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# Neutron irradiation effect on critical current of Nb<sub>3</sub>Sn wire under 8 T to 15.5 T

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Abstract. Superconducting magnets for fusion application will be irradiated by fast neutrons produced by fusion reaction, and it has been reported that the superconducting properties of the superconducting wires vary drastically by the irradiation. A bronze route Nb<sub>3</sub>Sn wire and an internal tin process wire were irradiated in a fission reactor up to  $1.7 \times 10^{23} \text{ n/m}^2$  (> 0.1 MeV neutron), and the change in the critical current was measured by 15.5 T superconducting magnet and a variable temperature insert. The 4.9 x 10<sup>22</sup> n/m<sup>2</sup> irradiation for the bronze route wire increased the critical current by 1.75 times, but the 7.9 x  $10^{22}$  n/m<sup>2</sup> irradiation showed 1.03 times increase for the bronze route wire and 0.72 times decrease for the internal tin process wire. The 1.7 x 10<sup>23</sup> n/m<sup>2</sup> irradiation for the internal tin process wire decreased the critical current severely and the critical magnetic field down to around 16 T. This was the first result that the high fluence neutron irradiation caused the degradation of both the critical current and the critical magnetic field in this type of a Nb<sub>3</sub>Sn wire. Some irradiation defects will become the magnetic flux pining sites and strengthen the pining force. But the strong irradiation will damage the superconducting phase and degrade the properties.

#### 1. Introduction

Large-scale plasma experimental devices have been designed and constructed in the world. One of the main targets is realization of fusion reaction, namely, deuterium - tritium reaction, which will generate 14 MeV neutrons. The ITER project is an international collaboration project (http://www.iter.org/) and the construction is in progress at Cadarache in France. The ITER is a pulse machine and will generate 14 MeV neutron periodically. To support the ITER project, JT-60SA project is running in Japan (https://www.qst.go.jp/site/jt60-english/). JT-60SA will not generate the fast neutrons, but the operation technology and the plasma research will give a lot of practical suggestions to the ITER project. The design of a helical system fusion reactor has been carried out and the three-dimensional neutron irradiation analysis was reported [1]. Regarding the neutronics analysis for ITER project, the pioneering research has been done and the local fluence distribution was reported [2]. In addition to the fusion application, high energy particle physics and the related accelerator engineering require the experimental data on the neutron irradiation effect of magnet materials when they design the devices. The energy level of the neutron coming out of the collision point is GeV class, and there is a big difference from the fusion. However, the systematic experimental facilities are anticipated in the world.

In 2000s, the investigation on the neutron irradiation effect on the superconducting magnet materials started at National Institute for Fusion Science under the collaboration research framework with Universities in Japan [3]. After the installation of 14 MeV neutron irradiation facility in Tokai

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campus of Japan Atomic Energy Agency (JAEA), the neutron irradiation research system with the fission reactor has been developed and 15.5 T superconducting magnet and a variable temperature insert (VTI) were installed in a radiation control area at Oarai center in Tohoku University [4,5]. The control system, the data acquisition system and others are still being improved little by little.

In this study, the neutron irradiation of 4.9 x  $10^{22}$  n/m<sup>2</sup>, 7.9 x  $10^{22}$  n/m<sup>2</sup>, 1.7 x  $10^{23}$  n/m<sup>2</sup> were carried out and the critical current after irradiation was measured in the range of 8 T to 15.5 T. The neutron irradiation effect on the critical current of Nb<sub>3</sub>Sn wires made by a bronze route and an internal tin process will be presented, and the mechanism of the change in the critical current will be discussed.

#### 2. Test Facilities, Test Procedures and Sample Wire

The test facility for the superconducting properties measurement system consists of 15.5 T superconducting magnet, the VTI and the control and data acquisition systems. The sample current capacity is 500 A, and the sample is cooled down by thermal conduction with high purity aluminum rod (over 99.999%) connecting to two sets of G-M refrigerator. The samples were capsuled with helium gas and sent to Belgium Reactor II (BR2) in Belgium. After the irradiation in the fission reactor, the samples were sent back to the Oarai Center in Tohoku University, and the post irradiation experiments were carried out in the radiation control area. The recent status of the test facilities has been reported in [6,7].

There are three CERNOX sensors on the sample holder as shown in Figure 1. CU type sensors were attached on both positive and negative electrodes and AA type sensor was equipped on the positive electrode. One test result is shown in Figure 2. The temperatures were measured at the rate of 1 Hz or 2 Hz and the sample current was recorded at the rate of 1 or 2 Hz and 10 Hz, independently. It is noticed that the temperatures of the both electrodes rise by joule heating when the current flow started. There will be several reasons for the temperature rise. Here, the joule heating was considered as the strongest factor. The behavior of the temperature rise depended on each test. The sample temperature was not always constant because the sample was cooled down by thermal conductivity. But the test temperature was below 5 K. The base temperature will be shown at each data set.

Since the sample temperature rises during the current flow due to the joule heating, the relation



Figure 1. Sample holder. The space between bus bar and sample holder was filled with super purity aluminum. Sample was set on back side.

Figure 2. One example of the temperature rise of sample holder during the current flow.



Figure 3. Comparison of V-I curves measured in vacuum with VTI at Oarai center and in LHe at HFLSM.



Figure 4. Effect of ramp rate on of irradiated and non-irradiated wires at 10 T.

between the voltage (the tap distance was about 5 mm) and the current (V-I curve) becomes different from that in LHe test. The example is shown in Figure 3 [7]. The wire was the bronze route Nb<sub>3</sub>Sn. The V-I curve obtained with VTI was approximated by a power function of  $V = C \times I^n$ , where C and n are constants, and the current at 20  $\mu$ V/cm was defined as the critical current of the wire under the given condition. In case of the critical current in LHe, the 10  $\mu$ V/cm was adopted as show in Figure 3.

As the temperature rise by the joule heating depends on the ramp rate of the current, the effect on the ramp rate on the critical current was investigated. The one results are shown in Figure 4. It is noticed that the fast ramp rate shows rather large critical current because the thermal conduction needs a time to transfer the heat to the sample wire which is generated in the sample holder by the joule heating. In this study, the ramp rate of 150 A/s was adopted as a measurement reference condition. As the sampling rate of the V-I curve was 10 Hz in the VTI system, the lower ramp rate was adopted when a certain number of data sets was required.

Two types of Nb<sub>3</sub>Sn samples were prepared. One is a bronze route Nb<sub>3</sub>Sn wire and the other is an internal tin process Nb<sub>3</sub>Sn wire. The cross section of both wires is shown in Figure 5. The bronze route wire provided JASTEC in Japan has very fine filaments and the internal tin wire provided by WST in China has 20 tin core filaments. Both wires were 32 mm long and 0.8 mm diameter, and they were heat treated at 650 degree in C for 240 hours. The total content of tin of both wires is not clear but the internal tin process wires looks contain more tin than the bronze process wire has.

The three neutron irradiation tests were carried out. In the first test, the neutron fluence (> 0.1 MeV) of 4.9 x  $10^{22}$  n/m<sup>2</sup> was achieved, and 7.9 x  $10^{22}$  n/m<sup>2</sup> and 1.7 x  $10^{23}$  n/m<sup>2</sup> of the fluence were irradiated in the second and the third irradiation tests, respectively. It must be written about the



Figure 5. Cross section of tested Nb<sub>3</sub>Sn wires. (a) JASTEC in Japan and (b) WST in China.

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residual gamma ray dose after the irradiation. The same size wires were inserted in the aluminum capsule and irradiated in BR2. After the irradiation, the wires were sent back to Oarai center and the gamma ray on the surface was measured. So, the neutron fluence and the decay time were the same. The measured values were 30.00 mSv/h for the internal tin process wire and 0.03 mSv/h for the bronze route process wire. Although the detailed investigation is required, it suggests that the isotope of Sn would emit strong gamma ray after irradiation.

### 3. Results and Discussion

The change in the critical current of the bronze route wire irradiated to  $4.9 \times 10^{22} \text{ n/m}^2$  is shown in Figure 6 together with the results of  $I_C/I_{C0}$ . The  $I_C$  in LHe is also plotted in the figure. The  $I_C$  with VTI is smaller than that in LHe because of the temperature rise by the joule heating as explained before. When the wire was irradiated to  $4.9 \times 10^{22} \text{ n/m}^2$ , the  $I_C$  increased in the range of 8 T to 15.5 T, and the ratio of the  $I_C$  of the  $4.9 \times 10^{22} \text{ n/m}^2$  irradiation to that of non-irradiated wire ( $I_{C0}$ ) becomes about 1.75 and there is no clear tendency to increase or decrease of  $I_C/I_{C0}$  against the magnetic field. The results of the bronze route wire irradiated to  $7.9 \times 10^{22} \text{ n/m}^2$  is shown in Figure 7. The critical current after the irradiation deceased in the range of 8 T to 15.5 T, and the ratio of  $I_C/I_{C0}$  is about 0.72. It is noticed that the almost same scatter of  $I_C/I_{C0}$  could be seen in both diagrams. Since the  $I_C/I_{C0}$  keeps the same value in the region of 8 T to 15.5 T, it is considered that the  $B_{C2}$  would not change significantly under such irradiations.

The reason of the change in the critical current has been recognized as follows: The neutron irradiation would cause a lot of small damage in the matrix, which is an atom-level irregular order like a cascading or knocking, and these defects would become flux pinning sites. When a certain amount of such damage is installed in the matrix, the pinning force would be increased so that the critical current would improve. However, as total amount of defects exceeds, the matrix becomes dirty and the superconducting phase is deteriorated resulting in the decrease of the critical current.

The experimental result in the case of further irradiation are shown in Figure 8 and 9. The samples are the internal tin process wires and irradiated to 7.9 x  $10^{22}$  n/m<sup>2</sup> (Figure 8) and 1.7 x  $10^{23}$  n/m<sup>2</sup> (Figure 9). The data were obtained under the current ramp rate of 150 A/s. In Figure 8, the critical current measured in LHe are plotted together. As in the results shown in Figure 6 and 7, the I<sub>C</sub>/I<sub>C0</sub> becomes almost constant of 1.03 in the range from 8 T to 15.5 T. There is a difference of I<sub>C</sub>/I<sub>C0</sub> between the bronze route Nb<sub>3</sub>Sn and the internal tin Nb<sub>3</sub>Sn when the 7.9 x  $10^{22}$  n/m<sup>2</sup> irradiation was carried out. The reason is not clear at present and the further investigation is expected to make it clear. In case of  $1.7 \times 10^{23}$  n/m<sup>2</sup> irradiation (Figure 9), the I<sub>C</sub>/I<sub>C0</sub> decreases as the magnetic field increases, and the result does not show the constant I<sub>C</sub>/I<sub>C0</sub>. When the critical current is below 50 A, there are only three or four sets of the data, and rather large uncertainties are considered. Therefore, the parentheses



Figure 6. Change in critical current and  $I_C/I_{C0}$  against magnetic field. Bronze route Nb<sub>3</sub>Sn wire. Neutron irradiated to 4.9 x  $10^{22}$  n/m<sup>2</sup>.



Figure 7. Change in critical current and  $I_C/I_{C0}$  against magnetic field. Bronze route Nb<sub>3</sub>Sn wire. Neutron irradiated to 7.9 x  $10^{22}$  n/m<sup>2</sup>.



Figure 8. Change in critical current and  $I_C/I_{C0}$  against magnetic field. Internal tin Nb<sub>3</sub>Sn wire. Neutron irradiated to 7.9 x  $10^{22}$  n/m<sup>2</sup>.





Figure 9. Change in critical current and  $I_C/I_{C0}$  against magnetic field. Internal tin Nb<sub>3</sub>Sn wire. Neutron irradiated to 1.7 x  $10^{23}$  n/m<sup>2</sup>.

Figure 10. Change in critical current and  $I_C/I_{C0}$  against magnetic field. Internal tin Nb<sub>3</sub>Sn wire. Neutron irradiated to 1.7 x  $10^{23}$  n/m<sup>2</sup>. Current ramp rate was 50 A/s.

are attached on these data. To make it sure, the sample ramp rate of 50 A/s was applied, and the larger number of experimental data points were obtained. The results are shown in Figure 10. The data of non-irradiated wire were also measured at the rate of 50 A/s. The trend lines in the Figure 10 are the same as those in Figure 9. The trend lines are still fitting the experimental data, so it is recognized that there is not significant difference between 150 A/s and 50 A/s data sets, and that the critical current decreases almost straightly to zero, though the critical current of non-irradiated wire decreases gradually. When these experimental plots are extrapolated to zero, the critical magnetic field is expected to be around 16 T. It means that the further neutron irradiation degrades the critical magnetic field and the wire is getting to lose the superconductivity, and finally it is considered that it will become the material which does not show the superconductivity anymore.

This experimental data on the deterioration of the critical magnetic field is the world first finding fact. If one can measure the critical current at 8 T or 10 T after the  $1.7 \times 10^{23}$  n/m<sup>2</sup> irradiation, it will be reported that there is still a certain critical current exist and a certain value of the I<sub>C</sub>/I<sub>C0</sub>. The important issue is that the superconducting wire is damaged and becomes dirty, and it is losing the superconductivity already, especially in the higher magnetic field. So, at this stage, a transition behavior from the superconducting to the normal conducting is being observed, which means no constant I<sub>C</sub>/I<sub>C0</sub> in the range of 8 T to 15.5 T. When the stronger magnetic field is applied to the sample irradiated to  $1.7 \times 10^{23}$  n/m<sup>2</sup>, the flux pinning is easily coming off.

The obtained data on  $I_C/I_{C0}$  in this study were plotted against the neutron fluence as shown in Figure 11. In the figure, several experimental data sets of Nb<sub>3</sub>Sn wires were collected from the



Figure 11.  $I_C/I_{C0}$  against neutron fluence. Published data were plotted together with the data obtained in this study.

published papers and plotted. (FNS; Fusion Neutron Sources, RTNS; Rotating Target Neutron Source, IPNS; Intense Pulsed Neutron Source, KUR; Kyoto University Reactor). The open round marks show the results of the bronze route Nb<sub>3</sub>Sn wire irradiated at KUR and the I<sub>C</sub> measurement was carried out at 6 T. The test results in this study are plotted on the almost same line as the data in KUR except for the data of  $1.7 \times 10^{23} \text{ n/m}^2$  irradiation. Therefore, it is noticed that there is no effect of the magnetic field under 8 T to 15.5 T when the I<sub>C</sub>/I<sub>C0</sub> is over about 1.0. It means that the induced irradiation defects have the enough ability to keep the flux pinning even under the 15.5 T, and that there is a potential that the critical current of the non-irradiated wire would be improved more. However, when the wire is irradiated much more, the I<sub>C</sub>/I<sub>C0</sub> drops below 1.0 and the dependence on the magnetic field comes up remarkable. Generally, the Nb<sub>3</sub>Sn wire has the critical magnetic field of over 24 T. But, as the neutron fluence increases, the I<sub>C</sub>-B<sub>C2</sub> relationship would shift to downward, the critical magnetic field decreased down to around 16 T in case of 1.7 x 10<sup>23</sup> n/m<sup>2</sup> irradiation. This is unexpected big drop of B<sub>C2</sub>.

The further irradiation will install much irradiation defects and the matrix will become dirty. The dirty matrix will not sustain the flux pinning anymore resulting in the decrease of the critical magnetic field. Due to the degradation of the critical magnetic field, the dependence of the critical current on the magnetic field becomes significant and the critical current drops near to zero under the higher magnetic field.

To confirm the mechanisms of the change in the  $I_C/I_{C0}$  mentioned above, the further investigations are planned and would be carried out in near future.

#### 4. Summary

The neutron irradiation tests on Nb<sub>3</sub>Sn wire were carried out at BR2 in Belgium under the condition of the cooling water temperature of 50 degree in Celsius. The fluence of over 0.1 MeV neutron was 4.9 x  $10^{22}$  n/m<sup>2</sup>, 7.9 x  $10^{22}$  n/m<sup>2</sup> and 1.7 x  $10^{23}$  n/m<sup>2</sup>.

The 4.9 x  $10^{22}$  n/m<sup>2</sup> irradiation increases the I<sub>C</sub> and the 7.9 x  $10^{22}$  n/m<sup>2</sup> irradiation showed the almost same I<sub>C</sub> as that of non-irradiated sample. The 1.7 x  $10^{23}$  n/m<sup>2</sup> irradiation decreased the I<sub>C</sub> and caused the drastic drop of B<sub>C2</sub>.

The neutron irradiation would make a lot of irradiation defects in the matrix and these defects would become the flux pining sits and reinforce the flux pining resulting in the increase of  $I_C$ . However, further irradiation would damage the superconducting phase and decrease the  $I_C$  and  $B_{C2}$ . The big degradation of the  $B_{C2}$  was shown in this paper for the first time in the world.

The irradiated wires were prepared by the bronze route process and the internal Tin process. It was hard to make notes about the difference of the irradiation properties on both wires in this study. The further investigation must be carried out.

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