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Impedance Evaluation of the SPS MKE Kicker with Transition Pieces between Tank and Kicker Module

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Abstract

In this paper we discuss longitudinal beam coupling impedance measurements performed with the coaxial wire method on a modified prototype of the SPS MKE kicker. The frequency dependent real and imaginary part of the distributed coupling impedance are obtained from the measured S-parameters by standard and improved log-formulae. A comparison with theoretical models and previous measurements is discussed as well.

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1 Introduction and Motivation

Recently, some theoretical and experimental work has been devoted to estimating the longitudinal coupling impedance of the SPS MKE kicker. The main reason is the excessive heating that could prevent it from working. In fact when the ferrite reaches the Curie temperature, it loses all its magnetic properties.

Analytical models have been worked out by L. Vos [1] and H. Tsutsui [2] and compared with simulations. Measurements on a prototype were also performed to eventually asses the theoretical predictions [3]. A comprehensive summary of the conclusions and the open questions is reported in [4].

To reduce the coupling between the kicker module and the cavity modes in the tank at medium frequencies, transition pieces were inserted inside the kicker tank to electrically connect the beam pipe in the ferrite to the tank itself; a schematic design is given in Fig. 1, while Fig. 2 shows a front view of the transition pieces. In this paper we report about measurements (analogous to [3]) on the modified kicker prototype (Sec. 2) and compare the longitudinal coupling impedance with previous results (Sec. 3).

2 Measurements

Applying the single wire measurement technique, a number of transmission measurements were carried out on the modified SPS MKE kicker, with an experimental set as similar as possible to the set-up described in an earlier paper [3]. For practical reasons we used flat flanges (15 cm long) at the kicker beam pipe port. The diameter of the wire was 0.5 mm.

In order to improve the matching of this wire (seen from inside the tank with respect to the 50 Ω coaxial cable) resistors were installed near either flange of the tank. The ohmic value of these low inductance carbon resistors is simply determined by the relation: $R = Z_c - 50\,\Omega$. The characteristic impedance Z_c of a thin wire in the ferrite loaded structure (see Fig. 1 in [3]) can be approximated as if it were an usual coaxial line (with a proper choice of the value of the outer diameter D [3]):

$$Z_c \approx \frac{Z_0}{2\pi} \ln\left(\frac{D}{d}\right). \tag{1}$$

The vertical (horizontal) aperture is 32 mm (140 mm); choosing $D = 40$ mm (and wire diameter $d = 0.5$ mm), then Z_c is about 263 Ω. Thus two matching resistors [1] of $R = 240\ \Omega$ were soldered at both ends of the wire (one in each flange). The remaining corrections were done during the data analysis.

The raw data (obtained using a HP-8753D vector network analyser) are shown as dotted lines in Figs. 3–4 (with cable response calibration); each measurement contains 801 points, the Intermediate Frequency (IF) bandwidth is 100 Hz and the Test Port Power is set to 0 dBm. The length L of the kicker (including the flanges) has been measured ($L = 2.3101$ m) and taken into account via the electrical delay correction function of the instrument. Its value was subtracted in the phase display. Correction procedures have been subsequently applied to both amplitude and phase data; comparison between raw and corrected data are also shown in Figs. 3–4. For the amplitude of S_{12}, we had to subtract the losses attributed to the matching resistors, which were simply obtained by taking the attenuation values at the lowest frequency point (around 100 kHz); they amount approximately 15 dB (that is in fact the distance between the solid and dotted lines in the upper part of Figs. 3–4). For the phase plots, we removed the phase ambiguities of 2π. Note that some resonances lead to fast phase variation vs. frequency; they may coincide and be mistaken for 2π phase jumps attributed to the phase ambiguity. Such a correction was not applied in [3] for frequencies beyond 1 GHz, since the interpretation of the data was too questionable; in the present case (see Fig. 4), it is done up to approximately 2 GHz. The correction might be possible also up to higher frequencies, but it is not done in this paper.

[1] The exact value of each resistor should have been 213 Ω.

In the previous kicker set-up (no transition pieces), cavity modes resonating in the kicker tank did contribute to fields on the beam axis (that is to the longitudinal coupling impedance) and the corresponding S_{12} is shown in Fig. 5 (dotted line). Comparing it to the S_{12} from the new design (Fig. 5, solid line), we can observe a reduction of transmission coefficient between 400 MHz and 800 MHz in the newer set-up. Note that with transition pieces there are much less resonances.

3 Coupling Impedance from Measured S-Parameters

To evaluate the coupling impedance, we use the formulae for distributed impedance systems, already applied in [3, 4]; a more detailed explanation and derivation can be found in [5, 6]. First of all, the "standard" logarithmic formula is:

$$Z_{log} = -2Z_c \ln\left(\frac{S_{12}^{DUT}}{S_{12}^{REF}}\right), \tag{2}$$

where DUT stands for Device Under Test while REF for REFerence measurement. Such a reference measurement in a smooth, homogeneous beam pipe has not been done for practical reasons. We assumed, instead, for the reference a lossless line of length L (that is $S_{12}^{REF} = \exp(-j\omega L/c)$). This delay has been included in the raw data via the time delay correction function of the network analyser; thus, what is plotted in Figs. 3–5 is directly the ratio $S_{12}^{DUT}/S_{12}^{REF}$. As pointed out by E. Shaposhnikova [7], it is very useful for accuracy enhancement to apply the "improved" log formula (see [4] and Appendix A),

$$Z_{LOG} = Z_{log}\left[1 + \frac{jc}{2\omega L_f}\ln\left(\frac{S_{12}^{DUT}}{S_{12}^{REF}}\right)\right], \tag{3}$$

instead of the standard one in particular when the impedance to be measured exceeds significantly the characteristic impedance Z_c of the wire forming the coaxial line in the DUT. L_f is the length of the ferrite module ($L_f = 1658$ mm) and c is the velocity of light.

A comparison between the two formulae for the coupling impedance and the theoretical estimate done in [2] is shown in Fig. 6. The real part agrees very well with the model, while the imaginary part differs substantially from the theoretical expectation for frequencies above 500 MHz. To understand the reason, the theoretical coupling impedance is converted to the S_{12} using Eq. (3) (Fig. 7). From the figure, it seems there are some mode(s) travelling through the kicker above 500 MHz. These mode(s) enhance the magnitude of the S_{12} about 20 dB, and reduces the phase with $2 \times 2\pi$. Probably $2 \times 2\pi$ phase jump by some mode(s) above 500 MHz caused large discrepancy of the imaginary part of the coupling impedance. Two possibilities can be considered: 1) there are some waveguide modes inside the beam aperture of the kicker module, 2) still there are some cavity modes excited. The first effect may be small because in the theory all waveguide modes inside the beam aperture are included. The second possibility may be reasonable because the measured data are somewhat in the middle of the old measurement [3] and the theory (see Figs. 5, 7).

It is interesting to compare the results from the old measurements [3] with the recent ones (obtained with the improved formula). For the real part, the low frequency contribution to the coupling impedance should be slightly bigger in the old kicker design (no transition pieces), as shown in Fig. 8; at higher frequencies, we can see the opposite behaviour (Fig. 9). The behaviour at very low frequencies is shown in Fig. 10, using the "standard" formula (Z_{log}).

Figure 10 shows also that at very low frequencies (below 30 MHz) the theory developed in [2] is not reliable anymore. The approximation of considering an homogeneously distributed impedance system breaks down at such frequencies. Another model to estimate the impedance of the RHIC injection kicker (with a design similar to MKE kicker), has been proposed in [8]. It is based on a lumped element equivalent circuit and predicts an impedance peak at low frequencies, similarly to Fig. 10.

4 Conclusion

We have discussed the results of coaxial wire measurements on a newer set-up (with transition pieces) of the SPS MKE kicker. So far the transition pieces have not been used but they are foreseen to be installed in all the SPS kickers of this type.

The transition pieces lower the coupling to the cavity modes in the kicker tank; they reduce (even slightly) the coupling impedance (below 200 MHz) providing a by-pass for the image currents between the kicker module and the tank.

The measurements confirm well (much better than in the old set-up) the theoretical predictions for the real part of the coupling impedance reported in [2]. Such a theory predicts (for a beam current of 132 mA) a power dissipated in the kicker of about 35 W [4] and this may have a consequence on the final design of the kicker. Such calculated power is only based on the first 5 coherent lines (200 MHz, 400 MHz, ...) of the bunch spectrum and doesn't take into account the wide-band signals in between these lines.

Moreover there may be some interest in repeating the heat measurement (referred in [3]) with the transition pieces installed. In fact the microwave energy passing through the kicker module in the old configuration (no transition pieces of Fig. 1), might lead to an additional (but not "real") heating of the thermo probes.

5 Acknowledgements

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Appendix A Improved LOG Formula

The improved LOG formula (Eq. (3)) used in the measurement is somewhat different from the form given by V.G. Vaccaro [5], which was further discussed by E. Jensen [9]:

$$Z_{Vaccaro} = Z_{log}\left[1 + \frac{jc}{2\omega L}\ln\left(\frac{S_{12}^{DUT}}{S_{12}^{REF}}\right)\right]. \tag{4}$$

We derive the formula according to Vaccaro's derivation.

Figure 11 shows the schematic drawing of the coupling impedance measurement for the SPS MKE kicker. In our case the length of the ferrite block is $L_f = 1.658$ m, while the total length of the DUT is $L =$ 2.3101 m. For the sake of simplicity, we assume $Z_{ch1} = Z_{ch2} = Z_c$. The matching resistors $R = Z_c - Z_{c0}\ \Omega$ are added at either end of the DUT. The experimental set-up is modelled (approximated) as a series of homogeneous transmission lines, each one with its own propagation constant (k or $\tilde{k}$) and its characteristic impedance (Z_{ch1}, Z_{ch2}, $\tilde{Z}_{ch}$ or Z_{c0}).

The Vector Network Analyser (VNA) measures the scattering transmission parameters of the overall system. The longitudinal coupling impedance depends (in a first approximation) only on the ferrite module parameters (such as L_f, $\tilde{k}$ and $\tilde{Z}_{ch}$). According to [5], we get

$$\tilde{k} = \sqrt{k^2 - jk\frac{\zeta}{Z_c}} \quad \text{and} \quad \tilde{Z}_c = Z_c\frac{\tilde{k}}{k}, \tag{5}$$

where ζ is the longitudinal coupling impedance per unit length and $k = \omega/c$. To get the coupling impedance, we need to calculate $\tilde{k}$ from measured data. Thus in the following we show the relation between $\tilde{k}$ and the (transmission) scattering parameters.

Providing two semi-infinite transmission lines with characteristic impedance Z_1 and Z_2, the transmission coefficient (from line 1 to line 2) can be written as [10]:

$$T = \frac{2Z_1}{Z_1 + Z_2}. \tag{6}$$

A line can be assumed to be semi-infinite when the signal reflected by any possible termination is negligible. This approximation is consistent with our configuration and we can use Eq. (6) to estimate the transmission of a signal going from one block to the next one. The main approximation of this reasoning is considering the transition region (namely L_1 and L_2) as homogeneous transmission lines (and they are not, since their cross section changes).

The transmission factor for each transition (going from the left to the right of Figure 11) are:

- From cable to transition region: Transmission factor is $Z_{c0}/(R + Z_{c0})$, since R is chosen to be $Z_c - Z_{c0}$.
- From transition region to ferrite block: Transmission factor is $2Z_c/(Z_c + \tilde{Z}_c)$.
- In ferrite block: The waves at the entrance of the ferrite block are attenuated and become $\exp(-j\tilde{k}L_f)$ times the original value at the exit of the block.
- From ferrite block to transition region: Transmission factor is $2\tilde{Z}_c/(Z_c + \tilde{Z}_c)$.
- From transition region to the cable: Transmission factor is 1, if $R = Z_c - Z_{c0}$.

The total transmission coefficient can be approximated as:

$$S_{12}^{DUT} \approx \frac{Z_{c0}}{Z_{c0} + R}\exp(-jkL_1)\frac{2Z_c}{Z_c + \tilde{Z}_c}\exp(-j\tilde{k}L_f)\frac{2\tilde{Z}_c}{Z_c + \tilde{Z}_c}\exp(-jkL_2), \tag{7}$$

having included the exponential factors $\exp(-jkL_i)$ ($i = 1, 2$) for propagation inside the transition regions. The transmission coefficient of the reference is

$$S_{12}^{REF} = \exp(-jk(L_1 + L_f + L_2)) \tag{8}$$

The coupling impedance Z_{LOG} of the ferrite block is ζL_f. The value ζ can be obtained from S_{12}, using Eqs. (5, 7, 8):

$$Z = \zeta L_f = -2Z_c \ln(\ldots) \left[1 + \frac{j}{2kL_f} \ln(\ldots)\right], \tag{9}$$

where

$$\ln(\ldots) = \ln\left(\frac{S_{12}^{DUT}}{S_{12}^{REF}}\right) + \ln\left(\frac{Z_{c0} + R}{Z_{c0}}\right) - \ln\left(\frac{2Z_c}{Z_c + \tilde{Z}_c} \frac{2\tilde{Z}_c}{Z_c + \tilde{Z}_c}\right). \tag{10}$$

The transmission coefficient $S_{12}^{DUT}/S_{12}^{REF}$ is observed with VNA. The second term in $\ln(\ldots)$ is compensated off-line. In our case, this term corresponds to $20\log((50 + 240)/50) = 15.3$ dB. The third term is neglected in the measurement.

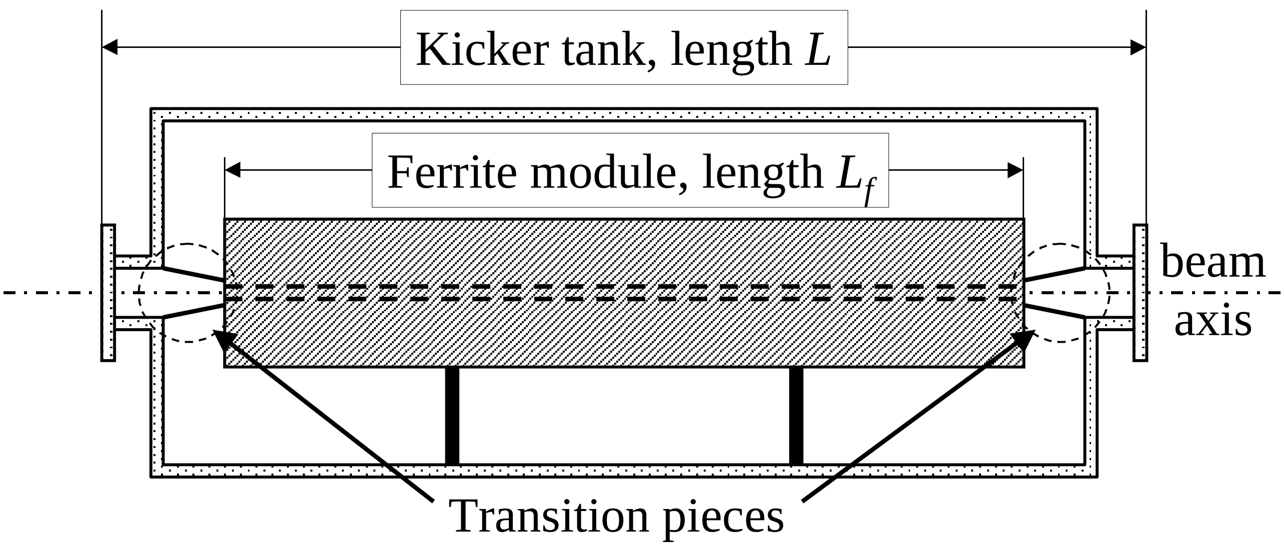

Figure 1: Schematic view of the kicker.

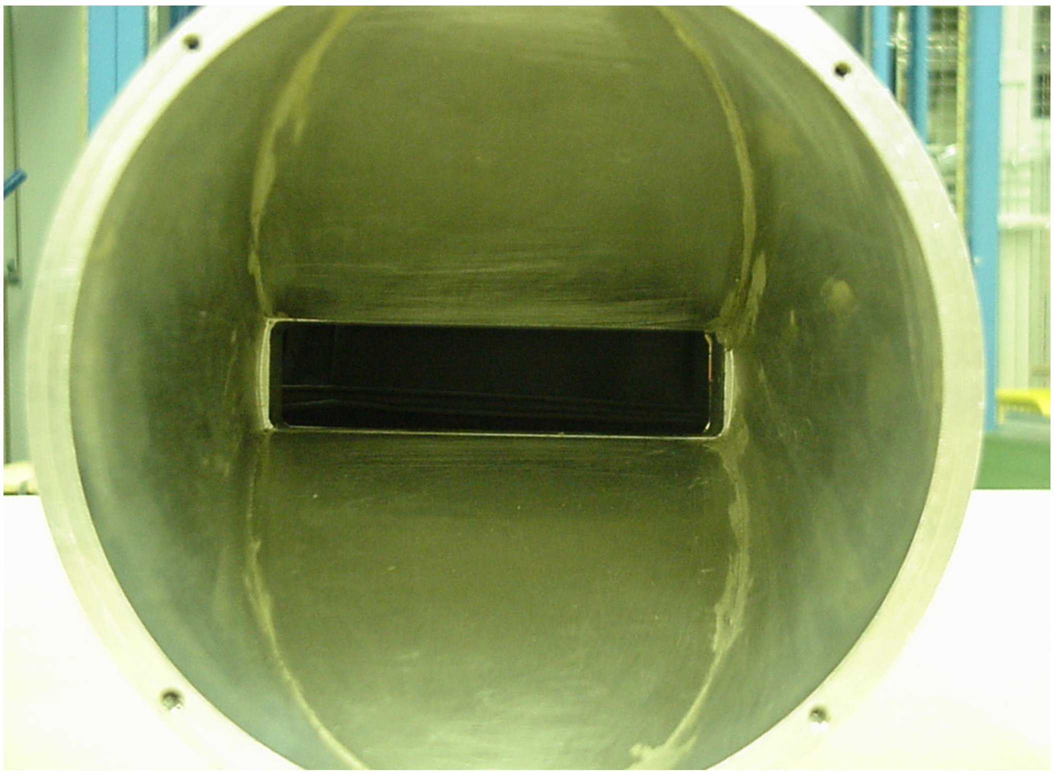

Figure 2: Frontal view of a transition piece: the beam pipe changes shape from rectangular (inside the kicker module) to circular (outside the kicker tank).

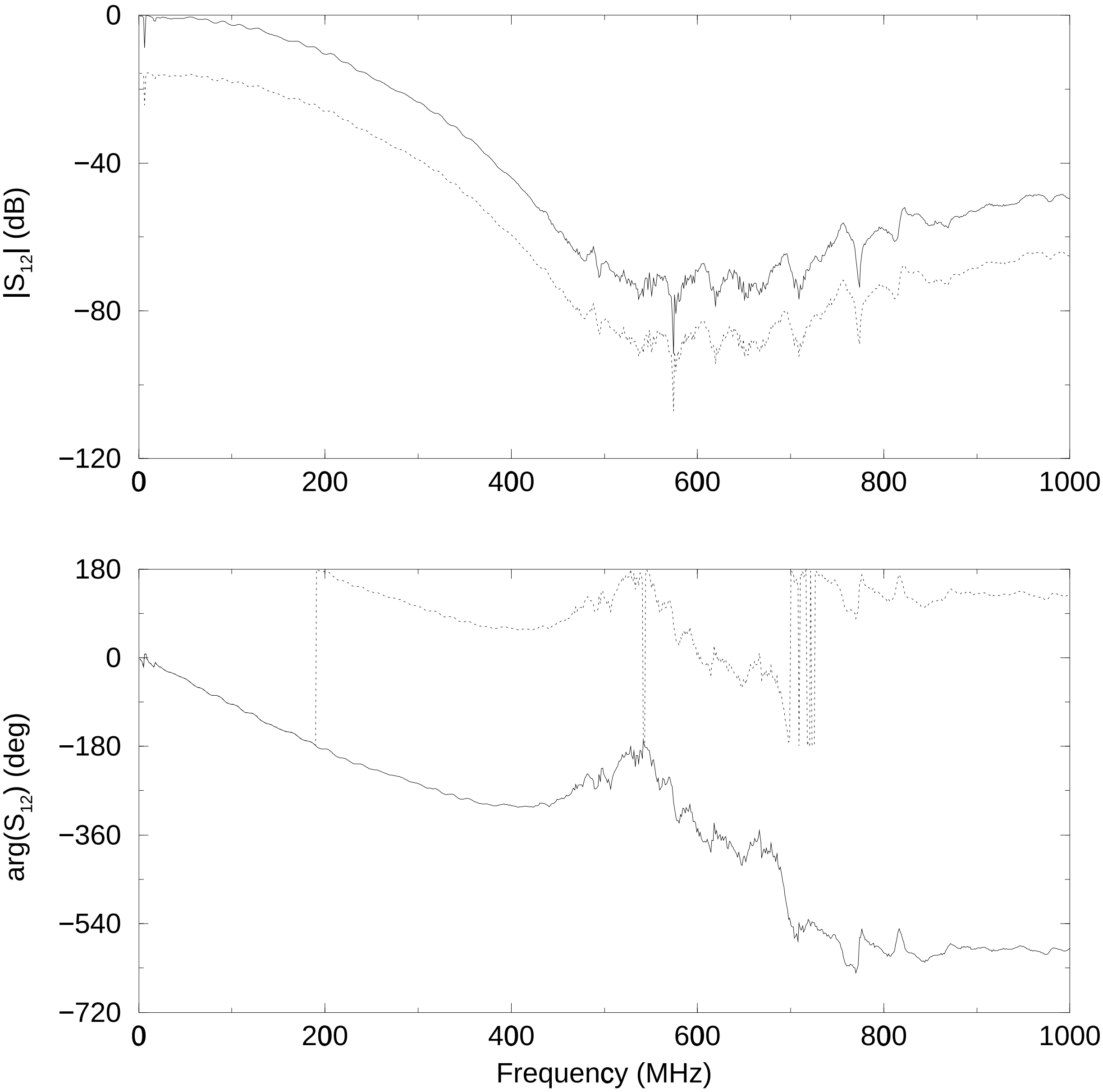

Figure 3: Raw data (dotted line) and corrected S_{12} (solid line) (0–1 GHz). Amplitude and phase of S_{12} from a network analyser with electrical delay $L = 2.3101$ m, cable calibration done, IF bandwidth 100 Hz and test port power set to 0 dBm (801 points).
The transmission coefficient S_{12} is noisy at high attenuation (below -80 dB) where many spurious effects (such as mechanical imperfections) start to be important.

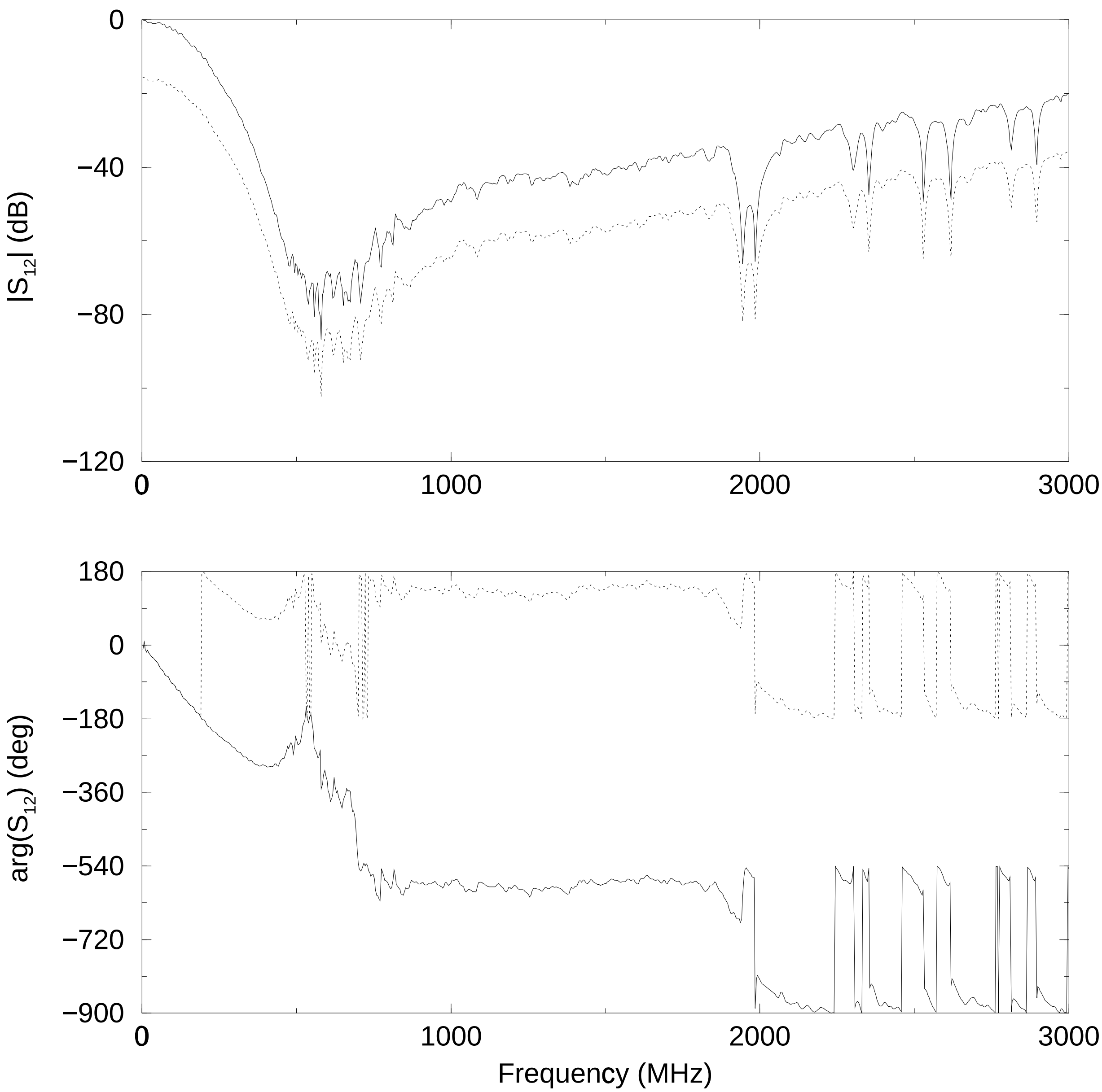

Figure 4: Raw data (dotted line) and corrected S_{12} (solid line) (0–3 GHz). Amplitude and phase of S_{12} from a network analyser with electrical delay $L = 2.3101$ m, cable calibration done, IF bandwidth 100 Hz and test port power set to 0 dBm (801 points).

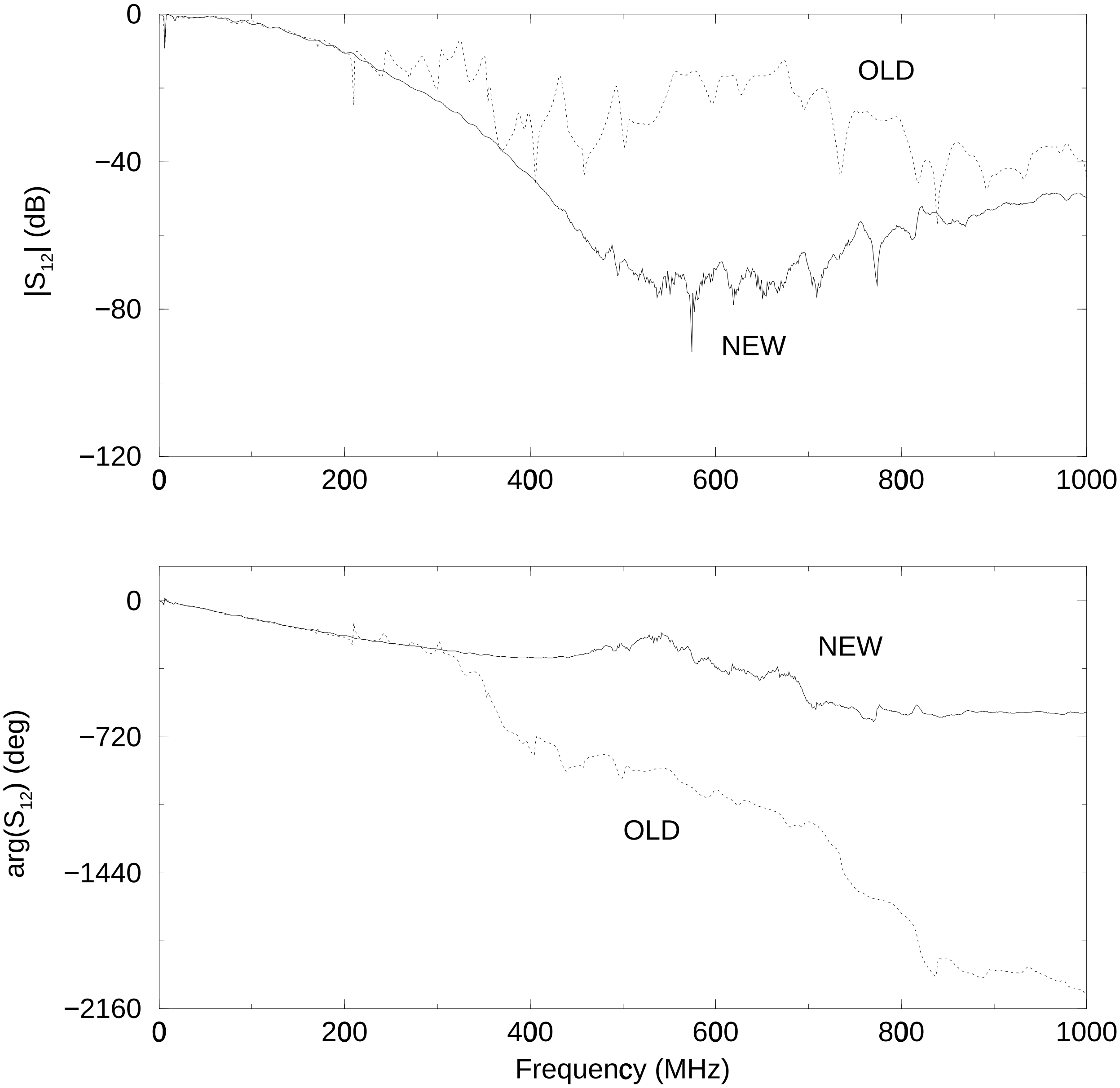

Figure 5: Latest measured data (solid) compared with previous one (dotted) from [3]. The mechanical modifications discussed in Sec. 1 have changed significantly the transmission response between 400 and 800 MHz.

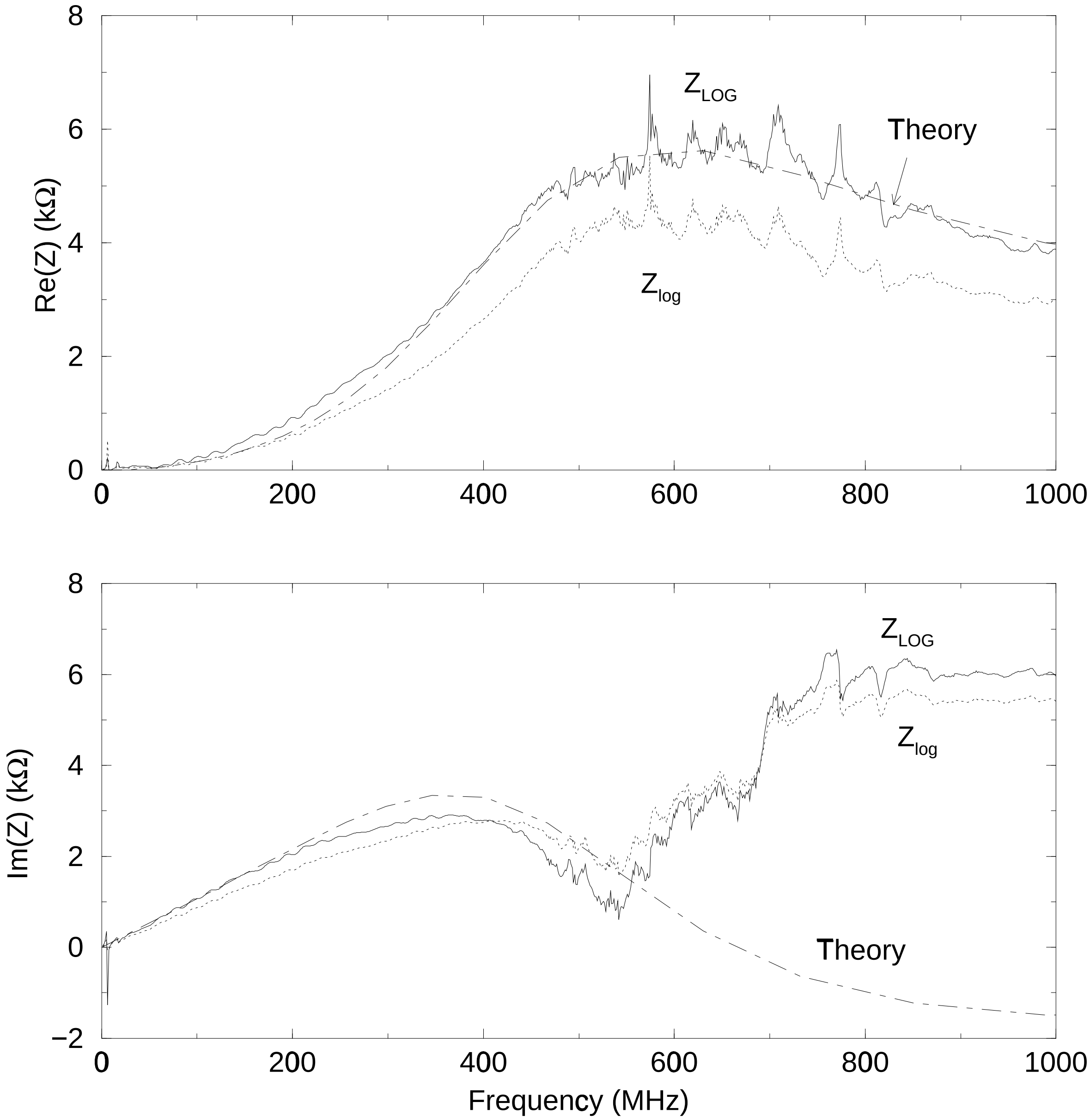

Figure 6: The coupling impedance (0–1 GHz) calculated from measured data with the "improved" logarithmic formula Z_{LOG} of Eq. (3) (solid line) and with the "standard" logarithmic formula Z_{log} (dotted line). The dot-dashed line represents the theoretical estimate in [2]. Note that, except for very low frequencies, resonances become visible around 500 MHz and higher, may be due to waveguide modes inside the beam aperture of the kicker module.

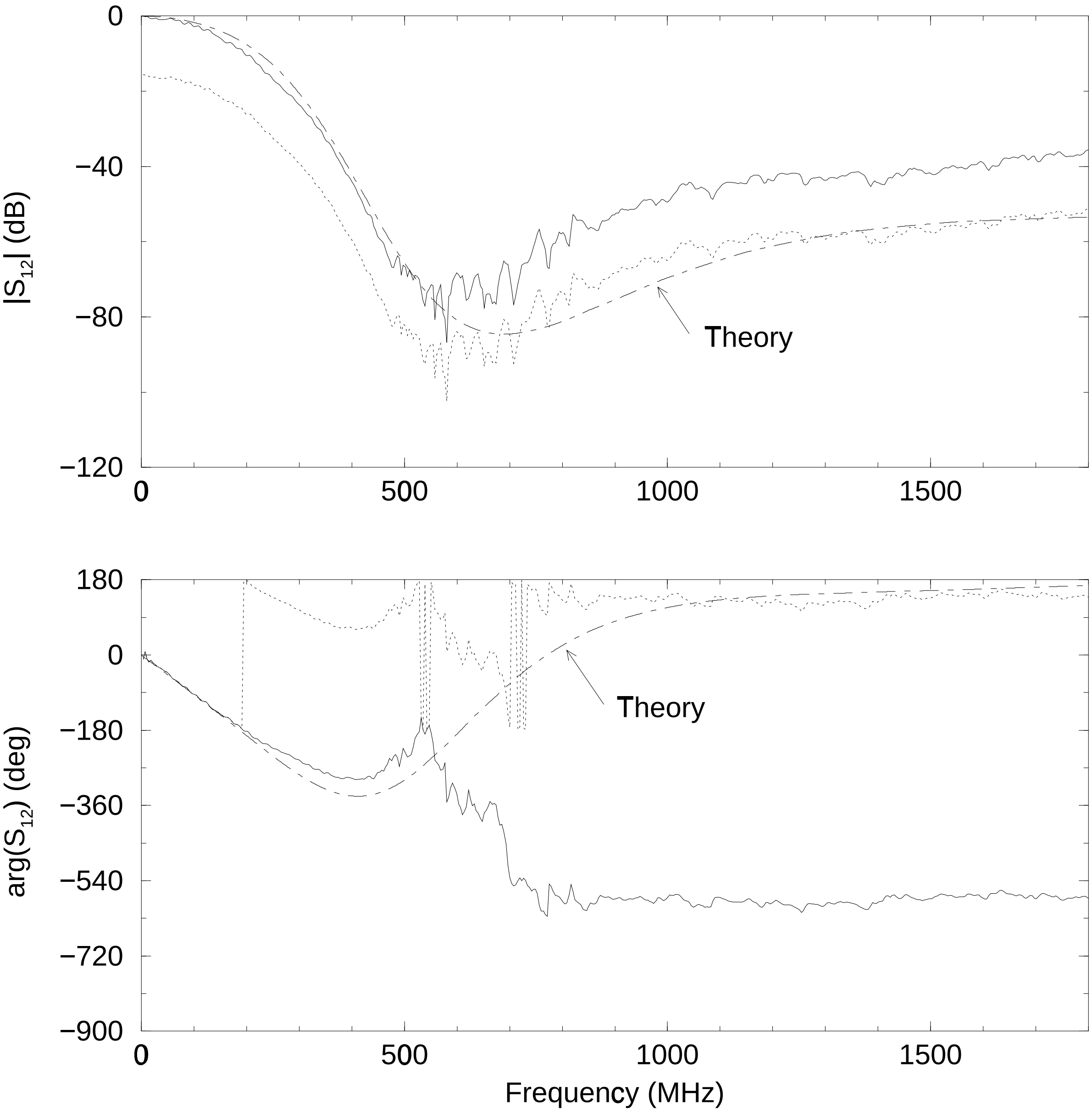

Figure 7: Transmission parameter S_{12} as a function of frequency. The solid, dotted, and dot-dashed lines show the corrected data, raw data, and the theoretical data using Eq. (3), respectively.

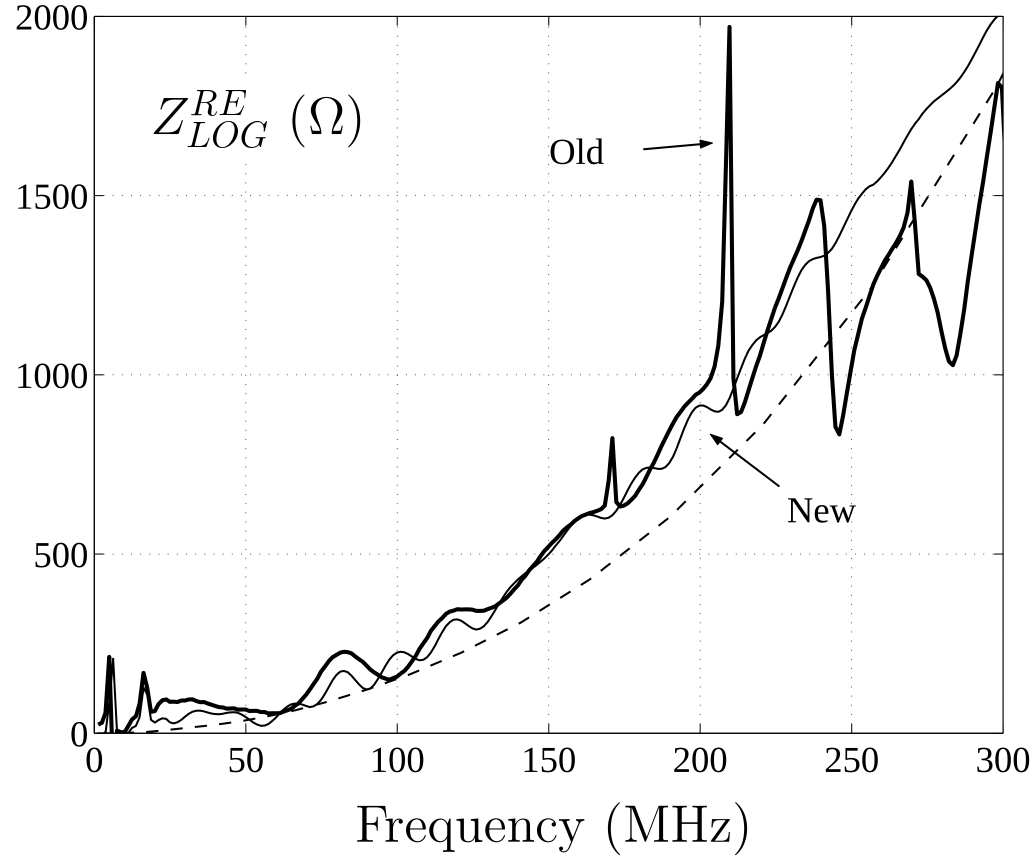

Figure 8: Real part (0–0.3 GHz) of the coupling impedance calculated from measured data with the "improved" logarithmic formula Z_{LOG}. The solid heavy line refers to the old measurements (no cones between the tank and the kicker module), while the thinner one is obtained from the new data. The dashed line represents the expected result from the theory in [2].

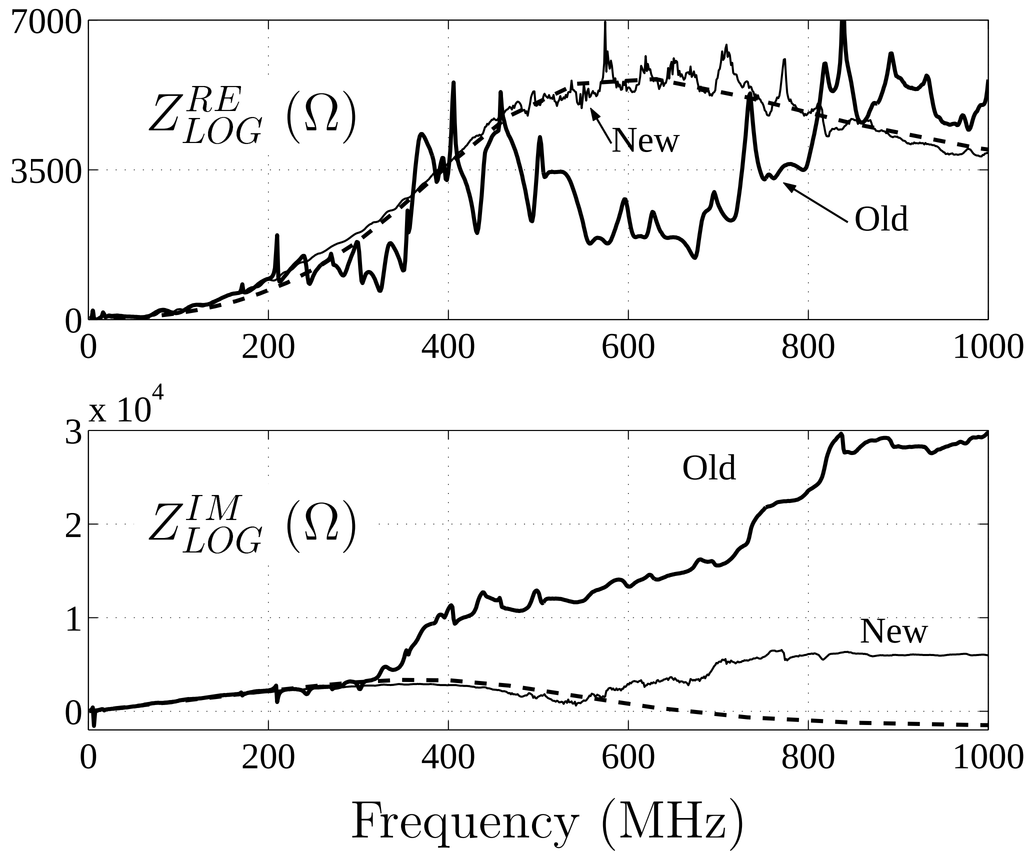

Figure 9: Real and imaginary part (0–1 GHz) of the coupling impedance calculated from measured data with the "improved" logarithmic formula Z_{LOG}. The solid thicker line refers to the old measurements (no cones between the tank and the kicker module), while the thinner one is obtained from the new data. The dashed line represents the expected result from the theory in [2].

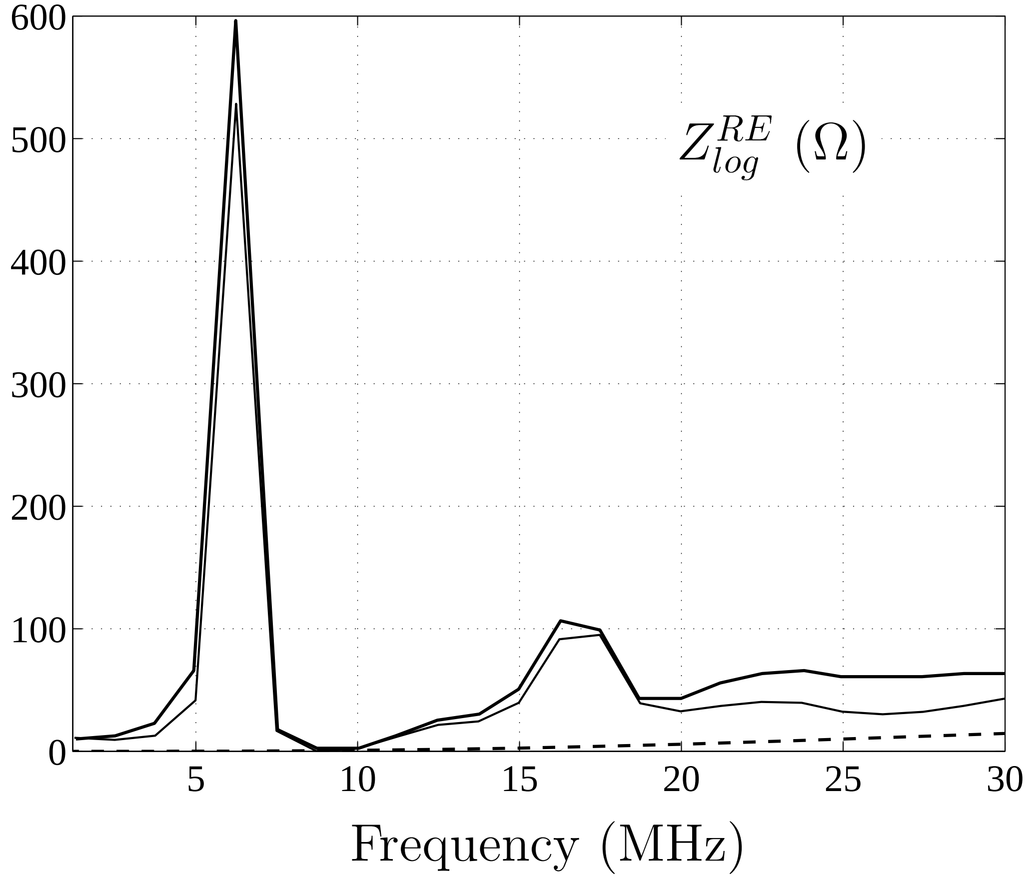

Figure 10: Real part (0–30 MHz) of the coupling impedance calculated from measured data with the "standard" logarithmic formula Z_{log}. The solid thicker line refers to the old measurement, while the thinner one is obtained from the new data. Dashed line represents the expected result from the theory in [2]: such theory is not anymore applicable at those low frequencies. Raw data has been corrected to avoid low frequency S_{12} to be greater than unity.

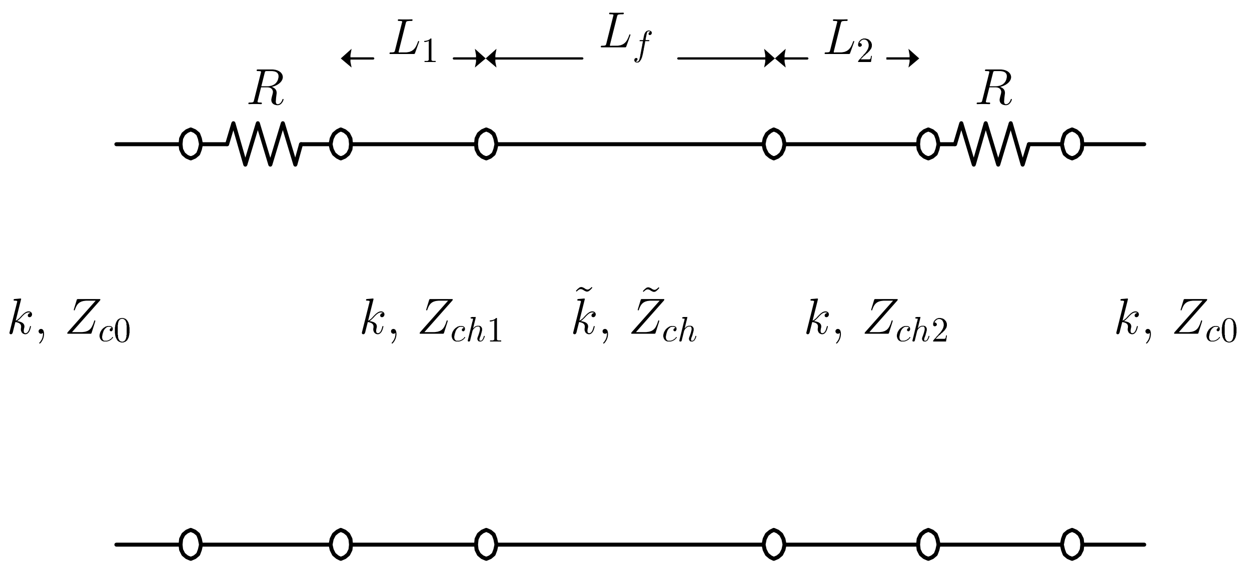

Figure 11: Conceptual ("electrical") drawing of the longitudinal coupling impedance measurement of ferrite kickers by coaxial wire method. Going from the left side to the right one, there is first a transmission line representing the cable ($k,\ Z_{c0}$), then the matching resistor R and the "transition" region of length L_1 ($k,\ Z_{ch1}$). The ferrite module ($\tilde{k},\ \tilde{Z}_{c0}$) follows and then again a transition region of length L_2 ($k,\ Z_{ch2}$), a matching resistor R and the cable ($k,\ Z_{c0}$). The kicker module has a total length $L = L_1 + L_2 + L_f$. The cable characteristic impedance is $Z_{c0} = 50\ \Omega$. We assume $Z_{ch1} = Z_{ch2} = Z_c \approx 263\,\Omega$.