EXPERIMENTAL AND THEORETICAL RESEARCHES OF A RESONATOR CONCEPT OF A DIELECTRIC WAKEFIELD ACCELERATOR

I.N. Onishchenko,V.A. Kiselev, A.F. Linnik, N.I. Onishchenko, G.V Sotnikov, V.V. Uskov
NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine
E-mail: onish@kipt.kharkov.ua

Wakefield excitation in a cylindrical dielectric waveguide or resonator by a regular sequence of electron bunches for application to high-gradient particle acceleration has been investigated theoretically and experimentally using an electron linac «Almaz-2» (4.5 MeV, 6.10^3 bunches of duration 60 ps and charge 0.32 nC each).

PACS: 41.75.Lx, 41.85.Ja, 41.60.Bq

1. INTRODUCTION

Along with laser acceleration in plasma and vacuum, a dielectric wakefield acceleration (DFWA) is one of the novel methods of high gradient acceleration of charged particles. Three issues arise in connection with intense wakefield excitation in a dielectric. A wakefield in a dielectric (Cherenkov radiation) excited by charged particles can be enhanced by using a regular sequence of relativistic electron bunches (multi-bunch operation) [1], an interference of many transverse modes to enlarge peak amplitude (multi-mode operation) [2], and a resonant accumulation of wakefield in a cavity resulting from many bunches (resonator concept) [3]. We wish to exploit the third approach while retaining working the other two. In the present work we attempt to clarify by theory and experiments the process of wakefield excitation in a cylindrical dielectric waveguide and resonator using a long sequence of relativistic electron bunches. The temporal evolution and spatial distribution of the excited wakefield are investigated by HF probes for both waveguide and resonator cases and comparison was made. Electron energy loss measured by a magnetic analyzer and the total energy of the excited HF wakefield measured by a calorimeter were compared to determine the energy balance.

2. THEORY

For a semi-infinite dielectric waveguide the problem of wakefield excitation was solved analytically [4]. There are two new peculiarities compared to the case of the infinite waveguide: an appearance of transition radiation and wakefield removal with group velocity from the waveguide entrance. As a result, the net field amplitude grows from the entrance to the trailing edge of the first bunch field and then decreases to the position of the first bunch. The field amplitude at a given cross-section grows and after the passage of several bunches it saturates; however, the saturation level does not depend on the total number of bunches but is determined by the distance to the entrance.

The more complicated problem with a hole for the bunches was solved in cylindrical geometry for a waveguide of finite length [5] and for a resonator [6]. Due to wakefields moving along the system with group velocity, the number of bunches whose wakefields can be coherently added giving maximum amplitude at the waveguide exit, is restricted in the first case by

$$N_{\max} \approx 1 + L/\Delta z\left(v_0/v_g - 1\right), \qquad (1)$$

where L is a waveguide length, Δz is a distance between bunches, v_0 and v_g are the bunch velocity and group velocity, respectively. The presence of the hole results in an appearance of oscillations with the group velocity of light in vacuum. These oscillations move ahead of bunch and form a weak field precursor. For the resonator, a single bunch excites a multibunch wakefield which is the same as the field in a semi-infinite waveguide [4] until it is reflected from the resonator exit. Excitation by a sequence of bunches results, first in the excitation of only the resonant fundamental mode, the frequency of which coincides with the bunch repetition frequency (mode-locking) and, secondly, in the linear growth of the field amplitude with time in proportion to the number of injected bunches. The saturation level is determined by a nonlinear electron-wave interaction for the NSC KIPT experiment with 4 MeV bunches [6]. It might be supposed that for higher energy (e.g. an experiment with 0.5 GeV bunches) the saturation could be caused the Q-factor of the resonator.

To demonstrate both multimode and multibunch regimes in a resonator case, a rectangular dielectric resonator (still without a vacuum channel) which provides equidistant resonant modes, was theoretically investigated [7]. It was shown that multimode operation is realized under the condition:

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

i.e., the length of the resonator L should be a multiple N of half-integer wave lengths of the resonant fundamental mode; a is the transverse size; the other transverse size b is supposed much larger, ε is the permittivity. For coherent summing of wakefields from injected bunches the coincidence of the fundamental mode frequency and the frequency f of bunch repetition should be fulfilled. This condition sets the transverse size of the resonator

$$a = v_0/2f\sqrt{\beta_0^2\varepsilon - 1}. \qquad (3)$$

Conditions (5) and (6) are the basis of the resonator concept of the rectangular DWFA.

3. EXPERIMENT

Experiments to study the excitation of wakefields in a cylindrical dielectric structure (waveguide or resonator) were performed using the linear resonant electron accelerator "Almaz-2" at the NSC KIPT.

3.1. EXPERIMENTAL SETUP

The scheme of the installation is described in [8]. An electron beam had the following parameters: energy 4.5 MeV, current 0.5 A, impulse duration 2 μsec, modulation frequency 2820 MHz. Therefore, we had a regular sequence of $6 \cdot 10^3$ bunches, 60 ps duration each spaced by 300 ps. The diameter and length of each bunch were 1.0 cm and 1.7 cm, respectively.

This sequence of electron bunches was injected into a dielectric structure made from Teflon (permittivity $\varepsilon = 2.1$, $\mathrm{tg}\delta = 1.5 \cdot 10^{-4}$ at a frequency $f = 3 \cdot 10^9$ Hz). The length of the dielectric structure was varied up to 65 cm, the outer diameter was 8.6 cm and the diameter of the hole was 2.2 cm. The dielectric structure was placed into a copper tube of length 100 cm.

3.2. WAKEFIELD SPATIAL DISTRIBUTION

The transverse topography of the excited field is found to be almost azimuthally symmetric. The radial dependence of the E_r – component of the field shows a small value on the axis and a maximum near the tube wall. The radial dependence of the longitudinal E_z – component shows a maximum it on the axis and a small value near the wall. Such topography of the excited field demonstrates that in the present experiment E_{0n} – waves are excited. Beyond-cutoff waveguides were used to estimate the contribution of higher radial modes. It was found that their total contribution is less than half of the fundamental mode. This result confirms theoretical conclusion [5] that a coincidence of the bunch repetition frequency with the fundamental frequency but not with the difference frequency between the non-equidistant frequencies of the higher modes results in survival of the resonant fundamental mode and suppression of the other modes.

The longitudinal distribution of the excited fields in the waveguide of finite length was measured in the following way. The dielectric structure was cut into several pieces of various length (1, 2, 5, and 10 cm) and the electric field was measured at exit of the structure, which is composed of a number of dielectric pieces to assemble the required length. The results of measurements of E_z after passing of $6 \cdot 10^3$ bunches are depicted in Fig.2 (curve 1). A linear growth of amplitude of the longitudinal component of the field along the dielectric waveguide was observed. This proves the theoretical result [5] according to which at the time when N_{max} bunches have passed through the structure a linear stationary longitudinal distribution of E_z has been established.

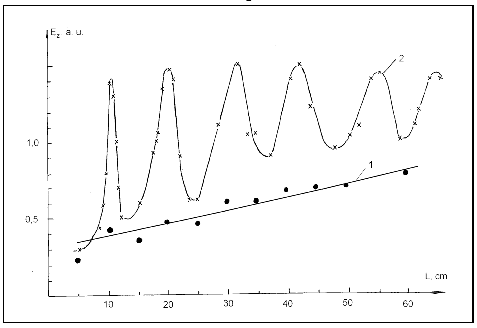


Fig.2. E_z dependence on dielectric length

In the case of the resonator, the longitudinal distribution of E_z obtained by measuring E_z at the exit end of each dielectric insertion consisting of a certain number of pieces is shown in Fig.2 (curve 2). As seen from Fig.2, the resonator electric field amplitude is larger than for the waveguide. Besides, the longitudinal dependence has a resonant character. Accumulation of wakefield in a dielectric resonator of appropriate length was proposed in [3] with the aim of enlarging the number of coherently contributing bunches. If the amplitude is proportional to the number of contributing bunches, we conclude that the resonator allows one to increase the number of contributing bunches approximately 4 times for length 10 cm and 2 times for length 65 cm. Resonant behavior is explained by the effective excitation at a coincidence (multiplicity) of resonator and bunch repetition frequencies.

3.3. WAKEFIELD TEMPORAL EVOLUTION

To determine the increase in the number of coherently contributing bunches for the resonator case, we changed the duration of the beam current macro-pulse. This was achieved by using a time delay of the HF-pulse of the master oscillator of the klystron feeding the linac, with respect to the high voltage pulse applied to the klystron. This results in beam duration in the range $\tau = 0.1 \ldots 2.0$ μsec without changing other beam parameters. In this way we could compose trains with a number of bunches $3 \cdot 10^2$ up to $6 \cdot 10^3$.

The results of measuring the dependence of the excited field amplitude upon beam pulse duration, i.e., upon the number of bunches, are shown in Fig.3 at a dielectric length 30 cm. It is seen that for the waveguide case (curve 1) the amplitude achieves saturation caused by the group velocity effect [4,5] at a time <0.1μsec (i.e. N_{max}<300). According to theory (1) for experimental conditions $v_0 / v_g = 2$, $N_{max}^{theory} = 3$. For the resonator case (curve 2) the saturation time is much longer and occurs at 0.3μsec (i.e. N= 900 bunches). The number of contributing bunches in the waveguide case can be estimated from Fig.2 by amplitudes ratio 4 for L=30 cm, and it makes N_{max} =225. This greatly exceeds the theoretical value and such a discrepancy must be explained in further research. Also, the physical mechanism of amplitude saturation is not revealed yet. Provisionally, we suppose that for low electron energy the reason for saturation is a nonlinear particle-wave interaction, but for super-relativistic bunches it might be the Q-factor. For smaller beam current 0.25 A (curve 3) the amplitude grows slower and does not achieve saturation.

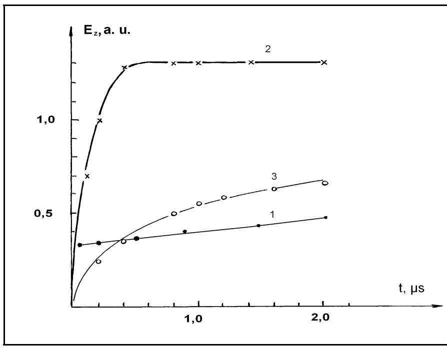
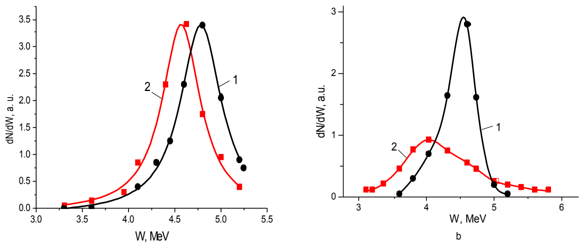


Fig.3. E_z dependence on pulse duration

3.4. ENERGY LOSS OF ELECTRON BUNCHES

To find the dependence of bunch energy loss on wakefield excitation, an electron energy spectrum was measured by magnetic analyzers at the accelerator exit (initial spectrum) and after passing the dielectric structure at a distance 100 cm from the linac exit (spectrum after excitation). In Fig.4 initial spectrum (curve 1) and spectrum after excitation (curve 2) for a dielectric length of 65 cm are presented. We find that the electron energy loss is 3% for waveguide (Fig.4,a) and 12% for resonator (Fig.4,b). For the resonator case accelerated electrons are observed.



a b

Fig.4. Electron energy spectra

3.5. CALORIMETER MEASUREMENTS

The total energy of excited wakefields was measured by a specially constructed sensitive calorimeter [9]. Electron bunches were deflected by a magnetic field or passed through a hole in the calorimeter. It was found that the total excited energy in the waveguide case is 1.4% of the initial beam energy. The dependence upon the number of bunches in the train is similar to one observed in amplitude measurements (Fig.3, curve 1). To explain this discrepancy of the calorimeter data with respect to the energy spectrum loss, we measured the damping of an excited field in the metal tube. It occurred 3 dB, i.e., 2 times. Thus we conclude that the entire beam energy loss of about 3% is expended on wakefield excitation, within reasonable energy balance.

CONCLUSIONS

1. The radial topography of excited wakefields was studied and it was established that the excited modes are predominantly of E_{0n}-type.

2. By changing the number of bunches it was shown that in the waveguide case the wakefield amplitude is built up by a small number of bunches (less 300), that is explained by a wakefield removal with group velocity.

3. The resonator concept was verified, so that at right choice of resonator parameters and bunch repetition frequency, more bunches contribute coherently and the amplitude of the wakefield grows considerably.

4. The electron energy spectra for waveguide and resonator cases were measured, from which it was concluded that for an electron energy of 4.5 MeV and current 0.5 A, and dielectric length of 65 cm, the energy loss during the interaction was 12% for the resonator and 3% for the waveguide.

5. Calorimeter measurements were found to be in agreement with results from the HF-probes and allow one to determine the overall excited wakefield energy.

Research supported by CRDF UP2-2569-KH-04 and Ukr DFFD 02.07/325.

REFERENCES

1. I.N. Onishchenko, V.A. Kiseljov, A.K. Berezin et al. Proc. of the PAC. New York. 1995, p.782.
2. T.B. Zhang, J.L. Hirshfield, T.C. Marshall, B. Hafizi // *Phys. Rev*. 1997, E56, p.4647.
3. T.C. Marshall, J.-M. Fang, J.L. Hirshfield, S.J. Park. AIP Conf. Proc. 2001, №569, p.316.
4. I.N. Onishchenko, D.Yu. Sidorenko, G.V. Sotnikov // *Phys. Rev.* 2002, E65, p. 066501-1-11.
5. N.I. Onishchenko, D.Yu. Sidorenko, G.V. Sotnikov // *Ukr. Fiz. Zh.* 2003, v.48, p.16.
6. V.A. Balakirev, I.N. Onishchenko, D.Yu. Sidorenko, G.V. Sotnikov // *Technical Phys. Lett*. 2003, v.29, №7, p.589.
7. N.I. Onishchenko, G.V Sotnikov. Coherent summation of wake fields excited by electron bunch sequence in planar multimode dielectric resonator // this issue, p.73-75.
8. V.A. Kiselev, A.F. Linnik, I.N. Onishchenko et al. The experimental stand for research of wakefield method of charged particles acceleration // this issue, p.76-78.
9. V.A. Kiselev, A.F. Linnik, I.N. Onishchenko, V.V. Uskov // *Instruments and Experimental Techniques.* 2005, №2, p.103-106.

ЭКСПЕРИМЕНТАЛЬНЫЕ И ТЕОРЕТИЧЕСКИЕ ИССЛЕДОВАНИЯ РЕЗОНАТОРНОЙ КОНЦЕПЦИИ КИЛЬВАТЕРНОГО ДИЭЛЕКТРИЧЕСКОГО УСКОРИТЕЛЯ

И.Н. Онищенко, В.А. Киселев, А.Ф. Линник, Н.И. Онищенко, Г.В. Сотников, В.В. Усков

Исследовано возбуждение кильватерных полей в цилиндрическом диэлектрическом волноводе или резонаторе регулярной последовательностью электронных сгустков для целей высокоградиентного ускорения частиц как теоретически, так и в эксперименте на линейном электронном ускорителе «Алмаз-2» (4,5 МэВ, $6 \cdot 10^3$ сгустков длительностью 60 пс и зарядом 0,32 нКл каждый).

ЕКСПЕРИМЕНТАЛЬНІ ТА ТЕОРЕТИЧНІ ДОСЛІДЖЕННЯ РЕЗОНАТОРНОЇ КОНЦЕПЦІЇ КІЛЬВАТЕРНОГО ДІЕЛЕКТРИЧНОГО ПРИСКОРЮВАЧА

І.М. Оніщенко, В.О. Кисельов, А.Ф. Лінник, М.І. Оніщенко, Г.В. Сотніков, В.В. Усков

Досліджено збудження кільватерних полів у циліндричному діелектричному хвилеводі або резонаторі регулярною послідовністю електронних згустків для цілей високоградієнтного прискорення часток як

теоретично так і в експерименті на лінійному електронному прискорювачі «Алмаз-2» (4,5 МеВ, $6 \cdot 10^3$ згустків тривалістю 60 пс і зарядом 0,32 нКл кожний).