ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB056

SARAF-PHASE II: TEST OF THE SRF CAVITIES WITH THE FIRST CRYOMODULE*

Guillaume Ferrand†, Stéphane Berry, David Darde, Gabriel Desmarchelier, Florian Hassane, Tom Joannem, Sébastien Monnereau, Nicolas Pichoff, Olivier Piquet, Thomas Plaisant
Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA-Irfu) Institut de Recherche sur les lois Fondamentales de l'Univers, Gif-sur-Yvette, France

Abstract

CEA is committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SARAF accelerator in order to accelerate 5 mA beam of either protons from 1.3 MeV to 35 MeV or deuterons from 2.6 MeV to 40 MeV. The SCL consists in four cryomodules. The first cryomodule hosts 6 half-wave resonator (HWR) low beta cavities (beta= 0.09) at 176 MHz. The low-beta cavities were qualified in 2021, as well as the power couplers and frequency tuners. The Low-Level RF (LLRF) system was qualified in 2022 with a dedicated test stand. This contribution will present the results of the RF tests of the first SARAF cryomodule at Saclay.

INTRODUCTION

In 2014, CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives, Saclay, France) was committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SNRC (Soreq Nuclear Research Center, Yavne, Israel), on the SARAF (Soreq Applied Research Accelerator Facility) site. CEA is currently driving the manufacturing of this new accelerator [1]. CEA planned the end of the commissioning of the last cryomodule for 2023.

The frequency of the entire accelerator was fixed to 176 MHz. The beam dynamics fixed the optimal "geometric betas" to 0.09 and 0.18. The SARAF-Phase II accelerator contains 13 superconducting cavities with $\beta_{opt} = 0.09$, called low-beta (LB) cavities, and 14 superconducting cavities for $\beta_{opt} = 0.18$, called high-beta (HB) cavities [2]. The first two cryomodules contain the LB cavities (6 and 7 cavities each), and the last two cryomodule the HB cavities (7 cavities each).

A full description and details about the design and the tests of the LB cavities can be found in [3]. All of them were successfully tested up to an accelerating gradient of 10 MV/m, the requirement being 7 MV/m. Considering the accelerating length of 155 mm @ $\beta = 0.091$, this corresponds to an accelerating voltage of 1.085 MV.

The couplers were already conditioned and tested with a dedicated test stand in 2019 and 2020. See [4] for more details about the coupler design and the test stand.

The equipped cavity, with couplers and tuners was tested with a dedicated test stand, called ECTS [5].

The qualification of the electronics included the Low-Level RF (LLRF) systems and the detection of arcs with photomultipliers and electron pick-up. The LLRF and most of the electronics were already tested with the ECTS test stand [6]. However, they were never tested in "operation" mode, that is, at the nominal frequency, with tuners compensating variations of He bath pressure and Lorentz detuning.

The first cryomodule was prepared for test in December 2022 (see Figure 1), and tests began in February 2023. This paper presents the RF tests of the first cryomodule, including warm and cold conditioning, tests at nominal field and in operation mode. These tests concluded the Saclay acceptance tests of the equipped cavities before shipment to SNRC and tests with beam in Israel.

Figure 1: Preparation of the first cryomodule for tests.

REQUIREMENTS

1. Warm conditioning

The first step was the warm conditioning of the RF couplers. All of them were conditioned on the cryomodule again after having been stored under vacuum during 3 years.

The pressure inside of the coupler is measured with a cold cathode gauge. The target (software threshold) was 2.10^{-6} mbar at room temperature for input power from 0 to 1 kW. Most of the multipactor effect is observed from 150 to 400 W. Conditioning was done with a repetition frequency of 1 Hz, with pulses from 20 µs to 1 s by factor 2 steps. The RF signal is increased by steps of 10 mV on the

* Work supported by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, France) and by Soreq Nuclear Research Center (SNRC, Israel)
† Guillaume.ferrand@cea.fr

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ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB056

LLRF. 1.0 V at the LLRF output corresponded to about 1.0 kW at the output of the RF amplifiers. The voltage is maintained as long as the pressure is higher than the target (2.10^{-6} mbar).

Couplers were conditioned by bunches of 2 or 3 couplers. The conditioning process is fully automatic, the operator defines the requirements, pulse length, RF signal steps, etc. and the automaton drives the cavities with the pressure target. If the pressure of all the pressure gauges decreases under 2.10^{-6} mbar, the RF signal increases a bit. If the pressure of at least one of the gauges increases to more than 2.10^{-6} mbar, it waits to reach the target before moving the signal. The same voltage is applied to all couplers, thus, the coupler that requires the longest conditioning steps defines the time required for the conditioning of the bunch of couplers.

2. Cold conditioning

The same conditioning as at room temperature is done on all the couplers at 4.2 K. At this temperature of the cavity, the temperature of the coupler varies from 30 K (close to the cavity) to room temperature, with a thermal bridge at 70 K in-between. The process is the same as the warm conditioning. The pressure target was 2.10^{-7} mbar, considering the cryopumping of the SC cavity.

3. Measure of the external quality factor of the coupler antenna

The external quality factor is almost equal to the loaded quality factor of the cavity, as the quality factor of the SC cavity is higher than the quality factor of the coupler by approximately three orders of magnitude. It was measured with a VNA directly on the ports of the cavity, in order to avoid mismatching due the RF amplifiers. The target was in the range $[7.4, 16.7].10^5$. The VNA measurement was completed with a decay measurement, and both values were compared.

4. Measurement of the frequency and frequency tuning

The initial frequency, with tuner fully disengaged must be between 176 005 000 Hz and 176 150 000 Hz to be able to tune the cavity. The tuner was tested to reach the target frequency of 176 000 000 Hz +/- 10 Hz.

5. Test at nominal field and consumption.

The requirement was to test the cavities at nominal field, i.e. 1.085 MV, during at least 30 minutes. The dynamic consumption must not exceed 10 W per cavity to reach the required performance. This test is done with a PLL integrated to the LLRF boards [6] in order to lock the LLRF frequency to the eigenfrequency of the SC cavity. The cryogenic consumption is measured thanks to the helium flow at the output of the cryomodule.

During this test, the sensitivity to the He bath pressure was measured. It must not exceed 5 Hz/mbar to be able to operate at SNRC without requiring fast tuning systems. The current frequency tuning system is mechanical and requires a few 100 ms to compensate frequency variations.

The Lorentz detuning was measured as well, without any requirement.

6. Test in operating mode

This last test was similar to the previous one, but was done at fixed frequency, 176 000 000 Hz (+/- the jitter of the RF generator).

The resonance frequency variations are compensated by the tuner. For this purpose, the tuner controller gets the phase difference between the injected signal and the cavity field and tries to make it equal to a given target (PLL algorithm). The algorithm is an "integral" loop with a given tuning range, it moves the stepper motor only if the difference between the phase and the target is above a predefined threshold. The cavity field is measured with a pick-up loop on the extremities of the HWR cavities. The tuners are driven with Phytron stepper motors and dedicated PhyMotion PLC modules. The PLL target is the same for tuners and for the PLL used for tests at nominal field.

The power must increase slowly in order to let the frequency tuner follow and compensate the Lorentz detuning without losing the cavity. During this process, the LLRF maintains the accelerating field with a PI (Proportional-Integral) loop on the transmitted power at 176 000 000 Hz. The PLL of the LLRF system is deactivated. The LLRF provides the required phases through EPICS to the PLC.

The delay between measurement and correction of the frequency is around 100 ms.

The field inside the cavity is maintained by the LLRF system. The magnitude stability must be better than 0.25%, and the phase stability better than 0.25°.

RESULTS

1. Warm conditioning

It took 6 days to condition the 6 couplers. Figure 2 shows an example of coupler conditioning for pulses from 100 ms to 800 ms, and repetition time of 1 s (1 Hz). During the conditioning, the pressure was maintained at 2.10^{-6} mbar. Figure 3 shows the variation of pressure during the conditioning. At the beginning of each iteration, a peak of pressure appears. Coupler #1 limited the conditioning time as it is the one that showed the higher pressure during the full conditioning process.

No electrical breakdown appeared during the test. But the pressure increased very fast up to 10^{-5} mbar during the very first iterations, without arcing.

Pumping is done through cavity #6 beam line. Thus, it was longer to condition cavity #1 to 5 than cavity #6.

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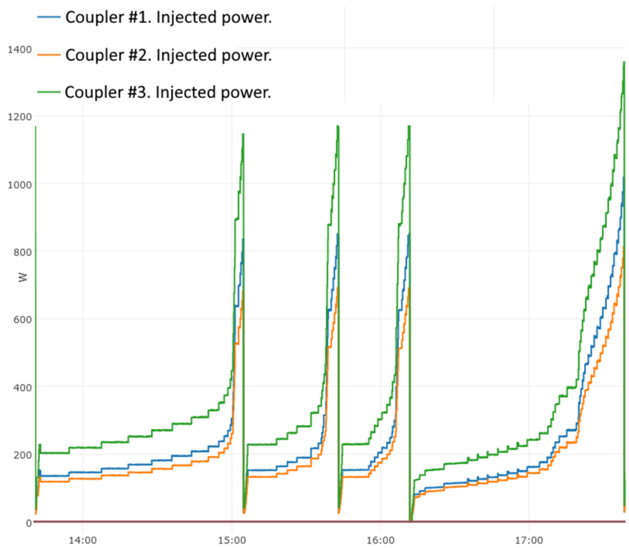

Figure 2: Conditioning of couplers 1 to 3 from 100 ms to 800 ms per pulse. Injected power.

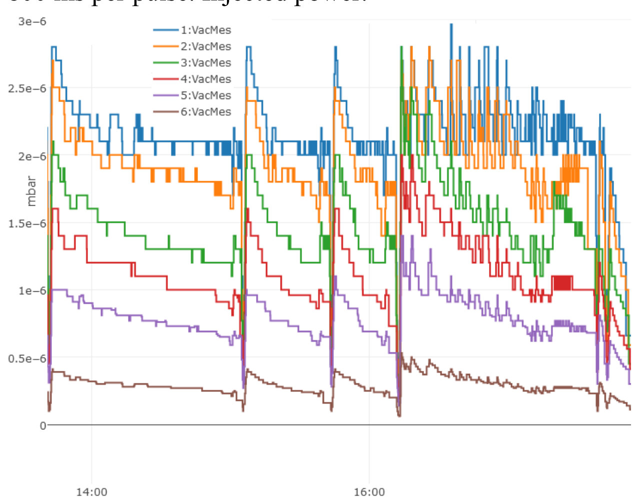

Figure 3: Conditioning of couplers 1 to 3 from 100 ms to 800 ms per pulse. Measured pressure on all cavities.

2. Cold conditioning

Before cold conditioning, all valves were closed, in such a way no external pumping was done. We observed that the cryopumping in the cavity was so efficient that it tended to pump the external pumps themselves. The pressure was lower with all valves of the beam line closed.

Cold conditioning of the couplers required 2 days at 2.10^{-7} mbar. Then, cavities were conditioned at different accelerating fields during a few minutes. Before conditioning, in some cases, the cavity showed a bit of multipacting around 0.4 MV. But a few minutes were enough to make it disappear.

3. External quality factor

The target was the range $[7.4, 16.7].10^5$. Table 1 shows the results. All couplers antennas are in the target range.

Table 1: External Quality Factor

Cavity	*1*	*2*	*3*	*4*	*5*	*6*
Qext	According to VNA					
($\times 10^5$)	14.9	13.6	13.0	13.8	15.5	15.3
Qext	According to decay time					
($\times 10^5$)	12.0	11.2	10.8	14.0	17.1	14.4

The measurement of Q_{ext} with the decay time gives the values shown in Table 1. This method is less accurate than the previous one, as it depends on the impedance of the amplifiers. The difference between both methods can reach 20%.

4. Measurement of the frequency and frequency tuning

Table 2 shows the initial frequency shift with respect to 176 MHz, before tuning. This was measured with the VNA. It must be higher than 5 kHz and lower than 150 kHz to be properly tuned.

Table 2: Initial RF Frequency Shift

Cavity	*1*	*2*	*3*	*4*	*5*	*6*
Freq. (kHz)	68	56	31	47	108	64

After tuning, all cavities reached 176 MHz +/- 10 Hz. The sensitivity of the tuners was measured between 1500 and 2900 Hz/turn, depending on the tuner position. The maximal number of turns was 55 for all tuners. The hysteresis of the frequency tuning was between 30 and 340 Hz after 10 turns back and forward.

5. Test at nominal field and consumption

Cavities were tested at least 40 min at nominal field. All cavities except cavity #6 reached the nominal field at first test.

Cavity #6 quenched a few times at nominal field. This is the last cavity, the one connected to the pumping bench. Moreover, this cavity was used, in clean room, for atmospheric pressure release, during the assembly of the beam line. This certainly explains a possible contamination of the cavity.

In order to understand if these quenches were due to the field emission, we put an X-ray detector on the beam axis, on cavity #1 side (as the cavity #6 side was not accessible due to the vacuum bench, and a movable cleanroom). We tried to see if, with conditioning, it was possible to increase the performances and decrease the X-ray emission.

The X emission was first measured at 25 µS/h in the bunker. It was conditioned during 100 min at 95% of the nominal field. After 10 min, X emission fell to 16 µS/h. After 100 min, it was 12 µS/h. At this point, cavity 6 was able to reach nominal field without quench. It was conditioned 90 min more at nominal field to reach 2.2 µS/h. This

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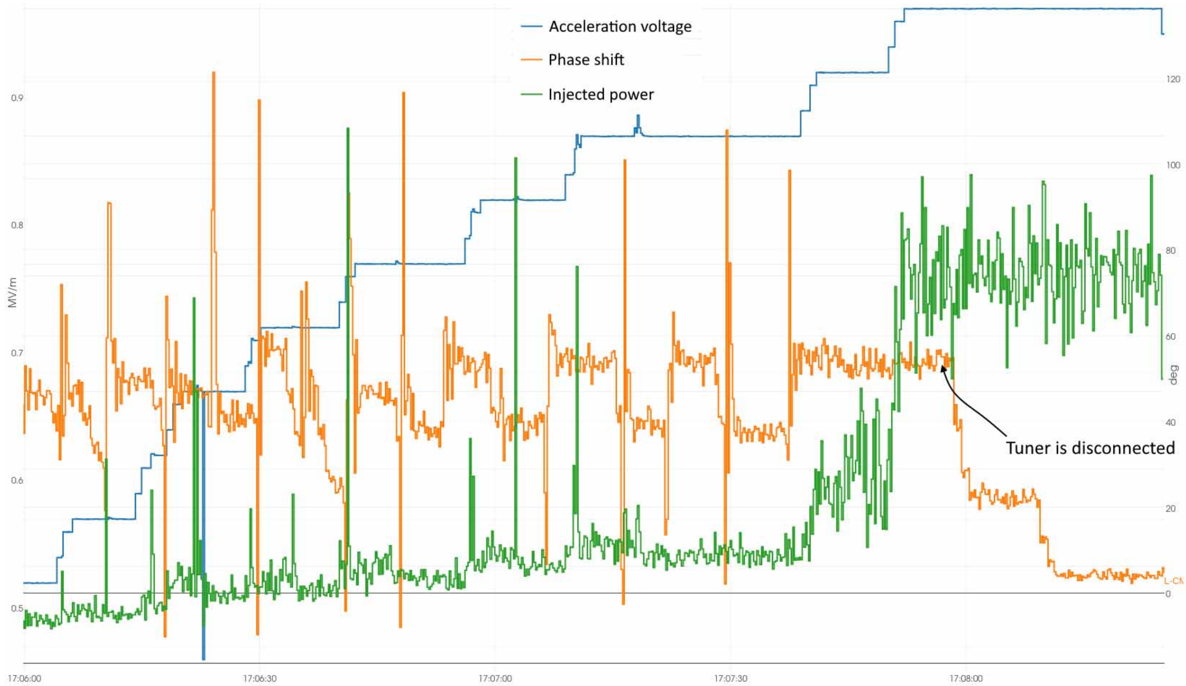

Figure 4: Test of cavity 5 in operation mode.

demonstrated that the first quenches were due to field emission. After conditioning, it was possible to reach 115% of the nominal field.

All cavities except cavity 6 showed a power consumption of 5 W +/- 2 W (target 10W), estimated from the gas He flow before and during the consumption test. Cavity 6 showed a consumption of 10 W +/- 2 W after conditioning.

Table 3 shows the sensitivity to the He bath pressure. It varies a lot from one to another cavity, but remains lower than the target of 5 Hz/mbar.

Table 4 shows the Lorentz detuning. This varies a lot with the cavity. It seems like it is slightly correlated with the initial frequency of the cavity, and thus to the pressure of the frequency tuner on the cavity at 176 MHz. This should be verified with more data.

Table 3: Sensitivity to He Bath Pressure

Cavity	*1*	*2*	*3*	*4*	*5*	*6*
Shift (Hz/mbar)	1.4	-0.5	1.7	0.6	1.7	2.9

Table 4: Lorentz Detuning

Cavity	*1*	*2*	*3*	*4*	*5*	*6*
Lorentz det. (Hz/MV^2)	277	265	230	208	332	183

6. Test in operating mode

Finally, the cavities were tested in operating mode, without beam. In this case, the cavities are at the operating frequency and the tuner tries to compensate the Lorentz detuning and helium bath pressure variations.

All cavities reached the nominal field. But it was more or less difficult depending on the cavity. For all cavities, we observed fast variations of the eigenfrequency of the cavities when the stepper motor was moving. In some cases, it could even lead to the divergence of the PI loop of the LLRF and loss of the cavity. In this case, the cavity was generally stuck in a very low multipacting barrier (around 20 kV). After having shut down the RF and waited 1 or 2 minutes, it was possible to relaunch the cavity.

Cavity #5 was the most difficult to operate at its nominal voltage, due to high Lorentz detuning and lower efficiency of the RF amplifier, leading to saturations. Figure 4 shows the test of cavity 5. Each time the signal is increased, the tuner tried to correct the Lorentz detuning, leading to variations of the phase, and sometimes spikes of the RF injected power.

The tuner was de-activated at 0.9 MV in order to reach the nominal field without vibration. We can see that, before 17:08, the phase shift remained between 40° and 60°, and, when the tuner is deactivated, at 17:08, when the field increases, the frequency moves, and the phase shift moves as well. The required power increases quickly as the cavity is slightly detuned in this situation.

Some tests were done in warm conditions with the tuner. A piezoelectric sensor was put on the coupler flanges, in order to measure vibrations coming from the cavity when the motor is running. We tested different configurations of the PhyMotion controllers. It looked like some configurations generate more vibrations than others. This will have to be tested with the second cryomodule, in order to find the best configuration that minimizes microphonics due to the tuner.

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CONCLUSION

Despite some difficulties due to the vibrations of the tuner motors, all the requirements were successfully verified.

First, all cavities reached their nominal field with no huge difficulty. Only one cavity required some conditioning at nominal field to reduce the field emission.

Then, power consumption was compliant with the cryogenic requirements. Even if the 6th cavity required a bit more cryogenic power than expected, the total cryogenic requirement for cavities is far less than the target.

The external quality factor of the couplers was compliant as well, for all couplers.

The only difficulty was with the effect of the vibrations of the tuner motors on the cavities. The control of the motors is certainly not optimal leading to microphonics in the cavities. Some new parameters will be tested with the following cryomodules to test the effect of them on the vibrations.

In parallel to the RF tests, the cryogenic lines and the solenoids were tested. All of these tests were successful as well. This validates the full design of the first SARAF-Phase II cryomodule.

After the qualification of the first cryomodule, it was sent to SNRC, in Israel for tests with beam. Tests with beam will begin as soon as possible this year.

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