Experimental Study of Coupling Impedance
Part I Longitudinal Impedance Measurement Techniques

J. J. Song

Advanced Photon Source

Argonne National Laboratory

Argonne, IL 60439

October 22, 1991

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 impedance and transverse impedance are estimated to be 2 Ω and 0.3 MΩ/m, respectively.

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

	Component	Number	Impedance Z_ℓ/n (Ω)	Impedance Zt (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

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 realtime 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

$$\Delta E \quad = \quad kq^2 \; = \; 2Z_L q^2 \frac{\int I_1 (I_1 - I_2) \; dt}{\left(\int I_1 \; dt \right)^2} \qquad (eV) \tag{1}$$

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:

$$k \; = \; 2Z_L \frac{\int I_1 (I_1 - I_2) \; dt}{\left(\int I_1 \; dt \right)^2} \qquad (V/pC), \tag{2}$$

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),

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

where T_o is the period of revolution of a beam around a storage ring, $I_b = q/T_o$ 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.

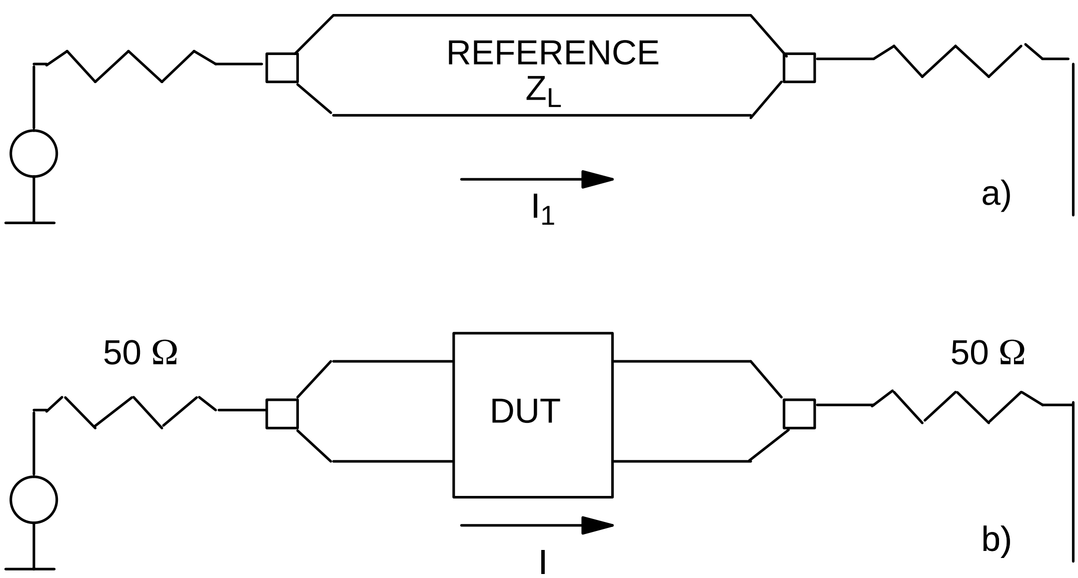

Fig. 1 a) A Schematic Diagram of A) Reference Beam Chamber, and B) A Device Under test (DUT).

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:

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

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

$$Z(\omega) \quad = \quad 2Z_L \frac{\left[I_1(\omega)–I_2(\omega)\right]}{I_1(\omega)} \qquad (\Omega) \tag{5}$$

where $I_l(\omega)$ 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,

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

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 Δf =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.

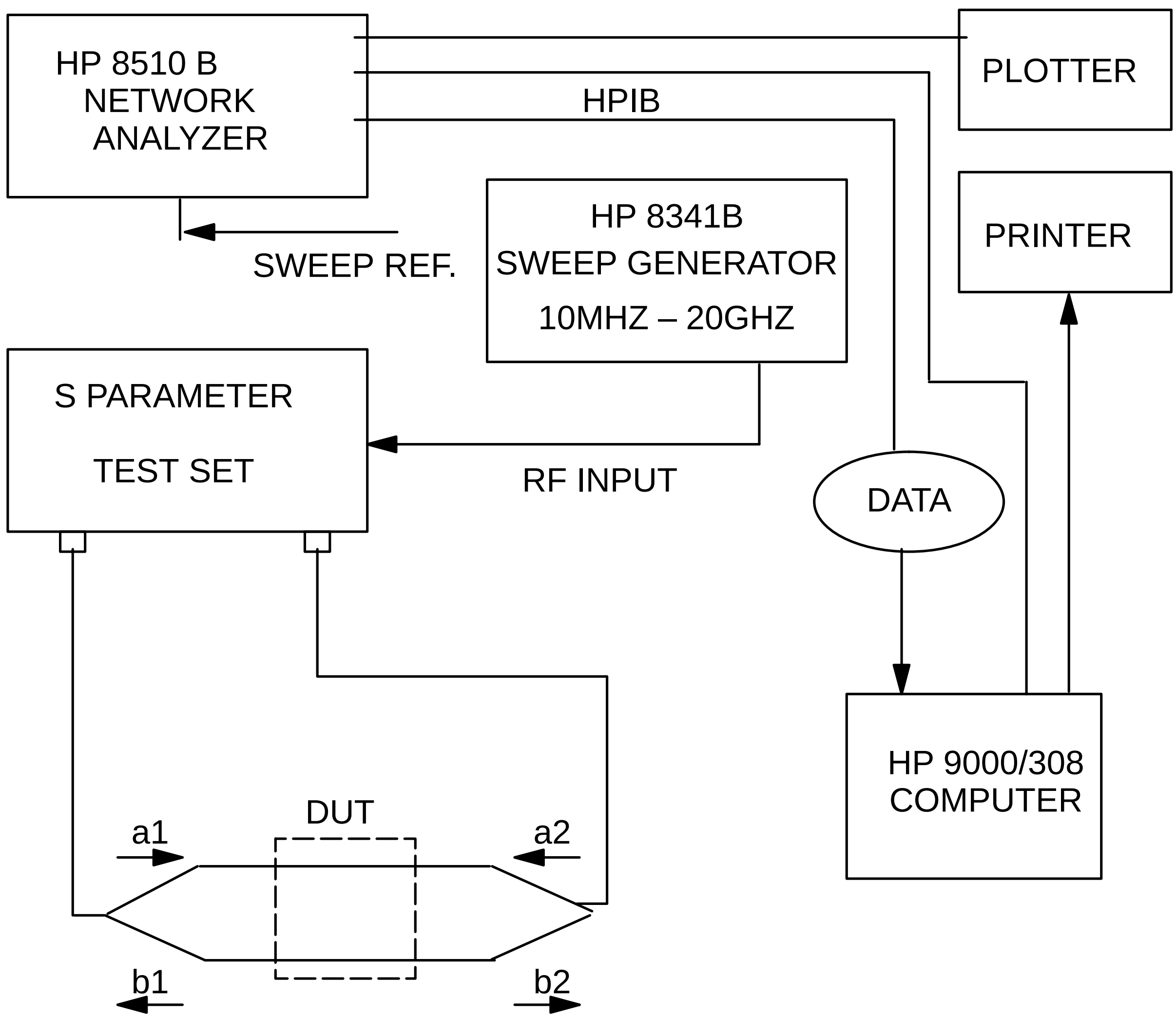

FIG. 2 EXPERIMENTAL SETUP ON A SYNTHETIC PULSE TECHNIQUE

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, Δf = 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 $\pm$ 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

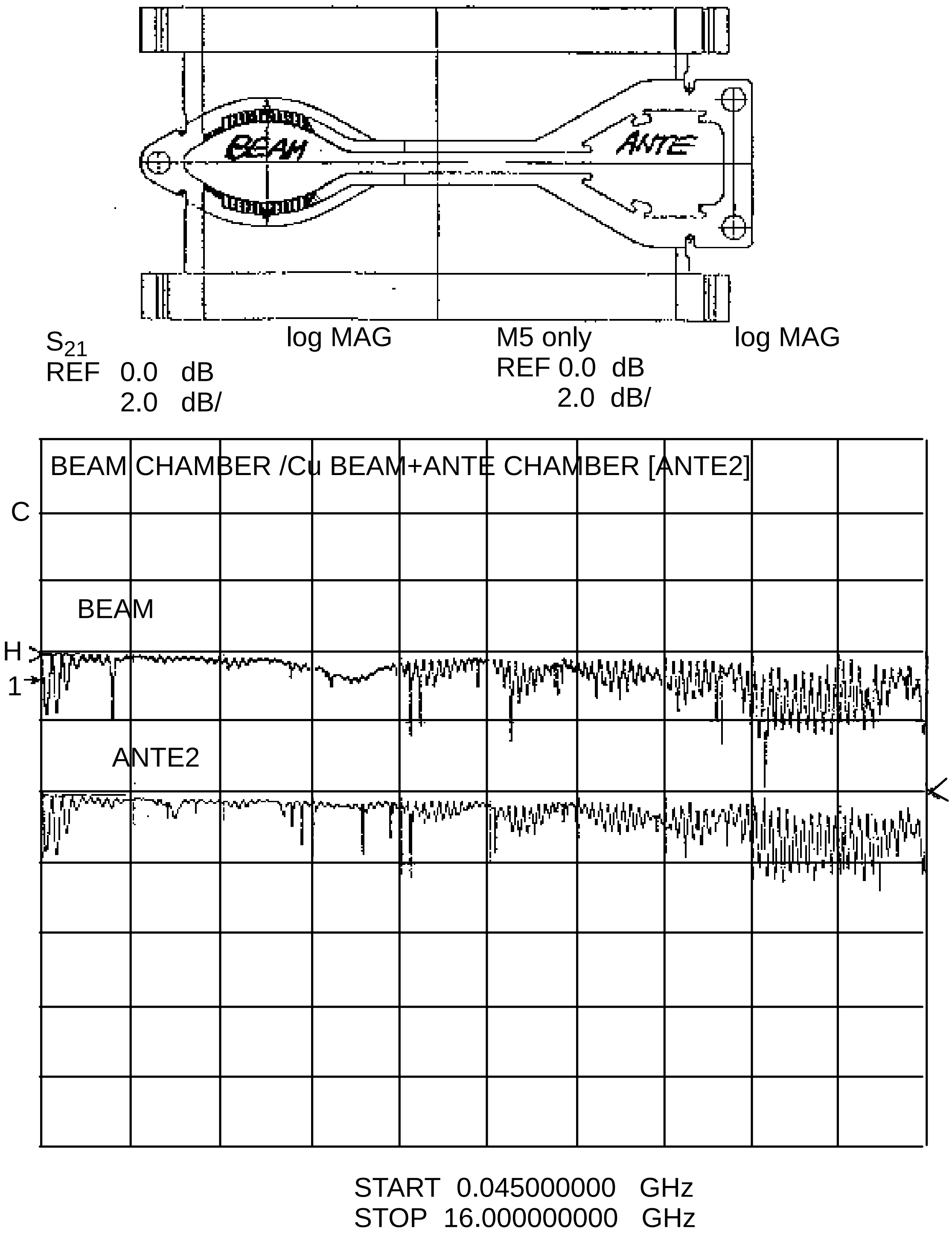

Figure 3-1 Typical transmission data (S_{21}) taken for BEAM (top) and ANTE2 (bottom) in the Frequency Domain.

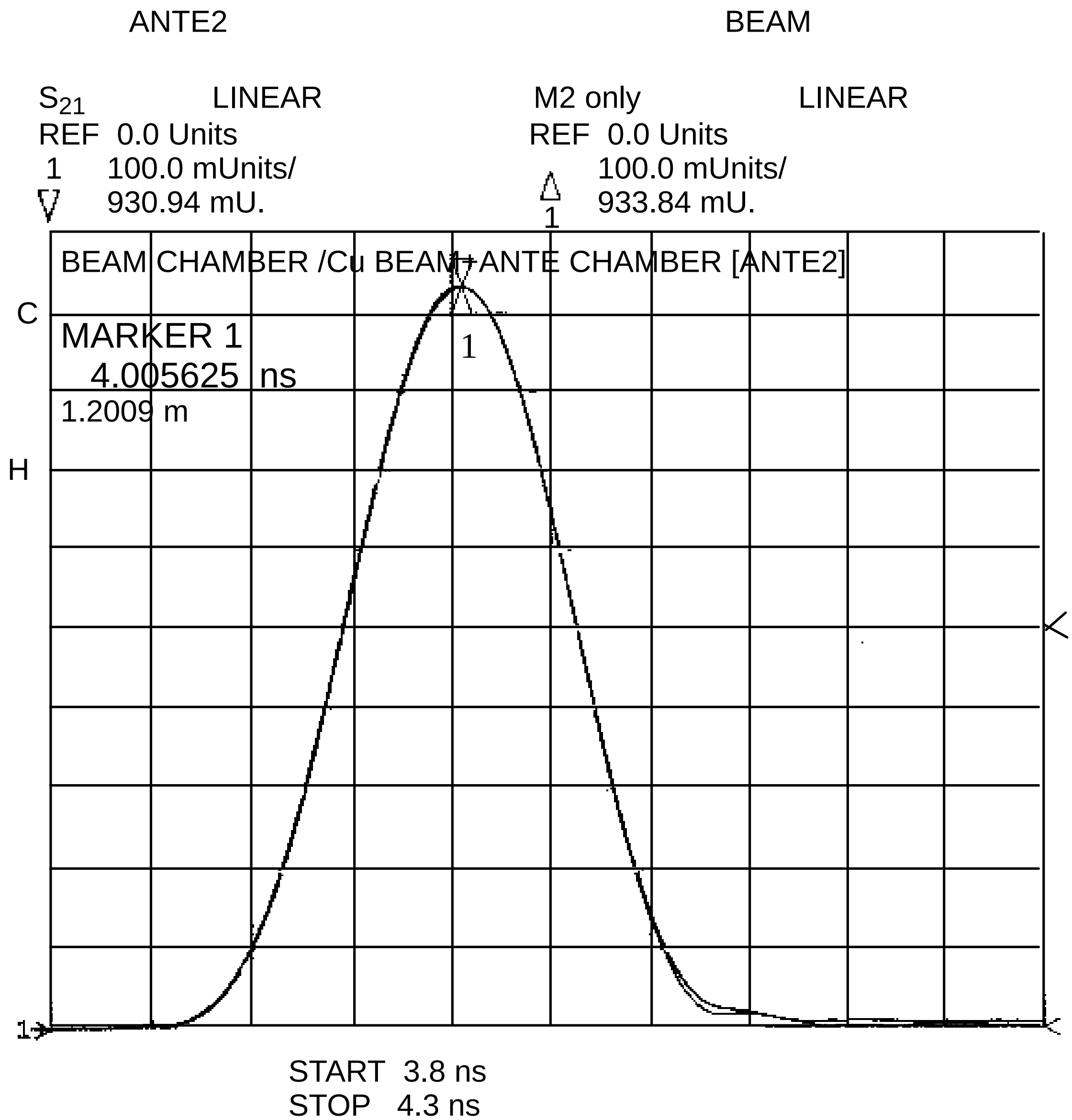

Figure 3–2 Their corresponding synthetic pulses with the BP mode: M2 for BEAM, S_{21} for ANTE2

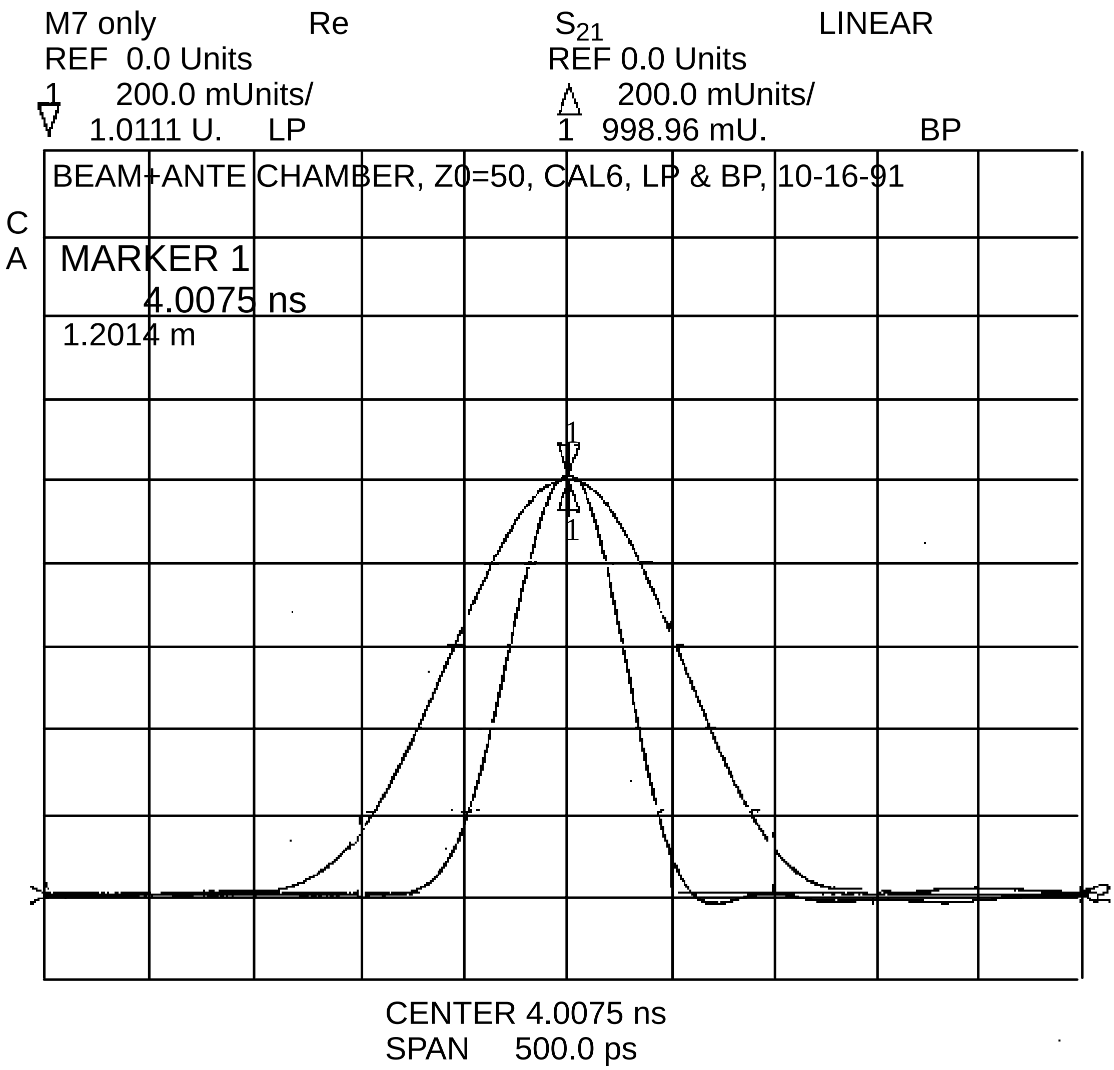

Figure 4 The synthetic pulses with two different time modes: the wide pulse for the BP mode, the short one for the LP mode

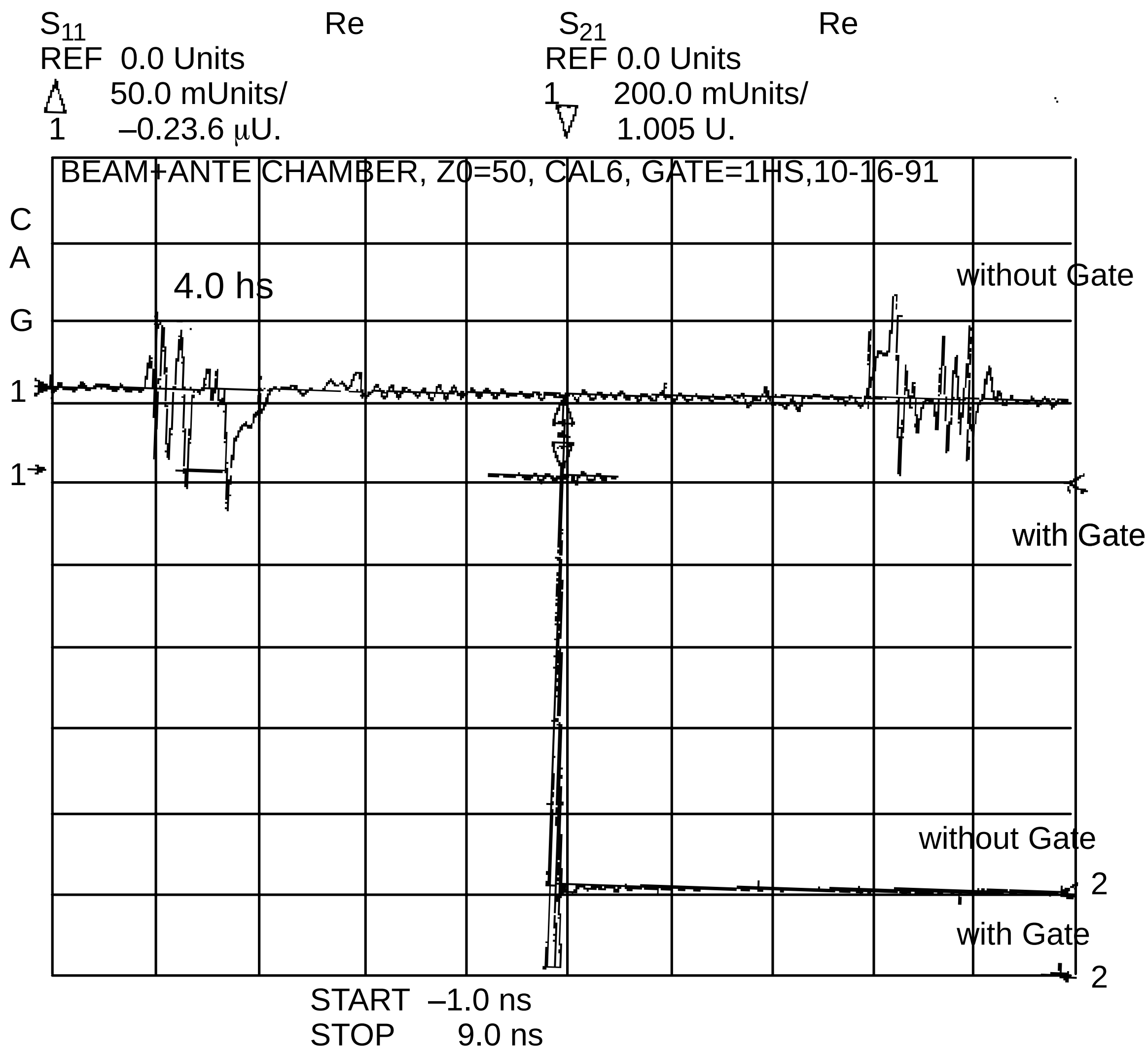

Figure 5-1 The S_{11} & S_{12} for ANTE2 with and without Gate in the TD: the top two graphs are S_{11} and the bottom two graphs are S_{21}.

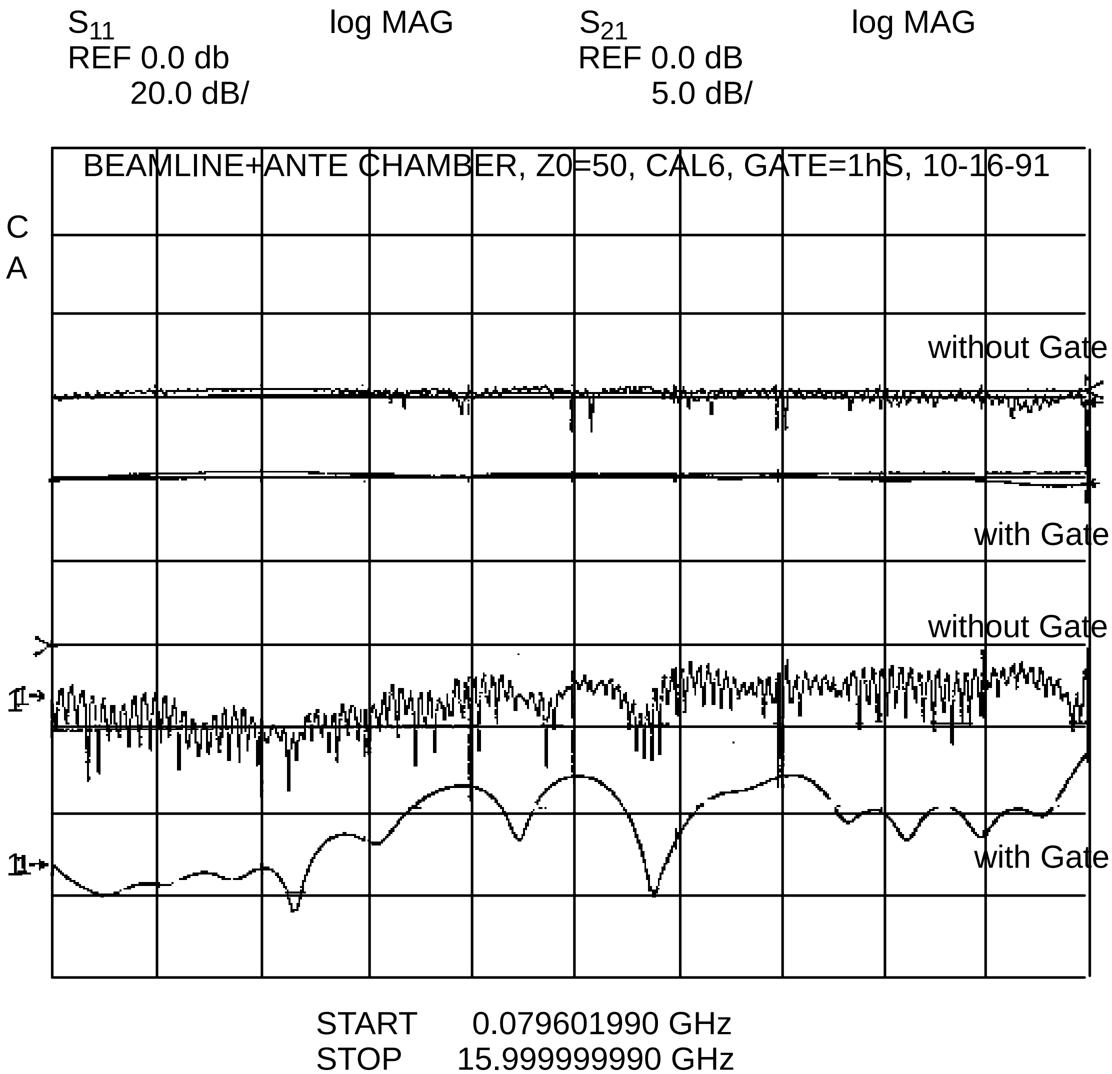

Figure 5-2 The S_{11} & S_{21} for ANTE2 with and without Gate in the FD: the top two graphs are S_{21} and the bottom two graphs are S_{11}.

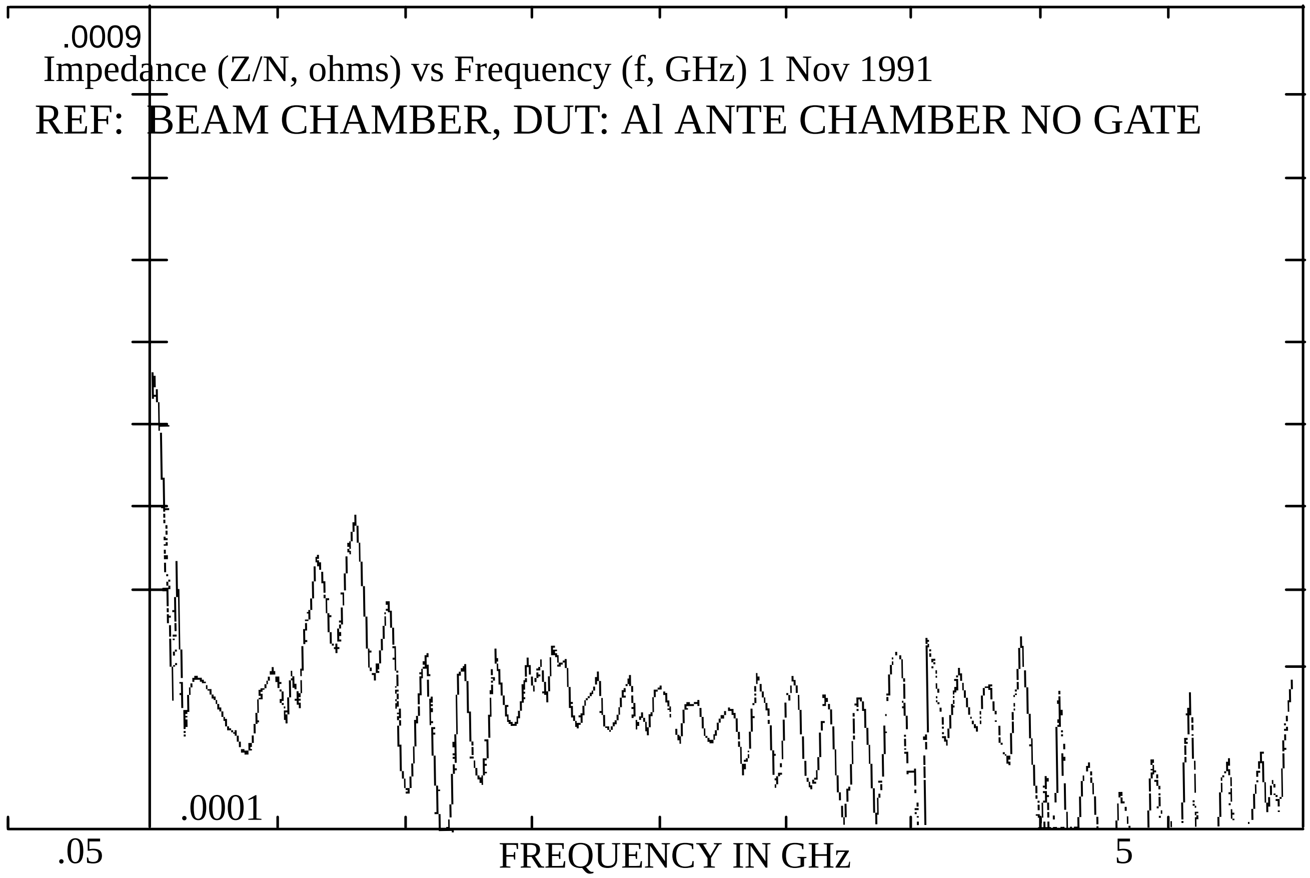

Figure 6-1 Broadband Impedance vs Frequency for ANTE3 without Gate

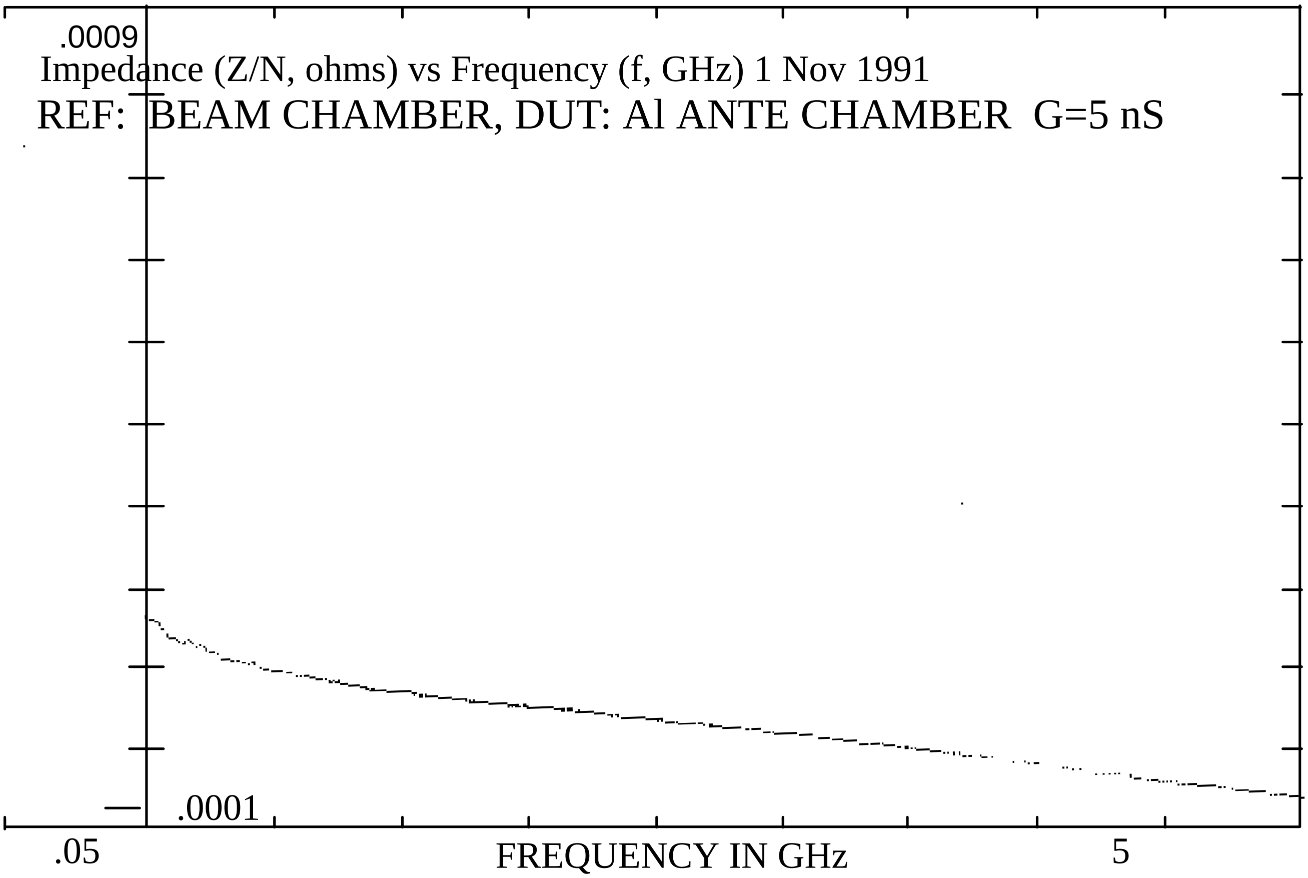

Figure 6-2 Broadband Impedance vs Frequency for ANTE3 with Gate=1nS

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

$$Z(\omega) = 2Z_L \frac{\left[S_{21}(\mathrm{ref}) - S_{21}(\mathrm{DUT})\right]}{S_{21}\ (\mathrm{ref})} \qquad (\Omega). \tag{7}$$

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 $1 \sim 1.5$ GHz. Since the impedance for ANTE3 is 2×10^{-5} Ω, the total impedance of the 120 transitions with and without the antechamber around the storage ring is 2.4×10^{-3} Ω, which is a little smaller than the computer-calculated value (2.4×10^{-3} Ω, 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).

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

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	BP		0.0046		0.001
(0-16 GHZ)	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	BP		0.0015		0.0003
(0-5 GHz)	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		

VI. ACKNOWLEDGEMENTS

The author would like to thank Dr. F. Caspers at CERN for stimulating discussions. Also thanks must be given to D. F. Voss, and E. Wallace for their technical support. This work was supported by U.S. Department of Energy, Office of Basic Sciences, under Contract W-31109-ENG-38.

VII. REFERENCES

[1] L. C. Teng, "Impedance and Current Limitations," DOE Review of APS Project at Argonne Nat'l Lab., March 6-8, (1990).

[2] W. Chou, Y. Jin, "Impedance Studies-Part 4: The APS Impedance Budget," ANL-LS Note-115, (1988); "Impedance and Bunch Lengthening in the APS," in Proc. of the Impedance and Bunch Instability Workshop ANL-APS, Oct. 31-Nov. 1, (1989).

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

[4] S. Chattopadhyay, "Introduction to Accelerator Physics" presented at the U.S. Particle Accelerator School, June 3-14, (1991).

[5] HP Product Note 8510-5A "Network Analysis, specifying calibration standards for the HP 8510 network analyzer."

[6] HP Product Note 8510-8 "Network Analysis, applying the HP 8510B TRL calibration for non-coaxial measurements."

[7] L. Walling, "Techniques for Beam Impedance Measurements Below Cutoff," in Proc. of the Coupling Impedance Measurement Techniques Workshop, ANL-APS, August 12-13, (1991).

[8] G. Lambertson, "Techniques for Beam Impedance Measurements above Cutoff," in Proc. of the Coupling Impedance Measurement Techniques Workshop, ANL-APS, August 12-13, (1991).

[9] HP Network Analyzer Operating and Programming Manual “Introduction to Time Domain Measurements using HP 8510B.”

[10] “Introduction to Programming the HP 8510B and HP Basic 5.1 Reference Manual,” (HP Part # 98613-90062).

[11] G. Jackson, “Experimental Methods in Accelerator Physics,” presented at the U.S. Particle Accelerator School, June 3-14, (1991).

[12] R. L. Kustom, et. al, “RF Impedance Studies of a Beam Chamber and Longitudinally Slot-Coupled Vacuum Pumping Antechamber,” IEEE Particle Accelerator Conf., 1304 (1987).

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.

<u>Remarks</u>

* 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) <u>Start with REF</u>.

* 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 thedifferent cal set #).

(B) <u>Setup with the device under test (DUT)</u>.

* 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: $|Z(\omega)|$, $Re[Z(\omega)]$, $Im[Z(\omega)]$ and $|Z(\omega)|/n$ and print the results on the HP printer. (To do these, do handcalculation 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}(REF) over S_{21}(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_{2l}

  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.

<u>AFTER MEASUREMENTS</u>

* 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;“CALS?;″
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=l
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 affays″,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)+l
```

```
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=l TO Poin
280     ENTER @Dt;Cal(I,J,l),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,l:Poin,1:2)
100   PRINT TABXY(1,20),“Loading ”;File_name$;” from disk”
110   ENTER @Don;Cal(*)
120   ASSIGN @Don TO *
130   MASS STORAGE IS “:DOS,C”
140   OUTPUT 716;“Corroff;”
150   OUTPUT 716;“Call;”
160   IF Numb=l THEN
170   Command$=“CALIRESP;”
180   ELSE
190   Command$=“CALIFUL2;”
200   END IF
210   OUTPUT 716;Command$
220   OUTPUT 716;“HOLD;”
230   FOR I=l 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=l TO Poin
290   OUTPUT @Dt;Cal(I,J,I),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$
1 10    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) = 2ZL[S21(ref)–S21(dut)]/S21(dut)
50    !ZL 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$[8O]
140   DIM B$[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_magl(1:801)
290   REAL Lin_mag2(1:801)
300   REAL Impl(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=l TO Points
450   V1 (I)=D(I, 1)
460   V2(I)=D(I,2)
470   Lin_magl(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$
5 1   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(1)=D(I,2)
590   Lin_mag2(I)=SQR(V3(1)^2+V4(1)^2)
600   NEXT I
610   INPUT “Select impedance(VREAL,VIMAG,LINMAG)”,Imp$
620   SELECT Imp$
630   CASE“VREAL”
640   MAT Impl= VI
650   MAT Imp2=V3
```

```
660    CASE “VIMAG”
670    MAT Impl= V2
680    MAT Imp2= V4
690    CASE “LINMAG”
700    MAT Impl= Lin_magl
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)=Impl(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=l TO Points
1010 IF E$=“Z” AND Z(I)>V THEN
1020    PRINT “I=”;I;“Z=“;DROUND(Z(I),3);” FREQ=“;DROUND(F(I),3)
1030    ELSE
1040    IF Z_divn(I)>V THEN PRINT
“I= ”;I;”Z/N=“;DROUND(Z_divn(I),3);” FREQ=”;DROUND(F(I),3)
1050    END IF
1060    NEXT  I
1070    INPUT “Do you want to change the reference voltage?”,An$
1080    IF UPC$(An$)=“Y” THEN GOTO 980
1090    PRINTER IS CRT
1100    Zavg=DROUND(SUM(Z)/Points,3)
1110    PRINT “ZAVG=”;Zavg
1120    GINIT
1130    GRAPHICS ON
1140    SEPARATE ALPHA FROM GRAPHICS
1150    VIEWPORT 0,125,10,90
1160    Vmax=MAX(Graph(*))
1170    Vmin=MIN(Graph(*))
1180    WINDOW 0,Points,Vmin,Vmax
1190    H=Vmax–Vmin
1200    INPUT “Enter first point”,First_point
1210    INPUT “Enter last point”,Last_Point
1220    FOR I=First_point TO Last_point
1230    PLOT I,Graph(I)
1240     NEXT I
1250    AXES Points/10,H/10,F–rst 1  _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 LABEI, Stp
1550 A$=”FREQUENCY IN GHz”
1560 MOVE 36,–160
1570 LABEL A$
1580 END
```

Appendix B 6

The loss parameter, k(σ), computation with Time Low Pass

“KCALC”

```
10     ! “KCALC” (Time Domain)
20     ! Data is transferred from disk
30     ! Dt = width of test pulse
40     ! K = the loss parameter, V/pC
50     !  = 2ZL∫ I1(I1–I2)dt/∫I1^2 dt
60     ! Q = total charge contained in the Gaussian bunch
70     ! = ∫Idt
80     ! A(*) mUnits derived from the reference pulse
90     ! C(*) inner product of A(*)
100    ! ZL = 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$[80]
200    REAL D(1:801,1:2)
210    REAL A(1:801)
220    REAL B(1:801)
230    REAL C(1:801)
240    REAL Vreal(1:801)
250    REAL Vimag(1:801)
260    Points=801
270    REDIM D(l:Points,1:2)
280    ASSIGN @Fast TO 716
290    MASS STORAGE IS “:,1500,1”
300    INPUT “Enter Reference data storage filename”,File name$
```

```
310   GOSUB Dat
320   Q=SUM(A)
330   Q=DROUND(Q,4)
340   PRINT “Q=”;Q
350   ! V11 = ∫I1^2  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 Vat
470   ! V22 = ∫I2^2 dt
480   V22=SUM(C)
490   V22–DROUND(V22,3)
500   PRINT “V22 = ”;V22
510   K=Zo*(V11–V22)/(Q^2*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=l TO Points
700     Vreal(I)=D(I,l)
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(σ), 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    ! = 2ZO integral II(Il–I2)dt/integral I1^ dt
60    ! Q total charge contained in the pulse
70    ! integral 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,V 1 1,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$[80]
200   INPUT “Enter # of points”,Points
210   ALLOCATE REAL D(1:Points,1:2)
220   ALLOCATE REAL A(l:Points)
230   ALLOCATE REAL C(l:Points)
240   ALLOCATE REAL Vreal(1:Points)
250   ASSIGN @Fast TO 716
260   MASS STORAGE IS “:,1500,1”
270   INPUT “Enter Reference data storage filename”,File_name$
280   GOSUB Dat
290   Q=SUM(A)
300   Q=DROUND(Q,4)
```

```
310    PRINT “Q = ” ;Q
320     ! V11 = integral I1^2 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,l)
680     NEXT I
690     MAT A= Vreal
700     MAT C= A . Vreal
710     RETURN
720     END
```