325MHz SSR Circulator Specification Verification Test Report

PIP2IT Project

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Revision History

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1. Test objective

To perform high power test on RF circulators and report results which verify the following specification:

- Isolation: 20 dB minimum
- Insertion loss: 0.3 dB maximum
- VSWR: 1.20:1 maximum
- RF bandwidth: 6MHz (159.5 to 165.5 MHz)
- Operation modes-The circulator shall provide appropriate reverse isolation for continuous full reflection at any phase angle to be verified at low power (high power test for this specification is also performed)

2. Test Setup

To fulfil objective specific test setup conditions are applied for circulator under test as listed below:

I. Calibration:

a. Full calibration of test setup:

For the test setup shown in the schematic below, we measure

- LLRF signal coming from synthesizer at 2 locations: RF synthesizer panel readout, Bruker SSA input coupler using power meter. LLRF measurements agree with each other with no offset.

- High power signal which forms the output of Bruker SSA is measured directly at 3 points- Bruker SSA output coupler (part of Bruker SSA assembly), Circulator port-1 coupler, Circulator port-2 coupler (includes insertion loss of circulator) and one in-direct measurement using calorimetry.

During the test, it was noticed that Bruker SSA output coupler was out of calibration (had an offset in measurements) and coupler connected to port-1 of circulator forward power measurement was reliable as it agreed with forward power calorimetric measurement and Bruker SSA front panel readout.

(Test setup schematic on next page)

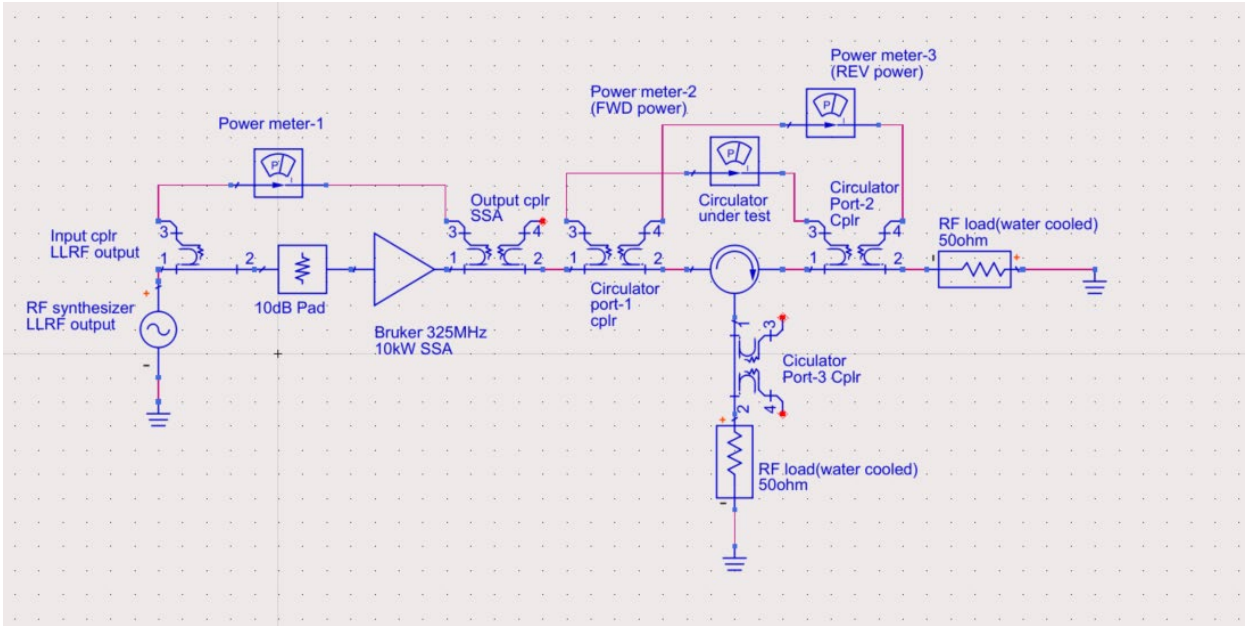


Figure 1: Full calibration test setup schematic

b. Calibration of couplers:

- Pre-test calibration.
- Post-test calibration.

Offset in circulator test measurements is created by insertion loss of directional couplers, effect of SSA, losses through 3” coax line delivering power to circulator. This offset is measured by connecting port-1 coupler to port-2 coupler with load and port-3 coupler with load as shown in the picture (on next page).

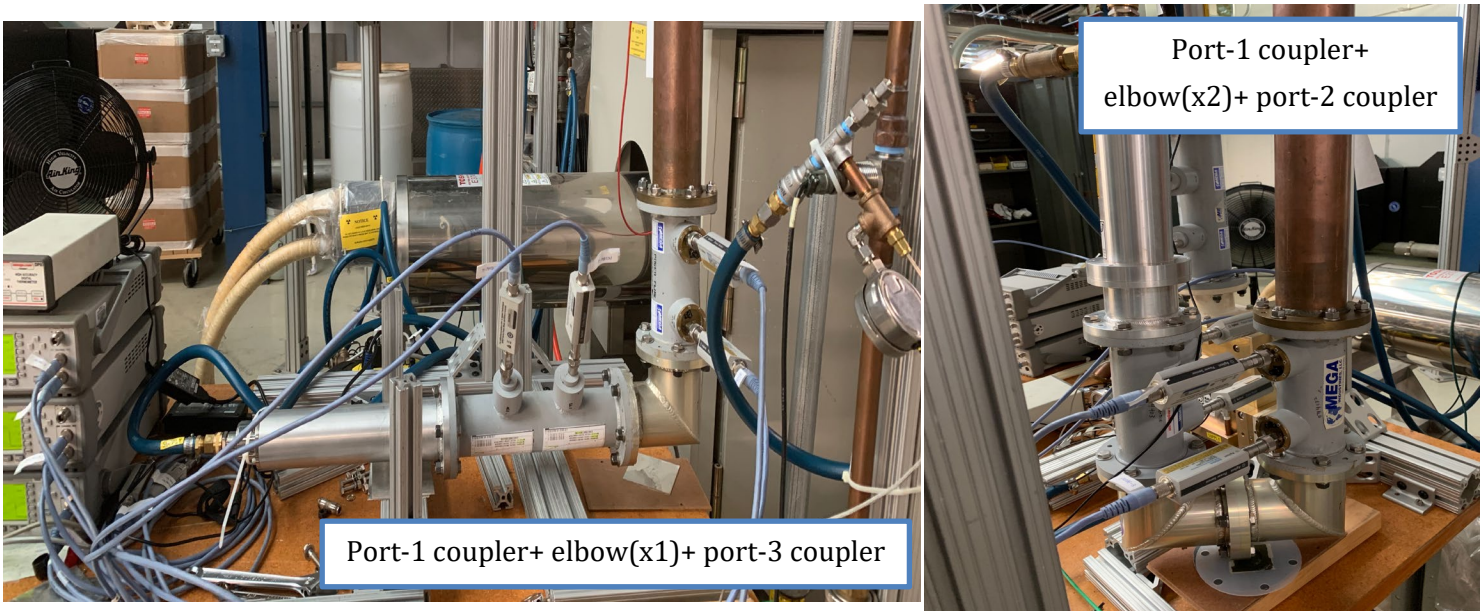


Figure 2: Pre and post-test calibration for offset measurement: port-1 coupler connected to port-3 coupler(left) and port-1 coupler connected to port-2 coupler(right).

II. Circulator test

a. Port-2 and port-3 terminated in matched load:

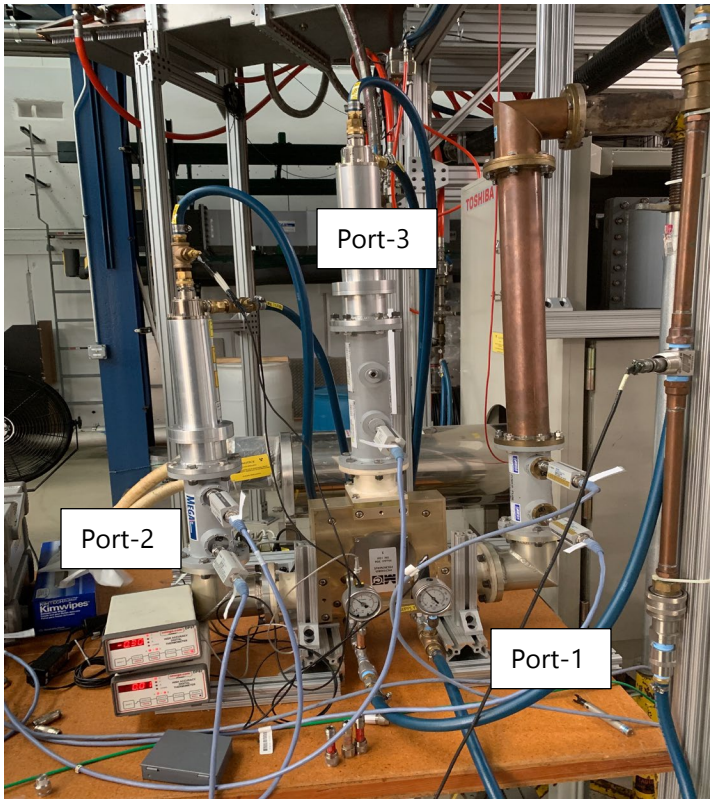


Figure 3: Port-2 and 3 terminated in matched load.

b. Short on port-2:

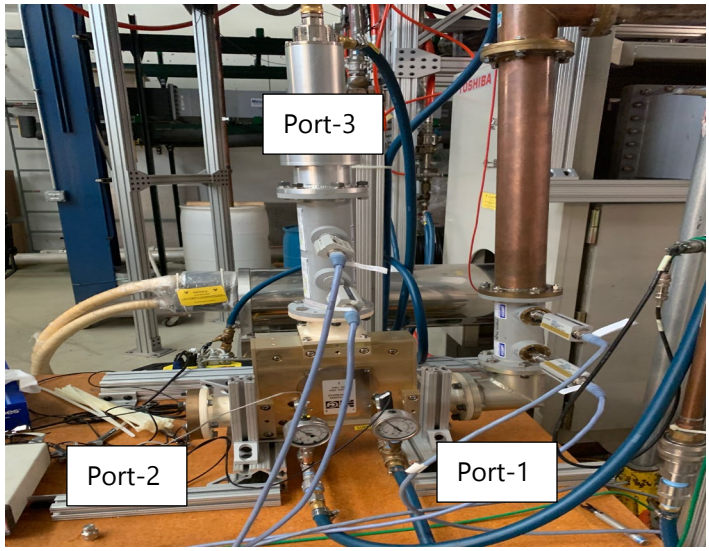


Figure 4: Short on port-2 test setup.

c. Sliding open on port-2:

Figure 5: Sliding open on port-2.

3. Calculations:

- **Insertion loss(dB)**= dB(Port-1 FWD power – port-2 FWD power)- Calculated offset(0.21dB for power sweep or 0.23dB for frequency sweep) [Calculated only when port-2 and port-3 of circulator terminated in matched load, for short on port-2 or sliding open on port-2 this measurement does not apply]

- **Insertion loss offset:** It is calculated by calibrating port-1 and 2, port-1 and 3 couplers following setup details mentioned in 2.1.
- **Return loss(dB)**= dB(port-1 forward power- port-1 reverse power)

Offset calculation:

	Measured Offset (dB)							
Calibration	Test- 1		Test-2		Test-3		Final offset (dB)	
Sweep	Power	Frequency	Power	Frequency	Power	Frequency	Power	Frequency
Port-1 coupler to port-2 coupler	0.207	NA	0.21	0.230	0.19	0.21	0.21	0.23
Port-1 coupler to port-3 coupler	0.066	NA	0.05	0.03	0.05	0.04	0.05	0.03

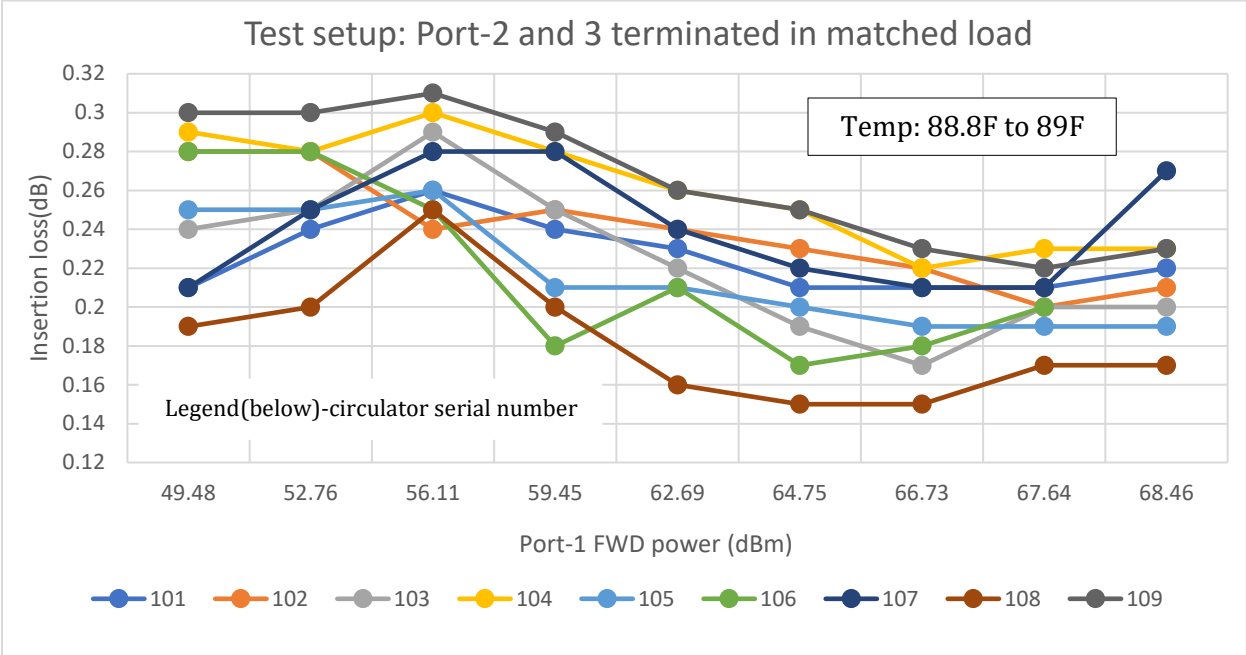
4. Test results

Insertion loss: Insertion loss is the ratio of output power to input power with the signal applied to the input. It is measured when port-2 and port-3 are terminated in matched load.

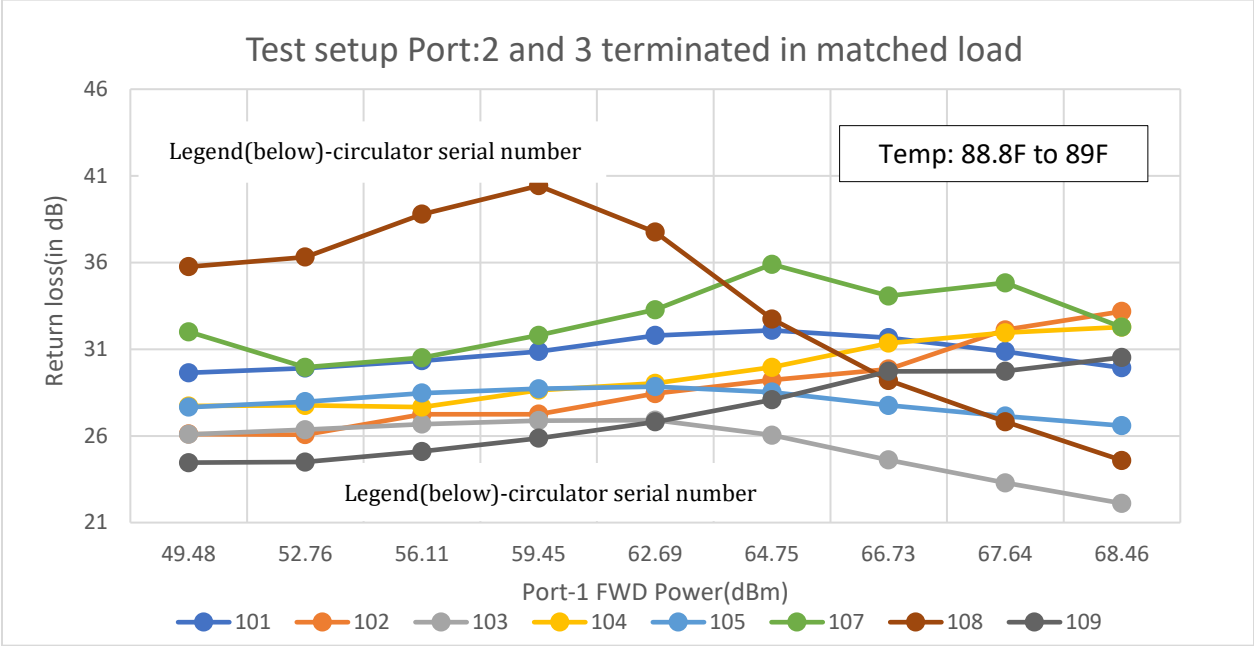
Return loss: is measured as ratio of Port-1 forward power to port-1 reverse power.

Insertion loss and return loss are measured at 1MHz frequency steps at low power (56 to 57dBm~ 500W) from 322 to 328MHz (spec bandwidth) and at center frequency from low power to rated power(7kW).

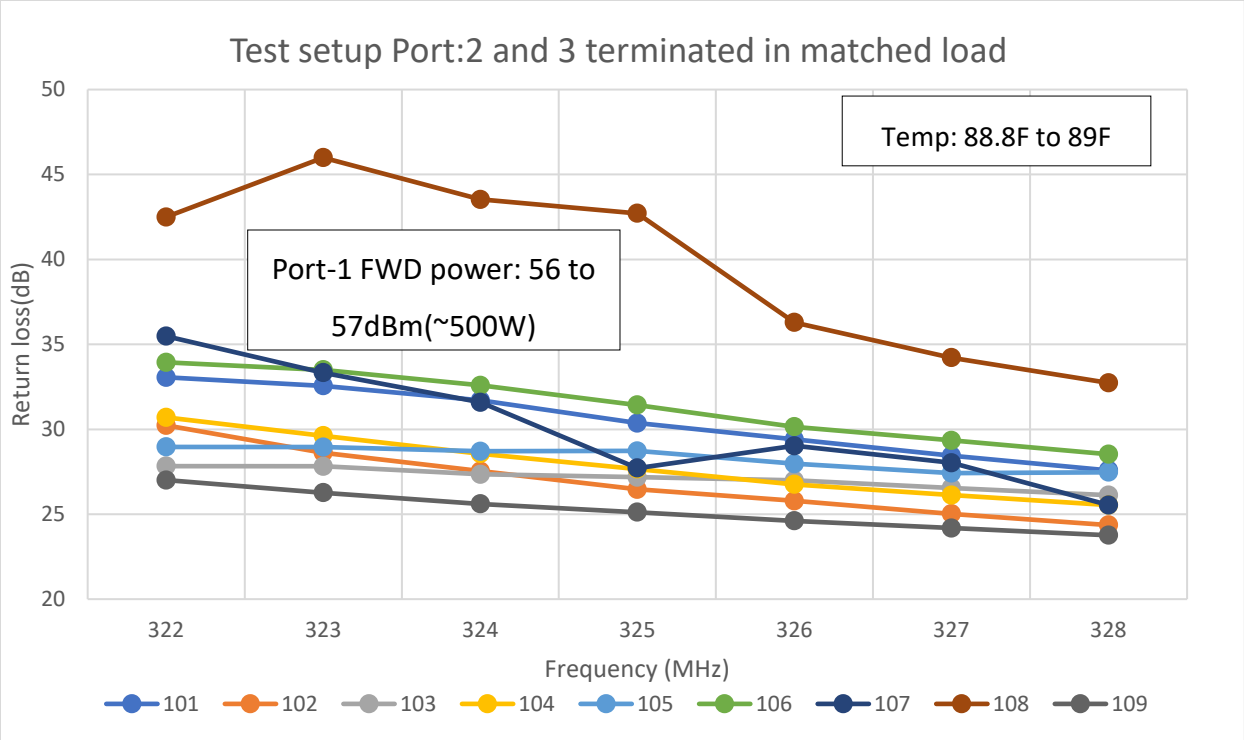
I. Test setup: Port-2 and port-3 terminated into a matched load.



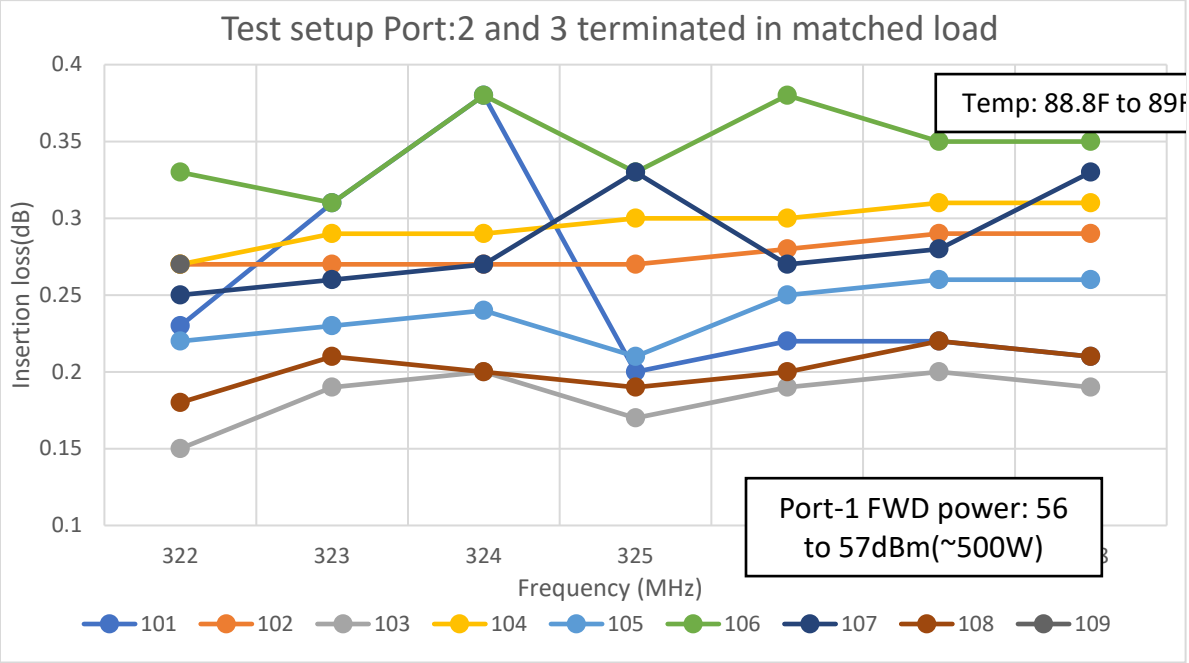
Plot 1: Insertion loss plot at discrete power levels at fixed frequency(325MHz) for all 9 circulators.



Plot 2: Return loss plot at discrete port-1 forward power level at fixed frequency (325MHz) for all 9 circulators.

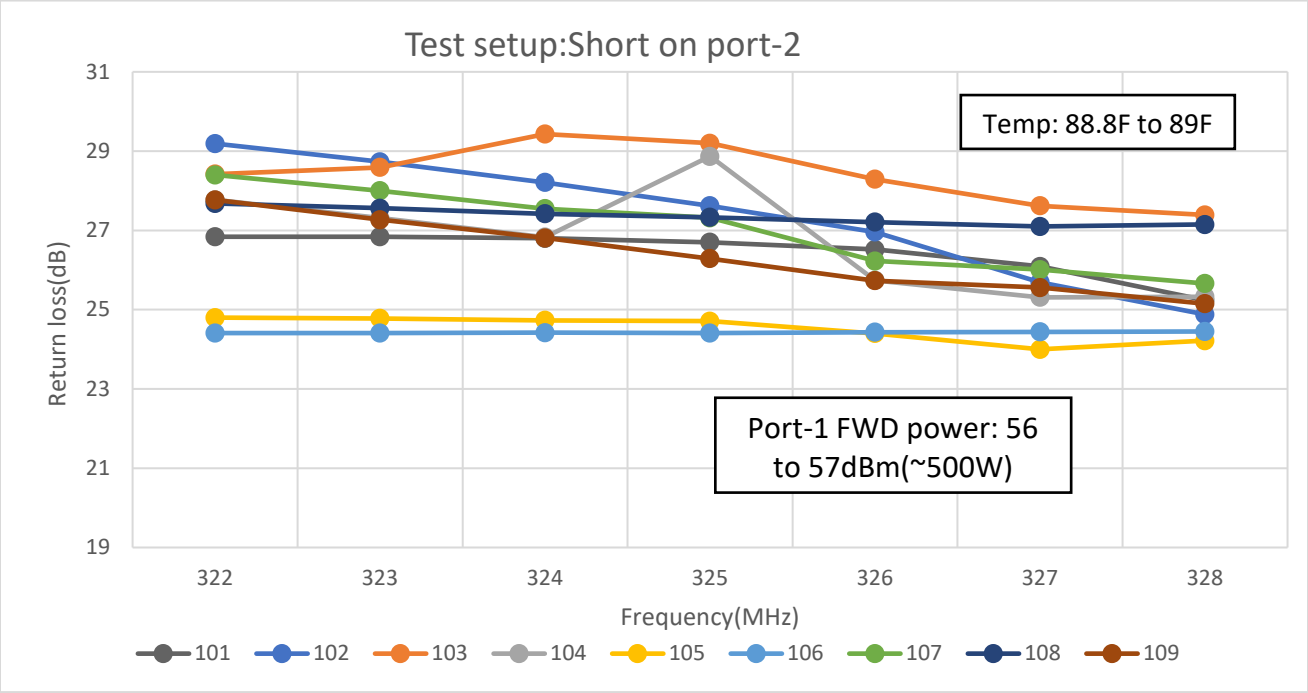


Plot 3: Return loss plot at discrete 1MHz frequency steps and fixed power level (~500W) for all 9 circulators.

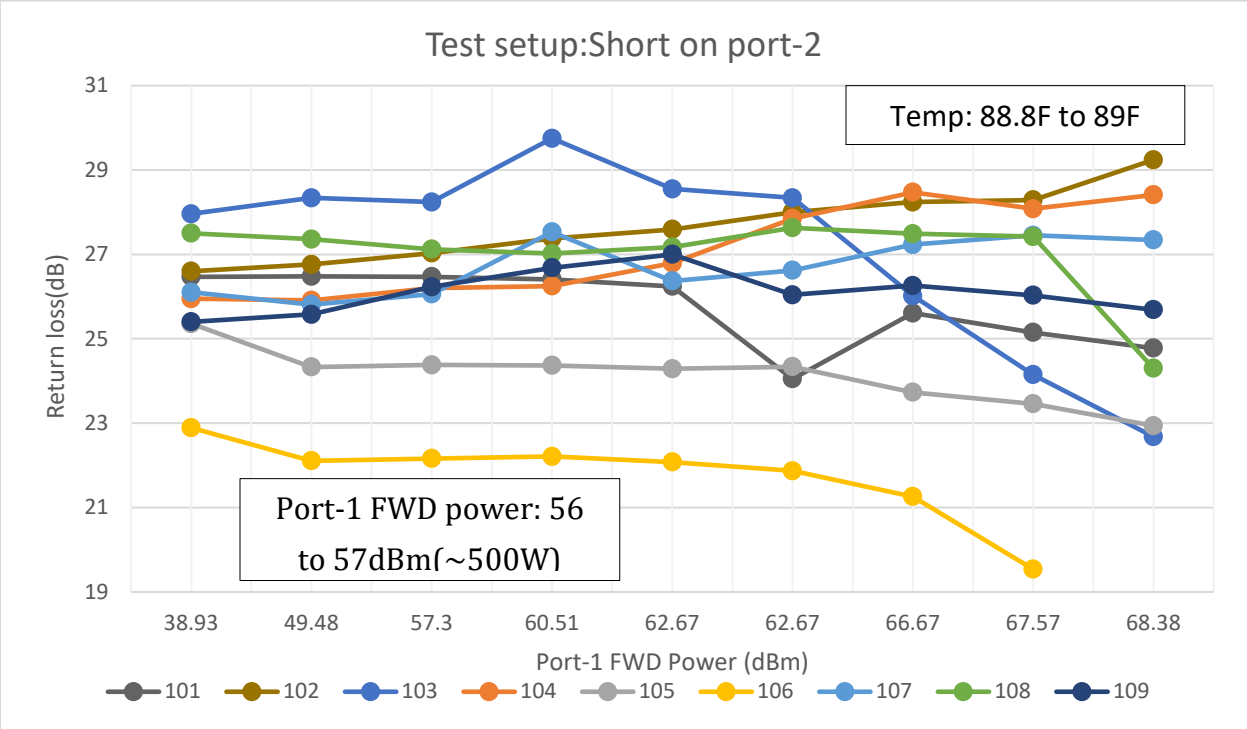


Plot 4: Insertion loss plot at discrete 1MHz frequency steps and fixed power level (~500W) for all 9 circulators.

II. Test setup: Short on port-2



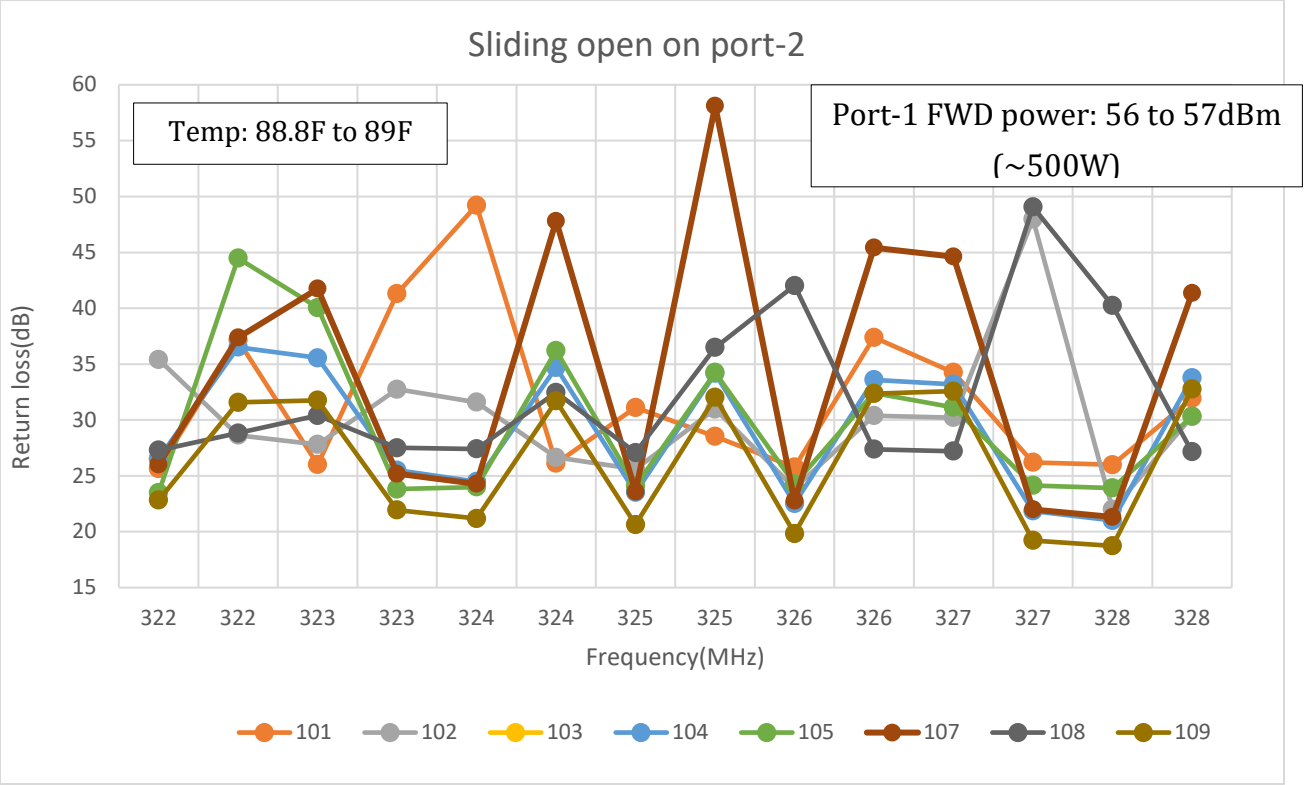
Plot 5: Return loss plot at discrete 1MHz frequency steps (322 to 328MHz) and fixed port-1 forward power level (~500W) for all 9 circulators.



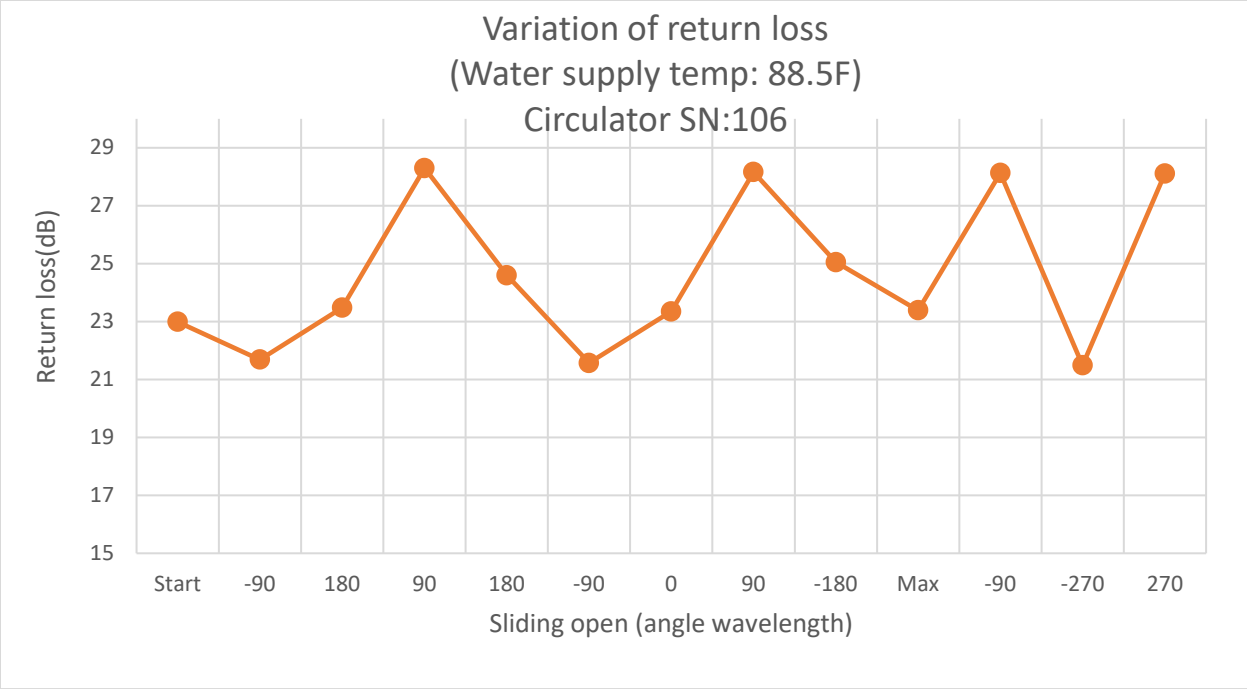
Plot 6: Return loss at discrete port-1 forward power levels for all 9 circulators

III. Test setup- Sliding open:

1-5/8" Sliding open is connected to port-2 and at a fixed port-1 forward power(~500W). Slide position determines the phase of the reflected wave entering port-2 and forwarded to port- 3 where is measured by port-3 coupler forward port.



Plot 7: Return loss plot for best and worst case reflection using sliding open for 8 circulators.



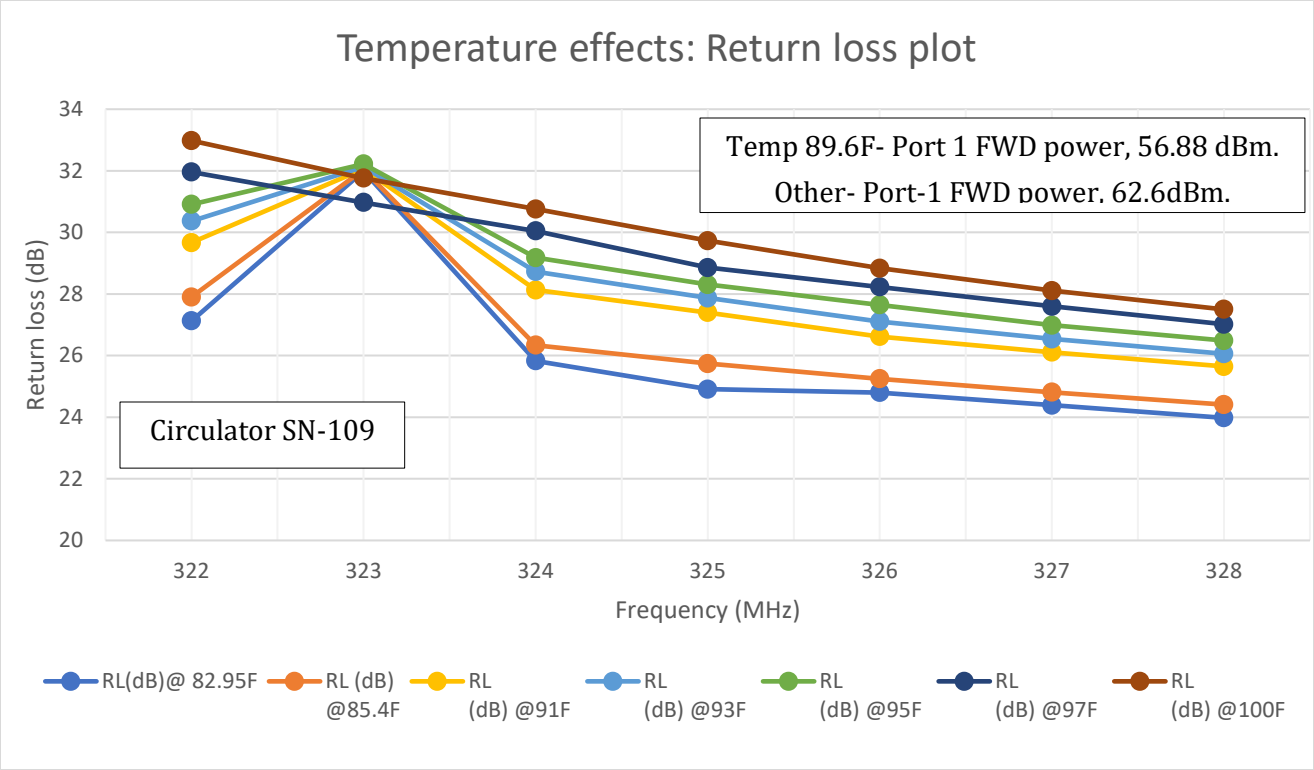
Plot 8: Return loss plot for best and worst case return loss using sliding open (for circulator SN-106)

IV. Temperature effects:

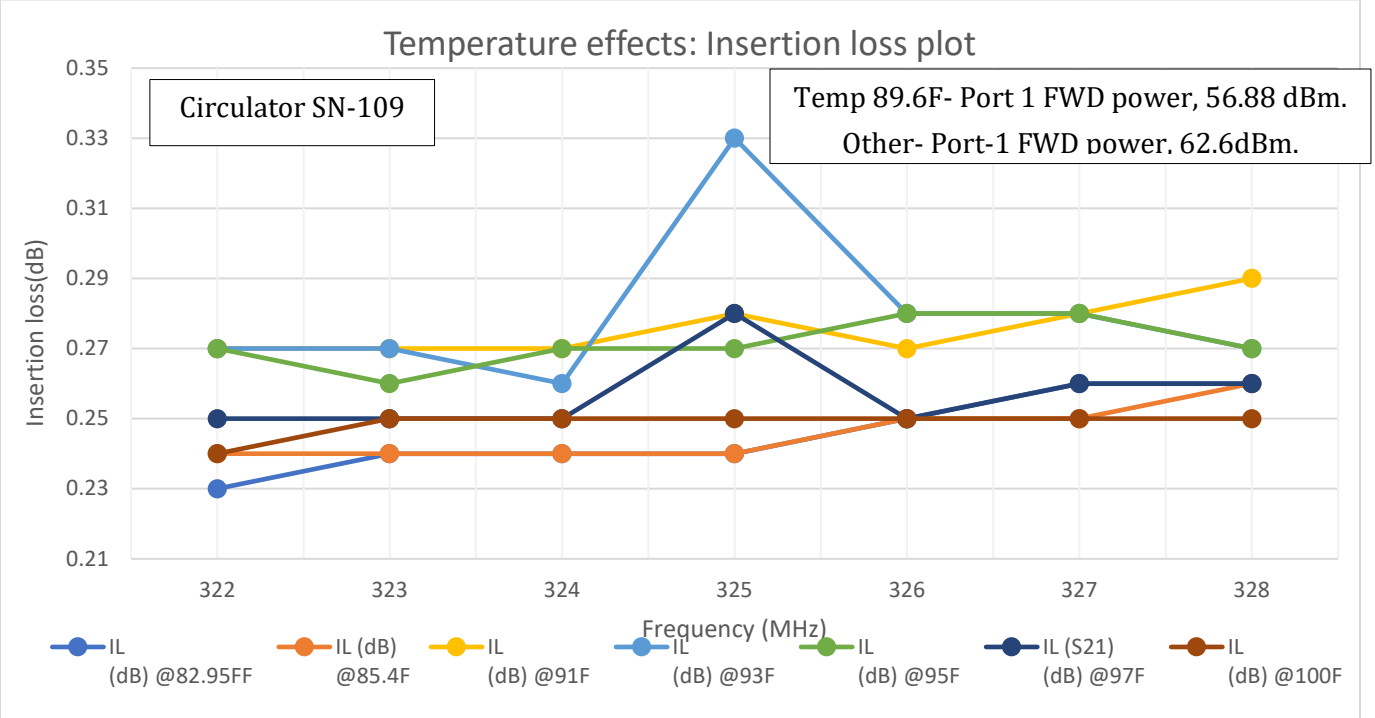
Circulator tuning is temperature sensitive, even a 2F change in temperature will cause a change in its performance (insertion loss and return loss). In order to study this in more detail, at a fixed port-1 power level water temperature at the skid is varied in steps of 2F from 82.95F to 100F with return loss, insertion loss measured at 322 to 328MHz). Since the water skid(Ms7) has a large water throughput, there is a varying response time associated with the change to take into effect. Also, set point temperature has a variable offset from the actual temperature (as measured at circulator flow thermometer).

Temperature values in the plots are the readout from thermometer connected to circulator supply.

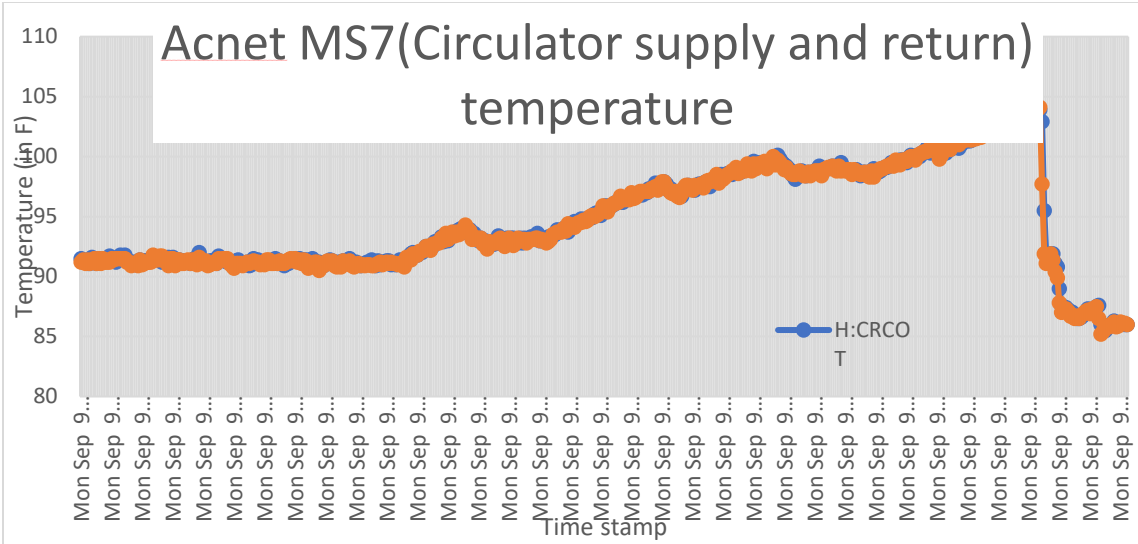
Test setup: Temperature sweep is performed on circulator SN-109 with Port-2 and port-3 terminated in matched load.



Plot 9: Return loss plot through 322 to 328MHz(discrete 1MHz steps) for 2F steps 82.95F to 100F.



Plot 10: Insertion loss plot through 322 to 328MHz(discrete 1MHz steps) for 2F steps 82.95F to 100F.



Plot 11: Acnet plot for circulator supply and return during temperature variation.

5. Lessons learnt:

1. In order to ensure water supply flow rate through the circulator is at the threshold limit (2.5gpm) or higher:
   - Avoid connecting ¼" elbow (as shown in the picture below) as it creates a lot of additional impedance on water flow.
   - Temperature probe shouldn't be fully inserted in the pipe as the it may cause water flow to be obstructed and flow rate to be reduced.

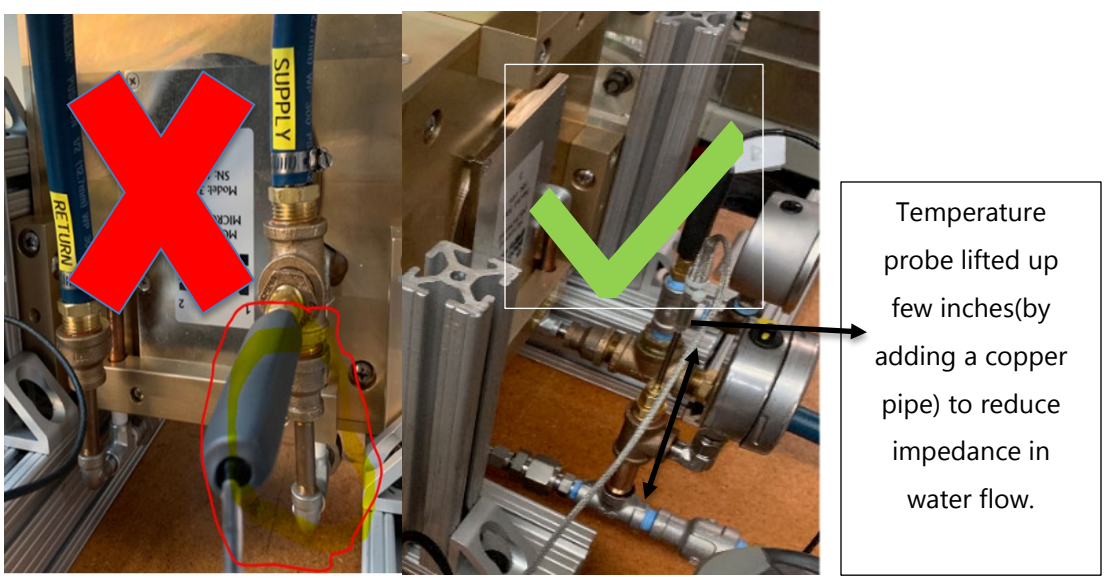


Figure 6: Plumbing for circulator, low flow rate(left) and optimum flow rate(right)

2. Use of sliding open: 1-5/8” sliding open is used to test reflections at any phase angle, average power rating for 1-5/8” at 7kW , 325MHZ is 11.43kW. Also, 1-5/8” line has no cooling apart from ambient air. During the test it was noted that temperature at certain points on the line was high enough to cause the foam spacers to melt/ deform. However, once this was noticed the sliding open was repaired and foam spacers were replaced with Teflon spacers and insulation tape replaced with high temperature tape. Going forward, power was increased gradually up to 500W (circulator port-1 power) and further measurements were carried out smoothly without any damage or excess heating to sliding open.
3. It was noticed circulator return loss was optimal (in most cases) at higher power levels, sliding open measurements and temperature sweep was done below circulator rated power.

6. Conclusion

Specification verification test was performed successfully on all 9 SSR circulators.

- All circulators meet the specification except circulator SN 106.
- SN 106 performance to be studied further once it’s installed.