Specification of the 2nd cryogenic plant for RAON

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Abstract. RAON is a rare isotope beam facility being built at Daejeon, South Korea. The RAON consists of three linear accelerators, SCL1 (1st SuperConducting LINAC), SCL2, and SCL3. Each LINAC has its own cryogenic plant. The cryogenic plant for SCL2 will provide the cooling for cryomodules, low temperature SC magnets, high temperature SC magnets, and a cryogenic distribution system. This paper describes the specification of the plant including cooling capacity, steady state and transient operation modes, and cooling strategies. In order to reduce CAPEX with the specification, two suppliers will consider no liquid nitrogen precooling, one integrated cold box, and one back-up HP compressor. The detail design of the plant will be started at the end of this year.

1. Introduction
Rare isotope Accelerator complex for ON-line experiments, RAON, is the first rare isotope beam facility in South Korea. Its project name is Rare Isotope Science Project (RISP) which belongs to Institute for Basic Science (IBS). This project was launched at the end of 2011 and the RAON will be constructed until the end of 2021.

Figure 1. Plot of the RAON facility layout

Figure 1 shows a layout of RAON facility. As RAON is an unique facility to provide the wide range of rare isotope beams for user. It has an In-flight Fragment (IF) separator facility and an Isotope Separation On-Line (ISOL) facility. [1] Also, it can serve a broad power range of stable and unstable...
beams using three superconducting linear accelerators. The first LINAC, SCL1, can accelerate several stable beams made by the first ECR ion source, and the third LINAC, SCL3, can accelerate some stable beams made by the second ECR ion source and also various unstable beams produced by ISOL facility. The second LINAC, SCL2, will reaccelerate the low energy stable or rare isotope beam came from the SCL1 and the SCL3.

These linear accelerators have their own cryogenic plants. Because configurations and heat loads of SCL1 and SCL3 are almost same, they have identical cryogenic plants. SCL2 is the longest LINAC and transfers the highest power beams among three LINACs. Also, its cryogenic plant (2nd cryogenic plant) has to cool down the LTS and the HTS magnets in the IF separator facility. Therefore, its cooling capacity is much bigger than the others.

This paper introduces the requirements of the 2nd cryogenic plant for the SCL2 and describes its important specifications. Specifications were discussed and investigated in detail during two industrial studies conducted with the suppliers. And then, they were finalized after an international review.

2. Structure and heat loads of SCL2

2.1. 2nd Superconducting LINAC

The low energy beams from the SCL1 are transferred to SCL2 via a 90 degree bending area which is called charge stripper section. Similarly, others from the SCL3 are served to SCL2 through a 180 degree bending area which is ‘Post (SCL3) To Drive LINAC (SCL1, SCL2) Transport line’ (P2DT).

SCL2 has three sections. The first section consists of 23 SSR1 cryomodules and the second section has 23 SSR2 cryomodules. These sections accelerate all beams. The last section is for a future project. In this project, it just transfers beams and consists of two SSR2 cryomodules. Table 1 shows characteristics of these cryomodules.

All cavities of SCL2 operate at 2.05 K. The 2nd cryogenic plant serves the sub-cooled liquid helium (4.5 K, 3 bara) to all cryomodules. In each cryomodule, LHe expanded by the 1st J-T valve is sub-cooled under 2.2 K via a heat exchanger. By the 2nd J-T valve, the sub-cooled helium becomes the 2.05 K superfluid helium.

Including P2DT, the cold mass of SCL2 is about 71 tons.

| Table 1. Cryomodules of SCL2 |
|-------------------------------|
| HWR cryomodule A | SSR1 cryomodule | SSR2 cryomodule |
| Type of cavity | HWR | SSR1 | SSR2 |
| No of cavities | 2 | 69 | 150 |
| No of cryomodules | 1 | 23 | 25 |
| Heat loads [W] | 2.05 K | 14.1 | 29.6 | 122.7 |
| | 4.5 K | 4.5 | 12.2 | 19.1 |
| | 35 – 55 K | 117.9 | 73.2 | 138.5 |

2.2. In-flight Fragment separator

IF separator consists of a high energy beam transfer (HEBT) section, one target, a pre-separator section, and a main separator section. In the HEBT, there are four normal conducting dipole magnets for 90 degree bending and one focusing normal conducting magnet in front of the target. The pre-separator has 7 high temperature SC magnets subjected to high radiation and these magnets operate at 35 K. After the hot cell zone, magnets consist of 13 quadrupole low temperature SC magnet triplets operated at 4.5 K and 7 dipole normal conducting magnets.

The cold mass of low temperature and high temperature SC magnets including iron yokes is about 178 tons.
2.3. Heat loads
The maximum cooling capacities of the 2nd cryogenic plant are 4,115 W at 2.05 K circuit, 1,309 W and 1.0 g/s liquefaction rate at 4.5 K circuit, and 18,818 W at 35 – 55 K circuit. The detail heat loads are listed in table 2. The non-isothermal heat loads and liquefaction loads are generated from a helium distribution system and vapour cooled current leads of low temperature SC magnets, respectively.

| Table 2. 2nd cryogenic plant heat loads |
|----------------------------------------|
| 2.05 K load, W | 4.5 K load | 35 – 55 K load, W |
|----------------|------------|-----------------|
| Isothermal     | Non-isothermal | Isothermal     | Non-isothermal | Liquefaction | Non-isothermal |
| Static         | 524        | 341             | 950            | 359         | 1.0           | 18,818         |
| Dynamic        | 3,250      | -               | -              | -           | -             | -              |
| Total          | 3,774      | 341             | 950            | 359         | 1.0           | 18,818         |

3. Specification of Cryogenic plant

3.1. Steady state operation modes
The cryogenic plant has 6 steady state operation modes which are “normal”, “beam commissioning”, “turndown”, “4.5 K standby”, “TS standby” and “maximum liquefaction” modes.

The normal mode is the most common mode and occurs with both beam and 100 % RF on. After cryogenic plant commissioning, the plant serves the accelerator commissioning. During this beam commissioning period, the 25 % RF power is turned on. If the beam is not serviced, the RF is turned off. This case is the turn down mode and the total heat comprises only the static loads.

During the short term maintenance period, the plant operates in the 4.5 K standby mode and it keeps the temperature of all cryogenic users at 4.5 K and 35 K. Also, some cryomodules can be separated from the LINAC in the 4.5 K standby mode. If there is any problem such as power failure, the cryogenic plant only cools down the thermal shields in the TS standby mode.

The maximum liquefaction means that the cryoplant operates in 4.5 K standby mode for all cryogenic units and it produces liquid helium in a LHe storage tank, simultaneously. The maximum liquefaction rate is measured by using the rising level in the LHe storage tank.

3.2. Cold-end conditions
Figure 2 and table 3 show a cold-end interface and the conditions of the cold box, respectively.
Table 3. Cold-end conditions of cold box

| Unit       | Modes                  | 2.05 K | 4.5 K | 4.5 K – 300 K | 35 – 55 K |
|------------|------------------------|--------|--------|--------------|-----------|
| Pressure   | Beam commissioning     | 3.0    | < 21   |              |           |
|            | Turndown               | 3.0    | < 21   |              |           |
|            | 4.5 K standby          | 3.0    | < 21   |              |           |
|            | TS standby             | 3.0    | < 21   |              |           |
| From cold box | Nominal               | 4.5    | < 35   |              |           |
|            | Beam commissioning     | 4.5    | < 35   |              |           |
|            | Turndown               | 4.5    | < 35   |              |           |
|            | 4.5 K standby          | 4.5    | < 35   |              |           |
|            | TS standby             | -      | -      |              | < 35      |
| Temperature | Nominal               | 4.5    | < 39   | < 4.8        | 300  ΔT < 20 |
|            | Beam commissioning     | 4.5    | < 4.8  | < 4.8        | 300  ΔT < 20 |
|            | Turndown               | 4.5    | < 4.8  | < 4.8        | 300  ΔT < 20 |
|            | 4.5 K standby          | 4.5    | < 5.2  | < 5.2        | 300  ΔT < 20 |
|            | TS standby             | -      | -      |              | 300  ΔT < 20 |
| To cold box | Nominal               | 176.9  | 61.0   | 1.0          | < 175     |
|            | Beam commissioning     | 63.5   | 60.2   | 1.0          | < 175     |
|            | Turndown               | 24.6   | 59.8   | 1.0          | < 119     |
|            | 4.5 K standby          | -      | 87.7   | 1.0          | < 119     |
|            | TS standby             | -      | -      | 1.0          | < 119     |

3.3.Cooldown strategy
Requirements for the cooldown of cavities and SC magnets are different. All cavities should be cooled down from 150 K to 50 K within two hours because of Q-disease. In case of the SC magnets, their cooldown rate is 1-3 K/hour from 300 K to 80 K to protect the magnets from thermal stress induced from thermal contraction. Therefore, the cryogenic plant has to cool them down separately and use each cooldown scheme for each of them.

At an initial operation period, the cryogenic plant will cool down all cryomodules, first because the cryomodules will be installed before SC magnets in our time schedule. Once some SC magnets are installed, they will be cooled down one by one and commissioned.
After the first long shutdown, the cryogenic plant will cool down the biggest cold mass first, the low temperature SC magnets. In this case, the estimated cool-down time is about 2 weeks. Therefore, the cryogenic plant does not need a cool-down/warm-up unit (CWU).

The cryogenic plant also cools down and warms up a single cryomodule or a single SC magnet. If there is any problem in a single cryogenic unit, it will be warmed up and disconnected from a cryogenic distribution system. After maintenance, it will be connected to a valve box of a cryogenic distribution system, and cooled down alone.

4. Important design choices

4.1. No liquid nitrogen pre-cooling
In case of the RAON accelerator, the cooldown time of the SCL2 is reasonable and their cold mass is small. So the cryogenic plant does not need a cool-down/warm-up unit. Similarly, use of the liquid nitrogen (LN2) pre-cooling scheme does not have many advantages except for the maximum liquefaction mode. Also, the OPEX of the cryogenic plant with the LN2 pre-cooling scheme is slightly higher than it of cryogenic plant without the LN2 pre-cooling scheme.

4.2. One integrated cold box
As the superfluid cryogenic plant (SCP) of Fermilab and the cryogenic plant (ACCP) of the ESS accelerator, the refrigerator for the SCL2 has one integrated cold box. As such, the cold box has a cold compressor string with heat exchangers and turbo expanders. One integrated cold box can reduce CAPEX and its space. [2]

4.3. One back-up HP compressor
The accelerator should be continuously operated and kept cold between long shutdowns. Backup systems for rotating machines such as warm compressors and cold compressors should be considered.

Because warm compressors are expensive, it is impractical that each compressor has its own back-up compressor. To satisfy stability of our accelerator operation within feasible economics, we will use one back-up HP compressor which can enable SCL2 to be operated without warm-up of cryogenic units.

Figure 3 shows how the back-up compressor will be used. If the VLP or the LP compressor has a failure, the 2nd LINAC will operate at 4.5 K. When the HP compressor has a problem, the back-up compressor replaces the failed compressor and the LINAC can be operating at 2.05 K.

Figure 3. Strategy of the compressor failure
4.4. Turn-down ratio and high efficiency
The turn-down ratio of the 2nd cryogenic plant is large. Keeping the high efficiency for the turn-down mode is an important issue. Solutions were suggested by two suppliers and one was applied.

5. Conclusion
This paper explains the important information for the cryogenic plant of SCL2 in the RAON accelerator. To operate the various cryomodules and superconducting magnets of SCL2, the required cold-end conditions of a cold box are presented. From industrial studies, technical specification was investigated, and checked by an international review.

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