Neutron Irradiation Effect on Nb_3Sn Wire

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Abstract

A Nb_3Sn wire which was manufactured for ITER TF coil conductor by a bronze route process was prepared for this study to investigate the neutron irradiation effect on the critical current in high magnetic field. The critical current of the virgin wire was measured in liquid helium with a 28 T hybrid superconducting magnet at High Field Laboratory for Superconducting Materials in Tohoku University. Also, the current was measured in vacuum with a heat conduction type variable temperature insert (VTI) at International Research Center for Nuclear Materials Science in Tohoku University. The wire was irradiated at below 100 degrees Celsius by fission neutron at BR2 in Belgium up to 4.9×10^{22} n/m^2 (> 0.1 MeV), and the critical current after the irradiation was evaluated with the VTI under the range of 8 T to 15.5 T. The difference of the critical current measured with two facilities was discussed focussing on joule heating of the sample holder made of pure copper, and the neutron irradiation effect on the critical current was investigated in the range of up to 15.5 T. As the results, the critical current measured in vacuum becomes lower than that in liquid helium because of the temperature rise of the sample holder where the sample was soldered, and the critical current was increased by the neutron irradiation, and the current ratio (I_C/I_{C0}) was almost constant of 1.75 in the range of 8 T to 15.5 T at around 4 K.

Keywords: Nb_3Sn wire, Neutron irradiation, Critical current.

1. Introduction

Nuclear fusion reaction of deuterium and tritium generates 14.1 MeV neutron and 3.5 MeV alpha particle. Since the alpha particle has positive charge, it stays inside the plasma with Larmor motion around a magnetic flux. On the other hand, the high energy neutron can come out straightly without any interruption of magnetic field and hits or penetrates the plasma facing components. Some neutrons stream out of the vacuum vessel and some penetrate through the vacuum vessel. Thus, almost all materials surrounding the plasma vacuum vessel will be irradiated by these neutrons.

A superconducting magnet creates a strong magnetic field to confirm the plasma in high ion density for a long time at high temperatures in 10 keV order. In the case of a Tokamak plasma device, like ITER [1] and JT60-SA [2], toroidal field

(TF) coils, poloidal field (PF) coils, and central solenoid (CS) modules will be fabricated and integrated to confirm the plasma robustly. In addition to these coils, correction coils will be installed to maintain the proper magnetic surface and reduce the instability of the plasma. All coils locate beside the plasma vacuum vessel, and will be irradiated by the neutrons.

The expected neutron fluence will vary depending on the location but the maximum design value will be limited to approximately 1.0 x 10^{22} n/m^2. This limitation comes from the experimental data shown in some papers [3,4], and no degradation of the conductor and the insulation layer is expected during the operation life of the device.

To investigate the neutron irradiation effect on the superconductivity, a 15.5 T supercondcuting magnet and a variable temperature insert (VTI) were installed at International Research Center for Nuclear Materials Science (Oarai Center) of Tohoku Univeristy [5,6] and some results on the neutron irradiation effect have been published [7]. Recently, effect on pinning force was studied [8], and the surface impedance process was applied to study RF property of NbTi film [9].

In this study, the following two items will be discussed based on the experimental data, the difference of the critical currents (I_C) measured in liquid helium (LHe) and in vacuum under the conduction cooling, and the increasing factor of the critical current by the neutron irradiation in the range of 8 T to 15.5 T to study the neutron irradiation effect quantitatively.

2. Test procedure and test sample

2.1 Variable temperature insert and sample holder

The sketch of the VTI is shown in Fig.1. It is equiped with two sets of G-M refrigerator and current leads. The sample is soldered on the sample holder which is located at the bottom of the VTI cryostat. The bottom part is inserted in the bore of the 15.5 T superconducting magnet and the sample current (< 500 A) is applied after the magnetic field reaches the set value.

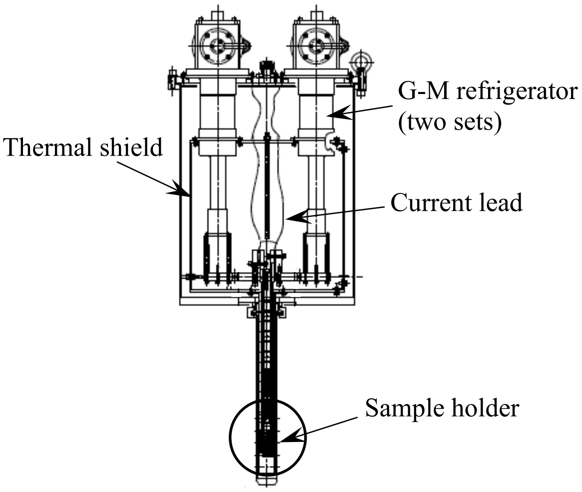

Fig. 1 Illustration of variable temperature insert.

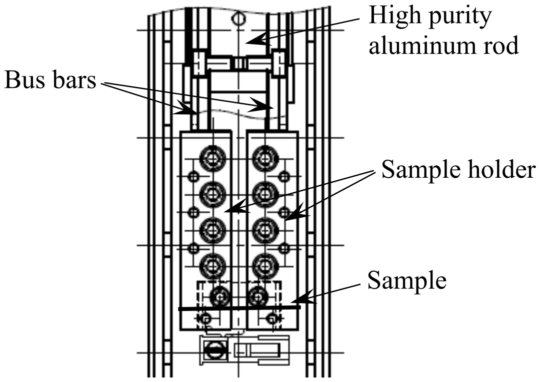

Fig. 2 Enlarged illustration of sample holder.

The sample holder part is enlarged and shown in Fig. 2. The sample is set in the vertical direction to the magnetic field. The high purity aluminum rod is sandwiched by two bus bars and each bus bar is connected to the sample holder plate. Nb_3Sn wires were embedded in the bus bars with solder to reduce the joule heating. The sample holder plate is made of oxygen free copper and no Nb_3Sn wires were soldered.

The heat including the joule heat and the radiation heat is transferred to the top of the high purity aluminum rod by the heat conduction and carried outside by the G-M refrigerators. Since the sample holder plate is made of oxygen free copper and no superconducting wires are soldered inside, some joule heating occurs in the sample holder plates, when the sample current is applied.

The sample holder set on the VTI is shown in Fig. 3. Two sample holder plates are connected by an AlN plate. Three CERNOX sensors are attached on the sample holder, and the voltage taps are soldered on the sample wire. The temperatures and the voltage were measured continuously during the test. The sample current and the voltage were measured with 10 Hz and the temperatures were measured with 2 Hz.

The critical current measurement in the LHe was carried out with a usual cryostat and the 28 T hybrid magnet. The

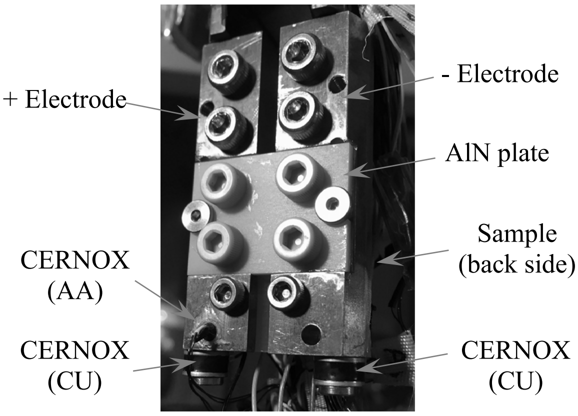

Fig. 3 Photo of sample holder. The sample wire was soldered on back side of sample holder.

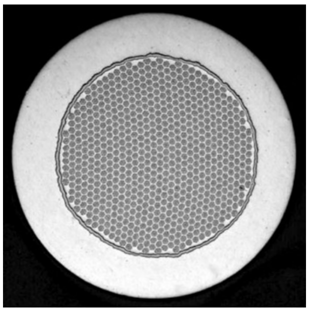

Fig. 4. Cross section of Nb_3Sn wire for ITER TF coil conductor supplied by JASTEC.

details of the 28 T hybrid magnet test facilities are described on the home page of the HFLSM [10].

The criteria for the I_C measured in LHe at HFLSM was 10 μV/cm, and 20 μV/cm was adopted for the tests with the VTI. Some explanation will be provided below.

2.2 Test sample

The Nb_3Sn wire was used in this study. The wire was fabricated for TF coil conductor of ITER with a bronze-root process, which was supplied by JASTEC in Japan. The wire was heat treated according to the standard heat treatment condition (650 dgrees C for 240 hrs) specified by ITER. The cross section of the wire is shown in Fig. 4. The diameter is 0.8 mm.

After the heat treatment, the wire was cut into 40 mm long and sent to BR2 for the fission neutron irradiation. The temperature during the irradiation was kept at below 100 degree C, and the fluence was 4.9 x 10^{22} n/m^2 (> 0.1 MeV). The irradiated sample was sent back to Oarai Center, and the I_C measurement was carried out in the radiation control area using the 15.5 T superconducting magnet and the VTI.

3. Test results and discussion

3.1 Difference of critical currents of non-irradiated wire

To invesigate the I_C measurent process, the I_C of the non-irradiated Nb_3Sn wire was measured in LHe at HFLSM and in vacuum with the VTI at Oarai Center. The V-I curves are shown in Fig. 5. The data obtained in LHe are presented with a small symbol and those measured with the VTI are shown with a round large symbol. Both tests were carried out under 15 T, and the ramp rate of the sample current was 150 A/s for the test in the vacuum.

Since the maximum sampling rate of the VTI system is 10 Hz, the number of data sets decreases when the ramp rate is faster. Therefore, the regression curve in a power function was calculated using the last data and one data before the last, then the current at the voltage of 20 μV/cm was determined as the I_C as shown in Fig. 5 taking account of the scatter of the data sets. In the case of the test at HFLSM, the current at the voltage of 10 μV/cm was adopted as the I_C. Due to the difference of the reference voltage level, 10 and 20 μV, there would be small difference but it would not impact so strongly on the discussion of the neutron irradiation effect.

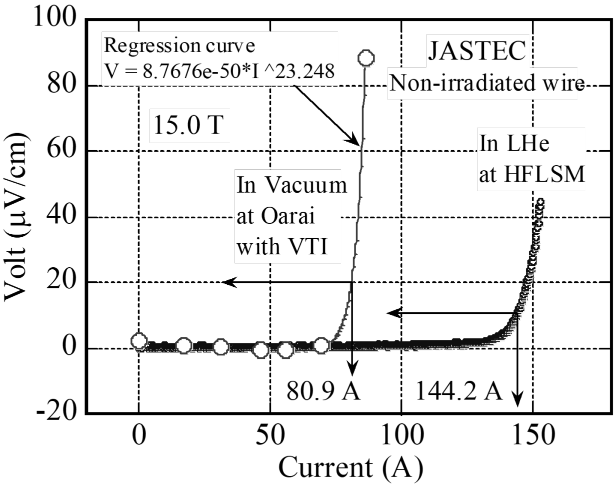

Fig. 5 Comparison of V-I curves measured in vacuum with VTI at Oarai center and in LHe at HFLSM. Sample was a non-irradiated Nb_3Sn wire.

The I_C results of both tests showed a significant difference, 80.9 A in vacuum and 144.2 A in LHe. This would be caused by the temperature rise of the sample holder plates where the joule heating occured. The details will be discussed below.

3.2 Effect of ramp rate of sample current

Since the VTI is cooled by the conduction cooling, the temperatures of the sample holder would rise during the current testing. Figure 6 shows the I_C measurement results of the irradiated and non-irradiated wires against the ramp rate at 15.5 T. When the ramp rate increases, the scatter expands gradually and there is a tendency of I_C increasing. Since it takes a certain time for the joule heat to transfer to the sample,

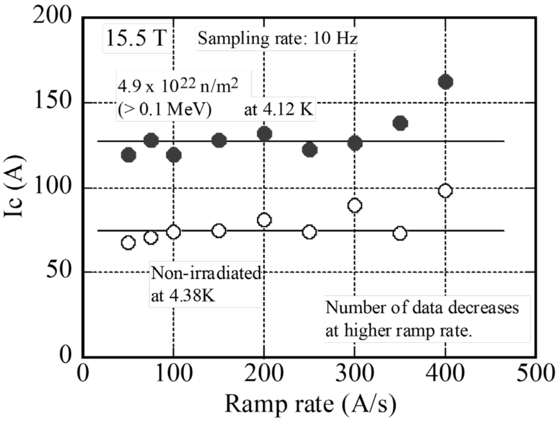

Fig. 6 Effect of ramp rate on of irradiated and non-irradiated wires at 15.5 T.

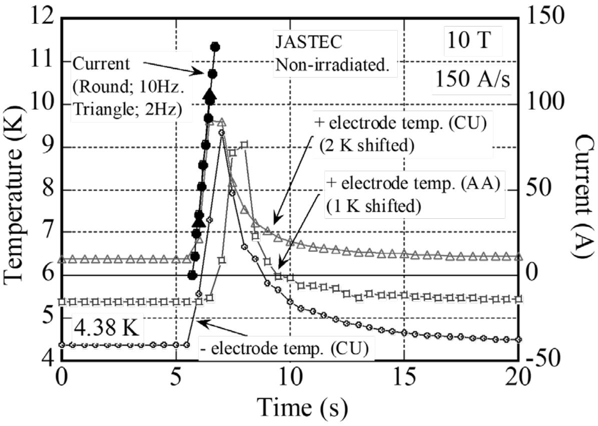

Fig. 7 Change in sample current and electrode temperature of non-irradiated Nb_3Sn wire at 10 T. Ramp rate was 150 A/s. Initial temperature was about 4.4 K. Square symbols and triangle symbols are shifted by +1 K and +2 K, respectively.

the I_C increases under the fast ramp rate. The same behavior is observed in both non-irradiated and irradiated. When Nb_3Sn wires would be soldered in the sample holder, the temperature rise would be reduced. Since the I_C seems to be stable at about 150 A/s, the data at that rate will be taken for the discussion.

3.3 Temperature rise of sample holder during critical current measurement test

The results of the temperature measurements and the sample current during the I_C test are shown in Fig. 7 (the non-irradiated wire) and Fig. 8 (the irradiated wire). The magnetic field was 10 T and the ramp rate was 150 A/s.

The temperature measured by CU type CERNOX is more sensitive than that by AA type. This is considered to come from the contact pressure of the sensor with a screw. The change in temperature is linear. The maximum temperature of the non-irradiated wire was 133.6 A and the irradiated wire showed 227.7 A. The joule heating is current^2 times resistance. Thus, the temperature should change in parabolic against time, if the resistance and the specific heat would not change depending on the temperature. However, the experimental data show almost linear in both wires, and it is considered that some heat would be absorbed by the high purity aluminum rod and the temperature dropped immediately when the sample current was shut down.

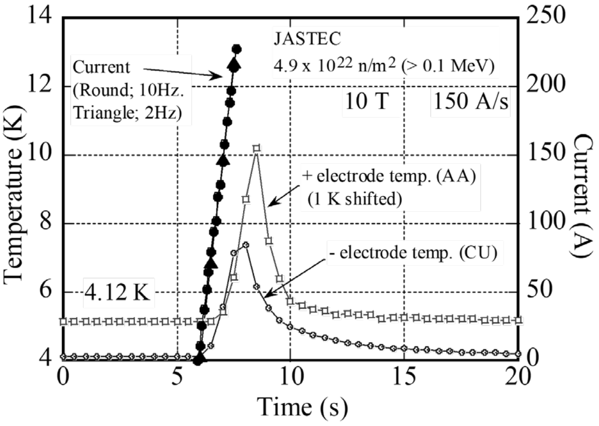

Fig. 8 Change in sample current and electrode temperature of 4.9 x 10^{22} n/m^2 (> 0.1 MeV) neuton irradiated Nb_3Sn wire at 10 T. Ramp rate was 150 A/s. Initial temperature was about 4.1 K. Square symbols are shifted by +1 K.

It is considered that the joule heating would occur in the sample holder and the other possiblity would be the soldered parts of both ends of the wire where the running current density would become large. In any case, the heat conduction capacity must be increased to reduce the temperature rise.

The temperature rise was about 4 or 5 K. Therefore, the I_C measured in vacuum would be lower than that at 4 K, and it would be expected that the decrement of the I_C would depend on the absolute value of the sample current.

3.4 Change in critical current by neutron irradiation

The I_C data obtained in this study are summarized in Fig. 9 against the magnetic field. There are two data sets of I_C measured in LHe (solid triangle symbol and open diamond symbol). The I_C data in vacuum of the non-irradiated wire (open round symbol) and of the irradiated wire up to 4.9 x 10^{22} n/m^2 (> 0.1 MeV) (solid round symbol) measrued under the ramp rate of 150 A/s are also presented.

The I_C data of the non-irradiated in vacuum are lower than those of measured in LHe and the slope of the data against the magnetic field is steeper than that of the data in the vacuum. As discussed above, the higher sample current generates the larger joule heating resulting in the large temperature rise.

The I_C data of the irradiated wire show the higher I_C than the non-irradiated wire. It is clear that the neutron irradiation improves the superconducting property significantly.

The ratio of the irradiated wire I_C to the non-irradiated wire

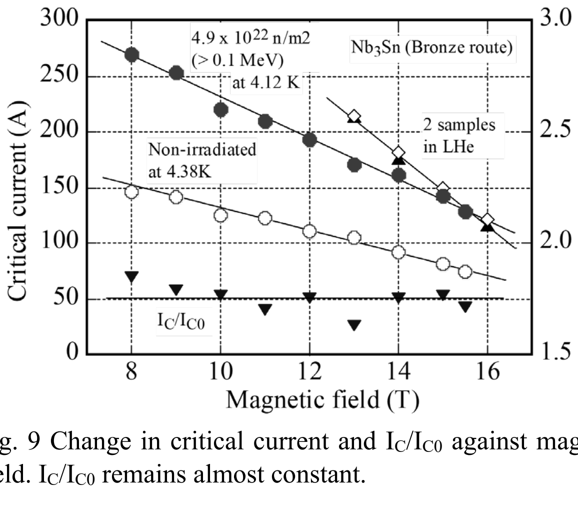

Fig. 9 Change in critical current and I_C/I_{C0} against magnetic field. I_C/I_{C0} remains almost constant.

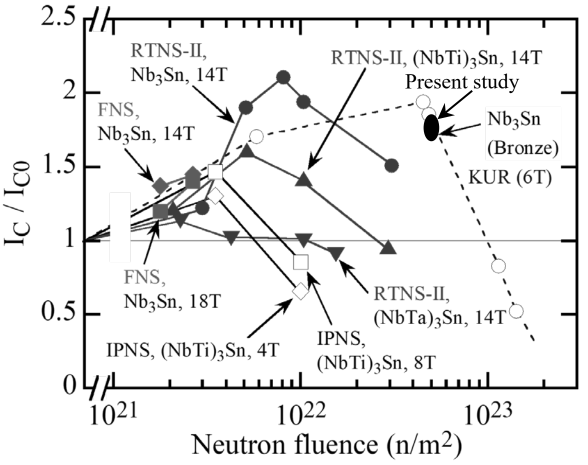

Fig. 10 Change in I_C/I_{C0} against neutron fluence of over 0.1 MeV. The result of this study locates on the same region as the data obtained at 6 T at KUR.

I_C, designated as I_{C0}, is plotted in Fig. 9. The ratio shows the current changing factor of the I_C by the neutron irradiation. As shown in Fig. 9, the current ratio is almost constant at about 1.75 in the range of 8 T to 15.5 T. Strictly speaking, there is an effect of the joule heating and the heating effect will be stronger in the high sample current region. Thus, the current ratio would change if the I_C data could be obtained in LHe.

The current ratio was plotted on the diagram of the relation between I_C/I_{C0} and the neutron fluence [11]. The present result locates on the same region of the data obtained at 6 T at Kyoto University Research Reactor (KUR). From this result, it is considered that the current ratio of the fission neutron irradiated wire would be almost the same in the range of 6 T to 15.5 T under the fluence of 4.9 x 10^{22} n/m^2 (> 0.1 MeV).

It was reported that the neutron irradiation induces the radiation damage in the crystal and the damaged area will become the pinning site of the magnetic flux which maintains the superconducting state. As the amount of the pinning site increases, the number of the pinned flux increases and the pinning force is strengthened. These will improve the I_C [11].

The higher and the lower neutron fluence region will be investigated in the near future.

4. Summary

The neutron irradiation effect on the I_C at high magnetic field was investigated with bronze route Nb_3Sn wire. The wire was heat treated and fission neutron irradiated at BR2. Then the I_C was measured with 15.5 T superconducting magnet and the VTI at Oarai center. In parallel, the I_C of the non-irradiated wire was measured with the 28 T hybrid magnet at HFLSM.

The main results are summarized as follows:

(1) The I_C obtained in vacuum at Oarai center is lower than that in LHe at HFLSM. The main reason is considered to be a joule heating in the sample holder plates where no superconducting wires were soldered and no high purity aluminum rod was attached.

(2) During the current testing, the temperatures of the sample holder plates increased according to the increment of the sample current, and dropped immediately when the current was shut down. The I_C would be affected by the ramp rate of the sample current and there is a tendency that the I_C becomes larger when the faster ramp rate is applied.

(3) The I_C of the neutron irradiated wire increased by about 1.75 times compared with that of the non-irradiated wire in the region of 8 T to 15.5 T. The neutron irradiation in this fluence region improves the I_C of the Nb_3Sn wire by inducing the radiation damage into the crystal which increases the pinning site for the magnetic flux. And the radiation damage will strengthen the pinning force and the I_C will be increased.

The neutron irradiation and the post irradiation experiments will be continued and the database will be extended.

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