LHC Project Note 151

1998-07-10
(dyachkov@alph04.triumf.ca)

Impedance Measurements on the LHC dump kicker prototype

C. Gonzalez, M. Morvillo, CERN and M. D'yachkov, TRIUMF

Keywords: kicker, beam impedance

Summary

In this paper we demonstrate that a thin layer of metallization on the inner surface of the ceramic pipe in an abort kicker will provide an effective way to screen the kicker's magnets from the electromagnetic fields generated by the LHC bunches.

The other objective of this paper was to measure the kicker impedance in a wide frequency range (up to 1 GHz).

1 INTRODUCTION

The main objective of these measurements was to demonstrate that a thin layer of metallization on the inner surface of the ceramic pipe in the abort kicker will provide an effective way to screen the kicker's magnets from the electromagnetic fields generated by the LHC bunches. The other objective was to measure the kicker impedance in a wide frequency range (up to 1 GHz). The abort kicker is shown in Figure 1.

2 MEASUREMENT SETUP

Impedance measurements were done on an LHC beam abort kicker prototype using an HP 8753D vector network analyzer (VNA) and the coaxial wire method. The data of the VNA were stored on disk using the HP-VEE (Hewlett-Packard Visual Engineer Environment) code.

The coaxial wire method [1] is a convenient bench method for the simulation of charged particle beams. It is based on the assumption that a bunch of a highly relativistic beam has an electromagnetic field distribution very similar to that of a short pulse on a coaxial line (TEM field). For longitudinal impedance measurements, the test bench set-up consists of a single conductor ("wire") in the center of the vacuum chamber, at the position of and replacing the beam. Here we used a 15 mm diameter and 1.37 m long brass tube centered in the structure. The radius of this (inner) tube is chosen here for practical reasons to have a characteristic impedance of $Z_c = 50\ \Omega$ taking into account the mechanical dimensions of the vacuum chamber (rectangular cross section with rounded corners [26 mm x 37 mm], see Figure 2). This characteristic impedance is equal to the coaxial line impedance of the cables between the VNA and the device under test (DUT)

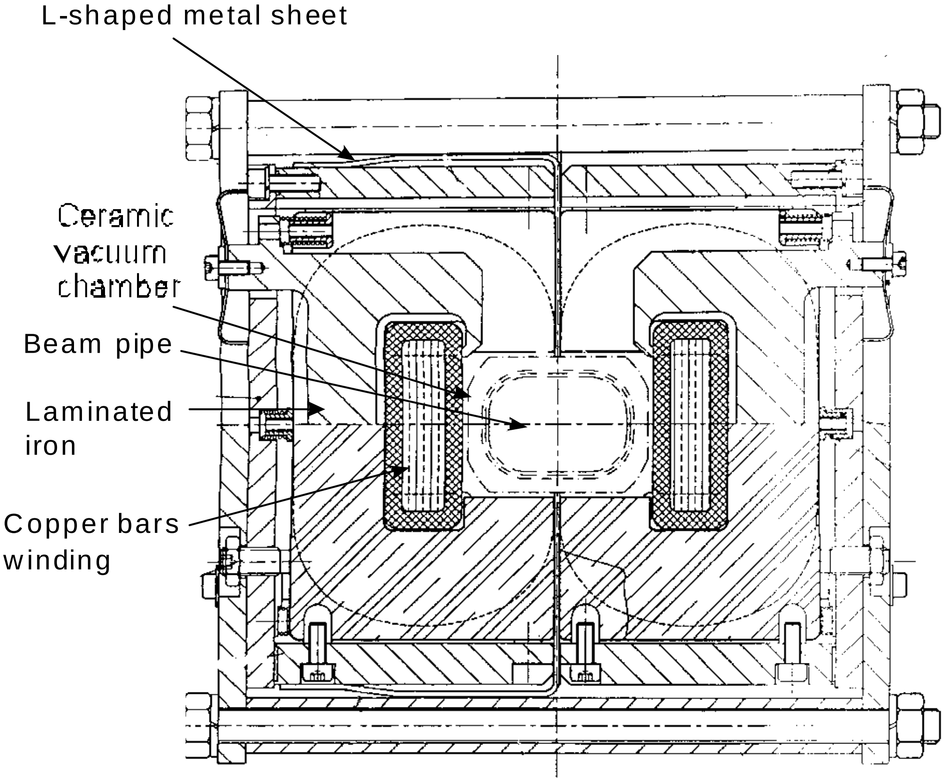


Figure 1. Abort kicker design

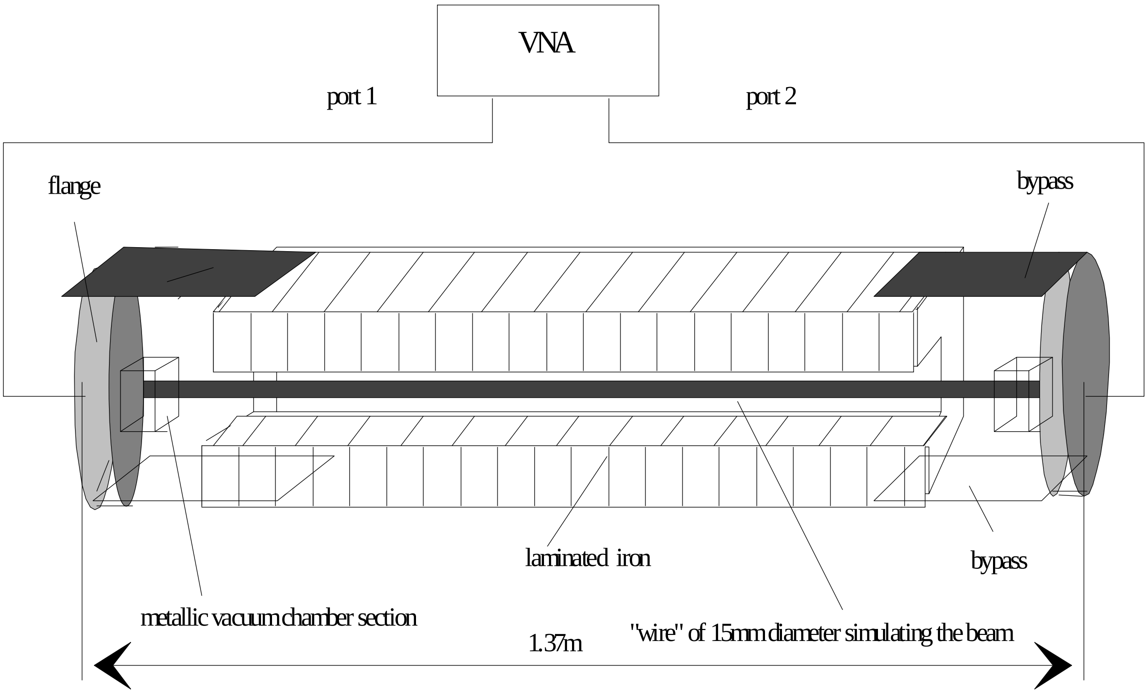


Figure 2. Simplified geometry (longitudinal cross section) of an LHC beam dump kicker with flanges and measurement set-up.

As shown in Figure 2 the beam dump kicker is a window frame type magnet made from two symmetric halves. The beam will be surrounded by a ceramic vacuum chamber which is coated with a thin metallic layer on its inside. The ceramic tube is the vacuum barrier as the kicker elements are in air. For the bench test the coated ceramic tube was replaced by a kapton foil with a 0.2 μm thick copper layer (Figure 3). It is self-supported by mechanical strain over a length of about 1.2 m connecting the metallic vacuum chamber sections (Figure 2) on either side. In order to measure the DC resistance of the metallized kapton sheet in situ, one of the flanges was DC isolated (0.1 mm kapton foil) against the metallic bench. The total DC resistance measured with a normal Ohmmeter between both flanges (only electrical connection via the copper-coated kapton) was found to be 0.7 Ω and thus corresponds roughly to the design value.

The usual reference measurement with a smooth metallic beam pipe of same length as the DUT was not carried out here as there is no significant change in characteristic impedance and in order to avoid the additional mechanical effort for a properly made piece of reference pipe. As shown in Figure 2, there are 4 “bypass” elements, made from 0.3 mm thick copper sheet which, when connected to the kicker modules, provide a low impedance path for the image current between the flanges and the kicker modules. Similar “bypass” elements will later be used as well when the kicker is installed in the machine.

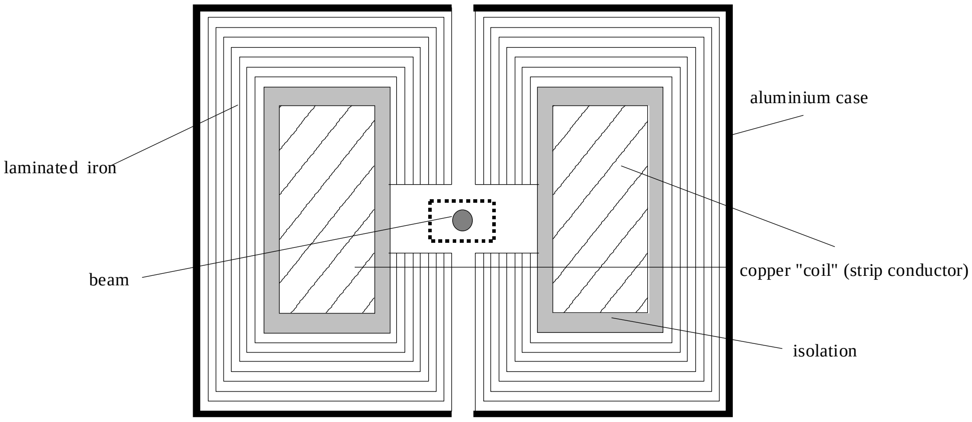


Figure 3. Cross-section of the abort kicker

Network analyzer measurements were carried out in the frequency domain, in transmission (see Figure 4), and results are displayed in both time and frequency domain. The coupling impedance can be determined from the measured transmission coefficients S_{21DUT} for the case of a single lumped impedance [2] by the formula

$$Z_{lumped} = \frac{2Z_{ref}\left(1 - S_{21DUT}/S_{21\mathrm{ref}}\right)}{S_{21DUT}\big/S_{21ref}}. \tag{1}$$

where Z_{ref} is the characteristic impedance of the bench setup and S_{21DUT}/S_{21ref} is the forward scattering coefficient S_{21DUT} normalized by the reference measuring system S_{21ref} (which by proper calibration can be made to be $S_{21ref} = 1$). This formula (1) is strictly valid only when we consider lumped elements (i.e. the length must be less than $\lambda/10$ at the maximum frequency).

In our case, as we did not do a reference measurement, we must compensate the delay of the DUT which is about 1.37 m long by using either an electronically adjustable delay on the VNA or in the off-line manual data treatment. Any error between electrical and mechanical length of the DUT leads to incorrect results in the lumped element formula .The lumped element model implicitly assumes that the DUT has zero electrical length. Note that in (1) all quantities are complex except Z_{ref} which is real.

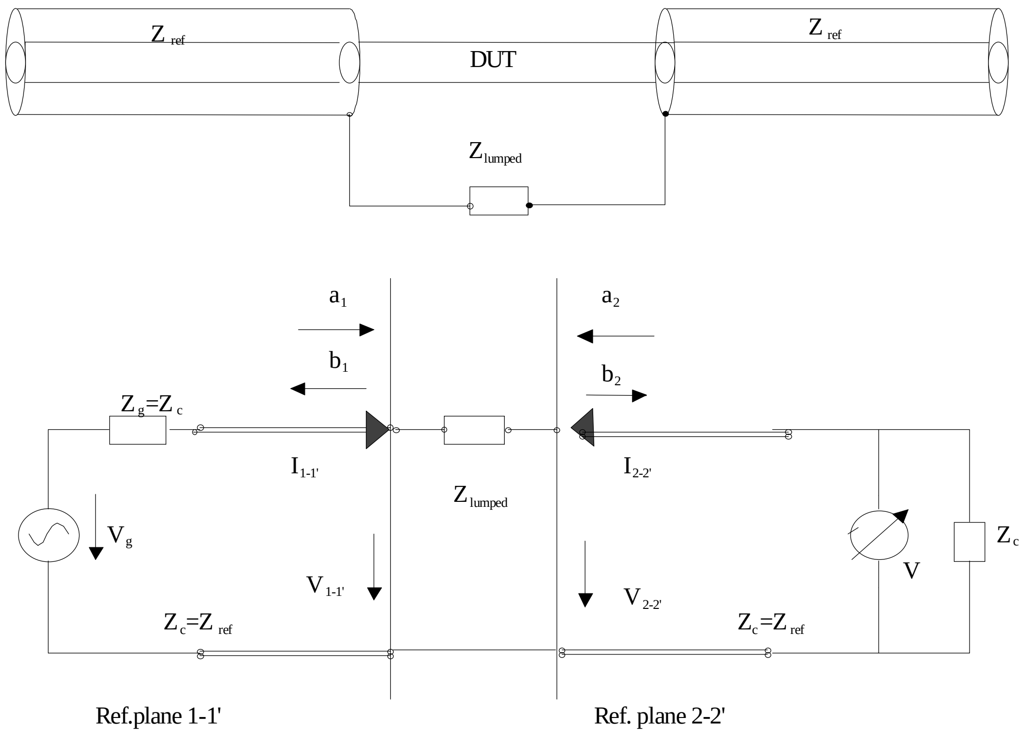


Figure 4. S-parameter measurement set-up for single lumped impedance.

In case of a distributed impedance the use of the so called "log" formulas (2) and (3) (better would be "ln" formula) is more appropriate as it takes into account the fact that the DUT is not lumped. In our case with a length of 1.37 meter for the DUT we certainly exceed the strict limit of validity for the lumped element model at 1 GHz. This does not necessarily imply that results obtained from (1) must be incorrect as both models (lumped and distributed approach) are merging for small impedance values to be measured. But for larger value of Z (2) and (3) are more reliable if the strict lumped element condition is no longer met.

$$\mathrm{Re}(Z_{\ln}) = -2Z_{ref}\,\ln\frac{|S_{21DUT}|}{|S_{21ref\cdots}|} \tag{2}$$

$$\mathrm{Im}(Z_{\ln}) = -2Z_{ref}\,phase(S_{21DUT}\,/\,S_{21ref}) \tag{3}$$

Note that in (1), (2) and (3) the forward scattering parameter S_{21} has to be used as a linear complex quantity and not in logarithmic format [dB], which is very common for VNA's and the phase in (3) is in radians. In our measurements we don't measure a reference line (S_{21ref}) but we perform only a transmission calibration to subtract the effect of the cables. So, when we use the formulae (2) and (3) we added an electrical delay to the S_{21DUT} equal to the electrical length of the DUT.

3 RESULTS

3.1 MEASUREMENTS WITH KAPTON FOIL

The transmission coefficient S_{21} that has been measured in the experiments with the resistive layer (kapton foil with 0.2 micron copper layer) is shown in Figure 5. The smooth line represents the theoretical value of attenuation of a circular cross-section coaxial line with the same characteristic impedance and the same inner and outer conductor resistance. The resistance of the outer conductor is assumed to be frequency independent, because the thickness of the resistive layer in our experiments was much smaller than the skin depth.

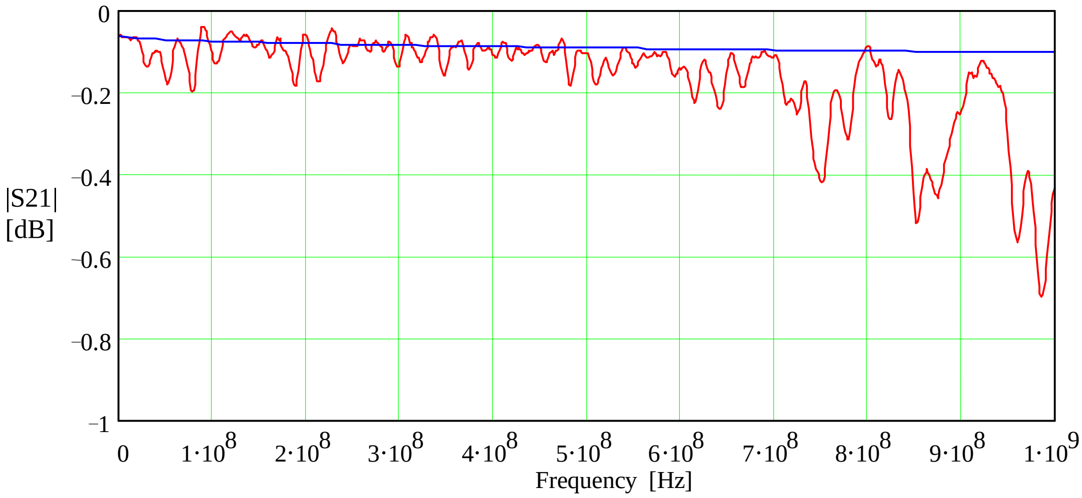
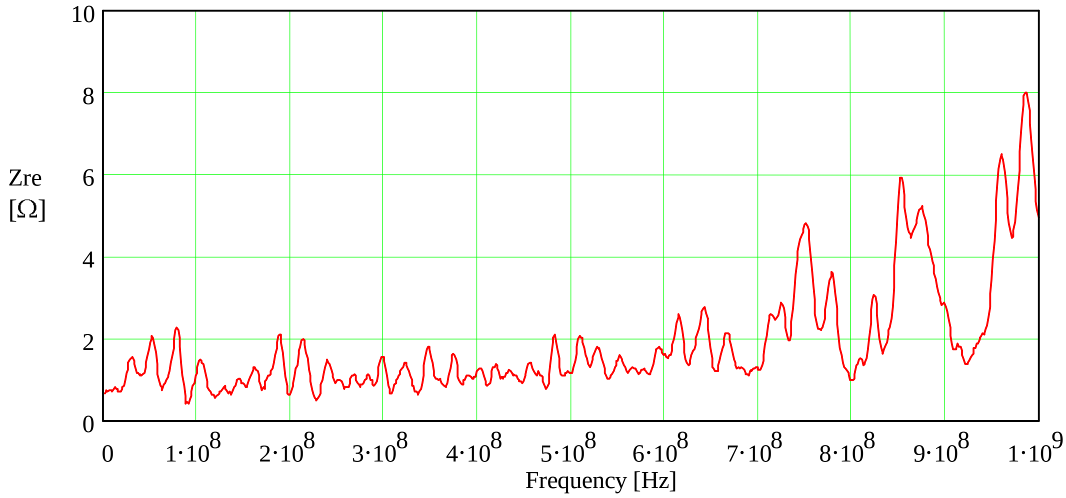


Figure 5. Transmission coefficient S_{21} for the kicker with the resistive layer as outer conductor. The measurements were taken with the kicker module closed. The coil of the kicker was connected to the power cable. The smooth line is the theoretical attenuation of a coaxial line with the same characteristic impedance and the same inner and outer conductor resistance.

One can see in the Figure 5-Figure 6 the effect of the multiple reflections in the kicker due to the mismatch at the two ends and the multiple reflections in the cable due to a small mismatch in the receiver port of the network analyzer. The bigger ripple above 700 MHz is due to the kicker while the smaller one is due to the cable. Knowing the length of the device (cable or kicker) and the speed of light it is straightforward to calculate the frequency spacing between two peaks of the transmission coefficient and in our case the theory and the measurements agree well (110 MHz and 33.7 MHz).
As one can see from Figure 6, the real part of the impedance of the pipe made of kapton foil at low frequencies is in good agreement with the DC measurements (0.7 Ohms).

The transmission coefficient is almost constant in the frequency range up to 300 MHz after which it starts to change (the real part of the impedance increases). This effect is most likely due to the resistive losses in the copper rod, or due to other factors, such as the imperfections of the electrical connection between the kapton layer and the flanges, which have not been properly taken into account.



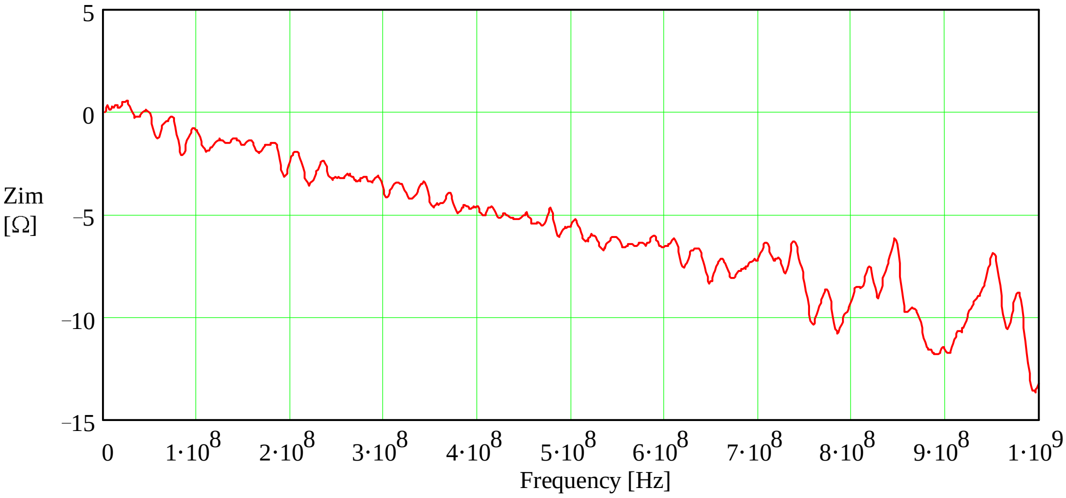


Figure 6. Real and imaginary parts of the impedance calculated by using formulae (2) and (3) from the transmission coefficient S_{21} .The measurements were done with the kicker module closed. The coil of the kicker was connected to the power cable.

3.1.1 SCREENING EFFECT OF THE RESISTIVE LAYER

In the following two measurements we studied the screening effect of the resistive layer. In the first case the "C"-shaped kicker magnets were moved close to each other and in the other they were placed approximately 15 cm apart. The coils were not connected to the power cable in both cases. The results of both measurements are shown on the same graph (Figure 7).

As one can see on the Figure 7 the two lines are almost identical. The fact that the impedance doesn't change if we move/connect the kicker magnets indicates that the metallized kapton foil (and therefore the metallized ceramic pipe with similar surface resistance) is very effective in shielding the kicker magnets form the EM fields produced by the LHC bunches.

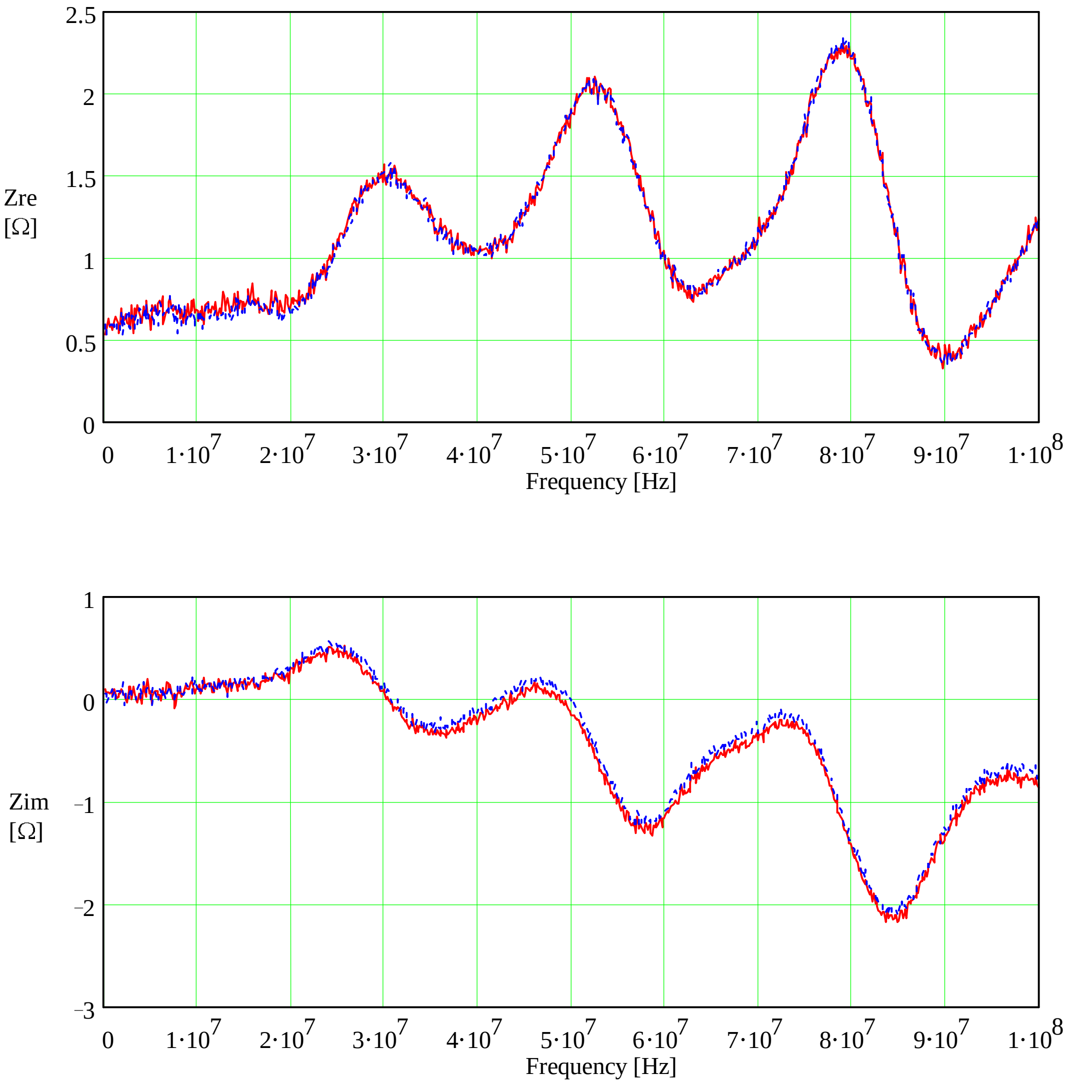


Figure 7. Real and imaginary parts of impedance of the resistive layer with kicker magnets closed and open. The coils were disconnected from the power cable.

3.1.2 EFFECT OF THE BYPASS

In all measurements described above the kapton layer and the flanges to which it was connected were isolated from the bench, so the current could only travel through the resistive layer. In the following measurements we compared the transmission coefficients with and without external bypass (the flanges were connected with 0.3-mm-thick copper sheets to the aluminum case which surrounded the magnets).

The effect of the bypass on the transmission coefficient can be seen only at very low frequencies. The ratio of the transmission coefficient measured with and without the bypass is shown on Figure 8. The maximum difference is observed at 0.1 MHz and 0.01 dB (which is equivalent to 0.05 Ohm). The difference becomes negligible at frequencies higher than 1 MHz.

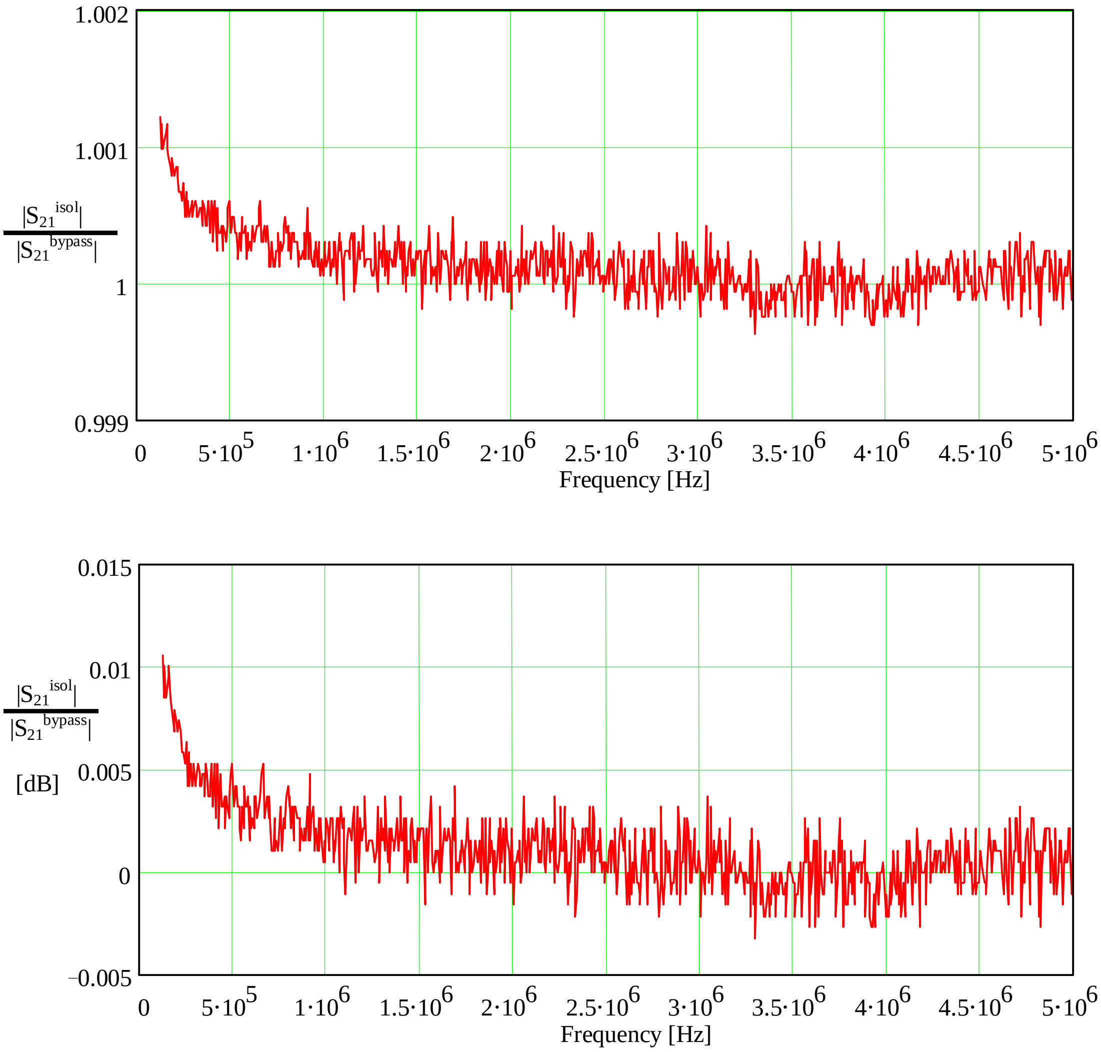


Figure 8. The ratio of the transmission coefficients S_{21} with the kicker body isolated and connected to the supports of the RF connectors with two copper sheets. A kapton (resistive) layer was used as an outer conductor. The kicker magnets were closed and the coils were connected to the power cable. Note the scale of the graph (0.02 dB/div).

Again, this is an indication that with or without electrical bypass the image currents will flow through the resistive layer and thus the EM fields will be confined inside the beam pipe and will not cause any significant heating effects on the kicker magnets. But at the same time, since the image current flows almost entirely through the resistive layer it may cause heating of the layer itself.

3.2 COPPER FOIL AS AN OUTER CONDUCTOR

Several measurements using a pipe made of 0.3 mm copper sheet have been also done, but are not shown in this report (a copper foil of such thickness cannot be used in the kicker magnet since it will not allow kicker to generate a sufficiently fast kick). The results were very similar to those where the pipe made of kapton foil was used as outer conductor.

3.3 MISSING RESISTIVE LAYER

The following measurements (Figure 9 and Figure 10) were done on the set-up in which nothing was used in place of the metallized ceramic pipe (i.e. the kicker body was acting as outer conductor). As expected the results were significantly different from those in which the pipe made of copper or kapton were used. It has been observed that in these cases the transmission coefficients strongly depend on the position of the two "C"-shaped magnets relative to the copper rod and also on whether the magnets are connected to the power cables and the RF stands. The results of these measurements are shown in Figure 9 to Figure 14.

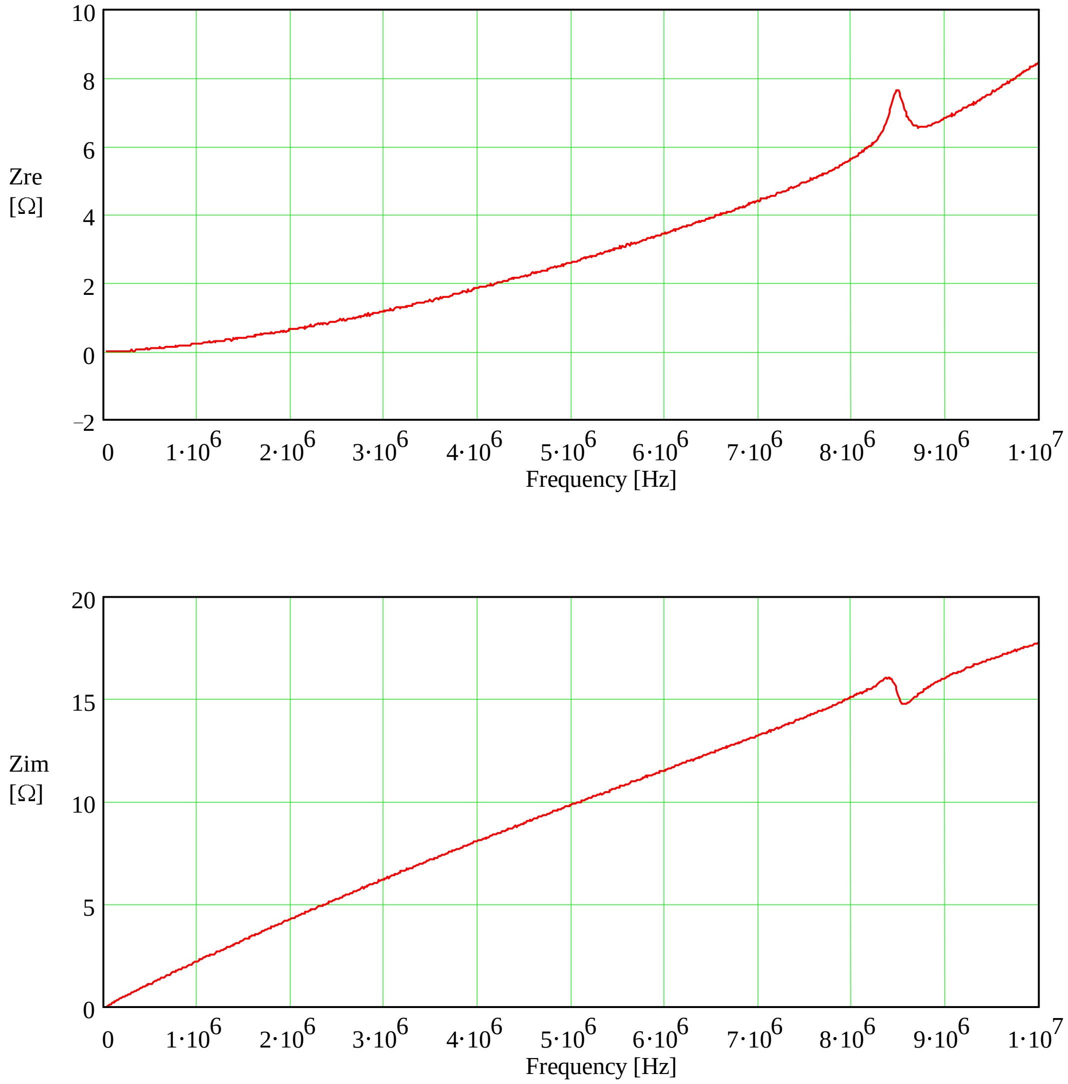
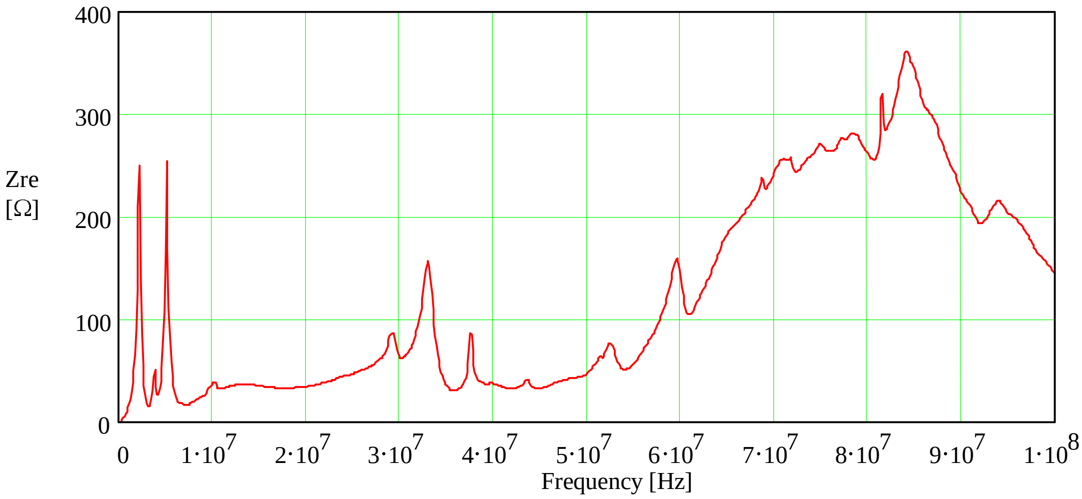


Figure 9. Impedance calculated from the measured S_{21} parameter. The measurements were taken without the resistive layer (the kicker body is acting as outer connector). The kicker body was connected to the supports of the RF connectors with four copper foils. The coil of the kicker was also connected to the distribution box, but the power cables were disconnected from the coil. Four L-shaped profiles made of nickel-plated copper were inserted between the two halves of the kicker.



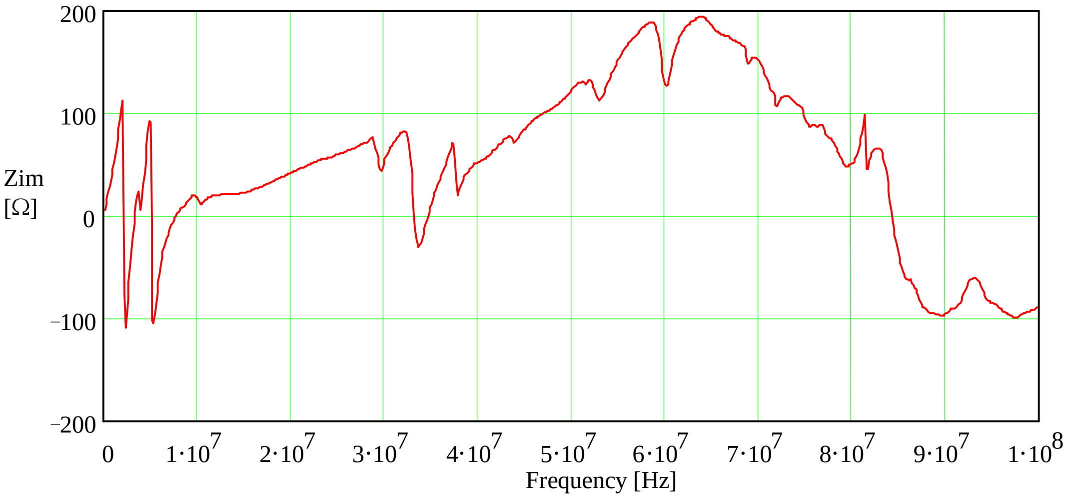


Figure 10. Measurement taken without the resistive layer. The kicker body is not connected to the supports of the RF connectors. The coil of the kicker is disconnected from the power cables.

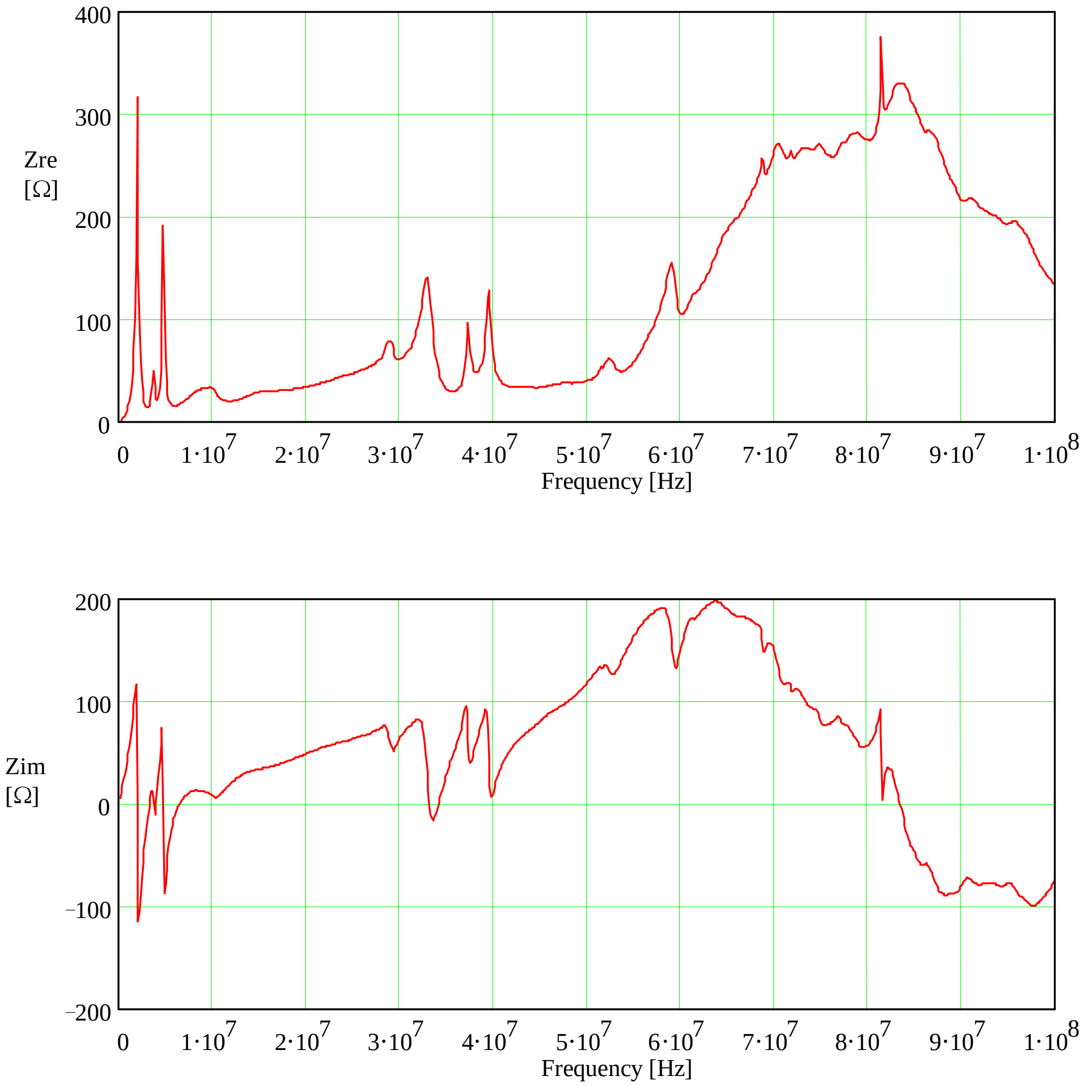
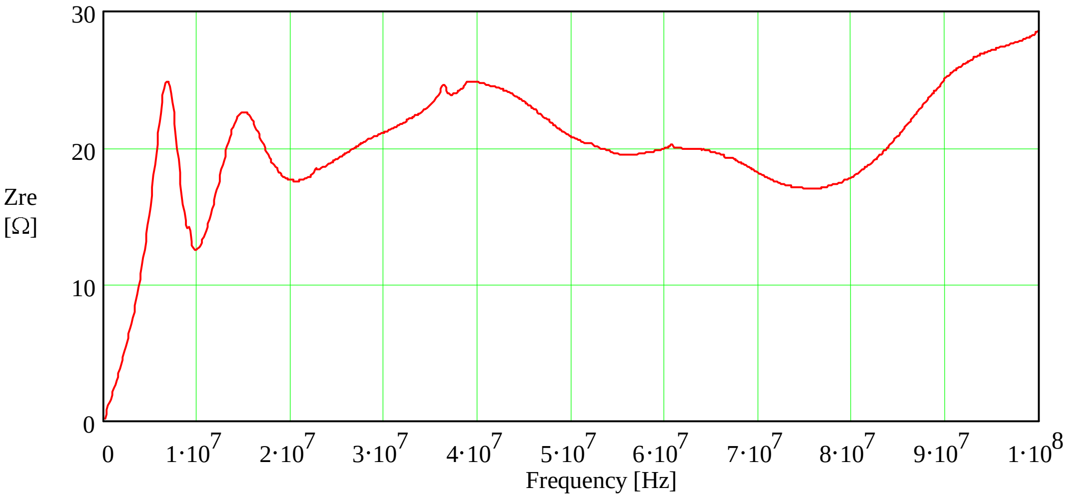


Figure 11. Measurement taken without the resistive layer. The kicker body is not connected to the supports of the RF connectors. The coil of the kicker is connected to the power cables.



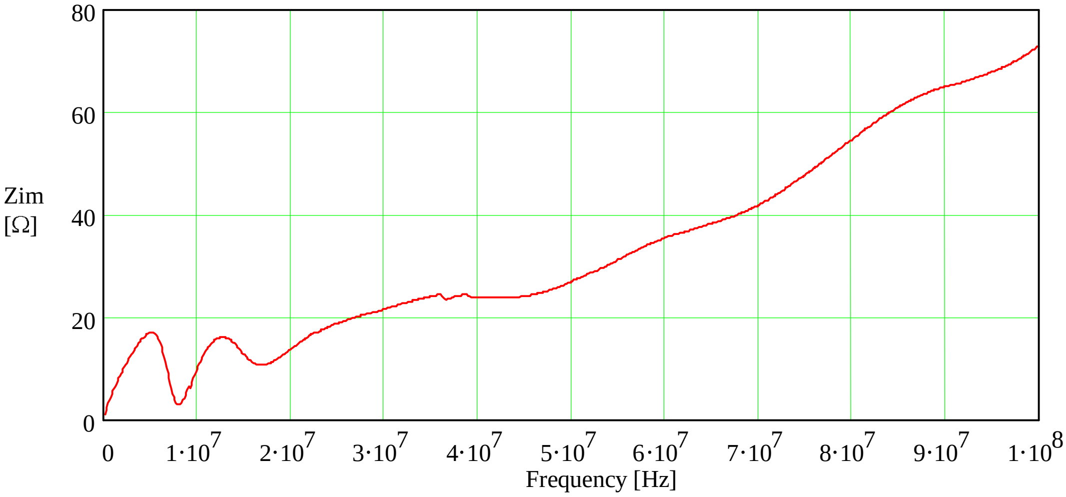


Figure 12. Measurement taken without the resistive layer. The kicker body is connected to the supports of the RF connectors with four copper foils. The coil of the kicker is connected to the power cables. (Note the different scale).

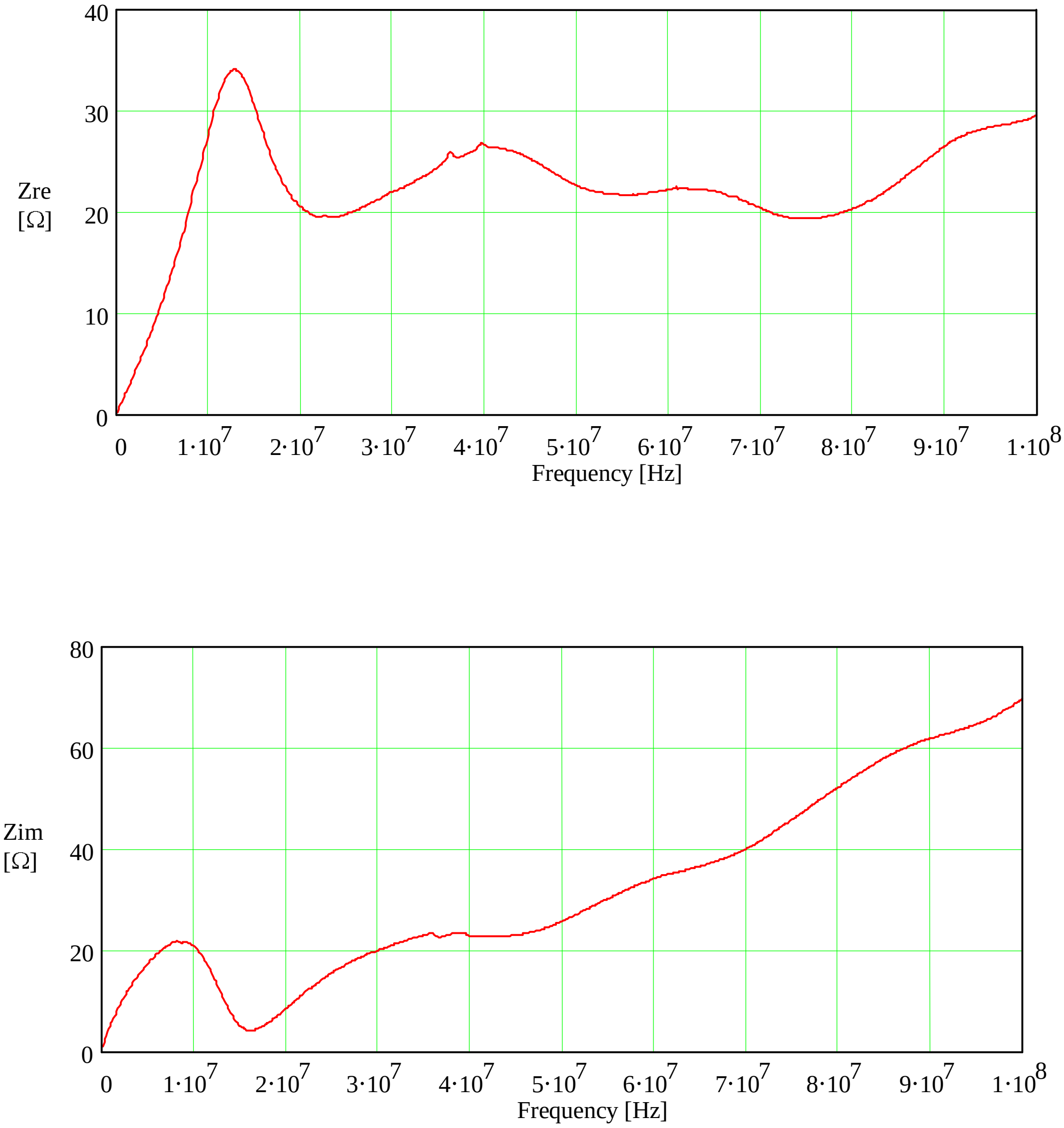


Figure 13. Measurement taken without the resistive layer. The kicker body is connected to the supports of the RF connectors with four copper foils. The coil of the kicker is disconnected from the power cables.

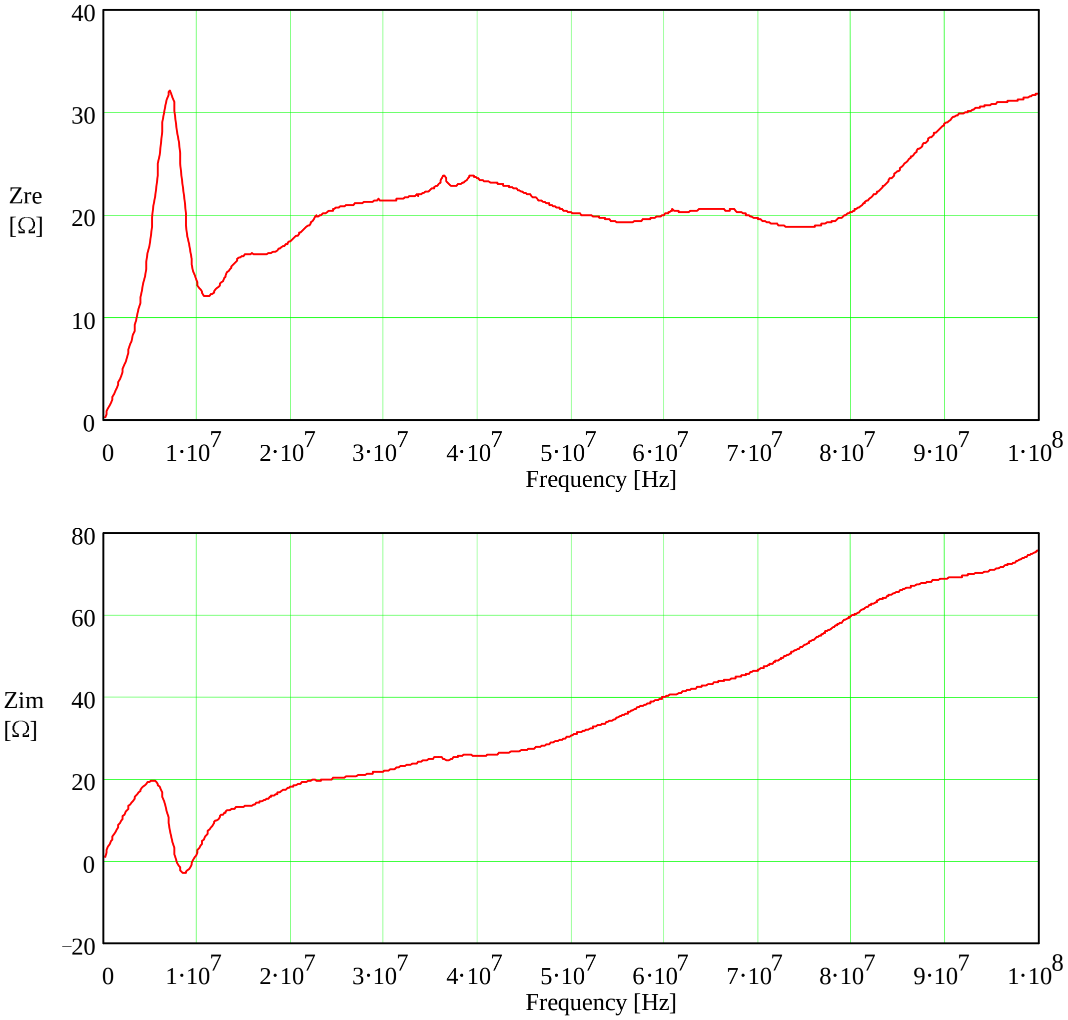


Figure 14. Measurement taken without the resistive layer. The kicker acts as outer conductor. The axis of the kicker is 10 mm away from the inner conductor axis. The kicker body is connected to the supports of the RF connectors with copper foils. The coil of the kicker is connected to the power cables.

4 MAFIA SIMULATIONS

It is not possible, with presently available memory size and reasonable computer time, to simulate the effect of a 0.2-micron layer of copper in the structure with 20 x 30 mm cross section using programs such as MAFIA [3] (the mesh would have been too big to process on the computers available to us). Therefore we tried to use a model in which a much thicker layer (d = 2 mm) but with a different conductivity (in order to keep the total square resistance constant) was used instead. Unfortunately, we have found that this method has a significant flaw: the ratio of the layer thickness to the skin depth is also changing when we make such transformation and therefore the results at high frequencies become irrelevant. For example, when the layer thickness is changed form 0.2-micron to 2 mm (10,000 times), the frequency at which the skin depth becomes comparable to the layer thickness is reduced to 10 MHz. Therefore the results for higher frequencies become irrelevant. Figure 15 (a, b) shows the results of MAFIA T3 calculations for two different values of conductivity. The conductivity used in calculations shown on Figure 15-a was 300 times higher than the one used for the calculations shown on Figure 15-b. One can see that the impedance strongly depends on the frequency in the former case and less in the latter.

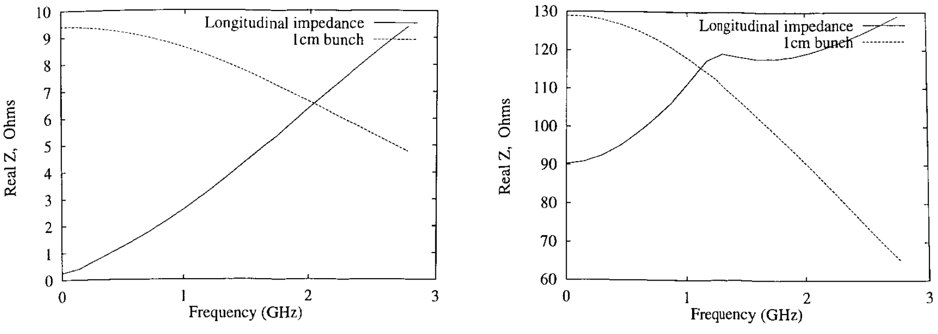


Figure 5: Real part of longitudinal impedance

Figure 5: Real part of longitudinal impedance

Figure 15. MAFIA (T3) simulations of a thin resistive layer. In the simulations the layer thickness was 2 mm. The length of the resistive layer was 150 mm. The graphs are shown for two different values of conductivity.

5 CONCLUSIONS

The impedance measurements of the prototype of the LHC abort kicker using a coaxial wire method have shown that the resistive layer provides a very good screening in the frequency range up to 1 GHz. This was in spite of the fact that the frequency at which the skin depth in the resistive layer becomes comparable to its thickness is more than 1 GHz.

It has been found that when there is good electrical contact between the resistive layer and the beam pipe the image current induced in the beam pipe will almost entirely pass through the resistive layer. Therefore the total impedance of the kicker is determined by the properties of the resistive layer, which is very small (less than 1 Ohm) and is virtually not affected by the elements such as magnet coils, cables etc. located outside the ceramic pipe.

The simulations done with the MAFIA T3 module have not been successful, because of the significant number of mesh points required for such calculations. It has been found that the simulation techniques in which thin resistive layers are substituted by thicker ones in order to reduce the number of mesh points can lead to incorrect results.

6 ACKNOWLEDGEMENTS

We would like to thank F. Caspers (PS-RF) and F.Ruggiero (SL-AP) for many fruitful discussions and supervising the kicker tests, and also thank to G. Schroeder (SL-BT) who helped to organize the test and also J.-C. Guillot for his help during the measurements.

REFERENCES

1 F. Caspers, *"Bench methods for beam coupling impedance measurements"*, Lecture Notes in Physics, Frontiers of Particle Beams: Intensity Limitation, Proceedings of a Topical Course Held by the Joint US-CERN School on Particle Accelerators at Hilton Head Island, South Carolina, USA, 7-14 November, 1990, Springer-Verlag, pp. 80-109.

2 H. Hahn, F. Pedersen, Report BNL. #50870 (1978).

3 T. Weiland, MAFIA Manual (1987)