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RF SCREENING BY THIN RESISTIVE LAYERS

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Abstract

We discuss the results of recent impedance measurements for an LHC dump kicker prototype, performed at CERN using the coaxial wire method. The kicker design includes a vacuum barrier consisting of a ceramic chamber internally coated with a thin metallic layer having good electric contact with the external beam pipe. For the bench test the coated ceramic tube was replaced by a kapton foil with a 0.2 μm copper layer having the same DC resistance of 0.7 Ω. The measurements show that this resistive coating provides a very effective RF screening down to frequencies below 1 MHz, where the skin depth is two orders of magnitude larger than the layer thickness and one could expect full penetration of the electromagnetic fields. We also present simulation results and analytic considerations in agreement with the measurements, showing that the return currents almost entirely flow through the copper layer down to frequencies where the reactive impedance of the kicker elements located behind it becomes comparable to the layer resistance. Finally we discuss the relevance of such coaxial wire measurements to the RF shielding by thin metallic layers in the presence of a higly relativistic proton beam.

1 INTRODUCTION AND SUMMARY

The question of how the RF impedance of thin metal films is to be computed and measured in practical situations may have a significant impact on the design of metallized ceramic chambers for kicker magnets or metal screens in the experimental beam pipes. These are examples of structures of finite length, while analytic results on electromagnetic penetration are available only for infinitely long structures (see for example [1, 2]).

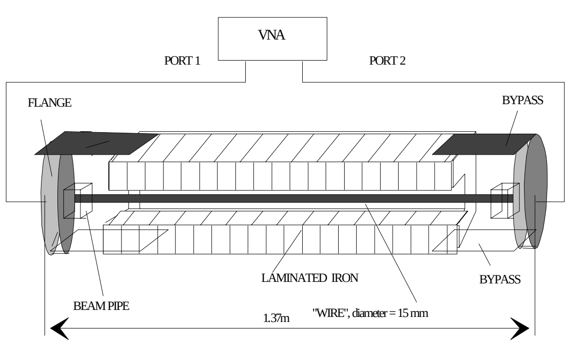

Figure 1: Longitudinal cross section of an LHC dump kicker with flanges and measurement setup.

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The coating resistance of ceramic chambers for kicker magnets should be low for good RF screening, but not too low to avoid eddy currents that would prevent kicker field penetration. In the LHC dump kicker, a good compromise is obtained with a DC resistance per square $R_\square = 0.1\,\Omega_\square$, corresponding to a $4.2\,\mu$m Ti layer or to a $0.2\,\mu$m Cu layer. The skin depth δ in copper at 1 MHz is about $60\,\mu$m and one may expect penetration at frequencies below 100 GHz. However, the effective skin depth $d_{\rm eff} = \delta^2/D$ at 1 MHz for a $0.2\,\mu$m copper coating on a ceramic tube with thickness $D = 3$ mm is only $1.2\,\mu$m according to Ref. [2] and RF shielding is expected above 6 MHz. A 0.1 mm thick kapton foil was used in the kicker impedance measurements discussed in Sec. 2, instead of the ceramic tube, and the effective skin depth at 1 MHz should then be about $36\,\mu$m. For a 0.2 μm copper layer one would therefore expect RF shielding only at frequencies above 200 MHz, while the measurements show a clear shielding effect already above 1 MHz.

The coaxial wire measurements have been successfully simulated using the program HFSS. Modelling the kicker by a cylindrical cavity having a thin screen of radius $a = 50$ mm and sheet resistance $R_\square = 0.2\,\Omega_\square$, the electric field created in the cavity by a sinusoidal signal at 5 MHz on the inner conductor is attenuated by a factor 1000 compared to the case without resistive screen. This confirms that the shielding effect does not require any dielectric. Several independent current sources with proper phase shifts have been used to model a beam, rather than an inner conductor; the results are virtually the same.

The same cylindrical structure used for the simulations with HFSS has been investigated analytically using field matching of the unknown longitudinal electric field $E_z(r = a)$. This yields an integral equation containing a dimensionless parameter $\zeta = Z_0/R_\square$, where Z_0 is the free space impedance. When ζ is large the screening is good. However field penetration is enhanced near resonant frequencies corresponding to coaxial cavity modes and may become significant if ζ is smaller than their quality factors. For a 0.2 μm copper layer $\zeta \simeq 4400$. When the cavity length tends to infinity there is no shielding.

2 MEASUREMENTS

The coaxial wire method is a convenient bench method for the simulation of charged particle beams. For longitudinal impedance measurements, the test bench setup (see Fig. 1) consists of a single conductor ("wire") in the centre of the vacuum chamber, at the position of and replacing the beam.

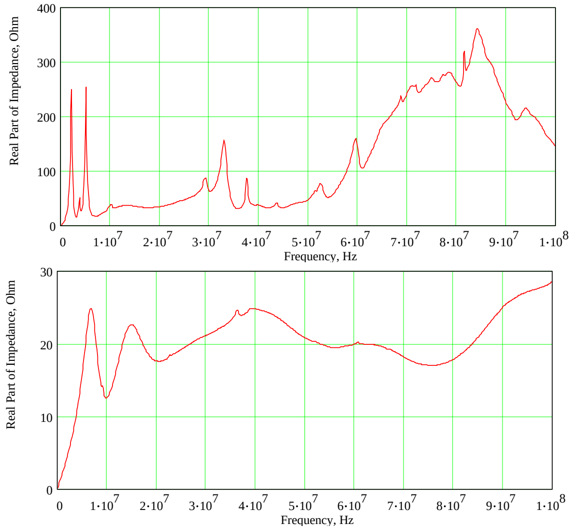

Figure 2: Real part of the impedance when the kicker body is either disconnected (top) or connected with four copper foils (bottom) to the supports of the RF connectors.

Figure 2 shows the effect of an external bypass, consisting of four 0.3 mm thick copper foils connecting the flanges to the aluminum case which surrounded the magnets, in the absence of the resistive layer.

The fact that the impedance doesn't change if we move/connect the kicker magnets, as shown in Fig. 3, indicates that the metallized kapton foil (and therefore the metallized ceramic pipe with similar surface resistance) is very effective in shielding the kicker magnets from the electromagnetic fields produced by the LHC bunches. In Fig. 4 we compare the transmission coefficients measured in presence of the resistive layer with and without external bypass. The effect of the bypass on the transmission coefficient can be seen only at very low frequencies: the maximum difference is observed at 0.1 MHz and is equivalent to $0.05\,\Omega$. The difference becomes negligible above 1 MHz.

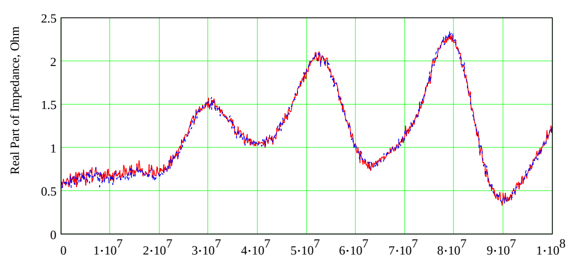

Figure 3: Real part of the impedance measured with the resistive layer for kicker magnets either closed or open (the two curves are indistinguishable). The resistive layer reduces the impedance significantly (compare to Fig. 2).

3 NUMERIC SIMULATIONS

An idealized, empty cavity-like object was used instead of kicker magnets with complicated geometry. The resistive layer, of radius a and length g as shown in Fig. 5, was assumed to have zero thickness and could thus be characterized by its sheet resistance $R_\Box$ and by the total resistance $R = R_\Box g/2\pi a$. This was easily modelled with the program HFSS (High-Frequency Structure Simulation) by Ansoft [3], that was adopted for the calculation.

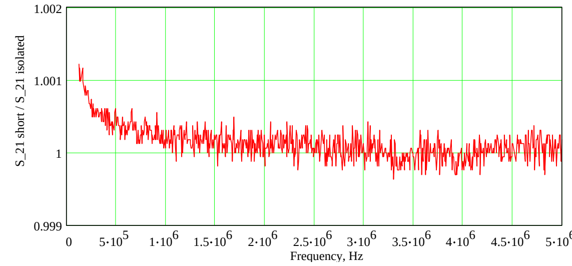

Figure 4: Ratio of the transmission coefficients S_{21} measured in presence of the resistive layer with and without external bypass.

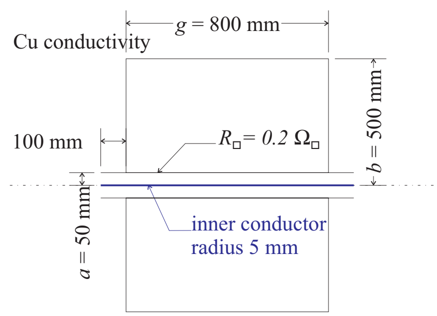

Figure 5: Pillbox cavity with cylindrical simmetry and resistive layer used in the simulations.

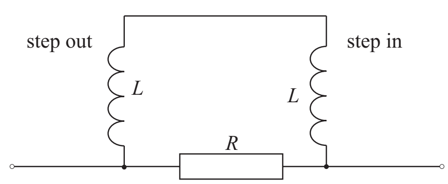

Figure 6: Equivalent circuit for the setup of Fig. 5.

In the cavity-like geometry which we considered, we find the simplified equivalent circuit shown in Fig. 6 to be valid for frequencies of up to 100 MHz, i.e. as long as the length can be considered short compared to the wavelength. As shown in Figs. 7 and 8, at 100 MHz the electric field is diminished outside of the layer by a factor of at least 100. A stronger attenuation is found at lower frequencies, down to a few MHz. At 100 kHz the electric field is still shielded, but the magnetic field starts penetrating. Each step in the beam chamber radius can be represented by a concentrated inductance L, the resistive layer by a resistor of in our case $R = 0.5\,\Omega$. Note that the latter is proportional to the length. Any possible kicker impedance Z will appear in parallel to the resistor. Hence, the value of R gives an easy worst case estimate for the impedance of the considered section, as shown in Fig. 9. An inductance $L = 100$ nH, associated with the geometric step of a typical kicker tank, corresponds to an impedance of about $6\,\Omega$ at 10 MHz. For a metallic layer with typical specific

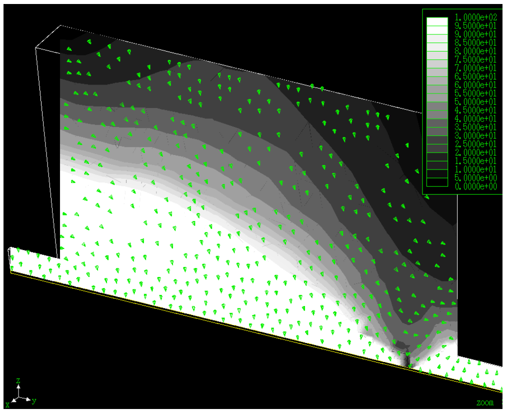

Figure 7: Electric field at 100 MHz, without the resistive layer. The arrows indicate the directions, the shading the intensity of the field, in arbitrary units. At this frequency, more than a quarter wavelength fits into the structure - note the electric field node at the right.

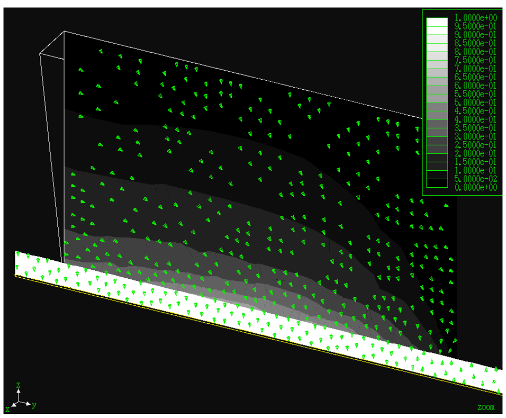

Figure 8: Electric field at 100 MHz, with the resistive layer. The same units as in Fig 7 were used, but for the shading the sensitivity was increased by a factor 100. Note the change of the electric field direction at the layer.

resistance of $1\,\Omega/\mathrm{m}$, the asymptotic regime where the image currents flow in the outer conductor and the resistive layer provides no shielding requires lengths of the order of several meters.

The wire does not only carry a current which is similar to that of a charged particle beam, but it is also a conductor. Consequently, it can be argued that the coaxial wire method makes a systematic error which may not be small in all cases. In HFSS, it is possible to excite the structure with ideal current sources (with infinite inner resistance) which resemble the ultrarelativistic beam much more. We distributed 16 short current sources along the axis of the structure. Their currents were equal but adjusted to have a phase advance from one to the next equivalent to a phase velocity of c, i.e., $\Delta\phi = (\omega/c)\,\Delta z$. The results of the simulation with current sources and those with an inner conductor are virtually identical outside of the resistive layer. They differ only in the vicinity of the axis.

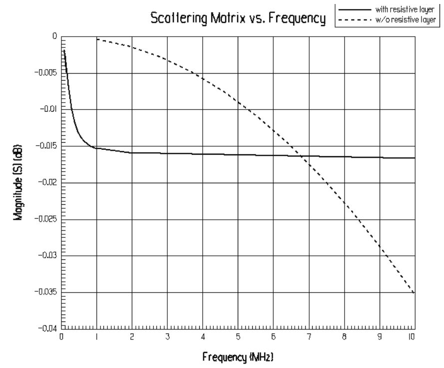

Figure 9: Transmission coefficient $\log|S_{21}|$, from 70 kHz to 10 MHz, with resistive layer (solid line) and without (dashed line). The impedance predicted by the equivalent circuit model of $R = 0.5\,\Omega$ corresponds to a transmission loss of -0.016 dB and agrees well with these simulation results above 1 MHz.

4 ANALYTIC CONSIDERATIONS

A charged particle travels on the axis of the cavity shown in Fig. 5 with a Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$ corresponding to the velocity $\beta = v/c$. We want to compute in frequency domain the electromagnetic fields induced by the charge in the cavity; these fields can be computed once the longitudinal electric field E_z is known in the gap g at $r = a$. It can be shown that $E_z(r = a)$ is determined by a Fredholm integral equation of the second kind. The kernel of the integral equation is built up from two parts: a pipe kernel, which involves the cut-off frequencies of the E_{0n} modes of the beam pipe, and a cavity kernel, which involves the resonant frequencies of the coaxial cavity corresponding to the boundary condition $E_z = 0$ at $r = a + d$, where $d \ll \delta$ is the layer thickness. For the resistive layer being an effective screen, it must carry almost all of the image current which flows along the beam pipe, which means that $\zeta E_z(r = a)$ must be as large as possible (here $\zeta = Z_0/R_\Box$). Without solving the Fredholm integral equation, what seems to be a formidable task, it can be seen that this will happen when ζ is large enough and the cavity kernel is small enough. Since this part of the kernel has poles at the resonant frequencies of the coaxial cavity, this means that these frequencies are not screened by the resistive layer. Since the integral over the kernel is taken along the gap g, the product $(\omega/c)\,g$ must not be too large. When $(\omega/c)\,g \to \infty$, it can be shown that $E_z(r = a)$ contains a factor $1/\beta^2\gamma^2$ which makes $E_z(r = a)$ much too small to provide any screening.

5 REFERENCES

[1] B. Zotter, ‘Longitudinal instabilities of charged particle beams inside cylindrical walls of finite thickness’, Part. Acc. **1**, 311-326 (1970).

[2] A. Piwinski, ‘Penetration of the field of a bunched beam through a ceramic vacuum chamber with metallic coating’, IEEE Trans. Nucl. Sci. **24**, 1364–1366 (1977).

[3] World-wide web page `http://www.ansoft.com/`