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A high field and cryogenic test facility for neutron irradiated superconducting wire

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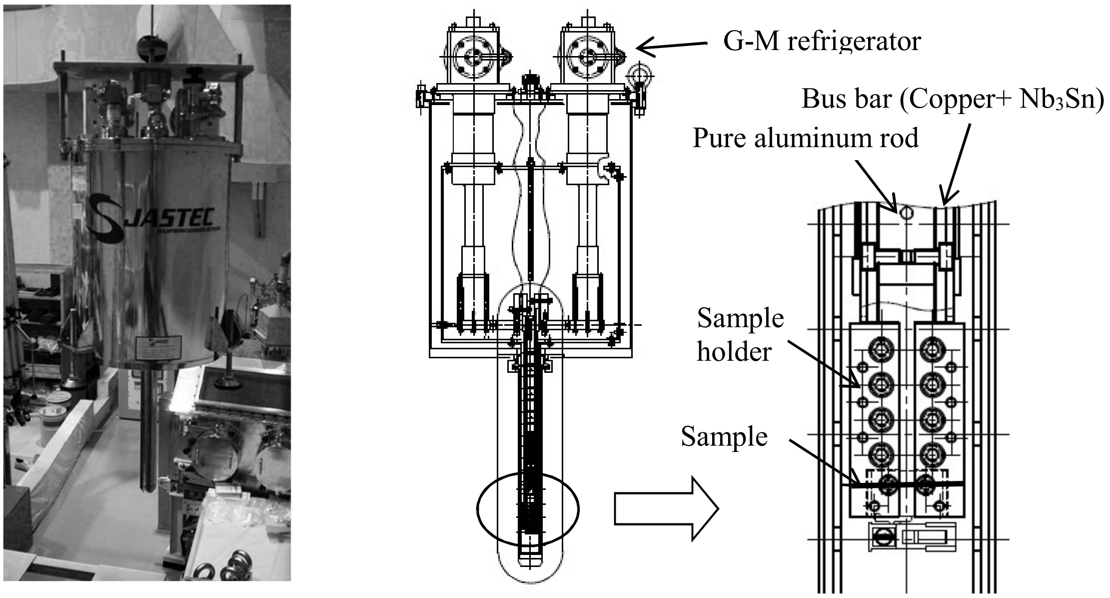
Abstract. A 15.5 T superconducting magnet and a variable temperature insert (VTI) system were installed at a radiation control area in Oarai center in Tohoku University to investigate the superconducting properties of activated superconducting materials by fast neutron. The superconductivity was measured at cryogenic temperature and high magnetic field. During these tests, some inconvenient problems were observed and the additional investigation was carried out. The variable temperature insert was designed and assembled to perform the superconducting property tests. without the liquid helium. To remove the heat induced by radiation and joule heating, high purity aluminum rod was used in VTI. The thermal contact was checked by FEM analysis and an additional support was added to confirm the decreasing the stress concentration and the good thermal contact. After the work for improvement, it was affirmed that the test system works well and all troubles were resolved. In this report, the improved technical solution is described and the first data set on the irradiation effect on Nb_3Sn wire is presented.

1. Introduction

Large scale plasma experimental devices aimed to realize deuterium-tritium or deuterium-deuterium reaction have been planned. ITER and JT-60SA are under construction [1,2] and design activities of DEMO or a prototype reactor are ongoing. Since some neutrons will stream out of the plasma vacuum vessel and pass through the shielding blankets, magnets in these devices will be irradiated by fast neutrons [3,4]. Also, high energy particle physics requires excellent performance of superconducting magnets under high energy particles irradiation, such as International Linear Collider and LHC HL upgrade project [5]. These projects are expected to achieve ultrahigh level nuclear reactions and generate a lot of high energy neutrons and particles in GeV order. Therefore, it calls the knowledge of neutronics in the magnet community and the investigations on the effect of the neutron irradiation on the superconducting properties.

The apparatus of the VTI is shown in Figure 1 (a) and the assembly drawing is shown in Figure 1 (b). And the sample holder part is enlarged in Figure 1 (c). The VTI has two sets of G-M refrigeration and the second stage of the refrigerator is connected to a high purity aluminum rod with a copper plate. Superconducting wire is set on the sample holder by soldering. The heat of radiation and joule heating is transferred to G-M refrigerators by the conduction cooling with the high purity aluminum rod. The contact part of the copper plate with the high purity aluminum rod is described in Figure 2. The heat comes up from the bottom of the VTI and transferred to the copper plate passing through the contact surface.

Some activities on the commissioning and studies on the activated superconducting strands have been performed and inconvenient troubles were recognized. In this paper, the typical troubles found during commissioning will be presented and the work done for improvement will be described. In addition, the experimental results of irradiated Nb_3Sn wire up to 1.0 x 10^{22} n/m^2 of over 0.1 MeV neutron will be reported as the first report.



(a) Apparatus of VTI. (b) Illustration of VTI. (c) Sample holder.

Figure 1. Variable temperature insert.

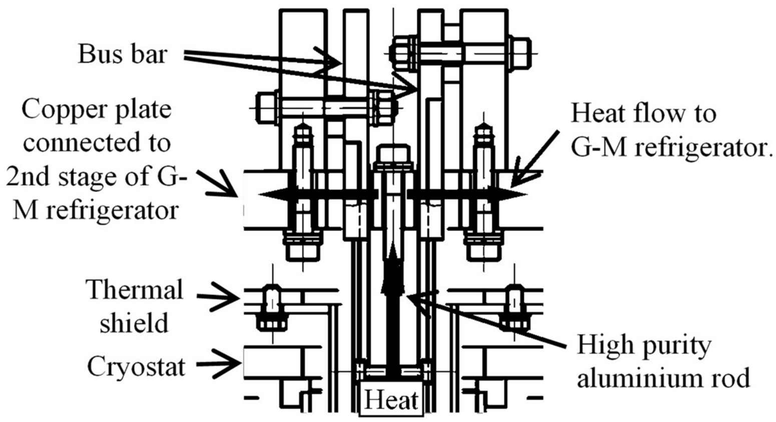


Figure 2. Connection part of copper plate with high purity aluminum rod.

2. Example of trouble

As part of commissioning tests, the current test at high magnetic field was carried out. One result tested at 15.5 T is shown in Figure 3. The sample was an unirradiated Nb_3Sn wire and three CERNOX sensors were attached. All three readings increased as the current was swept significantly. As the conduction cooling was adopted, some temperature rise was expected, but the result was too large of a temperature rise. From the results, it is recognized that the heat removal ability is less than the designed one. Also, it is noticed that the plus and minus electrodes temperatures are not the same and the sample temperature is almost the average of two electrodes temperatures. Since the heat removal ability depends on the thermal contact, both contact conditions of the bus bars would not be same.

Another result is shown in Figure 4. The current test was performed at 0 T, 2.5 T, 5.0 T and 7.5 T with an unirradiated Nb_3Sn wire. The current was swept up to 500 A in 20 seconds. A small temperature rise was observed at 0 T, 2.5 T and 5.0 T. The temperature rise became larger as the magnetic field

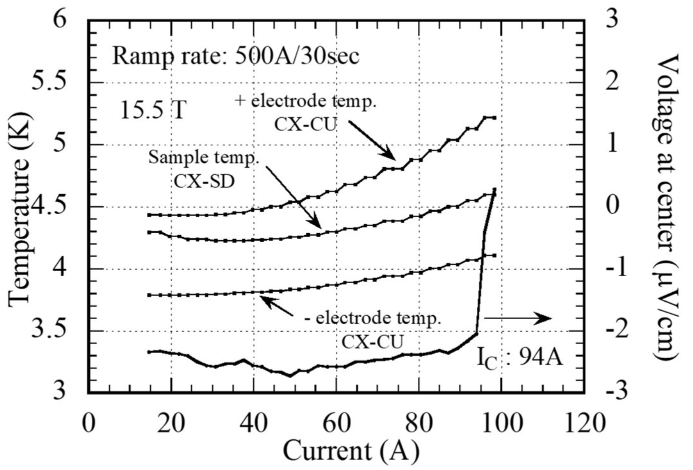


Figure 3. Current test results of unirradiated Nb_3Sn wire at 15.5 T.

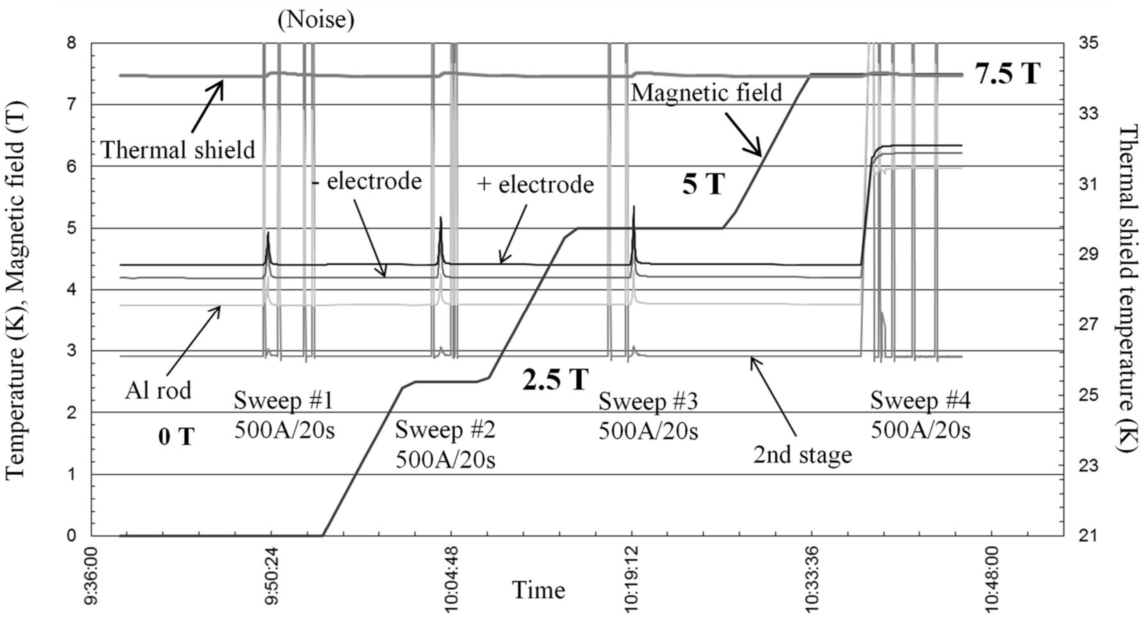


Figure 4. Temperature rise observed at high magnetic field with unirradiated Nb_3Sn wire.

increased. This seems to be caused by the effect of magnetic resistance. At 7.5 T, the temperatures of plus, minus electrodes and the aluminum rod did not return to the original temperature after the current test. Since the second stage temperature came back to the original position and the aluminum rod temperature did not return, it is considered that the heat transfer on the interface between the copper plate and the high purity aluminum rod was degraded by the electro-magnetic force.

3. Analysis of VTI and reassembled VTI

An illustration of the rod of VTI is shown in Figure 5. There is a thick copper plate connecting to the second stage of G-M refrigerator and a high purity aluminum rod which is sandwiched by a negative and a positive bus bars. The superconducting wire sample is soldered on the sample holder which locates at the top of the VTI rod. (See Figure 1) When the current is put into the sample wire under the high magnetic field, the electromagnetic in the vertical direction to the sample current acts on the sample, and the rod is bended like a cantilever beam. The expected maximum electromagnetic force is about 170 kN. (500 A x 15.5 T x 22.6 mm (span length of the sample wire) / 1000 mm) The fixed point becomes the thermal contact point. Therefore, it was considered that the contact point was deformed by the bending moment resulting in the degradation of the heat transfer. To confirm this consideration, the stress and deformation analysis was carried out with and without an additional support.

The results of the analysis are summarized in Figure 6. Two additional supports are considered. The first one is a fixer (attachment of copper) which pushes the contact surface of the high purity aluminum rod to the copper plate and keeps the gap between the copper plate and the aluminum less than 0.001 mm. The second is the L-type support made of 304 stainless steel. By adding these supports, the stress concentration at the corner of the aluminum rod decreased from about 40 MPa to about 17 MPa, and the stress concentration at the corner of the L-type support is about 100 MPa. The permanent deformation

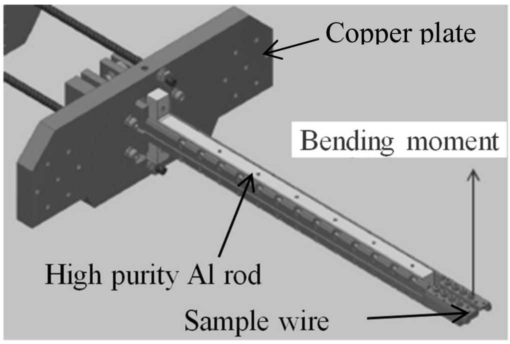


Figure 5. Structure of the rod of VTI.

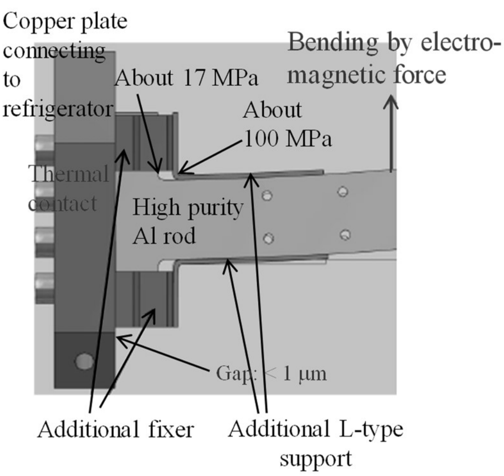


Figure 6. Results of stress and deformation analysis.

at the corner of the aluminum rod would be reduced by this support and the aluminum rod would be pushed to the copper plate more tightly.

A photo of the reassembled contact part of the VTI is shown in Figure 7. The aluminum rod was attached to the copper plate firmly. On the side of the copper bus bar, the soldered part is able to be seen. The Nb_3Sn wire was embedded to reduce the joule heating.

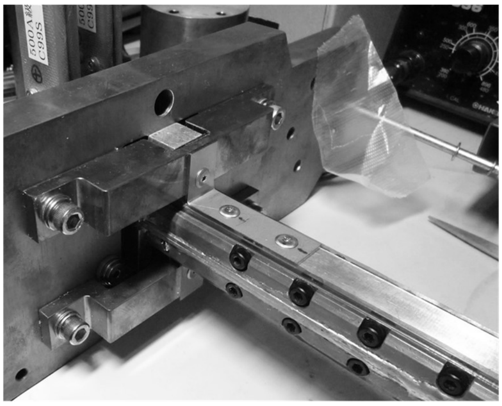
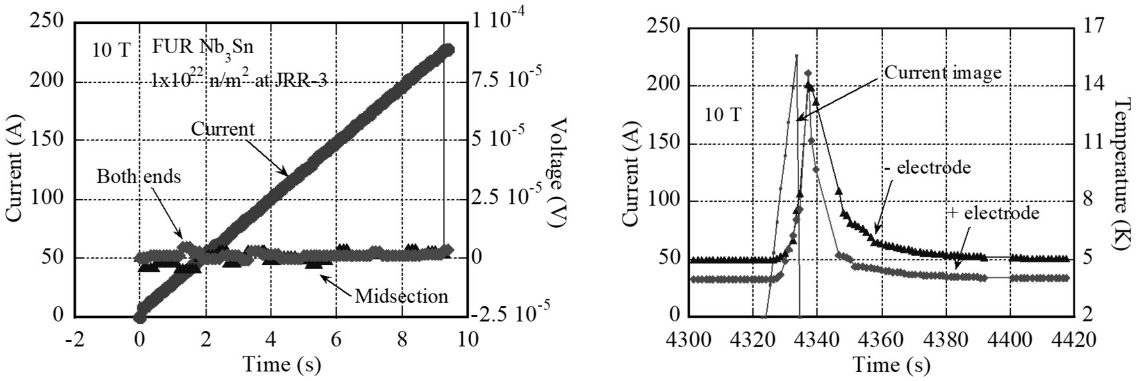


Figure 7. Reassembled contact part of high purity aluminum rod and copper plate.

4. Results of commissioning test

After the analytical activity, the improvement work has been performed in the company. The work was confirmed at the company and then the VTI was installed again at Oarai center of Tohoku University. The commissioning test was carried out using the 15.5 T superconducting magnet and the neutron irradiated Nb_3Sn wire (irradiated up to 1 x 10^{22} n/m^2 (> 0.1 MeV) at JRR-3, Japanese fission reactor for research) was set on the sample holder. The cooling of the VTI was performed without any troubles and the current test was carried out at cryogenic temperature. The Nb_3Sn wire was fabricated at Furukawa Electric Corporation Ltd [6,7].

Obtained data at 10 T is shown in Figure 8. A ramp rate was 250 A/ 10 s and the sampling rate of the current and the voltage was 10 Hz (Figure 8 (a)) and that of the temperature was 0.2 Hz (Figure 8 (b)). The maximum current was about 227 A and shut down successfully. The temperatures of negative and positive electrodes rose to about 14 K and cooled down again to the same temperatures as those before test within a couple of minutes. This temperature rise was caused by the joule heating at sample holder made of copper. The heat would be transferred to the CERNOX sensor and heat up the sensor. Therefore, there is a few seconds delay and cooled again by the heat conduction. The 500 A current test at 15.5 T



(a) Current and voltage vs time diagram.

(b) Current and temperature vs time diagram.

Figure 8. Commissioning test results at 10 T (Nb_3Sn irradiated to 1 x 10^{22} n/m^2).

will be performed in neat future. From these results, it is recognized that the heat transfer on the interface of the cooper plate to the high purity aluminum rod was improved, and that the VTI works well.

Figure 9 shows the effect of neutron irradiation on the critical current of low temperature superconducting wires [6]. Star symbols show the results obtained in this study and all other data was from samples irradiated by 14 MeV pure neutron at Fusion Neutron Source in JAEA (shut down in March 2017.) and the critical currents were measured at High Field Laboratory for Superconducting Materials in Tohoku University using liquid helium. The samples were immersed in the liquid helium and the sample temperature was kept at 4.2 K. As shown in Figure 8 (b), the negative electrode temperature in this study was around 5 K. So, the critical temperature might be a little bit low. But even if this consideration is included, there is a big difference in the critical temperatures of the irradiated samples. Namely, the star symbols are plotted around the solid round symbols. It suggents that the 14 MeV neutron irradiation would have a stronger effect than the fission neutron irradiation on the change in the critical current of Nb_3Sn wire.

Further investigations are needed. The critical current measurement of the neutron irradiated low temperature superconducting wires will be continued with the improved VTI system and the mechanism of the neutron irradiation effect would be clarified in near future.

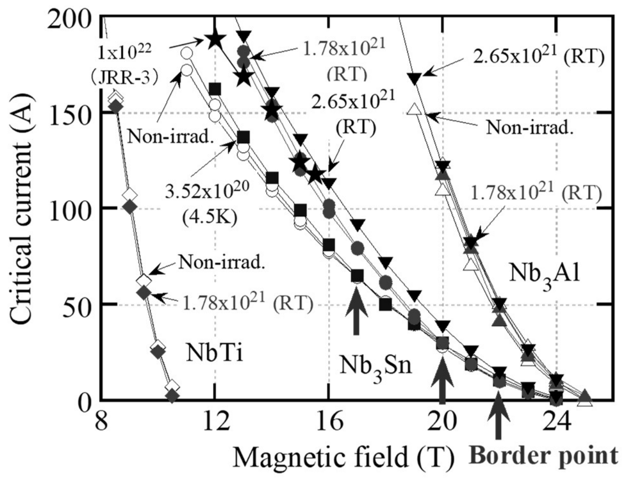


Figure 9. Comparison of critical currents after neutron irradiation.

5. Summary

During the several tests for the critical current measurement with the VTI system, the unexpected temperature rise was observed and the reason for the trouble was investigated. Then the improvements to the thermal connections of VTI system were implemented that allowed the system to function properly and the following conclusions to be made.

The interface between the copper plate and the high purity aluminum rod works as a heat transfer path and the thermal contact is very sensitive on the electromagnetic force. To keep the good contact condition, the mechanical support is important and the additional supports considered in the analytical investigation improved the performance of the VTI. The designed electromagnetic force has not been applied to the sample holder, but such commissioning test will be carried out in near future.

The neutron irradiated Nb_3Sn wire was investigated using the improved VTI and is was noticed that the fission neutron irradiation would have a weak effect than 14 MeV neutron irradiation on the change in the critical current. This is very new data and the following experiments would be performed continuously. The mechanism of the neutron irradiation effect on the critical current will be clarified and it would contribute to the development of the new low temperature superconductor.

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