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TESTS AT HIGH RF POWER OF THE ESS MEDIUM BETA CRYOMODULE DEMONSTRATOR

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Abstract

CEA is in charge of the 30 elliptical medium and high-beta cryomodules to be installed in the ESS tunnel in Lund, Sweden. Before launching the assembly of the series cryomodules, CEA developed a medium-beta cryomodule technology demonstrator in collaboration with IPNO, LASA and ESS. This paper briefly presents the cryomodule assembly and summarizes the main results of the high RF power tests performed in 2018 in a dedicated test stand in CEA Saclay.

The main ESS requirements were reached: E_{acc} = 16.7MV/m in cavities, $P_{forward}$ = 1.1 MW in power couplers, RF pulses length = 3.6 ms at 14 Hz. The piezo tuners efficiently compensated the Lorentz forces detuning and could stabilize the accelerating field better than 1% over the full length of the expected ESS 2.86 ms beam pulse without any LLRF regulation system.

Following this successful validation CEA started the assembly of the first ESS medium-beta series cryomodule.

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 (β=0.67) and 21 high-beta cryomodules (β=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.

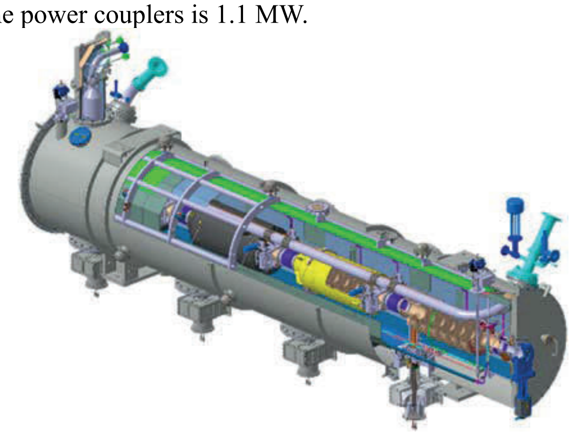

Figure 1: ESS medium-beta cryomodule general layout.

The prototyping phase consisting in the design, manufacturing and tests at high RF power of a prototype medium-beta cryomodule named M-ECCTD was a collaboration of CEA/Irfu and CNRS/IPNO. In 2017, the M-ECCTD cryomodule had been already assembled and installed in the test stand when an incident occurred and caused the sudden break of the cavity vacuum. Tests at high RF power were cancelled but cryogenic and low-level RF tests could be performed. Results are summarized in [4]. We dismounted the M-ECCTD after these tests. We replaced the damaged cavity and the broken power coupler by new ones and refurbished the 3 other cavities and couplers for remounting the cryomodule. We also replaced the heat exchanger previously mounted (plate exchanger) by the first heat exchanger of the series that is of a different technology (Hampson heat exchanger). This paper summarizes the results obtained during the RF power tests performed with the M-ECCTD in CEA Saclay between Sept. and Dec. 2018. In addition to test results, we present a short status of the series production that is starting.

RF POWER TESTS IN CEA TEST STAND

Figure 2 shows the Q-curves of the four RF cavities measured before the cryomodule reassembly. Cavity 4 did not reach the ESS specifications but we mounted it for schedule reasons.

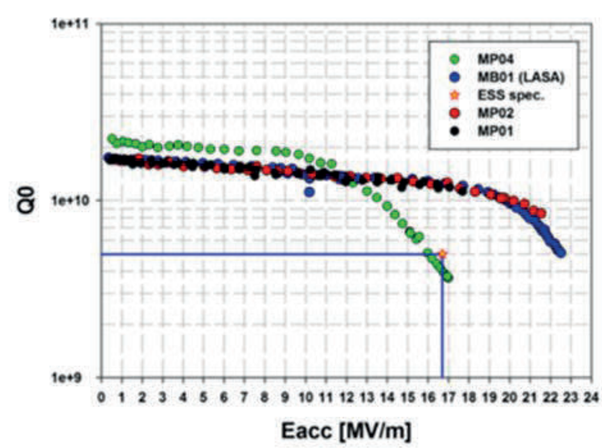

Figure 2: Q curves of the cavities before assembly in the M-ECCTD.

We performed the RF conditioning of the four power couplers up to 1.1 MW in TW and SW at 14 Hz and max

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pulse length of 3.6 ms on the test bench before cryomodule assembly (Fig. 3).

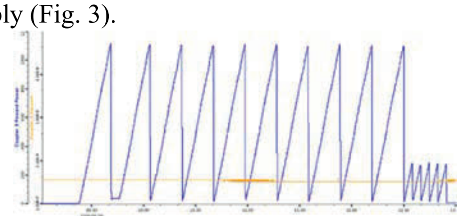

Figure 3: Example of RF power ramps up to 1.1 MW applied during RF conditioning of a coupler pair.

We installed the cryomodule in the CEA test stand by end of August 2018 (Fig. 4).The first operation was the RF conditioning of the power couplers up to the maximum power of 1.1 MW at room temperature with cavities off-resonance. The electron probes and arc detectors close to the coupler ceramic did not collect any electron current or light emission during the conditioning of the four couplers which duration was about 5 hours each. The interlock threshold on the pressure had been set at 1.10^{-6} mbar. The pressure threshold under which RF power is allowed to increase is $2.5\ 10^{-7}$ mbar. We performed a second RF conditioning cycle of the power couplers once the cavities were at 4.5 K.

Figure 4: M-ECCTD in the CEA test stand.

Then, the cryomodule was operated at 2 K. Some cryogenic instabilities appeared and the 2 K LHe level was stable only for periods of variable duration. The CEA test stand is fed with atmospheric, bi-phasic helium. A large amount of GHe generated by losses in the cryogenic LHe supply lines explains that the non-periodical formation of a gas plug in the high-pressure circuit of the heat exchanger. These instabilities should not be observed at ESS, where 3 bar supercritical helium is used. In order to improve test conditions, an additional phase separator that will equip the CEA test stand in order to lower the He gas ratio in the filling line and obtain a better cryogenic stability. We could however obtain a stable 2 K LHe level and pressure during periods exceeding 1 hour during which we could perform the tests at high RF power and cryogenic measurements of cavities RF dissipations.

Once the cavities are at 2 K we tuned them at the nominal ESS frequency 704.42 MH. Figure 5 shows the frequency shift versus the number of tuner screw turns. The linearity is very good, around 20 kHz per screw turn. Some hysteresis is visible in the low frequencies region where the mechanical plays not yet cancelled by the cavity stretching. Results are very similar to the ones obtained during the first M-ECCTD test [4].

We also checked the static frequency shift range obtained by applying a continuous voltage on the piezo stacks before testing the Lorentz detuning compensation at high gradient. The maximum range achieved is very comparable with the previous ones obtained in 2017 and are around 600 Hz to 880 Hz for 150 V.

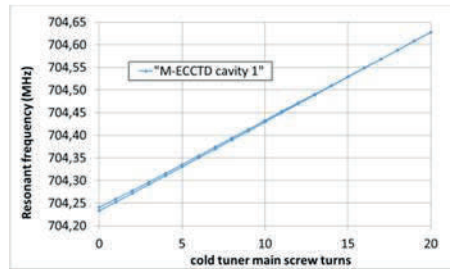

Figure 5: Cavity frequency shift versus screw turns.

Once the cavities are tuned at 704.42 MHz and 2 K LHe pressure and level are stable, we started in a first step to increase the RF field in the cavity applying the RF power in short pulses of 1 ms and at low repetition rate frequency (1 Hz or lower). This allowed a safe RF processing of the cavity/coupler before increasing progressively the repetition rate frequency up to 14 Hz and the pulse length up to 3.6 ms. The four cavities showed some e-field emission that needed to be processed. The low duty factor of maximum 4% limited the efficiency of the RF processing. However, using the general procedure described above, we could increase the field in each cavity up to the ESS nominal gradient of 16.7 MV/m at 14 Hz and 3.6 ms pulse length. Cavity 4 showed a stronger X-Ray emission than the three others. We had no time to process it as well as the three other ones, thus we do not know if we could clean it or not with a longer processing. However, Cavity 4 reached maximum gradients close to the ESS nominal gradient.

We applied 4P/P RF power pulses in order to generate the flat top cavity pulses with the ESS characteristics and filling time. All measurements were done in open loop. Without any piezo compensation, the Lorentz forces detuned the cavities and caused the drop of the cavity field and the phase shift that we could only partially compensated by a static pre-tuning of the cavity (Fig 6).

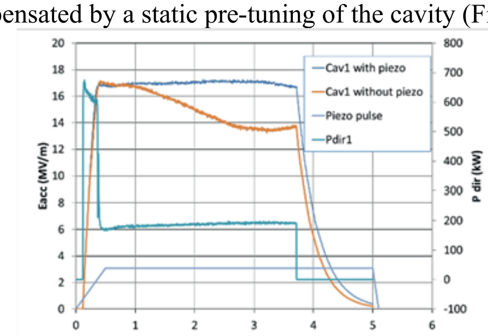

Figure 6: Cavity 1 pulse with static pre-tuning, with and without piezo compensation.

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Cavity static pre-tuning and piezo compensation with a simple pulse shape allowed flattening the cavity field along the whole 3.6 ms pulse (Fig 6). During the 2.86 ms of beam pulse we obtained Eacc=17.05+/-0.15 MV/m and +/-7 deg phase excursion. In the ESS LINAC the ESS LLRF system should be able to compensate the remaining phase shifts and stabilize the RF field amplitude within the ESS requirements.

We tested separately the four cavities at ESS nominal pulses (or close to with cavity 4) of 14 Hz, 3.6 ms pulse length and 16.7 MV/m without trying to reach higher fields during this first test sequence. The result is summarised on Fig. 7.

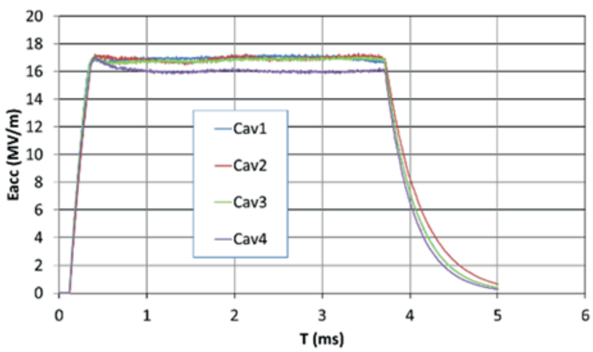

Figure 7: The four cavities pulses with static pre-tuning, piezo compensation and 4P/P klystron output pulse.

We ran cavity 1 and 2 together adjusting their two pulses each at the nominal ESS gradient. We observed no cross talk between these cavities.

During some periods of cryogenic stability, we could perform measurements of static cryogenic heat loads giving 19.5 W on the cold mass at 2 K. This value is close to the estimation of 17 W corresponding to the CEA operating conditions with a thermal shield at 80 K that is different from 40 K in the ESS LINAC.

We could also measure the RF heat loads of Cavity 1, compensating the cavities RF heat loads by a calibrated heater and keeping the GHe flow and pressure constant. RF dissipation of Cavity 1 measured at ESS nominal field is 4.5 W, compliant with the ESS requirement of 5 W maximum.

After the RF power tests we prepared the M-ECCTD cryomodule for its shipment to ESS Lund, where the ESS team will be test it again in the test stand developed for the validation of the series elliptical cryomodules.

SERIES CRYOMODULES

In parallel to the M-ECCTD activity, CEA started the production of the series cryomodules. 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, except the cavities (see next paragraph), the RF power couplers production and RF conditioning, the cryomodules assembly in CEA Saclay infrastructure.

The production of the 36 M-beta cavities is an In Kind Contribution of Italy (INFN/LASA) and the production of the 84 high-beta cavities is an In-Kind Contribution of UK (STFC) [1,2,3]. All cavities will be delivered to CEA already tested in vertical cryostat and ready to be mounted inside the cryomodules.

CEA placed all contracts before the completion of the test of the M-ECCTD demonstrator. Many components are already delivered and the assembly of the first medium-beta cryomodule of the series, CM01, is in progress with the 4 first cavities delivered by LASA and the 4 power couplers conditioned at the ESS requirements by CEA. The B&S Company is in charge of the assembly of the 30 ESS cryomodules in CEA's infrastructure (Fig. 8).


Figure 8: First ESS medium-beta cavity string rolled out the CEA clean-room on the 25 of March 2019.

CONCLUSION

Beginning of year 2018, we refurbished the first ESS prototype cryomodule with elliptical medium-beta cavity, named M-ECCTD, and we performed the RF power tests in autumn 2018. We reached the ESS requirements: Pmax=1.1 MW, Eacc=16.7 MV/m at 14 Hz and 3.6 ms pulse length. We could stabilize the cavity field better than 1% with phase excursion lower than +/-7 ° within the 2.86 ms ESS beam pulse length with only cavity pre-tuning and piezo compensation (No RF regulation).

This successful result is the validation of the technologies used for the ESS cryomodules of the series.

In parallel to the prototyping activities, we started the production of 30 cryomodules components and the assembly of the first medium-beta cryomodule.

REFERENCES

[1] M. Lindroos *et al.*, "ESS Progressing into Construction", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 4266-4270. doi:10.18429/JACoW-IPAC2016-FRYAA02

[2] C. Darve *et al.*, "ESS Superconducting RF Collaboration", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 1068-1070. doi:10.18429/JACoW-IPAC2017-MOPVA090

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS006

[3] P. Bosland *et al.*, “Status of the ESS Elliptical Cryomodules at CEA Saclay”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 945-947. doi:10.18429/JACoW-IPAC2017-MOPVA040

[4] F. Peauger *et al.*, “Preliminary Test Results of the First ESS Elliptical Cryomodule Demonstrator”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 691-693. doi:10.18429/JACoW-IPAC2018-TUPAF015