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New model of plasma heat load on the first wall

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HIGHLIGHTS

- A new analysis model for the plasma heat load on the FW is developed.
- The 3-dimensional FW heat load profile can be estimated with this model.
- This model is expected to be useful for the DEMO design.

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ABSTRACT

Scrape Off Layer (SOL) plasma circumnavigates the torus along magnetic field lines, and some part of it encounters a leading edge of the first wall (FW). This leads the concentration of the plasma energy in a small area, causing a hot spot. In a DEMO reactor that deals with a few hundreds of MW of plasma energy in the SOL, the leading edge problem is a critical issue in the FW design. For the design purposes in DEMO and power reactors, a new analysis method is introduced, where a flux tube is poloidally divided into the Apple Peel Like Elements (APPLEs) and each APPLE is enclosed by adjacent 4 magnetic field lines. Considering the contact area of the APPLEs on the FW and the radial energy transport between the APPLEs, FW heat load profile can be analyzed. The result of the case that the fusion power is 1.5 GW, and the major radius is 8.2 m, shows that the heat load is peaked to about 1 MW/m^2 near the inboard midplane and the baffle plate. This method is expected to be useful for the DEMO design.

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1. Introduction

Assessment of the first wall (FW) heat load profile is one of the key design issues to establish DEMO concepts, because heat load on the FW surface has a large influence on its thermal stress or temperature. The heat load will vary with the FW shape and the plasma condition such as the MHD equilibrium, the fusion power and so on. Thus, the FW surface has to be designed according to reliable heat load prediction. The steady heat load on FW mainly consists of the following factors: (1) the plasma radiation such as bremsstrahlung or line radiation, (2) charge-exchange neutrals, (3) the plasma heat flux along the magnetic field lines, (4) ripple loss alpha particles, and so on. In this paper, the new analysis model of the FW heat load caused by the plasma heat flux is developed. Some plasma particles in the SOL (Scrape Off Layer) region are transported to the FW along the magnetic field lines. It is known that this parallel heat flux profile can be expressed to decay exponentially in the radial direction and its decay length depends on the magnetic field line connection length [1,2]. The heat load analyses with this decay model for the ITER FW design are shown in Refs. [3–5]. In these references, the limiter phase heat load are mainly analyzed, where the magnetic surfaces are nearly circular in the poloidal cross section and the flux does not expand (i.e., the distance between the separatrix and the magnetic surface are constant in the poloidal direction). Thus, the FW contact area of the flux tube depends only on the magnetic field line incident angle, and the heat load can be expressed as the function of the distance from the separatrix and the incident angle. In the DEMO divertor configuration, however, the outer magnetic field lines can be interrupted by the FW surfaces (shown as Fig. 1). Consequently the connection length and the decay length change, and the distance between the magnetic surface and the separatrix is not constant. Such an interrupted magnetic field makes it difficult to estimate the heat load. In this research a new analysis model has been developed to solve this problem. In this model, a flux tube is

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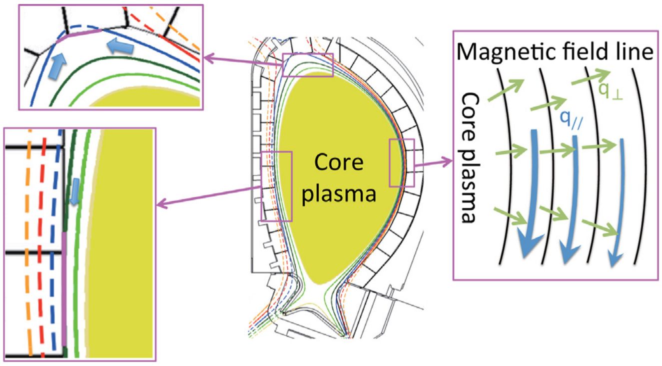

Fig. 1. The image of the magnetic field line interrupted by the FW. The plasma heat flux contacts on the FW (as shown with the purple line), and this causes the local heat load concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

divided into the smaller elements enclosed by adjacent 4 magnetic field lines. This element is called APPLE (Apple Peel Like Element) in this paper. Using the APPLE, the heat load can be estimated by taking into account the effect of the flux expansion, and the effect of interrupted magnetic field line. In this paper, the first calculation result with our model is presented. Section 2 describes our model, and the calculation result is shown in Section 3. Section 4 is the summary.

2. Analysis model

2.1. Basic idea

The basic idea to estimate the heat load on the FW caused by the plasma heat flux is shown in Fig. 2. The plasma energy out of the core plasma diffuses in the radial direction, and it is transported to the divertor and the FW along the magnetic field lines. The plasma heat flux along the magnetic field lines ($q_\parallel$) in each flux tube can be expressed as follows [6],

$$q_\parallel = q_{\parallel 0}(R_q e^{-\delta/\lambda_{\mathrm{near}}} + e^{-\delta/\lambda_{\mathrm{far}}}), \tag{1}$$

where δ is the distance between the separatrix and each flux tube at the outboard midplane, λ_{near} and λ_{far} are the width of the near SOL and the far SOL respectively, and the R_q is the ratio between the term of $e^{\lambda_{\mathrm{near}}}$ and $e^{\lambda_{\mathrm{far}}}$. The heat flux in the far SOL region will drop more slowly than that in the near SOL region. To represent this effect, the two decay length (λ_{near} and λ_{far}) are introduced. In this research, R_q and λ_{near} are assumed to be constant, and λ_{far} is assumed to be expressed as follows [1,2],

$$\lambda_{\mathrm{far}} = \frac{v_\perp L}{c_s}, \tag{2}$$

where $v_\perp$ is the particle velocity perpendicular to the field, c_s is the plasma sound speed, and L is the magnetic field connection length. It is assumed that $v_\perp$ and c_s are constant, and λ_{far} depends on only the connection length. Considering that the magnetic field line is interrupted by the FW, the connection length of each flux tube volume is different, thus, λ_{far} is different in each flux tube volume. The image of $q_\parallel$ decay is also shown in Fig. 2. Considering these effects, the heat load is calculated by the following 4 steps. First, λ_{far} and $q_\parallel$ in each flux tube volume are calculated from the connection length. Second, from the integration of $q_\parallel$ over each flux tube volume, the power included in each flux tube volume is calculated. Third, the flux tube volume power is normalized to the total flux tube volume power P_{out} (the power from the core plasma) that is artificially specified. Finally, from the flux tube volume power and the contact area, the FW heat load is calculated.

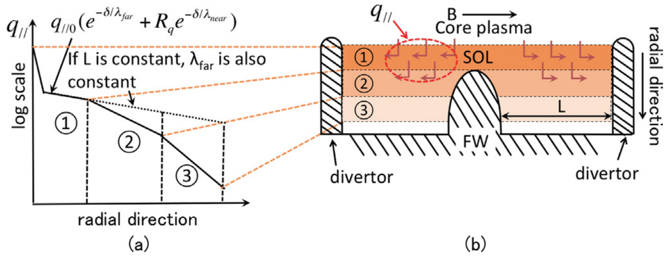

Fig. 2. The basic idea of heat load analysis on FW. The left figure (a) is an image of parallel heat flux with radial decay. The horizontal axis is the minor radius at the outboard midplane, the vertical axis means the value of parallel heal flux (log scale). The curve shows three radial areas, which are characterized by the decay lengths λ_{far} and λ_{near}. The right figure (b) shows schematically that the decay lengths λ_{far} and λ_{near} are dependent on the varying connection lengths of each magnetic field line due to interruption by FW. The image of three layers corresponds to the three radial areas shown in the figure on the left.

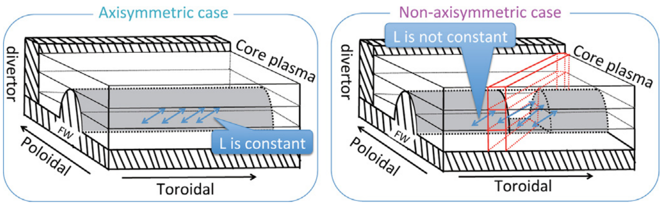

Fig. 3. The flux tube volume image of axisymmetric and non-axisymmetric case. In the non-axisymmetric case, connection length L is not constant in each flux tube volume. Thus, the volume should be divided to the smaller elements (expressed by the red lines) to use the basic idea. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Problem and solution

In the basic idea, the power in each flux tube volume is calculated from the connection length L, but, actually, the magnetic field line is interrupted by the FW in the toroidal direction, L is not constant in each flux tube volume and the basic idea cannot be used. To solve this problem, the flux tube volume is divided into the smaller elements. The image of this problem is shown in Fig. 3. Calculating the energy in the elements (which is expressed by the red lines in Fig. 3) with the basic idea, the FW heat load in the realistic geometry can be estimated. To divide each flux tube volume, the 3-dimensional (3D) magnetic field line trace code is used. Fig. 4 shows the dividing image. Each flux tube volume is divided into the Apple Peel Like Elements (referred to as APPLE in this paper). Each APPLE is defined as a volume element enclosed by the adjacent 4 magnetic field lines, having an elongated shape along the magnetic field lines with varying pitches. With the 3D magnetic field line trace code, the FW contact area of the APPLE, and the heat load at this area can be estimated and plotted. After all APPLE calculation being done, the total heat load map can be plotted on the FW developed figure. The magnetic field line traces are started from the points on each magnetic surface at the $\phi = 0°$ plane. An example is shown in Fig. 5. The square constructed by the 4 points in Fig. 5 is the cross section of each APPLE. To calculate the heat load, the radial direction sets of the APPLEs are considered (expressed by pink lines in Fig. 5). Figure. 5 also shows the image of each APPLE interrupted by the FW like Fig. 2. In this method, the connection length in each APPLE is almost constant, and the basic idea can be used.

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