DAE-BRNS Workshop on

Technology Development of Superconducting RF Cavities

RF testing of Superconducting RF Cavities

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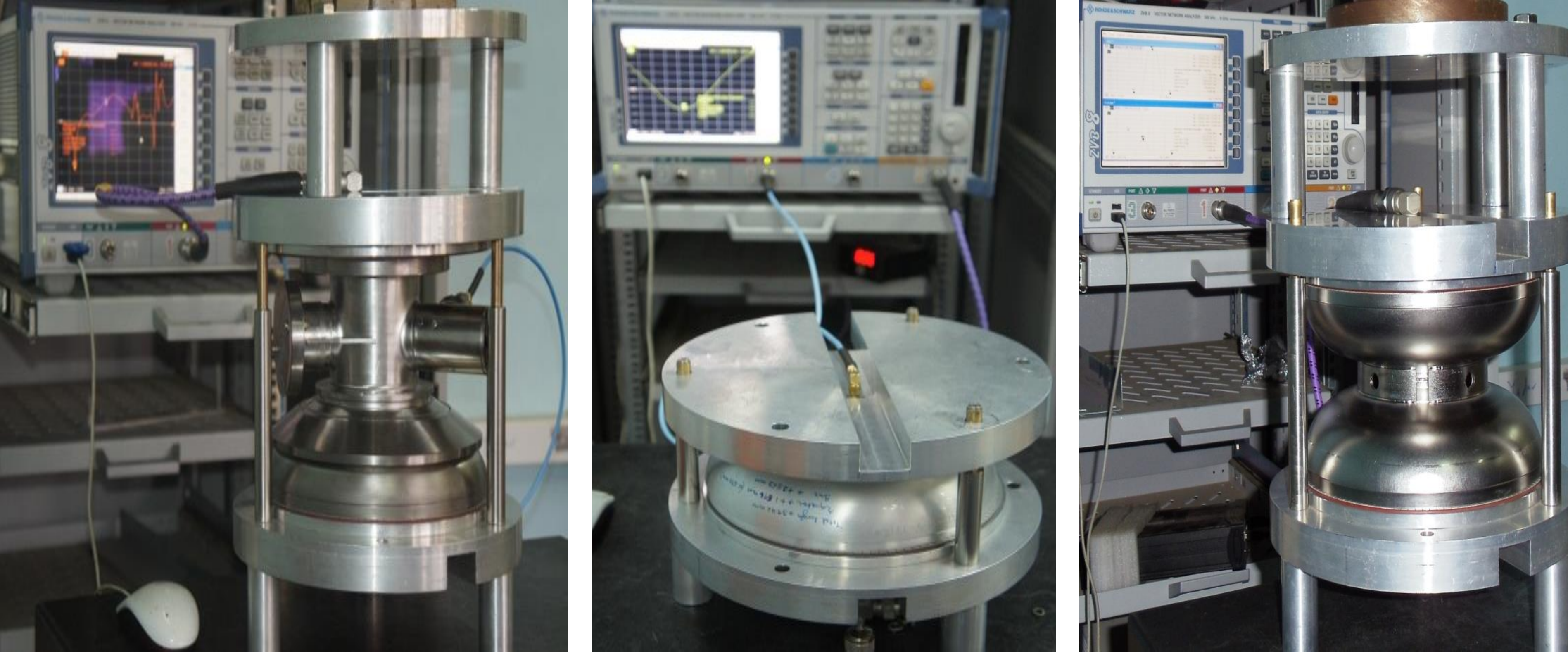
RF characterization of SCRF cavities is carried out at various stages of cavity fabrication before installation in actual particle accelerator. The tests are carried out at both room temperature and under cryogenic conditions

Multi-cell elliptical SCRF cavities start their journey as half cells which are then joined together by EB/Laser welding at iris to form a dumbbell structures or are joined to a beam pipe to form end cells. Then these dumbbells and end cells are welded together to form a multi cell cavity.

At RRCAT RF characterization is carried out for half cell, dumb-bell and end cell structures to ensure that the final welded cavity resonates at the design frequency with a good field flatness across the cells. PHPMD has developed test setups for room temperature characterization of Niobium(Nb) make 1300 MHz and 650 MHz cavity structures. These setups have been extensively used during last six years for testing of half-cell, dumb-bell and end cell structures, which have then utilized in fabrication of 1300 MHz, 650 MHz single cell & multi-cell cavities.



RF characterization of 1300 MHz end cell, half cell and dumbbell structures

For half cell/end cell structure RF characterization involves precise measurement of resonant frequency of the structure, which should correspond to the mechanical length of the cavity. These measurements are carried out in setup which provides conductive boundary to both the iris and the equator. The resonant frequency of the resultant cavity structure is then determined by measurement of either S11 or S21 using a VNA. For measurement pick antenna with very high quality factor is used so as not to disturb the cavity structure.

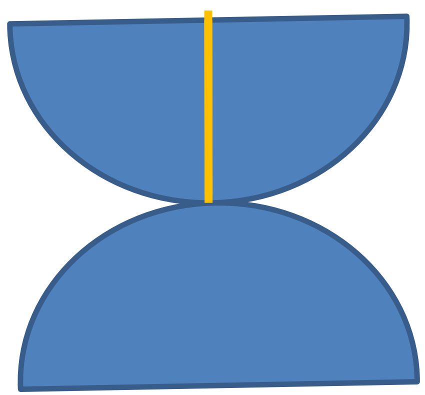
It is essential to have a good electrical contact on the iris and the equator side of the cavity for which a flat and high conducting surface is required, at PHPMD we are using RF laminates for this purpose which have very high dimensional accuracy.

RF characterization of dumbbell structures

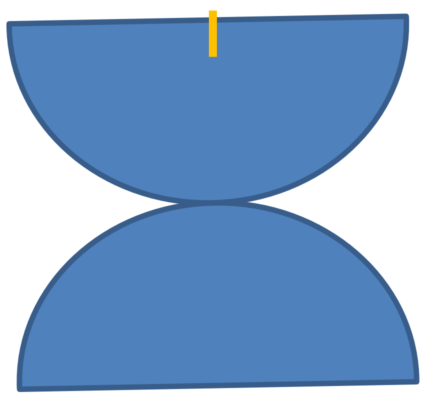
In case of dumbbell structures the RF measurement is more complex as mere measurement of the resonant frequency will not be enough. It is more important to identify the dumbbell asymmetry i.e. the difference in resonant frequency of the two cell which constitute the dumbbell. At PHPMD we have devised a method in which the frequency of two half cells are determined by using two antennas of different length. A short antenna is used to determine the π mode resonant frequency of the structure while a long antenna is used to identify the relative difference in frequency of the two cells.

RF qualification of a 650 MHz 0.92 Beta dumbbell structure. A copper clad RF laminate is used at the bottom and at the top equator to ensure good electrical contact. The VNA signal shows the S11 for the cavity structure.

RF characterization of dumbbell structures



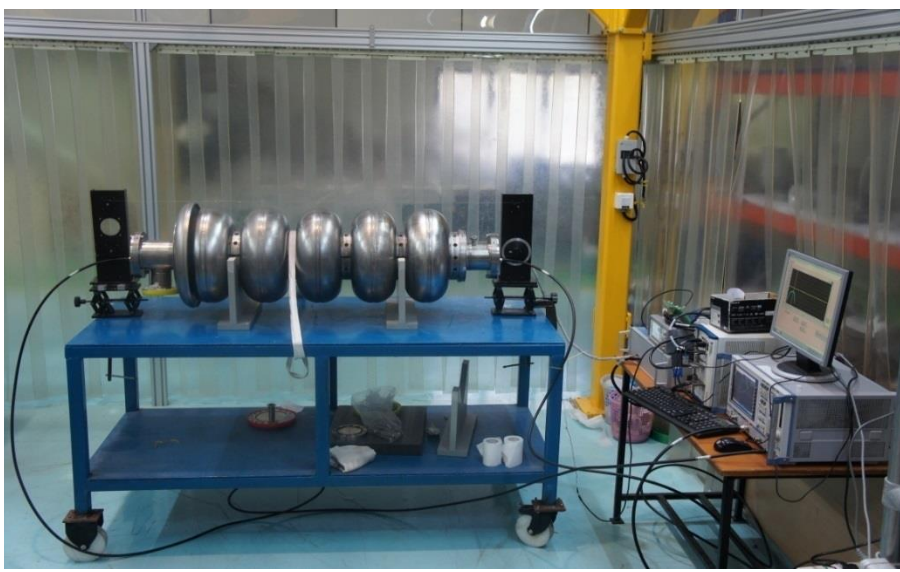
Long antenna

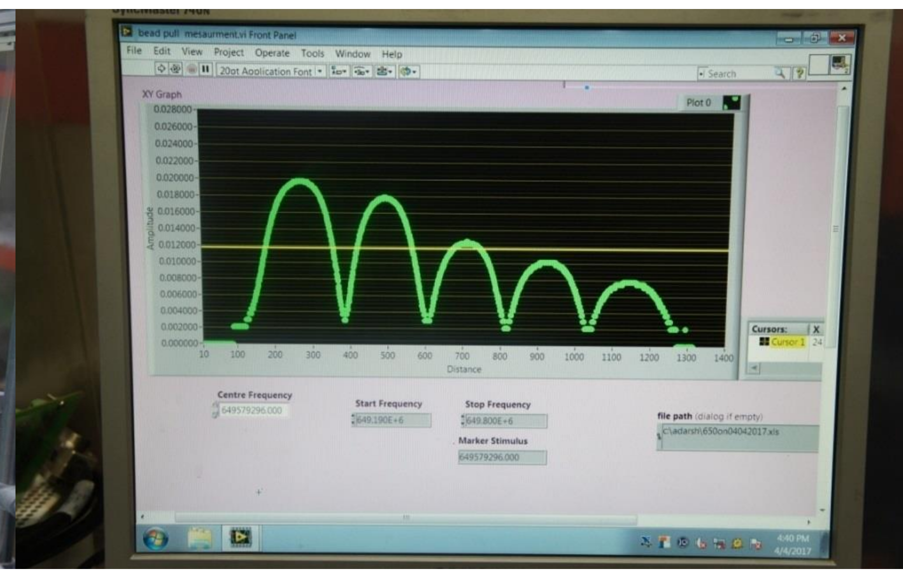


Short antenna

After RF characterization the dumbbell and end cell structures are either compressed or stretched to bring them at the correct resonant frequency and at the correct length. The result of RF measurement are used to determine the quantum and direction of the mechanical change. The structures are then welded together to form a multi cell cavity. These RF characterisation has been carried out for both 1300 MHz and 650 MHz (Beta 0.92) multi cell SCRF cavities developed at RRCAT.

After welding the multi cell cavity is qualified for its field flatness by bead-pull measurement. The bead pull measurement is a standard procedure in which a metallic bead or dielectric bead is to perturb the cavity along the beam axis and change in frequency is recorded. The change in frequency of the cavity is proportional to the square of electric field at the bead position. The change in frequency is measured by using a VNA while the bead is moved across the beam axis using stepper motor. A software developed by PHPMD team then move the bead across the cavity and plots the electric field strength as a function of the distance. The picture on left shows the bead pull test being conducted on 5 Cell 650 MHz cavity and the picture on right shows the electric field profile across the cavity.





Cryogenic characterization of SCRF cavities at RRCAT VTS

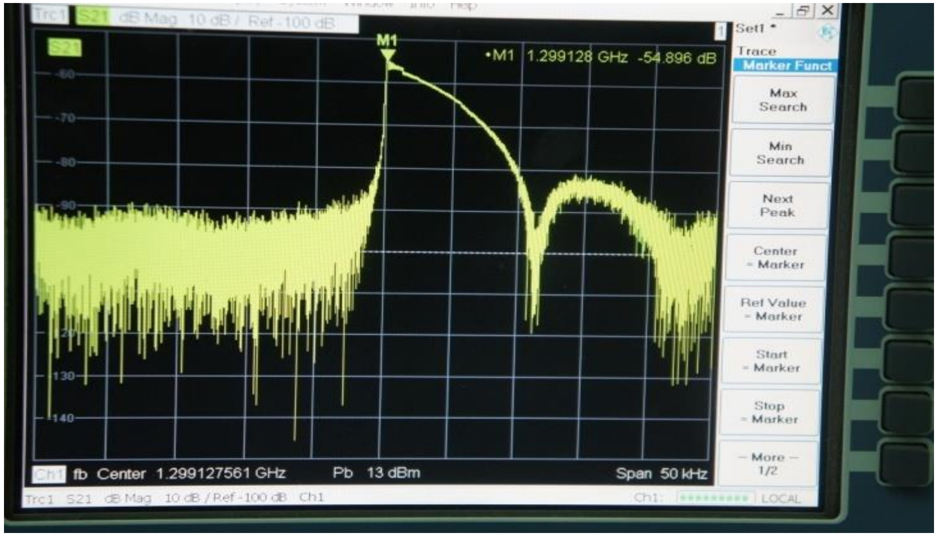
- Before a SRF cavity is mounted in a cryostat its performance is verified at cryogenic temperatures, typically at 2K/4.2K (cold test) in a vertical test stand (VTS). The maximum accelerating gradient (E_{acc}) that the cavity can sustain before quenching (becoming normal conducting) and the variation of intrinsic quality factor of the cavity (Q_0) with increase in (Eacc) are determined in a cold test.
- These tests are carried out on a cavity which is nearly critically coupled to minimize the RF power requirements and to reduce the measurement uncertainties.
- Two couplers are attached to the cavity one is used to feed incident power (Pi) to the cavity this coupler is at near critical coupling and the other is used to sense the electric field developed inside it (Field Probe (FP)) the FP has a quality factor ~ 100 times higher than the incident power coupler to ensure that it does not load the cavity significantly.
- The critically coupled SRF cavity has a loaded quality factor of the order of 10^{10} , its bandwidth is less than 1 Hz. Further its resonant frequency keeps changing due to effect of microphonics.
- In order to feed power to the cavity it is essential to have the frequency source (RF generator) frequency locked to the resonant frequency of the cavity, this is achieved by utilizing a Phase Lock Loop in which RF generator is used as a VCO.

Cryogenic characterization of SCRF cavities at RRCAT VTS

- What is the purpose?
- Determine the variation of Q_0 w.r.t. Eacc.
- Determine the radiation generated inside cavity w.r.t. Eacc
- Determine the maximum Eacc reached by cavity before Quench.

- Can a VNA be used to determine Q_0 of SRF cavity.

- No resonance frequency of the SRF cavities varies due to microphonics, further the decay time is very high (in seconds). The resonant frequency changes faster than power inside cavity can decay, thus VNA will always measure bandwidth much wider than it actually is. See fig. below.

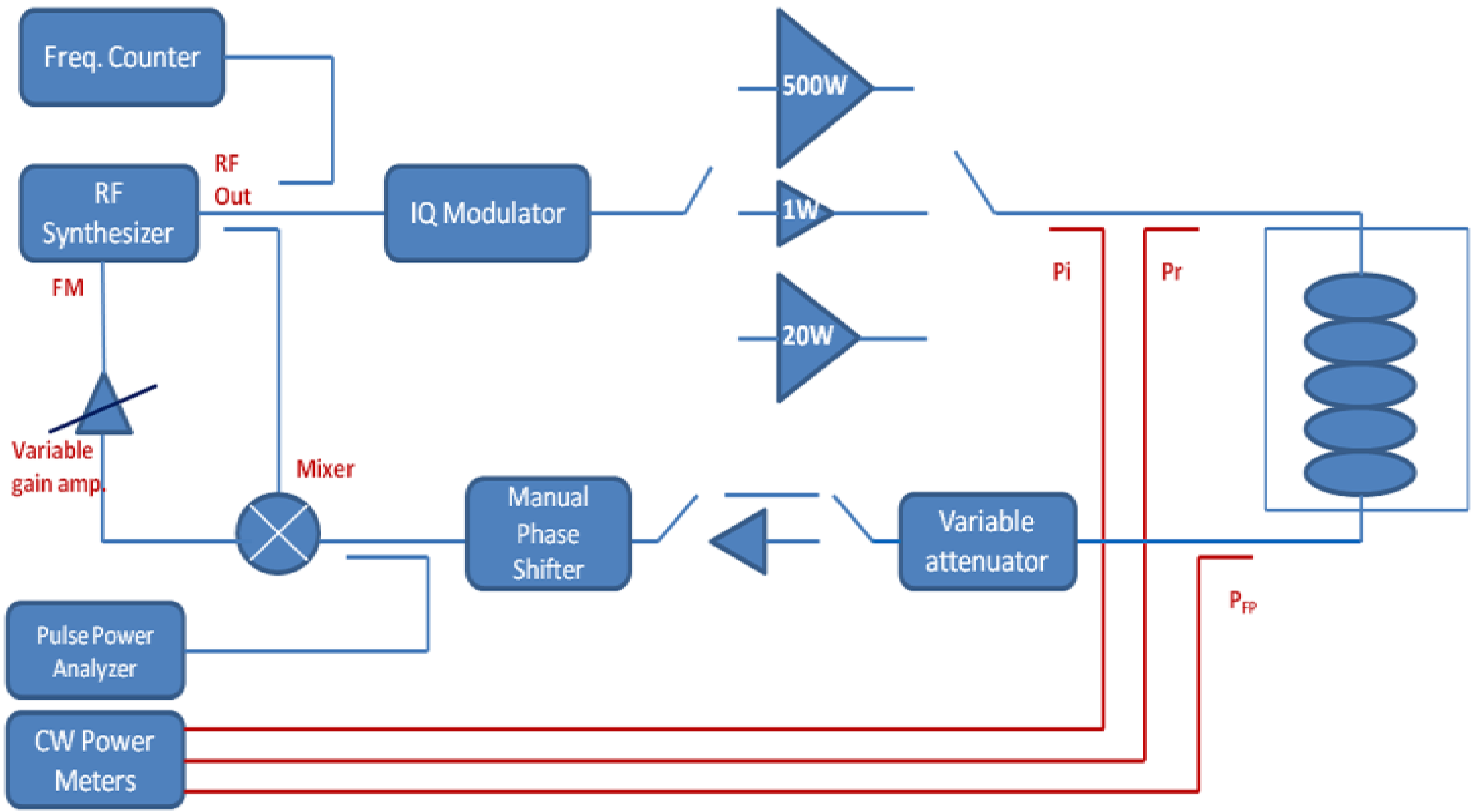


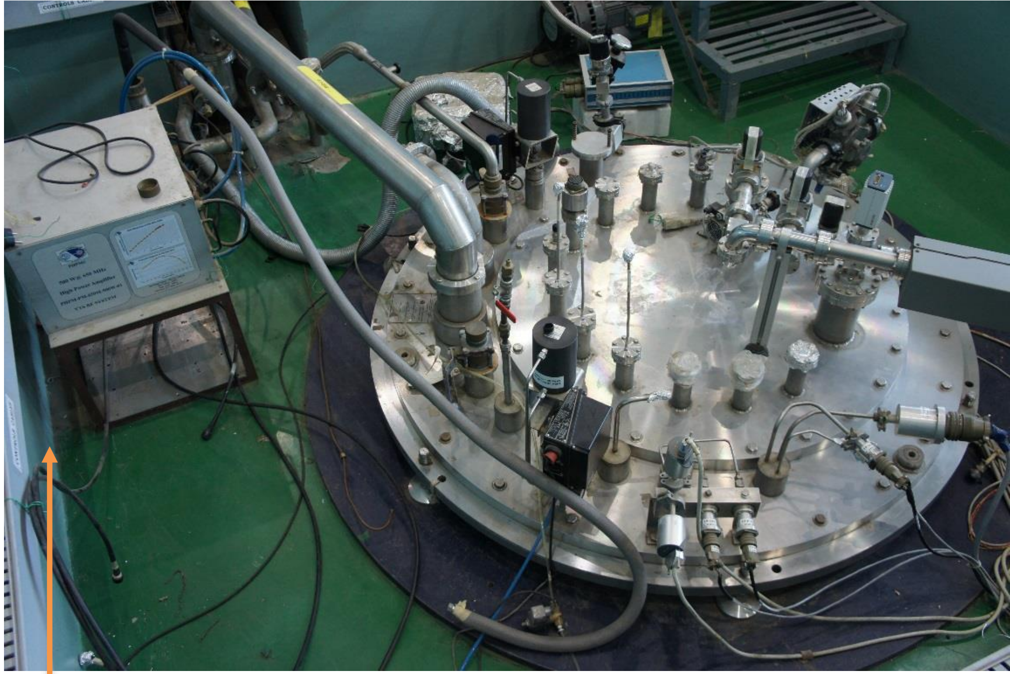
Cryogenic characterization of SCRF cavities at RRCAT VTS

- Can we measure Quality Factor of SRF cavity by doing decay measurement.

- Yes and No.
- For decay measurement to provide a faithful value of cavity quality factor the quality factor must remain constant through out the decay time. For SRF cavities Quality factor varies with stored energy and is constant only for low Eacc values where decay measurement can be used. For high Eacc values Q_0 is not a constant quantity and hence decay time measurement is not suitable.

Block diagram of the RF system of RRCAT VTS





Left image – LLRF system of RRCAT VTS installed in control room of VTS facility.
Right Image- 500 W 650 MHz RF amplifier developed by PHPMD installed at VTS pit.

VTS test procedure used at RRCAT

1. After the SCRF cavity is inserted in the VTS cryostat the cryostat is filled with liquid helium (4.2K). The pumping is then done to reduce the temperature of liquid helium bath to 2K.
2. First step in the RF characterization is to measure the resonant frequency of the cavity using a VNA. This measurement not only verify that the RF connections to the cavity are proper but it will also inform if the cavity has suffered a Helium Leak.
3. At 2K Helium is a super fluid and on rare occasions this super fluid can leak inside the cavity volume; which if happens will cause electrical breakdown inside the SRF cavity even at low accelerating field gradient. Even the power delivered by VNA can generate sufficient electric field inside the SRF cavity to cause electrical breakdown in low pressure Helium gas. The images on the next page will compare the VNA curves of a perfect cavity and a cavity which has suffered a Helium Leak.

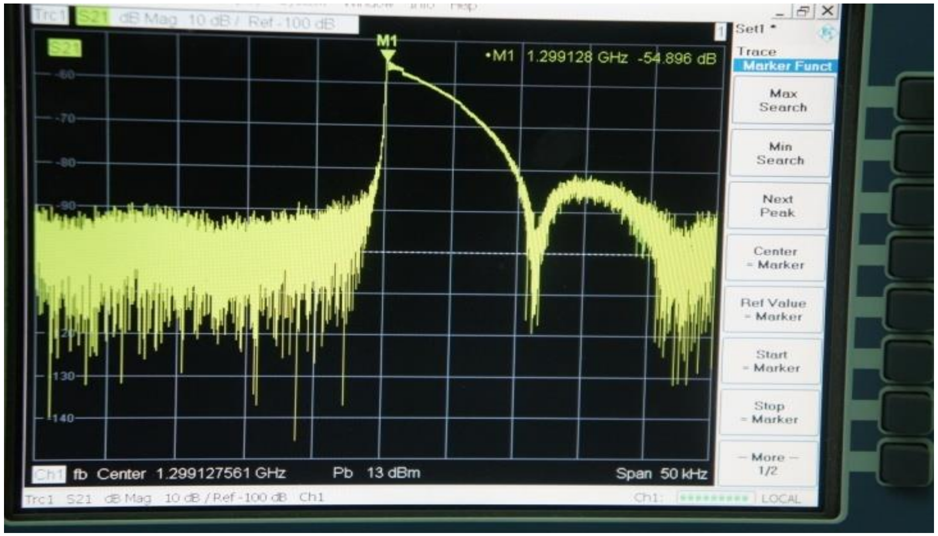


Fig. 1 - Response of a superconducting 1300 MHz Nb cavity at 4.2K. Notice the change in shape of the response curve. Due to very high quality factor of the cavity energy stored decay slowly, resulting in asymmetrical shape as evident above.

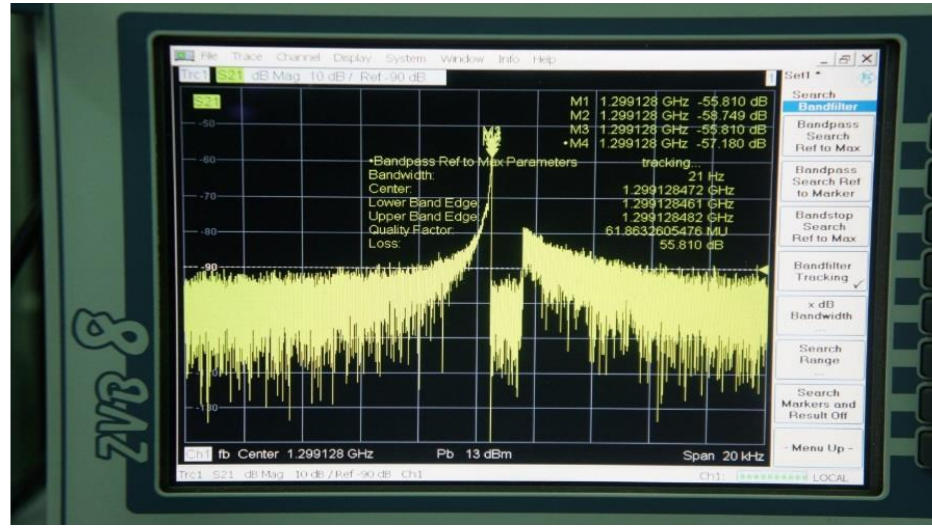


Fig. 2 - Response of a 1300 MHz SRF cavity as seen on VNA at 2 K, when cavity has suffered a helium leak. The low pressure gas environment results in electrical breakdown (after reaching a particular level) inside cavity leading to sudden loss in stored energy, which is indicated as a sharp dip in the S_{21} signal on the VNA

4. After VNA characterization the cable calibration is performed with as software assisted routine. The purpose of this step is to precisely identify the cable losses to have accurate measurement of the incident, reflected and transmitted power.

5. Locking of generator frequency to cavity resonance frequency. This is achieved by varying the

phase delay in the PLL.

6. Next step is to determine the quality factor of the transmitted power coupler. The transmitted power signal is directly proportional to the square of the Eacc. The relation between the two is given by

$$Eacc = kappa(\sqrt{P_{FP}} \cdot Q_{FP})$$

where kappa is constant for a given cavity.

7. The loss inside cavity is given by Pl = Pi – Pr –Pt.

8. The intrinsic quality factor of the cavity is given by $Q_0 = {}^{P_{FP}Q_{FP}}\!/_{P_l}$

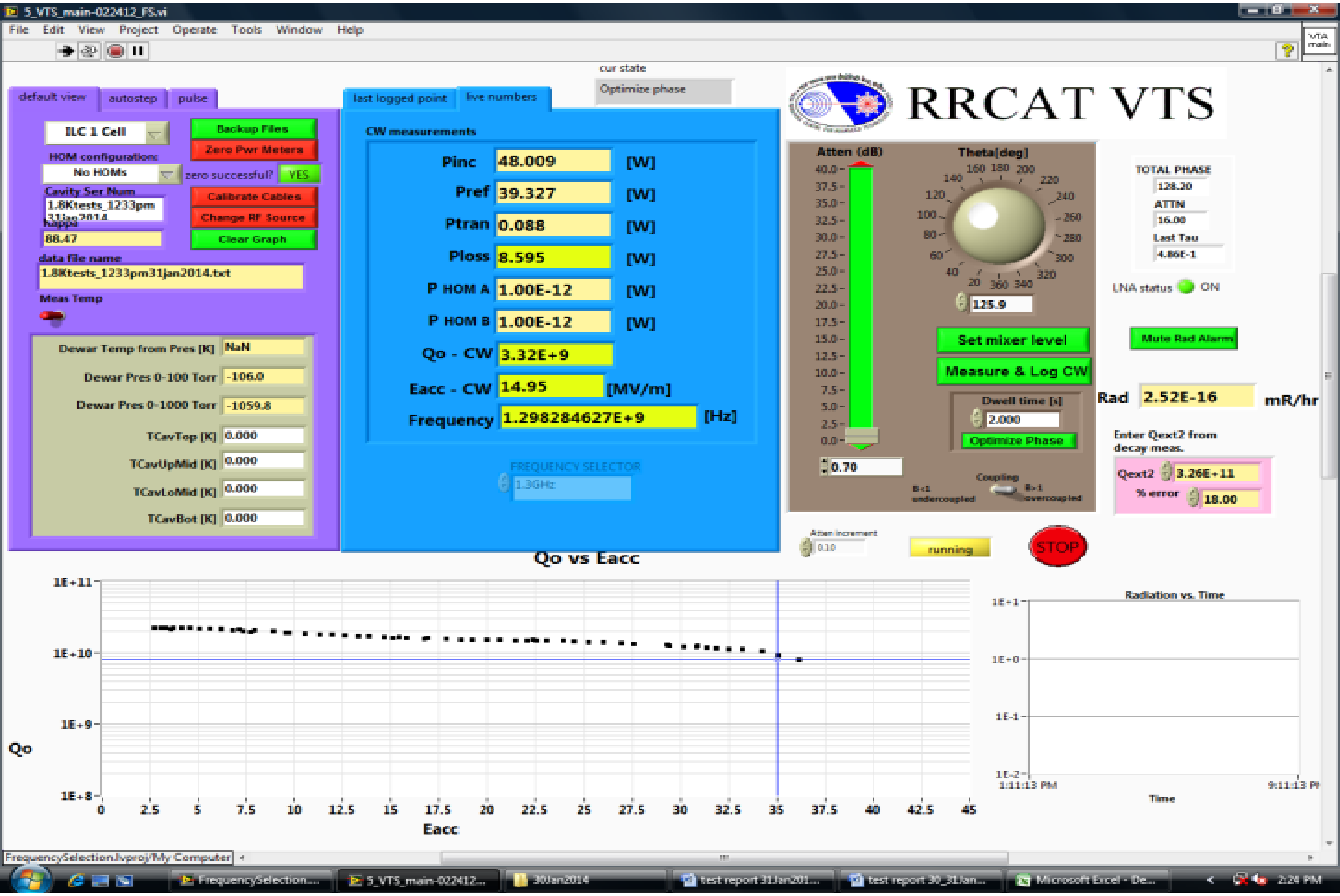
9. The incident power is slowly increased and the Q_0 and Eacc values are plotted till the cavity quenches.

Cavity Quench

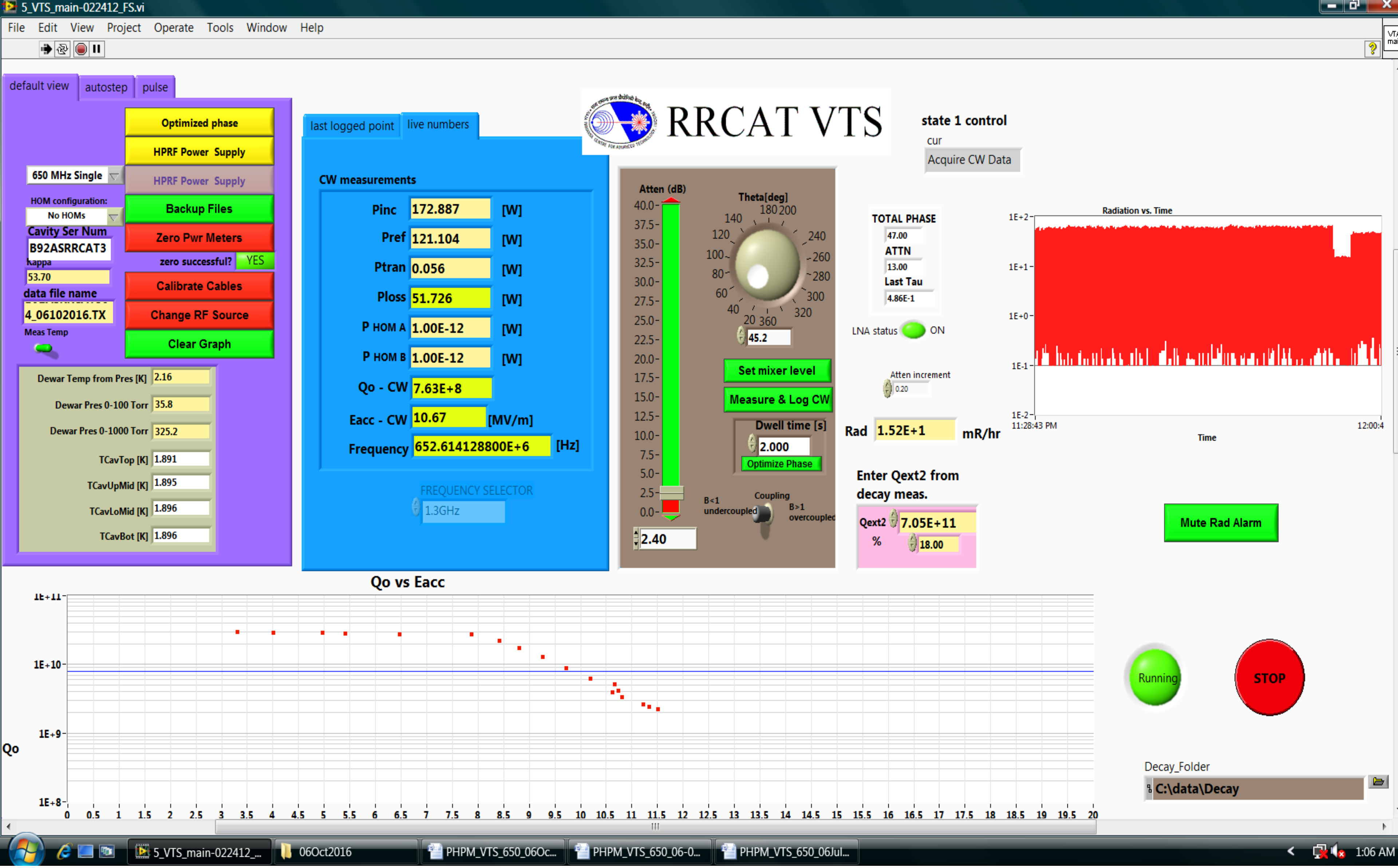
•In VTS tests the incident power is slowly increased till SRF cavity quenches (loses super conductivity) to determine the maximum gradient the cavity is able to handle.

• At quench the transmitted power signal suddenly dips to minimum as the cavity loses super conductivity and all the stored energy is dissipated, and then again starts increasing after some time as cavity cools and regains its superconductivity with cooling (see Fig. below). The test is concludes after the quench point is determined.

The P_{FP} of the transmitted power signal as observed on a peak power analyzer during quench conditions. The phenomenon is repeated periodically.



Result of first successful 1.3GHz single cell cavity test at RRCAT VTS

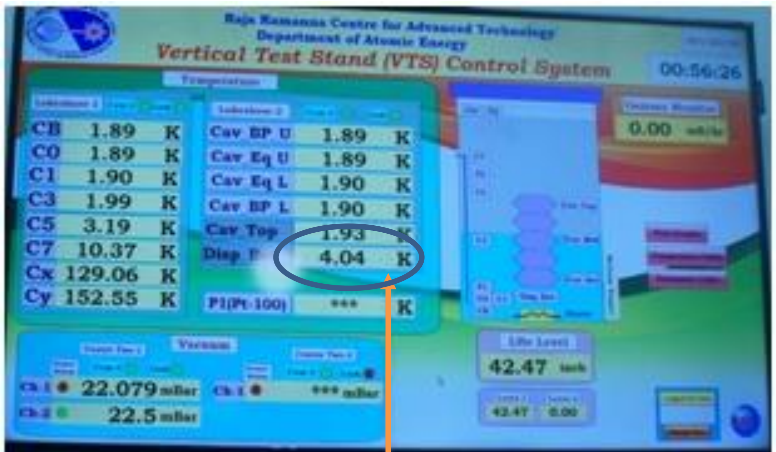


Result of VTS test conducted on 650 MHz single cell Beta = 0.92 cavity at RRCAT VTS

Problems encountered and experience gain

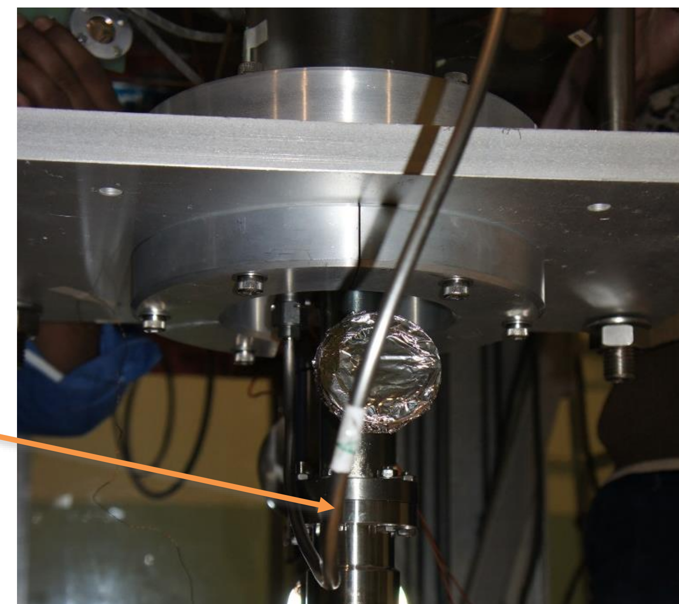
Electrical break down in the cable-coupler junction.

The incident power cable has Type-N male connector which is connected to the Type-N female connector of the cavity coupler. This connection is immersed in liquid Helium at 2K. During several test of 650 MHz single cell cavity we have observed that under conditions of high reflection from cavity the electrical break down occurs in this space

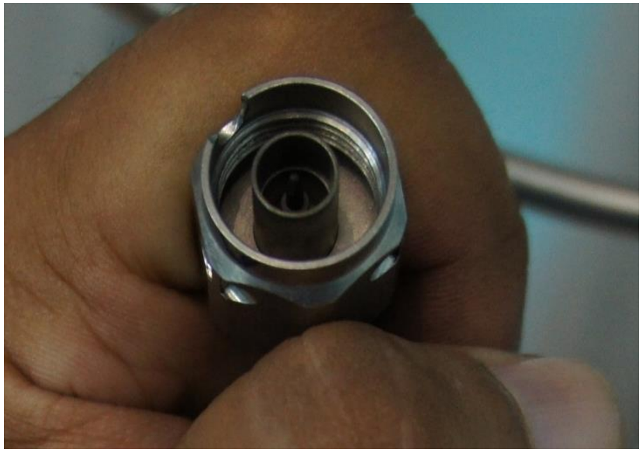


Sensor connected to N-type connector

Incident Power RF cable



- This phenomenon occurs ~80 W of forward power under high reflection from cavity.
- In consultation with FNAL USA, it was understood that this problem can be somewhat minimized by drilling holes in the RF connectors to improve Helium Flow.
- The drilling of holes was done; the breakdown shifted from ~80W to ~120W for the same cavity coupler combination.
- The electrical breakdown when happens **causes power loss without increase in radiation.** The software will show a drop in quality factor of the cavity as it will treat the power loss is happening inside the cavity.



Left image show the hole drilled in the coupler connector, right image is of N-Male connector of incident power cable, which is cut at the hole location to allow Helium Flow.

The incident power cable calibration changes during tests

- The Quality factor measurement of the cavity in VTS is done by measurement of the Pi, Pr and Pt and calculating power loss (Pi-Pr-Pt). The power loss value calculated thus is used for calculation of intrinsic quality factor of the cavity. The accuracy of this Quality factor measurement depends upon the precise measurement of cables loss.
- The problem is that the incident power cable has different loss at different power levels and at different reflection conditions. For a single cell cavity test we may have to provide power up to 50W while the initial cable calibration is done at ~100mW. The cable loss increases due to increase in temperature.
- In RRCAT VTS to mitigate this problem we perform calibration of incident power cable at various power levels to ensure the loss value used is reflective of the actual loss being provided by cable.

Thanks

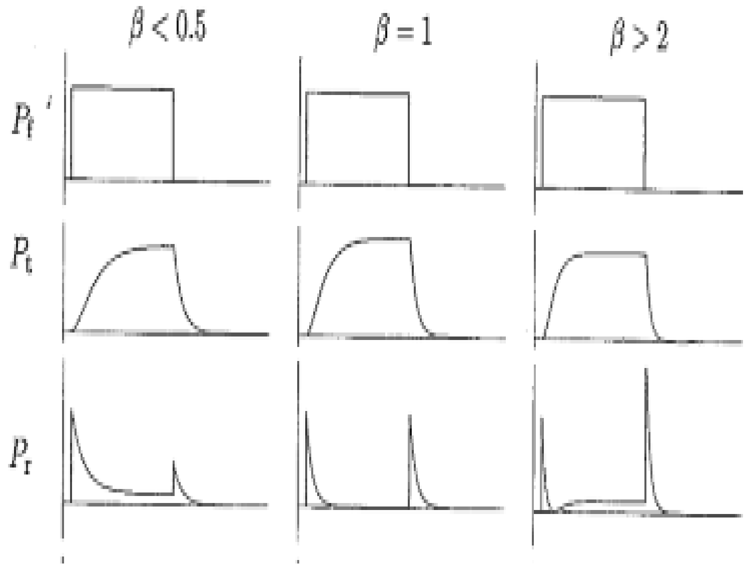
Extra Slides

- $\frac{1}{Ql} = \frac{1}{Qic} + \frac{1}{Q_0} + \frac{1}{Q_{FP}}$
-
- $Q_{0.}Pl = Q_{FP}.P_{FP\,=}\,\omega U$
- $Q = \omega.t_{decay}$

Incident and transmitted power couplers for 5 Cell 650 MHz cavity

Cavity coupling determination

- Cavity's coupling is determined by reflected power pulse shape. This is very important because entire calculation is depend on it. Reflected power pulse shape is given in fig 1. for different coupling.



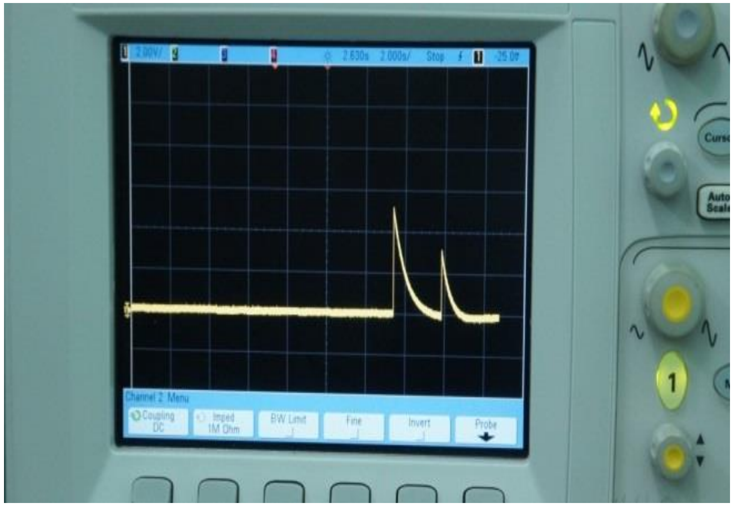


Fig. 2 - Reflected power pulse shape during test that shows cavity is under coupled.

If $\beta < 1$ then cavity is under coupled

$\beta = 1$ then cavity is critically coupled

$\beta > 1$ then cavity is over coupled

Decay measurement

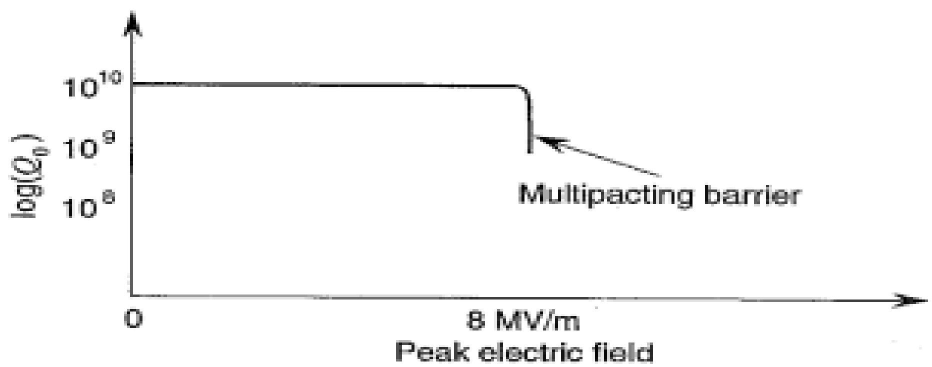
•Decay measurement is performed in order to calculate decay time of cavity and eventually field probe coupler's quality factor.

•The decay measurement is performed with cavity under lock conditions, the decay time τ is measured using a peak power analyzer from the decay waveform of P_{FP} signal. In this measurement RF power is switched off and decay of transmitted power signal is observed. The decay of transmitted power to -4.34dB gives the value of decay time.

• In this step field probe coupler's quality factor and coupling factors are calculated.

Problems that can occur during testing

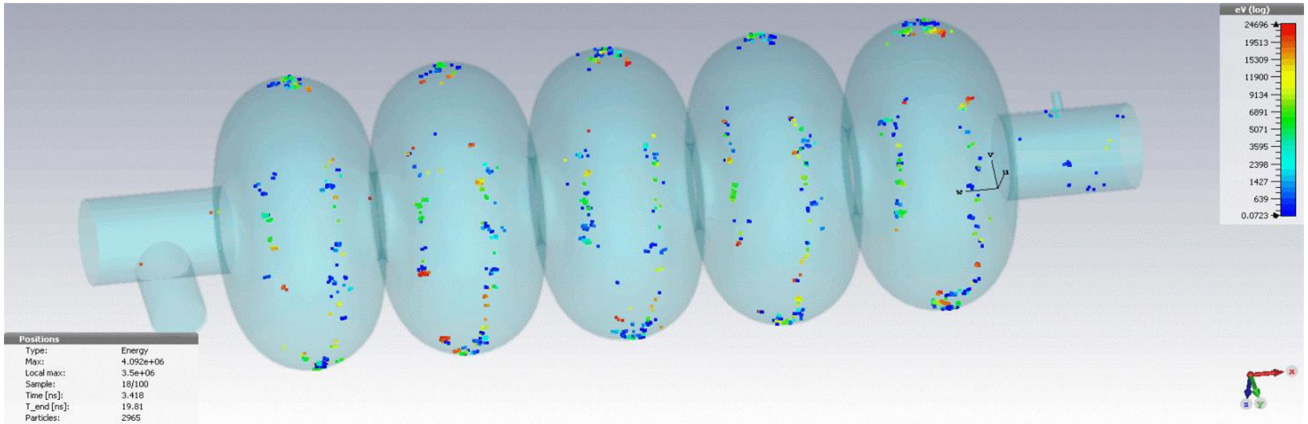
Multipacting :- Multipacting in rf structure is a resonant process in which a large number of electrons build up an multipacting, absorbing RF power so that it becomes impossible to increase the cavity field by increasing the incident power.

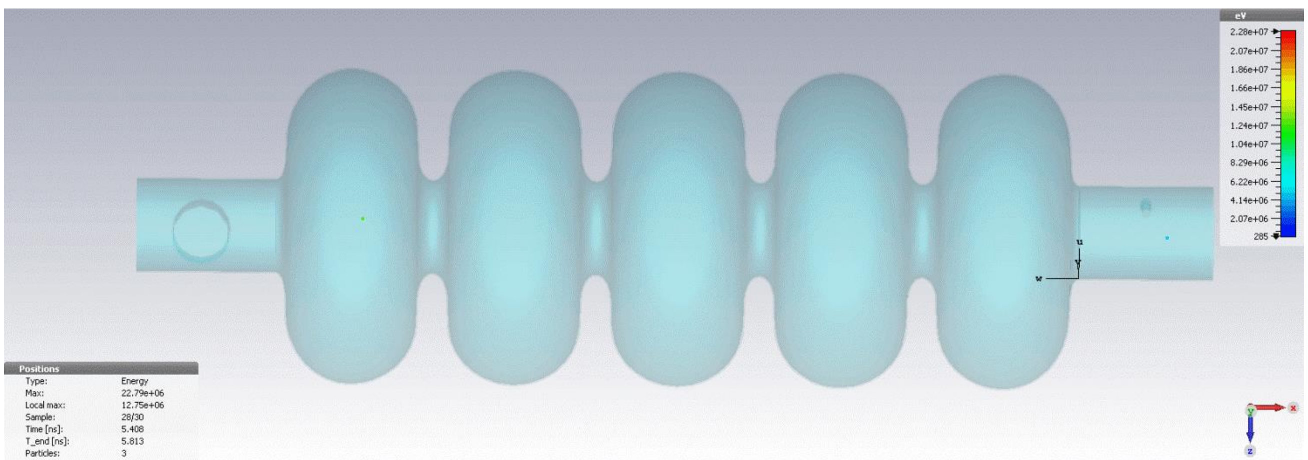


•One-surface MP is no longer a significant problem for elliptical shape structures

•However, two-point MP does survive near the equator of the elliptical cavity because the electron energies remain between 30 and 50 eV near the unity crossover of secondary yield. For analytic approximations to the fields in the equator region and resulting two-point MP

Multipacting animation





As multipacting is resonant process so it occured at some particular field level. In first animation particles are generated and then multipacting occurs but in second animation particles are swept by electric field.

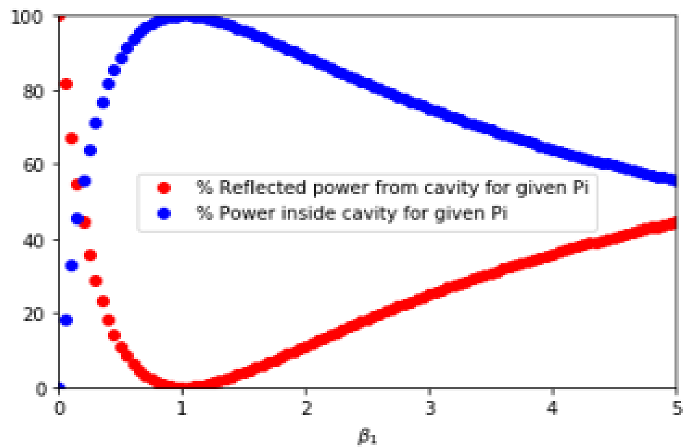
- Apply amplitude modulated RF power to process the multipacting.

Thermal breakdown and field emmision

- Thermal breakdown (quench) originates at sub-millimeter size regions that have rf losses substantially higher than the surface resistance of superconductor. These regions are called defects.
- RF current flows through the defect and produce joule heating.
- When the temperature at the outside edge of the defects exceed Tc, the superconducting region surrounding the defect becomes normal conducting resulting in increased power dissipation and eventually quench occurs.
- Defects must be avoided in order to prevent thermal breakdown.

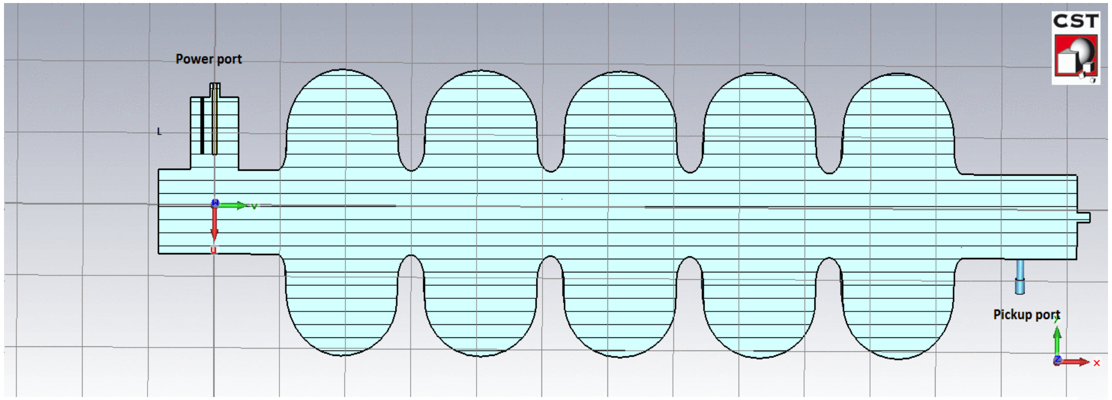
RF couplers designing for VTS test.

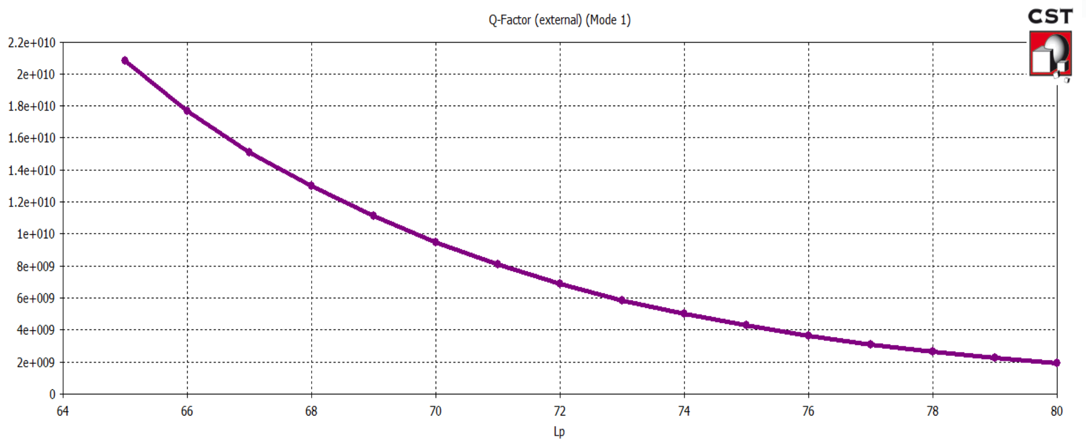
Coupling factor:- Coupling factor of power and pick up couplers are very important as power that can sustained by N- type connector at 30 mbar is limited by around 120 W. Coupling factor

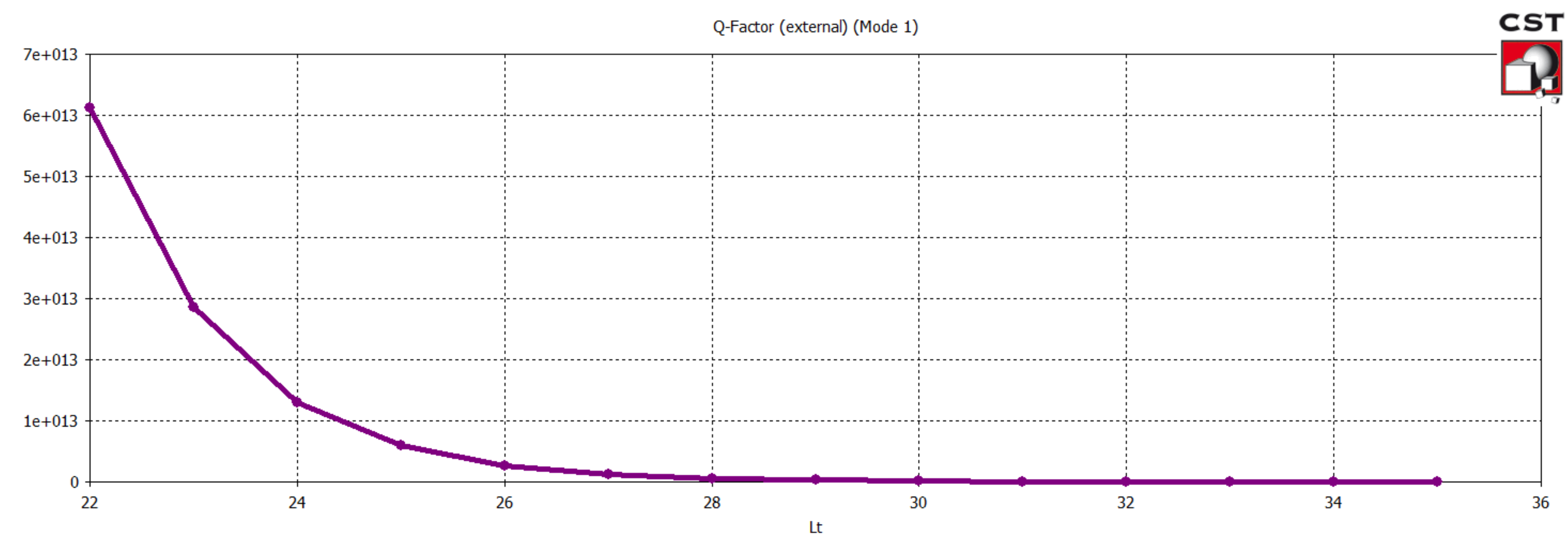


When the electric field gradient increases in the cavity, it's quality factor decreases due to heating. So if the cavity is under coupled (β1< 1) at low gradient, it will be more under coupled at high gradient. But if the cavity is over coupled (β1 > 1) at low gradient, it will be closer to critically coupled (β1 = 1) at high gradient. So an ideal condition would be that at start of the test the cavity must be overcoupled and it should be critically coupled at the design gradient. So an ideal starting low power value for β1 could be between 1.5 to 2.

Five cell 650 MHz, beta 0.92 cavity's couplers design






Q-Factor (external) (Mode 1)
CST
7e+013
6e+013
5e+013
4e+013
3e+013
2e+013
1e+013
0
22
24
26
28
30
32
34
36
Lt