Coupling Impedance of Vacuum Pumping Holes for the APS Storage Ring*

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Abstract

The coupling impedance of a single slot in a thick wall beam pipe was measured. The slot dimension is small compared to the wavelength of interest. The measurements were done by the wire method with the synthetic pulse technique[1]. Gating technique was also applied to obtain the reflection response for a structure that does not have appropriate calibration standards. The measured results are in good agreement with calculated impedance using analytical formulae given by other authors.

I. INTRODUCTION

In the design of storage ring components for the Advanced Photon Source (APS), it is often necessary to open vacuum pumping holes in the beam chamber wall. These holes are long and narrow, located in the longitudinal direction of the beam pipe to minimize their disturbance to the wall current. Since there are a great number of such holes in the storage ring, the impedance induced by these slots is of much concern.

This paper presents the result of a measurement on the coupling impedance due to a single slot using the wire method with synthetic pulse technique. Gating technique was applied to obtain the frequency domain reflection of the slot when calibration standards were not available for the beam chamber. The results show that this method is much more capable in measuring small signals than real pulse measurement. The measured impedance was compared with calculations.

II. THEORETICAL CALCULATION

In the past decades, extensive studies on the aperture coupling problem have been done by many researchers. Most of these studies were based on Bethe's theory of diffraction by small apertures [1]. An aperture is considered small if its dimension is less than a fraction of the wavelength of the excitation signal. Reflected and coupled fields were generated due to the existence of the aperture. These fields can be considered as excited by equivalent sources that consist of an electric dipole, a magnetic dipole, and a magnetic quadrupole[3]. The electric polarizability and magnetic susceptibility of these dipoles are readily available for circular, elliptic, and other common apertures [2], [3]. The beam coupling impedance of an aperture can be expressed in terms of these polarizabilities [3]. A long narrow slot can be approximated by an ellipse with a large eccentricity. The coupling impedance of such a rectangular slot is given by [4]:

$$Z(\omega) = \frac{jZ_0\omega w^4}{96\pi c b^2 \ell}\left(\ln\frac{4\ell}{w} - 1\right) \qquad (1)$$

where Z_0 is the characteristic impedance of the beam pipe and center wire structure; ω is the angular frequency of excitation; c is the speed of light; ℓ and w are the length and width of slot; and b is the radius of cylindrical beam pipe.

In Eq.(1), the slot is considered to be of zero thickness. According to R. Gluckstern [5], the coupling impedance of a circular hole in an infinitely thick wall will have a value which is 56 % of that for zero thickness. We can take this value as a reasonable estimation on the impedance reduction for the rectangular slot.

Note that the coupling impedance is purely imaginary below cut-off frequency of the beam pipe and is linearly proportional to the angular frequency ω.

In this measurement, the beam pipe has a rectangular cross section. Since Eq.(1) only applies to circular beam pipes, we use an estimated radius of the rectangular pipe for the calculation. The parameters for the test chamber are: Z_0=88 Ω; l=5 cm; w=0.4 cm; b=2 cm. The calculated result is shown in Fig. 3.

III. EXPERIMENTS

3.1 Coupling Impedance by Reflection

The experimental setup is shown in Fig. 1. The test chamber has a rectangular cross section with a dimension of 7 x 4 cm. A narrow slot is placed longitudinally in the middle of the common wall. The slot dimension is 5 x 0.4 cm. The thickness of the beam pipe is 0.64 cm. The measurements were made in the frequency domain (0.045--4.545 GHz) using a HP 8510B network analyzer. There are 201 data points measured for the reflection S_{11}. The average function of the analyzer was applied to reduce the noise level. The results were transformed into time domain by the built-in IFFT routine. Since there are no calibration standards available for the rectangular pipe, the calibration can only be made up to the end of the connecting cables. In order to eliminate all the reflections from the tapers and adapters, the Gating function was applied to the reflected synthetic pulse. In this way, the reflection due to the slot itself was obtained in the time domain as well as in frequency domain. This result can be used directly to estimate the coupling impedance of the single narrow slot.

There are two things one has to consider in this Gating technique. One is the influence of the taper on the magnitude of the pulse. The typical reflection coefficient of the taper is Γ = 0.3. Since the reflected pulse travels twice through the taper, its magnitude is reduced by a factor of $1 - \Gamma^2$ = 90 %. The other thing is that there is a DC current component contained in the synthetic pulse, which is the offset due to systematic error. If this component is not eliminated in the time domain

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data, then the resulting S_{11} in the frequency domain would be distorted dramatically at low frequencies. In order to eliminate this error, a reference chamber which has no slot in the chamber wall, was used. The time domain response of the reference chamber was subtracted from that of the slot. The obtained results in the time and frequency domains are shown in Fig. 2. The reflection detected by this method is on the order of 10^{-4}. This is far beyond the capability of real pulse measurement for detecting such a small reflection.

Suppose the conduction and radiation loss in the slot is negligible. After some derivation, we obtain the beam coupling impedance in terms of S_{11}:

$$\frac{|Z|}{n} = \frac{Z_L |S_{11}|^2}{n} \qquad (2)$$

where $n=f/f_0$, f_0 is the revolution frequency of the beam in the storage ring (271.55 KHz for APS) and Z_L is the characteristic impedance of the test chamber and center wire structure.

The coupling impedance of one slot obtained using Eq. (2) is plotted in Fig. 3. It can be seen that the result is in good agreement with the calculation of Eq.(1). The $\frac{|Z|}{n}$ of the slot is estimated to be $2 \times 10^{-8}\ \Omega$. The measured result deviates from the calculation when f>1.5GHz. This implies that the small hole approximation is valid for $f < 1.5$ GHz ($\ell < 0.2\lambda$).

3.2 Coupling Impedance by Radiation

In the previous section we obtained the coupling impedance due to the reflection under the assumption that the radiated energy loss through the slot is negligible. While the reflected energy corresponds to the imaginary part of the impedance Im(Z), the radiation energy loss contributes to the real part of the coupling impedance Re(Z). According to the derivation of S. Kurennoy [3], for a small hole($\ell/\lambda << 1$), we have the relation:

$$\frac{\mathrm{Re}Z}{|\mathrm{Im}Z|} \sim \left(\frac{\ell}{\lambda}\right)^3 << 1 \qquad (3)$$

Figure 4 shows the result for coupling measurement. The top two curves are S_{41}, S_{31}, which represent the signal coupled through the slot from port 1 to ports 4 and 3, respectively. These frequency domain responses are obtained by applying Gating function to the time domain synthetic pulse. Observe that S_{31} is about 20 dB higher than S_{41}; the slot behaves like a directional coupler in the measured frequency range. The bottom two curves are time domain synthetic pulse responses for ports 3 and 4. The second peak in S_{41} is from the multiple reflection of port 3 because the matching tapers do not have very good characteristic at these low frequencies. This can be verified from the 4-ns time delay between the two peaks which exactly corresponds to the length of the chamber. From the time domain result, we can see that the coupling signal, S_{31}, is 53 μunits while the reflected signal is 520 μUnits (see Fig. 3). Thus the energy radiated through the slot is about only 1 percent of that reflected by the slot. This verified the estimation of Eq.(3).

It is also observed from Fig. 4 that S_{31} has a linear dependence on frequency, since the top curve, which is for S_{31}, is quite similar to a logarithm curve on the semi-log plot. This conclusion holds only for a small slot ($\ell/\lambda << 1$). Figure 5 is the measurement result of the same slot for S_{31} up to a higher frequency (4 GHz). The linearity of S_{31} is only seen for f< 1 GHz. A resonance at 3 GHz is observed. Recall that the slot length is 5 cm; this resonance happened at half wave-length ($\ell = \lambda/2$). Similar resonance was also observed for reflection (S_{11}) at the same frequency (not shown here). Since both reflection and coupling were observed to have a reduced amplitude at resonance, one should anticipate that the transmission (S_{21}) has a maximum value when the half wavelength equals the slot length. Until now, we were not able to observe this directly from measurement.

Fig. 6 shows the measured coupling for different wall thicknesses. From top to bottom, the three curves are for wall thicknesses of 0.4, 3.2, and 6.4 mm, respectively. On this semi-log plot, the three curves are equally spaced by a 20-dB difference. This suggests that the coupling depends on wall thickness exponentially. This agrees with the prediction of M. Sands [6].

IV. CONCLUSION AND DISCUSSION

The beam coupling impedance of a single slot has been measured using the wire method with synthetic pulse technique. Gating was applied to eliminate the influence of tapers and adapters. The systematic error in the time domain response was corrected using a reference chamber. The measured results agree quite well with analytical formulae given by other authors. The impedance Z/n of a single slot was measured to be $2\times10^{-8}\ \Omega$. For small holes, the impedance is dominated by its imaginary part which is due to reflection. Its real part, which is due to radiation loss through the hole, is negligible. The small aperture approximation is valid when slot length is less than one-fifth of the wavelength. Both reflection (S_{11}) and coupling (S_{31}) have a linear dependence on frequency for small holes. Resonance was observed when the half wavelength equals slot length ($\ell=\lambda/2$). The influence of the wall thickness on reflection and coupling was also examined from measured results.

V. ACKNOWLEDGMENTS

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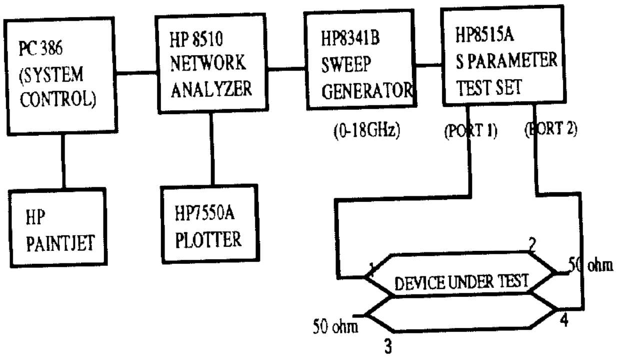

Fig. 1 Experimental setup for single slot measurement

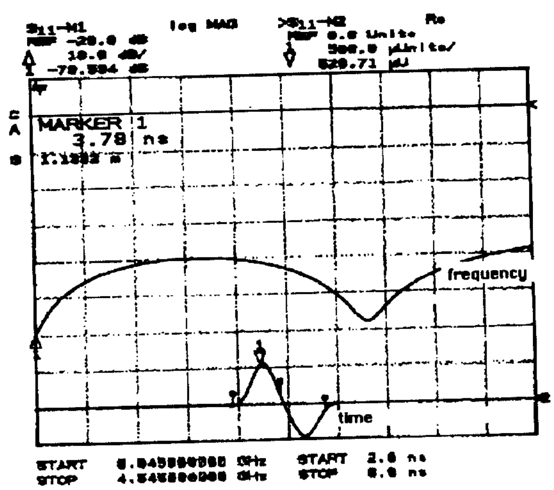

Fig. 2 Reflection of single slot measured in frequency and time domains

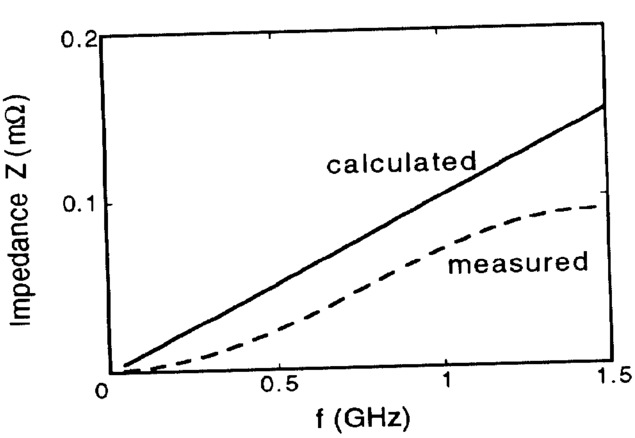

Fig. 3 Measured and calculated impedance of single slot.

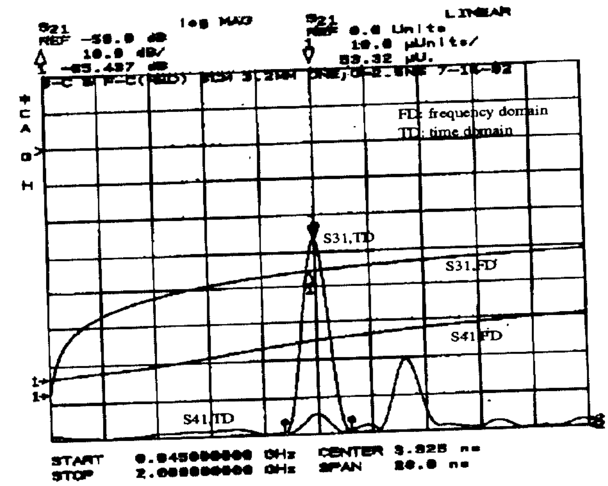

Fig. 4 Coupling of single slot in frequency and time domains

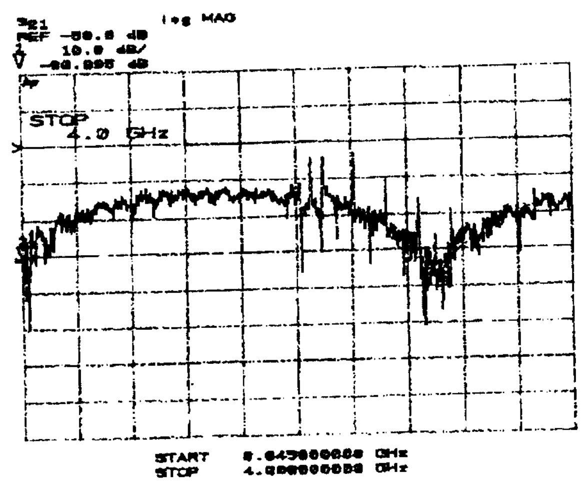

Fig. 5 Wide band characteristics of single slot.

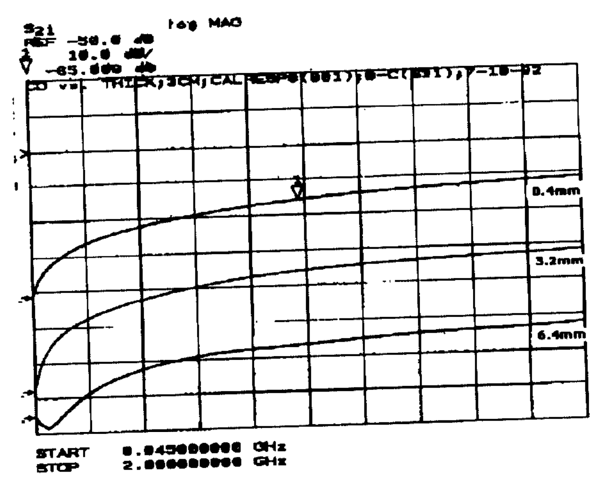

Fig. 6 Coupling of single slot in different wall thicknesses