Control systems for the 2 K cryogenic systems at KEK-STF and KEK-cERL

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Abstract. The Superconducting RF Test Facility and the compact Energy Recovery Linac are accelerator facilities at KEK that employ 1.3 GHz superconducting cavities fabricated using niobium. They should be cooled with liquid He at 2 K, for which cryogenic systems were developed at KEK. Home-made control systems were also introduced for stable and effective operation of the 2 K cryogenic systems. The performance of these cryogenic control systems has been improved in accordance with each beam operation.

1. Introduction

The 2 K cryogenic systems for the Superconducting RF Test Facility (STF) and the compact Energy Recovery Linac (cERL) have been established at KEK. External views of these accelerators are shown in Figure 1. STF is a test facility for ILC[1]. This accelerator has two cryomodules, which are called the capture cryomodule and CM-1,2A. The capture cryomodule includes two 9-cell cavities. CM1,2A includes 12 9-cell cavities and a superconducting magnet. The cERL accelerator is a test facility for the ERL accelerator[2]. It also has two cryomodules. One of these is the injector cryomodule, which includes three 2-cell cavities, and the other is the main linac cryomodule, which includes two 9-cell cavities. The 2 K cryogenic systems for these facilities are very similar, as shown in Figures 2 and 3[3].

The control system for the 2 K refrigerator of STF has been established, as have the control systems for the He liquefier and the 2 K refrigerator of cERL.

2. EPICS on PLC

EPICS is middleware that facilitates the construction of control systems. It is easy to make control programs in-house using EPICS. At KEK, EPICS is commonly used to control many kinds of accelerator components, including RF systems[4][5]. EPICS Input/Output Controllers (IOCs) can communicate with each other, which is convenient for actual operations at KEK. In practice, temperature data attached to cryomodules have been obtained from cavity control systems to control the cooling rate, and the 2 K cryogenic system can give permission to operate the RF after reaching 2 K. Recently, an embedded linux system on a programmable logic controller (PLC) that can run EPICS was made available[6]. EPICS, running on the PLC, can effect control cycles at frequencies greater than 10 Hz. This is sufficiently fast to control the cryogenic systems. The adopted PLCs were made by Yokogawa Electric Corporation.

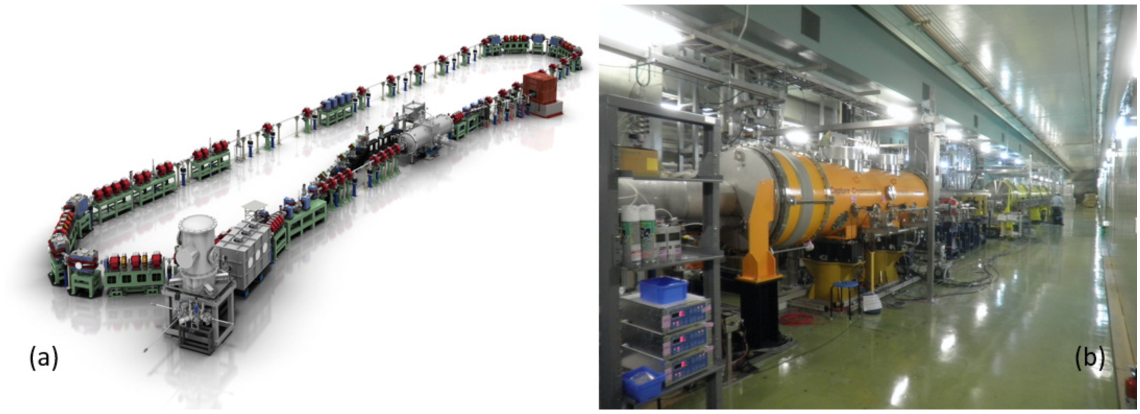

Figure 1. (a)cERL accelerator contains two cryomodules, which are called the injector cryomodule and the main linac cryomodule. The cavities in both cryomodules are operated at 2 K. (b)STF accelerator also contains two cryomodules, which are called the capture cryomodule and CM1,2A.

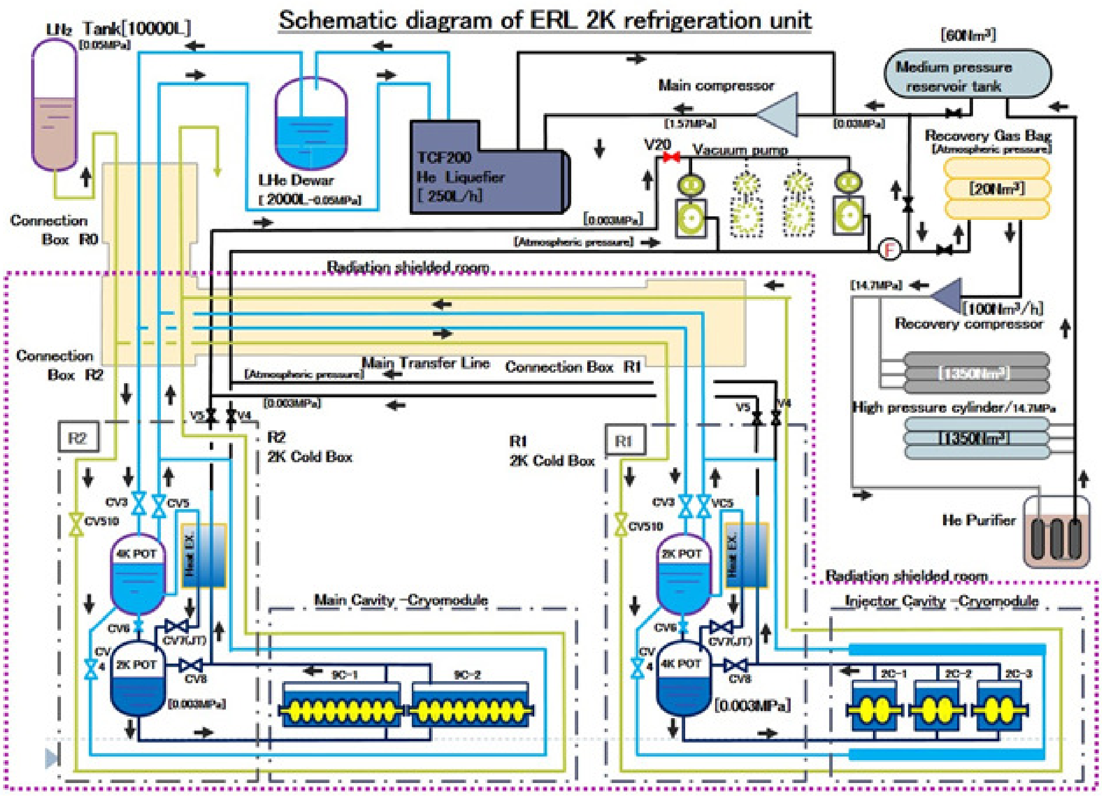

Figure 2. Schematic diagram of 2 K cryogenic systems for cERL.

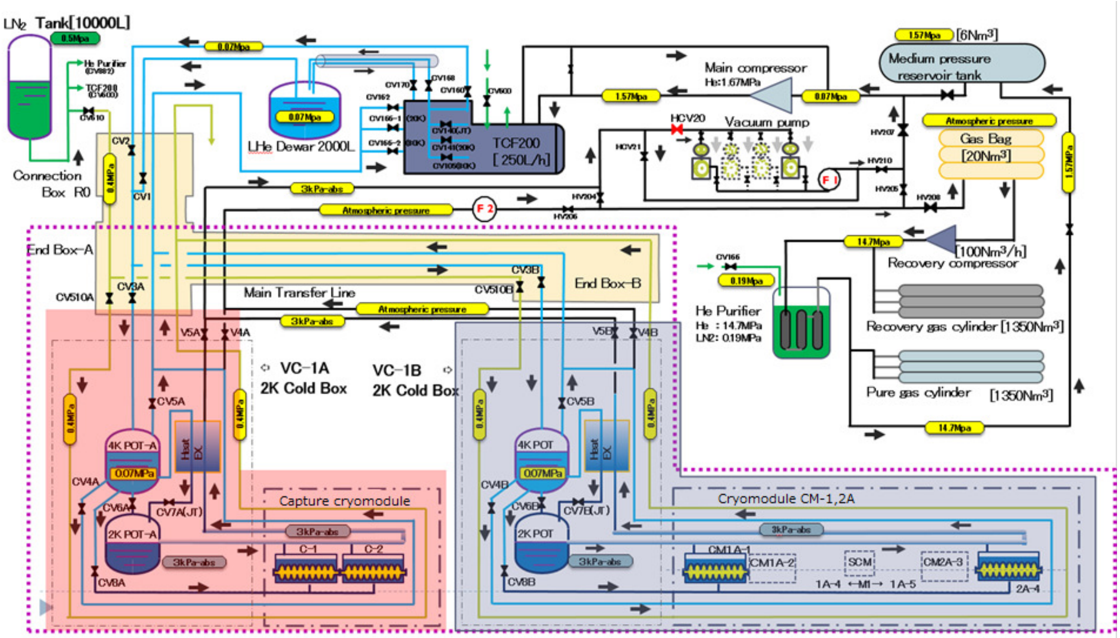

Figure 3. Schematic diagram of 2 K cryogenic systems for STF.

3. Stability of 2 K operation

The stability requirements for 2 K operation are shown in Table 1. The requirement for the liquid He level of the 4 K pot is not too strict, but the level should not be zero. The pressure difference between the 4 K and 2 K pots is more than 100 kPa during 2 K operation. The liquid He in the 4 K pot should separate these areas. Deviation is allowed, and so a proportional control loop is adopted to control the liquid He level. The required temperature for the superconducting cavity is 2 K. The temperature of 2 K He is controlled through control of the pressure of the 2 K He vessel. The saturated vapor pressure of liquid He corresponding to 2 K is 3.13 kPa. The target value for the control loop was set as 3 kPa, which corresponds to a temperature of 1.985 K. The resolution of the pressure sensor is 10 Pa. The fluctuations are at the level of the resolution. The 5 K and 80 K shields are cooled by liquid He and liquid N_2, respectively. The evaporation gas from the 5 K shield is recovered by the He liquefier. For stable operation of the liquefier, liquefaction of the return gas should be avoided. The evaporation gas from the 80 K shield should be released to the atmosphere. The liquid N_2 should not be released. Thermometers were installed in the vicinity of the outlet of the cooling pipes. The target value of the control loop was set higher than the boiling point. The average temperature of these shields were lower than the target value.

The accelerators have been operated successfully with these cryogenic systems, and there were no problems with the refrigerator performance.

4. Control of cooling rate

Generally, a superconducting cavity should be cooled slowly. The cooling rates for radiation shields are often not restricted. In case of the cERL main linac cryomodule, all of the cooling channels are restricted. The superconducting cavities are located in the 2 K region. If the cavity is deformed, some leakage might occur. The cooling pipes for the 5 K shield support the superconducting cavities, as shown in Figure 5. If the pipe is deformed, the superconducting cavity is also deformed. The ferrite HOM absorbers are located in the 80 K region. Ferrite is a brittle material that might crack due to the temperature gradient. To avoid these risks, the

Table 1. Stability of 2 K operation

	Requirement	Fluctuation
He level of 4 K pot	not zero	20 mm
He level of 2 K pot	70 % of 30-inch level sensor	±5 mm
Pressure of 2 K pot	3 kPa(1.985 K)	±0.01kPa(±0.001 K)
Temperature of 5 K shield	11 K	±1 K
Temperature of 80 K shield	105 K	±2 K

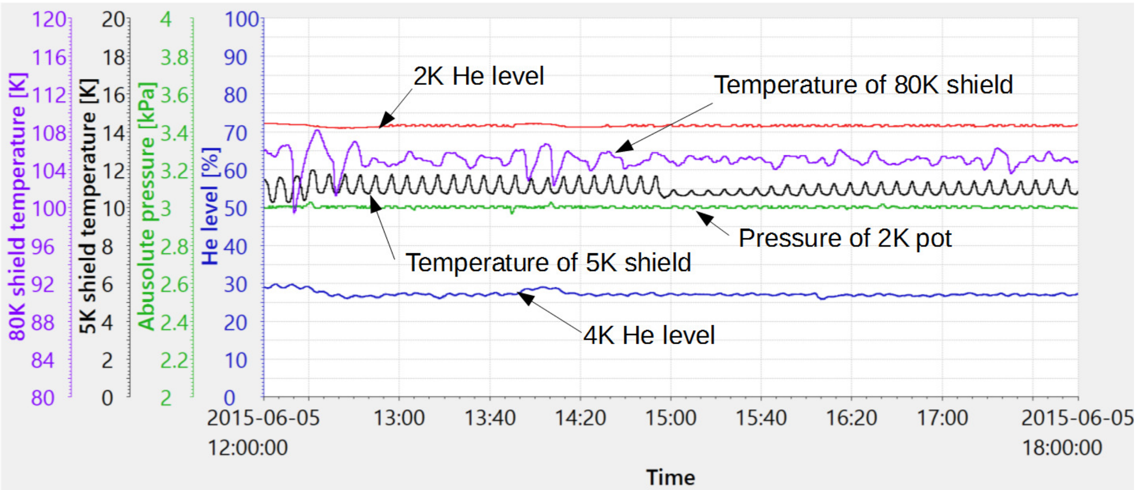

Figure 4. As an example, the behavior of the He levels and shield temperatures and pressure of the 2 K pot of the cERL main linac cryomodule are shown.

maximum cooling rate has been set at the measurement points. The number of measurement points were set at 29, 11, and 8 for the 2 K, 5 K, and 80 K regions, respectively, with two, one, and three thermometer groups for the three regions. The temperature differences in each group were restricted. All of the temperatures and temperature differences were controlled in a proportional–integral–derivative (PID) feedback program. Now the maximum cooling rates were set as 3 K/h from room temperature to 150 K, and the maximum temperature differences were set as 50 K.

The PID control program was applied to all of the feedback loops. To control the temperature, a valve to supply the coolant should be controlled. At first, many control loops were run independently, and the smallest required value for valve opening was adopted. However, a large overshoot was observed when switching the control target.

To avoid the overshoot, a new PID control program was used to calculate the deviation from the current value. A lot of parameters could be controlled simultaneously by using this program.

The simplest expression of the logic of PID control is shown below.

$$V = K_P(S-P) + K_I\int_0^t (S-P)\,\mathrm{d}t + K_D\frac{\mathrm{d}P}{\mathrm{d}t}$$

This calculation was performed as a recurrence formula on the PLC. The recurrence formula is shown below. It was confirmed that P or PI control is sufficient for our purposes, and therefore the D component of PID logic is omitted here.

$$V_n = K_P(S - P) + \Delta t K_I \sum_{i=0}^{n} (S - P_i)$$

The recurrence formula obtained from this equation is as follows.

$$\Delta V_n = -K_P(P_n - P_{n-1}) + \Delta t K_I (S - P_n),$$

where K_I and K_P are parameters for PI control. They are essentially constant and adjusted manually. S and P are the setpoint and measured value of the PI control program, respectively. This equation yields a value that indicates the amount to be moved from the actual valve opening. As Shown in the Figure 6, by selecting the smallest value, it could be controlled without temperature overshoot. A trend graph of the 80 K shield cooling is shown as an example in Figure 6.

A control cycle of period 1 s is sufficient for nearly all control loops, but some loops for the He liquefier required more frequent control. All of the control loops for the liquefier work in the control period 0.1 s. All of the control loops for the 2 K refrigerator work in the control period 1 s.

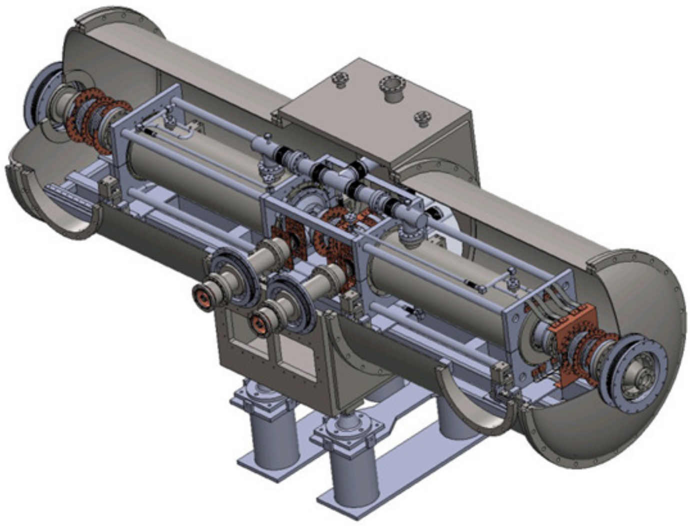

Figure 5. Cut-view of cryomodule for the cERL main linac. It has two 9-cell cavities. Four rods support the cavity. The rods also serve as cooling pipes for the 5 K shield. Ferrite HOM absorbers are attached in the 80 K region.

5. Pressure control for the compressor

The 5 K return gas is recovered by the He liquefier as shown in Figure 7. The pressure of the 4 K pot is controlled as 125 kPa. The pressure of the port to recover the cold gas is slightly higher than the inlet pressure of the compressor. To ensure flow of the 5 K return gas, the inlet pressure of the compressor should be sufficiently low. The return gas from the 2 K region is also recovered through the pump. When the inlet pressure of the compressor is increased, cooling of the 5 K shield is stopped. If the pressure increases further, then unwanted gas flow might occur.

When recovery of the 5 K return gas is started, sometimes the compressor power becomes insufficient. Then, the compression ratio of the compressor is reduced. Typically, the outlet

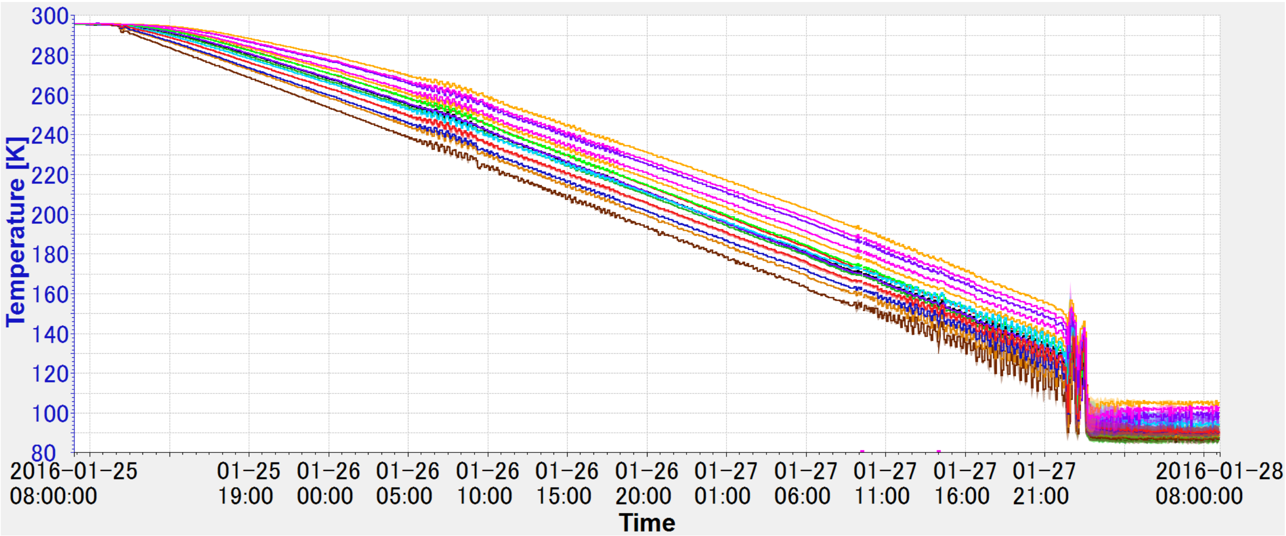

Figure 6. Trend graph of the 80 K shield cooling. Cooling rate is controlled below 3 K/h at all temperature measurement points.

pressure of the compressor is maintained at that time; however, for our purposes, the inlet pressure should be maintained.

To control the inlet and outlet pressure of the compressor, three valves (CV131A,CV131B, and CV132) are used as shown in Figure 7. Originally, the bypass valve (CV132) between the inlet and outlet of the compressor has been used to control the pressure of inlet pressure, while the charge and discharge valves (CV131A and CV131B) from the buffer tank were used to control the outlet pressure.

By reversing the roles of these valves, the problem might be solved. Or the control logic for the inlet pressure could be changed to use both the bypass valve (CV132) and discharge valve (CV131B). According to the simple test, it has been confirmed that the inlet pressure could be controlled by the charge and discharge valves, and the outlet pressure could be controlled by the bypass valve.

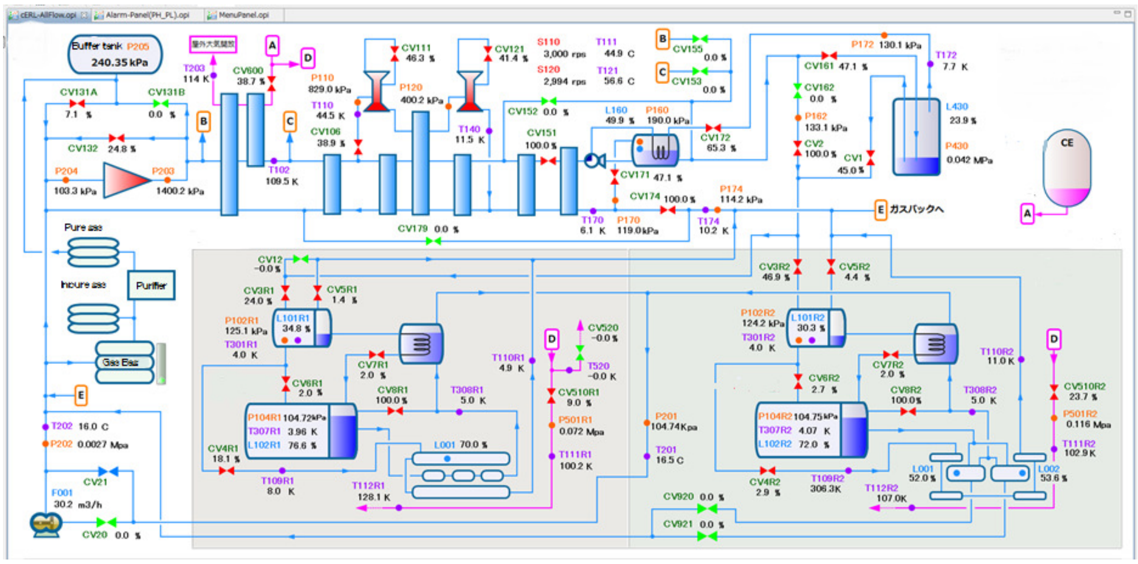

Figure 7. Operation display of 2 K cryogenic systems for cERL.

6. Summary

The 2 K cryogenic systems for KEK-STF and KEK-cERL have been established. These systems are controlled by EPICS. They are suitable for accelerator operation, and their performance is sufficient to operate superconducting cavities.

To control the cooling rate, a program that monitors many sensors to control a valve was developed. It works well, and it helped to shorten the cooling period.

The compressor control logic should be improved, and a program to address this is being developed.

References

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