Study of Loss Factor for Slots in the Vacuum Chamber*

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Abstract

Using 3-D wakefield calculation program MAFIA [1], the longitudinal loss factor (energy lost by the beam) and the transverse loss factor (transverse kick experienced by the beam) are systematically studied with the depth and the length of a slot as parameter values. When the bunch is longer than the slot, we find that simulation results agree with the early theoretical prediction by M. Sands [2], the loss factor decreases exponentially as the slot gets deeper. However, when the bunch is shorter than the slot, we find that the longitudinal loss factor decreases but the transverse loss factor does not change very much as slot gets longer. Finally, we compare the loss from a long slot with the loss from a number of holes whose diameter is equal to the slot width and covering roughly the same area as the slot.

I. INTRODUCTION

Energy loss by the beam from small holes and slots in the vacuum chamber was investigated by M. Sands [2] using H.A. Bethe's small hole theory [3] where a hole was replaced by the electric and magnetic dipole to calculate the field diffracted by the hole. In Sands' paper, the energy lost by the beam, i.e. the longitudinal loss factor (K_Z) is equal to the total radiated energy half of which is diffracted through the depth of the hole to the outside where the vacuum pumps are located while the other half is scattered back into the beam chamber. Sands' results may be summarized as follows:

1) If the bunch length (σ_Z, rms bunch length of Gaussian distribution) is larger than the slot length (slot is parallel to the beam direction), as the depth of the slot, namely the thickness of the vacuum chamber wall, gets larger, the evanescent mode in the slot is damped and consequently the power diffracted through the slot will decrease exponentially resulting in an exponential decrease in K_Z.
2) If a slot is longer than the bunch length, K_Z increases slowly and becomes independent of slot length.
3) For multiple holes whose radius is smaller than σ_Z, the total K_Z is given by gN times the K_Z for a single hole where N is the number of holes and g is the coherence factor, approximately equal to the number of holes within the bunch length σ_Z .

II. GEOMETRY USED IN MAFIA SIMULATION

The beam chamber and vacuum pump chamber configuration considered in this study is the rectangular waveguide coupled by a slot on the common wall (Fig. 1). The size of waveguide used is 8cm by 4cm and the slot length (l), width (w) and depth or thickness (t) are varied as parameter values. Since the vacuum pump chamber has a lot of complicated pump elements, our coupled waveguide model is only an approximation to the real situation. In order to reduce the number of mesh point used in MAFIA, we used the symmetry condition whenever applicable. For example, to simulate the configuration such as Fig. 1-a, instead of using two full waveguides, we used the symmetry condition at the central plane of the slot neck. By specifying the condition that the tangential electric field $E_{tan}=0$ at the central plane, we are simulating the situation where there is an electron beam in the beam chamber and a positron beam in the vacuum pump chamber, and we denote the longitudinal loss facor as $K_{Z,E}$. Similarly we can obtain $K_{Z,H}$ for Fig. 1-c. Finally, K_Z for the configuration of Fig. 1-a can be obtained from $K_Z=(K_{Z,E}+K_{Z,H})/2$.

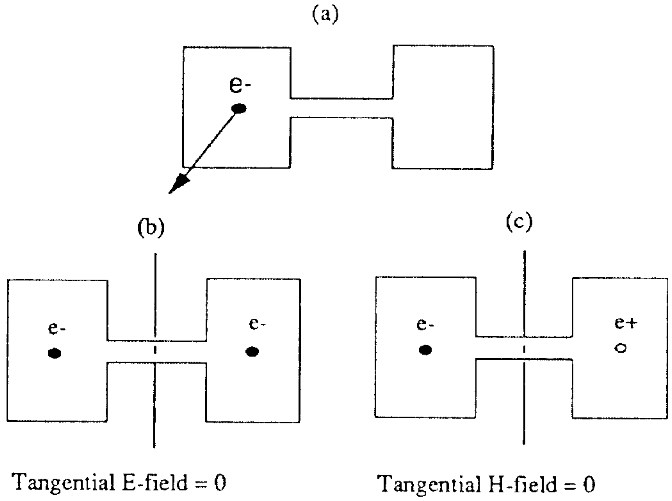

Fig. 1 Coupled waveguide configuration used in MAFIA simulation. (a) Geometry to be simulated (b) $E_{tan}=0$ at the central plane (c) $H_{tan}=0$ at the central plane

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III. SLOT THICKNESS EFFECT

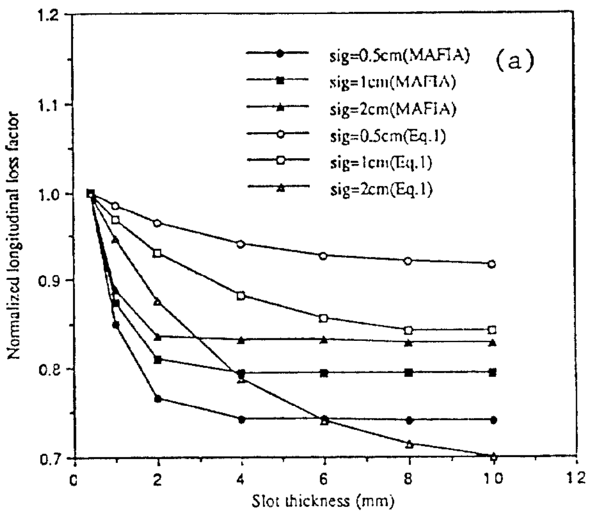
When the slot is infinitely thin, the energy left in the field diffracted through the slot to the outside or the vacuum pump chamber, U_{out}, and the energy scattered back into the beam chamber, U_{in}, will each be equal to $U_0/2$ where U_0 is the total radiated energy. However, for the slot whose thickness is finite, the evanescent field diffracted through the slot, assuming that the dominant frequency in the bunch spectrum is well below the cut-off frequecy of the slot, will decrease as $\exp(-2\pi t/\lambda_c)$ where t is the slot thickness and λ_c is the lowest cutoff wavelength. Then total diffracted energy loss may be expressed as

$$U=U_{out}+U_{in}=U_0[(1+a)+(1-a)\exp(-2\pi t/\lambda_c)]/2 \qquad (1)$$

where a is the portion of bunch spectrum above the cutoff frequency of the slot, and is determined by the bunch length and the slot length ($l>w$ in this study). Note that when $t=0$, U is equal to U_0. In M. Sands' paper, U is identified as K_z. This is a good approximation for short bunches. Contrary to this, Eq. (1) is valid for a bunch longer than the slot. Therefore, it may not be a good approximation to identify Kz with the total radiated energy U given by Eq. (1). Nevertheless it is interesting to compare U with the loss factor Kz as given by MAFIA. One may expect that the qualitative dependence on parameters are the same for these two quantities.

We computed K_z as a function of the thickness (depth) of the slot. The slot dimensions are taken to be l=1cm and w=0.4cm, and values of K_z normalized to unity at a slot thickness of 0.5mm, are plotted in Fig. 2-a. The simulation result shows that K_z for longer bunch decreases less than that for shorter bunch as t increases which is opposite to the behavior of U as expected from Eq. (1). In order to understand this unexpected behavior, we plot $K_{z,E}$ and $K_{z,H}$ separately (Fig. 2-b). We notice that $K_{z,E}$ ($K_{z,H}$) increases (decreases) as the slot gets thicker and become equal at a certain thickness. This trend was observed regardless of the bunch length and slot length. The reason for such a behavior may be explained as follows. For $E_{tan}=0$ (E-wall case), the electric wall current which is anti-parallel to the beam direction is perturbed by the presence of the slot. For a thick slot, electric wall currents are more perturbed at the edge of the slot resulting in an increase in $K_{z,E}$. This is also clear from the fact that, since we introduced the notch type resonator in our waveguide by specifying $E_{tan}=0$ on the slot surface, K_z would increase as the resonator gets deeper. For $H_{tan}=0$ (H-wall case), the magnetic wall current exists only on the surface of the slot and current intensity decreases as the thickness increases. Thus magnetic wall current is more perturbed for a thin slot resulting in the decrease in $K_{z,H}$ as the slot gets thicker. However, the behaviour in Fig. 2-a still remains to be explained.

Finally, transverse loss factor K_y was obtained by offsetting the beam in the direction perpendicular to the slot surface (the y-direction) and we found that K_y decreases as the slot gets thicker but more slowly than K_z.



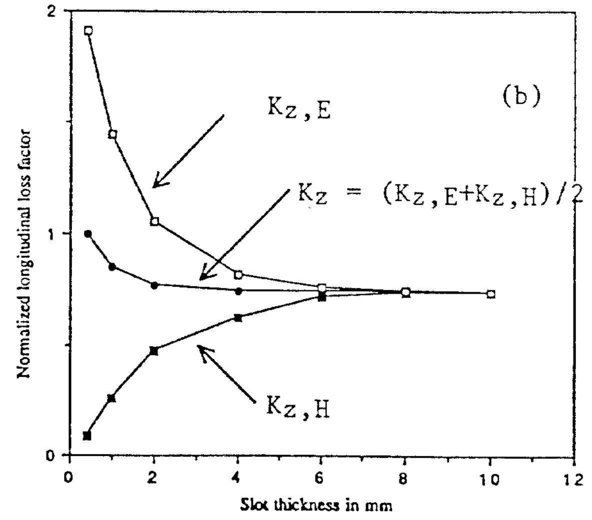


Fig. 2 Normalized loss factors for various bunch lengths as functions of slot thickness.

IV. SLOT LENGTH EFFECT

We studied the slot length effect in cases where the slot is longer than the beam bunch. In this study, the slot has a width w=0.4cm, a thickness t=0.4cm and a length which is varied as a parameter. According to M. Sands, K_z would increase slowly with the slot length regardless of the bunch length. However, Fig. 3-a shows three different behaviors depending on the bunch lengths σ_z=0.5cm, 1cm or 2cm. We also found that when we reduced the beam chamber size by a half, i.e. to a 4cm by 2cm waveguide, a similar trend was observed for σ_z=0.25cm, 0.5cm and 1cm. However, in the case of K_y, it does increase slowly as shown in Fig. 3-b.

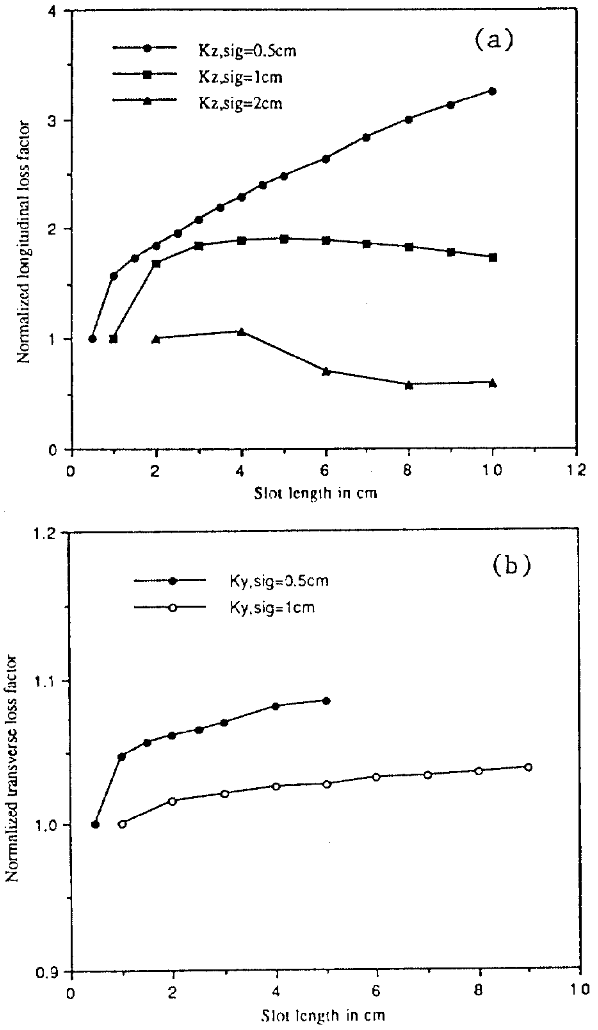


Fig. 3 Normalized loss factors as functions of slot length. The values for $\sigma_z = l$ are used as reference values.

V. SINGLE SLOT VERSUS MULTIPLE HOLES

Slots in the vacuum chamber wall are provided for vacuum conductance. For this purpose the slots may equally well be replaced by holes as long as they give the same opening area. It may in fact be easier to drill holes than to fabricate slots. Therefore, we compare the loss factors for two configurations. One is a long slot with a width of w=0.4cm and various lengths. For given slot length l, we compare with the second configuration of a number $N=l/w$ square holes with side equal to w. However, when l=2cm, we took N=4 instead of N=5 for neighboring holes are separated by 1mm. Thus, the opening areas for the two configurations, although not exactly the same, are quite similar. Fig. 4 shows K_z for these two configurations where σ_z=0.5cm. We can easily see that K_z for the multiple holes is proportional to the number of holes, whereas K_z for a single slot increases only slowly as the slot length increases. In addition, we also investigated how effectively one could reduce the loss factor by reducing the slot width. We replaced a single slot with w=0.4cm by two slots with w=0.2cm each. Suprisingly, K_z is reduced almost by a factor of ten. This is also true when we replaced a hole of r=0.2cm by four holes of r=0.1cm. All we discussed for K_z applies equally to K_y.

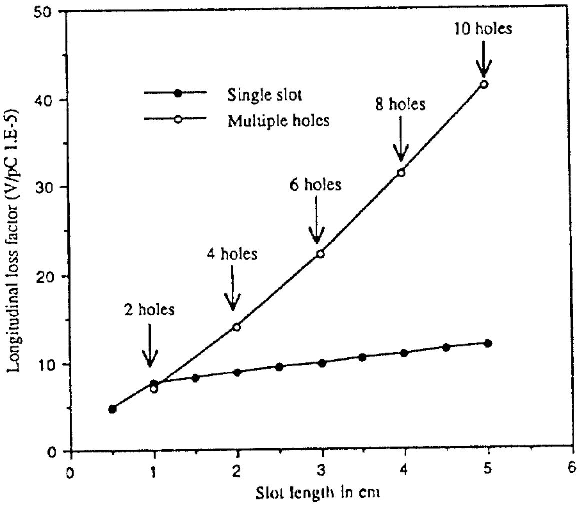


Fig. 4 Longitudinal loss factors for a single slot and for multiple holes as functions of slot length.

VI. CONCLUSION

In this study, we investigated the effect of slots in the vacuum chamber wall on the loss factor of the beam. We found that the contribution to the longitudinal loss factor is quite small, typically of the order of 10^{-6} ~ 10^{-4} V/pC/slot. But its behavior is sensitive to the variation of beam bunch length, slot size and vacuum chamber size. The contribution to the transverse loss factor for the slot is also marginal, typically 0.1 ~ 1 V/pC/m/slot and is rather insensitive to the variation of parameter values. We believe that, in order to understand the effects correctly, we need to calculate the impedance semi-analytically in a manner similar to the semi-analytical study of the pill-box cavity. Finally, for either the longitudinal or transverse effect, the proper geometry of the opening which yields the smallest loss factor is that which causes the least interruption in the wall current, namely long slender slots instead of multiple holes.

VII. REFERENCES

[1] R. Klatt et al., "MAFIA -A Three Dimensional Electromagnetic CAD System for Magnets, RF Structures, and Transient Wake-field Calculations," *Proceedings of the 1986 Linear Acclerator Conferences*, June 1986, pp. 276-278.

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[3] H.A. Bethe, "Theory of Diffraction by Small Holes," Physical Review, vol. 66, pp. 163-182, October 1944.