MEASUREMENT OF THE TRANSVERSE RESISTIVE WALL IMPEDANCE OF A LHC GRAPHITE COLLIMATOR AT LOW FREQUENCY

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Abstract

The largest contribution to the LHC transverse resistive wall impedance is given by the graphite collimators. Such a contribution is predicted by analytical calculations. A series of laboratory measurements were performed to experimentally validate the analytical results in the case of small gaps and in a low frequency regime where the skin depth becomes comparable to the collimator thickness. The measurement method consists in determining the dependence of a probe coil input impedance on the surrounding materials and was applied to sample graphite plates, stand alone LHC collimator jaws and a full collimator assembly. After reviewing the measurement procedures, problematics and stages, the results are compared to analytical predictions and numerical simulations.

INTRODUCTION

The prediction of the transverse resistive-wall impedance of the LHC collimators is of paramount importance for its consequent impact on the ultimate LHC luminosity. The interest on this kind of studies is even more enhanced due to the fact that in a regime determined by i) the poor electric conductivity of the collimator material, ii) small collimator gaps and iii) the interest in low frequencies (of the order of the first LHC beam unstable betatron frequency, 8 kHz), the analytical theories developed in the last years (see [1] and included references) differ from classical thick wall predictions. Such a regime corresponds to cases in which the collimator material skin depth is comparable (or larger than) the material thickness. While the classical theory predicts an increasing real and imaginary part of the transverse impedance with 1/f, more recent calculations estimate (below a certain frequency which depends on geometry and material conductivity) a decreasing real part (down to 0 at DC) and a constant imaginary part. This is why this effect is referred as 'inductive by-pass effect' [2] or 'redistribution effect' [3]. The comparison between classical and novel theories in the case of two graphite plates 15 cm long, 1 cm thick and separated of 10 mm (gap) is shown in Fig. 1

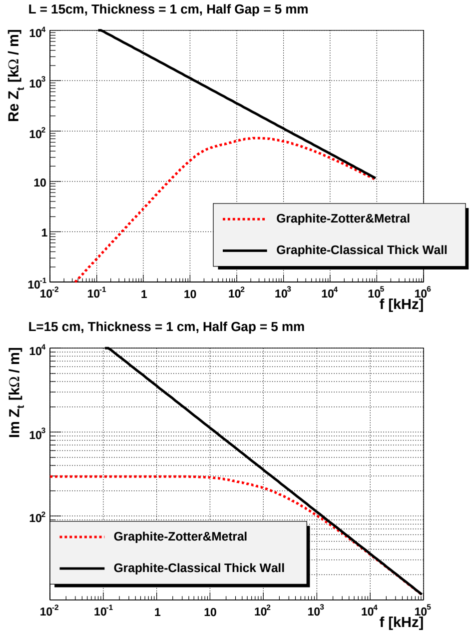

Figure 1: Real and imaginary part of the calculated transverse impedance for graphite plates, comparison between classical and novel theories.

As already discussed in [4] a campaign of laboratory measurements and numerical simulations was launched in order to benchmark the theory. In this paper we will recall the studies results achieved so far with particular emphasis on the experimental part method, problematics and accomplishments.

LABORATORY MEASUREMENTS METHOD

A classical way for measuring the coupling impedance of an accelerator component consists in reproducing the electro-magnetic interaction between the particles beam and the component by stretching a thin conductive wire along the reference beam trajectory inside the Device Under Test (DUT) and powering it with an RF source. Usually, a Vector Network Analyzer is used as RF source and at the same time allows measuring the scattering parameters of the resulting network, that, compared to similar measurements on a reference vessel, allow calculating the DUT longitudinal impedance. The transverse impedance is than calculated repeating the measurement at different wire transverse positions and looking at the variation of the longitudinal impedance. Theoretical and experimental aspects

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of this method are very well addressed in [5] and [6]. However, such a method has very poor sensitivity at low frequencies, for which the signals to be measured are extremely small.

An alternative method for transverse coupling impedances is based on a two-wires system. This is discussed in detail in [7] and in the following we review the basic steps.

Any beam that oscillates in a transverse coordinate induces electromagnetic fields on the surrounding materials. Neglecting the electric field and only considering the magnetic field B, the the transverse impedance results:

$$Z_T = \frac{i}{\beta I \Delta} \int_0^{2\pi R} (\vec{v} \times \vec{B})_T ds \qquad (1)$$

where $\pm\Delta$ is the beam oscillation amplitude, $\beta = \mathrm{v}/\mathrm{c}$ and I is the beam current. The term that drives the correspondent force (acting back on the beam and potentially perturbing its stability) is the dipole moment $\Delta \cdot \mathrm{I}$. The same effect occurs substituting the beam by two wires powered with opposite currents or by a wire loop of (unperturbed) impedance Z_0. The B field induced by the loop on the surroundings acts back generating a voltage on the loop,

$$V = j\omega B L \Delta = Z_B \cdot I \qquad (2)$$

where L is the loop length and $\mathrm{Z_B}$ is the consequent variation of the loop impedance. Measuring the total loop impedance $\mathrm{Z_{meas}}$ allows calculating $\mathrm{Z_B = Z_{meas} - Z_0}$ that according to Eq.1 and Eq.2 gives the beam induced field B and the related transverse impedance as:

$$B = \frac{I Z_B}{j\omega L \Delta} \qquad (3)$$

$$Z_T = \frac{c\, Z_B}{\omega \Delta^2} \qquad (4)$$

Also this method has poor sensitivity at low frequencies, but improved results can be achieved by substituting the two wires by a multi-turn probe coil as proposed in [3]. The variation of the input coil impedance $\vec{\mathrm{Z}}_{\mathrm{coil}}^{\mathrm{DUT}}$ in the presence of the DUT, compared to a reference measurement $\vec{\mathrm{Z}}_{\mathrm{coil}}^{\mathrm{REF}}$, gives the transverse beam coupling impedance associated to the DUT, according to:

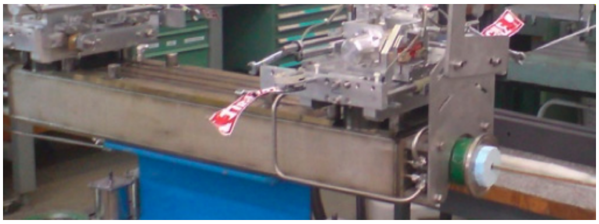
$$Z_T^{meas} = \frac{c}{\omega} \frac{Z_{coil}^{DUT} - Z_{coil}^{REF}}{N^2 \Delta^2}, \qquad (5)$$

where N is the number of turns of the coil and Δ the coil width. The comparison with a reference material by computing the difference $Z_{coil}^{DUT} - Z_{coil}^{REF}$ is meant to isolate the resistive wall part of the DUT impedance. This is rigorous in the ideal case of having a measurement in free space as a reference. In practice, it is convenient to use as reference high conductivity materials (like copper or brass) with the same DUT geometry. Depending on the materials under test and the geometry (gap values), at very low frequencies the resistive wall impedance of the reference material may well become larger than the one of the DUT and the measured quantity $\mathrm{Z_T^{meas}}$ results negative. In this cases, one has to take as exact the reference material resistive wall impedance and retrieve the one of the DUT as

$$Z_{RW}^{DUT} = Z_T^{meas} - Z_{RW}^{REF} \qquad (6)$$

(a) Sample plates $15 \times 10 \times 1\mathrm{cm}$

(b) Stand alone jaws $120 \times 10 \times 2.5\mathrm{cm}$



(c) Collimator assembly (jaws $120 \times 10 \times 2.5\mathrm{cm}$)

Figure 2: Pictures of the measurement setup three stages.

LABORATORY MEASUREMENTS SETUP

The probe coil method described above was used for benchmarking theory and characterizing a LHC graphite collimator. This was done in three stages differing in the DUT type: 1) sample graphite plates, 2) stand alone graphite jaws and 3) a collimator assembly. Pictures of the three setups are shown in Fig. 2.

A summary of the measurement stages and conditions is shown in Table 1. In order to cope with the different measurement sessions in terms of DUT length and amplitude of the impedance to be measured, several coils have been fabricated, differing in length, width and number of windings N. The higher N the higher the probe coil impedance and the better the sensitivity, but the lower the frequency of the first coil self-resonance, that sets the upper frequency limit for which the measurement can be performed.

For each measurement stage at least two different

Table 1: Geometry and material properties of the three different measurement stages (see text)

Stage	Geometry			Mat.	ρ_c
	L [cm]	h [cm]	t [cm]		[$\mu\Omega\cdot$m]
1	15	10	1	graph.	13
2	120	6.6	2.5	graph.	13
3	160 *, 120 **	6.6	2.5	CFC	5

* collimator in which the CFC jaws are assembled.
** reference jaws and analytical calculations

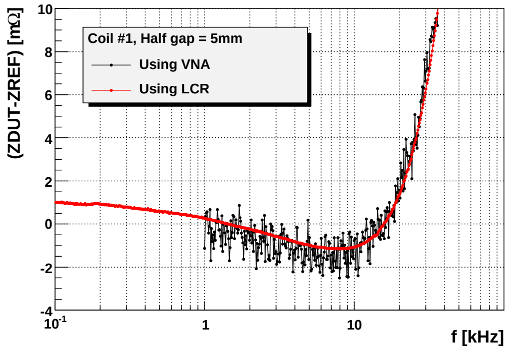


Figure 3: Comparison between VNA and LCR noise levels.

probe coils were fabricated. Typical parameters were $\Delta = 2.5\mathrm{mm}$ and $5 < \mathrm{N} < 14$.
The measurement setup included a test phase for comparing two different methods for measuring the probe coil impedance. One based on a Vector Network Analyzer (VNA) in reflection mode, as proposed in [3] and a second using an LCR meter [8]. At frequencies below 10 kHz, where the quantity to measure $\mathrm{Z}_{\mathrm{coil}}^{\mathrm{DUT}} - \mathrm{Z}_{\mathrm{coil}}^{\mathrm{REF}}$ is very small, the second method proved to be less noisy (see Fig. 3) and all the results that will be presented refer to measurements with the LCR meter.

Always in the setup phase and when looking at low frequencies, with both the VNA and the LCR, even in the case of low statistical error, we identified some systematic (coherent in all the considered frequency range) variation of the measured probe coil impedance when measuring the same DUT and reference materials in different periods. Such systematic drift was due to temperature variations in the region immediately surrounding the coil. This is evident in Fig. 4, that shows 60 consecutive measurements of the coil impedance at frequencies around 1 kHz while keeping the coil within copper jaws at constant gap. After 53 measurements (measurement number 203 on the plot) the temperature around the coil was voluntarily decreased of about 2 degrees. This caused an abrupt change of the coil impedance, of an amount well larger than the $\mathrm{Z}_{\mathrm{coil}}^{\mathrm{DUT}} - \mathrm{Z}_{\mathrm{coil}}^{\mathrm{REF}}$ difference to be measured in most configurations relevant for the LHC collimator case.
So far, there was no time to investigate in more detail this effect (i.e. determining the coil impedance temperature coefficient, systematically correcting the results for the measured temperature etc...). For the results shown later in this paper, the systematic dependence on temperature was minimized by performing fast measurement sessions, thus interleaving very little periods between the DUT and the reference measurement.

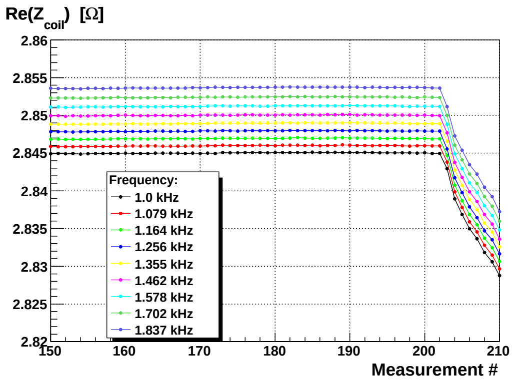


Figure 4: Variation of the measured coil impedance when changing the environment temperature ($\Delta\mathrm{T} \approx 2$ degrees after measurement number 203).

MEASUREMENT RESULTS

For each set of measurements a number of gap (transverse distance between the plates or jaws) values were scanned, in order to compare measurements and theory for different absolute values of the associated transverse impedance. The minimum gap value g was assessed by the condition $\mathrm{g} \geq 2\Delta$, whereas its maximum was determined by the minimum measurable impedance. Measurements with gaps from 5 to 20 mm were completed, even though only some result examples will be presented in this paper. The achieved reproducibility and accuracy can be inferred from the plots in Fig. 5, which reports the results (in terms of the difference $\mathrm{Re}(\mathrm{Z}_{\mathrm{coil}}^{\mathrm{DUT}}) - \mathrm{Re}(\mathrm{Z}_{\mathrm{coil}}^{\mathrm{REF}})$) of measurements performed with sample plates at two different gaps and with two different coils. The experimental results (solid lines) are compared with the correspondent analytical prediction (square dots). Both the reproducibility and the accuracy (as agreement with theory) are well below 1% down to f=1 kHz.

The real and imaginary part of the measured transverse resistive wall impedance for graphite plates with half gap of 5 mm are shown in Fig. 6. This confirms, also for the imaginary part, the almost perfect agreement with theory. Similar results have been achieved when measuring standalone jaws.

As already discussed in [4], the measurement stages 2 and 3 (see Table 1) were meant not only to benchmark the theory, but also to investigate experimentally possible differences in the transverse impedance between standalone collimator jaws and their assemblage in a collimator. In the latter case the effect of RF screens and other material

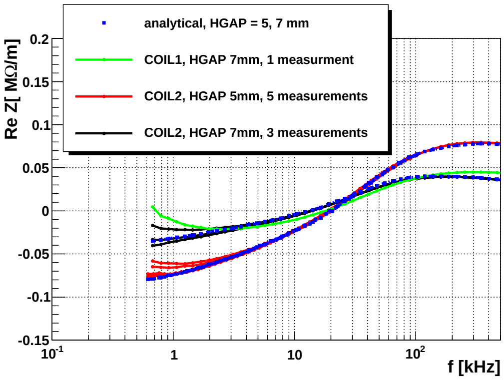


Figure 5: Measurements results accuracy and reproducibility using two different coils and two different gaps.

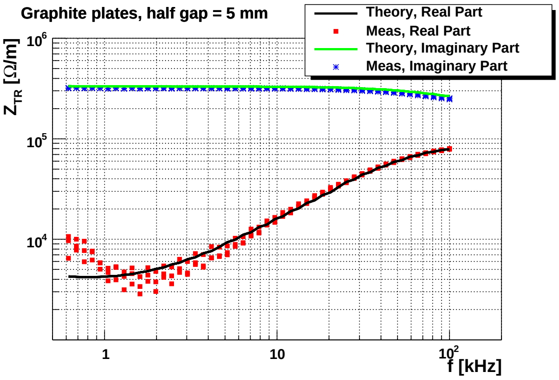


Figure 6: Real and imaginary part of the transverse impedance of graphite plates (stage 1 in Table 1).

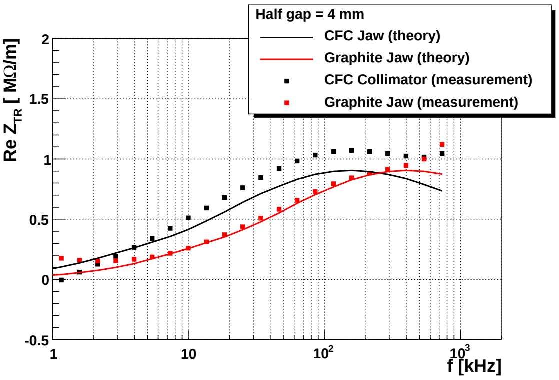


Figure 7: Real part of the transverse impedance of graphite jaws and CFC collimator assembly (stage 2 and 3 in Table 1).

surrounding the jaws is very difficult to predict analytically or simulate. The available jaws and collimator assembly were not fabricated with the same graphite, but this was properly considered in the theoretical predictions. The real part of the transverse impedance for such two configurations is shown in Fig. 7, for a half gap of 4 mm and using a 2 m long probe coil with N=7 and $\Delta = 3.25\,\mathrm{mm}$. As for the sample plates, theory and measurements have a very good agreement for the stand-alone jaws. The agreement is poorer in the case of the collimator assembly, especially for frequencies above 10 kHz. Consequently, comparing the measured traces of stage 2 (red dots in the plot) and 3 (black dots), their difference can only be partially attributed to the difference in material resistivity (i.e. the difference between the red and black lines). So far, after the first set of measurements, a collimator assembly was not available for investigating in more detail these results.

OUTLOOK AND FINAL REMARKS

The measurement campaign aiming at bench-marking novel analytical theories in a ”low frequency” regime was successful, the measurement results agree within 1% with theory down to f=1 kHz. This is also confirmed by numerical simulations [9] not presented here. The method and the challenges related to the measurements have been discussed. Even accounting for the effect of the collimator assembly on the RW impedance, the impact of the collimation system on the total LHC impedance and all the corresponding analysis of beam stabilities is valid, see [10].
It must be remarked that analytical calculations and numerical simulations refer to infinitely long structures, whereas measurements are obviously performed on devices with finite length. In addition, the laboratory experiments have the hypothesis that only Eddy currents are responsible for the impedance at low frequency and therefore with the probe coil method we neglect the effects of lossless dielectric materials and thus the related imaginary part of the impedance. As a consequence, measurements of prototype dielectric collimators is difcult and not solved yet. Nevertheless, all these studies are already contributing to the design proposals for the LHC phase 2 collimation and provided preliminary results of prototype materials and geometries.

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