SCL3 cryogenic plant process design for RAON

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Abstract. RAON, Rare isotope Accelerator complex for ON-line experiments, is a facility for rare isotope beams in S. Korea. It has three superconducting linear accelerators, SCL1, SCL2, and SCL3. They could serve a broad power range of stable and unstable ion beams. The third superconducting linac, SCL3, which could accelerate rare isotope beams made by an ISOL (Isotope Separation On-Line) facility, consists of three types of cryomodules with two kinds of SC cavities, QWR (Quarter Wave Resonator, 81.25 MHz) and HWR (Half Wave Resonator, 162.5 MHz). A cryogenic plant for SCL3 will cover three cryogenic circuits, bath cooling for QWR at 4.5 K, bath cooling for HWR at 2.05 K, and forced cooling for thermal shields of all cryomodules at 35 – 55 K. ALAT who was a winner in this bidding and has studied our requirements and process designs will supply the cryogenic plant with a helium management system. This paper shows results of the process designs and current status including final heat loads from SCL3, specifications of equipment, a layout, and exergy efficiencies at operating modes.

1. Introduction

The Rare isotope Accelerator complex for ON-line experiments (RAON) which has a heavy ion superconducting linear accelerator is under the construction in Daejeon, S. Korea (Figure 1). The schedule of this project is from the end of 2011 to the end of 2021 and tunnels for the accelerator will be ready by the end of this year. It will start to install a cryogenic system at the early of the next September when a cryogenics building, a compressor building, and outdoor area for helium inventories will be ready.

Figure 1. Image of RAON facility(left) and current status(right, July 2018)
The linear accelerator (LINAC) will produce various stable and unstable beams for researches in basic science and applications. For example, it can accelerate high intensity stable ions from protons up to 600 MeV to uranium atoms up to 200 MeV/u [1]. Also it delivers high quality Rare Isotope (RI) beams, which are produced by Isotope Separator On-Line (ISOL) system, such as the 108 atoms per second of the $^{132}$Sn neutron-rich reference isotope with 18.5 MeV/u of beam energy. There are five experimental buildings and several experiment systems such as the Korea Broad acceptance Recoil spectrometer and Apparatus (KOBRA) for nuclear astrophysics and the Large Acceptance Multi-Purpose Spectrometer (LAMS) for the symmetry energy equation of state [2].

RAON consists of two injectors including ECR ion sources for the stable heavy ions, the In-Flight (IF) fragmentation separator and the ISOL for the RI beams, and three SuperConducting LINACs (SCL) for accelerating ion beams. The high quality RI beams accelerated by the third SCL (SCL3) go to low energy experimental buildings or to high energy experimental buildings via the second SCL (SCL2) which can reaccelerate RI beam up to a few hundreds of MeV/u. Also, the stable heavy ions which are produced by the injector of the first SCL (SCL1) will have high beam energy through both SCL1 and SCL2. The beams accelerated by SCL1 and SCL2 can produce several high energy RI beams after the target, and then a particular RI beam of them will be collected by the IF fragmentation separator [3].

There will be cryogenic plants for accelerators. First, a SCL3 cryogenic plant with a helium recovery system shall be installed by middle of 2020 according to the schedule of the SCL3 and ISOL. Second, a SCL2 cryogenic plant will be installed by early of 2021 [4]. Cryogenic plants for the upgrade of the beam energy and SCL1 will follow at the next stage.

A contract of the SCL3 cryogenic plant was awarded and signed to a consortium of Air Liquide Advanced Technologies (ALAT) and Hanyang ENG (HYE). ALAT is in charge of the cryogenic plant, control systems, and an external purifying system. HYE supplies the helium inventories, a LHe dewar, and a N$_2$ system and installs the whole system. A kick-off meeting was held in South Korea and all input data were clarified and frozen.

During the 2nd quarter of this year, there are two Basic Design Reviews (BDRs) on Temperature-Entropy (T-S) diagrams, Piping and Instrumentation Diagrams (PIDs), a preliminary functional analysis, and a brief layout. This paper summarized the results of the BDRs.

### 2. Cryogenic requirements

#### 2.1. 3rd Superconducting LINAC

Cryogenic parts of SCL3 consist of cryomodules and a Cryogenic Distribution System (CDS). The RI beams are accelerated by two types of cavities, QWR (Quarter Wave Resonator, 81.25 MHz) and HWR (Half Wave Resonator, 162.5 MHz). In case of QWRs, they need a fast cooldown to avoid Q disease. HWRs with heat treatments at the high temperature have no specific requirement for the cooldown.

| Type of cavity | QWR Cryomodule | HWR Cryomodule A | HWR Cryomodule B |
|---------------|----------------|-----------------|-----------------|
| No. of cavities | 1              | 2               | 4               |
| No. of cryomodules | 22             | 14              | 19              |
| Heat loads [W]  | 2.05 K         | -               | 14.1            |
|                 | 4.5 K          | 25.7            | 4.5             |
|                 | 35 – 55 K      | 83.3            | 117.9           |
|                 |                |                 | 181.5           |
There are three kinds of cryomodules in SCL3 for the cavities. Each QWR cryomodule has one QWR operating at 4.5 K. Each HWR cryomodule A and each HWR cryomodule B have two HWRs and four HWRs which are operating at 2.05 K (36 mbar), respectively. Table 1 shows the specification of them. There is one normal conducting magnet next to each cryomodule to focus the beams.

The plant serves the sub-cooled Supercritical Helium (SHe, 4.5 K, 3.0 bara) to all cryomodules via the CDS. In each QWR cryomodule, LHe expanded by the 1st J-T valve and the helium of 4.5 K and 1.3 bara is supplied to the cavities. In each HWR cryomodule, LHe expanded by the 1st J-T valve is sub-cooled under the 2.2 K via a heat exchanger. By the 2nd J-T valve, the sub-cooled helium becomes to the 2.05 K superfluid helium.

The CDS consists of a Distribution Box (DB), main transfer lines, valve boxes, and sub-transfer lines to connect each valve box with each cryomodule. The CDS has five process pipes, which are 4.5 K sub-cooled SHe supply pipe, 1.3 bara Gas Helium (GHe) return pipe, 36 mbara Sub-atmospheric Pressure (SP or Very Low Pressure, VLP) helium return pipe, 35 K and 14.5 bara thermal shield supply pipe, and 55 K and 14.0 bara thermal shield return pipe.

2.2. Heat loads

The maximum cooling capacities of SLC3 cryogenic plant are 894 W at the 2.05 K circuit, 1,035 W at the 4.5 K circuit, and 10,172 W at the 35 – 55 K circuit. Types and details of heat loads are summarized in Figure 2 and Table 2. Q1 is a static heat load at the VLP return pipe and Q2 is a static heat load at the SHe supply pipe. Q3 is a static heat load at GHe return pipe and Q4 is the sum of thermal shield loads of the cryomodules and the CDS.

For the isothermal heat loads, there are L1 and L2. Dynamic heat loads of L1 are produced by 6 kW Radio Frequency (RF) powers and beam losses of HWR beam lines. Static loads of L1 are conduction and thermal radiation loads from high temperature to jacketed HWRs. For the L2, dynamic loads came from 4 kW RF powers and beam losses of QWR beam lines. Static loads are from thermal conduction loads and radiation loads.

| Table 2. Heat loads of the SCL3 cryogenic plant |
|------------------------------------------------|
| 2.05 K load, W | 4.5 K load, W | 35 – 55 K load, W |
|                |  |  |  |
| Static         | 199 | 176 | 378 | 259 | 10,172 |
| Dynamic loads  | 519 | -   | 401 | -   | -       |
| Total          | 718 | 176 | 779 | 259 | 10,172 |
2.3. Cold end conditions

From the heat loads and pressure drop by SCL3 and the CDS, cold end conditions of a cold box of this plant are determined (Table 3). There are six operation modes, a nominal operation mode, a beam commissioning mode, a turndown mode, a 4.5 K standby mode, a 4.5 K standby mode with a maximum liquefaction, and a thermal shield (TS) standby mode. The nominal mode means that SCL3 operates with 100% continuous RF power to accelerating the RI beams up to 18.5 MeV/u. The beam commissioning mode is for accelerating the beams at the low beam energy with 25% continuous RF power. If there is no RF and only static heat loads from the cryomodules, the cryogenic plant will be on the turndown mode and the modules stay at 2.05 K.

| Unit | Modes | 2.05 K | 4.5 K | 35 – 55 K |
|------|-------|--------|--------|-----------|
| From cold box | Pressure | bar | Nominal | - | 3.0 | < 15.0 |
| | Beam commissioning | - | 3.0 | < 15.0 |
| | Turndown | - | 3.0 | < 15.0 |
| | 4.5 K standby | - | 3.0 | < 15.0 |
| | TS standby | - | 3.0 | < 15.0 |
| | Nominal | - | 4.5 | < 35.0 |
| | Beam commissioning | - | 4.5 | < 35.0 |
| | Turndown | - | 4.5 | < 35.0 |
| | 4.5 K standby | - | 4.5 | < 35.0 |
| | TS standby | - | - | < 35.0 |
| To cold box | Temperature | K | Nominal | > 4.5 | 1.25 | ΔP > 0.5 |
| | Beam commissioning | > 5.3 | 4.9 | ΔT > 20 |
| | Turndown | > 7.1 | 5.0 | ΔT > 20 |
| | 4.5 K standby | - | > 5.5 | ΔT > 20 |
| | TS standby | - | - | ΔT > 20 |
| | Nominal | 33.7 | 48.7 | > 95.3 |
| | Beam commissioning | 18.3 | 33.2 | > 95.3 |
| | Turndown | 9.3 | 27.1 | > 95.3 |
| | 4.5 K standby | - | 37.8 | > 95.3 |
| | TS standby | - | - | > 95.3 |

Table 3. Cold end conditions of the cold box
3. Basic design

3.1. Process design

The cold box of the SCL3 cryogenic plant is very similar with a cold box of the SHINE cryogenic system [5]. Figure 3 shows a brief process flow diagram.

The plant consists of five oil lubricated screw compressors including one standby compressor, four process vacuum pumps, an Oil Removal System (ORS), and the cold box which has three static gas-bearing turbines, three magnetic bearing cold compressors, four blocks of heat exchangers (or seven heat exchangers), two 80 K adsorbers, a 20 K adsorber, and two phase separators.

There are only three pressure stages with no medium pressure stage. The four screw compressors make the High Pressure (HP) stage of gas helium up to 15 bar a. According to the number of the operating compressors and the frequency of a compressor with a Variable Frequency Drive (VFD) motor, the mass flow rate of the process helium and the electric power consumption can be changed at the each operation mode.

Between the VLP stage and the Low Pressure (LP) stage, the three cold compressors and the four process vacuum pumps pressurize the helium from 32 mbar a up to 1.05 bar a. Due to this “mixed” compression cycles, the plant can control the mass flow rate of the cold compressor string without any problem at the surge line [6, 7].

Figure 3. Brief process flow diagram of SCL3 cryogenic plant

Figure 4. Exergy destruction of the SCL3 cryogenic plant at nominal mode
One of particular features is that there is no by-pass line and small inlet valve for the cold compressor string and the cold compressors will be protected by the 2nd phase separator which is connected with the string to measure the 2.05 K heat loads on a commissioning stage of the plant.

The other is that the plant can reduce the cooling power by two methods. One is to decrease the operating pressure manually and the other is to reduce the mass flow rate automatically.

3.2. Exergy analysis

The definition of exergy for a cryogenic plant is well summarized at the papers [8, 9]. According to the definition, a detailed exergy analysis of the plant had been calculated by ALAT. Figure 4 shows the dissipated energy of each component of the plant in detail and Figure 5 summarizes the exergy efficiency at each operation mode.

Compared with the electrical power input into the system, 51.1% of the exergy input is transferred to the cold box and others are dissipated in the compressors (43.0%), process vacuum pumps (2.8%), motors (2.3%), ORS (0.5%), and pipes (0.3%).

In the cold box, the final exergy efficiency of the plant is 26% including 2.05 K circuit (12.9%), 4.5 K circuit (7.1%) and TS circuit (6.0%). Others are dissipated in the turbines (14.1%), the heat exchangers (7.5%), the cold compressors (2.0%), valves (0.7%), and etc (0.8%).

The SCL3 cryogenic plant can reach the high efficiency at each mode except for TS standby mode because the number of compressors and the frequency of the VFD compressor can be changed at each mode. During the LINAC commissioning, it will be expected to save OPerating EXPenses (OPEX) because three compressors only operate at the beam commissioning and turndown modes.

3.3. Equipment

Kaeser standard compressors will serve the HP helium (14.5 bara) to the cold box and SCL3. Parallel operation is a well-proven technology from the JT-60SA project [10]. The SCL3 cryogenic plant will use three general compressors (FSD575) without VFD and one compressor (FSD575 SFC) with VFD at the nominal mode. The design of ORS is almost same as that of JT-60SA cryogenic plant [10]. For the reliable operation and maintenance, there is one back-up VFD compressor and it will alternate with each compressor every two weeks.

Process Vacuum Pump System (PVPS) is based on the Leybold oil-sealed pumps (SV630). The pumps are already used and proven in the RAON project [11] and other institutes such as CERN, DESY, and IHEP [6, 12, 13]. Because these pumps use the same oil with that of the screw compressors, the helium through PVPS can go to the compressors without ORS. What we have to consider is the oil contamination in the process pipes and lines between PVPS and the screw compressors because these pipes are connected with LP process pipes. Non-return valves are installed to solve this problem.
Table 4. Utilities of the SCL3 cryogenic plant

|                        | Compressor building | Cryogenics building | Outdoor area |
|------------------------|---------------------|---------------------|--------------|
| Installed electric power [kW] | > 1871              | < 94                | < 34         |
| Cooling water (ΔT = 10) [Nm3/hr] | < 120               | < 5                 | -            |
| Instrument air [Nm3/hr]          | 10                  | 25                  | 5            |
| LN₂ consumption [g/s]           | -                   | -                   | 10           |

For the cryogenic machines, the static gas-bearing turbines which are designed by ALAT will be used. To operate the cryogenic plant with the high reliability, the magnetic bearing for the cold compressors designed by ALAT will be used instead of a ceramic ball bearing.

Such as normal plants, the Aluminium plate fin heat exchangers which are vacuum brazed will be used. The 80 K adsorbers and the 20 K adsorber have one by-pass line respectively for the automatic regeneration of each adsorber.

3.4. Utilities
Table 4 shows the maximum consumption of utilities at the nominal operation.

Figure 6. Layout of cryogenics/compressor buildings
3.5. Layout
In the Figure 6, the size of each building is about 29 m by 66 m. In these buildings, there will be three cryogenic plants for the RAON. Unfortunately, a lot of compressors and process vacuum pumps shall be installed at the same place. So the layout shall be optimized for three cryogenic plants. The screw compressors for SCL3 will be installed in parallel, and all pipes and cables between two buildings will be installed along the wall for a regular maintenance.

4. Schedule
The Kick-off meeting was held on both 17th and 18th January, 2018 in Deajeon, South Korea. All input data were frozen. At the end of April and June, there were two basic design reviews. During the reviews, the preliminary PIDs, the preliminary functional analysis and the TS diagrams were checked. Now, according to the results of reviews, some designs have been modified.

After agreements on the results of BDRs, the detail design will start right after. The consortium will finalize the PIDs with control logics and make 3d drawings for the cold box and 2d drawings for the pipes and cable trays. The documentation of them will be reviewed at the end of this year.

The assembly of cold box will start at the early of 2019 and procurements of some components such as heat exchangers, compressors, and turbines which require long delivery time will start after the BDR approval.

Installation of the compressors and PVPS is going to start from September of 2019 and the cold box and the recovery system will be installed from February of 2020.

5. Conclusion
The SCL3 cryogenic plant is at the basic design stage. T-S diagrams meet the cryogenic requirements of SLC3. The preliminary PIDs will be updated after HAZOP and functional analysis review. Also the final PIDs including the control logic are expected to be finalized at the end of this year.

The exergy efficiency of this plant is expected to 26.0% at the nominal operation mode. Also, at the other operation modes, the plant is going to operate with high efficiency.

To reduce the CAPEX and increase the efficiency, the standard compressors and the standard process vacuum pumps are chosen but a maintenance strategy shall be planned for these machines. Also it is required to optimize the layout of SCL3 cryogenic plant in the buildings.

The plant will be installed from September of 2019 and an acceptance test will be expected on June, 2020.

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References
[1] H. J. Kim, H. C. Jung, and W. K. Kim 2016 Proc. of the Int. Particle accelerator Conf. 2016 (Busan), pp 935 ~ 937
[2] T. Shin, B. H. Kang, G. D. Kim, Y. J. Kim, Y. K. Kwon, Y. H. Park, K. Tshoo, C. C. Y 2016 New Physics: Sae Mulli Vol. 66, No. 12, pp1500~1510
[3] D. Jeon, et al. 2014, Journal-Korean Physical Society 65(7) pp 1010 ~ 1019
[4] S. Yoon, T. Ki, K. W. Lee, Y. Kim, H. C. Jo, and D. G. Kim 2017, IOP Conf. Series: Materials Science and Engineering 278 (2017) 012103
[5] Z. Quyang, S. Wang, J. Sun, L. Zhang, L. Lei, X. Deng 2018, The 8th international workshop on cryogenics operation(IHEP, Beijing), presentation material
[6] P. Lebrun and L. Tavian 2013, Proceedings of CAS-CERN Accelerator School: Superconductivity for Accelerators (2013) April 24 – May 4, Erice
[7] F. Millet, S. Claudet, G. Ferlin 2005, LHC project Report 857
[8] X. L. Wang, P. Arnold, W. Hee, J. Hildenbeutel, and J. G. Weisend II 2016, IOP Conf. Series: Materials Science and Engineering 101 (2015) 012012
[9] C. Hoa, B. Lagier, B. Rousset, F. Michel, P. Roussel 2015, Physics Procedia 67 (2015) 54-59
[10] C. Hoa, et al. 2016, IOP Conf. Series: Materials Science and Engineering 171 (2017) 012047
[11] S. Yoon, J. H. Shin, K. W. Lee, S. Lee, C. J. Choi 2016, 7th International workshop on cryogenic operations, poster
[12] B. Petersen 2014, 6th International workshop on cryogenic operations, presentation
[13] S. Li, R. Ge, Z. Zhang, Y. Liu, M. Sang, L. Bian, R. Han, J. Zhang, L. Sun, M. Xu, R. Ye, J. Zhang 2015, Physics Procedia 67 (2015) 863-867