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PERFORMANCE ANALYSIS FROM ESS CRYOMODULE TESTING AT CEA

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Abstract

CEA Saclay is in charge of the production of 30 elliptical cavities cryomodule as part of the in Kind contribution to the ESS superconducting. The two medium and high beta prototypes and the three first of each type of the series cryomodules have been tested at CEA in slightly different conditions than at ESS (both in terms of cryogenic operation as well as RF conditions). The goal of these tests was to validate the assembly procedure before the delivery of the series to ESS where the final acceptance tests are performed.

This paper summarizes the main results obtained during the tests at CEA with particular attention to the field emission behaviour.

INTRODUCTION

CEA is in charge of the production of 30 cryomodules of the ESS LINAC [1, 2, 3]. This is one of the main French in-kind contribution to the ESS accelerator construction. CEA is delivering 9 medium-beta cryomodules (β=0.67) and 21 high-beta cryomodules (β=0.86).

Previous papers presented the cryomodule design (Figure 1), which is similar to medium and high-beta cryomodules with four 704 MHz elliptical cavities [3]. The cryomodule design has been made in a collaboration with CEA and IJCLab where CEA was in charge of the cavity packages Medium and High Beta and IJCLab was in charge of the cryostat of the cryomodule.

For the series production, CEA provides all the components except the M-Beta cavities provided by LASA and the H-Beta cavities provided by STFC. The cryomodules are assembled at CEA Saclay by a private Company under the supervision of CEA.

CEA has tested the two prototype cryomodules and has also the three first cryomodules of the series of each type before sending them to ESS. They are tested a second time at ESS in nominal conditions for the final acceptance.

The main objectives of the tests at CEA are to:

- Check the quality of the assembly and procedures by measuring the cavities and couplers performances
- Verify the Qext of the power couplers
- Check that the performances of the tuners (stepper motor and piezo actuators) meet the requirements of ESS
- Measure cryogenic heat loads (static and dynamic)

A total of seven M-Beta cryomodules and eight H-Beta cryomodules have been delivered to ESS. All seven M-Beta cryomodules have passed the RF power tests performed at ESS for the acceptance. The first H-Beta has also been accepted but the second H-Beta presents a leak between the LHe circuit and the insulating vacuum that is only visible at cold with superfluid helium. The acceptance tests are still in progress on the following cryomodules that have been delivered.

Nominal gradients are respectively 16.7 MV/m and 19.9 MV/m for medium and high-beta cavities and the maximum power transferred by the power couplers is 1.1 MW at 14 Hz, 3.6 ms pulse length.

This paper summarizes the results of the RF power tests performed at CEA on eight cryomodules.

CEA TEST STAND

The CEA test stand (see Fig. 1) is about 100 m from the cryomodule assembly hall. It is equipped with a liquefier that can deliver 90l/h of 4K LHe at 1.1 bar to the 2000 l Dewar close to the cryomodule. The experimental conditions are different between CEA and ESS: the thermal shield can be cooled only by N2 to 80 K (@ESS, 50 K), the Liquid Helium (LHe) cooling is performed at 4 K – 1 bar whereas ESS cools with SHe at 3 bars. 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 the helium boiling at 1 bar and containing a too high rate of GHe bubbles. This caused some difficulties in the first tests performed on the prototype CM00. We fixed this issue by adding a small phase separator to remove part of the GHe generated in the last 10 meters of the 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 RF power source is a 704MHz klystron with a home-made modulator. It can generate 1.2MW RF pulses of 3.6 ms length at 14 Hz. 4P/P pulse is possible with our current setup. The RF distribution line is equipped with an RF switch that can send the RF power to 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 instead of 4 cavities @ ESS.

RF instrumentation (electron pick-up, arc detector, and RF measurements) used mainly for coupler protection are based on home-made electronics boards developed for projects where CEA is involved. These systems permit to acquire data and realize fast protection functions in order to switch RF off in less than 20µs.

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Figure 1: ESS cryomodule in CEA teststand.

The fast acquisition system for this instrumentation is based on the single board computer IFC 1210 from IOxOS Technologies, which receives two FMC mezzanine modules with 8 channels ADC 3111 from IOxOS Technologies. Timing control is done with a PMC-EVR-230 card from Micro Research Finland (MRF) installed on the IFC 1210 device and synchronized with a VME-EVG-230 (EVG: Event generator) which drives the RF power source.

Beckhoff EtherCAT modules are also used for the slow acquisition and control of the RF instrumentation.

The control for all these systems [4] has been developed in EPICS, based on the ESS EPICS Environment (EEE).

For the cryogenic needs (temperatures, vacuum, valves control, slow interlock…), Siemens PLC based on Siemens PLC 1500 generation has been used with a homemade control/command system dedicated to those devices and communicating via TCP/IP: Muscade®.

Stepper motor (Phytron) has a dedicated Siemens controller (ET200S) with a muscade interface while piezo actuators are simply driven by a Voltage amplifier and waveform generator controlled in EPICS Environment.

Test at CEA

The duration of each test was about 3 months for the first cryomodules. This duration has been reduced for the serial part 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 temperature.

Couplers

We systematically perform the RF conditioning of the power couplers at room temperature before cooling down the cavities. Degassing, electron emission, and light events occurred during conditioning due to multipacting barriers. The power couplers are easily conditioned in about 3h to 7h. These short duration can be reached thanks to the high pumping speed (roughly 60 l/h) group installed directly on the beamline, which allows to recover quickly acceptable pressure when degassing occurs during RF conditioning (See Fig. 2).

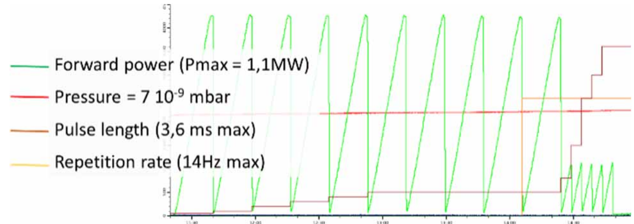

Figure 2: Typical ramps of RF power during coupler conditioning at room temperature.

The power couplers are then conditioned a second time at cold temperature, during the time the cavities are cooled from 4K to 2K. We generally never observe any sign of activity during this phase, except in one coupler (among the 32 tested) that needed some more conditioning after the cooling phase.

Although the couplers are equipped with an antenna bias, this system was never needed and used during RF coupler conditioning.

The decay measurement of the cavity field is used to calculate the loaded-Q adjusted by the position of the coupler into the cavity. The Figure 3 shows the results for 4 medium-beta cryomodules (prototype and three series cryomodules) and high-beta cryomodules (only series cryomodules). The dotted line shows how ESS specification for coupling.

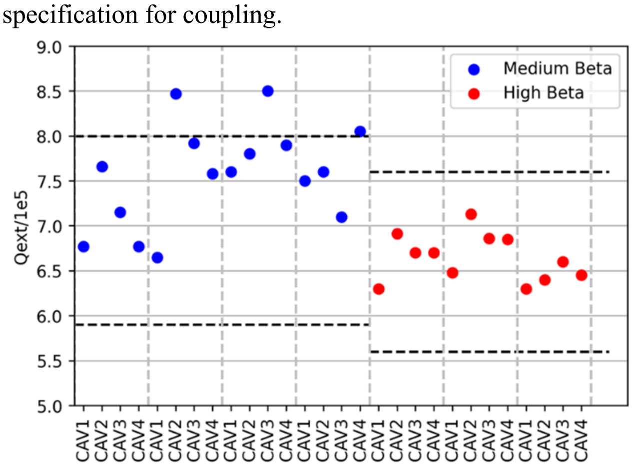

Figure 3: QL results.

Tuners

Stepper motor: Figure 4 shows the frequency shift versus the number of tuner screw substeps. The linearity is very good, around 20 kHz per screw turn. Some hysteresis is visible in the low frequencies region where the mechanical plays are not yet canceled by the cavity stretching. At the nominal cavity frequency, all the 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. Compared to the 1kHz

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bandwidth of the cavity/couplers, this small hysteresis allows easy tuning at the nominal frequency.

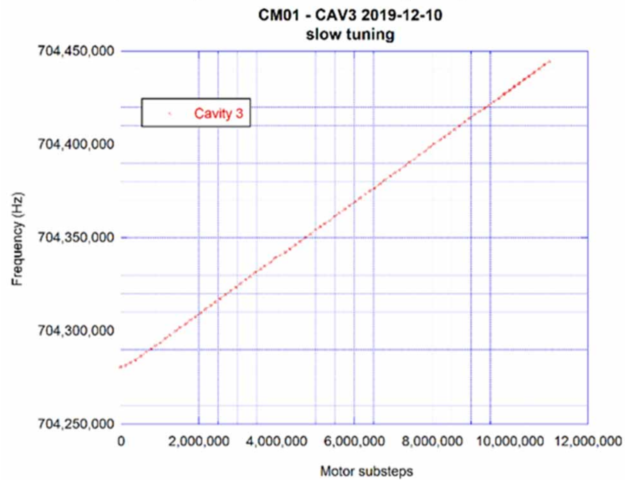

Figure 4: Variation of frequency versus motor sub-steps.

Piezo actuators: static frequency shift range is checked by applying a continuous voltage on the piezo stacks. The cavity detuning 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.

Cavity Test

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

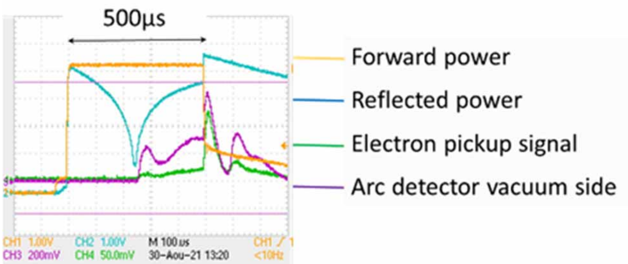

Figure 5: Electron pickup and arc detector signals monitored during an RF pulse of a cavity non-fully conditioned.

Green and purple curves of Figure 5 show activity in the cavity and the coupler. This activity is mainly detected during the transient RF phase in the power coupler. When this activity is detected, the ramping of the RF power is stopped until the signals of the activity disappear (green and purple curves flat in the background). Then the RF ramp up re-starts until the next barrier is treated the same as the previous one. The repetition rate can be sometimes increased for faster conditioning. It requires generally 4 to 8 hours before reaching the maximum field at the nominal pulse length of 3.6ms and repetition rate of 14 Hz.

Otherwise, the activity could be easily suppressed with the help of the DC bias of the coupler with a voltage of about 300V. In these cases, only the cavity multipacting (between 11MV/M and 14MV/m) required time for conditioning. The cavity can then reach its nominal field (Fig.6) in less than 2h.

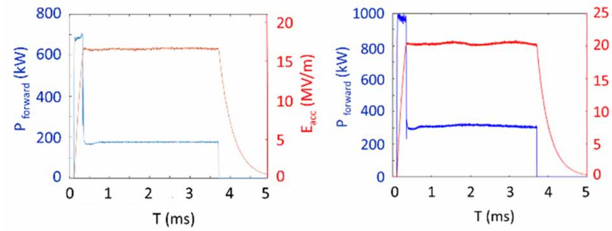

Figure 6: Cavity pulses at ESS nominal field (medium beta 16.7 MV/m left and high beta 19.9 MV/m right).

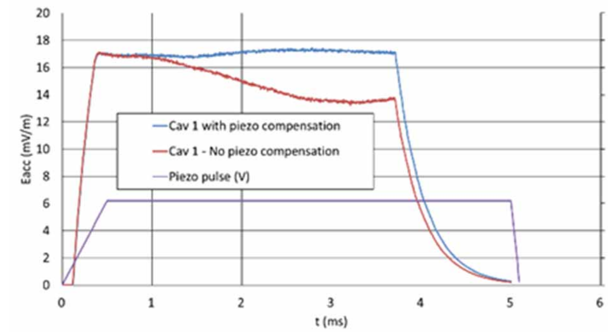

Figure 7: Medium-beta cavity pulses at the nominal field without and with piezo compensations.

Medium beta and high beta cavities reach the ESS nominal field as shown in figure 6. 4P/P RF power pulses are applied to decrease the filling time with a length of about 300µS for a 4P pulse. Lorentz forces detuning is compensated with some klystron frequency detuning and with the piezo of the tuner. A simple manual optimization of the piezo pulse (delay, amplitude, and shape) show good efficiency for compensation (Fig.7). The tests have been performed in an open loop for cavity amplitude and phase.

Cavity Performances

The Figure 8 shows the performances for all series cryomodules tested at CEA. All the cavities achieved the nominal voltage, except the first cavity of CM31 limited by quench (but solved at ESS in nominal cryogenic condition).

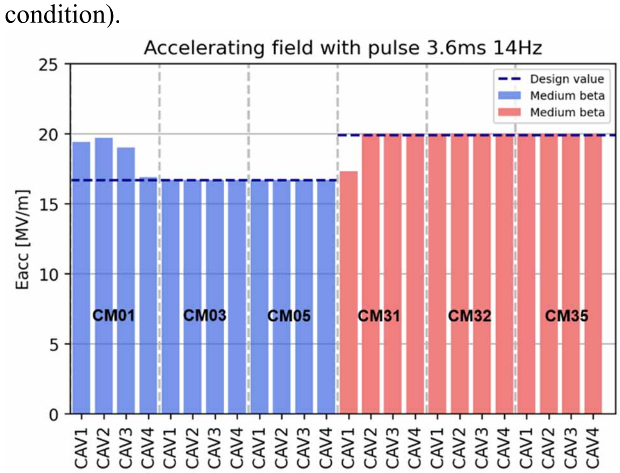

Figure 8: Cavity field at nominal pulse.

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The dynamic heat load per cavity at nominal gradient is measured between 1W and 3W with few exceptions between 4W and 5W (linked with strong field emission). These performances are in the ESS specifications, less than 5 W and 6.5W, respectively for medium beta and high beta cavities.

All the cavities have shown electron field emission at different levels. Eight X-ray GM detectors, several scintillators connected to photomultipliers and two neutron detectors are placed around the cryomodules. The experimental setup and results obtained with these detectors are presented in [5] and [6].

A clear correlation between the electron current measured in the FPC and the radiation detected has been shown, meaning that part of the electrons produced in the FPC can enter the cavity and hence being accelerated [7].

If the activity of the coupler is not completely canceled by conditioning, the high voltage biasing system is used to remove the coupler multipacting and then reduce the dose rate.

As shown in Fig. 9 below, the cavities located at cryomodule ends seem to present higher field emission than those in the middle.

All the high beta cryomodules have shown strong field electron emission and have generated neutrons at high gradient [5] and [6].

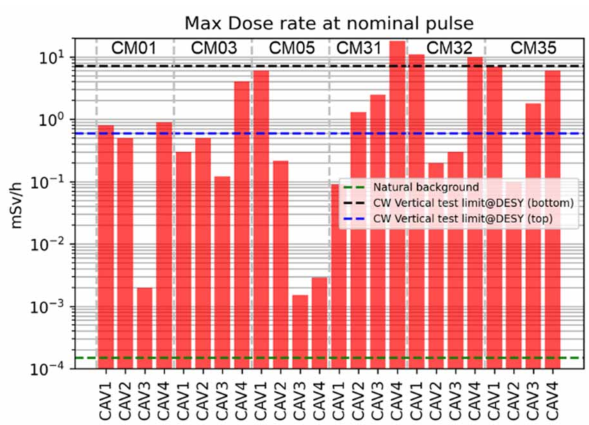

Figure 9: Cavity field emission at nominal pulse.

CONCLUSION

Eight ESS elliptical cryomodules have been successfully tested at CEA. The main performances are within the ESS specifications despite the difficulties caused by the difference between the cryogenic system of CEA and ESS. The tests performed at ESS on these cryomodules confirmed the results obtained at CEA and validated that the transportation from CEA to ESS has not degraded the cryomodule's performances [8].

All the cryomodules have shown X-Ray emission at different levels, and for H-Beta cryomodules the X-Ray emission has been accompanied by a production of Neutrons. This had some consequences on the RF tests that we have shortened in order to limit the activation of the materials. It had also consequences on the subsequent handling and transportation for which we had to apply dedicated procedures for radio-activated components.

REFERENCES

[1] C. Madec *et al.*, "The ESS Elliptical Cavity Cryomodules Production at CEA", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21),* Campinas, SP, Brazil, May 2021, pp. 2536-2539. doi:10.18429/JACoW-IPAC2021-WEXB01

[2] P. Bosland *et al.*, "Tests at high RF power of the ESS medium beta cryomodule demonstrator", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1940-1943. doi:10.18429/JACoW-IPAC2019-TUPTS006

[3] O. Piquet *et al.*, "Results of the RF power tests of the ESS cryomodules tested at CEA", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 1186-1188. doi:10.18429/JACoW-IPAC2022-TUPOTK002

[4] A. Gaget *et al.*, "The control system of the elliptical cavity and cryomodule test stand demonstrator for ESS", in *Proc. 17th Int. Conf. on Acc. and Large Exp. Physics Control Systems. (ICALEPCS'19)*, New York, USA, New York, NY, USA, Oct. 2019, pp. 1538-1543. doi:10.18429/JACoW-ICALEPCS2019-THAPP02

[5] E. Cenni *et al.*, "Time Resolved Field Emission Detection During ESS Cryomodule Tests", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 1192-1195. doi:10.18429/JACoW-IPAC2022-TUPOTK004

[6] G. Devanz., "Instrumentation for High Performance Cavities and Cryomodule Field Emission Analysis", presented at SRF'23, Grand Rapids, MI, USA, paper FRIBA02, this conference.

[7] G. Devanz *et al.*, "High power testing of ESS FPCs on the elliptical cavities cryomodules", presented at *TTC collaboration meeting,* Feb. 2020, CERN, Geneva, Switzerland.

[8] C. Maiano *et al.*, "Production, Test, and Installation of the ESS Spoke, Medium, and High Beta Cryomodules", in *Proc. 31st Int. Linear Accel. Conf, (2022)*, Liverpool, UK, Aug.-Sep. 2022, pp. 685-690. doi:10.18429/JACoW-LINAC2022-TH1PA02