Weighted PIC simulation for vapor shielding at wall under transient heat loads

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Vapor shielding at solid walls

Transient heat loads vaporize surface and “shields” incoming plasma. Numerous physical phenomena should be considered during “Vapor shielding at walls”.

Sheath is important. ➔ PIC simulation
Transient events and erosions

Rough Estimation of ELM heat flux at ITER

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divertor Area</td>
<td>2~5 m²</td>
</tr>
<tr>
<td>$W_{\text{ped}}$</td>
<td>~100 MJ</td>
</tr>
<tr>
<td>$\Delta W_{\text{ELM}}/W_{\text{ped}}$</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>$W_{\text{ELM}}$</td>
<td>1-10 MJ</td>
</tr>
<tr>
<td>ELM energy density</td>
<td>0.3-2.0 MJ/m²</td>
</tr>
<tr>
<td>ELM heat flux (1ms)</td>
<td>0.3-2.0 GW/m²</td>
</tr>
</tbody>
</table>

Slow transient
(∼10s, ∼20 MW/m²)

⇒ Recrystallization (W), Melting

ELM
(0.1~ 1 ms, 0.1~10 GW/m²)

⇒ Partial melting, Evaporation

Disruption
(a few ms, 1~10 GW/m²)

⇒ Melting, Droplet, Evaporation (Massive)

For > 1.0 MJ/m² transient loads, natural mitigation by vapor shielding is expected.

G. Federici et al., PPCF(2003)

WEIGHTED PIC FOR VAPOR SHIELDING
Outline

Intro: Vapor shielding, phenomena and importance

PIC simulation for vapor shielding
  Weighted PIC, Multi component, Heat transfer for Vapor

Erosion of Be and W walls

Pulse shape dependence

Summary
**Overall simulation model**

**PIC code treats**

- 1 dimensional in space and 3 dimensional in velocity (1d3v)
- Sheath & magnetic pre sheath calculation
- Sputtering by particle bombardments based on a semi-empirical model.
- Monte-Carlo collision for ionization & Recombination (OPEN-ADAS based)
- Radiation cooling due to line and Recomb&Brems. (OPEN-ADAS based)
- Other collision processes (Coulomb, Ion-neutral) are treated by the BC model.

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**Heat transfer**

- Temperature profile
- Surface temperature
- Melting, ablation
- Sputtering

**Particle-In-Cell (PIC)**

- Vapor amount
- Surface ejected particles (Be, W and/or electron)
- The Langevin heat bath (Numerical heating & Fueling)
- Boundary at fixed potential
- Heated plasma (electron & He, H, D)

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K. Ibano et al. CPP(2016); K. Ibano et al. NME(2017); K. Ibano et al. NF (2019)
Because of strong variations in ejection flux as a function of surface temperature, vapor particles are needed to be analyzed by weighted particles.

Weight = number of actual particle in a super cell

Conventional PIC

Electron : Ion : Vapor = 2 : 2 : 1

Weighted PIC

Electron : Ion : Vapor = 24 : 24 : 1
A&M simulation by weighted particles

Special attentions were paid for Collision, Ionization, Recombination and Radiation cooling.

Ionization $w_{\text{vapor}} < w_{\text{electron}}$

Add “charges” to a randomly selected electron in the same cell.

Radiation $w_{\text{vapor}} > w_{\text{electron}}$

Radiation energy (excitation) is taken from electrons in a same cell.

WEIGHTED PIC FOR VAPOR SHIELDING
Simulation of Multi Components Plasma

In ELM, background (BG) and ELM plasma should be separately treated. ➔ Multi components model.

Plasma temperature and density are solved, and A&M process are also separately treated for both plasma components.
Heat transfer and vaporization

1D heat transfer calculation

- Re-meshing as surface eroded. (moving boundary)
- Latent heat was considered by subtracting energy from heat flux.
- If temperature exceeds ablation point (boiling point at A.P. or artificial), corresponding layer was counted as “ablated.”

W wall under 10 GW/m²
(pulse starts at 100 μs, ends at 300 μs)
Plasma-vapor interactions are calculated to determine the shielding effects of vapor (and sputtered particles).

Main contributions are:
- Radiation (for electron)
- Ion-neutral collisions (for ion)

Generalized collisional radiation model is used.

Be is good radiator in styles of neutral and ion.
At first, we assumed collisions are negligible for higher energy ions. However, collisions between hydrogen ions and Al/Be neutrals may play major role. Ion stopping via collision needs to be considered. A TA binary collision like model was integrated in the code.
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Summary
Simulated profiles during ELM

At the beginning of ELM, more electrons reach to wall than ions, then sheath potential is developing.
Further ELM particles are arriving. At the same time, $T_{surf}$ increases. The vapor cools down electrons. The sheath potential drops.
The vapor clouds well developed. Ti also decreases, and ne~ni. The sheath potential disappears. ➔ different heat transmission.
Heat flux during an ELM pulse

Time evolution of incoming heat flux during ELM (assuming square pulse).

Radiation cooling dissipates electron energies. Ion-neutral collisions scatters ions. Heat flux of both electrons and ions are decreased by vapor.

**ELM**
- \( \sim 1 \text{ keV}, 5 \times 10^{19} \text{m}^{-3} \)
- \( \sim 3 \text{GW/m}^2 \)
- 0.2ms pulse
- 2T magnetic field
  (\( \sim 6^\circ \) incident angle)
- the Be wall component

**Total Heat Flux**
- without Be cooling
- with Be radiation cooling
- with Be rad+collision dissipation
Estimated erosion amounts

Erosion due to sputtering, vaporization, ablation are considered. Reduced erosions are predicted for the cases with vapor shielding. For >10 GW/m² cases, W erosion is larger than Be due to less effective shielding.

~1 µm of Be layer on W will effectively shield a 10 GW/m² pulse.
Estimation of W tile lifetime

G. Federici et al., PPCF(2003)

10 mm thick W tile lifetime analyzed by G. Federici.
(1.0 ms triangular pulse)

5 MW/m² are 10 MW/m² are inter-ELM heat flux values.

Direct comparison is not accurate due to the pulse length and shape difference. Longer pulse shows less erosion.
Even with the severe condition assumed in this PIXY calculation, the 10 mm thick W wall survives $10^7$ ELMs if the energy density is < 1MJ/m².
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Pulse shape dependence

Summary
Most of heat flux tests are taken by square shape waves, but actual ELM pulse is triangular.
Pulse shape: Laser loads

The surface reaches higher temperature when the peak heat flux comes later.

- Slow thermal diffusion during a heat flux pulse.
- Lower thermal conductivity at higher temperature.
Pulse shape dependence on ELM simulation

- Ion heat flux is dissipated by ion-neutral collisions.
- Three pulse shapes (Symmetric triangle, negative ramp, and rectangular) were analyzed.

$\sim 1 \text{ keV}, \ 5 \times 10^{19} \text{m}^{-3}, \ \sim 3 \text{GW/m}^2$

$0.2 \text{ms pulse, 2T magnetic field (} \sim 6^\circ \text{ incident angle)}$

The W wall component

Again, ion heat flux is dissipated by ion-neutral collisions.
Three pulse shapes (Symmetric triangle, negative ramp, and rectangular) were analyzed.
Within same energy flux, shorter time width pulses show higher erosion. (due to higher peak heat flux value)
Within triangle pulses, negative ramp pulses show smaller erosion than symmetric triangle.
Some erosions are needed for vapor shielding. However, for pulses causing higher erosions, vapor shielding becomes less effective (the incoming pulse energy is higher than the dissipatable energy).
Vapor shielding effects are apparent (>0.5) when erosion thickness exceeds $10^{-7}$m (Triangle) and $10^{-6}$m (Rectangular). Vapor shielding can be more effective to the triangle than the rectangular.
1-d PIC (Two components) and heat transfer models were coupled to simulate vapor shielding phenomena at a solid surface. Weighted PIC was applied in order to treat the temperature dependent vapor flux.

Erosion amounts were estimated for 3~10 GW/m$^2$ square pulse, 0.2 ms ELM loads. Reduced erosions were estimated for Be and W walls.

Less erosions are observed for triangular pulse shapes. Lower vapor shielding thresholds (in terms of erosion thickness) are observed for triangular pulse shapes.

Thank you for your attention.
Sputtering yields are calculated from an empirical model. Yields are determined by the energy and the angle of incidence. The code reads table data of sputtering yields.
Within same energy flux, shorter width pulses show higher erosion. (due to higher peak heat flux value)
Within triangle pulses, negative ramp pulses show smaller erosion than symmetric triangle.
Erosion vs Heat flux factor

- Weighted PIC for Vapor Shielding

Graphs showing the relationship between erosion thickness and heat flux factor for different shapes and conditions.

- Symmetric Triangle
- Symmetric Triangle no VS
- Negative ramp
- Negative ramp no VS
- Half Width Square
- Half Width Square no VS
- 0.2 ms Square
- 0.2 ms Square no VS
Erosion vs Peak Heat flux

Within same energy flux, shorter width pulses show higher erosion. (due to higher peak heat flux value)
Within triangle pulses, negative ramp ramp pulses show smaller erosion than symmetric triangle.
Heat transfer and vaporization

1D heat transfer calculation
- Multi layer. (e.g. Al/W, Be/W)
- Re-meshing as surface eroded. (moving boundary)
- Latent heat was considered by subtracting energy from heat flux.
- If temperature exceeds ablation point (boiling point at A.P. or artificial), corresponding layer was counted as “ablated.”

W wall under 10 GW/m² (pulse starts at 100 μs, ends at 300 μs)
In case of “radiation cooling only”, only electrons are cooled. Electron sheath (negative potential) is formed due to the Te \ll Ti and ne > ni condition.