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A MEASUREMENT OF THE LONGITUDINAL COUPLING IMPEDANCE OF THE RC NETWORKS USED AT THE INSULATED FLANGES OF THE AGS VACUUM CHAMBERS

D. Kasha

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Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

Accelerator Division
Alternating Gradient Synchrotron Department
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

Accelerator Division
Technical Note

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A MEASUREMENT OF THE LONGITUDINAL COUPLING IMPEDANCE OF THE RC NETWORKS USED AT THE INSULATED FLANGES OF THE AGS VACUUM CHAMBERS

D. Kasha and J.M. Brennan

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Introduction

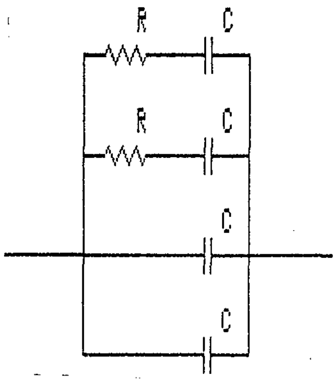
The beam pipe in the AGS is made up of sections approximately 3 meters long, joined to each other with an insulated Marman flange. The insulation provides a d.c. break in the current path that would otherwise exist along the chambers and return outside the magnet gap via common ground. Such a path would constitute a shorted turn for the magnet, and currents induced there would act to decrease the magnetic field acting on the beam in an unpredictable way.

As protons travel within the beam pipe, they induce an image charge on the inside of the beam pipe wall. The motion of this image charge is a current equal to the beam current, which can be as high as 2.5 A at the fundamental frequency. The insulated flange also interrupts the image current, and so two RC networks are installed outside the Marman flange, bridging the insulation to provide an a.c. current path. An immediate consequence of this arrangement is that the image current is forced to travel on the outside surface of the chamber. Damping networks are used at various places to suppress resonances of these external currents. These networks are also called RC networks but are not the subject of this study.

Ideally, the RC networks would be an open for very low frequencies and a short for all other frequencies. At high frequencies (~ 50 MHz), a parasitic inductance and finite resistance of the circuit components from which the RC networks are made lead to resonances that make the effective impedance of these networks far from small.

In this study, a test setup was constructed to measure the coupling impedance of the RC networks and the insulated flange. Then a program was written to model the impedance of the actual circuit of RC network (including parasitic components) and insulated flange. This impedance is the longitudinal coupling impedance at the insulated flange. The coupling impedance was deduced from laboratory measurements of the transmission coefficient at the flange.

Figure 1 is a diagram of the bridging networks on which these measurements were made.



R = 33 Ohm
C = 50 nF
Two such networks are used in parallel across the insulated flange; the two R-C combinations are branch 1, and the two C's in parallel are branch 2 in each network.

Fig 1. Actual RC network.

Measurements

A test fixture comprising the insulated Marman flange was adapted to 3 1/8 inch 50 Ohm coaxial line. The two RC networks were mounted across the gap from the Marman clamp, to the adaptor plate on the insulated Marman flange side, to approximate the setup used in the AGS ring. The 3 1/8 inch coax line then adapted to 50 Ohm (Z_o) cable to connect to the test equipment. The setup therefore represents an unknown impedance placed in a 50 Ohm circuit (Fig. 2). An HP8753A network analyzer was used to measure the transmission coefficient, S21 magnitude and phase of the setup.

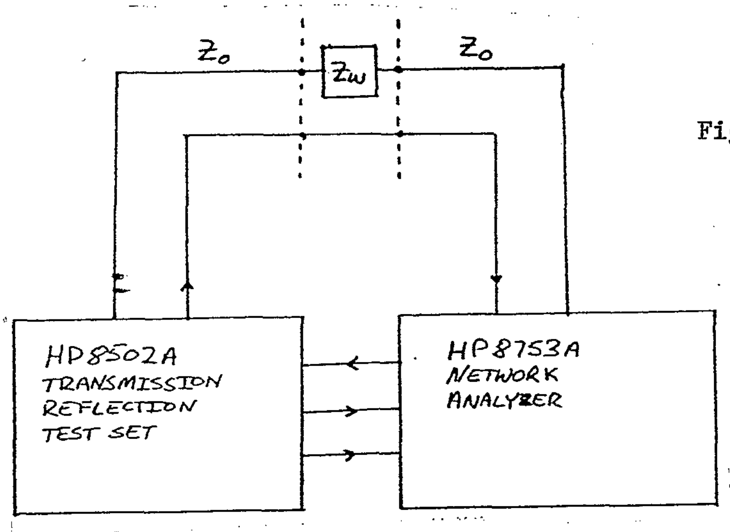


Fig. 2. Test setup used to measure S21.

Hahn and Pedersen[1] show that a localized unknown impedance, Zw, located in a line of impedance Z_o is related to the transmission coefficient by,

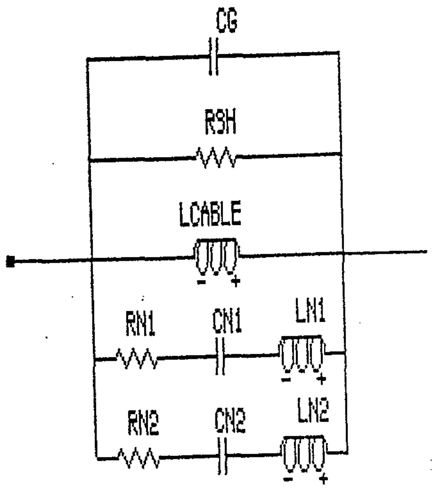
$$S21 = [1 - (Z_w/(Z_w + 2\ Z_o))]e^{-ikl}$$

where: $k = 2\pi/\lambda$
l = total length of the line

The phase factor was eliminated by dividing the transmission coefficient of the device under test by the transmission coefficient of an equivalent length 50 Ohm line connected in place of the device under test. This was done within the network analyzer since it is a digital device and can store several spectra and perform arithmetical operations upon them. Figure 3 shows the phase corrected transmission coefficients for the system without and with the RC networks.

Computer Model

A program was written to calculate the impedance of a network which approximates the unknown impedance Zw. The network model is shown in Fig. 4. Cg represents the capacitance of the two Marman flanges separated by the ceramic coating and vacuum gasket. Lcable represents the inductance of the return path that makes a DC connection between the two sides of the insulated flange. This is a complicated path; it goes along the outside of the chambers, through some RC networks and into the girder ground, then back up into the adjacent chamber. The test set did not attempt to model this inductance accurately because it must vary a great deal from one chamber pair to another, and, moreover as will be shown below, it has little effect on the coupling impedance at relevant frequencies. Rsh represents the rf dissipation losses associated with the gap (including resistive and radiation losses).



Lcable = 1.4 μH
CG = .6 nF
RSH = 700 Ohm
RN1 = 8.25 Ohm
CN1 = 200 nF
RN2 = .025 Ohm
CN2 = 200 nF
LN2 = 16 nH

RN1, CN1 and LN1 are branch 1.
RN2, CN2 and LN2 are branch 2.

Fig. 4. Network model.

There are two RC networks installed at each flange, they are in the horizontal plane, one inside and one outside the ring.[2] The two networks are considered in parallel in the calculation. This is a good approximation up to frequencies whose quarter wave length is longer than half the circumference of the Marman flange, approximately 200 MHz. Rn1 is the parallel combination of the four physical 33 Ohm resistors in the two RC networks. Cn1 and Cn2 are the parallel combination of the four physical 50 nF capacitors in branches 1 and 2 respectively.

LN1, Ln2, and Rn2 are the key ingredients of the model. They represent the finite lead resistance and inductance of the real-world components. If it were not for these effects, the behavior of the RC networks would be trivial and give a coupling impedance which drops continuously with frequency. The measurements show, however, that a resonance exists at ~ 60 MHz and the coupling impedance peaks there (transmission coefficient dips). The values of the inductances were chosen to fit the frequency and depth of the dip in the transmission coefficient. The value of Rn2 was estimated from standard engineering formulae.[3]

Determining the model parameters from the measurements was a bootstrap process. Starting with the lowest frequency resonance observed (where component values can be taken literally), we discern from Fig. 3(c) a hint of a resonance somewhere below 300 kHz. This must be Cn2 (200 nF) resonating against the cable return path, giving Lcable = 1.4 μH. From Fig. 3(a), with no RC network, Lcable is seen to resonate against the flange capacitance; Cg, at 6.3 MHz giving a value for Cg of .6 nF. The width of the resonance at 6.3 MHz determines the value for shunt resistance, Rsh = 700 Ohm.

The resonance at 60 MHz, with both RC networks in place, is primarily caused by the parasitic inductance in branch 2 (see Fig. 1) resonating against the flange capacitance, Cg. This sets a value of 16 nH for Ln2. One can see from Fig. 5 that the resonance of Ln2 and the flange capacitance is very sharp and leads to a high impedance at 60 MHz, greater than 100 Ohms. A series resonance is also seen in Fig. 5 where the impedance drops to a very low value. This is the series resonance of Cn2 and Ln2 at about 2.8 MHz.

The action of branch 1 is seen in Fig. 6. No resonance peaks occur because of the presence of the physical resistor Rn1 (= 8.2 Ohms), but on the other hand, the impedance is quite high, ~ 10 Ohms, over a broad frequency range. The calculation for the full network is shown in Fig. 7. In this case the value for Lnl (= 40 nH) was chosen to yield a transmission coefficient equal to the measured value at 60 MHz. Compare Figures 7(c) and 3(c). Figure 8 shows the impedance and transmission coefficient of the test fixture with no RC networks present, demonstrating the resonance of the insulated flanges against the return cable inductance.

It is clear what the idea behind the design of the RC networks is; branch 1 gives a flat impedance with a rather high value over a wide range of frequencies from 1 to 100 MHz while branch 2 gives a very low value in the range 1 to 10 MHz, but a sharp peak and high value (> 100 Ohms) in the area of 60 MHz. The combination of the two is compromise and gives the impedance shown in Fig. 7(a).

It should be recalled that it is not necessarily the absolute magnitude of the impedance that is relevant to the behavior of the machine. The more useful quantity is the normalized impedance, Z/n, where n is the frequency at which Z is evaluated divided by the revolution frequency. This quantity tends to be independent of machine circumference and makes it meaningful to compare Z/n for two different machines. This quantity is plotted in Fig. 9 and shows that the peak in Z is mitigated by the high harmonic number, n.

Conclusion

A quantitative measurement of the longitudinal coupling impedance of the RC networks has been made. The very low frequency region was not accurately modeled in the test fixture but these frequencies are below the revolution frequency of the AGS and are essentially irrelevant. It has been shown that the major shortcoming of the RC networks is caused by the parasitic inductance of the components from which they are made. The Z/n value of the RC networks is small, ~ .2 Ohm, but since there are very many of them, ~ 168 (at PUE locations they are shorted out) in the machine, the total impedance is indeed significant: 34 Ohms. Consider that the measured Z/n for the CERN PS is under 5 Ohms.[4]

Two obvious improvements suggest themselves: reduce the number of RC networks by removing the insulated coating from the Marman flanges, and improve the design of the limited number of RC networks that will inevitably remain. At the CERN PS the RC networks are not made from ceramic disk capacitors and carbon composition resistors from the stockroom. They are made from microwave-grade leadless capacitors soldered to a thin film resistor on a heavy copper substrate.

One caveat should be added. These data were taken on one set of RC networks on a model of the AGS vacuum chambers. We have no idea of the distribution of resonant frequencies of all the 168 RC networks throughout the ring. To say the total Z/n is given by this measurement times number of RC networks is a worst case statement. It is essential to make a chamber by chamber survey of all the actual RC networks in the machine. That work will be carried out soon after the delivery of the new HP8753 network analyzer.

References

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3. Ott, H. Noise Reduction Techniques in Electronic Systems. Wiley and Sons, New York, 1976. p. 116.

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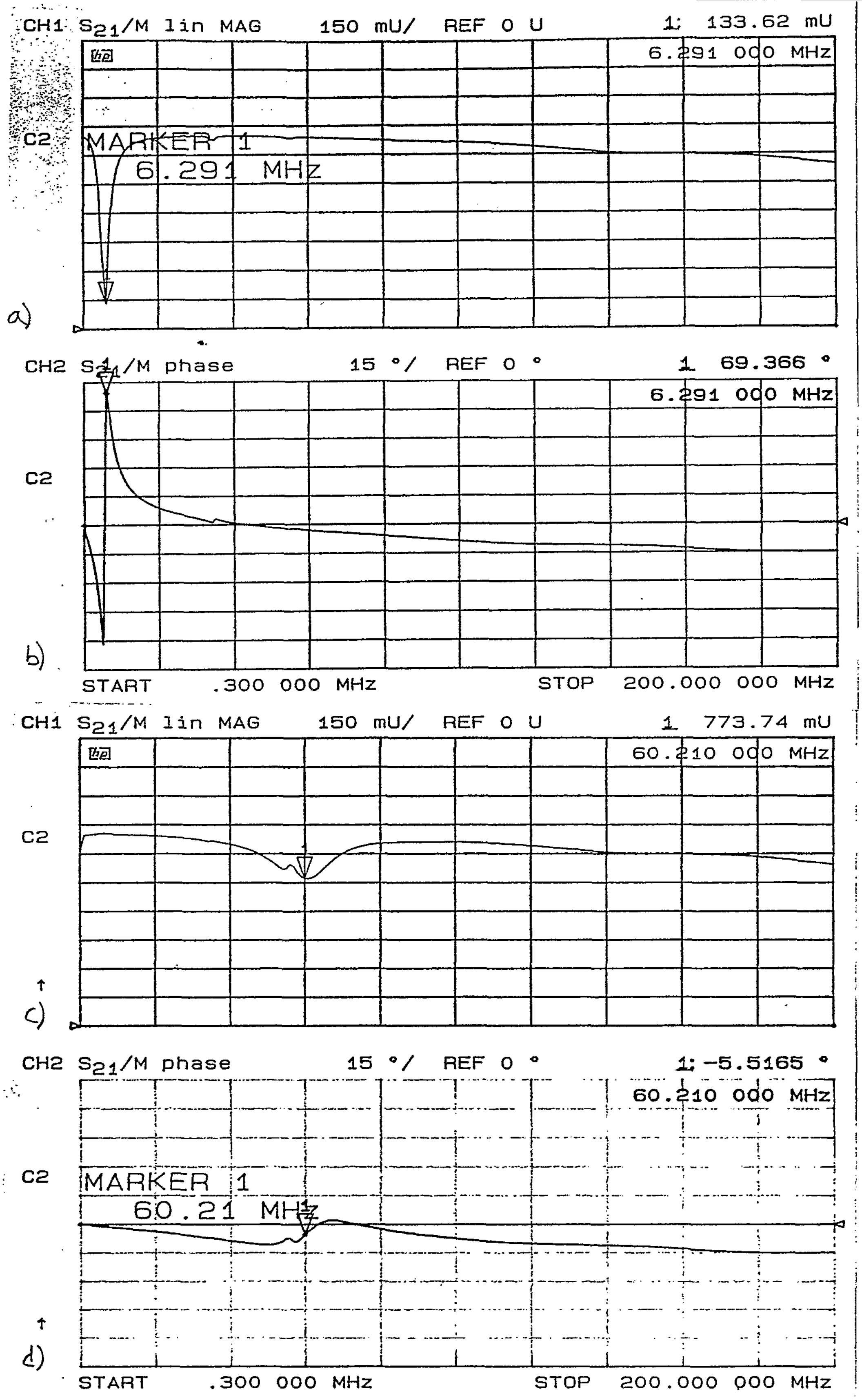

Figure 3. Measurements of test setup with HP8753A Network Analyzer
a) S21 magnitude with no RC network b) S21 phase with no RC network
c) S21 magnitude with 2 RC networks d) S21 phase with 2 RC networks

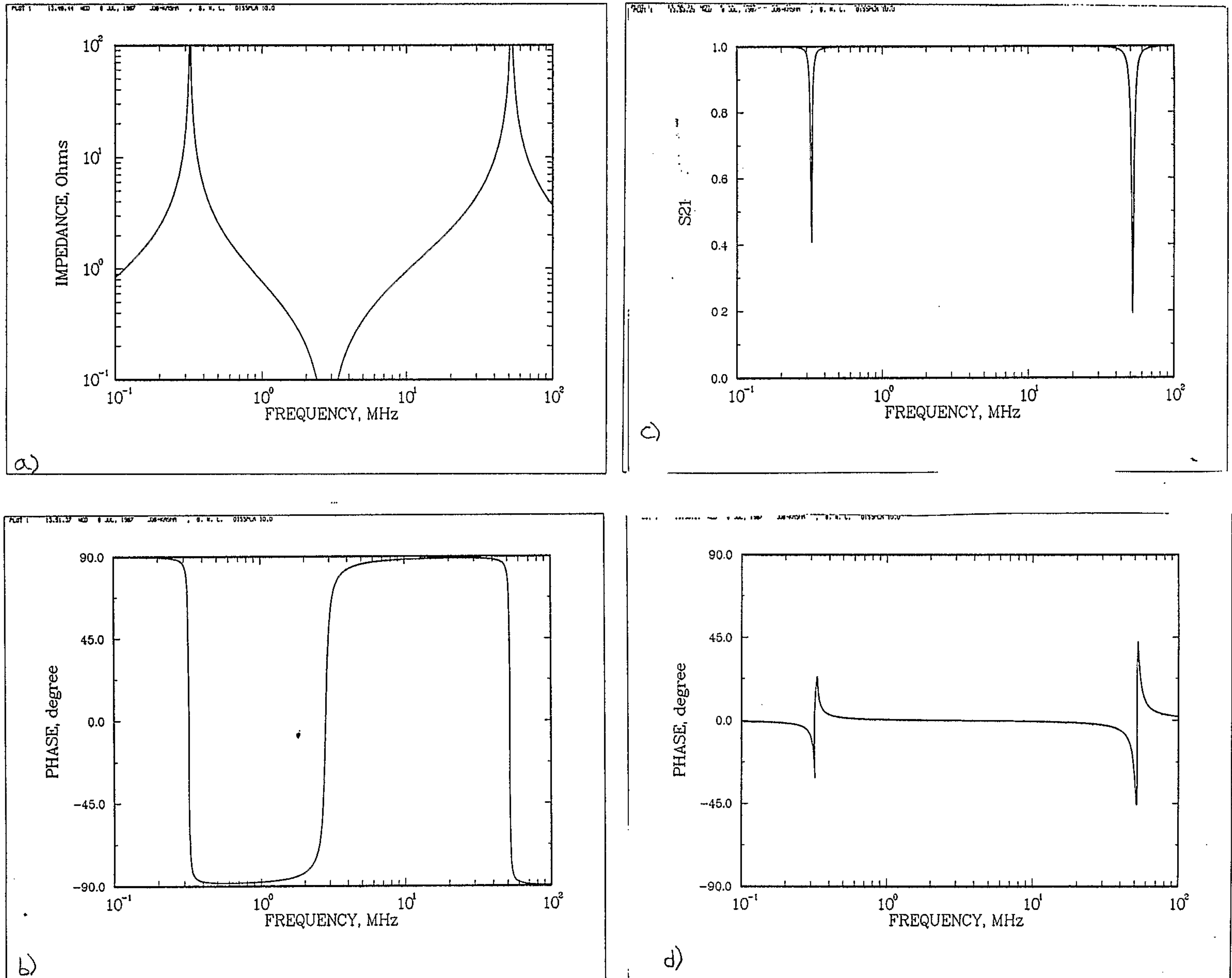

Figure 5. Calculated Impeadance and S21 with branch 2 of the RC network
a) Impedance magnitude b) Impedance phase c) S21 magnitude d) S21 phase

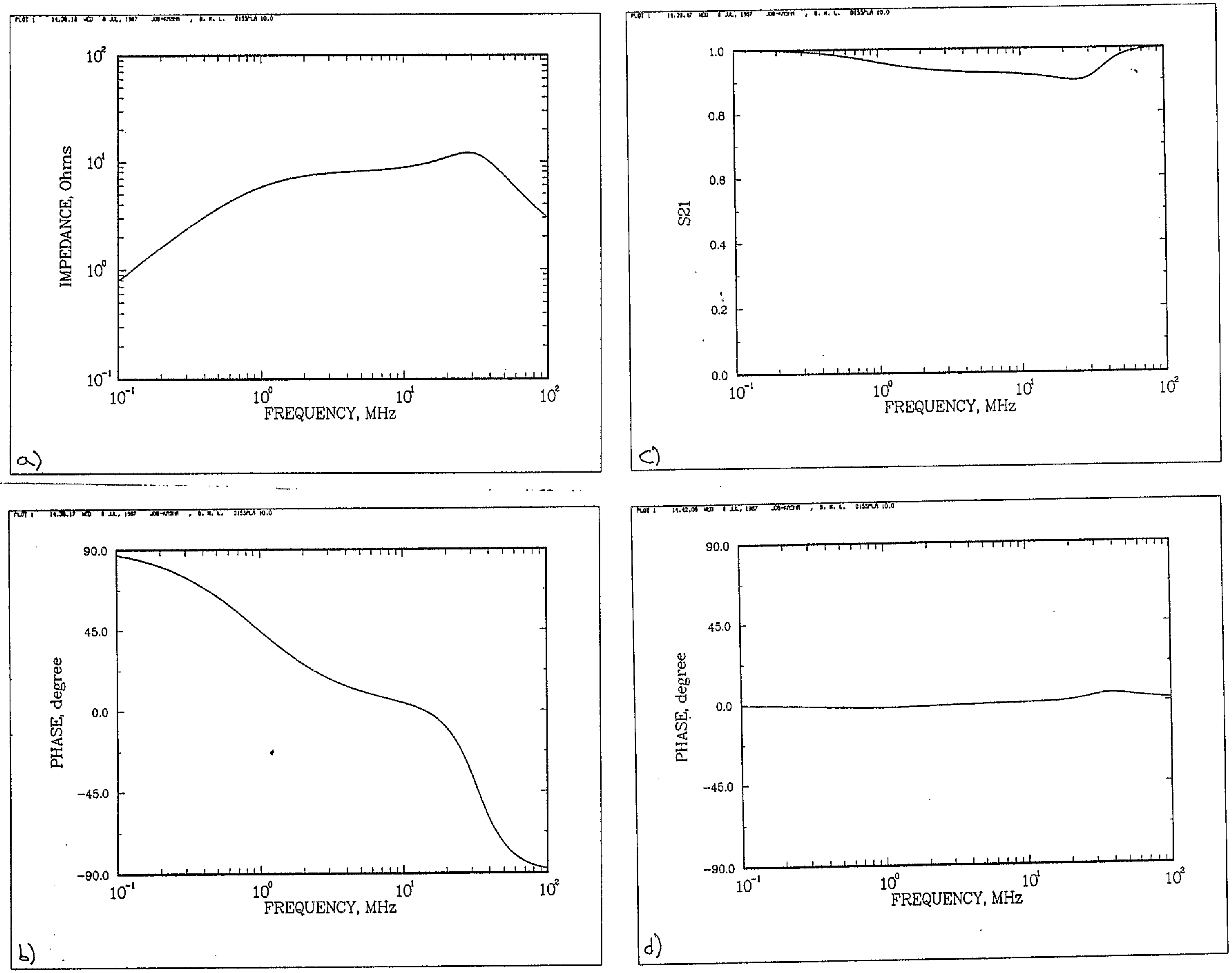

Figure 6. Calculated Impeadance and S21 with branch 1 of the RC network
a) Impedance magnitude b) Impedance phase c) S21 magnitude d) S21 phase

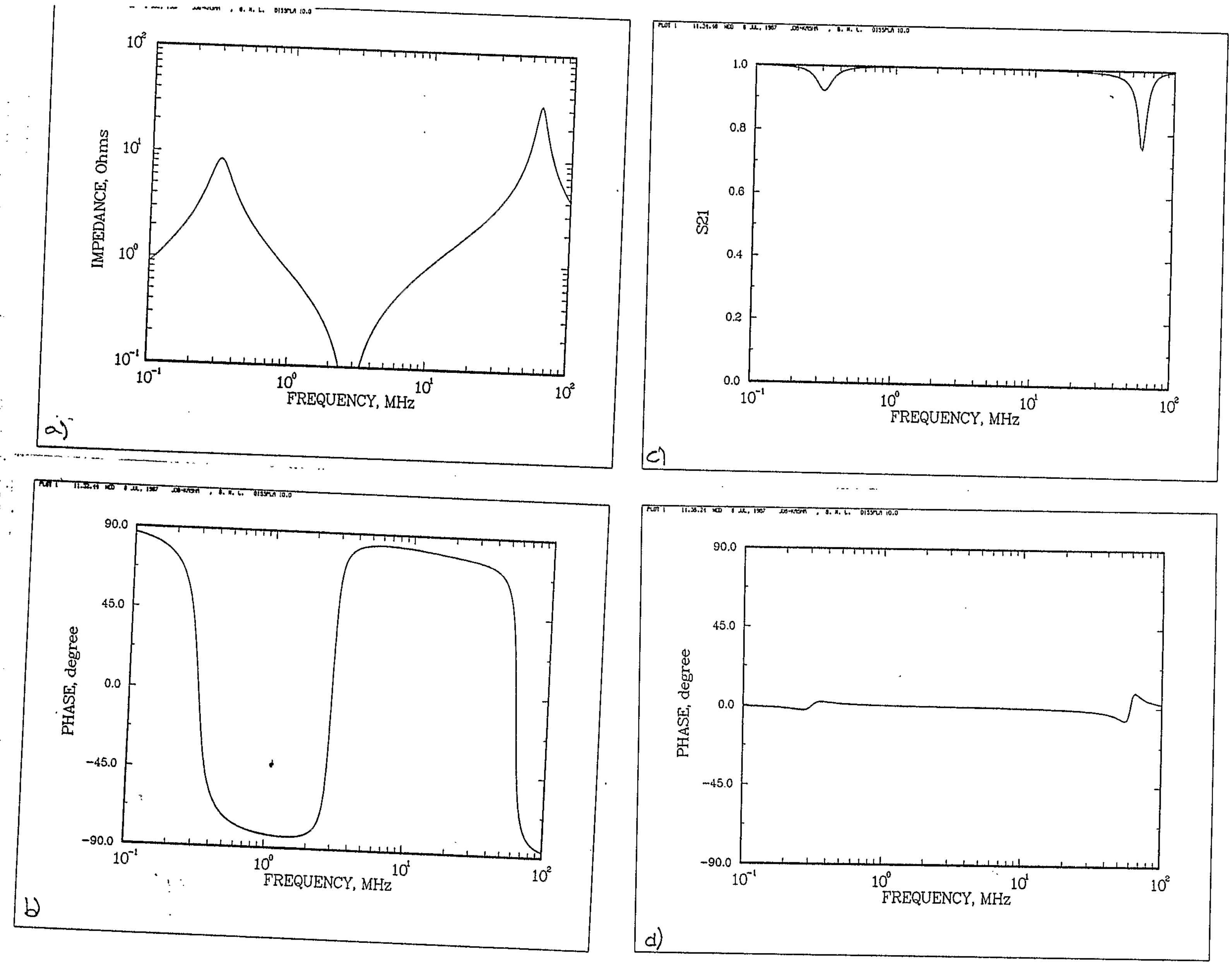

Figure 7. Calculated Impeadance and S21 with branch 1 and 2 of the RC network
a) Impedance magnitude b) Impedance phase c) S21 magnitude d) S21 phase

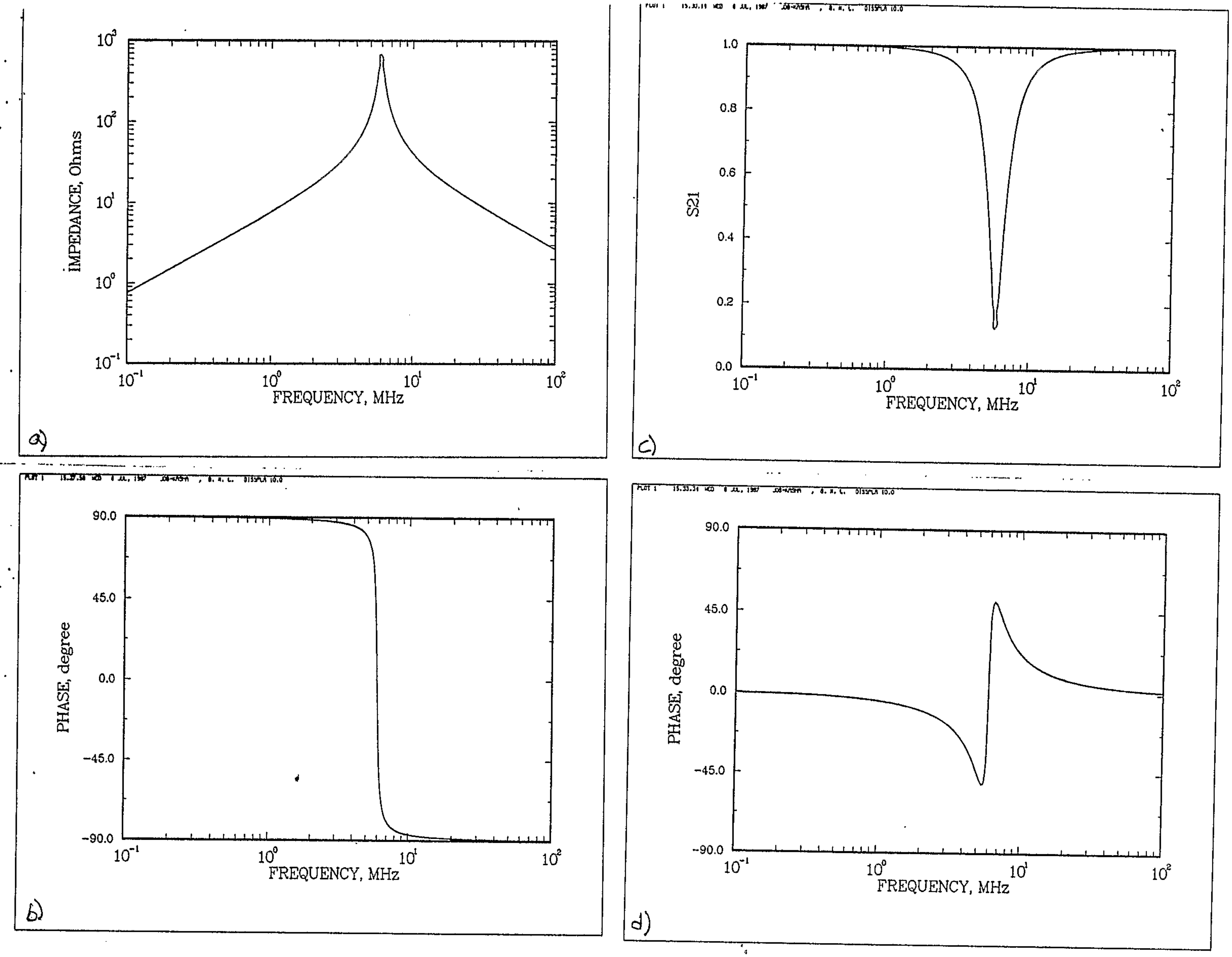

Figure 8. Calculated Impeadance and S21 with no RC network
a) Impedance magnitude b) Impedance phase c) S21 magnitude d) S21 phase

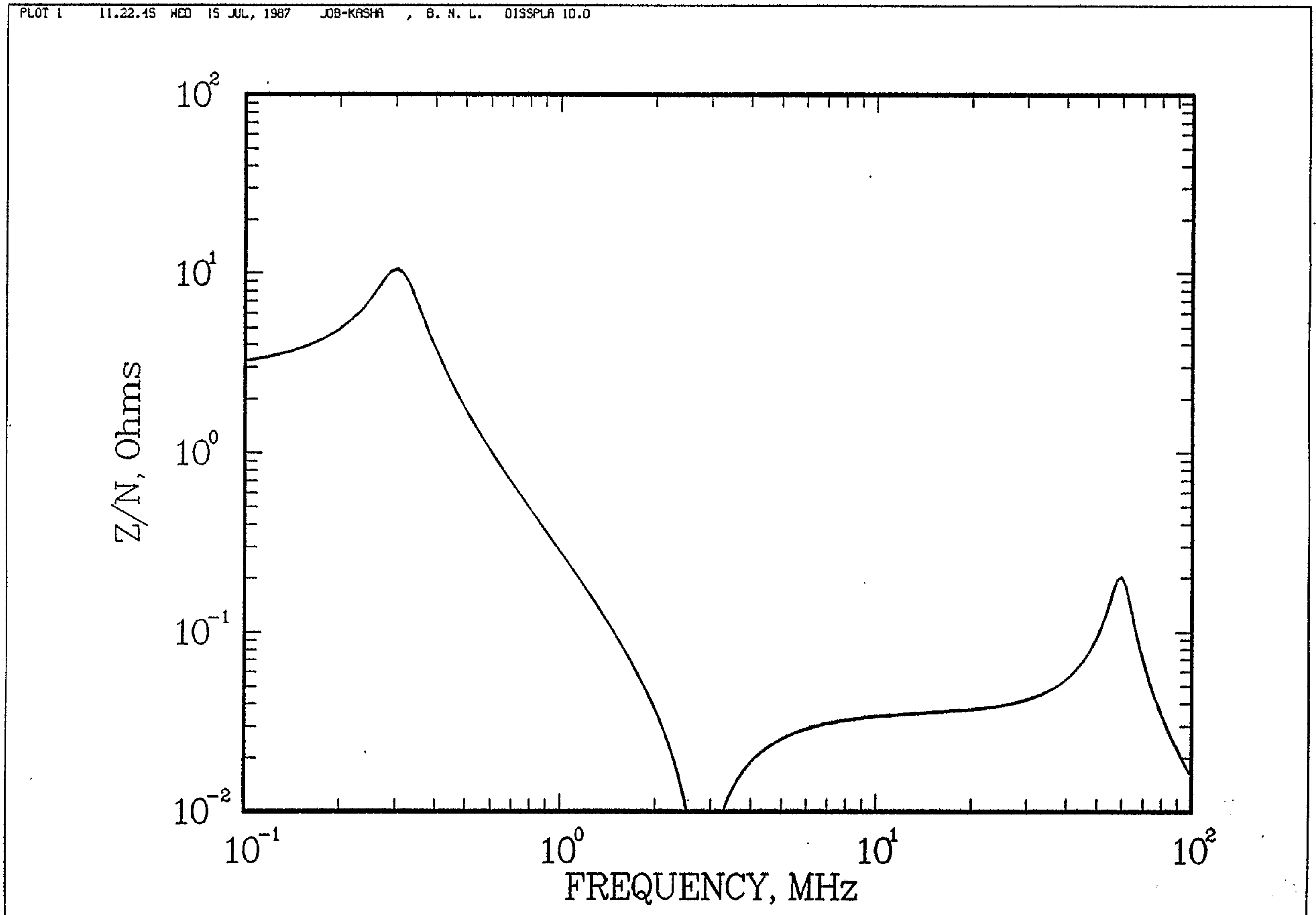

Figure 9. Z/n for the test setup with the RC network