Plug-in Wire for 200-pixel Superconducting Tunnel Junction X-ray Detector Array for Helium-3 Cryostat

'S Shiki¹, G Fujii¹, M Ukibe¹

¹Department of Nanoelectronics, National Institute of Advanced Industrial Science and Technology, 1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

E-mail: s-shiki@aist.go.jp

Abstract. A plug-in wire system is designed for a 200-pixel superconducting tunnel junction (STJ) X-ray detector array for a helium-3 cryostat. The STJ array and the room-temperature electronics are electrically connected by wire modules that have connectors at both ends. Two types of wire module are used to balance the electric conductance and thermal conductance under various temperature conditions. One type uses a copper-based miniature coaxial cable harness, and is utilized to electrically connect the room-temperature electronics to the 3 K stage. The other type uses woven wire looms of twisted-pairs of NbTi wire, and is used to electrically connect the 3 K stage to the helium-3 stage. With the installation of all wire modules, the temperature of the cold stage is less than 310 mK, and the holding time is more than 80 hours. The plug-in wire system is suitable for large-scale STJ X-ray detector arrays.

1. Introduction
Superconducting tunnel junction (STJ) X-ray detectors are promising for materials analysis because of their high energy resolution and high counting rate capability. 100-pixel STJ arrays have been applied in fluorescence yield X-ray absorption spectroscopy [1,2] and elemental analysis of scanning electron microscopy [3]. However, to realize a more practical analytical instrument based on STJ X-ray detectors, it is necessary to overcome the following two technical difficulties. One is achieving throughput equal to that of a silicon drift detector by making a large pixel array. The other is developing a scalable wiring system for connecting the STJ array detectors in the cold stage of a helium-3 cryostat and the room-temperature (RT) readout electronics. Large-format STJ arrays (1000-pixel array with an area of 10 mm²) have been already developed [4]. However, realizing the scalable wiring system is still difficult because in a conventional wiring system for a cryostat, all wires are usually soldered by hand. Therefore, we have developed a plug-in wire system in which all electrical wires are attached to connectors at both ends. These connectors are used to electrically connect the STJ array to the RT electronics. In this paper, we show the performance of a helium-3 cryostat with the plug-in wire system designed for a 200-pixel STJ array.

2. Cryostat configuration
The plug-in wire system is installed in a cryostat consisting of a ³He sorption cooler and a pulse tube refrigerator supplied by Niki Glass Company. The cryostat can achieve a temperature of below 1 K, which is the operation temperature of a Nb STJ (Fig. 1).
In the cryostat, three different temperature conditions are used to achieve a cold temperature environment for efficient STJ detector operation. The temperatures in these three conditions are 30 K, 3 K, and 300 mK, respectively. The 30 and 3 K conditions are maintained by the pulse tube refrigerator and the 300 mK condition is maintained by the $^3$He sorption cooler. There are three stages for the three temperature conditions for utilizing the different temperature environments (30 K, 3 K, and 300 mK) for experiments, called the first stage, second stage, and $^3$He stage, respectively. All stages are under the vacuum conditions for thermal insulation from the RT environment. With this configuration, our cryostat could hold a temperature of about 300 mK for 130 hours before the installation of the plug-in wire system.

3. Plug-in wire system

To achieve a long cooling time, the thermal flow from RT to the $^3$He stage via wires utilized for electrical connections is normally minimized by using wires made of high-resistivity materials, which makes the total resistance between the STJ detectors and RT electronics large. To reduce the noise of readout electronics, it is necessary to keep the resistance between detectors and readout electronics as small as possible. To meet these contradictory requirements, the plug-in wire system is divided into three portions based on the temperature conditions, which are RT to the first stage (RT-1S), first stage to second stage (1S-2S), and second stage to $^3$He stage (2S-$^3$He), respectively. In each portion, the electrical connection is realized using a wire harness module with 50 lines for 25 STJ pixels. The number of wire harnesses is determined by the pixel number of STJ arrays. Two lines are required for one STJ pixel because a common ground is not used in our cryostat. Therefore, eight wire harnesses are necessary in a portion for the 200-pixel array.

Electrical connections between wire harnesses in different portions are established by four extension boards, at RT and in the first stage, second stage, and $^3$He stage, respectively, without soldering by hand. The extension board at RT has a 50-pin D-Sub connector and a 50-pin surface-mount connector (Cabline-SS). The other three extension boards have two 50-pin surface-mount
connectors. In addition, the 50-pin D-Sub connector on the extension board at RT is linked to a hermetically sealed male/male 50-pin D-Sub connector of a vacuum feedthrough.

A wire harness consisting of 50 AWG42 coaxial cables and 50-pin connectors is used in the RT-1S and 1S-2S portions. The coaxial cable (resistance: 7 Ω/m) is made of tin-doped copper with an unknown dopant concentration. Because in the RT-1S and 1S-2S portions, the reduction of the thermal flow from RT is the most important. If conventional cables made of pure Cu (resistivity: 5-6 Ω/m) are used, the heat load to the second stage will be approximately 0.5 W, which exceeds the cooling capability of the pulse tube refrigerator.

In the remaining portion (2S-3He), a wire harness consisting of woven wire looms of 25 twisted pairs of AWG42 NbTi wires is used because NbTi becomes a superconductor at the temperature in this portion and exhibits low thermal conductivity in addition to zero resistance (Fig. 2). In this portion, low thermal conduction and high electrical conduction are realized simultaneously.

The thermal flow through the above wire system was estimated as follows. The thermal flow can be determined using the total cross section, wire length, and wire thermal conductivity [5-6]. The total length of all wires in the harness is 1.0 m. The thermal conductivity of AWG42 coaxial cable at above 8 K has not been reported in the literature. However, we assumed that the thermal flow in the coaxial cable is almost equal to that in BeCu with a diameter of 0.33 mm because the thermal conductance of the coaxial cable is approximately half of that of a 0.86-mm semirigid coaxial cable of BeCu at temperatures below 8 K [7]. The estimated thermal loads for the first, second, and 3He stages are 3 W, 30 mW, and 1.4 μW, respectively. With these thermal loads, it should be possible to obtain a long holding time at 300 mK in our cryostat. The temperature and holding time were measured to investigate the effect of the plug-in wire system on cooling performance.

4. Cooling performance
The temperature of the $^3$He stage was measured to investigate the effect of the plug-in wire system on cooling performance (Fig. 3). The temperature of the cold stage was less than 310 mK, and the holding time was more than 80 hours. The holding time decreased by approximately 50 hours due to the installation of the plug-in wire system. The main reason for the holding time reduction is thermal load through the coaxial cables between RT and the second stage. For 200 pixels, the cooling performance is sufficient for experiments. However, since the thermal load increases with increasing number of pixels, the thermal load for a 1000-pixel STJ array would be much larger than the cooling capability of the $^3$He sorption cooler. Therefore, the heat load through the wire harnesses should be reduced by using conductor materials with low thermal conductivity, such as phosphor bronze, constantan, manganin, or stainless steel, instead of tin-doped copper.

The $^3$He cryostat was combined with fluorescence yield X-ray absorption spectroscopy [8] on beamline BL-11A in the Photon Factory at the High Energy Accelerator Research Organization (KEK) to show the reliability of the plug-in wire system. A cold finger with a length of approximately 70 cm was attached to the $^3$He stage to realize high sensitivity to fluorescent X-rays from a sample. Figure 4 shows the temperature curve of the $^3$He stage. The temperature of the $^3$He stage is 317 mK, with a holding time of 35 hours. Some peaks appear in the temperature curve. The peaks occurred when the experimental configuration was changed. The holding time decreased by 45 hours due to the installation of the cold finger. The main reason for the reduction in holding time is the heat capacity of the cold finger and the thermal load through the support of the cold finger. The cooling performance of the $^3$He cryostat is sufficient for fluorescence yield X-ray absorption spectroscopy experiments with a synchrotron source, for which a holding time of more than one day is required.

![Temperature curve of a helium-3 cryostat with proposed plug-in wire system.](image)
5. Conclusion
A scalable plug-in wire system was developed for large-format STJ arrays. The proposed plug-in wires for a 200-pixel STJ array were installed in a cryostat with a $^3$He sorption cooler. The temperature of the cold stage was less than 310 mK, with a holding time of 80 hours, using the plug-in wire system.

Acknowledgement
This work was carried out as part of Toyota's collaborative research program. This work was performed under the approval of the Photon Factory Program Advisory Committee (Proposal No. 2017G625).

References
[1] Friedrich S, Harris J, Warburton W K, Carpenter H M, Hall J A, Cantor R 2014 J. Low Temp. Phys. 176 553–559
[2] Shiki S, Ukibe M, Kitajima Y, Ohkubo M 2012 J. Low Temp. Phys. 167 748–753
[3] Fujii G, Ukibe M, Shiki S, Ohkubo M 2017 X-Ray Spectrometry 46 325–329
[4] Fujii G, Ukibe M, Shiki S, Ohkubo M 2017 J. Low Temp. Phys. 184 194–199
[5] Garwin R L 1956 Rev. Sci. Instruments 27 826–828
[6] Olson J R 1997 Cryogenics 33 729–731
[7] Kushino A, Kasai S, Ukibe M, Ohkubo M 2018 J. Low Temp Phys 193 611–617
[8] Shiki S, Zen N, Ukibe M, Ohkubo M 2009 AIP Conference Proceedings 1185 409–412