TEST CHARACTERIZATION OF SUPERCONDUCTING SPOKE CAVITIES AT UPPSALA UNIVERSITY

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Abstract

As part of the development of the ESS spoke linac, the FREIA Laboratory at Uppsala University, Sweden, has been equipped with a superconducting cavity test facility. The cryogenic tests of a single and double spoke cavity developed by IPN Orsay have been performed in the new HNOSS horizontal cryostat system. The cavities are equipped with a low power input antenna and a pick-up antenna. Different measurement methods were investigated to measure the RF signal coupling from the cavity. Results from the tests confirm the possibility to transport the cavities from France to Sweden without consequences. We present the methods and preliminary study results of the cavity performance.

INTRODUCTION

After decades of studies, spoke cavities are considered compact structures at low frequencies and having an excellent RF performance in both low and medium velocity regimes. These advantages make them attractive for modern accelerator facilities, including the ESS proton accelerator where double-spoke resonators (DSR) will be used for the medium energy section [1].

The Facility for Research Instrumentation and Accelerator Development (FREIA) is developing the RF system for ESS superconducting spoke cavities. This project contains three phases: (1) test of the first RF source, (2) test of the prototype cavity and (3) test of the prototype cryo-module [2]. In the second phase, the bare spoke cavity is tested at low power-level to confirm its vertical test performance at IPN Orsay. Then, a spoke cavity equipped with an RF power coupler will be tested at high power with the tetrode-based RF system from phase 1. Since self-excited loops have a lot of advantages for testing high gradient, high-Q cavities, FREIA developed a test stand based on a self-excited loop for demonstrating the performance of superconducting cavities at low power-level.

Table 1: Main Parameters of Spoke Cavities

Parameter	Hélène (SSR)	Germaine (DSR)
Frequency (MHz)	360	352.2
Beta (optimal)	0.2	0.5
R/Q_0 (Ω)	117	426
E_{pk}/E_{acc}	6.56	4.33
B_{pk}/E_{acc} $(mT/MV/m)$	13.4	6.89
G (Ω)	89	130

We received a single spoke cavity (Hélène) and a double spoke cavity (Germaine) from IPN Orsay, and performed cold tests at FREIA to validate our test protocol, hardware and cryo system. Test results in FREIA are consistent with the ones obtained at IPN Orsay [3]. Table 1 shows the main RF properties of the two spoke cavities [3,4].

CRYOGENIC TESTING

The cryogenic testing of both cavities was carried out at FREIA using the self-excited loop test stand shown in Fig. 1. In the loop, the cavity is a narrowband filter and starts from noise to oscillate by itself. In this way, the cavity field amplitude is unaffected by the ponderomotive instability and there is no need for an external frequency source and tracking feedback. Therefore, the self-excited loop is ideally suited for high gradient, high-Q cavities operated in continuous wave (CW) mode [5].

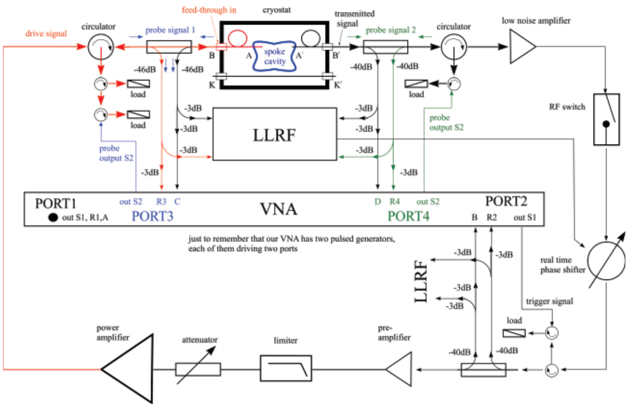

Figure 1: Schematic of the FREIA self-excited loop.

With this test stand, the loop can be tuned by 40 dB variable attenuation and 270 degree trombone phase shifter, and can reach up to 100 W CW power and 100 dB maximum gain. A digital phase shifter is under development. Also a new high-precision measurement of super-conducting cavities quality factor has been studied [6].

Two cavities are set inside the new HNOSS horizontal cryostat system at the same time [7]. Six identical cryo-cables are installed inside the cryostat; four of which connect the cavity ports with RF feedthroughs on a cryostat flange, while the other two cables connect back to back with a RF through as reference. The warm part of the system is calibrated using a vector network analyser (VNA) with two-ports S parameters, together with a power meter for power calibration. By connecting the

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VNA to the reference cryo-cables and extracting the S parameters the cold part can be calibrated. Afterwards the effect of each cable separately is calculated by transfer matrices (T-matrices), then converted to S-matrices and finally de-embedded in the VNA.

The 4 K experiments were carried out first, followed by a cool down to 2 K. During this cool down, frequency and Q_0 measurement are performed in order to measure pressure sensitivity and the residual resistance. Finally, tests at 2 K are performed.

Gradient Measurement

Both cavities are equipped with a fixed-length low power input antenna and a pick-up antenna. By decay time measurement at 4 K the external quality factor of the input antenna Q_{in} is measured to 1×10^9 for the Hélène cavity and 1.6×10^9 of Germaine. The measured Q_0 of both cavities as a function of accelerating gradient is shown in Fig. 2 and 3. In the vertical test, the low-field Q_0 factor of Hélène reached 6.8×10^9 at 2 K and 1×10^9 at 4 K, while these values for Germaine are 1.6×10^{10} and 2×10^9 for 2 K and 4 K, respectively. The tests at 4 K are limited by maximum RF input power, both for Hélène and Germaine.

In both cold tests, we encountered multipacting barriers at low field level. In order to pass them, we set the lowest attenuation to obtain the highest gain to amplify the small signal as quickly as possible. Once the loop has gone through a barrier, reflection goes down and forward power increases but is limited by limiters and the maximum amplifier output.

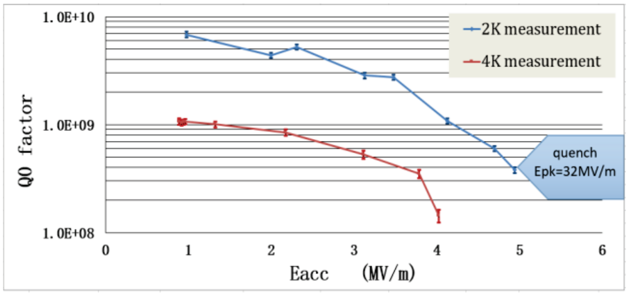

Figure 2: Low power summary of Hélène (single spoke).

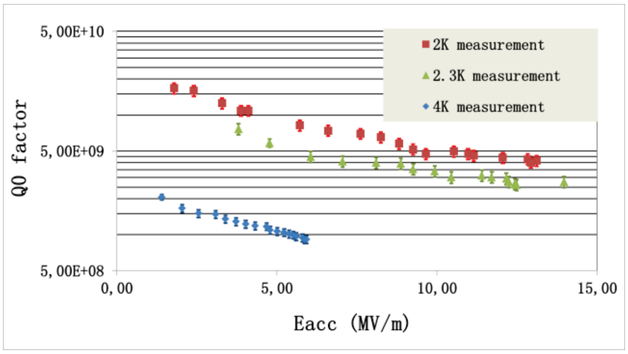

Figure 3: Low power summary of Germaine (double spoke).

In the measurement of Hélène 2 K, we encountered a thermal quench at accelerating gradient of E_{acc}=5 MV/m, corresponding to a peak surface electromagnetic field of E_{peak}=32 MV/m, and a peak magnetic field of B_{peak}=66 mT/(MV/m). The quench traces for the forward, reflected and transmitted power are shown in Fig. 4. In a self-exited loop, when the cavity encounters a thermal quench, the dissipated power at the cavity walls creates a normal-conducting surface region and the Q-factor goes down quickly. The power of the signal that runs in the loop also goes down due to the unmatched coupling of the cavity. This means that the dissipated power on the cavity wall becomes much smaller and less heat is generated. Once the field level is low enough, the cavity cools down and again turns superconducting. Consequently, the loop signal increases until the next thermal quench occurs. The process resembles a Q switch turning on and off regularly [8].

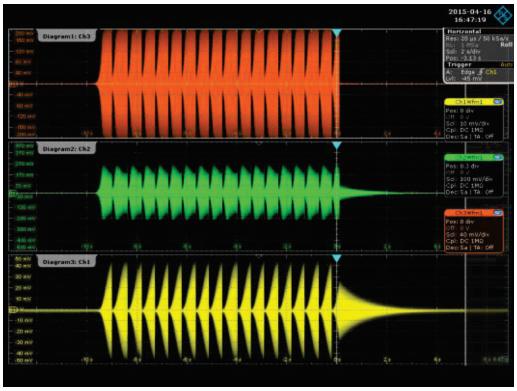

Figure 4: Transient trace of Hélène under Q switch at 2 K, where red (top), green (middle) and yellow (bottom) signals are the forward, reflected and transmitted voltage, respectively.

Residual Resistance

The surface resistance R_s of a niobium superconducting cavity is the sum of the Bardeen-Cooper-Schrieffer (BCS) surface resistance R_{BCS} and the residual resistance R_{res}, which fulfils [9]

$$R_s = R_{BCS}(T) + R_{res} \qquad (1)$$

On the other hand, the formula $G=Q_0\times R_s$, where G is the so-called geometry factor, depends only on the cavity shape and R_s could be determined by measuring the Q_0 factor as a function of temperature. The surface resistance vs temperature curve at a fixed gradient is taken during cool down from 4 K to 2 K and is shown in Fig. 5. Here, the BCS resistance is calculated by the approximated formula given by equation 4.43 in Ref [10].

Since the data below 100 mbar failed to save in the first measurement, the preliminary result of the surface resistance is above 2.5 K. In this measurement, the residual resistance of Germaine is no more than 15 nΩ.

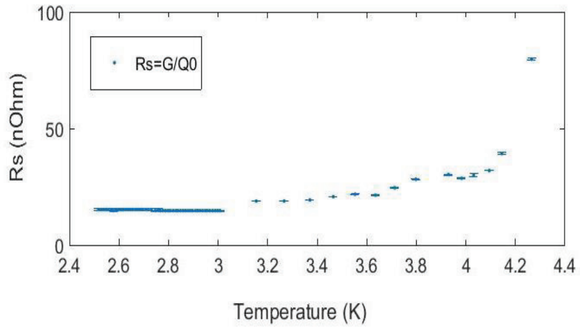

Figure 5: R_s vs. T measurement of Germaine at fixed gradient.

Pressure Sensitivity

Helium pressure fluctuations inside the tank detune the cavity resonance frequency. Measuring the frequency sensitivity to the helium pressure provides information on the mechanical stability of the cavity. There are several ways to carry out cavity mechanical stability measurements. One direct way is to measure the frequency shift while monitoring transient pressure at the same time, which requires a stable field level. Another simple way is to measure the resonance frequency shift when cooling down from 4.2 K to 2 K while the helium pressure is reduced from roughly one bar to 30 mbar.

Figure 6 shows how the helium pressure and resonant frequency of the cavities drift over a certain period. Note that both cavity vessels are fixed on a table by four points inside the cryostat and cavities are tested without a tuning system.

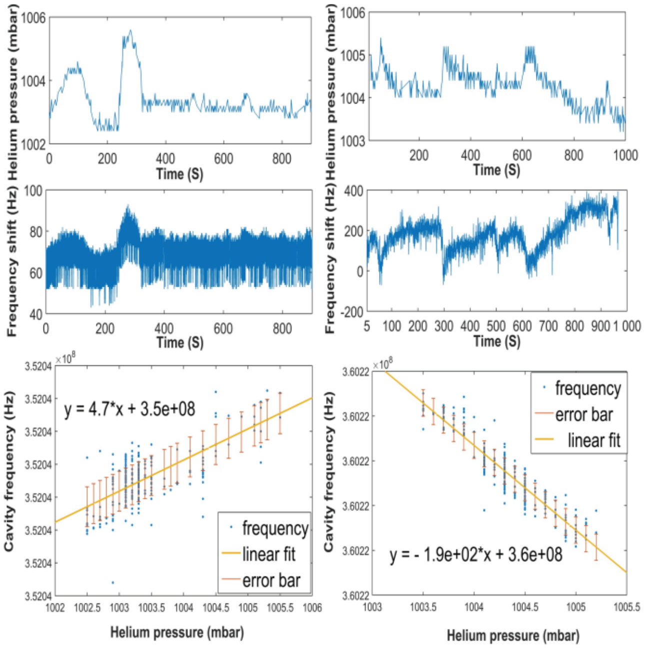

Figure 6: pressure sensitivity of Germaine (left) and Hélène (right), where top and middle graphs are the helium fluctuation and frequency shift, respectively.

In the measurement we determined Hélène's pressure sensitivity to be -190 Hz/mbar. This result is consistent with the -200 kHz frequency shift measured during cool down from 4.2 K to 2 K and the corresponding pressure reduction from 1000 mbar to 30 mbar. For the double spoke cavity Germaine we measured +4.7 Hz/mbar, which is consistent with the 5 kHz frequency shift from 4.2 K to 2 K.

Lorentz Force Detuning

Static Lorentz force detuning of the spoke cavities was studied at FREIA. RF power deforms the walls of the spoke cavities, which generally results in a reduction of resonant frequencies. The frequency shift is proportional to the square of the accelerating field and the proportionality constant K_L is the Lorentz force detuning coefficient. This frequency shift is usually small but the effect of pressure sensitivity must be taken into account in order to achieve higher accuracy. When measuring the static Lorentz force detuning, both spoke cavities are kept at different power levels over a certain period while keeping track of the helium pressure. Then, the frequency shifts for different accelerating gradients at the same pressure situation are recorded for analysis.

The static Lorentz force detuning measurement at 4 K of Hélène and Germaine are shown in Fig. 7 and 8, respectively. These values are lower than those obtained through simulations, a difference which we attribute to the mechanical support of the cavities in the cryostat.

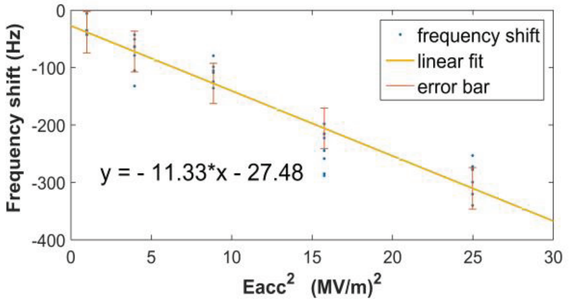

Figure 7: static Lorentz detuning curve of Hélène.

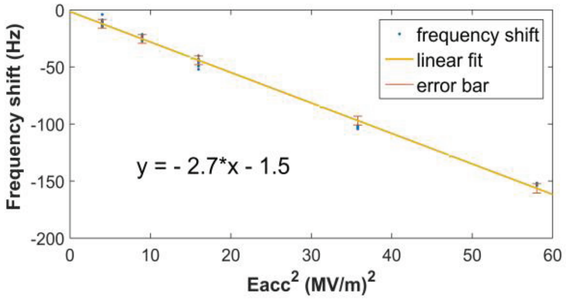

Figure 8: static Lorentz detuning curve of Germaine.

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Microphonics

We studied microphonics by operating the cavities in the self-excited loop and monitoring to the signal with a Rohde & Schwarz (RTO 1024) oscilloscope with a built-in I/Q demodulation option. Subsequent off-line analysis of the demodulated signal reveals the frequency as a function of time, as shown in Fig. 9. By taking the Fourier transform we finally get the microphonics spectrum from the measurement. A vibration mode of 8 Hz was found in both cavities. Next step is to continue investigating where the undesired noise source come from.

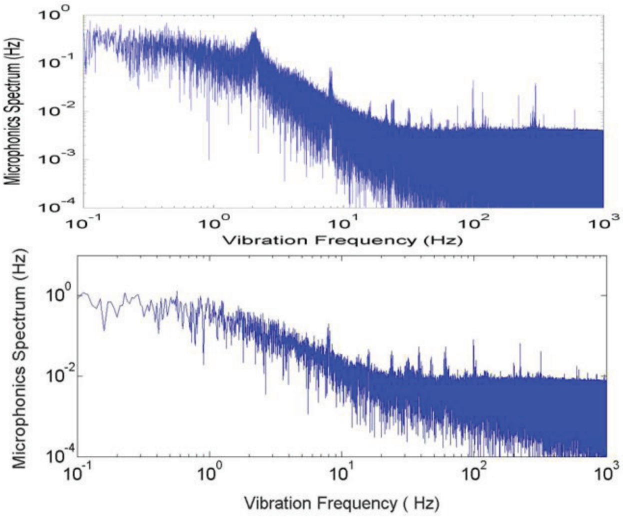

Figure 9: Fourier transform of the variation of the cavity frequency with time (microphonics spectrum). Hélène (up) measured at T=4 K, Eacc=1 MV/m and one bar, Germaine (down) measured at T=4 K, Eacc=2 MV/m and one bar.

CONCLUSION

We have developed methods to test superconducting cavities at FREIA using a self-excited loop after checking the hardware and cryo-system, and developing our test methodology. The first cavities we tested are the single spoke cavity Hélène and the double spoke cavity Germaine, both designed and built by IPN Orsay. Our test results are consistent with IPNO's. The test technology of low and high power test is still under investigation to increase the measurement accuracy.

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