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A0 North Cave - SCRF Test Stand
Power Monitor Loss Factor Calibration

The current quality factor (Q) measurement system at the SCRF Test Stand relies upon absolute power measurements to calculate the stored energy within a cavity. It also relies upon ratio-metric measurements between the forward, reflected, and pickup probe power levels to make coupling coefficient calculations. Thus, the calibration of the loss factors associated with the system's power monitoring is critical to measurement accuracy. This report summarizes the results and limitations of the recent loss factor measurements.

A block diagram of the Q measurement system is shown in Figure 1. Node 1 is typically connected to the TWT source which drives the cavity. The power levels of interest are the forward (FWD) and reflected (REF) powers at the cavity detuned short plane at node 11 and the pickup probe power level at node 12. The power levels at these nodes are inferred from power meter measurements at nodes 5, 6, and 8.

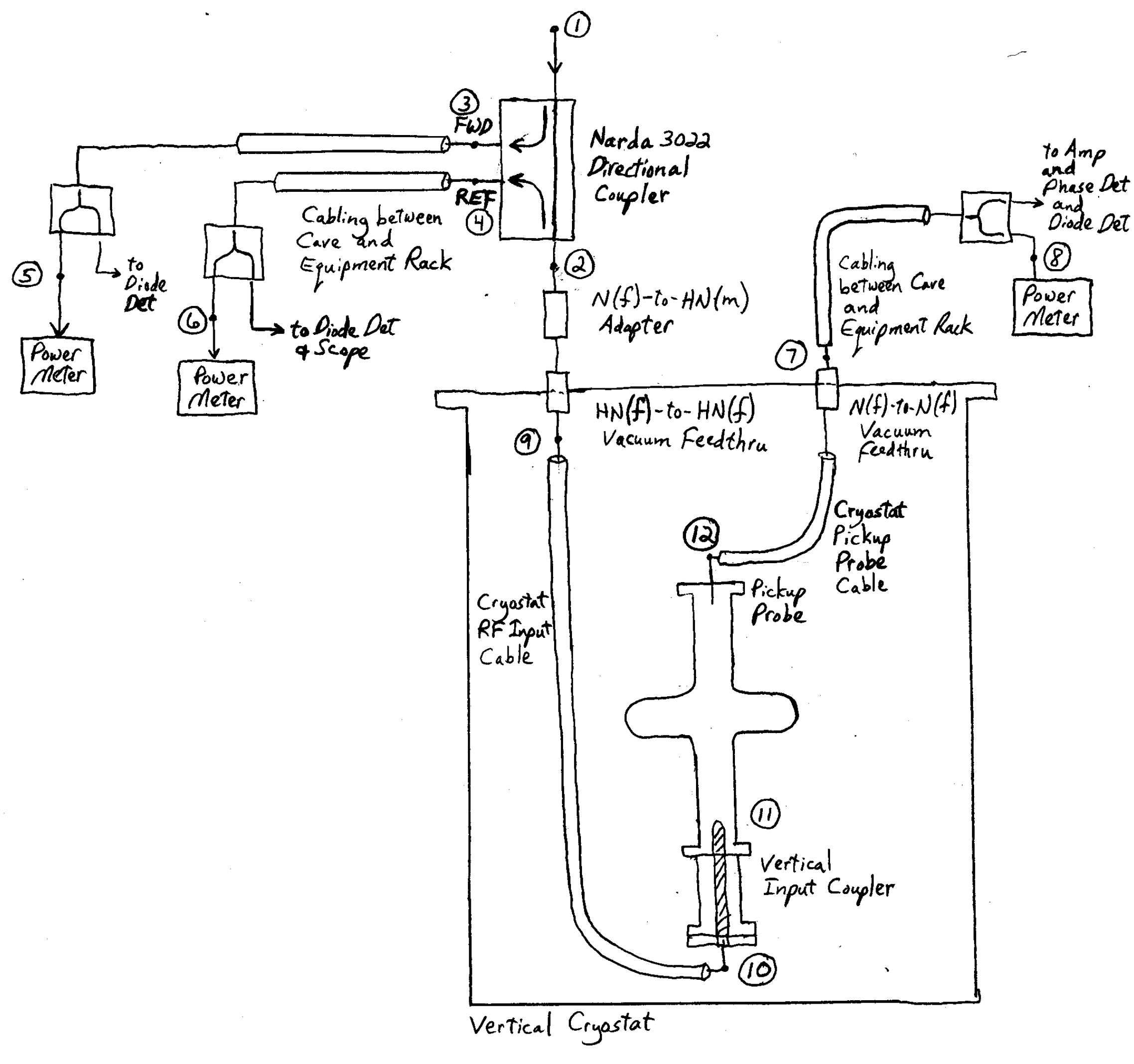

Figure 1: A0 North Cave – SCRF Test Stand – Q Measurement System - Simplified Block Diagram

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Calibration Factor Measurement Summary

FWD Power @ 3.9 GHz		
	Attenuation/Coupling Factor (dB)	**Measurement Uncertainty (dB)**
Coupling from Directional Coupler Input (1) to FWD Power Meter (5) (1) -> (5)	-27.6	+/- 0.4
Directional Coupler Insertion Loss (1) -> (2)	0.13	+/- 0.05
Cryostat RF Input Cable Losses (Including the Vertical Input Coupler) (2) -> (11)	1	+/- 0.4
Total*	**-26.47**	+/- 0.85

REF Power @ 3.9 GHz		
	Attenuation/Coupling Factor (dB)	**Measurement Uncertainty (dB)**
Coupling from Directional Coupler Output (2) to REF Power Meter (6) (2) -> (6)	-27.7	+/- 0.4
Cryostat RF Input Cable Losses (Including the Vertical Input Coupler) (2) -> (11)	-1	+/- 0.4
Total*	**-28.7**	+/- 0.8

Pickup Probe Power @ 3.9 GHz		
	Attenuation/Coupling Factor (dB)	**Measurement Uncertainty (dB)**
Cryostat Pickup Probe Cabling Loss (12) -> (7)	-0.7	+/- 0.3
Cave (7) to Equipment Rack (8) Cabling (7) -> (8)	-7.55	+/- 0.3
Total*	**-8.25**	+/- 0.6

* Be sure to include the attenuation factor of any attenuator that is added to the system

Attenuators @ 3.9 GHz		
	Attenuation/Coupling Factor (dB)	**Measurement Uncertainty (dB)**
6 dB	-7.48	+/- 0.1
10 dB	-10.08	+/- 0.1
20 dB	-19.4	+/- 0.1

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Forward Power Monitor Loss Factor Calibration

Directional Coupler FWD Power Coupling (Node 1 to Node 5) :

A NWA was used to measure the FWD power transmission from node 1 to node 5. A simple Thru response NWA calibration was used on the NWA test port setup which consisted of the NWA test ports and two Times-Microwave strip-flex cables. Due to the large physical distance between nodes 1 and 5, one of the test port cables was approximately 40 feet in length. It was believed that a full 2 port calibration would be more susceptible than a Thru response calibration to variations due to flexing the test port cable. This flexing was unavoidable since the calibration had to be performed between the ports at the NWA outside the cave while the test port cable had to be re-routed to node 1 inside the cave for the measurement. The results of the transmission measurement are shown in figure 2.

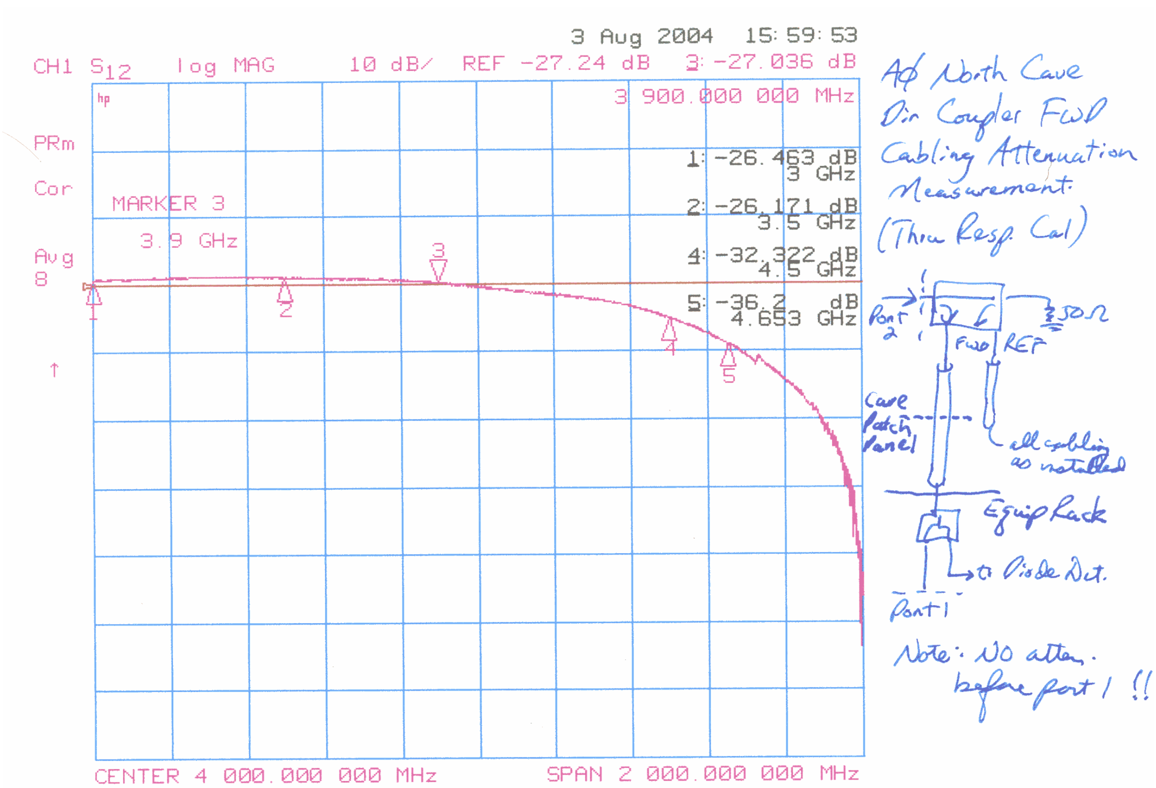

Figure 2: FWD power coupling transmission from node 1 to node 5.

The power level of interest is at node 11. The above measurement is between node 1 and node 5. The calibration must also take into account the loss between nodes 1 and 11. This loss was determined from two separate measurements. One was between nodes 1 and 2 (the directional coupler insertion loss) and the other was between nodes 2 and 11 (Cryostat RF Input Cable Loss). The attenuation factors of these components are of opposite sign to the FWD transmission losses between nodes 1 and 5 since the FWD power at nodes 2 and 11 are lower than the FWD power at node 1.

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Directional Coupler Insertion Loss (Node 1 to Node 2) :

The directional coupler insertion loss was measured on a separate occasion to be **0.13 dB +/- 0.05 dB at 3.9 GHz**. The measurement was performed with a NWA using a full 2-Port calibration.

Cryostat RF Input Cable Loss (Node 2 to Node 11):

The measurement of the RF Input Cables loss is complicated by the fact that the loss is a function of temperature. The temperature during cavity measurements is at low temperatures below 4K. Access to the cable at these temperatures is restricted, thus a simple transmission response is difficult to measure.

Instead, a reflection measurement at Node 2 was used. Assuming that Node 11 is an open circuit (perfect reflection) away from the cavity resonance and that there are no reflections between nodes 2 and 11, a reflection measurement simply gives the round trip losses between nodes 2 and 11. The one-way loss is simply ½ of the round trip losses. This measurement can be taken in-situ at any temperature.

Unfortunately, due to non-ideal connectors between nodes 2 and 9 and at node 10, the reflection measurement suffers from multiple reflections. The worse the VSWR of the connectors, the more pronounced is the evidence of multiple reflections in the reflection measurement. Furthermore, node 11 is not a perfect reflection. Measurement data at both room temperature and 4 K is shown in figure 3.

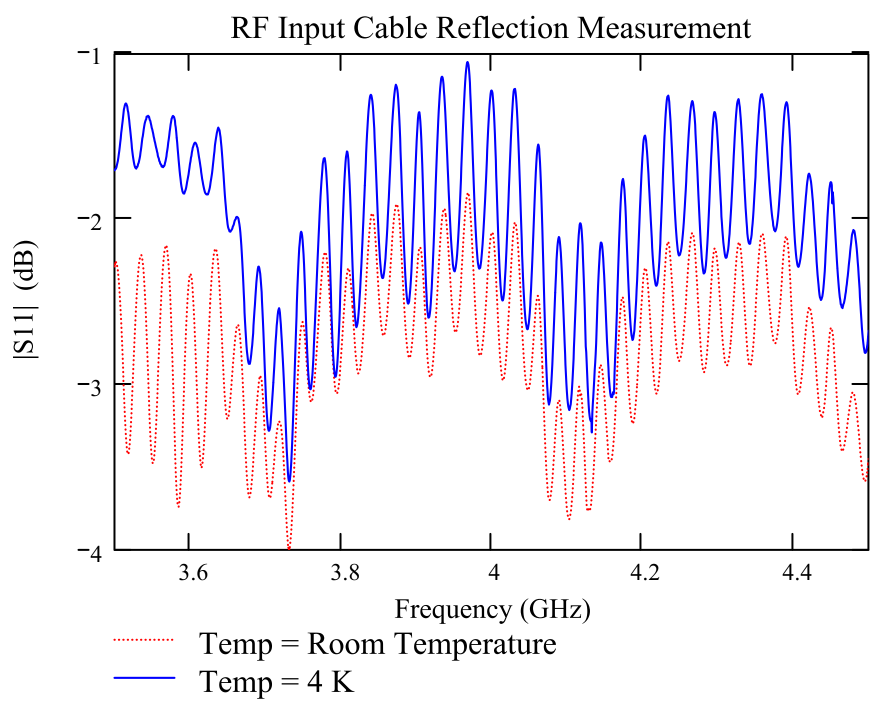

Figure 3: RF Input Cable Reflection Measurements at Room Temperature and at 4 K

Clearly the average of the |S11| is higher at 4 K due to the increased conductivity (reduced losses) at lower temperatures.

To gain an appreciation for how easily the mathematical model for the reflection measurement becomes complicated by the presence of reflective adapters, the equations are presented in figure 4.

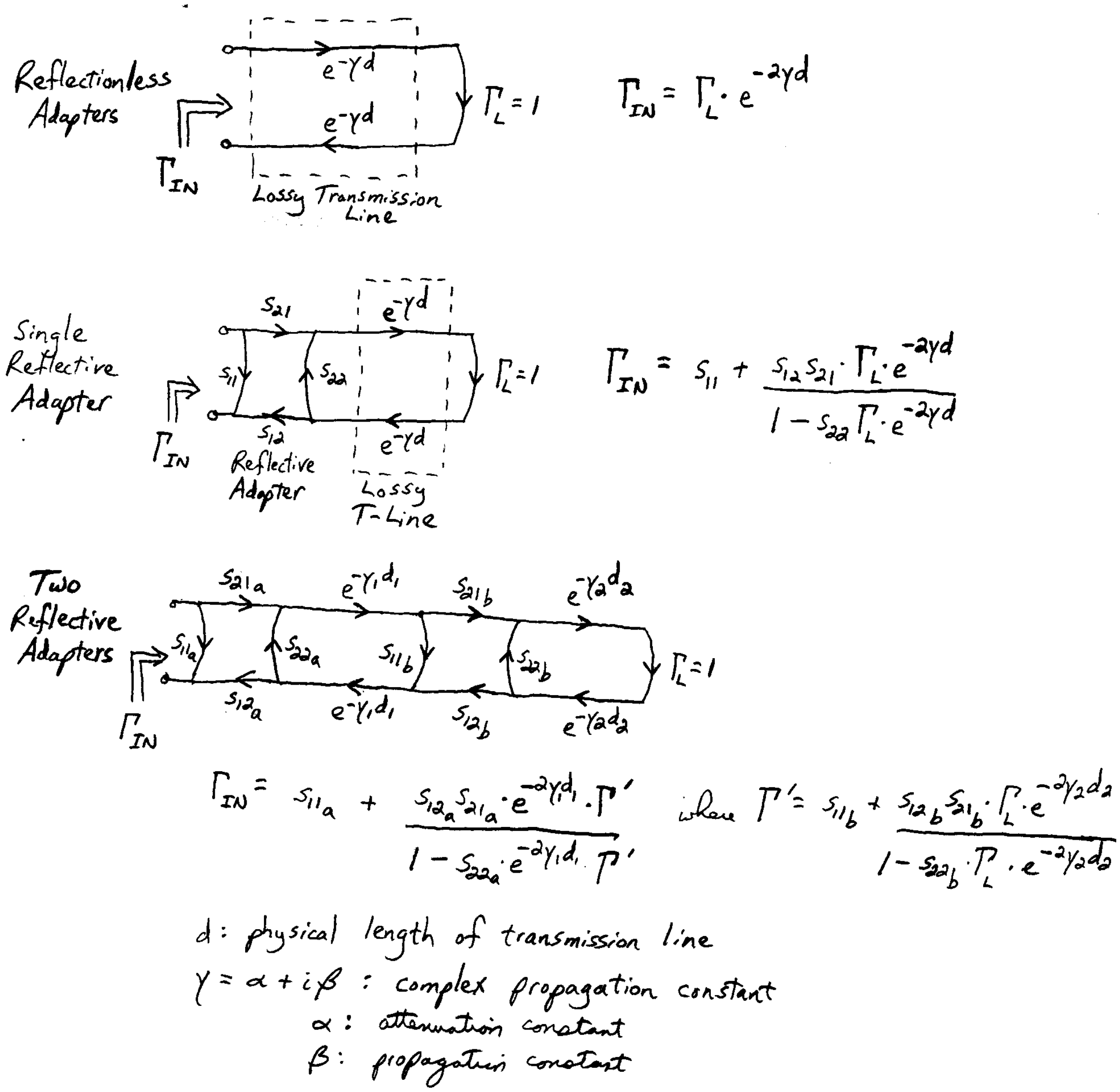

Figure 4: Mathematical model of the Reflection Measurement for various conditions; 1.) with reflection-less adapters (ideal case), 2.) with a single reflective adapter, 3.) with two reflective adapters

In the ideal case of reflection-less adapters, the attenuation of the cable can easily be inferred from the magnitude of the input reflection coefficient. Adding just one reflective adapter at the measurement plane begins to complicate the formula for the measured reflection coefficient. These complications can be minimal if one can assume that the load reflection coefficient is purely reflective, that the reflective adapter is a loss-less, reciprocal network whose s-parameters are not a function of frequency, and that the attenuation constant of the cable is not a function of frequency. With these assumptions the load reflection coefficient is simply unity and there are clear relationships between the connector's s-parameters. Thus it would be relatively straightforward to fit a model to the measured data. Practically, however, the assumption of frequency independence for the s-parameters and the attenuation constant could only be used over a narrow frequency range. Furthermore, the assumption of a purely reflective load does not take into account any radiation losses out of the open circuit end.

If we could make these assumptions the magnitude of the reflection coefficient will be periodic in frequency with a period (in Hertz) equal to the inverse of the round trip propagation delay of the cable. This is true since the expression for a single reflective adapter includes a bilinear transformation followed by a translation. The bilinear transformation transforms the load reflection coefficient on the connector output ($\Gamma_L e^{-2\gamma d}$) to the reflection coefficient at the connector's input. Since, in the complex plane, the load reflection coefficient locus is a circle, the input reflection coefficient locus is also a circle due to the properties of the bilinear transformation.

In the case of two reflective adapters, the formula is more complicated. Typically there will be two periodic fluctuations; one associated with the cable length between the two adapters and the other with the cable length between the second adapter and the reflective load. However, the geometric picture is not as straight forward since the locus of the reflection coefficient on the output of the first adapter ($\Gamma' e^{-2\gamma_1 d_1}$) is no longer a circle but a collection of points from a circle, ($\Gamma' e^{-2\alpha_1}$), each of which is rotated through a frequency dependent angle $e^{-i2\beta_1 d_1}$. Again, under strict assumptions, the data could be fit to a model to extract the one-way attenuation.

Even if the one-way attenuation could be calculated under the strictest of assumptions, the calculation of the losses during actual measurements will be highly dependent upon the standing wave ratios along the line which are a function of the coupling to the cavity.

Clearly, reflective adapters should be avoided in a good Q measurement system.

It is to be noted that a calibration routine does exist for correcting for the directivity of the directional coupler. This routine was developed at DESY by Markus Huening. It is believed that this routine takes advantage of the changing load that the cavity presents during filling. A similar technique might be of use for calibrating out the effects of the input transmission line to the cavity.

The current calibration has assumed that the cable attenuation value lies somewhere in between the extremes of the reflection data. Thus the calibration factors presented here have used the average of the reflection data to calculate the cable losses. From the above data, the average value at 4 K was approximately –2 dB. This would correlate to a **one-way loss of approximately 1 dB**.

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Reflected Power Monitor Loss Factor Calibration

Directional Coupler REF Power Coupling (Node 2 to Node 6) :

Similar to the FWD power calibration, a NWA was used to measure the REF power transmission from node 2 to node 6. Again, a simple Thru response NWA calibration was used. The results of the transmission measurement are shown in figure 5.

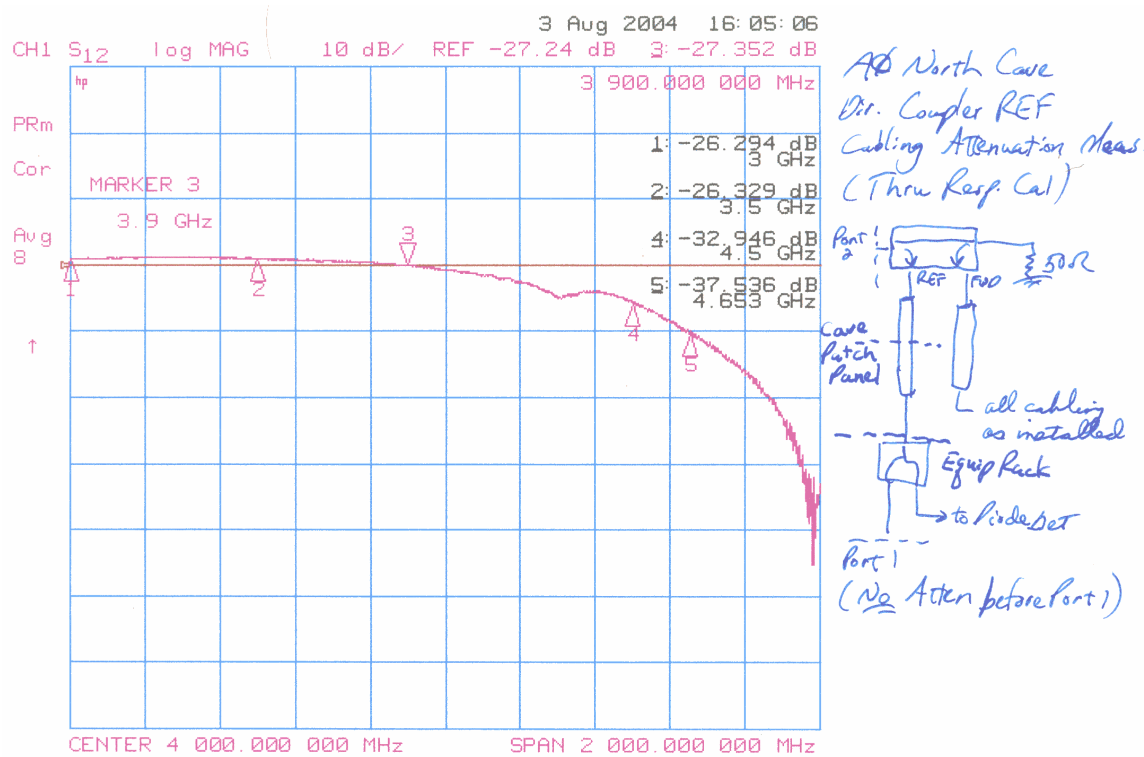

Figure 5: REF power coupling transmission from node 2 to node 6.

The insertion loss of the directional coupler is not used in the REF power calibration because the measurement was taken at node 2 and not at node 1 as in the case of the FWD power transmission calibration measurement.

Cryostat RF Input Cable Loss (Node 2 to Node 11):

The loss between node 2 and node 11 (Cryostat RF Input Cable) is needed for the REF power calibration. The attenuation factor associated with the Cryostat RF Input Cable is the same as that measured using the reflection measurement which was discussed above. However, for the REF power calibration, this attenuation factor should be of the same sign as the REF transmission losses between nodes 2 and 6 since the REF power at node 11 is higher than the REF power at node 2.

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Pickup Probe Power Monitor Loss Factor Calibration

Pickup Probe - Cave to Equipment Rack Cabling (Node 7 to Node 8) :

Similar to the FWD and REF power calibrations, a NWA was used to measure the pickup probe cabling transmission losses from node 7 to node 8. Again, a simple Thru response NWA calibration was used. The results of the transmission measurement are shown in figure 6.

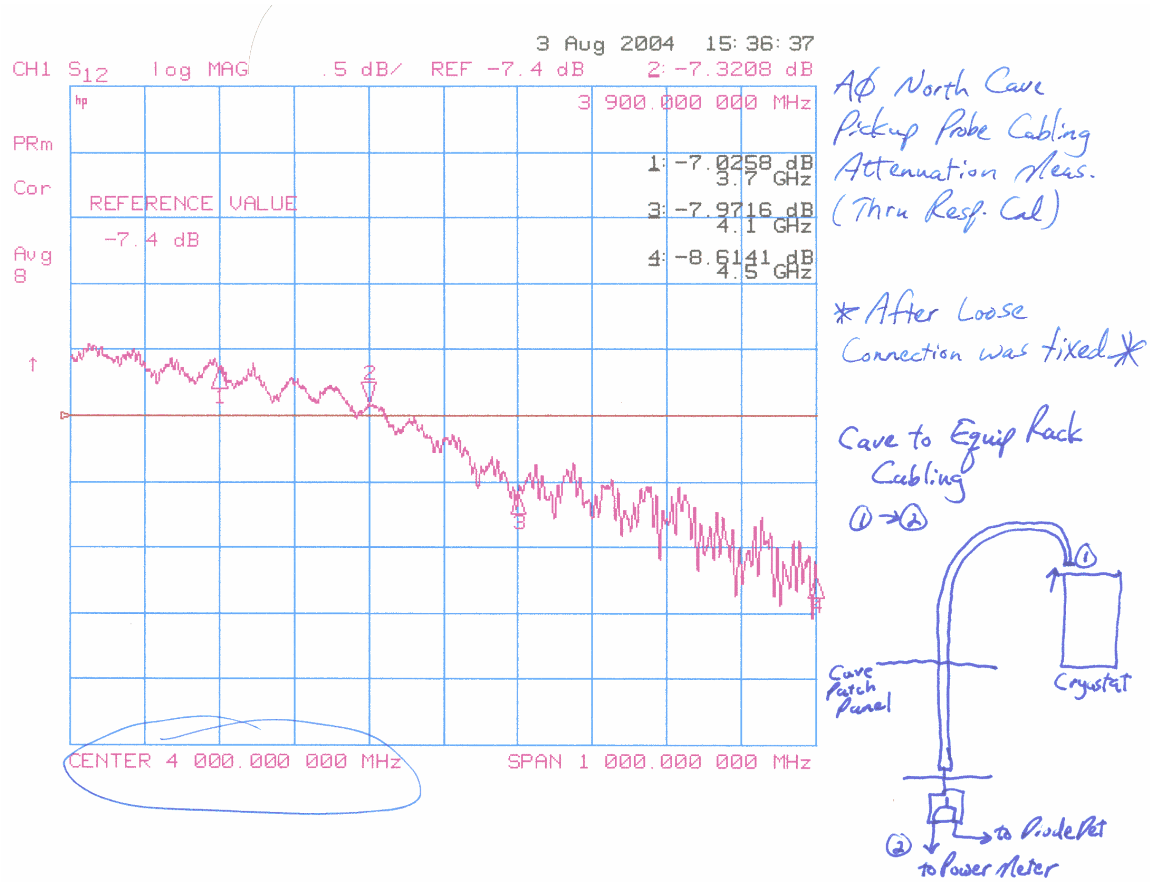

Figure 6: Pickup Probe – Cave to Equipment Rack transmission measurement from node 7 to 8.

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Cryostat Pickup Probe Cable Loss (Node 12 to Node 7):

The Cryostat Pickup Probe Cable loss was determined using a reflection measurement similar to the Cryostat RF Input Cable loss measurement. Again, the losses at a measurement temperature of 4 K are of interest.

The reflection measurements are shown in figure 7 at room temperature and at 4 K. Again, the reflection coefficient magnitude is higher at 4 K due to the reduced losses at colder temperatures. The pickup probe cabling is less complicated than the RF input cabling because there is only 1 reflective adapter between the measurement plane and the open circuit at the pickup probe feedthrough. This is clearly evident in the data. The gradual downward slope in the data is most likely due to frequency dependent losses.

Again, an average value of the reflection data was used to determine the cryostat pickup probe cabling losses. From the data, the average value at 4 K was approximately –1.4 dB around 3.9 GHz. This would correlate to a **one-way loss of approximately 0.7 dB**.

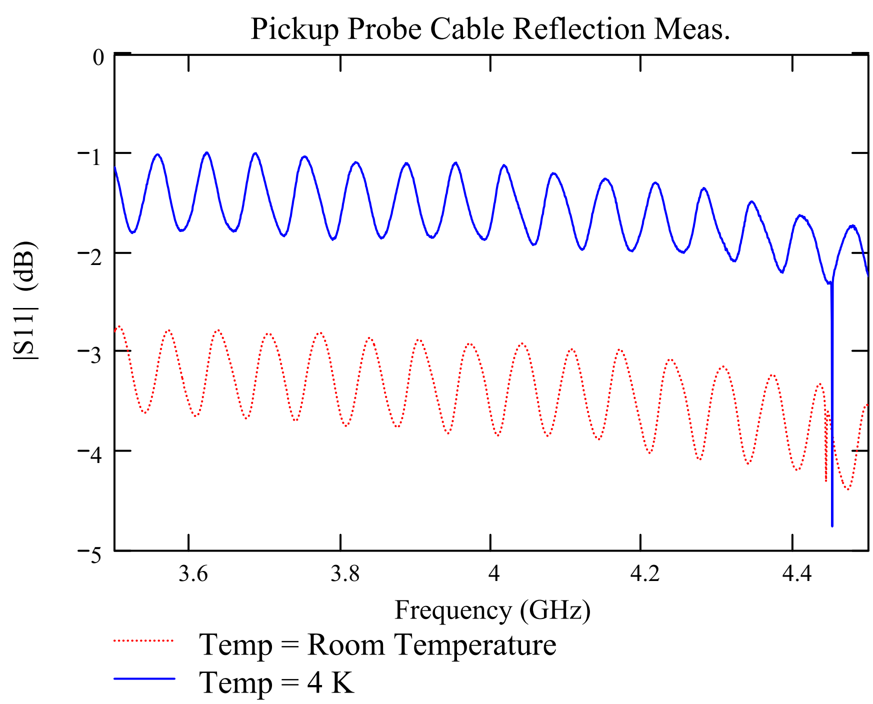

Figure 7: Cryostat Pickup Probe Cabling reflection measurement at Room Temperature and at 4 K

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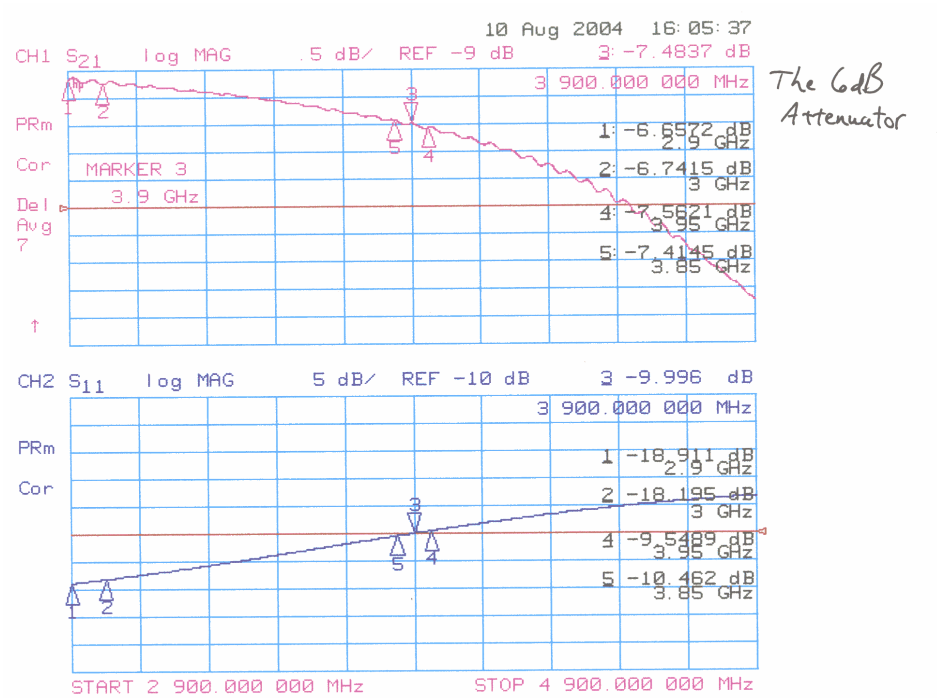
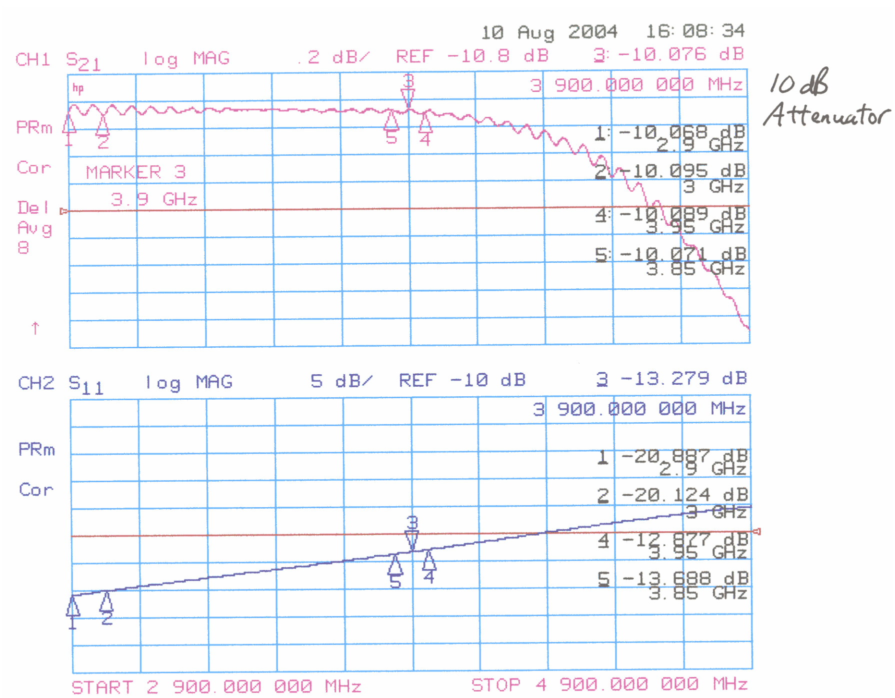
Attenuators

A few of the attenuators which have been used in previous measurements were also characterized. The results are shown below.





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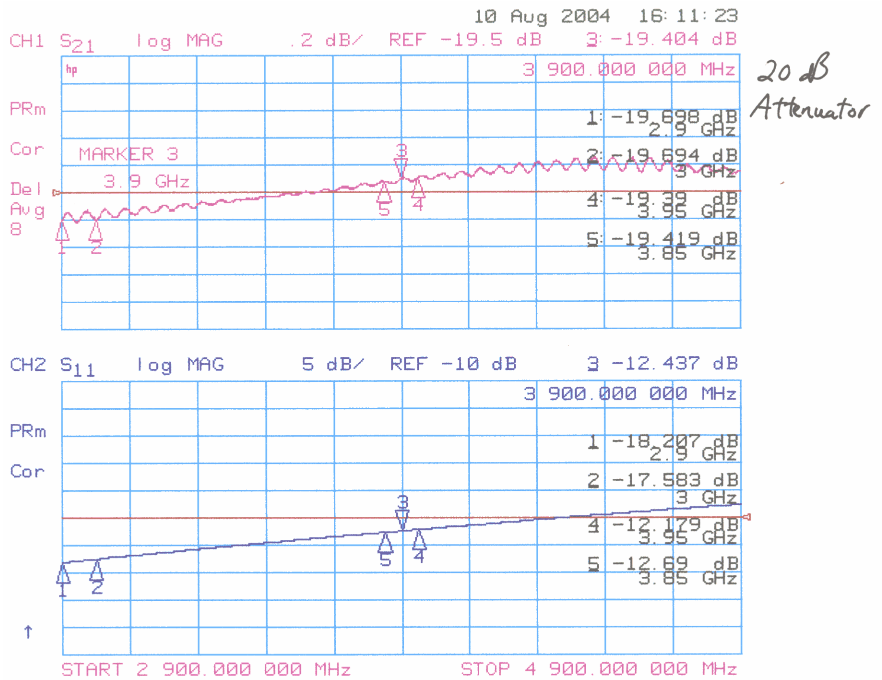

Comments

It is worth noting that during room temperature measurements of the RF input cable, two bad connections were found which could have affected previous measurements. Both connectors on the cryostat heliax cable were found to have intermittent connections which under certain circumstances could produce resonant losses near 3.5 GHz. The connector at the cryostat top plate was improperly assembled onto the heliax cable. It was replaced. The connector at the bottom end was a solderless captivated center conductor connector (Andrews F4PNR-HC) which exhibited intermittent problems. It was replaced with a more robust center contact connector (F4PNR-H).

A problem with the pickup probe cabling was also found. During these measurements a loose connection was found at the cave patch panel. This connection was fixed. However, it is possible that it affected previous measurements. Before the loose connection was fixed, resonant losses as high as an additional 6.5 dB were seen at 3 GHz.

It is extremely important that all connections in the system be solid and reliable. This should be confirmed periodically and after the cabling has been disturbed.

Reflective adapters should be avoided in a good Q measurement system.

A calibration routine for the directivity of the coupler as well as for the input transmission line should be investigated. This will most likely require a vector measurement system at the Test Stand. The current measurement system only monitors the magnitude of the forward and reflected waves.

Finally, the attenuators should be replaced with higher frequency designs. The ones used so far exhibit a relatively high reflection coefficient in the desired frequency range.