BEAM COUPLING IMPEDANCES OF FAST TRANSMISSION-LINE KICKERS

S.S. Kurennoy, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

Fast transmission-line kickers contain no ferrite and consist of two long metallic parallel plates supported by insulators inside a beam pipe. A beam is deflected by both the electric and magnetic fields of a TEM wave created by a pulse propagating along the strips in the direction opposite to the beam. Computations of the beam coupling impedances for such structures are difficult because of their length. In the paper, the beam coupling impedances of transmission-line kickers are calculated by combining analytical and numerical methods: the wake potentials computed in short models are extended analytically to obtain the wakes for the long kickers, and then the corresponding beam impedances are derived. At very low frequencies the results are compared with simple analytical expressions for the coupling impedances of striplines in beam position monitors.

1 TRANSMISSION-LINE KICKERS

In the planned Advanced Hydrotest Facility (AHF) [1], the 20-ns beam bunches will be extracted from the 50-GeV main proton synchrotron and then will be transported to a target by an elaborated transport system. The beam transport system splits the beam bunches into equal parts in its splitting sections so that up to 12 synchronous beam pulses can be delivered to the target for the multi-axis proton radiography. The fast beam extraction from the synchrotron will be provided by the transmission-line kickers. The traveling-wave ferrite-free kickers consist of two long metallic parallel plates supported by ceramic insulators inside a beam pipe. The metallic plates (strips) together with the vacuum chamber walls form two 50-Ω transmission lines, Fig. 1, and have matching terminations at their ends. The beam bunches are deflected by the combined action of the electric and magnetic fields of a TEM wave created by a voltage pulse propagating along the strips in the direction opposite to the beam.

(a)

Positive HV Conductor

Negative HV Conductor

Vacuum Insulation

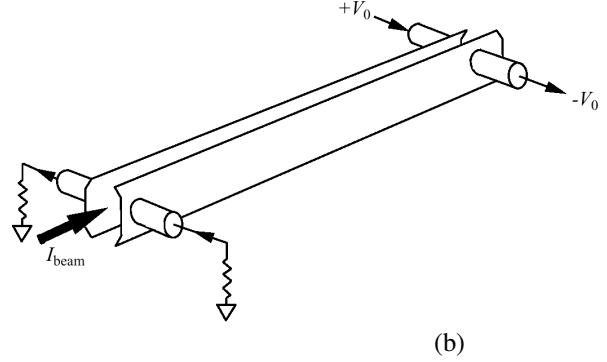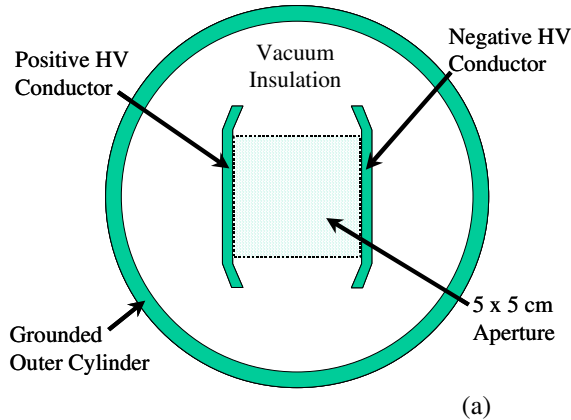Grounded Outer Cylinder

5 x 5 cm Aperture

(b)

Figure 1: Transverse cross section (a) and schematic (b) of the AHF transmission-line extraction kicker [1].

The kicker plates are placed inside a circular cylindrical pipe of radius b=76.2 mm, which tapers down on both ends to the regular cylindrical beam pipe of radius b_0=25.4 mm. The length of the kicker plates is L=8 m, and there is an option to make the plates smoothly tapered following the beam envelope while keeping the line characteristic impedance equal to Z_c=50 Ω. The plate tapering will not be considered here; its effect on the beam coupling impedances is expected to be small.

2 COUPLING IMPEDANCES

The kicker design is similar to the design of stripline beam position monitors (BPMs), except that the plates are rather far from the walls and much longer. Analytical results for the beam coupling impedances of a stripline BPM are available [2]. For two striplines of length L in a cylinder of radius b, each with a subtended angle φ_0 and matched to the impedance Z_c on both ends, the coupling impedances of the BPM in the ultra relativistic limit are:

$$Z(\omega) = \frac{Z_c}{2}\left(\frac{\varphi_0}{\pi}\right)^2\left(\sin^2\frac{\omega L}{c} + j\sin\frac{\omega L}{c}\cos\frac{\omega L}{c}\right), \qquad (1)$$

$$Z_x(\omega) = 8\frac{Z_c c}{\pi^2 \omega b^2}\sin^2\frac{\varphi_0}{2}\left(\sin^2\frac{\omega L}{c} + j\sin\frac{\omega L}{c}\cos\frac{\omega L}{c}\right),$$

where c is the speed of light, f=$\omega/(2\pi)$ is the frequency of interest, $\exp(j\omega t)$ is used for the time exponent, and the transverse impedance Z_x is in the perpendicular to the strips (horizontal) plane. For the 2-strip BPM, Z_y=0. It is not clear, however, whether Eqs. (1) will work for the kicker, which differs significantly from a BPM with striplines flush with the chamber wall.

We calculate the coupling impedances of transmission-line kickers using direct numerical simulations with the time-domain code T3 code in MAFIA code package [3]. The code computes the wake potentials created by a rigid

Gaussian (in z) ultra relativistic bunch. The coupling impedance is calculated as a Fourier transform of the wake potential divided by that of the bunch. To explore a relatively large frequency range, up to 1-2 GHz, the bunch length is chosen to be $(-5\sigma_z,5\sigma_z)$ with σ_z equal to a few cm, and the wake potentials are calculated up to tens of meters after the bunch. The main difficulty for the numerical approach in this problem is that, due to the structure length, the required mesh in MAFIA models needs to be enormously large. To overcome this difficulty, a combined approach is applied: the wake potentials, computed with T3 in short kicker models, are extended analytically to those for the long kickers, and then the corresponding beam impedances are derived.

2.1 Extending Wake Potential to Long Structures

To explain our approach, Fig. 2 shows the longitudinal wake potentials calculated with the T3 code for two short kicker models with the plate lengths of 0.8 m and 1.6 m, respectively. Except for the kicker length, the two models are identical: both have two 2-mm thick metallic ridges protruding 35 mm inside the kicker chamber (in the vertical symmetry plane in Fig. 1a) and 10-cm long conical transitions at the ends of the kicker chamber.
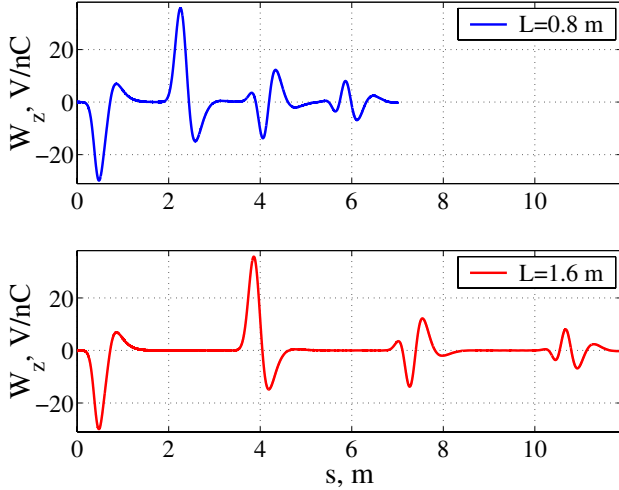

Figure 2: Wake potentials of σ_z=10 cm Gaussian bunch in two kicker models with ridges and conical transitions.

One can see a significant similarity of the two wake potentials in Fig. 2: the peaks are almost identical, only their separation is different. From a physical viewpoint, it means that only the discontinuities at the ends of the kicker plates contribute to the wakes, and in between the excitation waves propagate along the chamber without experiencing any resistance (resistive losses are small, see below). If we take the wake potential for L=0.8 m and extend it by inserting segments of the length 2·(1.6-0.8)=1.6 m of zero W_z at the points between its peaks where W_z=0, the resulting "extended" wake potential perfectly overlaps that for the model of length L=1.6 m. To be fair, one should add that such a trick works only when the bunch and structure lengths are adjusted so that the wake peaks are well separated, and that no higher-

mode resonances are excited, which would otherwise produce some ripples of the wake potentials between the peaks. But as long as this goal is achieved, we can extend the calculated wake potentials to very long structures!

To obtain the impedance for the real-size kicker, we compute the wake potential up to 12.5 m in its L=0.8 m model, and then extend it to the 8-m long structure by inserting W_z=0 segments of the length 2·(8-0.8)=14.4 m between the wake-potential peaks, as described above. The resulting wake potential extends beyond 100 m. Obviously, direct computations of such a long wake are impossible due to convergence problems even if it could be done in a reasonable time. Performing the Fourier transform of the extended wake potential and dividing it by the spectrum of the driving bunch, we obtain the longitudinal coupling impedance of the kicker, see Fig. 3.
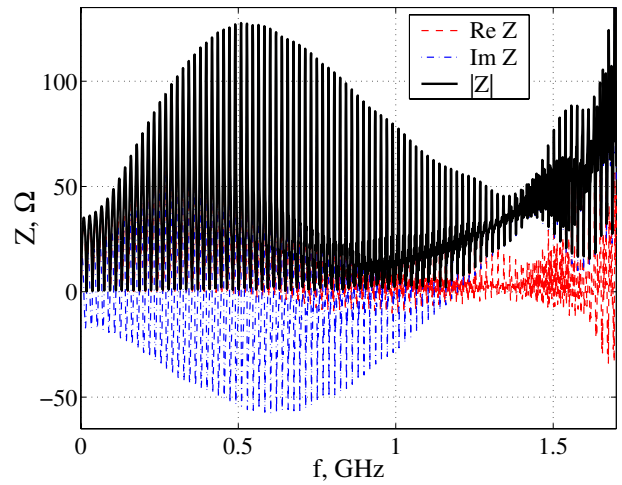

Figure 3: Longitudinal coupling impedance of the L=8 m kicker with ridges and 10-cm conical transitions.

The impedance behavior in Fig. 3 is different in three frequency regions. Below 1.3 GHz, equidistant peaks have the period defined by the kicker length, with nodes near $f=nc/(2L)$, n=0,1,2,… However, the peak magnitudes are much higher than Eqs. (1) predict, and are modulated by an envelope curve that appears to be the same for the shorter kicker models, i.e. independent of the kicker length. After this "comb" region, the impedance is purely imaginary (inductive) at frequencies 1.3-1.5 GHz. The third region, above 1.5 GHz (the kicker-box cutoff frequency), has many resonances, as one can expect. Note that the impedance peaks in the latter region should be infinitely high and thin (δ-functions), since the wall finite conductivity was not included in our simulations. Their apparent widths and heights are caused by a finite resolution of our computations (the wake potentials are truncated), and should we calculate longer wakes, these peaks would be higher and thinner. For the real kicker, the peak parameters in this region depend on the conductivity of kicker plates and walls. To the contrary, the impedance peaks in the "comb" region do not change for longer wakes, since their heights and shapes are defined by the termination impedances and the strip dimensions.

Figure 4 compares the reduced longitudinal impedance $|Z/n|$ (where $n = f/f_0$, $f_0 = 207.7$ kHz is the beam revolution frequency in the AHF ring) of the kicker with that given by (1) for $\varphi_0 = \pi$: $Z_c|\sin(\omega L/c)|/(2n)$. The resistive-wall contribution to the kicker impedance, assuming stainless-steel walls and plates, is also plotted, and it is rather small. The accurate value of the effective subtended angle was calculated using 2-d electrostatics: 0.954π with ridges and 0.974π without them, see [4] for details. The presence of ridges reduces the longitudinal impedance of the kicker by about 25%. For the layout without ridges, where the comparison with a BPM is more justified, the analytical low-frequency estimate is low by about a factor of 2. At intermediate frequencies, 400-600 MHz, the difference is even larger, factors of 3-5, cf. Fig. 3.
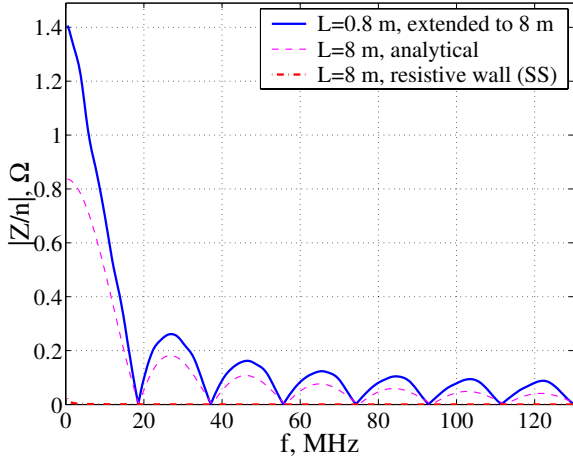

Figure 4: $|Z/n|$ of the kicker with ridges and transitions compared to analytical predictions at low frequencies.

2.2 Transverse Impedance

From formulas (1), the horizontal transverse impedance at very low frequencies, $\omega L/c \ll 1$, is purely inductive and proportional to the plate length L:

$$Z_x \cong jZ_c \frac{8L}{\pi^2 b^2}\sin^2\frac{\varphi_0}{2}. \qquad (2)$$

It is not obvious, however, what value of b should be chosen in (2). The distance from the beam to the kicker plate, 18 mm, seems much more relevant here than the kicker box radius, and leads to an estimate $|Z_x| = 1$ MΩ/m. MAFIA computations for short models of various length confirm this dependence, $|Z_x| \sim L$. They show also that the vertical transverse impedance is purely inductive up to high frequencies, a few hundred MHz, and the value of $|Z_y|$, near 4 kΩ/m, is independent of L, which means that it is caused only by the transitions at the kicker-box ends.

Similar to the longitudinal case, the horizontal wake potential W_x for $L = 1.6$ m kicker model was extended to the 8-m long kicker. The resulting transverse impedance is plotted in Fig. 5. Its low-frequency value $|Z_x| = 635$ kΩ/m agrees with expectations from results for short models, while the oscillation pattern is in agreement with Eqs. (1).
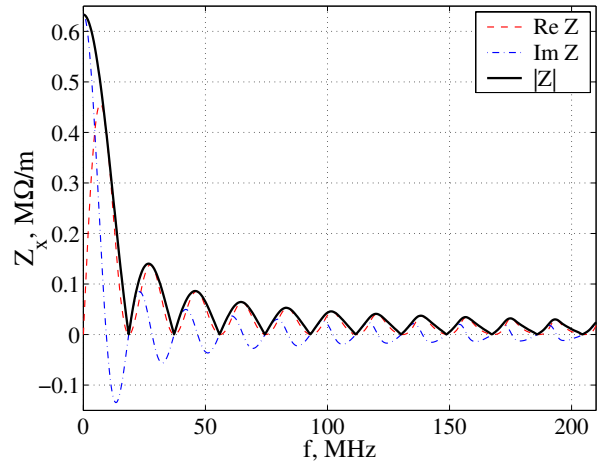

Figure 5: Horizontal transverse coupling impedance of the kicker with ridges and transitions at low frequencies.

4 CONCLUSIONS

The method of extending the wake potentials computed in short models to long structures was introduced. Within its limitations discussed in *2.1*, the method was applied for calculating the beam coupling impedances of the AHF ferrite-free traveling-wave long extraction kickers. Below a few MHz, the impedances are inductive: $|Z/n| = 1.4$ Ω with 35-mm deep ridges and $|Z/n| = 1.8$ Ω without them; the horizontal transverse impedance $|Z_x| = 635$ kΩ/m is not affected by the ridges presence, while the vertical one is $|Z_y| = 3.7$ kΩ/m with and $|Z_y| = 4.5$ kΩ/m without the ridges. The first node of the coupling impedances is reached near $c/(2L) = 18.7$ MHz. Equations (1) for the BPM impedances give a good qualitative picture of the kicker impedances, especially their frequency dependence, but quantitatively are low by a factor of 2-3 even for Z_L at low frequencies. The conical transitions at the ends of the kicker box do not have a significant effect on the beam impedances at low and intermediate frequencies. The cone length of 5 to 10 cm was found quite adequate, see [4] for details.

It would be interesting to compare the coupling impedances for this type of the extraction kickers with those for the ferrite kickers (e.g., see [5]) assuming the same transverse kick and beam aperture in both cases.

5 REFERENCES

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[5] S.S. Kurennoy, D. Davino, Y.Y. Lee, "Reducing beam coupling impedances of SNS ring extraction kickers", Proceed. PAC01, Chicago, 2001, p.1838.