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HIGH POWER TESTING OF THE FIRST ESS SPOKE CAVITY PACKAGE

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Abstract

The first double spoke cavity for the ESS project was tested with high power in the HNOSS cryostat at the FREIA Laboratory. This cavity is designed for 325.21MHz, pulsed mode with 14 Hz repetition rate, up to a peak power of 360 kW. The qualification of the cavity package in a horizontal test, involving a superconducting spoke cavity, a fundamental power coupler (FPC), LLRF system and RF station, represents an important verification before the module assembly. This paper presents the test configuration, RF conditioning history and first high power performance of this cavity.

INTRODUCTION

The superconducting spoke section of the ESS linac accelerates the beam from the normal conducting section to the first family of 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 IPN Orsay and will be grouped by 2 in 13 cryomodules [2].

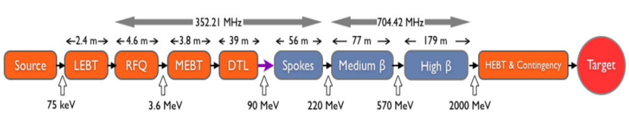

Figure 1: The layout of ESS accelerator.

Figure 1 shows the layout of ESS accelerator and the nominal operation parameters of spoke section are shown in table 1.

Table 1: Main Parameters of Spoke Cavities

Parameter	ESS Spoke cavity
Frequency [MHz]	352.21
Temperature [K]	2
Pulse duty factor [%]	4
Repetition rate [Hz]	14
Nominal gradient [MV/m]	9
Optimal Beta	0.5

A double spoke cavity (Romea) has been fabricated and selected for the horizontal test. It completed its vertical test at IPN Orsay with an excellent performance of maximum Eacc of 15 MV/m @ Q_0= 4×10^9, showing a successful cavity design and processing [3]. Equipped with the fundamental power coupler (FPC) and cold tuning system (CTS), this cavity package was shipped to FREIA and installed in the HNOSS cryostat. In this test, Romea has no magnetic shield and relies on the HNOSS magnetic shield which is located at room temperature in the vacuum vessel. The object of this test thus becomes the validation of the complete chain of high power RF amplifier, high power RF distribution, FPC, spoke cavity package and LLRF system. All these infrastructures provide a mechanical environment similar to its operation in the linac.

RF CONDITIONING

The warm and first cold coupler conditioning were done by using IPN Orsay's system followed by the new FREIA conditioning system to verify its performance. All coupler conditioning used a traditional signal generator driven loop. The warm RF processing before cooldown took about 40 hours, lots of outgassing occurred through the forward power region of 40-70kW at short pulses. At the first phase, the coupler conditioning finished when a forward power of 120 kW was reached with 2.86 ms pulse duration. The FREIA conditioning system was then tested with ESS cavity package to verify the logic and related hardware.

Compared to the FPC conditioning, the cavity RF conditioning is done by a self-excited loop (SEL). Since the tuner feedback controller is still under development, SEL naturally becomes a substitute for following the cavity resonant frequency without feedback. In order to produce pulses in the SEL, a RF switch controlled by a programmable trigger signal is introduced.

Cavity conditioning has been implemented in two phases. The first phase introduces a frequency modulation around the resonant frequency at a very low power level in order to sweep the field distribution forth and back along the coupler walls in a controlled manner. The subsequent phase is also completed with the SEL but by only ramping up the RF power with a fixed pulse length of 2.86 ms, with a procedure described in [4]. After about 30 hours of conditioning, the cavity package reached and was stably kept at 9 MV/m peak accelerating gradient.

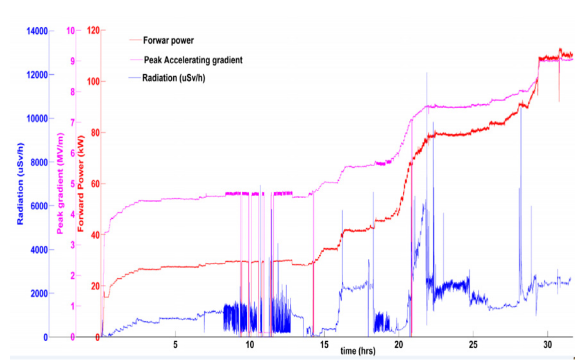

Figure 2: Cavity RF Conditioning history at FREIA.

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Figure 2 shows the major conditioning curves. Three major multipacting (MP) regions have been found during the cavity package conditioning. High X-ray activity was detected during the heavy MP, which increased the coupler temperature.

HIGH POWER PERFORMANCE

Q factor measurement of the cavity package is based on the calorimetrical method. The cavity package was operated at a pulse mode with 14 Hz repetition rate and 2.86 ms duration. Limited by the FPC, the peak power was 120 kW, which still adequately built a field with a peak gradient of 9 MV/m. The preliminary result of the quality factor of the cavity package vs. gradient curve is shown in Fig. 3.

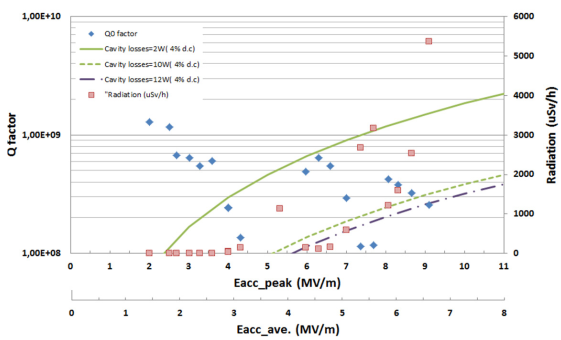

Figure 3: Cavity package performance as a function of accelerating gradient.

The Romea cavity package gives a Q factor of 1.4×10^{9} at low field and 2.8×10^{8} at 9 MV/m. An unexpected high heat load and several MP regions were found during the test. All MP regions were consistent with those that happened during the conditioning processing but were much easier to go through.

When the cavity was operating at its design field, a high radiation of 6 mSv/h at 90 degree angle of beam direction was observed. High radiation implies MP or field emission in the cavity package, and it leads to high heat loads and low Q factor. Many possible causes have been considered and corresponding improvements are being studied. Considerations are focusing on the following hypotheses. Firstly, the coupler temperature was higher than expected during RF on. The heat from the coupler transfers to the cavity causing a higher heat load. Secondly, during the cold conditioning of the coupler, the cavity was cold and could have easily cryopumped the outgassing from the coupler. Also, a poor vacuum of 10 mbar from the cavity was found during warm up. Last but not least, the cavity package may have been polluted during assembly.

In the third quarter of 2017, FREIA will redo the test of this cavity package with a new FPC and post processed cavity to study and verify the cavity's behaviour.

Dynamic Heat Load

The average cavity package dissipated power at 9 MV/m is about 12 W at 4% duty cycle.

Two different methods of dynamic heat load measurements have been used in order to cross check the system performance. For the first method, the helium inlet to the 2K tank (used as a buffer for the cooling of the cavity) was kept closed when applying RF power to the cavity. An absolute heat load of the whole cavity package was calculated from the helium gas flow readout value at atmospheric pressure and room temperature. The second mthod comprises a higher accuracy heat load measurement based on pressure rise. The helium level in the 2K tank was kept between 60% and 80% during the whole test. A known amount of resistive heat is applied to the helium bath. Once the system is stabilizes both inlet and outlet valves of the cryostat are closed and the pressure rise as a function of time is recorded for 3 minutes. These values are then part of the heat load calibration curve. Finally, RF power is loaded in the cavity and the dynamic load is calculated by comparing with the calibration curve.

The heat load measurement has been implemented twice. Each measured point was firstly determined until all parameters, such as helium flow, coupler temperature and pressure were stable. The two methods mentioned above were used to crosscheck the results and they show good agreement with each other. A second run with more measurement points but with the system left to stabilize only in pressure was also recorded. These three sets of measurements are shown in Fig.4, where an unexpected high heat load of the Romea cavity package is seen and possible reasons are listed above.

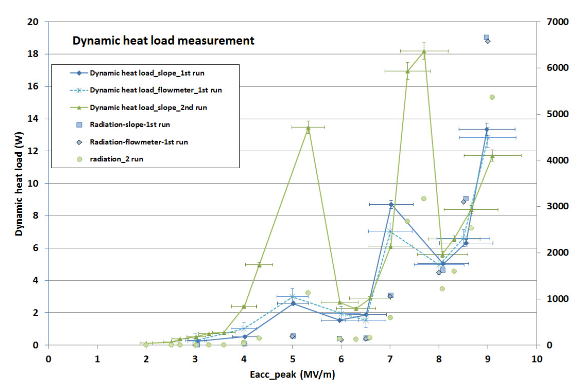

Figure 4: Dynamic loss vs. accelerating gradient.

Dynamic Lorentz Detuning

The main source of distortion in a pulsed accelerator is Lorentz force. Due to the pulsed operation, the cavity wall is deformed by dynamic Lorentz force (DLF) caused by an accelerating electromagnetic field, leading to extra RF power requirement. Since the DLF is repetitive and predictable, its behaviour has been measured by using an FPGA-based LabView program at FREIA. By monitoring and manipulating the complex signal from the cavity during the pulse, the measured signals like forward voltage and transmitted voltage, are first calibrated and

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normalized using equation 1. With the calibration, cavity detuning therefore can be calculated by using the state space equation of a superconducting cavity given by equation 2 [5]. Here $\overrightarrow{V_c}$ and $\overrightarrow{V_f}$ are the complex transmitted and forward voltage of the cavity while $\omega_{1/2}$ and $\Delta\omega$ are the instantaneous half bandwidth and detuning of the cavity respectively.

$$\begin{cases} \overrightarrow{V_c} = c_1 \cdot \overrightarrow{V}_{f,meas} + c_2 \cdot \overrightarrow{V}_{r,meas} \\ \overrightarrow{V}_f = c_1 \cdot \overrightarrow{V}_{f,meas} \end{cases} \tag{1}$$

$$\frac{d\overrightarrow{V}_c}{dt} + (\omega_{1/2} - j\Delta\omega)\overrightarrow{V}_c = 2\omega_{1/2}\overrightarrow{V_f} \tag{2}$$

The experimental result, shown in Fig. 5, suggests that there is a 400 Hz frequency shift at the peak accelerating gradient of 9 MV/m @ 2.86 ms pulse length. The shift is comparable to the cavity bandwidth. The fast frequency compensation with a cold tuning system will be validated in the later stage.

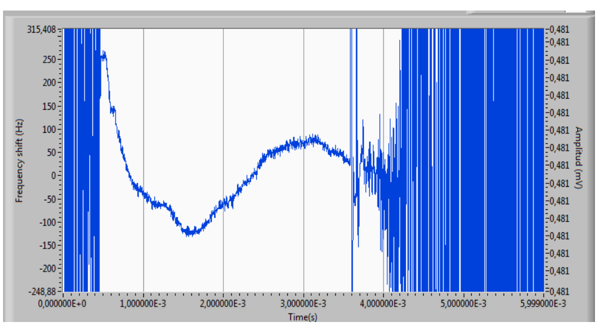

Figure 5: Dynamic Lorentz detuning of ESS spoke cavity during 2.86 ms pulse.

Mechanical Modes

We also studied the mechanical modes of the ESS spoke cavity at 2 K by stimulating the cavity with forward amplitude modulation while monitoring the transmitted 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 shift as a function of time. The strength of the cavity package vibration at a given modulation frequency was then obtained by taking the Fourier transform.

Figure 6 shows the fit of mechanical modes obtained by sweeping the modulation frequency up to 800 Hz Note that the slow tuner was in contact with cavity in a fixed position during this measurement. Two major mechanical modes of 265 Hz and 343 Hz are found, which give a similar result when compared to IPN Orsay's simulation and will be considered in further DLF compensation development with the piezo tuners.

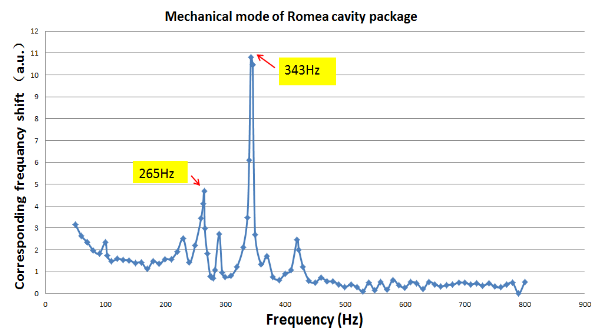

Figure 6: Fit of mechanical modes of ESS spoke cavity.

Pressure Sensitivity

Helium pressure fluctuations inside the tank detune the cavity resonance frequency. Measuring the frequency sensitivity as a function of the helium pressure provides information about the mechanical stability of the cavity.

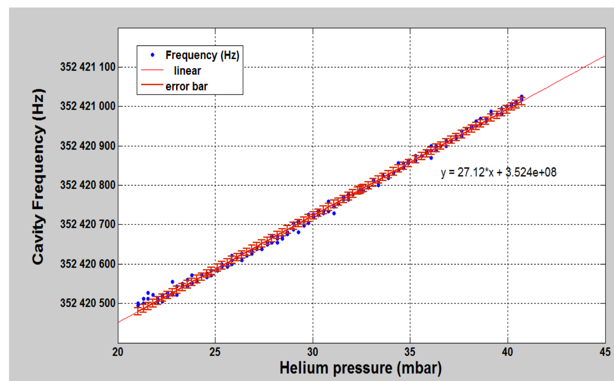

Figure 7: Cavity frequency shift as a function of helium pressure from 20 to 40 mbar.

In this test, by keeping the inlet and outlet valves closed, the helium pressure in the 2K tank subsequently increased due to the static heat load. By checking the cavity frequency as a function of pressure from 20 to 40 mbar, as shown in Fig.7, a pressure sensitivity of +27 Hz/mbar is measured. This result has a good agreement with the 28 kHz frequency shift measured during cool down from 4.2 K to 2 K. Because of different fabrication procedures, this value varies between cavities from different manufacturers, thus the pressure sensitivity measurement can be helpful for optimizing production procedures.

PRODUCTION TESTING PLAN

In the third quarter of 2017, the cavity Romea will go through an extra HPR and will be installed with a new fully conditioned FPC at IPN Orsay. Afterwards, it will be sent to FREIA to repeat the high power test.

Once the dynamic heat load and Q factor of the cavity package match the specifications, FREIA will then prepare the acceptance testing of the spoke prototype crymodule. This is the first prototype with two dressed spoke cavities that will be installed in the ESS linac. The difference between the coming cryomodule test and the

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individual cavity package test in HNOSS is that two cavities will be installed in an ESS cryomodule prototype each with its own magnetic shield integrated with the cavity. Then a busy schedule will follow by testing another 13 spoke crymodules at FREIA before delivering to ESS.

CONCLUSION

The qualification of the cavity package with high power test represents an important verification before the module assembly. The first spoke cavity assembled with all ancillary components was installed in HNOSS cryostat and completed the high power test base on self-exited loop at FREIA.

This cavity was operated at the pulse mode of 2.86 ms duration and 14Hz repetition rate. A maximum power of 120 kW was reached, which successfully built up a field of 9 MV/m. A high radiation of 6 mSv/h and high heat load of about 12 W is observed with the cavity package operating at its design field. The radiation does not seem to reduce significantly with accumulated running hours. Possible reasons and solutions are under study. The dynamic Lorentz detuning was studied by a signal generator driven system without frequency feedback. A frequency shift of about 400 Hz was determined during the pulse flat top. Top two mechanical modes of the cavity package of 343 Hz and 265 Hz are found, which show a good agreement with the simulation.

Another high power measurement of ESS spoke cavity package is planned in the near future.

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