# WAKEFIELDS EXCITATION IN PLASMA, PRODUCED BY A SEQUENCE OF ELECTRON BUNCHES IN NEUTRAL GAS, ACCELERATING AND FOCUSING ELECTRONS BY THEM

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Experiments on wakefield excitation by a long sequence of relativistic electron bunches in plasma, formed by head bunches of the same sequence in neutral gas of various pressure are presented. The ranges of pressure are found, in which beam-plasma discharge is developed, that leads to intensification of plasma generation. Acceleration and focusing of bunches electrons that is determined by ratio of the bunch length to its diameter and detuning between bunches repetition frequency and wakefield frequency, are investigated.

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## 1. INTRODUCTION

Acceleration of charged particles by wakefields excited in plasma by a relativistic electron bunch or a sequence of bunches, is a promising method to accelerate electrons with the acceleration rate of several orders of magnitude higher than used in conventional accelerators [1-3]. Besides wakefields provide focusing of the accelerated electrons by orders of magnitude greater than focusing by magnetic systems [4].

In this paper we study the excitation of wakefield in plasma by a long sequence of bunches as they pass through the neutral gas at different pressures, unlike to [1], where plasma was produced by a plasma gun. We have previously shown [5] that during the injection of a sequence of bunches in the neutral gas at atmospheric pressure plasma is created with the resonant density, for which the plasma frequency $\omega_p$ coincides with the frequency of bunches $\omega_m$. We study the acceleration and focusing of electron bunches by excited plasma wakefield in the presence of detuning $\Delta\omega = \omega_p - \omega_м$ arising from the change plasma density. To enhance the focusing effect bunches were made of elongated shape by means of aperture, that led, as we have shown in [6], to the prevalence of radial component of the wakefield [7].

## 2. EXPERIMENTAL SETUP

Experimental study were carried out with setup, scheme of which is shown in Fig.1

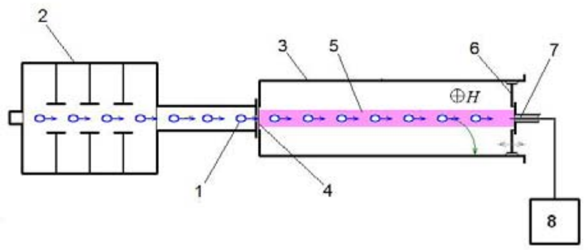



*Fig. 1. 1 – sequence of bunches , 2 - electron accelerator, 3 – interaction chamber, 4 - diaphragm, 5 - plasma column, 6 - movable plug, 7 - microwave probe, 8 – oscilloscope*

Relativistic electron beam produced by a linear resonant accelerator. Beam parameters: energy – 4.5 MeV, pulsed current – 0.5 A, pulse duration – 2 µs, modulation frequency – 2805 MHz. Each pulse consists of $6\times10^3$ bunches with a duration of each one – 60 ps and the time interval between them – 300 ps. Beam diameter at the exit from the accelerator 10 mm, bunch length – 17 mm, charge of bunch – 0.16 nC.

Beam was injected into a rectangular waveguide of cross-section (72×34) $mm^2$ and length of 25 cm. Neutral gas pressure in the waveguide can be varied from 760 to $5\times10^{-2}$ Torr. As the neutral gas was air. The waveguide was pumped through the pipe, and was filled with neutral gas through the leak. When closing the exit end of the waveguide with a metal plate in the center of which the probe was mounted, the cavity was formed. To measure the beam current passing through the waveguide, the probe was replaced by Faraday cup with a diameter of 15 mm. The energy loss of electrons bunches were determined using a magnetic analyzer. The transverse size of bunches was estimated by the beam portrait on a glass plate.

## 3. RESULTS OF EXPERIMENT

### 3.1. EXCITATION OF WAKEFIELD

The dependence of the amplitude of Ez-component of the excited wakefield on neutral gas pressure is shown in Fig. 2 (curve 1). Two ranges of pressure was observed - $10^{-2}$…10 and 400…760 Torr, in which the intense wakefield are excited. In these ranges more efficient generation of plasma is explained by fact that in addition to collisional ionization of the gas a beam-plasma discharge (BPD) is developed. In the first range there is an avalanche-like increase of the plasma density in the microwave field of beam-plasma instability (classic BPD) is developed. Unlike classic ERP using beams with energies of tens of keV and observed at gas pressures of $10^{-3}$…$10^{-4}$ Torr, in our experiments with a beam of 4.5 MeV this pressure range is shifted to higher pressures. This is due to a decrease in the ionization cross-section for the electron beams of relativistic energies, that requires a higher density of gas to generate the critical plasma density, at which BPD starts developing. In the second area of higher pressure collisional ionization is intensified, as well as BPD is developed on the base of beam-dissipative instability. In both ranges, the growth of plasma density stabilizes at a level when resonance of frequency of bunches repetition and plasma frequency is satisfied ($\omega_p = \omega_m$).

Fig. 2 (curve 2) shows the change in the beam current which passed through the system and was measured by Faraday cup diameter of 1.5 cm. It is seen that the beam current, registered by Faraday cup, decreases in the pressure range where the wakefield amplitude increases. This decrease is the result of spread of the electrons by transverse component of the exciting wakefield.

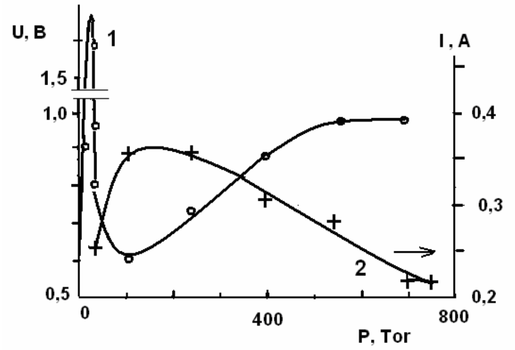
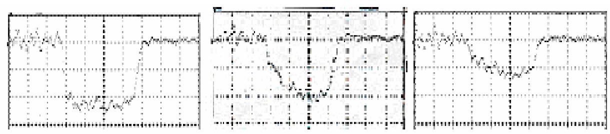



*Fig. 2. Dependence of amplitude of the Ez-component of the excited wakefield (curve 1) and magnitude of the beam current (curve 2) on neutral gas pressure*

In the pressure range where the amplitude of Ez-wakefield is small, it is required more time to reach resonant plasma density ωp ≈ ωм. It is concluded from oscillograms of Ez wakefield, shown in Fig. 3. At atmospheric pressure, the maximum amplitude of the excited wakefield is achieved in a short time. At pressure 300 Torr maximum field is achieved only by the middle of the current pulse (Fig. 3, b), and at pressure 40 Torr wakefield amplitude not at al reaches its maximum value (see Fig. 3, b).



*a* b c

*Fig. 3. Oscillograms of Ez-component of the excited wakefield at different pressures: a) 760 Torr, b) 300 Torr, c) 40 Torr*

The slow growth of wakefield and its small value in Fig. 3,b,c indicates that the plasma density is below the resonant value ωp ≈ ωм, i.e. there is a detuning between bunches repetition frequency ωм and plasma frequency ωp in this pressure range.

Detuning $\Delta\omega = \omega_p - \omega_m$ caused by change in the plasma frequency at plasma density reducing can be obtained both at a decrease in gas pressure, and at a decrease in the beam current.

**3.2. ACCELERATION BY WAKEFIELD**

The presence of the detuning leads to that part of the sequence of bunches, the shifting along phase, fall into the accelerating phase of the excited wakefield and take the energy of the wakefield excited by previous bunches. Electrons which lost their energy on wakefield excitation and the electrons accelerated by wakefield (up to 6 MeV) were observed using a magnetic analyzer, which is located at the waveguide exit (see electron energy spectra in Fig 4).

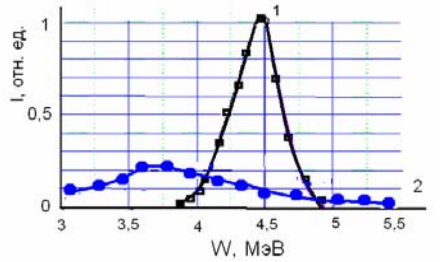
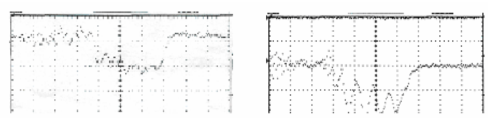



*Fig. 4. Energy spectra of electrons (1-input, 2-after interaction with plasma)*

**3.3. FOCUSING BY WAKEFIELD**

In the presence of detuning at pressure in the range from 200 to 40 Torr the various parts of the sequence of bunches, shifting on phase, are occurred in defocusing or focusing radial wakefield. Bunches, which fell in defocusing phase, radially diverse and do not reach the chamber exit. The passage focused bunches is improved. This leads to the beats of the beam current, registered by Faraday cup at the exit (Fig. 5, b). At atmospheric pressure (Fig. 5, a) the beats are absent because in this case there is no detuning.



*a* b

*Fig. 5. Oscilograms of beam current at chamber exit (a-250 Torr, b - 40 Torr)*

Studies of focusing were carried out at gas pressure f = 760 Torr for two cases: 1) the current $I_b$ = 0.5 A, diameter of the bunch *a* and its length *l* are comparable (*a* = 10 mm, *l* = 17 mm) and 2) the current $I_b$ = 0.25 A, diameter of the bunch appreciably less than its length (*a* = 10 mm, *l* = 17 mm). The second case was realized by diaphragming of the bunch and provided preferential excitation of the radial component of the wakefield. In the second case the current was decreased to create a detuning and moving of bunches along phase, and bunch shape was changed to emphasize the focusing effect.

Fig. 6 shows oscillogram of excited wakefield for the first case. It is seen that the amplitude of the excited field is growing during the whole pulse, that indicates that all bunches are in the decelerating phase of the excited field. At that, as it is evident from the measurements of beam diameter on the darkening of the glasses (Fig. 7), part of electrons of each bunch are in the focusing phase of the excited field and keep within the same transverse dimension, and the other part are defocused.

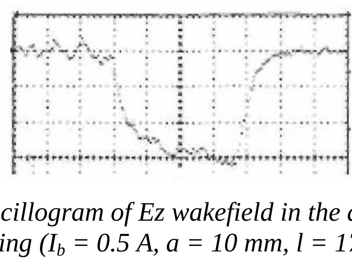


*Fig. 6. Oscillogram of Ez wakefield in the absence of detuning ($I_b$ = 0.5 A, a = 10 mm, l = 17 mm)*

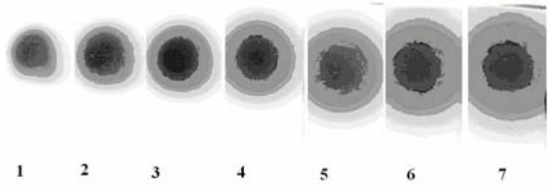



*Fig. 7. Beam diameter at different distances from the exit foil ($I_b$ = 0,5 A, a = 10 mm, l = 17 mm): 1)0 cm, 2) 5 cm, 3)7cm, 4) 9cm, 5)11cm, 6)13cm, 7)15 cm*

When reducing the beam diameter to 4 mm, accompanied by a decrease in the current two times, oscillograms of the wakefield showed beats (Fig. 8), which are connected with the fact that at decrease in current nonresonant plasma is created, that is caused by weakening ionization process.

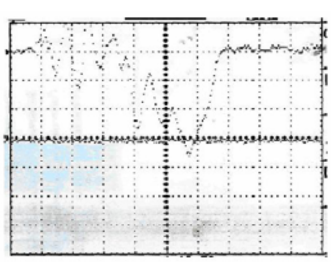


*Fig. 8. Oscillogram $E_z$ wakefield in the presence of detuning ($I_b$ = 0,25 A, a = 4mm, l = 17mm)*

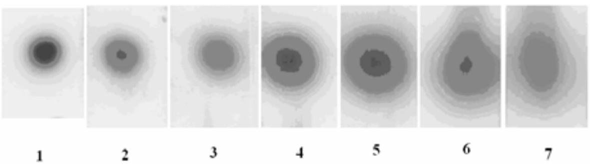



*Fig. 9. Beam diameter at different distances from the exit foil ($I_b$ = 0,25 A, a = 4 mm, l = 17 mm): 1)0 cm, 2) 5 cm, 3)7cm, 4) 9cm, 5)11cm, 6)13cm, 7)15 cm*

Appeared detuning leads to that various part of the sequence of bunches gets into focusing or defocusing phase of wakefield. This is proved by measurements of the bunches diameter on the darkening portraits on the glass plate (Fig. 9), on which is observed focusing and defocusing effect is observed.

## 4. CONCLUSIONS

1. Studies of wakefield excitation in plasma produced by a sequence of bunches of relativistic electrons as they pass through the neutral gas at different pressures have shown that there are two ranges of pressure – 400…760Torr and $10^{-2}$…10Torr, in which the maximum amplitude of the wakefield and plasma frequency is close repetition frequency of bunches.
2. The energy spectrum of electrons at exit shows both energy loss by exciting electrons and the tail of f accelerated electrons.
3. Focusing of bunches by excited plasma wakefield is investigated in the resonant case and in the case of detuning between the repetition frequency of bunches and plasma frequency.
4. The beats of wakefield amplitude and beam current associated with the detuning are revealed

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## ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНЫХ ПОЛЕЙ В ПЛАЗМЕ, ОБРАЗУЕМОЙ ПОСЛЕДОВАТЕЛЬНОСТЬЮ ЭЛЕКТРОННЫХ СГУСТКОВ В НЕЙТРАЛЬНОМ ГАЗЕ, УСКОРЕНИЕ И ФОКУСИРОВКА ИМИ ЭЛЕКТРОНОВ


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Представлены эксперименты по возбуждению кильватерных полей длинной последовательностью релятивистских электронных сгустков в плазме, образуемой головными сгустками этой же последовательности в нейтральном газе различного давления. Найдены области давлений газа, в которых развивается пучково-плазменный разряд, приводящий к интенсификации генерации плазмы. Исследованы ускорение и фокусировка электронов сгустков, определяемые отношением длины сгустка к его диаметру и расстройкой между частотой следования сгустков и частотой возбуждаемого кильватерного поля.


## ЗБУДЖЕННЯ КІЛЬВАТЕРНИХ ПОЛІВ У ПЛАЗМІ, ЯКА СТВОРЕНА ПОСЛІДОВНІСТЮ ЕЛЕКТРОННИХ ЗГУСТКІВ У НЕЙТРАЛЬНОМУ ГАЗІ, ПРИСКОРЕННЯ ТА ФОКУСИРОВКА НИМИ ЕЛЕКТРОНІВ


***В.О. Кисельов, А.Ф. Лінник, І.М. Онищенко, В.І. Приступа***



Представлено експерименти по збудженню кільватерних полів довгою послідовністю релятивістських електронних згустків у плазмі, яка створена головними згустками тієї ж послідовності в нейтральному газі різного тиску. Знайдено області тиску газу, в яких розвивається пучково-плазмовий розряд, що приводить до інтенсифікації генерації плазми. Досліджені прискорення та фокусировка електронів згустків, які визначаються відношенням довжини згустку до його діаметру і розстройкою між частотою слідування згустків і частотою збуджуваного кільватерного поля.