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Progress report for the second cold test of crab cavity for the HL-LHC Project experiments

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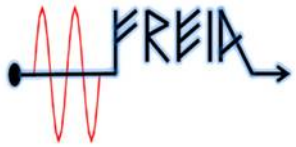

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Abstract

The test of Double-Quarter Wave (DQW) crab cavity NWV01 was done in GERSEMI vertical test stand at FREIA laboratory in the beginning of 2023. This cavity was already tested in FREIA before (in September, 2020 [1]) with an old Valve Box configuration. This time the main goals were three-fold: study the effect of having no active pumping on the cavity in between tests, to demonstrate that the facility can keep a certain temperature gradient during cooling down and perform cold test, and knowledge transfer of the procedure for measuring cavities.

1 Introduction

The major upgrade of the Large Hadron Collider (LHC) at CERN towards High-Luminosity LHC (HL-LHC) will employ crab cavities to actively optimize the peak luminosity. These crab cavities are based on superconducting Radio Frequency (RF) cavity technology and their deployment for a hadron collider is a new challenge of this research field.

The FREIA laboratory has been involved in prototyping activities on one of the crab cavities, so-called Double Quarter Wave (DQW) resonators.FREIA laboratory developed a vertical cryostat for superconducting cavity measurement and the crab cavity was the first project to use this new cryostat. In 2020, FREIA successfully performed a cold test of a prototype crab cavity (NWV01 [1]) and identified several issues to be improved, such as vacuum leak, controlling thermal gradient during cooling down, and arcing in an RF feedthrough [1]. In 2021, another experiment was planned after CERN cleaned the cavity with high pressure water rinsing and issues identified in 2020 were all solved [2]. However, another major issue was revealed due to the transportation of the cavity from CERN to Uppsala. A pick-up antenna fell off during the transport and this gave rise to potential scratches on the cavity inner surface. The cavity was transported back to CERN where the antenna connection was consolidated and the transport box was also improved. This report describes the results of the second attempt in 2023 to perform the cold test of the same crab cavity. The objectives include evaluation of all the improvements that have been implemented for three years.

2 Experimental Setup

The GERSEMI cryostat with liquid insert was used for the cavity test. Details of the test from the cryogenic point of view are given in [3]. RF reception test was done in two stages. First, after cavity was extracted from the transportation box, HOM modes triplet were observed at 1.83 GHz, 1.85 GHz and 1.88 GHz. When the cavity was mounted on the insert frame, the fundamental mode was also measured at 402.6 MHz using a 30 dB preamplifier.

The next step is the build up of the RF circuit. The setup for cavity characterization is shown in figure 1. To track cavity resonance, a Phase Lock Loop (PLL) provided by CERN was used, where all RF inputs should be down-converted below 60 MHz by a local oscillator so that the PLL can lock the cavity resonance.

For precise characterization of a resonator, the attenuation of all RF paths need to be measured, including the RF power meter's calibration. Calibration procedure can be divided in

[1] named as *NioWave001* in FREIA logbook

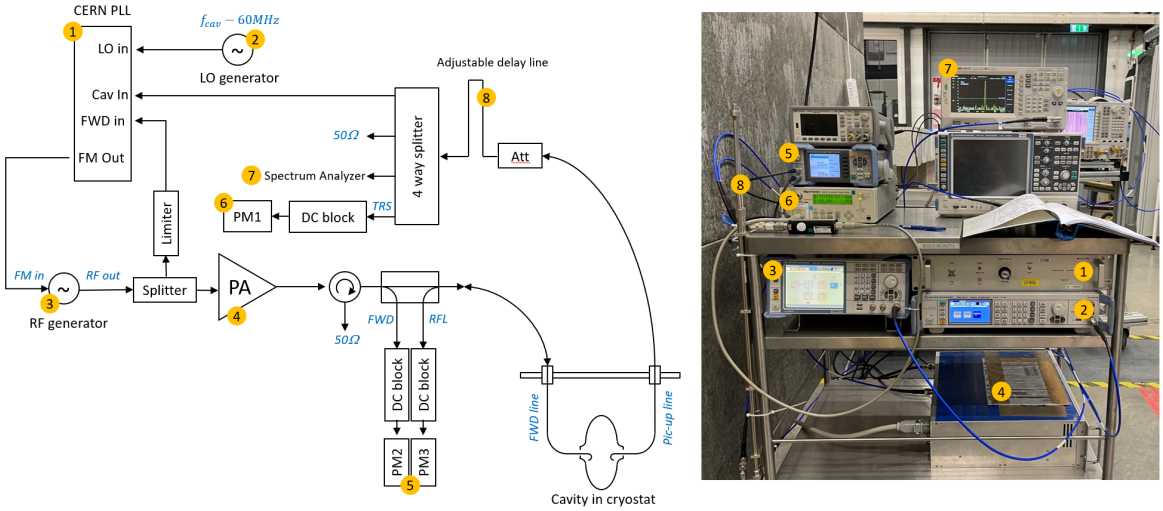

Figure 1: Setup for cavity characterization. 1 - CERN PLL box, 2 - local oscillator, 3 - main RF generator, 4 - power amplifier, 5 - power meters for forward and reflected power, 6 - power meter for transmitted power, 7 - spectrum analyzer, 8—phase shifter (trombone).

two components: calibration of warm and cold parts. The warm part includes all acquisition equipment and RF transmission lines up to the cryostat's flanges. The cold part includes all RF transmission lines and the cavity inside the cryostat. "Cold" calibration should be done when the cavity is successfully cooled down.

In order to reach maximum RF performance, a superconductive cavity should be cooled down (specially during phase transition) with a minimal possible ambient magnetic field. For this reason Gersemi is equipped with active compensation coils. We can compensate the earth's magnetic field in a 60×60×60 cm volume down to < 2 μT along the cryostat's axis. For real time monitoring of the residual magnetic field a dedicated cryo rated sensor was mounted on one of the cavity's flanges.

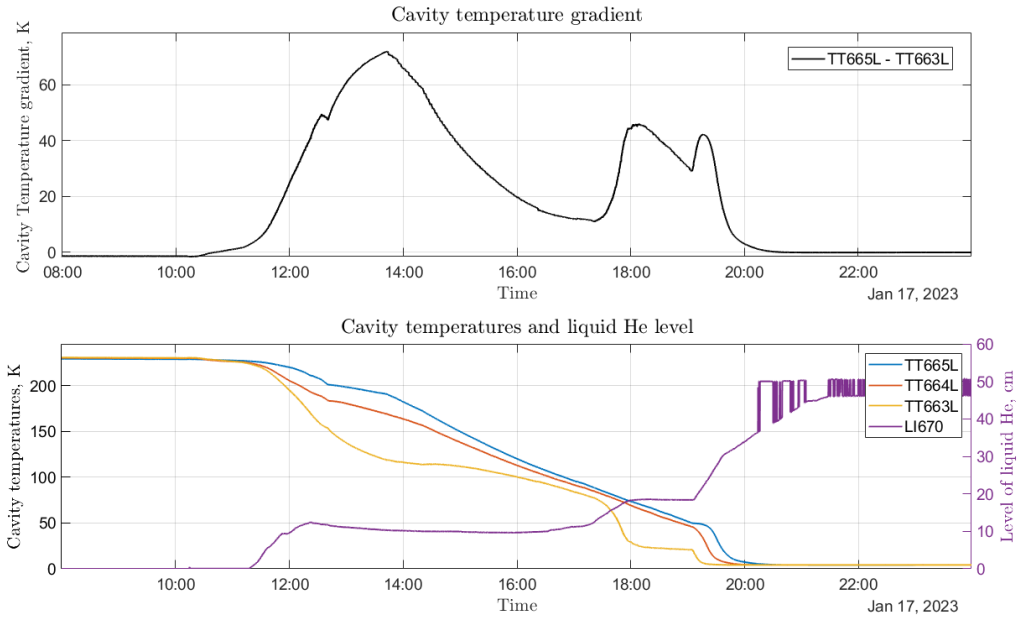

Figure 2: Detail of the cooldown of the cavity to 4 K wrt temperature and liquid helium level in the cryostat.

Regarding radiation protection, the Vertical cryostat and all its instrumentation were covered by high density concrete blocks to prevent radiation leakage. A radiation sensor was mounted on the top for real time monitoring. The maximum value of radiation during the test was 8.43 μSv/h at 2.62 MV.

3 Cooldown

The cool down process from room temperature to 4 K is shown in figure 2. The maximum temperature gradient along the cavity, i.e. the difference between the temperature at the top and the bottom of the cavity, was 72 K.

To cooldown from 4 K to 2 K, we as usual pump down the helium circuit from atmospheric pressure to ca. 35 mbar, which corresponds to a cavity temperature of 2 K. Pumping time was around 21 hours. During the pumping we recorded the relative shift of the cavity's resonance frequency, see figure 3. From this graph, the cavity's pressure sensitivity can be derived, being 12 Hz/mbar. It can be also seen that this pressure to frequency curve obeys a linear behavior, which represents a smooth cavity deformation. The points spread outside the line are VNA setup artifacts and not to be taken into account for the calculations.

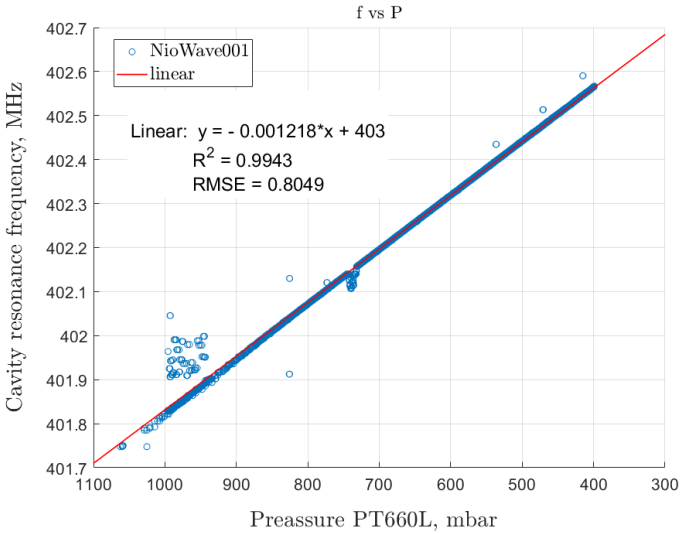

Figure 3: Change of cavity resonance frequency during the pumping of the Helium circuit (2 K pumping). Cavity's pressure sensitivity is 12 kHz/mbar.

4 Cavity performance

Determining the quality factor Q_t of a field probe (pick-up antenna) is a crucial part of a vertical test and is called "Q_t calibration". Q_t defines a precision of deriving a stored energy in the cavity U, which is necessary for calculation of cavity deflection voltage. To get an accurate result Q_t calibration should be performed at low deflection voltage and minimum of reflection power. Unfortunately, this type of cavity has a strong multipacting barrier below 0.5 MV, so the cavity's field probe calibration was done at 1 MV of deflection voltage. Seemingly this is too high, but as observed later, the Q_t value stayed the same in the range from 0.6 MV to 1.4 MV. The results of Q_t calibration are shown in table 1.

Regarding the cavity's quality factor Q_0, Figure 4 shows the measured Q_0 of the cavity versus the deflection voltage V_t for two different scans (blue and violet points), together with

Table 1: Cavity's field probe coupling calibration.

Parameter	Value	Units
Centering frequency f_c	403.001	MHz
Forward Power P_{fwd}	0.308	W
Reflected Power P_{ref}	0.100	W
Transmitted Power P_{trm}	0.001	W
$\beta_{overcoupled}$	3.674	
$\beta_{pick-up}$	$5.41 \cdot 10^{-3}$	
Q_0 calibration	$1.25 \cdot 10^{10}$	
Q_t calibration	$2.31 \cdot 10^{12}$	
Q_{ext} calibration	$3.41 \cdot 10^{9}$	

the influence to Q_t calibration when using different deflection voltages for its calculation (red points). A flat behavior of Q_0 around $1.3 \cdot 10^{10}$ from 0.5 MV to 1.5 MV can be observed. Although our preliminary setup is not equipped with an X-ray detector inside the cryostat to monitor the radiation dose from the field emission, the exponential increase of the helium flow (FT551, represented as orange points) from the 2 K bath, starting from 1.5 MV, confirms that a significant amount of power has been dissipated in the cavity due to the field emission. For the first scan (blue points), the cavity reached 2.6 MV with Q_0 dropping down to $\sim 1.45 \cdot 10^9$, while for the second scan (violet points) an even faster degradation in the cavity performance can be observed.

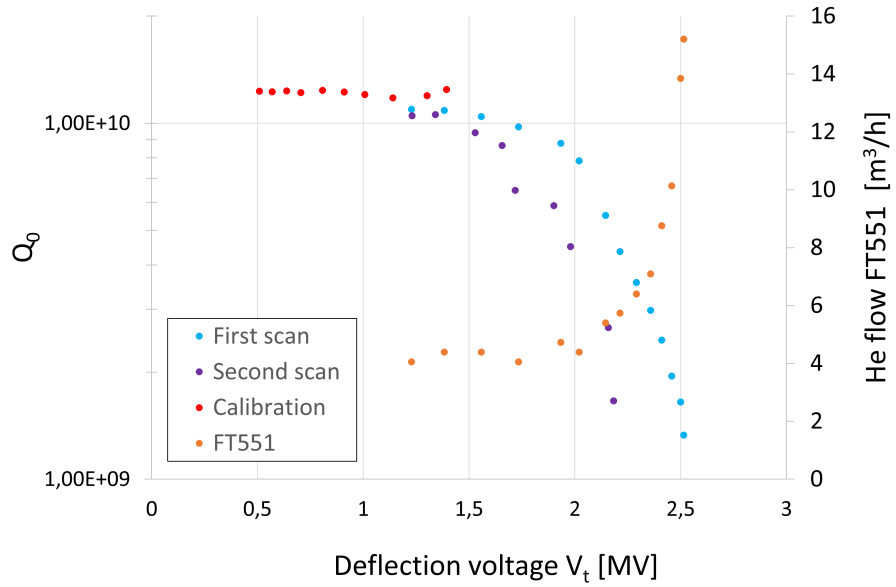

Figure 4: Q_0 versus deflection voltage V_t curve. Red points: calibration; blue points: first scan; violet points: second scan; orange points: helium flow from the cavity.

5 Results

A performance of the same cavity has been measured at different institutions, see Figure 5. Experimental results from previous tests at CERN show a degradation of cavity performance from test to test, which can be explained by inner surface contamination during vacuum connection and operation. The flat top of Q_0 versus V_t curve observed in the current test show better performance than in older tests, until we reach the field emission onset.

After the previous cavity test at FREIA, when the fallen pick-up antenna was found, the cavity was reassembled at CERN after modifying the pick-up port to be more robust and after

an additional high pressure water rinsing of the cavity's surface. We assume that the fallen antenna scratched the inner surface of the cavity during transport, and that this surface's damage may be impossible to be eliminated without a chemical surface treatment. Thus, the remaining surface damage might be what caused the high field emission.

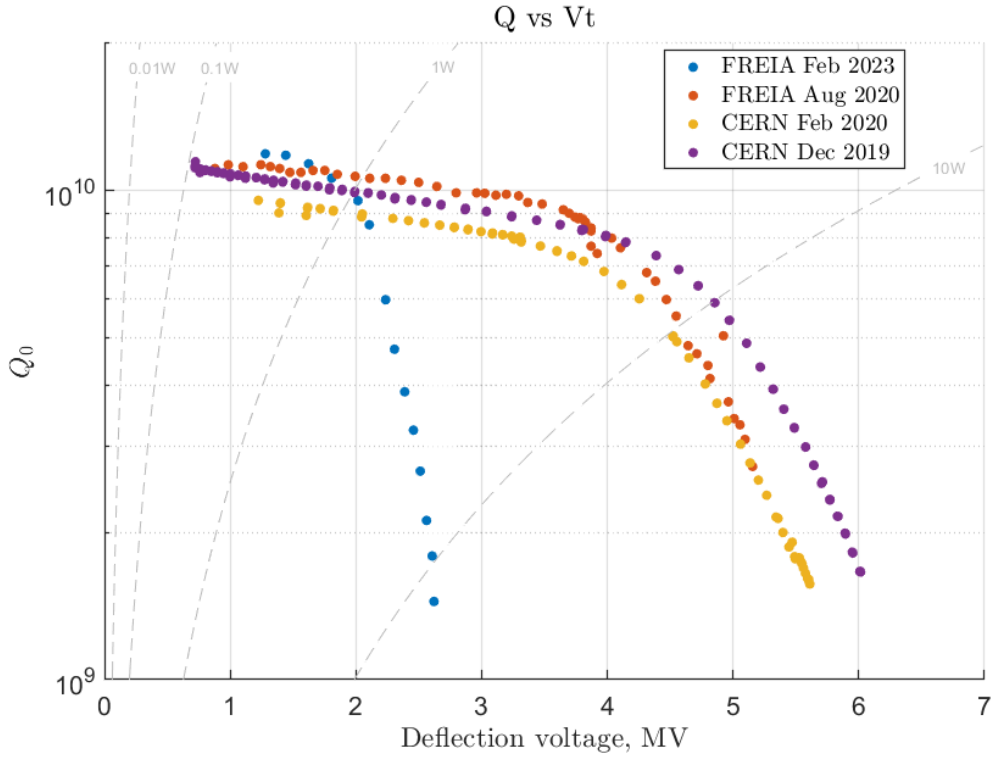

Figure 5: Comparison Q_0 vs V_t plot of the NioWave001 Crab cavity

6 Conclusions

Since this CERN prototype crab cavity has been tested at FREIA and at CERN, it has given the opportunity to cross-validate measurement techniques, testing setups and conditions, and has given the possibility to investigate the cavity's performance during multiple openings of the cavity's beam vacuum.

One of the newly found weak points in the testing chain is the transportation of superconductive cavities over long distances, which has a higher risk than handling the cavities once they are at the test facility. Mechanical vibrations and shocks during transportation can cause the structural damage of fragile instrumentation such as RF antennas. It can not only change the coupling strength of antennas but it may also damage the cavity's inner surface, making it impossible to reach high acceleration gradients. To restore the cavity's performance after contact of instrumentation with its inner surface, a combination of high pressure water rinsing and chemical surface polishing is mandatory.

7 Acknowledgments

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