ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THAFP05

A WIRELESS METHOD FOR BEAM COUPLING IMPEDANCE MEASUREMENTS OF THE LHC GONIOMETER

C. Antuono*,[1], C. Zannini, CERN, Geneva, Switzerland
M. Migliorati, A. Mostacci, University of Rome "La Sapienza" and INFN, Rome, Italy
[1] also at University of Rome "La Sapienza", Rome, Italy

Abstract

The beam coupling impedance (BCI) of an accelerator component should be ideally evaluated exciting the device with the beam itself. However, this scenario is not always attainable and alternative methods must be exploited, such as the bench measurements techniques. The stretched Wire Method (WM) is a well established technique for BCI evaluations, although nowadays its limitations are well known. In particular, the stretched wire perturbs the electromagnetic boundary conditions. Therefore, the results obtained could be inaccurate, especially below the cut-off frequency of the beam pipe in the case of cavity-like structures. To overcome these limitations, efforts are being made to investigate alternative bench measurement techniques that will not require the modification of the device under test (DUT). In this framework, a wireless method has been identified and tested for a pillbox cavity. Its potential for more complex structures, such as the LHC crystal goniometer, is explored.

INTRODUCTION

The beam coupling impedance represents the electromagnetic interaction between a particle beam and the accelerating structure. As a driving term for collective effects, its vital function in the context of beam stability and quality is well-known and it is therefore crucial to be able to estimate it, either in simulations or measurements. Ideally, one should assess the beam impedance by directly stimulating the device with the beam. Nonetheless, in many instances, this approach proves unfeasible, requiring the use of alternative methods to account for the effect of the beam. Nowadays, various bench methods are employed, but their limitations are also known and documented, as in the case of the Wire method [1, 2]. Consequently, new techniques should be developed to overcome these limitations.

A possible solution, which will not require the modification of the Device Under Test (DUT), named Wireless method, is proposed in Refs. [3, 4]. An exact formula to obtain the longitudinal beam coupling impedance of the accelerator beam chambers is presented and validated. Its feasibility and possible extension to resonant structures is presented in this paper supported by simulations studies, with a possible application to a more complex device, the LHC crystal goniometer.

* chiara.antuono@cern.ch

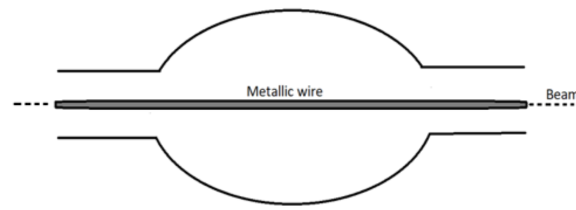

Figure 1: Wire method setup.

BEAM IMPEDANCE MEASUREMENTS: METHODS AND THEIR LIMITATIONS

The measurement of the longitudinal beam coupling impedance is usually performed using a standard technique: the stretched Wire Method (WM) [1], which implies the insertion of a metallic wire along the beam axis of the DUT as shown in Fig. 1.

In fact, the excitation produced by the relativistic beam, in particular its current pulse, can be approximated with a current pulse having the same temporal behavior but flowing through a wire stretched along the beam axis. However, one should note that the introduction of the stretched wire, and therefore of a metallic conductor along the device, modifies the Electro-Magnetic (EM) boundary conditions of the initial DUT. In such a structure, the propagation of Transverse Electro-Magnetic (TEM) modes with zero cut-off frequency is allowed, with the undesired consequence of depleting the resonant frequencies of the structure and introducing additional losses. This behavior occurs specifically below the cut-off frequency of the beam pipe of the device, as already demonstrated in Ref. [2]. As a result, the method gives inaccurate results for resonant structures in the aforementioned range. On the other hand, for resonant structures, a possible alternative technique is the bead-pull method, as described in Refs. [5–7]. It relies on a perturbation introduced by a small object that samples the field in the cavity and it can be related with the change in resonant frequency. Furthermore, the latter can be related to the shunt impedance of the cavity. Nonetheless, this approach requires the use of a pulling system, which may not be particularly convenient or straightforward to implement, especially when considering a portable general-purpose setup. To overcome those limitations and to avoid introducing undesired perturbations (e.g. a change in boundary conditions), the attention has been focused on the development of a Wireless method.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THAFP05

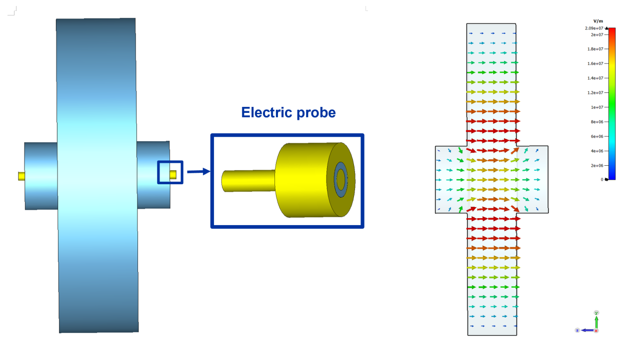

Figure 2: On the left: pillbox cavity excited using the coaxial probe setup. On the right: electric field lines of the fundamental resonating mode TM_{010} obtained through CST simulations. The cavity radius is 11 cm and the pipe radius is 2 cm. The wall electrical conductivity is 3000 S/m.

THE NEW WIRELESS METHOD FOR RESONANT STRUCTURE

The longitudinal beam coupling impedance is related to the energy loss of the electromagnetic wave propagating in the structure. Therefore, it is intrinsically linked to the transmission scattering parameter of the Transverse-Magnetic (TM) mode propagating in the DUT [3,4]. Therein, a formula relating the beam impedance and the TM mode transmission scattering parameter is presented and validated both analytically and in simulations for resistive wall beam chambers. In this framework one can think of applying the same process for resonant structures namely, exciting the DUT with a TM mode and relating the scattering parameters to the beam impedance. For beam chambers, the DUT is excited using the ideal TM mode waveguide excitation provided by the frequency domain solver of CST Studio Suite [8]. For resonant structures, a feasible way to excite a TM mode is to employ a coaxial probe setup placed on the beam axis of the DUT. This idea is tested in the EM CST simulations of the simplest resonant structure, the pillbox cavity, as depicted in Fig. 2.

Indeed, the probe placed on axis of the DUT excites the fundamental mode of the cavity which is longitudinally directed, the TM_{010}, meaning, the excitation of an electromagnetic wave with a non zero electric field along the longitudinal axis (see Ref. [5]). In this manner, it becomes possible to assess the interaction between this wave and the surrounding through the scattering parameters. In Fig. 3, the simulated transmission scattering parameter obtained with the setup shown in Fig. 2, is displayed. We can observe that the resonances in the S_{21} (which is equal to S_{12} due to the reciprocity theorem) are consistent with the beam coupling impedance modes of the given pillbox cavity, as summarized in Table 1.

This implies that the coaxial probe setup is capable of providing the necessary excitation required for the DUT in the given research context (i.e. with the purpose of computing the beam coupling impedance).

Table 1: Expected resonant frequencies and quality factor of the impedance modes obtained with CST WakeField simulations for the pillbox cavity depicted in Fig. 2.

Mode number	Frequency, f_r	Quality factor, Q
1	1.05 GHz	86
2	2.47 GHz	133
3	3.85 GHz	172

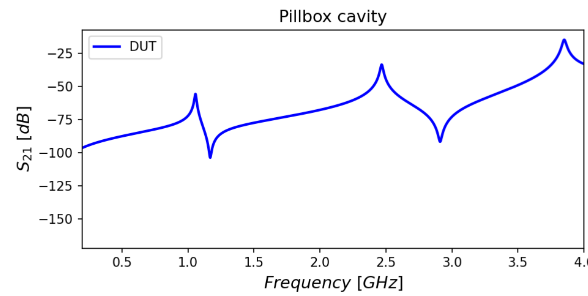

Figure 3: Module of the transmission scattering parameter from CST Frequency Domain simulations for the pillbox cavity depicted in Fig. 2.

However, the probe setup excitation is an external coupling circuit which might perturb the DUT, if its coupling contribution is not properly controlled and possibly taken into account. Therefore, the probes need to be inserted in such a way that they are able to excite the modes, having a good signal to noise ratio, but without perturbing the intrinsic resonances of the DUT. In other word, the coupling circuit of two probes does not have to load the cavity, meaning that it has to be in the "undercoupled regime". It can be fullfilled accounting also for the reflection scattering parameters with a standard technique used in the context of radio-frequency measurements, as explained in Ref. [5]. To calculate the beam coupling impedance, along with the resonant frequencies, two additional parameters are required: the associated quality factors and the shunt impedances. Consequently, the complete impedance behaviour can be reconstructed. The quality factor, specifically the unloaded one, which pertains to the cavity itself and disregards any contributions from excitation, can be extracted from the transmission scattering parameter as explained in Ref. [5]. In order to compute the shunt impedance of each resonance the following formula is used [9]:

$$Z = \frac{Z_{TM}}{2\pi}\left(1 - \frac{|S_{21}^{\mathrm{DUT}}|}{|S_{21}^{\mathrm{REF}}|}\right), \quad (1)$$

where Z_{TM} is the mode impedance of the first TM mode propagating in the beam pipe, S_{21}^{DUT}, S_{21}^{REF} are the transmission scattering parameters of the DUT and of a reference equivalent structure deprived of the impedance sources.

Virtual Measurements Results

The longitudinal impedance expected for the pillbox cavity is computed with the WakeField (WF) solver of

68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2023, Geneva, Switzerland JACoW Publishing
ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THAFP05

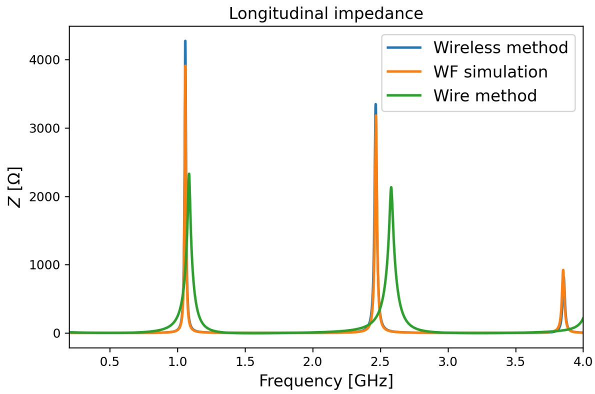

Figure 4: Comparison between the simulated longitudinal impedances of the pillbox cavity of Fig. 2. The orange curve is the expected impedance from the WF solver, the blue one is the impedance obtained with the Wireless method and the green one is the impedance obtained with the WM.

CST and compared with the simulated impedance obtained applying the Wireless method and the Wire method in Fig. 4. The agreement between the proposed method and expectations is very promising and the advantage compared to the standard Wire method is evident. In fact, the green impedance curve clearly exhibits the detuning effect of resonances and additional losses characteristic of the application of the Wire method to a pillbox cavity. Notably, the blue curve follows the orange, both in terms of resonant frequencies and shunt impedance. Although a slight deviation is evident in the latter, it remains within a tolerable margin, not surpassing a maximum relative error of 10 %. This difference can be attributed, at least in part, to the intrinsic limitations of the simulation accuracy.

Possible Application to Complex Structures

After the potential of the Wireless method has been verified for the simple case of a pillbox cavity, the following step involves the evaluation of more complex accelerating structures, such as the LHC crystal goniometer depicted in Fig. 5. As previously done, the expected longitudinal

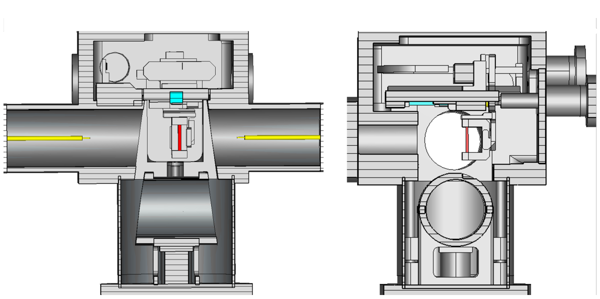

Figure 5: Cross sections of the geometric CST model of the LHC crystal goniometer. The displayed scenario is the operational case for the ion run. The crystal (red brick) is inserted in the beam pipe and therefore the replacement chamber retracted (proton run: the replacement chamber is inserted).

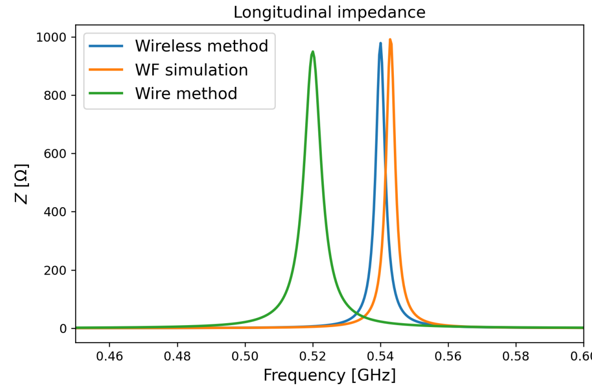

Figure 6: Comparison between the simulated longitudinal impedances of the LHC crystal goniometer depicted in Fig. 5. The orange curve is the expected impedance from the WF solver, the blue one is the impedance obtained with the Wireless method and the green one is the impedance obtained with the WM.

impedance is compared with a preliminary impedance computation obtained applying the Wireless method and the Wire method in Fig. 6. Again, the advantage with respect to the Wire method is clear and the agreement with the expectations is promising, even in light of a bigger discrepancy in the resonance frequency. This can once more be ascribed to the simulations accuracy, particularly when accounting for the increased complexity in the component's design. Future studies aimed at obtaining improved impedance data and over a wider frequency range are currently underway.

CONCLUSIONS

A Wireless method to compute the longitudinal beam coupling impedance of a resonant structure is presented. Simulation studies on a pillbox cavity are conducted and therefore a virtual implementation of the bench measurement is performed, exploiting the coaxial probe setup as a TM excitation. The setup allows for a direct determination of frequencies and quality factors of the impedance resonances from the scattering parameters. From these raw data, the shunt impedance is therefore inferred through the wireless formula and consequently the impedance spectrum can be reconstructed in the frequency range of interest. The very good agreement with expectations and, in particular, the advantage compared to the Wire method are evident. Since the coaxial probe setup employed as the excitation in the virtual measurements is standard and widely used in RF measurements, the method holds promise for the development of a real bench measurement technique to obtain the beam impedance. The first measurement results are very encouraging and will be the object of a dedicated publication. Furthermore, preliminary simulation studies demonstrate the potential of the method for more complex structures, as shown in the case of the LHC crystal goniometer.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THAFP05

REFERENCES

[1] V. G. Vaccaro, "Coupling impedance measurements: an improved wire method", INFN Sez. Napoli, Naples, Italy, Rep. INFN-TC-94-023, Nov. 1994. https://cds.cern.ch/record/276443?ln=en

[2] V. G. Vaccaro, M. Panniello, and M. R. Masullo, "The Stretched Wire Method: A Comparative Analysis Performed by Means of the Mode Matching Technique", in *Proc. LINAC'10*, Tsukuba, Japan, Sep. 2010, paper THP081, pp. 932–934.

[3] C. Antuono, "Improved simulations in frequency domain of the Beam Coupling Impedance in particle accelerators", Master thesis, DIET Dept., University of Rome "La Sapienza", Rome, Italy, 2021.

[4] C. Antuono, M. Migliorati, A. Mostacci, E. Metral, and C. Zannini, "A Wireless Method to Obtain the Impedance From Scattering Parameters", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2213–2216. doi:10.18429/JACoW-IPAC2022-WEPOTK063

[5] D. M. Pozar, *Microwave Engineering*, Hoboken, NJ, USA: Wiley, 2011.

[6] B. Spataro, A. Mostacci, L. Palumbo, B. Spataro, and F. Caspers, "RF coupling impedance measurements versus simulations", 2005. https://api.semanticscholar.org/CorpusID:2080491

[7] D. El Dali et al., "Numerical Calibration of the Bead-Pull Setup for Beam Coupling Impedance Evaluation", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 607–609. doi:10.18429/JACoW-IPAC2022-MOPOTK062.

[8] CST Studio Suite, Dassault System, https://www.simuleon.com/simulia-cst-studio-suite/

[9] G. R. Lambertson, A. F. Jacob, R. A. Rimmer, and F. Voelker, "Techniques for Beam Impedance Measurements Above Cutoff", in *Proc. EPAC'90*, Nice, France, Jun. 1990, pp. 1049–1052.