TO THE PROBLEM OF WAKE-FIELD EXCITATION FOR ADVANCED ACCELERATOR CONCEPT

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Abstract

Theoretical investigations, simulation, performed and planned experiments on basing and proving of the novel concept of particles acceleration that uses localized Cherenkov radiation of the relativistic electron bunches in dielectric waveguide are overviewed. Principles of the novel two-beams acceleration scheme are reduced to use: a – multimode character of excited Cherenkov radiation in dielectric waveguide, giving in localization and increasing of wake fields; b – regular sequence of bunches (multi-bunch operation), providing summation of wakefields of coherently radiating bunches; c – "resonator" model analogous to locked mode with an optical key in laser problem that allows to overcome restriction on number of coherently radiating bunches.

INTRODUCTION

Classical Vavilov - Cherenkov radiation [1-3] usually considered for the case of infinite dielectric medium [4], manifests essential peculiarities for the case of boundedness of the dielectric medium [5]. Peculiar features of this radiation caused by longitudinal and transversal boundedness of dielectric occur important for the problem of wake field method of charged particles acceleration, namely for wakefields excitation in bounded dielectric by superlight electron bunch or regular sequence of bunches [5]. It is supposed that driving bunch excites wake field in dielectric, and particles to be accelerated are located in accelerating phase of this field.

Acceleration by high intensity wakefields excited by a relativistic electron bunch of large charge [6] or by a short intense laser impulse [7] is considered firstly in plasma as the most perspective method among novel methods of charged particles acceleration, allowing to create high-gradient (10^6 - 10^7 V/cm) accelerators of new generation. Simultaneously the study of analogous processes in dielectric was carried out too. In contrast to plasma dielectric has one important key advantage caused by its electrodynamics properties. So in dielectric waveguide all radial modes are synchronous with moving relativistic particle and consequently are excited on Cherenkov resonance («multimode» excitation). Arising behind electron bunch dielectric wake field as a result of addition of all excited radial modes looks like a sequence of the localized short impulses (peaks) of opposite sign and large amplitude. In plasma waveguide only the principal radial eigen mode is excited; because the other radial modes have a phase velocity smaller than particle velocity.

For excitation of the intense dielectric wakefields it is necessary to use a large charge of driving electron bunch. It can be achieved, as well as in a plasma case, using the equivalent replacement of the bunch with large charge by a sequence of bunches with much smaller charge of each bunch («multi-bunch» excitation) [8]. Repetition rate of bunches should coincide or multiple with frequency of following of excited local peaks of Vavilov - Cherenkov radiation. In this case, besides increasing of wakefields amplitude due to multimode excitation, there will be an additional growth of amplitude of the wake field, caused by coherent addition of fields of separate bunches.

Additional advantage of the dielectric alternative is the opportunity of manufacturing of knots from dielectric as solid body with micron precision that is especially important at modularity.

The basic deficiency of the scheme with the dielectric wakefields is the breakdown in dielectric at rather low electric fields. Results of theoretical investigations [9] of dielectric breakdown are encouraging at very short impulse duration of applied voltage. At impulse duration in femtosecond range, (namely such duration are characteristic for wakefields in a dielectric), field gradient, not giving to breakdown by tunnel ionization, can attain 1 GeV/m. Another serious problem in the considered scheme of generation of high gradient wakefields is transversal instability of bunches [10], so-called instability "head-tail" at which the transversal electric field of wake wave, excited by the previous bunches, throws out the subsequent bunches and/or accelerated bunches on waveguide walls. For overcoming this difficulty it is necessary to use external systems of alternating focusing/defocusing quadruples.

EXPERIMENTAL INVESTIGATIONS OF DIELECTRIC WAKEFIELD ACCELERATOR CONCEPT

Use of dielectric in wake field method of charged particles acceleration began rather recently [11-15]. The experimental confirmation of wakefields excitation in dielectric lined metal waveguide is performed in [11] at use 21 MeV driving bunches with charge 2.0-2.6 nC and 15 MeV test bunches with much smaller charge. Accordingly to the theory in this experiment accelerating gradient 0.3-0.5 MeV/m were observed. For obtaining higher amplitude it is proposed [12] to take the larger charge of bunch (100 nC, length 1 mm), propagating through the waveguide covered inside with dielectric (inner radius of 2.0 mm, outer radius of 5.0 mm, permittivity 3.0). It is predicted, that peak wake field will

achieve 240 eV/m, i.e. 14 times exceeding the field on SLAC.

Sequence of electron bunches

Coherent addition of wakefields from separate bunches at use of a sequence of bunches ("multibunch" operation) for the first time is proposed in [13,14] for the plasma wake field and it is shown, that excitation of a plasma wake field in this case is equivalent to excitation by one bunch with the aggregate charge of a sequence of bunches [14]. For the case of dielectric for the first time this problem was theoretically surveyed in [15], and experimentally explored in [16]. In experiment a train of bunches, received at 2 MeV linear electron resonance accelerator was used. A train consisted of 3-6 10^3 bunches, frequency of following of bunches was 2825 MHz, diameter of a separate bunch was 1.0 cm, length was 1.7 cm, number of electrons in each bunch was 2 10^9. Exterior and interior radii of the dielectric pipe of 70 cm length (3.5 cm and 1.1 cm, accordingly) were chosen so that frequency of wake field peaks coincided with frequency of following of bunches. Judging by increasing of radiation intensity and electric field in dielectric waveguide with increasing of number of bunches the conclusion about coherent addition of the fields excited by separate bunches was made. It proves to be true also measuring of an energy loss of electrons (up to 500 кeV) depending on number of transit bunches. The electrons accelerated in excited fields were observed. It was the additional evidence of presence of excited wake fields.

Multimode operation

In [17] the theory of dielectric wakefields excitation, showing both specified advantage - "multimode" and "multibunch" operation – for the plane geometry (the sheet beam propagates between two dielectric plates) is given. For one bunch the sequence of the alternating peaks wakefields is received. The amplitude of peaks linearly grows with increasing of number of bunches in a sequence. An excited spectrum is close to equidistant. As shown in a general view for collinear acceleration in wakefields [18], for such spectrum "transformation ratio" (i.e. the ratio of wake field to decelerating field in the bunch) can exceed value 2. This question is for the present unclosed and discussed in [19]. The experimental verification of the theory of "multimode" excitation is carried out in [20] for cylindrical geometry (the dielectric pipe in length of 110 cm with exterior and interior diameters 33 mm and 9 mm, accordingly) with 6-MeV 10-nC per bunch. Four excited eigen frequencies (23, 27, 31, and 35 GHz) close to theoretically calculated ones are measured. In cylindrical case explored in [21,22] it is shown that wakefields localization in this geometry is less expressed and promptly comes to stochastic behavior. It is caused in particular by nonequidistance of eigen frequencies for round geometry. For this reason the rectangular geometry of the waveguide should be chosen providing both equidistance of eigenfrequencies and the finite transversal sizes of waveguide that is peculiar to experiment.

TRANSITION RADIATION

The longitudinal boundedness present at actual experiments, gives in not less important aftereffects at dielectric wakefields excitation. In [5,23] for cylindrical semi-infinite dielectric waveguide and for rectangular semi-infinite dielectric waveguide [24] the influence of input boundary on process of wake field excitation is investigated. Two important effects are detected and explored. First of them is caused with excitation of transition radiation by electrons at waveguide input. This radiation distorts precision structure of accelerating wakefields and, hence, is parasitic. It is possible to avoid its negative influence, using a coherence of excitation of wakefields at multimode and multibunch operation with no coherence for the transition radiation. The second effect concludes to a removal of excited radiation with group velocity from input boundary. It means, that beginning from some amount of bunches the next bunch "does not find" on an inlet the field excited by the first bunch, etc. As a result in coherent summation of the fields of separate bunches restricted number of bunches take part. The amount of bunches is determined by a difference between velocity of a bunch and group velocity of excited modes. For actual conditions it gives in restriction of wakefields intensity.

RESONATOR CONCEPT

To overcome this essential difficulty the resonator concept is proposed [25]. The essence of the proposition consists in use of the resonator, i.e. presence of a reflecting boundary between which wake field impulse is trapped and oscillates, being excited by a sequence of short bunches. Parameters of the resonator are chosen so that the period of wake field peaks coincided with distance between bunches and the length of the resonator is equal to a half-integer or multiple of wakefields period. In this situation wake field of moving bunch will be propagates in the resonator behind a bunch, and after reflecting from exit will come to the input plane just at the moment when the next bunch enters the resonator. Thus the "memory" from a previous bunch at high Q-factor of the resonator remains for a long time, providing coherent addition of fields of large number of bunches. Wakefields remain well generated since behind exclusion of the lowest mode the length of the resonator is almost aliquot to a half-wave of each mode. As a result of such type the device represents the laser resonator with the locked mode, supplied with bunch as "optical key". Simulation [25] has shown that wakefields are reflected from boundaries and their amplitudes increase with increasing of amount of bunches. The resonator concept allows using modular system. By ideal scenario if we take a train of 105 MeV bunches each of charge 1 nC and distance between bunches of 10.5 cm and inject it in the resonator of length 10.5 cm which parameters are chosen so that

periodicity of wake field in resonator also was 10.5 cm then each bunch will lose about 100 MeV as due to simulation decelerating field was 0.95 MeV/m. Test bunches to be accelerated were located in the middle between driving bunches. Energy increasing on 100 MeV at charge 1 nC each of them would absorb the energy 0.1 J. Acceleration of a test bunch up to 1 TeV would need 10^4 modules.

As in real experiments for transmission of bunches the channel in dielectric is necessary, solutions of all numbered electrodynamics problems with a channel becomes actual. In resonator concept it was made in [26,27] where channel influence on intensity and topography of wakefields is taken into account, and also process of acceleration of test electrons is surveyed.

RECTANGULAR GEOMETRY

The rectangular geometry explored in [24], is represented actual in connection with the unique micron scale design [28] of accelerator based on the dielectric wakefields and developed in Universities of Columbia and Yehl and Omega-P, Inc. The essence of it consists in the following. The new accelerator LACARA [29] created in BNL, based on acceleration of 50 MeV pulsed electron beam by the wave of 1 TW CO_2 (10.6-µm) inside of solenoid (2 m, 6 T). In result it is gained 100 MeV rotating electron bunch about 3 % by energy spread and duration 1 psec with frequency of the laser, carrying out one revolution for 35 fsec. At output in beam stopper the channel displaced from an axis cuts out a short impulse of a beam that allows receiving during one impulse of the laser 30 microbunches of 3.5 fsec duration and a charge 1-3 pC each. With the help of magnetic quadrupoles microbunches are converted to bunches of almost rectangular cross-section 10-µm × 150-µm. However for obtaining smaller emmitance (1 mm-mrad) of the beam it is supposed to use 500 MeV electron bunch from the linear resonance accelerator with superconducting resonator structures, and 5 TW CO_2 laser to apply only to "cutting" 1-µm 1-pC microbunches. Such train of microbunches is injected in the planar dielectric waveguide where summation wakefields of separate microbunches gives in accelerating rates more than 1 GeV/m. At energy of driving bunch 500 MeV the elaboration of TeV accelerator demands about 1000 modules.

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