ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC53

A WIRELESS METHOD FOR BEAM COUPLING IMPEDANCE BENCH MEASUREMENT OF RESONANT STRUCTURES

C. Antuono*[1], C. Zannini, CERN, 1217 Meyrin, Switzerland
M.R. Masullo, A. Passarelli, INFN - Naples Unit, 80126 Naples, Italy
M. Migliorati [2], A. Mostacci [2], University of Rome "La Sapienza", 00185 Rome, Italy
[1] also at University of Rome "La Sapienza", 00185 Rome, Rome, Italy

Abstract

The Beam Coupling Impedance (BCI) is a crucial aspect in the world of accelerator physics, as it describes the electromagnetic interactions between charged particle beams and the accelerator structure. The measurement and quantification of BCI is an essential requirement to assess and mitigate its impact, particularly when introducing new components or addressing issues in existing devices. The stretched Wire Method is a well-established technique for BCI evaluation, although it has well-known limitations particularly evident when dealing with cavity-like structures. In such cases, the estimates obtained below the cut-off frequency of the beam pipe can be inaccurate, where this frequency range holds particular relevance for many accelerator applications. To overcome these recognized limitations, an alternative bench measurement technique has been identified and thoroughly examined. This novel approach has been subjected to comprehensive testing in both virtual and real measurements, with a particular focus on a pillbox cavity.

INTRODUCTION

The Beam Coupling Impedance (BCI) characterizes the electromagnetic interaction between a particle beam and the accelerating structure. Its crucial role as a driving factor for collective effects and its importance in ensuring beam stability and quality is widely acknowledged [1]. Hence, maintaining under control the impedance budget of an accelerator and effectively implementing mitigation strategies when necessary become paramount. This requires an accurate estimate of the BCI. While the ideal approach involves the direct excitation of the device with the beam, practical constraints often require the development of alternative methods to account for beam effects.

Various bench methods are currently employed, such as the well-established technique of the stretched Wire Method [2] or the Bead-pull Method [3, 4]. However, their limitations are well-known and studied. For example, the Wire Method yields inaccurate results below the cut-off frequency of the beam vacuum chamber [5]. Moreover, stretching a wire may be not straightforward or safe in operational terms, especially when dealing with complex devices, such as collimators with small jaw apertures or intercepting devices (i.e. crystals), with a significant risk of damaging the component itself. Consequently, there is the need for the development of new techniques to overcome these limitations. One promising solution, named the Wireless Method, is currently under investigation and it is described in [6, 7], where an exact formula for determining the longitudinal beam coupling impedance of accelerator beam chambers has been validated. In this paper, we complement its feasibility and potential extension to resonant structures, as previously discussed in [8], by summarizing the bench measurements conducted, for the first time, on a pillbox cavity, serving as a proof of concept of the proposed Wireless Method.

STANDARD BENCH IMPEDANCE METHODS FOR RESONANT STRUCTURES

In this section, we provide an overview of the standard bench methods employed for beam coupling impedance measurements with their limitations.

The Stretched Wire Method

The stretched Wire Method [2] implies the insertion of a metallic wire along the beam axis of the Device Under Test (DUT) as shown in Fig. 1, simulating the Electro-Magnetic (EM) field excitation produced by the relativistic beam. The

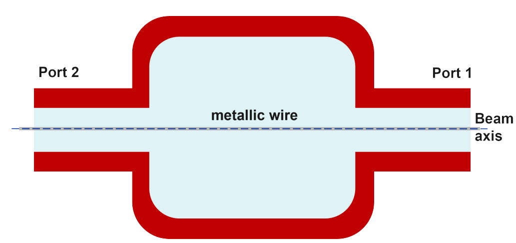


Figure 1: Schematic of the Wire Method setup.

longitudinal beam coupling impedance is related to the measured scattering parameters through the following formula [2]:

$$Z_l = -Z_c \ln \frac{S_{21}^{DUT}}{S_{21}^{REF}} \left[1 + \frac{\ln S_{21}^{DUT}}{\ln S_{21}^{REF}} \right], \quad (1)$$

where Z_c is the characteristic impedance of the Transverse Electro-Magnetic (TEM) coaxial line (DUT and stretched wire). The S_{21}^{DUT} is the transmission scattering parameter of the DUT (e.g. with the stretched wire inside). The S_{21}^{REF} is the reference transmission scattering parameter referring to the case in which the impedance source is removed (i.e. using a straight beam-pipe with the stretched wire). The

* chiara.antuono@cern.ch

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC53

introduction of the stretched metallic wire along the device modifies the EM boundary conditions of the original DUT. This allows the propagation of TEM modes with zero cut-off frequency, resulting in the undesired detuning of the DUT resonant frequencies and the introduction of additional losses. This phenomenon is particularly evident below the cut-off frequency of the beam pipe, as demonstrated in [5]. Consequently, the method provides inaccurate results for resonant structures within this frequency range.

The Bead-pull Method

For resonant structures, an alternative technique is the bead-pull method, as described in [3,4,9]. This method relies on a perturbation introduced by a small object that samples the field in the cavity, which can be correlated with the change in resonant frequency. Furthermore, this frequency shift can be linked to the shunt impedance of the cavity, allowing the reconstruction of the BCI using the resonator model [10]. The relative frequency shift Δf with respect to the intrinsic resonant frequency f_R can be written as follows [9]:

$$\frac{\Delta f}{f_R} \approx \frac{\int_{\Delta V} \left[\mu_r \mu_0 |\mathbf{H_0}|^2 - \epsilon_r \epsilon_0 |\mathbf{E_0}|^2\right] dV}{\int_{V_0} (\mu_r \mu_0 |\mathbf{H_0}|^2 + \epsilon_r \epsilon_0 |\mathbf{E_0}|^2) dV}, \quad (2)$$

where, the first integration is over the volume ΔV of the perturbing bead, and the second is over the volume V_0 of the unperturbed cavity. $\mathbf{E_0}$ and $\mathbf{H_0}$ represent the fields of the unperturbed cavity. The constants μ_r and ϵ_r are the relative magnetic permeability and electric permittivity of the bead material, respectively. The method requires exciting the appropriate beam impedance resonances of the DUT, particularly the Transverse-Magnetic (TM) resonances. This can be achieved using a coaxial probe setup, as depicted in Fig. 2 [9].

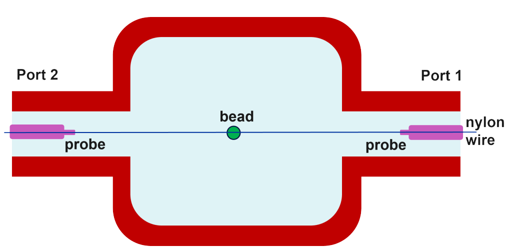


Figure 2: Schematic of the Bead-pull Method setup.

From the frequency shift one can compute the shunt impedance R_S through the following equation [4]:

$$R_S = \frac{Q_0}{4\pi f_R k_{SL}} \left(\int_0^D \sqrt{\frac{\Delta f(z)}{f_R}} dz \right)^2 , \quad (3)$$

where D is the length of the cavity, Q_0 is the unloaded quality factor of the cavity and k_{SL} is the calibration constant of the bead, dependent only on the geometry and the material of the bead. Nonetheless, calibrating the bead involves numerous simulations [4] or measurements on a reference cavity [3]. Furthermore, employing this approach requires the use of a pulling system which may not be convenient or straightforward to implement, particularly in the framework of a portable general-purpose setup.

THE NEW WIRELESS METHOD

Over the years the attention has increasingly shifted towards the development of a Wireless Method to address the aforementioned limitations. In this section, we delve into the concept, its implementation in real bench measurements and the corresponding results when applied to a pillbox cavity.

The Idea and Concept

The Wireless Method aims to address the constraints of the existing approaches by providing a technique that does not require the modification of boundary conditions. The main concept revolves around exciting the DUT using a TM wave. This approach links the BCI, related to the energy loss of the electromagnetic wave propagating in the structure, to the transmission scattering parameter of the TM mode. The relationship has been thoroughly explored and validated both analytically and through simulations for resistive wall beam chambers in previous works [6, 7].

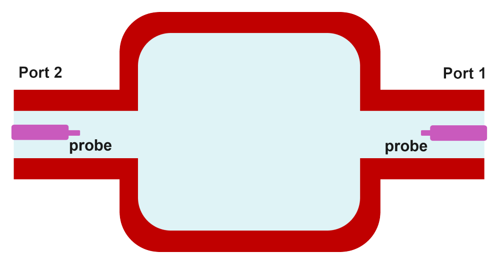


Figure 3: Schematic of the Wireless Method setup.

For resonant structures, a similar approach has proven effective in virtual measurements, as detailed in [8]. Here, the TM mode is excited employing a coaxial probe setup placed on the beam axis of the DUT, as shown in Fig. 3. Afterwards, the transmission scattering parameter $S_{21(12)}$ can be linked to the BCI using the following equation, similarly to the resonant Wire Method in [11]:

$$Z = -\frac{Z_{TM}}{2\pi} \left(1 - \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right), \quad (4)$$

where Z_{TM} is the TM mode impedance (which can be analytically computed or directly measured), S_{21}^{DUT} refers to the 2-Port DUT, while the S_{21}^{REF} refers to the corresponding reference structure without the impedance source (e.g. a smooth reference beam pipe). However, the excitation of the probe acts as an external coupling circuit, which could potentially perturb the DUT, if its coupling contribution is not adequately controlled and accounted for. Therefore, controlling the probe penetration is crucial to mantain a good signal to noise ratio while avoiding perturbations of the actual DUT resonances. This can be be addressed by also considering

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC53

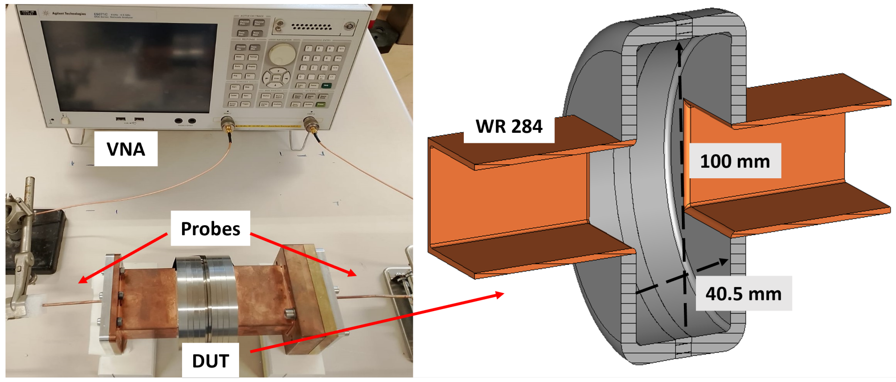


Figure 4: Bench measurement setup for the wireless method. The DUT is a pillbox cavity. Two coaxial probes with straight pin (electric probe) are placed on the longitudinal axis of the DUT (i.e. the beam-axis). The probes are connected to the input port of a Vector Network Analyzer (VNA) able to measure scattering parameters.

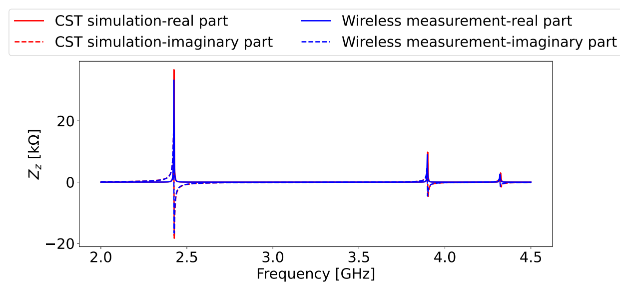
the reflection scattering parameters, employing a standard technique commonly used in radio-frequency measurements, as explained in [9].

The Bench Measurements for a Pillbox Cavity: Experimental Results

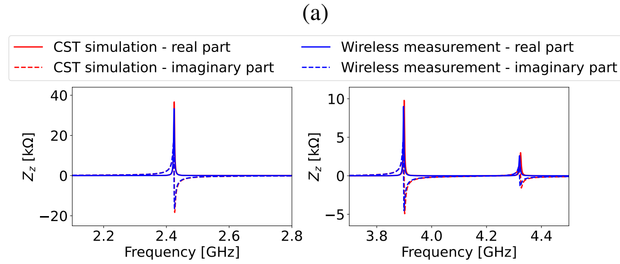
The bench measurements with the Wireless Method are conducted using the setup shown in Fig. 4. The longitudinal BCI expected for the pillbox cavity shown in Fig. 4 is computed with the Wake Field (WF) solver of CST Studio Suite® [12] and the results are compared with the measured impedance obtained by applying the proposed method in Fig. 5. The agreement between the Wireless Method and the expected values is highly promising, underlining the advantage compared to the standard stretched WM, as discussed and demonstrated in [8]. Specifically, the Wireless Method provides a good determination of the resonant frequency and the quality factor, as summarized in Table 1. Furthermore, the real and imaginary part of the impedance are also obtained with good accuracy for most of the resonances, the relative error remaining always below 10%.

Table 1: Resonant frequencies, quality factors, and shunt impedance of the pillbox cavity in Fig. 4: comparison between measured and expected data.

(a) Measured			(b) Expected		
f_r [GHz]	Q	R_s [kΩ]	f_r [GHz]	Q	R_s [kΩ]
2.424	770	36.7	2.425	750	33.3
3.900	1050	9.0	3.897	1073	9.8
4.320	780	2.7	4.324	830	3.0



(a)



(b)

Figure 5: Longitudinal impedance spectrum: comparison between bench measurements data with the Wireless Method (blue curves) and CST simulations (red curves). Figure 5a is the impedance spectrum below the beam pipe cut-off frequency, Fig. 5b is a zoom on some specific resonances.

CONCLUSION

A Wireless Method to compute the longitudinal beam coupling impedance of a resonant structure using the TM wave excitation of the DUT is presented. A real bench measurement setup is implemented, exploiting the coaxial probe as the TM excitation. The setup allows for a direct determination of frequencies and quality factors of the impedance resonances from the scattering parameters, offering clear advantages over the standard stretched Wire Method. Moreover, from these raw data, the shunt impedance is inferred using the wireless formula, facilitating the reconstruction of the beam coupling impedance spectrum in the frequency range of interest. The results demonstrate a preliminary proof-of-concept of the Wireless Method, demonstrating good agreement with expected values and highlighting its advantages over the wire method. Further testing on more complex structures is currently underway, aiming to validate and refine the methodology.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC53

REFERENCES

[1] A.W. Chao, *Physics of collective beam instabilities in high energy accelerators*, New York: Wiley, 1993.

[2] V.G. Vaccaro, "Coupling impedance measurements: an improved wire method", INFN, Rep. INFN/TC-94/023, pp. 1049–1052, 1994.

[3] A. Mostacci, L. Palumbo, B. Spataro, F. Caspers, *RF coupling impedance measurements versus simulations*, in *First CARE-HHH-APD Workshop on Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons*, CERN, Geneva, Nov. 2004, pp. 175-182.

[4] D.M.F. El Dali, G. De Michele, S. Fanella, E. Métral, and C. Zannini, "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

[5] 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.

[6] C. Antuono, "Improved simulations in frequency domain of the Beam Coupling Impedance in particle accelerators", Ph.D. Thesis, CERN, Rep. CERN-THESIS-2021-026, 2021.

[7] C. Antuono, M. Migliorati, A. Mostacci, E. Métral, 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

[8] C. Antuono, M. Migliorati, A. Mostacci, and C. Zannini, "A Wireless Method for Beam Coupling Impedance Measurements of the LHC Goniometer", in *Proc. 68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams (HB'23)*, Geneva, Switzerland, Oct. 2023, pp. 407–410. doi:10.18429/JACoW-HB2023-THAFP05

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

[10] L. Palumbo, V.G. Vaccaro, and M. Zobov, *Wake fields and impedance*, LNF/94/041, 1994. doi:10.48550/arXiv.physics/0309023.

[11] H. Hahn and F. Pedersen, *On coaxial wire measurements of the longitudinal coupling impedance*, *BNL Technical Report 50870*, Brookhaven National Lab.(BNL), Upton, United States, April 1978.

[12] Dassault Systèmes, *CST Studio Suite*, https://www.3ds.com/products/simulia/cst-studio-suite