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Fuzz Growth under Fusion Reaction and Estimation of Blanket's lifespan

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Abstract. Tungsten has been regarded as a candidate of plasma facing material (PFM) in magnetic fusion reactor (MFR) due to its high strength, high thermal conductivity, and low erosion rates. Alpha particles, as the by-product of the D-T fusion reaction, will collide onto the Tungsten divertor and form nanotendrils structures called “fuzz” with an estimation of 3.4 MeV energy. In this paper, we simulated by Stopping and Range of Ions in Matter (SRIM) to investigate the diffusing time and damage rate of the alpha particles on Tungsten. To describe the fuzz generation, the concepts in the diffusion model are utilized to describe the fuzz generation with corresponding techniques (e.g., Fick's Migration Law). Through this diffusion model, we can derive an estimated lifespan for a divertor blanket that matches the design of general fusion reactors. These results pave a path to investigate the irradiation damage for Tungsten in divertor blankets.

1. Introduction

Tungsten(W) has already become one of the most vital materials for the blanket and divertor in fusion reaction owing to the high thermal conductivity, low sputtering yield, and tritium retention [1]. Nevertheless, there is an obvious drawback of tungsten, especially under the condition of the bombardment. As shown in the laboratory plasma device, a fiber structure called “fuzz” is generated on a tungsten surface. Fuzz can decrease the temperature of a thermally loaded surface and increase its resistance to thermal loads [2]. Besides, it will affect tritium enhancement, i.e., prevent further release of W [3]. To guarantee the duration and working efficiency of tungsten, there is a great necessity to investigate the generating mechanism of fuzz, which is still not clear now in the fusion field.

The W-coated graphite surface fiber structure on NAGDIS-II in 2006 was the first study of the irradiation damage for Tungsten(W) [4]. Subsequently, many studies focused on fuzz growth in the plasma device and simulating condition [5]. Most of them investigated kinetic energy (Particles' temperature), i.e., all kinds of hypothetical models exist, e.g., 3D diffusion model [5]. These models explain the mechanism of fuzz generation by agglomeration with helium and calculate helium kinetic energy loss to simulate a real situation in a fusion reactor. However, the time-related function to estimate the lifespan of the tungsten is seldom discussed.

In order to arrange structure reasonably and reduce cost, the prediction of the lifespan is necessary. Contemporarily, the growth of the fuzz layer shows a linear dependence on the square root of time at the surface temperatures of 1120K and 1320K. Besides, the threshold for producing fuzz of ion energy



is about 30eV [6]. Different researches have explained the fuzz generation in different methods. It should be noted that the fuzz growth mechanism has much in common with the assuming diffusion-controlled model [6]. Previous studies analyzed the impacts of fuzz generation on tungsten through experimental or laboratory data, basing on diffusion theory. Nonetheless, accurate data cannot be exposed to the public, i.e., it's compulsory to come up with a simulation measure.

In this study, a diffusion model is provided to explain the growing generation of fuzz. Moreover, it will combine with the simulation data in SRIM(TRIM) to derive an apposite lifespan prediction of tungsten. This paper is organized as follow: the utilized method (diffusion model and simulation with SRIM) will be introduced in Sec. 2; the results and discussions of the simulation results as well as analytical descriptions will be presented in Sec. 3; a summary will be given in Sec. 4 eventually.

2. Method

2.1 Diffusion Model & Fuzz Generation

Alpha particle is a by-product of the D-T fusion reaction. Inside the reactor, alpha particles will penetrate the Tungsten blanket, migrate, and agglomerate. Eventually, it forms small He bubbles that will burst out, generating nanotendrill structures called “fuzz”. Figure 1 represents a possible mechanism for the fuzz generation. One sees the agglomeration of He bubbles inside the Tungsten metal sheet, which is similar to the migration of vacancy inside a material [5]. With the increase of time, the vacancy will migrate randomly inside metals. As a result, we apply Fick's law of migration and introduce the concept of diffusion to describe this fuzz-generating process. The reasons are multiple: (1) Migration of He bubbles can be regarded as a vacancy diffusion lied inside the Tungsten blanket; (2) there is a significant concentration difference between the alpha particle present in the chamber and the blanket; (3) there are two types of materials that are being observed. Consequently, diffusion activities will take place at a more rigorous rate.

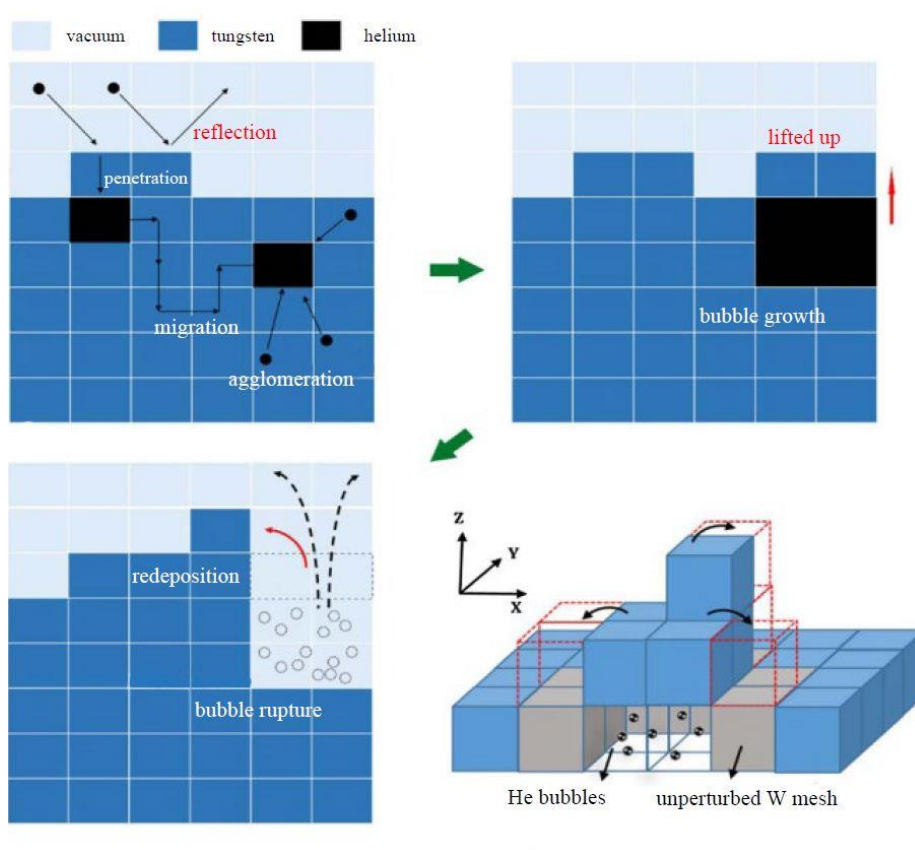


Figure 1. A Sketch of Mechanism for Fuzz Generation under Helium Bombardment [5]

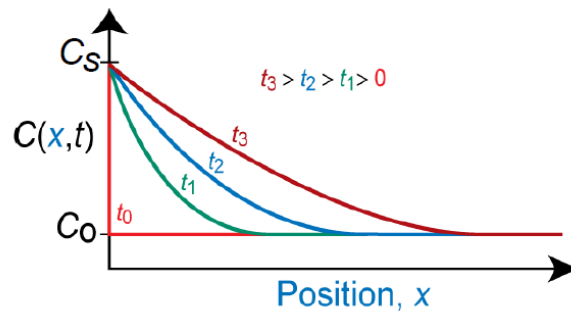


Figure 2. Time-Relevant Diagram for Diffusion

According to Fick's Law of migration, the diffusing process is a function of both time and position for a non-steady-state diffusion as $C = C(x, t)$. Figure 2 shows a time-relevant diagram for diffusion. As diffusing time increases, the concentration gradient over a certain depth will tend to be linear, from the surface concentration to the original concentration at a distance x below the surface. Furthermore, the lifespan of a fusion reactor is designed to be functional for several decades, which requires a long duration. Consequently, we made a linear assumption that the concentration gradient will linearly decrease as depth increases from the surface to the inside of the Tungsten divertor blanket.

2.2 SRIM

The SRIM(TRIM) [6] Monte Carlo simulation application is generally used to compute a common radiation damage exposure unit as known as displacement per atom (dpa). For this purpose, an international standard has been designed for SRIM to determine dpa definition [7]. SRIM can provide concluded data of displacement cascade, amendable distribution, and simulated plot. The diffusion model describes dpa as creating the vacancy, i.e., dpa is the common ground between diffusion model and SRIM. Thus, it seems probable to derive data according to with diffusion model by SRIM.

The SRIM(TRIM) allows two kinds of particles for bombardment within the various condition to simulate the real helium punch in a fusion reactor. The two particles are called ions and targets, respectively. According to the D-T nuclear fusion reaction, the alpha particles possess initial energy of 3.4MeV. When they punch the tungsten surface, their energy will be lower than that magnitude. We assumed a worst-case scenario that no energy loss would occur for Helium ions generated. For both an appropriate simulation result and a rapid simulation process, the total number of ions is set to 1500, with autosave number 100.

3. Results and Discussion

3.1 SRIM Simulations

Figure 3 depicts all the helium ions trajectories through a 6um depth in tungsten layer1. According to the results, helium ions tend to stop in the depth of approximately 5.5um by the 3.4MeV energy. Figure 4 illustrates the ion ranges distribution after 1500 ions simulation. X-axis means the tungsten depth, while Y-axis denotes a feature similar to the density of helium in tungsten, which is amendable by exchanging the unit. Figure. 5 represents dpa in successive columns. Red space means vacancies in tungsten produced by helium bombardment under every different target depth. SRIM uses displacement conditions to describe atom damage level. The denser red points are, the more displacement appears in that depth. Obviously, the depth where most helium ions stay owns crucial damage brought by helium ions.

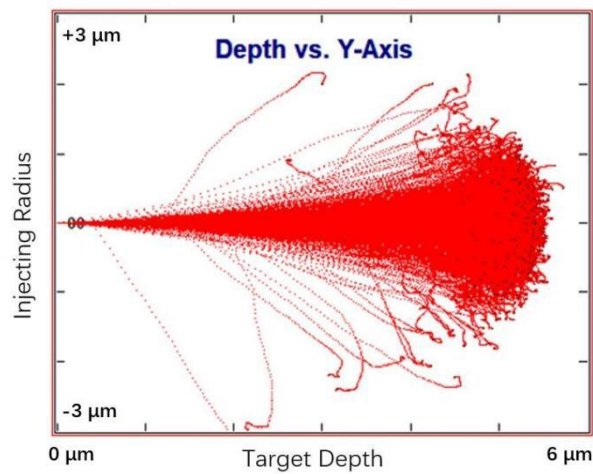


Figure 3. Trajectories of Particles collected from SRIM Collision Simulation.

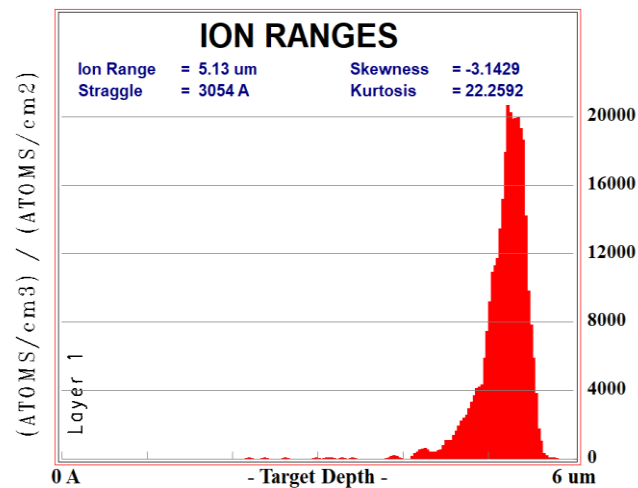


Figure 4. Statistic of Ion Location at the End of Simulation

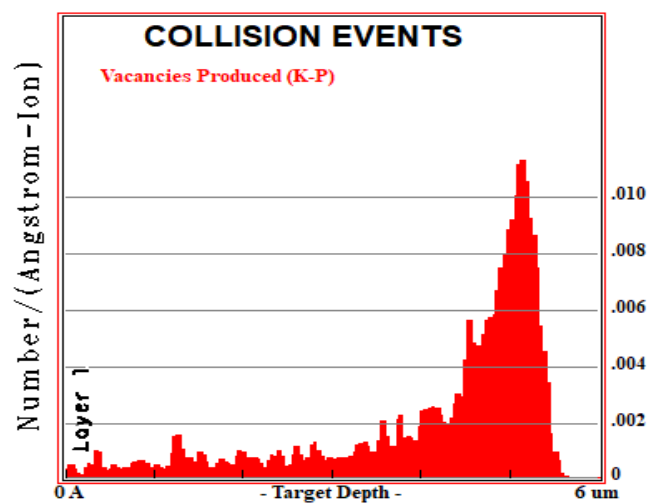


Figure 5. Collision Ratio at Different Position

3.2 Diffusion Time Calculation

We apply techniques in the diffusion model, specifically Fick's Second Law of migration, to derive the diffusion time of Helium particles in Tungsten metal. The temperature in a fusion reactor is extremely high. Correspondingly, the surface metal temperature inside the reactor is expected to be high. According to relevant research, we assume a fusion reactor's temperature to be $T=1320K$ [8]. As a result, the coefficient of diffusion, D , under fusion condition, is found to be [8] $D_{1320K} = (2.0 \pm 0.5) \cdot 10^{-11} cm^2/s$. Concerning the original concentration of diffusing material C_0 , we assume the concentration of He particles tungsten divertor blanket before the nuclear reaction is significantly lower than the surface concentration as well as the depth concentration (C_s and C_x). This is based on the assumption of well-developed metal processing technologies of modern industries. As a result, the original concentration of diffusing material inside mother material C_0 is ignored.

The surface concentration level C_s is determined according to related research, where the concentration of alpha particle, C can be derived via the equation [6]:

$$C = \left(\frac{q}{D}\right)^{\frac{1}{2}} \quad (1)$$

where q is the adatom formation under ion bombardment; the ion is an alpha particle; D is the diffusion coefficient under fusion conditions [9]. Parameter q is expressed as [6]:

$$q = j \cdot Y_a \quad (2)$$

where j represents the ion flux and Y_a is the coefficient of bombardment-induced adatom formation [9]. For a typical D-T fusion reaction, the Helium particle has expected energy of $E_\alpha = 3.4 MeV$. Therefore, the surface metal blankets which contains the plasma will experience a surface particle flux $j_s = 5 \cdot 10^{18} particles/cm^2s$ according to relative research and an adatom formation coefficient of $Y_a \cong 10^{-3} adatom/particle$ [8]. With a predetermined coefficient of diffusion D_{1320K} , we can derive the surface alpha particle concentration of $C_s = 1.83 \cdot 10^{13} adatom/cm^2s$ using equation (4) and (5). The depth-wised ion flux j_x is derived via SRIM, and related calculation is given by the following equation [6]:

$$j_x = \rho_w / P \quad (3)$$

where ρ_w is the Tungsten volume density, unit in $atoms/cm^3$, and ratio P unit in $(atoms/cm^3)/(atoms/cm^2)$. The depth-wised concentration level, C_x , is then derived using Eq. (1) and (2). The diffusion time t is then calculated using Fick's Second Law of Diffusion.

Based on our linear assumption, one needs a scale to represent the gradient difference with increasing depth. We derived an equation to calculate the percent drop in flux at depth x . In other words, we expect the He ion flux to have the same percentage drop over each cycle of the diffusion process we simulated. The equation is given as:

$$\%drop = j_x / j_s \cdot 100\% \quad (4)$$

where j_x is the ion flux at the target depth, j_s is the ion flux at the surface. Our further data is derived using this simulation-resulted factor because of the current restrictions.

3.3 SRIM-Derived Damage Rate Calculation

Since the lack of bombardment figure in the laboratory, it cannot know a real situation about Tungsten particle punched by Helium. Therefore, the level of Tungsten damage should be shown in a new factor, Vacancy. Under the 3D and diffusion model, a Helium particle will create vacancy by migration, agglomeration, and other Helium atoms try to enter into the vacancy made by it. Vacancy disarranges initial Tungsten atoms, so it's feasible to regard vacancy as damage done by bombarding alpha particles to Tungsten blankets.

By applying SRIM, a collision event diagram is derived, and parameters are read. The horizontal axis represents target depth that describes positions at which Helium particles collide with Tungsten; the vertical axis represents the vacancy rate R_{vc} for a particular collision simulation. The final collision-generated vacancy V_w is derive via the equation shown below:

$$V_w = R_{vc} \cdot P_A \cdot j_x \quad (5)$$

where R_{vc} is the peak vacancy rate read via the collision diagram; P_A is the percent vacancy remained due to annealing, we set this parameter to be $P_A = 0.01$. We applied equation (4) to derive the total vacancy in Tungsten, V_W . Due to the condition of Tungsten, we need to compare vacancies with the original Tungsten atoms arrangement. i.e., V_W over the density of Tungsten to derive damage rate in one cycle.

$$TM = V_W / \rho_W \cdot 100\% \quad (6)$$

where TM is the total damage rate in one cycle.

3.4 Discussions

The diffusion-related data we obtained are listed in Tables 1 and 2. Only one simulation cycle is carried out, and final results are authenticated by conducting the same simulation procedures five times.

Table 1. Results for Diffusing Time Calculation for Blanket Surface

x, μm	j_s , atoms/ cm^2	q_s , adatom/ cm^2	C_s , adatom/ cm^2
0	5.00×10^{18}	5.00×10^{15}	1.8257×10^{13}

Table 2. Results for Diffusing Time Calculation for the First Cycle

x, μm	j_x , atoms/ cm^2	q_x , adatom/ cm^2	C_x , adatom/ cm^2
5.2002×10^{-6}	3.0658×10^{18}	3.0658×10^{15}	1.2381×10^{13}

Correspondingly, the percent drop is found by applying equation (4) that $\%drop = 60\%$. Therefore, we assume a 40% decrease of He ion flux within the Tungsten metal blanket and derive the rest of the depth-wised flux j_x by multiplying this factor. Then, diffusing time is calculated using Fick's Law of migration. Damage rate is also obtained by applying equations (5) and (6). The damage rate and diffusing time are tabulated together, shown in Table 3. The rest of the data is derived via the linear assumption and plotted using MATLAB in Figure 6.

Table 3. Table of Diffusing Time and Total Damage Rate

	x, μm	Diffusing Time, hrs.	Total Damage Rate, %
Surface	0	N/A	0
1st Cycle	5.2002×10^{-6}	32.79	5.28×10^{-5}

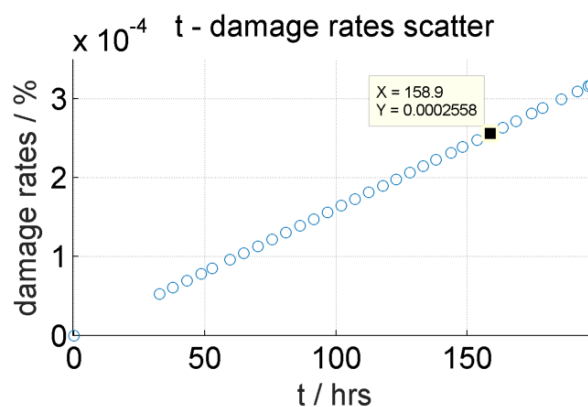


Figure 6. Total Damage Rate as a function of Time.

In order to interpret the equation plot, an equation of total damage rate can be derived:

$$TM = 1.61 \cdot 10^{-4} \cdot (\text{hrs} \cdot t)^{-1} \cdot 100\% \quad (7)$$

where T_M represents the total damage rate, and t is the time of the diffusing process. The slope of this linear equation is the damage generation rate as the result of He ion bombardment into Tungsten blanket.

Equation (7) can be regarded as an approximation of the actual damage rate of the divertor blanket in a certain fusion reactor. By putting in a time duration of 30 years, which is the expected lifespan for a fusion reactor, we found the total damage rate is around 42.3%. Here, we are assuming a worst-case scenario by directly using the Helium flux at the surface of D-T plasma. In fact, the expectation of actual surface concentration will be lower than what we derived due to the distance between the plasma and the divertor. Nevertheless, the experimental damage rate is considered acceptable and suitable in a real situation where less than half of the Tungsten blanket remains intact after 30 years of bombardment.

Such approaches in this research have a drawback that the actual depth-wised flux is assumed to be linear rather than accessing from the lab. In other words, such an assumption is based on the interpretation of multiple simulations rather than actual lab observation. As a result, there will be a discrepancy between the experiment and our simulations.

4. Conclusion

In summary, we investigated the relationship between the fuzz generation and the related damage generation by simulations from SRIM and diffusion model. According to our results, a linear correlation is found between the fusion reaction time and the total damage rate. The obtained correlation equation can be a basic guideline on the damage analysis of the Tungsten divertor blanket. Besides, it can act as a method to find the desired lifespan for a Tokamak fusion reactor. Nevertheless, the applied linear assumption is based on simulation rather than actual observation, indicating a possible discrepancy between the equation and the actual damage rate. Thus, further research should be focused on the comparison between experimental and simulation results.

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