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THREE YEARS OF OPERATION OF THE SPIRAL2 LINAC: CRYOGENICS AND SUPERCONDUCTING RF FEEDBACK

P.-E. Bernaudin†, M. Aburas, M. Di Giacomo, A. Ghribi, P. Robillard, L. Valentin,
GANIL, Caen, France

Abstract

The superconducting LINAC of SPIRAL2 at the GANIL facility is in operation since October 2019. Its 26 superconducting quarter wave resonating cavities (88 MHz) are operated at a nominal gradient of 6.5 MV/m, but most of the cavities can be operated up to 8 MV/m. They are integrated into 19 cryomodules and cooled down at 4 K by a dedicated refrigeration cryogenic system.

In this paper, we will present a feedback after five years of operation of the cryogenic system, focusing on the main problems that have been faced, and on the diverse evolutions performed in order to improve the cryogenic system and to increase its reliability. We will also provide a feedback of the superconducting cavities performances status after three years of operation.

THE CRYOGENIC SYSTEM

Cryogenic System Overview

The SPIRAL2 cryogenic system is based on a HELIAL LT Air Liquide cold box. Fed by two Kaeser screw compressors, this cold box supplies 4 K liquid helium (1.3 kW) and 60 to 70 K helium gas to cool down cavities and thermal screens respectively.

The cryogenic distribution is composed of a 9 m long vertical line, linking the ground floor located cryoplant to the LINAC tunnel, and by 19 cryogenic valves boxes, connected one to the next to form the horizontal cryolines. Five valves per valves box supplies the cryogenic fluids to each cryomodule (2 valves for the thermal screen circuit, 2 valves for the liquid helium one, and 1 valve for the cryomodule cool down). Various non insulated, auxiliary lines are available for conditioning, warm gas collection, etc. For more details about the SPIRAL2 cryogenics system please refer to Ref. [1].

LINAC Cool Down

From 2017 up to today, the LINAC has been cooled down and warmed up once a year. Each cool down lasts three full weeks, plus a fourth week dedicated to thermalization of cryomodules and various controls and tuning operation. Hence the accelerator's cryogenics is in nominal configuration four weeks after the beginning of cool down.

As the niobium cavities have not been baked against the 100 K effect, the LINAC cool down is performed in a way that minimizes the time spent by each cavity in the 50-150 K temperature window. The temperatures of all the cavitiies are slowly decreased to 150 K, to allow homogeneous cool down of the cold mass, and once the 150 K threshold is reached, the process is accelerated as fast as possible. The acceleration is applied to only one cryomodule at a time, due to the volumetric flow rate capacity of the compression station and takes one full day per cryomodule. The volumetric flow rate capacity of the compression station limits the number of simultaneous fast cool down to one cryomodule at a time, so these phases shall be properly programmed to avoid any overlap.

Thermo-acoustic Oscillations (TAO)

The cryogenic operation has been hampered by two TAO (Taconis) issues since 2017 [2].

The cryoplant's main dewar (5 000 L) suffered from TAO once connected to the LINAC. This problem was detected early and easily solved using a dedicated buffer volume of a few litres.

More critical was the TAO that appeared on the cryogenic valves boxes. Positioned on the 5 K helium return line, it was detected only thanks to the cavity RF instabilities. A solution was hastily developed: the helium vessels inside the cryomodules were linked to the faulty connection point on the valves boxes using a warm line and a needle valve. This solution allowed RF operation, but it has some drawbacks; thus an alternative, more suitable solution based on a pre-tuned hydraulic RLC circuit, was developed in parallel with operation. After preliminary tests in 2021, it was installed early this year and successfully tested in July 2022.

Other Cryogenic Issues

The main cause of downtime over the last five years of cryogenic operation were linked to utilities. Several air utility failures were suffered, stopping completely the cryoplant. These failures were overcome thanks to upgrades performed on the GANIL air utility system in 2020; the cryogenic team is also working on a backup air supply system, to provide 2-hours autonomy to the cryoplant.

Main electrical power failures cause one cryogenic emergency stop per year. In particular, the cycle compressors are sensitive to voltage drops. Water refrigeration stops also caused several compression station trips.

In such cases, 3-5 hours are necessary to recover the LINAC's operational status from a cryogenic point of view.

During the five years of cryogenic operation, only two failures were caused by the cryogenic system, both in 2021. During the cool down, the cryoplant stopped. This stop was caused by mishandling of cryomodules cool down sequence by the cryogenics operators. During cold box restart, another operator mistake caused one turbine break. Thanks to the availability of spare turbines, the installation was quickly restarted with no impact on beam schedule.

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† bernaudin@ganil.fr

Later in 2021, the main cycle compressor stopped three times within 36 hours. The cause was the same each time: the disconnection of a wire to an internal temperature sensor. The problem was definitively fixed during the 2022 winter maintenance.

From a general point of view, cryogenics is a very minor source of beam downtime, as is evident from Fig. 1. To be fair, the dozen of downtime hours caused by the 2021 compressor station failure does not appear on these statistics because the beam was already down due to other reasons.

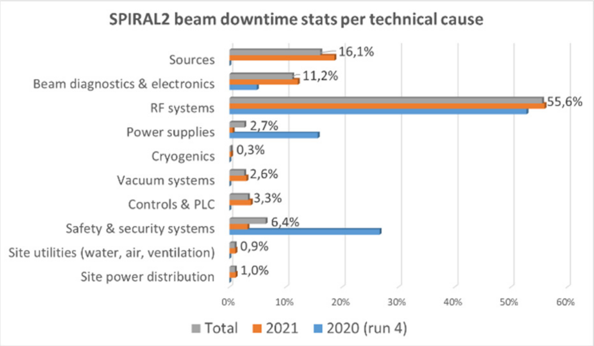

Figure 1: SPIRAL2 beam downtime statistics (in percent), classified by technical cause (in % of beam downtime).

Most cryogenic connexions, both in the cryomodules and between valves boxes, are CF flanges. Hence helium cold leak rates are a significant concern; they are monitored twice a year for each cryomodule and cryogenic lines vacuum section. The result of this monitoring is shown in Fig. 2. Over time, leaks tend to get more homogeneous (initially, leak tightness was much better inside high beta cryomodules, which is not the case anymore). Only one section (valves boxes section A) shows significant cold leaks. They remain manageable thanks to the dynamic pumping system, and only further diagnostic (localization) is intended in a near future.

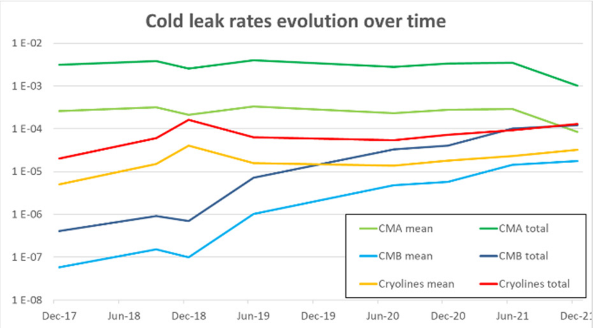

Figure 2: SPIRAL2 cryomodules and cryogenic lines cold leaks evolution. For each family (low beta cryomodules, high beta cryomodules, cryogenic lines), both the total leak rates and the mean leak rate values of the various volumes are shown (in mbar.L/s).

Advanced Control and Monitoring

The control of the diphasic helium bath pressure is the critical point of cryogenic stability. Available RF power margins require a ±5 mbar pressure stability. PID standard control proved unable to satisfy this requirement and thus advanced feedback, based on a linearized model and a LQ controller, was developed. Full details can be found in Ref. [3].

This modelling effort led to the development of a heat load observer. This virtual sensor computes in real time the helium mass flow in and out of each cryomodule, based on the various sensors and actuators. For more details, please refer to Ref. [4].

THE SUPERCONDUCTING CAVITIES

Performances and Evolution

Performances of the superconducting (SC) cavities are monitored on a yearly basis. Except cavity B13, all cavities can be operated at 8 MV/m since their installation on the LINAC. Cavity B13 limitation at 6.2 MV/m (quench gradient) predates its installation on the accelerator.

Figure 3 show the evolution of the cavities performances since their test stand acceptance. Table 1 show the total losses (RF and static evolution) over time.

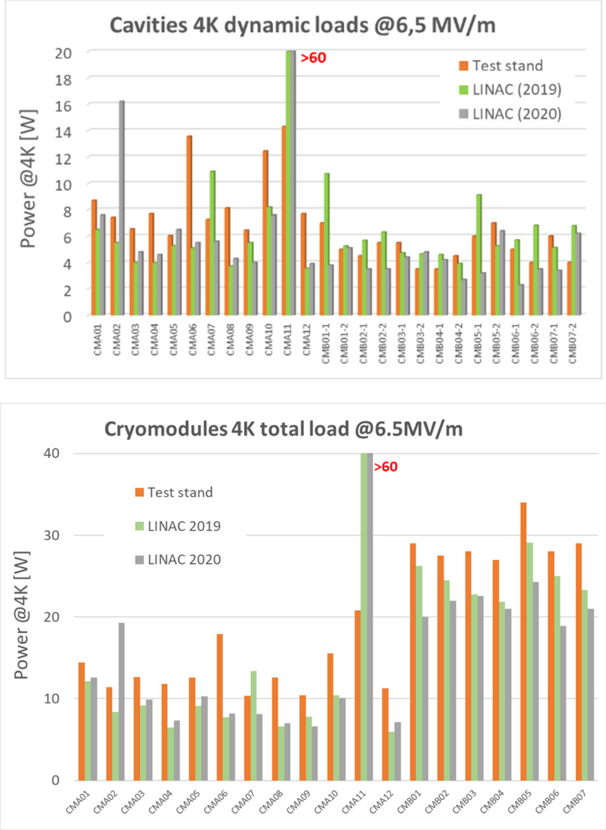

Figure 3: SPIRAL2 cryomodules deposited heat load at 4 K during acceptance tests, and on the LINAC in years 2019 and 2020. Top: dynamic loads for each cavity; bottom: total load for each cryomodule. Cavities at nominal gradient in both cases (6.5 MV/m).

The decrease of heat load from the test stands to the accelerator are the consequence of three factors: first, on the accelerator, static load was reduced thanks to the use of 65 to 70 K helium, instead of nitrogen, for the thermal screens of the cryomodules. Second, it appears clearly on the dynamic load graph that the low beta cavities heat load was significantly reduced, hence the result of RF conditioning. This conditioning effect is also observed between 2019 and 2020 for the high beta cavities. Lastly, calibration of the accelerating gradient is a significant source of error. All gradients have been calibrated using beam energy during the 2019 run, showing significant differences with the calibration values used since the acceptance tests.

Only cavity A2 shows a loss of performances since the beginning of operation; significant field emission is observed, with no consequence as it is only used at low gradient; all other (including A11) cavities performances remain stable.

Table 1: Total Cryomodules Load Evolution

Item	Test Stands	2019	2020
CMA (minus A11)	141.0	97.1	106.5
A11	20.8	>65	66.6
CMB	202.5	172.7	149.8
Total	364.3	338	322.9

A11 Cavity Issue

One cavity does not behave as the other ones: #11 low beta cavity's heat load at nominal gradient is extremely high. While the cavity was compatible to SPIRAL2 specifications when qualified on the tests stands, the dynamic load was measured around 65 W on the accelerator. Extended tests were performed in order to understand the origin of the problem. These tests allowed to locate the heat source on the lower section of the cavity. As the magnetic field zone is located on top of the cavity, this definitively proves that the issue is caused by a normal conducting area on the cavity. This cavity is slightly different from the other low beta ones: the sealing between the cavity itself and the removable bottom is different. It is therefore foreseen that the issue is linked to this sealing method. It is assumed that only a complete re-assembly in clean room might solve the issue. As the cavity runs steadily despite its high heat load, this operation is not foreseen in a near future. Only pressure control valve's flow coefficient (Kv) has been modified successfully to get more operational margin.

In Situ Helium Processing of B2 Cavity

X-ray field emission might be fatal to beam operation, even if it has no consequence on the cavity operational status. The accelerator Beam Loss Monitors (BLM) are used to tune the beam acceleration, but they can be blinded if the X-rays emitted by the cavities are intense enough. This phenomenon happened in 2021 on high beta cavity #2. It was therefore necessary to perform the first in-situ helium processing of a SPIRAL2 SC cavity.

Helium was injected inside the cavity using the FPC pumping port. RF parameters were progressively raised to:

- Cavity pressure: 1.2 10^{-5} mbar
- Peak field : 9.2 MV/m (peak)
- Pulses length : 3.5 ms
- Duty cycle: 35%

In less than 3 hours of such treatment, the BLM hits decreased from 2500 to 50 counts/sec at nominal gradient (6.5 MV/m).

Cryomodule Maintenance Perspectives

One site maintenance capacity is enhanced in parallel to regular operation. Early in 2022, the ISO5 GANIL clean room, its water treatment system and the operator's proficiency have been qualified. To do so, a low beta spare cavity has been prepared at GANIL (and tested at CEA Saclay, as the GANIL SC cavities test stand is not yet available). The performance of the cavity is the same as after the initial acceptance test, as shown in Fig. 4; hence GANIL has proved its capacity to treat SC cavities on-site. The same activity will be performed on a high beta cavity, in order to qualify the specific tooling and procedures.

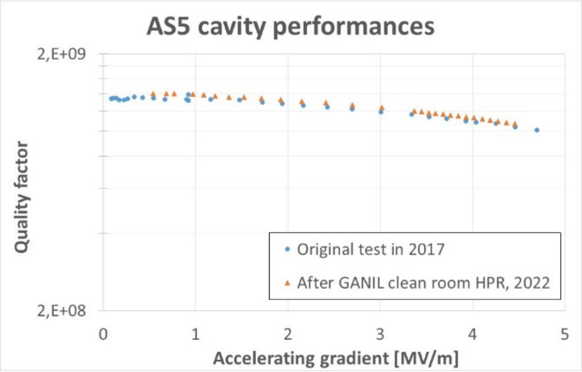

Figure 4: Spare low beta cavity performances upon reception and after HP rinsing in the GANIL clean room, 2022.

GANIL also participates to a national effort in order to develop a plasma processing apparatus, compatible with the SPIRAL2 LINAC. This work involves several accelerator (CEA/DACM, CNRS/IJC Lab) and plasma (IP Paris/LPP, CNRS/INSP) laboratories and the goal is to deliver an operational system late in 2024.

CONCLUSION

SPIRAL2 cryogenics system is running since 2017 and experienced no significant problem since. Work is going on in order to improve its stability and reliability, especially against potential TAO resurgences.

In the meantime, the 26 SC cavities are running with stable performances, apart from some field emission which remains low enough not to be a hindrance to beam operation, or weak enough to be helium processed in a few hours. GANIL is working to improve its maintenance and test capacity in case of significant cavity failure.

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