Novgorod, Russia, 2005, V.1, P.303-310.
[7] V.A. Kiselev, A.F. Linnik, T.C. Marshall, I.N. Onishchenko, N.I. Onishchenko, G.V. Sotnikov, V.V. Uskov, 12th Advanced Accelerator Concepts Workshop, 10-15 July 2006: AIP Conference Proceedings 2006, V. 877, p. 851-858.
[8] A.K. Berezin, Ya.B. Fainberg, V.A. Kiselev, A.F. Linnik, V.V. Uskov, V.A. Balakirev, I.N. Onishchenko, G.L. Sidel’nikov, and G.V. Sotnikov. Plasma Physics Reports, 1994, V. 20, No.7, pp. 596-602.