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Abstract

The SNS Accumulator Ring is designed to contain a proton bunch of $2*10^{14}$ particles at 1 GeV with a repetition rate of 60 Hz for achieving 2 MW output power. This will be the highest intensity of proton beams in the world. Care must be taken to prevent collective instabilities. An accurate impedance budget of the ring components supported by experiments is essential. We have conducted measurements of coupling impedance for the SNS ring. The work involves a strip-line BPM and a window-frame dump-kicker magnet. The conventional wire method is employed with improved formulas. Both longitudinal and transverse impedance is obtained. The measured longitudinal impedance of the BPM agrees reasonably well with theoretical predictions based on an ideal transmission line configuration. For the dump-kicker magnet, the measured longitudinal and transverse impedance is compared with equivalent circuit models. In this paper we present our experimental results, analyses and suggestions for future work.

I. Introduction

The subject of collective instabilities caused by the interaction between beam particles and their surroundings is one of the main factors that determine the ultimate performance of accelerators, especially for high intensity rings. The interaction strength is characterized by the coupling impedance of accelerator components. For each new particle accelerator - in particular for machines aiming at high beam currents such as the SNS - the careful establishment of an "impedance budget" is a prerequisite for reaching the desired performances. During the ASAC

Review in October 1998, the review committee pointed out: "An estimate of the ring impedance has begun, but more resources should be applied soon to this important aspect of the ring to understand the impedance budget, the growth rates of instabilities, the possible need for feedback systems, and the importance of coherent effects on the injection painting procedure. This work should include an analysis of the effects of the wakefields resulting from the close proximity of the collimators and the high density edges of the beam." Therefore, an important piece of the ring design is to measure the coupling impedance of some critical ring components and to compare with theory, modeling and simulation in order to gain confidence in the ring design.

Our initial plan of the impedance measurement was to start with a strip-line type BPM. Since the coupling impedance of a strip-line BPM is well predicted by the transmission line theory, this would allow us to validate the method of measurement. Then, we would perform the measurement of a Booster dump kicker. The design of the SNS extraction kicker is very similar to the Booster dump kicker in that they use the same window frame ferrite magnets. The difference is in that there are two sections in the Booster dump kicker, while the SNS will use as many as 14 sections. The coupling impedance of the extraction kicker is probably the largest among all the SNS ring components, that raises some concerns. In our plan both longitudinal and transverse impedance would be measured.

In Section II we present a brief introduction to the wire method and some theoretical development in our work. Section III is devoted to the measurement of the longitudinal impedance of a strip-line BPM and a comparison with theory. The measurement of both longitudinal and transverse impedance of the Booster dump kicker is detailed in Section IV. A summary follows in Section V.

II Wire method for coupling impedance measurements

The conventional wire method has been widely used for bench test of coupling impedance of accelerator components [1-5]. An accelerator component with a thin metallic wire on its beam axis can be regarded as a two-port microwave circuit, of which the scattering coefficients can be measured with a microwave network analyzer. The test usually requires two independent, consecutive measurements of the transmission coefficients S_{21} of the Device Under Test (DUT) and a smooth reference beam pipe (REF). In a matched condition between the REF/DUT and the network analyzer, the longitudinal coupling impedance $Z_{//}$ of the DUT can be found from the measured transmission coefficients S_{21} as [3]

$$Z_{//} = 2Z_0\left(\frac{S_{21}^R}{S_{21}^D} - 1\right) \quad . \tag{1}$$

Here Z_0 is the characteristic impedance formed by the reference pipe with the axial wire as a coaxial transmission line structure; the superscripts R and D represent REF and DUT, respectively. This formula is often referred to as the HP formula in the literature.

In 1993 V. G. Vaccaro derived a more rigorous and accurate formula, based on the transmission line theory, to calculate the coupling impedance with the wire method [6]. He shows that in a strictly matched and symmetric condition, i.e. $S_{11}=S_{22}=0$, the longitudinal coupling impedance should be calculated as

$$Z_{//} = Z_0 \ln\left(\frac{S_{21}^R}{S_{21}^D}\right)\left(1 + \frac{\ln S_{21}^D}{\ln S_{21}^R}\right) \quad . \tag{2}$$

If the coefficient $S_{21}{}^D$ for the DUT is close to the coefficient $S_{21}{}^R$ for the REF, which is usually the case for many accelerator components, Eq. (2) can be approximated by

$$Z_{//} \cong 2Z_0 \ln\frac{S_{21}^R}{S_{21}^D} \quad . \tag{3}$$

This is usually called the log formula for the longitudinal coupling impedance calculation in the wire-method. Equation (3) will reduce to Eq. (1) if we expand the logarithm and take only the linear terms.

For the transverse coupling impedance measurement with the wire method, one way is to insert two parallel wires in the device being tested in order to produce a dipole current moment. Vaccaro also shows that the transverse coupling impedance can be calculated by:

$$Z_{\perp} = \frac{cZ_0}{\omega\Delta^2} \ln\left(\frac{S_{21}^R}{S_{21}^D}\right)\left(1 + \frac{\ln S_{21}^D}{\ln S_{21}^R}\right) \quad , \tag{4}$$

where Δ is the separation of the two wires in the DUT or REF.

Strictly speaking, the reflection coefficient S_{11} =0 can not be satisfied simultaneously for both REF and DUT in measurements. In practice, there are always imperfections, which result in mismatching. Following Vaccaro's approach, we have found that if S_{11} is not zero, a corrected S-parameter S_c can be found from [7]

$$S_c^2 + \frac{S_{11}^2 - S_{21}^2 - 1}{S_{21}} S_c + 1 = 0 \tag{5}$$

to yield

$$Z_{//} = Z_0 \ln\left(\frac{S_c^R}{S_c^D}\right)\left(1 + \frac{\ln S_c^D}{\ln S_c^R}\right) \quad . \tag{6}$$

Equation (6) has exactly the same form as Eq. (2), except that S_{21} is replaced by S_c. Applying Eq. (6) requires both the transmission coefficients S_{21} and reflection coefficients S_{11} in measurements, that is not a difficult task. If S_c^D is close to S_c^R, which is usually the case for most accelerator components, we can then approximate Eq. (6) as

$$Z_{//} \cong 2Z_0 \ln\left(\frac{S_c^R}{S_c^D}\right) \quad . \tag{7}$$

If S_{11}=0, i.e., the line is matched, we have S_c=S_{21}, and we recover Eqs. (2) and (3).

Similarly, we can have a formula for the transverse coupling impedance measurement:

$$Z_{\perp} = \frac{cZ_0}{\omega\Delta^2} \ln\left(\frac{S_c^R}{S_c^D}\right)\left(1 + \frac{\ln S_c^D}{\ln S_c^R}\right) \quad . \tag{8}$$

In practice, if the coupling impedance of an accelerator component is not very large and the matching is reasonably good, the Vaccaro's formulas, i.e. Eqs. (2-4), are simpler to use and should provide adequate accuracy.

III Measurement of a strip-line BPM

Based on the ideal transmission line theory, the longitudinal coupling impedance of a strip-line BPM can be calculated as [8]

$$Z_r = NZ_c\left(\frac{\phi_0}{2\pi}\right)^2 Sin^2\left(\frac{\omega l}{c}\right)$$

$$Z_i = NZ_c\left(\frac{\phi_0}{2\pi}\right)^2 Sin\left(\frac{\omega l}{c}\right)Cos\left(\frac{\omega l}{c}\right) \quad . \tag{9}$$

Here N is the number of the strip-line probes in the BPM, Z_c is the characteristic impedance of a strip line, ϕ_0 is the angle subtended by the probe, l is the length of the strip line, and ω is the signal frequency. The strip-line BPM in the measurement, i.e. the DUT, is a device designed and fabricated for RHIC. It contains two probes, each of which has a characteristic impedance of 50 Ω, a length of 0.275 m, a subtended angle ϕ_0 of 80 degree. In order to compare with the theoretical result from Eq. (9), the REF used in the measurement is the same mechanical structure as the DUT, except that the two probes are taken out.

The schematic of the measurement is shown in Fig. 1. A network analyzer HP 8753C plus an S-parameter test set HP 85047A, which requires 50 Ω cables to its input/output signals, are employed to obtain the scattering coefficients. A thin copper wire is installed on the axis of the DUT and REF, that forms a coaxial transmission line structure with a characteristic impedance of more than 300 Ω. In order to match the REF or DUT to the network analyzer, two wide-band resistors are inserted on each end of the device. Though this is not the best way of doing match, it reduces mechanical support considerably in the experiment.

Figure 2 shows the reflection coefficient S_{11} of the REF from the measurement. It is clear that S_{11} is not zero, and match is not perfect, especially at higher frequencies. The linear amplitude and phase of the transmission coefficients S_{21} of the DUT and REF are plotted in Fig. 3 (a) and (b). Note that the phases of the DUT (squares) and REF (diamonds) are so close that they overlap in the plot. Applying Eqs. (5) and (7) yields the longitudinal coupling impedance of the strip-line BPM, shown in Fig. 4, where the theoretical result from Eq. (9) is also plotted for comparison with the measurement. The agreement is reasonably good. The discrepancy is first attributed to the coupling between the two probes, that is not included in Eq. (9). Other factors of causing the discrepancy include the end effect of the real transmission-line probes and distributed parameters, espècially at higher frequencies.

When a beam passes a strip-line BPM, the beam sees the coupling impedance due to not only the stripe lines, but also the contributions from other mechanical structures such as bellows, steps, tapers, etc., in the device. In order to demonstrate this effect, a different REF made of a smooth beam pipe is also employed in a separate measurement. In this case the measured longitudinal impedance of the same BPM is shown in Fig. 5, which is substantially larger than that in Fig. 4. This suggests the importance of measurements, which take all effects of a real device into consideration, while theory can only deals with simpler, more ideal configurations.

IV. Measurement of Booster dump kicker

The mechanical structure of the Booster dump kicker is shown in Fig. 6. The DUT contains two sections of window frame ferrite magnets, each of which has a dimension of 4.65" (height) x 6.23" (width) x 16" (length), and a ferrite thickness of 1". A copper sheet break of 1 mm in thickness is inserted in the top, as well as the bottom, of the magnet to reduce beam power loss. The setup for the longitudinal coupling impedance measurement is similar to that for the BPM. A smooth beam pipe with the same length as the DUT's is used as the reference (REF). With a thin central wire, it forms a coaxial transmission line with characteristic impedance of about 370 Ω. Matching 50 Ω of the network analyzer to 370 Ω of the reference line is achieved by adding at each end of the line a parallel resistor of 53.8 Ω and a series resistor of 342 Ω, respectively, which provides forward and backward matching.

Figure 7 shows the Smith chart of the reflection coefficient S_{11} in the REF line. Matching is quite good and the impedance appears to be a single dot around 50 Ω in the chart within the frequency range from 0.3 to 100 MHz. The transmission coefficients S_{21} of the DUT and REF are plotted in Fig. 8, where (a) shows the linear magnitude and (b) plots the phase. Applying Eq. (3) to the experimental data yields the longitudinal impedance of the kicker magnets, shown in Fig. 9. The real part of the impedance has a peak value of about 110 Ω around 25 MHz, and then decreases monotonously when the frequency increases. The imaginary part of the impedance is inductive within the test frequency range. The measurement also shows that the longitudinal coupling impedance of the window frame magnet is not sensitive to external loads.

The measurement of the transverse coupling impedance requires a dipole current moment which can be generated with two parallel wires. By employing wide-band transformers, the common mode signal from a network analyzer can be converted to differential mode signals inside the DUT or REF. Matching is still to be made, e.g., by resistive networks. The transmission coefficients of the DUT and REF from the measurement, when the load terminal is open, are plotted in Fig. 10, where the S_{21} phases for the DUT and REF are so close that the two curves are overlapped in Fig. 10 (b). The transverse coupling impedance is calculated by Eq. (4). In Fig. 11 (a) and (b), we plot the real and imaginary part of the transverse coupling impedance of the dump-kicker magnet with different loads. When a 18 m long, open-end 50 Ω cable is connected to the magnet power supply terminals, its transmission coefficient and the transverse coupling impedance show resonant structures, which are potted in Fig. 12 and Fig. 13.

V. Summary

The coupling impedance of a strip-line BPM and a Booster dump-kicker magnet has been measured for the SNS project. The conventional wire method is employed for the bench test, with newly derived formula to calculate the coupling impedance from experimental data. For the strip-line BPM, the longitudinal coupling impedance has been measured and compared with theory. The agreement is reasonably good, that validates our experimental method. The work also shows that the theory based on simple, idealized configuration can not fully represent a real device. For the dump-kicker magnet, both the longitudinal and transverse impedance has been measured. In comparison with the models, which are not shown in this report, the measurement has provided useful information about the parasitic power loss in the magnet, which should be investigated further. Both the longitudinal and transverse impedance of the dump-kicker magnet appears to be very high. This has raised some concerns about 14 sections of the extraction kicker magnets for the SNS ring, which may lead to instabilities. Our experience also suggests that the coupling impedance of other critical components such as the RF cavity, collimators on the SNS ring should also be measured before the ring design is finalized.

Acknowledgements

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Figure Captions

Fig. 1 Schematic of measurements of longitudinal coupling impedance.

Fig. 2 Magnitude of the reflection coefficient S_{11} of the REF for a strip-line BPM.

Fig. 3 Transmission coefficients S_{21} of the strip-line BPM: (a) Linear Magnitude, (b) Phase.

Fig. 4 Longitudinal coupling impedance of the strip-line BPM.

Fig. 5 Longitudinal coupling impedance of the strip-line BPM with a smooth beam pipe as the REF.

Fig. 6 Mechanical structure of the Booster dump kicker.

Fig. 7 Reflection coefficient of the REF for the dump-kicker magnet: Smith chart.

Fig. 8 Transmission coefficients in the dump kicker measurement: (a) Linear magnitude, (b) Phase.

Fig. 9 Longitudinal impedance of the Booster dump kicker, where the data point at the lowest frequency corresponds to 1.297 MHz.

Fig. 10 Transmission coefficients for the transverse impedance measurement: (a) Linear magnitude, (b) Phase.

Fig. 11 Measured transverse impedance of the dump kicker with different loads, where the lowest frequency in the measurement is 0.3 MHz: (a) real part, (b) imaginary part.

Fig. 12 S_{21} linear magnitudes of the DUT and REF when the DUT is terminated to an open 50 Ω cable.

Fig. 13 Transverse impedance of the dump kicker with an open 50 Ω cable as the load.

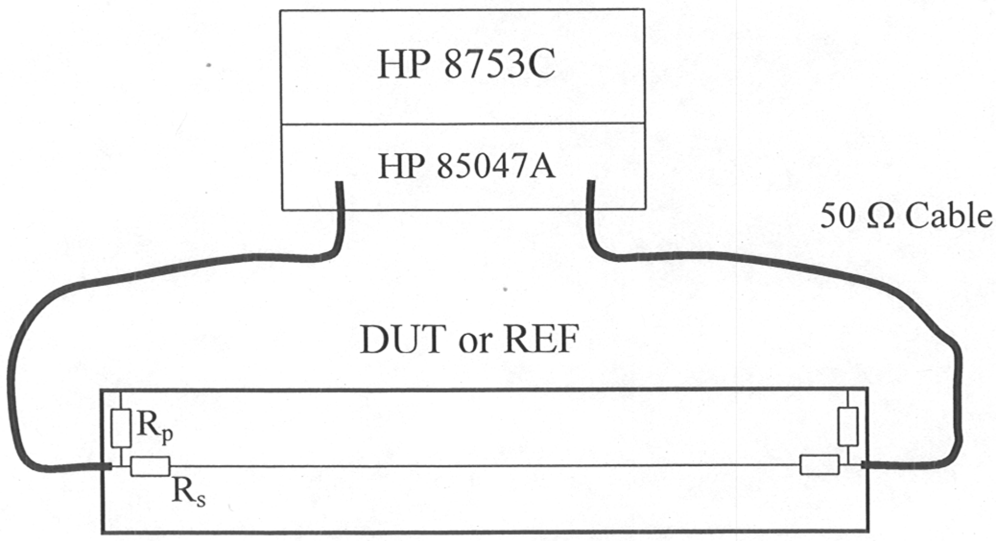

Fig. 1 Schematic of measurements of longitudinal coupling impedance.

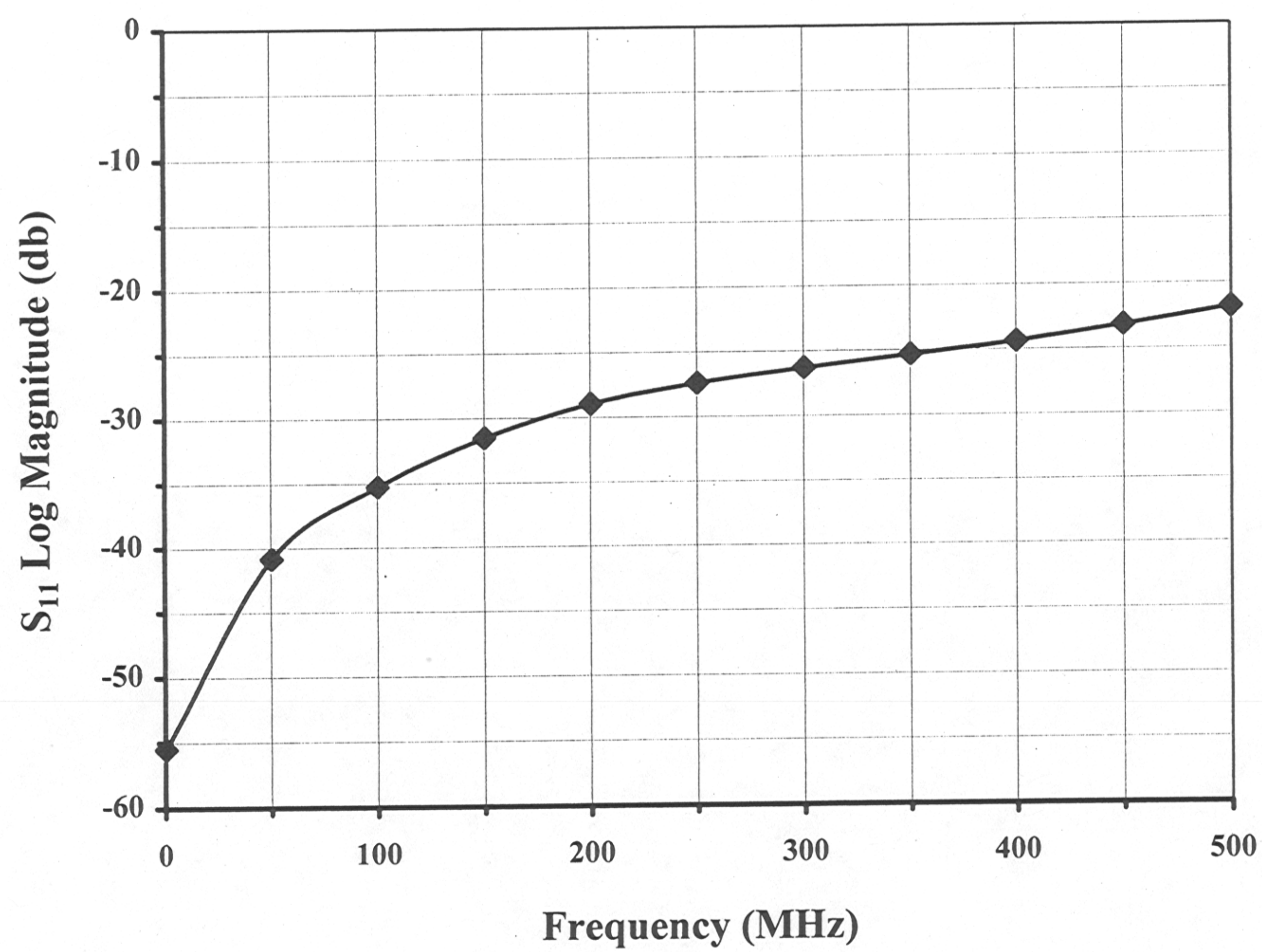

Fig. 2 Magnitude of the reflection coefficient S_{11} of the REF for a strip-line BPM.

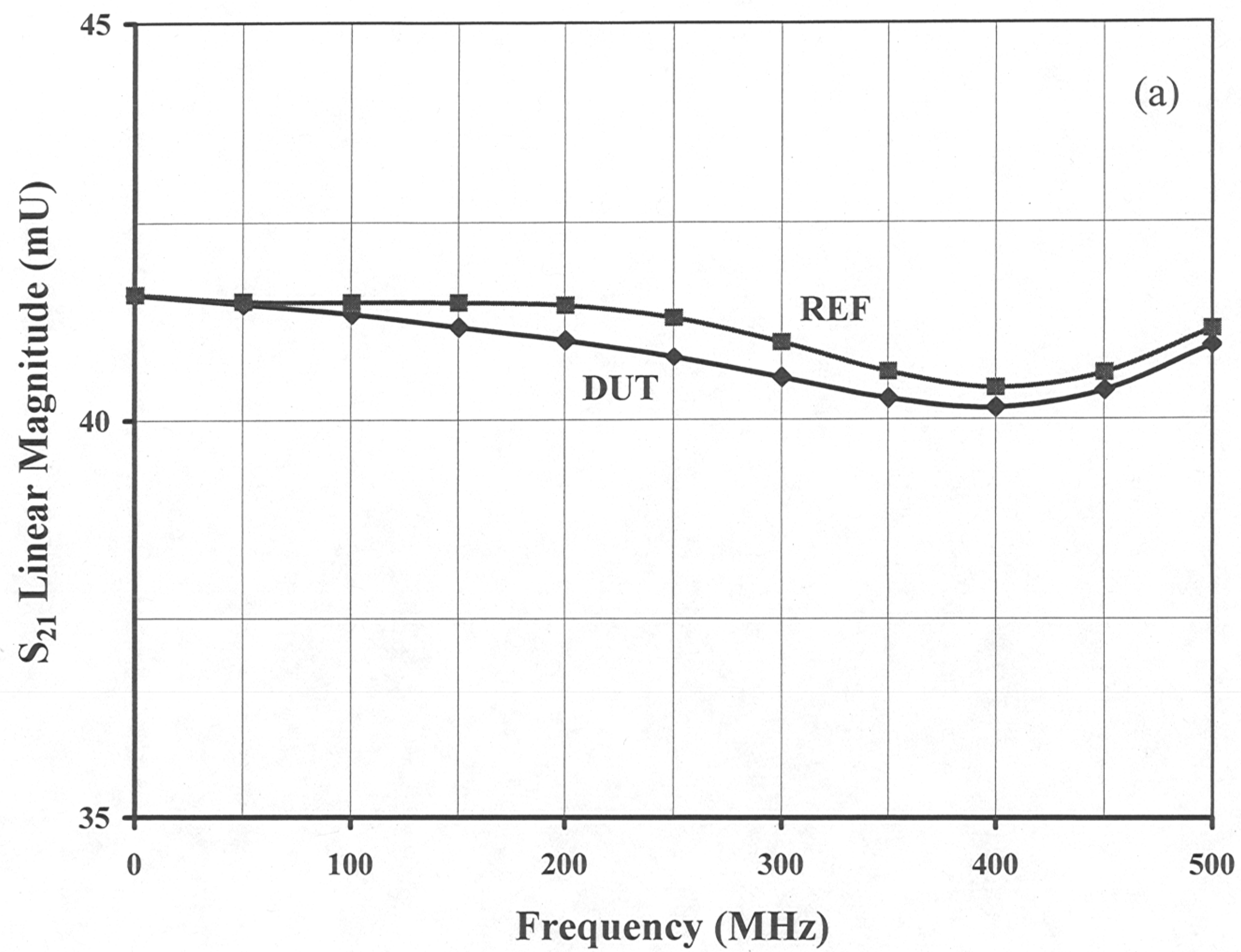

Fig. 3 Transmission coefficients S_{21} of the strip-line BPM: (a) Linear Magnitude

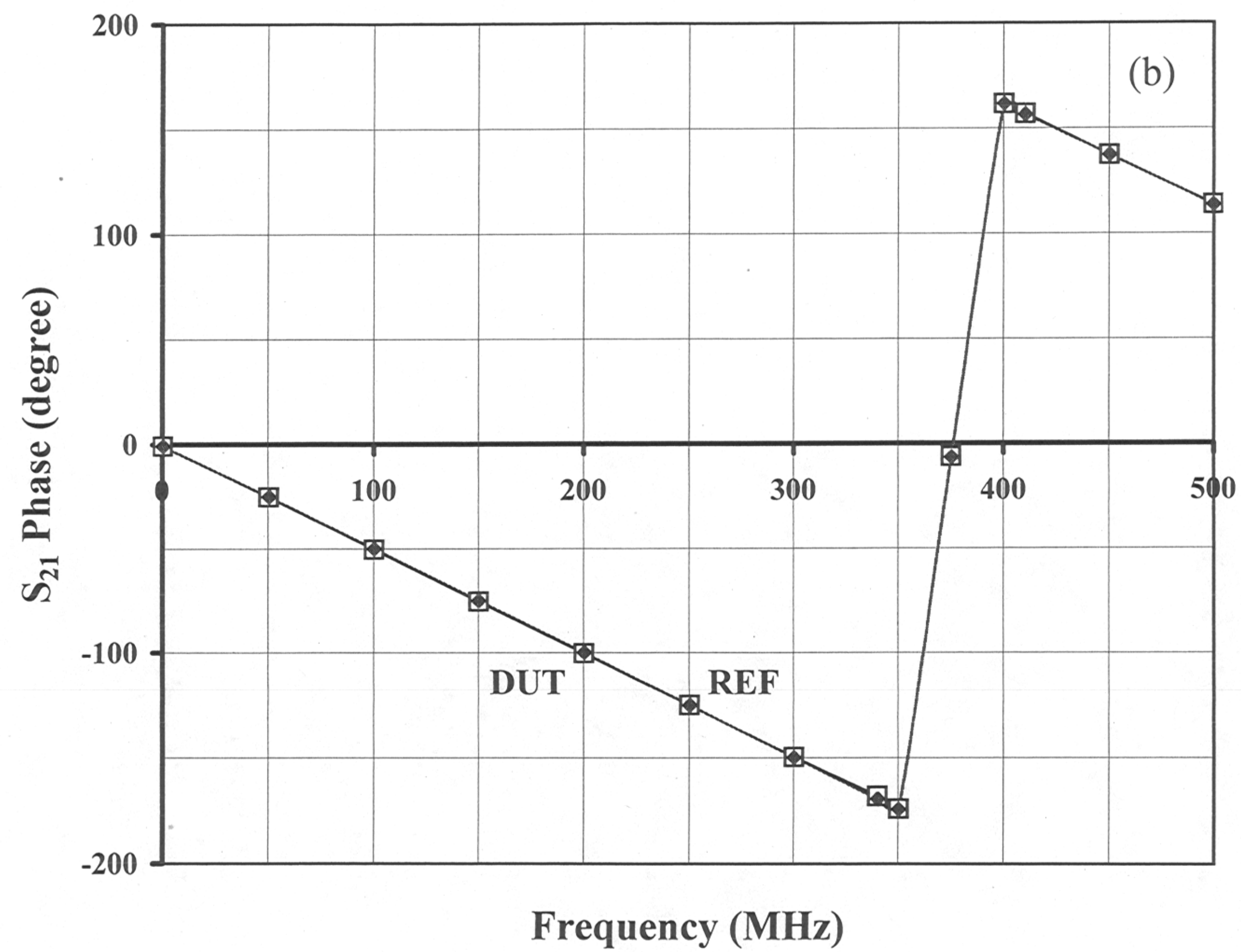

Fig. 3 Transmission coefficients S_{21} of the strip-line BPM: (b) Phase.

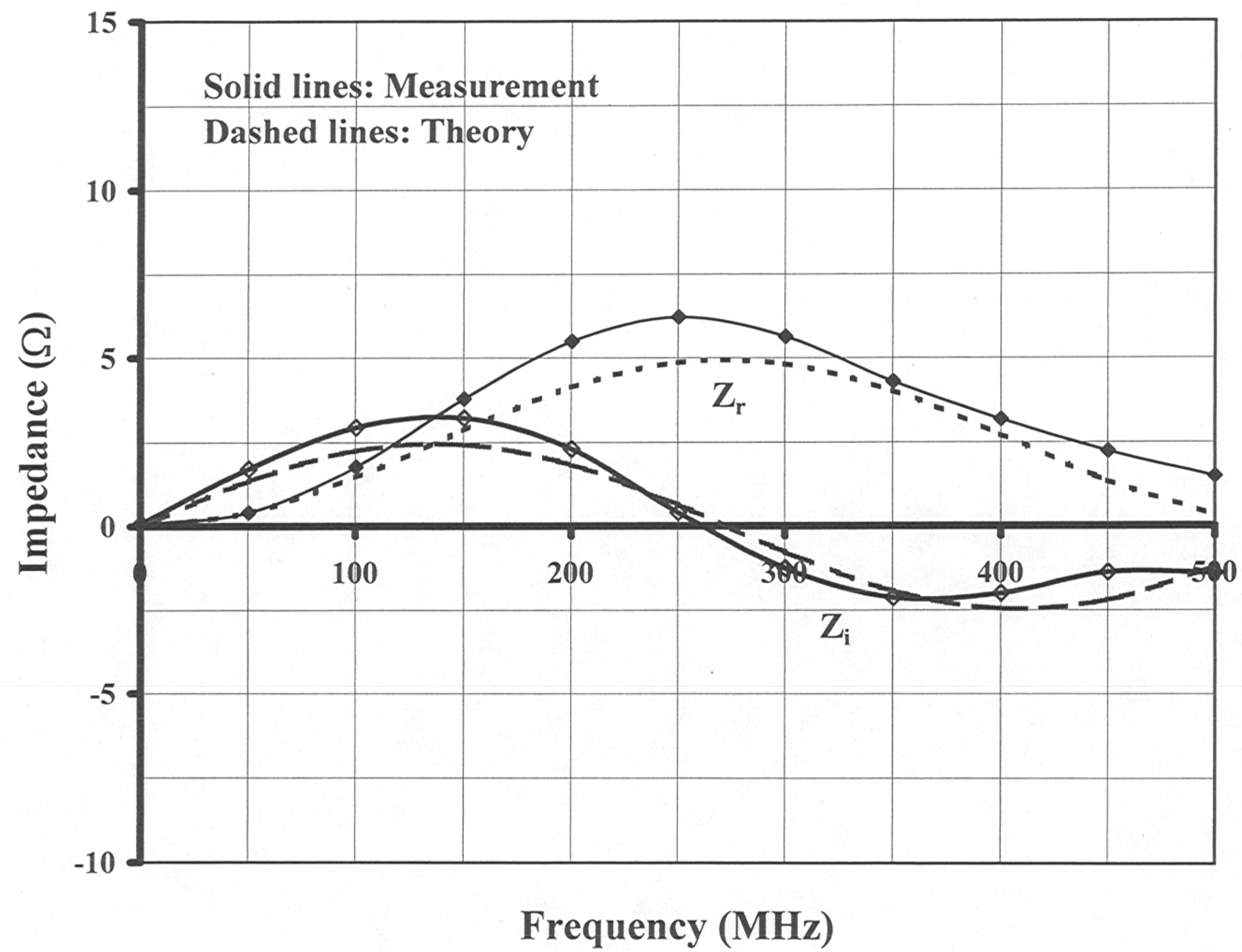

Fig. 4 Longitudinal coupling impedance of the strip-line BPM.

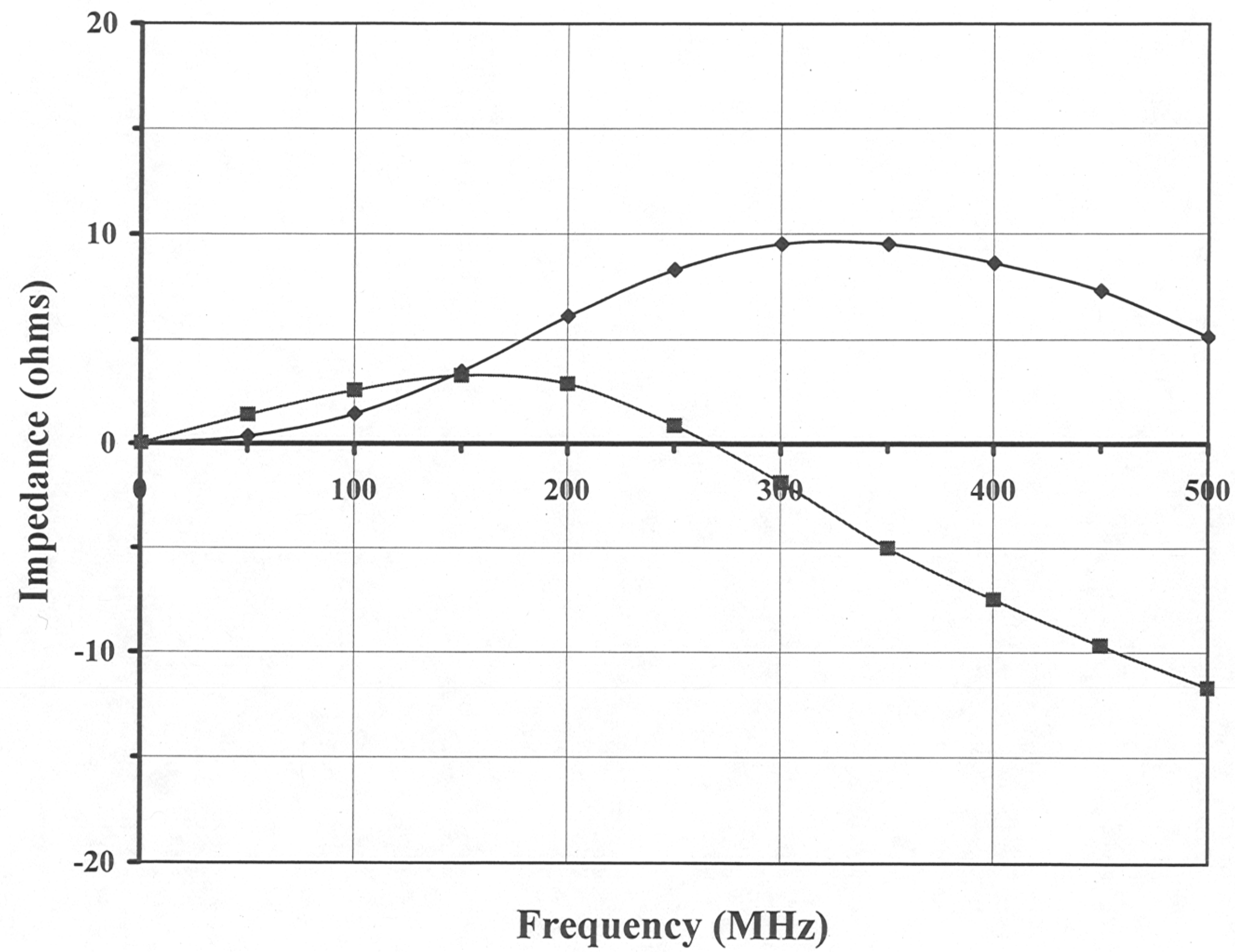

Fig. 5 Longitudinal coupling impedance of the strip-line BPM with a smooth beam pipe as the REF.

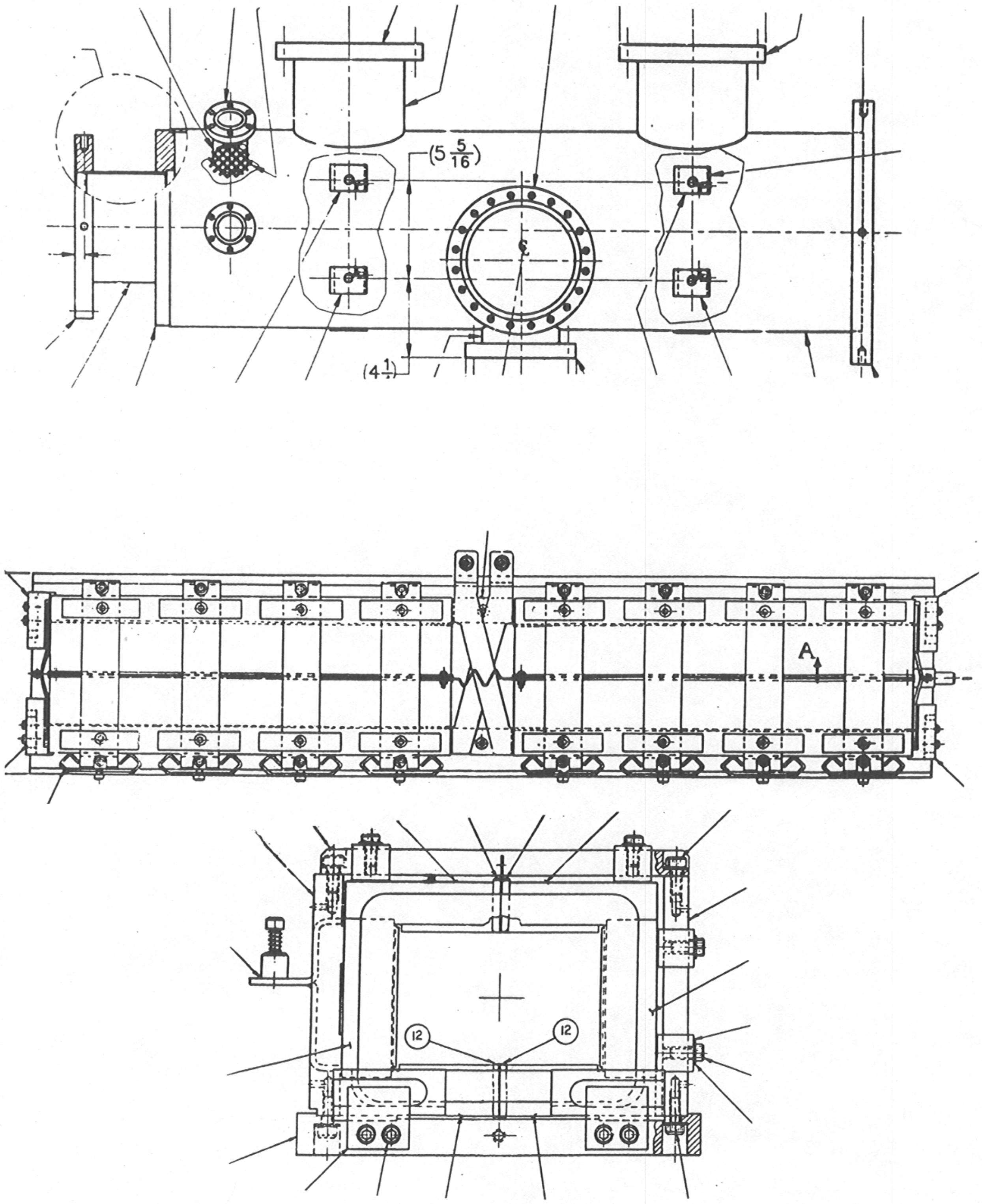

Fig. 6   Mechanical structure of the Booster dump kicker.

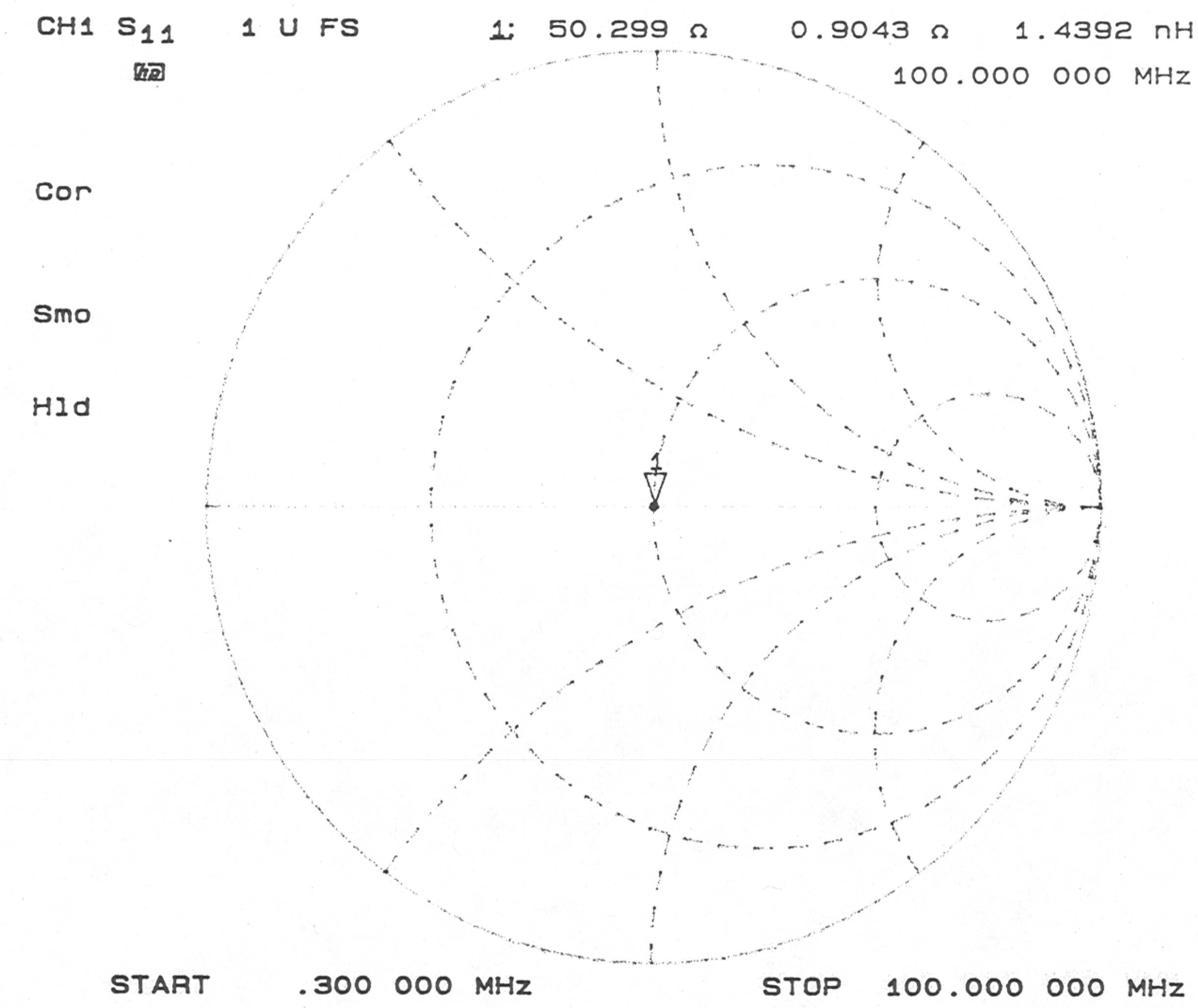

Fig. 7 Reflection coefficient of the REF for the dump-kicker magnet: Smith chart.

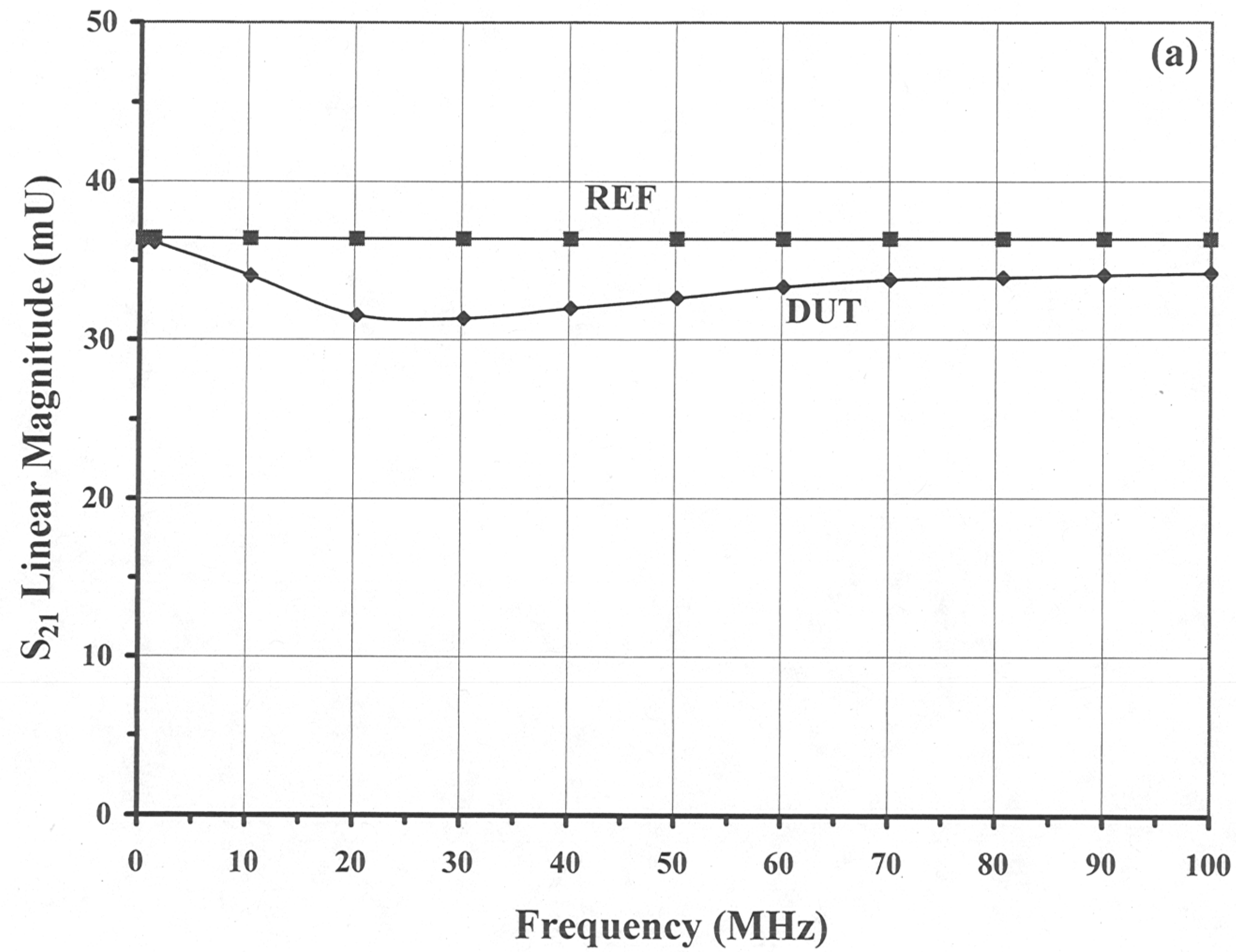

Fig. 8 Transmission coefficients in the dump kicker measurement: (a) Linear magnitude.

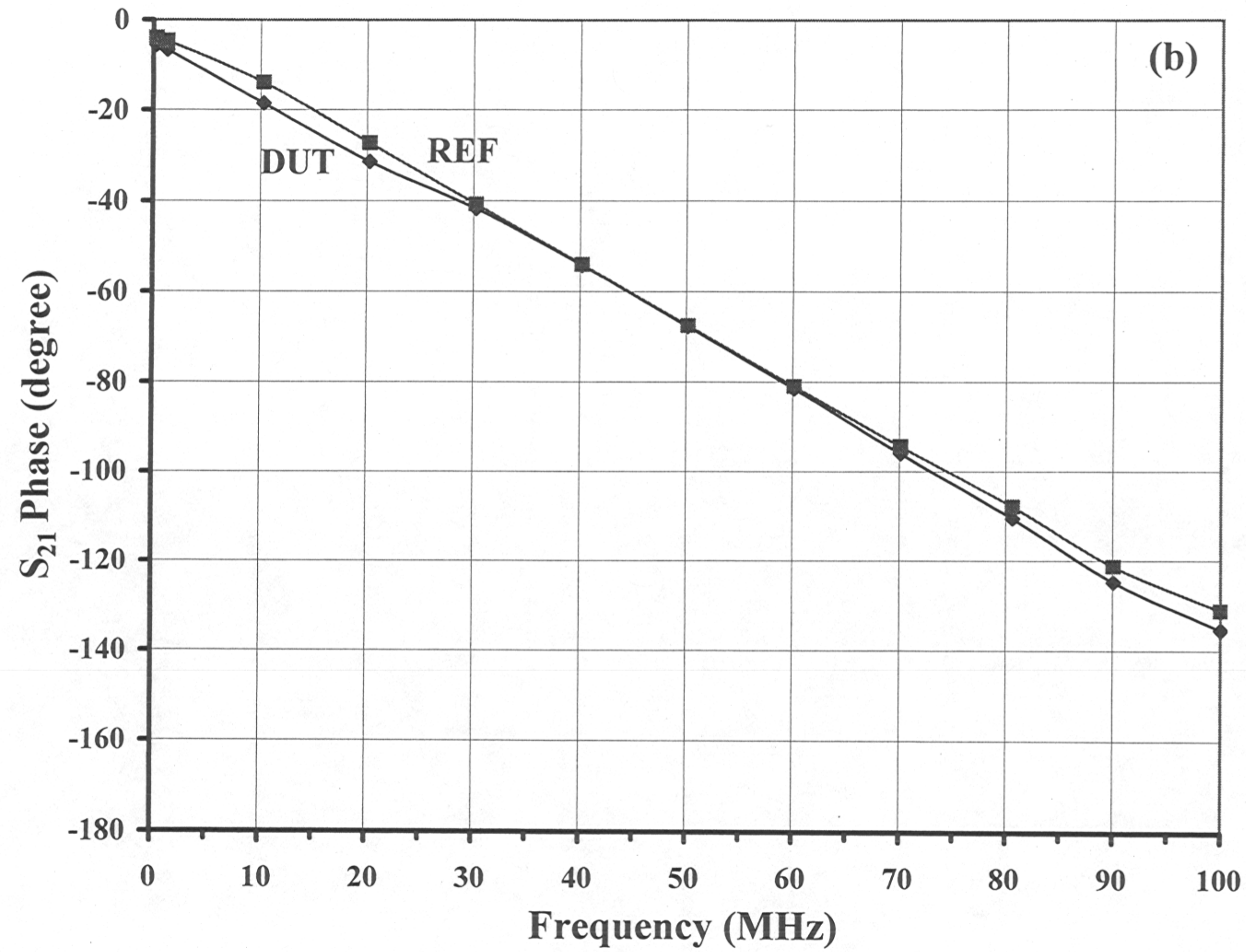

Fig. 8 Transmission coefficients in the dump kicker measurement: (b) Phase.

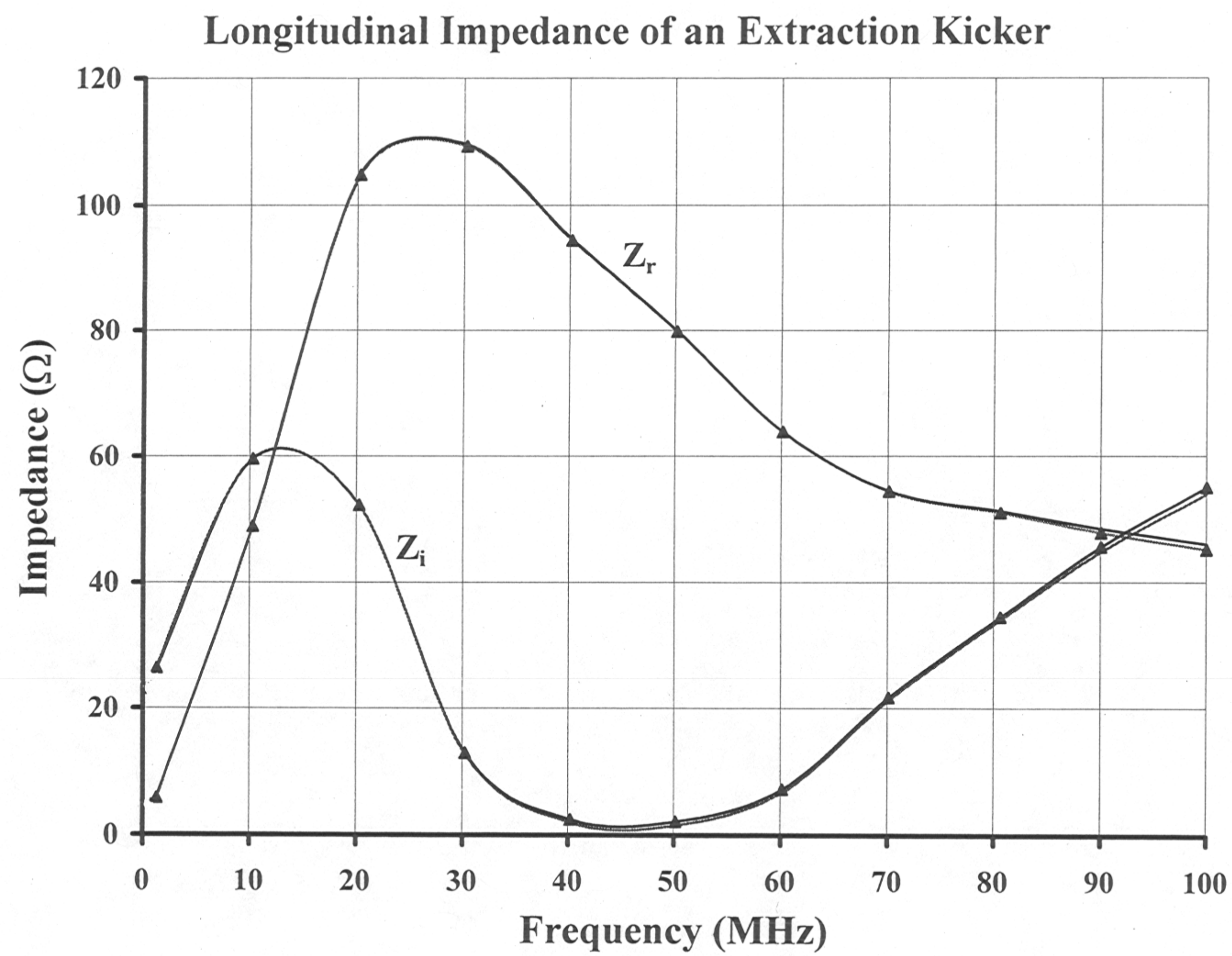

Fig. 9 Longitudinal impedance of the Booster dump kicker, where the data point at the lowest frequency corresponds to 1.297 MHz.

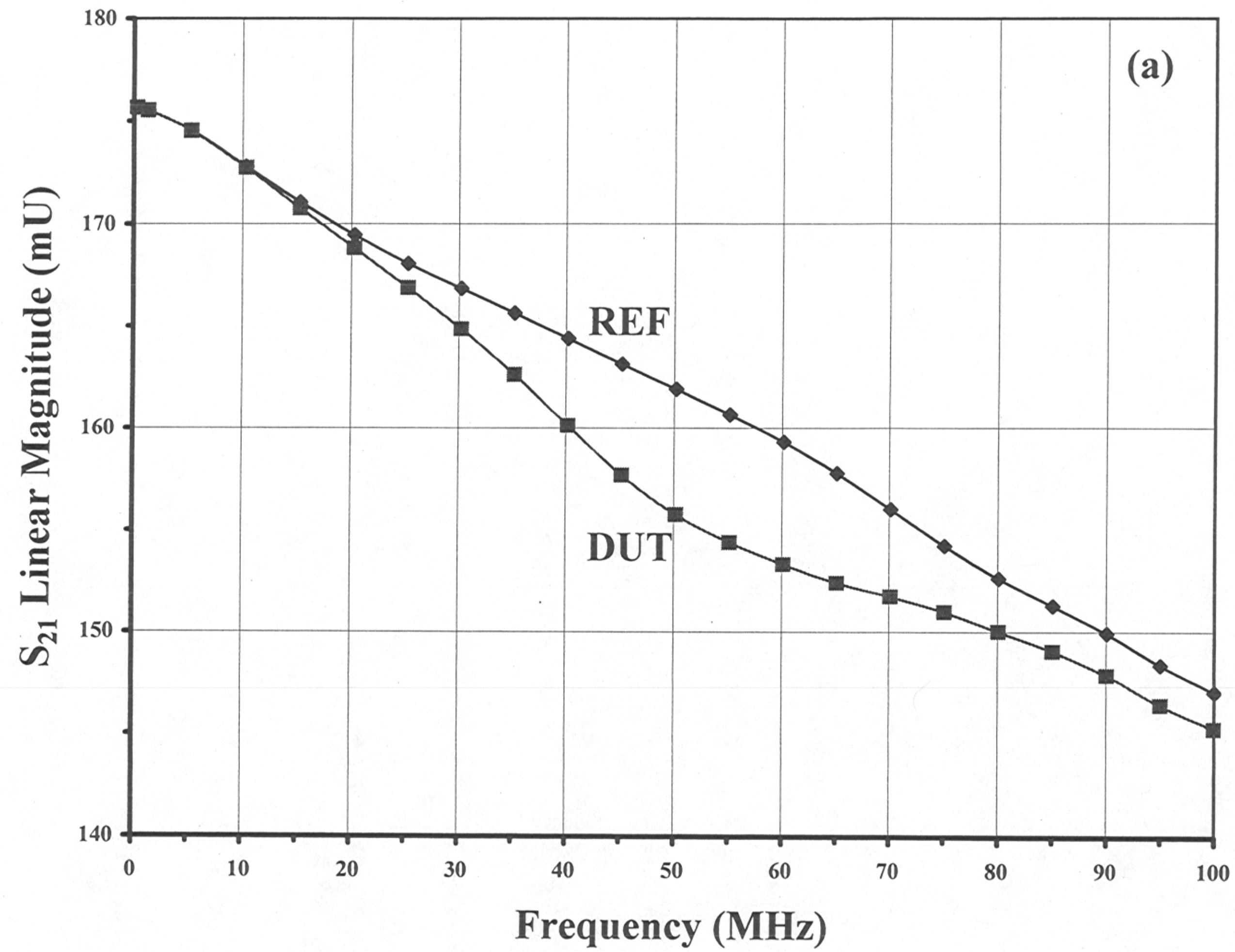

Fig. 10 Transmission coefficients for the transverse impedance measurement: (a) Linear magnitude.

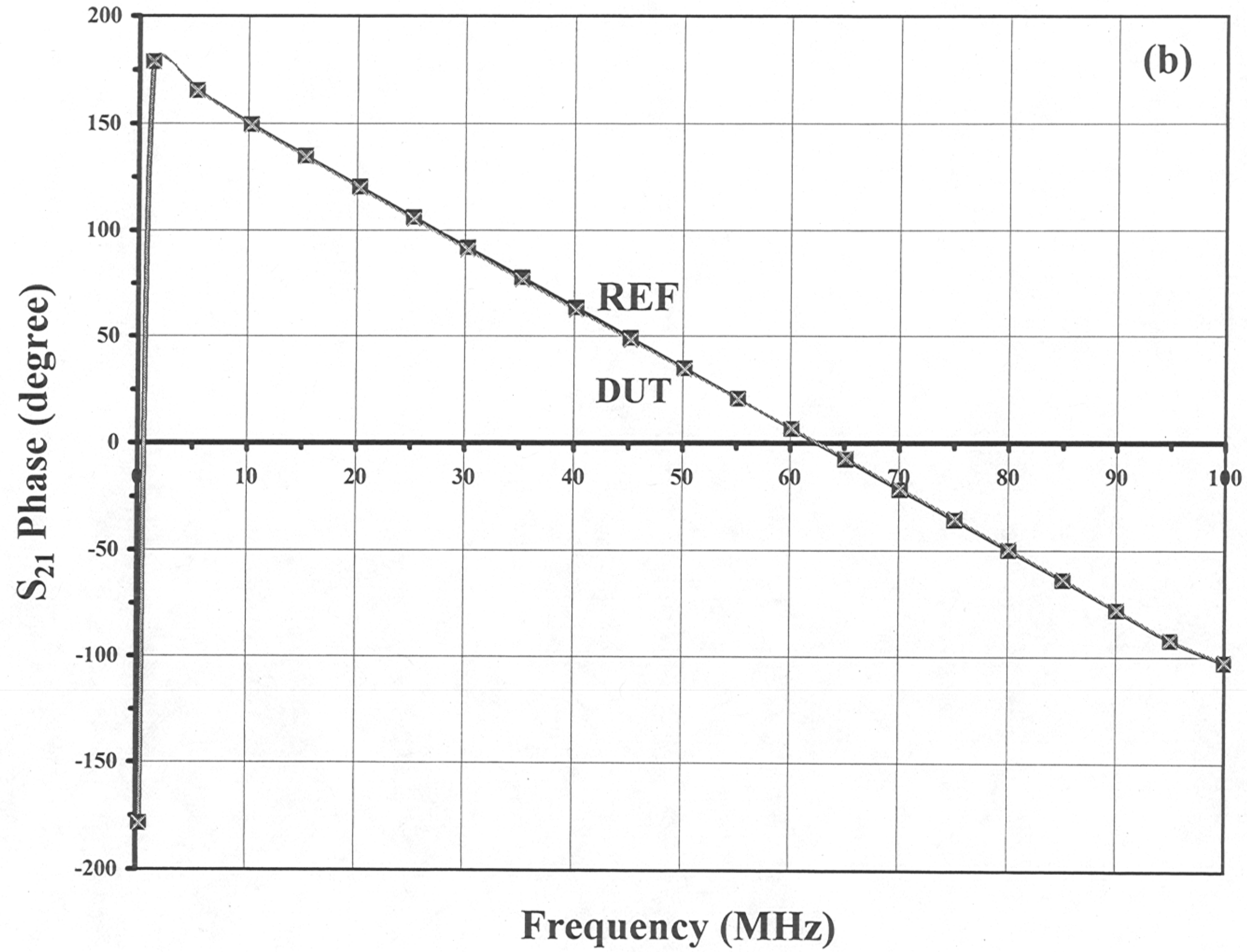

Fig. 10 Transmission coefficients for the transverse impedance measurement: (b) Phase.

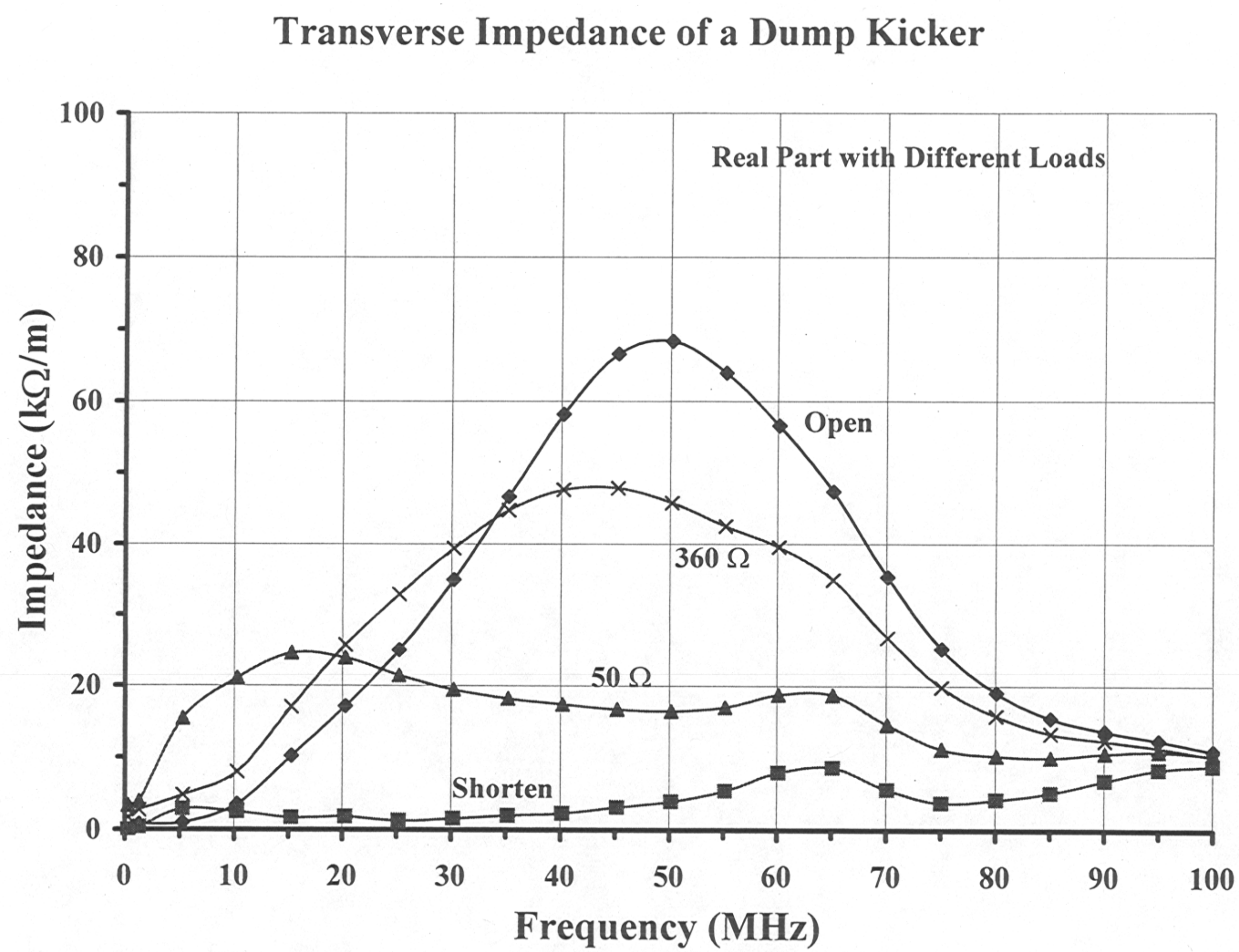

Fig. 11 Measured transverse impedance of the dump kicker with different loads, where the lowest frequency in the measurement is 0.3 MHz: (a) real part.

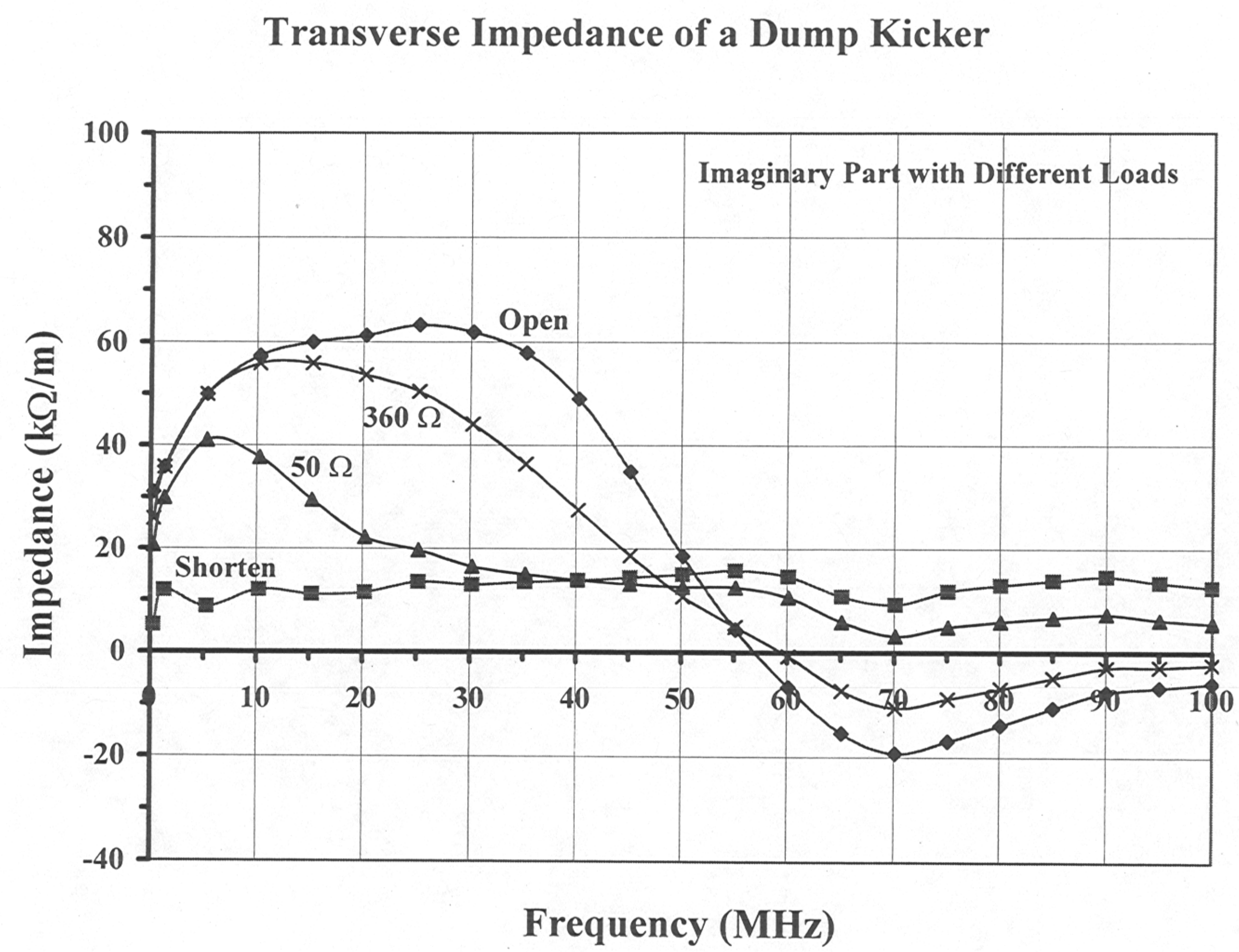

Fig. 11 Measured transverse impedance of the dump kicker with different loads, where the lowest frequency in the measurement is 0.3 MHz: (b) imaginary part.

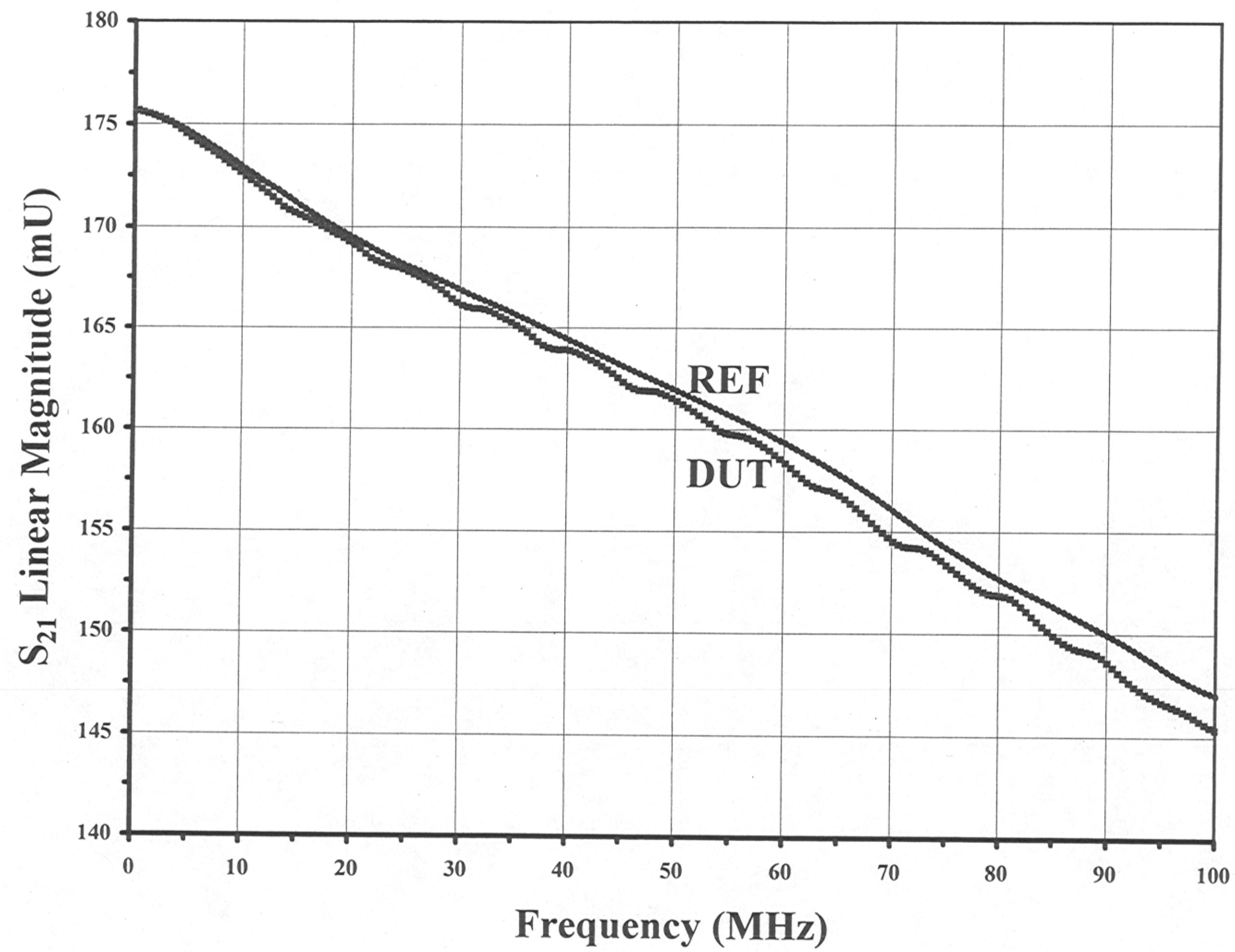

Fig. 12 S_{21} linear magnitudes of the DUT and REF when the DUT is terminated to an open 50 Ω cable.

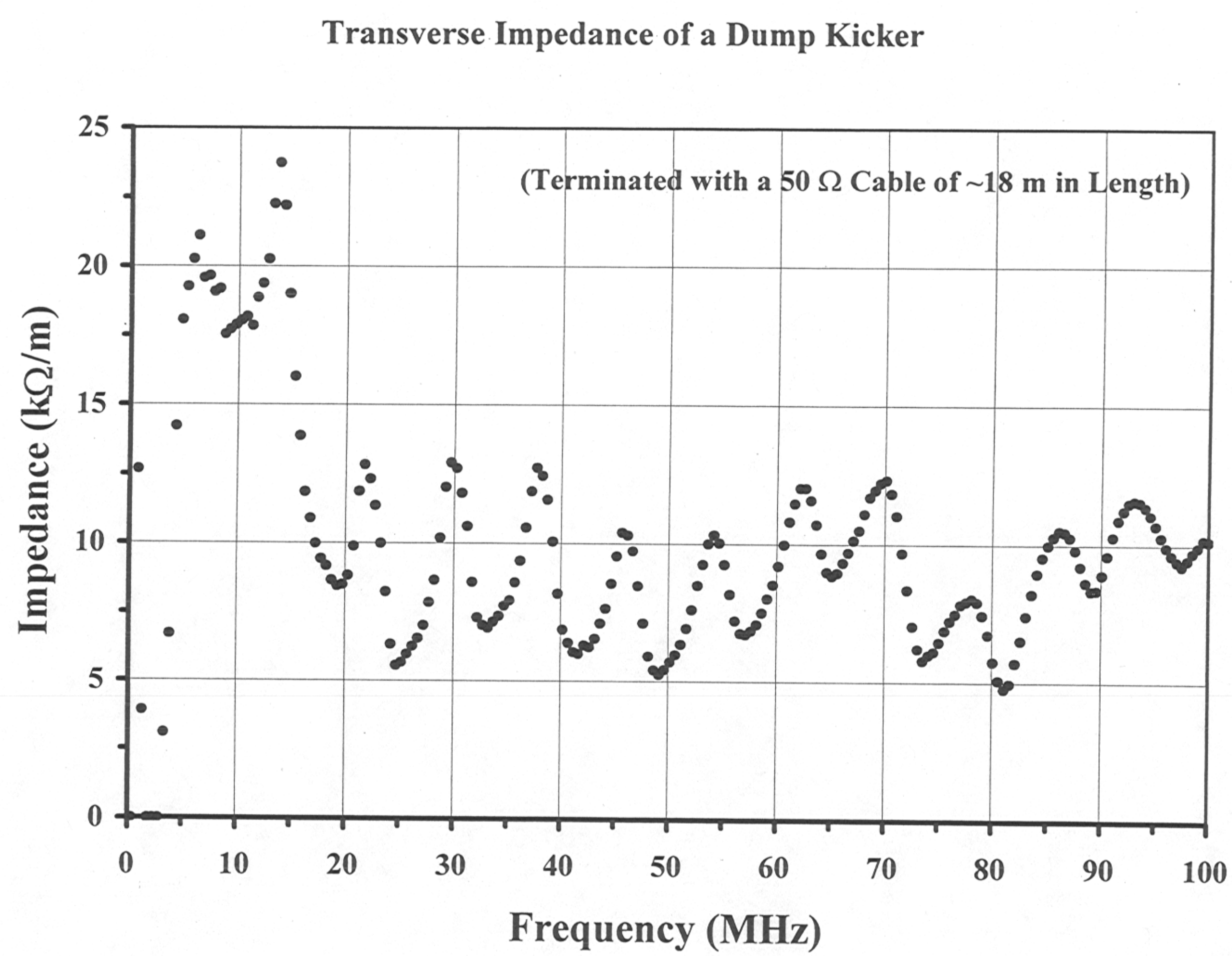

Fig. 13 Transverse impedance of the dump kicker with an open 50 Ω cable as the load.