WAKEFIELDS OF SHORT BUNCHES IN THE CANAL COVERED WITH THIN DIELECTRIC LAYER

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Abstract

In new generation of accelerators shorter and shorter bunches are considered. In addition to the usual wakefields, excited in corrugated or resistive vacuum chambers, other harmful wakes can be excited in smooth beam tubes, covered by thin dielectric layer. Analytical approximation and results of computer simulations are presented for various bunchlengths and dielectric thickness. It is shown that a 50 μm long bunch, travelling through a tube with ceramic coating of only 0.1 μm gives rise to large amplitude wakefields, comparable to usual wakes in accelerating cavities. This effect can be dramatic for long transport lines. Dielectric coatings in the tubes can be of different types. A few examples, like oxide layer in aluminum tubes, are finally discussed. Derived estimations are also given for corrugated metallic surfaces, which can have similar behaviour to dielectric coated tubes.

1 INTRODUCTION

The wakefields, excited by intensive bunches in accelerating structures and transport lines, are of major concern in the design of future for Linear Colliders and X-ray Free Electron Laser, because they can give rise to large energy spreads and transverse instabilities. In new generation of accelerators, shorter and shorter bunches are considered. For example, bunches of 25 μ and less are foreseen in the SASE FEL of the TESLA facility [1]. In addition to the usual wakefields, excited in corrugated or resistive vacuum chambers, other harmful wakes can be excited in the beam pipes, which have not really "smooth" surface. In the range of high frequencies, the usual roughness of the surface can be sufficient to reduce the phase velocity down to the speed of the travelling particles, generally close to the speed of light.

2 SINGLE MODE WAKES

We consider bunches of finite length σ, travelling with a speed close to the speed of light, through round pipes of radius a, filled with dielectric material between a and $a+\delta$. Longitudinal and transverse wakefields will be induced, but we restrict to longitunal fields throughout this analysis. We assume that the higher order modes, of wave numbers k_n, are suppressed by the finite bunchlength σ

$$\exp[-\frac{1}{2}(\sigma k_n)^2] \ll 1 \qquad (1)$$

but keeping, on the other hand, the lowest mode k_0, because of the non-zero thickness of the dielectric layer

$$\sigma k_0 \leq 1 \qquad (2)$$

The wave number for main mode k_0 can be easily evaluated for the ultrarelativistic case. The longitudinal electric component E_z for the m-azimuthal mode is well known in the vacuum part $r < a$

$$E_z(r) = e(z-ct)(\frac{r}{a})^m \qquad (3)$$

In the thin dielectric layer, E_z is decreasing rapidly and become zero at the metallic boundary. It can be approximated at first order in the dielectric canal vanishing on metallic part by

$$E_z(r) = E_z(a)(1 - \frac{r-a}{\delta}) \qquad (4)$$

The expression of the wave number can be established directly from Maxwell equations

$$k_0^2 = \frac{a\epsilon}{1-\epsilon} \frac{\frac{dE_z(r>a)}{dr}}{\int_0^a E_z(r) r dr} \qquad (5)$$

where ϵ is the dielectric constant of the layer. Finally, we obtain simply

$$k_0^2 = \frac{2\epsilon}{a\delta(\epsilon-1)} \qquad (6)$$

This derived formula is in quite agreement with ref. [3].

From the expressions 2 and 6 it is possible to give an estimation of the minimal thickness of the layer, which generate large wake amplitude :

$$\delta \geq \frac{2\epsilon\sigma^2}{a(\epsilon-1)} \qquad (7)$$

We note that the dielectric constant dependance is very weak. Taking a dielectric constant of 2, the previous simply

$$\delta \geq \frac{4\sigma^2}{a} \qquad (8)$$

Assuming for example a bunchlength of 25 μ and a pipe diameter of 20 mm, a dielectric coating of only 0.25 μ is very harmful. Numerical simulations, by means of the code already used in Ref.[2], were caried out to check this single mode regime. Fig.1 shows the wake potentials for a σ= 25 μ long bunch, moving in the pipe of radius a=50 mm for different thickness of dielectric layer (δ=0.0125, 0.05, 0.2, 0.8 and 3.2 μm). The amplitude of the induced fields habe been normalized by the quantity $Z_0 c/\pi a^2$.

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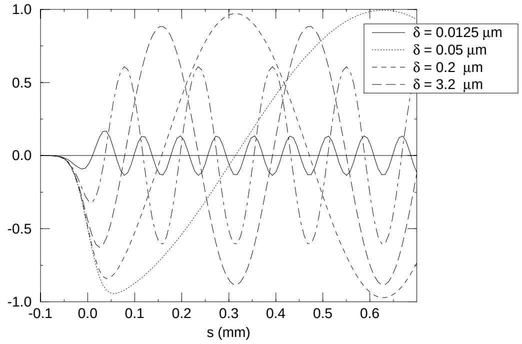

Figure 1: Wake potentials of a 25 μ bunch in .the tube of the radius a=50 mm for different thickness of dielectric layer δ=0.0125, 0.05, 0.2, 0.8 and 3.2 μ

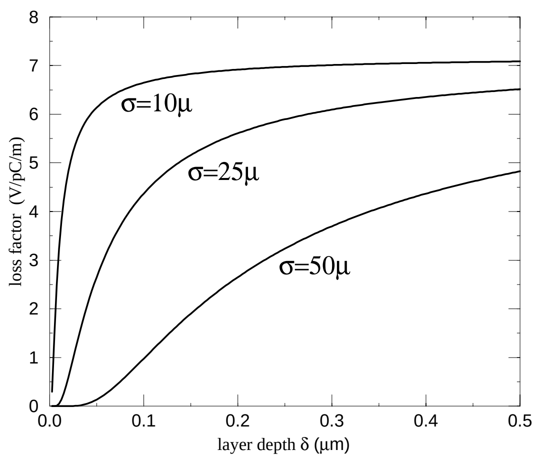

Figure 2: Loss factor (in V/pC/m) vs. layer thickness for different bunchlengths σ= 10, 25 and 50 μ

We note that the mode frequency scales with the square root of the layer thickness, as expected (see expression 6). Numerical results are in quite agreement with the description, given in Ref.[3], of the amplitude of the synchronous fields

$$E_z = \frac{Z_0 c}{\pi a^2} \exp[-\frac{1}{2}(K_0\sigma)^2] \tag{9}$$

The loss factor per unit length, integral of the bunch wake potential with the charge distribution is given by

$$K_{loss} = \frac{Z_0 c}{2\pi a^2} \exp[-(K_0\sigma)^2] \tag{10}$$

The dependence of the loss factor on the layer thickness is shown on Fig.2 for different bunchlengths.

3 CASE OF SLIGHTLY CORRUGATED PIPES

Some very small corrugations on beam pipes can behave like ”ceramic” layers. The equivalent ”dielectric” constant depends of course on the details of corrugation. However,

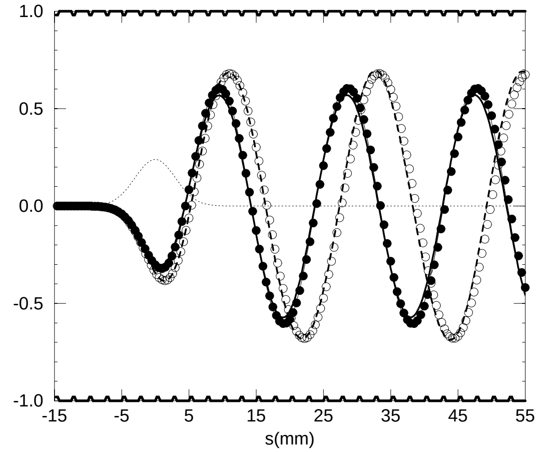

Figure 3: Normalized wake potentials (σ=3 mm) in slightly corrugated tube (dark lines) for periods 1.25 and 4.5 mm (solid lines) and 2.5 mm (dashed line) and in tubes covered with ceramic layer (same thickness as radial size of protuberances) of dielectric constant 2 (empty circles) and 1.6 (solid circles).

assuming that the sizes of the protuberances are not too much different, we can predict an equivalent ”dielectric” constant in the range of 2. With the aim of comparing the wakefields induced in ceramic layer and in slightly corrugated tubes, calculations by means of the code NOVO for the latter case, and described in [4], were carried out. At first, a tube of radius $a = 50mm$ with small irises of 1 mm height and 0.5 mm width was chosen. A σ=3 mm bunchlength was selected in order to excite the same wave with k_0=0.28 mm^{-1} according to expression (6) for $\epsilon = 2$. The normalized wake potentials are shown on Fig.3 for different periods (1.25, 2.5 mm and 4.5 mm). We note that both 1.25 and 4.5 mm periods give the same wakes, up to several σs after the bunch. The wakes induced in tubes, coated with ceramic layers (dielectric constant 2 and 1.6) of the same thickness as radial size of the protuberances are also shown.

We observe very good agreements between both kinds of pertubated pipes. We conclude that the same wake formulae can be used. In the reality, the rough pipe surface has no perfect periodic corrugation, but exhibits random protusions. This random nature results in some decoherence of the induced fields, but only for the long-range wakefield, as it is shown on Fig.4, where the wakes are plotted for a 10 meters long tube, with a diameter of 100 mm, filled of 1 mm protusions, randomly spaced between 1 and 9 mm. A wake, excited by a 1 mm thich ceramic layer of dielectric constant 1.5 is also shown for comparison.

4 DISCUSSIONS

For short bunch acceleration and transportation, notice must be taken of the wakefields, which can be excited in

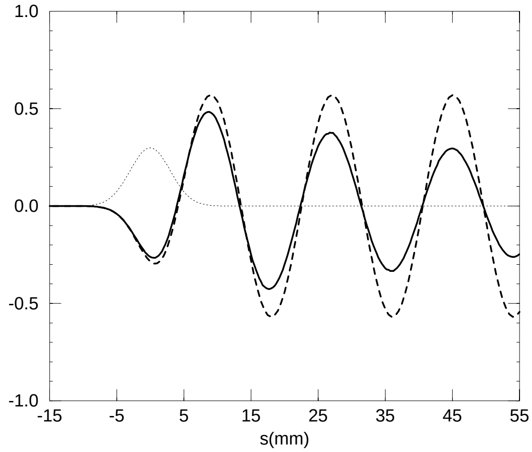

Figure 4: Normalized wake potentials (σ=3 mm) in a "real" tube, filled with randomly spaced protusions (solid line) and filled with dielectric material (dashed line).

beam tubes, covered by very tiny dielectric layers, or very slightly corrugated. The amplitudes of the wakes are comparable to those, induced in accelerating periodic structures. For aluminum vacuum chambers, the thickness of ceramic layer can vary in the range of a few nanometers, and can be harmful for very small bunches, in the range of 10 μ. Furthermore, the roughness of the surface can give a significant effect, and not only for very short bunches.

5 ACKNOWLEDGEMENT

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