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Framework of Collaboration Investigation on Neutron Effect on Superconducting Magnet Materials

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A fusion reactor will generate D-T neutron and the kinetic energy of the neutron will be converted to the thermal energy and electrical energy. The neutron has huge energy and will be able to penetrate a shielding blanket and stream out of ports for neutral beam injections. The penetrated and streamed out neutrons will reach superconducting magnets and make some damages on the magnet system. To investigate the neutron irradiation effects on the superconducting magnet materials, a collaborative network must be organized and the irradiation researches must be performed. This report will describe the framework of the collaboration investigation which has been established among neutronics, superconducting magnet and fusion system. After showing the collaboration scheme, some new results on 14 MeV neutron irradiation effect are presented. Then, a three years new project which was adopted as one of "Nuclear basic infrastructure strategy study initiatives" by MEXT will be introduced as an example of collaborative program among superconducting materials, fission reactor and high magnetic field technology.

Keywords: collaborative research, neutron irradiation effect, superconducting magnet materials, Nb_3Sn, Nb_3Al, fusion device, pinning, knock-on effect.

1. Introduction

International Thermonuclear Experimental Reactor (ITER) project is in progress, and design activity of DEMO plant will start as part of ITER broader approach (BA) program. ITER will generate D-T neutron (14 MeV) and shielding blankets will be installed in the plasma vacuum vessel [1]. The neutron will be able to penetrate the blanket and stream out of the neutral beam injection ports. So, the neutrons will reach superconducting magnets and cause activation and changes in the superconducting properties [2,3]. In case of JT-60SA which will be constructed under the ITER BA program, the device will not have the shielding blankets and D-D neutron (2.45 MeV) will easily irradiate the superconducting magnets. To reduce the irradiation, some resin with boron will be arranged on the outside surface of the vacuum vessel.

Since the superconducting magnets will be irradiated by fusion neutrons and the properties of the magnet materials will be changed by the irradiation, the database of the neutron irradiation must be constructed and the mechanisms of the property change and the general tendency of the irradiation effects must be discussed and clarified. To study the neutron irradiation effect on the superconducting magnet materials, the neutron irradiation facility must be arranged. Also, the evaluation system of the superconducting properties after irradiation must be installed in the radiation controlled area, because the samples will be activated by the neutron irradiation.

On the design of the fusion reactor system, the collaborative investigations among researchers in system engineering, neutronics, superconducting magnet, power supply and so on have to be performed considering the construction and operation of the superconducting magnet system. The exchange of the knowledge and discussion is very important and fruitful to understand the background of each research field and carry out the reasonable design. In this study, the special collaboration scheme among fission reactor engineering, neutronics, superconducting materials, fusion engineering has been organized and the framework has been constructed little by little under the inter-University scheme.

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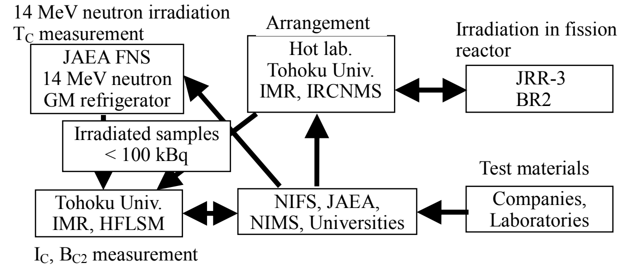

Fig. 1 Collaboration network for neutron irradiation effect on superconducting magnet materials.

In this paper, the collaboration network established will be explained and some test results obtained in the collaborative work will be presented. Also, the outline of the new project to install the superconducting magnet in a radiation controlled area will be introduced.

2. Collaboration Network

The collaboration scheme is shown in Fig. 1. There is a core meeting controlling all activities on the neutron irradiation investigation performed within this framework. Originally, the basic activity of the meeting has been supported by NIFS collaboration research program started in 2004. The samples are provided by NIFS, NIMS, JAEA and some companies and send to Fusion Neutronics Source (FNS) in Japan Atomic Energy Agency (JAEA) or JRR-3 (fission reactor) in JAEA through International Research Center for Nuclear Materials Science (IRCNMS, so-called Ooarai center) of Tohoku University. The irradiated samples are kept at radiation controlled areas in FNS and Hot Lab in Ooarai center and are sent to High Field Laboratory for Superconducting Materials (HFLSM) in Tohoku University after checking the residual radioactivity. Since the maximum Bq per one sample is limited to 100 kBq in HFLSM, some samples must wait for the reduction of residual radioactivity. The superconducting properties of non-irradiated and irradiated samples are evaluated in HFLSM using 28 T hybrid superconducting magnet. After measuring the properties, the samples are transferred back to FNS or Ooarai center and kept in usual way.

The participants in the frame work have meetings to expand the investigation to two directions, the application research and the basic research as described above. To realize the fusion reactor, the systematic study must be performed. However, the present status is on the phase developing the test facilities and test procedures for activated samples. The collaboration network established here is expected to be strengthened and widened more.

3. Change in Superconducting Properties

For the irradiation tests, NbTi, Nb_3Sn and Nb_3Al strands were taken up firstly and 14 MeV neutron irradiation tests started at FNS. After irradiation, the critical current and the critical magnetic field were measured at HFLSM. The irradiated samples were soldered on the sample holder in a radiation controlled area at Laboratory of α-Ray Emitters neighboring to HFLSM in Katahira campus of Tohoku University and then the sample holder was brought into the 28 T hybrid superconducting magnet.

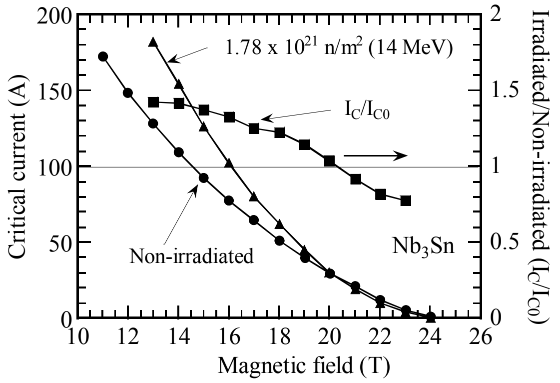

Fig. 2 Change in critical current of Nb_3Sn strand (0.7 mm diameter) against magnetic field. Non-irradiation and after 14 MeV neutron irradiation of 1.78×10^{21} n/m^2 at room temperature are compared.

A special cup was attached to the sample holder to reduce the scattering of small particles when the sample should be melt away in liquid helium during the critical current measurement. Also, a filter was inserted in the recovery line of the helium gas to collect the activated particles when melting should occur. After the test, the cryostat and surrounding area was investigated by a survey meter for safety.

The test results are shown in Fig. 2. Since the NbTi and Nb_3Al strands did not show the clear change after the irradiation as far as the data obtained, only the Nb_3Sn strand data was plotted. After the 14 MeV neutron irradiation of 1.78×10^{21} n/m^2, the critical current increased remarkably around 13 T. The critical magnetic field (B_{C2}) which was measured by shifting the magnetic field under the constant current of 0.1 A showed no clear change after the irradiation and it was about 25.5 T. It is recognized that the increment of the critical current depends on the magnetic field and it becomes zero at the higher magnetic field because of no change in B_{C2}.

The relation between the ratio of I_C/I_{C0} and neutron fluence is shown in Fig. 3. Where I_C is the critical current of irradiated sample and I_{C0} is the non-irradiated one. The data were referred from [4-6]. Some tendencies are observed in the figure. (1) I_C/I_{C0} increases once and decreases. But there is materials (samples) dependence. (2) Improved samples by the third element addition show lower increment of I_C. (3) The peak position of I_C/I_{C0} is shifting to the smaller fluence direction depending on the higher energy neutron irradiation. (KUR: Fission reactor.

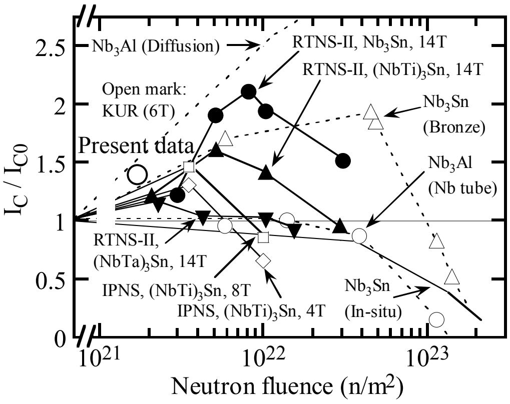

Fig. 3 Summary of neutron irradiation effect on critical current of Nb_3Sn wires. Round and triangle open symbols show the results at Kyoto University Research Reactor. Irradiation was done at around 355 K. Others were irradiated at cryogenic temperature.

RTNS-II: 14 MeV neutron source. IPNS: Spallation neutron source.) (4) Nb_3Sn made by bronze process without the third element showed higher I_C/I_{C0} at peak position, while the sample by in-situ process was not improved. (5) Nb_3Al showed the different results depending on the fabrication process, diffusion process and Nb tube process.

The present results at 13 T and 14 MeV neutron fluence of 1.78 x 10^{21} n/m^2 was plotted with a rather larger round open symbol. The increment of the I_C is very clear and I_C/I_{C0} becomes larger than previous data sets. It is not easy to explain the mechanisms of the I_C increment because the material and fabrication process are different. However, it is considered that the pinning force and/or number of pinning sites will be increased by the knock-on effect of the high energy neutron. The data will be obtained more in near future and the discussion will be performed systematically.

Voltage-current curves of Bi2223 tapes are shown in Fig. 4. The neutron irradiation was carried out in JRR-3 and the V-I curve measurement was performed in the hot lab in Ooarai center. The test conditions were at 77 K and under self-magnetic field. Although the data is a little scattered, there is no clear difference on the V-I curve. So, it would be concluded that there is no irradiation effect of neutron up to 1 x 10^{21} n/m^2.

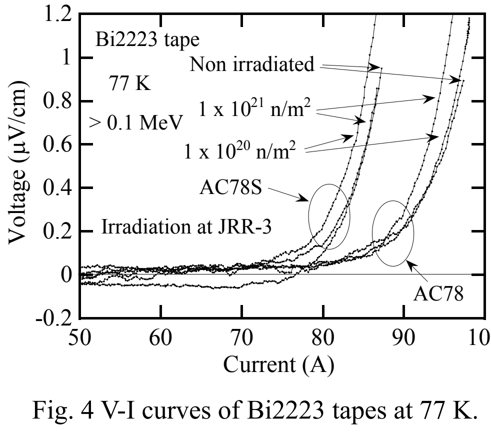

Fig. 4 V-I curves of Bi2223 tapes at 77 K.

4. New Proposal on Neutron Irradiation Study

A high magnetic field superconducting magnet is needed at the radiation controlled area to perform the tests of superconducting properties after neutron irradiation. To reduce the He gas load to air conditioning in the radiation controlled area, the magnet will have thermal conduction cooling system and not require a lot of liquid helium. Also, 500 A class current lead with thermal conduction system will be useful and the sample temperature will be controlled to be variable constant.

To prepare a superconducting magnet and the current lead, a proposal was composed and sent to MEXT in Japanese Government. The research frame was "Nuclear Basic Infrastructure Strategic Study Initiatives" and the area was the "Promotion of Effective Utilization of Hot Labs." The representative of the proposal is Professor Tatsuo Sikama at Tohoku University and NIFS, NIMS and HFLSM in Tohoku University are the collaborative institutions. The proposal title is "Study on neutron irradiated superconducting magnet materials at cryogenic temperatures and under high magnetic fields" and the investigation duration is three years. The purpose of this study is "Establishment of Center of Excellence for radioactive materials research at cryogenic temperatures and under high magnetic field." Fortunately, the proposal was adopted by the government and the activity started at the autumn in 2008. To realize the above purpose, the following facilities will be installed at the radiation controlled area in Ooarai center.

- Cryogenic system for 15.5 T superconducting magnet.
- Control system for 15.5 T superconducting magnet.
- 15.5 T superconducting magnet.
- Variable temperature insert and current leads.
- Measurement system.
- Magnetic field evaluation including shielding structure.
- 500 A power supply for sample.
- Support facilities.

The engineering design of the conduction cooled 15.5 T superconducting magnet and the cryogenic system already started. The inner bore diameter is 52 mm and it is room temperature space. The conceptual design of the variable temperature insert also started to discuss among the core members of the collaborative investigation network. It is the first trial in the world to cool down the sample by thermal conduction under the condition of 500 A related current. The final performance test of the facility will be carried out in winter of 2011. The project is a good success of the collaborative network.

In addition to the initiative program, the investigation and discussion on a cryogenic neutron irradiation system in a fission reactor began. The Japan Materials Testing Reactor (JMTR) locates at Ooarai in Ibaraki prefecture is now under repair work. It will restart in 2010 and the reopening of the irradiation service to Universities and Institutions is scheduled in 2011. In timing with this repairing, the cryogenic system for keeping the sample temperature less than 10 K during neutron irradiation will be designed and installed. A superconducting sample with lead wires for four probe method will be in the capsule and set in near the core of the fission reactor. On the conceptual design, the gamma-ray heating is assumed to be around 0.1 W/g (Fe) and the maximum neutron fluence will be around 2x 10^{22} n/m^2. To avoid the complicated procedures of High Pressure Gas Safety Law in Japan, the several GM refrigerators for 4 K will be combined and one cryogenic system with about 10 W at 4 K will be formed.

The sample will be irradiated at less than 10 K and the irradiated sample will be inserted into the 15.5 T superconducting magnet to measure the superconducting properties without rising the sample temperature up to 300 K. It will be a good simulation for superconducting magnet for fusion application

5. Summary

On the progress of design and fabrication of the D-D or D-T burning plasma devices and plants, the collaboration among various disciplines becomes more important and essential. To realize the special components for fusion plats, collaborative investigation is absolutely imperative. In this paper, the new trial to establish the collaborative project was introduced and the new results on neutron irradiation effects were presented. In addition, the contents of the new proposal adopted by MEXT, Japanese Government, were described.

The collaborative research network on neutron irradiation effect on superconducting magnet materials has been established. There are mainly two purposes. One is for design and fabrication activity providing the database. The other is academic activity to clarify the mechanism of the change in superconducting properties by neutron irradiation.

Under the collaboration of newly established network on neutron irradiation study, the superconducting property of Nb3Sn, Nb3Al and NbTi wires was investigated. As the results, it was clarified that the critical magnetic field did not change remarkably after 14 MeV neutron irradiation of 1.78 x 10^{21} n/m^2, though the critical current at lower magnetic field increased. Also, it was observed that the critical current of Nb3Al did not increase at the magnetic field range of 20 T to 25 T. As for the Bi2223 tapes, after the irradiation of 14 MeV neutron of 8.69 x 10^{20} n/m^2 and fission neutron of 1 x 10^{21} n/m^2, V-I curves were measured at 77 K under self-magnetic field, and no clear change was observed.

A new proposal entitled “Study on neutron irradiated superconducting magnet materials at cryogenic temperatures and under high magnetic fields” has been adopted by MEXT, Japanese Government, as a “Nuclear Basic Infrastructure Strategic Study Initiatives.” The promotion of integrated researches of various disciplines will be accelerated through the program, and the new facilities such as a 15.5T superconducting magnet will be opened for researchers at Universities and Institutions as special equipment for inter-University research. This new collaborative network will be expected to boost the realization of the component integration and DEMO plant.

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