Experimental Study of Coupling Impedance Part I Longitudinal Impedance Measurement Techniques

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Abstract

Beam coupling impedances for the 7-GeV APS storage ring have been numerically estimated [1]. In order to confirm these calculations, measurements of the coupling impedance of various vacuum components around the main storage ring were done with a coaxial wire method. In this paper, the procedure of the longitudinal impedance measurement techniques will be described. As an example, sections of the *Cu* beam chamber, the *Cu* beam+antechambers, and the *Al* beam+antechambers were used as a device under test (DUT) to obtain the results. The transverse impedance measurements will be described in a separate paper.

I. 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 [2], using the 2D, 3D MAFIA codes and the TBCI code. The results are summarized in Table 1 as the APS impedance budget. However, due to the complexity of the task, the computer simulation was not feasible in some cases and some numbers shown in Table 1 resulted from scaling the 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 due mainly to the transitions between the beam chamber and the insertion device (ID) section. The maximum permissible longitudinal

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TABLE 1 APS Impedance Budget (after W.Chou, Ref.2)

ADVANCED PHOTON SOURCE

Component	Number	Impedance	
		Z_L/n (Ω)	Z_t (M Ω /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)		2 Ω	0.3 M Ω /m

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impedance and transverse impedance are estimated to be 2Ω and $0.3 \text{ M}\Omega/\text{m}$, respectively.

The coupling impedance of the APS vacuum chamber components was measured with a coaxial wire method, using a synthetic pulse technique [3]. The coaxial wire method is a widespread 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, giving a higher dynamic range and better repeatability.

II. LOSS PARAMETER AND IMPEDANCE

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

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

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 (REF), 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, k , can be computed from measurements by the integration of the current over the pulse length such as:

$$k = 2Z_L \frac{\int I_1(I_1 - I_2) dt}{(\int I_1 dt)^2} \quad (\text{V/pC}), \quad (2)$$

It must be pointed out that k is also a function of particle bunch length, σ . The power loss of one bunch can be calculated from eq. (1),

$$P_b = \Delta E/T_0 = I_b^2 Z_{tot} \quad (W), \quad (3)$$

where T_0 is the period of revolution of a beam around a storage ring, $I_b = q/T_0$ is the average beam current, and Z_{tot} is the total impedance. It should be noted that the total impedance for a vacuum component is the sum of the individual mode impedances weighted by the frequency spectrum of the exciting bunch.

Fig. 1 a) A SCHEMATIC DIAGRAM OF A) REFERENCE BEAM CHAMBER, AND B) A DEVICE UNDER TEST (DUT).

Alternatively, the broadband impedance [4] represents the impedance of the nonresonant device (e.g. any little discontinuity around the storage ring), which is given as:

$$\underline{Z} = \frac{Z(\omega)}{n} \quad (\Omega), \quad (4)$$

assuming that $Q=1$, where $n = \omega/2\pi f_0$ and $f_0 = 1/T_0$ 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,

$$Z(\omega) = 2Z_L \frac{[I_1(\omega) - I_2(\omega)]}{I_1(\omega)} \quad (\Omega), \quad (5)$$

where $I_1(\omega)$ and $I_2(\omega)$ are the current measured in the FD with the REF and the DUT, respectively. The wake potential should be referred at this point, which is defined as the integrated perturbed electromagnetic energy acting on the beam bunch with a unit charge and can be also derived by transforming eq. (5) into the TD,

$$W_b(t) = - \frac{2Z_L [I_1(t) - I_2(t)]}{q} \quad (\text{V/pC}). \quad (6)$$

III. EXPERIMENTAL SETUP & MEASUREMENT

As depicted in Fig. 2, a Network Analyzer (HP 8510B) 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. Some calibrations frequently applied are: a) 1-PORT calibration for reflection only, b) THRU & ISOL calibration for transmission only, c) FULL 2-PORT calibration for reflection and transmission, and d) TRL calibration [6] or TSD calibration [7] for non-coaxial devices. When there is no reference chamber available, the TSD calibration could be used to calibrate the test system up to the DUT.

The frequency span was varied from 45 MHz to 18 GHz, depending on the appropriate synthetic pulse length. The effective pulse lengths, σ_{rms} , with frequency span of $\Delta f = 16$ GHz, are 37.5 psec with Time Low Pass mode and 75 psec with Time Band Pass mode; these are approximately the same scale as the positron beam in the APS storage ring. The cut-off frequency of the reference pipe also determines the choice of frequency span. Above cut-off, other modes in addition to TEM waves could be generated and propagated through the pipe; that is not the case for the actual particle beam. But as suggested by Lambertson [8], TM or TE waves could be eliminated with microwave absorbers and, simultaneously, TEM signals can be transmitted through the wire without significant loss. The effects of other modes on the impedance measurement would be minimal, as long as the DUT doesn't have a resonant structure and the signal from the reference pipe is available to cancel those effects.

An HP 9000/308 computer was used for data acquisition and control of the system. Basically, data was collected with the REF and the DUT in the FD to get the impedance, Z or Z/n , after the appropriate calibration was done.

FIG. 2 EXPERIMENTAL SETUP ON A SYNTHETIC PULSE TECHNIQUE

The TD option computes a synthetic pulse via FFT to get the loss parameter, k . There are two modes available to get the synthetic pulse: Time Band Pass mode (BP) and Time Low Pass mode (LP). The BP mode is the general-purpose time domain mode, which is useful in making TD measurements for bandpass devices. But due to the band-limited nature of this mode, only the magnitude of the response is meaningful and displayed. The LP mode simulates the traditional TD Reflectometer measurement with either the Step or Impulse. It contains more information about the impedance such as the nature of the impedance or "magnitude & phase." But the resolution of the TD measurement with the LP is less than with the BP since

the number of points chosen in the LP is limited by the frequency span [9].

Detailed step-by-step procedures for measurement and calculation are contained in Appendix A. Several small computer codes, written mainly by D.F. Voss using HP Basic 5.1 [10], are summarized in Appendix B. Some of the powerful features of the HP 8510B were used such as "windowing" and "gating." "Windowing" works only in the TD and is achieved by mathematical 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. "Gating" is 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. But keep in mind that it doesn't improve the physical resolution of the DUT itself. A gate span is limited by the frequency span and gate shape used for measurements. Typically, the minimum gate span was 0.2 nsec or 6 cm for the frequency span, $\Delta f = 16$ GHz, and the "wide" gate shape.

Temperature variation around the network analyzer should be minimized to stabilize the signal from the source, especially during the calibration. The room temperature was also 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- Ω matching Al rod. Their characteristic impedances are 125, 88, and, 50 Ω respectively. Thin wire should be used with a high-Q structure, otherwise the wire causes a frequency shift and a de-Queing in the resonant structure [11]. It seems to be workable to use the 50- Ω line to measure the broadband impedance, Z/n , of the nonresonant device. Moreover, the elliptical-Al center rod makes the 50- Ω match of the test chamber to the rest of the test system so that it gives a lesser reflection and has a higher signal-to-noise ratio.

The test system consists of various APS chamber pieces (each 60 cm long), and the transition portions (30 cm each). 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 (see Fig. 3). The cutoff frequency of the beam pipe is about 4.6 GHz and 16 GHz for the 1-cm slot. There are as many as 120 transitions between beam chambers, with and without antechambers, around the 1104-m circumference main ring.

The transition portion is tapered at 10° to eliminate multiple reflections due to sharp discontinuities. But keep in mind that these tapered portions work as a step for the lower frequency region below

a few hundred MHz. The parameters of the test system and of the APS storage ring are summarized in Table 2.

Table 2. Test system and APS storage ring parameters

Characteristic impedance of the center conductor,	Z_L	=	125, 88, 50 Ω
Sweep frequency,	Δf	=	45 MHz ~18 GHz
Nominal beam energy,	E	=	7.0 GeV
Revolution Frequency,	f_0	=	271.55 kHz
Beam chamber-cutoff freq.	f_{cut}	=	4.6 GHz
Bunch length, rms	σ_{rms}	=	5.3 mm
Bunch length, FWHM	σ	=	27.5 ps
Number of bunch,	n_b	=	20
Bunch current,	I_b	=	5 mA

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

$$Z(\omega) = 2Z_L \frac{[S_{21}(\text{ref}) - S_{21}(\text{DUT})]}{S_{21}(\text{ref})} \quad (\Omega). \quad (7)$$

IV. RESULTS and DISCUSSION

Small sections of the *Cu* beam+antechambers (one with a tapered transition to the antechamber [ANTE1] and the other with an abrupt transition to the antechamber [ANTE2]) and *Al* beam+antechamber [ANTE3] were used as the DUT and the *Cu* beam chamber [BEAM] was used as the reference pipe. Their physical lengths are the same within ± 1 mm or ± 3.3 psec. Typical transmission data (S_{21}) taken for BEAM and ANTE2 in the FD are shown in Fig. 3-1. Small transmissions from both BEAM and ANTE2 are seen in the low frequency region (≤ 0.5 GHz) and in the high frequency region (≥ 13.5 GHz). The low frequency fluctuations come mainly from the transition cones (not from the DUT itself) and the high frequency losses are mostly from connections and contacts through the test system. These transmissions can be eliminated by either THRU calibration and/or gating as you will see later. Their corresponding synthetic pulses with the BP mode are also shown in Fig. 3-2. They simulate the Gaussian particle bunches in the test chambers, of which each peak represents a propagation time as well as an average transmission coefficient. Their propagation times are about 4.006

nsec for both and average transmission coefficients are 933.84 mU for BEAM and 930.94 mU for ANTE2. Since the two signals are almost identical, the loss parameter with ANTE2 (due to the 1-cm slot and the abrupt transition to the antechamber) is expected to be small. In addition, the data for ANTE1 (tapered transition) and ANTE2 (abrupt transition) were taken to compare the difference (even though there is no figure presented in this paper). The measurements showed that there was no difference in terms of the loss parameter due to the shape of the transition to the antechamber (at least within measurement error).

It might be interesting to compare the synthetic pulse method with the real-time pulse measurement at this point. Real-time pulses of 150 ps FWHM were used to measure the k-loss parameter of the same chambers mentioned above [12]. The loss parameter determined from the real-time pulse measurement appeared to be three times greater than that resulting from the synthetic pulse method. Moreover, the TD measurement with the real-time pulse for the small k-values was repeatable only up to 0.002 V/pC. This was because of the amplitude jitter in an Avtech AVH-C Pulser. With the synthetic pulse method, the repeatability error was 4×10^{-4} V/pC with the frequency span, $\Delta f = 16$ GHz, and the k-value was measured to be 1.8×10^{-3} V/pC with the LP mode.

It is quite useful to discuss how the impedance measurement (or k-parameter) is affected by the time mode used to produce the synthetic pulse. The synthetic pulses are computed via a FFT and then plotted as in Fig. 4: the wide pulse is from the BP mode and the short pulse is from the LP mode. The pulse length of the BP mode is about twice that of the LP mode. Also, the pulse with the BP mode doesn't provide the real part of the transmission coefficient separately, but only provides the magnitude. Since we are only interested in a real part, the synthetic pulse with the BP mode is not fully suitable to use for the loss parameter calculation. The value of k using the BP mode is on the whole smaller than the value found from using the LP mode.

As mentioned earlier, one can use "gating" to eliminate unnecessary reflections from the connections, the contacts, and/or the transition portions through the test assembly attached to the DUT. These are illustrated in Fig. 5-1 (TD) and in Fig. 5-2 (FD). In Fig. 5-1, the reflection coefficient (S_{11}) and the transmission coefficient (S_{21}) with Cu beam+antechamber [ANTE2] are plotted in the TD from -1 nsec to 9 nsec. The first top curve is S_{11} without Gate and the second signal is S_{11} with Gate = 1 nsec. Clearly seen, all the reflections were removed when the Gate was on, except the portion of interest or the

DUT itself (30 cm long with Gate = 1 nsec). The bottom two curves are S_{21} with and without Gate; peaks are at 4 nsec. The curves are not much different from each other but S_{21} with Gate has a little higher peak than without Gate (even though it is hard to see in this time scale). By converting data back to the FD, one can distinguish gated signals from the original signals. In Fig. 5-2 the top graph is S_{21} without using Gate (the curves with noise or a high-frequency fluctuation) and the second graph is S_{21} with Gate = 1 nsec (the smooth curves). The scale is the same for all. The reference level was lowered to see the second curve clearly. Also S_{11} with and without Gate are shown. S_{11} with Gate went down by 20 ~ 40 dB over the frequency span up to 16 GHz. How effectively one can remove unwanted reflections up to the DUT! Typical graphs were plotted: in Fig. 6-1 the broadband impedance, Z/N , vs frequency was plotted when there was no Gate and in Fig. 6-2 with Gate = 0.5 nsec, using the data from ANTE3 and the reference chamber. With Gate, the measured impedance seemed to be averaged over the frequency span. In fact, the value of Z/N is reduced overall simply because it represents the impedance of nothing but the DUT.

Most of the results on the impedance measurement with the beam+antechambers are tabulated in Table 3: one for the Cu beam+antechamber and the other Al beam+antechamber. Also shown is the comparison between the LP and the BP for the loss parameter calculation although the BP pulse isn't fully suitable to use. The Z/N values are averaged out around the cutoff frequency of the beam chamber, and the Z/N values with * are peak values and the corresponding peak frequencies were around 1 ~ 1.5 GHz. Since the impedance for ANTE3 is $2 \times 10^{-5} \Omega$, the total impedance of the 120 transitions with and without the antechamber around the storage ring is $2.4 \times 10^{-3} \Omega$, which is a little smaller than the computer-calculated value ($2.4 \times 10^{-3} \Omega$, see Table 1).

Several conclusions can be made: 1) use the appropriate Cal Set and Gating to get the impedance and the loss parameter of the DUT only, 2) use the Time Low Pass mode (LP) to get the synthetic pulse and then get the loss parameter of the DUT, 3) the contribution of the impedance of the antechamber to the APS impedance budget is negligible (about 0.3% of the total).

Device under Test		Cu beam+ante chamber [ANTE2]		Al beam+ante chamber [ANTE3]	
		Z/N (Ohm)	k (V/pC)	Z/N (Ohm)	k (V/pC)
CAL 6 (0-16 GHz)	BP		0.0046		0.001
	LP	1 E-4 [5 E -4]	0.0018	1 E-4[3 E -4]	0.0063
	LP+Gate	1 E -4	0.0037	1 E -4	0.0038
	repeatability		0.0004		
CAL 5 (0-5 GHz)	BP		0.0015		0.0003
	LP	1.3 E-4[6 E-4]	0.0025	6 E-5[3 E -4]	0.0009
	LP+Gate	1 E -4	0.0022	<u>2 E -5</u>	<u>0.0008</u>
	repeatability		0.0002		

Table 3 Broadband Impedance and Loss Parameter
for Ante Chambers with BP or LP, and with & without Gate

Fig.3-1 Typical transmission data (S_{21}) taken for BEAM (top) and ANTE2 (bottom) in the Frequency Domain.

Fig.3-2 Their corresponding synthetic pulses with the BP mode:
M2 for BEAM, S₂₁ for ANTE2.

Fig.4 The synthetic pulses with two different time modes: the wide pulse for the BP mode, the short one for the LP mode.

Fig.5-1 The S_{11} & S_{21} for ANTE2 with and without Gate in the TD: the top two graphs are S_{11} and the bottom two graphs are S_{21} .

Fig.5-2 The S_{11} & S_{21} for ANTE2 with and without Gate in the FD:
 the top two graphs are S_{21} and the bottom two graphs are S_{11}

Fig.6-1 Broadband Impedance vs Frequency for ANTE3 without Gate

Fig.6-2 Broadband Impedance vs Frequency for ANTE3 with Gate=1nS

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Appendix A

MEASUREMENT PROCEDURE of LONGITUDINAL IMPEDANCE

PREPARE MEASUREMENTS

- * Preset to the default setting for HP 8510B. ($Z_L=50$, etc.)
Check the calibration which is about to be used (frequency span, # points, average #, step, etc.)
For the calibration, use Impulse, Step, Time Low Pass, the appropriate number of points, and average number.
HP codes may be needed: "XFER_CAL" to save the CAL SET to the computer and "GET_CAL" to load the CAL SET from the HP 8510B.
 S_{21} should be read less than 0.1 dB over the frequency span. If not, the test system needs to be recalibrated.
For a signal less than 80 dB, the isolation process should not be omitted.
- * Connect the reference chamber (REF) into the HP8510.
Check for any significant loss in S_{21} (i.e. any peculiar discontinuity). If so, try to remove it and push the restart button.
- * Write the experimental parameters and conditions: characteristic impedance, temperature, cal set #, date, title, etc.

Remarks

- * Plot whatever you read and measure on the HP plotter.
- * Read the file to be used for the calculation into the memory of the HP 8510B and save it onto both the hard disk (HD) and a floppy disk for backup.
HP codes may be needed: use "XFER_MEM" to save the data to computer and "LOAD_MEM" to load the data to HP 8510B.
- * Write any important information for the measurements in the log book (e.g. the file names you save).

DURING MEASUREMENTS

(A) Start with REF.

- * Read S_{11} in channel 1 and S_{21} in channel 2 in the frequency domain (FD).
Read S_{21} into the memory of the HP 8510B and then save it to the HD of the computer.
- * Transfer above data into the time domain (TD) via FFT.
Read S_{11} in channel 1 and S_{21} in channel 2 in the TD.

Read S_{21} again by expanding the appropriate time-span (center at the peak).

Read S_{21} into the memory of the HP 8510B and then save it to the HD.

- * Repeat (A) with the different frequency span (or with the different cal set #).

(B) Setup with the device under test (DUT).

- * Read S_{11} in channel 1 and S_{21} in channel 2 in the FD, using the same scale as the REF, if possible.

Read S_{21} into the memory of the HP 8510B and then save it to the HD.

- * Calculate the impedances: $|Z(\omega)|$, $\text{Re}[Z(\omega)]$, $\text{Im}[Z(\omega)]$ and $|Z(\omega)|/n$ and print the results on the HP printer. (To do these, do hand-calculation first and use the HP code later.)

Use the HP code "ZCALC" to calculate the impedances above and plot Z vs f .

- * Transfer above data into the TD via FFT.

- * Read S_{11} in channel 1 and S_{21} in channel 2 in the TD, using the same scale as the REF.

Read S_{21} again by expanding the same time-span as the REF (you may use "GATE" in order to remove an unnecessary ringing or noise).

Plot $S_{21}(\text{REF})$ over $S_{21}(\text{DUTs})$.

Read S_{21} into the memory of the HP8510 and then save it to the HD.

Calculate the loss parameter $K(\sigma)$, using the real part of S_{21} .

HP codes may be needed: "KCALC" for k-computation with LP, and "KCALC2" for k-computation with BP.

- * Repeat (B) as you do at the end of the (A) with the different frequency span (or different cal set #).
- * Try to plot $K(\sigma)$ vs σ if necessary.

AFTER MEASUREMENTS

- * Recheck the experimental parameters and conditions, especially any change during the measurements.
Compare the results with any available computer simulation and recheck the experimental measurements.
- * Try to notice any missing data, plot, print and/or calculation.
- * Backup the data files onto the 3.5" floppy disk.
- * Write anything to remember and anything to repeat the following day in the log book.

Appendix B 1
Save Calibration into HD "XFER_CAL"

```
10  !XFER_CAL June 4,1991
20  INTEGER Numb,Poin,Hdr,Lgth,I,J
30  ASSIGN @Dt TO 716;FORMAT OFF
40  OUTPUT 716;"CAL?;"
50  ENTER 716;I
60  PRINT "CAL SET ";I
70  OUTPUT 716;"CALI?;"
80  ENTER 716;Cal$
90  C$=CHR$(34)
91  Pt=POS(Cal$,C$)
92  PRINT "Pt =";Pt
94  SELECT Cal$
95    CASE "UNDEFINED"
96      PRINT "Turn on cal set and PRESS CONTINUE"
97      PAUSE
98    CASE "RESPONSE"
99      Numb=1
100   CASE "ONE-PORT 2-PORT"
101     Numb=12
102  END SELECT
103  PRINT "Active Cal type =";Cal$
104  PRINT "PRESS CONTINUE TO TRANSFER CAL SET"
110  PAUSE
120  PRINT "Number of arrays for FREQ. RESP. = 1"
130  PRINT "Number of arrays for 2-PORT CALIBRATION = 12"
140  INPUT "Enter number of arrays",Numb
150  OUTPUT 716;"FORM3;POIN;OUTPACTI"
160  ENTER 716;Poin
170  INPUT "Enter filename for cal set",File_name$
180  MASS STORAGE IS ":",1500,1"
181  Rec=Poin*16*Numb/256
182  Rec=INT(Rec)+1
190  CREATE BDAT File_name$,Rec
200  ASSIGN @Don TO File_name$
210  ALLOCATE Cal(1:Numb,1:Poin,1:2)
220  FOR I=1 TO Numb
230  OUTPUT 716 USING "K,ZZ";"OUTPCALC",I
240  ENTER @Dt;Hdr,Lgth
250  PRINT "Header =";Hdr
260  PRINT "Length =";Lgth
```



```
270   FOR J=1 TO Poin
280     ENTER @Dt;Cal(I,J,1),Cal(I,J,2)
290   NEXT J
300 NEXT I
310   OUTPUT @Don;Numb,Poin,Hdr,Lgth,Cal(*)
320   ASSIGN @Don TO *
330   MASS STORAGE IS ":DOS,C"
340   END
```

Appendix B 2
Load Calibration into HP 8510B "GET_CAL"

```
10 !"GET_CAL" Oct 7,1991
20 ! Get cal set from disk and transfer to 8510
30 INTEGER N,Numb,Poin,Hdr,Lgth,I,J
40 ASSIGN @Dt TO 716;FORMAT OFF
50 MASS STORAGE IS ":",1500,1"
60 INPUT "Enter cal set filename",File_name$
70 ASSIGN @Don TO File_name$
80 ENTER @Don;Numb,Poin,Hdr,Lgth
90 ALLOCATE Cal(1:Numb,1:Poin,1:2)
100 PRINT TABXY(1,20),"Loading ";File_name$;" from disk"
110 ENTER @Don;Cal(*)
120 ASSIGN @Don TO *
130 MASS STORAGE IS ":DOS,C"
140 OUTPUT 716;"Corroff;"
150 OUTPUT 716;"Call;"
160 IF Numb=1 THEN
170   Command$="CALIRESP;"
180 ELSE
190   Command$="CALIFUL2;"
200 END IF
210 OUTPUT 716;Command$
220 OUTPUT 716;"HOLD;"
230 FOR I=1 TO Numb
240   OUTPUT 716 USING "14A,2Z,A";"FORM3;INPUCALC";I;"
250   OUTPUT @Dt;Hdr,Lgth
260   PRINT "Header #";I;" =";Hdr
270   PRINT "Length #";I;" =";Lgth
280   FOR J=1 TO Poin
290     OUTPUT @Dt;Cal(I,J,1),Cal(I,J,2)
300   NEXT J
310 NEXT I
320 OUTPUT 716;"SAVC;"
321 INPUT "Enter cal set #",N
330 OUTPUT 716;"CALS"&VAL$(N)&";"
340 OUTPUT 716;"CONT;"
350 LOCAL 716
360 END
```

Appendix B 3
Save Data into HD "XFER_MEM"

```
10  !"XFER_MEM" July 26,1991
20  ! Transfer data from analyzer to computer memory/disk
30  INTEGER Points
40  DIM A$(80)
50  REAL D(1:801,1:2)
60  Points=
70  REDIM D(1:Points,1:2)
80  ASSIGN @Fast TO 716
90  INPUT "Enter file information",A$
100 INPUT "Enter data storage filename",File_name$
110 MASS STORAGE IS ":",1500,1"
120 CREATE BDAT File_name$,60
130 ASSIGN @Don TO File_name$
140 INPUT "Enter memory #",M
150 OUTPUT 716;"DEFM"&VAL$(M)&";"
160 OUTPUT 716;"DISPMEMO;"
170 OUTPUT 716;"FORM4;OUTPMEMO;"
180 ENTER 716;D(*)
190 OUTPUT @Don;A$,D(*)
200 ASSIGN @Don TO *
210 MASS STORAGE IS ":DOS,C"
220 LOCAL 716
230 END
```

Appendix B 4
Load data into HP 8510B "LOAD_MEM"

```
10  !"LOAD_MEM" July 8,1991
20  INTEGER Points
30  DIM A$[80]
40  REAL D(1:801,1:2)
50  Points=801
60  REDIM D(1:Points,1:2)
70  ASSIGN @Fast TO 716
80  INPUT "Enter data storage filename",File_name$
90  MASS STORAGE IS ":",1500,1"
100 ASSIGN @Don TO File_name$
110 ENTER @Don;A$,D(*)
120 ASSIGN @Don TO *
130 PRINT A$
160 OUTPUT 716;"FORM4;INPUData;";
170 OUTPUT 716;D(*)
180 MASS STORAGE IS ":DOS,C"
190 LOCAL 716
200 END
```

Appendix B 5

Impedance Computation and Plot "ZCALC"

```

10  ! ZCALC (Frequency Domain)
20  ! ZCALC is HP-code of the longitudinal impedance
30  ! calculation from the measurements:
40  !  $Z(w) = 2Z_L[S21(ref)-S21(dut)]/S21(dut)$ 
50  !  $Z_L$  is the characteristic impedance of the center conductor
60  ! S21 is the forward transmission measurement
70  !Data is transferred from disk
80  REAL Frev,Start,Stp,Freq,Inc
90  INTEGER I,Points,ZL,First_point,Last_point
100 DUMP DEVICE IS 701,EXPANDED
110 Frev=2.74E-4          !Revolution frequency
120 ZL=50
130 DIM A$(80)
140 DIM B$(80)
150 DIM C$(80)
160 DIM Ref$(40)
170 DIM Dut$(40)
180 REAL D(1:801,1:2)
190 REAL V1(1:801)
200 REAL V2(1:801)
210 REAL V3(1:801)
220 REAL V4(1:801)
230 REAL Zf(1:801)
240 REAL F(1:801)
250 REAL N(1:801)
260 REAL Z(1:801)
270 REAL Dif(1:801)
280 REAL Lin_mag1(1:801)
290 REAL Lin_mag2(1:801)
300 REAL Imp1(1:801)
310 REAL Imp2(1:801)
320 REAL Z_divn(1:801)
330 REAL Graph(1:801)
340 Points=801
350 REDIM D(1:Points,1:2)
360 ASSIGN @Fast TO 716
370 MASS STORAGE IS ":",1500,1"
380 INPUT "Enter reference data storage filename",Ref_name$
390 ASSIGN @Don TO Ref_name$
400 ENTER @Don;A$,D(*)

```

```
410 ASSIGN @Don TO *
420 PRINT A$
430 INPUT "Enter reference device",Ref$
440 FOR I=1 TO Points
450   V1(I)=D(I,1)
460   V2(I)=D(I,2)
470   Lin_mag1(I)=SQR(V1(I)^2+V2(I)^2)
480 NEXT I
490 INPUT "Enter DUT data storage filename",Dut_name$
500 ASSIGN @Don TO Dut_name$
510 ENTER @Don;A$,D(*)
520 ASSIGN @Don TO *
530 MASS STORAGE IS ":DOS,C"
540 PRINT A$
550 INPUT "Enter device under test",Dut$
560 FOR I=1 TO Points
570   V3(I)=D(I,1)
580   V4(I)=D(I,2)
590   Lin_mag2(I)=SQR(V3(I)^2+V4(I)^2)
600 NEXT I
610 INPUT "Select impedance(VREAL,VIMAG,LINMAG)",Imp$
620 SELECT Imp$
630   CASE "VREAL"
640     MAT Imp1= V1
650     MAT Imp2= V3
660   CASE "VIMAG"
670     MAT Imp1= V2
680     MAT Imp2= V4
690   CASE "LINMAG"
700     MAT Imp1= Lin_mag1
710     MAT Imp2= Lin_mag2
720 END SELECT
730 INPUT "Enter start frequency in GHz",Start
740 INPUT "Enter stop frequency in GHz",Stp
750   Inc=(Stp-Start)/(Points-1)
760 FOR I=1 TO Points
770   Dif(I)=Imp1(I)-Imp2(I)
780   Zf(I)=2*Z0*Dif(I)
790   F(I)=Start+Inc*(I-1)
800   N(I)=F(I)/Frev
810   Z(I)=Zf(I)/Imp2(I)
820   Z_divn(I)=Z(I)/N(I)
830 NEXT I
```

```
840 INPUT "Select graph to plot(Z,Z/N)",Plot$
850 SELECT Plot$
860 CASE "Z"
870     MAT Graph= Z
880     E$="Z"
890 CASE "Z/N"
900     MAT Graph= Z_divn
910     E$="Z/N"
920 END SELECT
930 IF E$="Z" THEN
940     PRINT "MAX Z=";DROUND(MAX(Z(*)),3)
950 ELSE
960     PRINT "MAX Z/N=";DROUND(MAX(Z_divn(*)),3)
970 END IF
980 INPUT "Enter reference value",V
990 PRINTER IS 26
1000 FOR I=1 TO Points
1010 IF E$="Z" AND Z(I)>V THEN
1020     PRINT "I=";I;"Z=";DROUND(Z(I),3);"  FREQ=";DROUND(F(I),3)
1030 ELSE
1040     IF Z_divn(I)>V THEN PRINT
1050     "I=";I;"Z/N=";DROUND(Z_divn(I),3);"  FREQ=";DROUND(F(I),3)
1060 END IF
1070 NEXT I
1080 INPUT "Do you want to change the reference voltage?",An$
1090 IF UPC$(An$)="Y" THEN GOTO 980
1100 PRINTER IS CRT
1110 Zavg=DROUND(SUM(Z)/Points,3)
1120 PRINT "ZAVG=";Zavg
1130 GINIT
1140 GRAPHICS ON
1150 SEPARATE ALPHA FROM GRAPHICS
1160 VIEWPORT 0,125,10,90
1170 Vmax=MAX(Graph(*))
1180 Vmin=MIN(Graph(*))
1190 WINDOW 0,Points,Vmin,Vmax
1200 H=Vmax-Vmin
1210 INPUT "Enter first point",First_point
1220 INPUT "Enter last point",Last_point
1230 FOR I=First_point TO Last_point
1240     PLOT I,Graph(I)
1250 NEXT I
1260 AXES Points/10,H/10,First_point,Vmin,Points/2,1,3
```

```
1260 AXES Points/10,H/10,Points,Vmax,Points/2,1,3
1270 CSIZE 4
1280 MOVE 15,Vmin
1290 LORG 1
1300 Vmin=DROUND(Vmin,3)
1310 LABEL Vmin
1320 MOVE 1,Vmax
1330 LORG 3
1340 Vmax=DROUND(Vmax,3)
1350 LABEL Vmax
1360 INPUT "Do you want to expand the plot?",An$
1370 IF UPC$(An$)="N" THEN GOTO 1420
1380 INPUT "Enter vmin",Vmin
1390 INPUT "Enter vmax",Vmax
1400 GCLEAR
1410 GOTO 1180
1420 VIEWPORT 0,125,0,90
1430 WINDOW 0,100,-200,200
1440 MOVE 1,185
1450 D$=DATE$(TIMEDATE)
1460 B$="Impedance ("&E$&","ohms) vs Frequency (f,GHz)"&D$
1470 LABEL B$
1480 MOVE 1,165
1490 C$="REF: "&Ref$&","&"DUT: "&Dut$
1500 LABEL C$
1510 MOVE 0,-160
1520 LABEL Start
1530 MOVE 85,-160
1540 LABEL Stp
1550 A$="FREQUENCY IN GHz"
1560 MOVE 36,-160
1570 LABEL A$
1580 END
```


Appendix B 6

The loss parameter, $k(\sigma)$, computation with Time Low Pass
"KCALC"

```

10  ! "KCALC" (Time Domain)
20  ! Data is transferred from disk
30  !  $D_t$  = width of test pulse
40  !  $K$  = the loss parameter, V/pC
50  !  $= 2Z_L \int I_1(I_1 - I_2)dt / \int I_1^2 dt$ 
60  !  $Q$  = total charge contained in the Gaussian bunch
70  !  $= \int Idt$ 
80  !  $A(*)$  = mUnits derived from the reference pulse
90  !  $C(*)$  = inner product of  $A(*)$ 
100 !  $Z_L$  = characteristic impedance of transmission line, ohms
110 REAL Q,V11,V22,K
120 INTEGER I,Points
130 PRINT "Dt=nanoseconds per point"
140 PRINT "Dt=0.2 for 0 to 16 GHz"
150 PRINT "Dt=0.5 for 0 to 5 GHz"
160 INPUT "Enter dt",Dt
170 PRINT "ZL=Characteristic impedance of transmission line"
180 INPUT "Enter ZL",ZL
190 DIM A$(80)
200 REAL D(1:801,1:2)
210 REAL A(1:801)
220 REAL B(1:801)
230 REAL C(1:801)
240 REAL Vreal(1:801)
250 REAL Vimag(1:801)
260 Points=801
270 REDIM D(1:Points,1:2)
280 ASSIGN @Fast TO 716
290 MASS STORAGE IS ":",1500,1"
300 INPUT "Enter Reference data storage filename",File_name$
310 GOSUB Dat
320 Q=SUM(A)
330 Q=DROUND(Q,4)
340 PRINT "Q = ";Q
350 !  $V_{11} = \int I_1^2 dt$ 
360 V11=SUM(C)
370 V11=DROUND(V11,3)

```

```
380 PRINT "V11 = ";V11
390 PRINTER IS 26
400 PRINT File_name$
410 PRINT A$
420 PRINT "Q = ";Q
430 PRINT "V11 = ";V11
440 PRINTER IS CRT
450 INPUT "Enter DUT data storage filename",File_name$
460 GOSUB Dat
470 !  $V_{22} = \int I_2^2 dt$ 
480 V22=SUM(C)
490 V22=DROUND(V22,3)
500 PRINT "V22 = ";V22
510 K=Z0*(V11-V22)/(Q2*1000*Dt)*Points
520 K=DROUND(K,3)
530 PRINT "K = ";K
540 PRINTER IS 26
550 PRINT File_name$
560 PRINT A$
570 PRINT "V22 = ";V22
580 PRINT "K = ";K
590 PRINTER IS CRT
600 MASS STORAGE IS ":DOS,C"
610 STOP
620 Dat: !
630 ASSIGN @Don TO File_name$
640 ENTER @Don;A$,D(*)
650 ASSIGN @Don TO *
660 PRINT A$
670 PRINT "PRESS CONTINUE"
680 PAUSE
690 FOR I=1 TO Points
700   Vreal(I)=D(I,1)
710   Vimag(I)=D(I,2)
720   A(I)=SQR(Vreal(I)2+Vimag(I)2)
730 NEXT I
740 MAT B= A
750 MAT C= A . B
760 RETURN
770 END
```

Appendix B 7

The loss parameter, $k(\sigma)$, computation with Time Band Pass
"KCALC2"

```

10 ! "KCALC2" (TIME DOMAIN)
20 ! Data is transferred from disk
30 ! Dt = width of test pulse
40 ! K = the loss parameter, volts/picocoulomb
50 ! =  $2Z_0 \int I_1(I_1 - I_2)dt / \int I_1^2 dt$ 
60 ! Q = total charge contained in the pulse
70 ! =  $\int I dt$ 
80 ! A(*) = mUnits derived from the reference pulse
90 ! C(*) = inner product of A(*)
100 ! Z0 = characteristic impedance center conductor, ohms
110 REAL Q,V11,V22,K
120 INTEGER I,Points
130 PRINT "Dt=nanoseconds per point"
140 PRINT "Dt=.5 for 0 to 16 GHz"
150 PRINT "Dt=1.5 for 0 to 5 GHz"
160 INPUT "Enter dt",Dt
170 PRINT "Z0=Characteristic impedance of center conductor"
180 INPUT "Enter Z0",Z0
190 DIM A$(80)
200 INPUT "Enter # of points",Points
210 ALLOCATE REAL D(1:Points,1:2)
220 ALLOCATE REAL A(1:Points)
230 ALLOCATE REAL C(1:Points)
240 ALLOCATE REAL Vreal(1:Points)
250 ASSIGN @Fast TO 716
260 MASS STORAGE IS ":",1500,1"
270 INPUT "Enter Reference data storage filename",File_name$
280 GOSUB Dat
290 Q=SUM(A)
300 Q=DROUND(Q,4)
310 PRINT "Q = ";Q
320 ! V11 =  $\int I_1^2 dt$ 
330 V11=SUM(C)
340 V11=DROUND(V11,6)
350 PRINT "V11 = ";V11
360 PRINTER IS 26
370 PRINT File_name$
380 PRINT A$
390 PRINT "Q = ";Q

```

```
400 PRINT "V11 = ";V11
410 PRINTER IS CRT
420 INPUT "Enter DUT data storage filename",File_name$
430 GOSUB Dat
440 ! V22 = integral I2^2 dt
450 V22=SUM(C)
460 V22=DROUND(V22,6)
470 PRINT "V22 = ";V22
480 K=Z0*(V11-V22)/(Q^2*1000*Dt)*Points
490 K=DROUND(K,6)
500 PRINT "K = ";K
510 PRINTER IS 26
520 PRINT File_name$
530 PRINT A$
540 PRINT "V22 = ";V22
550 PRINT "K = ";K
560 PRINTER IS CRT
570 MASS STORAGE IS ":DOS,C"
580 STOP
590 Dat: !
600 ASSIGN @Don TO File_name$
610 ENTER @Don;A$,D(*)
620 ASSIGN @Don TO *
630 PRINT A$
640 PRINT "PRESS CONTINUE"
650 PAUSE
660 FOR I=1 TO Points
670     Vreal(I)=D(I,1)
680 NEXT I
690 MAT A= Vreal
700 MAT C= A . Vreal
710 RETURN
720 END
```