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The resistively matched transition for measuring the coupling impedance of RHIC devices.

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Abstract

A resistive match has been developed as part of the measurement setup to determine the longitudinal coupling impedance of RHIC devices. Even though various calibration techniques have been implemented the broadband resistive match provides a smooth transition from the 50 Ω impedance of the HP8753C Network Analyzer to the 188 Ω characteristic impedance of the setup and can allow for valid measurements with a simple through reference calibration. The match has been tested for accuracy using both a narrowband quarterwave cavity and a broadband prototype bellow. In both cases an analytical approximation could be used together with a computer model to check the measured results. The errors in the calibrated measurement method have been tested to be less than 10% for frequencies up to 2 GHz.

1. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) is a complex of two storage rings where beams of heavy ions (up to Au) will be collided. One of the common problems in the design of a storage ring is to keep under control the impedance budget [1], since it can effect the longevity of the stores, as well as determine instabilities in various parts of the cycles. In this respect a setup [2] to measure the longitudinal coupling impedance of the devices under prototype or construction has been prepared.

As part of the program various calibration schemes have been developed and implemented, and particular care has been given to the design of the transitions, since they will be permanent part of all measurements. In order to test the validity of the methods, and to estimate the accuracy of the results, both a narrowband quarterwave cavity and a broadband bellow have been used to benchmark the setup: in both cases their impedance can be calculated using the available computer codes and an analytical approximations.

2. THE SETUP AND RESISTIVE MATCH

The setup is based upon the HP8753C Vector Network Analyzer with time domain capabilities. The most critical part of the measurements is the development of an environment that allows for easy calibration without introducing large errors.

A coaxial structure is made by using the 2 7/8" (73 mm) ID beam pipe that will be used in most of the RHIC rings and, as an inner conductor, a 1/8" (3.1 mm) rod. The choice of such rod is the result of a tradeoff between a reliable and repeatable coaxial structure and the need to maximize the characteristic impedance Z_0. Since Z_0 is a log function of the ratio of the radii, it is clear that reducing the inner radius any further will bring the advantage of a higher impedance (which is welcome especially for the measurement of narrowband devices), but at the price of endangering the solidity of the apparatus. The Z_0 of such structure is 188 Ω. The end flanges are the ideal location for the most important task of adapting the 50 Ω characteristic impedance of the network analyzer to the 188 Ω of the wire/beampipe assembly.

One of the most important pictures to judge a good setup is the measurement of the transmission through the apparatus itself: any deviation from a straight line with attenuation is the result of undesired mismatches that sometimes can be higher than the impedance that is being measured. This can cause errors in the measurements as will be discussed later. The through measurement of the setup is shown in Fig. 1.

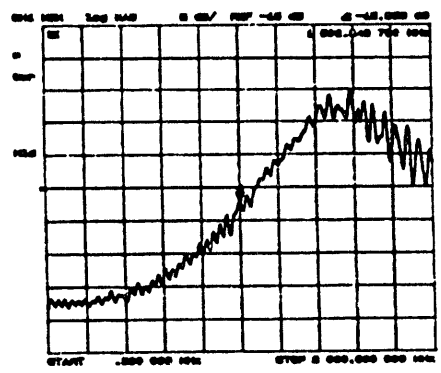

Fig. 1 - Setup through measurement

3. BROADBAND MEASUREMENTS

3.1. Bellow - analytical approximation and computer model

A prototype bellow has been chosen as the ideal device to test the performance of this setup in a broadband environment, since not only various low frequency approximations are known for modeling the longitudinal impedance, but also its simple geometry allows computer simulations and calculations of the same impedance. In the case when the wavelengths are much larger then the pipe radius, the bellow impedance can be approximated by [3]:

$$Z = i \times \omega \times \frac{l \times d}{4 \times \pi \times c \times b}$$

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where Z_0 is the impedance of free space, c is the speed of light, b the pipe radius, d the corrugation depth and l the effective length of all the corrugations ($l \times d/2$ is the total area inside the corrugations). In the case of the prototype used in this test, the inductance is $L = Z/\omega = 3.3$ nH.

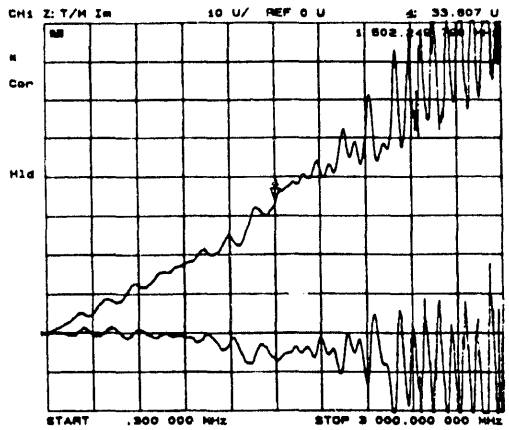

Fig. 2 - Bellow frequency response with resistive match

The time domain solver of the MAFIA codes can also be used to estimate the wake caused by a short bunch traveling through the structure. From this it is possible to calculate the coupling impedance. These simulation show an inductance of 3.2 nH, in good agreement with the analytical approximation [4].

3.2. Bellow - Gated Measurements

Because of the nature of the measurement, the bellow's low impedance signal is of comparable size with the reflected waves. The reflections due to the mismatches remain visible, but the gating capabilities of the HP8753C network analyzer are very successfully used to eliminate the reflected waves. Fig. 2 shows the measured response, and Fig. 3 shows the same measurement after a 7 ns gate is applied to the time domain impulse response obtained with an FFT. The bellow's inductance is determined by the slope of the imaginary part of the impedance (the real part being close to zero shows a good result of the calibration method), and from the picture it is possible to get approximately $Z = 33\ \Omega$ at 1.5 GHz (or $L = 3.50$ nH), in remarkable agreement with the calculated value [5]

3.3. Effects of gating signals

Applying a time gate obviously limits the bandwidth of the measured response to a low Q. Typically, the measurable Q is determined by the setup length, which sets the time length of the maximum gated response as twice the travel time between transitions (this time could be reduced by the reflections due to the device under test). This means that in case of a higher Q, a longer setup must be used to allow for the natural field decay within the gated interval. In such case though, the response signal is likely to be much larger than the noise introduced by the reflections and therefore eliminate the need for a gate. It is simple to show from standard theory that the bandwidth of the measurement is $\Delta f = 2/\tau$, where τ is the delay between the DUT and the transition; practical size limitations set this delay τ to about 6 ns, or in turn, the maximum measurable Q with a gated signal at approximately 3 to 6, depending upon the center frequency of the measurement.

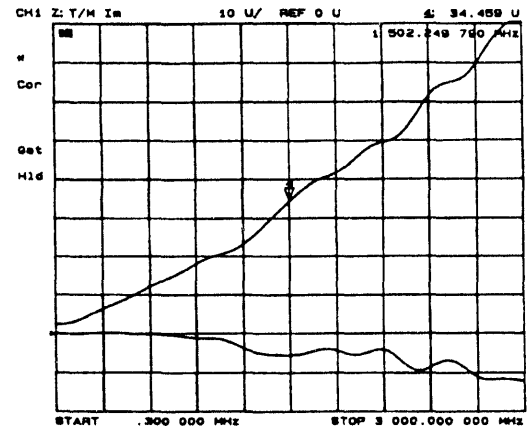

Fig. 3 - Bellow frequency response after gating

4. Narrowband Measurements

A stainless steel quarterwave resonator was built to test the resistively matched setup in a high Q environment. The theoretical resonant frequency and quality factor have been calculated with the code Superfish [6], considering the different losses between copper and stainless steel.

Also a theoretical approximation can be used to calculate the resonator's R/Q:

$$\frac{R}{Q} = \frac{4}{\pi} \times Z_0$$

when the effects of the end capacitance are neglected. The calculated R/Q from Superfish is 25.65, whereas it is 25.50 from a more detailed well known analysis, showing that

Inserted Parallel Res.	Effective Cavity Res.	First Resonance Center Freq. (MHz)	BW (MHz)	Q	R/Q	C (pF)	L (nH)	Z
100	100	152.805	40.623	3.762	26.58160553	39.18336453	27.68625038	26.58160553
250	243	151.087	16.72	9.015	26.95507488	39.0798473	28.39448153	26.95507488
500	475	151.563	8.633	17.557	27.054736	38.81360707	28.40995893	27.054736
1000	887	150.836	4.61	32.719	27.10963049	38.9217083	28.60481147	27.10963049
2500	1843	150.667	2.219	67.89	27.14685521	38.91193529	28.67621871	27.14685521
5000	3100	151.572	1.331	113.91	27.21446756	38.58350483	28.57599487	27.21446756
open	9817	152.442	0.442	345.14	28.44353016	36.7056031	29.69609588	28.44353016

Table 1- Summary of cavity measurements results

the resonators shunt resistance and quality factors are [7]:

$$R = \frac{4 \times \eta \times \left(\ln \frac{b}{a}\right)^2}{\pi^2 \times \delta \times \left[\left(\frac{1}{a}\right) + \left(\frac{1}{b}\right) + \frac{2}{l} \times \left(\ln \frac{b}{a}\right)\right]}$$

and

$$Q = \frac{\frac{2}{\delta} \times \ln\left(\frac{b}{a}\right)}{\left(\frac{1}{a}\right) + \left(\frac{1}{b}\right) + \frac{2}{l} \times \ln\left(\frac{b}{a}\right)}$$

where a and b are the inner and outer diameter, l the cavity length, δ the skin depth and η the free space impedance.

A sliding resistive insert was used to modify the shunt resistance of the resonator thus changing the Q of the structure. The form factor R/Q, which should not be effected by Q changes, was monitored to see how the measurement would vary from the predicted value. Table 1 summarizes the measurements results [9], plotted in Fig. 4.

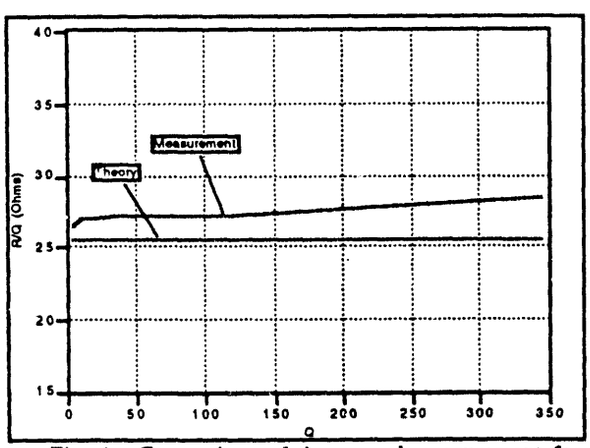

Fig. 4 - Comparison of theory and measurement for the quarterwave cavity

5. ERRORS

The plot of Fig. 4 is a typical example of the errors characteristic of these measurements: systematic errors are dominant, whereas the statistical errors are minimal, thanks to the small effective noise bandwidth of the modern network analyzers. It can also be noted that the 110 dB of dynamic range available on these instruments is allowing good measurements of narrowband devices. As a matter of fact, the highest measured Q is 350, the natural Q of the stainless steel resonator and there is potential for improvements. The slope of the curve in Fig. 4 shows how much higher Q can be measured with acceptable accuracy. It is also to be noted that from Table 1 that inserting the shunt resistors affected the cavity resonance too. This can be explained considering the fact that the resistors have their own capacitance, which was loading the structure. With simple perturbation theory it is possible to see that the expected fractional change in R/Q due to the external resistors is about 1.5%, thus slightly reducing the actual measurement error.

6. CONCLUSIONS

A measurement setup that applies the resistive matching with the wire method has been implemented and its application in the simple through reference calibration has been successfully tested up to 2 GHz by showing a good performance in two well known test cases. It was also possible to estimate the errors to be less than 10% which is acceptable given the status of the current computer codes and models used to predict instabilities. This has been observed for quality factors Q ranging from 1 to 350, the upper limit coming only from the quality factor of the stainless steel resonator.

With such setup it is possible to measure devices such as kickers or position monitors where it is not possible to develop an accurate model for use in computer codes. The front end electronics of the position monitors, for example, couple strongly to the beam and must therefore be accounted for in the measurements. Simple structures with symmetry or without dispersive materials, like bellows or transitions can be determined with the use of the available computer codes within the limits of CPUs and memory size. The good agreement of either method in the 'known' cases is proof of interchangeability of technique and therefore the easiest solution should be the preferred choice.

7. ACKNOWLEDGMENTS

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