ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO066

FIRST HIGH POWER TEST OF THE ESS HIGH BETA ELLIPTICAL CAVITY

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Abstract

ESS, the European Spallation Source, will adopt elliptical multi-cell superconducting cavities with a beta value of 0.86 to accelerate the proton beam up to 2 GeV at the last section of the linac. A 5-cell high-beta cavity for ESS project was tested with high power at FREIA Laboratory. A pulse mode test stand based on a self-excited loop was used in this test. The qualification of the cavity package involved a 5-cell elliptical cavity, a fundamental power coupler, a cold tuning system, LLRF system and a RF station. These tests represented an important verification before the series production. This paper presents the test configuration, RF conditioning history, first high power performance and experience of this cavity package.

INTRODUCTION

The ESS elliptical SRF linac section is composed of two types of state-of-the-art 704.42 MHz cavities, medium-beta (MB) of 0.67 and high-beta (HB) of 0.86, to accelerate the proton beam from the spoke superconducting linac up to full energy [1]. A total of 84 5-cell HB elliptical cavities are designed at CEA and will be grouped by 4 in 21 cryomodules [2]. Figure 1 shows the layout of the ESS accelerator.

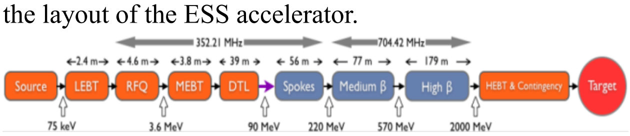

Figure 1: The layout of the ESS accelerator.

The nominal operation parameters of HB section are shown in Table 1 [3].

Table 1: Main Parameters of 5-cell HB Cavities

Frequency [MHz]	704.42
Beta_optimum	0.86
Operating gradient [MV/m]	19.9
Temperature [K]	2
G [Ohm]	241
R/Q [Ohm]	435
Lacc [m]	0.915
Bpk/Eacc [mT/MV/m]	4.3
Epk/Eacc	2.2
Qext	7.6×10^5
π and 4π/5 mode separation [MHz]	1.2

FREIA, at Uppsala University, was established in order to support the development of instrumentation and accelerator technology and started high power test of ESS double spoke cavity tests in 2015 [4, 5]. In 2018, FREIA laboratory also implemented the first high power test of overall HB elliptical cavity package. A power conditioning stand for klystron and a RF test system were commissioned in this test. An optimal procedure for both klystron and power coupler conditioning was used to reduce the time and effort of overall power conditioning. The object of this test thus became the validation of the complete chain as used in ESS: klystron, high power circulator, RF load, high power RF distribution, fundamental power coupler (FPC), HB elliptical cavity, cold tuning system (CTS) and low level RF system (LLRF).

RF CONDITIONING

The warm coupler conditioning was completed with an effective conditioning time of 20 hours and finally achieved 1 MW peak power with a standing wave regime at 14 Hz repetition rate @ 500 µs and 300 kW peak power with 14 Hz repetition rate @ 2600 µs. Lots of outgassing happened at low power with short pulses, as shown in Fig. 2 (a). At the first phase of 50 µs @ 1Hz, the first arcing occurred in the FPC at about 600 kW, afterward it was very hard to increase the RF power without severe outgassing. Half of the total warm conditioning time (10 hours) was taken to reach 1 MW and completed the first phase. Figure 2 (b) shows all following phases which went smoothly through. The conditioning procedure was finally finished by 2 hours power sweeping from 15 kW to 300 kW with 2.6 ms and 14 Hz repetition rate. The choice of pulse duration is limited by the capacity of the modulator prototype. In order to condition and sweep as much area as possible in the FPC, the cold conditioning of the FPC was carried out by the same system but at two different frequencies, with one slightly higher and one slightly lower than the cavity resonant frequency. Each frequency was about 100 kHz away from the cavity resonant frequency of 704.08 MHz at 2K (with free end), in order to make sure there was no RF coupled in to build a field in the cavity.

Compared to the FPC conditioning, the RF conditioning of the cavity with its power coupler, so-called cavity package, is done by a self-excited loop (SEl) at resonant frequency. 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. In the vertical test, this cavity showed high performance but unfortunately quenched at 18 MV/m,

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therefore the test range at high power was first limited up to 15 MV/m [6]. A soft multipacting barrier from 9 to 12 MV/m was encountered and successfully processed. After about 3 hours of conditioning, the cavity package reached and was stably kept at 15 MV/m flattop accelerating gradient.

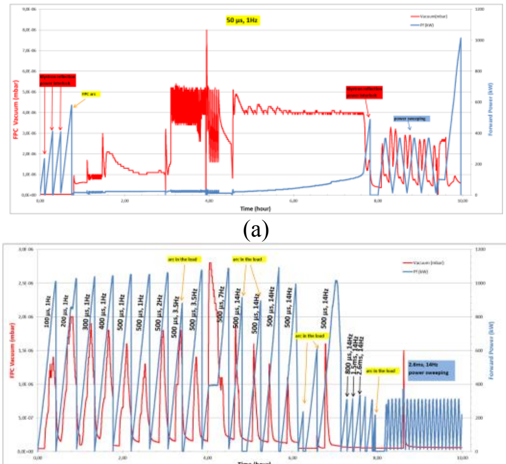
(a)
(b)

Figure 2: (a) HB cavity RF conditioning history with 50 μs and 1 Hz repetition rate; (b) HB cavity RF conditioning history with longer pulse duration at different repetition rate, where the blue curve represents the RF power and the red one represents the coupler vacuum.

HIGH POWER PERFORMANCE

The Q factor measurement of the cavity package is based on the self-exited loop at FREIA. The cavity was operated at a pulse mode of 2.55 ms duration and 14 Hz repetition rate. With a peak power less than 200 kW, a field with a flattop gradient up to 16 MV/m was successfully reached. The preliminary result of the quality factor of the cavity package vs. gradient is shown in Fig. 3.

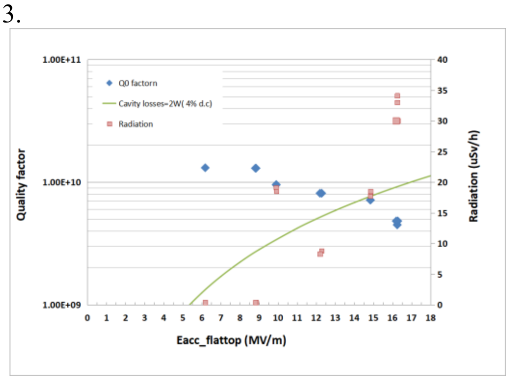

Figure 3: HB cavity package performance as a function of accelerating gradient.

The HB cavity package gives a Q factor of 1.3×10^{10} at low field and 7.1×10^{9} at 15 MV/m. X-ray radiation was start from 10 MV/m, which implied field emission in the cavity package. After 30 minutes conditioning, the cavity performance has unfortunately no significant improved.

The average cavity package dissipated power at 15 MV/m is about 2 W with 2.55 ms pulse. To assured the measurement accuracy, the dynamic heat load was recorded from 0.2 W and above. 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 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 at atmospheric pressure and room temperature. The second method comprises a higher accuracy heat load measurement based on pressure rise. The helium level in the 2K tank was kept between 76% and 78% during the whole test. A known amount of resistive heat was applied to the helium bath. Once the system was stabilized both inlet and outlet valves of the cryostat were closed and the pressure rise as a function of time was recorded for 1 minute. These values were then part of the heat load calibration curve. Finally, RF power was loaded in the cavity and the dynamic load was calculated by comparing with the calibration curve.

Nonpropagating Longitudinal Modes

For a multi-cell cavity, monitoring the longitudinal modes of the first passband is usually adopted as an effective way of checking the cavity condition during transportation and cool down procedures. Longitudinal modes of the first passband of the ESS HB cavity were studied at different temperatures and the characteristics of 5 modes are listed in Table 2. The measurement result shows that the relative frequency distance between different modes has been kept the same, which implies that no unexpected issue has happened during cool down. On the other hand, the frequency distance between π mode and 4π/5 mode is bigger than1.2 MHz, which fulfills the ESS requirement.

Table 2: The Characteristics of 5 Modes of First Passband

Parameters	T emperature		
	300 K	4 K	2 K
π mode	702.991	704.120	704.081
4π/5 mode	701.761	702.889	702.848
3π/5mode	698.464	699.592	699.551
2π/5 mode	694.370	695.494	695.454
π/5 mode	691.104	692.22	692.187

Lorentz Force Detuning

For a pulsed accelerator such as ESS, the dynamic Lorentz force detuning (LFD) caused by the deformation of the cavity wall with an accelerating electromagnetic field leads to beam instability. By monitoring and manipulating the complex signal from the cavity during the pulse, LFD at different accelerating gradients have been studied by using a FPGA-based LabView program at FREIA. The forward pulses with step pulse profile were used, as shown in the top graph of Fig. 4, RF power 6 dB higher than the flattop was applied during the filling time.

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The LFD experimental result of 15 MV/m, shown in the bottom picture of Fig. 4, suggests that there is around 220 Hz frequency shift with 2.55 ms pulse length. Please note that the cavity was restricted by the stepper motor during the test. The LFD coefficient is therefore about -1 Hz/(MV/m)^2 with tuner contacted condition , which is in agreement with the simulation [3]. For a nominal accelerating gradient of 19.9 MV/m, the shift will be 1/3 of the cavity bandwidth. The fast frequency compensation with piezo tuners has been successfully tried with the above pulse settings and an optimal piezo operation is under study.

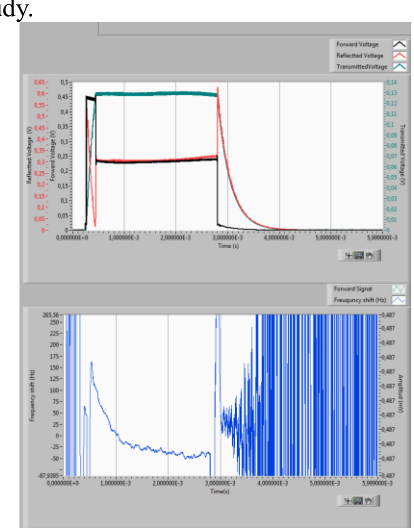

Figure 4: Top: Forward (black), reflected (red) and transmitted (green) signal during 2.55 ms pulses. Bottom:Dynamic Lorentz detuning of ESS HB elliptical cavity at 15 MV/m.

Pressure Sensitivity

Helium pressure fluctuations inside the tank detune the cavity resonance frequency. During cool down from 4 K to 2 K, the frequency sensitivity as a function of the helium pressure has been carried out from 50 to 800 mbar. As shown in Fig. 5, a pressure sensitivity of +37 Hz/mbar is measured.

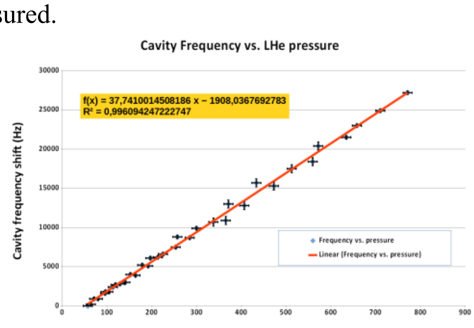

Figure 5: Cavity frequency shift as a function of helium pressure from 50 to 800 mbar.

Tuning Sensitivity

The cold tuning system is attached to the HB cavity to adjust its resonant frequency in order to counteract the frequency detuning. The HB CTS integrates two different functions: a slow tuning capability over a wide frequency range by using a stepper motor and a fast tuning system by means of piezoelectric actuators inserted in the mechanical system of the CTS. The behavior of the slow tuning system was studied at 2 K at FREIA, as shown in Fig. 6. A tuning sensitivity of 17.3 KHz/motor turn, corresponding to 173 kHz/mm, was found. Here the distance is defined as the longitudinal deformation of the cavity.

Several tuning runs were repeated back and forth around the resonant frequency in order to check the linearity of the CTS and a well agreement of tuning sensitivity was determined.

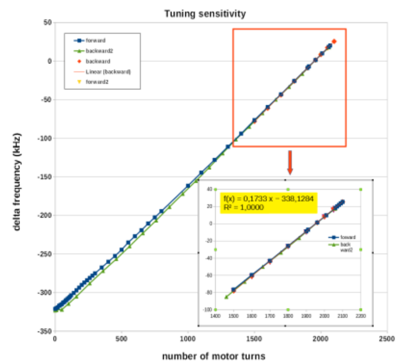

Figure 6: Tuning sensitivity of ESS HB elliptical cavity.

CONCLUSION

The first ESS HB elliptical cavity assembled with all ancillary components was installed in the HNOSS cryostat and successfully completed the high power test based on self-exited loop at FREIA. This qualification of the cavity package represents a milestone before the module assembly.

The longitudinal modes of the first passband were monitored at different temperature. Same frequency difference with neighboring modes confirmed that this cavity was well kept during installation and test procedure. This cavity was operated at the pulse mode of 2.55 ms duration and 14 Hz repetition rate. A Q factor of 1.3×10^{10} at low field and 7.1×10^{9} at 15 MV/m was determined. The dynamic Lorentz detuning was studied by a signal generator driven system with step forward pulse, LFD coefficient of -1 Hz/(MV/m)$^{2.}$ is measured. The study of fast detuning compensation is undergoing. Furthermore, this cavity was found to have a pressure sensitivity of +37 Hz/mbar and a tuning sensitivity of 173 kHz/mm.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871. The authors wish to thank our collaborators from CEA who help us with the installation and testing and helpful discussions with ESS experts. Also many thanks to all colleagues of FREIA for their hard work on the cavity tests.

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