Long term operation of the superconducting triplet quadrupoles with cryocoolers for BigRIPS in-flight separator at RIKEN

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Abstract. The BigRIPS in-flight separator and the radioactive isotope (RI) beam delivery lines in the RIKEN RIBF (Radioactive Isotope Beam Factory) project are characterized by the superconducting triplet quadrupoles (STQs) with cryocoolers. STQ magnet is a superferric quadrupole triplet with large apertures. They are cooled by liquid helium bath cooling method in a single cryostat with two cryocoolers. A Gifford-McMahon (GM)/Joule-Thomson cryocooler re-condenses evaporating helium gas in the helium vessel and a GM cryocooler cools the thermal shield and current leads by conduction. We have operated 22 STQ systems for more than ten years. Most of the cryocoolers have been continuously operated since 2006 without warm-up the magnets. We report operational experiences in the long-term operation of the STQ systems. Cold maintenance methods of cryocoolers, degradation of cooling capacity, and, failures of compressors are discussed.

1. Introduction
The BigRIPS in-flight fragment separator in the RIKEN Radioactive Isotope Beam Factory (RIBF) project has been operated for longer than 10 years. A total of ~1,500 RI beams, including 140 new isotopes, were produced and 165 experiments with unstable nuclei have been performed from March 2007 to June 2018. The large ion-optical acceptance of the BigRIPS separator and the radioactive isotope (RI) beam delivery lines enabled successful productions of the RI beams and is achieved by large aperture superconducting triplet quadrupoles (STQ) as focusing elements [1].

Except the five STQs in the first stage of the BigRIPS separator, where all the beam line elements are surrounded by radiation shields, the 22 STQs in the second stage of the BigRIPS separator and the RI beam delivery lines has been operated in a unique thermal cycle [2]. These 22 STQs, called as STQ6–STQ26, together with the “prototype” modelSTQ, are so called “stand-alone” superconducting magnet systems in which each triplet is installed in the single cryostat with two cryocoolers. We operate these STQ systems for more than ten years without warm-up the magnets by the continuous operation of the cryocoolers.

We report operational experiences in the long-term operation of these STQ systems. Maintenance of cryocoolers, degradation of cooling capacity, and, failures of compressors are discussed.

2. STQ with cryocoolers
In this section we summarize the design of STQ magnet system. Details of the magnet and cryostat design, magnet specifications, and, R&D studies are described in ref. [2].
2.1. Magnet and Cryostat Design

STQ magnet is a quadrupole triplet with the field gradient of 14.1 T/m and the warm bore radius of 120 mm. They are designed as iron-dominated quadrupoles, with the pole-tip and the yoke radii of 170 mm and 480 mm, respectively. Three quadrupoles, have an identical cross section and lengths of the iron yoke are 440 mm, 740 mm, and 940 mm, for Q500, Q800, and Q1000. Their nominal currents and stored energies are 142 A, 137 A, and, 125 A and 0.17 MJ, 0.19 MJ, and 0.27 MJ. The combination of Q500-Q800/Q1000-Q500 triplet are connected rigidly to each other and installed in a single cryostat as shown if Figure 1. The total weight of the 4 K-cold mass is 9.4 t / 10.2 t for the Q500-Q800/Q1000-Q500 triplet.

Figure 2 shows a schematic diagram of the cryostat of the STQ with cryocoolers. Superconducting coils together with iron yokes, are cooled by liquid helium bath cooling method in the He vessel which contains 500 l of liquid helium. A Gifford-McMahon cooler using a Joule-Thomson expansion (GM/JT cooler), with the cooling capacity of 2.5 W at 4.3 K, cools the He vessel. The GM/JT cooler consists of two independent coolant helium circuits, called expander- and JT-circuits. The expander circuit is a two-stage GM-cooler and serves as pre-cooler for the JT line. The JT-circuit liquefies helium gas, that evaporates in the He vessel, with the re-condensing heat exchanger unit. The temperature of the heat exchanger unit can be tuned around 4.5 K by changing the opening of the JT-valve. A single-stage Gifford-McMahon (GM) cooler with the cooling capacity of 90 W at 80 K cools a shield surrounding the He vessel and the High-Tc superconducting (HTSC) power leads (PLs). The cold head of the GM cooler is attached to the cooling copper plate in the cryostat to cool the PLs by heat conduction.

2.2. System Design and Operations

Since the STQ with cryocoolers is characterized by a large cold mass but small heat loads, we adopt a unique thermal cycle operation. Once we cool down the magnets by transferring liquid nitrogen and liquid helium from external Dewars to the cryostat, we operate the cryocoolers continuously and never warm up the magnets. The sufficient liquid helium level in the He vessel kept by the GM/JT cooler and the well cooled HTSC power leads by the GM cooler enable us to excite magnets according to the beam time schedule.

The liquid helium level in the He vessel and the temperature of the HTSC power leads are used in the interlock system for safe operations of the magnet. If the temperature of the HTSC power lead exceeds 70 K, the excitation current is discharged. The 24-inch superconducting liquid helium level sensor is installed in the He vessel, so that the liquid helium level above 80% ensures that all the superconducting coils are well cooled in the liquid helium bath. The alarm level of the liquid helium level interlock is set to be 80%.
The pressure of the He vessel is usually kept in the range from 7 to 9 kPaG with the on/off control of the 2 W heater installed in the He vessel, since the cooling capacity of the GM/JT cooler is 2.5 W and the total 4 K-heat load of the cryostat is less than 2 W. If the pressure of the He vessel exceeds 20 kPaG, which is the cracking pressure of the safety check valve for the He vessel, the liquid helium level starts decreasing.

3. Operational Experiences

Most of the cryocoolers have been continuously operated since 2006 and the operation time of the cryocoolers is longer than 100,000 h for STQ6 - STQ15, and 90,000 h for STQ16 - STQ23. The scheduled maintenance of the cryocoolers are performed yearly and all the displacers of the GM/JT and GM coolers are replaced every 8,000 ~ 9,000 h of operation time, since the regenerator material in the displacer deteriorates its performance with time. Since we never warm up the magnet, the GM cooler maintenance is performed in a helium atmosphere using a transparent gas bag. This “cold” maintenance method is well established by cryocooler maintainers [3].

3.1. Long term operation of the STQ systems

In this subsection we discuss how we operate the STQ system using long-term trend of data. Since the degradation of the cooling capacity of the GM cooler appears as an increase of the GM head temperature, we show in figure 3 a long-term trend (from 2008 to July 2018) of the GM head temperature and that of the power lead (PL1) in the STQ7 cryostat as an example. Arrows on the bottom axis indicate when the scheduled regular maintenances were carried out. The discharge (P_H) and suction (P_L) pressures of the compressor are also plotted. A gradual increase of the GM head temperature between the maintenances indicates the importance of the periodic maintenances.

On the other hand, the situation of the GM/JT cooler is much more complex. If the 4K heat load is constant, the average heater power output simply indicates the excess cooling capacity of the GM/JT cooler. However, the temperature of the GM cooler varies as shown in figure 3, so that the temperature of the thermal shield and the 4K heat load are not constant. Figure 4 shows a long-term trend of the average heater output $P$ in the STQ7 cryostat. The temperature of the thermal shield $T$ and the liquid helium level in the He vessel is also plotted using the Temp. and Level axis to the right. The dates of the regular maintenances are indicated as arrows on the bottom axis. A typical helium loss was approximately 10~20 l for each maintenance and we typically refilled 50 ~ 70 l of liquid helium once in 2~3 years. It is clearly seen that the average heater output decreases as the temperature of the thermal shield increases.

**Figure 3.** A long-term trend of the GM head and the power lead (PL1) temperature of STQ7.

**Figure 4.** A long-term trend of the average heater output $P$ and the thermal shield temperature $T$ of STQ7.
3.2. Hardware Failures

During the long-term operation of 22 STQ systems, we have experienced several hardware problems. The failures of the GM/JT compressor for the STQ24 and the GM compressor for the STQ14 happened in January and September 2012, respectively. The compressor in the expander circuit of the STQ24 GM/JT unit failed with the total operation time of 17,245 h. We repaired the STQ24 GM/JT compressor unit by replacing the broken rotary compressor in the expander circuit. On the other hand, the temperature of the GM cold head of the STQ14 increased several times in 2012. We found that the flow rate of the coolant helium gas in the STQ14 GM compressor unit was 20% less than the ordinary rate, so that we replaced the original GM compressor with the total operation time of 60,084 h with a new compressor unit.

Other hardware problem occurred in maintenance is the failures of JT valve of the GM/JT cooler. The JT valve of the GM/JT cooler for STQ18 did not work in 2015 and the same failure happened in the STQ19 GM/JT cooler in 2016, with the total operation time of 69,190 h and 78,737 h, respectively. We repaired both GM/JT coolers by replacing the JT valves.

Furthermore, ageing of the pressure sensors in the compressor units is now becoming noticeable. We repaired two GM compressor and four GM/JT compressor units with the total operation time of 70,087 ~ 103,855 h by replacing deteriorating sensors in the high-pressure lines.

3.3. Temperature rises of the GM cold heads

In addition to the scheduled yearly maintenance we were forced to perform unscheduled maintenances due to unexpected temperature rises of the GM cold heads. We experienced two types of temperature rises. One is rapid, typically 5~10K/week; temperature rises randomly occurred in several STQs. Another type is gradual increase of the temperature, typically 4~5 K/month, often occurred in the STQ13 GM cooler. The gradual rises of the STQ13 GM cooler was caused by tiny leakage of the coolant gas from the compressor unit. The cooling capacity is recovered by charging the coolant gas.

On the other hand, when the rapid increase of the GM head temperature occurred, we were forced to replace the displacer in most cases, since the temperature of the power leads must be under 70 K to excite coils. Operation period between the rapid temperature rise and the last maintenance was in the range of 1,200~6,700 h. We list the unscheduled maintenances of the GM cooler in Table 1. We consider that this rapid temperature rise is related to a blockage of coolant gas flow in the displacer, since the difference of the discharge and suction pressure of the compressor unit was found to be about 0.1~0.2 MPa larger than its usual value. Although impurity of the coolant gas is the most likely cause of the blockage, the unexpected temperature rises of the GM cold heads is still under investigation.

| Year | Systems                  |
|------|--------------------------|
| 2009 | STQ8                     |
| 2010 | STQ8, STQ11              |
| 2011 | STQ9                     |
| 2012 | STQ6, STQ8, STQ9, STQ14, STQ18 |
| 2013 | STQ16                    |
| 2015 | STQ17                    |
| 2016 | STQ9, STQ10, STQ25      |
| 2017 | STQ21                    |

3.4. Pressure increase of the He vessel

We usually keep the He vessel pressure in the designed range by tuning the opening of the JT-valve of the GM/JT cooler together with the heater control. However, if the total 4 K heat load of the cryostat
becomes more than the cooling capacity of the GM/JT cooler, the He vessel pressure does not decrease to 7 kPaG and the heater does not turn on at first, and the He vessel pressure begins to increase finally. If the He vessel pressure exceeds the cracking pressure of a safety check valve, the liquid He level starts decreasing. This undesirable situation happened many times when the temperature of the thermal shield exceeded 60 K due to deterioration of the GM coolers. In order to keep the necessary liquid helium level to excite coils, we were forced to replace the GM/JT cooler itself or the displacer of the expander circuit in such cases. This kind of pressure rises occurred mostly in the STQ systems listed in Table 1.

We have also experienced another type of the pressure increase of the He vessel. The degradation of cooling capacity of the GM/JT cooler causes the pressure increase of the He vessel even with the well-cooled thermal shield. We have experienced two kinds of the degradation of the GM/JT cooler. One is the degradation caused by the blockage of the JT-circuit, in which the temperature of the JT cold head $T_{JT}$ rises above 4.5 K. We replaced the deteriorated GM/JT cooler with a spare GM/JT cooler. The cooling capacity of the deteriorated GM/JT cooler was recovered by flushing the JT-circuit after warming up. Other kind of degradation is caused by the abnormal temperature (>15 K) of the expander head $T_{exp}$ which is normally below 14 K. After the replacement of the displacer, the expander head temperature became below 14 K and the cooling capacity was recovered. We list the deteriorated GM/JT coolers in Table 2. We consider that the degradation of the cooling capacity of the GM/JT cooler is also caused by impurity in the coolant gas helium. Preparation of spare cryocoolers are essential for a long-term operation.

| Date of operation stop | Total operation time (h) | Time from last maintenance (h) | Reason |
|------------------------|--------------------------|-------------------------------|--------|
| STQ17 May 20 2011      | 38,773                   | 6,476                         | $T_{JT}$ ~ 4.7 K |
| STQ17 Jun. 4 2012      | 47,913                   | 6,719                         | $T_{exp}$ ~ 16 K |
| STQ13 Mar. 22 2013     | 69,439                   | 5,113                         | $T_{exp}$ ~ 23 K |
| STQ15 Nov. 10 2014     | 82,003                   | 1,518                         | $T_{exp}$ ~ 18 K |
| STQ10 Nov. 17 2014     | 83,017                   | 1,855                         | $T_{exp}$ ~ 18 K |
| STQ11 Jun. 3 2017      | 106,985                  | 5,983                         | $T_{JT}$ ~ 4.6 K |

4. Conclusions
We have operated the 22 STQ systems for more than ten years. We have summarized the mechanical failures we have experienced. We have experienced the unexpected rise of the GM cold head temperature and the rapid increase of the He vessel pressure many times in our long-term operation of 22 STQ systems. Although we consider that they are caused by impurity in the coolant gas helium, the origin of the degradation of the cooling capacity is still under investigation.

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References
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