APERTURE COUPLING MEASUREMENT IN A TEST CHAMBER FOR THE ADVANCED PHOTON SOURCE (APS)*

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Abstract

Aperture coupling measurements have been made using two identical rectangular chambers. A common wall between them has holes of various size, thickness, shape and number. The transverse electromagnetic (TEM) wave, which propagates in one rectangular chamber, couples through the aperture and radiates into the other chamber. The measured results are compared with the diffraction model and used to estimate the coupling impedance of a circulating beam. The results of these measurements was applied to the detailed design of some of the vacuum components in the Advanced Photon Source.

1. INTRODUCTION

In the Advanced Photon Source (APS) storage ring, the Photon Absorber is designed to use a multi-slot structure on the wall around the beam chamber. Slot opening could be as much as 4 mm wide and several cm long. They are longitudinally oriented in order to minimize the disturbance to the wall current. The loss parameter $K(\sigma)$, impedance $Z(\omega)$, and coupling coefficient k vary with slot length, wall thickness and number of slots. In order to test the behavior of such a structure, aperture coupling chambers were made to simulate the real beam chamber and photon absorber. The longitudinal and cross-sectional view of the structure is shown in Fig.1.

The aperture coupling through a single hole was first analyzed by Bethe [1] and the analysis was later applied to estimate the energy loss of the charge particle beam in a high energy accelerator by Sands [2]. Bethe showed that when a plane electromagnetic wave is incident onto an infinite conducting plane with a small circular hole, the diffracted field is the sum of the fields that would be radiated by an electric and a magnetic "dipole" located at the hole. In this so called "diffraction model", it is assumed that the wavelength of the incident field is much larger than the size of the hole (i.e. in low frequency limit).

The coaxial wire method with synthetic pulse technique [3] is used to simulate the behavior of real beam, by measuring the S parameters of the center wire and beam chamber coaxial structure. The measured frequency domain data are transferred into time domain by Inverse Fast Fourier Transform(IFFT) to obtain the synthetic pulse response.

2. FORMULAS

In the aperture coupling structure, the loss parameter $K(\sigma)$, impedance $Z(\omega)$ and coupling coefficient k are parameters that need to be determined by measurement. For a given beam bunch with length σ, and charge q, the beam energy loss after passing a certain structure is given by [4]:

$$\Delta E = K(\sigma)\, q^2 \qquad \text{(eV)} \qquad (1)$$

in which the loss parameter $K(\sigma)$ is given by:

$$K(\sigma) = 2Z_0 \frac{\int I_1(I_1-I_2)dt}{(\int I_1 dt)^2} \qquad \text{(V/pC)} \qquad (2)$$

where Z_0 is the characteristic impedance of the center conductor and reference chamber, and I_1,I_2 are currents flowing through the reference chamber and device under test, respectively. Here, the reference chamber is the structure shown in Fig.1 with a common wall having no slot. K is a function of beam length σ, in the same way as impedance Z is a function of frequency ω. K can be measured either by real time pulse or by synthetic pulse response obtained via IFFT.

Longitudinal impedance Z is given as [4]:

$$Z(\omega) = 2Z_0 \frac{S_{21}(\mathrm{ref})-S_{21}(\mathrm{DUT})}{S_{21}(\mathrm{ref})} \qquad (\Omega) \qquad (3)$$

where S_{21}(ref) and S_{21}(DUT) are transmission S parameters of the reference chamber and device under test, respectively.

The coupling coefficient k is a measure of coupled energy with respect to the input energy in dB:

$$k = -10 \log_{10} \frac{\int I_3^2 dt + \int I_4^2 dt}{\int I_1^2 dt} \qquad \text{(dB)} \qquad (4)$$

where I_3 and I_4 are the backward and forward coupled currents, respectively.

3. EXPERIMENTAL SETUP

Fig.2 shows the experimental system for the aperture coupling measurement. A HP8510B Network Analyzer is used to measure the 4X4 S parameters of the device under test. Only four of them need to be measured due to the symmetry of the structure. S_{11} and S_{21} are the reflection and transmission respectively of the upper chamber. S_{31} and S_{41} are backward and forward coupling between the upper and lower chambers.

The common wall between the upper and lower chambers can be replaced in order to have different slot parameters. For ease of the mechanical work, the cross sections of these chambers are of rectangular shape unlike the elliptical shape of the real beam chamber. Each chamber has a center wire to propagate the TEM wave. The appropriate taper and transitions are used for connection to the coaxial measurement system. The diameter of the center wire is 9.5 mm and its characteristic impedance is 88 Ω.

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Depending on the synthesized pulse length σ, frequency spans were varied from 1.6 GHz to 16 GHz. An IBM PC 386 was used for data acquisition, processing, and controlling of the system, via HP-IB, using HPBASIC. The HP8510B time domain option was used to do IFFT. The isolation of the system between input and output port is about -110 dB in frequency domain. The contact between the two chambers is improved by having vise-grips and RF finger springs, which gives better repeatability.

4. RESULTS

4.1 Coupling vs thickness

Forward coupling of one 5-cm slot with wall thicknesses 0.4 mm, 3.2 mm, 6.4 mm is shown in Fig.3. The scale is 10 dB/div. There are about 20 dB difference among these curves. Results are also given in Table 1: the coupling coefficient k and loss parameter K. Applying By equation (4) to the time domain data, the coupling coefficient is computed. The coupling coefficient k is larger with a thinner wall. The loss parameter K shows very little variation with wall thickness.

Table 1 Coupling coefficient k and loss parameter K of one 5 cm slot

Thickness(mm)	0.4	3.2	6.4
k (dB)	-68	-86	-106
K (V/pC)	6.8E-4	7.1E-4	5.5E-4

4.2 Coupling vs slot length

Backward coupling in the FD for 3-cm and 5-cm slots are shown in Fig.4. The top curve is for 5-cm slot and bottom one for 3-cm slot. The wall thickness is 6.4 mm. Frequency span is 45 MHz to 5 GHz, with 800 data points. Large coupling is observed for the 5-cm slot at 2.24 GHz. But for the 3-cm slot the resonance starts from 4.5 GHz. These resonances are related to half wavelength coupling as well as higher order modes existed in the chamber.

The frequency domain data are transferred into time domain to obtain synthetic pulse and coupling coefficient k. Coupling coefficient k is -118 dB for the 3-cm slot and -119 dB for the 5-cm slot. In order to compare with diffraction model, coupling coefficient k is calculated using these parameters for length, width, thickness and chamber effective radius, etc [2]. The difference of coupling coefficient k between the 3-cm slot and 5-cm slot is 4.5 dB. The reduced slot length significantly weakens the coupling between chambers.

4.3 Coupling vs number of slots

Backward coupling of multi-slot structures are shown in Fig.5. Here serial slots means that slots are arranged one after another in the longitudinal direction. Parallel slots are slots placed side by side on the chamber wall with the same longitudinal position. One can see that with more slots opened on the common wall, coupling increases significantly. In this case the synthetic pulse response given by the HP8510B is not applicable to the k calculation. The bandwidth of the resonance response shown in Fig. 3,4,5 is typically 5 MHz. The correct time domain response can only be obtained when the frequency step is small enough, compared with this value. Otherwise the frequency domain sampling theorem is not satisfied and time domain aliasing accurs. If the present 2-MHz frequency step is further decreased, the bandwidth becomes too narrow to obtain meaningful results.

Fig.6 shows the impedance of one 5 cm long slot. The wall thickness is 6.4 mm. Result is obtained by Eq.(3). Here the impedance is normalized as:

$$\underline{Z} = \frac{\underline{Z(\omega)}}{n} \qquad (\Omega) \qquad (5)$$

in which $n = \omega / \omega_0$ and ω_0 is the storage ring beam revolution frequency. A large impedance value at 2.24 GHz was observed due to the lower chamber resonance. This is under further investigation.

5. CONCLUSION AND FUTURE PLAN

The coupling coefficient, k, is larger with thinner walls, but the loss parameter does not vary much. The coupling coefficient of a single 3-cm slot is 9 dB less than that of a 5 cm-slot for 6.4 mm wall thickness. Decisions on slot length will be made upon further verification of this measurement. For a multi-slot common wall, much stronger coupling was observed in the frequency domain.

Capability of detecting weak signals is greatly improved by using the synthetic pulse technique on the HP8510B Network Analyzer. The repeatability is also much better than real time pulse measurement, due to the high stability and precision of the HP8510B. A different synthetic pulse length is obtained by simply changing the frequency span, thus making the technique very flexible.

At present, wide band and small step measurement in FD can't be obtained at the same time, because the number of data points is limited to 800 in the HP 8510 Network Analyzer. To simulate a beam of the bunch length about 30-50 ps, a wide frequency band is necessary while keeping the frequency step small to avoid time domain aliasing. It is planned to establish a automated measurement system controlled by the IBM PC, with the frequency band from DC to 16 GHz, sampling step 1 MHz.

6. ACKNOWLEGEMENT

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7. REFERENCES

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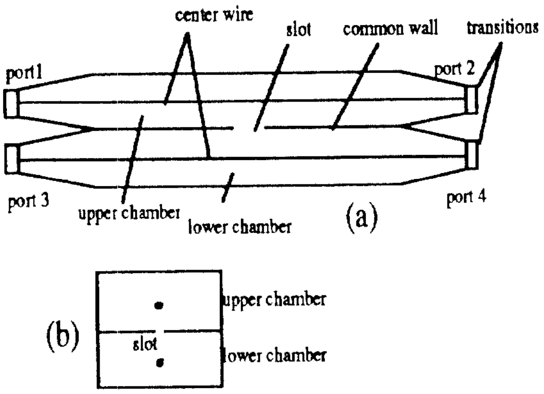

Fig.1 (a) Side view and (b) cross sectional view of the aperture coupling chambers.

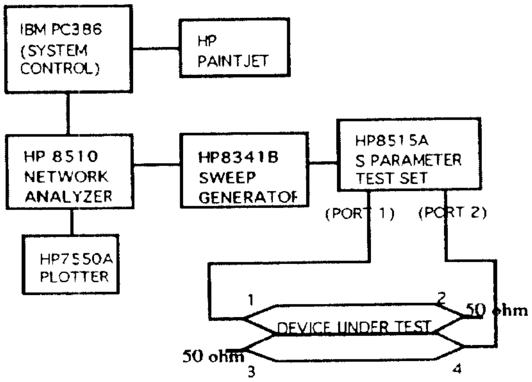

Fig.2 Measurement System Setup

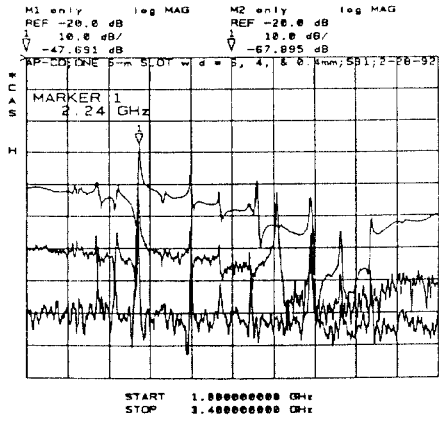

Fig.3 Coupling of one 5 cm slot with wall thickness 0.4, 3.2, and 6.4 mm from top to bottom: -20 dB reference level is shown by the arrow.

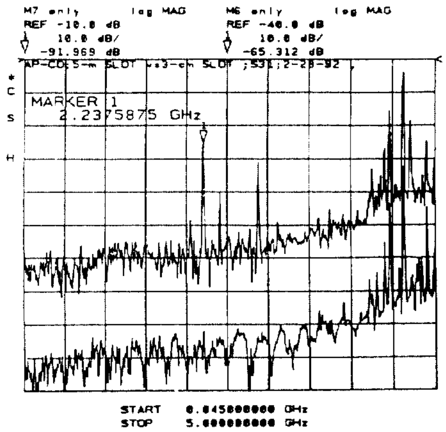

Fig.4 Backward coupling of one 3 cm slot (bottom graph) and 5 cm slot (top graph): reference level shown by arrow are -40 dB for bottom and -10 dB for top, respectively.

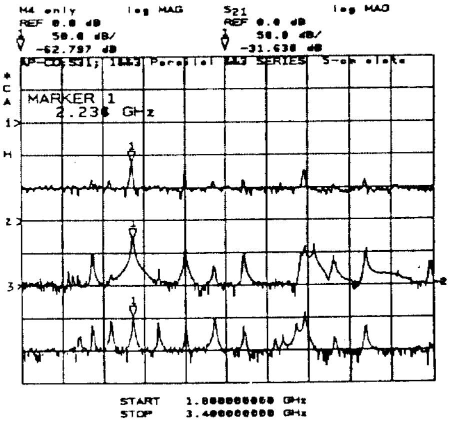

Fig.5 Backward coupling: (top) for one 5 cm slot; (middle) for three parallel slots; (bottom) for three serial slots with wall thickness 6.4 mm and 0 dB reference shown with numbered arrows.

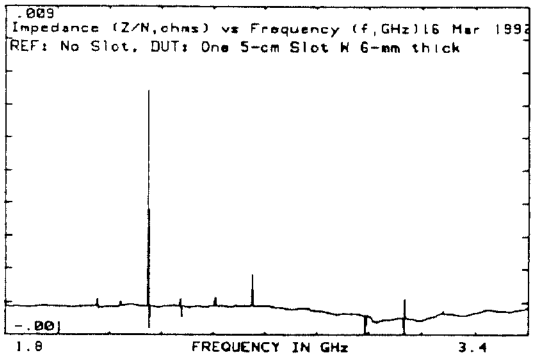

Fig.6 Broadband impedance of one 5 cm slot, obtained from Eq.(3) with wall thickness of 6.4 mm.