Improvement of Plug-in Wire for 200-pixel Superconducting Tunnel Junction X-ray Detector Array on Helium Three Cryostat

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Abstract. The design of plug-in wire system is improved for 200-pixel superconducting tunnel junction (STJ) array of X-ray detector on a helium three cryostat. The electrical connections between the STJ array to the room temperature electronics consists of plural wire modules, which have connectors at the both ends. A flexible coaxial cable with electrical conductors of stainless steel (SUS-FFC) is manufactured and attached to make the electrical connection between room temperature to the 3 K stage. After the installation of SUS-FFC, temperature of the cold stage is 302 mK, and the holding time is more than 115 hours. Compared with the previous setup, the temperature of 3He stage decreased 5 mK, and the holding time increased 30 hours.

1. Introduction

Superconducting tunnel junction (STJ) X-ray detector is promising for materials analysis because of its high energy resolution and high counting rate capability. STJ arrays of one hundred pixels were applied in the field of fluorescence yield X-ray absorption spectroscopy [1,2] and elemental analysis of scanning electron microscope [3]. In order to realize a practical analytical instrument based on STJ X-ray array detectors with hundreds of pixels [4], it is necessary to develop a scalable wiring system between STJ array detectors at a cold stage of a helium three cryostat and readout electronics in room temperature (RT) for its realistic operation including a maintenance.

In our previous study, a scalable wiring system was realized utilizing a plug-in wire system, in which all electrical wires are attached to connectors at the both ends and the electrical connections between the 200-pixel STJ array to the RT electronics are established via the connectors[5]. However, the temperature and the holding time of a helium three stage were reduced due to the heat load from RT to the 3 K stage through miniature coaxial cables made of copper alloy.

Stainless steel is a unique electronic conductor material with low thermal conductivity that can be used in printed circuit boards. In this study, a new design of the plugin wire system was investigated utilizing a flexible flat cable with conductor material of stainless steel (SUS-FFC) to improve cooling performance of the 3He cryostat. Miniature coaxial cable harness made of copper alloy are replaced by SUS-FFCs, and cooling performance was tested.
2. Design of the plugin wire system

The plugin wire system of previous study was designed for a helium three cryostat for an array of 200-pixel STJ x-ray detector, as follows [5]. The cryostat is a pulse tube cooler combined with a 3He sorption cooler with base temperature of 0.3 K, which is the operation temperature of Nb-STJ. The cryostat has four temperature stages, RT, 30 K, 3 K, and 0.3 K. The number of conductors is 400 to operate 200-pixel STJs. The four hundred conductors consist of 8 sets of 50 wires. A set of wires consists as follow (Fig. 1a). Two harnesses of miniature coaxial cable are set at RT - 30 K, and 30 K - 3 K. Woven loom of 25 NbTi twisted pair is set at 3 K - 0.3 K. All harnesses have surface mount connector at the both ends. The length of each cable is 1 m. Printed circuit boards were used to connect cables. Before installation of plugin wire system, the temperature of 0.3 K stage is 300 mK, and the holding time is 130 hours. The temperature of 0.3 K stage increased 7 mK, holding time decreased 50 hours due to the installation of plugin wire system. Another experiment showed that the temperature rise in 0.3 K stage was caused by heat load to 3 K stage through miniature coaxial cables, because the temperature was still high even when NbTi cables at 3 K - 0.3 K removed. The fact suggested that the performance of the 3He cryostat will be recovered when the heat load is reduced.

The material properties of the plugin wire system are revisited to improve the holding time. The heat load depends on some material properties, such as cross section, length, and thermal conductivity. The cross section is already smallest in the available cables in the market. The length should not be long to avoid increase of readout noise. For these reasons, conductor material was reconsidered. Stainless steel is well known low thermal conductivity material, which is widely used in printed circuit board technology, especially in the field of flexible heaters. SUS-FFCs were manufactured to realize low thermal conductivity and simple electrical connection at the same time (Fig. 2). The details of SUS-FFC is as follow. The layer structure of SUS-FFC is summarized on Table 1. The number of
conductors is 50. The line width is 100 μm, and space between lines is 150 μm. Both ends of SUS-FFC is formed 0.5 mm pitch FFC plug. The length of flat cable is 200 mm.

Table 1. Layer structure of a flexible flat cable with conductor of stainless steel.

| Layer               | Material                              | Thickness [μm] |
|---------------------|---------------------------------------|----------------|
| Coverlay            | Polyimide / thermosetting resin        | 25 / 25        |
| Conductor           | SUS403                                | 30             |
| Bonding film        | FR-4                                  | 40             |
| Substrate           | Polyimide                             | 25             |
| Support substrate   | Polyimide                             | 125            |

Plugin wire system of this study is as follow (Fig. 1b). The number of conductors is 400, and the 400 conductors consist of 8 sets of 50 cables. A set of cables consists of three harnesses. The first harness is 50-miniature coaxial cables with length of 1 m is set to connect vacuum feedthrough to a SUS-FFC. The second harness is the SUS-FFC, which connects between RT to 3 K. The middle of the SUS-FFC is fixed to 30 K stage to avoid increasing heat load to 3 K stage. The third harness is a woven loom of 25-NbTi twisted pairs with a length of 1m, which is set at 3 K - 0.3 K. All connections between harnesses are made using surface mount connectors mounted on printed circuit boards.

The heat load through the SUS-FFC is estimated as follow. The heat flow \( \dot{Q} \) of the wire from region 1 to region 2 is given by

\[
\dot{Q} = -\frac{S}{L}(\Theta_2 - \Theta_1),
\]

where \( \Theta \) is the integral of the temperature-dependent thermal conductivity, \( \kappa \), calculated as

\[
\Theta = \int_0^T \kappa \, dT,
\]

S is the cross section, and L is the length. The values of \( \Theta \) are 3000 W/m, 50 W/m and 0.2 W/m at the temperature of RT, 30 K, and 3 K respectively [6,7]. The cross section of 400 conductors is \( 1.2 \times 10^{-6} \) m², and the length is 0.1 m. Therefore, the heat flow values are estimated as 40 mW and 0.6 mW for 30 K stage and 3 K stage, respectively. The heat flux values are about one fifteenth of the values in the previous setup.

3. Results and Discussions

Temperature of the 0.3 K stage was investigated to confirm the effectiveness of the new plugin wire system. The temperature of 3 K stage is not increased due to the installation of the plugin wire system. The heat load through the SUS-FFC do not reduce the cooling performance of 3 K stage. Fig. 3a shows a cooling curve of the 0.3 K stage in a cooling run. The temperature of the 0.3 K stage is 302 mK and the holding time is 118 hours. The holding time was increased by 30 hours compared to the previous setup.

The 3He cryostat was combined to the apparatus of fluorescence yield X-ray absorption spectroscopy [8] on BL-11A in the photon factory in High Energy Accelerator Research Organization (KEK) to show the reliability of the plug-in wire system. A cold finger with length of approximately 70 cm was attached to the 0.3 K stage to realize high sensitivity to fluorescent X-ray from a sample. Fig. 3b shows a temperature curve of 3 K stage. The temperature of 0.3 K stage is 308 mK and the holding time is 83 hours. Some peaks were seen on the temperature curve when experimental configuration changed. The holding time of the 3He cryostat exceeded three days for fluorescence yield X-ray absorption spectroscopy experiment in synchrotron source. The cryogenic performance recovered utilizing SUS-FFCs.
To realize thousands of pixel STJ array, it is required to investigate FFC with conductor material superconductors, such as NbTi, Nb, or high temperature superconductors, for the connection of 3 K – 0.3 K.

![Figure 3](image)

**Figure 3.** (a) Temperature curve of a helium three cryostat after the installation of a plugin wire system. (b) Temperature curve of a helium three cryostat mounted on an X-ray absorption spectroscopy apparatus. The spikes in temperature curve is due to change of setup in other experiments.

4. Conclusion

The plugin wire system for 3He cryostat is investigated to realize scalable wiring system for STJ X-ray detector array of hundred pixels. The cooling performance 3He cryostat is improved replacing from miniature coaxial cables of copper alloys to flexible flat cable with conductors of stainless steel.

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