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Heat and Particle Deposition on the Plasma-Facing Components

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Abstract. The interaction of plasma with plasma-facing components (PFCs) in tokamaks is of increasing interest because of implications for ITER and next-step devices. The heat and particle fluxes interacting with solid objects can be studied by means of particle-in-cell (PIC) simulations.
The aim of this work is to use the existing family of PIC codes SPICE to simulate the heat and particle flux distribution on PFCs. The output of the simulations is then used in new heat equation solver, which calculates the temperature of the PFCs. This solver provides us a testbed for the parallel sparse matrix code development as well as for the complex application aimed at study of the melting of tiles.

Introduction

Since the beginning of the plasma confinement studies in tokamaks the interaction of the edge plasma with the vessel wall is one of the basic problems. To define the plasma volume, two methods are used — limiter and divertor.

Both approaches face the same issues which are related to the interaction of plasma particles with the component tiles. They are exposed to the particle flux coming from the scrape-off layer. This flux causes erosion, heating and melting of the tiles and the particles coming from the plasma depose on the divertor or limiter whilst forming hydrocarbon layers. The melting and erosion is an obvious problem [*Lipschultz et al.*, 2012] which can cause destruction of the wall material and the right shape of the tiles and gaps between them should be found to reduce this. The particle deposition and layer formation study is important with respect to the tritium experiments because we should avoid the accumulation of the radioactive material in the vessel [*Komm et al.*, 2011].

These problems can be effectively studied by means of sheath simulations and subsequent use of the simulation output. The SPICE code used at IPP has been successfully used in the past years to perform simulations for comparison with the experimental data and the following use is expected [*Komm et al.*, 2010, *Komm et al.*, 2011]. The SPICE code has been developed into a parallelized version that allows us to split the computation across multiple processors. However, the part of the code solving the Poisson equation is still not paralellized and further improvements of the code are considered. The first step is to implement a parallel solver of the aforementioned equation. It has been decided that the development of the parallelized Poisson equation solver will be split into two phases. In the first phase, we will create a simpler code to simulate similar problem (the heat equation) and this software will be used as a testing environment for the implementation of the MUMPS parallel solver[*Amestoy et al.*, 2001] which is intended to be used in SPICE. After the both codes will be finalized, we should be able to incorporate the heat equation solver into the SPICE model. In this article, the presentation of a current status of the heat equation model will be presented.

The HESS Model

Motivation

The new model is not onlu used as a testbed for the solver implementation, but more importantly can be used to study the tile heating and melting. The recent studies show that the tiles subjected to huge heat flux can easily melt during the operation of the tokamak [*Sergienko et al.*, 2007]. It is necessary to determine condition at which tiles start melting, where and when the tile will melt.

Using these results and incorporating the heat equation solver into the SPICE model, we should be able to study the whole melting process, because the SPICE model supports on-the-fly erosion of the tile geometry.

Currently, the model (Heat Equation Solver for SPICE) has been developed into a working standalone application which can produce first estimates using the flux computed by SPICE.

Model

The model has been proposed as a simple solver of the heat equation

$$\frac{\mathrm{d}T}{\mathrm{d}t} - \alpha \Delta T = q \tag{1}$$

where T is the temperature function (in our case two-dimensional matrix with time-dependent elements), α is a material constant (thermal diffusivity) which can be rewritten using thermal conductivity k, density ρ, and specific heat capacity c_p as $\alpha = \frac{k}{\rho c_p}$. The right side of the equation defines the temperature change caused by external heat sources or heat loss/heating by radiation, in this model we will use this term as a representation of the heat flux coming from the plasma.

The model uses the discrete square grid combined with the finite differences method. An implicit method is used as a solving a sparse matrix-defined system of linear equations is needed to obtain the temperature function. For the purpose of discretisation, we define the grid step δx, the time step δt and the dimensionless scaling parameter $\mu = \frac{\alpha \delta t}{\delta x^2}$. The equation system for the temperature function is defined as

$$\begin{aligned} T(t+\delta t, x, y) \cdot (1+4\mu) - \mu T(t+\delta t, x-\delta x, y) & \\ -\mu T(t+\delta t, x+\delta x, y) & \\ -\mu T(t+\delta t, x, y-\delta x) & \\ -\mu T(t+\delta t, x, y+\delta x) & = T(t, x, y) \end{aligned} \tag{2}$$

then. We have used the common form of the implicit method $(f(t+\delta t) = (f(t+\delta t) - f(t))/\delta t)$ as well as the Laplace operator $(\Delta f(x,y) = (f(x-\delta x, y) + f(x+\delta x, y) + f(x, y-\delta x) + f(x, y+\delta x))/\delta x^2)$ [*Press et al.*, 1992]. The x and y denote the dimension coordinates as seen in Figure 1 running from 1 to n_x and n_y. We assume that no external energy sources or radiation losses are present in the volume of the tile providing that $q = 0$. This equation defines a sparse matrix when we treat $T(t, x, y)$ as a time-dependent vector with $n_x \times n_y$ elements.

Boundary Conditions

At the boundaries, we can simply provide the constant temperature condition using the form derived in the equation (2). As the SPICE model or other sources produce the data in the form of the surface heat (energy) flux, we need to adapt the formula to accomodate this. At first we need to determine the form of the flux-representing term q. Using the energy flux Q_S coming from the plasma through the surface of the grid element S, we can write the flux term as

$$q(x,y) = \frac{Q_S(x,y) S}{mc}, \tag{3}$$

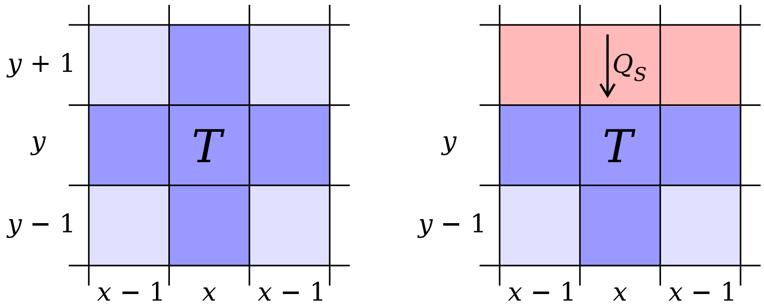

Figure 1. The grid geometry used in the HESS model. Left panel: Volume of the tile. Right panel: Surface condition using constant flux. Blue squares denote the tile volume, red ones the plasma.

using the mass of the element m and its specific heat c assuming that the flux does not change in time. Because the equation (2) does not take into account the empty space beneath the boundary of the tile material, we have to make an assumption regarding the temperature there. As the first order assumption, we assume that the temperature is constant in the direction of. Then, we can re-write the equation (2) for example as

$$\begin{aligned} T\left(t+\delta t, x, y\right) \cdot (1+3\mu) - \mu T\left(t+\delta t, x-\delta x, y\right) & \\ -\mu T\left(t+\delta t, x+\delta x, y\right) & \\ -\mu T\left(t+\delta t, x, y-\delta x\right) &= T\left(t, x, y\right) + q(x,y)\,. \end{aligned} \quad (4)$$

In this case the flux comes from the top side of the grid element at coordinates (x, y) as seen in the Figure 1.

Implementation

To meet the compatibility criteria set by the SPICE model, FORTRAN 90 was used, the sparse matrix solver was solved using Umfpack library (the same as in the SPICE code). The output an input files are read from Matlab binary files. The preliminary testing was done in Matlab as well and it has confirmed that the model is valid after comparison with the analytical solution of the heat equation.

Simulations

As part of the cooperation with the TEXTOR group simulations of the particle flux were provided for the comparison with the gap tritium deposition experiment [*Komm et al.*, 2011]. Together with the data for the heat flux which we have used them as an input for the tile heating simulation. The aim of the simulations is to compare the shaped and non-shaped tiles. Their parameters can be seen in Figure , the inclination of the magnetic field was set to 3°, 10°, and 20°. For the heating simulation, we have set the discharge duration to 1000 ms and the boundary conditions of constant flux were used (the top and side flux is taken from the SPICE model and the bottom flux (cooling) is set to be $1 \cdot 10^5$ Wm^{-2} to represent the thermal contact between the tile and tile holder.

At first, the heat flux from SPICE is obtained. Graphs showing these data are in Figure 3. We can see that the shaping provides a significant reduction of the energy flux to the plasma wetted side for small angles because the tile edge is now shielded by the rounded edge of an adjacent tile. However, this advantage is diminished with the increasing inclination of the magnetic field lines.

These flux data were processed by the HESS model. The temperature at the edge was extracted and is shown in the graphs in Figure 4. We can see that the temperature is consistent with the conclusions for the flux data. The plasma wetted side is shadowed by the rounded

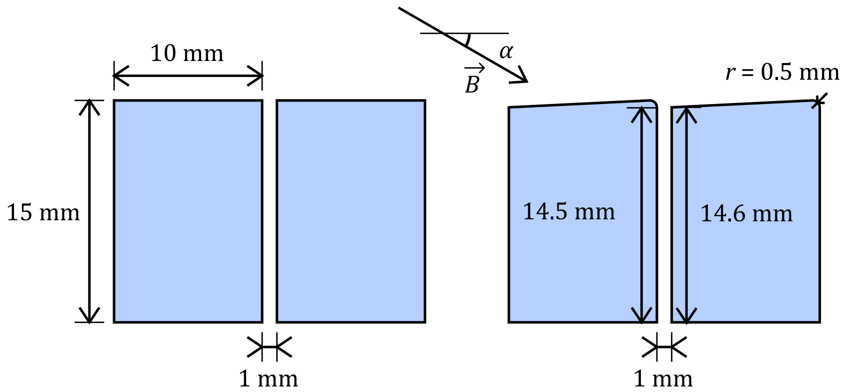

Figure 2. TEXTOR shaped (right) and non-shaped (left) tiles with the magnetic field orientation.

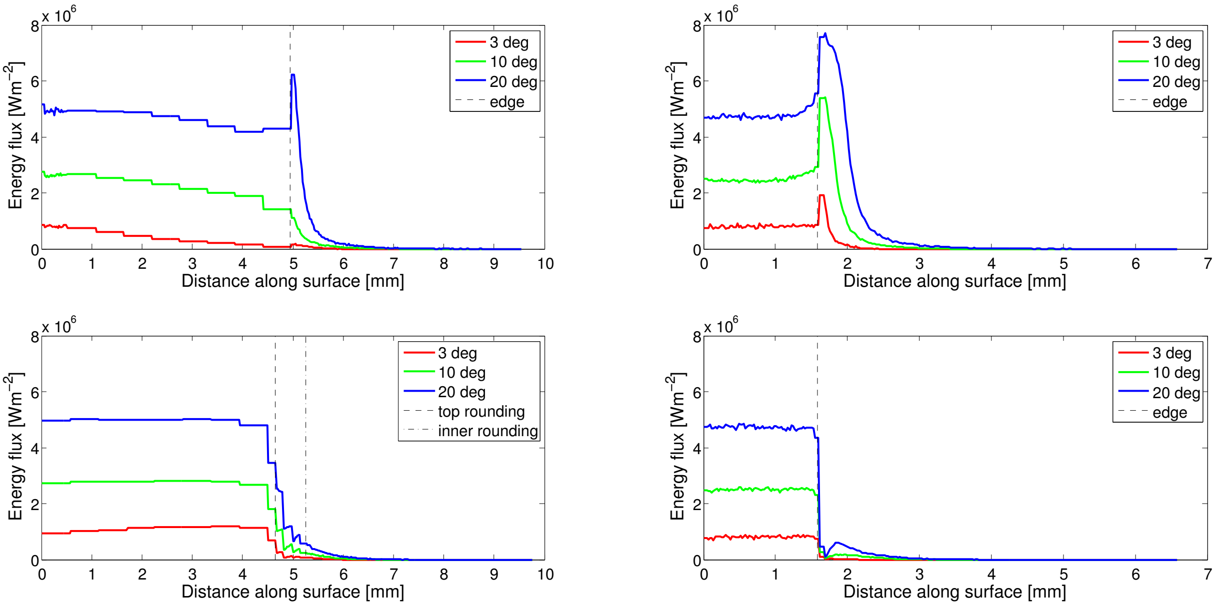

Figure 3. Edge energy flux calculated by the SPICE model. Upper two panels show the comparison of the plasma wetted side of the tile, lower two compare the plasma shadowed side. Left graphs show the shaped tile, right graphs show the non-shaped one.

region and thus less heated whereas the temperature of the top surface is increasing due to its slight tilt compared to the non-shaped tile. At 20° inclination the difference is almost negligible.

Conclusions

In order to provide the large processor number scaling for the SPICE code, the simple model was created. The scaling possibilities are now ready to be tested on this platform using the MUMPS solver and to be incorporated to the SPICE family afterwards.

Main application of this model is to calculate how the tiles in the tokamak heat up with incident energy flux with respect to the melting limit. Currently, the model was used in cooperation with R. Dejarnac to estimate temperature evolution in JET lamella melting experiment.

Baseline testing of the model was made using the data from the simulations made for TEXTOR group. A comparison between shaped and rectangular tiles was made. The obtained results agree with the assumption that the shaping should reduce not only the particle deposition, but overall heat influx as well — the disappearance of the temperature spikes on the tile edges was confirmed.

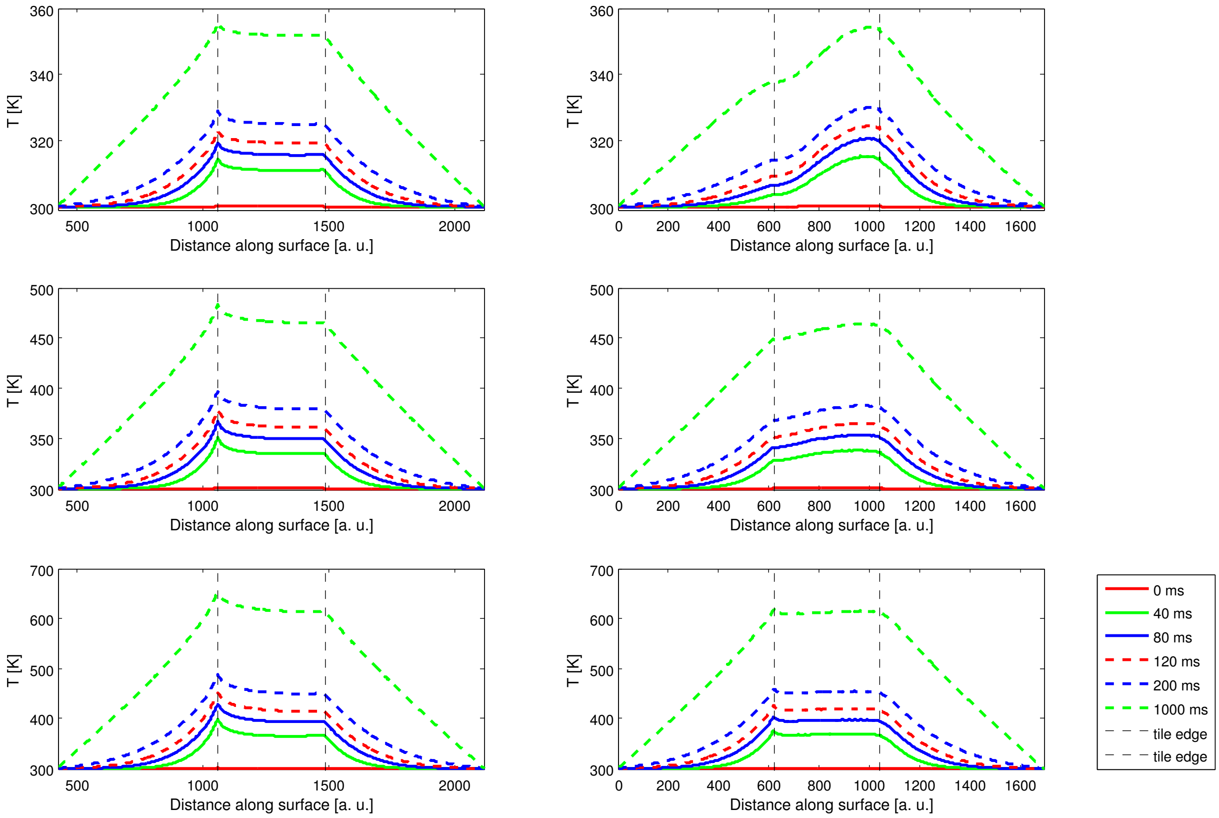

Figure 4. The temperature of the edge of the tile. The varying magnetic field inclination is from the top 3°, 10°, and 20°. The left column represents the non-shaped tiles, the right one the shaped ones. The left part of each graph shows the plasma wetted side, the middle part is the top side and the right part is the plasma shadowed side.

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