COMPARISON BETWEEN LABORATORY MEASUREMENTS, SIMULATIONS AND ANALYTICAL PREDICTIONS OF THE RESISTIVE WALL TRANSVERSE BEAM IMPEDANCE AT LOW FREQUENCIES

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Abstract

The prediction of the resistive wall transverse beam impedance at the first unstable betatron line (8 kHz) of the CERN Large Hadron Collider (LHC) is of paramount importance for understanding and controlling the related coupled-bunch instability. Until now only novel analytical formulas were available at this frequency. Recently, laboratory measurements and numerical simulations were performed to crosscheck the analytical predictions. The experimental results based on the measurement of the variation of a probe coil inductance in the presence of i) sample graphite plates, ii) stand-alone LHC collimator jaws and iii) a full LHC collimator assembly are presented in detail. The measurement results are compared to both analytical theories and simulations. In addition, the consequences for the understanding of the LHC impedance are discussed.

INTRODUCTION

When calculating resistive-wall impedances of particle accelerators components, in the case of poor conductive materials, beams very close to the component wall and for frequencies low enough to have material skin depths comparable to (or larger than) the wall thickness, novel theories(see [1] and included references) differ from the classical thick wall prediction. In particular, 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].

NUMERICAL SIMULATIONS

Classical numerical simulation codes that solve in the frequency or time domain typical problems of beam coupling impedance provide poor accuracy below 1 MHz, i.e. in the frequency regime of interest mentioned above. However, other programs optimized for low frequency problems (like the design of non-destructive testing devices using eddy currents or the optimization of transformers) are suitable in such regime. One of this codes, Ansoft Maxwell©, was used to predict the real part of the resistive wall transverse impedance for a number of relevant cases in which classical and novel theories diverge [4]. The simulations are based on the representation of a particle beam traveling through a Device Under Test (DUT) by a thin wire conductor. In particular, two wires, powered with a current of equal peak intensity $\hat{I}$ and opposite phase, are needed to create the dipolar field associated with the transverse impedance. At first the real part of the longitudinal impedance Z_L can be determined as: $\Re[\mathrm{Z_L}] = 2\Delta\mathrm{P}/\hat{\mathrm{I}}^2$, where $\delta\mathrm{P}$ is the power lost in the DUT, which, in the numerical simulations, is calculated by integration of the ohmic losses over the volume of the DUT.

The transverse impedance characteristic of the two wires setup is expressed according to [5] $\mathrm{Z_{TR}}(\omega) = \mathrm{c}/\omega\mathrm{Z_L}/\Delta^2\mathrm{L}$, where c is the speed of light, Δ the wires spacing and L the DUT length. The real part of the transverse impedance results:

$$\Re[Z_{TR}](\omega) = \frac{c}{\omega}\frac{2\delta P}{\hat{I}^2\Delta^2 L}. \quad (1)$$

The real part of the transverse impedance as computed by the numerical simulation for a 1 m graphite pipe is shown in Fig. 1. The results are compared to the analytical prediction for the same geometry and material, and the agreement is within 1%. Comparable simulations were carried out for collimator-like structures with analog agreement with the analytical calculations and all results are reported in [4].

LABORATORY MEASUREMENTS

The two wires setup used for the simulations discussed above can be in principle applied for laboratory experiments. However, at low frequencies the method normally suffers of a low signal to noise ratio. A better sensitivity 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 $\mathrm{Z_{coil}^{DUT}}$ in the presence of the DUT, compared to a reference measurement $\mathrm{Z_{coil}^{REF}}$, gives the transverse beam coupling impedance associated to the DUT, according to:

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

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 $\vec{Z}_{coil}^{DUT} - \vec{Z}_{coil}^{REF}$ is meant to isolate the resistive wall part of the DUT impedance. This is rigorous in

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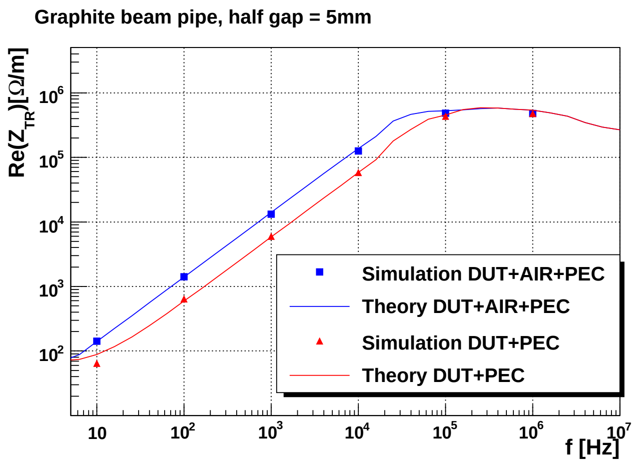

Figure 1: Real part of the transverse impedance as calculated by numerical simulations [4] and analytical models [1] for cylindrical graphite and copper beam pipes. PEC stands for Perfect Conductor

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]		[$\mu\Omega$·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

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.

Setup

A number of laboratory experiments were carried out, trying to reproduce in three different stages the geometry and material property conditions represented by the present LHC collimators, namely

1. sample graphite plates
2. stand alone LHC collimator jaws
3. a full LHC collimator assembly.

The geometry and material resistivity of the different measurement stages are summarized in Table 1. Every time, copper with same dimensions of the DUT and resistivity $\rho_c = 1.7 \cdot 10^{-8}\,\Omega \cdot \mathrm{m}$ was used as a reference. The DUT and reference material resistivity follow from dedicated measurements and were used for the analytical calculations.

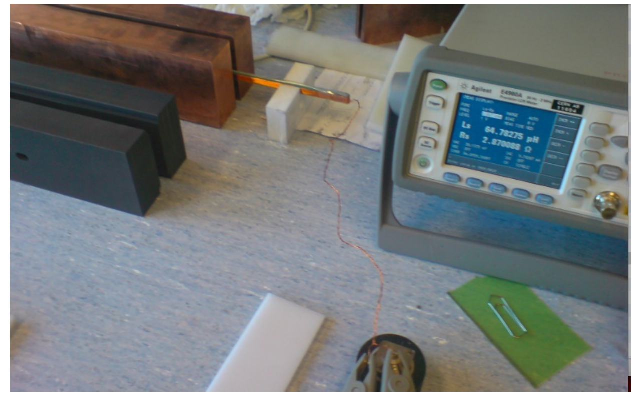

Figure 2: Experimental setup example: LCR meter, graphite and copper jaws, probe coil inside the copper jaws.

For each measurement stage at least two different probe coils were fabricated, differing in length, number of turns N and width Δ. Typical parameters were $\Delta \geq 2.5\,\mathrm{mm}$ and $5 \leq N \leq 14$. The higher N, the higher the measurement sensitivity, but the lower the frequency of the first coil self-resonance (i.e. the lower the upper limit of the measurable frequency band).

One of the most challenging aspects of the measurements was related to the very small absolute value (smaller than $5\,\Omega$ at low frequencies) and relative variation (fractions of $\mathrm{m}\Omega$) of the relevant observable quantity (i.e. the input impedance of the probe coil). Initial tests based on the determination of the coil impedance by measuring the network scattering parameters with a Vector Network Analyzer (HP 8751A or Agilent 4395A) provided excellent results down to 10 kHz but exhibited an unacceptable signal to noise ratio for lower frequencies. The noise figure resulted much smaller when using a LCR meter (Agilent E4980A). This instrument operates only up to 2 MHz, but higher frequencies were not significant due to the occurrence of the first coil self-resonance for all the used coils. The dominant source of uncertainty resulted in a systematic variation of the coil impedance with temperature. It was verified that a fraction of degree is sufficient to induce an impedance change comparable to the relative impedance difference (DUT-REF) that has to be measured. For this reason, accurate results were only achieved setting up the experiments in temperature controlled rooms and interleaving a very short period in between the reference and the DUT measurements. A picture of the laboratory measurement setup is shown in Fig. 2.

Results

The real and imaginary part of the transverse impedance of graphite plates, as measured in the laboratory (and then calculated according to Eq.(2) and predicted by theory, are shown in Fig. 3. The experiment was performed with a half gap of 5 mm and only from 1 to 100 kHz in order to have quick measurements and small systematic errors

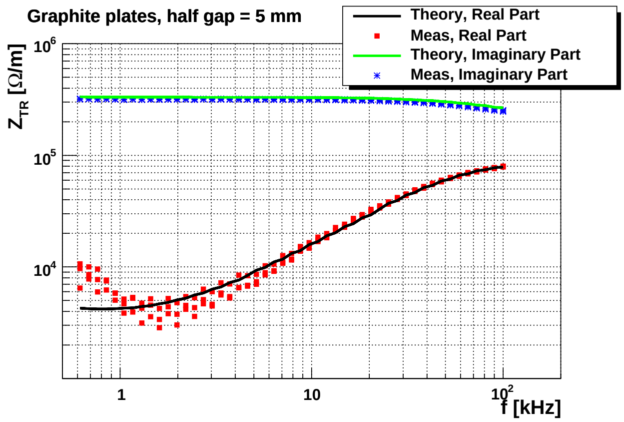

Figure 3: Real and imaginary part of the transverse impedance of graphite plates (stage 1 in Table 1).

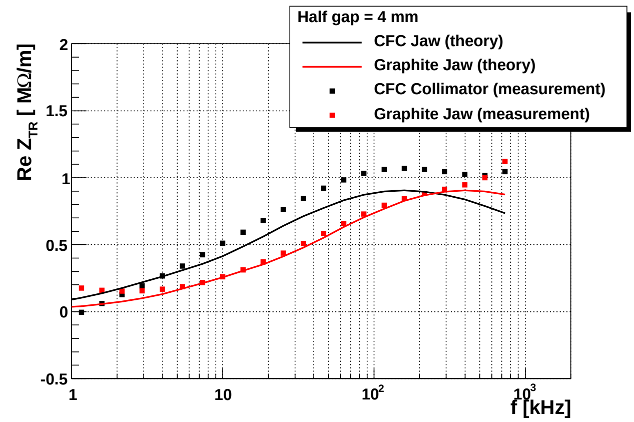

Figure 4: Real part of the transverse impedance of graphite jaws and CFC collimator assembly (stage 2 and 3 in Table 1).

due to temperature fluctuations. Actually, such frequency range represents very well the band of interest for both validating the theory and characterizing the LHC resistive wall impedance. A 20 cm long probe coil with N=14 and $\Delta = 2.6\,mm$ was used. The agreement between measurements and theory is excellent down to 1 kHz, when noise and systematic errors starts affecting the very small real part of the impedance. Furthermore, such agreement was crosschecked using different coils and various half gaps (from 2.5 to 10 mm).

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 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. 4, 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). Further analysis and possibly a new measurement session may be required for better understanding the collimator assembly.

CONCLUSIONS AND OUTLOOK

Both the numerical simulations and laboratory measurements discussed in this paper confirmed the validity of the analytical predictions of the resistive wall transverse impedance in the new regime discussed in the introduction [1]. It must be remarked that analytical calculations and numerical simulations refer to infinitely long structures, whereas the 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.

The beam stability analysis presented in [6] is still valid and at the moment only about half of the nominal intensity can be stabilized with Landau damping. Furthermore, the results presented here suggest similar studies within the collimation upgrade activities aimed at bringing the LHC to its nominal luminosity.

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