RF testing of C100 cavities in the VTA

Document Number: C100R-PR-VTA-CAV-VTRF **Approval Date:** 1 June 2021

Revision Number: R2 **Periodic Review Date:** 14-Jul-2023

Document Owner: C. Wilson

1.0 Purpose and Scope

This procedure describes how to perform the cryogenic RF testing of C100 cavities in the VTA. RF testing limits for the C100R project are gradient administration limit of 27 MV/m, Radiation administrative limit at 1000 mrem/hr, any neutron radiation, power > 100 W, or quench.

The cavity test criteria to pass the test is Eacc >= 20 MV/m with Q >= 8e9 and radiation below 0.03 mrem/hr.

2.0 References

Select the VTA RWP from this list.

3.0 Terms and Definitions

1. **VTA** – Vertical Test Area.
2. **HOM** – High-Order Modes.
3. **VNA** – Vector Network Analyzer
4. **CCG** – Cold Cathode Gauge
5. **PLC** – Programmable Logic Controller
6. **FCC** – Field Control Chassis
7. Forward Power and Incident Power are interchangeable terms, they both mean the power level at the input of the cavity.
8. Field emission and radiation are interchangeable terms.

4.0 Process Details

The requirements for being allowed to perform the cryogenic RF test of a C100 cavities in the VTA are as follows:

- Radiation Worker 1
- Read and signed the VTA Operational Safety Procedure
- Trained on and signed the VTA Radiological Work Permit
- Approval as a "Qualified RF Operator" by the VTA Facility Manager

The cryogenic RF test of C100 cavities in the VTA involves the following steps:

1. Setup and cables calibration
2. Low-field measurements
3. High-power measurements

Each of these steps is described in the following sections.

The following information should be recorded in the VTA RF Test Logbook located by the production RF test system computers:

- Operator name and date
- Dewar number and top plate ID number
- Cavity vacuum pressure measured by the CCG on the top plate, in mbar.
- He pressure in Torr as indicated on the VAT Controller indicator.
- He liquid level in centimeters (see Allen-Bradley PLC screen of the dewar)
- Dewar temperature in Kelvin (convert using table below), the temperature for the high-power cavity RF test is 2.07 K.

Dewar Helium Pressure (Torr)	Dewar Temperature (K)
23.08	1.99
23.77	2.00
24.47	2.01
25.19	2.02
25.92	2.03
26.66	2.04
27.42	2.052
28.20	2.06
28.98	2.07
29.78	2.08
30.60	2.09
31.43	2.10
32.27	2.11
33.13	2.12
34.00	2.13
34.88	2.14
35.78	2.15
36.69	2.16
37.61	2.17
38.55	2.18
39.50	2.19
40.46	2.2

1. Setup and cables calibration

1.1. Finding the frequencies of the TM_{010} passband with a VNA

1. Connect the cable from Port 1 and Port 2 of the VNA to the fundamental power coupler (FPC) feedthrough and the field probe (FP) feedthrough on the dewar top plate, respectively.
2. Measure S21 on the VNA and set the output power to the maximum level (typically 0-10 dBm).
3. Set the IF bandwidth to 300 Hz
4. Set the number of points to a minimum of 1601
5. Set the Span to 2 MHz
6. Set the center frequency to 1497 MHz. A sharp peak corresponding to the π mode resonant frequency should be visible on the screen. If not, increase the span.
7. Set Marker Function -> Marker Search -> Max; Tracking -> On
8. Record the marker frequency
9. Repeat steps 6-8 for the following center frequency values corresponding to the 7 passband resonant modes:

π-mode	1496.7075 MHz
6π/7 mode	1495.4680 MHz
5π/7 mode	1492.0414 MHz
4π/7 mode	1487.1299 MHz
3π/7 mode	1481.7767 MHz
2π/7 mode	1476.9200 MHz
π/7 mode	1473.6405 MHz

10. Set CW Frequency to π mode +/- 50 KHz for cable calibration.

1.2. Cable calibration

1. At the patch panel in the VTA control room, connect the RF cables for the RF system being used to the dewar with the cavity to be tested: Incident Power -> A; Transmitted Power -> B; Incident Power -> C; Reflected Power -> D
2. In the VTA high bay, locate the rack next to Dewar 6. Connect HOM power meter jumper cables to dewar.
3. Locate the RF Production System Rack in the control room. Verify the RF ENABLE ON/OFF is OFF.
4. Set the frequency of the signal generator to the value f=1800 MHz + f0 +/- 50 KHz where f0 is the resonant frequency of the π-mode of the cavity.
5. Run the LabVIEW program named **VTA_main.vi**.
6. A window will appear as shown in figure 1:

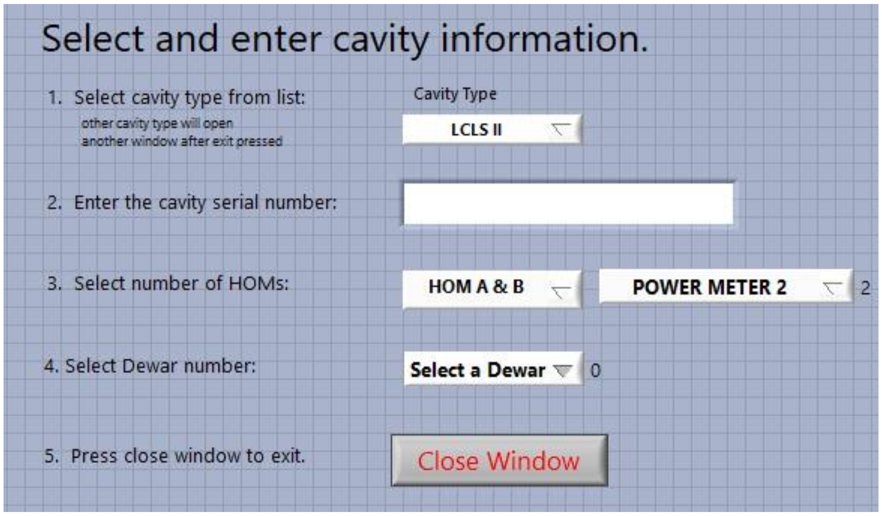


Figure 1:

•Select the cavity type from the list matches and displays the square root (R/Q)/L of the cavity under test.
•The cavity serial number can be determined from the SRF Work Center Plan located here. You will need to log into Pansophy Docushare with a CUE password.
•If HOMs are used, select HOM A & B. If no HOMs are used, select No HOMs.
•When all the information is filled in, press the CLOSE button to continue to the main RF testing screen.

7. In LabView, zero the power meters by clicking the red button labeled Zero Pwr Meters.

8. On the frequency counter, verify the RF is off cavity resonance before continuing.

9. Run the cable calibration program by clicking the red button labeled Calibrate Cables.

10. Refer to Appendix A for complete cable calibration instruction.

2. Low-field measurements

The measurements described in this section should be performed prior to the high-power RF test.

2.1. Preparation for RF testing

With reference to figure 2, follow steps 1 – 3.

1. Assure the flexible tubing is plugged into the pressurized He port at the dewar. Assure valve V1 is closed

2. Open valve V3, then open valve V2. This will purge air out of the small tubing section. After ~15 seconds, close valve V2

3. Open valve V1and adjust V3 such that the pressure measured by gauge G1 is above zero but the poppet relief valve RV is not triggered.
4. This allows He gas to purge the input power RF cable and will prevent a discharge when high-power RF flows through the cable.

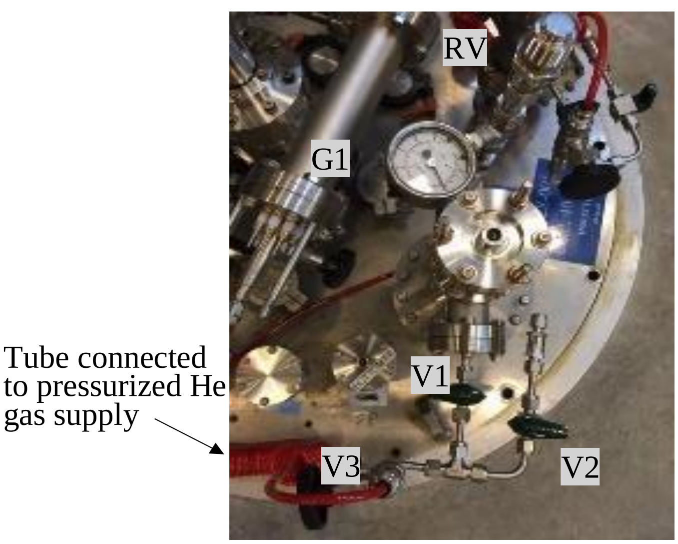


Figure 2. Hardware for He purging of the input power RF cavity on the C100 cavity pair test stand.

5. Close the dewar shield.

6. Notify personnel working in test area that a high power RF test is about to begin. Verify they are wearing a dosimeter, and ask if they are authorized to be in the VTA during high-power RF testing.

7. Post the VTA as a Radiation Area per instructions in RWP.

8. At the PSS Status Chassis:
   - Fill in the log book with date, cavity id, dewar number, dewar temperature and RF Test.
   - Move the key from disable to enable position and press dewar under test grey square icon so it is red.

9. Turn on the high power amplifier located in test area.

10. In the software, set the Attn slide switch to 40 dB.

11. Turn high power RF on by moving the RF switch on the FCC Interface chassis from OFF to ON.

12. Verify the cavity is not locked, by verifying transmitted power meter is reading ~0 W.

2.2. Cable calibration check

The steps described in this subsection can be applied anytime during the high-power RF test to check the consistency of the cable calibration at different power levels.

1. In the LabView cavity test software, select the Live Numbers tab.

2. Set the attenuation slider switch such that the cavity incident power (Pinc) displayed in LabView is ~1 W.

3. Click ‘Measure and Log’ button in the software.

4. Verify the |Ploss/Pincident| ratio displayed in the software is less than 0.003.

   a If it is not, redo the Forward Power Into Detuned Cavity Step in the cable calibration routine at ~1W.
   b Repeat the cable calibration check from step 1.
   c If the ratio is not less than 0.003, turn high power off. Check that cable connections at the dewar are tight and repeat steps 2 – 4. Note that changing cables or tightening connectors may require at least a partial cable calibration.

5. Once |Ploss/Pincident| ratio is less than 0.003, the cable calibration check is complete.

2.3. Initial Cavity Tuning

1. In software, set Q_{ext2} = 1000. (CW mode: Q_{ext2} > 100; Decay mode: Q_{ext2} <= 100)

2. Set the frequency of the signal generator to the value f=1800 MHz + f0 where f0 is the resonant frequency of the π-mode of the cavity.

3. Verify the transmitted power, reflected power and phase error signals are connected to the oscilloscope.

4. Set the SEL Loop to CLOSED on the LabView screen.

5. In the software, switch to the 'live numbers' read back tab. The software will report the most recent power levels.

6. Increase incident power to ~ 1 W. This is done in the software by slowly reducing the attenuator slider switch.

7. Once incident power is ~ 1 W, click on the software button labeled 'Set Mixer Level'.

   Set Mixer Level adjusts the variable attenuator voltage so the transmitted power crystal detector voltage is within its 10 V range. A simple way to check this is to set the oscilloscope channel vertical scale to 1 V/division. Set the zero-level to the bottom line of the oscilloscope screen. When the trace goes beyond the scopes vertical scale, the signal is greater than 10 V.

8. Using the phase knob on the LabView screen, tune the cavity to the center frequency. The Ptran crystal detector trace on the scope will rise several volts above 0V when approaching lock frequency. Press Set Mixer Level if the trace rises above 10V.

9. Press Optimize Phase button to get finer phasing using the FCC.

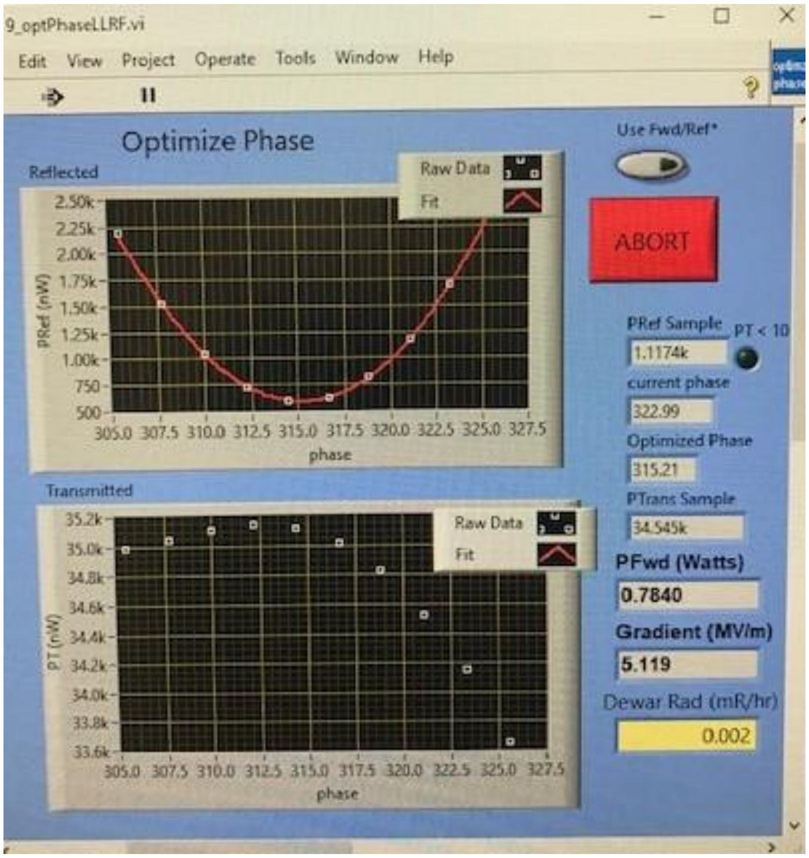


Figure 3. A well phased cavity will have a similar shape as shown in the graphs.

10. Record the cavity lock frequency and the dewar pressure as indicated on the Dewar VAT Controller in the log book.

2.4. Measure cavity coupling

1. In software, set Q_{ext2} = 1 to put the software into the Decay measurement mode.
   CW mode: Q_{ext2} > 100; Decay mode: Q_{ext2} <= 100

2. On the scope, decrease the volts/division for the reflected power signal until the trace reads above zero.

3. Set the horizontal time scale for 2 seconds.

4. Using the RF ON/OFF switch on the chassis, turn RF OFF and watch the Pt power decay on the scope. When it is decayed, turn RF ON. The scope will display a decay shape on reflected power, press the stop/run button on the scope to stop scrolling and freeze the screen.

5. The shape of the reflected power signal during the decay indicates the cavity coupling. An example of the overcoupled, undercoupled and critically coupled cavity pulse shape is shown in figure 4. Note the relative amplitude of reflected power peaks when RF power on vs. RF power off.

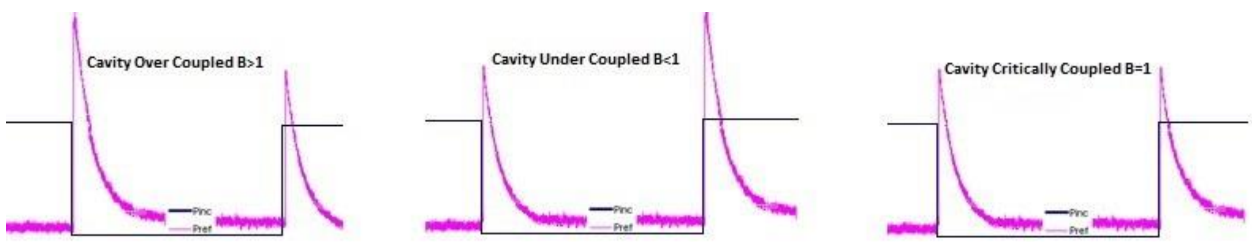


Figure 4. Examples of oscilloscope traces for overcoupled, undercoupled and critically coupled cavities.

6. If the cavity is critically coupled, carefully watch the power meter to determine if the reflected power decays and recovers as shown in figure 5. If it does, the cavity is overcoupled, otherwise it is undercoupled.

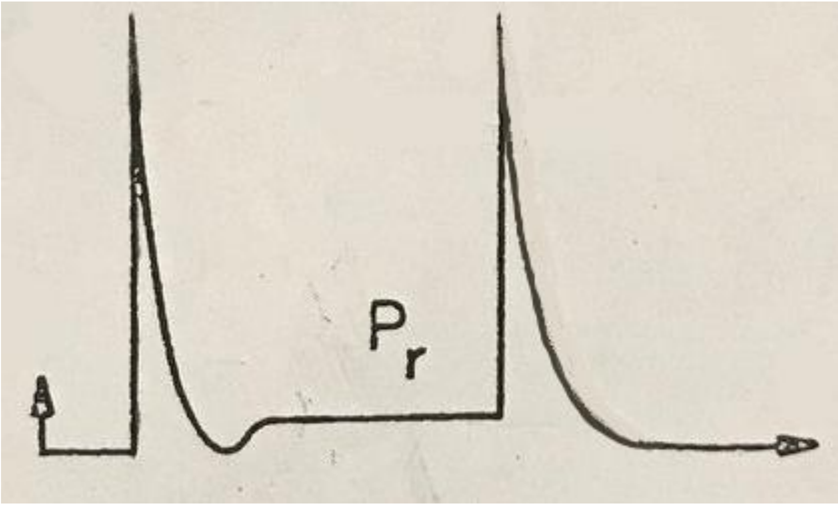


Figure 5. A cavity that is critically coupled will have a transition on the reflected power where it transitions towards 0W and recovers at a slightly higher value. Undercoupled cavities do not have this transition.

7. Record the coupling in the log book.

8. In software, set B switch to B > 1,overcoupled, or B < 1, undercoupled, based on the results of this measurement.

9. Press the stop/run button on the scope to resume scrolling.

2.5. Q_{ext2} measurement and low-field Q_0 measurement

Note: If field emission is greater than 0.03 mR/hr, do not measure Q_{ext2}. It will not be accurate. Steps 1-10 should be followed in order to measure the low-field Q_0 as a function of the He bath temperature.

1. Adjust the attenuation slider so that E_{acc} is between 4 - 6 MV/m. Around 1 - 3 W.
2. In software, click the button labeled Set Mixer Level and then Optimize Phase.
3. In software, set Q_{ext2} = 1. The message below the coupling switch will read Decay Measurement.
4. Press 'Measure & Log'. The RF system will perform a decay measurement.
5. A window will appear which displays the decay curve. Close the window to return to the main VI.
6. Perform at least three decay measurements at the same power level. There should be at least three sets of decay measurements that have similar values, within the E_{acc} range 4 - 6 MV/m.
7. Press the button labeled Click to Update Qext2. Scroll through the decay measurements and select the one which represents the average values measured. This is the Qext2 that will be used in the main VI to calculate gradient.
8. In the logbook, record in table format:

   E_{acc}, Q_0, Q_{ext1}, Q_{ext2}, Q_{ext2} % error, Q_{HOMA}, Q_{HOMB}, Tau and radiation.

3. High-power RF measurements

The test will capture data for Q_0 versus E_{acc}, Radiation versus E_{acc} and frequency versus E_{acc}^2 curves.

1. Starting at 1.5 MV/m, press the buttons labeled Set Mixer Level and then Optimize Phase.

2. Press the button labeled Click to Update Lorentz on the VI.

3. In the left tab labeled Autostep, set the step size to be 0.5 MV/m then, press the button labeled Click to Run Auto Step. The Autostep algorithm will decrement the attenuation slider control such that gradient changes by the value entered in the Step Size control.

4. During the Q vs E measurement, check the following conditions:

   i. Incident power is below 100 W to avoid overheating cables

   ii. Dewar radiation is below 1000 mR/hr

   iii. The cavity is not quenching

   iv. HOM A & B power is below 10W

   If any of the above conditions are not met, turn off high power using the manual switch and turn off Autostep.

5. Record the following information during the initial Q vs E curve measurement:
   - Gradient at onset of field emission, FE onset > 0.03 mR/hr
   - Qo and radiation 20 MV/m
   - Maximum gradient and the associated Qo

6. If there is FE onset, measure Q vs Eacc points at 30 second intervals to ensure the radiation measured is accurate. The radiation monitoring system uses an average over time to determine dose rate.

7. The initial Q vs E curve measurement is complete when the cavity reaches a limit, and RF processing is ineffective. Limits include:
   - Quench
   - Gamma radiation > 1000 mR/hr
   - Any neutron radiation detected
   - Incident power >100W
   - Administrative gradient E > 27 MV/m

8. If the cavity is quench limited below 25 MV/m, measure the unscaled quench fields in the passbands.
   i. Set the RF source to the $6/7\pi$ mode.
   ii. Start at 1 MV/m and increase power until the cavity quenches.
   iii. Verify that HOMA and HOMB power stays below 10 W.
   iv. Record the point just before the quench by pressing the measure and log button in the software and writing the value in the logbook. Repeat for all of the passbands.

9. Repeat Q vs E measurement for a second clean curve. Press the Click to Update Lorentz button before measuring the clean curve.

10. Measure a new Q vs E curve with 1 MV/m steps to the limit. The curve should be a clean static curve similar to the previously measured curve without new processing or activation. Repeat the curve until this requirement is met. Record the following information:
    - Gradient at the onset of field emission.
    - Qo and radiation at 20 MV/m.
    - Qo at maximum gradient.

11. If the Lorentz value is not within the range of range -6 to -4 $Hz/(MV/m)^2$, it is very likely that there is an error in the cable calibration. The cable calibration should be repeated as well as the RF test.

12. When the Q vs E measurements are complete:
    i. Turn off high power RF on the FCC chassis.
    ii. In the software, press 'backup files'. A copy of the log file will be placed on the network at: O:\srfee\LabVIEWData\VTACavityTest. The subfolder is dependent on the frequency of the cavity.
    iii. In the high bay, turn off the high power amplifier.
    iv. At the PSS System panel, press the red dewar square icon. It will turn grey.
    v. If no other test is being performed, turn the key switch to the disable position.
    vi. Open the dewar shield.

13. If no other testing is taking place, unpost the radiation area as per RWP. If another high power RF test is occurring at this time, notify the tester that the C100 cavity test is complete, and that they must unpost the radiation area per the RWP at the conclusion of their testing for the day.

14. Stop purging the input power cable with Helium gas as follows: (**ATTENTION**: if the steps are not followed in the prescribed order, several hundred liters of liquid helium can be contaminated with air!)

    i With reference to Fig. 2, close valves V1 and V3.
    ii Unplug the flexible tubing from the pressurized He gas port at the dewar.

15. Fill out the cavity performance traveler.

Appendix A: Detailed Cable Calibration Steps

The calibration steps can be done in any order. It is advised to do forward power to detuned cavity last.

Step 1. Reflected Power from VTA

A. Verify RF Power off in control room.
B. At the dewar, measure network analyzer power out (cable GH) using power meter. For S21 configuration, measure network analyzer power out at port 1.Record the measured network analyzer power out in logbook.
C. At dewar, connect cable GH to cable AB as shown in figure A1.
D. In cable calibration VI, click button labeled 'Reflected Power From VTA'
E. A pop-up will appear, enter the network analyzer power out (from Step 1.B, above) in the yellow highlighted field. Click Done when finished.
F. Disconnect cable GH from cable AB.

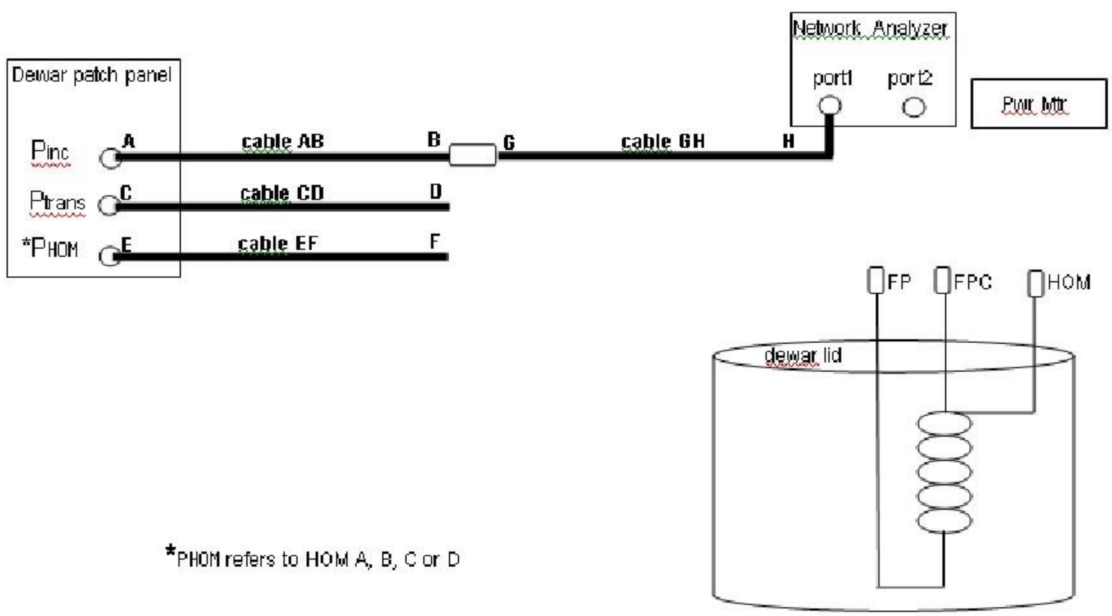


Figure A1. Connect cable AB to cable GH to measure the reflected power from VTA.

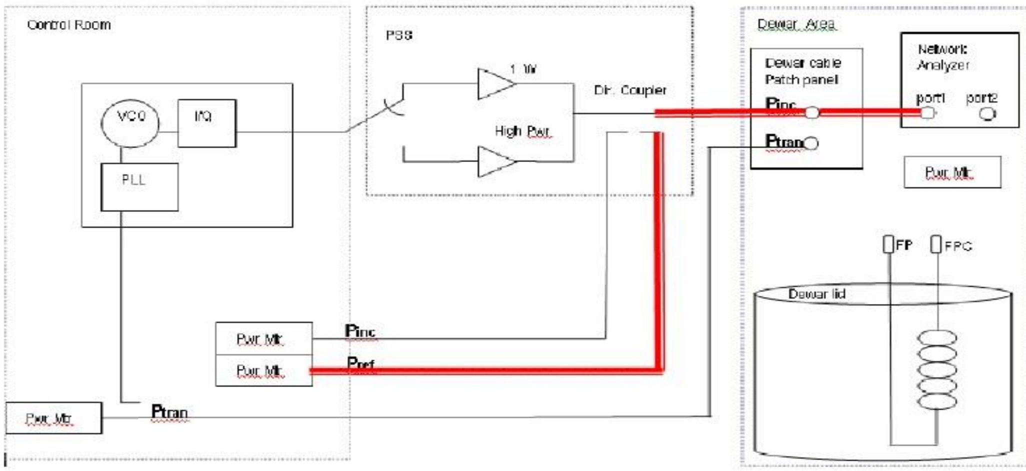


Figure A2. Block diagram representation of 'reflected power from VTA' cable calibration step.

Step 2. Incident power measured at dewar

A. Connect cable AB to power meter cable as shown in Figure A3.
B. Turn RF on in control room. The power comes from a 1 Watt amp when the PSS system is not configured for high power testing.
C. In cable calibration VI, set Atten to 20 dB using slide control.
D. Set frequency of the signal generator so that the frequency measured by the frequency counter is = Pi mode frequency + 50 kHz.
E. At dewar, record measured power on cable AB in the logbook.
F. In cable calibration VI, click button labeled 'Pi measured @ dewar'.
G. A pop-up screen will appear, enter the Pi measured at the dewar from Step 2E, above. Click Done when finished.
H. Turn RF Power off in control room.

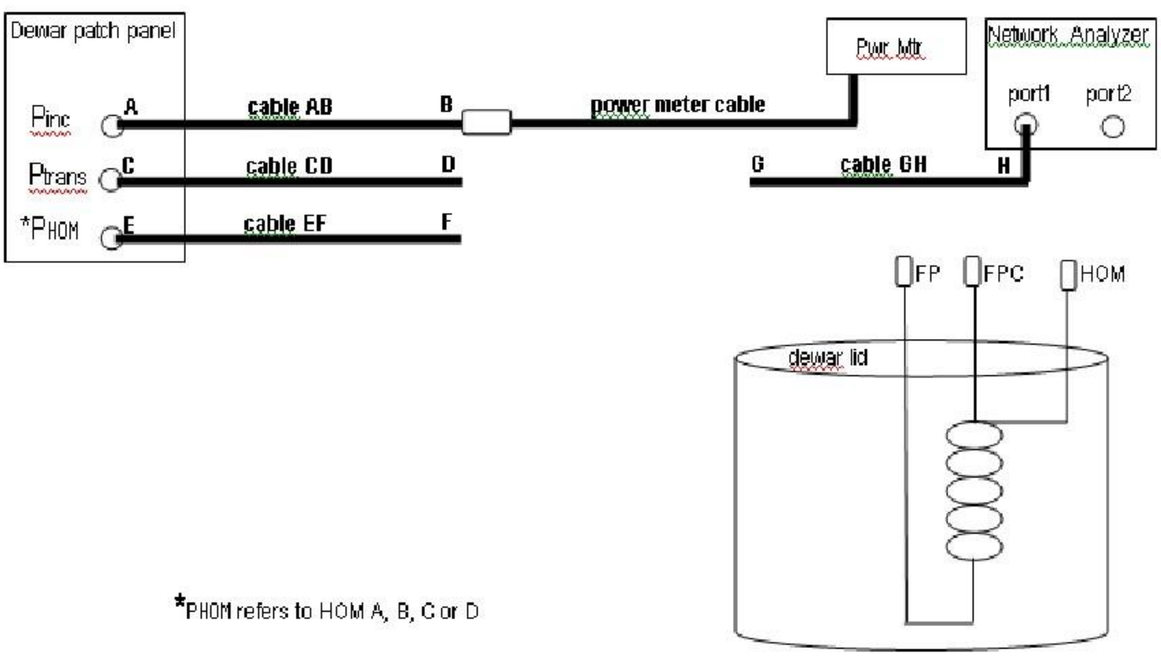


Figure A3. Connect cable AB to cable GH to measure the reflected power from VTA.

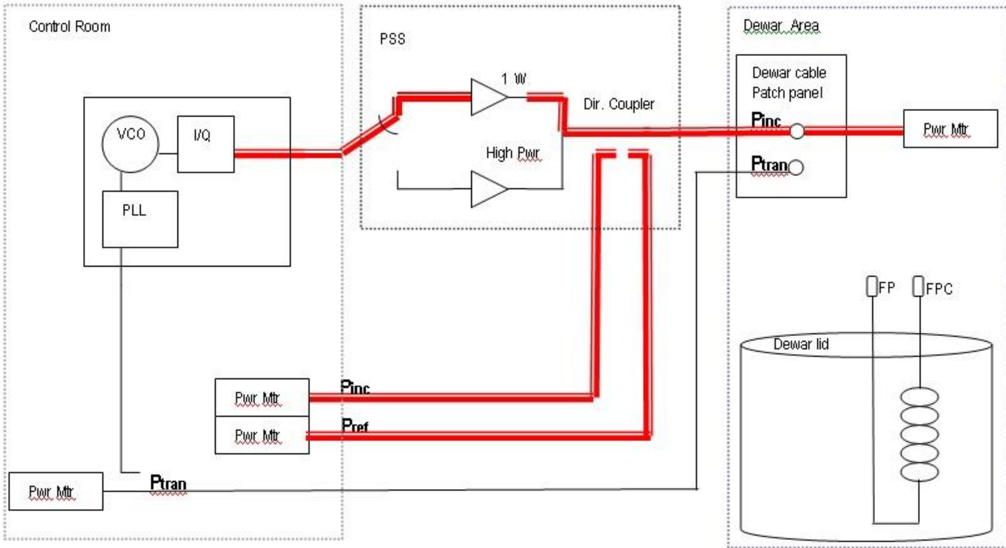


Figure A4. Block diagram representation of 'incident power measured at dewar' cable calibration step.

Step 3. Ptrans, PHOMA and PHOMB to transmitted power meters

A. At dewar, connect cable CD to cable GH as shown in Figure A5.

B. In the cable calibration VI, click button labeled 'Transmitted Power Into Control Room'.

C. A pop-up screen will appear, enter the network analyzer power out measured in step 1B. Click Done when finished.

D. Repeat this step for each HOM cable shown as cable EF in Figure A5.

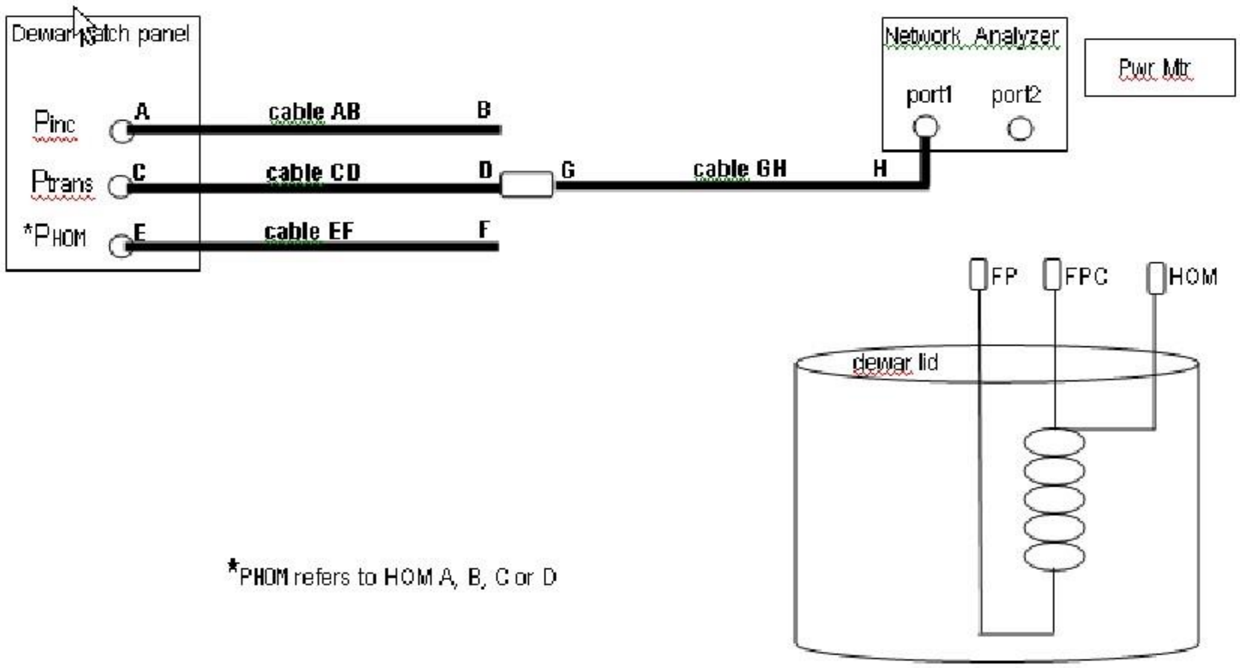


Figure A5. Connect cable CD to cable GH to measure the transmitted power to control room.

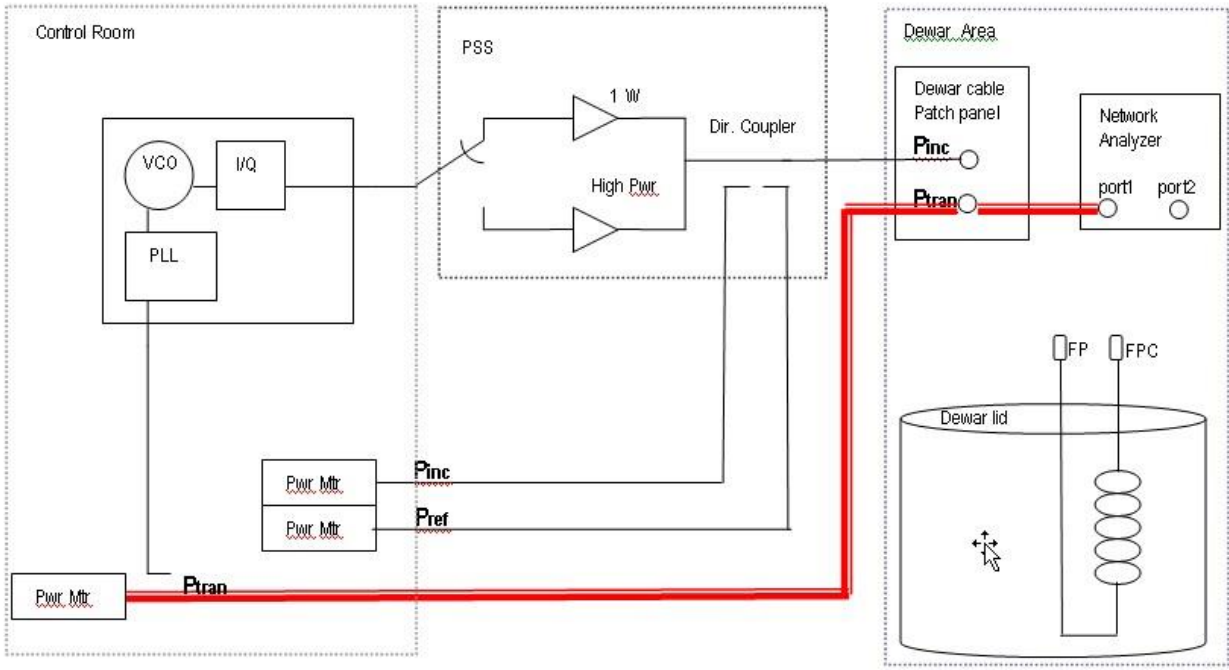
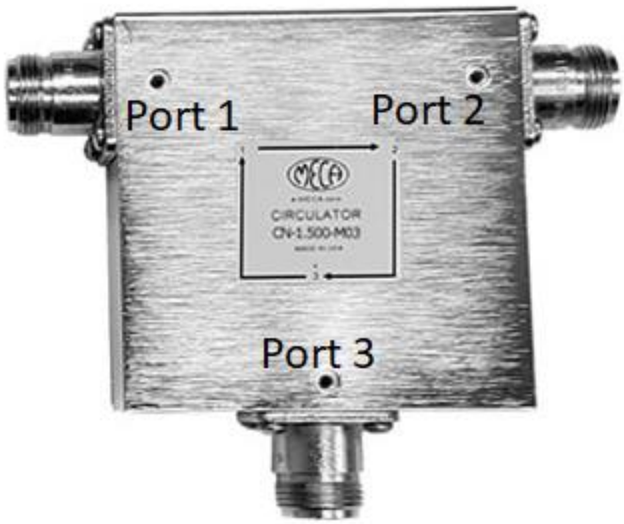


Figure A6. Block diagram representation of 'transmitted power to control room' cable calibration step.

Step 5. Transmitted and HOM Cable Return Loss



A. At dewar, connect circulator ports 1, 2, and 3 as shown in figure A7:

   Port 1: Cable GH, from port 1 of network analyzer

   Port 2: N male to male connector.

   Port 3: Power meter sensor.

B. Place the connected circulator just above the top plate connector and look at the power meter value. Record the measured power in the logbook.
C. Connect port 2 of circulator to top plate field probe (FP) connector.
D. Record the measured power in the logbook.
E. Repeat steps B-D for HOM A and HOM B top plate connectors if instrumented.
F. In cable calibration VI, click button labeled 'Transmitted Cable Return Loss'.
G. A pop-up screen will appear, enter the open (Step 5B) and field probe (Step 5D) power measurements. Click Done when finished.
H. In cable calibration VI, click button labeled 'HOM A Cable Return Loss'.
I. A pop-up screen will appear, enter the open (Step 5B) and HOM A (Step 5D) power measurements. Click Done when finished.
J. In cable calibration VI, click button labeled 'HOM B Cable Return Loss'.
K. A pop-up screen will appear, enter the open (Step 5B) and HOM B (Step 5D) power measurements. Click Done when finished.

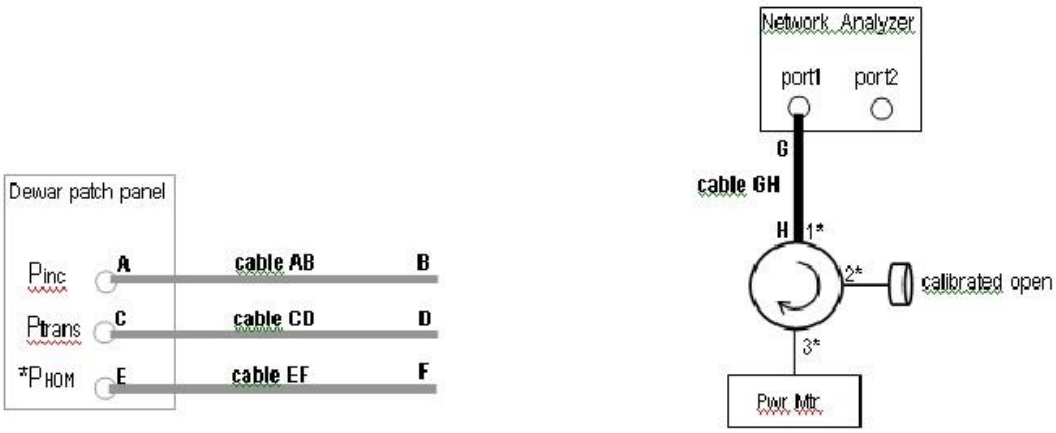


Figure A7. Cable GH, calibrated open and power meter connected to circulator for 'Transmitted Cable Return Loss' open measurement.

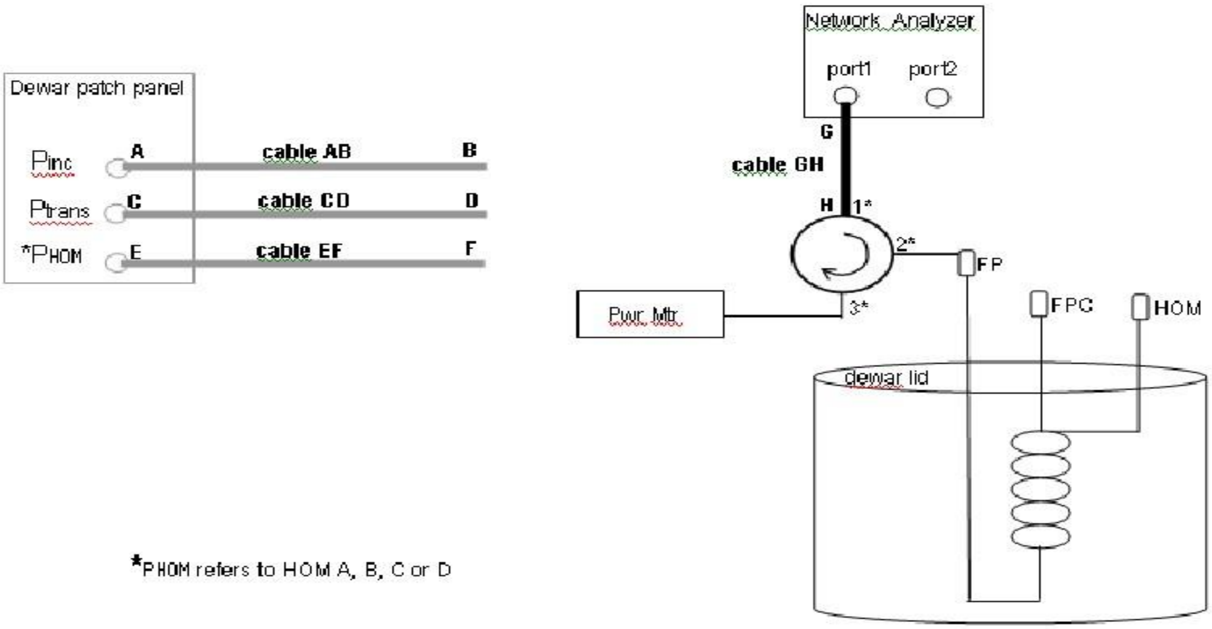


Figure A8. Cable GH, cavity field probe (FP) and power meter connected to circulator for 'Transmitted Cable Return Loss' field probe measurement. The same measurement is made for each HOM if instrumented.

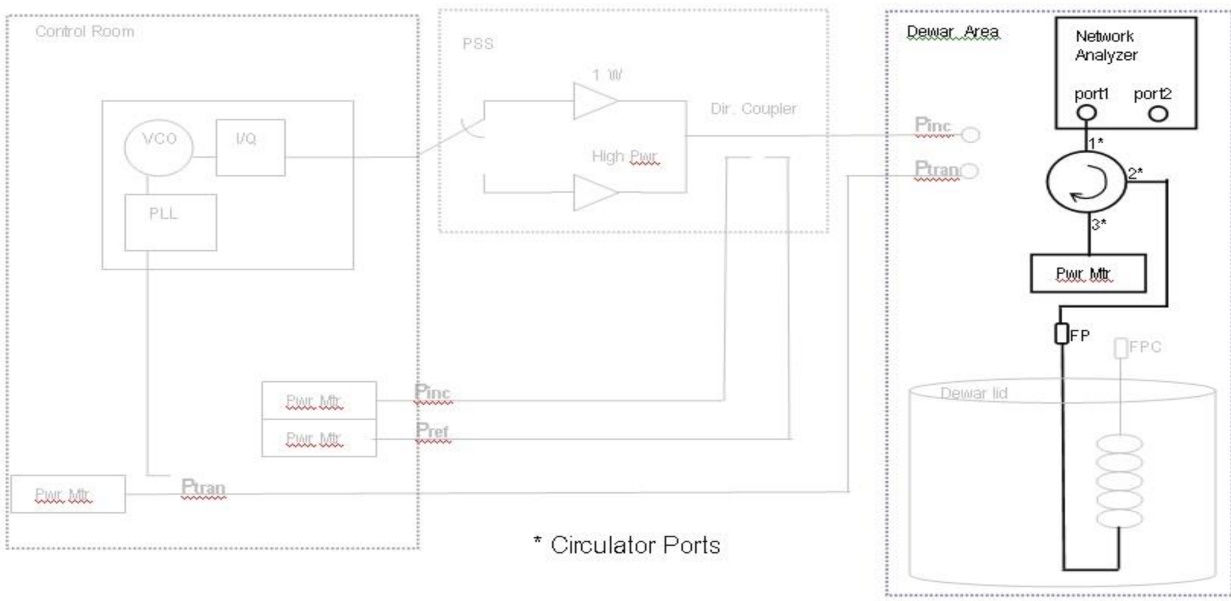


Figure A9. Block diagram representation of 'transmitted cable return loss' field probe cable calibration step.

Step 6. Fwd Pwr to detuned cavity

A. Connect all cables from dewar patch panel to dewar as shown in figure A10:

- cable AB to Fundamental Power Coupler [FPC] port
- cable CD to Field Probe [FP] port
- each HOM cable represented by cable EH to the HOM ports

B. Clear area and close dewar lid.

C. Turn RF on using the switch on the FCC chassis. In cable calibration VI, set Atten to 10 dB using slide control.

D. Verify the transmitted power meter,Pt, reads ~ 0 W.

E. In cable calibration VI, click button labeled 'Foward Power into Detuned Cavity'.

F. A pop-up screen will appear and quickly disappear without any operator interaction.

G. Turn RF power off.

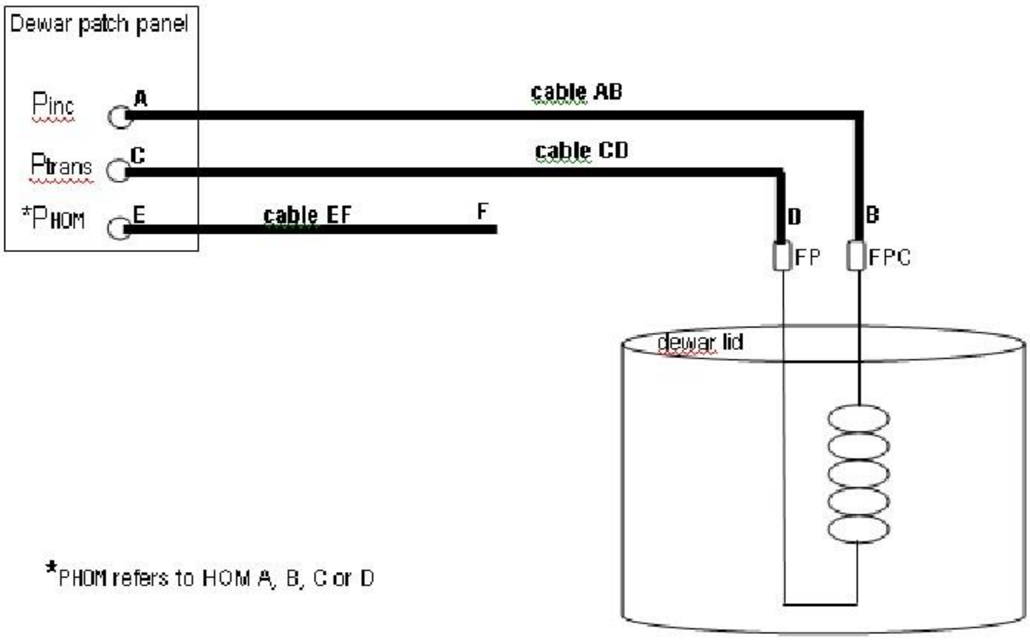


Figure A10. Cable AB to Fundamental Power Coupler (FPC) port and Cable CD to Field Probe (FP) port for 'Incident power to detuned cavity' cable calibration step.

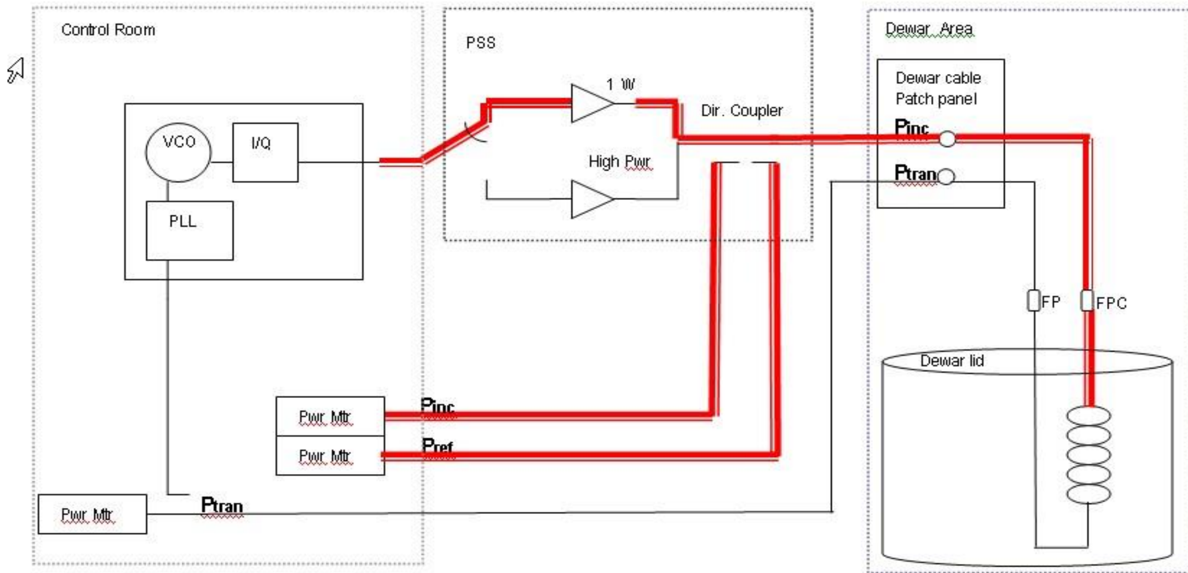


Figure A11. Block diagram representation of 'Forward Power to detuned cavity' cable calibration step.

Upon completing the cable calibration, click the button labeled ‘DONE’ in the cable calibration VI.

A window will open to display the difference between the current calibration and the last calibration performed in the dewar. Percent difference = (10^(difference/10) – 1)*100

Difference (dB)	Percent Difference
0.01	0.23 %
0.03	0.69 %
0.05	1.16 %
0.07	1.62 %
0.10	2.33 %
0.30	7.15 %
0.50	12.2 %
0.70	17.5 %
1.00	25.9 %
2.00	58.5 %

Good calibrations will have a difference of a 0.05 dB or less, provided that no cables have been replaced.

If the cable calibrations are within a 0.05 dB difference or less, the calibration is within the range of the last calibration. Click on the button labeled ‘Click to Save and Close’ to exit the calibration comparison window.

If the cable calibrations are not within the 0.05 dB difference, the calibration is not within the range of the last calibration. Press ‘Click to Save and Close’ and repeat the portion of the cable calibration which was not with in 0.05 dB range. Partial calibration values can be written to the file without overwriting the other calibration data.

Select ‘Click to Close With No Changes to skip writing new calibration data to the calibration file.

The main VI will be displayed. The calibration is finished.

Record the power meter correction factors from the VTA_main.vi screen. They are displayed in the *PM corr fac* cluster as **Ci, Cr** and **Ct**.

5.0 Revision History

Rev #	Revision or update:	Effective:
Release	R1 Initial Release	09/15/2011
Release	R2 Corrected Release	06/11/2021

6.0 Approvals

Approved by:	Signature:	Date:
Document Owner	C. Wilson	
SRF Cavity Production Group Leader	K. Davis	
C100 Project Manager	K. Davis	

Completion of Routing for Approval

From: **DocuShare Document Routing Service**
Subject: **Re: C100R-PR-VTA-CAV-VTRF-R2.docx**
Date: **Thursday, July 8, 2021 10:57:08 AM EDT**

Type	Title	Actions
DOC	C100R-PR-VTA-CAV-VTRF-R2.docx RF testing of C100 cavities in the VTA	

Status: Approved

Recipient	Response	Date	Added Versions	Response Versions
Step 1: Approval, 100% respond				
Christiana Wilson	Approved	07/14/21	-	1 (Version-134086)
Kirk Davis	Approved	07/19/21	-	1 (Version-134086)