ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2023, Vol. 87, No. 5, pp. 580–584. © Allerton Press, Inc., 2023.
Russian Text © The Author(s), 2023, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2023, Vol. 87, No. 5, pp. 660–664.

Cryogenic System of a Superconducting Undulator, Based on Indirect Cooling

S. V. Khrushchev[a, b, *], **V. M. Tsukanov**[a, b], **V. A. Shkaruba**[a, b], **N. A. Mezentsev**[a, b], **and A. N. Safronov**[a]

[a] *Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*

[b] *SKIF Synchrotron Radiation Facility, Boreskov Institute of Catalysis, Siberian Branch, Russian Academy of Sciences, Koltsovo, 630559 Russia*

**e-mail: Khruschev@mail.ru*

Received November 28, 2022; revised December 15, 2022; accepted January 25, 2023

Abstract—A description is given of a cryogenic system of a superconducting undulator with a period of 15.6 mm, a magnetic field of 1.2 T, and a magnetic gap of 8 mm, based on indirect cooling. Nitrogen heat pipes are used as heat conductors from the magnetic system to the first stage of cryocoolers in order to accelerate the process of initial cooling. The magnetic system is completely cooled using gaseous helium instead of cryogenic liquids. The design of the cryogenic system, the cooling process, and the functioning of the system in different modes are described.

DOI: 10.3103/S1062873822701829

INTRODUCTION

To improve the efficiency of using a magnetic system of superconducting insertion devices (wigglers and undulators), we must minimize the difference between its magnetic gap and the vertical aperture in the device cryostat. The design for the insertion devices we recently created is therefore based on indirect cooling [1, 2], where the magnetic system is in a vacuum, and heat is removed from it using tubes with circulating liquid helium.

ADVANTAGES OF SUPERCONDUCTING INSERTION DEVICES WITH INDIRECT COOLING

The magnetic system of the direct-cooled insertion device is located entirely in a tank filled with liquid helium. The helium tank has a cold vacuum chamber located inside the magnetic gap of the magnetic system, which has the temperature of liquid helium. A cold vacuum chamber, to avoid its heating by a passing beam, must have a copper screen inside it (i.e., a liner with a temperature below 20 K).

The magnetic system of the plug-in device with indirect cooling is in a vacuum. Inside the magnetic gap, it is sufficient to have only a vacuum chamber with a temperature below 20 K, separated by a gap from the magnetic system.

In the latter case, we can reduce the magnetic gap while maintaining the same vertical aperture, thus increase the magnetic field. In our devices, the magnetic gap was reduced by 1 mm upon switching to indirect cooling [1, 2].

In addition to the above, the transition to indirect cooling allows precooling without the use of liquid helium. Only gaseous helium in cylinders is used. These features are discussed below.

CRYOGENIC SYSTEM OF THE UNDULATOR

The magnetic system of the undulator consists of upper and lower halves connected to each other through spacers. Each half is a 6063 aluminum alloy plate with coils attached to it. A hole is made along each of the plates to pass liquid helium, cooling the plates and thus the coil. A small helium tank (about 40 L) is fixed above the magnetic system and filled with liquid helium in working condition. The holes in the plates are connected to the helium tank by flexible pipes: one end of the hole is at the bottom of the tank, and the other is at the top (Fig. 1). Helium from the bottom of the tank flows through the holes in the plates and, when the temperature of the magnetic system is higher than that of liquid helium, evaporates and exits in the form of gas in the upper part of the tank.

Two gold-plated copper heat exchangers are installed inside the helium tank, connected to the second stages of two SRDK-415 cryocoolers with a nominal temperature of 4.2 K. A neck in the upper part of the helium tank has an emergency bursting disc and a safety valve for gas discharge in case of quench, along

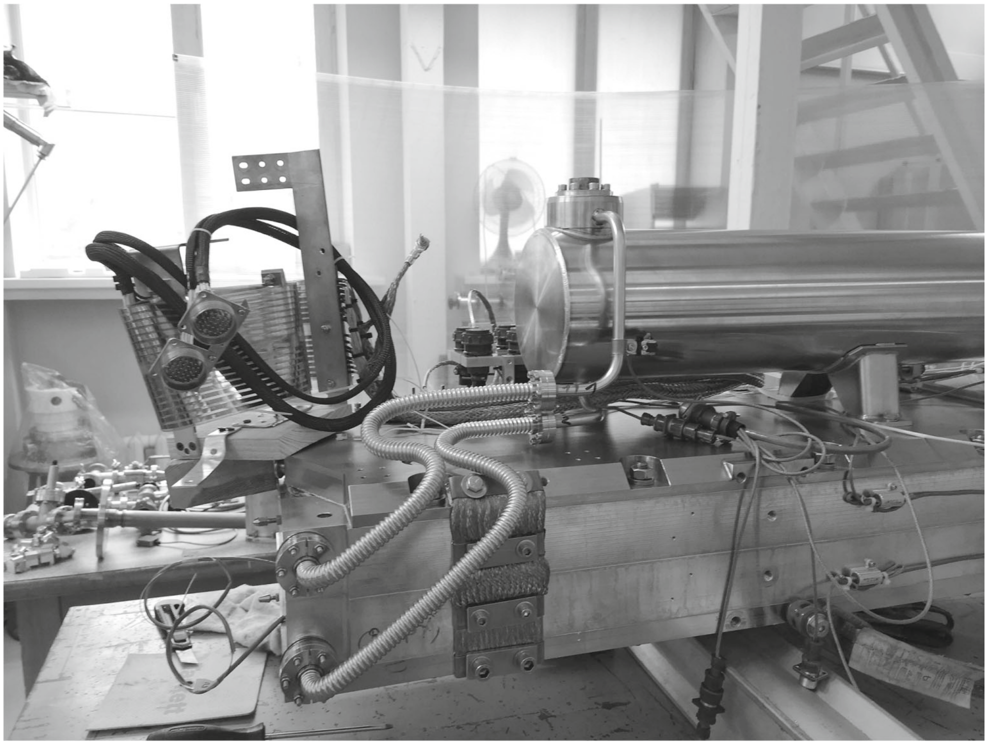

Fig. 1. Connection of a helium tank with longitudinal holes in the magnetic system. The figure shows the entrance to the lower half of the magnet and the exit from the top.

with a filler neck that, if necessary, can be used to fill liquid helium (during many months of active testing, it was never used).

NITROGEN HEAT PIPES FOR PRECOOLING

Nitrogen heat pipes are used for precooling; they ensure a thermal connection between the first stages of SRDK-408 cryocoolers with a nominal temperature of 60 K (the temperature at these stages in operation drops to approximately 40 K) and the magnetic system [3–5]. Heat pipes accelerate precooling from room temperature to liquid nitrogen temperature.

COOLING THE UNDULATOR WITHOUT USING LIQUID HELIUM

Vacuum volumes are pumped out before precooling the undulator. A cylinder with gaseous helium is connected to the helium tank through a reducing gear set at an overpressure of 0.5–0.7 bar. All four cryocoolers are turned on.

Two cooling circuits operate in parallel when cooling the device. At relatively high temperatures, the heat from the magnetic system is mainly removed by nitrogen heat pipes (Fig. 2). Their efficiency in the cooling process is up to 100 W.

Heat pipes need optimum thermal regime for their efficient operation. The first stages of cryocoolers with a nominal temperature of 60 K, to which the heat pipes are connected, have excessive efficiency, so it is necessary to keep the temperatures on them from dropping too low, which can cause premature freezing of nitrogen in the heat pipes and terminate their work. In working with nitrogen heat pipes, we used two options for temperature stabilization at the first stages of cryocoolers. In our first “dry” wiggler, compact heaters were installed at the first stages of the cryocoolers, and the required thermal regime was maintained by software from an external power source [6]. The heating technque was subsequently tested by turning off the cryocoolers [7]. Both ways worked, but the second option has now been abandoned. Active manipulation of cryocooler compressors during the cooling process can affect their service life. The second option also practically excludes the participation of the helium circuit during the operation of nitrogen heat pipes, since turning off the coolers leads to an increase in temperature not only in the first stages but also in the second ones, which cool helium in the helium tank. The currently used control program provides for the possibility of using any option.

The graph (Fig. 3) shows the process of one cooldown with all its nuances. Upon cooling, one of the main thermal sensors (contact in the cable) worked unstably for an interval of 33–43 h, which

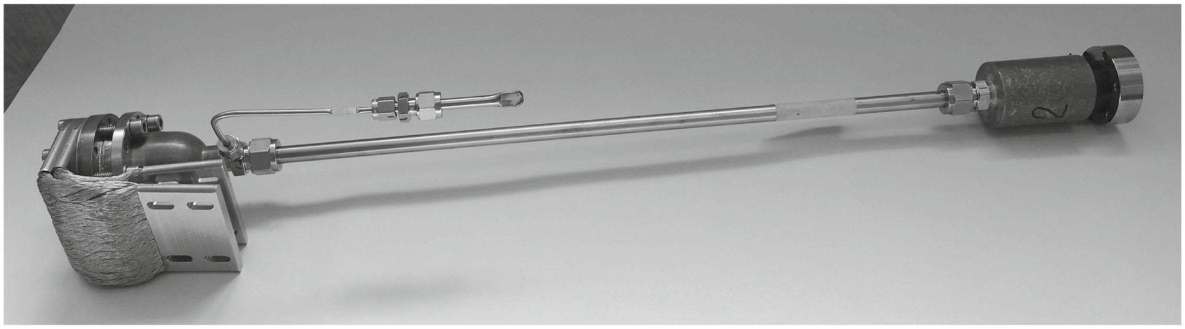

Fig. 2. Nitrogen heat pipe.

resulted in a slowdown in the cooling process because of an overcooling of one of the heat pipes. Interval 131–155 h reflects an emergency power outage when the cooling system was completely stopped, resulting in an increase in all temperatures. This did not cause any technical problems, except for an increase in the total cooldown time. Restoring operation only required restarting the compressors. Over 40 h were lost due to a power outage.

The nitrogen cooling system was turned off at 73° (after 175 h of chilling).

The efficiency of each heat pipe can be individually assessed by the temperature difference between specific temperature sensors T01 and T02, located on the upper surface of the magnet near the heat pipes, and temperature sensor T03, located on the bottom surface of the magnet, almost equidistant from the first two (Fig. 4).

After the nitrogen cooling system is switched off (nitrogen freezing in the heat pipes), only the helium cooling circuit participates in the operation (Fig. 4). The helium circulating through the upper and lower halves of the magnetic system is cooled in the helium tank by the second stages of cryocoolers with a nominal temperature of 4.2 K.

The overall efficiency of the cooling system can be estimated from the change in temperature at the temperature sensor T03, located on the lower surface of the magnet, almost equidistant from the heat pipes (Fig. 5).

Our results show the cooling efficiency at the moment the heat pipes were turned off (after 176 h) changed negligibly. This suggests the contribution from the helium system by this time already exceeded the one from nitrogen substantially. In terms of the magnitude of the change in the cooling rate at the moment the heat pipes were turned off (after 176 h),

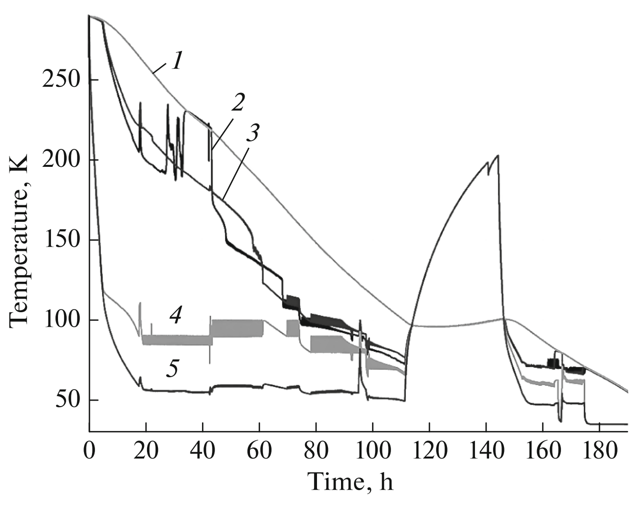

Fig. 3. Operation of the nitrogen cooling system: (*1*) temperature at the bottom of the magnet, (*2*) temperature at the input end of the magnet, (*3*) temperature at the output end of the magnet, (*4*) temperature at the recondensing head of the heat pipe, and (*5*) temperature at the first stage of the cryocooler.

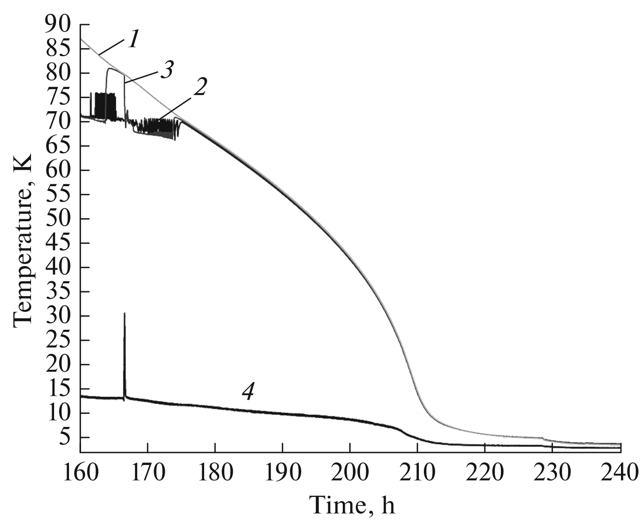

Fig. 4. Operation of the helium cooling system: (*1*) temperature at the bottom of the magnet, (*2*) temperature at the input end of the magnet, (*3*) temperature at the output end of the magnet, and (*4*) temperature at the second stage of the cryocooler.

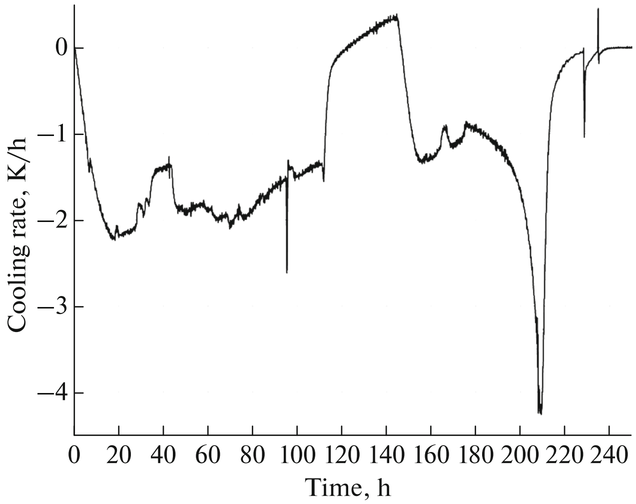

Fig. 5. Overall efficiency, the derivative of the temperature on the magnetic system vs. time (sensor T03).

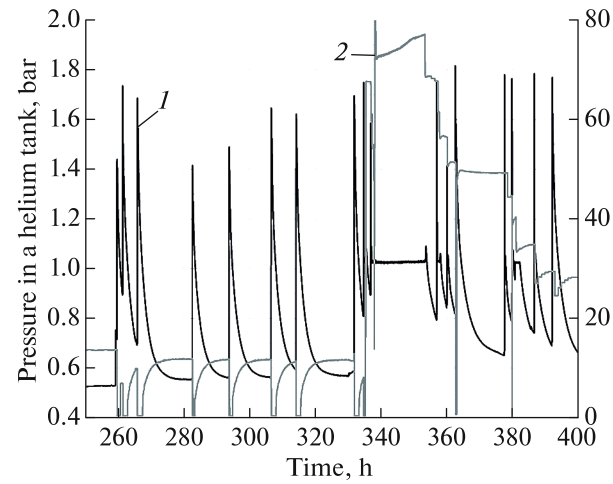

Fig. 6. Behavior of the pressure and helium level in a helium tank during the quench of superconductivity: (*1*) pressure in the helium tank and (*2*) liquid helium level in the tank.

the helium system was ten times more efficient than the nitrogen system.

One conventional 40 L cylinder (120–150 bar) of helium is sufficient for a complete cooling cycle. Upon cooling, 5–10% of the liquid accumulates in the tank, which is already enough for the normal operation of the device.

The cooling system of the device with indirect cooling is quite simple. A helium cylinder is connected to the helium tank through a low-pressure gas reducing gauge, which enables setting the pressure in the helium tank of the cryostat with sufficient accuracy. The cylinder can be installed at any (reasonable) distance from the cryostat. A plastic tube 6 mm in diameter was used to connect the cylinder and the cryostat.

The efficiency of the helium cooling circuit depends on the pressure in the tank. We improved the safety valve by adding a spring and an adjusting screw that helps to adjust the overpressure from 0.35 to 2 bar.

During operation, a pressure sensor was installed between the cylinder and the reducing gauge, measuring the remaining helium in the cylinder and, if necessary, stopping the helium supply. Measuring the dynamics of pressure in the cylinder allowed us to evaluate the efficiency of the helium system in the cooling process. Unfortunately, the pressure sensor was installed after the magnet had cooled.

CRYOGENIC SYSTEM IN THE SUPERCONDUCTIVITY QUENCH

During normal operation, the efficiency of the cryogenic system is sufficient to maintain the pressure in the helium tank below atmospheric pressure (0.7 bar). The temperature of the magnetic system drops to 3.5 K. The minimum temperature of the magnetic system is determined by the balance between the productivity of cryocoolers, which is 2 W at 4.2 K and fall along with temperature, and a parasitic heat influx to the magnet [8]. In our case, the measuring chamber of the magnetic measurement system contributes largely to the heat gain.

Two curves in Fig. 6 demonstrate the absolute pressure in the cryostat and the helium level. High-pressure peaks are caused by quench of superconductivity.

The initial part of the graph (250–339 h) shows the work immediately after cooling down with one helium cylinder. The cylinder is enough to fill the tank by approximately 12% of the volume. At this level in the tank, quenches of superconductivity do not affect it.

The tank was subsequently refilled. The cylinder was replaced, and the helium level was raised to over 75%. As a result, each quench led to a significant loss of helium (level change from quench to quench from 75 to 50, 35, and 30%). The lower the helium level before the quench, the smaller the corresponding loss. The loss also depended on the setting of the safety valve; the higher the set pressure, the higher the helium level stabilization value. When the valve was set to 1.8 bar, the filling of the tank stabilized at 20%.

There is thus no need to fill the tank by more than 10–15% during operation. The filling level of the tank does not affect the operation of the magnet.

The system recovers after a quench with no external intervention: approximately 3 h after the quench, the pressure in the tank drops to atmospheric pressure and the undulator is ready for operation again. It takes about 7 h to achieve a reduced pressure of 0.7 atm.

CONCLUSIONS

Our cryogenic system with indirect cooling makes it much easier to work with device. No cryogenic liquids are required to cool the magnet. The initial cooling of the magnet does not require the participation of technical personnel. One cylinder of compressed (120–150 bar) helium is sufficient to bring the device mounted on the ring into working condition. Superconductivity quenchs do not require the intervention of technical personnel, which greatly simplifies the maintenance of the device installed on the ring. All of these advantages compensate for the increase in cooldown time.

FUNDING

This work was performed as part of agreement no. 075-15-2021-1359 with the RF Ministry of Science and Higher Education and State Task no. FWUS-2021-0004 for the Institute of Solid State Chemistry and Mechanochemistry.

CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

REFERENCES

1. Shkaruba, V.A., Bragin, A.V., Volkov, A.A., et al., *Phys. Part. Nucl. Lett.*, 2020, vol. 17, no. 4, p. 542
2. Shkaruba, V.A., Bragin, A.V., Volkov, A.A., et al., *Pis'ma Fiz. Elem. Chastits At. Yadra.*, 2020, vol. 17, no. 4, p. 567.
3. Tsukanov, V.M., Khrushchev, S.V., Mezentsev, N.A., et al., *AIP Conf. Proc.*, 2020, vol. 2299.
4. Bragin, A.V., Khruschev, S.V., Mezentsev, N.A., et al., *Proc. 13th IIR Int. Conf. Cryogenics 2017*, Dresden, 2017, p. 400.
5. Khrushchev, S., Lev, V., Mezentsev, N., et al., *Phys. Procedia*, 2016, vol. 84, p. 90.
6. Bragin, A., Gusev, Ye., Khrushchev, S., et al., *Phys. Procedia*, 2016, vol. 84, p. 54.
7. Shkaruba, V., Bragin, A., Erokhin, A., et al., *AIP Conf. Proc.*, 2020, vol. 2299, p. 020005.
8. Khruschev, S., Mezentsev, N., Shkaruba, V., et al., *Proc. 15th IIR Int. Conf. Cryogenics 2019*, Prague, 2019, p. 0043.

Translated by O. Zhukova