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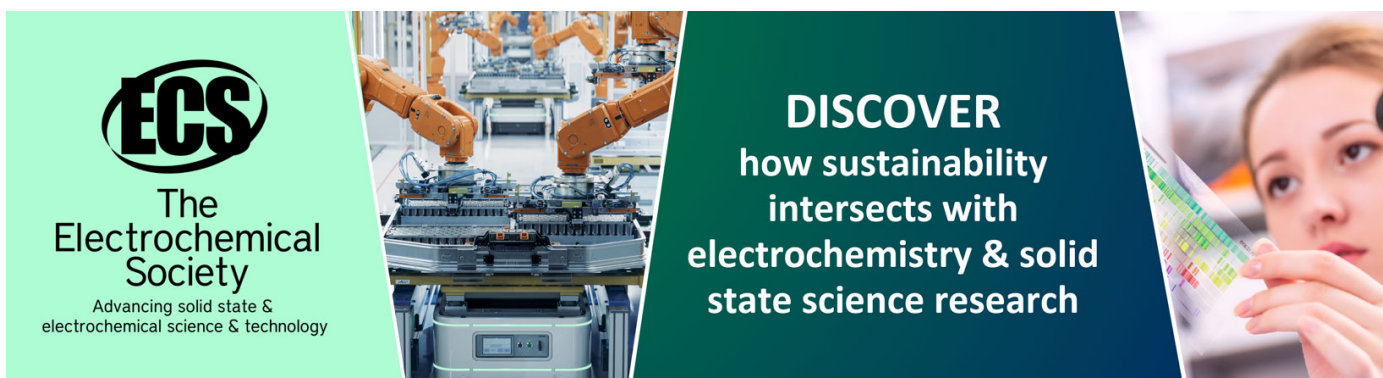
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To cite this article: K Kusaka 2020 *J. Phys.: Conf. Ser.* **1559** 012071

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Long term operation of the superconducting triplet quadrupoles with cryocoolers

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Abstract. Superconducting triplet quadrupoles (STQs) with cryocoolers characterize the BigRIPS in-flight separator and radioactive isotope (RI) beam delivery lines in the RIKEN RIBF (Radioactive Isotope Beam Factory) project. The STQ magnet is a large-aperture superferic quadrupole triplet cooled by liquid helium bath cooling method in a single cryostat. The STQ cryostat is designed to be operated continuously with a Gifford-McMahon (GM)/Joule-Thomson (JT) cryocooler and a GM cryocooler. We operate 22 STQ systems for more than twelve years without warm-up the magnets. We report operational experiences, such as degradation of cooling capacity and failures of compressors, in the long-term operation of the STQ systems. Replacement of ageing cryocooler unit is discussed to improve the cooling capacity.

1. Introduction

The BigRIPS in-flight fragment separator in the RIKEN Radioactive Isotope Beam Factory (RIBF) project has been operated since 2007. The RIBF project is aimed at making significant progress in the studies of exotic nuclei far from stability. A total of ~1,500 RI beams, including 142 new isotopes, were produced and 184 experiments with unstable nuclei were performed from March 2007 to December 2019. The large ion-optical acceptance of the BigRIPS separator enabled successful productions of the RI beams and is achieved by large aperture superconducting triplet quadrupoles (STQ) as focusing elements, since the RI beams have large angular and momentum spreads [1].

The BigRIPS is a beam line device to produce RI beams in two-stage separator scheme [1]. The first stage, consisting of five STQs (STQ1~STQ5) and 2 room temperature dipoles, serves to produce and separate RI beams. The second stage and RI beam delivery lines deliver tagged RI-beams to downstream experimental setups by identifying RI-beam species in an event-by-event mode. Since the five STQs on the first stage of the BigRIPS are exposed to the high radiation from the production target and the beam dumps, they are cooled by a liquid helium cryogenic plant to cope with beam heat loads. On the other hand, all other STQs in the RIBF beam lines are operated with cryocoolers. There are total 22 STQs, which are called as STQ6~STQ26, together with the “prototype” modelSTQ, and each triplet is installed in the single cryostat with two cryocoolers [2].

We operate these STQ systems for more than twelve years without warming up the magnets. The continuous operation of the cryocoolers enables us unique thermal cycle operation of the superconducting magnets [3]. We report operational experiences in the long-term operation of these STQ systems. Degradation of cooling capacity and mechanical failures of compressors are discussed. Replacement of ageing cryocooler unit is also discussed based on the test results.



2. STQ with cryocoolers

In this section we summarize the design of STQ magnet system [2]. Details of the magnet design and specifications are described in ref. [4].

2.1. Magnet and Cryostat Design

The ion-optics design of the BigRIPS separator and the RIBF beam lines requires a quadrupole magnet with the field gradient of 14.1 T/m and the warm beam bore radius of 120 mm. Three different quadrupoles, named Q500, Q800 and Q1000, with the nominal effective length of 500 mm, 800 mm and 1000 mm are used to form the triplet combinations of Q500-Q800/Q1000-Q500 as a basic focusing element of the RIBF beam lines [1].

We designed them as “energy saving” superconducting quadrupole magnets. We introduce a cold iron yokes with the length of 440 mm, 740 mm, and 940 mm, for Q500, Q800, and Q1000 magnets. They have identical cross section with the hyperbolic-shape poles and the radii of the pole-tip and the yoke are 170 mm and 480 mm, respectively. Flat race-track-shape superconducting coils are orderly wound with a thin NbTi superconducting wire and supported by the iron-yoke. The nominal currents and stored energies of Q500, Q800, and Q1000 magnets 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. We adopt the liquid-He bath cooling method for STQ cryostat. Superconducting coils together with iron yokes, are cooled by liquid helium in the He vessel. The 4 K-cold mass of the Q500-Q800/Q1000-Q500 triplet weighs 9.4 t / 10.2 t. Details of the magnet design and specifications are described in ref. [4].

Figure 1 shows a schematic diagram of the STQ cryostat with cryocoolers. The helium vessel contains 500 l of liquid helium and cooled by a 4 K cryo-cooler, SHI model SG308SC, which is a Gifford-McMahon cooler using a Joule-Thomson expansion (GM/JT cooler), with the cooling capacity of 2.5 W at 4.3 K. 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 temperature of the second stage of the expander-circuit T_{exp} is monitored using a H_2 vapor gauge or a Pt-Co sensor and is usually below 14 K. 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 T_{JT} can be tuned around 4.4 K by changing the opening of the JT-valve. The refrigerator unit is mounted on the cryostat using Wilson seal, so that it can be dismantled even when the He vessel is filled with liquid helium.

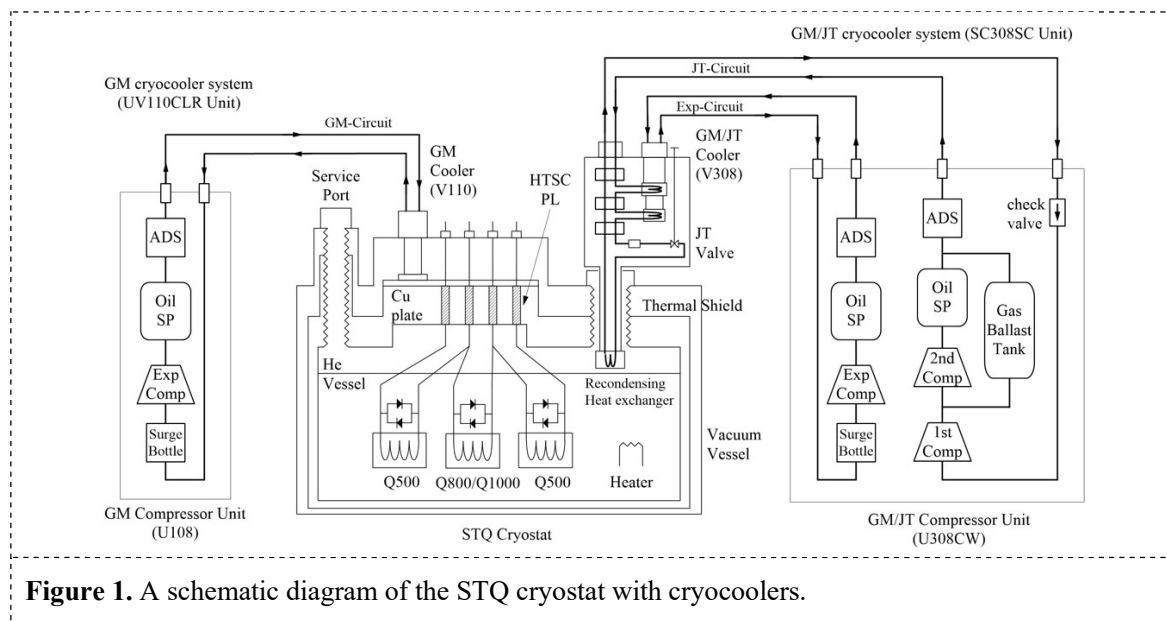


Figure 1. A schematic diagram of the STQ cryostat with cryocoolers.

On the other hand, a single-stage Gifford-McMahon (GM) cooler, SHI model UV110CLR, with the cooling capacity of 90 W at 80 K cools the shield surrounding the He vessel and the High-Tc superconducting (HTSC) power leads (PLs). The model UV110CLR consists of the compressor unit U108 and the refrigeration unit V110. The refrigeration unit V110 is a gas-driven cryocooler and suitable for cold maintenance. The cold head of the V110 unit is attached to the cooling copper plate in the cryostat to cool the PLs by heat conduction.

2.2. System Design and Operations

The STQ with cryocoolers is characterized by 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.

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, we install heaters in the He vessel. 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. 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.

3. Long term operation of the STQ systems

Most of the cryocoolers have been continuously operated since 2006 and the operation time of the cryocoolers is longer than 130,000 h. The scheduled maintenance of the cryocoolers are performed yearly. All the displacers of the GM/JT and GM coolers are replaced every 8,000 ~ 9,000 h of operation time and the adsorbers (ADSs) in the compressor units are also replaced every 25,000 ~ 30,000 h of operation 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]. In the following two subsections we report how we operate the STQ system using long-term trend of data.

3.1. PL temperature and GM cooler operation

Since the degradation of the cooling capacity of the GM cooler appears as an increase of the GM head temperature, we show in figure 2 a long-term trend (from 2008 to July 2019) of the GM head temperature T_{Head} and that of the power lead (PL1) in the STQ10 cryostat as an example. Arrows on the top axis indicate when the scheduled maintenances were carried out. The maintenances in which the ADS in the compressor unit was replaced are denoted by letter “A”. The discharge (P_D) and suction (P_S) pressures of the compressor are also plotted.

As discussed in Ref. [5], we occasionally experienced unexpected temperature rises of the GM cold heads randomly occurred in several STQs. Two types of temperature rises are seen in Fig. 2. One is gradual increase of the cold head temperature happened in early summer 2012. Since both the discharge and suction pressures decreased, it is caused by tiny leakage of the coolant gas. Another type is rapid temperature rises happened three times in the period from October 2015 to May 2017. We were forced to perform unscheduled maintenances indicated by the arrows with letter “D” in Fig. 2. 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, we consider that this rapid temperature rise is caused by a blockage of coolant gas flow in the displacer. We consider that the replacement of the ADS in the compressor unit is effective to remove impurities in the coolant gas helium. Unexpected temperature rises did not occur after the replacement of the ADS in Dec. 2017.

3.2. GM/JT cooler operation and its cooling capacity

Figure 3 shows a long-term trend of the average heater power output P in the STQ10 cryostat. The liquid helium level in the He vessel and the temperature of the thermal shield T are also plotted using

the Temp. and Level axis to the right. The dates of the regular maintenances are indicated as arrows on the top axis, too. A typical helium loss during maintenance was approximately 10~20 l, if the GM/JT cooler is maintained without being dismantled from the cryostat [3].

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 head varies as shown in figure 2, so that the 4K heat load did not stay constant depending on the temperature of the thermal shield. If the total 4 K heat load of the cryostat becomes more than the cooling capacity of the GM/JT cooler, the heater does not turn on at first, and the He vessel pressure begins to increase. If the He vessel pressure exceeds the cracking pressure of a safety check valve, the liquid He level starts decreasing. This undesirable situation happened in Aug. 2011 and the period discussed in the subsection 3.1.

The degradation of cooling capacity of the GM/JT cooler causes the pressure increase of the He vessel and the helium loss, 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 abnormal temperature (>15 K) of the expander head T_{exp} which is normally below 14 K. In this case we replaced the deteriorated GM/JT cooler with a spare GM/JT cooler. The spare GM/JT cooler were used twice for the STQ10 cryostat from Nov. 2014 to Sept. 2015 and from June to Sept. 2017. These two periods are indicated by the double allows with letter “S” in Fig. 3. The cooling capacity of the deteriorated GM/JT cooler was recovered by replacing the expander displacer. Preparation of spare cryocoolers are essential for a long-term operation.

Another type of the degradation of cooling capacity is caused by the blockage of the JT-circuit, in which the temperature of the JT cold head T_{JT} rises above 4.5 K. When this type of degradation occurred in non-beam-time periods, we manually stopped the GM/JT compressor and restarted after one hour warm up. This operation is indicated as the arrows with letter “R” in Fig. 3. The cooling capacity was recovered by warming up the JT-circuit and the helium loss could be avoided in most cases. However, as seen in Fig. 3, we have lost ~30 l of liquid helium in January 2019, since the degradation occurred on the weekend and the manual stop and restart of the GM/JT compressor was delayed two days. We consider that impurity accumulation in the coolant gas helium is now becoming noticeable after the long-term continuous operation.

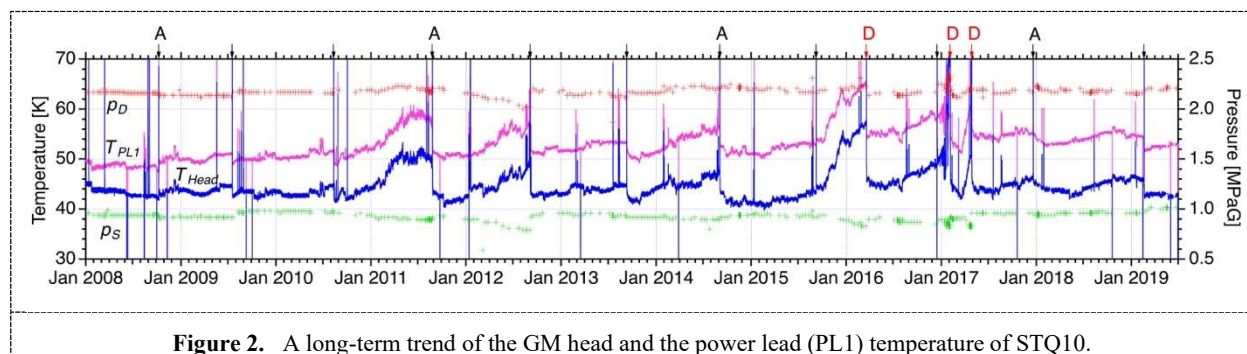


Figure 2. A long-term trend of the GM head and the power lead (PL1) temperature of STQ10.

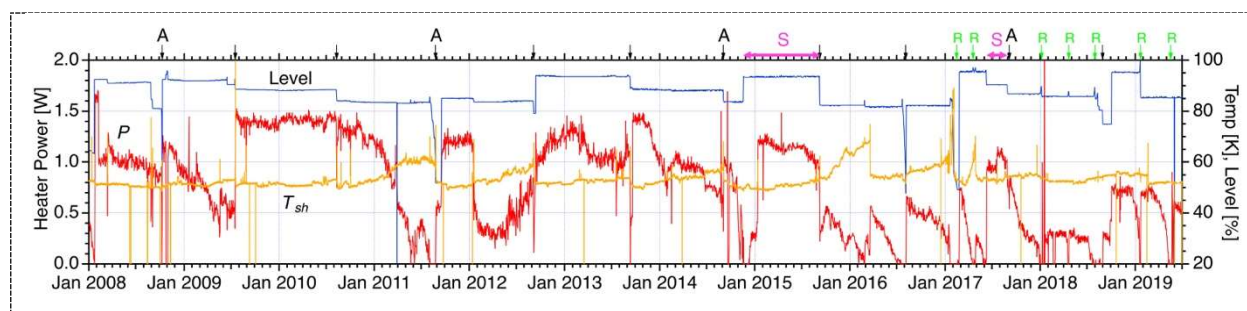


Figure 3. A long-term trend of the liquid helium level, the average heater power and the shield temperature of STQ10.

3.3. Aging Deteriorations and Hardware Failures

During the long-term operation of 22 STQ systems, we have experienced several hardware problems. In the scheduled maintenance of the STQ18 and STQ19 systems, the JT valves of the GM/JT coolers were broken 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. Beside these two failures of JT valve, the most of hardware problems are failures of compressor units. In most cases compressors suddenly stopped and did not re-started, so that we were forced to replace them with spare compressors. We list the experienced failures of compressor unit in Table 1.

Table 1. List of hardware failures in compressor unit.

Failed part	System	Total operation time (h)
Rotary compressor for Expander-circuit	STQ24 GM/JT	17,245
Pressure control valve	STQ14 GM	60,084
PLC error	STQ11 GM/JT	71,775
Pressure sensor (HPS)	STQ16 GM/JT	70,087
	STQ11 GM/JT	82,448
	STQ20 GM/JT	100,023
	STQ21 GM/JT	100,563
	STQ23 GM	80,603
	STQ6 GM	103,855
	STQ25 GM/JT	63,135
Check valve in JT suction line	STQ7 GM/JT	106,985

Except the GM/JT compressor for STQ24, these failures can be considered as aging deterioration of mechanical parts. Although we repaired these compressors by replacing failed parts with new ones, both cryocooler units, SHI model SG308SC and model UV110CLR, are now discontinued products. Supply of their maintenance parts will stop in the near future. Furthermore, as discussed in the previous section, impurity accumulation in the coolant gas helium is now becoming noticeable. We thus start planning the replacement of both cryocooler units.

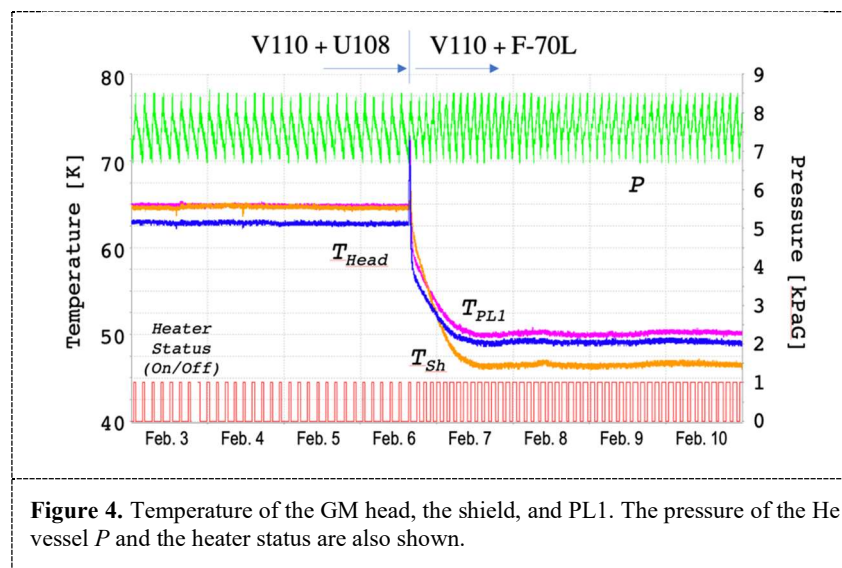
4. Replacement of cryocoolers

Since the STQ system is characterized by the large cold mass with small 4K heat load, it is preferable to replace the discontinued cryocooler unit with new products without warming up the magnet. Since the 4K cooler is mounted on the STQ cryostat with the Wilson seal, a new 4K cooler with the same interface can be mounted without modifying the cryostat. We are developing a new re-condensing type 4K cooler system using a 4K GM cooler, SHI model RDE-418D4, since there is no successor product of the GM/JT cooler on the market. However, the cooling capacity of the model RDE-418D4 is 1.8W at 4.2 K, which is smaller than that of the GM/JT cooler currently used. We need to reduce the 4K heat load of the cryostat, since

In order to reduce the 4K heat load without modifying the cryostat, lowering the thermal shield temperature is effective. In the present system the thermal shield temperature is in the range from 45 K to 65 K and is determined by the cooling capacity of the shield cooler, SHI model UV110CLR. If we replace the currently used compressor U108 with a larger one, the thermal shield temperature falls down and the 4K heat load of the cryostat is reduced. We tested this scenario by replacing the compressor unit U108 with SHI F-70L in the STQ20 and the STQ24 systems in Feb. 2019.

We tested F-70L compressor in the STQ24 system from Feb. 8 to Feb. 26 and in the STQ20 system from Feb. 26 to Mar. 11. These two STQ systems were chosen as the typical cryostats with high and low 4K heat load. The average heater output in the STQ24 helium vessel before replacing the compressor was 0.5 W and that of STQ20 was 1.7 W in these periods. We show in Fig. 4 how the GM head temperature, T_{Head} and the shield temperature T_{Sh} of the STQ24 cryostat are changed by replacing the

shield cooler compressors as an example. The pressure of the helium vessel P and the on/off status of the heater output are also shown. It is clearly seen that the temperature T_{Head} and T_{Sh} fall down from 63 K to 49 K and from 65 K to 46 K after the replacement. The duty of the heater output increases from 23 % to 63 % and the corresponding average heater power increases from 0.5 W to 1.3 W. Assuming that the cooling capacity of the GM/JT cooler is constant, the reduction of the 4K heat load is estimated to be 0.7 W. The similar but less significant change was observed in STQ20 system. The temperature T_{Head} (T_{Sh}) in the STQ20 cryostat changes from 49 (50) K to 45 (46) K after the replacement. The duty of the heater output and the corresponding average heater power increase from 84 % to 92 % and from 1.7 W to 1.8 W. Since the thermal shield was well cooled in the original STQ20 system, the reduction of the 4K heat load is not significant in this case. These test operations encourage us a possible replacement of new cryocoolers in the STQ system without warming up the magnet.



5. Conclusions

We have operated the 22 STQ systems for more than twelve years. 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. We consider that they are caused by impurity in the coolant gas helium. We also summarized the mechanical failures we have experienced. Aging degradation of the cryocooler system is becoming noticeable. A possible replacement of new cryocoolers without warming up the magnet is discussed.

Acknowledgments

The author thanks Kazuhiko Deguchi of Nagase Techno-Engineering Co., Ltd. for helpful discussion and providing the test apparatus. He also thanks the RIBF cryogenic operators for constant monitoring of all the STQ systems.

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