ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK002

RESULTS OF THE RF POWER TESTS OF THE ESS CRYOMODULES TESTED AT CEA

O. Piquet, C. Arcambal, P. Bosland, S. Berry, A. Bouygues, E. Cenni, G. Devanz, T. Hamelin, C. Madec, C. Mayri, P. Sahuquet, Q. Bertrand, CEA, Gif sur Yvette, France
P. Pierini, ESS, Lund, Sweden
D. Sertore, INFN, Milano, Italy
M. Ellis, STFC, Daresbury, United Kingdom

Abstract

Eight of the medium and high beta cryomodules delivered to ESS by CEA are tested at CEA before delivery; the two medium and high beta prototypes and the three first of each type of the series. The goal of these tests is to validate the assembly and the performances on few cryomodules before the next cryomodules of the series are delivered to ESS. This paper summarizes the general results obtained during the tests at 2 K and at high RF power, Pmax = 1.1 MW. The cavities reach the ESS requirements, Eacc = 16.7 MV/m (Medium beta) and 19.9 MV/m (High beta) with an efficient compensation of the Lorentz detuning by the piezo tuner over the full RF pulse length of 3.6 ms at 14 Hz. After the successful tests at CEA, the first cryomodules have been shipped to ESS where the final acceptance test are performed.

INTRODUCTION

In the framework of its In Kind contribution for the construction of the ESS accelerator [1, 2], CEA developed a stand to perform the tests of the elliptical ESS cryomodules at high RF power (Fig. 1). The goal of these tests is to validate the quality of the assembly and the performances of few cryomodules before the next cryomodules of the series are delivered to ESS and tested there [3, 4].

We have already tested seven cryomodules over eight scheduled; the 2 medium and high beta prototypes (CM00 and CM30), 3 medium beta cryomodules of the series (CM01, CM03 and CM05) and the 2 first high beta (CM31 and CM32).

Previous papers have already presented test results obtained on the medium beta cryomodule demonstrator CM00 [5]. This paper presents a summary of the results we have obtained during the tests of the seven cryomodules.

THE TEST STAND

The test stand is about 100 m from the cryomodule assembly hall. It is equipped with a liquefier that can deliver 90 l/h of 4 K LHe at 1.1 bar to the 2000 l Dewar close to the cryomodule. The cryomodule is equipped with an internal Hampson heat exchanger (HX) that is well adapted to the supercritical helium fluid used at ESS, but is not adapted for diphasic helium at 1 bar containing a too high rate of bubbles. This caused some difficulties in the first tests performed on the prototype CM00. We fixed this issue adding a small phase separator to remove part of the GHe generated in the last 10 meters of cryogenic line between the Dewar and the cryomodule. This small phase separator allows the HX to run and we obtain an easy regulation of the 2 K LHe level above the cavities.

The thermal shield is cooled at 80 K with LN2. This is a second difference with the ESS nominal cryogenic conditions where the liquefier delivers 40 K GHe at 20 bars to cool the thermal shield.

The RF power source is a 704 MHz klystron with a home-made modulator. It can generate 1.1 MW RF pulses of 3.6 ms length at 14 Hz. The RF distribution line (Fig. 1) is equipped with an RF switch that can send the RF power in one of the two branches at the entrance of the test stand. Each branch is equipped with a power divider that can distribute the power in one cavity or two cavities. We can test one cavity at a time, or two maximum together. Test with the four cavities running altogether is not possible at CEA.

The cryogenic and tuners control/command system is based on Muscade/Anibus. The RF control/command system is based on EPICS.

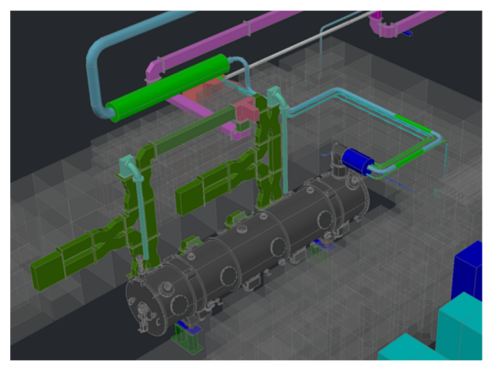

Figure 1: Test stand of ESS cryomodule at CEA.

RF POWER TESTS AT 2 K

The duration of each test was about 3 months for the first cryomodules. This duration is now reduced to about five weeks; two weeks for the installation in the test stand, cavity vacuum pumping and coupler conditioning at room temperature and three weeks for the test at cold.

We systematically perform the RF conditioning of the power couplers at room temperature before cooling down the cavities. The power couplers are conditioned in about 4 h to 7 h. This short duration can be reached thanks to the high pumping speed group, roughly 60 L/h that allows to recover quickly acceptable pressure when high degassing occurs during RF conditioning (Fig. 2).

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK002

The operations linked to the connection of the high speed pumping group, including baking, takes about five days duration.

Figure 2: High speed pumping group (~60 L/h) connected to the beam gate valve of the cavity string.

Power couplers conditioning starts when the pressure is lower than 1. 10^{-8} mbar with a threshold set at 5 10^{-8} mbar. Standard RF conditioning of the power couplers consists in automated cycles of RF power ramps up to 1.1 MW applying short pulses and low repetition rates at the beginning, progressively increasing at each cycle the pulse length up to 3.6 ms and the repetition rate up to 14 Hz. P_{max} is limited at 400 kW for pulse lengths longer than 500 µs. Each coupler is equipped with 4 diagnostics for the protection: a Penning pressure gauge, an electron pickup and a window for an arc detector on the vacuum side of the ceramic window. An arc detector is also on the air side of the ceramic window. The diagnostics signals are monitored (Fig. 3) and electronics provide the fast protection of the couplers (< 20 µs) with the diagnostics signals.

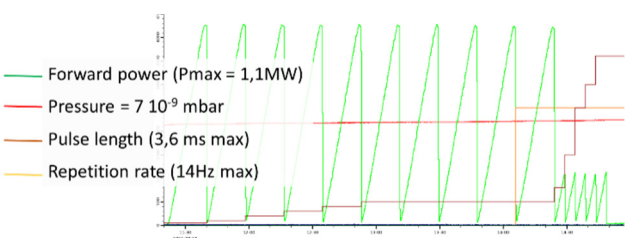

Figure 3: Typical ramps of RF power during coupler conditioning at room temperature.

The doorknobs are equipped with an antenna bias system that we never use during RF conditioning of the power couplers.

The duration of cooling from 300 K to 2 K is typically two days before regulating the LHe level above the cavities. The four tuners, fixed on the cavities and helium tank through weak thermal contacts, need more than four days before reaching temperatures lower than 30 K (Fig. 4).

The power couplers are conditioned a second time at cold, during the time the cavities are cooled from 4 K to 2 K. We generally never observe any sign of activity during this phase, except in one coupler (among the 28 tested) that needed some more conditioning after the cooling phase.

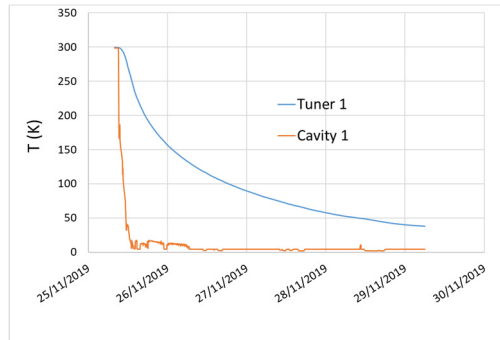

Figure 4: Temperature of a cavity 1 and of its tuner during cooling down of CM01.

For all the cryomodules, the static heat load (without RF and with closed cryogenic valves) was measured around 18 W, as expected with the thermal shield cooled at 80 K.

The cavities at 2 K could be tuned at the ESS frequency of 704.42 MHz. All tuners have shown similar linear frequency shift responses 0.97 Hz +/- 0.04 per motor step for medium beta and 0.92 Hz +/- 0.04 per motor step for high beta. The hysteresis is very small (< 30 Hz) and difficult to measure precisely. The small hysteresis compared to the 1 kHz band width of the cavity/couplers allows an easy tuning at the nominal frequency 704.42 MHz.

The frequency shift due to the piezo stacks with a static voltage of 150 V is 650 Hz +/- 40 for the medium beta cavities and 590 Hz +/- 50 for the high beta cavities.

The power couplers Qext have been found close to the targets: Qext = 7.35 +/- 0.56 105 for medium beta (target 7.5 105) and Qext = 6.64 +/- 0.26 105 for high beta (target 6.5 105).

Once the cavity is tuned at 704.42 MHz, the accelerating field is slowly increased starting with short RF pulses at low repetition rate and low RF power. All cavities needed careful RF conditioning. Typical RF pulses monitored are shown on Fig. 5.

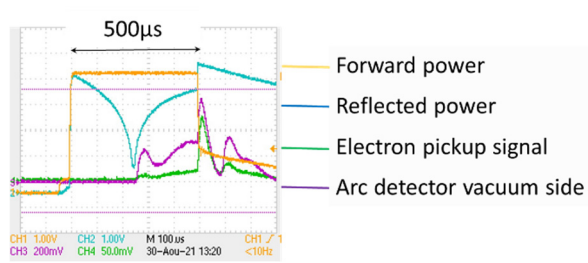

Figure 5: Electron pickup and arc detector signals of an RF pulse during conditioning.

Green and purple curves in Fig. 5 show activity in the cavity and the coupler. When this activity is detected, we stop ramping up the RF power and wait until the signals of the activity disappear (green and purple curves flat in background). Then the RF ramp up restarts until the next barrier that is treated the same than the previous one. The repetition rate can be sometimes increased for a faster conditioning. It requires generally 6 to 8 hours before reaching the maximum field at the nominal pulse length 3.6 ms and repetition rate 14 Hz.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK002

Medium beta and high beta cavities reach the ESS nominal field as shown in Fig. 6. RF power pulses are applied in 4P/P mode to decrease the filling time. Lorentz forces detuning is compensated with some klystron frequency detuning and with the piezo of the tuner. Simple square piezo pulses show good efficiency for compensation. The tests have been performed in open loop.

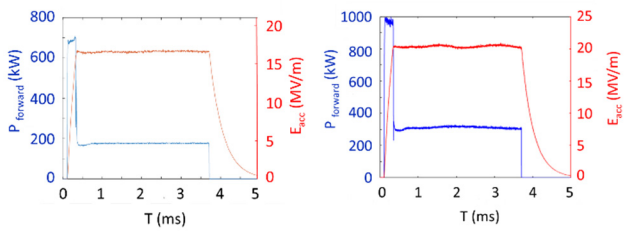

Figure 6: Cavity pulses at ESS nominal field (medium beta 16.7 MV/m left and high beta 19.9 MV/m right).

The estimations of the cavity heat loads have been performed measuring the power sent to the cavity heaters after switching on or off the RF power of the cavity and keeping the LHe level and pressure constant. Typical heat loads measured on the medium beta cavities at nominal field is about 1 to 2 W (specification: 5 W per cavity) and about 4 W for high beta cavities (specification: 6.5 W per cavity). Few cavities showing high electron field emission have higher dissipation. A high beta cavity dissipates about 7 W at nominal field.

All the cavities have shown electron field emission at different levels. Eight X-ray GM detectors, two scintillators and two neutron detectors are arranged around the cryomodules. Results obtained with this set of detectors are presented in [6].

We never detected any neutron during the test of medium beta cryomodules but we have detected neutrons with the high beta cryomodules when we activated the cavity in position 4 that showed high field emission. These two high beta cryomodules have been radio-activated. A NaI(Tl) scintillators detected radioactive Nb92m with the main gamma decay ray at 934 keV and a half-life of 10.2 days. For cryomodule CM31, we could simulate a scenario that can describe the observations of the main radioactivity spots that were found in front of cavities 3 and 2. In this scenario, electrons are emitted at the 1st iris of cavity in position 4 (Fig. 7).

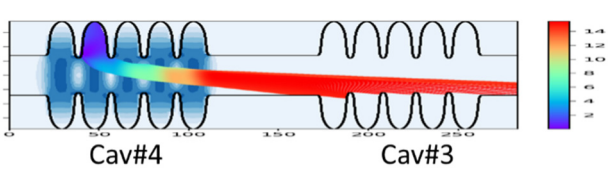

Figure 7: Trajectories of electrons emitted at the 1st iris in a high beta cavity at the nominal field 19.9 MV/m.

The electrons are accelerated by the cavity and can exit with an energy of 15 MeV. They can hit the next cavities and induce, by bremsstrahlung, gamma rays which react with the Nb93 of the cavity sheets and produce Nb92m.

About 100 days after the test, the radioactivity of the cryomodule has decreased below the natural background of radioactivity. However special transport procedures have to be applied for components that have been radio-activated. These procedures will be applied for the three high beta cryomodules tested at CEA and transported to ESS.

CONCLUSION

Seven ESS elliptical cryomodules over the eight scheduled have been successfully tested at CEA. The main performances are within the ESS specifications. The medium beta cryomodules of the series tested at CEA, CM01, CM03 and CM05, have been shipped to ESS Lund. The tests performed at ESS confirmed the results obtained at CEA. The transports from CEA to ESS on the 1450 km long road have not degraded the cryomodules performances. The high beta cryomodules CM31 and CM32 tested at CEA are going to be shipped applying the procedures for radio-activated components.

The production of the elliptical cryomodules at CEA is now in the industrial phase, with a delivery throughput of about 1 cryomodule per month. All the remaining cryomodules will be only tested at ESS, except a last high beta cryomodule, CM33 that will be tested at CEA before.

ESS needs seven medium beta cryomodules and two high beta cryomodules for starting the beam operation. Six medium beta and one high beta are already delivered and the last will be delivered soon. The assembly of the seventh medium beta cryomodule is almost complete and this cryomodule should be shipped before summer 2022.

REFERENCES

[1] C. Madec *et al.*, "The ESS Elliptical Cavity Cryomodules Production at CEA", in *Proc. IPAC'21,* Campinas, Brazil, May 2021, pp. 2536-2539. doi:10.18429/JACoW-IPAC2021-WEXB01

[2] C.G. Maiano, "Status of the ESS Cold Linac Module and Cavity Components", in *Proc. 20th Int. Conf. on RF Superconductivity (SRF'21)*, East Lansing, MI, USA, Jun.-Jul. 2021, paper MOOFAV04.

[3] N. Elias, X. T. Su, W. Gaj, P. Halczynski, M. Sienkiewicz, and F. D. Skalka, "Heat Loads Measurement Methods for the ESS Elliptical Cryomodules SAT at Lund Test Stand", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOTK025, this conference.

[4] N. Elias *et al.*, "ESS Elliptical Cryomodules Tests at Lund Test Stand", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOTK026, this conference.

[5] P. Bosland *et al.*, "Tests at High RF Power of the ESS Medium Beta Cryomodule Demonstrator", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1940-1943. doi:10.18429/JACoW-IPAC2019-TUPTS006

[6] E. Cenni *et al.*, "Time Resolved Field Emission Detection During ESS Cryomodule Tests", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOTK004, this conference.