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S. Pestchanyi

***Abstract*—A simplified model, describing turbulent plasma transport in far SOL has been proposed for calculation of the plasma heat and particles fluxes to the first wall and divertor targets of the DEMO tokamak. The model has been implemented into the TOKES code for simulation of the wall heat flux distribution along the tokamak first wall. First simulations of the wall heat flux, using this model, predicts more pronounced 'hot spots' at the top of the DEMO wall in comparison with the exponential heat flux decay model, commonly used for simulation of the flux.**

***Index Terms* — DEMO, TOKES, far SOL, wall heat flux simulation.**

I. INTRODUCTION

First wall (FW) of the DEMO reactor should protect the breeding blanket and mechanical construction elements of the burning plasma exposure. The plasma impacts the wall surface by heating and by energetic particles. The heat load on FW during steady state burning mainly consists of the following factors: (i) the plasma photonic radiation, (ii) the plasma heat flux along the magnetic field lines, (iii) charge-exchange neutrals, (iv) alpha particles, produced by fusion reaction and partially leaked into the scrape-off layer (SOL).

Assessment of the FW heat load is one of the key design issues determining the DEMO reactor, because the heat flux there is a challenge for the FW armor material both due to high operation temperature and considerable erosion rate by sputtering. Cooling system of the first wall in DEMO should provide stable operation in the wide range of surface heat fluxes: from 0.3 MW/m^2 up to 1 MW/m^2 [1].

The power P_{sep} crosses the separatrix due to stationary diffusion process and due to intermittent MHD turbulent convective flux of so called 'blobs'. Each blob is a magnetic tube of several cm cross section, filled with plasma of the density and temperature, much larger than those of SOL, which separated from the core plasma. Sketch of the blob is shown in Fig. 1. Heat flux in the near SOL directed along the magnetic field. Perpendicular profile of the flux determined by plasma cross-diffusion and can be approximated with sufficient accuracy as exponentially decaying across the SOL with the decay length of few millimeters in the outer midplane. In contrast, the blobs propagated from separatrix to the wall with rather high velocity across SOL, perpendicular to the magnetic field due to $\vec{E}\times\vec{B}$ drift; simultaneously, the plasma inside the blob flows along the magnetic field and deposits the plasma energy onto the wall through the blob ends by parallel plasma convection and by electron thermoconductivity along the field lines. Each blob spans along the magnetic lines in SOL, where all the lines cross the wall. Partitioning of the total heat flux crossing the separatrix between diffusive and convective channels is not known. Reasonable estimations [1] suggest the convective turbulence transfers 10-40% of total heat flux by charged particles and the rest falls on the diffusion channel.

The last baseline DEMO1 configuration [2] with the aspect ratio k=3.1 and 18 TF coils (R=8.8 m, a=2.8 m, B=5.4 T, q_{edge}=3, Ip = 19.5 MA, S the surface area ~1551 m^2) and the fusion power of P_f = 2 GW is considered in the paper. During deuterium-tritium nuclear reaction 20% of the fusion power released with charged particles inside the tokamak core.

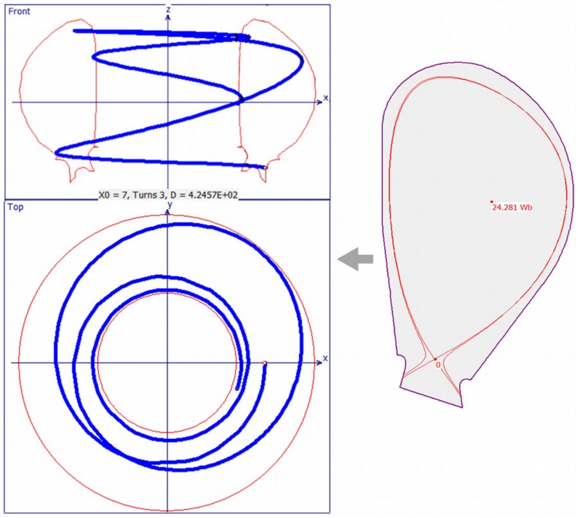

Fig. 1. 3D view of one blob inside the tokamak and its projection onto the poloidal plane. The blob is a magnetic tube of several cm cross section, filled with plasma of the density and temperature, much larger than those of SOL. After coming out of the separatrix the blob stretched along magnetic field from inner divertor target to the outer one. Radial movement of the blob tube results in poloidal and toroidal motion of the blob ends along the first wall.

According to the PROCESS code calculation [1] 2h burning can be achieved with P_{add} = 50MW of additional power resulting in about P_{exh} = 450 MW of thermal power exhaust inside the core in the nominal operation [2]. The minimum heat power crossing the separatrix with particles is about P_{sep} =

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130 MW. The PROCESS code gives $P_{sep} \sim 231$ MW, which corresponds to $P_{rad,core} \sim 226$ MW of radiation from the bulk DEMO1 plasma [1]. In our simulations further we will use this estimation of power, crossing the separatrix and $P_{sep,far\ SOL} = 46$ MW for the turbulent plasma transport in the far SOL.

Heat flux deposition to the DEMO first wall determined by the blob perpendicular velocity, by the parallel heat flux (electrons and ions) and by the magnetic field configuration (expansion factors along the field lines and crossing angle between the magnetic field line and the wall surface). The blob perpendicular velocities and the blob sizes are determined by the plasma parameters and by the effective collisionality in SOL. Analytical models for these parameters and experimentally measured values are available from literature [3,4]. Accurate description of the blobs dynamics and of the time dependences for the parallel heat flux along the blob is nontrivial. As a first approximation, the exponential decay assumption for the dependence of the parallel heat flux on the radial coordinate in the midplane is used nowadays [5]. This assumption gives rather rough approximation for the real flux dependence, however reliable enough to give right description of the heat flux distribution along the reactor first wall. Simulation of the DEMO wall heat flux in exponential decay approximation has been implemented in the TOKES code, developed over the past decade at FZK-KIT for integrated 2D simulations of transient events in tokamaks [6-8]. The result of the simulation for the exponential midplane flux decay length of λ_q=10 cm and $P_{sep,far\ SOL} = 46$ MW is shown in Fig. 2.

In this paper a new model for the FW heat load caused by the plasma turbulent particle and heat flux associated with plasma blobs (ii) is developed. In this model we fully refuse from the exponential flux decay approximation, describing instead perpendicular blob filament flight across SOL and parallel plasma transport inside the blob.

A model of the blobs moving with constant radial velocity and depositing heat flux to the wall due to these processes has been developed and implemented into the TOKES code.

II. MODEL FOR PLASMA TRANSPORT INSIDE BLOB

A. Physical Assumptions of the Model

The intermittent turbulent heat flux in far SOL is assumed to be transported by means of the blobs. Blob movement model, implemented into the TOKES code, describes the plasma parameters evolution during its flight across SOL. This model is a simplification of the real blob dynamics due to ∇B plasma polarization and associated $\vec{E}\times\vec{B}$ drift at outer side of the SOL [9,10]. This model is to be used for engineering studies and optimization of various DEMO first wall designs. The TOKES model assumes that the blob separated from the

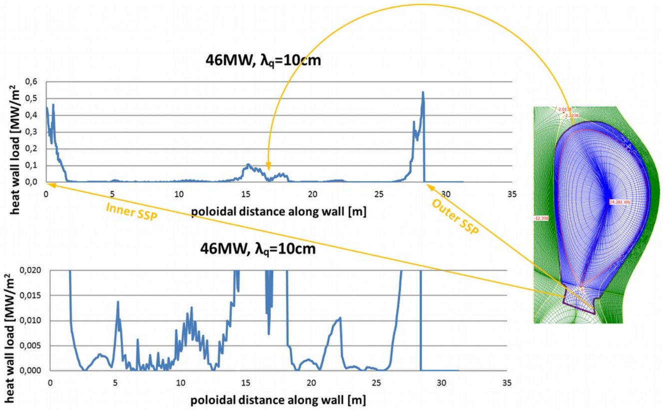

Fig. 2. Turbulent heat flux distribution along the DEMO first wall. Shown is the result of TOKES simulations using the exponential midplane flux decay assumption with λ_q=10 cm and $P_{sep,far\ SOL} = 46$ MW.

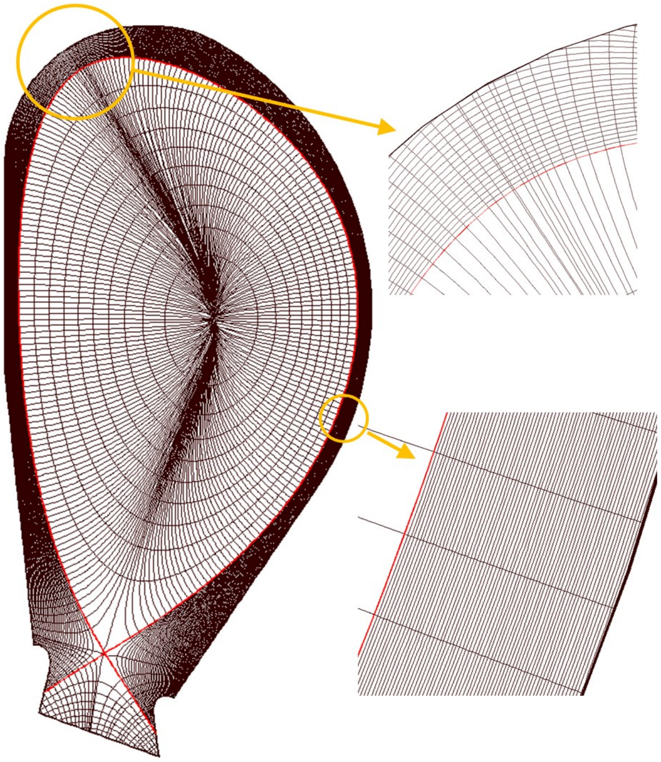

Fig. 3. Magnetic flux coordinates with the calculation grid used for TOKES simulations of the blob motion and for the plasma dynamics inside the blob. The calculation grid covers all the space inside the DEMO first wall. Inserts at the right hand side show the calculation grid in SOL and illustrate the intersections of the grid lines (aligned with magnetic surfaces) with the wall.

separatrix as a tube of $1\div10$ cm in diameter, spanned along magnetic field and filled with constant temperature and density of the order of the plasma parameters close to the separatrix, i.e. $T_e \sim 100\div1000$ eV, $n_e \sim (1\div3)\times10^{19}$ m^{-3}. The blob is assumed to move $\perp$ to magnetic field with prescribed velocity $v_\perp(r) \sim 100\div1000$ m/s, with plasma being frozen-in into the magnetic field. These values, T_e, n_e, $v_\perp(r)$, are the input parameters of the model.

Fluid dynamics approach is used for simulation of the plasma inside the blob. Heat deposited onto the wall at the intersections with blob. The blob faces, where plasma heats the wall, moved along the first wall with the blob motion. The heat flux is due to simultaneous action of electron and ion thermoconductivity, and due to the plasma convection along the blob tube.

B. Numerical implementation

The numerical solution of the fluid dynamics system of equations is done using the 'magnetic flux coordinates', which are the curvilinear, orthogonal coordinates, aligned with the DEMO magnetic field, see Fig. 3. The calculation grid consists of ~100 layers aligned with magnetic field in SOL and each layer is divided on up to ~300 cells. Initially blob is represented by one layer of cells adjacent to the separatrix. The blob dynamics includes parallel plasma and heat transport along magnetic field with corresponding energy deposition to the wall at the layer ends. This process lasts over the time, equal to the blob shift to the next layer with prescribed velocity $v_\perp$, however, during this time the blob does not shifted perpendicularly. Then, the plasma with temperature and density profiles at the last moment is shifted to the next layer of cells. Plasma from the first and the last cells, which have no counterparts in the next layer, is deposited to the wall. Then the process is repeated with the next layer and so on. After the blob disappears, fully depositing its energy and particles onto the wall, the calculated heat flux distribution along the wall is renormalized on the prescribed total power of the turbulent far SOL cross-transport channel. This renormalization can be done from one blob to arbitrary total power, because we assume that there should be many blobs and total power is linearly dependent of the number of blobs.

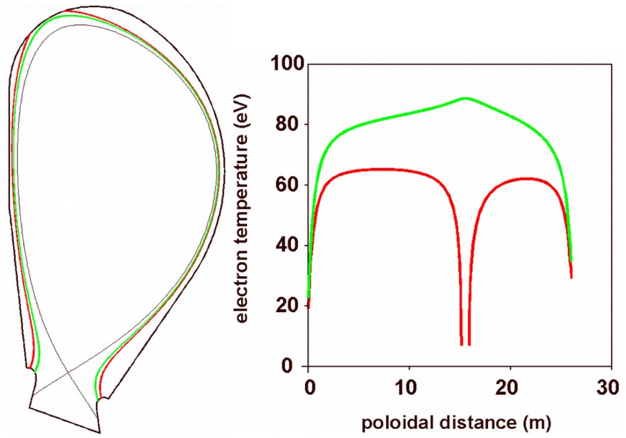

Fig. 4. Blob motion from the separatrix toward the first wall. In the left panel shown are two blob positions: just before touching upper wall (green) and after the touching (red). Right panel shows corresponding electron temperature distributions along the blob.

III. SIMULATION RESULTS

After implementation of the above described model simulation have been performed for the initial blob parameters: $T_e = 100$ eV, $n_e = 10^{19}$ m^{-3}, assuming constant perpendicular velocity of the blob $v_\perp$ =400 m/s at the midplane and total power $P_{\text{sep,far SOL}} = 46$ MW, which is in range of the DEMO parameters [1,3].

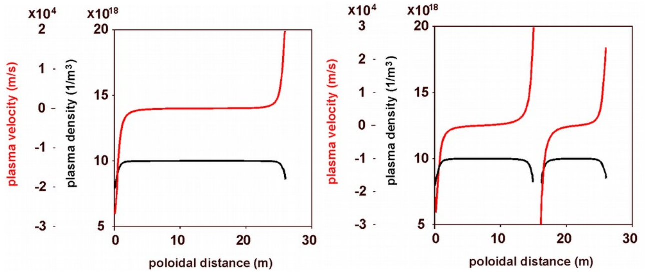

Fig. 5. Velocity and density distributions of the plasma along the blob, corresponding to the two time moments shown in Fig. 4. Left panel shows the distributions just before touching upper wall; right panel – after the touching.

Analysis of the simulation results has shown characteristic peculiarities of the blob evolution. After splitting from the pedestal the blobs are spanned from outer divertor target to the inner one. During the blob flight in SOL its faces moved along the divertor targets and baffles. Electron and ion temperatures of the blob plasma drop to nearly zero at the blob interfaces with the wall due to contact with the wall. This is why the temperatures gradients arise along the blob in both directions from the blob centre to its ends. These temperatures gradients generate electron- and ion-thermoconductivity fluxes to the blob interfaces with the wall. Simultaneously, these temperatures gradients determine the plasma pressure gradients along the blob, hence the blob plasma is accelerated in directions from the blob centre to its ends, thus generating the plasma convective fluxes, which deposited energy and plasma particles onto the wall at the moving interfaces with the blob. The blob position and its electron temperature profile at this stage of blob evolution are shown in Fig. 4 in green color. Corresponding plasma density and the plasma velocity profiles along the blob are plotted in the left panel of Fig. 5.

However, at some time moment, shown in Fig. 4 in red color, the blob touches upper wall by its central part. After this touch the electron and ion temperatures there drop to very low values, thus generating temperature and pressure gradients, and hence, the thermoconductivity flux to this new touching point. Simultaneously, the plasma inside the blob starts to accelerate in direction to this new touching point due to the pressure gradients, as it shown in Figs. 4 and 5. As a result, the blob is cut in two parts, which evolutes further separately. Large electron and ion temperatures gradients are generated along the blob near the touching positions because the temperatures there drops from maximum along the blob value of several tens of eV to nearly zero, see Fig. 4, red curve. The effect of the blob cut by the wall determines large electron thermoconductivity flux at this wall position, where magnetic surface touches wall for the first time. Peak on the heat flux curve, shown in Fig. 6, near the poloidal coordinate of ~16 m is due to this effect. Further blob movement results in consequential cutting of the blob cuttings, thus producing several smaller maxima at the wall heat flux curve, seen in Fig. 6.

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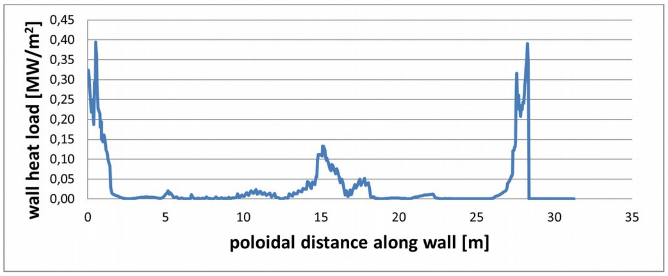

Fig. 6. Heat flux distribution over the first wall of DEMO tokamak calculated using the TOKES code using the newly proposed model for plasma dynamics along the blob. The result corresponds to $T_e = 100$ eV, $n_e = 10^{19}$ m^{-3}, $P_{\mathrm{sep,far\ SOL}} = 46$ MW. The poloidal coordinate along the wall is the same as in Fig. 2