Impedance of a Perforated Liner and Its Impact on the SSC Collider

W. Chou and T. Barts
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave., Dallas, TX 75237

Abstract

Various approaches (analytical, numerical, and experimental) have been tried to investigate the impedance and wakefields of a liner. At low frequencies, the results obtained from different approaches are in agreement. At high frequencies, the simulations show that the resonance peaks and the associated long term wakes are related to the periodicity of the hole distribution. The dependence of the impedance on the size, shape and pattern of the holes and slots has been studied. The rounded short slots of random distribution is recommended for minimizing the impedance. The rf coupling between the area inside the liner and the annulus is negligibly small in the frequency range of interest. The impact of the liner on the safety margin and resistive wall instability has been studied.

I. INTRODUCTION

The synchrotron radiation in the SSC Collider will cause a large amount of gas load from the photon-induced desorption process and may result in a poor vacuum in the beam tube. A possible solution to the problem is to install a perforated liner inside the bore tube [1]. The introduction of the liner brings up a number of issues that need to be studied. Among them, one is the increase of the rf impedance. The increments come from the holes (or slots) as well as from the smaller ID of the liner.

The impedance of the holes and slots has been studied by means of 3D simulations (MAFIA [2] and HFSS [3]), analytical modeling [4], wire measurements [3] and electron beam measurement [5]. The impedance increments of the bellows, beam position monitors and other components due to a smaller liner ID have also been computed. The increase of the impedance implies the decrease of the safety margin, which is defined as the ratio of the instability threshold impedance to the machine impedance. This is now under study to determine the minimum allowable ID of the liner.

II. LOW FREQUENCY REGION

A. Analytical Model

For some structures, such as a pipe attached to a small pillbox or a pipe with small holes on its surface (i.e., the perforated liner), the longitudinal and transverse impedances can be approximated by a pure inductance L at low frequencies (below the cutoff):

$$Z_{\|}(\omega) = i\omega L\,, \quad Z_{\perp}(\omega) = i\,\frac{2c}{b^2}\,L \tag{1}$$

in which b is the radius of the pipe, c the velocity of light. When a Gaussian bunch traverses the pure inductance, it will generate the longitudinal and transverse wake potentials [2]:

$$W_{\|}(z) = \frac{c^2\,L}{\sqrt{2\pi\sigma^3}}\,z\,e^{-\frac{z^2}{2\sigma^2}}\,,\;\; W_{\perp}(z) = \frac{2c^2\,L}{\sqrt{2\pi}\sigma\,b^2}\,e^{-\frac{z^2}{2\sigma^2}} \tag{2}$$

in which σ is the rms bunch length. The magnitudes and locations of the peaks of the wake potentials are:

$$W_{\|}^{max(min)} = \pm\,\frac{c^2\,L}{\sqrt{2\pi}\,\sigma^2}e^{-1/2}\,, \quad \text{at } z=\pm\sigma \tag{3}$$

$$W_{\perp}^{max} = \frac{2c^2\,L}{\sqrt{2\pi}\,\sigma\,b^2}\,, \quad \text{at } z=0 \tag{4}$$

B. MAFIA Results

The inductance of a small hole with diameter d at low frequency has been worked out [4]:

$$L = \frac{Z_0}{48\pi^2\,c}\,\frac{d^3}{b^2}\,, \tag{5}$$

in which $Z_0 = 377\ \Omega$. Therefore, the peak of the wakes of each hole are given by (all dimensions in meters):

$$W_{\|}^{max} = \frac{Z_0\,c}{48\pi^{5/2}\sqrt{2e}}\,\frac{d^3}{\sigma^2 b^2} = 0.0577 \times \frac{d^3}{\sigma^2 b^2}\,\left(\frac{\mathrm{V}}{\mathrm{nC}}\right) \tag{6}$$

$$W_{\perp}^{max} = \frac{Z_0\,c}{24\pi^{5/2}\sqrt{2}}\,\frac{d^3}{\sigma b^4} = 0.00019 \times \frac{d^3}{\sigma\,b^4}\,\left(\frac{\mathrm{V}}{\mathrm{nC}\cdot\mathrm{mm}}\right) \tag{7}$$

Eqs. (6)-(7) can be compared with the MAFIA results as shown in Figs. 1a-b. When the hole size is small and bunch length large, the theory and simulations agree with each other. However, when the hole becomes larger ($d \geq 4$ mm) or the bunch becomes shorter (σ=0.25 and 0.6 cm), the simulation results appear to be larger than what the theory would predict. This probably indicates the breakdown of the low frequency assumption.

The hole shape in the simulations is a square rather than a circle. It would thus give an inductance larger than that of a circular one as predicted by Eq. (5). On the other hand, Eq. (5) is derived from a zero-thickness liner. The finite thickness (1 mm) used in the simulations would lead to a smaller inductance [6]. It is interesting to see from Fig. 1 that these two effects seem to cancel each other and result in a good agreement between Eqs. (6)-(7) and the MAFIA results.

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

0-7803-1203-1/93$03.00 © 1993 IEEE

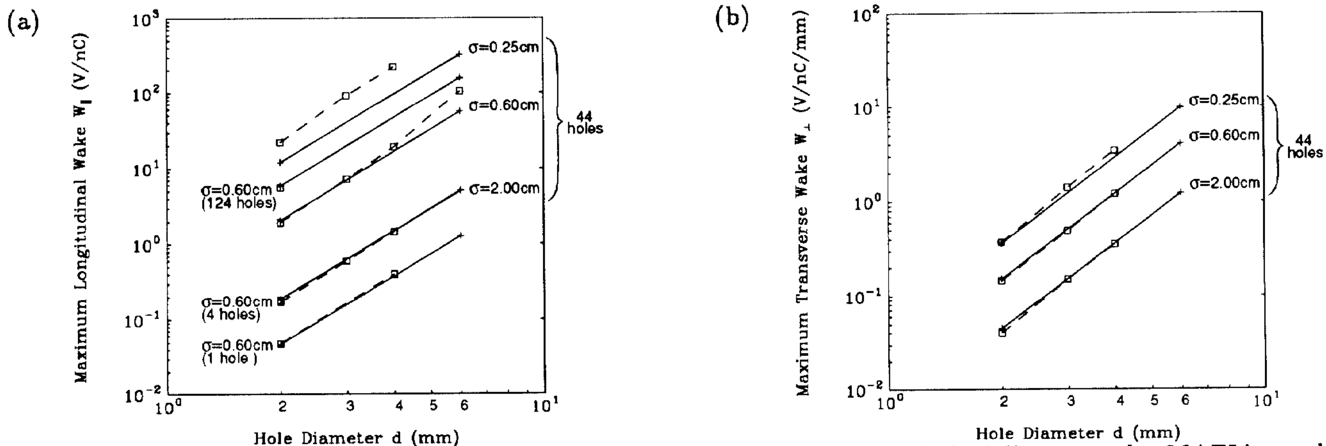

Figure 1. The solid lines are computed using Eqs. (6)-(7). The squares and dashed lines are the MAFIA results. (a) $W_{\parallel}^{max}$, (b) $W_{\perp}^{max}$.

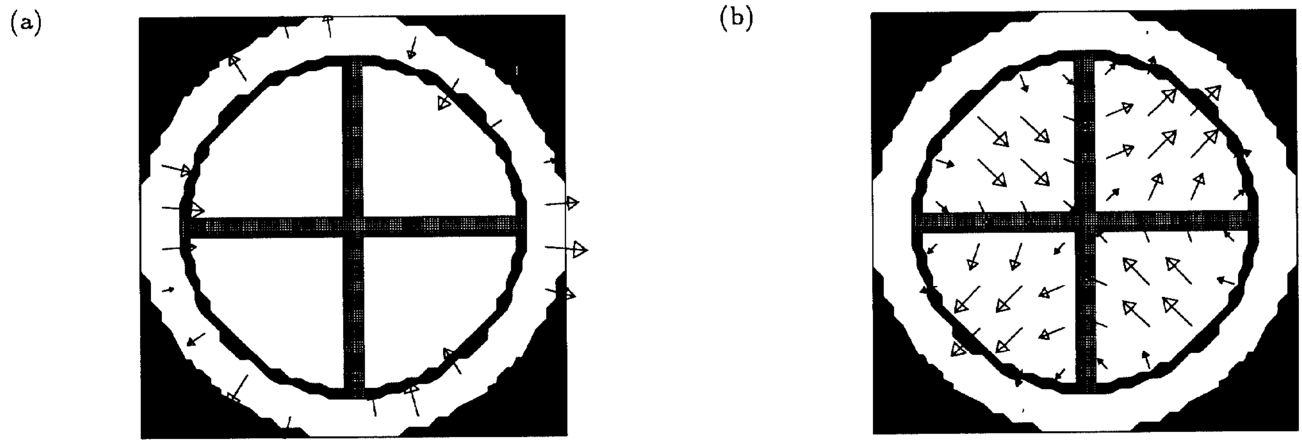

Figure 2. Electric field vectors for: (a) The TE31 mode (10.4 GHz) and (b) The TE21 mode(11.5 GHz).

III. HIGH FREQUENCY REGION

A. Fields in the Annulus

The annulus region allows the existence and propagation of a TEM wave, which has zero cutoff and travels with the speed of the light. In order to understand whether this should be a concern, the frequency domain simulation with periodic boundary conditions was carried out. Many modes have been identified and compared with the theoretical values of the frequencies. The errors are in general less than 1%. Two of them are shown in Fig. 2a-b. Up to 30 GHz, no coupling is seen between the inner and outer regions. Therefore, the impact of the co-axial structure to the impedance is considered to be insignificant.

B. Periodic Distributions of Holes on a Liner

When the holes are periodically arranged along the axis with 1 cm spacing, resonance peaks above the cutoff (~ 7 GHz) are observed in the longitudinal impedance spectrum as shown in Figs. 3a-b. Below the cutoff, the spectrum agree with the analytical value (5) within a few percent. imilar results have also been obtained for the transverse impedance.

C. Random distribution of Holes on a Liner

One effective way to reduce the resonance impedance is to destroy the periodicity of the hole distribution. This is demonstrated in Figs. 4a-b, when the spacing between two neighboring holes in the axial direction is randomized. Compared with Figs. 3a-b, the low frequency impedance remains about the same (as it should be due to the additivity), whereas the resonance peaks at high frequencies are greatly suppressed. However, by using the same technique, the reduction in the transverse direction is less dramatic. This needs further study.

D. Slots vs. *Holes*

When the holes are replaced by the slots that have the same area and have the major axis parallel to the pipe axis, the low frequency impedance is reduced, whereas the long term wakes and high frequency resonances are enhanced because it becomes easier to resonate [2]. Therefore, the trade off should be studied carefully. The short slots with rounded edges seem to be a good compromise.

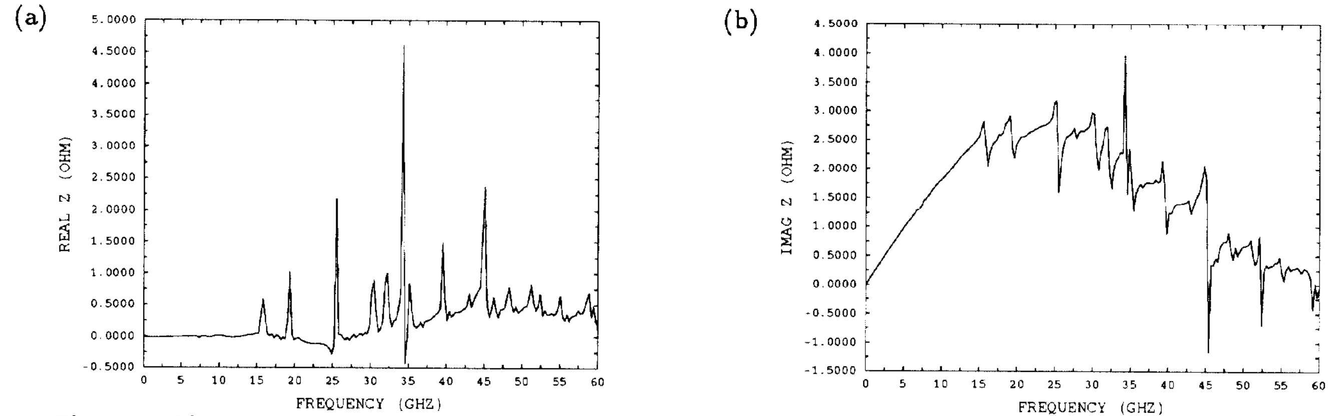

Figure 3. The longitudinal impedance for a liner with 420 square holes (2mm), periodically distributed.

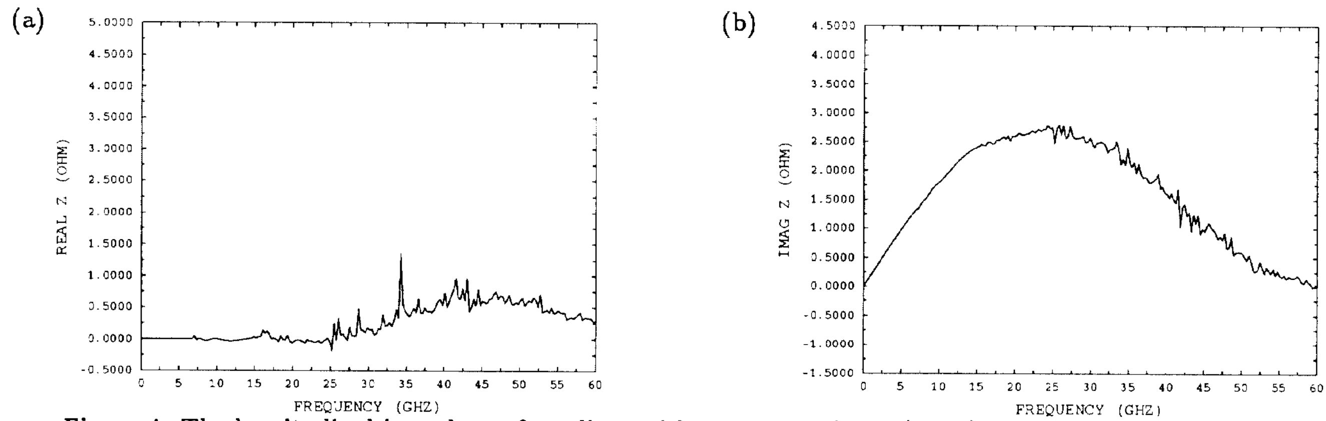

Figure 4. The longitudinal impedance for a liner with 420 square holes (2mm), randomly distributed.

IV. SAFETY MARGIN

The baseline beam tube ID is 33 mm. The impedance threshold before any coherent transverse instability could occur is 270 MΩ/m. Assuming the liner ID be 25.3 mm (as designed for the string test), hole diameter 2 mm, and 4% area coverage of the holes on the liner surface, then the safety margin will be reduced by a factor of 3, as listed in the table below.

Case	$Z_{\perp}^{(liner)}$ MΩ/m	$Z_{\perp}^{(others)}$ MΩ/m	$Z_{\perp}^{(total)}$ MΩ/m	Safety Margin
Baseline	-	40	40	6.7
With liner	37	80	117	2.3

There are several possible measures that will increase the safety margin: (a) To increase the threshold impedance by increasing the longitudinal emittance and rf voltage at injection of the Collider; (b) To reduce the machine impedance by maximizing the liner ID and optimizing the size and shape of the holes or slots.

V. RESISTIVE WALL INSTABILITY

The growth time of the resistive wall instability is proportional to ID^{-3}. The baseline specification is 110 turns. When a liner of 25.3 mm ID is installed, the growth time will be reduced to 50 turns. It will be further reduced if the stainless steel pieces are introduced near the BPM for thermal insulation purposes. As a consequence, the requirement of the feedback system becomes more demanding.

VI. REFERENCES

[1] H. T. Edwards, SSCL-N-771 (1991).

[2] W. Chou and T. Barts, "Wakefield and Impedance Studies of a Liner Using MAFIA," *Proc. Computational Accelerator Physics Conference (CAP93)*, San Francisco, February 22-26, 1993; also see SSCL-Preprint-204 (1993).

[3] L. Walling, private communication.

[4] S. Kurennoy, CERN Report SL/91-29; R. L. Gluckstern, CERN Report SL/92-05.

[5] Measurements of the liner impedance with large size holes have been made by J. Simpson's group using the short electron pulses of AATF at ANL. The results show that a better resolution is required in order to perform quantitative analysis.

[6] R. L. Gluckstern and J. A. Diamond, IEEE MTT, v. 39, p. 274 (1991).