CONCEPT OF DIELECTRIC WAKEFIELD ACCELERATOR DRIVEN BY A LONG SEQUENCE OF ELECTRON BUNCHES*

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Abstract

It is considered the scheme of a new type of a collinear two-beam accelerator based on the wakefield excitation in a rectangular dielectric resonator by a sequence of relativistic electron bunches and acceleration those bunches from the same sequence, that are occurred in accelerating phases of the excited wakefield due to the introduction detuning between the bunch repetition frequency and the fundamental transversal mode of excited wakefield.

INTRODUCTION

Particle accelerators, as unique tools for solving the frontier high energy physics problems, possesses excessive sizes and cost that requires great efforts and large financial expenses for their building. Discovery of a new particle - the Higgs boson, crucial in determining the consistency of the standard model, - requires a focus on the creation of Higgs factory, based on the collider with the necessary energy and luminosity of the colliding beams. If basing on traditional methods of acceleration, such colliders are also large in size and high in cost. This motivates research and development aimed at finding and implementing new methods of high-gradient acceleration into accelerator physics and technology to decrease the collider size. Promising of these is the acceleration in the wakefield excited in plasma or dielectric structure by intensive bunch or a powerful laser pulse.

This paper discusses the concept of the electron accelerator based on the acceleration with the wakefield excited in a dielectric structure by a regular sequence of relativistic electron bunches. By accelerating rate dielectric wakefield methods are intermediate (more than 1 GeV/m) between traditional methods with metal structures (less than 0.1 GeV/m) and plasma wakefield method (up to 100 GeV/m).

To increase the amplitude of the accelerating wakefield it is proposed to use together three approaches:

- "multi-bunch" scheme [1,2] is to increase the wakefield due to the coherent summation of the wakefields of the individual bunches of the sequence;
- "multi-mode" scheme [3,4] is to increase the wakefield due to the summation of many equidistant transverse modes of the wakefield excited in the dielectric structure of rectangular cross-section;
- "resonator" scheme [5,6] is to increase the wakefield due to the use of the resonator, which provides energy accumulation of excited wakefields for the whole sequence of bunches, i.e. allows avoiding transport of energy away from the structure with the group velocity [7,8], which limits the number of bunches, which wakefields build-up leads to the total wakefield increase.

To solve the problem of bunches injection to accelerate with excited wakefields, it is provided to produce exciting and accelerated bunches from the same sequence by introducing the detuning between the bunch repetition frequency and the frequency of the fundamental eigenmode of the dielectric structure.

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"MULTI-BUNCH" SCHEME

We have firstly shown both theoretically and experimentally [1,2] that in the dielectric structure a regular sequence of short relativistic electron bunches, each of moderate charge, coherently excites the wakefield of the same amplitude as one bunch with an equivalent total charge, provided that the bunch repetition frequency coincides with the frequency of the fundamental mode of the structure. At that, for this frequency the phase velocity of the excited wave should be equal to the bunch velocity.

Figure 1 shows experimentally obtained [2] wakefield amplitude excited in cylindrical structure depending on the time, i.e. upon the number of bunches in the sequence with bunch repetition frequency f_b = 2.805 GHz.

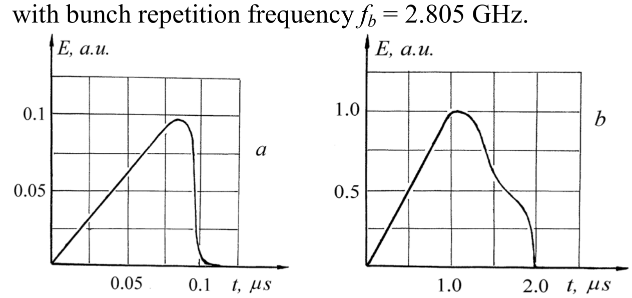

Figure 1: Oscillogram of envelope wakefield excited by a sequences of 300 bunches (a) and 6000 bunches (b).

It is visible (Fig. 1a) that for short duration (0.1 μs or 300 bunches) wakefields of all bunches are summarized coherently. For long duration (2.0 μs or 6000 bunches) the maximum number of bunches, which wakefields are summarized coherently, is equal to N_{max}=3000 bunches. The cease of amplitude growth is caused by possible mismatch of bunch repetition frequency and the wakefield frequency.

"MULTI-MODE" SCHEME

For cylindrical geometry in [1] the expression for a excited wakefields was shown containing the sum over transversal modes, however, the analysis of their summationon was not done. In [3] for plane geometry, in which excited modes are equidistant f_m=f_0(m+1/2), except

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the principal one with frequency f_0, the essential increase of wakefield amplitude was shown. Summation of such modes leads to "peaking" of the sinusoidal form of wakefield along with corresponding increase in its amplitude. For a Gaussian bunch of charge 2nC/mm, energy 30 Mev, length 3.0mm, and propagation distance 100 cm, the summation of 20 excited modes with a comparable amplitude leads to amplitude increase up to total field 5.5 MeV/m, and the wakefield form looks like a sequence of sharp alternating-sign peaks.

For a dielectric waveguide of rectangular cross-section, due to the vacuum channel for bunches, transversal modes are non-equidistant [4] unlike to the case of whole filling. Nevertheless the rectangular geometry possesses by better "equidistance", than cylindrical one with non-equidistant roots of Bessel functions. In the rectangular structure electron bunches excite wakefield, which can be presented in the form of the sum of LSM and LSE waves. Each of families of LSM and LSE waves consists of even and odd modes. At injection of electron bunches along the symmetry axis of the structure only odd modes are excited at which the E_z component of excited field on the axis is nonzero.

For the dielectric structures presented in Figure 2, dispersive dependences $f(k_z)$ for the first ten odd modes of LSM wave (Figure 3) are calculated [4]. The dielectric structure represents a copper rectangular waveguide of cross-section 8.5×18.0 cm^2, along the narrow or wide sides of which Teflon plates are placed. To provide Cherenkov resonance at bunch repetition frequency the thickness of plates are taken equal to 2.19 cm for structure of the 1st type and 1.67 cm for structure of the 2nd type.

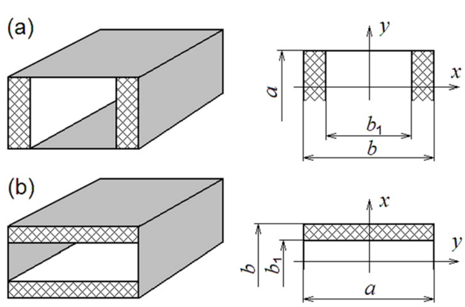

Figure 2: Waveguides with dielectric plates: (a) – along narrow (1st type); (b) – along wide walls of the waveguide (2nd type).

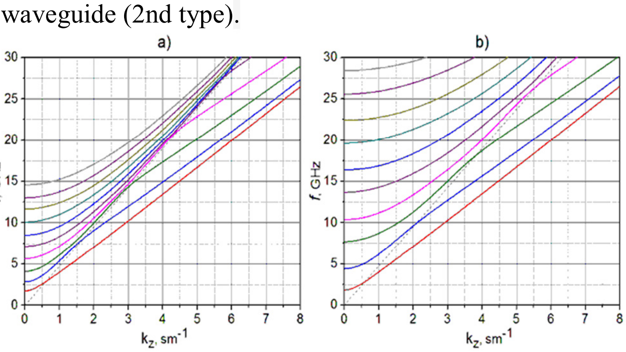

Figure 3: Dispersion curves of rectangular dielectric structures of the 1st type (a) and the 2nd type (b).

As it is seen from Figure 3, the distances between dispersive curves for case of structure of the 1st type is less than the distance for case of structure of the 2nd type. Therefore at wakefield excitation by a bunch of the finite length, determining the excited frequency range, it can expect that in the first case the more amount of almost equidistant modes will be excited and, therefore, the total amplitude of wakefield should be higher.

"RESONATOR" SCHEME

For the semi-infinite waveguide case the wakefield excited by a bunch, injected at waveguide entrance, consists of the transition radiation, Cherenkov radiation in infinite waveguide and so-called "quenching" wave [7,8]. The essence of the latter is that the excited field propagates in the waveguide with a group velocity so the wakefield behind the bunch looks like wakefield train of the length determined by a difference of phase velocity v_p, equal to bunch velocity v_0, and group velocity v_g of the excited wave. It leads to that not all bunches of the sequence give a contribution to a total field since beginning from the bunch number $N_{max}=1+L/\Delta z\cdot(v_0/v_g-1)$, where L is waveguide length, Δz is period of bunch repetition, the total field growth is stopped.

In "resonator" scheme [5,6] this problem can be overcome, and all bunches of a sequence give an identical contribution to the growth in amplitude of the total wakefield, so it is increased proportionally to number of bunches N_b. To provide summation of wakefields of each bunch, summation of transversal modes and resonator modes, i.e. operation of all three schemes, fulfillment of resonant conditions is required, from which conditions at length and the transverse size of the dielectric resonator follow.

For the cylindrical resonator filled with dielectric of dielectric permeability ε its length has to be multiple to number of half waves of the fundamental mode and at resonator length $L_r = Na\sqrt{\beta_0^2\varepsilon-1}$, $\beta_0 = v_0/c$, where N is number of the longitudinal mode being in Cherenkov resonance with a bunch, a is resonator radius, longitudinal modes with $l=Nm$ automatically are equidistant that provides "peaking" of the wakefield and increase of its amplitude. For fulfillment of multi-bunch scheme the transversal size of the resonator should be chosen accordingly to the expression $a = v_0/2f_0\sqrt{\beta_0^2\varepsilon-1}$. For bunches of energy 4 MeV, bunch repetition frequency f_b=2.805 GHz, ε=2.1, N=3 we should have the resonator with L= 15.68 cm and a=5.05 cm.

In Figure 4 calculated eigen frequencies of the resonator with mentioned parameters and Cherenkov frequencies of the bunch (circles) are shown. It is visible that the longitudinal harmonic with $N=3$ (principal eigen mode) and all modes with $l=Nm$ are in Cherenkov resonance with the bunch.

Thus, the consistency of possible application of all three schemes for increase in amplitude of excited wakefield is shown.

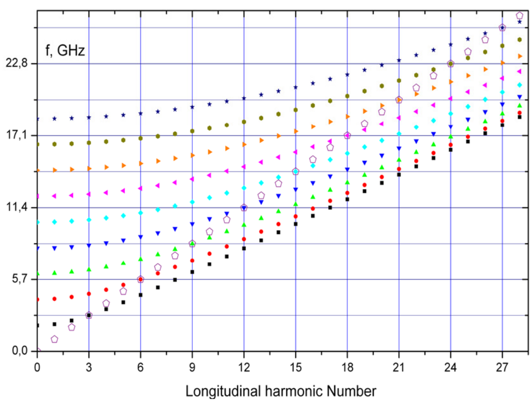

Figure 4: Resonator eigen frequencies for 9 transversal modes and Cherenkov frequencies of the bunch (circles) at parameters stated above.

SCHEME OF BUNCHES INJECTION TO BE ACCELERATED

Selecting of bunches to be accelerated from the same sequence is provided by frequency detuning Δf between bunch repetition frequency f_b and frequency of the fundamental resonant mode f_0 of the dielectric resonator, i.e. $\Delta f = f_b - f_0 \neq 0$. As a result, exciting and accelerated bunches turn out from the same sequence, and there is no need for a separate injector of accelerated bunches. For point bunches at detuning Δf number of exciting bunches is equal $N_{max}=(1/4)\times(f_b/\Delta f)$. The next portion of bunches will be occurred in accelerating phases.

CONCEPT OF DIELECTRIC WAKEFIELD ACCELERATOR

Considered above several separate approaches to enhance wakefield excitation and use it for high gradient acceleration allow to formulate a concept of dielectric wakefield accelerator based on a long sequence of relativistic electron bunches to unite all mentioned approaches.

The scheme of wakefield dielectric accelerator realizing three schemes, – “multi-bunch”, “multi-mode”, and “resonator”, - for increase in amplitude of excited wakefield and the scheme of frequency detuning for selecting accelerated bunches from the general sequence, is presented in Figure 5.

A sequence of $6{\cdot}10^3$ electron bunches (each of energy 4.5 MeV, charge 0.16 nC, duration 60 psec, diameter 1.0cm, and angular spread 0.05 mrad) from linac "Almaz-2" are injected into the dielectric resonator of the type presented in Figure 2. Bunch repetition frequency is 2.805GHz that can be varied within 2 MHz by changing master oscillator frequency to provide required frequency detuning.

For realization of the “resonator” scheme the short-circuiting piece of a waveguide of the same transversal sizes is connected to the waveguide output. As a short-circuiting device the mobile plunger serves. In the center of plunger the high-frequency probe is located to measure E_z component of wakefield. The topography of longitudinal and transversal components of the fields excited in semi-infinite dielectric structure, is measured by means of mobile radio-frequency probes. Measurements of averaged power of the excited fields are carried out by means of power measurer M3-52 and M3-54 in five various frequency ranges: (2÷4), (2÷10), (8÷12), (12÷17) and (17÷25) GHz.

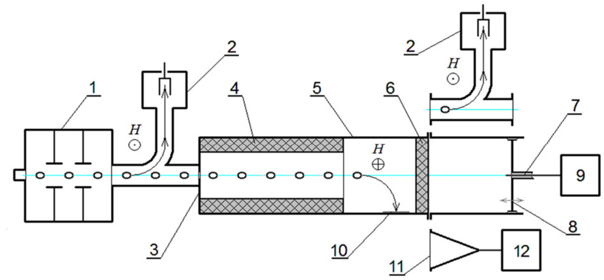

Figure 5: Scheme of the installation: 1-linac, 2-magnetic analyzers, 3-diaphragm, 4-dielectric plates, 5-rectangular copper waveguide, 6-Teflon stub, 7,8-short-circuiting plunger, 9-oscillograph, 10-glass plate, 11-horn antenna, 12-power measurer.

Energy losses by electron bunches are estimated by change of energy spectra of relativistic electron bunches before and after their passing the dielectric structure which are measured by means of the magnetic analyzers located at the exit of the accelerator and at the exit of structure. For the same purpose prints of the bunch, deflected by transverse magnetic field, on the glass plates placed inside waveguide near its output are used.

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