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Design of operation logic for SCL3 cryogenic distribution system for RAON

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Abstract

The operation mode, sequences, and logic of the cryogenic distribution system for Superconducting Linac 3 of RAON are described. The systematic construction of the cryogenic distribution system is introduced, and the roles of transfer lines and instruments are explained. The flow of operation modes and the operation strategies in each operation mode are designed with consideration of the system structure, the requirement of the cryogenic system, and the cryogenic fluid properties. The operation modes are grouped into cool-down process, warm-up process, and steady states in normal operations. The step-by-step operation sequences of the instruments in each operation mode is clarified. In the cryogenic distribution system of RAON, the thermal shield circuits for all cryo-modules are cooled down concurrently, and the fluid mass flow rates are controlled by using virtual flow meters. The most important tasks during the cool-down process of the superconducting cavities are to shorten the cool-down time and keep the steady and low pressure inside the cavities. The cold helium circuits (the SHe, GHe, and VLP lines) are cooled down one by one for the cryo-modules from 300 to 4.5 K. After that, all the HWR cavities are pumped down to 36 mbar at the same time to further cool down to 2.05 K. The warm-up process from 2.05 to 4.5 K is operated without emptying the reservoirs. The cryogenic plant and the CDS are warmed up together by circulating the helium gas.

Keywords Cryogenic system · Control logic · Liquid helium · Accelerator cavity · RAON

1 Introduction

The rare isotope accelerator complex for online experiments (RAON) is a heavy-ion accelerator facility, which is under construction in Daejeon, Republic of Korea. RAON is equipped with various experimental facilities that support the exploration of challenging basic science fields such as nuclear science, atomic and molecular science, physical science, and biomedical science.

RAON is the first accelerator facility that combines an isotope separation online (ISOL) system and an in-flight fragmentation (IF) system. The schematic diagram of RAON is shown in Fig. 1. In the ISOL system, proton beams are accelerated by the cyclotron to 70 MeV and collide the ISOL target with 70 kW of beam power to generate rare isotope (RI) beams. Then, the RI beams are accelerated by the post accelerator, super-conducting linac 3 (SCL3) to 18.5 MeV/u, which can be applied to the low-energy experiments or further accelerated through SCL2 to perform the high-energy experiments. In the IF system, the heavy ion beams injected by SCL1 or SCL3 are further accelerated by the driver linac, SCL2, then collide with the IF target to generate RI beams. SCL1/SCL3 and SCL2 are designed to accelerate uranium to 200 MeV/u (proton to 600 MeV) with 400 kW of beam power. The requirements of the RAON accelerator system were described by D. Jeon et al. in detail [1].

SCL1 and SCL3 are designed as the same configuration, which accelerate beams with 22 quarter-wave resonators (QWRs) and 104 half-wave resonators (HWRs). On the other hand, SCL2 consists of two kinds of single-spoke resonators (SSRs), which are named as SSR1 and SSR2 in RAON. 69 SSR1 are followed by 150 SSR2 in SCL2. The resonant cavities are made of Nb material, which has the critical temperature of 9.2 K. Thus, the cavities are installed in cryo-modules (CMs) and are maintained as 4.5 K (QWR)

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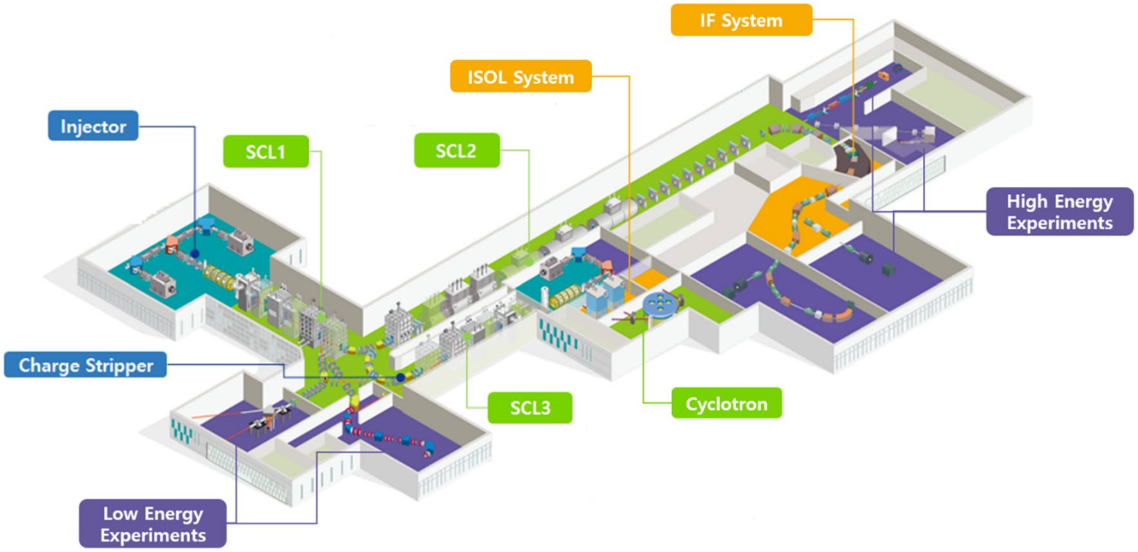


Fig. 1 Main constructions of RAON facility

and 2.05 K (HWR and SSR) in operation by helium bath cooling.

There is a respective cryogenic system for each superconducting linac. Each cryogenic system consists of a cryogenic plant (CP), a cryogenic distribution system (CDS), and CMs. The CP is in charge of helium refrigeration and recovery. The CDS delivers the cryogenic fluids to CMs, which supply the cryogenic environment for superconducting cavities. The cryogenic plant is required to cover the static heat load of the cryogenic system and the dynamic heat load from the radio frequency (RF) power and the beam losses. The designed parameters of the CPs for SCL2 and SCL3 have been introduced by Yoon et al. [2, 3]. The CP, CDS, and CMs for SCL3 have been installed so far, and the commissioning of SCL3 is under preparation.

This paper aims to introduce the operation modes, sequences, and control logic of CDS for SCL3, which is an essential part of operating the cryogenic system. It requires well understand of the characteristics of the cryogenic fluid and engineering know-how for handling a large-scale cryogenic fluid system to design a safe, reliable, and energy-efficient CDS operation logic.

The requirements of the cryogenic system and the technical challenges the engineers face in designing and operating the CDS of superconducting linac, such as ESS linac and SPIRAL 2 linac have been reported [4, 5]. However, the step-by-step operation sequences and control strategy of the instruments have not been published yet. Compared to these linacs, there are two main differences in the structural characteristics of RAON so we designed a unique operation logic for RAON. One is that we have much more valve boxes and cryo-modules with respect to larger heat loads during the chill-down process. On the other hand, the cavities require a fast cool-down from 150 to 50 K temperature regime. For these reasons, we have to cool-down the CMs one by one for stable operation. Additionally, the heaters that are installed on the reservoirs in the CMs and the end box are used to smooth the wide mass flow rate change.

In this paper, the operation sequence and the controlled parameters in each operation mode will be described, and the consideration for the design of CDS operation logic will be discussed. Moreover, the readers will find the ideas, such as the virtual flow meter concept to control the mass flow rate, the valve operating method to control the cool-down time, and the consideration of the temperature stratification during the warm-up process.

2 CDS FOR SCL3

The structure of the cryogenic system for SCL3 is illustrated in Fig. 2. The CDS includes a helium distribution box (DBx), the main transfer lines, the sub-transfer lines, the valve boxes (VBxes), and an end box (EBx). The DBx is a valve box that controls the connection between the CP and the CDS for various SCL operation modes. When SCL3 is operated separately, the DBx will connect the SCL3 CP to SCL3 CDS and disconnect SCL1 and SCL2 by valve control. The main transfer lines deliver helium to valve boxes, and the sub-transfer lines transfer helium from the VBxes to CMs. The VBxes are used to control the helium flow to the CMs. The EBx is the return point of the main transfer line.

As mentioned in Sect. 1, there are 22 quarter-wave resonators and 104 half-wave resonators in SCL3. The resonant cavities are installed in three different types of CMs: QWR, HWRA, and HWRB. A QWR cavity is installed in

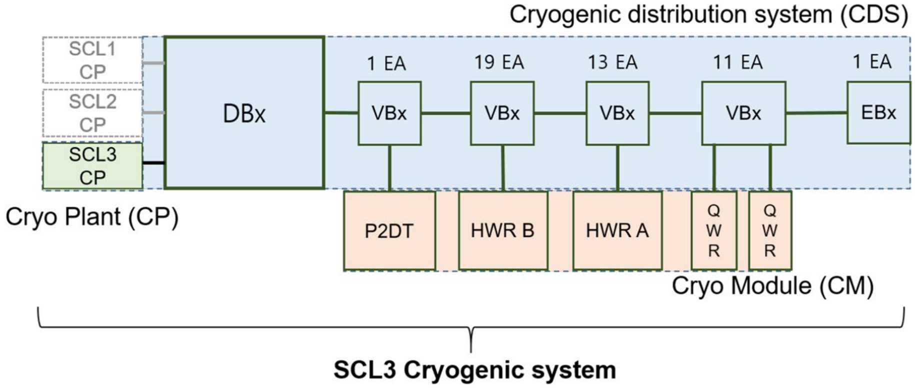


Fig. 2 Structure of cryogenic system for SCL3

Table 1 Number of cryo-modules and resonant cavities in SCL3

Type of CM	P2DT	HWRB	HWRA	QWR
Type of resonators	HWR			QWR
No. of CM	1	19	13	22
No. of cavity in each CM	2	4	2	1
Total No. of cavity	2	76	26	22

each QWR CM, and two QWR CMs are controlled by a QWR VBx as shown in Fig. 2. The difference between the HWRA and HWRB is the number of cavities: two cavities in an HWRA CM and four cavities in an HWRB CM, and P2DT is identical to HWRA. The numbers of CMs and cavities in SCL3 are summarized in Table 1.

The schematic diagram of the SCL3 CDS and CMs is depicted in Fig. 3. The configuration of DBx, VBx, CM, and EBx can be seen in the figure. As shown in the figure, the helium flows are circulated between the CP and the CDS by the main transfer lines. The main transfer lines include a thermal shield supply (TSS) line, a thermal shield return (TSR) line, a sub-cooled liquid helium supply (SHe) line, a helium gas return (GHe) line, and a very low-pressure return (VLP) line. The TS lines are used to cold down the thermal shields in the vacuum chambers to around 50 K by high-pressure cold helium gas. The sub-cooled liquid helium is supplied to the SHe line, and the vaporized gas is returned through the GHe and VLP lines. The VLP line is evacuated to 32–36 mbar to cool down the HWR cavities to 2.05 K.

Additionally, there are other transfer lines that are used in some transient states or in emergency cases. The warm

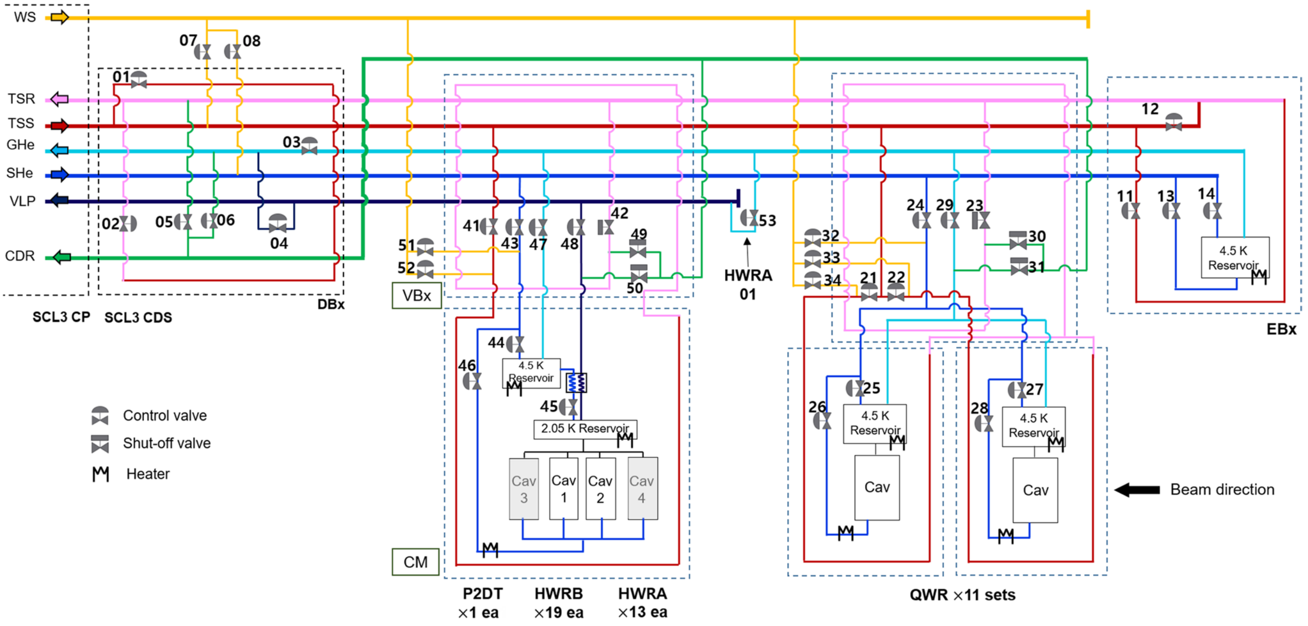


Fig. 3 Schematic diagram of SCL3 CDS and CMs (SCL3 CP to SCL3 CDS connection case). *Two cavities in HWRA and P2DT cryo-modules; four cavities in HWRB cryo-modules

supply (WS) line supplies the room temperature helium to warm up or purge the system in some operation modes by opening the control valves in each subsystem (V07, V08; V32, V33, V34; V51, V52). The cool-down return (CDR) line is designed to return the helium gas in the cool-down process or in emergency cases by controlling the cool-down return valves (V05, V06; V30, V31; V49, V50). Moreover, there is a safety line to release pressure in emergency cases, which is omitted in the figure. As the construction of the safety system hardware is complicated, it will be introduced separately in future work. The conditions of the transfer lines in normal operating of SCL3 are listed in Table 2. In the normal operating state, the WS, CDR, and safety line are disconnected from the main flow lines, and the valves on these lines are closed.

When SCL3 CP and SCL3 CDS are connected, the configuration of DBx can be simplified as shown in Fig. 3. V01 and V02 controls the helium gas flow to the thermal shield of DBx; V03 distributes the return flow to the GHe line and VLP line with V53 in the first HWRA (HWRA01) VBx; V04 is used to return the helium gas in the VLP line through the GHe line to the CP.

The role of EBx is to bypass the extra helium flow to maintain the stable operation of the cold box (CBx) and the CDS. On the liquid helium circuit, the mass flow that supplies and returns to the CBx can be balanced by vaporizing the liquid helium in the reservoir in EBx when the CBx is operated as the liquefaction mode. The by-pass line on the thermal shield circuit, where V12 is installed, ensures adequate helium gas flow to the thermal shield circuit in the main transfer lines, and the by-passed helium gas is used to cool down the TSR line and the thermal shield of the TSR line.

The configuration of the QWR and HWR VBxes are similar to each other. There is an inlet valve (or an outlet valve) in each distribution line to the VBx. However, there are two main differences between them. First, the VLP line is only in the HWR VBx because the target temperature of the HWR cavities is 2.05 K. Second, the TSS and SHe lines in QWR VBx are divided into two substreams; on the other hand, the TSR and GHe line from the two CMs are converged in the VBx. Thus, V21 and V22 control the helium flow to the two CMs. There is one inlet valve, V24, on the SHe line because the flow rate to each CM can be controlled by the valves in the CM (V25, V26, V27, V28).

Table 2 Condition of transfer line in normal operating of SCL3

	Temperature (K)	Pressure (kPa)
Cold helium supply (SHe) line	4.5	300
Helium gas return (GHe) line	5	125
Very low pressure (VLP) line	4	3.2–3.6
Thermal shield supply (TSS) line	35	1500
Thermal shield return (TSR) line	55	1450
Warm supply (WS) line	300	300
Cool-down return (CDR) line	4.5–300	105
Safety line	4.5–300	< 130

In each QWR CM, a liquid helium reservoir is installed on the top of the cavity to make sure the liquid helium jacket is fully filled with the liquid helium. In each HWR CM, a 2.05 K reservoir is on the top of cavities. For cooling down the HWR cavities to 2.05 K, the liquid helium in a 4.5 K reservoir is expanded up to 36 mbar in the 2.05 K reservoir through the JT valve, V45, and the cavity is submerged in the superfluid helium.

3 Operation logic

3.1 Design of operation mode

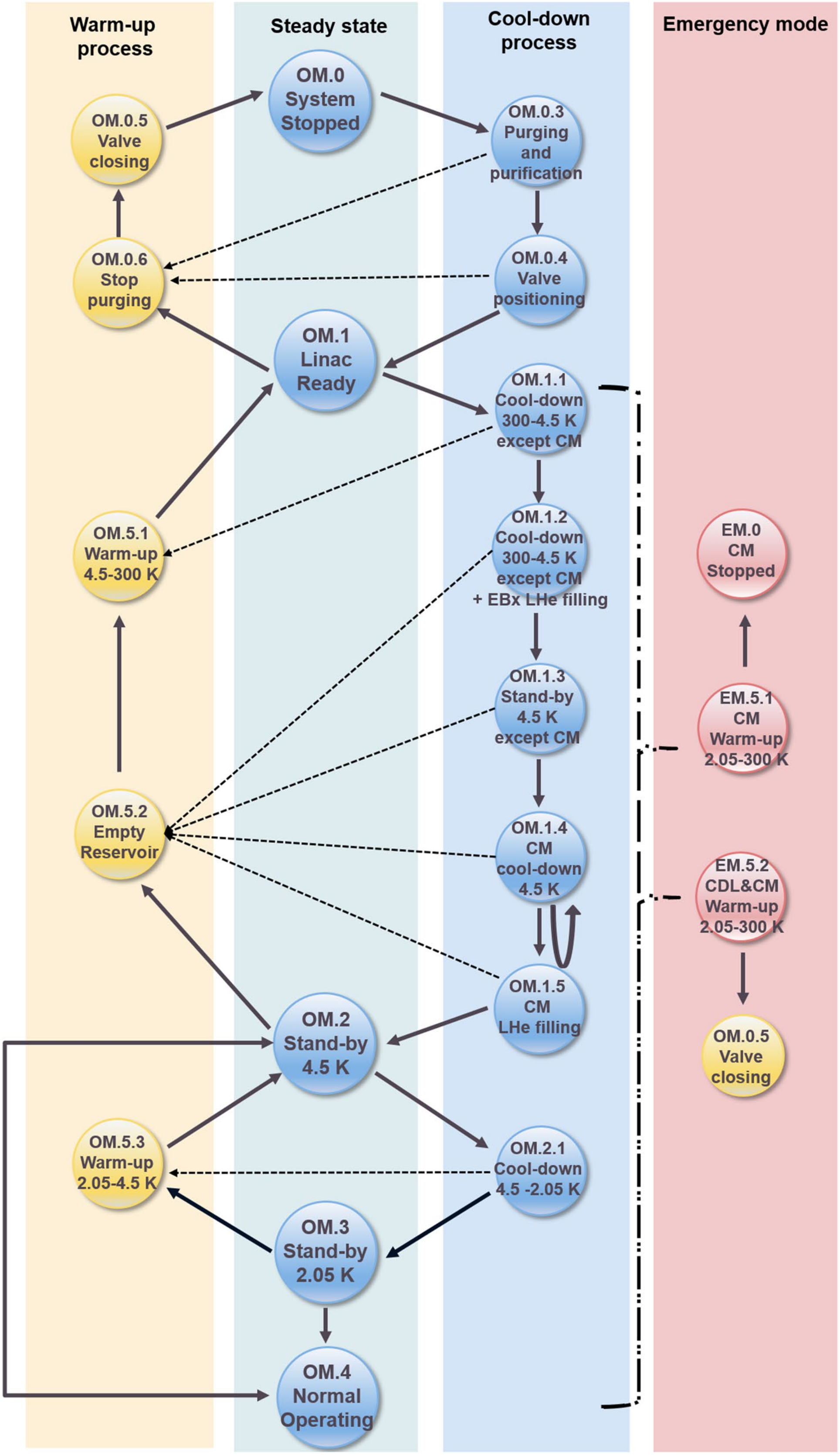
It is a big challenge to operate the cryogenic system of RAON because of the complicated structure of the CDS and the extreme conditions that the system requires for cool-down, warm-up, steady-steady operations, etc. To operate the CDS system safely and efficiently, the operation process is distinguished as various operation modes, and the operation logic for each operation mode is designed.

Figure 4 exhibits the overall operation modes and the operation sequences. The operation modes can be classified into steady modes and transient modes. The transient modes include the cool-down process and the warm-up process. Nevertheless, the emergency mode is defined to cope with the accident occurred during the operation. The operation mode moves in the direction of the arrow. The solid line represents the normal operation case. The dotted line that points to the warm-up process is a special case that the operator actively decides to warm up the system when the cryogenic system is in the normal operation condition, which is different from the emergency mode.

Two emergency modes are defined here. In EM.5.1, a certain CM is in a failure mode and needs to be warmed up, and the other parts of the cryogenic system are still in normal operating condition. In EM.5.2, the pressure of the cryogenic system is released, and the entire system is warmed up to stop the cryogenics system safely. The emergency mode is manually determined by the operators.

This flow chart only reflects the requirements of the cryogenic system. The signals from other systems like the global safety and protection system, RF system, beam delivery system, and the experimental system should be also received to determine the operation mode. For example, when the operation mode moves from OM.0.4 to OM.1, not only the finish of the valve positioning but also the completion of RF conditioning at the room temperature and control system

Fig. 4 Design of operation modes and sequences for SCL3 CDS



ready, etc. are required. The OM 0.1 is for the instrument check and OM 0.2 is for the vacuum check. In this paper, they are not discussed because they are the normal processes before the start of operation.

3.2 Control logic and sequence in each operation mode

3.2.1 OM.0.3 purging and purification

This process is to purge the transfer lines in the cryogenic system and purifies the helium flows that circulate in the CBx and CDS. This mode is operated through the following steps: valve ON, pressurization, flow circulation.

At the beginning of OM.0.3, the valves in CDS are all closed, and a pressure gap may occur between the inlet and outlet of the valves. To decrease the risk in a pressurized system, it is necessary to equalize the transfer line pressures in CDS and CBx by valve opening before circulating the flows. The cryogenic valves should be opened slowly when there is a large pressure or temperature difference between the inlet and outlet of the valves. In our case, all of the valves on TS lines are opened before the pressurization process, but the valves on the cold helium circuit of VBxes, CMs, and EBx keep closed because of the different pressures of the supply line and the return line. The TSS and TSR lines need to be pressurized to 15 bara, and the SHe line and the GHe line need to be pressurized to 3 bara and 1.3 bara, respectively.

The flow circulation starts, once the pressurization is finished, and the pressures are stable in the CDS. When purging the cavities and the reservoirs, it should carefully control the valve opening to keep the pressure of GHe and VLP lines under 1.3 bara. One of the biggest challenges in operating the CDS is to manage the helium mass flow rate to each subsystem. It is important not only in the purging process but also in the overall cool-down process. To supply the required helium flow to each subsystem, we use the virtual flow meter (VFM) to monitor the helium flow rates. Arpaia et al. reported the calculation method of the virtual flow rate of helium flow [6, 7].

OM.0.3 ends when the measured purity in the cold box is lower than the standard value, and the other parameters like pressure, temperature, mass flow rate, vacuum, etc. are in normal condition.

3.2.2 OM.0.4 valve positioning

OM.0.4 is the preparation mode of OM.1.1. Before the cool-down process, the CBx circulates the room-temperature helium.

In OM.1.1, the main transfer lines, EBx, and the thermal shield lines in all vacuum chambers will be cooled down at the same time. Thus, the valves on those lines should keep open and be controlled. The cooldown of the cold helium lines of VBxes and CMs will start in OM.1.4; therefore, the valves on the cold helium lines (V24–29; V43–38) should be closed.

There are some valves that need valve opening regulation. The 4.5 K reservoir of EBx is cooled from the bottom of the reservoir, so the valve opening of V13 and V14 should be increased and decreased, respectively. V12 also needs to be regulated to get sufficient helium flow to cool down the TSR line. V04 and V53 are opened to cool down the VLP line and return the warm helium gas through the GHe return line, and the VLP is disconnected with the CBx. The valves on the cold helium circuit of VBx and CM are closed to separate the CMs from the main transfer lines. The phase ends when the valve openings are in the right position.

3.2.3 OM.1. linac ready

After the valve positioning in OM.0.4, if the helium flows keep in a steady state, the CDS system will be in the state of ready to cool down. The signal is sent to the main control system of RAON where the states of all the systems in RAON are monitored. If all the systems are ready, the cool-down process will begin manually.

3.2.4 OM.1.1 Cool-down 300–4.5 K except CM

In this mode, the cool-down process of the CBx, CDS, and thermal shields of CMs will start at the same time. Thus, the supply temperature of CBx changes from 300 K to the final steady-state temperature, and the mass flow rates also change during the transient process. This is the main reason for cooling down the CMs separately since the cavities need to be cooled down quickly to avoid hydrogen trapping, which decreases the performance of the cavity. The final goal is to cool down the inlet temperature of TSS as 35 K, the outlet temperature of TSR as 55 K, the inlet temperature of SHe as 4.5 K, the outlet temperature of GHe and VLP as 5 K, and the temperature of thermal shields to approximately 55 K. The cool-down process will continue in OM.1.2. OM.1.1 finishes when the 4.5 K reservoir in EBx is cooled down to 4.5 K, and 10% of the liquid helium level is observed in the reservoir.

3.2.5 OM.1.2 Cool-down 300–4.5 K except CM + EBx LHe filling

OM.1.2 is the continuous mode of OM.1.1. The cool-down strategy is the same as that in OM.1.1 except the cold helium line in EBx. When the liquid helium level in the 4.5 K reservoir of EBx is higher than 10%, the valve opening of V14 is increased to fill the liquid helium, and the cool-down valve, V13 is closed.

It should be noticed that in this case the CBx is in the liquefaction mode, which means the mass of helium gas returned through the GHe line is less than that of the liquid helium supplied to the CDS. Increasing the helium gas flow to the return line is beneficial not only to improve the performance of the CBx but also to cool down the gas helium return line (GHe and VLP lines) more efficiently. Thus, an electrical heater is installed in the reservoir, and it is operated when the liquid helium level is observed stably increasing in the reservoir. When the liquid helium level reaches 70% of the height, V14 is automatically controlled by PLC control to keep the liquid level.

The phase-end criteria are as follows. First, cooldown of the GHe and VLP lines is completed; second, cooldown of the TSR line and the thermal shield in each subsystem is finished; thirdly, the liquid helium level reaches 70% of the 4.5 K reservoir in the EBx.

3.2.6 OM.1.3 stand-by 4.5 K except CM

The standby mode is set to stabilize the system when a part of the cryogenic system is completely cooled down. The system may not be in a steady state although the temperature and liquid level seem stable because the structures connected to the cryogenic system still emit unstable heat to the cryogenic system and have not reached the thermal equilibrium, yet. Adnan Ghribi et al. observed the decrease in the heat load over time by measuring the decrease of the liquid level in the reservoirs [8]. By performing the test, one can precisely measure the stabilization time of the system. If the test is not available, we can calculate the changes in mass flow rates through the valves on liquid filling lines (V14, V25, V27, V44, and V45) by using VFM to derive the heat load.

3.2.7 OM.1.4 CM cool-down 4.5 K

The VBx and the connected CM(s) are cooled down one by one in the beam direction for the requirement of fast cool-down of the QWR cavities from 150 to 50 K within 2 h. The reason for the fast cool-down is to avoid Q disease [9]. Although the vacuum-baked HWR cavities do not require the fast cool-down, it is decided to fast cool down the HWR cavities for insurance as requested by the cavities' part of RAON. Moreover, one should always pay caution to keep the pressure of the cavity not higher than 1.3 bara.

The cool-down process (OM.1.4) moves to the next subsystem, once the cool-down process (OM.1.4) and the reservoir filling process (OM.1.5) are finished for the previous set of VBx and CM.

1. QWR

During the CM cool-down process, the gas helium is returned to the CBx through the CDR line because the GHe and VLP lines in the main transfer lines are already cooled down. The outlet valve, V31, is opened first to avoid the sudden increase of pressure in the cavities.

Then, the reservoir inlet valve, V25 and V27 are opened slowly to 100%. When the pressure becomes stable, the inlet valve, V24, is slowly opened. There is a large temperature difference between the inlet and outlet of V24. To avoid thermal stress in piping and disturbance to the main SHe line, V24 should be opened very carefully at a speed of 1% per time, and the pressure stability should be checked each time. At that time, the helium gas flows from the inlet of the SHe line to the top of the 4.5 K reservoir, then to the CDR line through the GHe line. The purpose is to reduce the thermal stress and disturbance by gently blowing the cold helium and cool down the SHe line slowly. The maximum valve opening is limited by the pressure of the reservoirs, which is not allowed to be higher than 1.3 bara.

Once the SHe line is sufficiently cooled down and the pressure is stable in the SHe line, V26 and V28 are slowly opened to cool down the cavities and 4.5 K reservoirs from the bottom of the cavity through the cool-down line. The valves are regulated to satisfy the designed function of cavity temperature and cool-down time. V25 and V27 still keep 5% of the valve opening to cool down the filling line and cryogenic valves on the top of the 4.5 K reservoir. The phase ends when the liquid level is as high as 50% in the 4.5 K reservoir.

2. HWR (HWRA, HWRB, P2DT)

The cool-down strategy is similar to QWR. Firstly, the SHe line is cooled down by opening V43, V44, V45, and V50. Secondly, the cavities and 2.05 K reservoir are cooled down by regulating V46. The phase ends when the liquid level is as high as 50% in the 2.05 K reservoir.

One of the challenges is that there is no inlet valve in each cavity and the helium mass flow rate to each cavity is passively determined by the pressure drop. Thus, the valve opening of V46 should be controlled to make sure all the cavities pass 150–50 K within 2 h. To test the cool-down time of the cavities, cool-down experiments are conducted in the RAON test facility. Figure 5 shows the temperature variation during the cavity cool-down of an HWRB CM (four cavities). The temperatures of Cavity 1 and Cavity 2 are almost the same, and the temperatures of Cavity 3 and Cavity 4 are also similar to each other. It is because the positions of Cavity 1 and Cavity 3 are symmetrical to those of Cavity 2 and Cavity 4, respectively (Fig. 3). Cavity 1 and Cavity

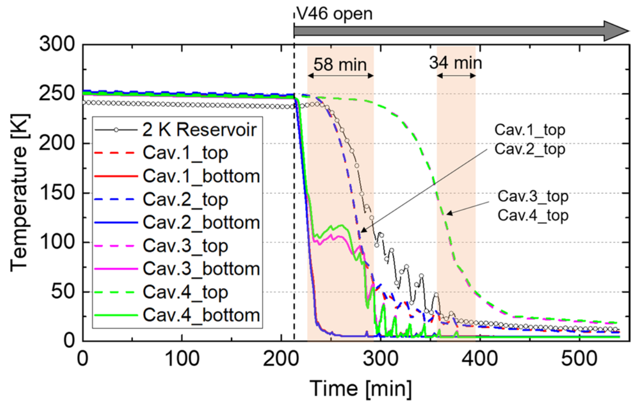


Fig. 5 Temperature data of 2 K reservoir and cavities in HWRB CM during the cool-down test

2 are cooled down much faster than Cavity 3 and Cavity 4. Thus, the cool-down time of Cavity 3 and Cavity 4 is controlled within 1 h in the experiment by V46.

3.2.8 OM.1.5 CM LHe filling

1. QWR

When the liquid helium level in the 4.5 K reservoir of QWR is higher than 50%, the outlet valve of the GHe line, V29, is slightly opened to cool down the GHe line. Then, the valve openings of the cool-down valves, V26 and V28, are slowly closed with the designated speed, and the valve openings of V25 and V27 are increased to fill the liquid helium. In this process, the pressure of the cavities should be controlled under 1.3 bara. When the outlet temperature of GHe becomes stable, the valve opening of V29 is increased and, the V31 is closed. V25 and V27 are used to regulate the liquid level, and V29 is used to regulate the pressure of the reservoir. When the liquid helium level reaches 70% of the height, the liquid level is controlled by PLC control of V25 and V27.

2. HWR

When the liquid helium level in the 2.05 K reservoir is higher than 50%, the outlet valves of GHe and VLP are slightly opened. Then, the valve openings of the cool-down valves, V46, are slowly closed at the designated speed. At the same time, the valve openings of V44 and V45 are increased to fill the liquid helium to the 4.5 K reservoir and 2.05 reservoir. When the outlet temperature of the VLP line is stable, V50 is closed, and the opening of V48 is increased. Similarly, when the outlet temperature of the GHe line is stable, the opening of V47 is increased. V44 and V45 are used to regulate the liquid levels and V47 and V48 regulate the pressures of the 4.5 K reservoir and 2.05 K reservoir, respectively. The phase ends when the liquid levels in the two reservoirs reaches 70%.

3.2.9 OM.2 Stand-by 4.5 K

If OM.1.4 and OM.1.5 of all the CMs in SCL 3 are finished, the CDS moves to OM.2. As the same as OM.1.3, the purpose of this mode is to thermally stabilize the cryogenic system. When the cryogenic system is stabilized at 4.5 K, it can manually move to OM.2.1 to be further cooled down to 2.05 K, or it also can move to OM.4 to operate all systems at 4.5 K for RF conditioning or other purposes during the commissioning period.

3.2.10 OM.2.1 Cool-down 4.5–2.05 K

To cool down the 2.05 K reservoir and the HWR cavities, the VLP line is pumped down to 32 mbar by the cold compressors and 2 K pumps (hybrid type). Thus, the VLP line should be disconnected from the GHe by closing V04 and V53. Additionally, since the VLP line is disconnected from the CBx in OM.0.4-OM.2, it should be connected in this operation mode. V44 and V45 automatically control the liquid levels in the reservoirs as 70% by PLC control. The pressures of the 4.5 K and 2.05 reservoirs are controlled by regulating the outlet valves, V47 and V48, respectively.

3.2.11 OM.3 Stand-by 2.05 K and OM.4 Normal Operating

The entire cool-down process is finished. After the stabilization of the cryogenic system in OM.3, the cryogenic system is ready to operate with beams. However, the cryogenic system can move to OM.4, only if all other systems are also ready to operate with beams. In OM.4, the cryogenic system handles the variation of the heat load from the cavities.

3.2.12 OM.5.3 warm-up 2.05–4.5 K

The warm-up process is divided into three steps: OM.5.3, OM.5.2, and OM.5.1. In OM.5.3, the 2.05 K reservoirs and cavities of HWR CMs are warmed up to 4.5 K. Since the pressure of VLP line, 2.05 K reservoirs, and cavities are under vacuum pressure, it should be pressurized by the evaporated vapor to 1.3 bara.

To pressurize the 36 mbar part, V45 is closed to avoid the helium flow from the 4.5 reservoir to the 2.05 K reservoir. Then, the cold compressors in the CBx are stopped, and the VLP line is disconnected from the CBx. In this case, the VLP line, 2 K reservoirs, and HWR cavities are in an isochoric pressurization process. The superfluid helium in the controlled volume is vaporized by the heat leak from

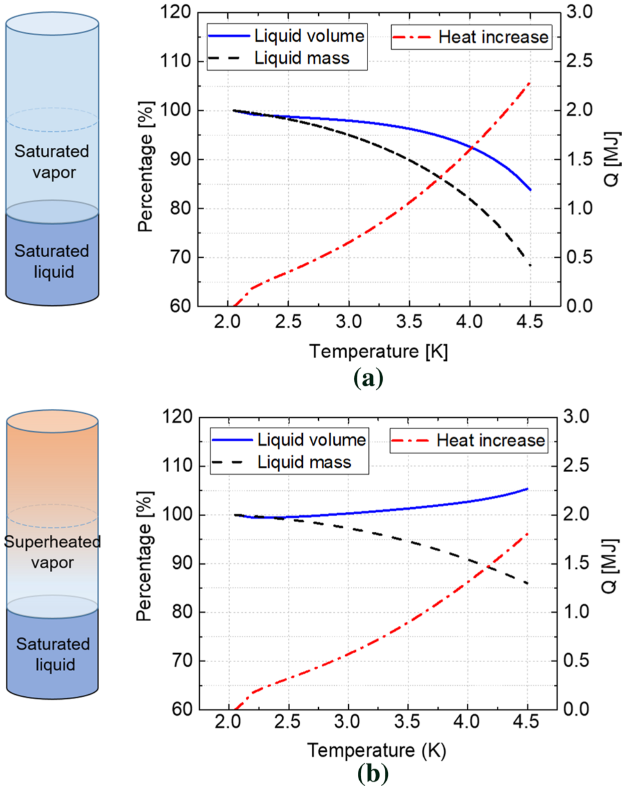


Fig. 6 Variation of liquid volume, liquid mass, and heat increase of helium during the isochoric process in saturation temperature from 2.05 to 4.5 K when **a** Case1: $T_{vapor} = T_{sat}$, **b** Case 2: $T_{vapor} = T_{sat} + 2K$ (in the case of initial volumes of liquid and vapor are 1 m^3 and 2 m^3, respectively)

the environment and the heat from the electrical heater in 2.05 K reservoirs. Phase change and energy transfer during this process are shown in Fig. 6. The control volume can be simplified as the cylinder shows. The initial volumes of liquid and vapor are set as 1 m^3 and 2 m^3, respectively. The vapor volume is set larger than the liquid volume because of the large volume of the VLP line. The helium properties from HEPAK are used in the calculation. Figure 6a shows the case when the vapor is in the saturated state. Both liquid volume and liquid mass decrease as the fluid temperature increases. 2.3 MJ of heat is needed to warm up to 4.5 K and pressurize to 1.3 bara. Although both liquid volume and liquid mass decrease, the liquid volume only decreases by 16% when the liquid mass decreases by 32% because of the decrease in liquid density. Figure 6b shows the case when the vapor is in a superheated state, which is closer to the real situation. The vapor temperature is assumed as 2 K higher than the liquid temperature. As shown in the figure, the liquid volume even increases as the temperature increases. The reason is the superheated vapor has a lower density than the saturated vapor. In this case, the temperature increases to 4.5 K with a heat increase of 1.8 MJ. Figure 7 shows the experimental data of the liquid helium level during the warm-up process from 2.05 to 4.5 K performed at our test facility of cryomodules. Since the outer wall temperature of the 2 K reservoir is measured in the test, the measured data is a little higher than the fluid temperature. In the experiments, the level meter fails to measure the liquid helium level near the lambda point. After the phase transition, it is observed that the liquid helium level increases until the maximum readable level of the level meter, which is similar to our calculation results. The physical properties of helium make it difficult to empty the liquid helium bath, and in our system, it is proved that the 2.05 K reservoirs and the cavities can not be emptied before they reach the pressure of 1.3 bara. Thus, we designed the operation logic that the 2.05 K reservoir is warmed up to 4.5 K (pressurized to 1.3 bara) in OM.5.3, and then the 4.5 K reservoir and the 2.05 K reservoir are emptied at the same time in OM.5.2.

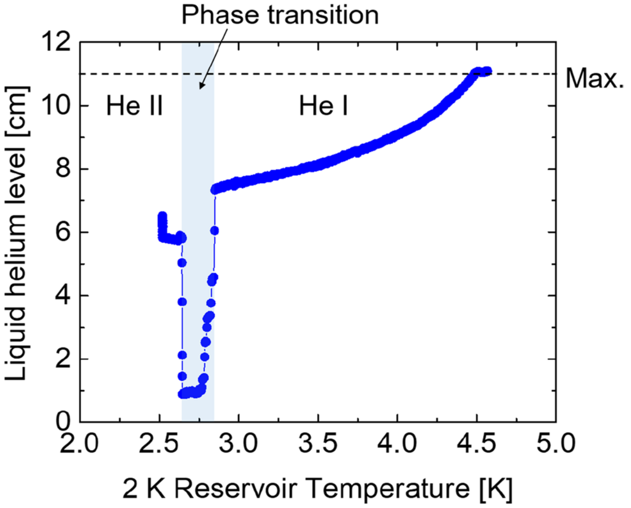


Fig. 7 Test data of liquid helium level in 2.05 K reservoir during the warm-up process from 2.05 to 4.5 K

When the pressure of 2.05 K reservoir reaches 1.3 bara, V45 is opened to avoid the pressure increase of the cavities. After that, the VLP and GHe lines are connected by opening V04 and V53 to return the warm gas from the VLP line to the CBx through the GHe line.

3.2.13 OM.5.2 empty reservoir

In OM.5.2, the liquid helium in all reservoirs and cavities are emptied by operating the heaters. The empty time depends on the static heat loads and heat capacities of the heaters.

During this process, the CBx stops supplying liquid helium to the CDS. Supplying the warm gas by the CBx is also not applicable. If the warm gas is supplied to the SHe line before emptying the reservoirs, the cryogenic system with experience a large pressure oscillation because of fast vaporization, and it will cause damage to the system. Thus, the SHe line is disconnected from the CBx, and the cryogenic plant is only connected with the GHe, TSS, and TSR lines of CDS.

The heaters are turned off when the liquid level is below 5% of the height to avoid overheating of the reservoirs. The static heat loads are used to vaporize the remained liquid helium.

3.2.14 OM.5.1 warm-up 4.5–300 K

The warm-up process of CBx is manually chosen and the CDS and CMs are warmed up from 4.5/35 K to 300 K by circulating the helium flows supplied from the CBx step by step. Since the CBx is warmed up at the same time, the temperatures of helium flows supplied by the CBx increase from 4.5/35 K to 300 K according to the warm-up sequence of CBx. The CMs are warmed up through the cool-down lines instead of the liquid-filling lines. Thus, the opening of V14, V25, V27, V44, and V45 is set as 5%, and the opening of V13, V26, V28, and V46 is increased and regulated by using VFM.

The phase ends when the temperature of CDS is equalized to the room temperature. Then, the system moves to OM.1 to purging the room-temperature helium gas.

3.2.15 OM.0.6 and OM.0.5

When the temperature of CDS is stable at room temperature, the CBx shops circulate the helium gas, and purging & purification is stopped. Then, the valve is closed one by one to avoid a pressure trap. Once all valves go to the safety positions and the parameters of temperature and pressure are not changed and stabilized, the system moves to OM.0.

4 Conclusion

The cryogenic engineers face numerous challenges in operating such a sensitive and large-scale cryogenic distribution and superconducting systems. An efficient operation strategy is needed with consideration of the cryogenic fluid characteristics and special requirements. This paper explained the operation modes, sequences, and logic for a cryogenic system of RAON. It includes the operation strategies of the RAON cryogenic system in detail, which are rarely found in the literature. The control of instruments is explained step by step, and the consideration from the engineering point of view is analyzed during the operation process, which will be a valuable reference material for operating a large-scale cryogenic system of the accelerator.

The design of the emergency modes in operation logic, the alarm and interlock in each operation mode, and the hazard & failure mode effect analysis for various emergency situations will be discussed in future work.

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