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Conditioning Experience of the ESS Spoke Cryomodule Prototype

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Abstract

The prototype cryomodule (CM) for the ESS double spoke cavities is tested in the FREIA laboratory at Uppsala University. One of the goals of this test is to establish an efficient way to assess one series cryomodule within six weeks. One of the possible challenges is a conditioning process of the coupler and cavity multipacting. This study will be the first practical experience of double spoke cavity conditioning in a CM, and will lead to a standard conditioning recipe for future projects containing superconducting spoke cavities. In this paper, a preliminary result of CM testing is shown with a special focus on the conditioning processes.

INTRODUCTION

The Double Spoke Cavity (DSC) for the European Spallation Source (ESS) will be operated at 9MV/m and 352.21 MHz with a long RF pulse (3.2 ms) and 14 Hz repetition rate. Table 1 summarizes the important parameters of this cavity. Each cryomodule (CM) consists of two DSCs, and 13 CMs will be installed in the ESS Linac [1].

Table 1: Main Parameters of DSC

Parameter	ESS DSC
Frequency (MHz)	352.21
Temperature (K)	2
Repetition rate (Hz)	14
RF Pulse length (ms)	3.2
Beam pulse length (ms)	2.86
β (optimal)	0.5
E_{acc} (MV/m)	9
P_c (W)	2
Q_{ext}	1.8×10^5
Operation band-width (kHz)	2

The FREIA laboratory [2] will take responsibility of the series CM testing, using two high-power tetrode stations. Before the series production, we have engaged in prototype CM testing [3-5] with a prototype valve box since February 2019.

The goal of the prototype test is to assess our infrastructure, learn practical aspects of CM handling, and estimate the required time for series CM testing. Considering installation, cooling down, and warming up, the time available for the CM conditioning and RF testing should be determined.

The infrastructure is under development until the beginning of the series module testing, and not all of the devices are ready for driving two cavities simultaneously. Especially, one of the power stations is out of operation at the time of writing this report. Therefore, during the prototype test, we decided to exchange the RF circuit when we switch over to different cavities. This required extra time for the experiment (half a day for swapping the circuit, calibration, and interlock setup), but would not influence the series testing once the other power station is ready.

COUPLER CONDITIONING

The fundamental power couplers were conditioned up to 400 kW at an off-resonance frequency (353 MHz). The conditioning process was divided into two steps. One was at room temperature (300 K), and turned out to be the bottle-neck of all the conditioning procedure. The latter was at cold (4.2 K) and could be smoothly achieved once the warm conditioning was thoroughly carried out. The conditioning parameters are summarized in Table 2. In both conditioning processes, the RF pulses were increased from short length to the nominal pulse value. At each pulse length, the forward power was increased from 1 kW to 400 kW. When an outgassing exceeded the vacuum upper limit, the RF power was decreased by 3 dB, and the system waited for the recovery of the vacuum level to the lower limit.

Table 2: Main Parameters of DSC Conditioning

Parameter	Value
Pulse repeat rate (Hz)	14
Vacuum upper limit (mbar)	5×10^{-6}
Vacuum lower limit (mbar)	5×10^{-7}
pulse length step (μs)	20, 50, 100, 250, 500, 1000, 2000, 3200
MP bands in forward power (kW)	20-30 and 40-50

Figure 1 shows the conditioning history of one cavity (Romea, CAV1) as a function of live time, in which the infrastructure was operational. The warm conditioning took about 50 hours for one cavity, and a cross-contamination was observed when the other cavity (Giulietta; CAV2) was conditioned after CAV1. The reconditioning of CAV1 took about 20 hours. In total, therefore, about 6 days were required to condition two cavities. This can be potentially improved by simultaneous conditioning of the two cavities with one extra turbo-molecular pump at the other end of the beam pipe, at which only one pump is currently in use and limits the speed of vacuum recovery.

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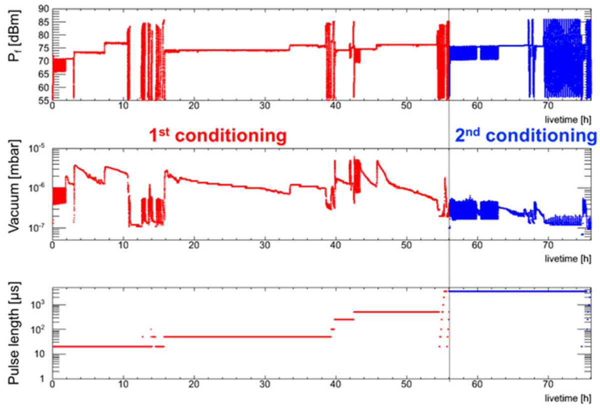

Figure 1: History of coupler warm conditioning (CAV1)

The cold conditioning took only two hours for each cavity, and no significant outgassing was observed. As shown in Figure 2, the processing was accomplished in 2 hours. Also, no substantial cross-contamination was observed at cold between CAV1 and CAV2.

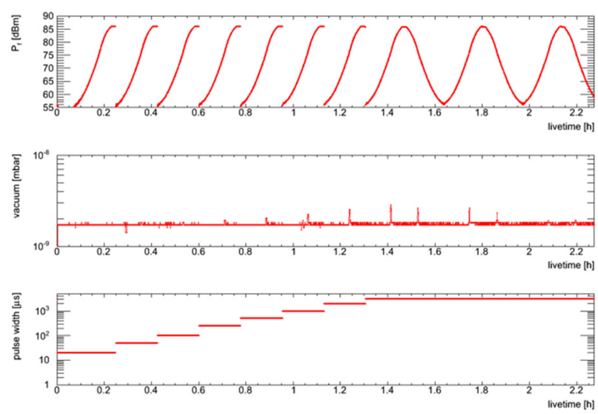

Figure 2: History of coupler cold conditioning (CAV1)

CAVITY CONDITIONING

The cavity shows three multipacting-bands (MP-bands): 2-3 MV/m, 5-6 MV/m, and 7-8 MV/m. The conditioning was carried out first by a short pulse length (1 ms) to reach the nominal E_{acc} (9 MV/m), and was reprocessed by the nominal pulse length (3.2 ms) as shown in Figure 3.

The cavities were conditioned one by one with a Self-Excited Loop (SEL) for CAV2, and with an open loop for CAV1. In both cases, it took one working day to reach the nominal gradient levels.

A strong field emission appeared in CAV2 after its cold tuning system was tested. We decided to conduct a small thermal cycle up to 40 K, and observed substantial outgassing up to 10^{-4} mbar from 25 K. After this thermal cycle, the field emission disappeared. Probably, hydrogen contamination on the cavity surface was redistributed during the thermal cycle, and the work function at the peak electric field might be decreased.

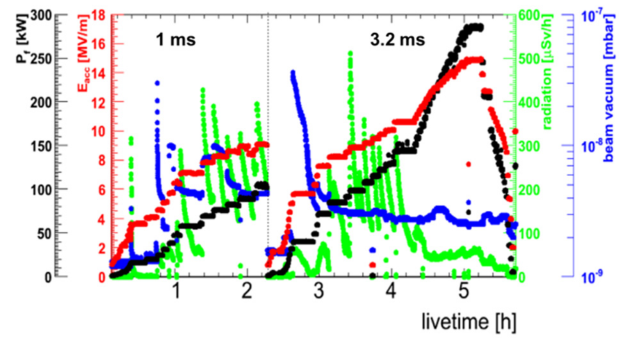

Figure 3: History of cavity MP conditioning (CAV1)

CAVITY PERFORMANCE

The dynamics heat loads of the cavities were evaluated by a calorimetric method using the helium flow from the cryomodule Ref. [Rocio]. Currently, the accuracy of the heat load measurement is limited to 0.3-0.5 W and the estimated dynamic heat load at the nominal field level is within the uncertainty.

The fields levels were estimated by two different methods. One is from the transmitted RF signal from the pick-up antenna with a coupling Q factor (Q_t) given by the vertical testing at IPN Orsay. The other is from the forward RF signal to the cavity sampled by the directional coupler (coupling 50 dB) with a loaded Q (Q_L) given by the field decay. They resulted in a consistent field measurement, and both cavities met the spec (9MV/m). Table 3 summarizes the cavity performance. The CAV1 field reached at 15 MV/m. The CAV2 field was limited at 10.5 MV/m by quench.

Table 3: Cavity Performance

Parameter	Value
CAV1 maximum E_{acc} (MV/m)	15
CAV1 P_c @ 9MV/m (W)	< 2
CAV2 maximum E_{acc} (MV/m)	10.5
CAV2 P_c @ 9MV/m (W)	< 2

LESSON LEARNED

We have learned some important practical aspects of the cryomodule, and have been improving the system correspondingly.

1. Down time of the coupler conditioning

The coupler conditioning at warm required six days in live time, but the process was often interrupted and the real time was longer by factor four. Figure 4 shows the causes of the down times. At the beginning, the system was not designed for safe 24 hours operation. We developed software interlocks with a watch-dog system for automatic processing over nights and weekends. The system trouble was due to blocked flow meters, trouble shooting of the high-power station, and communication and hardware issues in LLRF. They were all localized and all the solutions

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were prepared during the prototype testing. The technical intervention was required to deal with other activities in the bunker, and will not happen during the series CM testing.

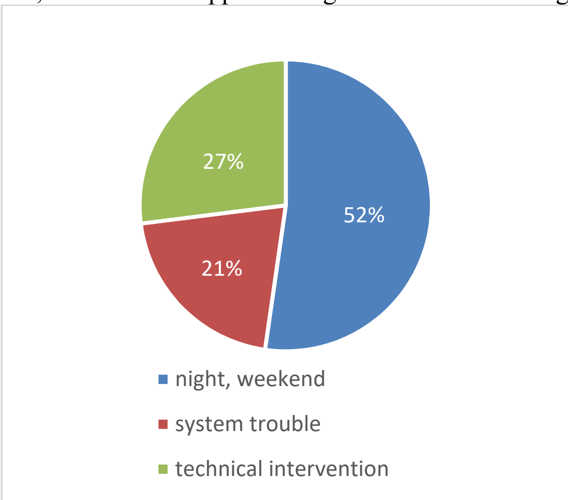

Figure 4: cause of down times

2. Quench and over powering

The external quality factor Q_{ext} of the ESS DSC is around 1.8×10^5 to cope with the high beam current, and corresponding operation band-width is about 2 kHz. For a cavity of Residual Resistivity Ratio (RRR) 300 without 120C baking, the quenched cavity around 10 K critically couples to the fundamental power coupler, associated with a frequency shift by the normal conducting transition within the band-width. This implies that the cavity can be over-powered if the RF is not cut immediately after a quench event. As the first cavity conditioning was tried at 4.2 K without appropriate interlocks, a quench and over powering caused the over-pressure (1.9 bar) of the cryomodule which led an opening of a rupture disc. After this incident, we deployed a safety interlock system which monitors gas helium pressure and other cryogenic parameters both in hardware and software. Moreover, we decided to condition the cavities at 2 K with the interlock pressure at 67 mbar. Fast interlock on the cavity field was also deployed such that anomalous deficit inside one pulse will cut the RF within one pulse. A more sophisticated quench detection system using Q_L [6] was implemented in our FPGA to be deployed before the series CM testing.

ESTIMATED TIME FOR CONDITIONING

Table 4 shows the estimated live time for CM conditioning from the experience of the prototype CMs. This does not include the down time due to the system trouble. Considering the time for circuit calibration and other setups, the cavity testing in 2 weeks would be feasible.

The bottle-neck of all the process is the warm conditioning of the coupler. This can be accelerated by simultaneous conditioning of two cavities. With the extra vacuum pump, the conditioning time can be potentially improved from 140 hours to 70 hours, in which cross-contamination is taken into account. This will further accelerate the process and will shorten the required time from two weeks.

Table 4: Estimated Processing Time

Parameter	Value
Coupler warm conditioning (h)	140
Coupler cold conditioning (h)	4
Cavity MP conditioning (h)	12
Cavity performance test (h)	12
Total live time (d)	7

CONCLUSION

The prototype cryomodule for the ESS DSC was conditioned and was tested at the FREIA laboratory. The experiment revealed that the warm coupler conditioning would be the bottle-neck of all the process, due to the cross-contamination between two cavities. Once the infrastructure is fully ready for the series testing, the series CM testing by RF would be feasible in due time.

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