Spiral 2 Cryogenic System for The Superconducting LINAC

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Abstract. SPIRAL 2 is a rare isotope accelerator dedicated to the production of high intensity beams (E = 40 MeV, I = 5 mA). The driver is a linear accelerator (LINAC) that uses bulk Niobium made quarter wave RF cavities. 19 cryomodules inclose one or two cavities respectively for the low and the high energy sections. To supply the 1300 W at 4.2 K required to cool down the LINAC, a cryogenic system has been set up. The heart of the latter is a 3 turbines geared HELIAL®LF (ALAT²) cold box that delivers both the liquid helium for the cavities and the 60 K Helium gaz for the thermal screens. 19 valve-boxes insure cryogenic fluid distribution and management. Key issues like cool down speed or cavity RF frequency stability are closely linked to the cryogenic system management. To overcome these issues, modelling and simulation efforts are being undertaken prior to the first cool down trials. In this paper, we present a status update of the Spiral 2 cryogenic system and the cool down strategy considered for its commissioning.

1. Introduction
The GANIL’s SPIRAL 2 Project [1] aims at delivering high intensities of rare isotope beams by adopting the best production method for each respective radioactive beam. The unstable beams will be produced by the ISOL Isotope Separation On-Line method via a converter, or by direct irradiation of fissile material. The driver will accelerate protons, deuterons and heavy ions. It consists of high performance ECR sources, a RFQ, and the superconducting light/heavy ion LINAC. The driver is also asked to provide all the energies from 2 MeV/u to the maximum designed value (see Table 1). The SPIRAL 2 LINAC [2] is based on superconducting (SC), independently-phased resonators. In order to allow the required broad ranges of particles, intensities and energies. It is composed of two families of short cryomodules developed by CEA/Irfu⁴ (Saclay) and IN2P3/IPN-O (Orsay)⁵ teams. The first family is composed of 12 quarter-wave resonators (QWR) (one cavity/cryomodule) optimized for $\beta_0 = 0.07$ relative velocity, and the second family of 14 QWR (two cavities/cryomodule) optimized for $\beta_0 = 0.12$. Resonance frequency is 88.0525 MHz and maximum gradient in operation of the QWRs is

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\[ E_{\text{acc}} = V_{\text{acc}}/\beta_\lambda = 6.5\, MV/m. \] Developed by IN2P3/LPSC (Grenoble), the RF power couplers shall provide up to 12 kW continuous wave (CW) beam loading power to each cavity. SPIRAL2 superconducting cavities will operate at liquid helium temperature. The total refrigeration power for the cavities (1300W@4.3K) and for the thermal screens (3000W@60K) is provided by a HELIAL LF refrigerator (see sec. 2).

2. Cryogenic System Overview

The cryogenic system of Spiral 2 [3] can be divided into two main parts:

- **Production**: This is the cryoplant where most of the refrigeration thermodynamic cycle occurs.
- **Operation**: This includes the cryodistribution and the cryomodules/cavities in the LINAC where most of the thermal load is localised.

### 2.1. Cryoplant

The cryoplant is centred on a Helial LF cold box. The latter is LN\(_2\) pre-cooled and 3 turbines geared (two for the Brayton cycle and one for the last stage expansion)[4]. It uses two Kaeser compressors and two oil removal systems that deliver up to 90 g/s at 16 bar\(_{\text{abs}}\) to the high pressure circuit. The low pressure circuit is at 1.05 bar\(_{\text{abs}}\). For the helium phase separation, a 5000 L dewar is used. As part of the cryoplant, a recovery system is operated independently. It controls the recovery of impure helium, its compression at 200 bar\(_{\text{abs}}\), its storage and its purification before re-injection into the main cycle. It also controls the distribution of LN\(_2\) and GN\(_2\) to the different Spiral 2 facilities.

### 2.2. Cryodistribution

The cryodistribution system of Spiral 2, represented in figure 1, has different purposes depending of the operating cryogenic modes of the accelerator. It allows, in chronological order, to:

1. Condition, pump and purge the different cryogenic subsystems.
2. Efficiently cool down the LINAC’s superconducting cavities.
3. Manage the cold returns either through the main refrigeration cycle or the GHe recovery system.
4. Ensure stable operating conditions of the accelerator (pressure and temperature stability of the cavities).
5. Efficient cryogenic modes transitions without creating an important unbalance of the GHe refrigeration cycle.
6. Efficient warm up of the accelerator.

The first component of the cryodistribution system is a connection box. It represents the interface between the cryoplant and the LINAC’s superconducting cavities. It connects to the LHe dewar through a cryogenic coaxial line (for LHe transfer) and to the cold box through a tri-tube cryo-line. The latter insures feeding the thermal screens of the cryomodules (60 K) and the cold returns (both 80 K and 5 K). After the connection box, a 7 m long funnel transfers the cryofluids to the 4 branches central valve-box. The central valve-box re-distributes He in three directions, to the 13th cryomodule (in the beam direction) and to the neighbouring 3 branches valve-boxes.

The valve-boxes are vital components of the cryodistribution. They are equipped with 5 cryogenic valves. Their detailed role is described in more details in section 3.4.

The isolation vacuum of the cryodistribution system is divided in three independent regions. The connection box, the funnel and the central 4 branches valve-box share a common isolation
vacuum. In the LINAC, east and west side valve-boxes have respectively two common isolation vacuum volumes (see Figure 1). Every cryomodule has its own isolation vacuum.

![Cryodistribution system overview](image)

**Figure 1.** Cryodistribution system overview

### 2.3. Cryomodules & Cavities

Design of both cryomodules and cavities families [5] has been performed independently in two different laboratories, with only minimal standardization (power couplers being one of the few common components). One of the most important differences that should be mentioned is the design of the frequency tuning system. For the high beta family, a plunger introduced in the cavity changes the resonance frequency to the required value. For the low beta family, the frequency tuning is achieved by compressing the cavity, hence introducing a risk that has to be managed properly. All cavities were tested in a vertical cryostat (VC) and achieved the specified requirements, both in terms of gradients and of quality factor. All cryomodules were tested individually on dedicated test benches [6]. From a cryogenics point of view, all cryomodules but one are consuming less cryogenic power than the project objectives. Static cryogenic losses estimation proved to be very reliable for low beta cavities. The best cryomodule is performing exactly to the computed values, while the average cryomodule is less than one third above. Performances are further from the expectations for high beta cryomodules, but they remain below the target value thanks to the low RF consumption of the cavities.

### 3. LINAC Pre-commissioning & Commissioning

#### 3.1. Cryoplant commissioning

The Spiral 2 cryoplant has been commissioned independently from the cryomodules. In order to do that, it was necessary to artificially mimic the cavities and the screens thermal loads.

For the thermal screens, a simulator has been installed at the ColdBox interface to the LINAC. The simulator includes a heat exchanger exchanger that delivers an equivalent load of 3000W at 60K to HP circuit thanks to 10 distributed high-load cartridge heaters. A valve allows to control the gas flow and 3 temperature transmitters complete the control system at the input and the output of the exchanger.

The thermal load at 4.3K required by the cryomodules cavities and instrumentation is simulated by a heater in the liquid helium dewar. It delivers a maximum equivalent power of 1500W.

Three main modes of operation have been tested to approve the cryoplant for the next steps. They are described in table 1. Mode 1 that corresponds to the maximum capacity of the cold box was expected to deliver 1100 W at 4.3 K, 3000 W at 60 K and an additional Helium liquefaction
Table 1. Modes of Spiral 2 commissioning tests: Requirements and measurements.

|                | Mode 1 | Mode 2 | Mode 3 |
|----------------|--------|--------|--------|
| **Load** cav [W] | 1100   | 370    | 553    |
| **Load** scr [W]  | 3000   | 1500   | 1500   |
| $P_{dewar}$ [bar abs] | 1.3 ± 0.02 | 1.3 ± 0.007 | 1.3 ± 0.005 |
| $LT_{dewar}$ [L/h]  | 10     | 68     | 0      |

of 10 L/h. The result was a liquefaction of 68 L/h. Modes 2 and 3 mimic the thermal behavior of the capacities respectively in the static and the dynamic configurations (maximum RF loaded). These two latter modes have been tested for stability of operation and showed a good agreement with the specifications.

![Figure 2](image1.png)  
**Figure 2.** Results of the commissioning of the Spiral 2 cryoplant in mode 1 (1100 W in the LHe dewar and 3000 W at 60 K). Left: Pressure stability in the dewar. Right: LHe level in the dewar.

3.2. Command and Control System

Cooling down the Spiral 2 superconducting LINAC and maintaining the cavities in optimum conditions for the required operations strongly depend on the command and control system. This system allows to monitor the different sub-systems of the cryogenic setup, to manage the different modes of cryogenic operation and to communicate with other automation systems such as of vacuum and radio-frequency.

3.2.1. Architecture  The architecture, represented in figure 3, is centred on the Concentrator PLC. The concentrator communicates with different automation systems including but not limited to:

- Type A cryomodule PLC: Manages a type A cryomodule with its matching valve-box.
- Type B cryomodule PLC: Manages a type B cryomodule with its matching valve-box.
- ColdBox PLC: Manages the LHe refrigeration system
- Helium recovery PLC: Manages the recovery system
- Other systems: security, vacuum, RF
Figure 3. Command/Control architecture layout of the Spiral 2 cryogenic system. (1) CABTF Microbox for temperature acquisition — (2) Motor Brushless for cavity frequency tuning — (3) MKS isolation vacuum gauge measurement box — SCADA : Supervisory Control and Data Acquisition — HMI : Human Machine Interface.

It also manages most of the cryodistribution system (excluding the valve-boxes) and the isolation vacuum for the cryodistribution (including the valve-boxes).

3.2.2. Modes of operation

There are different modes of operation:

- Warm Mode: This is the mode where most of the preliminary verifications prior to the cool down mode happen.
- CoolDown Mode: This is the mode where the screens and the cavities cool down sequences described in subsections 3.5 and 3.4 are triggered.
- Normal Mode: In this mode, temperature and pressure parameters for the cavities are within the specifications. Authorisations for RF and beam operation are given.
- Dewar Mode: This mode corresponds to a ColdBox Fault. Operation rely only on the LHe dewar during a limited amount of time that depends of the LHe level in the dewar.
- Safe Mode: In this mode, frequency tuning system is brought to its safe position in order not to break the cavities during accidental warm up. This mode is also triggered for a number a faults that prevent the operator to monitor or operate the system.

3.3. Cryomodules & Valve-boxes installation

Cryomodules and Cryo-valve-boxes are installed in the LINAC tunnel according to the following sequence:

(i) Cryomodule installed in position $P_i$
(ii) Cryomodule in position $P_i$ is checked by survey beam
(iii) Matching valve-box is installed and connected to cryomodule $P_i$ and to neighbouring valve-boxes.
(iv) Cryomodule and valve-boxes isolation vacuum are leak checked
(v) Cryo-connections are leak-tested and pressure-checked
(vi) Instrumentation control procedures: Temperature transmitters, level transmitters, pressure transmitters, heaters, other electrical connections, cavity RF parameters, safety devices, etc...

Once a minimum of two cryomodules is correctly installed, room temperature inter-cryomodule sections are inserted and connected to the cryomodules on both sides. This connection is critical as it may cause a pollution of the cavities through the beam tube vacuum, and hence degrade its performances. Therefore, it is performed under a portable laminar flow (ISO5 class cabin) by specially trained personnel. These connection procedures have been prototyped in real conditions on one high beta cryomodule.

3.4. Single Cryomodule cooldown approach

Both types of cryomodules have been tested with prototype valve-boxes. Thermal screens were cooled with LN$_2$ and the cool down of cavities was either slow or fast for system approval [6]. This approach is not adapted for cooling the superconducting LINAC. Therefore, a new strategy that takes into account the different operation constraints shall be considered. This approach is introduced in a “single-block” cool down and discussed in further details for the LINAC in subsection 3.5. Taking as an example a high-$\beta$ cryomodule (same single-block cooling down approach as low-$\beta$), different steps are required in order to achieve stable cryogenic operation conditions. These steps are represented in figure 4 and described here below :

(i) Thermal screens and RF couplers cooldown : While the thermal screens temperature $TT_{11} < 80\,K$, both feeding valve $FCV_{010}$ and return valve $FV_{011}$ are open with $FCV_{010}$ at fixed value (non regulated). Once $TT_{11}$ reaches 80 $K$, $FCV_{010}$ becomes regulated to maintain thermal screen temperature around 80 $K$.

(ii) Magnetic shield, RF couplers and cavities cooldown : We begin filling the cavities from the bottom in order to take advantage of cold He vapors to cooldown the top. At this stage both $FCV_{001}$ (LHe input) and $FCV_{005}$ (cold return) are open at 100%. Once the cavities temperature is below 8 $K$, we open $FCV_{002}$ at 100% while maintaining $FCV_{001}$ and $FCV_{005}$ open.

(iii) Level and pressure regulation : When the level transmitter $LT_{200}$ on the phase separator indicates a non zero value, we close $FCV_{001}$ and regulate $FCV_{002}$ on $LT_{200} = 40\%$. Once the instruction is achieved, $FCV_{005}$ is regulated on $P_{cav} = 1.3\,bar_{abs}$.

Part of stage (i) and stage (ii) can be simultaneous in order to achieve a cooling down time between 160 $K$ and 40 $K$ in less than four hours and therefore avoid the $Q$ disease [7].Cooldown time between 20 $K$ and 4.3 $K$ is also optimised in order to favor slow cooldown for the superconducting transition.

3.5. LINAC cooldown strategy

Cooling down the superconducting LINAC is not a simple replication of the tests splash cooling of the cavities, nor is it a replication of the single-block approach described in subsection 3.4. In fact, multiple parameters have to be taken into account. Some of them are specific to the cavities. Others are related to the environment (LINAC and cryoplant). Before starting the cooldown, some preparatory parallel actions have to be undertaken :

- Automation and control functional verifications
- Piping Helium conditioning
- Isolation vacuum pumping
When all the subsystems are verified, the cooldown of the cryodistribution system starts. As it can be seen in figure 1, a circulation of cryofluid requires us to go through the two edge cryomodules. The procedure, described in subsection 3.4, is then engaged first for the left part and then for the right part of the LINAC cryodistribution system. For every part of the circuit, we begin with the $60/80 \text{K}$ circuit and then finish with $\text{LHe}/5 \text{K}$ circuit.

When the cryodistribution is thermalised and the two edge cryomodules are in LHe regulation mode, we start cooling down the next cryomodules two by two. We start by cooling down the thermal screens for two cryomodules. When they are at $80 \text{K}$ we begin cooling down the cavities and engage the thermal screens cooldown for the next couple of cryomodules.

An important detail of the operation is the transition from stable refrigeration conditions for part of the system to a sudden increase of the heat load when cooling down the next part. As helium cryogenic refrigeration is based on constant flow, we compensate the unbalance for every step-transition by predictively increasing the heat load on the dewar. Therefore, we stabilise

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6 At this stage of development, the actual choice of beginning by the left or by the right part of the cryodistribution line is random.

7 One type A and one type B six successive times and then all the remaining type A at once.
the system to a virtual load before transitioning to a real thermal load when engaging a new cooldown of another part of the system. It is obvious that the predictive simulated load on the dewar requires careful calculations. The first cooldown will also bring important data to optimise the described procedure.

In order to optimise the cooling down strategy, modelling efforts are being undertaken using the SymCryogenics library for Matlab/Simulink [8]. The coldbox has already been successively modeled and efforts to model the cryodistribution and the cryomodules are ongoing. When built, the model will help predictively adapt the operating parameters in order to maintain a stable pressure in the cavities. Cascade of instabilities will be some of the effects we will look forward to understand when facing real data with modelling results. It is foreseen to apply the optimised methods obtained to systems like EURISOL[9] where more stringent LINAC operation conditions will be required.

4. Conclusion

More than 10 years of work by hundreds of technical and non technical staff in multiple institutes have been necessary for the completion of the system. Cryogenics is obviously vital for its operation at the expected energies. Previous experiences with large refrigeration systems have shown that medium sized systems like Spiral 2 are not to be under-estimated. The next months will therefore be very important for the final cryogenics commissioning. Spiral 2 will also be one of the step-stones that will hopefully pave the road for even more ambitious projects like EURISOL, where cryogenics will be as essential as for Spiral 2.

4.1. Acknowledgements

This work has been funded by ”Region Normandie” as well as the city of Caen, CNRS and CEA. We would like to thank all contributors from CEA-IRFU, CNRS-IPNO, IFJ-PAN (Krakow) and GANIL without whom fabrication/approval of the cryomodules and the valve-boxes and integration in the Spiral 2 LINAC beam line would not have been possible. We also would like to thank F. Bonne and P. Bonnay (SBT/CEA) for the SymCryogenics library that is being used for optimisation of the cool down strategy of the Spiral 2 LINAC.

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