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PRELIMINARY TEST RESULTS OF THE FIRST ESS ELLIPTICAL CRYOMODULE DEMONSTRATOR

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Abstract

Two ESS elliptical cavities cryomodule prototypes (one medium beta cryomodule and one high beta cryomodule) are being developed and will be fully tested at CEA Saclay before starting the series production of 30 cryomodules. This paper presents the preliminary test results of the first medium beta cavities cryomodule demonstrator. The measurements of the cryogenic performances for cryomodule components and circuits are given when the thermal shielding is cooled at 80 K and the cavities at 2 K. The first RF test results performed at low power are also reported.

INTRODUCTION

The European Spallation Source ESS is under construction at Lund, Sweden [1]. The ESS linac will deliver a 62.5 mA proton beam in pulse mode (2.86 ms – 14 Hz) at the energy of 2 GeV. The superconducting part of the linac operating at 2 K consists of 352 MHz spoke cavities and two families of 704 MHz elliptical cavities. Four elliptical cavities will be assembled in a 6.6 meter long cryomodule and a total of 120 elliptical cavities will be integrated in 30 cryomodules (9 medium beta cryomodules and 21 high beta cryomodules).

In order to validate the elliptical cryomodule design made by CEA Saclay and IPN Orsay, two prototypes (one medium beta and one high beta) are being developed and will be tested at CEA Saclay before starting the series production. The first prototype cryomodule M-ECCTD has been assembled with prototype medium beta cavities and has been installed in the CEA testing bunker in July 2017 [2].

The cryogenic behaviour and performances of the module are the first high priority to qualify as well as the behaviour of the cavities, the couplers and cold tuning system in a cryomodule configuration at low RF power. This paper presents the preliminary test results for these aspects.

CRYOMODULE TEST PREPARATION

The M-ECCTD cryomodule has been installed in the dedicated test station at CEA Saclay which has been specifically developed for ESS (see Fig. 1). The test station is equipped to perform tests at 2 K and 1.1 MW RF power in the ESS pulsed mode characteristics. The control system allows monitoring the cryomodule instrumentation and allows making regulations on the helium level and some of the components temperatures. The slow tuners are operated by a PLC and the piezo stacks foreseen for the Lorentz forces detuning compensation are actuated by Noliac power supplies.

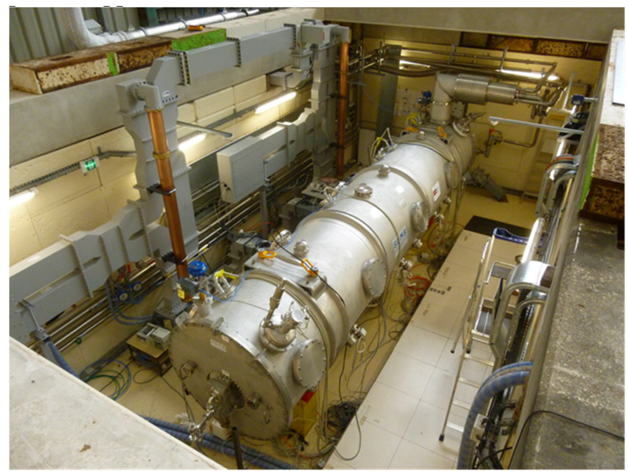

Figure 1: M-ECCTD cryomodule installed in the test station at CEA (with roof removed).

The following conditions have been reached before starting the different measurements:

- Insulating vacuum inside the cryostat between 6x10^{-6} and 2x10^{-5} mbar and cavity vacuum bellow 5x10^{-6} mbar.
- Coupler antenna thermalized with forced air circulation and coupler outer flange at room temperature (heaters turned on) to avoid condensation

The cooling conditions are slightly different in the CEA test station from the future configuration of ESS at Lund. The two main differences are summarized in Table 1.

Table 1: Cryomodule Testing Conditions

	CEA Saclay test station	ESS (Test stand 2 and linac)
Delivered helium pressure	1.2 bara LHe	3 bara supercritical
Cooling of the thermal shield	LN_2 at 77 K	GHe at 40/50 K

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CRYOGENICS TEST RESULTS

Thermal Shield

The thermal shield temperature is monitored by 6 sensors positioned at different places on the aluminium panels and on the cooling circuits. The thermal shield has been cooled down to 100 K in about 12 hours and was regulated at 80 K for 13 consecutive days. The permanent state was reached during the last 7 days of operation.

The temperature homogeneity is satisfactory. For a set point of 80 K, the measured temperature varies form 79 K to 83.5 K along the different places.

The thermal losses are evaluated with the speed of warming-up, using the following equation:

$$\boldsymbol{P_{loss} = m \times \frac{\int_{T_i}^{T_f} C_p(T)dT}{\Delta t}} \qquad (1)$$

with m the mass of the thermal shield in kg, Cp the heat capacitance of aluminium in J/kg.K and Δt the time step in s. Considering a mass of 200 kg, an average power loss of 73 W is measured just above 80 K.

2 K Cold Mass

The 2 K cold mass includes the cavities, the cold extremity of the power couplers, the intercavities bellows and the cold extremity of the cold-warm beam transitions. The initial temperature of the cavities is around 270 K when the thermal shield is at 80 K. When the cooling down at 4.2 K starts with liquid helium, the top of the cavities reaches the temperature of 150 K after 3 hours, and 50 K after 50 minutes only. The resulting cooling speed is 2 Kelvin per minute. The cavities were kept at 4.2 K for 3 days without any issue due to the cryomodule. When the pumping of the helium bath starts, the cavities reach temperatures between 2.2 K and 1.8 K. The cryomodule was kept in this temperature range during a total of 140 hours.

The heat load evaluation was performed during the last two days of operation, when the liquid helium level was high enough to fill completely the cavity tanks and the diphasic line. The measured liquid helium level is between 90 and 93 % which corresponds to the lower part of the diphasic tube.

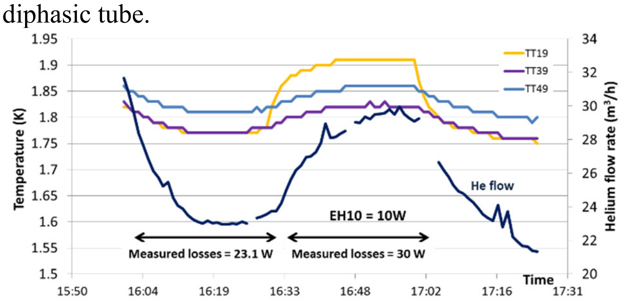

Figure 2: Thermal losses evaluation in the 2 K cold mass.

As shown in Figure 2, the temperature of three cavities (TT19, TT39 and TT49) and the gaseous helium flow at 293 K (in m3/h) are measured simultaneously. Stable cavity temperatures are reached for about 10 minutes where cavity #1 (TT19) is at 1.81 K, and cavity #2 and #3 are at 1.77 K. At this moment the helium flow is 23 m3/h. The estimated heat load is 23.1 W. Then an additional power of 10 W is put on cavity #1 (TT19) with the heater EH10. The temperature TT19 increases. A very short period of stable temperature and a gaseous helium flow of 30 m3/h give an estimation of 30 W total heat load. The measured static heat load is then 20 W approximately.

Cold Tuning System

The cold tuning system has very weak contact with the cavity and helium tank. Cooling and warming up is mainly due to radiation of the thermal shield and cold mass inside the insulation vacuum. About one week is necessary to reach the temperature of 27 K. However this long time is not an issue because the temperature of the tuner has a rather small effect on the cavity tuning process as shown in the next section of this paper.

Magnetic Shield

The magnetic shield is mounted on the cavity covered 10 layers of MLI. It is directly facing the thermal shield at 80 K. Like the tuner, the temperature of the magnetic shield is also floating. It is fixed to the cavity with weak links and poor contacts with the helium tank at 2 K. Using the following equation (2), the theoretical equilibrium temperature of the magnetic shield is estimated to 70 K in case of no direct contact between the shield and the cavity and with the thermal shield at 80K.

$$\boldsymbol{T_{mag.sh.} = \sqrt[4]{\frac{T_h^4 - T_c^4}{2}} = \sqrt[4]{\frac{83^4 - 2^4}{2}} \approx 70\ K} \qquad (2)$$

After one week at cold temperature, the temperature of the magnetic shield is at 36 K which is much lower than the expected temperature of 70 K. This shows that the thermal contacts are not negligible. However the radiation heat loads on the 2 K by the cavity string are estimated to about 0.7 W which is only 5 % of the total heat load on the 2 K mass (13.2 W in total with a thermal shield at 50 K). Modification of the present configuration to improve the insulation of the shield and the cavity would lead to negligible gain. Thus we choose to not change the present configuration.

Comparison between Calculations and Measurements of Heat Loads

Table 2 compares the heat load measurements with the thermal losses that have been recalculated with a thermal shield cooled at 80 K and the losses previously calculated with a thermal shield at 50 K.

Table 2: Global Heat Balance in W

	TS at 50 K	TS at 80 K	CM 2 K (with TS at 50 K)	CM 2 K (with TS at 80 K)
Calculated	50.7	49.7	13.2	19.6
Measured	-	73	-	23

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The difference of 23.3 W on the thermal shield is not fully understood. It can be explained by additional heat loads by radiation of the 30 layers insulations. If the hypothesis on the radiation flux value is increased from 1.5 to 2.5 W/m² the measurements of 73 W will fit with calculations.

For the 2K cold mass, the difference of 3.4 W can be explained by thermal contacts between the cold mass or cooling circuits and a component at an intermediate temperature (thermal shield or spaceframe). Direct heat radiation through holes in the thermal shield that have not been efficiently closed by MLI could also increase the heat load.

In addition to these probable causes of additional losses the optimization of the GHe flowing inside the power coupler external conductor has not been done in the short period of tests, which can bring a very high additional heat loads.

RF TEST RESULTS AT LOW POWER

Cavities and Couplers

The cryomodule integrates three prototype cavities with the CEA design (Cavity #2, #3, #4) and one with the INFN/LASA design (Cavity #1). The frequency and external coupling factor measured in different conditions are presented in Table 3 for Cavity #1 and #4.

Table 3: Frequency and Qext Measurements

	Target	**Cav. #1**	**Cav. #4**
F (MHz) at room temp. and vacuum	703.160	702.960	702.972
F (MHz) at 4.2 K	704.173	704.122	704.126
F (MHz) at 2 K	704.150	704.066	704.071
F (MHz) at 2K after tuning	704.420	704.420	704.420
Qext at cold	5.9×10^5 to 8×10^5	6.96e5	7.4e5

From vacuum to 2 K, the average frequency shift is 1010 kHz, which is consistent with calculation predictions.

The two measured Qx are within the tolerances required by ESS.

Cold Tuning Systems

The slow tuning operations were performed when the cryomodule was relatively well thermalized. As shown in Table 3, Cavity #1 and #4 were successfully tuned at the ESS frequency of 704.42 MHz. A tuning range of 360 kHz have been achieved. The measured sensitivity of the slow tuning system is around 20 kHz per screw turn (1 screw turn corresponds to 1280000 motor steps). Small excursions of +/- 1000 Hz, with way back at 704.42 MHz have been done. Figure 3 shows a very small hysteresis even though the helium bath pressure was not well stabilized during these measurements.

The resonant frequency variation as a function of a continuous drive signal on piezo actuators has been measured. The maximum range achieved is ^{2} applied with piezo n°2 of cavity #4. The measured sensitivity is between 5.3 and 5.7 Hz/V and the maximum hysteresis are 130 Hz for piezo n°1 of cavity #1 and #4, and 190 Hz for piezo 2 of cavity #4.

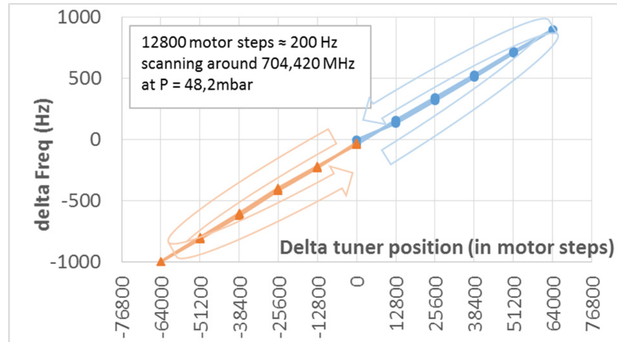

Figure 3: Slow tuner hysteresis measurement.

CONCLUSION AND PERSPECTIVE

The cryogenic tests and the low power RF measurements were successfully performed to validate a large part of the cryomodule design. The very good general cryogenic behavior of the cryomodule has been verified. The thermal shield and the 2 K cold mass can be easily cooled down without any issue generated by the cryomodule itself. The LHe level at 2 K has been kept stable in the diphasic tube for long periods without the need of a long optimization of the cryogenic parameters.

Estimations of the cryogenic heat loads have been made during short time periods during which the helium bath pressure and temperature could not be completely stabilized. However the measurements are reliable enough to give a rough idea of the global thermal loads. Extra MLI will be installed on the thermal shield and 2 K cold mass on the next cryomodule assembly to try to reduce the additional heat loads measured.

Low power RF measurements have been performed on two cavities. Frequency and power coupler Qext measurements are in accordance to the expected values. Cavities could be easily tuned at the ESS machine frequency. The linearity, the tuning range and the hysteresis have been checked. The piezo stacks have been actuated with success and the frequency shifts measured are as expected.

The M-ECCTD cryomodule has been dismounted just after these preliminary tests, allowing a deep expertise of each components. A new cryomodule assembly phase is on-going with new preparation phases for the cavities and power couplers. A new generation of assembly tooling will be used for the cavity string in clean room. The cold mass dressing and the cryostating phase will be performed with upgraded toolings in building 124N at CEA, chosen for the series phase. A new period of cryomodule tests is foreseen in June 2018 with high power RF.

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