RF Impedance Measurement Status for the 7-GeV Advanced Photon Source (APS)*

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Abstract

Beam-coupling impedances (Z) for the 7-GeV APS storage ring have been numerically estimated. In order to confirm these calculations, the wire method with a synthetic pulse technique was used to measure the beam coupling impedance of various vacuum components around the main storage ring. A section of the beam+antechambers, a vacuum isolation valve with and without the RF shielding screen, an insertion device, and a photon absorber were used as a device under test (DUT) to obtain the results. The results were compared with the computer simulations and the Z or k-dependance on bunch length was studied.

1. INTRODUCTION

The beam coupling impedance (Z) must be kept small so that the desired operating current is achieved. A computational investigation has been carried out to estimate the coupling impedance of a large variety of structures in the APS ring. This was done mainly by W.Chou [1], using the 2D, 3D MAFIA codes and the TBCI code. The results are summarized in Table 1 as the APS impedance budget. However, the computer simulation was not feasible in some cases due to the complexity of the task and some numbers shown in Table 1 were scaled from PEP-data sheet (pump port, kicker, etc.). As seen, the largest longitudinal impedance is contributed by the RF cavities (even though the contribution of the fundamental mode has been subtracted from the calculation) and the transverse impedance is mainly contributed by the transitions between the beam chamber and the insertion device (ID) section. The maximum permissible longitudinal impedance and the transverse impedance are estimated to be 2 Ω and 0.3 MΩ/m, respectively.

TABLE 1 APS Impedance Budget (after W.Chou, Ref.1)

Component	Number	Impedance Z_l/n (Ω)	Z_t (MΩ/m)
1. RF Cavity (HOM)	15	0.2	0.02
2. Transition between chamber & ID section	34	0.03	0.06
3. Transition between chamber & rf section	3	0.1	0.003
4. Crotch absorber	160	0.01	0.002
5. Shielded bellows	160	0.04	0.007
6. Shielded transitions	80	0.02	0.003
7. Flange full-penetration weldment	480	0.01	0.008
8. Elliptical tube weldment	80	1E-3	1E-3
9. Shielded end conflat	80	1E-3	1E-3
10. Valve	80	0.01	0.01
11. Beam position monitor	360	0.02	
12. Transition between chamber w. & w/o ante chamber	120	3E-3	1E-3
13. Resistive wall		0.01	0.01
14. Space charge		1E-5	0.03
15. Others (kickers, bumpers, ion pump ports, etc.)		0.3	
Subtotal		1	0.15
Budget (subtotal X 2)		2Ω	0.3 MΩ/m

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The coupling impedance of the APS vacuum chamber components was measured with a coaxial wire method, using a synthetic pulse technique [2]. The coaxial wire method is a wide-spread tool for bench measurements of beam coupling impedance. By sending a short pulse through the center wire of a transmission line or a vacuum chamber, the current distribution on the inner surface of the beam chamber can be obtained which corresponds similarly to the current distribution produced by a passing beam bunch. When the electromagnetic field distribution has been perturbed by any discontinuity, a reaction on the center wire takes place similar to that of a perturbed wake field on the particle beam bunch.

The measurement procedure employed here is known as a synthetic pulse technique. Since any pulse defined as a function of amplitude over time can also be defined by its frequency spectrum of amplitude and phase, the synthetic pulse can be generated in the time domain (TD) via fast Inverse Fourier Transform (FFT) from measurements taken in the frequency domain (FD). This leads to higher spectral density than real-time pulse measurements, thus giving a higher dynamic range and better repeatability.

2. LOSS PARAMETER AND IMPEDANCE

For a given particle beam bunch with charge, q, the energy loss of the bunch is

$$\Delta E = Kq^2 = 2Z_L\, q^2 \frac{\int I_1(I_1-I_2)\, dt}{(\int I_1\, dt)^2} \qquad \text{(eV)}, \quad (1)$$

where Z_L is the characteristic impedance of the transmission line or the wire running through the beam pipe, I_1 is the current flowing through the reference chamber, I_2 is the current flowing through the DUT (see Fig.1), and K is the loss parameter which is physically the energy loss in eV for a bunch with a unit charge passing through the vacuum component. Thus the longitudinal loss parameter can be computed from measurements by the integration of the current over the pulse length. It must be pointed out that K is also a function of particle bunch length, σ.

Broadband impedance [3] represents the impedance of the non-resonant device (e.g. any little discontinuity around the storage ring), which is given as:

$$Z = \frac{Z(\omega)}{n} \qquad (\Omega), \quad (2)$$

assuming that Q=1, where $n = \omega/\omega_o$ ($\omega_o = 2\pi/T_o$ is the revolution frequency of a beam in a storage ring) and $Z(\omega)$ is the individual mode impedance of the DUT in the FD. $Z(\omega)$ can also be computed from the measurements,

$$Z(\omega) = 2Z_L \frac{[I_1(\omega)-I_2(\omega)]}{I_1(\omega)} \qquad (\Omega), \quad (3)$$

where $I_1(\omega)$, $I_2(\omega)$ are the current measured for the REF and the DUT in the FD, respectively.

3. EXPERIMENTAL SETUP

As depicted in Fig.1, a Network Analyzer (HP8510B) was used to measure the two-port S-parameters of the DUT. The S-parameter or the scattering matrix represents a linear algebraic relation between the incoming and outgoing signals for any device. The measurement calibration features in the HP 8510B [5] were used in order to reduce or eliminate some of the system error which could be produced by any mismatch or imperfection of the connection or cable itself.

The frequency span was varied from 45 MHz to 18 GHz, depending on the appropriate synthetic pulse length. The effective pulse lengths with the frequency span of Δf =16 GHz, σ_{rms}, are 37.5 psec with Low Pass mode (LP) and 75 psec with Band Pass mode (BP) which are comparable to the bunch length of the 7-GeV APS positron beam. The cut-off frequency of the reference pipe also determines the choice of frequency span. Above cut-off, modes in addition to TEM waves could be generated and propagated through the pipe. An HP 9000/308 computer was used for data acquisition and the control of the system. After the appropriate calibration was done, the data was collected using the REF and the DUT in the FD to get the impedance, Z or Z/n, .

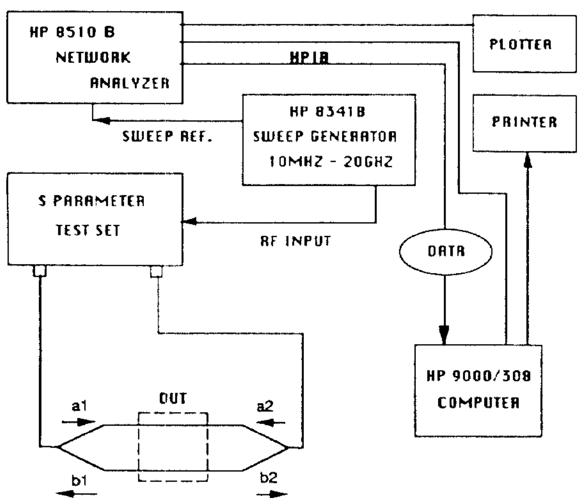

Fig.1 Experimental setup

The TD option computes a synthetic pulse via FFT to find the loss parameter, k. There are two modes available to obtain the synthetic pulse: BP mode and LP mode, but only the LP mode can be used to compute the loss factor K [4]. Some of the powerful features of the HP 8510B were used including: 1) "Windowing", (available only in the TD) achieved by mathematically filtering in the FD. It can improve viewing the dynamic range of the response of the DUT in the TD, but at the expense of increased pulse width. Usually the "normal" mode was used, 2) "Gating", a time-filtering tool which allows one to select the response at a particular portion of the DUT in the TD. Converting "gated" data back to the FD, one can see the frequency response at that particular portion of the DUT as well.

Temperature variation around the network analyzer is minimized to stabilize the signal from the source, especially during calibration. The room temperature was kept at 72 ± 3 °F to get a reliable signal from the DUT.

Three different types of center conductors were utilized: a 2 mm-brass wire, a 9.5 mm-Cu pipe, and an elliptical 50 W-matching Al rod. Their characteristic impedances are 125, 88, and, 50 Ω, respectively. Thin wire is used with a high-Q structure, otherwise the wire causes a frequency shift and a de-Queing in the resonant structure [5]. The test system consists of various APS vacuum components (60 cm long each), and the transition portions (30 cm each). Each transition portion is tapered at 10 ° to eliminate multiple reflections due to sharp discontinuities. The parameters in the test system and in the APS storage ring are summarized in Table 2.

In the impedance computation, the use of the transmission coefficient (S_{21}) instead of the reflection coefficient (S_{11}) reduces the error in Z(ω) because the multiple reflections must be considered for the S_{11}.

Table 2. Test system and APS storage ring parameters

Characteristic impedance of the center conductor,	Z_o	=	125, 88, 50 Ω
Sweep frequency,	Δf	=	45 MHz ~18 GHz
Nominal energy,	E	=	7.0 GeV
Revolution Frequency,	f_o	=	271.55 kHz
Beam chamber-cutoff freq.	f_{cut}	=	4.6 GHz
Single Bunch length, rms	σ_{rms}	=	5.3 mm
Single Bunch length,	FWHM	=	27.5 ps
Number of bunches,	n_b	=	20
Bunch current,	I_b	=	5 mA

4. MEASUREMENTS AND RESULTS

4.1 Vacuum isolation valves

A VAT Gate valve (Model S-47) was tested against a general-purpose vacuum valve in which there is no RF shielding. The RF shielding screens on Model S-47 line up with the APS beam chamber and consist of 64 RF liners, each of which measures 1.8 mm wide, 45 mm long, and 0.1 mm thick, with a 1.3-mm gap between liners.

Fig.2 shows the resonances of the valve, when there is no RF shielding. These resonances are strong enough (Z/n ~ 0.08 Ω, Q ~ a few 10^3 at many frequencies) to drive the longitudinal coupling-bunch instability.

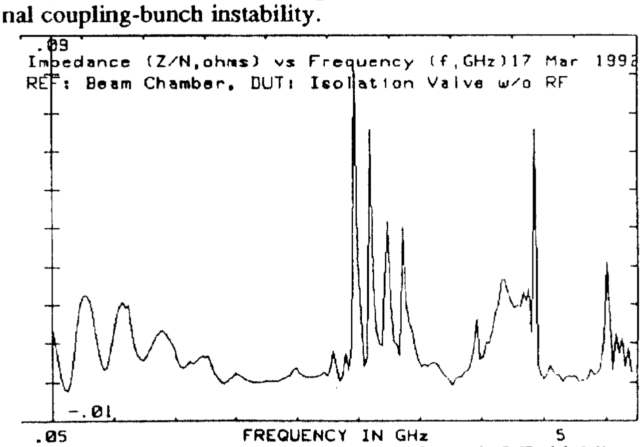

Fig. 2 Broadband impedance for the valve w/o RF shielding

Resonances with the model S-47 valve appear due to the fact that there are the gaps in the flanges between the beam chamber and the S-47. The broadband impedance is much smaller (~ 0.01 Ω) and the Q value is lower (< 20) for these gaps at 2.3 GHz. Closing the flange gaps with 1mm RF gaskets significantly reduces the impedance down to 3×10^{-4} Ω, and using the "Gate" tool (G = 0.2 nsec) selects only the impedance due to the RF liners (4×10^{-5} Ω). These results are summarized in Table 3. The total impedance of 80 valves (0.03 Ω) is somewhat higher than the calculated value (0.01 Ω), but its contribution to the total impedance budget is minimal (1.5 %, see Table 1).

Table 3 Loss parameter and impedance for the isolation valve (* means a peak value).

Isolation valve	Loss factor K (V/pC)	Impedance Z/n (Ω)
w/o RF, gasket	0.1	0.08^*
w RF but w/o gasket	0.01	0.002^*
w RF, gasket,w/o Gate	4×10^{-3}	4×10^{-4}
w RF,gasket,Gate	2.5×10^{-3}	4×10^{-5}

4.2 Beam chambers

Small sections of the beam+antechambers (one with a tapered transition to the antechamber [ANTE1] and the other with an abrupt transition to the antechamber [ANTE2]) were used as the DUT, and the beam chamber [BEAM] was used as the reference pipe. The beam chamber has an elliptical cross section with major axis 2a = 8.5 cm, and minor axis 2b = 4.2 cm, which connects to the antechamber through a 1-cm slot. The cutoff frequency of the beam pipe is about 4.6 GHz and 16 GHz for the 1-cm slot.

In the measurements, the reproducibility error was 6×10^{-4} V/pC for Δf =16 GHz span and the k-value was measured to be 2×10^{-3} V/pC. In addition, the data for ANTE1 (tapered transition) and ANTE2 (abrupt transition) were collected and compared. The measurements showed that there was no difference within measurement error in terms of the loss parameter due to the shape of the transition to the antechamber.

4.3 Photon absorber

Photon absorbers are used to absorb unwanted synchrotron radiation to prevent most of the photons from striking the wall of a vacuum chamber. In order to do this effectively, part of the photon absorber must be placed into a beam chamber (intrusion) and the geometry requires RF shielding to prevent coupling of the beam into the absorber region. To determine an RF shielding structure, test chambers were made to measure the coupling due to an aperture between two identical chambers through holes of various sizes, thicknesses, shapes, and numbers. Some preliminary results on aperture coupling experiments is presented separately in these proceedings [6].

Intrusion measurements were done with the two models. The old geometry has a round shape and the new geometry is designed to be sharply irrupt and then slowly tapered as shown in Fig.3. The reflection response in the TD due to the round intrusion as a function of the penetration into the beam chamber is shown in Fig.4. The frequency span Δf=16 GHz or equivalent synthetic pulse σ_{rms} = 37.5 psec was used and Gate =1 nsec was opened to cover all the reflection around the round intrusion (7 cm long). The computed K-values for these intrusions are also shown in this figure. Data for the sharp intrusions has not yet completely taken, but some initial data indicates that the loss factor for the sharp intrusion is much smaller than that of the round intrusion.

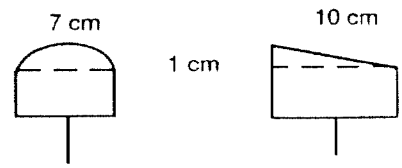

Fig. 3 Intrusions (round & sharp)

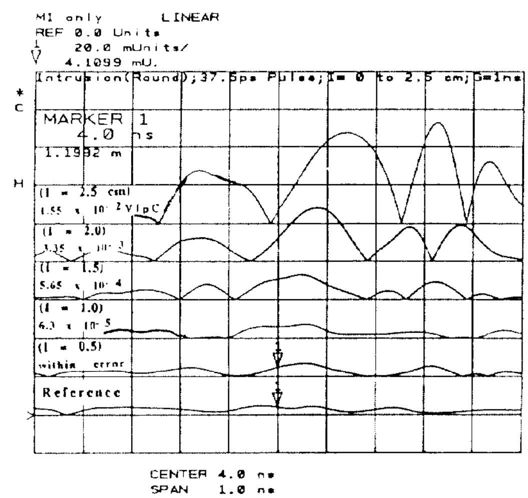

Fig.4 TD transform of the S11 for the round intrusion with I = 0 to 2.5 cm and their loss factor, k.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] W.Chou, Y.Jin, "Impedance Studies-Part 4: The APS Impedance Budget," ANL-LS-115, 1988; "Impedance and Bunch Lengthening in the APS," in Proc. of the Impedance and Bunch Instability Workshop (1990).

[2] F.Caspers, "Beam Impedance Measurement By the Wire Method using a Synthetic Pulse Technique," IEEE-Trans. on Nuclear Science, V NS-32, 1914 (1985).

[3] S.Chattopadhyay, "Introduction to Accelerator Physics," presented in US Particle Accelerator School," June 3-14,1991.

[4] J.J.Song, "Experimental Study of Coupling Impedance Part I Longitudinal Impedance Measurement Techniques," APS Light Source Note, Oct., 1991.

[5] G.Jackson, "Experimental Methods in Accelerator Physics," presented in US Particle Accelerator School, June 3-14, 1991.

[6] J.J.Song, et.al., "Aperture Coupling Measurement in a Test Chamber for the Advanced Photon Source (APS)," in these proceedings.