WAKEFIELD EXCITATION IN PLASMA-DIELECTRIC STRUCTURES BY A SEQUENCE RELATIVISTIC ELECTRON BUNCHES

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The results of theoretical and experimental studies of the influence of the plasma in the transit channel of dielectric structure on the efficiency of wakefield excitation by a sequence of relativistic electron bunches are presented. The dielectric structure of circular cross-section with Teflon (ε=2.1; $tg\delta=2\cdot10^{-4}$) The plasma in the channel dielectric structure is formed by passing bunches of relativistic electrons through the neutral gas as a result of impact ionization and acceleration of plasma electrons in the excited wake wave. It is shown that when the gas pressure in the range 10^{-2}…1 Torr, an increase of the amplitude of the excited wakefield due to changes in the topography of the main electromagnetic mode. In the pressure range 0.1…1 Torr observed focusing electron bunches due to the presence of bunches in the decelerating the total longitudinal electromagnetic field and Langmuir wave and at the same time focusing field of the Langmuir wave.

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INTRODUCTION

Acceleration of particles by wakefield, excitation bunches of relativistic electrons as they propagate in slowing media is a perspective and actively developing direction in high-energy physics. Due to extra high accelerating gradients, wakefield acceleration techniques allow to reach higher energies of the accelerated particles with much smaller length of the accelerating systems.

To accelerate charged particles wakefield that is excited by relativistic electron bunches as the slowing media used or plasma [1] or a dielectric structure [2]. If you use a dielectric structure with the transit channel filled with plasma, then in addition to plasma wakefield will be excited the own wave dielectric structure, modified by the presence of plasma in channel.

Usually dielectric structures are calculated so that when you use a regular sequence of relativistic electron bunches has taken place synchronism between the fundamental mode of the excited wakefield ω_0 and a repetition frequency ω_m bunches ($\omega_0 = \omega_M$), as a result of the Cherenkov’s resonance field from each bunch add together coherently.

1. THEORY

The performed theoretical studies of electrodynamics of dielectric waveguide with an axial transit channel, filled with plasma (so called hybrid plasma-dielectric waveguide) show that the presence of plasma in transit channel leads to changes in the topography of the principal mode of the dielectric wakefield, so that in the channel r=0…1.0 cm wakefield becomes volumetric. Caused by this the growth of the coupling coefficient of bunches with a wave provides an increase of the longitudinal field amplitude in the channel more for higher plasma density (Fig. 1).

Note that in a strong magnetic field such a situation occurs at plasma densities, for which $\omega_p \geq \omega_0$. For a sequence of bunches the situation is complicated by the fact that the presence of plasma in the channel violates the resonance condition of the coincidence bunch repetition frequency ω_{rep} and frequency of the excited with Cherenkov dielectric field ω_0. As a result at the presence of plasma the total wakefield beat is arisen for a long sequence of bunches. It limits the linear growth of wakefield with the increase of number of bunches, so that the maximum field is significantly reduced compared with the case without plasma. The situation is aggravated in the resonator case because of the need to comply with additional resonance with the eigen frequencies of the resonator ω_n, i.e. $\omega_{rep}=\omega_0=\omega_n$. For experimental verification of the above conclusions on the role of plasma presence in the transit channel (increasing or suppressing wakefield excitation), we carried out experiments both with a resonator, in which plasma suppresses the excitation because of the emerging resonance detuning $\omega_{rep}\neq\omega_0\neq\omega_n$, and with a waveguide, when the plasma presence accordingly to theory (see Fig. 1) causes an increase of the excited field in comparison with the case without the plasma.

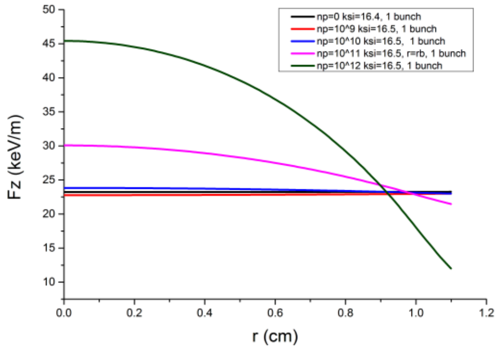


Fig. 1. Topography of excited wakefield in transit channel of cylindrical dielectric waveguide filled with plasma of different densities

In the waveguide case, besides the absence of the eigen resonator frequency ω_n, it is needed to get rid of the bunch repetition frequency ω_{rep}, which in the plasma presence occurs detuned with the frequency of Cherenkov dielectric wakefield ω_0 ($\omega_{rep}\neq\omega_0$). For that we should realized a single bunch regime by taking the waveguide length L = λ (λ is the dielectric wave length). In this case, bunches excite wakefield independently, each carries off excited wakefield from the waveguide with group velocity v_g, so that the next bunch flies into the waveguide, free of the wakefields of previous bunches. Therefore, in experiment the envelope of the wakefields of all $6{\cdot}10^3$ bunches has an amplitude, equal to the wakefield amplitude excited by a single bunch.

2. EXPERIMENTAL SETUP

The scheme of experimental setup is shown in Fig. 2. Relativistic electron bunches produced by resonant electron accelerator "Almaz-2M" (energy 4.5 MeV, number of bunches $6{\cdot}10^3$, bunch charge 0.26 nC, bunch duration 60 ps at intervals between bunches 300 ps, bunch repetition frequency 2805 MHz) penetrate through a titanium foil with a thickness of 30 microns and enter into the dielectric waveguide of circular cross section, filled with dielectric (Teflon F-4, $\varepsilon = 2.04$; $tg\delta = 2{\cdot}10…4$) with transit channel of diameter 21 mm for the passage of bunches.

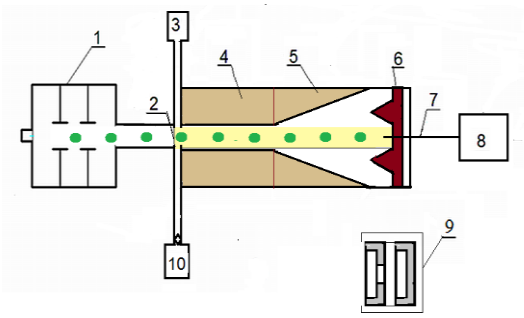


Fig. 2. Scheme of experimental setup: 1 – accelerator "Almaz-2M"; 2 – titanium foil; 3 – vacuum meter; 4 – dielectric waveguide; 5 – dielectric cone; 6 – ferrite absorber; 7 – microwave probe; 8 – oscilloscope; 9 – double Faraday cup; 10 – vacuum pump

For realization of the waveguide case it is needed to avoid reflections of the excited wakefield. For this purpose, the dielectric insert is ended with dielectric cone, and on Teflon vacuum cap ferrite absorber is placed. For obtaining single bunch regime the length of the dielectric insert was chosen equal to length of the excited dielectric wave $L = \lambda$. To study focusing relativistic electron bunches double Faraday cup (9) is used in which the focusing effect is determined by the presence of the beam current increase in the second cup and a simultaneous decrease in the beam current in the first cylinder. Plasma in the transit channel of the dielectric waveguide is produced by the beam itself when it passes through the neutral gas of regulated pressure filling the transit channel due to the beam-plasma discharge (BPD) with the excited wakefield developing at pressure 1 Torr and due to the collisional ionization by beam electrons at higher pressures.

3. INFLUENCE OF THE PLASMA IN THE TRANSIT CHANNEL ON WAKEFIELD EXITATION EFFECIENCE

As shown by the oscillograms of the microwave signals envelope obtained by means of a microwave probe placed at the exit of the dielectric waveguide having a dielectric insert of length L = λ under neutral gas pressure in the transit channel in range 0.02…1 Torr, the amplitude of excited wakefield (Fig. 3,b) exceeds the amplitude of wakefield excited in the dielectric waveguide without plasma (see Fig. 3,a,c).

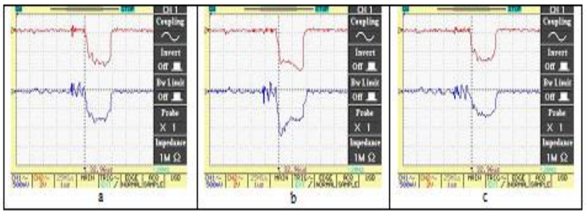


Fig. 3. Oscillograms of the envelope of the microwave signals of wakefields (blue oscillograms) for various gas pressure: a – 10…3 Torr; b – 0.5 Torr; c – 140 Torr. Red oscillograms – beam current

The dependence of the amplitude of the excited longitudinal wakefield on the axis for the wide range of the gas pressure in the case of a waveguide and a single bunch regime is shown in Fig. 4 (red curve). It is seen that in the pressure under which BPD develops and plasma is formed the wakefield wave topography in the channel becomes volumetric (in agreement with the theory (see Fig. 1)), that increases the coupling coefficient of the bunch with the wakefield wave and leads to the increase in the excited wakefield amplitude compared with the case without gas injection (see Fig. 4, the horizontal red line).

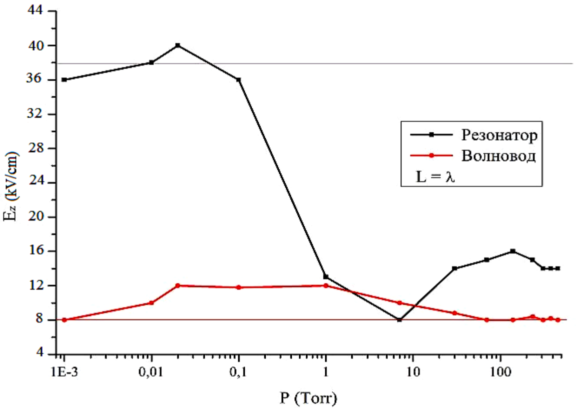


Fig. 4. The dependence of the longitudinal component E_z of the excited wakefield upon neutral gas pressure in the transit channel of the dielectric structure

In the case of dielectric resonator (matching elements were removed and metal exit plug was installed) under conditions of the double-resonance $\omega_{rep}=\omega_0=\omega_n$ (coincidence of Cherenkov frequency ω_0 with bunch repetition frequency ω_{rep} and simultaneously with eigen frequency of the resonator ω_n) the wakefield amplitude grows significantly. This is due to the fact that the number of bunches which contribute to the total wakefield is limited by quality factor Q (for conventional Q it is hundreds of bunches), whereas in the case of the waveguide the number of bunches, determined by the waveguide length and the group velocity, does not exceed tens of bunches. However, unlike the waveguide case with a single bunch regime in the resonator case all bunches involved in wakefield build-up excitation, i.e. bunch repetition frequency ω_{rep} comes into play, and resonator eigen frequencies ω_n are presented. The presence of plasma at pressures under which BPD develops leads to detuning of both resonances and to a reduction in the wakefield amplitude (see Fig. 4, black curve) compared with the case of without gas injection, i.e. without plasma (see Fig. 4 horizontal black line)

4. EXPERIMENTAL RESULTS ON FOCUSING BUNCHES

In the case of the waveguide (matched exit) in a single bunch regime ($L = \lambda$) both mentioned resonances are absent and all bunches are in the same conditions of exciting bunches-drivers. Fig. 5 shows theoretically obtained [3] the dielectric and plasma wakefields excited by a single bunch for two plasma densities.

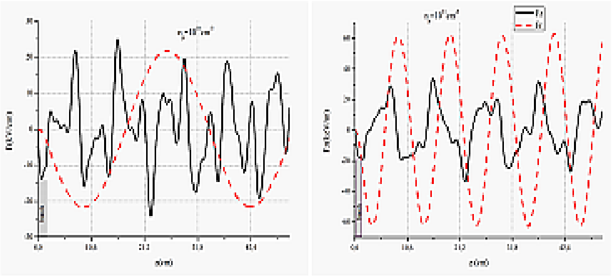
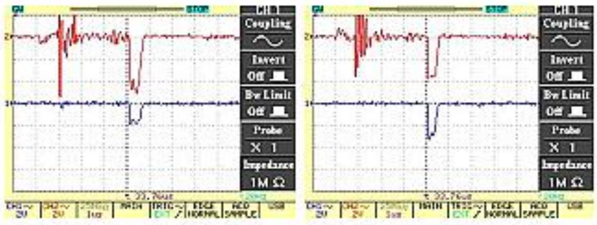

a b

Fig. 5. The total longitudinal component of dielectric and plasma wakefields (solid) and transverse component of plasma wakefield (dashed curve) for plasma densities:
a – $n_p=10^{10}$ cm^{-3}; b – $n_p=10^{11}$ cm^{-3}

It is evident that the bunch of finite length and finite radius is occurred in its own wakefield – longitudinal dielectric (decelerating) and radial plasma (focusing) ones. Radial defocusing dielectric field with its almost uniform longitudinal field over radius is absent. As a result of bunch-driver will be focused by its excited plasma wakefield along with the focusing due to compensation in the plasma of its radial electric field [4].



a b

Fig. 6. Oscillograms of beam current taken with double Faraday cup: top - first cylinder; bottom - second cylinder; a – P = 10…3 Torr; b – P = 0.5 Torr

Fig. 6 shows the waveform of the beam current, experimentally obtained with a double Faraday cup at vacuum $P = 10^{-3}$ Torr (see Fig. 6,a) and at neutral gas pressure in the transit channel of dielectric waveguide P = 0.5 Torr (see Fig. 6,b). The increase in current in the second cup while its reducing in the second one evidences focusing electron bunches, more at a higher plasma density (namely for gas pressure P = 0.5 Torr).

CONCLUSIONS

Shown that in the presence of plasma in transit channel of dielectric waveguide of length $L = \lambda$ (single bunch regime), produced during passage of a sequence of relativistic electron bunches through the neutral gas in the pressure range 10^{-2}…1 Torr, the increase of the total excited wakefield amplitude on the waveguide axis in accordance with the theory. For this case, focusing of the relativistic bunches-drivers is observed as they are occurred not in the decelerating phase of the total longitudinal field dielectric and plasma wakefields but simultaneously in the radial focusing field of the plasma wakefield (for relativistic bunches radial defocusing dielectric wakefield is negligible as longitudinal one is almost radially uniform).

In the resonator case plasma filling suppresses wakefield excitation due to occurrence of detuning resonances - coincidence of Cherenkov frequency ω_0 with bunch repetition frequency ω_{rep} and simultaneously with the resonator eigen frequency ω_n.

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REFERENCES

1. P. Chen, J.M. Dawson, R.W. Huff, T. Katsouleas. Acceleration of electrons by the interaction of a bunched beam with a plasma // *Phys. Rev. Lett.* 1985. v. 54, № 7, p. 693-696.
2. W. Gai, P. Schoessow, T. Cole. Experimental Demonstration of Wake-Field Effects in Dielectric Structures // *Phys. Rev. Lett*. 1988, v. 61, p. 2756-2758.
3. R. Knyazev, G.V. Sotnikov. Focusing wakefield for accelerated bunch in a plasma-dielectric waveguide // *Journal of Kharkiv University*. 2012, № 1001, p. 64-68.
4. G. Hairapetian, P. Devis, C. Joshi, C. Pelegrini, T. Katsouleas. Transverse dynamic of a short relativistic electrons bunch in a plasma lens // *Phys. Plasma*. 1995, v. 2 (6), p. 2555-2561.

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ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНЫХ ВОЛН В ПЛАЗМЕННО-ДИЭЛЕКТРИЧЕСКИХ СТРУКТУРАХ ПОСЛЕДОВАТЕЛЬНОСТЬЮ СГУСТКОВ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ

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Представлены результаты теоретических и экспериментальных исследований влияния плазмы в канале диэлектрической структуры на эффективность возбуждения кильватерных волн последовательностью сгустков релятивистских электронов. В экспериментах использовалась диэлектрическая структура круглого поперечного сечения с диэлектриком из фторопласта ($\varepsilon = 2{,}1$; $\mathrm{tg}\delta = 2\cdot10^{-4}$). Плазма в канале диэлектрической структуры образуется при прохождении сгустков релятивистских электронов через нейтральный газ в результате ударной ионизации и ускорения электронов плазмы в поле возбуждаемой кильватерной волны. Показано, что при давлении газа в диапазоне 10^{-2}…1 Торр наблюдается увеличение амплитуды возбуждаемого кильватерного поля в результате изменения топографии основной электромагнитной моды. В диапазоне давлений 0,1…1 Торр наблюдается фокусировка электронных сгустков, обусловленная нахождением сгустков в тормозящем суммарном продольном поле электромагнитной и ленгмюровской волн и одновременно в фокусирующем поле ленгмюровской волны.

ЗБУДЖЕННЯ КІЛЬВАТЕРНИХ ХВИЛЬ У ПЛАЗМОВО-ДІЕЛЕКТРИЧНИХ СТРУКТУРАХ ПОСЛІДОВНІСТЮ ЗГУСТКІВ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ

В.О. Кисельов, А.Ф. Лінник, І.М. Оніщенко, В.І. Приступа, Г.В. Сотніков, Г.П. Березіна

Представлені результати теоретичних і експериментальних досліджень впливу плазми в каналі діелектричної структури на ефективність збудження кільватерних хвиль послідовністю згустків релятивістських електронів. В експериментах використовувалася діелектрична структура круглого поперечного перерізу з діелектриком з фторопласту ($\varepsilon = 2{,}1$; $\mathrm{tg}\delta = 2\cdot10^{-4}$). Плазма в каналі діелектричної структури утворюється при проходженні згустків релятивістських електронів через нейтральний газ у результаті ударної іонізації і прискорення електронів плазми в полі кільватерної хвилі, яка при цьому збуджується. Показано, що при тиску газу в діапазоні 10^{-2}…1 Торр спостерігається збільшення амплітуди збуджуваного кільватерного поля в результаті зміни топографії основної електромагнітної моди. У діапазоні тисків 0,1…1 Торр спостерігається фокусування електронних згустків, обумовлене знаходженням згустків у гальмуючому сумарному поздовжньому полі електромагнітної і плазмової хвиль і одночасно в фокусуючому полі плазмової хвилі.