

A study of beryllium moderator thickness for a fission chamber with fast neutron measurements

Wen-Di Wang^{1,2} · Hong-Rui Cao^{1,2} · Jing Cao^{1,2} · Guo-Liang Yuan³ · Ze-Jie Yin^{1,2}

Received: 1 April 2016/Revised: 2 November 2016/Accepted: 26 November 2016/Published online: 7 August 2017
© Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Chinese Nuclear Society, Science Press China and Springer Nature Singapore Pte Ltd. 2017

Abstract The detection efficiency of the fission chamber (FC) is very important for studying the neutron flux measurement (NFM) system in ITER. In this article, we mainly focus our attention on the influence of the moderator. With the Monte Carlo particle transport simulation tool named Geant4, we make a simulation of FC detection efficiency with different levels of thickness of a beryllium moderator. Two manufactured FCs for ITER-NFM systems are then used to test the parameters and performance. The test results agree well with our simulation.

Keywords Fission chamber · Fast neutron · Neutron flux monitor · ITER · GEANT4

This work was supported by the National Natural Science Foundation of China (Nos. 10976028 and 11375195) and the National Magnetic Confinement Fusion Energy Development Research (No. 2013GB104003).

✉ Wen-Di Wang
349697638@qq.com; wwdbbs@mail.ustc.edu.cn

✉ Ze-Jie Yin
zjyin@ustc.edu.cn

¹ State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China

² Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

³ Southwestern Institute of Physics, Chengdu 610041, China

1 Introduction

Because of the persistence of the energy crisis, controllable fusion energy has drawn people's attention. The agreement for the ITER (International Thermonuclear Experimental Reactor) project was signed between seven countries in 2006. Its purpose is the collaborative research of practical controllable fusion technology. Of the seven countries, China has taken responsibility for a series of detection projects.

Most of our attention concerns the operating conditions and parameters of the plasma in the ITER reactor. A series of plasma diagnostic systems have been proposed [1–3]. The NFM system with a fission chamber as the detector is an important diagnostic system within the ITER. Because the neutron flux is a significant parameter in the calculation of fusion reaction power, the spatial and time distribution of the plasma varies with discharge situations. For example, the plasma ion temperature and density distribution can vary [4, 5]. After considerable studies for scientific feasibility, two fission chambers were designed and manufactured for the NFM system. They serve as the neutron acquirement front ends [6–8].

In the ITER reactor, high-temperature plasma radiates a large number of hard X-rays, γ -rays, and neutrons. Background radiation will severely influence the measurement results from the fission chamber. Therefore, rigorous shielding must be applied around the fission chamber [9–14]. Research on FC shielding and moderators began with the design of the NFM system. In 2009, simulations used polyethylene and graphite as a moderator. The simulations mainly considered the intrinsic detecting efficiency over different incident angles [15–17]. In 2012, beryllium and boron carbide were considered as moderator

materials [18]. However, there remain two deficiencies in this research. First, all discussion of the fission chamber moderator was made without confirmed FC parameters, especially the γ -ray sensitivity. Therefore, the suggested thickness of the moderator is generally higher than the actual requirement. Second, all the discussions about the moderator lacked the support of experimental results. Here, we offer a new simulation using a low-thickness beryllium moderator with a thickness between 20 and 50 mm. Furthermore, we conducted an experiment to measure the FC parameter and tested the effectiveness of the moderator. The results agree well with our simulated results.

The fusion reaction in ITER contains two stages: D–D fusion and D–T fusion. The neutron energy spectrum in the D–D process is a Gauss Fusion Spectrum, with an average energy reading of 2.45 MeV. In the D–T process, it is 14.1 MeV. That means the sensitivity of the FC in the D–D process should be higher than that of the D–T process. Therefore, early work applied uranium-235 (U-235) as the fission material with beryllium as the moderator in the D–D process. And in D–T fusion, uranium-238 (U-238) was applied as a fission material, with boron as a shield material. The combination of two FCs with different sensitivities is a good method for obtaining a wide range of neutron measurements. Also, the combination demonstrates that the moderators lead to a flat energy curve when the magnitude of beryllium moderator thickness is about 100 mm; this also ensures the other particles likely are shielded [19].

In the experiment that measures the FC parameter, we find that the FC is actually extremely insensitive to γ -rays. In the experiment, the FC is set, without shielding, within a very high cobalt-60 (Co-60) radiation field, with the absorbed dose at about 100 Gy/h. But the measured count is about 40 cps. From the energy spectrum of Co-60, we can estimate that the γ -ray detection efficiency of the FC has a magnitude of 10^{-9} . Since the detection efficiency of the FC we used in the experiment is 1 (unless the γ -ray flux is extremely larger than the neutron flux), it may not be necessary to use multilayer shielding, or very thick moderators, to eliminate the γ -ray's contribution. This experimental detail will be introduced with the moderator test in the Experiment section. Therefore, our simulation covers the low-thickness situation, with the beryllium moderator between 20 and 50 mm. In the end, we will provide the FC detection efficiency of each simulated situation.

2 Simulation

According to the analysis, the magnitude of the energy spectrum in the ITER reaction ranges from 0.1 to 10 MeV. As a result, we chose seven energy levels, based on the

energy spectrum of mono-energetic neutron sources within the experiment. The final selections are 0.1, 0.144, 0.25, 0.565, 0.75, 1, 1.2, 2.5, 5, 7.5, 10, 12.5, and 14.8 MeV. The processing of the FC is simulated with the Monte Carlo particle transport simulation tool Geant4. The simplified model is shown in Fig. 1a. The irradiated body contains three components: the stainless steel shell, the beryllium moderator, and the FC in the center. The thickness of the outermost shell is 3 mm. The thicknesses for the simulation of the moderator are: 20, 30, 40, 42.5, 45, 47.5, and 50 mm. In the thickness range between 40 and 50 mm, we add three extra choices for simulation data to get the detailed results we desire within the vicinity of the experimental moderator thickness.

The FC model is simulated according to the manufactured FC designed for ITER. The structural detail of the ITER FC is shown in Fig. 1b. According to the design handbook, it is a 50×500 mm cylindrical structure. The fissile layer is coated with 1 g of fissile material. Also, there is a 1-cm area, which is filled with argon, from the fissile layer to the electron collector. According to our analysis, we chose to use U-235 as the best option for fissile materials in the D–D reaction, and U-238 in the D–T reaction. Since their structure is the same, this difference does not affect the simulation result.

The Geant4 simulation must be similar to the experimental environment. Figure 2b is the schematic view of radiation scene as described by Geant4. In the figure, we can see the neutron injection from the bottom of the figure, as well as the scattering in the moderator. At every energy dot, we conduct a 10^7 particles simulation. The results of the simulations are shown in Fig. 3.

In Fig. 3, we can see the influence of a beryllium moderator. The x-coordinate refers to the various energy points. And the y-coordinate refers to the normalized detection efficiency (N/N_{\max}). Here, N_{\max} refers to the maximum

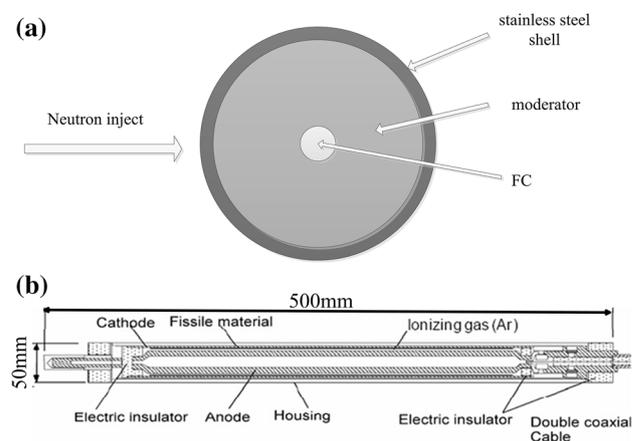


Fig. 1 Simplified model of FC and moderator (*top view*) (a) and structural schematic of FC used in ITER (b)

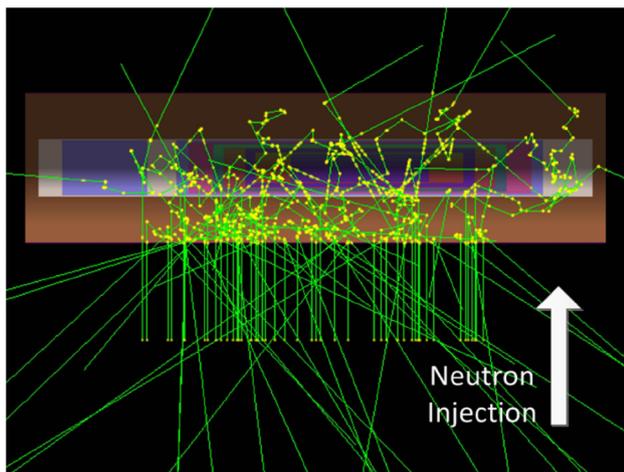


Fig. 2 (Color online) The schematic view the radiation scene described by Geant4



Fig. 4 (Color online) Experimental environment of FC anti- γ performance

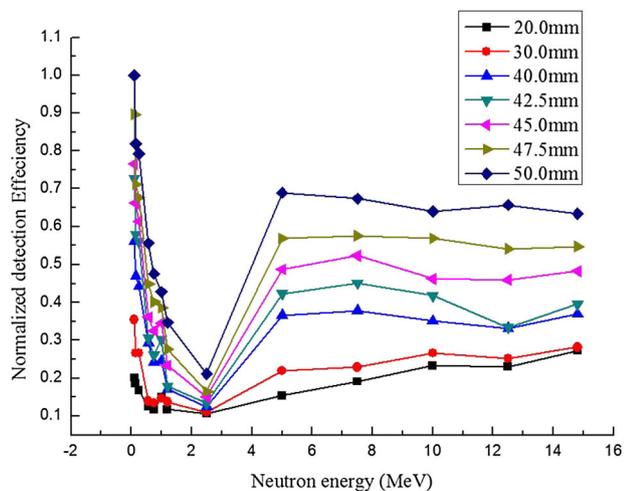


Fig. 3 (Color online) Simulation results of the detection efficiency with various thicknesses of the beryllium moderator

efficiency of the neutron detection obtained with all moderators. The curves going from the bottom to the top are the 20–50 mm beryllium moderators. It can be inferred that the detection efficiency will continue to increase as the thickness of the moderator grows larger than 50 mm in both the high-energy and low-energy segments.

3 Experiments

We provide two experiments to support the simulation results. First, we need to ensure that the FC is not sensitive to other particles in ITER reactions, especially those of γ -ray reactions. So, we conducted the γ -ray radiation test in the China Institute of Measurement and Testing Technology. Second, we conduct the moderator effect experiment in the China Institute of Atomic Energy.

As we mentioned above, there are two FCs in the NFM system. One is manufactured by CNNC—Beijing Nuclear Instrument Factory (marked FC-I). The other is supported by ITER (marked FC-II). In the experiment, we test the anti- γ and the moderator performance with both FCs.

3.1 The FC anti- γ performance experiment

The FC anti- γ performance experiment is designed to ensure that the FC is not sensitive to other particles in D–D and D–T reactions. Since we can already discriminate for the α -particle, we mainly consider the influence of γ [20].

As shown in Fig. 4, part 1 is the FC. It is placed transversely at a distance from the radiation source such that the radiation adsorbed dose is about 100 Gy/h. Part 2 is the cobalt-60 (Co-60) source. It will be pulled out of the shield when the experiment begins. Part 3 is the connecting fiber to the NFM system. The FC count will be calculated during the end system.

Because of the background counts, we must first measure the FC counts without radiation. Then, we set the discrimination threshold to 0.32 V to eliminate the α -particles and record the data every 100 s. The results are listed in Table 1.

From Table 1, we can see that in such a high-radiation field the average counts of FC-I and FC-II are 8.94 and 4.08 cps. From this experiment, it can be ascertained that we are able to use the least thick moderator in simulation. In the beryllium moderator experiment, we choose the 50 mm beryllium layer as a moderator.

3.2 The beryllium moderator experiment

The experimental environment is shown in Fig. 5.

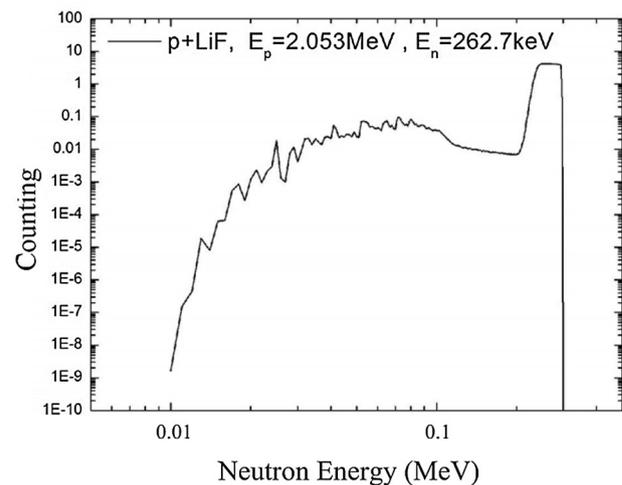
As shown in Fig. 5a, part 1 is the moderator, which we used to make the simulation model in Fig. 1. The only

Table 1 Counting rate of FCs in the very high Co-60 radiation field

FC-I (with source) Counting rate (cps)	FC-I (without source) Counting rate (cps)	FC-II (with source) Counting rate (cps)	FC-II (without source) Counting rate (cps)
5443	4555	4464	4258
5326	4309	4436	4207
5321	4498	4560	4108
5308		4679	
5285		4764	
5406		4758	
		4596	
		4427	
		4708	

**Fig. 5** (Color online) Environment of beryllium moderator experiments (a) and the comparative beryllium moderator experiments (b)

difference is that the moderator is a 50 mm-thick beryllium ball layer. That leaves the equivalent thickness as an unknown. Parts 2 and 3 are the target and its accelerator, in which protons will be accelerated to hit the Li target. As a result, the accelerator will release neutrons. The accelerator is able to provide seven different mono-energetic neutrons. The provided energy levels are 0.144, 0.25, 0.565, 1.2, 2.5, 5, and 14.8 MeV. The energy spectrum examples of the accelerator are shown in Fig. 6 in which the mono-energetic neutron with 0.25 MeV is given. From this figure, we

**Fig. 6** Energy spectrum of typical mono-energetic neutron source

can see the particle energy is concentrated in the small vicinity of 0.25 MeV. Therefore, it is able to meet our experimental requirements.

By considering the influence of the neutrons reflection off both the wall and the ground, we can conduct a comparative experiment to measure the influence of the reflected neutrons, in the same situation as shown in Fig. 5b. In Fig. 5b, part 1 is the neutron emission hole of the accelerator. Part 2 is a trapezoidal lead brick, which is able to fully shield the direct injection neutron. Part 3 is the FC, covered by a beryllium moderator, which is connected to the NFM system. In this experiment, since the direct injection neutrons are almost all shielded by the lead brick, the NFM system counts mainly come from reflected neutrons.

At every energy point, we measure the output 3–4 times for each FC and calculate the average. After normalizing the results, we arrive at the result shown in Fig. 7a. For the purpose of comparison, we add the results of the 40–45 mm simulation to the figure. We also provide the original error analysis results in Fig. 7b.

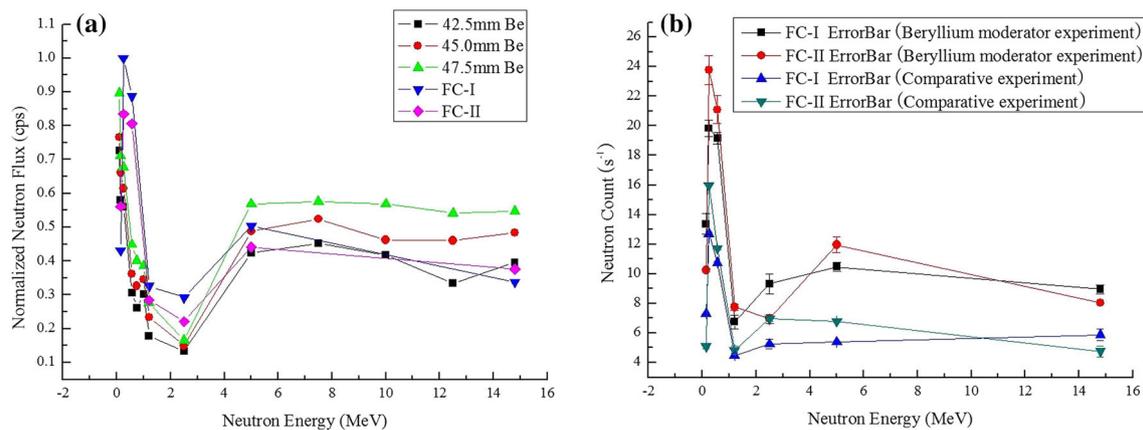


Fig. 7 (Color online) Results (a) and error analysis (b) of beryllium moderator experiments

In Fig. 7b, the black and red lines are the result of the beryllium moderator experiment. The blue and green lines are the comparative experiment's result. We can see that the standard deviation of each line is very small under the same experimental conditions. Since the whole experiment lasts for about 2 days we can conclude that the experimental results are stable over a long period of time. Therefore, the results in Fig. 7a are accurate and credible.

The x -coordinate is the neutron energy, and the y -coordinate is the normalized detection efficiency. In the figure, we can see that the measured results match the simulation well with the 45- and 42.5 mm curves. At the energy point of 14.8 MeV, the relative error is a bit high. The relative errors between FC-I and FC-II, as well as the 42.5 mm curve for the energy point at 14.8 MeV are 14.67 and 4.97%, respectively. By considering the measuring error, we find that the FC-I result is acceptable and that the FC-II result matches the simulation fairly well.

4 Conclusion

The moderator of the ITER-NFM system is a problem that has been discussed since the beginning of the project. The simulations of the moderator material, its thickness, and its incident angle have all been discussed in detail. For this study, we selected beryllium as the moderator and conducted a series of simulations and experiments. The greatest advantage of our work is the use of a low-thickness moderator. It can help people save a lot of space and costs associated with solving other problems, e.g., FC electronic transmission, high voltage supply, and pre-amplifier shielding.

However, our work still has room for improvement. The moderator we used is a 50 mm layer filled with beryllium balls. It is very difficult to simulate the detailed situation without the diameter, distribution, and other parameters of

the moderator. Therefore, our simulation is only approximately equivalent to the actual application in the ITER. Furthermore, the influence of the FC's background radiation generated in ITER is not taken into consideration. Low strength moderation is based on the conclusion that there is no evidence to show that the background radiation's influence is much stronger than neutrons. We will continue to focus on this research area in the future.

Acknowledgements The authors would like to thank all the professors and doctors in the Southwestern Institute of Physics, and other colleagues in the University of Science and Technology of China, for their assistance in experiments and valuable discussion in the result analysis.

References

- ITER Team. ITER design description document diagnostics 5.5. B neutron diagnostics (2003)
- S.A. Lazerson, I.T. Chapman, STELLOPT modeling of the 3D diagnostic response in ITER. *Plasma Phys. Controlled Fusion* **55**(8), 084004 (2013). doi:[10.1088/0741-3335/55/8/084004](https://doi.org/10.1088/0741-3335/55/8/084004)
- G.A. van Swaaij, K. Bystrov, D. Borodin et al., Dissociative recombination and electron-impact de-excitation in CH photon emission under ITER divertor-relevant plasma conditions. *Plasma Phys. Controlled Fusion* **54**(9), 095013 (2012). doi:[10.1088/0741-3335/54/9/095013](https://doi.org/10.1088/0741-3335/54/9/095013)
- J.W. Yang, Q.W. Yang, G.S. Xiao et al., Fusion neutron flux monitor for ITER. *Plasma Sci. Technol.* **10**, 141–147 (2008). doi:[10.1088/1009-0630/10/2/01](https://doi.org/10.1088/1009-0630/10/2/01)
- J.W. Yang, W. Zhang, X.Y. Song et al., Development of a prototype neutron flux monitor for ITER. *Nuclear Fusion Plasma Phys.* **25**, 2 (2005). doi:[10.3969/j.issn.0254-6086.2005.02.005](https://doi.org/10.3969/j.issn.0254-6086.2005.02.005)
- B. Yang, Development of a high sensitive fission chamber. *Nuclear Electron. Detect Technol.* **23**, 5 (2012)
- Z.G. Dong, A wide range ionization chamber for neutron flux measurement system. *Nuclear Electron. Detect Technol.* **33**, 11 (2013)
- V. Khripunov, Nuclear performance of the D–D phase of ITER. *Fusion Eng. Des.* **51–52**, 281–287 (2000). doi:[10.1016/S0920-3796\(00\)00248-9](https://doi.org/10.1016/S0920-3796(00)00248-9)
- M. Angelone, P. Batistoni, L. Petrizzi et al., Neutronics experiment on a mock-up of the ITER shielding system at the Frascati

- neutron generator (FNG). *Fusion Eng. Des.* **42**, 255–260 (1998). doi:[10.1016/S0920-3796\(97\)00169-5](https://doi.org/10.1016/S0920-3796(97)00169-5)
10. H. Freiesleben, W. Hansen, D. Richter et al., Neutron and photon flux spectra in a mock-up of the ITER shielding system. *Fusion Eng. Des.* **42**, 247–253 (1998). doi:[10.1016/S0920-3796\(98\)00139-2](https://doi.org/10.1016/S0920-3796(98)00139-2)
 11. J.F. Briesmeister. MCNP-A general monte-carlo code for neutron and photon transport version 4B. LANL Report, Los Alamos National Laboratory (1997)
 12. Y. Kaschuck, A. Krasilnikov, A. Alekseyev et al., Neutron flux monitoring system for ITER-FEAT (abstract). *Rev. Sci. Instrum.* **72**(1), 823 (2001). doi:[10.1063/1.1323487](https://doi.org/10.1063/1.1323487)
 13. V. Goiffon, F. Corbiere, S. Rolando et al., Multi-MGy radiation hard CMOS image sensor: design, characterization and x/gamma rays total ionizing dose tests. *IEEE Trans. Nuclear Sci.* **62**(6), 2956–2964 (2015). doi:[10.1109/TNS.2015.2490479](https://doi.org/10.1109/TNS.2015.2490479)
 14. H. Hirayama, H. Nakashima, M. Morishima et al., Progress and prospects of calculation methods for radiation shielding. *J. Nuclear Sci. Technol.* **52**(11), 1339–1361 (2015). doi:[10.1080/00223131.2015.1021283](https://doi.org/10.1080/00223131.2015.1021283)
 15. G.L. Yuan, J.W. Yang, G.S. Zhang et al., Neutronics calculations of neutron flux monitor for ITER. *Nuclear Fusion Plasma Phys.* **29**(1), 67–71 (2009)
 16. K. Asai, T. Iguchi, T. Nishitani et al., Improved in situ calibration technique for ITER ex-vessel neutron yield monitor. *Fusion Eng. Des.* **81**(8–14), 1497–1502 (2006). doi:[10.1016/j.fusengdes.2005.09.046](https://doi.org/10.1016/j.fusengdes.2005.09.046)
 17. V. Khripunov, ITER first wall as a source of photon neutrons. *Fusion Eng. Des.* **56–57**, 899–903 (2001)
 18. C. Li, Q. Wang, L. Li et al., Optical calculations of neutron flux monitor for ITER. *Nuclear Electron. Detect. Technol.* **32**, 5 (2012)
 19. G.L. Yuan, Q.W. Yang, J.W. Yang et al., Fusion neutron flux detector for the ITER. *Plasma Sci. Technol* **16**, 2 (2014). doi:[10.1088/1009-0630/16/2/14](https://doi.org/10.1088/1009-0630/16/2/14)
 20. S.P. Li, S.F. Xu, H.R. Cao et al., A real-time n/γ digital pulse shape discriminator based on FPGA. *Appl. Radiat. Isot.* **72**, 30–34 (2013). doi:[10.1016/j.apradiso.2012.10.00](https://doi.org/10.1016/j.apradiso.2012.10.00)