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# Longitudinal coupling impedance measurements of a bellow at low frequencies

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# RHIC Project
BROOKHAVEN NATIONAL LABORATORY

## RHIC/RF Technical Note No. 12

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## 1.0 Introduction

A bellow similar to the ones to be used in the RHIC interconnects has been measured by applying the wire method. Even though resistive matching networks were used to minimize unwanted reflections, time domain gating was needed to obtain a valid measurement. This note describes the results of the measurements and shows how its proper implementation can lead to excellent results even for very low impedance broadband devices. The simplicity of the geometry makes it a perfect case for testing the method, since the measurements results can be compared to an extremely simple low frequency model.

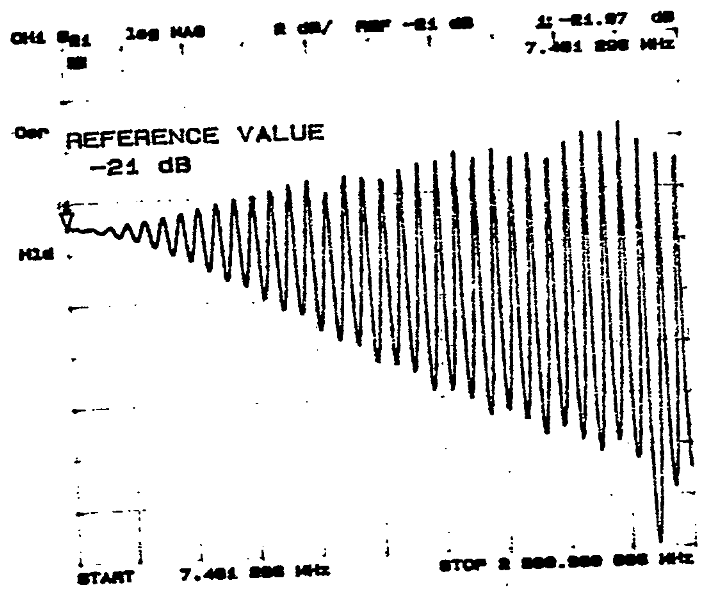
## 2.0 The application of wire method

A set of pipes the same size of the RHIC beampipe have been prepared and equipped with microwave flanges to provide an optimal environment for coupling impedance measurements. They are used in this particular case to measure the broadband behavior of a bellow. The choice of a 1/8" rod as inner conductor is the result of a compromise between setup repeatability and high characteristic impedance. In this particular case, the 2 7/8" ID of the RHIC beampipe and the inner rod combine for $Z_0 = 188\ \Omega$.

An inherent critical step of the method is the design of the transitions from the 50 Ω environment of the network analyzer to the characteristic impedance of the coaxial setup, in this case 188 Ω. Resistive matching is being developed for this particular configuration, in order to maximize the power transmitted through the system and to minimize the reflections due to the discontinuities.

This match allows the use of a simple straight pipe as reference calibration to compare with the device measurement and is acceptable in most of the cases. As is it can be seen in Fig. 1, the match is at present acceptable only at low frequencies whereas the higher part of the band still has reflections that can strongly affect the measurements results.

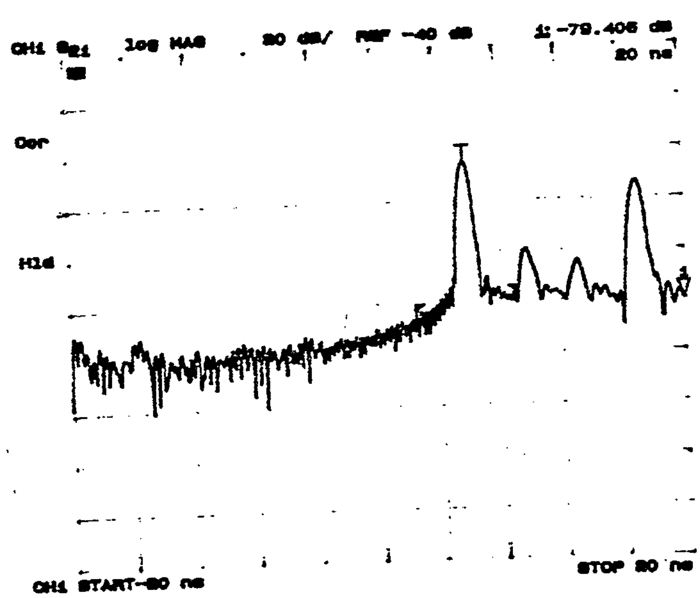
FIGURE 1. . Forward transmission coefficient ($S_{21}$) for the resistive match




# 3.0 Measurement results: the pipe reference

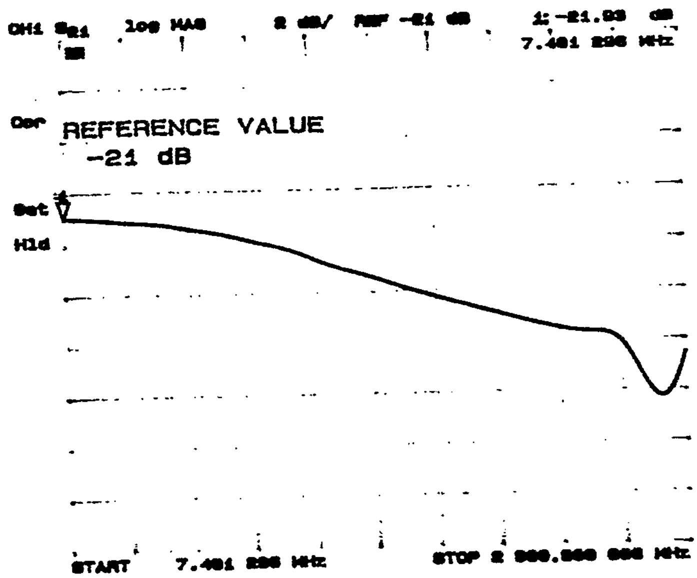
Fig. 1 shows the results of a transmission through a straight pipe. The big ripple is due to the imperfections in the resistive matches, which are still under development. For very broadband devices though it is possible to apply an FFT and gate the clean part of the measurements by nulling the reflections due to the mismatches.

FIGURE 2. The time domain response of the transition from 50 to 188 Ω



This method introduces limits in the bandwidth of the device measured and in its physical size: in some extreme cases the reflections introduced inside the device overlap with the "clean" signal and make it impossible to gate the signal. In this case the more sophisticated TRL calibration is required. Fig 2 shows the time domain picture of the transmission, and the position of the gate later applied. This results in the corrected plot of Fig. 3. The slope is due to the increased losses at higher frequencies in the coaxial line.

**FIGURE 3. The frequency response after gating out reflections**




## 3.1 Measurement results: the prototype bellow

Having taken the transmission through a straight pipe as a reference, the bellow is then measured similarly. Again the time domain gating is crucial.

**FIGURE 4. Bellow coupling impedance after gating**

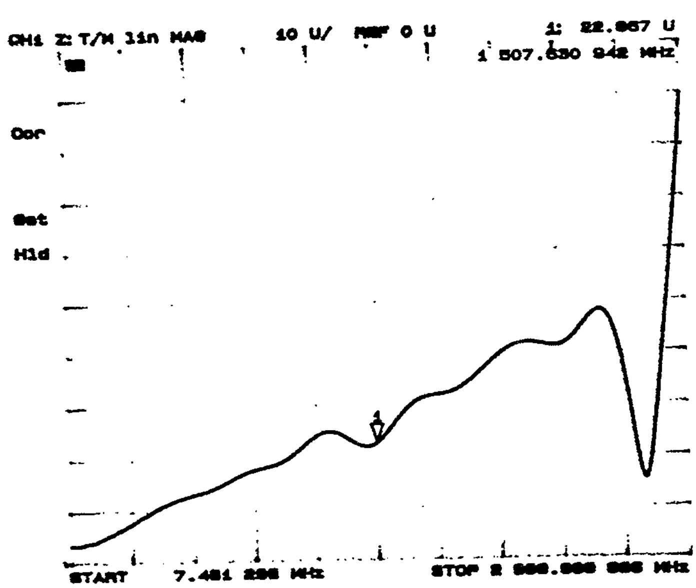
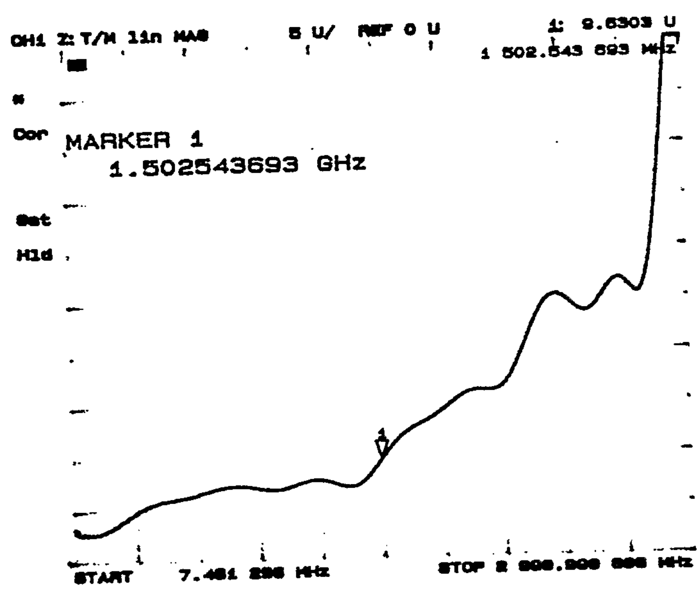


Fig. 4 shows the bellow impedance in ohms as a function of frequency and the inductive part can be easily extrapolated from its slope.

$$L = \frac{Z}{\omega} = \frac{30}{2\pi 1.5 \times 10^9} = 3.2nH$$

in order to verify the measurements and the method, half of the corrugations are covered with copper tape, and the measurement is repeated. Fig. 5 shows the impedance of this configuration. The result is remarkably consistent, as the vertical scale of Fig. 5 is half the scale of Fig 4.

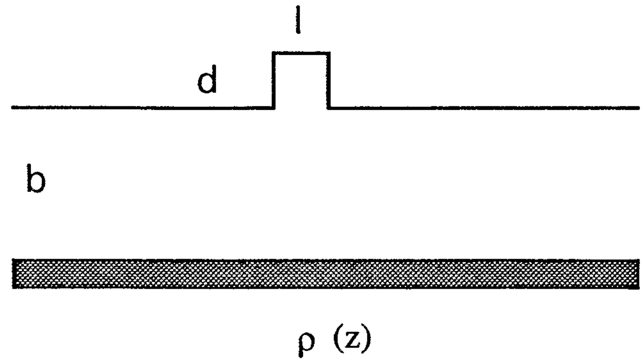
**FIGURE 5. Bellow impedance after gating (half the bellow is covered with conductive tape)**




## 4.0 A simple theoretical verification

The inductive part of a bellow can be approximated by considering the simple geometry of Fig. 6. A beam current density ρ(z) travelling on a pipe of radius b with step of length l

**FIGURE 6. Single corrugation model used**




and depth d will cause a magnetic field inside the so formed "cavity" $B\theta \cong 2\frac{\rho}{b}$ (for d<<b). The magnetic flux associated $\Phi = l\, dB_\theta$ generates a voltage

$$V = \int_{gap} Es \times ds = \frac{1}{c}\dot{\Phi} = i\omega\frac{2ld\rho}{cb}$$

Since $V = -Z_0 J$ and $J = \rho c$, it is possible to calculate the impedance of this geometry to be

$$Z = i\omega Z0\frac{ld}{2\pi cb}$$

where $Z_0 = 377\ \Omega$ and c is the speed of light.

This shows how in the low frequency approximation the impedance is proportional to the volume of the corrugation, and in the present case it is possible to consider the bellow as a series of these corrugations. The inductance of this model is then:

$$L = Z0\frac{0.5dltot''''}{2\pi cb} = 3.3nH$$

where the length $l_{tot}$ is the total length of the measured bellows (in this case d=0.7 cm and $l_{tot}$=17 cm); the numerator has a factor 0.5 to take into account the actual volume of the multiple corrugations.This result is also consistent with TBCI runs by scaling runs previously performed on a similar geometry.

The comparison between the inductance of the bellow measured ion the bench and the approximated calculation is than summarized as follows.

| **Bellow Size** | **Calculated** | **Measured** |
|---|---|---|
| Full | 3.3 nH | 3.2 nH |
| Half | 1.65 nH | 1.6 nH |

## 5.0 Conclusions

The coupling impedance of a bellow is a typical case of a device that because of its simplicity can be computed rather accurately. It is therefore a very valuable test for the wire technique to be used to measure devices that are not simple to analyze. As it is the case for all measurements, the choice of the method and its proper application is the most important task. If in the case of AGS Booster components all the measurements were successfully performed by directly applying resistive matching, in this case time domain gating was needed. This combination has proven itself to be a good compromise between simplicity and performance. Even though the bellow's low frequency behavior has been measured and characterized, the higher frequency performance above pipe cutoff is definitely more critical to identify as the wavelengths became comparable to the sizes of the corrugations and the narrowband impedances start to appear. More work is under way to estimate the measurements errors and the high frequency narrowband impedances of the device.

## 6.0 Acknowledgments

The technical help of Bob Sikora is fundamental throughout the whole setup development, building the very precise microwave connectors and all the hardware used in the measurements. Tom Shea provided support as well as lots of useful suggestions and comments.

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