RF TEST OF ESS SUPERCONDUCTING SPOKE CAVITIES AT UPPSALA UNIVERSITY

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Abstract

The European Spallation Source (ESS) is an accelerator-driven neutron spallation source built in Sweden. It will deliver the first protons to a rotating tungsten target by 2019 and will reach the full 5 MW average beam power in the following years. The superconducting Spoke cavities are considered compact structures at low frequencies and having an excellent RF performance in both low and medium velocity regimes, therefore ESS will include a total of 26 double-spoke cavities. The testing of the double-spoke prototype cavity at high power has been conceded to Uppsala University, Sweden, where the Facility for Research Instrumentation and Accelerator development (FREIA) has been equipped with superconducting cavity test facility.

A bare spoke cavity has been tested at the FREIA Laboratory with a self-exited loop at low power level to confirm its vertical test performance at IPNO. Similar test results as IPNO's previous test were obtained with FREIA system. In this paper we present the methods and preliminary study results of the cavity performance.

INTRODUCTION

The superconducting spoke section of the ESS linac accelerates the beam from the normal conducting section to the first family of the elliptical superconducting cavities [1]. This spoke section includes a single family of β=0.5 bulk niobium double spoke cavities, operating at a temperature of 2 K, and at a frequency of 352.21 MHz. A total of 26 spoke cavities are designed at IPNO and will be grouped by 2 in 13 cryomodules [2].

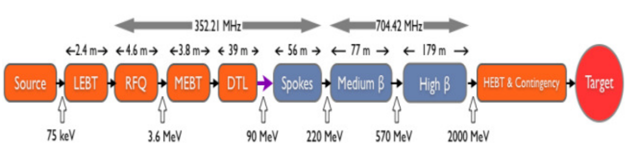

Figure 1: The layout of ESS accelerator.

The FREIA laboratory at Uppsala University is established in order to support the development of instrumentation and accelerator technology [3]. Since a self-exited loop has a lot of advantages for testing high gradient, high-loaded Q cavities. FREIA developed a test stand based on a self-exited loop for demonstrating the performance of superconducting cavities at low power level. One of the ESS spoke cavity prototypes, Germaine, has been tested in 2015 with the FREIA system.

CRYOGENIC TESTING

The cryogenic testing of double spoke cavity Germaine was carried out at FREIA with a self-exited loop test stand. We use a vector network analyzer (VNA) as receiver when running the SEL. To protect the system from radiation, the cavity is located in the bunker and a few meters from the control and measure system. The function of the VNA in this loop is double fold: it provides a convenient cable calibration and can also be used as receiver in the measurement. This way of using the VNA gives us both true powers and the phase information of signals even beyond the equipment limits. We also developed a digital phase shifter and gain-controller, based on NI FlexRIO FPGA and NI 5782R data acquisition modules. With this digital system, we can vary the loop delay with high-precision, from which we obtain the reflection coefficient as a function of loop delay.

This system was commissioned with a single spoke cavity Hélène from IPNO [4].

Gradient Measurement

The low power test of Germaine, which equipped with a fixed-length low power input antenna and a pick-up antenna, started in June 2015 and lasted until shipping it back to IPNO in January 2016. In general, the measurements could be divided into three runs. The measured Q_0 as a function of accelerating gradient is shown in Fig. 2.

The first run was performed in June. The 4 K experiments were carried out first and followed by cool down to 2 K. By decay time measurement at 4 K, Germaine shows the external quality factor of the input antenna of 1.6×10^9. The low-field Q_0 factor reached 1.6×10^{10} at 2 K and 2×10^9 at 4 K, respectively.

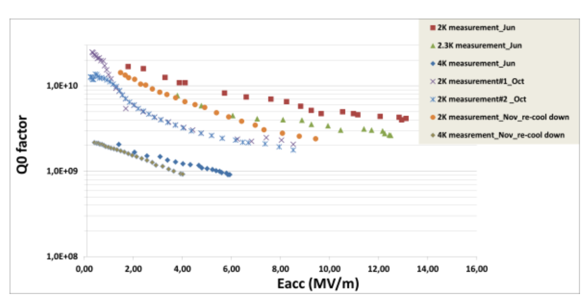

Figure 2: Q_0 factor vs. Eacc curve of Germaine at FREIA.

We also found the pick-up antenna was shorted with the cavity wall. The external Q value was roughly in the order of 1×10^{16}, which is much higher than the design

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value 1×10[12]. Such high Q_t led to super low transmitted power from the cavity, which requires a higher gain to run the loop also introduces a lot of noise into the system. Lots of multipacting barriers were encountered and caused unstable situation at low field level. In order to pass them, we set the lowest attenuation in order to obtain the highest gain to amplify a small driven signal as quickly as possible. When we opened the cavity in a portable cleanroom in October, we checked the antenna and it was unscrewed and touched the cavity tube, then after fixing the antenna, we closed the cavity.

At the second run Germaine was retested at 2 K without any extra post processing. Before the RF measurement, we took more than an hour for conditioning. The blue and purple curves in the Fig. 2 show that the performance of the cavity decreases significantly. Due to the Q-slope curve dropped down quickly at low fields, we suspect a Q-disease rather than cavity pollution.

Finally, we warmed up and re-cooled down the cavity to check the cavity performance. Limited by the tight schedule, the last run was taken after re-cool down from 200 K. The cavity's Q-slop improved much both at 2K and 4 K, but was still affected by Q-disease.

During the RF measurements, resonance frequencies of Germaine in three different temperature situations have been studied. These results will help us with the frequency control during the cavity fabrication and post-processing, as shown in Table 1.

Table 1: Resonance frequency of Germaine

Temperature	Resonance frequency
300 K	351.533 ± 0.001MHz
4 K	352.038 ± 0.001MHz
2 K	352.032 ± 0.001MHz

Residual Resistance

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. 3. Here, the BCS resistance is calculated by the approximated formula given by equation 4.43 in Ref [5].

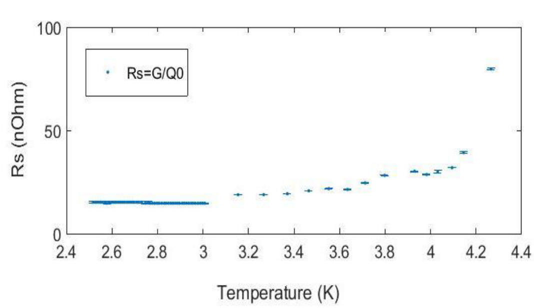

Figure 3: Rs vs. T measurement of Germaine at a fixed gradient.

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.

Pressure Sensitivity

Helium pressure fluctuation is one of the main sources of cavity resonance frequency detuning. Figure 4 shows how the helium pressure and resonant frequency of the cavities drift over a certain period. Note that the cavity vessel is fixed on a table by four points inside the cryostat and cavities are tested without a tuning system. In the measurement we determined that the ESS double spoke cavity has a pressure sensitivity of +4.7 Hz/mbar, while the test result of IPNO is +5.5 Hz/mbar. This result is consistent with the 5 kHz frequency shift measured during cool down from 4.2 K to 2 K and the corresponding pressure reduction from 1030 mbar to 30 mbar.

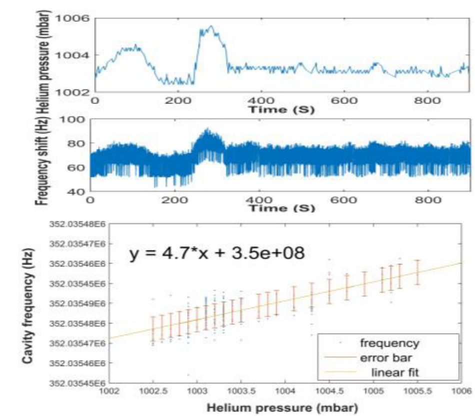

Figure 4: Pressure sensitivity of Germaine, where top and middle graphs are the helium fluctuation and frequency shift, respectively.

Lorentz Force Detuning

Firstly, we track the frequency shift with a spectrum analyzer while increasing the field. When measuring the static Lorentz force detuning, the spoke cavity is 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.

After fixing the antenna, we loosened the mechanical support in the cryostat in order to decrease the mechanical restriction to the cavity. A static Lorentz force factor at 2 K of -7.4 Hz/(MV/m)² in this run is very close to the value of IPNO of -8.1 Hz/(MV/m)², as shown in Fig. 5.

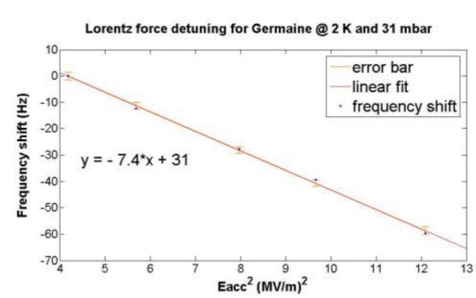

Figure 5: static Lorentz detuning curve of Germaine after pick-up coupler repaired.

A convenient method to determine the coefficients of the dynamic Lorentz force detuning is to modulate the radiation pressure at angular frequency in order to excite one resonant mode only. To this end, one can drive the cavity in CW mode at some relatively high gradient V_0, introduce a small periodic modulation of the cavity voltage and sweep the modulation frequency. This will allow one to measure the amplitude and phase of the cavity frequency modulation as a function of sweep frequency ω, known as the Lorentz transfer function [6].

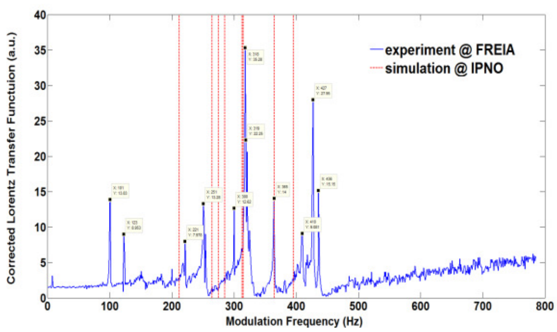

Figure 6: multi-peak dynamic Lorentz force detuning curve of Germaine.

By sweeping the modulation frequency up to 800 Hz, the fit of a multi-peak dynamic Lorentzian curve at 2 K is shown in Fig.6. Compared to the simulation result from IPNO, most of the simulation shows a good agreement to the test data. Note that an unexpected harmful frequency of roughly 100 Hz was found in the test. This frequency can be easily excited by the alternative electric frequency of 50Hz, which should be paid a higher attention.

Microphonics

We studied microphonics both at 2 K and 4 K by operating the cavities in the self-excited loop and monitoring 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. 7. By taking the Fourier transform we finally get the microphonics spectrum from the measurement. A vibration mode of 8 Hz was found in both cases. Next step is to continue investigating where the undesired noise source comes from.

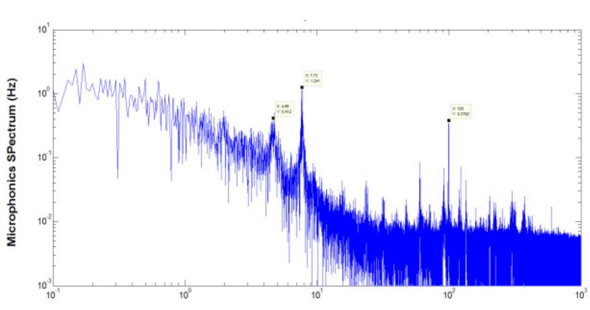

Figure 7: Microphonics measurement at 2K @31mbar. There are 3 main resonances: 4.6, 7.7 and 100 Hz.

Tuner Sensitivity

The cold tuning system (CTS) is attached to cavities to adjust the resonant frequency of the cavities in order to counteract the frequency detuning. The spoke CTS integrates two different functions [7]: a slow tuning capability over a wide frequency range by using a stepping motor; and a fast tuning system by means of piezoelectric actuators inserted in the mechanical system.

The behavior of the slow tuning system was studied both at 2 K and 4 K at FREIA. A tuning sensitivity of 66 KHz/mm @ 2 K as well as 75.8 KHz/mm @ 4.2 K was found. The corresponding tuning range by motor is 116.2 kHz @ 4.2 K. Though the CTS is installed in a vertical position in IPNO while it is horizontal in HOSS at FREIA, both two results agree with each other quit well, as shown in Fig. 8.

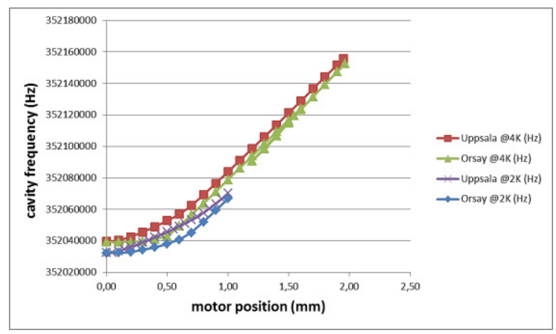

Figure 8:Tuning performance of double spoke cavity's CTS.

CONCLUSION

The first step of a test stand based on a self-exited loop was developed at FREIA. The first ESS cavity we tested was a bare double spoke cavity Germaine, which was designed and built by IPN Orsay. The RF performance and mechanical behavior of the cavity at low power level was studied extensively at FREIA. Similar test results as IPNO's previous tests were obtained with the FREIA system. In the next step, the spoke cavity with a RF power coupler will be tested at high power in the horizontal cryostat with the tetrode based RF system.

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