Simple formula for surface roughness wakes

M. Blaskiewicz

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Collider Accelerator Department

Brookhaven National Laboratory

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For energy recovery linacs (ERLs) the energy spread induced by wakefields grows throughout acceleration and deceleration. Too much fractional momentum spread at low energy will complicate beam transport. This note uses some analytical results and a simple model of surface roughness correlation functions to obtain a wakefield formula that is very fast and easy to compute.

The resistive wall wake will be used for comparison. For resistive wall we used the low frequency approximation for the longitudinal wake potential

\[ W(s) = \frac{d}{ds} H(s) \frac{cL}{2\pi b} \sqrt{\frac{Z_0 \rho_e}{\pi s}}, \quad (1) \]

where \( Z_0 = 377\Omega \), \( s \) is the lag distance, \( H(s) = 1 \) for \( s > 0 \) and is zero otherwise, \( c \) is the speed of light, \( L \) is the length of the resistive section, \( b \) is the pipe radius, and \( \rho_e \) is the electrical resistivity. When applying equation (1) and in formulas below we use integration by parts to obtain actual voltages. The numerics are very straightforward and will not be discussed.

For the wake potential due to surface roughness we used Stupakov’s formula [1]. Define

\[ W(s) = \frac{d}{ds} H(s) Re(\Phi(s)). \]

In MKS units

\[ \Phi(s) = \int_{-\infty}^{\infty} dk_z \int_{-\infty}^{\infty} dk_x |k_z|^{3/2} \frac{\left| s(k_x, k_z) \right|^2}{\epsilon_0 b^2 \sqrt{\pi}} \left( 1 - i \frac{\sqrt{s}}{\sqrt{\pi}} \right) \exp \left( \frac{k_x^2 + k_z^2}{2k_z s} \right) \quad (2) \]
where the angular brackets denote statistical averages and
\[
\hat{s}(k_x, k_z) = \int_0^L \int_0^{2\pi b} dz dx \frac{h(z, x)}{(2\pi)^2} \exp(ik_z z + ik_x x),
\] (3)
with surface roughness \(h(x, z)\) where \(z\) is measured along the beam direction. For \(h = h_0 \cos k z\) one has
\[
<|\hat{s}(k_x, k_z)|^2> = \frac{h_0^2 L b}{8\pi} \delta(k_x) \delta(k_z - k).
\]
and
\[
W_0(s) = \frac{d}{ds}H(s)Lh_0^2 k^{3/2} \cos(ks/2) + \sin(ks/2) 8s^{1/2} \epsilon^0 \pi^{3/2} b. \tag{4}
\]
Figures 1 and 2 show the input and results of an ABCI [2] simulation and equation (4). For these parameters the agreement is excellent. Other parameters have been checked and the amplitude of the wake is always good within a factor of 2. With this level of agreement it seems likely the theory is reasonably accurate. We go on to consider the wake due to surface roughness.

We need a statistical model of wall roughness to get \(<\hat{s}^2>\). For simplicity we take a stationary random process and a correlation function given by
\[
<h(x_1, z_1)h(x_2, z_2)> = C(x_1 - x_2, z_1 - z_2)
\]
\[
= h_0^2 \exp \left( \frac{(x_1 - x_2)^2}{2\sigma_x^2} - \frac{(z_1 - z_2)^2}{2\sigma_z^2} \right), \tag{5}
\]
where \(h_0\) is the rms distortion, \(\sigma_z\) is the correlation length along the axis of the pipe and \(\sigma_x\) is along the circumference. Using the Wiener-Khinchin theorem
\[
<|\hat{s}(k_x, k_z)|^2> = \frac{bL}{(2\pi)^3} \int_{-\infty}^{\infty} dx dz C(x, z) \exp(ik_z z + ik_x x) \tag{7}
\]
\[
= \frac{bLh_0^2 \sigma_x \sigma_z}{(2\pi)^2} \exp(-k_x^2 \sigma_x^2/2 - k_z^2 \sigma_z^2/2). \tag{8}
\]
Inserting (8) in (2) and doing the \(k_z\) integration yields.
\[
\Phi(s) = \frac{\sqrt{2}(1 - i)h_0^2 \sigma_x \sigma_z}{(2\pi)^2 \epsilon_0 b \sqrt{s}} \int_0^\infty dk_z \frac{k_z^2 \exp(-k_x^2 \sigma_x^2/2 + ik_z s/2)}{\sqrt{\sigma_z^2 k_x - is}}. \tag{9}
\]
In (9) the square root has a positive real part and a negative imaginary part for $s > 0$. The integral is done numerically. Figure 3 shows the net voltage for a pipe of radius 1 cm and length equal to 4 passes up and 4 passes down in CBETA. Generalizing equation (2) to flat chambers has been considered by Stupakov and Bane [4] who employed earlier work [5]. The main point here is that the surface impedance due to wall roughness is a spatially localized thing. We can take an effective surface impedance as a function of frequency and use impedance boundary conditions. Figure 8 in [3] shows the low frequency, longitudinal resistive wall wake for elliptical pipes. For all values the impedance is within 10% of the wake for a round pipe with the smaller aperture. It is likely we will not know $<s^2>$ to better than 10%.

References

Figure 2: wakefields from Stupakov’s formula and ABCI.


Figure 3: bunch current and induced voltage

370m of Al, $b=1\text{cm}$, $h_0=2\mu\text{m}$, $\sigma_{x,z}=10\mu\text{m}$

Figure 3: bunch current and induced voltage