4th International Workshop on
Models and Data for Plasma-Material Interaction in Fusion Devices

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

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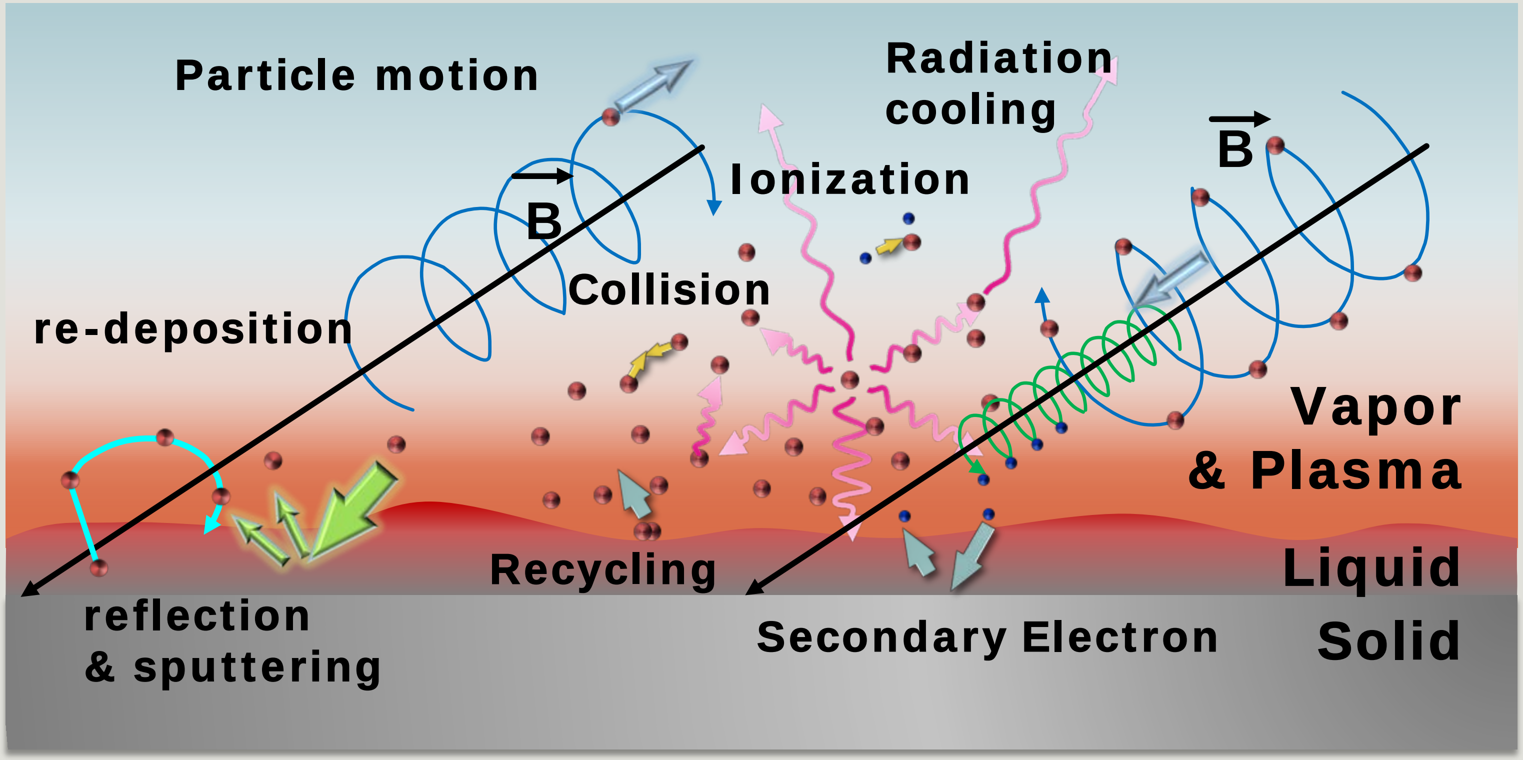
Vapor shielding at solid walls



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

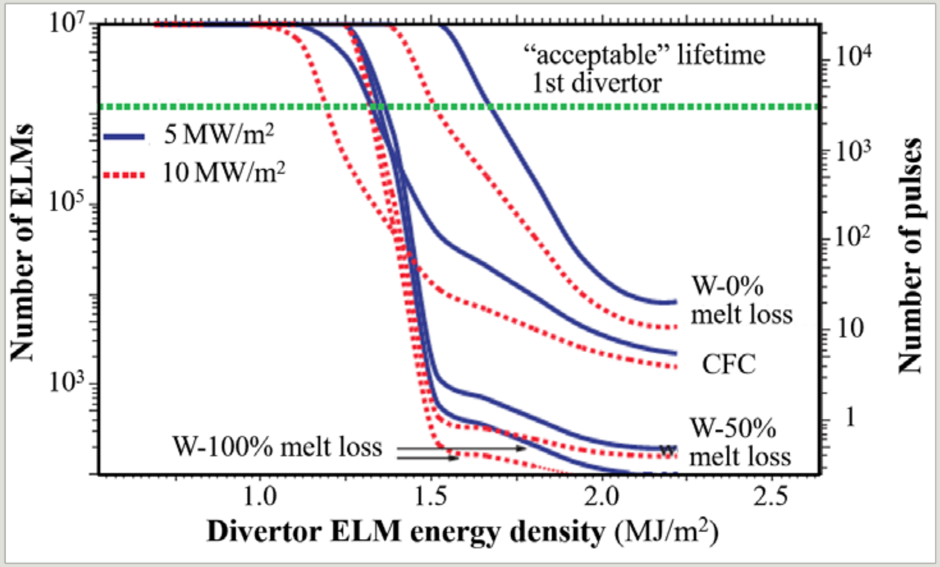
Sheath is important. ➔ PIC simulation

Transient events and erosions

Rough Estimation of ELM heat flux at ITER

	ITER
Divertor Area	2~5 m^2
W_{ped}	~100 MJ
$\Delta W_{ELM}/W_{ped}$	0.01-0.1
W_{ELM}	1-10 MJ
ELM energy density	**0.3-2.0 MJ/m^2**
ELM heat flux (1ms)	**0.3-2.0 GW/m^2**

G. Federici et al., PPCF(2003)



Slow transient ➔ Recrystallization (W), Melting
(~10s, ~20 MW/m^2)

ELM ➔ Partial melting, Evaporation
(0.1~ 1 ms, 0.1~10 GW/m^2)

Disruption ➔ Melting, Droplet, Evaporation (Massive)
(a few ms, 1~10 GW/m^2)

For > 1.0 MJ/m^2 transient loads, natural mitigation by vapor shielding is expected.

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

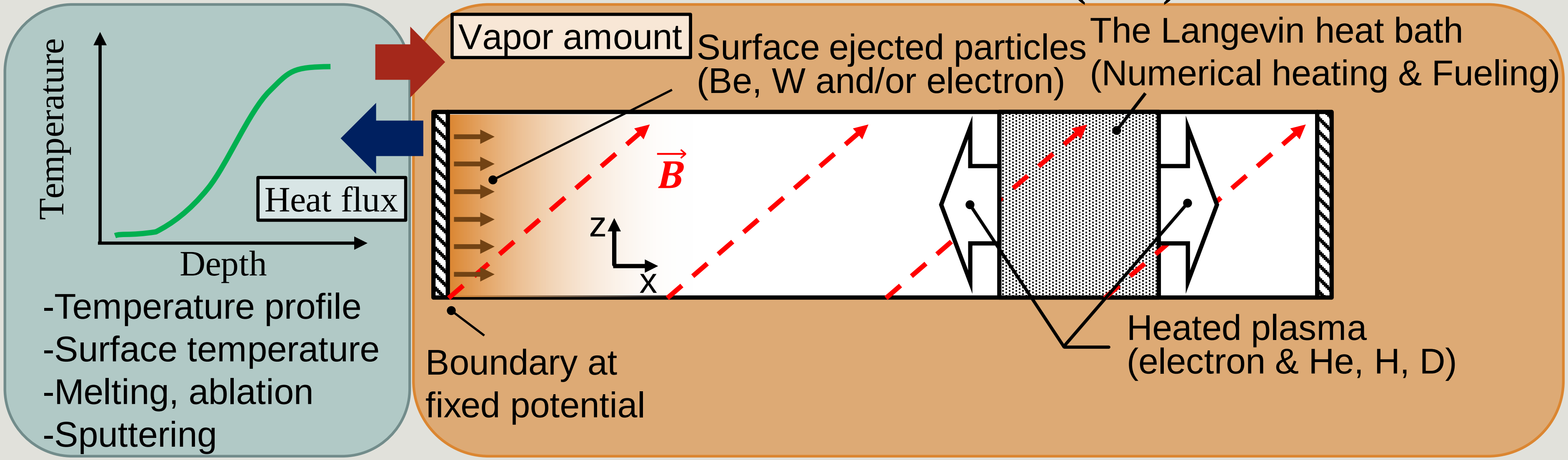
Overall simulation model

PIC code treats

K. Ibano et al. CPP(2016); K. Ibano et al. NME(2017); K. Ibano et al. NF (2019)

- 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.

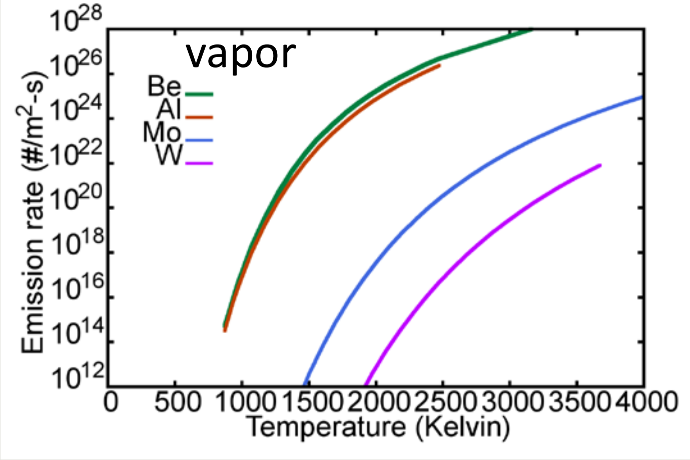
Heat transfer **Particle-In-Cell (PIC)**



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

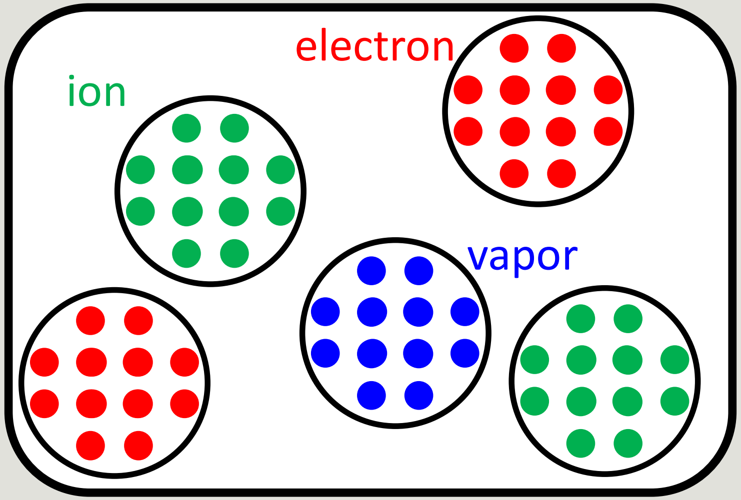
Weighted particle in PIC

Because of strong variations in ejection flux as a function of surface temperature, vapor particles are needed to be analyzed by weighted particles.



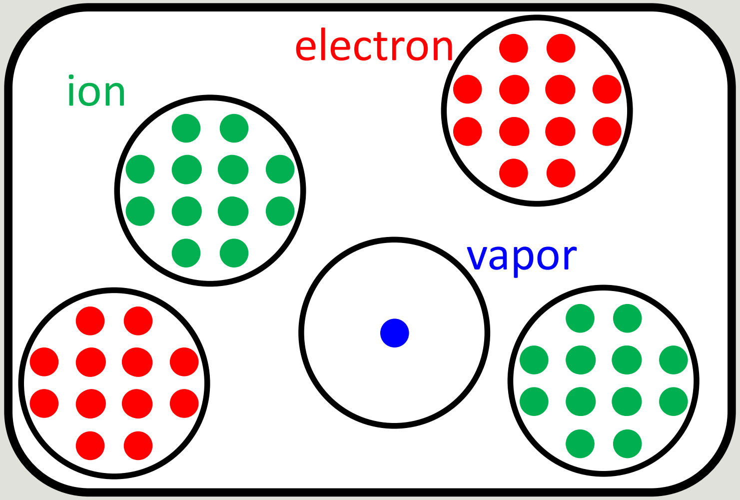
Weight
= number of actual particle in a super cell

Conventional PIC



Electron : Ion : Vapor = 2 : 2 : 1

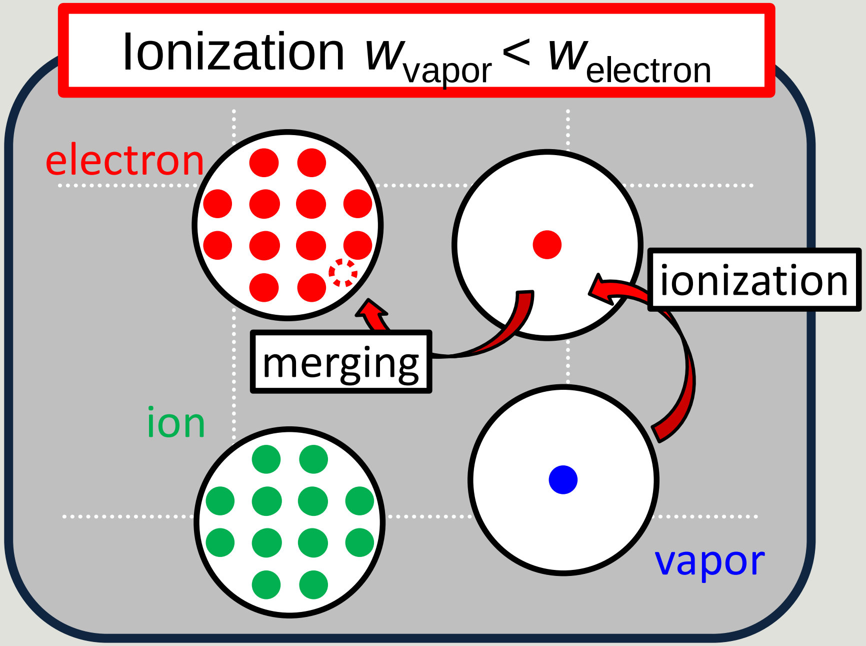
Weighted PIC



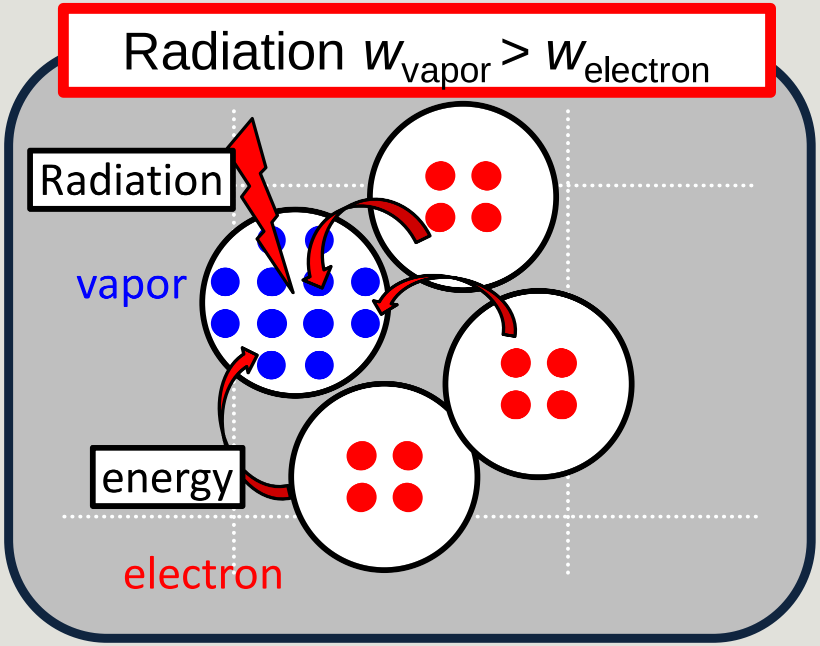
Electron : Ion : Vapor = 24 : 24 : 1

A&M simulation by weighted particles

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



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



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

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

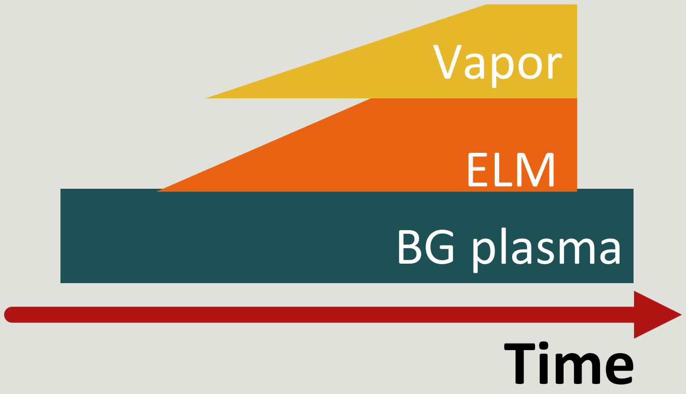
Radiation energy (excitation) is taken from electron**s** in a same cell.

Simulation of Multi Components Plasma

GIF movie

In ELM, background (BG) and ELM plasma should be separately treated.

➔ Multi components model.

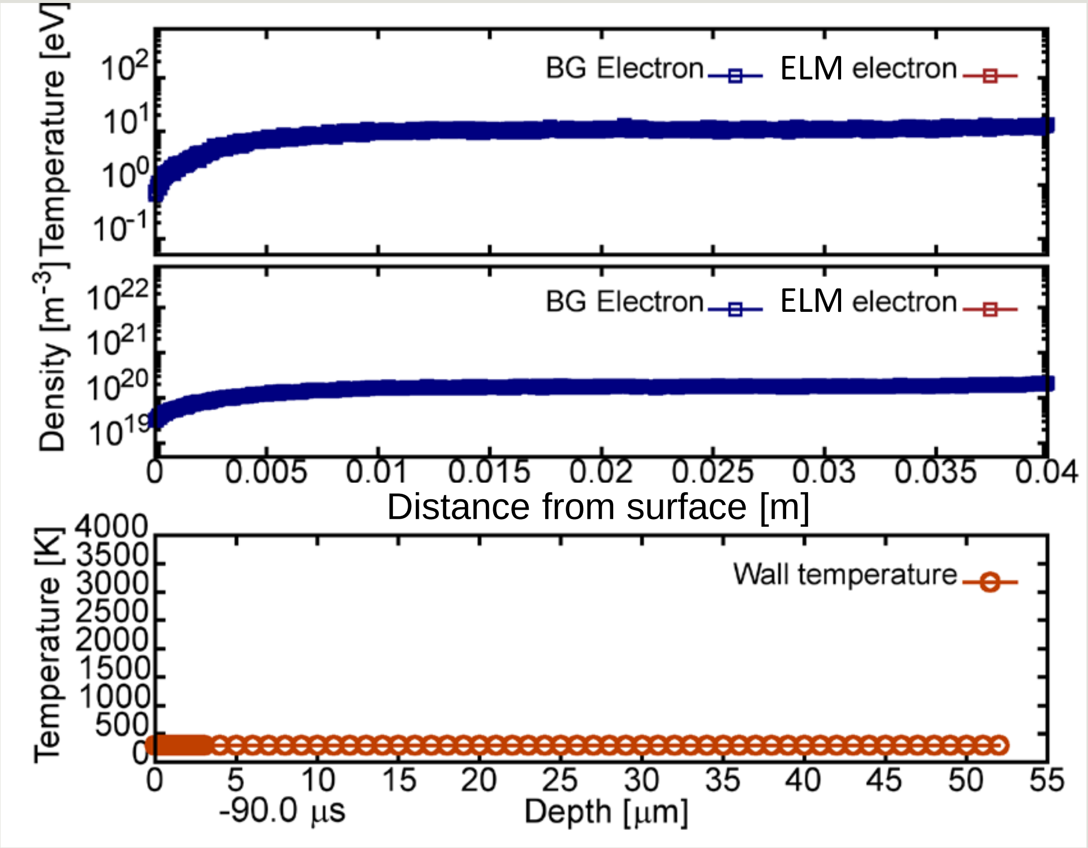


Vapor

ELM

BG plasma

Time

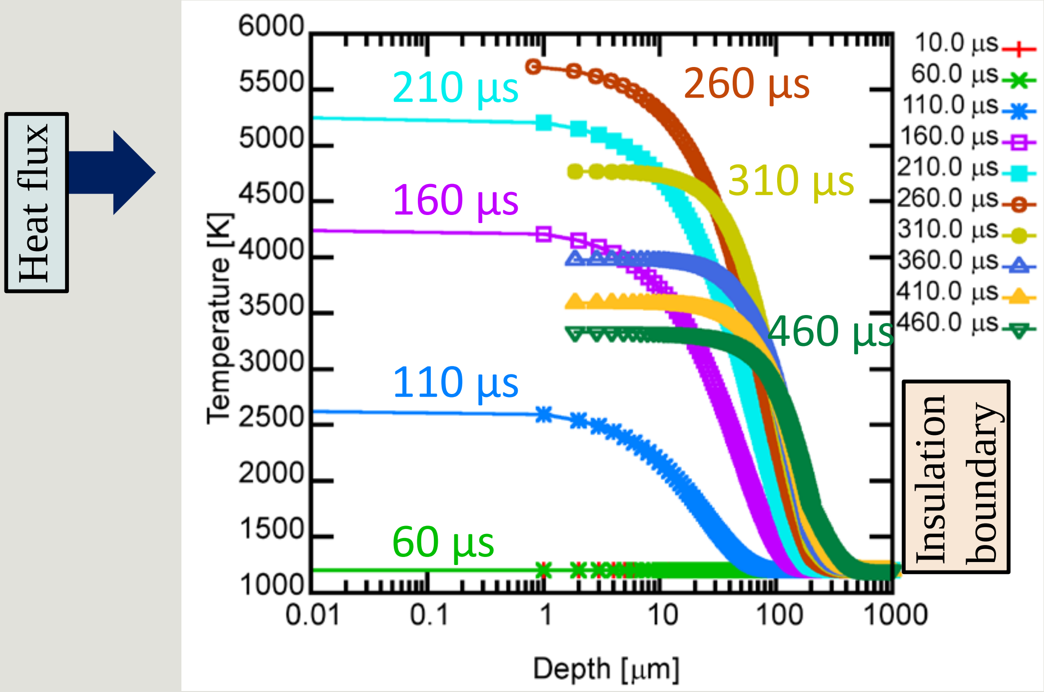


Plasma temperature and density are solved, and A&M process are also separately treated for both plasma components.

Heat transfer and vaporization

1D heat transfer calculation

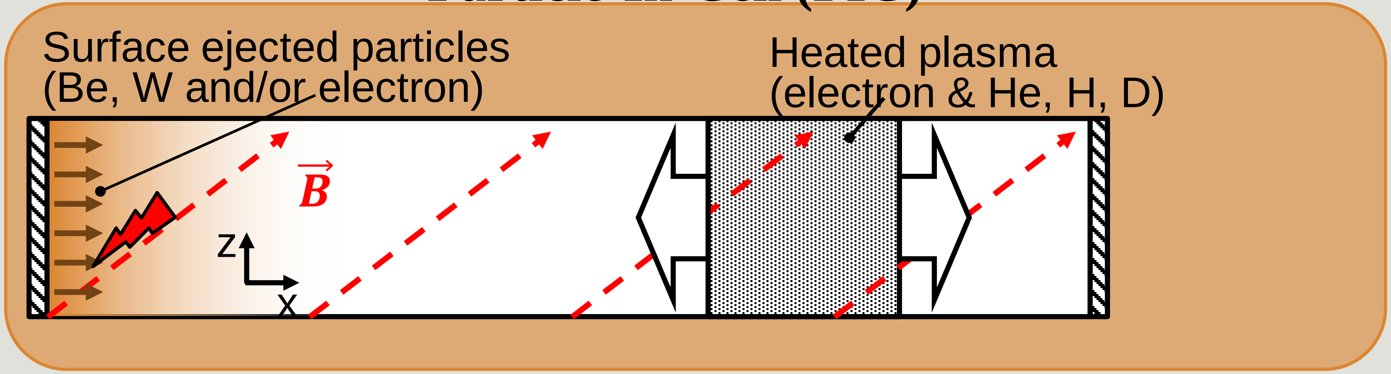
- Re-meshing as surface eroded. (moving boundary)
- Latent heat was considered by subtracting energy from heat flux.
- If temperature exceeds ablation point (boiling point at A.P. or artificial), corresponding layer was counted as “ablated.”



W wall under 10 GW/m^2
(pulse starts at 100 μs, ends at 300 μs)

Dissipation: Radiation power

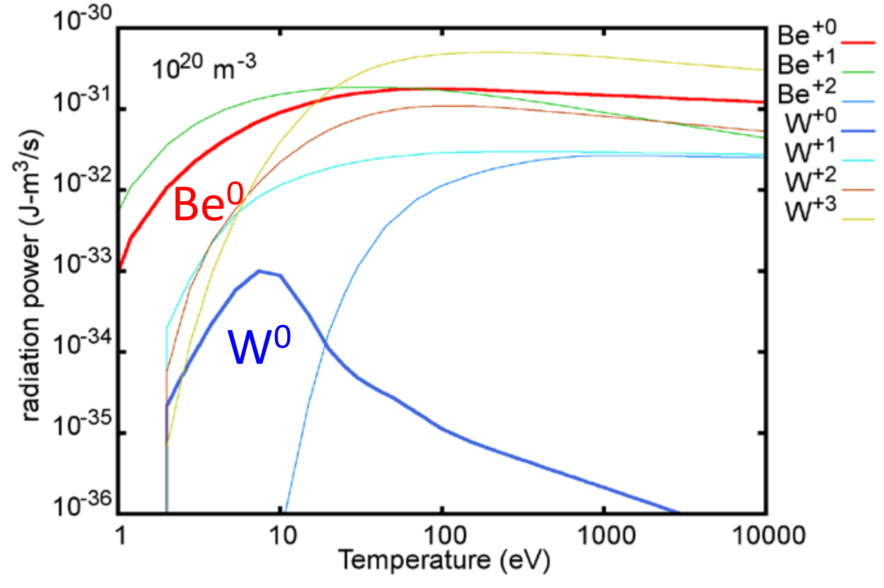
Particle-In-Cell (PIC)



Plasma-vapor interactions are calculated to determine the shielding effects of vapor (and sputtered particles).

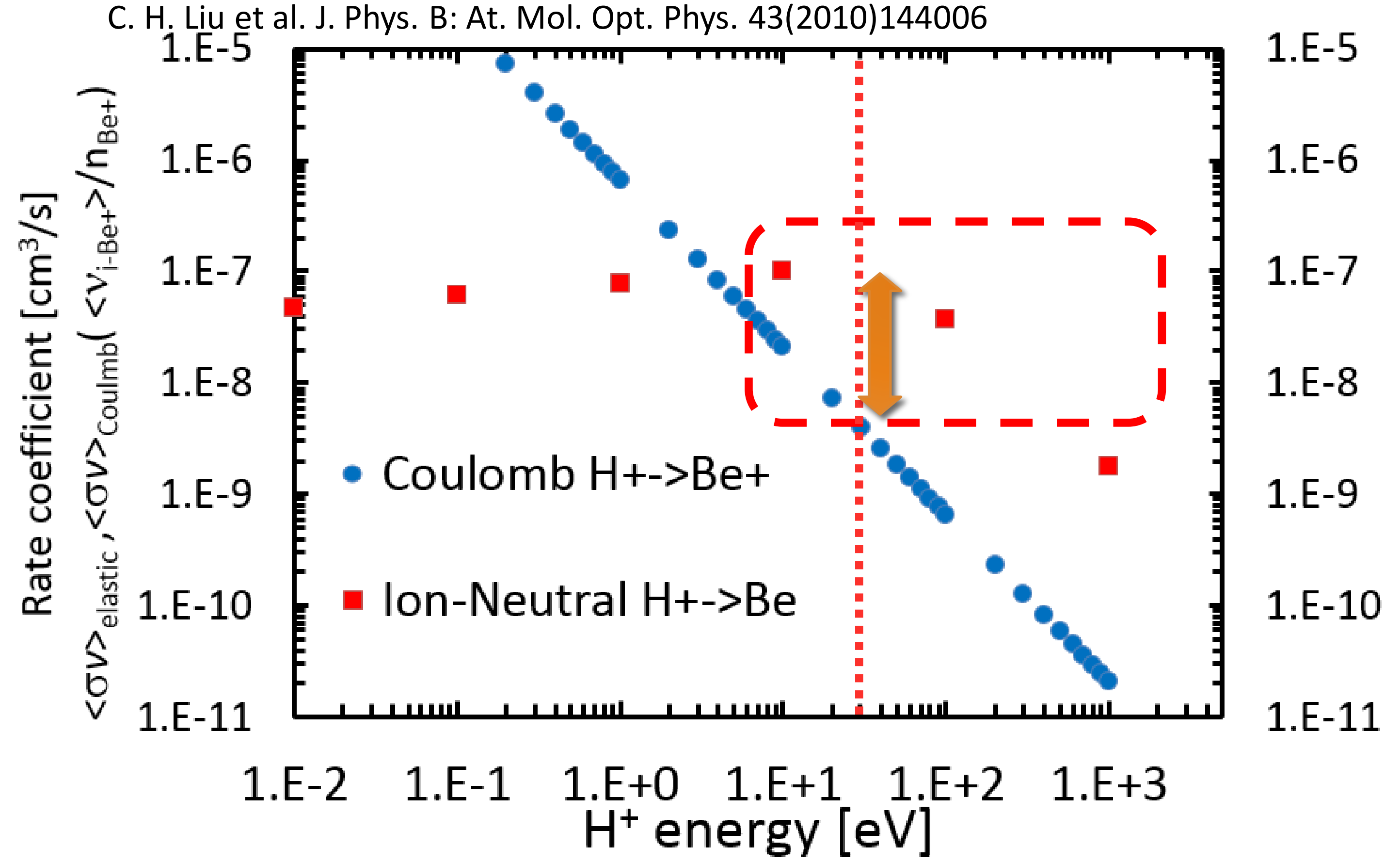
- Main contributions are
  - Radiation (for electron)
  - Ion-neutral collisions (for ion)

Generalized collisional radiation model is used.



Be is good radiator in styles of neutral and ion.

Dissipation: Ion-Neutral Collisions


C. H. Liu et al. J. Phys. B: At. Mol. Opt. Phys. 43(2010)144006

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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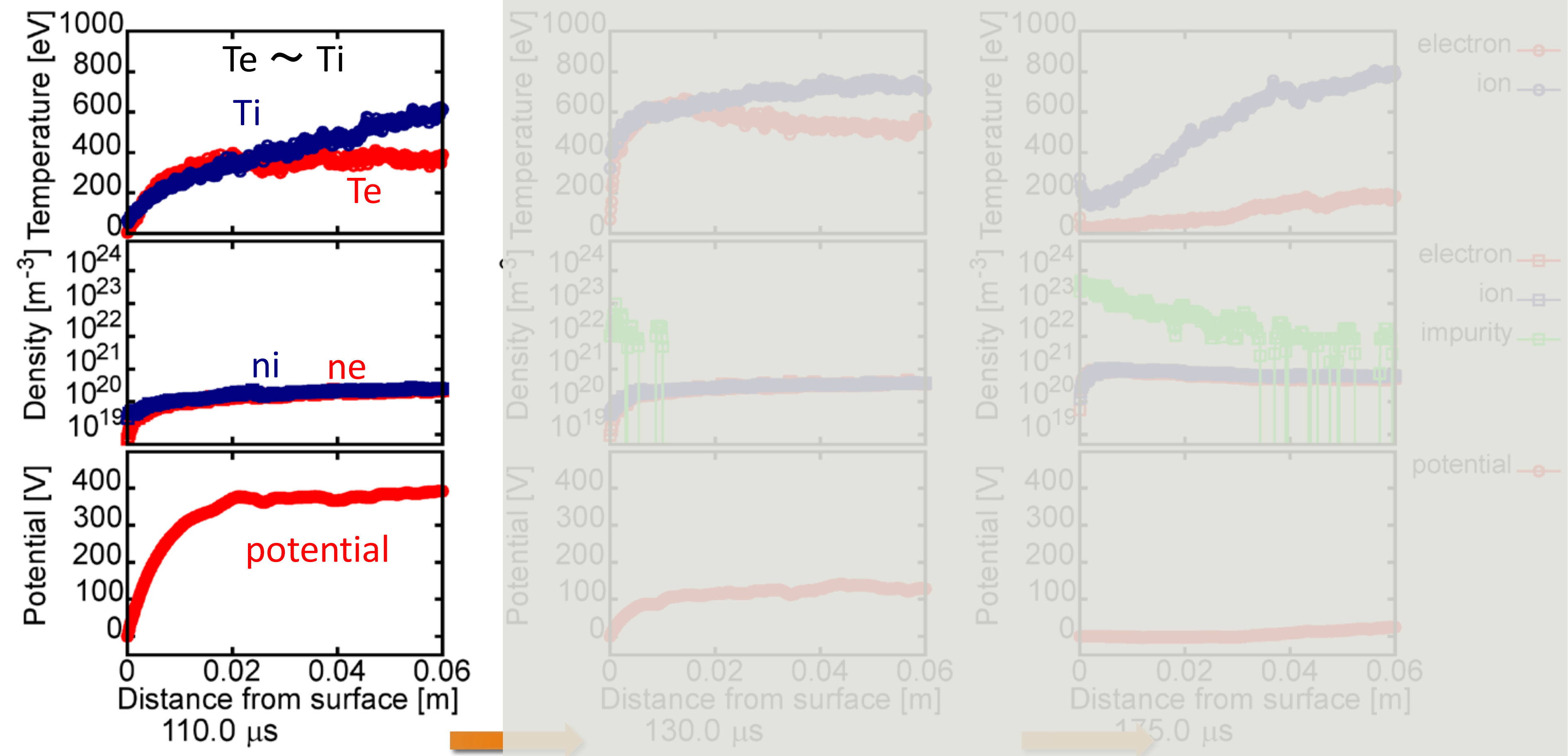
Simulated profiles during ELM

at Beginning of ELM

Be vapor starts

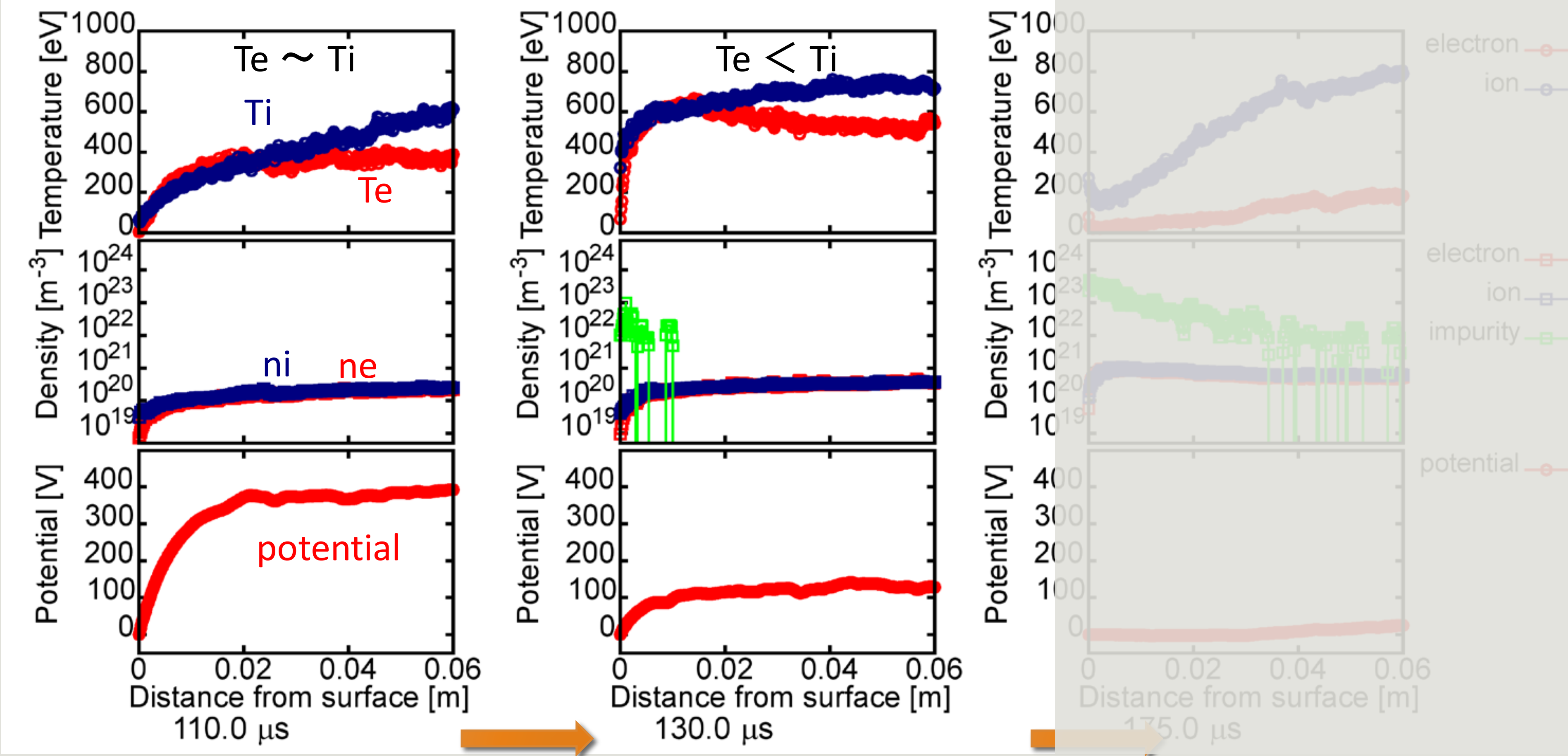
Sheath disappear



At the beginning of ELM, more electrons reach to wall than ions, then sheath potential is developing.

Simulated profiles during ELM

at Beginning of ELM **Be vapor starts** **Sheath disappear**



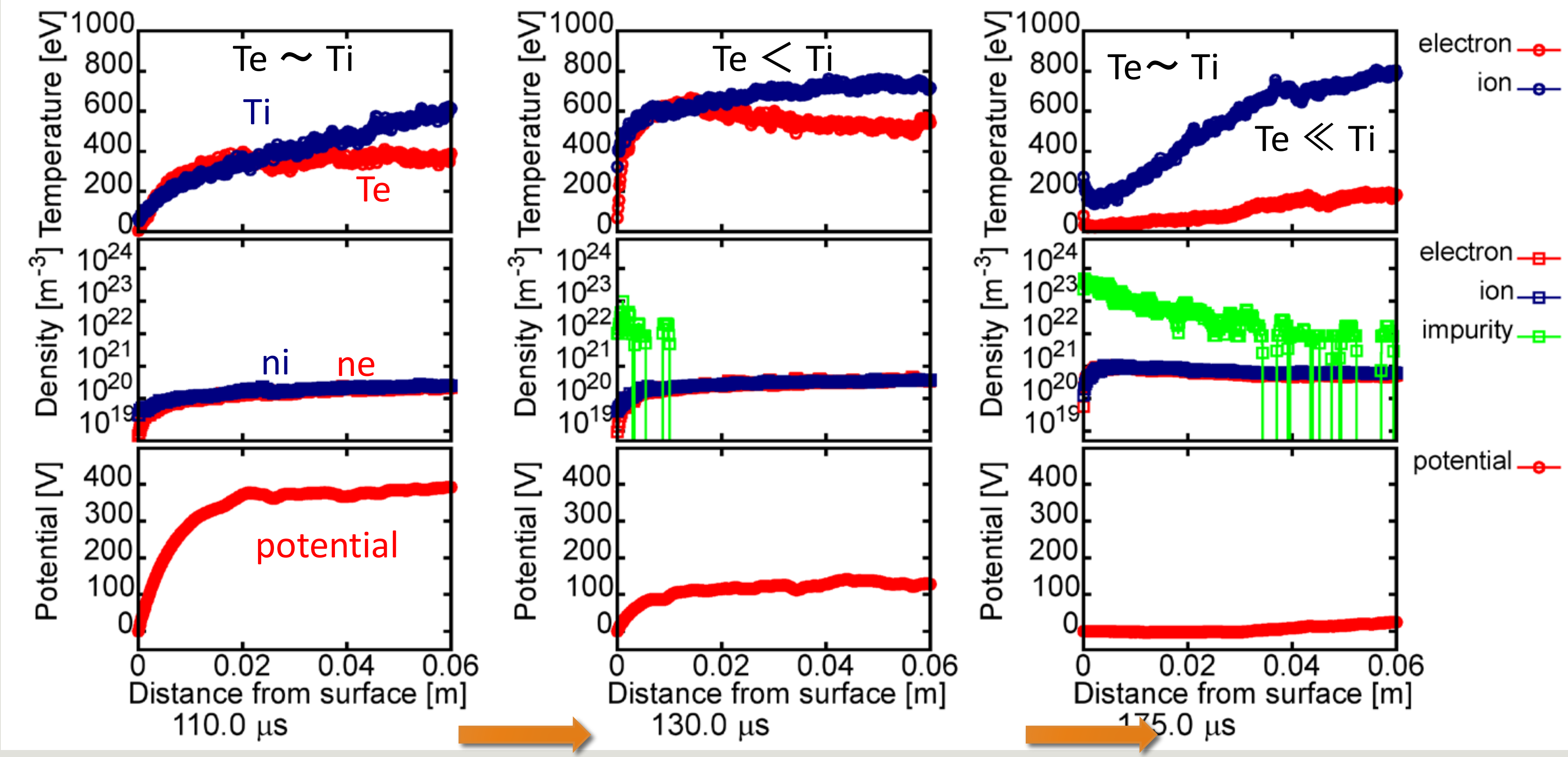
Further ELM particles are arriving. At the same time, Tsurf increases. The vapor cools down electrons. The sheath potential drops.

Simulated profiles during ELM

at Beginning of ELM

Be vapor starts

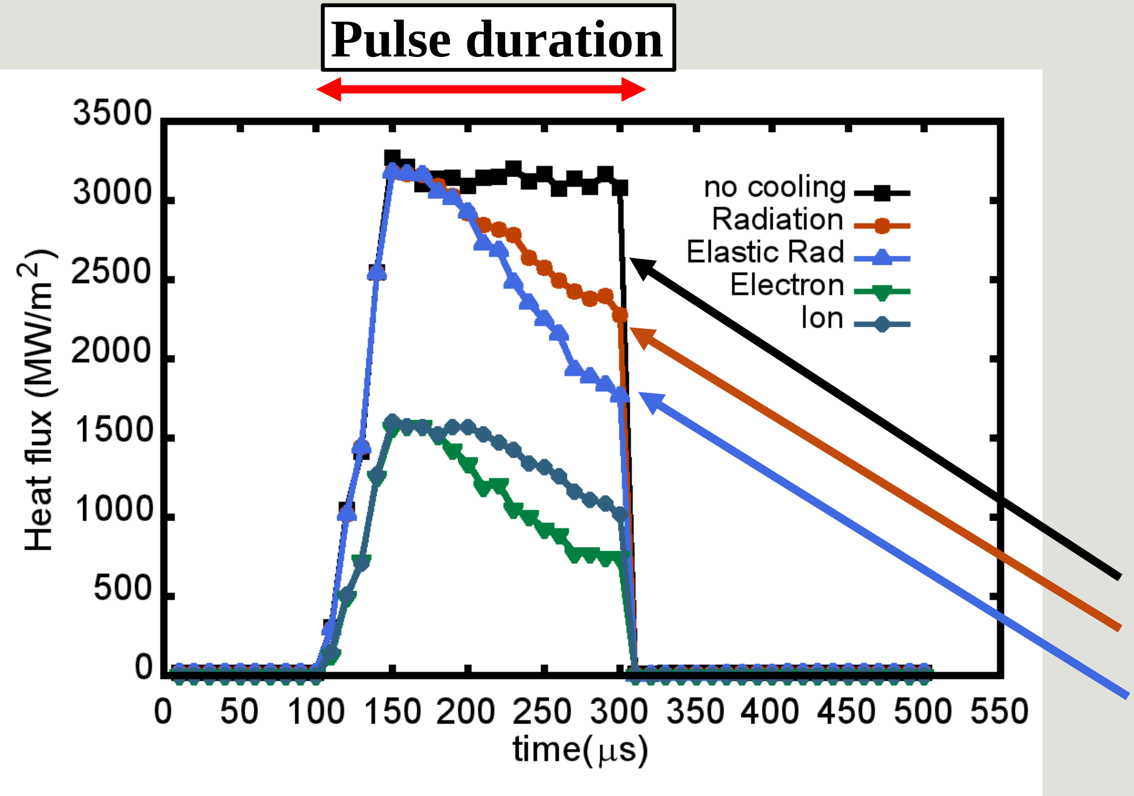
Sheath disappear



The vapor clouds well developed. Ti also decreases, and ne∼ni.

The sheath potential disappears. ➔ different heat transmission.

Heat flux during an ELM pulse



ELM

~1 keV, 5 × 10^{19}m^{-3}

~3GW/m^2

0.2ms pulse

2T magnetic field

(~6° incident angle)

the Be wall component

Total Heat Flux

-without Be cooling

-with Be radiation cooling

-with Be rad+collision dissipation

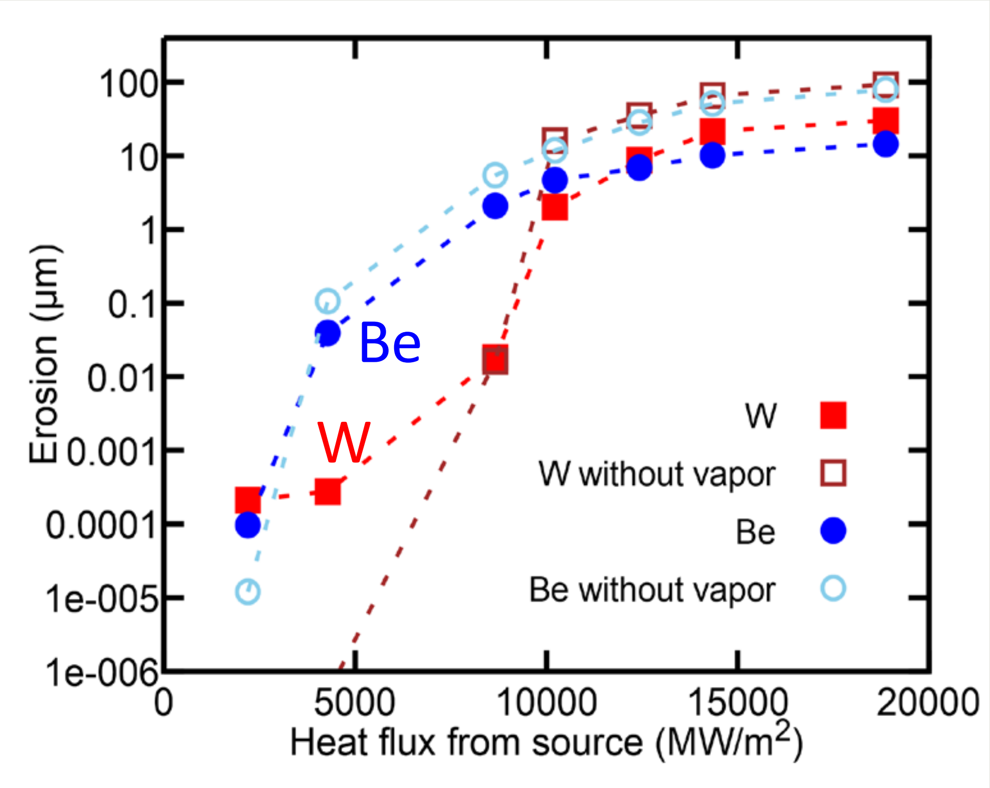
Time evolution of incoming heat flux during ELM (assuming square pulse).

Radiation cooling dissipates electron energies.

Ion-neutral collisions scatters ions.

Heat flux of both electrons and ions are decreased by vapor.

Estimated erosion amounts



ELM

~1 keV, 3~20 GW/m^2

0.2ms pulse

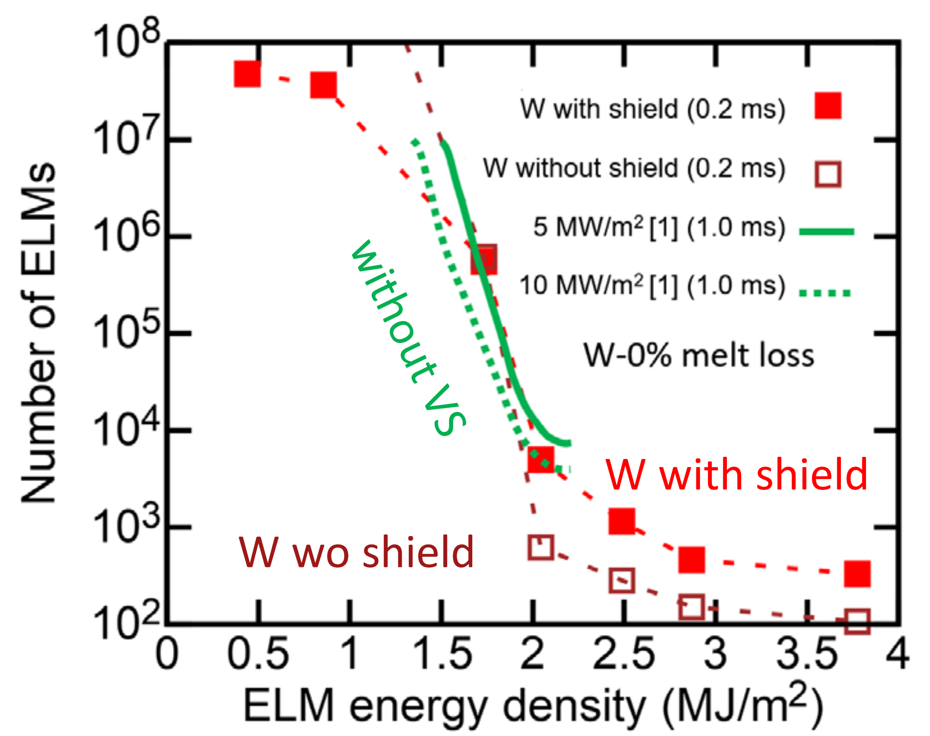
magnetic field

(~6° incident angle)

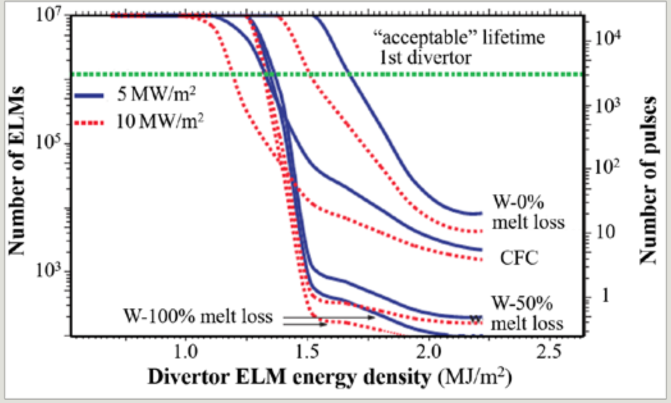
Self-sputtering is considered only in vapor shielding cases.

Erosion due to sputtering, vaporization, ablation are considered.
Reduced erosions are predicted for the cases with vapor shielding.
For >10 GW/m^2 cases, W erosion is larger than Be due to less effective shielding.
~ 1μm of Be layer on W will effectively shield a 10 GW/m^2 pulse.

Estimation of W tile lifetime



G. Federici et al., PPCF(2003)



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

5 MW/m^2 are 10 MW/m^2 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/m^2.

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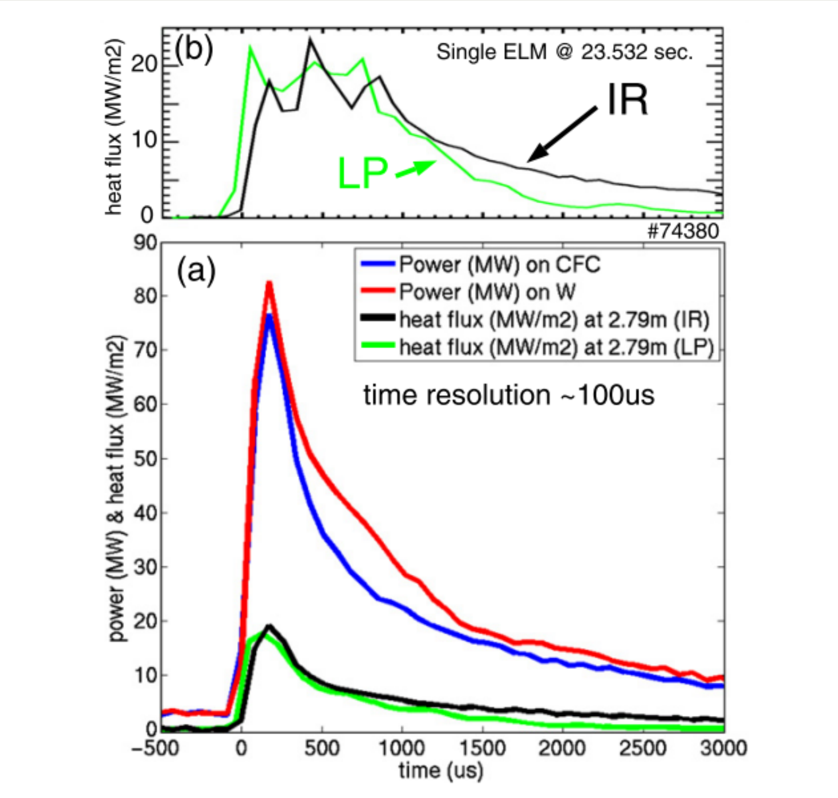
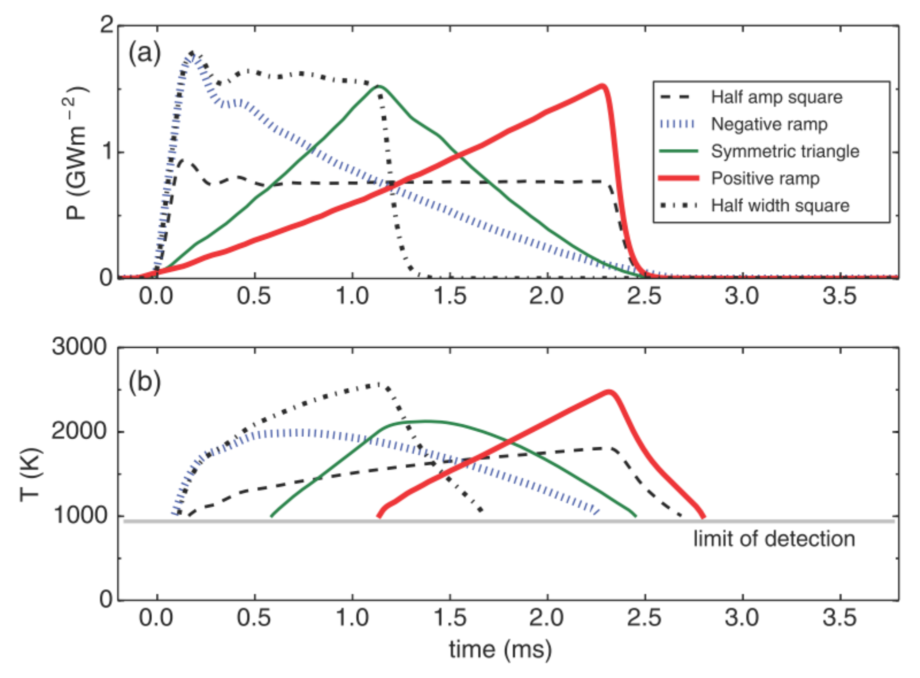
Pulse shape dependence

T. Eich *et al* 2011 J. *Nucl. Mat.* **415 S865-S859**

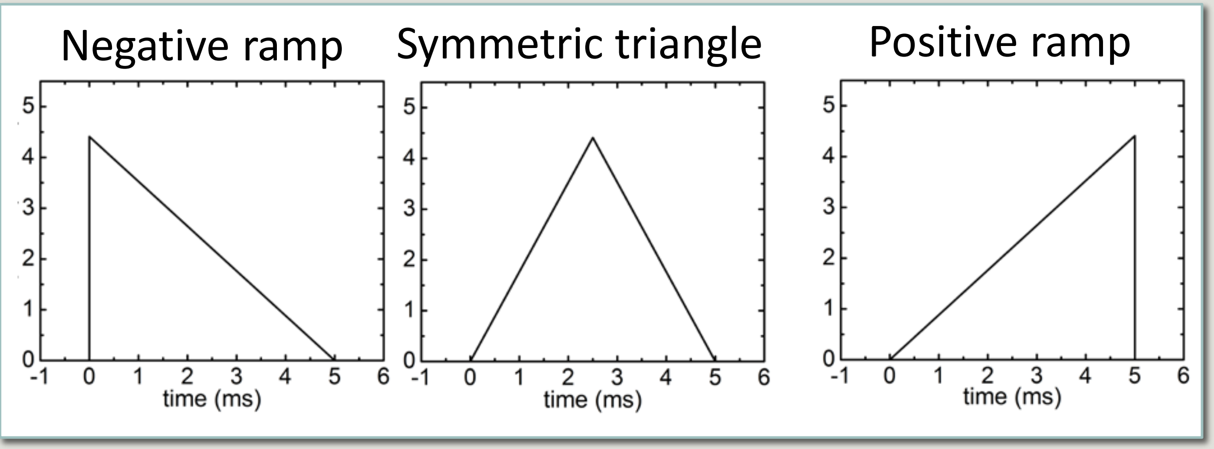
J.H. Yu *et al* 2015 *Nucl. Fusion* **55** 093027

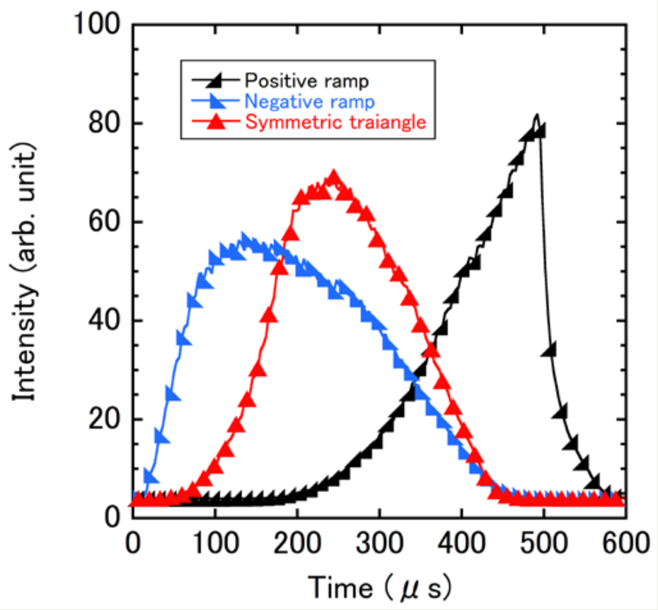




Most of heat flux tests are taken by square shape waves, but actual ELM pulse is triangular.

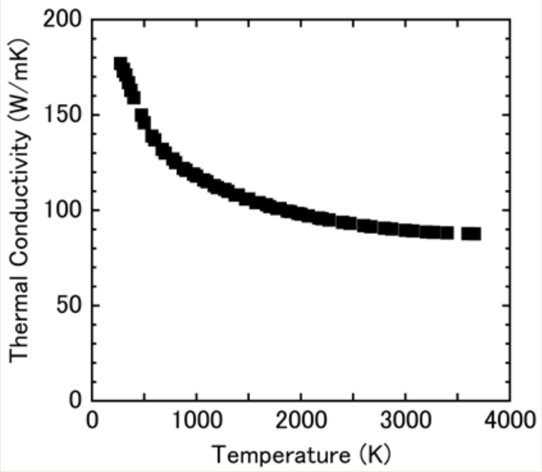
Pulse shape: Laser loads





Surface luminescence of W under different shape laser pulses

Thermal conductivity of W



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

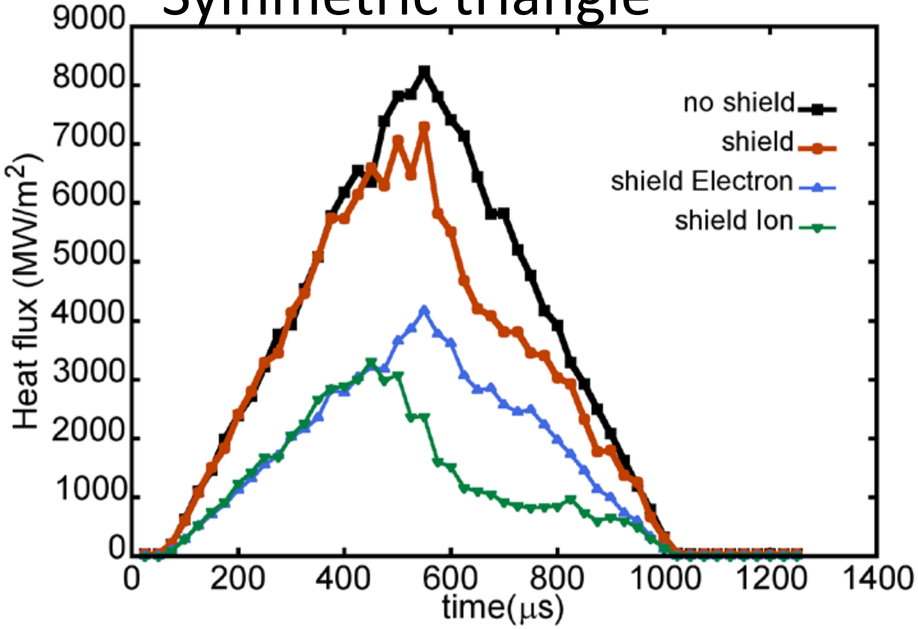
➔ Slow thermal diffusion during a heat flux pulse.

➔ Lower thermal conductivity at higher temperature.

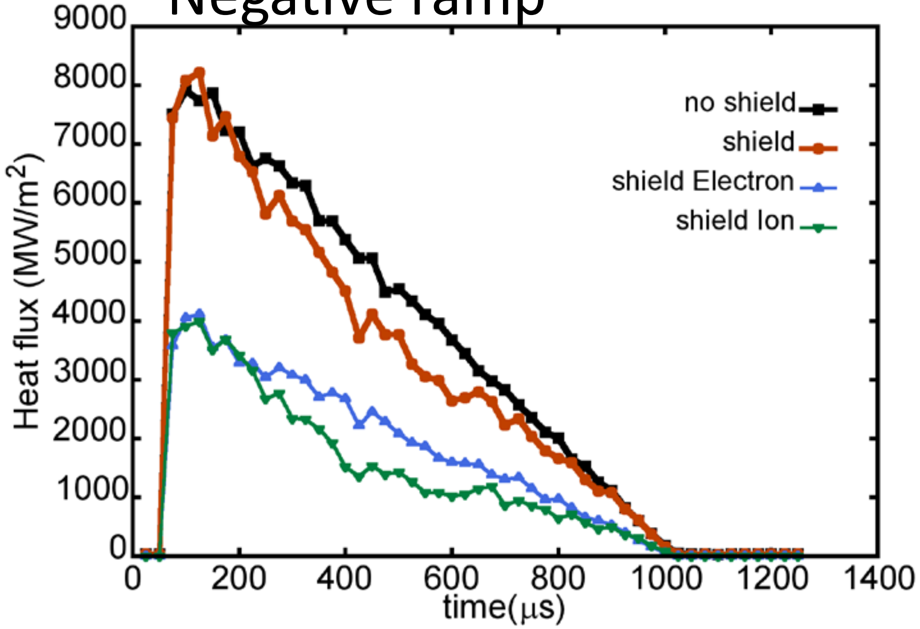
Pulse shape dependence on ELM simulation

~1 keV, $5\times10^{19}\mathrm{m}^{-3}$, ~3GW/$\mathrm{m}^2$
0.2ms pulse, 2T magnetic field (~6° incident angle)
the W wall component

Symmetric triangle



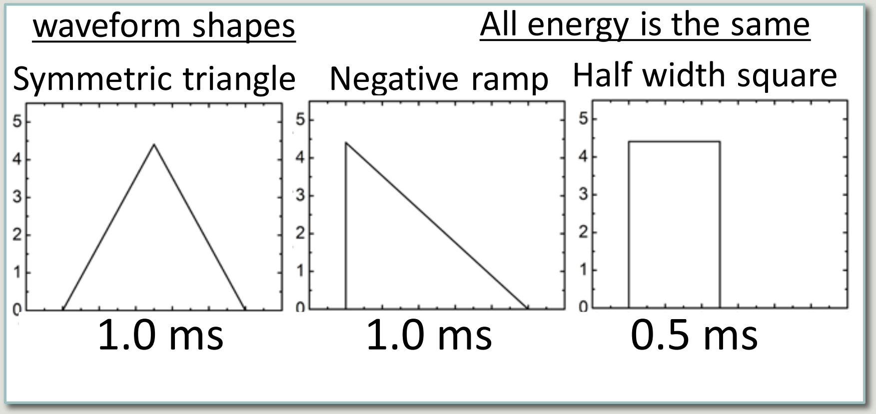
Negative ramp

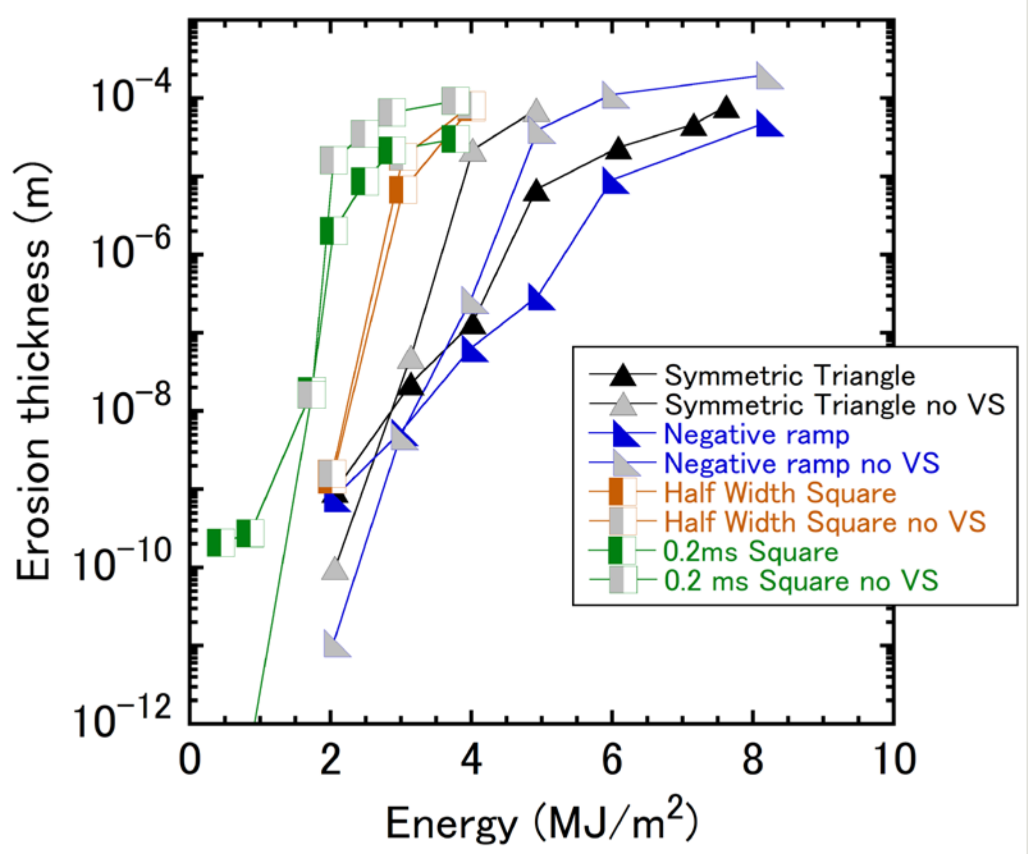


Again, ion heat flux is dissipated by ion-neutral collisions.

Three pulse shapes (Symmetric triangle, negative ramp, and rectangular) were analyzed.

Erosion vs Energy density



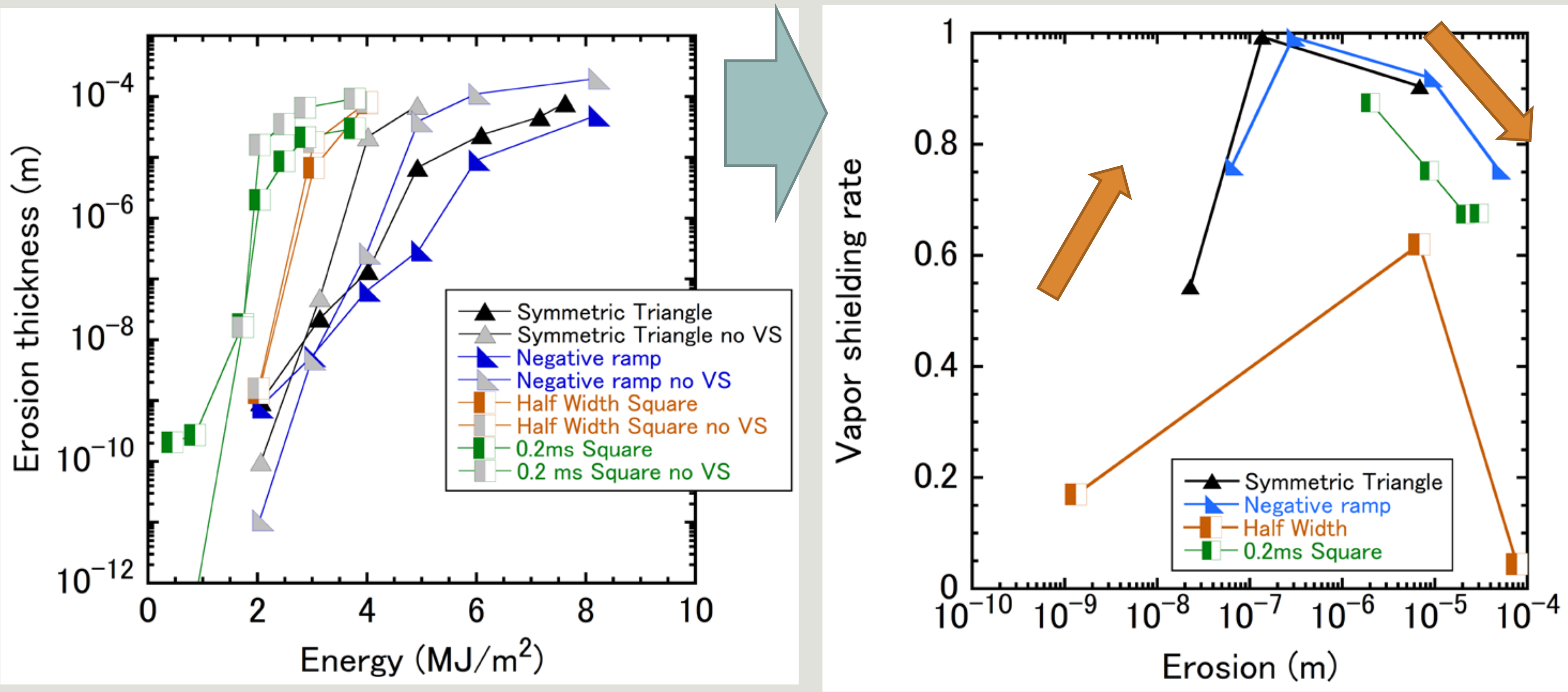


Within same energy flux, shorter time width pulses show higher erosion. (due to higher peak heat flux value)

Within triangle pulses, negative ramp pulses show smaller erosion than symmetric triangle.

Vapor shielding rate

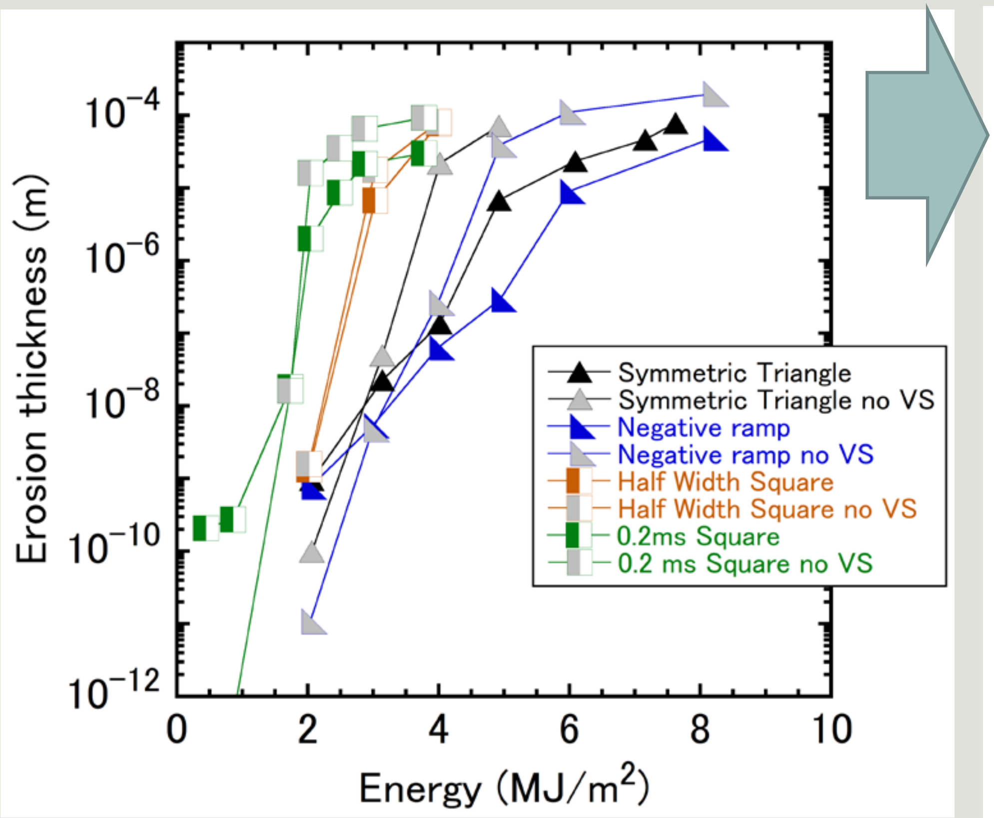
Vapor shielding rate $=(\delta_{\text{shield}} - \delta_{\text{no shield}})/\delta_{\text{no shield}}$ δ:erosion thickness

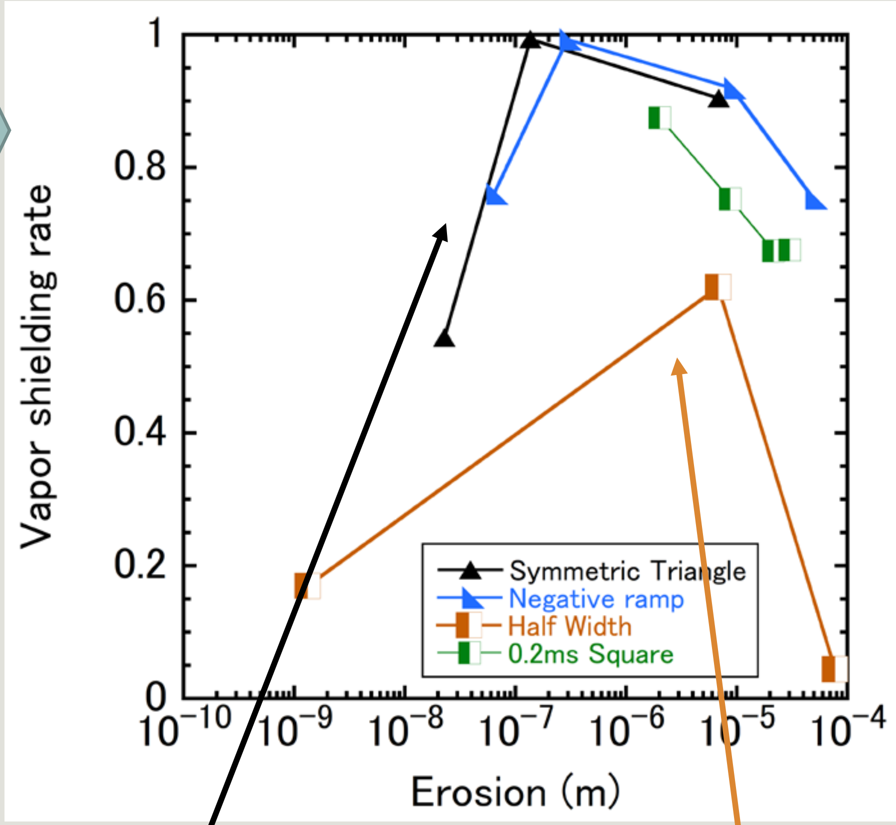


Some erosions are needed for vapor shielding. However, for pulses causing higher erosions, vapor shielding becomes less effective (the incoming pulse energy is higher than the *dissipatable* energy).

Vapor shielding rate

Vapor shielding rate =$(\delta_{\text{shield}} - \delta_{\text{no shield}})/\delta_{\text{no shield}}$ δ:erosion thickness





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.

Summary and Conclusion

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.

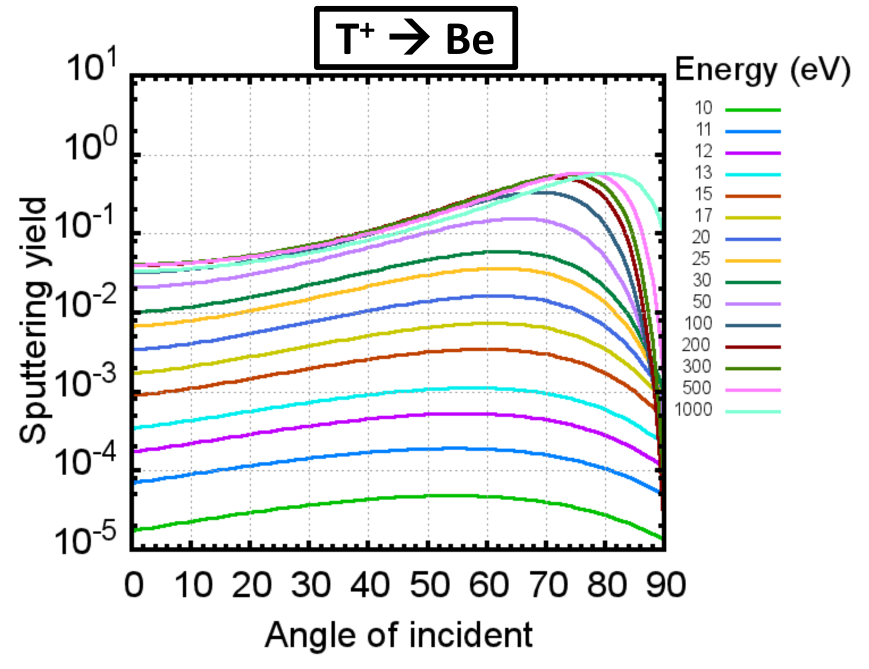
Erosion amounts were estimated for 3~10 GW/m^2 square pulse, 0.2 ms ELM loads. Reduced erosions were estimated for Be and W walls.

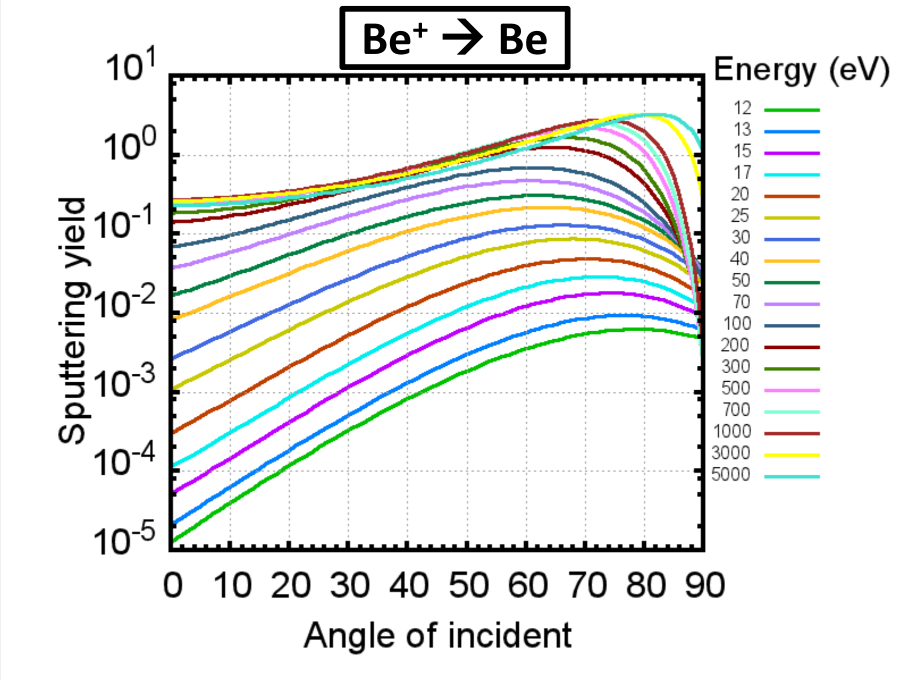
Less erosions are observed for triangular pulse shapes.

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

Thank you for your attention.

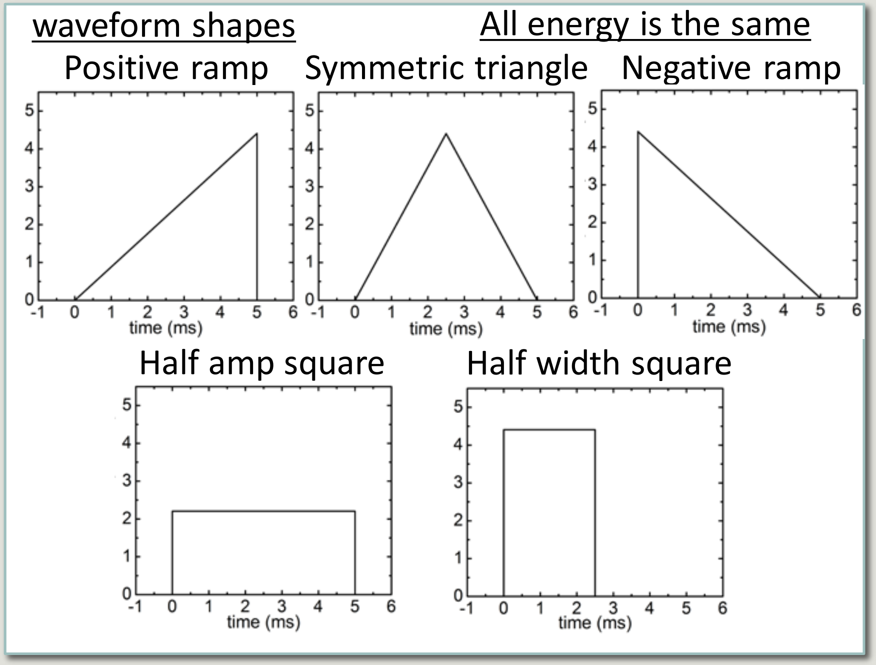
Sputtering

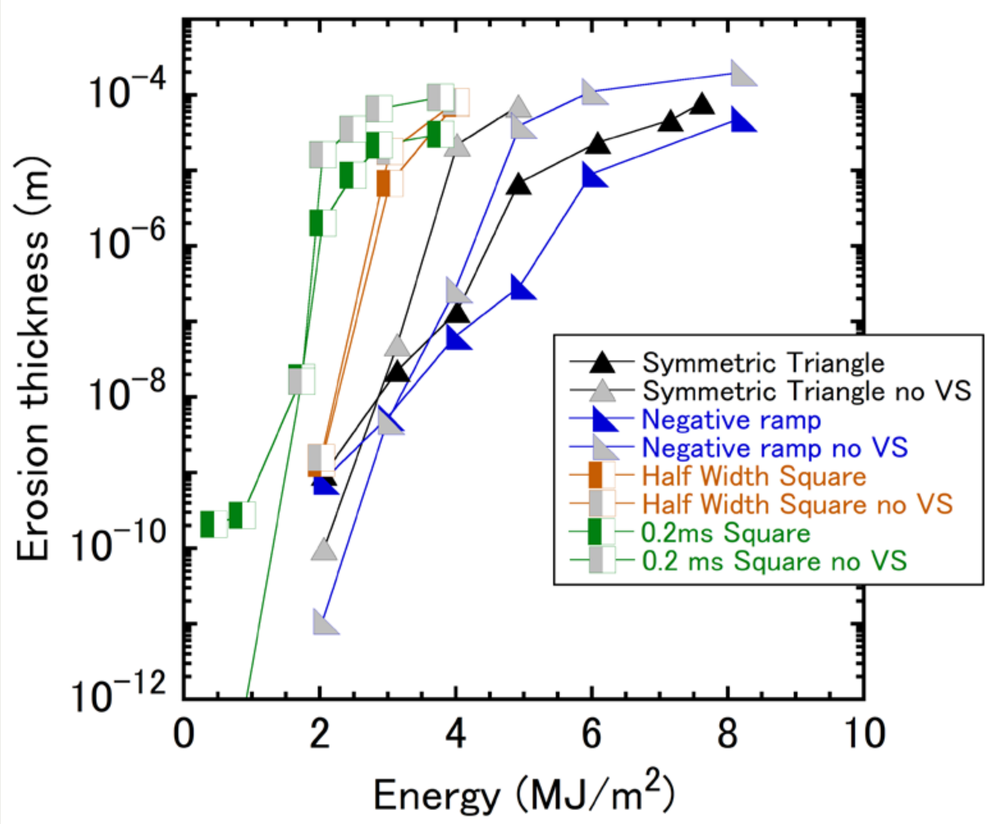




Sputtering yields are calculated from an empirical model. Yields are determined by the energy and the angle of incidence.
The code reads table data of sputtering yields.

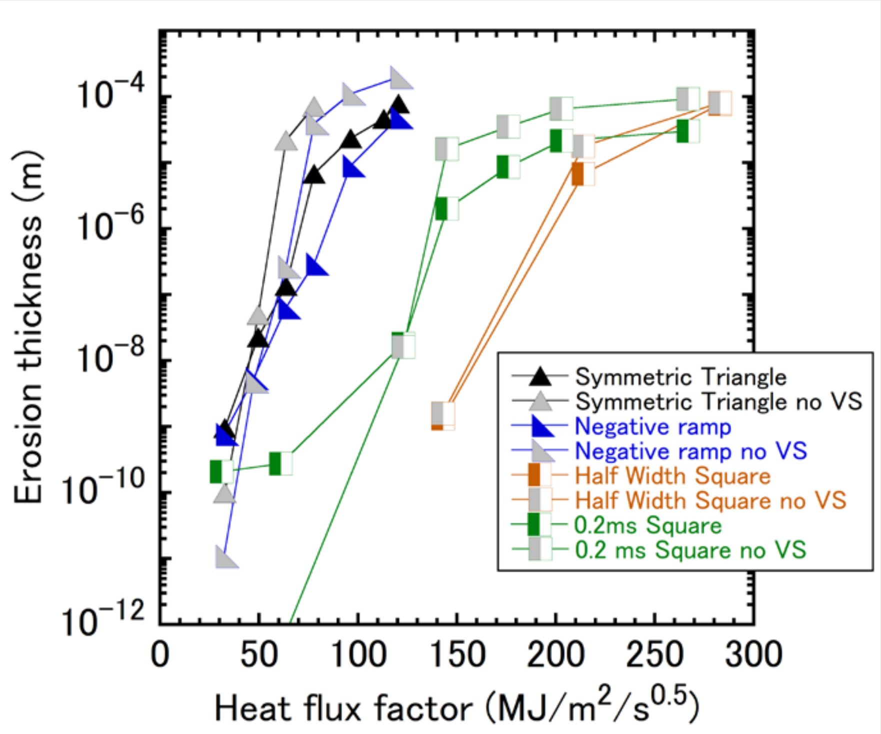
Erosion vs Energy flux

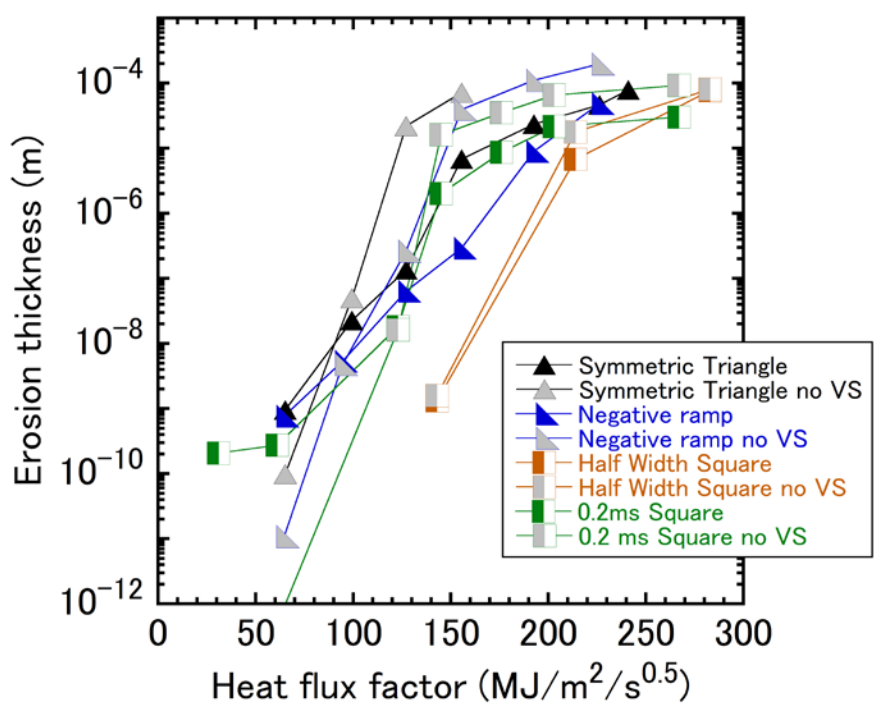




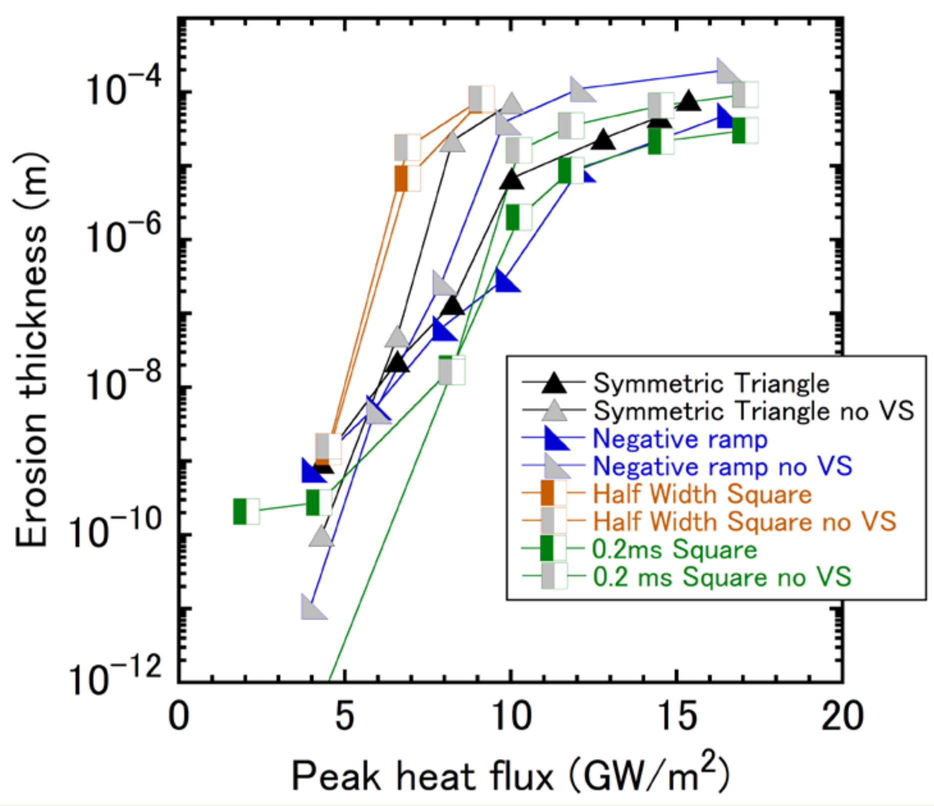
Within same energy flux, shorter width pulses show higher erosion.
(due to higher peak heat flux value)
Within triangle pulses, negative ramp pulses show smaller erosion than symmetric triangle.

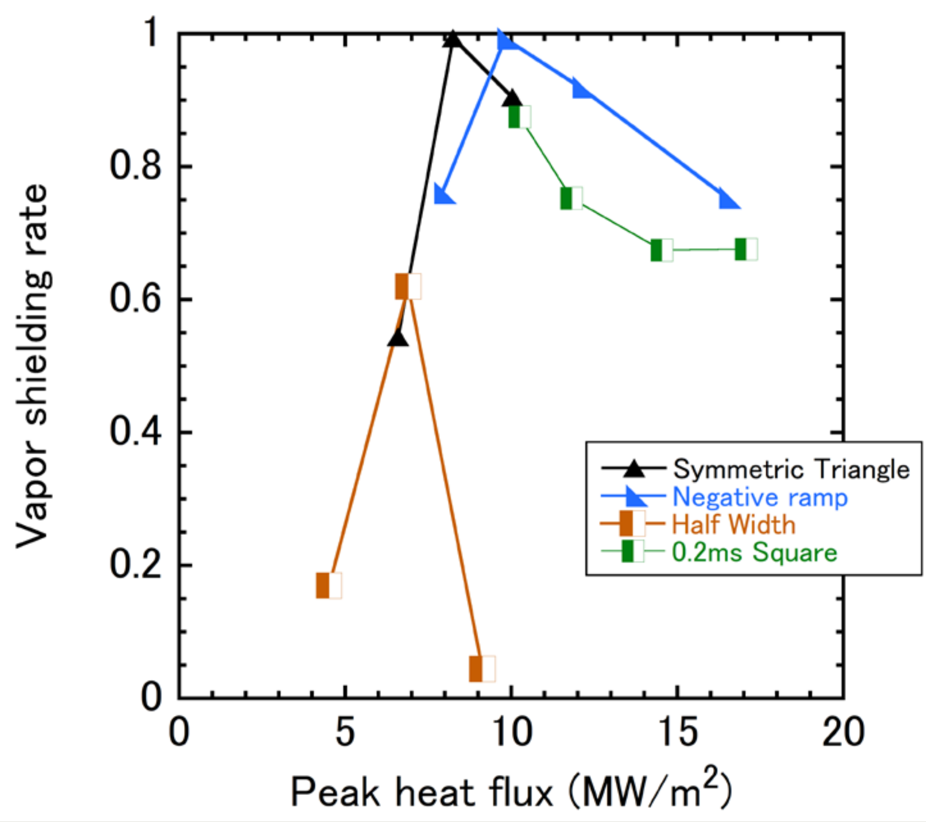
Erosion vs Heat flux factor





Erosion vs Peak Heat flux





Within same energy flux, shorter width pulses show higher erosion.
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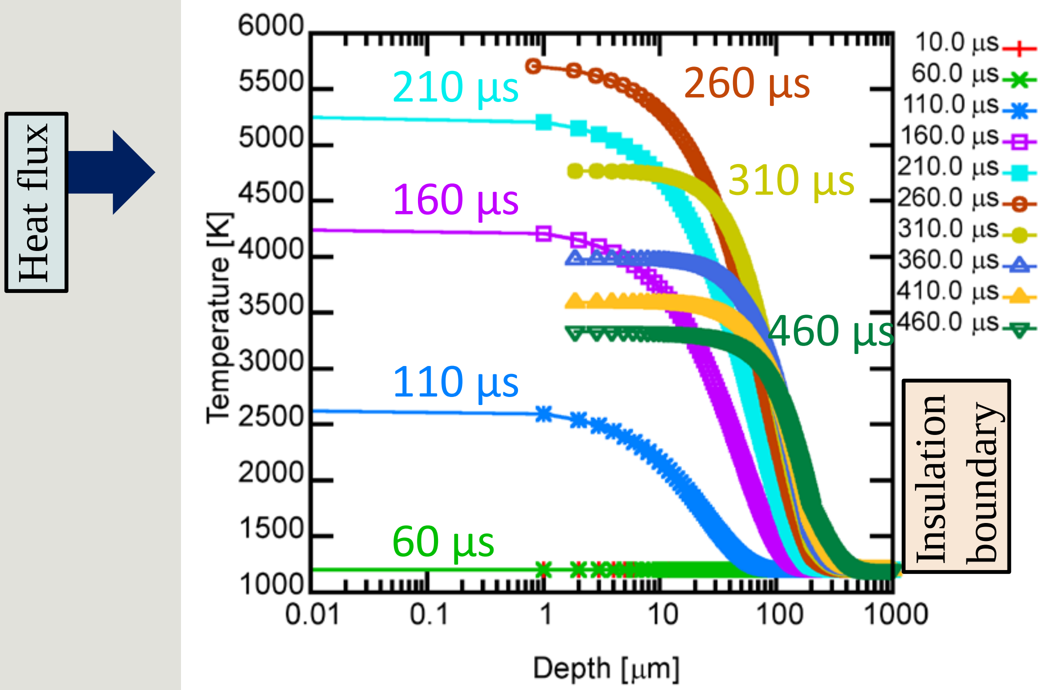
Within triangle pulses, negative ramp pulses show smaller erosion than symmetric triangle.

Heat transfer and vaporization

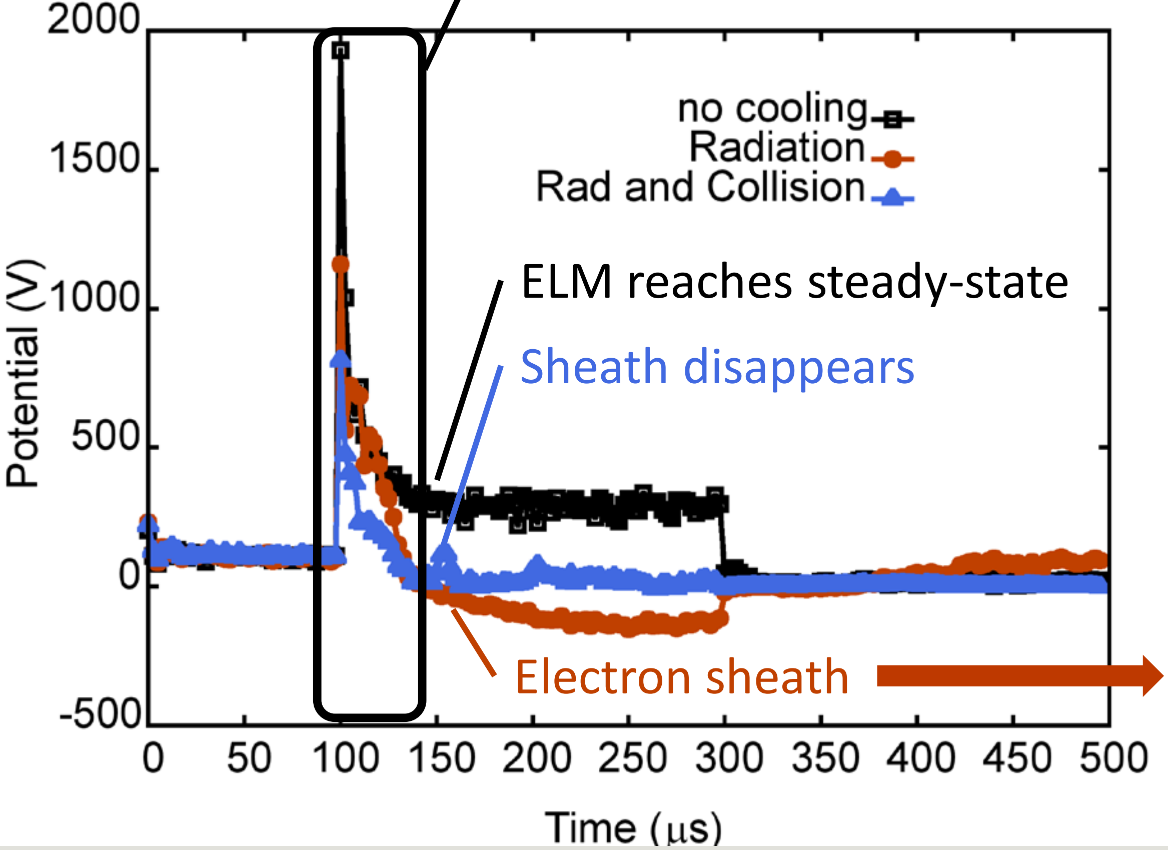


W wall under 10 GW/m^2
(pulse starts at 100 µs,
ends at 300 µs)

<u>1D heat transfer calculation</u>

- 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.”

Temporal change of potential near wall



Wall is 0V (grounded)

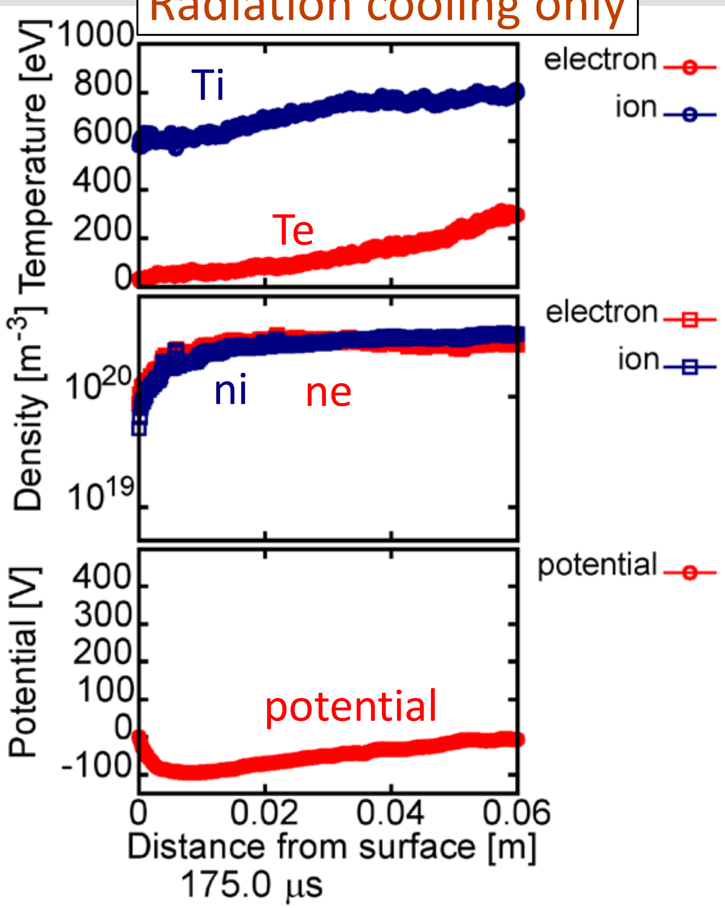
Electron reaches first

ELM reaches steady-state

Sheath disappears

Electron sheath

Radiation cooling only



In case of “radiation cooling only”, only electrons are cooled.
Electron sheath (negative potential) is formed
due to the Te << Ti and ne > ni condition.