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SUPERCONDUCTING RING CYCLOTRON FOR RIKEN RI BEAM FACTORY IN JAPAN

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ABSTRACT

Since 1997, RIKEN Nishina Center has been constructing the Radioactive Isotope Beam Factory (RIBF) and succeeded in beam commissioning of its accelerator complex at the end of 2006. The world's first superconducting ring cyclotron (SRC) is the final booster in the RIBF accelerator complex which is able to accelerate all-element heavy ions to a speed of about 70 % of the velocity of light. The ring cyclotron consists of 6 major superconducting sector magnets with a maximum field of 3.8 T. The total stored energy is 235 MJ, and its overall sizes are 19 m diameter, 8 m height and 8,300 tons. The magnet system assembly was completed in August 2005, and successfully reached the maximum field in November 2005. The first beam was extracted at the end of 2006 and the first uranium beam was extracted in March 2007. However operation of the helium refrigerator was not satisfactory although the commissioning of SRC was successful. Operation was stopped every two month due to degradation of its cooling power. In February 2008 the reason of the degradation was revealed to be oil contamination. Operation of the cryogenic system was restarted from August 2008 after hard task to clean up the helium refrigerator and to add oil separators to the compressor. After restoration long-term steady operation to keep the magnet superconducting continued for about 8 months with no sign of degradation of cooling capacity.

KEYWORDS: Large scale superconducting magnet, low Tc superconductor, helium refrigerator, operation, ring cyclotron.

INTRODUCTION

RIKEN Nishina Center has been constructing the Radioactive Isotope Beam Factory (RIBF) to open and develop new fields in nuclear science and technology since 1997 [1]. The RIBF will be a next generation facility which is capable of providing the world's most intense RI beams over the whole range of atomic masses. Powerful heavy ion accelerators are essential for the RIBF because RI beams are generated by projectile fragmentation reactions of intense stable ion beams. To realize that, the cyclotrons of the fRC (fixed frequency Ring Cyclotron), the IRC (Intermediate Ring Cyclotron) and the SRC have been developed as post-accelerators for the existing accelerator complex in RIKEN, which consists of the K540-MeV ring cyclotron (RRC) and a couple of different types of injectors. This new cyclotron system is designed to provide a wide range of heavy ion beams, boosting energies up to 400 MeV/nucleon in the case of relatively light elements (atomic mass number < 40) and 350 MeV/nucleon in the case of heavier elements up to uranium. The goal is to reach beam intensity higher than 1 pμA (6 x 10^{12} #/s).

FIGURE 1 shows a plan view of the SRC. It is the first superconducting ring cyclotron with the ever largest K-value of 2600 MeV, which expresses the maximum bending power of the extracted beam from the cyclotron. The SRC mainly consists of six superconducting sector magnets [2, 3], four main RF resonators, one flattop RF resonator and injection and extraction elements. The injection bending magnet (SBM) is also superconducting. The maximum stored energy is 235 MJ. The total weight amounts to 8300 t. Its diameter and height are 19 m and 8 m, respectively. Remarkable elements of this cyclotron are the iron plates of about 1 m thickness which cover the magnetic valley regions between the sector magnets as an additional magnetic and radiation shielding. They reduce the leakage field from the sector magnets and decrease the magneto motive forces at the maximum bending power. FIGURE 1 shows the cross-section and plan views of the sector magnets. Each sector magnet is 7.2 m long and 6 m high and weighs about 800 t. The sector angle is 25 degrees. The maximum sector field is 3.8 T, which is required to accelerate U88+ ions at 350 MeV/nucleon. Main components of the sector magnet are a pair of superconducting main coils, four sets of superconducting trim coils, a cryostat, thermal insulation support links, twenty-two pairs of normal conducting trim coils, warm-poles and a yoke. All the magnets were assembled in the vault in August 2005, proceeding

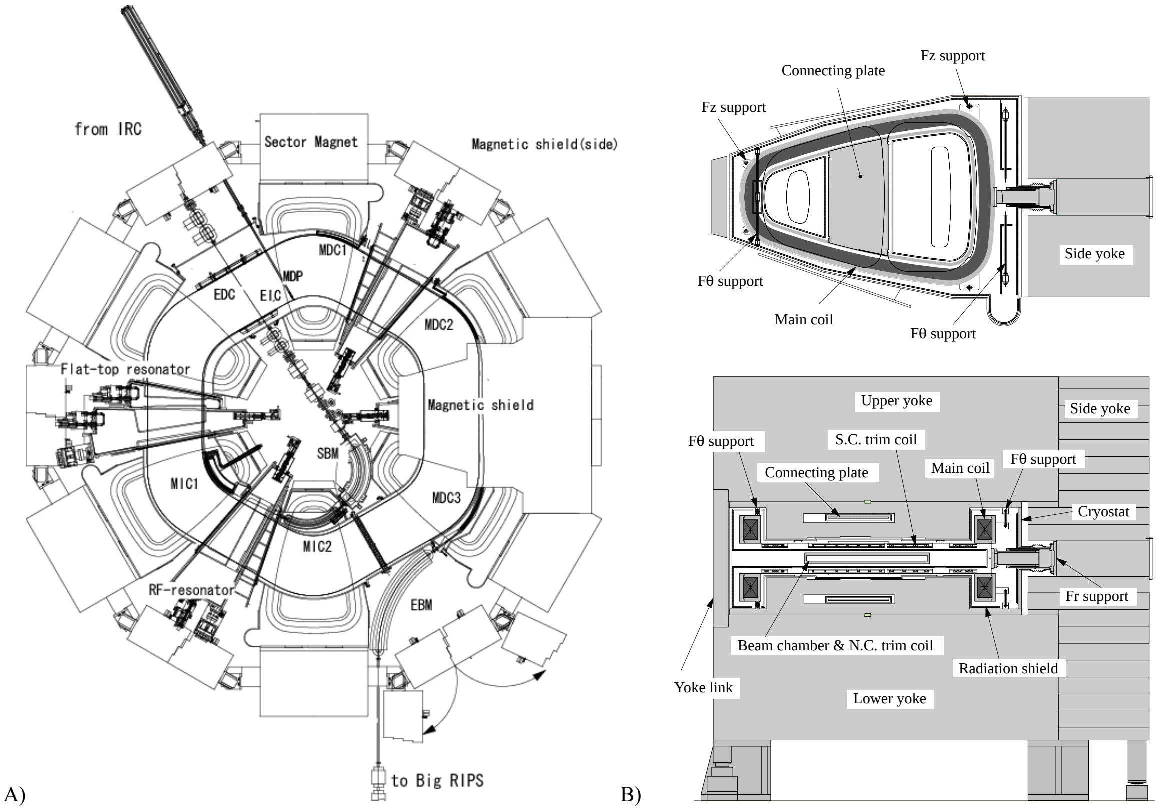

FIGURE 1. A) A plan view of the SRC. B) Cross-section and plan views of the sector magnets.

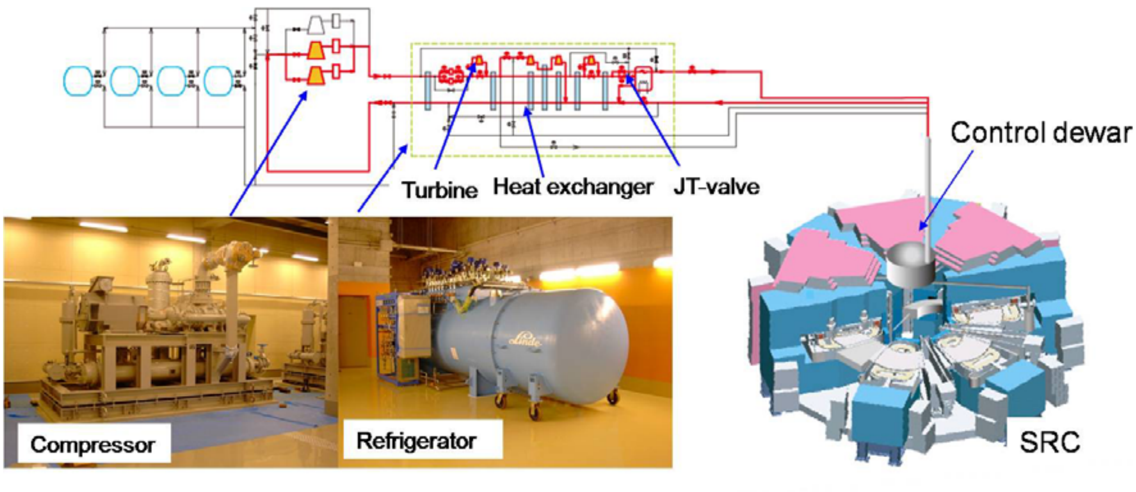

FIGURE 2. Outline of the cryogenic system for the SRC.

to the commissioning of the SRC.

SUCCESSFUL COMMISSIONING

The cryogenic cooling system consists of four helium reservoir tanks, three compressors (one for backup), a helium refrigerator and a control Dewar for the magnet. The control Dewar, which is located on top of the SRC, gathers the pipes and cables from the six sector magnets to make a closed circuit as shown in FIGURE 2. The cooling capacity of the helium refrigerator is 620 W at 4.5 K, 4000 W at 70 K and circulation of 4 g/s helium gas for cooling of the current lead. It is estimated that it takes three weeks for this system to cool the cold masses of 142 ton from room temperature to 4.5 K. The cooling capacity of the system was designed to be more than 1.5 times of the estimated heat loads on the whole superconducting magnet system. FIGURE 3 is the inside of the helium refrigerator TCF200s. It consists of 4 expansion turbines, 7 heat exchangers and pipes between the elements. Two 80 K adsorbers and 20 K adsorber are installed to remove impurities at each temperature. A phase separator is located in front of the liquid helium supply line to the superconducting magnets.

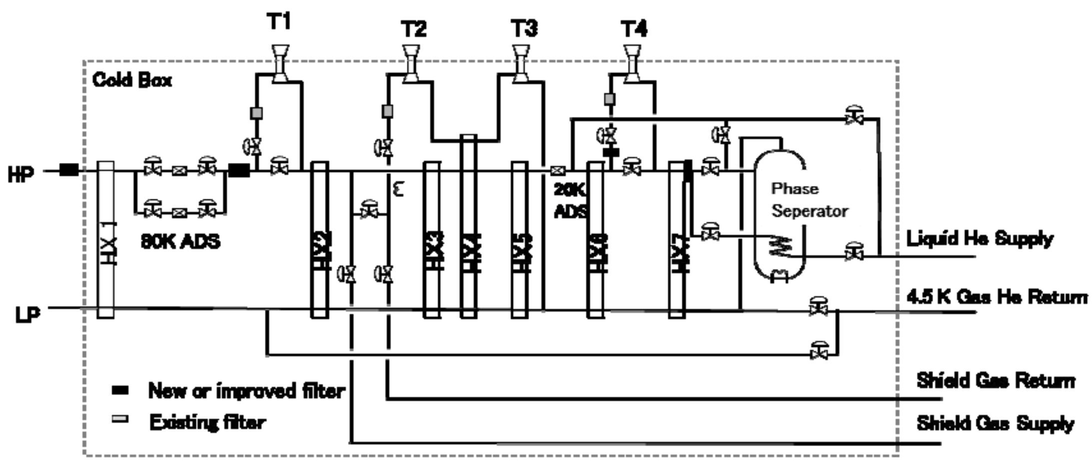

FIGURE 3. Diagram for the SRC helium refrigerator. T1-T4 stand for the first – forth tubines, HX1-7 stand for the 1st-7th heat exchangers. The new or improved filters are shown with the existing ones.

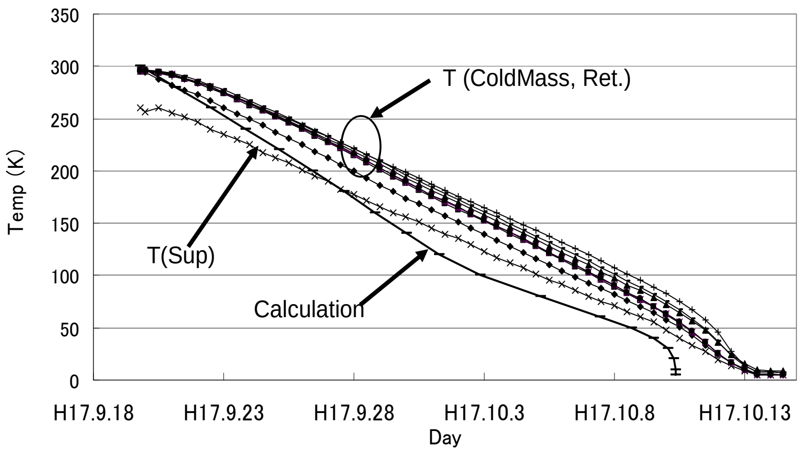

FIGURE 4. Temperature trend graphs of the SRC superconducting magnets in the first cool-down.

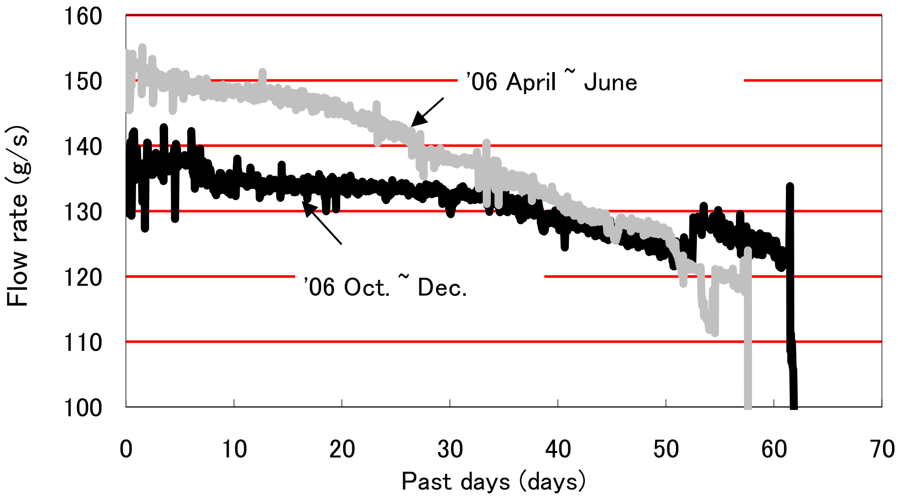

FIGURE 5. Flow rate thorough the first turbine in 2006-2007 operations.

Cool-down and excitation tests including magnetic field measurements were performed after the completion of the assembly of the superconducting sector magnets. After purification operation in the cryogenic cooling system, cool-down of the cold mass was started on 9/19/2005 and all the main coils transitioned to superconducting phase on 10/13. FIGURE 4. Cool-down curves of the SRC superconducting magnets. The temperatures of the cold masses smoothly fell into the liquid helium temperature. The temperature of the inlet gas from the helium refrigerator was so tuned that the temperature difference between the inlet gas and the cold mass was kept below 50 K. The calculated cool-down curve is also shown in FIGURE 4. It took 23 days to cool down the coils, two days were longer than the calculation had predicted. The excitation test was started from 10/21 with small currents and all the coils were fully excited on 11/7 without quench. But the tests were stopped in the next morning until the middle of March, 2006 due to a big trouble about helium leakage into thermal insulating vacuum. The coils were fully excited again on 4/15 and the field measurements were performed for about two months. Finally a fast shutdown test from full excitation was carried out. In the series of the tests, the following check points were focused. The first point is that cooling capacity of the cryogenic system for the superconducting magnets is enough to cool-down the cold mass from room temperature to liquid helium temperature. The second point is that the coils can be excited without quench and large magnetic forces can be supported. The third point is that the coils can be safely shut-down. In shut-down process, strong coupling between the main coils and the trim coils and eddy current losses in the aluminum plates for the superconducting trim coil supports were concerned. The fourth point is that generated fields are good enough to accelerate the ions in this cyclotron. Especially the dispersion of magnetic fields among the six sector magnets and accuracy of TOSCA calculation were concerned. The final point is that operations of the helium refrigerator are stable. All the parts necessary for the first beam were installed and tested after the series of the tests on the superconducting magnets. The beam commissioning for the SRC started after beam vacuum and radio frequencies were ready. The first beam was extracted at the end of 2006. The first uranium beam was extracted in March 2007 [4]. In May uranium beams were supplied for new isotope search experiments.

OIL CONTAMINATION OF HELIUM REFRIGERATOR

The cryogenic system for SRC successfully cooled-down the large superconducting magnets to carry out the magnetic field measurements and beam commissioning from 2006 to 2007. However the operation of the refrigerator itself was not so satisfactory that it was stopped every two month due to the degradation of the cooling power. FIGURE 5 shows that flow rate in the helium cooling system gradually decreases, increasing the temperature of the 80 K stage adsorber and decreasing the pressure of the T1 inlet. This suggests that some impurity accumulates somewhere around the first turbine. Regeneration of the 80 K stage adsorber alone did not improve the situation. The refrigerator had to be stopped every two months to warm it up to room temperature and remove the impurity. Some investigations especially on the impurities such as H_20, N_2 carried out during their operation did not give us any suggestion about the reason why the cooling capacity degrades in such short period as two months. In February 2008, however, a few drops of oil found at the seat of the cryogenic valves in the helium refrigerator for SRC gave us the key to solve the problem, starting the investigation about the oil contamination.

Firstly the investigation how much oil is included in the helium refrigerator and where the oil comes from was focused. Infrared spectroscopy about the oils made it clear that they come from the screw compressor not from the vacuum pump and so on. The filter located at the just upstream of the first turbine was opened to check whether the oil reach there going through the 80 K adsorber made from charcoal which can protect oil from the compressor. The mixture of the charcoal and oil was found there, strongly indicating that

FIGURE 6. The left photo shows cutting process of the heat exchanger unit from the refrigerator. The right one shows a cleaning process of the heat exchangers in a factory.

oil comes from the compressor too much enough to run over the 80 K adsorber due to its saturation and disperse to the lower temperature stage of the helium refrigerator. Next the 1st heat exchanger (HX) was inspected, finding much oil there, furthermore, finding it very difficult to remove the oil by cleaner of AK225 (HCFC-225ca) from the HXs which has complicated structure and sits in sideway. Only less than ten percent of the contained oil in the 1st HX could be removed after many try and errors. So the unit of the 1st – 5th HXs was decided to be cut from the refrigerator in April to clean in the factory as shown in FIGURE 6, which allow us to clean them in the various sitting angle and to access to the lower temperature region in the helium refrigerator. FIGURE 6 shows the cleaning process of the heat exchanger unit in the factory. This cleaning let us know the correct volume of the contaminant of the oil and charcoal from the 80 K adsorber. In RIKEN site, the inspection on the lower temperature region gives us the volume of the oil using NVR (Non Volatile Residue) technique. Finally it was revealed that the oil of about 2000 cc was contained in the helium refrigerator and the cleaning was carried out so as to decrease the contained oil up to about 4 cc. The exchange of the charcoal in the 80 K adsorber was hard task due to the limited access to their inside. Filling charcoal to the vessel for the 80 K adsorber without spaces is important to prevent degradation of the charcoal which gives damages to the seats of the cryogenic valves and the heat exchangers in the helium refrigerators. It was successfully performed after many try and error.

In parallel with the cleaning process, additional oil separators were designed after reconsiderations of the oil separation system in the compressor unit. Originally it consists of four oil separators. The 1st is demister type, the 2 and 3rd ones consist of coalescer elements and the 4th consist of the charcoal and molecular sheaves. The coalesce elements (the 1.5 th separator) and the 5th separator made of charcoal were decided to be added as shown in FIGURE 7. The estimated oil contamination is about 20 ppb which is about one fifth of the original designed values. Furthermore, the filters against incoming oil were installed before and in the inside of the helium refrigerator as shown in the FIGURE 3. The recovery process including many welding points for the pipe and covering super insulators was the next important issues. Especially welding was hard task in limited space of the inside of the refrigerator.

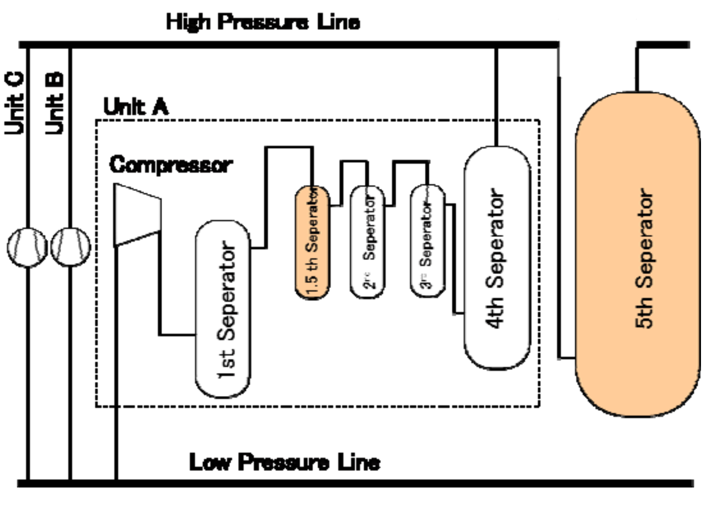

FIGURE 7. The oil separators for the helium compressors. The 1.5th and 5th separators were newly installed.

OPERATION AFTER RESTORATION

Permission to make the high pressure gas was given on 8/28/2008 from Saitama prefecture after all the process for recovery. The test for the compressor running and the stand-alone operation of the refrigerator was performed before cool-down the superconducting magnets for SRC was started. Tests on the helium compressor were carried out to check performances of the oil separation systems where the 2-stage separators were newly installed. Measured data showed that oil contamination was lower than the level which the cold trap monitor can detect (40 ppb) while designed contamination is 20 ppb. The test result shows that cooling power in the stand-alone operation is 1378.2 W at 4.5 K while initial cooling power was 1410.4 W in 2004. The degradation, which is allowable for the cool-down of the SRC magnets, may rise from pressure drops because of the adding the some filters in the high pressure lines of the refrigerators.

The test results about compressor and refrigerator mentioned above let us proceed to the next stage of operation of the helium refrigerator in the connection with the superconducting magnets. After purification operation for about 1 week, cool-down operation of the superconducting magnets was started. It took about 22 days to cool-down the superconducting magnets from room temperature to 4.2 K, indicating no degradation of cooling power compared with first cool-down when the refrigerator contained no oil. After the end of cool-down operation, liquid helium was transferred to the helium vessel for the magnets and steady operation was attained on 10/3/2008. The superconducting magnets were excited to accelerate uranium and calcium beams in the SRC in November and December of 2008. The stable steady operation is continuing until 6/4/2009 without any severe trouble requiring us to stop the refrigerators. FIGURE 8 shows the flow rate trend through the helium refrigerator with the trends during 2006-2007 operation. Long-term operation lasted about 240 days, showing no sign of degradation of the flow rate, while operation in 2006 and 2007 was terminated around 60 days due to degradation. These trend graphs clearly suggest that this phenomenon occurred due to oil contamination in the refrigerators and the present refrigerator was very clean. In 2006-2007 the refrigerator was warmed up every two months to room temperature to recover cooling power. It is understood now that the frequent warm-ups made the oil to disperse to all the pipes of the refrigerator.

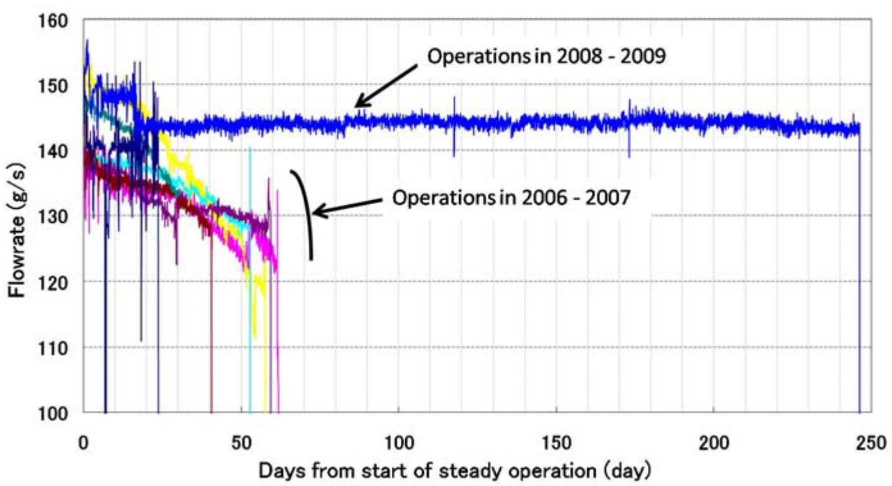

FIGURE 8. Flow rate trends in the helium refrigerator in 2008-2009 operation with those in 2006-2007 operation which were ended at about sixty days.

In the long term operation, monitoring oil contamination from the compressor is very important for preventing oil contamination of the helium refrigerator again. Cold trap measurement after the final stage is performed once every two months and oil contamination after each separator was measured once a month. Oil volume in the drain of the each separator is continuously monitored. Any data related with oil separator performance showed no sign abnormal increase of the oil impurity in the helium gas which is injected to the helium refrigerators.

SUMMARY

The SRC was successfully commissioned from 2005 to 2007. However, operation of the cryogenic system for the SRC magnets was not satisfactory due to degradation of cooling power. In the beginning of 2008 it was revealed that the degradation was caused by oil contamination from the helium compressor. Oil in the helium refrigerator was cleaned up and the two stages of oil separator were added to the existing ones. The long steady operation which started from 10/3/2008 continued for about 240 days with no sign of degradation of the cooling power.

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