Evaluation of Radiation Skyshine and Groundshine of a D-D Tokamak Using Monte Carlo Method

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Abstract—Computational analyses were performed to evaluate the radiation skyshine and groundshine from the D-D Tokamak EAST under various design cases. The Monte Carlo transport code MCNP-4C, the nuclear data library FENDL-2 and a simplified geometrical model were used. The influence of different filling materials for tokamak vacuum vessel and shielding hall roofs on the environmental dose rate distribution were investigated. The results indicate that the direct contribution to environmental radiation from the D-D neutron source decreases rapidly with the radial distance increasing and then the skyshine radiation dominates. In addition, the groundshine effect makes significant contribution to the environmental radiation.

Keywords—skyshine; groundshine; tokamak; Monte Carlo

I. INTRODUCTION

Radiation leakage into the environment from a nuclear fusion reactor or experimental facility is mainly due to the skyshine effect because the roof of the fusion facility hall is generally not so thick as compared with the vertical wall. In addition, the groundshine effect also plays a significant role for some shielding design cases. Therefore, the evaluation of the radiation skyshine and groundshine from a fusion facility is of great concern from the viewpoint of safety. The accurate estimation of radiation skyshine and groundshine leads to reasonable shielding design of fusion facilities and reduction of the external radiation dose.

There exist a few studies on radiation skyshine of fission reactors, high energy accelerators, and other nuclear facilities [1-3]. However, the investigations on the fusion neutron skyshine problem are still limited. Some experiments and analyses for a D-T fusion neutron source have been performed [4]. But for D-D fusion neutron source, no experiments and studies are found available so far.

The superconducting tokamak EAST [5], which is under construction in the Institute of Plasma Physics of Chinese Academy of Sciences, will perform D-D plasma experiments and the production rate of 2.45 MeV neutrons will achieve the level of $10^{15}$ n/s. Consequently, it is of great interest to assess the dose rate level outside tokamak building and investigate the effects of radiation skyshine and groundshine from neutrons and neutron-induced secondary gammas. In this work, Monte Carlo analyses were performed to investigate the effects of skyshine and groundshine from EAST on the environmental radiation field.

II. CODE, NUCLEAR DATA AND GEOMETRICAL MODEL

The Monte Carlo transport code MCNP-4C [6] was used in this study due to its powerful capability of geometry modeling and rich collections of variance reduction techniques. The latest issued fusion evaluated nuclear data library FENDL-2 [7] was employed with MCNP-4C. The D-D fusion neutron source was assumed to be isotropic and uniformly distributed in the plasma zone with the energy of 2.45 MeV. This approximation of neutron source modeling has only slight influence on the environmental radiation field analysis as indicated by previous investigation [8]. The source neutron intensity is $1 \times 10^{15}$ n/s.

Since the purpose of this work is to investigate the effects of skyshine and groundshine on the environmental radiation field, a simplified cylindrical model of EAST was used as shown in Fig. 1. This model includes the vacuum vessel (VV) and the toroidal field coils (TFCs) which were proved to be the most important shielding components [9]. The VV comprises a double-wall structure with filling material (boronated or pure water) in the inter-space. The TFCs are homogenized and the volumetric fraction is set to be 50% to consider the void between each TFC set. The roof, vertical wall and floor of the shielding hall are 1, 1.5 and 0.4m thick concrete, respectively. It should be pointed out that the actual tokamak hall of EAST is in rectangular shape and it was approximated by a cylinder shape in this model. A sphere of air with the radius of 1000m (not shown in Fig. 1) was specified over the ground outside the shielding hall in the model. An 8m thick soil layer was included in the model to take the ground into account. Some imaginary torus cells with minor radius 50 cm (not completely shown in Fig. 1) were specified outside the shielding hall at the mid-plane of the machine as detectors for dose rate calculations.

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Figure 1. MCNP model of EAST tokamak
III. RESULTS AND DISCUSSION

The neutron and neutron-induced secondary photon fluxes were calculated with the MCNP-4C code in the detector cells by the track length estimator in a parallel computer environment using PVM software. The dose rates were obtained by multiplying the fluxes by the neutron/photon flux-to-dose rate conversion factors [10]. The statistical errors of the neutron/photon fluxes are below 10%.

According to the design of EAST, the boronated water is loaded in the inter-space of VV to improve neutron shielding and the pure water as a candidate material. The influence of these filling materials on radiation skyshine and groundshine were investigated. In addition, the effects of different designs of hall roof on environmental radiation were also evaluated.

A. Effect of filling material

To investigate the influence of different filling materials of the VV, the dose rates outside the shielding hall were calculated for the cases of boronated water, pure water and vacuum with 1m thick concrete roof of shielding hall. Fig. 2 gives the calculated dose rates as a function of distance. It is found that the highest dose rate for the case of pure water is ~14µSv/h, which is reduced by a factor of ~3 while compared with the case of vacuum. However, the results indicate that there is no significant shielding improvement for boronated water when compared with pure water. The results also show that the secondary gamma-rays dominate the dose rates within short distance for all cases. The contribution from neutrons increases with the distance increasing and becomes dominant at ~20m for boronated water, ~30m for pure water and ~15m for vacuum. In addition, for the neutron dose rate distribution there is a peak at ~20m for all cases, which is mainly due to the neutron skyshine effect.

Furthermore, a peak is found at the distance of ~20m for the neutron flux of skyshine and groundshine, which is consistent with the neutron dose rate peak abovementioned. For photon flux, the direct contribution is dominant within ~40m and then the skyshine becomes the major term. It is also noted that within ~10m the contribution of groundshine is larger than that of skyshine for photons.

B. Effect of roof thickness

Because skyshine is strongly subjected to the roof thickness, three design cases (i.e. 1.0m, 0.5m and void concrete roof) were investigated with the filling material as boronated water. Fig. 4 gives the dose rates as a function of distance. It shows that the environmental radiation field varies considerably while the roof thickness reduced less than 0.5m. The neutrons dominate dose rate overall for the cases of 0.5m and void while the neutrons dominate within ~20m for the case of 1m roof. In addition, the largest dose rate is found to appear at ~17m for the cases of 0.5m and void roof instead of at the wall corner for the case of 1m roof. This is clearly due to the strengthened effects of skyshine and groundshine while roof thickness reduced.
Fig. 5 displays the neutron/photon fluxes as a function of distance for different roof thickness. It is indicated that skyshine dominates the dose rate both for neutrons and photons in the cases of 0.5m and void roof. The groundshine of neutron and photon radiation also makes significant contribution. The direct contribution across the vertical wall of shielding hall decreases rapidly and becomes negligible with distance increasing.

IV. CONCLUSIONS

Monte Carlo analyses were performed to investigate skyshine and ground from a D-D fusion tokamak in different design cases. The results show that the dose rate level is reduced by a factor of ~3 for the case of pure water as filling material of VV compared to the case of vacuum. However, the use of boronated water doesn’t provide a significant shielding improvement compared to pure water. For the case of 1m thick roof, direct contribution dominates the dose rate within short distance and decreases with distance increasing. The skyshine becomes dominant in large distance. With the roof thickness reduced to 0.5m and void, skyshine effect is greatly strengthened and dominates the environmental dose rate overall. Groundshine also makes significant contribution.

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REFERENCES