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THE ESS ELLIPTICAL CAVITY CRYOMODULES PRODUCTION AT CEA

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Abstract

CEA in Kind contribution to the ESS superconducting LINAC includes 30 elliptical medium and high-beta cryomodules. CEA is in charge of the production of all the components (except the cavities delivered by INFN and UKRI) as well as the assembly of the cryomodules and a few cryogenic and RF tests. The power couplers operating at a maximum power of 1.1 MW on a 3.6 ms pulse at 14 Hz are conditioned at high RF power on a dedicated stand. The assembly of the cryomodules is performed at CEA by a private Company under the supervision of CEA. This paper presents the status of the cryomodules production, the infrastructure dedicated to this project as well as a few tests results at CEA Saclay.

INTRODUCTION

CEA is in charge of the production of 30 cryomodules of the ESS LINAC [1, 2]. This is one of the main French in-kind contribution for the ESS accelerator construction. CEA is delivering 9 medium-beta cryomodules ($\beta = 0.67$) and 21 high-beta cryomodules ($\beta = 0.86$). Previous papers presented the cryomodule design (Fig. 1), which is similar for medium and high-beta cryomodules with four 704 MHz elliptical cavities [3]. 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.

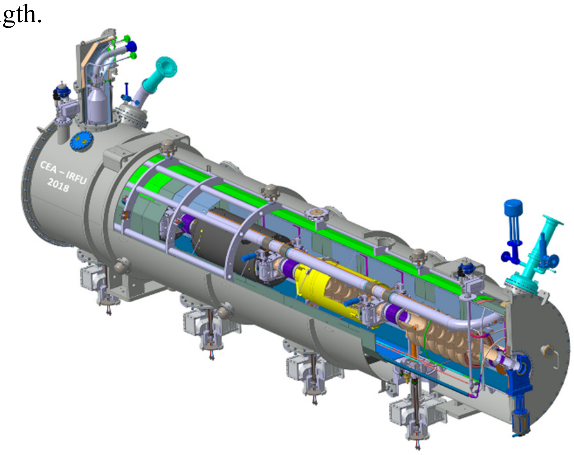

Figure 1: ESS medium-beta cryomodule general layout.

The project started with a prototyping phase consisting in the design, manufacturing and tests at high RF power of a prototype medium-beta cryomodule named M-ECCTD (or CM00) in collaboration with CNRS/IPNO. The results obtained during the RF power tests performed with the M-ECCTD in CEA Saclay were reported in previous articles [4, 5].

In parallel, call for tenders for the manufacturing of all the cryomodules components, but the cavities, were launched.

COMPONENTS PRODUCTION

Previous papers [3] gave details of the scope of the CEA In-Kind Contribution to the ESS accelerator [2]. The CEA contribution includes the delivery of all cryomodules components, the RF power couplers production and RF conditioning [6], the cryomodules assembly in CEA Saclay infrastructure. The production of the 36 medium-beta cavities [7] is an In Kind Contribution of Italy (INFN) and the production of the 84 high-beta cavities is an In-Kind Contribution of UK (UKRI). All cavities will be delivered to CEA qualified and ready for assembly in the cryomodules.

In order to cope with the schedule and minimize the impact of possible delays from manufacturer, CEA started the production of the series cryomodules in 2018 before the prototype test completion [4]. 40 main contracts were signed mostly with French vendors and there were a few minor design changes to be implemented after the prototype test. Before the assembly started, a buffer of 3 components was created and a delivery throughput of one set of components per month to limit storage on site was asked. Many components (60%) are already delivered and storage areas were created for the large components.

The couplers production was launched in 2017 and awarded to PMB. The 6 preseries couplers were on specifications (1.1 MW, 14 Hz, 3.6 ms). During the conditioning of the first series couplers, the temperature of the ceramic abnormally increased and was followed by a vacuum increase which stopped the conditioning. After a careful inspection of the ceramic, a crack was found in the ceramic. CEA stopped the production, conducted a careful analysis and found out that Titanium Nitride (TiN) coating was not complying with the specifications [6]. PMB changed the TiN subcontractor and the production could resume. All the medium beta couplers are now conditioned (Fig. 2).

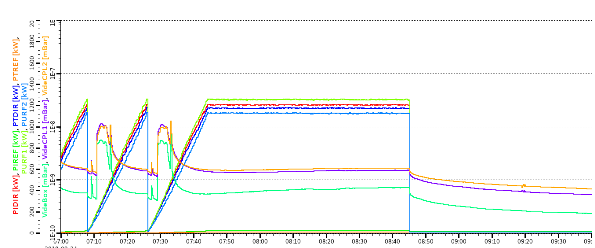

Figure 2: Typical RF conditioning of couplers with vacuum and power measurements.

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ASSEMBLY

For the assembly of the medium-beta prototype cryomodule, CEA used a temporary assembly hall (the series assembly area was occupied by the assembly of last XFEL cryomodules). During the assembly of the first series cryomodule, CEA set the halls in 7 work-stations: two in the clean room and five in the halls. CEA finalised the procedures and updated and multiplied the tooling to cover the assembly needs and parallel work (Fig. 3).

Figure 3: CM04 and CM05 cavity string in the clean room and cryomodules CM01 and CM30 (also named H-ECCTD) in the assembly hall.

In June 2018, the assembly of the series cryomodules was awarded to B&S International Company. Since Oct. 20, ten persons are on CEA site: 2 operators are doing the assembly in the clean room, 1 vacuum technician intervenes on all the work station, a welder, an alignment engineer and 3 operators are performing the assembly in the halls and 1 warehouseman inspects, prepares and supplies the different workstation with components. B&S Company shall hire one more operator to sustain the delivery throughput of one module per month. CEA trained B&S Company operators to assemble five cryomodules and then supervises B&S Company in the assembly.

As reported in the previous section, components had manufacturing issues and could not be delivered on time. CEA decided to stop cryomodules assembly in Dec. 2019. Unfortunately, due to COVID-19 pandemic and the French lock-down, CEA was closed for 2 months and B&S Company could resume the work on June 2020. Up to now, B&S Company has assembled 3 cryomodules and 2 more are partially assembled.

QUALITY

CEA put in place the quality process and follow-up since the beginning of the ESS cryomodule project. The QA plan was written including the follow up of both the components production and the assembly.

For the components, standardized structure and follow-up has been set up such as kick-off meetings, monthly meetings or/and reports, inspection at vendors at critical time, manufacturing inspection before shipping, incoming inspection at CEA. The contracts were followed by a contract manager and a technical coordinator who takes the decision on the technical issues. In addition, the documentation is checked and prepared in folders for ESS.

For the assembly, from CEA existing documentation, B&S Company has updated the assembly procedures, inspection reports, hold point reports and other quality documents. Those documents are filled by the operators for each cryomodule and monitored by CEA quality team. CEA quality team follows also the non-conformances (Fig. 4), especially taking care of the NCR solving and closing.

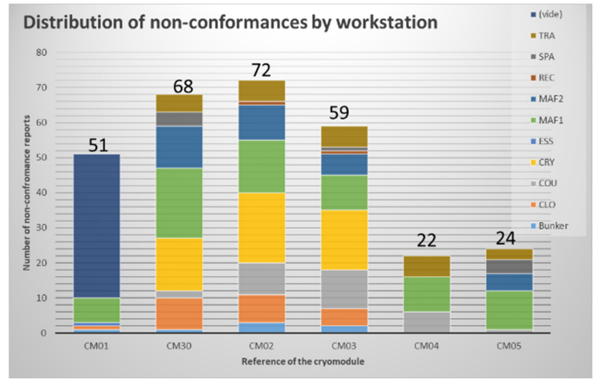

Figure 4: Non-conformances distribution as a function of the cryomodule number and the workstation.

For example, for the workstation where the cavities string gets dressed with magnetic shield and tuner and the diphasic tubes is welded (MAF1), the improvement in the welding procedures (measurement of the O_2 contain in the Ar gas used to weld Ti) and the optimisation of the welding tools decreased the number of non-conformances. For COU workstation (assembly of the coupler to the cavity), the improvement of the workstation and the modification of connector positions allow the decrease of non-conformance from CM30 to CM05.

TESTS REPORT AT CEA

Objectives and Experimental Conditions

The main objectives of the tests at CEA are to:

- Check quality of the assembly and procedures by measuring the cavities and couplers performances
- Verify the Q_{ext} of the power couplers on the 1st medium-beta and high-beta cryomodule
- Measure cryogenic heat loads (static and dynamic)

The experimental conditions are different between CEA and ESS: the thermal shield can be cooled only by N_2 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 and only 2 cavities can be powered at the same time instead of 4 cavities @ ESS.

CEA will perform cold RF power tests of:

- 2 prototype cryomodules (medium-beta and high-beta)
- 6 series cryomodules of each type (3 medium-beta and 3 high-beta)

Main General Results (CM01, 02, 03)

For all the cryomodules tested, the 2 K LHe level above the cavities could be regulated easily. The static heat load

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was measured at 17 W for CM01 and CM03 with regulation valve closed and decreasing LHe level and is equal to the specifications re-estimated with a thermal shield at 80 K. The static heat load is overestimated since the heat exchanger is not fully operational in CEA cold conditions (saturated helium at 1 bar in the High Pressure line instead of supercritical helium). The dynamic heat load per cavity at ESS nominal gradient was difficult to estimate (a few watts were measured but are within the measurements uncertainties) and less than the 5 W specified. More precise measurements will be performed at ESS.

The slow tuner frequency shift versus motor steps is the expected 1 Hz per motor step. The frequency shift is smooth and the hysteresis is low as can be seen on Fig. 5.

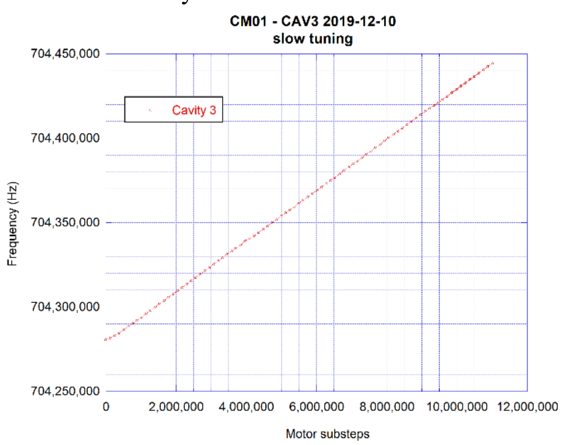

Figure 5: Variation of frequency versus motor sub-steps for CM01cavity position #3.

The conditioning of power couplers at 300 K and at 2 K was reproducible up to the maximum RF power: 1.1 MW, 3.6 ms 14 Hz and lasts 3 hours in both warm and cold conditions

Process of cavity/coupler during the first ramp up of the cavity field was required. Degassing, electron emission, and light events occurred during conditioning. ESS pulse and field could be reached in 6 to 8 hours and cavities performances were on requirements:

- medium-beta cavities (CM00, 01, 02, 03): 17 MV/m, 3.6 ms, 14 Hz
- high-beta cavities (CM30): 20 MV/m, 3.6 ms, 14 Hz

All cavities tested still showed X-Ray at different level after one day of RF run (which was already the case in vertical cryostat but could not be compared due to very different measuring setups).

Lorentz force detuning compensation by piezo tuner for cavities at high gradient is efficient with simple manual optimization of the piezo pulse

Particularities in Cryomodule Test Results

Despite the very good results obtained, the tested cryomodules had particularities.

During the tests of CM30 (prototype high-beta cryomodule), abnormal behaviour of the LHe regulation cryogenic valves were observed : the valve used to fill the cavities from the bottom never closed completely and the valve regulating the LHe level inside the diphasic pipe had 2% aperture whereas the usual aperture is around 40% with no RF power and no heater. The inspection of the valve (seat and needle) after a warm-up did not identify any non-conformity. Despite the issue, the helium bath at 2 K was maintained above the cavities during the tests of the cavities at high gradient. One high-beta cavity was on specifications 20 MV/m, 3.6 ms, 14 Hz; 3 cavities were at 3.6 ms but 17 MV/m, 1 Hz limited by high field emission issues. CEA conducted an analysis of the NCRs recorded during CM30 assembly and preparation for the tests. Modifications of some assembly procedures and of the pumping groups in the test stand were implemented.

For CM02, the turbomolecular pump installed on beam vacuum failed during the cold RF power test and some aluminium particulates were found between the turbomolecular pump and the cryomodule gate-valve. As expected, the cavities showed very high X-Ray and the cryogenic was unstable. The accelerating gradient at 3.6 ms, 14 Hz, after the event were above specifications for the 2 cavities opposite to the turbomolecular pump. The two cavities close to the turbo pump were limited at 15.3 MV/m and 9.1 MV/m. CM02 has been dismounted. All the cavities and all the couplers will be reconditioned and tested. CM02 will be reassembled. The pumping setup has been modified and the cavity string is now pumped by an ionic pump.

STATUS OF THE FIRST CRYOMODULES ASSEMBLED AT CEA

CM00 (prototype medium-beta cryomodule) was tested at CEA end of 2018 and delivered to ESS beginning of 2019. Tests at ESS have been performed until March 21.

CM01 is the first series cryomodule. It was tested at CEA at the end of 2019 and shipped to ESS in Sept. 2020. Preparation of the acceptance tests at ESS are in progress.

CM30 (prototype high-beta cryomodule) tests began at CEA in March 2020, then due to pandemic, there were stopped for 5 months. In Sept. and Oct. 2020, the tests were completed. This cryomodule will be refurbished in a spare medium-beta cryomodule.

CM02 was tested at CEA in Jan. 21. As reported, due to the failure of the turbomolecular pump, it is disqualified and has been dismounted: cavities and couplers are being reprocessed.

CM03 had been successfully tested at CEA in March 2021 and is being prepared for delivery to ESS.

CM04 and CM05 are being assembled.

CONCLUSION

The production site is in place. B&S Company has already assembled 3 cryomodules and 2 more are being mounted. The tests stand is operational and the tests performed at CEA validated both the design and the performance of the cryomodule.

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