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ON THE ESTIMATION OF THE WAKE POTENTIAL FOR AN ULTRARELATIVISTIC CHARGE IN AN ACCELERATING STRUCTURE

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On the Estimation of the Wake Potential for an Ultrarelativistic Charge in an Accelerating Structure

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ABSTRACT

The method to derive the analitic estimations for wake fields of an ultrarelativistic charge in an accelerating structure, that are valid in the range of distances smaller or compared to the effective structure dimensions. The method is based on the approximate space-time domain integrating of the Maxwell equations in the Kirchhoff formulation.

The method is demonstrated on the examples of obtaining the wake potentials for energy loss of a bunch traversing a scraper, a cavity or periodic iris-loaded structure.

Likewise formulae are derived for Green functions that describe transverse force action of wake fields.

Simple formulae for the total energy loss evaluation of a bunch with the Gaussian charge density distribution are derived as well. The derived estimations are compared with the computer results and predictions of other models.

1. INTRODUCTION

Wake field of a single bunch of charged particles traversing a resonant cavity or periodic accelerating structure is of considerable interest for high-energy particle accelerators and storage rings due to its strong effect on longitudinal and transverse particles dynamics (if a charged bunch is travelling close to the speed of light then the space charge forces are negligible compared to forces of the interaction of the charge self-field with an external environment). Naturally the correct knowledge of wake field is also required for wake-field accelerators.

The optimal description of the wake fields, in particular for computer simulations of beam dynamics, is that when fields can be calculated by convolution of the bunch charge density distribution and the Green wake function, which is defined as wake potential. Wake potential represents the electromagnetic time response of the environment caused by a leading particle towards the particle behind as a function of the distance between the particles. In this paper wake potential is solely defined the Green function for the energy loss, i. e. longitudinal wake-field forces.

Known analitic solution for the wake potential is an infinite sum over the resonant eigenfunctions. The series terms are analitically calculated only for closed cylindrical cavity [1]. In other cases computer methods for calculations and summation of series terms are used. Unfortunately the summarized series converge rather slowly in particular for short distances, therefore high frequency approximation of the opticle resonator model is added to computer summarized series [2, 3].

Wake potential also can be evaluated based on the knowledge of energy loss by a bunch of finite length and the causality condition for particles moving at the speed of light, which means that there is no wake contribution from particles which are behind the considered particle. Energy loss evaluations for a bunch of finite length were obtained in the physical optics approximation with the diffraction model of a bunch self-field scattering on a perturbing obstacle [4—6]. Based on this model formulae for wake potential in the range of very short distances were derived [6].

Nevertheless nowadays only computer methods of a time domain integration of the Maxwell equations (see for example [7]) give the main information about wake fields. However it should be noted that the wake field of a point charge and therefore wake potential cannot be obtained with the computer programs, because of computer resource limitation (the number of mesh points varies inversely with the bunch length to the third power for given accuracy of field evaluation).

Generally wake potential can be derived as a solution of the Kirchhoff space-time integral equations together with boundary conditions. It seems unreal to get exact solution in broad band of distances. However it is possible to derive accurate solution in the range of distances compared to the structure dimensions. In further consideration it will be shown how formulae for wake potentials can be derived based on general principles of electromagnetic field theory and mathematical formalism.

Analogously to the Panofsky—Wenzel theorem there is the relationship for calculation the transverse wake by integration the wake potential, so formulae for transverse wake will be derived as well.

This method also predicts a set of simple formulae for wake fields of a bunch with Gaussian charge distribution traversing scrapers and cavities. Results will be presented in MKS units.

2. MODEL CONCEPT AND MATHEMATICAL FORMALISM

Superposition, causality and conservation of energy are the basic principles of the model concept. The total electromagnetic field $(\vec E_{tot}, \vec H_{tot})$ in any structure can be considered to be the superposition of the bunch self-field $(\vec E_b, \vec H_b)$ in free space and actual wake field $(\vec E_w, \vec H_w)$

$$\vec E_{tot} = \vec E_b + \vec E_w, \qquad \vec H_{tot} = \vec H_b + \vec H_w .$$

According to the Kirchhoff space-time domain integral formulation of the Maxwell equations (some authors call it as space-time Kirchhoff—Kotler—Sobolev equation, see for example Ref. [8]) the value of an electromagnetic field component at any point of some volume is determined by the integration the functions vs electromagnetic field over the boundary surface surrounding the volume. This is valid entirely for points lying on the boundary surface. Together with boundary conditions it gives the integral equation which can be solved by iterations. However not too long study reveals the fact that required number of iterations depends upon time interval of interest. If the time interval multiplied by the light velocity is less or compared to the actual structure dimensions then the result of the first iteration is very close to the exact solution. In further consideration this estimation for magnetic field components will be used.

Taking into account the boundary conditions for the total field on metallic surface

$$[\vec n \times \vec E_w] = -[\vec n \times \vec E_b], \qquad \vec n \cdot \vec H_w = -\vec n \cdot \vec H_b$$

the relation for the magnetic wake field at the point lying on the boundary surface takes the following form

$$\vec H_w(\vec x\, t) = -\int_{surf}\left\{ \varepsilon_0\left[\frac{\vec n'}{R}\times\frac{\partial \vec E_b}{\partial t'}\right] + \left[\frac{\vec n'\vec H_b}{R} + \frac{\partial}{\partial t'}\left(\frac{\vec n'\vec H_b}{c}\right)\right]\frac{\vec x-\vec x'}{R^2}\right\}\frac{dS'}{2\pi} \qquad (2.1)$$

where $R=|\vec x-\vec x'|$, $\vec n'$ is the unit normal to the surface, ε_0 is dielectric constant of free space, c is the light velocity and all field components in the right-hand side are taken in the retarding time moment

$$t' = t - R/c .$$

Total energy loss U of a bunch is equal to the energy of the wake field left behind in the volume that can be calculated by the time integrating over the field energy flux $P(t)$ directed inside the volume:

$$U = \int P(t)\, dt ,$$

$$P(t) = -\int_{surf} (\vec n\,[\vec E_b \times \vec H_w])\, dS \qquad (2.2)$$

that in its turn is calculated by integrating the Poynting vector along the boundary surface using (2.1). On the other hand total energy loss of a bunch can be described with wake field $V(s)$ and charge density distribution $q(s)$:

$$U = \int V(s)\, q(s)\, ds\,,$$

$$V(s) = \int_0^{\infty} W(s')\, q(s-s')\, ds\,, \tag{2.3}$$

where s is the particle position in the bunch. Wake field distribution $V(s)$ is in its turn the convolution of the wake potential $W(s)$ and the charge distribution. Note that the wake field distribution is in the relation with energy flux

$$V(s) = P(t=s/c)/q(s)/c\,. \tag{2.4}$$

As it can be seen from the comparison of (2.2) and (2.3) the formula for wake potential is easily derived if integral for energy flux in (2.2) is transformed to the proper form as for wake field in (2.3).

If a bunch moves in free space or in longitudinally constant shape tube in z-direction at speed $\vec{V}$ close to that of light the bunch self field has only transverse components and is described as

$$\vec{E}_b = I(z,t)\, \vec{R}(x,y)\,, \quad \vec{H}_b = \varepsilon_0 [\, \vec{V} \times \vec{E}_b]\,,$$

$$I(z,t) = \frac{q(s)}{2\pi\varepsilon_0}\, \delta(s-ct+z)\,, \tag{2.5}$$

where $\delta(z)$ is the delta-function and $q(s)$ is the charge density distribution in a bunch. Function $\vec{R}(x,y)$ normally can be expanded in an infinite sum of azimuthal modes. In a cylindrical tube of radius b

$$R_r(r,\varphi) = \frac{1}{r} + \sum_{m=1}^{\infty} \left(\frac{\Delta}{r}\right)^m \left[1+\left(\frac{r}{b}\right)^{2m}\right] \frac{\cos(m\varphi)}{r}\,,$$

$$R_\varphi(r,\varphi) = \sum_{m=1}^{\infty} \left(\frac{\Delta}{r}\right)^m \left[1-\left(\frac{r}{b}\right)^{2m}\right] \frac{\sin(m\varphi)}{r}\,,$$

where m is the azimuthal number, Δ is the displacement of coordinate axis against the bunch trajectory.

And finally Green function of transverse wake $G(s)$, that determines the transverse momentum kick $\Delta p_\perp(s)$ upon particles in a

bunch by the transverse forces of wake fields according to

$$\Delta p_\perp(s) = \int_0^{\infty} G(s')\, q(s-s')\, ds'\,.$$

Analogously to the Panofsky—Wenzel theorem there is the relationship which is used for calculation the Green function of transverse wake by integrating the wake potential

$$G(s) = -\frac{\partial}{2\partial\Delta} \int_0^{s} W(s')\, ds'\,. \qquad (2.$$

This statement can be easily derived based on the theorem in frequency domain and the Fourrier transformation.

3. BEAM SCRAPER IS A LONELY IRIS IN A BEAM TUBE

This is the simplest structure, for which wake fields are of interest. Actually, when an intense bunch traverses a scraper, the later can significantly degrade the energy spread and bunch emittance due to the longitudinal and transverse wake field forces.

Let b, a, L be consequently the radius of a beam tube, the inner hole radius and the longitudinal scraper length.

Energy flux $P_m(t)$ of the m-th azimuthal field mode is

$$P_m(t) = 2\, P_m^s(t) + P_m^{in}(t)\,, \tag{3.1}$$

where P_m^s is on the left or right side and P_m^{in} is inside a scraper. The later is equal to zero for the azimuthally symmetric fields according to (2.1), (2.5), so that longitudinal effects do not depend upon scraper thickness.

The first part $P_m^s(t)$ according to (2.1), (2.2) and (2.5) is

$$P_m^s(t) = \Delta^{2m} \frac{q(ct)c}{4\pi^2\varepsilon_0} \int_a^b \frac{dr}{r^m} \int_a^b \frac{dr_0}{r_0^m} \int_0^{2\pi} \frac{\partial q(s')}{\partial s'} \frac{\cos((m+1)\varphi)}{R}\, d\varphi\,,$$

$$s' = ct - R\,,$$

$$R = \sqrt{r^2 - 2rr_0\cos\varphi + r_0^2}\,.$$

Using (2.4) and substitution of variables, integration by parts and integration over the variable r the above formula is transformed to the formula for the wake field distribution along the bunch

$$V^s_m(s)=\frac{1}{\pi\varepsilon_0}\left(\frac{\Delta}{a}\right)^{2m}\left\{q(s)\,K_m-\frac{1}{\pi a}\int\limits_0^\infty q(s')\,F_m\!\left(\frac{s-s'}{a}\right)ds'\right\}.$$

It was used that bunch length and radius of a scraper aperture are less than beam tube radius. Function K_m is defined as

$$K_m=\begin{cases}\ln\,(a/b) & \text{for } m=0\\ 1/2m & \text{for } m\geqslant 1\end{cases}$$

and the function $F_m(x)$ is

$$F_m(x)=\frac{1}{x}\int\limits_0^\alpha\frac{\cos(m\varphi-\psi)\,d\varphi}{\cos\psi(\cos\varphi+x\cos\psi)^m},$$

$$\operatorname{tg}\psi=\sin\varphi/\sqrt{x^2-\sin^2\varphi},$$

$$\alpha=\begin{cases}\arccos\,(1-x^2/2) & \text{for } 2\geqslant x\geqslant 0\\ \pi & \text{for } x\geqslant 2\end{cases}$$

Nonvanished second part in the right-hand part of (3.1) is due to the fact that energy loss into transverse modes increases when a bunch goes into a scraper because of the bunch self-field reconstruction inside scraper apertura as the consiquence of boundary conditions. This part can be rewritten in the following form

$$P^{in}_m(t)=\frac{1}{2\varepsilon_0}\left(\frac{\Delta}{a}\right)^m q(ct)\int\limits_0^L H(ct+z,z)\,dz, \qquad (3.2)$$

where

$$H(t,z)=\frac{c}{2\pi^2\varepsilon_0}\left(\frac{\Delta}{a}\right)^m\times$$

$$\times\int\limits_0^L dz'\int\limits_0^\pi\left\{-\frac{q'(s')}{R}+\frac{q'(s')}{R}(z-z')-\frac{q(s')}{R^2}\,(z-z')\right\}\cos m\varphi\,d\varphi,$$

$$s'=ct-R-z'.$$

After simple transformations (3.2) gives the second part of the

transverse wake field distribution

$$V^{in}_m(s)=\frac{1}{4m\pi^2\varepsilon_0}\left(\frac{\Delta}{a}\right)^{2m}\int\limits_0^{\sqrt{L^2+(2a)^2}-L}\left(\frac{q(s-s')}{s'}-\frac{q(s-s'-2L)}{s'+2L}\right)\times$$

$$\times\sin\left(2m\arcsin\frac{\sqrt{s'(s'+2L)}}{2a}\right)ds'.$$

So the total wake potential is

$$W_m(s)=\frac{1}{\pi\varepsilon_0}\left(\frac{\Delta}{a}\right)^{2m}\left\{K_m\delta(s)-\frac{1}{\pi a}F_m\left(\frac{s}{a}\right)+\frac{1}{4\pi a}\Phi_m\left(\frac{s}{a};\frac{L}{a}\right)\right\}, \qquad (3.3)$$

where

$$\Phi_m(x,y)=\frac{\sin(\theta_1)-\sin(\theta_2)}{mx},$$

$$\theta_1=\begin{cases}2m\arcsin\left[\sqrt{x(x+2y)}/2\right] & \text{for } 0\leqslant x\leqslant\sqrt{y^2+4}-y\\ m\pi & \text{anywhere else}\end{cases}$$

$$\theta_2=\begin{cases}2m\arcsin\left[\sqrt{x(x-2y)}/2\right] & \text{for } 2y\leqslant x\leqslant\sqrt{y^2+4}+y\\ m\pi & \text{anywhere else}\end{cases}$$

According to (3.3) the amplitude of the longitudinal wake field experienced by the central particle of a Gaussian bunch with r. s. m. length $\sigma\leqslant a$ is

$$V_0=\frac{2Q}{(2\pi)^{3/2}\varepsilon_0\sigma}\left\{\ln\left(\frac{b}{a}\right)-\frac{\sigma}{a\sqrt{2\pi}}\right\}$$

and the total energy loss of a bunch is

$$U=\frac{Q^2}{(2\pi)^{3/2}\varepsilon_0\sigma}\left\{\ln\left(\frac{b}{a}\right)-\frac{\sigma}{a\sqrt{\pi}}\right\}.$$

Finally the Green function of transverse wake field according to (2.6) and (3.3) is

$$G_m(s)=\frac{\Delta^{2m-1}}{2\pi\varepsilon_0 a^{2m}}\left\{1-\frac{2m}{\pi a}\int\limits_0^s\left[F_m\left(\frac{s'}{a}\right)-\frac{1}{4}\Phi\left(\frac{s'}{a};\frac{L}{a}\right)\right]ds'\right\}. \qquad (3.4)$$

For practical use formula (3.4) can be simplified for two extremal cases:

$L \leqslant a$ (thin scraper)

$$G_m(s)=\frac{\Delta^{2m-1}}{2\pi\varepsilon_0 a^{2m}}\left\{1-\frac{2ms}{a}+\frac{m}{\pi}\sqrt{\frac{sL}{2a^2}}\right\};$$

$L \geqslant a$ (very long scraper)

$$G_m(s)=\frac{\Delta^{2m-1}}{2\pi\varepsilon_0 a^{2m}}\left\{1+\frac{m}{\pi}-\frac{2m}{\pi}\int_0^{s/a} F_m(x)\,dx\right\}. \qquad (3.7)$$

4. CAVITIES

Notations for scrapper radii mentioned above are valid also for a cavity. The new additional parameter g defines the cavity gap length. However the method slightly differs from previous consideration.

In this case field energy fluxes from different sides of cavity are not summed but partially compensated and the reflection at the right side of the wake field emitted from the left side must be taken into account. So one part of energy flux is

$$P_m^s(t)=2\int_a^b r\,dr\int_0^{2\pi} E_b(t)\,[H(ct)-H_0(ct+g)]\,d\varphi\,, \qquad (4.1)$$

where $H(ct)$ is the magnetic field induced on the right side of a cavity by its «own» current and $H_0(ct)$ is the field induced by the left-side current.

The second part of the energy flux is due to the deformation of a bunch self field in the right-hand tube connected with a cavity. Corresponding energy flux is exactly the same as energy flux (3.2) inside scraper apertura of the length equal to the cavity gap size, i. e. $L=g$. Using this fact and above expression one can derive the total wake potential

$$W_m^c(s)=\frac{\Delta^{2m}}{\pi^2\varepsilon_0 a^{2m+1}}\left\{\frac{s+g}{\sqrt{s(s+2g)}}F_m\left(\frac{\sqrt{s(s+2g)}}{a}\right)-\right.$$

$$\left.-F_m\left(\frac{s}{a}\right)+\frac{1}{4}\Phi_m\left(\frac{s}{a};\frac{L}{a}\right)\right\}, \qquad (4.2)$$

where $F_m(x)$ and $\Phi_m(x, y)$ are already known functions. This estimation is valid for any integer m and for that range of distances s when no wave created by the leading particle can reach the outer wall of the cavity, be reflected and arive back before time moment $t=s/c$, since this wake potential does not depend upon the cavity radius.

With the help of (4.2) and remember (2.6) formula for the transverse wake is appearing in the following form

$$G_m(s)=\frac{m\Delta^{2m-1}}{\pi^2\varepsilon_0 a^{2m+1}}\left\{\int_0^s \Phi_m\left(\frac{s'}{a};\frac{g}{a}\right)\frac{ds'}{4}-\int_s^{\sqrt{s(s+2g)}} F_m\left(\frac{s'}{a}\right)ds'\right\}. \qquad (4.3)$$

As examples in Fig. 1 are shown wake potential ($m=0$) and Green functions for dipole ($m=1$) and quadrupole ($m=2$) wakes

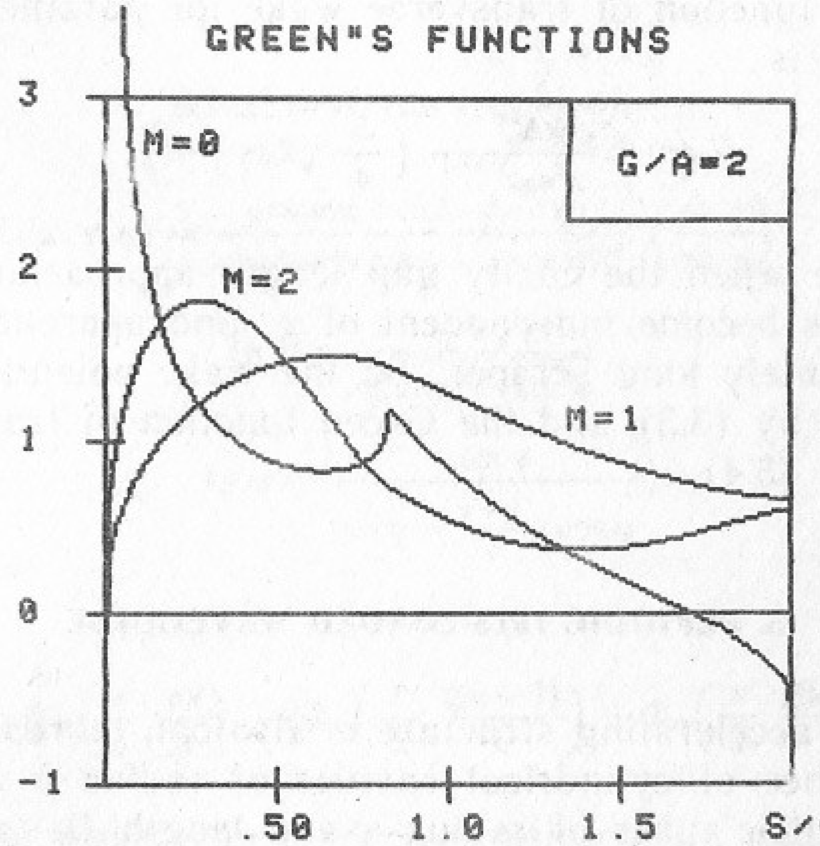

Fig. 1. Wake potential ($m=0$) and Green functions for dipole ($m=1$) and quadrupole ($m=2$) wakes.

of a bunch traversing a cavity with the relative gap length $g/a=2$. Potential is normalized by $1/\pi^2\varepsilon_0 a$ and Green functions are normalized by $(\Delta/a)^{2m-1}/\pi^2\varepsilon_0 a^2$. For practical use when

$$\frac{s}{a}\leqslant\frac{a}{2g} \quad \text{and} \quad \frac{s}{g}\leqslant 1 \qquad (4.4)$$

wake potentials are approximated by

$$W_m(s) = \frac{\Delta^{2m}}{\pi^2 \varepsilon_0 a^{2m+1}} \left(\sqrt{\frac{g}{2s}} - 1 \right).$$

This formula gives when $m=0$ the estimation for energy loss of the central particle in a Gaussian bunch

$$V_0 = \frac{Q}{2\pi^2 \varepsilon_0 a} \left(\sqrt{\frac{g}{2\sigma}} - \frac{1}{2} \right)$$

and the total energy loss of a bunch in a cavity

$$U = \frac{Q^2}{2\pi^2 \varepsilon_0 a} \left(\sqrt{\frac{g}{\sigma}} - 1 \right).$$

The Green function of transverse wake for parameters obey the condition (4.4) is

$$G_m(s) = \frac{m\Delta^{2m-1}}{\pi^2 \varepsilon_0 a^{2m+1}} \left(\frac{5}{4} \sqrt{2gs} - s \right).$$

In the case when the cavity gap length approaching to infinity wake potentials become independent of g, and approaching the formulae for infinitely long scraper. So the wake potential for energy loss is defined by (3.3) and the Green function of transverse wake is described by (3.4).

5. PERIODIC IRIS-LOADED WAVEGUIDE

Iris-loaded accelerating structure is also can be represented by a periodic sequence of cylindrical cavities of radius b and length g joint by concentric tubes of radius a and length $D-g$, so that the period of structure is D.

The first order approximation of the wake potential per a cell when a bunch moving in periodic structure is equal to the wake potential when the same bunch traversing a cavity of the adequate parameters.

Deriving more precise formulae needs taking into account induced by the currents of all irises additional part to the magnetic field on an iris considered by integrating the function versus bunchs field along the surface of crescent regions seeing from considering point.

Taking this into account the wake potential is described by

$$W_m^s(s) = W_m^c(s) + \frac{\Delta^{2m}}{\pi^2 \varepsilon_0 a^{2m+1}} \times$$

$$\times \sum_{k=1}^{\infty} \left\{ \frac{s+g}{\sqrt{s(s+2g\varkappa)}} \, I_m^{\varkappa}\left(\frac{\sqrt{s(s+2g\varkappa)}}{a} \right) + \frac{1}{4} \Psi_m^{\varkappa} \right\}, \qquad (5.1)$$

$$\varkappa = 1 + k\frac{D}{g},$$

where

$$I_m^{\varkappa}(x) = \int\limits_{\beta(x,1)}^{\beta(x,0)} f_m(x,1,\varphi)\,d\varphi - \int\limits_{\beta(x,\varkappa)}^{\beta(x,\varkappa-1)} f_m(x,\varkappa,\varphi)\,d\varphi - \int\limits_{\beta(x,1/(\varkappa-1))}^{\beta(x,(\varkappa-1)/\varkappa,0)} f_m\left(x, \frac{\varkappa}{\varkappa-1}, \varphi\right) d\varphi,$$

$$\beta(x,\nu) = \arccos \frac{1 - \frac{x^2}{2}(1-\nu)}{\sqrt{1+x^2\nu}},$$

$$f_m(x,\nu,\varphi) = \frac{\cos(m\alpha + (\alpha-\varphi) - \psi)}{x\nu \cos\psi (\nu\cos\varphi - x\cos\psi)^m} \left(\frac{\sin\alpha}{\sin\varphi} \right)^{m+1},$$

$$\operatorname{tg}\psi = \frac{\sin\varphi}{\sqrt{(x/\nu)^2 - \sin^2\varphi}},$$

$$\operatorname{tg}\alpha = \frac{\nu\sin\varphi}{\cos\varphi - \frac{\nu-1}{\nu} x\cos\varphi},$$

and finally

$$\Psi_m^{\varkappa} = \Phi_m\left(\frac{s}{a}; \frac{g\varkappa}{a}\right) - 2\Phi_m\left(\frac{s}{a}; \frac{g(\varkappa-1)}{a}\right) + \Phi_m\left(\frac{s}{a}; \frac{g(\varkappa-2)}{a}\right),$$

Transverse wakes can be derived using (5.1) and (2.6).

CONCLUSION REMARKS

Aiming to varify the derived formulae the comparison with computer results for wake fields was carried out. As it came out the computer results based on the method [7] compare very well for the bunch length up to the structure aperture size.

The derived formulae were also compared with the results of summation of eigenfunctions for SLAC and LEP accelerating structures, presented in Refs [2, 3]. There is a sufficiently good agreement. However in the range of very small distances the derived formula for wake potential gives an increasing to an infinite value like $1/\sqrt{s}$ instead of the finite value result of summation.

The derived formulae for energy loss in cavity and iris-loaded structure can be also used for evaluation the energy loss by a point particle of finite kinetic energy, if one changes σ to the effective particle field length a/γ, where γ is the relativistic factor. By using this substitution in (4.5) the formula for energy loss in a cavity takes form

$$U = \frac{Q^2}{2\pi^2\varepsilon_0 a}\left(\sqrt{\frac{g}{a}\gamma} - 1\right)$$

that slightly differs from the formula predicted by Lowson [9] when $\gamma \gg 1$.

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К оценке потенциала поля излучения ультрарелятивистского заряда в ускоряющей структуре

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