DEVELOPMENT OF HIGH INTENSITY D-T FUSION NEUTRON GENERATOR AND ITS EXPERIMENTAL CAMPAIGNS

Yican Wu* and FDS Team
Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
Email: yican.wu@fds.org.cn

Abstract

Advanced nuclear systems, such as fusion systems, generally have features of large size, complex structure, spatially heterogeneous distribution of components and materials, and high energy and high flux as well as a wide and complex energy spectrum of neutrons. To confront these challenges, the FDS Team have been developing the high intensity D-T fusion neutron generator (HINEG) and performed a series of neutronics experiments. HINEG is an important platform for fusion technology and safety research, and it can also extend the nuclear technology applications.

Keywords: Fusion, HINEG, Neutronics experiment, Nuclear technology

1. INTRODUCTION

A high intensity D-T fusion neutron generator is an important experimental platform for research and development (R&D) of advanced nuclear energy systems and nuclear technology applications. Since the 1970s and 80s, in order to perform fusion neutronics experiments, several accelerator-based fusion neutron sources have been developed by the USA, Russia, China, Japan, Germany, Italy and other countries. The main operating accelerator-based fusion neutron sources such as TUD facility of the Technical University of Dresden reached a maximum neutron yield of 1×10^{12} n/s [1], FNG facility of the Italian Agency for New Technologies, Energy and Sustainable Economic Development achieved the neutron yield of 1×10^{11} n/s [2], and so on.

In order to validate new developed methods and codes and satisfy the research demands on neutron physics of innovative fusion reactors, the Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences (CAS)/FDS team have been developing the High Intensity D-T Fusion Neutron Generator (HINEG) [3-5], and have performed several neutronics experiments. HINEG, accelerating deuterium ions to hit tritium targets to produce 14.1 MeV mono-energetic neutrons, can be directly used to represent the neutron environment in future fusion reactors. Meanwhile, the application of HINEG can also be extended to neutron radiography, neutron radiotherapy, and other nuclear technology applications.

2. THE R&D ACTIVITIES OF HINEG FACILITY

Three development phases have been planned for the HINEG facility: HINEG-I, HINEG-II and HINEG-III. HINEG-I has been constructed and successfully produced the D-T fusion neutrons with yield up to 6.4×10^{12} n/s. HINEG-I is an important research platform for basic research on neutronics such as validation of neutronics theory and software, measurement and validation of nuclear data, radiation shielding and protection, etc. Figure 1 shows the scene of HINEG-I. In order to produce high-intensity neutrons, D-T fusion neutron generator needs to use high-current deuteron beam, which will bring high heat-flux on the target and affact the reliable operation of the facility. The high efficiency heat dissipation target has been developed based on the method coupling jet impingement array and strong shear flow. The heat flux current of deuteron beam on target reaches more than 20 kW/cm^2, while the target maximum temperature in the target spot is kept below 200℃. Meanwhile, a high intensity ion beam accelerating tube has been used with the high-gradient uniform electric field and the space charge lens of magnetic mirror fields. HINEG-I has been coupled with the Lead-based Zero Power Critical/Subcritical Reactor CLEAR-0, which is uniquely featured with the accurate inverse reconstruction ability of neutron energy spectrum based on energy and space discretization technology, in order to perform the physical and engineering validation of advanced nuclear energy systems. For the measurement of neutrons with wide energy spectrum and high flux, HINEG-I has been equipped with neutron measuring instruments for broad energy spectrum based on characteristic peak detection.

Figure 1 The scene of HINEG-I

HINEG-II aims at a high neutron yield of 10^{15}~10^{16} n/s by improving the high speed rotating tritium target system and high intensity ion source, which relies on fast rotating copper solid targets with the deuterium and tritium present on a thin coated layer of titanium hydride. The R&D for key components of HINEG-II is on-going. HINEG-II can support the research on validation of advanced nuclear technology, such as materials irradiation, component neutronics performance.

HINEG-III is designed as a volumetric fusion neutron source with yield of 10^{18} n/s, which is used for integration testing of nuclear system engineering. HINEG-III is based on the gas dynamic trap, and the design and preliminary research are in progress.

3. EXPERIMENTAL CAMPAIGNS

As an important platform for fusion technology and safety research, HINEG can be used to carry out the neutron activation and irradiation testing for structural and functional materials to assess the performance and reliability. The fusion neutron irradiation testing is being performed on China Low Activation Martensitic (CLAM) steel [6-7], which has been developed by INEST and selected as the candidate structural material for International Thermonuclear Experimental Reactor Test Blanket Module (ITER TBM). Meanwhile, its application can also be extended to nuclear medicine, radiotherapy, neutron imaging and other nuclear technology applications. Recently, a series of experiments are planned and performed on HINEG, such as neutronics performances of fusion reactor blanket, irradiation testing of shielding blanket, biological effects of neutron irradiation, 14 MeV neutron radiography, etc.

As example 1, a dual function lithium-lead (DFLL) test blanket module (TBM) [8] has been developed by FDS team to demonstrate the technologies of the liquid lithium–lead breeder blankets. In order to validate the neutronics design of DFLL-TBM, especially the tritium breeding performance, experiments have been carried out at D-T neutron source with DFLL-TBM mock-up. Activation foils were used to measure the reaction rate of In, Al and Nb at different depth positions in the mock-up, while Li glass detector was used to measure the tritium production rates. Calculation has been performed by Super Multi-functional Calculation Program for Nuclear Design and Safety Evaluation (SuperMC) [9] with FENDL3.1 library. SuperMC, developed by FDS Team has series of efficient calculation methods such as Global Window Weight Generator (GWWG), by which the calculation for typical deep penetration problem, ISPRA-Fe experiment, is speed up by 4397 times. The comparison of experimental data and corresponding calculated results was presented, and the deviation between the calculated results and the experimental ones are less than 10%. The result indicates an agreement between SuperMC calculations and experimental data.

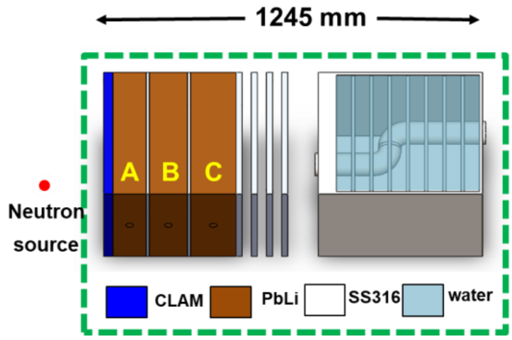

Figure 2 Configuration of DFLL-TBM mock-up neutronics experiment

As example 2, dose effect of high-energy neutron radiation in Caenorhabditis elegans was performed on HINEG. In this experiment, C. elegans is used as the experimental subject to study high-energy neutron radiation dose effect of HINEG and the underlying mechanism was discussed. It is found that radiation has a strong inhibitory effect on brood size and lifespan with 1.83Gy, indicating the existence of neutron hyper-radio sensitivity. The experiment results demonstrate that the neutron dose has a clear dose effect on the individual damage and the importance of neutron low dose radiation protection as result of hyper-radio sensitivity and provides scientific basis for low-dose radiation protection of neutron.

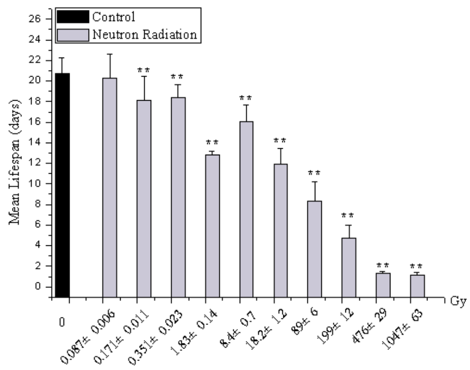

Figure 3 Neutron radiation affects lifespan

As example 3, a fast neutron radiography (FNR) system has been designed and constructed based on HINEG facility. FNR is a very promising and powerful non-destructive inspection technology. It provides images free of artifacts and with reasonable contrast for robust sample containing mixed low-Z/high-Z materials, and is able to differentiate isotopes of an element. The spatial resolution of FNR system is mainly limited by the low intensity of neutron source, low detection efficiency and high scattered neutrons ratio. A series of experiments has been carried out on HINEG to evaluate the spatial resolution of the designed FNR system. And a spatial resolution of less than 0.5mm has been obtained.

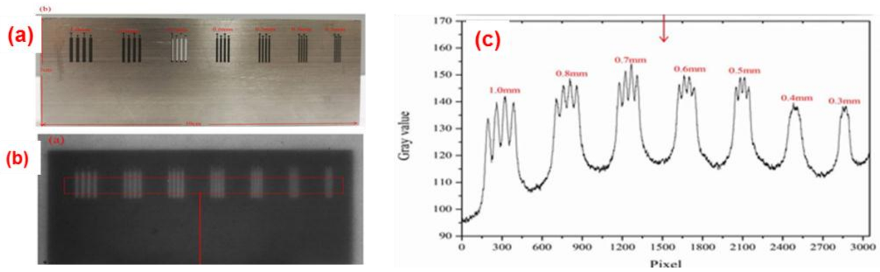

Figure 4 The experimental sample and result of FNR system

4. CONCLUSION

In this paper, the latest R&D activities and experimental campaigns of HINEG have been presented. HINEG-I is equipped with neutron measuring instruments for broad energy spectrum based on characteristic peak detection, and has produced a neutron yield of 6.4×10^{12} n/s. Meanwhile, HINEG-I has been coupled with CLEAR-0, which is uniquely featured with the accurate inverse reconstruction ability of neutron energy spectrum based on energy and space discretization technology, and gives a new way for the development of advanced neutron sources. Additionally, a series of experimental campaigns have been performed, including validation of neutronics performances of fusion reactor blanket and several nuclear technology applications.

ACKNOWLEDGEMENTS

This work has been supported by the Informatization Project of Chinese Academy of Sciences (XXH13506-104), the National Magnetic Confinement Fusion Science Program of China(2014GB112000), the National Magnetic Confinement Fusion Science Program of China(2015GB116000), the National Natural Science Foundation of China(11605233, 71671179), the National Science and Technology Innovation Fund, the Chinese Academy of Sciences (CXJJ-17-M175). Besides, the authors would like to show their gratitude to other members of the FDS Team for supports to this research.

REFERENCES

[1] A. Klixa, et al., Measurement and analysis of neutron flux spectra in a neutronics mock-up of the HCLL test blanket module, Fusion Eng. Des. 85 (2010) 1803-1806.
[2] M. Martone, et al., The 14 MeV Frascati neutron generator, J. Nucl. Mater. 212 (1994) 1661-1664.
[3] Y. Wu, Chen Z, Hu L, et al. Identification of safety gaps for fusion demonstration reactors. Nature Energy 1 (2016) 16154.
[4] Y. Wu. Development of high intensity D-T fusion neutron generator HINEG. Int. J. Energy Res. 42 (2018) 68-72.
[5] Y. Wu. Multifunctional neutronics calculation methodology and program for nuclear design and radiation safety evaluation. Fusion Sci. Technol. https:// doi.org/10.1080/15361055.2018.1475162.
[6] Q. Huang, FDS Team, Development status of CLAM steel for fusion application, J. Nucl. Mater. 455 (2014) 649-654.
[7] Q. Huang, Status and improvement of CLAM for Nuclear application, Nucl. Fusion 57 (2017) 086042.
[8] Y. WU, FDS Team, Design Analysis of the China Dual-Functional Lithium Lead (DFLL) Test Blanket Module in ITER, Fusion Eng. Des. 82 (2007) 1893-1903.
[9] Y WU, J SONG, H ZHENG, et al., CAD-Based Monte Carlo Program for Integrated Simulation of Nuclear System SuperMC, Ann. Nucl. Energy 82 (2015) 161-168.