First High Power Test of the ESS High Beta elliptical Cavity package

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Abstract

The first high-beta elliptical cavity for ESS project was tested with high power in the HNOSS cryostat at FREIA Laboratory. This cavity is designed for 704.42 MHz, a pulse mode with 14 Hz repetition rate, up to peak power of 1.5 MW. The qualification of the cavity package in a high power test, involved an elliptical superconducting cavity, a fundamental power coupler, cold tuning system, LLRF system and klystron system, represented an important verification before the module assembly. This report presents the test configuration, RF conditioning history and first high power performance of this cavity package.
### Table of Contents

1. Introduction ........................................................................................................................................... 6

2. Test stand ............................................................................................................................................. 8
   2.1. Klystron conditioning stand ............................................................................................................. 8
   2.2. RF test stand ................................................................................................................................. 10
   2.3. Test software ............................................................................................................................... 12
   2.4. Test programme ........................................................................................................................... 13

3. Conditioning ....................................................................................................................................... 14
   3.1. FPC conditioning parameter ......................................................................................................... 14
   3.2. FPC warm conditioning ............................................................................................................... 16
   3.3. FPC cold conditioning ................................................................................................................. 19
   3.4. Cavity package conditioning ........................................................................................................ 22

4. Cool down and resonant frequency measurement ................................................................................. 24
   4.1. Cool down procedure .................................................................................................................... 24
   4.2. Resonant frequency ....................................................................................................................... 26

5. Cavity measurements .......................................................................................................................... 27
   5.1. Quality factor measurement ......................................................................................................... 27
   5.2. Dynamic heat load ........................................................................................................................ 28
   5.3. Q measurement error estimation ................................................................................................ 31
   5.4. Q_{ext} of FPC measurement ........................................................................................................ 42
   5.5. Longitudinal modes measurement ............................................................................................... 46
   5.6. Dynamic Lorentz force detuning .................................................................................................. 47
   5.7. Cavity voltage filling time ............................................................................................................. 49
5.8. Pressure sensitivity ................................................................. 54
5.9. Tuner sensitivity ................................................................. 54
5.10. Piezo test .................................................................................. 56
6. Summary .................................................................................... 58
References .................................................................................... 59
1. Introduction

ESS, the European Spallation Source, will be an accelerator-driven facility contributing for academia and industry scientific research topic using neutron beams. The project started construction in 2013 aims to deliver first neutrons in 2020 [1]. The linear accelerator shown in Figure 1, or linac, is thus a critical component of the whole project. As with the ESS Spoke SRF linac, the Elliptical SRF linac is composed of state-of-the-art SRF technology components. The Elliptical SRF linac is composed of two types of 704.42 MHz cavities, medium-beta (0.67) and high-beta (0.86) supported by the RF system, to accelerate the proton beam from the spoke superconducting linac up to full energy [2]. The high-beta section is using 5-cell elliptical cavities, 86 cavities in total, with every 4 unites hosted in 6.6 m long cryomodules.

![Figure 1: The layout of ESS linac](image)

The high-beta elliptical cavities were designed and fabricated at CEA-Saclay. A numerical simulation analysis of the cavity design, in particular the RF coupling, the control of high order mode excitation, damping and propagation had been conducted, as well as a mechanical design of the cavity with its stiffeners and the helium tank. The main parameters of the high-beta cavities are shown in Table 1 and Table 2 [3][4].

Table 1: Main RF parameters of ESS high-beta elliptical cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>704.42</td>
</tr>
<tr>
<td>Beta_optimum</td>
<td>0.86</td>
</tr>
<tr>
<td>Number of cells</td>
<td>5</td>
</tr>
<tr>
<td>Operating gradient [MV/m]</td>
<td>&lt;19.9</td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>2</td>
</tr>
<tr>
<td>G [Ohm]</td>
<td>241</td>
</tr>
<tr>
<td>R/Q [Ohm]</td>
<td>435</td>
</tr>
<tr>
<td>Lacc [m]</td>
<td>0.915</td>
</tr>
<tr>
<td>Bpk/Eacc [mT/MV/m]</td>
<td>4.3</td>
</tr>
<tr>
<td>Epk/Eacc</td>
<td>2.2</td>
</tr>
<tr>
<td>$\pi$ and $4\pi/5$ mode separation [MHz]</td>
<td>$7.6 \times 10^7$</td>
</tr>
</tbody>
</table>

* Note that the high-\(\beta\) cavity was quench at 18 MV/m in the vertical test at CEA, therefore an accelerating gradient of 15 MV/m was chose at FREIA for safety reason. After the loaded Q correction, actually only about 14 MV/m was achieved.
Table 2: Mechanical parameters of ESS high-beta cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness of the cavity [kN/mm]</td>
<td>1.47</td>
</tr>
<tr>
<td>Tuning sensitivity $f/z$ [kHz/mm]</td>
<td>217</td>
</tr>
<tr>
<td>Lorentz detuning factor $KL$ [Hz/(MV/m)$^2$]</td>
<td></td>
</tr>
<tr>
<td>Free end</td>
<td>-21.1</td>
</tr>
<tr>
<td>Fixed end</td>
<td>-0.71</td>
</tr>
</tbody>
</table>

The FREIA laboratory (Facility for Research Instrumentation and Accelerator Development) at Uppsala University is established in order to support the development of instrumentation and accelerator technology [5][6]. Since 2015, FREIA has completed high power test of ESS double spoke cavity [7][8][9].

In 2018, FREIA laboratory also implemented the first high power test of high-beta elliptical cavity package. A power conditioning stand for klystron and a RF test system were commissioned in this test. Optimal procedures for both klystron and power coupler conditioning were used to reduce the time and effort of overall power conditioning. The object of this test thus became the validation of the complete chain of klystron, high power circulator and RF load, high power RF distribution, fundamental power coupler (FPC), high-beta elliptical cavity package, cold tuning system (CTS) and low level RF system (LLRF).

Figure 2: High-beta elliptical cavity
2. Test stand

2.1. Klystron conditioning stand

The RF power system was conditioned independently before sending RF into the cavity. The high power test stand at FREIA for ESS high-beta elliptical cavities consists of a Toshiba 704 MHz prototype klystron, a PPT modulator, a 704 MHz ferrite circulator with Thales protection load, waveguide distribution, water cooling system, HNOSS horizontal cryostat [10] and LLRF based on either self-excited loop (SEL) or signal generator. Note that only the prototype modulator and the klystron has been tested before installation, the klystron control system, the circulator and the load were first commissioned with full power at FREIA. Figure 4 shows the RF power system for 704 MHz cavity installed at FREIA.

Figure 3: The RF power system for 704 MHz cavity installed at FREIA

The conditioning of the RF power system is done by using a LLRF control system developed by Lund University and an automatic conditioning software developed at FREIA. The LLRF control system, had been installed and integrated into the EPICS control system at FREIA, it will be used to regulate the superconducting cavities [11]. During the conditioning, pulses with different amplitude, duration and repetition rate producing by this LLRF system provide a similar situation in the linac tunnel. Figure 4 shows the diagram of RF conditioning system at FREIA.
During the conditioning, some problems were found:

1) The modulator were showing unusually high ripple in several modules.
2) The circulator performance was sensitive to the temperature so that a dedicated cooling system was required. Reflection can drift from -30 to -20 dB during start of pulse due to internal heating. Furthermore, variations in both cooling temperatures as well as internal temperatures directly affected the gain of klystron.
3) The Thales Load was damaged by sever internal arcing. After repair, the ceramic window still suffered with sustainable arcing due to uneven quality of the window. All operational parameters are corresponding well with the Toshiba FAT. Finally, the Toshiba 704 MHz prototype klystron has commissioned onsite up to 1MW due to limitation set by RF load, as shown in Figure 5. Table 3 and Table 4 list some parameters of both the klystron and the modulator after successful conditioning.

Figure 4: Diagram of klystron conditioning system at FREIA
Figure 5: The gain curve of klystron at 704.42 MHz

Table 3: Parameter of klystron after conditioning at FREIA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum reach power [MW]</td>
<td>1</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>1-14</td>
</tr>
<tr>
<td>Pulse duration [ms]</td>
<td>≤3.5</td>
</tr>
</tbody>
</table>

Table 4: Parameter of modulator after conditioning at FREIA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate [Hz]</td>
<td>1-14</td>
</tr>
<tr>
<td>RF on duration * [ms]</td>
<td>2.8</td>
</tr>
<tr>
<td>Modulator response time** [ms]</td>
<td>0.2</td>
</tr>
<tr>
<td>Pulse duration*** [ms]</td>
<td>2.6 (2.55)</td>
</tr>
</tbody>
</table>

* Time duration for the modulator enables RF on.
** Time length for all internal components to be ready for stable operation.
*** Time duration for RF output pulses. RF on duration = Modulator response time + Pulse duration. In the case of high-β cavity, to avoid the ripple at the beginning of the pulse, only 2.55 ms pulse duration was used.

2.2. RF test stand

Since the tuner feedback controller is still under development at ESS, SEL naturally becomes a substitute for following the cavity resonant frequency without feedback [12]. This SEL was built based on the same conception design for the ESS spoke cavity only with some replacement of RF.
components due to different frequency operation range. Thus most high power tests for high-beta cavity were done by this pulse SEL with a help of the timing system and interlock in the Lund LLRF system. The timing reference for this LLRF system comes from two sources. There is a global timing which gives the triggers when the beam pulse is coming. Another is a well-controlled phase reference system which is used to measure the phase of the cavities [13].

During the high power test at FREIA, the Lund LLRF system worked for triple functions:

1) The klystron used in this test was used for producing RF powers within 2.6 ms with 14 Hz repetition rate. In order to synchronize the FPGA data acquisition system and the RF power station, a blanking signal of 2.8 ms pulse length @ 14 Hz was provided from the Lund LLRF timing system.

2) Another programmable trigger signal with a pulse length of 2.55 ms @ 14 Hz, so-called pulse control signal in the diagram block, was produced by the Lund LLRF system with a purpose of switching on/off a RF switch which controls the SEL in a pulse mode. This control signal was also used as an external trigger for all power meters which monitors RF power to/from the cavity. Note that the pulse length of 2.55 ms was limited by the PPT modulator.

3) The Lund system integrated all interlock signals from the FPC and the loop and sent out an overall interlock control during RF on.

The block diagram of the pulse SEL for the 5-cell high-beta cavity package at FREIA is shown in Figure 6 and some key parameters of this SEL are listed below:

- The maximum peak power is around 1 MW (limited by the load);
- The maximum loop gain can reach up to 180 dB;
- A control voltage attenuation with range of 3 to 40 dB;
2.3. **Test software**

Several LabView interfaces developed by FREIA were operated at this test run, most of them were successfully tested before on ESS spoke cavities and some were modified based on new requirements of high-beta cavity test. There were a klystron automatic conditioning interface, a cavity monitoring interface during cooldown and warm up, an automatic coupler conditioning system and a RF measurement interface. Figure 7 and Figure 8 show some examples of these LabView interface.

![Diagram of SEL block at FREIA](image-url)
2.4. Test programme

By using above hardware and software, following typical measurements for high-beta elliptical cavity had been conducted:
• RF behaviour of cavity during cool down;
• Modes distribution and frequency separation of first passband,
• Coupler conditioning and cavity package conditioning;
• Cryogenic heat loads,
• Loaded Q factor, eigen and external Q, \( Q_0 = f(E) \) curve,
• Dynamic Lorentz detuning and mechanical modes,
• Field emission onset and multipacting barriers,
• Sensitivity to helium pressure fluctuations,
• Tuning sensitivity and piezo function study.

3. Conditioning

3.1. FPC conditioning parameter
Prior to the high power test, the FPC went through RF processing both at room temperature and 2K by using FREIA conditioning system with CEA’s procedure, as shown in Figure 9. This FPC conditioning system has been tested on ESS spoke cavity, which algorithm and details could be found in [14]. The Lund system was chosen as a pulse power source, in which a pulse profile is programmed by a preset rising time, pulse width and pulse amplitude. In order to avoid an overshot from output of the klystron, a 5\( \mu \)s pulse rising time was added throughout the coupler conditioning. On the other hand, different repetition rates were adopted to balance the outgassing risk and condition efficiency. From the initial pulse length 50 \( \mu \)s up to 400 \( \mu \)s were completed with 1Hz repetition rate, while 500 \( \mu \)s were regularly increased from 1Hz to 14 Hz and all rest conditioning phases with pulse duration longer than 500 \( \mu \)s were only done by 14Hz. All conditioning phases with pulse duration shorter than 800 \( \mu \)s were conditioning up to 1MW, and RF power up to 300 kW were conditioned for pulses from 800 to 2600 \( \mu \)s. Meanwhile, the coupler vacuum was chosen as a leading preventive indicator. The main idea of a RF-vacuum feedback system is to regulate RF power as a function of vacuum pressure around the coupler. In this way, vacuum limits avoid local overheating or electrical arcing within the vacuum side, which otherwise would damage the fragile ceramic window in the coupler.
Figure 9: FREIA RF conditioning system interface

Some key parameters are listed in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop control time [s]</td>
<td>1</td>
</tr>
<tr>
<td>Pulse repeat rate [Hz]</td>
<td>1, 2, 3, 5, 7, 14</td>
</tr>
<tr>
<td>Vacuum upper limit [mbar]</td>
<td>5e-6</td>
</tr>
<tr>
<td>Vacuum lower limit [mbar]</td>
<td>2e-6</td>
</tr>
<tr>
<td>Hardware Vacuum threshold [mbar]</td>
<td>8e-6</td>
</tr>
<tr>
<td>Initial pulse length [µs]</td>
<td>50</td>
</tr>
<tr>
<td>pulse length step</td>
<td>50 µs, 100 µs, 200µs, 300 µs, 400 µs, 500 µs, 800 µs, 1.5 ms, 2.6 ms,</td>
</tr>
</tbody>
</table>

*One step of power applied to the klystron output in this software is defined as 1kW.
3.2. **FPC warm conditioning**

The warm conditioning was completed with an effect conditioning time of 20 hours and finally achieved 1 MW peak power with a standing wave regime at 14Hz repetition rate at 500 µs and 300 kW peak power with 14Hz repetition rate at 2600 µs. A lot of outgassing happened at low power with short pulses, as shown in Figure 10. At the first phase of 50 µs @ 1Hz, the first arcing occurred in the FPC at about 600 kW, then it was very hard to increase the RF power without severe outgassing issue. Half of the total warm conditioning time-10 hours was took to reach 1MW and completed the first phase. All following phases were smoothly went through and finally finished by 2 hours power sweeping from 15 kW to 300 kW with 2.6 ms and 14 Hz repetition rate.

Please note that there are some major issues happened during the conditioning procedure:

1) The high reflection from the circulator to the klystron causes interlocks. For the circulator's performance shifted along the RF power due to its narrow bandwidth and high sensitivity of operation temperature. It was necessary to manually fine tune the temperature feedback of the cooling water system throughout whole conditioning and test. Nevertheless, the reflection from circulator due to mismatch triggered the 5kW interlock threshold from time to time (red marks displayed in the conditioning history).

2) On the other hand, variations in both cooling temperature and circulator internal temperature directly affect the gain of klystron. Figure 11 shows the conditioning history for longer pulses, in which the output power from klystron increased while extending the pulse duration even though the input power to klystron has been kept exactly the same. In order to limit the output power below the limitation of FPC, the input power level was adjusted manually according to the klystron gain during the conditioning and test.

3) The prototype circulator as well as the prototype RF load has not gone through any full power test before settling at FREIA. After installation of the klystron and the RF distribution, the RF load has been damaged by severe internal arcing during the klystron conditioning. The load was gradually pushed up to 1 MW after repaired while also retightening the flange, unfortunately, similar kind of arcing still happened at high average power and occasionally at high peak power in the load (yellow marks displayed in the conditioning history).
Figure 10: FPC warm conditioning history at 50 µs, 1Hz phase
Figure 11: FPC warm conditioning history
3.3. **FPC cold conditioning**

HNOSS was cooled by LN2 for about 24 hours and the 4 K tank was also cooled with LHe. By conduction the cavity got to be at 270 K before starting its cooling. The cavity package in HNOSS was then cooled down from 270 K to 4 K with a cool down rate higher than 1K/min. Then cool down from 4 K to 2 K was within an hour [15].

As to condition and sweep as much area as possible in the FPC, the cold conditioning of FPC was completed by the same system but two different frequencies, with one slightly higher than and the other slightly lower than the cavity resonant frequency. Each frequency is about 100 kHz away from the cavity resonant frequency of 704.08 MHz at 2K, in order to make sure there has no RF coupled in and built a field in the cavity. Meanwhile the transmitted power from the cavity was monitoring during the conditioning to cross-check the cavity situation. Some of parameters were adjusted in the cold conditioning and list in Table 6.

The choice of two frequencies standing at both sides of the cavity resonant frequency is driven by a slight impedance difference from the cavity system, which lead a different field distribution of standing wave along the FPC wall. This method can thus condition the FPC with a high efficiency. To this end, two methods are normally considered. First is keeping the generator signal fixed while changing the resonant frequency by detuning the cavity with the CTS. The second approach is changing the frequency of the generator instead of moving the cavity. In the case of high-β cavity test, the CTS has not been tested before the cold conditioning. Therefore, in order to keep the simplicity of the test and avoid the unknown risk from unverified component, the second approach is adopted at FREIA. While at ESS tunnel, where the source frequency is fixed, the first method will be the first option.

The history of cold conditioning is shown in Figure 12 and Figure 13. Only few outgassing happened when increasing the repetition rate and each cold conditioning procedure was smoothly finished within 5 hours.

<table>
<thead>
<tr>
<th>Table 6 : Main Parameters of High-beta Cavity Cold Conditioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Loop control time [s]</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Vacuum upper limit [mbar]</td>
</tr>
<tr>
<td>Vacuum lower limit [mbar]</td>
</tr>
</tbody>
</table>
Figure 12: Cold conditioning for high-beta cavity FPC at 703.98 MHz
Figure 13: Cold conditioning for high-beta cavity FPC at 704.18 MHz
3.4. **Cavity package conditioning**

A major difference, compared to the FPC conditioning, is that the cavity RF conditioning was done by the pulsed self-excited loop as describe in chapter 2.

The cavity conditioning had been implemented about 300 kW forward power level by increasing both pulse duration and repetition rate. Whole conditioning procedure was done by gradually increasing the average RF power in order to minimize the radiation in the cavity, as shown in Table 7. The first phase was ramping forward power from low up to 300 kW with initial pulse duration of 500 µs and 1Hz repetition rate. Afterward the same procedure was repeated with 1.5 ms, 2ms and 2.55 ms pulse duration. The subsequent phase was also completed with the SEL but only by ramping up the RF power with a fixed pulse length of 2.55 ms and 14 Hz repetition rate. The final pulse length of 2.55 ms was used for all RF test due to the stability of high voltage in the modulator.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration (µs)</th>
<th>Repetition rate</th>
<th>RF input power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>1</td>
<td>15-300</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>1</td>
<td>15-300</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>1</td>
<td>15-300</td>
</tr>
<tr>
<td>4</td>
<td>2550</td>
<td>1 and 14</td>
<td>15-300</td>
</tr>
</tbody>
</table>

Figure 14 shows the cavity package conditioning history of 2.55 ms pulse at 14 Hz. High radiation was found around the forward power about 110 kW. After about 3 hours of conditioning, the cavity package reached and was stably kept at 14 MV/m flattop accelerating gradient for more than 30 minutes. The corresponding forward power was 180 kW. During conditioning and further measurements with 14 Hz repetition rate, a lot of interlocks were triggered due to the arcing in the RF load.
Figure 14: Cavity package conditioning history with 2.55 ms pulse at 14 Hz
4. Cool down and resonant frequency measurement

4.1. Cool down procedure

There were two test runs in June and August respectively. Before the first cooldown of the cavity package, the LN2 shield was cooled from room temperature to 120 K within 20.5 hrs.

Figure 15 shows the first cooldown history, from which an average cooling rate, bigger than 1 K/min, was kept in the temperature region from 150 to 50 K to avoid Q-disease in the cavity.

The cooldown rates for the first run for high-β cavity package were considered from a starting temperature of 272 K. Different cooldown rates based on different temperature sensors conditions are:

i) from 272 K ≤ all TTs (except TT125 and TT126) ≤ 50 K, cooldown rate = 2.31 K/min;

ii) from 150 K ≤ all TTs (except TT125 and TT126) ≤ 50 K, cooldown rate = 1.15 K/min.

![Figure 15: First cooldown history of the high-β cavity package](image)

Figure 16 and Figure 17 show the second cooldown history completed a month later, from which an average cooling rate, bigger than 2 K/min was kept in the temperature region from 150 to 50 K.

Different cooldown rates based on different temperature sensors conditions in this run are:
i) from 210 K ≤ with only checking TT104, TT117 and TT118 ≤ 50 K, cooldown rate = 2.96 K/min

ii) from 150 K ≤ with only checking TT104, TT117 and TT118 ≤ 50 K, cooldown rate = 2 K/min

Figure 16: Temperature overview of the second test

Figure 17: Second cooldown history of the high-β cavity package
Note that most thermal sensors did not give a correct reading except TT118. One potential reason for that is adopting a new type of glue. More details about the cooldown can be found in [15] and [16].

4.2. Resonant frequency

During cooldown, the resonant frequency of the high-beta elliptical cavity was checked via an S parameter measurement to study the cavity behavior. The cavity resonant frequency shifts as a function of temperature is shown in Figure 18 and Figure 19. Table 8 lists the key frequencies of the high-beta cavity at three different temperatures, from which the frequency increment due to cryo-constriction was about 1.129 MHz from 300 K to 4 K, while a frequency decreasing of 40 kHz happened from 4 K to 2 K since the helium pressure decrease from 1 atmosphere to 31 mbar.

Table 8: Resonant frequency of the high-beta elliptical cavity

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Resonant frequency [MHz]</th>
<th>Frequency shift [MHz]</th>
<th>Frequency shift [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K</td>
<td>702.991 ± 0.001</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4 K</td>
<td>704.12 ± 0.0005</td>
<td>-1.129 ± 0.001</td>
<td>0.16</td>
</tr>
<tr>
<td>2 K</td>
<td>704.081 ± 0.0005</td>
<td>-1.09 ± 0.001</td>
<td>0.155</td>
</tr>
</tbody>
</table>

Figure 18: Cavity frequency checking during cooldown from 300 K to 4 K. Here, the red curve and the pink curve are the temperature of the cavity and the blue curves are the cavity frequency.
Figure 19: Cavity frequency checking during cooldown from 4 K to 2 K. Here, the red curve is the temperature of the cavity, the blue curve is the cavity frequency and the black curve the pressure in the helium tank.

5. Cavity measurements

5.1. Quality factor measurement
The Q factor measurement of the cavity package is based on the SEL 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 14 MV/m was successfully reached (this value is corrected by the $Q_L$ from decay measurement). The preliminary result of the quality factor of the cavity package vs. gradient is shown in Figure 20. The high power test of the high-beta cavity package started in June 2018 and lasted until shipping it back to CEA in September.
Figure 20: High-β cavity package performance as a function of accelerating gradient.

The high-β cavity package gives a Q factor of $1 \times 10^{10}$ at low field and $4.9 \times 10^9$ at 14 MV/m. X-ray radiation started from 8 MV/m, which implied field emission in the cavity package. After 30 minutes conditioning, the cavity performance unfortunately has not significantly improved.

5.2. Dynamic heat load

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, as shown in Figure 21. 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 2 minutes, as shown in Figure 22. 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.
The pressure rise method has been tested with the ESS spoke cavity before and the details have been described in [9].

Figure 21: Layout while implement a pressure slope measurement (Both the inlet and outlet of 2 K tank, the red valves shown in the picture, were kept closed during measurement)

![Diagram of layout](image1)

Figure 22: Different pressure rise as a function of time by a known resistance for 2 minutes

A heat load calibration curve was built by repetition of the relative pressure rise measurements. The pressure gradient as a function of heat power fulfills the Equation

\[
\text{Slope}_{RF} = \text{Slope}_{1W} \times P_{dynamic} + \text{Slope}_{static}
\]

(5.1)
Where $Slope_{RF}$ is the measured pressure gradient for a certain heat load,

$$P_{dynamic}$$ is the corresponding dynamic heat load with respect to a certain $Slope_{RF}$, in [W],

$Slope_{1W}$ is the dynamic heat load coefficient in [1/W],

$Slope_{static}$ is a pressure gradient offset depends on the static heat load.

Through the calibration curve shown in Figure 23, the dynamic heat load calculation of high-$\beta$ cavity is,

$$Slope_{RF} = 0.0024 \times P_{dynamic} + 0.0145$$  \hspace{1cm} (5.2)

Finally, RF power was loaded in the cavity and the dynamic load was calculated by using this calibration curve.

![Calibration curve](image)

Figure 23: Calibration pressure gradient as a function of heat power

All measurement points of dynamic heat load during the test in August are listed in Table 9. Please note that the static heat load was re-measured just before the Q measurement and a new value of $Slope_{static} = 0.0155$ was used for all the calculation.
Table 9: Dynamic heat load of high-\( \beta \) cavity package in the second run

<table>
<thead>
<tr>
<th>( E_{acc_flattop} ) [MV/m]</th>
<th>pressure rise slop</th>
<th>dynamic RF load [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>0.016</td>
<td>0.2</td>
</tr>
<tr>
<td>7.7</td>
<td>0.0163</td>
<td>0.33</td>
</tr>
<tr>
<td>8.6</td>
<td>0.0169</td>
<td>0.58</td>
</tr>
<tr>
<td>10.5</td>
<td>0.0181</td>
<td>1.08</td>
</tr>
<tr>
<td>12.9</td>
<td>0.0198</td>
<td>1.79</td>
</tr>
<tr>
<td>14.1</td>
<td>0.0213</td>
<td>2.41</td>
</tr>
</tbody>
</table>

5.3. Q measurement error estimation

5.3.1. Gradient measurement uncertainty

Equation (5.3) gives the definition of accelerating gradient. In practice, the flattop gradient can be obtained either through the transmitted or the forward power. In the test of the high-\( \beta \) cavity, a discrepancy of the flattop accelerating gradient was found from two independent methods, with the related formula given in Equation (5.4) and (5.5). Several calibrations have been thoroughly carried out and no calibration issue has been found. Note that \( Q_t \) in Equation (5.4) is totally depended on the value from the vertical test, which has a risk of slightly value change because of many reasons. In our case, forward power is chose for the gradient calculation.

\[
E_{acc} = \frac{V_c}{L_{eff}} \tag{5.3}
\]

\[
E_{acc\_peak\_pt} = \frac{\sqrt{R/Q \times P_{t,max} \times Q_t}}{L_{eff}} \tag{5.4}
\]

\[
E_{acc\_peak\_pf} = \frac{\sqrt{4 \times R/Q \times P_{f,max} \times Q_t}}{L_{eff}} \tag{5.5}
\]

Where \( V_c \) is the cavity voltage, in [V],
$L_{eff}$ is the effective accelerating length, in [m],
$P_{t,max}$ is the maximum transmitted power at the flattop gradient, in [W],
$Q_t$ is the external quality factor of the pick-up antenna,
$R/Q$ is the shunt impedance of the cavity, in [$\Omega$],
$E_{acc,peak,P_t}$ is the flattop gradient calculated via $P_{t,max}$, in [MV/m],
$Q_L$ is the loaded quality factor of the cavity,
$P_{f,max}$ is the maximum forward power during the pulse, in [W],
$E_{acc,peak,P_f}$ is the the flattop gradient calculated via $P_{f,max}$, in [MV/m].

Most of the error propagation of an Equation of the type $x = f(u,v)$ can be done by using the following fundamental Equation[21]

$$
\sigma_x^2 = \sigma_u^2 \left( \frac{\partial x}{\partial u} \right)^2 + \sigma_v^2 \left( \frac{\partial x}{\partial v} \right)^2 + 2\sigma_{uv} \left( \frac{\partial x}{\partial u} \right) \left( \frac{\partial x}{\partial v} \right)
$$

(5.6)

If $u$ and $v$ are uncorrelated, then $\sigma_{uv}^2 = 0$.

In the case of $E_{acc,peak,P_f}$ measurement, $Q_L$ and $P_{f,max}$ come from independent measurements. The propagation of errors of the flattop gradient thus can be simplified as

$$
\frac{\Delta E_{acc,peak,P_f}}{E_{acc,peak,P_f}} = \frac{1}{2} \sqrt{\left( \frac{\Delta Q_L}{Q_L} \right)^2 + \left( \frac{\Delta P_f}{P_f} \right)^2}
$$

(5.7)

- **Uncertainty of $Q_L$ measurement**

$Q_L$ value came from the decay measurement of the transmitted voltage. The cavity voltage profile was recorded by FPGA, in which the voltage error came from the ADC board capacity. The ADC board used at FREIA provides 14 bits resolution and has no more than 50 µV variation in each voltage sampling. The uncertainty of the sampling of voltage profile was negligible in the calculation. The decay part of the cavity profile after the forward power has been cut was then completed an exponential curve fitting, from which the decay time of cavity voltage was obtained, as shown in Figure 24. The fitting uncertainty is less than 2%. The final $Q_L$ value came from the average of several decay time measurements. Integrating
the error from curve fitting and the mean value calculation, the total uncertainty of \( \frac{\Delta Q_L}{Q_L} \) is not worse than 5%.

Figure 24: Decay time calculation by exponential curve fitting of transmitted signal

- Uncertainty of forward power measurement

The uncertainty of the forward power measurement usually is given by

\[
\frac{\Delta P_f}{P_f} = \sqrt{(\delta C_f)^2 + (\Delta P_{fm})^2} \\
(5.8)
\]

\[
P_f = P_{fm} \times C_f \\
(5.9)
\]

\[
\Delta P_{fm} = P_{fm} \times \delta P_{cal} + P_{\text{min}} \\
(5.10)
\]

Where \( P_{fm} \) is the measured forward power, in [W],
\( P_{\text{min}} \) is the sensitivity limit of the power sensor, in [W],
\( \delta P_{cal} \) is the fractional uncertainty in the absolute power measurement,
\( \delta C_f \) is the fractional uncertainty in cable calibration,
\( \Delta P_{fm} \) is the error in \( P_{fm} \), in [W].
Keysight N1912A power meters were adopted for all power measurements in this test, which aim for accurate power reading with low measurement noise. 2 µW of sensitivity limit for the power sensor was negligible in the error calculation. Therefore the measurement uncertainty of the forward power is recalculated as

\[
\frac{\Delta P_f}{P_f} = \sqrt{\left(\frac{\delta C_f}{C_f}\right)^2 + \left(\frac{\delta P_{cal}}{P_{cal}}\right)^2}
\]  

(5.11)

In the case of HB cavity, the biggest portion of the forward power error is contributed by the phase uncertainty of standing wave of the forward signal, which is belong to the part of the fractional uncertainty in cable calibration. More details are discussed in the following part in this section. A total uncertainty of ±13% of the forward power measurement is found.

- Uncertainty of an absolute power measurement

Table 10 summarizes the major sources of uncertainty in an absolute power measurement [22]. All items, except mismatch uncertainty, come from the specifications of E9322A sensor and Keysight N1912A power meter over a temperature range of 25 ± 10 °C. Mismatch uncertainty is however dependent on the local loop setting, which is calculated from the specified standing wave ratio (SWR) of the device and the sensor, as shown in Equation (5.12). In the pulsed SEL (shown in Figure 6), both the 4-way splitter and the power sensor contributed to the mismatch uncertainty. The SWR of the 4-way splitter and the power sensor were about 1.12.

\[
U_{\text{mismatch}} = \pm \frac{SWR_{\text{splitter}} - 1}{SWR_{\text{splitter}} + 1} \times \frac{SWR_{\text{sensor}} - 1}{SWR_{\text{sensor}} + 1} \times 100\%
\]

(5.12)

<table>
<thead>
<tr>
<th>Identify significant uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter uncertainty</td>
<td>±0.813%</td>
</tr>
<tr>
<td>Zero uncertainty</td>
<td>±0.015%</td>
</tr>
<tr>
<td>Sensor calibration uncertainty</td>
<td>±4.2%</td>
</tr>
<tr>
<td>Standard uncertainty of mismatch at 750 MHz</td>
<td>±0.59%</td>
</tr>
</tbody>
</table>
Root Sum of the Squares (RSS) is adopted to combine uncertainties of power measurement and can be calculated by Equation (5.13) [22]. It is based on the fact that most of the errors, although systematic, are independent and therefore could be combined as random variables.

\[
U_c = \sqrt{\left(\frac{U_{mismatch}}{2}\right)^2 + \left(\frac{sys_{rss}}{2}\right)^2}
\]  

(5.13)

Where \(sys_{rss}\) is the RSS of the meter uncertainty, the zero uncertainty and the sensor calibration uncertainty.

With the significant uncertainty values of the power measurement at FREIA, the combined standard uncertainty was ± 2.2% and the expanded uncertainty was ± 4.4% [22]. Note that only the expanded uncertainty was used as the uncertainty of an absolute power measurement from a power meter in all following calculations.

- Uncertainty of cable calibration

The fractional uncertainty in cable calibration was calculated as

\[
\delta C_f = \sqrt{\frac{(\Delta S_{21})^2}{S_{21}^2} + \left(\frac{\Delta P_1}{P_1}\right)^2 + \left(\frac{\Delta P_2}{P_2}\right)^2 + \left(\frac{\Delta Phase_{sw}}{Phase_{sw}}\right)^2}
\]

(5.14)

Where \(\Delta S_{21}\) is the total uncertainty in the \(S_{21}\) measurements,

\(\Delta P_1\) and \(\Delta P_2\) are the error in absolute power measurements,

\(\Delta Phase_{sw}\) is the phase uncertainty of the standing wave of the forward signal.

The cable calibration for the forward power included following three parts:

1) \(S_{21}\) measurement of the cable from the waveguide directional coupler to the control room. Since the cable used for forward power monitoring was about 50 meters long and is paved from the site to the control room, it is not easy to make a direct \(S_{21}\) measurement by a VNA. Here the \(S_{21}\) parameters of forward, reflected and reference cables were measured in pairs, from which the \(S_{21}\) parameter of each cable can be calculated by solving the Equations.

2) The path after the forward cable to the power meter sensor is made up of a bandpass filter and a 6dB-splitter. A signal generator was first calibrated against a power meter for an absolute power measurement and later used as a power source and reference. Another absolute power measurement was completed by the on-site power meter. The difference between these two power readings was the losses on the path.
During the test, a standing wave was usually built in the path between the cavity and the circulator due to the impedance mismatch. Since the forward power is measured through the waveguide directional coupler which located at a fix position, the reading is therefore strongly affected by the phase of the standing wave. In the case of HB cavity test, forward power was detected from four different ports at a waveguide directional coupler (directivity > 40 dB) in order to study the phase variation. This waveguide directional coupler is about 42 cm long therefore the forward power measurements cover a wave length distance. Then the average of this four ports measurement is used as the compensation of the phase uncertainty in the forward power calibration. Please note that all waveguide directional couplers have been calibrated at the factory and therefore the coupling factor variation is not counted in the error estimation.

Here the error estimation of mean value is based on the least square value and Equation (5.15) is involved.

\[
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i
\]

\[
\sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2}
\]

\[
\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{N}}
\]  

(5.15)

Note that the measurements have only been taken at four ports, therefore in order to set the mean value within 95% confidence interval, another coefficient of \( t_\xi = 3.18 \) is added [23].

\[
\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{N}} t_\xi
\]  

(5.16)

At the same time, the absolute power measurements from these four ports have observed with ± 8% uncertainty (include cable calibration uncertainty). The total phase uncertainty is increase to be the square root \( \sqrt{(\sigma_{\bar{x}})^2 + (8\%)^2} = 9.7\% \).

With the uncertainty of ±4% of the S21 measurement using a VNA (N5221), the expanded uncertainty ± 4.4% of the absolute power measurement and the phase uncertainty ± 9.7% of the standing wave of the forward signal, the fractional uncertainty in cable calibration of 12.2% was obtained.

- Uncertainty of accelerating gradient
Considering that the sensor calibration uncertainty did not drift significantly within the power range, one substituted Equations (5.11) in Equation (5.7) and obtained the accelerating gradient uncertainty of 7%.

5.3.2. **Heat load measurement uncertainty**

Two different methods had been applied to the heat load measurement. The measurement accuracy of liquid helium evaporation method mainly relied on the flowmeter measurement placed after the sub-atmospheric pumps. In the high-β cavity test, the pressure sensor (PT102) close to the 2 K tank has been found not operating properly, therefore the pressure regulation used an alternative pressure sensor (PT552) after the re-heater instead of PT102. Since this sensor PT552 is close to the only regulating value, it brought big challenges to the PID system and the flow measurement thus has higher uncertainty [16]. Therefore, the pressure rise method is mainly used for the heat load measurement. This section will only discuss the measurement uncertainty of the pressure rise method calculated by

\[
Slope_{RF} = Slope_{1W} \times P_{dynamic} + Slope_{static}
\]  

- Uncertainty of pressure gradient measurement

The linear regression was applied to every pressure gradient measurement. With a given set of time measurement \(x\) and corresponding instantaneous helium pressure \(y\), the pressure gradient is given by a least-square fitting [24]

\[
y = ax + b
\]

The uncertainty \(\sigma_i\) associated with each pressure measurement \(y_i\) was known, and that of the time measurement done by a data acquisition system was so small therefore that it was neglected.

The best-fit model parameters of \(a, b\) and corresponding uncertainties are calculated as

\[
a = \frac{S_{xx}S_y - S_xS_{xy}}{\Delta} \\
b = \frac{S_{xy}S_{yy} - S_xS_{xy}}{\Delta} \\
\sigma_a^2 = \frac{S_{xx}}{\Delta}, \quad \sigma_b^2 = \frac{\Delta}{\Delta}
\]  

\(5.18\)
Namely, \( a \) is the pressure gradient \( \text{Slope}_{RF} \) at a certain applied power and \( \sigma_a \) is its uncertainty. Where according to the fundamental error estimation of a least-square fitting, following sums are define as

\[
S \equiv \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \quad S_x \equiv \sum_{i=1}^{N} \frac{x_i}{\sigma_i^2} \quad S_y \equiv \sum_{i=1}^{N} \frac{y_i}{\sigma_i^2}
\]

\[
S_{xx} \equiv \sum_{i=1}^{N} \frac{x_i^2}{\sigma_i^2} \quad S \equiv \sum_{i=1}^{N} \frac{x_i y_i}{\sigma_i^2}
\]

\[
\Delta \equiv SS_{xx} - (S_x)^2
\]

(5.19)

- Uncertainty of \( \text{Slope}_{1W} \) and \( \text{Slope}_{static} \)

The heat load calibration curve consisted of pressure gradients at different heater power. The pressure gradient offset due to the static heat load (\( \text{Slope}_{static} \)) and the pressure gradient increment per dynamic heat load (\( \text{Slope}_{1W} \)) were calculated by linear fitting of pressure gradients and heater powers. The pressure at each certain power was measured for 2 minutes and the corresponding pressure gradient was given by the linear regression. The uncertainty of each linear regression calculated by Equation (5.18) was therefore re-used for the calculation of the uncertainty of the calibration curve as given in Equation (5.2) and graphically in Figure 23. Table 11 illustrates the uncertainty of each pressure measurement at different heater power.

<table>
<thead>
<tr>
<th>Heater power [W]</th>
<th>Uncertainty of each pressure measurement [mbar]</th>
<th>Pressure gradient uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
<td>1.32×10^{-4}</td>
</tr>
<tr>
<td>1</td>
<td>0.05</td>
<td>1.32×10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>1.58×10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>1.58×10^{-4}</td>
</tr>
<tr>
<td>5</td>
<td>0.07</td>
<td>1.84×10^{-4}</td>
</tr>
<tr>
<td>7</td>
<td>0.1</td>
<td>2.63×10^{-3}</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>2.63×10^{-3}</td>
</tr>
<tr>
<td>12</td>
<td>0.1</td>
<td>2.63×10^{-3}</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
<td>2.63×10^{-3}</td>
</tr>
</tbody>
</table>
With a known heater power range from 0 to 15 W, the calibration curve was established with the following parameters

\[ \text{Slope}_{1W} = 0.0024 \pm 1.65 \times 10^{-5} \]

\[ \text{Slope}_{\text{static}} = 0.0145 \pm 9.9 \times 10^{-6} \]

Note in the case of HB cavity, a new static heat load was tested several times just before the RF test and an average value of 0.0155 was used in the calculation.

If Equation (5.1) used in the pressure rise method is rewritten, the dynamic heat load is usually given by

\[ P_{\text{dynamic}} = \frac{\text{Slope}_{RF} - \text{Slope}_{\text{static}}}{\text{Slope}_{1W}} \]  \hspace{1cm} (5.20)

Here, \( \text{Slope}_{RF} \), \( \text{Slope}_{\text{static}} \) and \( \text{Slope}_{RF} \) are obtained from independent measurements and the fractional uncertainty in a dynamic heat load measurement is

\[ \frac{\Delta P_{\text{dynamic}}}{P_{\text{dynamic}}} = \sqrt{\frac{\Delta \text{Slope}_{RF}^2 + \Delta \text{Slope}_{\text{static}}^2}{(\text{Slope}_{RF} - \text{Slope}_{\text{static}})^2} + \left(\frac{\Delta \text{Slope}_{1W}}{\text{Slope}_{1W}}\right)^2} \]  \hspace{1cm} (5.21)

The first part in the right hand side of Equation (5.21) represents the relative slope difference due to RF power on, which is the dominating part of the uncertainty of the dynamic heat load. The second part represents the uncertainty of the pressure gradient increment per dynamic heat load, which comes from the calibration and is a constant over the whole measurement.

Table 12 lists the uncertainty of each dynamic heat load at different gradients. A higher fractional uncertainty of the dynamic heat load measurement at low field is found. It is because of the RF loss is very small at a low field, which means the denominator of the first part in the right hand side of Equation (5.21) is very close to zero and the measurement uncertainty is therefore increase significantly.
Table 12: Uncertainty of the dynamic heat load by using static heat load as a reference point.

<table>
<thead>
<tr>
<th>$E_{acc}$ [MV/m]</th>
<th>Dynamic heat (W)</th>
<th>Uncertainty of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>0.33</td>
<td>61.75%</td>
</tr>
<tr>
<td>8.6</td>
<td>0.57</td>
<td>35.29%</td>
</tr>
<tr>
<td>10.5</td>
<td>1.07</td>
<td>19.01%</td>
</tr>
<tr>
<td>12.8</td>
<td>1.78</td>
<td>11.68%</td>
</tr>
<tr>
<td>14.2</td>
<td>2.42</td>
<td>8.67%</td>
</tr>
</tbody>
</table>

5.3.3. Unloaded Q measurement uncertainty

The unloaded quality factor $Q_0$ of the cavity package running in a pulsed mode is calculated through

$$Q_0 = \frac{V_{c,ave}^2}{R/Q \times P_{cw}} \quad (5.22)$$

Where, $V_{c,ave}$ is the average cavity voltage built during the pulse and can be obtained via Equation (5.27), $P_{cw}$ is the continuous wave heat load with respect to the dynamic heat load measured in the RF time, unit in [W], and can be obtained through Equation (5.24).

The uncertainty of an unloaded Q measurement at a certain gradient is given by

$$\frac{\Delta Q_0}{Q_0} = \sqrt{\left(2 \frac{\Delta V_{c,ave}}{V_{c,ave}}\right)^2 + \left(\frac{\Delta P_{cw}}{P_{cw}}\right)^2} \quad (5.23)$$

- Uncertainty of $P_{cw}$

$$P_{cw} = P_{dynamic} \times \frac{1}{T_{RF} \times \frac{1}{R_{rep}}} \quad (5.24)$$
Dividing the dynamic heat load by the duty factor of pulse can easily give the continuous wave heat load at a certain gradient. Here, $T_{RF}$ is the pulse duration (2.55 ms) and $R_{rep}$ is repetition rate (14 Hz). The uncertainty of the continuous wave heat load was the same as the value of the uncertainty of the dynamic heat load.

- Uncertainty of cavity voltage measurement

During a pulsed mode measurement, the total RF power dissipated at the cavity wall contributed to the heat load and was impossible to distinguish the fraction due only to the flattop gradient. So the average cavity voltage is defined as the integration of the cavity voltage during the pulse divided by the pulse duration.

At the FREIA high power test stand, the cavity voltage profile was recorded by the FPGA-based program, in which the measured voltage signal needed to be multiplied by a calibration factor to convert to the true signal. A peak measurement of the forward power during a pulse was continually done by the power meter. With the max forward power, the corresponding square of max cavity voltage can be obtained by

$$V_{c,max,Pf}^2 = \frac{R}{Q} \times Q_L \times P_{f,max}$$

(5.25)

The integration of the cavity voltage profile then can be normalized

$$V_{c,norm}^2 = \frac{\sum V_{c,FPGA}^2 \times \Delta t}{V_{c,max,FPGA}^2}$$

(5.26)

And used in

$$V_{c,ave}^2 = \frac{V_{c,max,Pf}^2 \times V_{c,norm}^2}{T_{RF}}$$

(5.27)

Here, $V_{c,FPGA}$ is the cavity voltage at the certain stage during RF on,

$V_{c,max,FPGA}$ is the maximum voltage during RF on,

$\Delta t$ is the sampling time of 1 µs in the FPGA program.

The ADC board in the FPGA provides 14 bits resolution in each voltage sampling. The uncertainty of the integration of the whole voltage profile was negligible in the calculation compared to the uncertainty of the max transmitted power.
Thus the uncertainty of the cavity voltage measurement is dominating by max forward power measurement

$$\frac{\Delta V_{c,ave}^2}{V_{c,ave}^2} \approx \sqrt{\left(\frac{\Delta V_{c,max, Pf}^2}{V_{c, max, Pf}^2}\right)^2}$$ (5.28)

Equation (5.29) shows the uncertainty calculation in which the result of Equation (5.11) is used as an input.

$$\frac{\Delta V_{c,max, Pf}^2}{V_{c, max, Pf}^2} = \sqrt{\left(\frac{\Delta Q_L}{Q_L}\right)^2 + \left(\frac{\Delta P_{f, max}}{P_{f, max}}\right)^2}$$ (5.29)

Table 13 lists the error estimation of $Q_0$ measurement of HB elliptical cavity.

<table>
<thead>
<tr>
<th>Eacc [MV/m]</th>
<th>$Q_0$</th>
<th>Uncertainty of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>1E+10</td>
<td>63.29%</td>
</tr>
<tr>
<td>8.6</td>
<td>7.23E+09</td>
<td>37.94%</td>
</tr>
<tr>
<td>10.5</td>
<td>5.85E+09</td>
<td>23.55%</td>
</tr>
<tr>
<td>12.8</td>
<td>5.47E+09</td>
<td>18.16%</td>
</tr>
<tr>
<td>14.2</td>
<td>4.94E+09</td>
<td>16.38%</td>
</tr>
</tbody>
</table>

5.4. $Q_{ext}$ of FPC measurement

Two different methods were adopted to study the $Q_{ext}$ value of the FPC and got a good agreement both at room temperature and 2 K. The external Q factor of the high-beta cavity with a medium-beta FPC is $5.2 \times 10^5$.

5.4.1. $Q_{ext}$ of FPC with doorknob at room temperature

In a radio frequency cavity, the coupling factor of the port of forward power is defined by Equation (5.30) and can be calculated by the SWR.
\[ \beta = \frac{Q_0}{Q_{\text{ext}}} \]  \hspace{1cm} (5.30)
\[ \beta = 1 / \text{SWR} \quad \text{when the system is under coupled} \]  \hspace{1cm} (5.31)
\[ Q_0 = Q_L (1 + \beta) = \beta Q_{\text{ext}} \]  \hspace{1cm} (5.32)

Through Equations (5.30)-(5.32), the external quality factor of FPC at warm temperature can be obtained by:

\[ Q_{\text{ext}} = (1 + \text{SWR}) Q_L \]  \hspace{1cm} (5.33)

At FREIA, a waveguide-to-N-type adopter, as shown in Figure 25, was connected with the doorknob and the HB cavity and was used for the measurement of \( Q_{\text{ext}} \) of FPC. Before the measurement, two adaptors were connected back-to-back through a short piece of waveguide (Figure 25 (b)) for the calibration. Within a frequency range of 704 ±2.5 MHz, these adaptors had a consistent (uniform) performance with a variation of S12 value of 0.03 dB, while that of S11 was about 0.04 dB. The insert loss of each adopter was about 0.5 dB.

![Figure 25: (a) waveguide-to-N-type adapters used for 704 MHz cavity measurement, (b) Adapters calibration with a short piece of waveguide](image)

Figure 26 shows an example of SWR result of the high-beta cavity with FPC completed by VNA S parameter measurement. For validation, this test was repeated at different time and under different calibrations and all results are shown in Table 14. The SWR value was found around 30 with a variation of 20% due to the cable phase change at different bending situation. Please note that \( Q_0 \) of the high-beta cavity at room temperature came from a S21 measurement after the CTS installation.
as shown in Figure 27, $Q_0$ factor of $1.9 \times 10^4$ was used to roughly estimate the $Q_{ext}$ factor of the FPC. Therefore, this method is only valid for a rough estimation, for the $Q$ factor of cavity was measured with high attenuation due to mismatching of the cavity and the pick-up antenna. Also the path from adopter down to the doorknob was without calibration in this measurement. An accurate measurement should be done through S12 while the cavity is cold.

Figure 26: Example of SWR measurement of high-beta cavity with FPC at room temperature

Figure 27: S21 measurement of high-beta elliptical cavity at room temperature
Table 14: Test result of SWR at different test run

<table>
<thead>
<tr>
<th>Test run</th>
<th>SWR</th>
<th>Qext</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.1</td>
<td>5.7×10^5</td>
</tr>
<tr>
<td>2</td>
<td>32.3</td>
<td>6.3×10^5</td>
</tr>
<tr>
<td>3</td>
<td>35.6</td>
<td>7×10^5</td>
</tr>
<tr>
<td>4</td>
<td>33.1</td>
<td>6.5×10^5</td>
</tr>
<tr>
<td>5</td>
<td>26.5</td>
<td>5.2×10^5</td>
</tr>
<tr>
<td>6</td>
<td>28.4</td>
<td>5.6×10^5</td>
</tr>
</tbody>
</table>

5.4.2. Qext of FPC at 2K

At a cold temperature of 2 K, the Qext of FPC is equal to the Q_L. Several approaches of Q_L, including the S21 bandwidth measurement, calculation through the decay time measurement and the calculation through a half bandwidth measurement, have been carried out. Both calculations from the decay measurement (Figure 24) and from the half bandwidth measurement (as shown in Figure 28) have a good agreement of 5.2 ×10^5. Here, the half bandwidth measurement was carried out by monitoring the complex signals of cavity signals and its details could be found in [9]. However, a Q_L value of 6.9 ×10^5 is found in the S21 measurement, as shown in Figure 29. The reason of the Q_L discrepancy is still under study. Since the first two measurements showed the same value, the Q_L value of 5.2 ×10^5 is used in the cavity voltage calculation, which is later reinforced in the forward power calculation with a given filling time.

Figure 28: Q_L calculation through a half bandwidth measurement
5.5. Longitudinal modes measurement

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 15. 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 $\pi$ mode and $4\pi/5$ mode is bigger than 1.2 MHz, which fulfills the ESS requirement.

Table 15: First passband of high-beta elliptical cavity

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Frequency [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300 K</td>
</tr>
<tr>
<td>$\pi$ mode</td>
<td>702.991</td>
</tr>
<tr>
<td>$4\pi/5$ mode</td>
<td>701.761</td>
</tr>
<tr>
<td>$3\pi/5$ mode</td>
<td>698.464</td>
</tr>
<tr>
<td>$2\pi/5$ mode</td>
<td>694.370</td>
</tr>
<tr>
<td>$\pi/5$ mode</td>
<td>691.104</td>
</tr>
</tbody>
</table>
5.6. **Dynamic 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. Details about this program and test procedure could be found in reference [9].

In this study, forward pulses with step pulse profile were used, as shown in the top graph of Figure 30, a RF power 6 dB higher than the flattop was applied during the filling time. The LFD experimental result of 13 MV/m, shown in the bottom picture of Figure 30, 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 $-1.3 \text{ Hz/(MV/m)}^2$ with tuner contacted condition, which is in agreement with the simulation [25]. For a nominal accelerating gradient of 19.9 MV/m, the shift will be $1/2$ 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 and a preliminary result of online compensation of piezo is shown in Figure 31.
Figure 30: Top: Forward (black), reflected (red) and transmitted (green) signal during 2.55 ms pulses. Bottom: Dynamic Lorentz detuning of ESS HB elliptical cavity at 13 MV/m.

Figure 31: LDF compensation study with piezo 1
5.7. **Cavity voltage filling time**

5.7.1. **Simulation**

In order to get high efficiency of the linac operation, the fill of the cavity are on the order of 300 µs, so the total RF pulse length is approximately 3.5 ms and the total duty factor is 4.9 % [26]. Some filling time simulations were done at FREIA in order to provide more theoretical instruction for test. Figure 32 and Figure 33 show the required filling power as a function of loaded Q with/without detuning, in which Equation (5.34) was used for calculation. The cavity filling time discussed in this report is defined as the time period at which the cavity is charged to a desired voltage $V_0$ from zero.

\[
P_{\text{fill}} = \frac{V_0^2 (w_0^2 + Q_L^2 \Delta \omega^2)}{4 \left( \frac{R}{Q} \right) Q_L \omega_0^2 [1 + e^{-\frac{\omega_0 T_{\text{fill}}}{Q_L}} - 2e^{-\frac{\omega_0 T_{\text{fill}}}{2Q_L}} \cos(\Delta \omega T_{\text{fill}})]}
\]

(5.34)

Where $V_0$ is the desired cavity flattop voltage;

$T_{\text{fill}}$ is the filling time;

$Q_L$ is the loaded quality factor of cavity;

$\Delta \omega$ is the detuning of the cavity.

Firstly, only the ideal charging without detuning was considered. According to the 300 µs filling curve as shown in Figure 32, a filling power of 681 kW is needed with a reference $Q_L$ of $7.6 \times 10^5$. Secondly, required filling power with different cavity detuning was studied and shown in Figure 33. Detuning usually comes from instabilities during the accelerator commissioning, such as dynamic Lorentz force detuning, microphonics and helium fluctuations. More power is thus required to compensate the higher power reflection from the cavity caused by frequency mismatching. Considering the design $Q_L$ of $7.6 \times 10^5$ in the case of high-beta cavity, 1% more filling power is required for 200 Hz detuning, while 34% more filling power is required for 1000 Hz detuning.
Figure 32: The required filling power with respect to different load Q and filling time with zero detuning for $E_{acc}=19.9$ MV/m

Figure 33: The required filling power with different cavity detuning for $E_{acc}=19.9$ MV/m

Two-step forward pulse profile will be used for the ESS high-beta elliptical cavity. With a requirement of 300 µs filling time, a forward power of 681 kW is needed during the charging stage.
followed by cutting down to 253 kW for maintaining a gradient of 19.9 MV/m. With a peak power of 1.1 MW, according to the power conditioning of the Toshiba klystron at FREIA, the fastest filling time of the ESS high-beta cavity calculated by Equation (5.34) is therefore about 211 µs with the design Q<sub>L</sub> of 7.6×10<sup>5</sup>. The comparison of these step pulse profiles is shown in Figure 34.

Figure 34: Examples of forward power profiles to ESS high-beta cavity at 19.9 MV/m without beam for (a) 300 µs or (b) 211 µs filling times

5.7.2. Filling time test result

According to the above simulation, two-step forward pulse profile was applied to the ESS high-beta cavity in the high power test without beam. Please note that according to the gradient limit of this cavity, a gradient of 13.2 MV/m is chose instead of 19.9 MV/m. The corresponding simulation is shown in Figure 35 and Figure 36, from which a forward power of 314 kW and 569 kW is needed during the charging stage in order to manage a filling time of 300 µs and 180 µs respectively.
Figure 35: The required filling power with respect to different load Q and filling time with zero detuning for $E_{acc}=13.2$ MV/m

Figure 36: Forward power vs. accelerating gradient while load $Q=5.2 \times 10^5$

Figure 37 shows the test result of the cavity voltage as a function of time during a pulse with an open loop driven by the Lund LLRF, in which the forward power of 316 kW is needed during the
charging stage in order to manage a filling time of 300 µs, afterward the forward power was cutting down to 162 kW for maintaining a gradient of 13.2 MV/m.

![Figure 37: Cavity voltage profile with 300 µs filling time while Eacc=13.2 MV/m](image)

During operation, a two-step forward pulse profile with a first step 6 dB higher than the second one will be used. Figure 38 shows the case of a filling time of 180 µs when adopting 6 dB two-step forward pulses, the first step of the forward power was 600 kW while the second part was 162 kW. Please note that ramping up from zero to a flattop gradient, the cavity voltage was affected by the LFD, therefor the required power is slightly higher than the simulation value.

![Figure 38: Cavity voltage profile with 6 dB two-step forward pulse profile while Eacc=13.2 MV/m](image)
5.8. **Pressure sensitivity**

Helium pressure fluctuations inside the tank detune the cavity resonant 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 Figure 39, a pressure sensitivity of +37 Hz/mbar is measured.

![Cavity Frequency vs. LHe pressure](image)

Figure 39: Cavity frequency shift as a function of helium pressure from 50 to 800 mbar.

Note that the mechanical contraction of the cavity from 4K to 2K is very small, thus the frequency shift caused by this temperature change can be ignored. Also during the cool down the CTS is totally disconnected with the cavity, therefore, this frequency sensitivity as a function of the helium pressure would be different as the one at operation.

5.9. **Tuner sensitivity**

The cold tuning system (CTS) is attached to the cavity to adjust its resonant frequency in order to counteract the frequency detuning. The CTS function with cavity was fully studied at the second run. Please note that at the first test run in June, it was not possible to tune the cavity frequency due to a poor connection of motor cable at the cryo side. After repaired the cable connection after warm up the cryostat, a direct welding between connections has been solved and the tuning system worked as expected. The behavior of the slow tuning system was studied at 2 K at FREIA with SEL, as shown in
Figure 40. Throughout the CTS measurement, the temperature of motor (TT06X) was monitoring, less than 10 K temperature increasing when operating the stepper motor. A tuning sensitivity of 173 KHz/mm was found. Here the distance is defined as the longitudinal deformation of the cavity. Several runs round the operation range have been completed and a good linearity of the CTS has been found. From the test result, this stepper motor tuning range is bigger than 340 kHz.

![Tuning sensitivity graph](image)

Table 16: Parameters for motor operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor driving current [A]</td>
<td>1.1</td>
</tr>
<tr>
<td>Eacc [MV/m]</td>
<td>500</td>
</tr>
<tr>
<td>Frequency accuracy [Hz]</td>
<td>±300</td>
</tr>
</tbody>
</table>

Some missing step issue has been observed while continue running the motor at one go, as shown in red circle marks in Figure 41.
Figure 41: Missing steps while pulling the motor at one go

5.10. **Piezo test**

Two piezo performances with DC voltage were studied. Table 17 shows the characterization of both piezos at different temperatures.

<table>
<thead>
<tr>
<th>parameters</th>
<th>Cavity temperature</th>
<th>Piezo1</th>
<th>Piezo2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance [µF]</td>
<td>4.7 K</td>
<td>1.82</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>2K</td>
<td>2.05</td>
<td>1.98</td>
</tr>
<tr>
<td>Resistance [Ohm]</td>
<td>4.7 K</td>
<td>6.28</td>
<td>6.25</td>
</tr>
<tr>
<td>Inductance [mH]</td>
<td>4.7 K</td>
<td>871</td>
<td>923.8</td>
</tr>
</tbody>
</table>
Both piezos were charged with a DC voltage within a range of ±80V meanwhile the frequency shift was monitoring. Figure 42, Figure 43 and Figure 44 show the tuning range with a DC voltage of piezo1, piezo2 and both piezos active. The summary of piezo tuning range is listed in Table 18.

Figure 42: Piezo 1 tuning range with DC charge

Figure 43: Piezo 2 tuning range with DC charge
Table 18: Tuning range of piezo

<table>
<thead>
<tr>
<th>Piezo</th>
<th>Tuning range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>390Hz to -610Hz</td>
</tr>
<tr>
<td>2</td>
<td>370Hz to -580Hz</td>
</tr>
<tr>
<td>1 &amp; 2</td>
<td>1000Hz to -800Hz</td>
</tr>
</tbody>
</table>

6. Summary

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

This cavity was operated at the pulse mode of 2.55 ms duration and 14 Hz repetition rate. A Q factor of $1 \times 10^{10}$ at low field was determined (Figure 20). The dynamic Lorentz detuning was studied by a signal generator driven system with step forward pulse, LFD coefficient of $-1.3 \text{ Hz/(MV/m)}^2$ 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.
References


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