ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK005

MEASURING THE COUPLING IMPEDANCE OF VACUUM COMPONENTS FOR THE APS UPGRADE USING A GOUBAU LINE *

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Abstract

The Planned upgrade of the Advanced Photon Source to a multi-bend achromat (MBA) will increase the x-ray brightness by two to three orders of magnitude. Storing such an intense beam stably inside the narrow gap vacuum chambers requires sophisticated and appropriately designed rf-components that helps to minimize rf-heating and collective instabilities associated with the impedance of these small-aperture vacuum components. As part of this effort, my research focuses on impedance measurement and simulation of various MBA vacuum components. In this paper, we briefly introduce the novel Goubau line (G-line) test fixture for the impedance measurement, and then present our measurement data along with simulations for various vacuum components designed for the APS Upgrade (APS-U).

INTRODUCTION

The proposed APS-U will provide a generational leap in storage ring performance by reducing the emittance of the present APS by a factor of ~100, thereby increasing the brightness and coherent flux by a factor of 100 to 1000. To tightly focus such an intense electron beam requires stronger magnets with narrower gap apertures, which in turn may generate various collective effects due to the interaction of the electron beam with its surroundings. The strength of the interaction to a particular vacuum component is characterized by its coupling impedance. Although the theory of coupling impedance is well-developed and there are various simulation codes to calculate the impedance, rf measurements continue to provide an important verification tool to test the design specifications of manufactured components.

There are two impedance measurement methods: the traditional coaxial wire method [1], and the recently developed Goubau line (G-line) method [2, 3]. Traditional coaxial wire has a long established history, while the G-line method is just evolving, and here we present the first impedance measurements that employ a two-horn G-line setup. The G-line provides easy set up without any specialized matching networks, less perturbation to the device under test (DUT) because of the micron-sized wire, broad-band measurements over a wide frequency range, smooth impedance matching, and quick data acquisition, which makes it superior in many respects to the traditional stretched wire method [2, 4, 5]. This paper will briefly introduce the novel G-line system, and present our first results that use it to evaluate the impedance of critical APS-U vacuum components.

* Work supported by U.S. Department of Energy, Office of Science under the Contract No. DE-AC02 – 06CH11357
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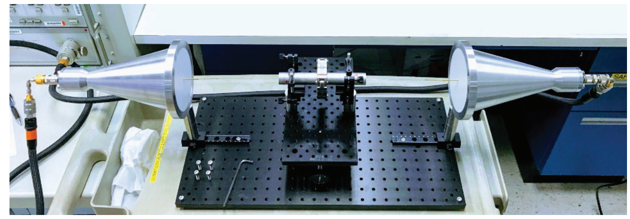

Figure 1: Experimental G-line setup designed at Argonne National Lab to measure the coupling impedance of a vacuum component (device under test) placed in the middle.

GOUBAU LINE (G-LINE)

The G-line is a dielectric-coated single wire transmission line based on the principle of Sommerfeld-like surface waves [6], wherein the interface between the central conductor, a thin dielectric coating, and vacuum serve to propagate electromagnetic waves over long distances. The fundamental TM surface wave mode has a radial electric and azimuthal magnetic field that falls off inversely with distance close to the wire [7], and can therefore represent the Coulomb field of an ultra-relativistic electron. Electromagnetic fields of the fundamental TM mode are excited by a launcher cone or horn, propagate along the single wire through the DUT, and are then received by the receiver cone. The G-line cone has a central brass conductor with prescribed shape that, together with the cone, serves to smoothly match the input coaxial cable impedance to that of the dielectric-coated wire.

The bench setup designed for APS-U impedance measurements consists of two horns (or cones) that have similar dimensions to those described in Goubau's seminal paper [5], as shown in Fig. 1. The cones are made from aluminum with a tapered length of 210 mm and maximum diameter of 130 mm. The launching and receiving cones are symmetric, face each other, and contain central brass tapers that are connected by a thin, 29 American Wire Gauge dielectric-coated wire. The white, circular teflon spacers seen at each horn opening in Fig. 1 position the central brass taper along the horn axis while also damping higher order modes. Each horn is designed to transform the TEM mode of the coaxial cable into the fundamental TM surface wave of the wire.

G-LINE MEASUREMENT PROCEDURE

Each measurement begins by mounting the device under test (DUT) on a standard optics board between the two horns. The magnet wire is then threaded through the central axis of the DUT and soldered to the central brass conductor of both horns. Finally, the DUT is manually centered in the G-line vertically with knobs and horizontally using screws.

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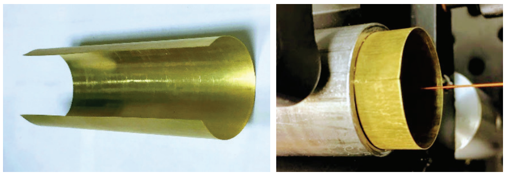


(a) (b)

Figure 2: (a) The brass REF sleeve. (b) Sleeve after its partial insertion into the DUT.

The first step in recording the forward transmission coefficient of a DUT is to make a reference (REF) measurement. This REF is prepared by inserting a thin (0.1 mm) brass sleeve into the DUT. The sleeve is engineered to fit perfectly into the inner circumference of the 22-mm nominal APS-U beam chamber, and to electromagnetically isolate the DUT from the G-line system as shown in Fig. 2. The sleeve is made of brass so that it is flexible enough to make good rf-contact with the DUT while also being easy to insert and remove without disconnecting the central wire or disturbing the experimental set up. The length of the brass sleeve must be less than or equal to that of the DUT to get an accurate measurement without unphysical transmission peaks. After isolating the DUT response with the help of the brass sleeve, we calibrate the Network Analyzer so that the S_{21}-signal becomes completely flat. Then we gently remove the sleeve and measure the normalized S_{21} response of the DUT with respect to the REF structure. We use a single term through transmission calibration for all of our measurements.

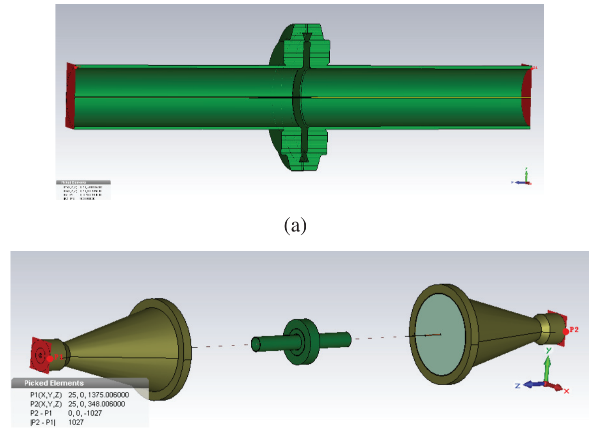
BENCHMARKING OF THE G-LINE

Since the application of the G-line to impedance measurement is new, it is important to verify that system works as designed. Thus, we initially benchmarked the performance of the G-line system by comparing simulations and measurements for a simple cylindrical cavity, 2.54 mm wide and 24.2 mm radius, as the DUT.

Benchmarking from Simulations

The first benchmark we performed was to compare the simulated S_{21}-parameter using an idealized setup to that of the full G-line system. The simulations used the transient solver in CST Microwave Studio [8], while the DUT was chosen to be a pill-box type cavity whose dimensions matched the cavity formed when two flanges are joined together without any rf-gasket. Each flange is attached to a 90 mm stainless steel beam pipe with a 22 mm diameter, so that the total DUT length is about 180 mm. Figure 3 shows the simulation CAD models both with and without the G-line, where the 287 micron central copper wire is coated with 20 mirons of polyimide having a dielectric constant of 3.5.

Figure 4 compares the S_{21}-parameter obtained from simulations of just the cavity (black curve) to that of the full G-line system (red curve). We see that the two methods predict the same position and width of the resonance peak, and



(b)

Figure 3: CAD models to simulate S_{21}-parameter of a 2.54 mm wide pill box type cavity, (a) without the G-line system, and (b) the same cavity in the G-line system.

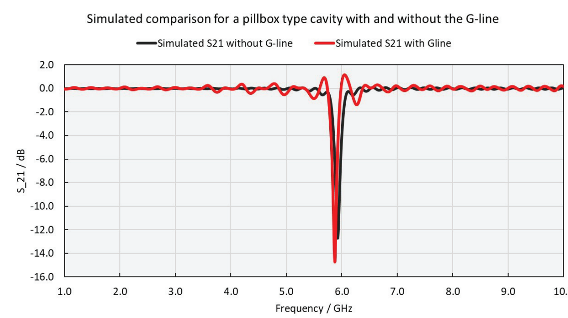


Figure 4: Simulation plot comparing the S_{21}-parameter obtained for a 2.54 mm wide pill box type cavity both with (red) and without (black) the G-line system.

agree reasonably well in terms of the resonance height. From this simulation comparison we can conclude that the novel Goubau line setup is a very effective way to measure the forward transmission coefficient of a cavity-like structure.

Benchmarking from Measurements

To benchmark the experimental G-line setup to the simulations, we formed the same cylindrical cavity by chain clamping two flanges together without any gasket as shown in Fig. 5. We then used the G-line to measure the S_{21}-parameter, which we compare to the simulation in Fig. 6. Here, the black curve represents the simulated response of the cavity from Fig. 4, while the green curve was measured using the G-line.

We have computed the longitudinal impedance from the measured S_{21}-parameter of the benchmark cavity using the lumped impedance formula given by Hahn and Pedersen [9],

$$Z_{\parallel}^{HP}(\omega) = 2Z_c \left(1 - S_{21}^N\right)/S_{21}^N, \qquad (1)$$

where ω is the frequency, S_{21}^N the is normalized transmission coefficient of the DUT, and $Z_c \approx 60\ln(b/a)$ is the characteristic impedance of the REF transmission line of inner radius a and outer radius b.

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Figure 5: Chain clamp along with two flanges to form a cylindrical cavity for the experimental measurements.

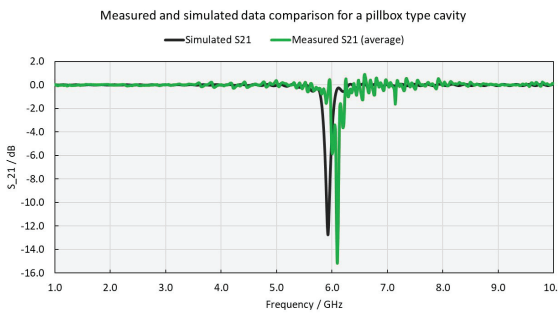


Figure 6: Comparison between the measured (green) and simulated (black) S_{21}-parameter for a pillbox type cavity.

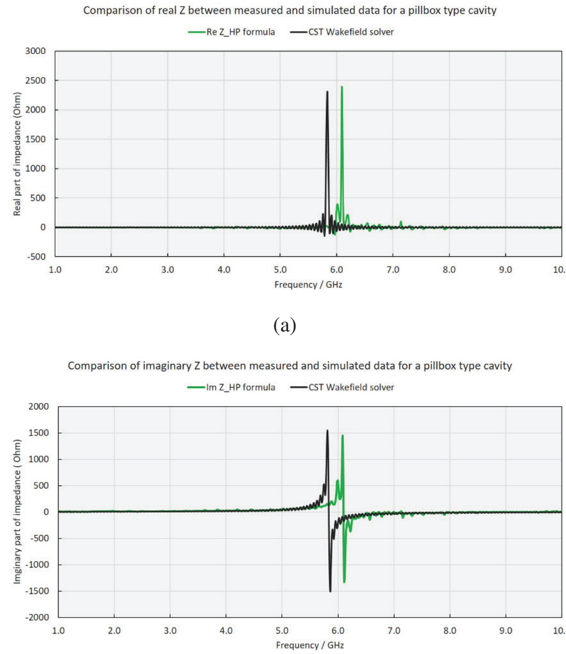
We compare the calculated impedance with the simulated results obtained by using CST Wakefield solver with the wake-length of 5000 mm in Fig. 7. Both the real and imaginary parts of the impedance look very similar, but the resonance position is slightly shifted. To understand this mystery, we varied the cavity radius in our CST simulations and found that the discrepancy in the resonant frequency can be accounted by a cavity that is 0.4 mm smaller.

It is clear from the above benchmarks that the novel Goubau line technique provides a very effective and appropriate way to evaluate the coupling impedance. Indeed, for the ∼1 m distance between cones the G-line losses are negligible and the impedance formula (1) is valid [3, 9].

MEASUREMENT OF A GATE VALVE

An important part of gate valves is their rf-liner, which ideally serves to electromagnetically shield the electron beam from the large opening that houses the gate valve doors. Simulation of the impedance caused by these rf-liners is challenging due to their intricate geometry, and experience has shown that gate valves can get hot. In addition, typical gate valve vendors do not have their own rf-engineers, so the impedance costs and predictions of rf-liners must be verified by the APS using bench measurements.

The measured and simulated transmission coefficient of this gate valve is shown in Fig. 8. The measurements do not show any resonance peaks up to 10 GHz as observed in simulations, and the agreement is quite good. Since the measured response of S_{21}-parameters for the gate valve are within the noise level of our Network Analyzer, we did not calculate the impedance for this component.



(b)

Figure 7: Comparison between measured (green) and simulated (black) impedance for the pillbox type cavity made from joining two flanges, where (a) plots the real part and (b) compares the imaginary part.

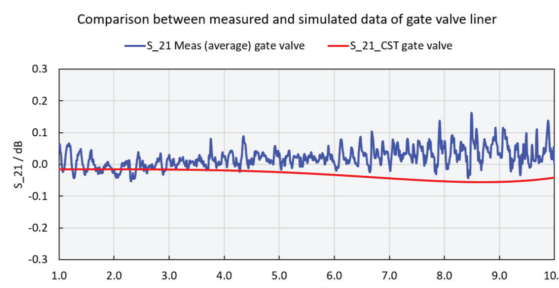


Figure 8: Comparison between the measured (dark blue) and the simulated (red) data for a gate valve liner.

CONCLUSION AND FUTURE WORKS

Our measurements and simulations demonstrate that the G-line bench setup is a relatively simple and yet very effective method to measure the coupling impedance of vacuum components. We plan to soon publish the measurement results of several other components including the BPM-bellows assembly, pumping cross, several flange designs.

ACKNOWLEDGMENT

The authors would like to thank X. Sun for CST help, and B. Stillwell and J. Carter for providing simulation .stl files and for ordering the measurement and test equipment, and finally the US-NSF, the Division of Physics of Beams of the APS, and TRIUMF for IPAC'18 travel support.

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