Theoretical Modeling of Shielding for Plasma Flow and Electron Beam Heating

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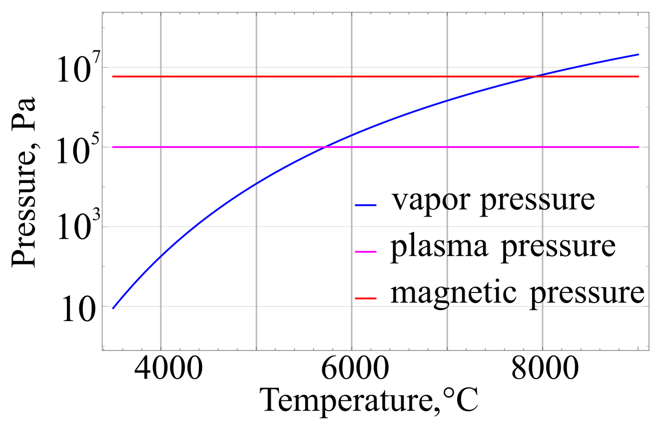
Motivation

1. High heat fluxes are expected in future devices
2. Absorbed energy by tungsten is limited by shielding for QSPAs
3. Electron beam can put in more energy before shielding
4. Theoretical simulation needed to understand differences



Thermal conductivity equations

Heat conduction equation and equations rate of evaporation and energy looses from the surface are:

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\chi(T)\frac{\partial T}{\partial x} + N(x,t) \qquad (1)$$

$$\dot{x}_{surf}(t) = \frac{P(T(x_{surf}(t),t))}{\rho}\sqrt{\frac{M}{2\pi m R T(x_{surf}(t),t)}} \qquad (2)$$

$$L(T(x_{surf},t))\frac{dx_{surf}}{dt} + \alpha(T)\sigma T(x_{surf},t)^4 = \chi(T(x_{surf},t))\frac{\partial T(x_{surf},t)}{\partial x} \qquad (3)$$

where T is the temperature, x is the distance from initial surface, t is the time, C is the thermal capacity, χ is the thermal conductivity, N is power density, x_{surf} is the thickness of evaporated layer, σ is the Boltzmann constant, α is the emissivity, $L(T)$ is the specific heat of evaporation, P is the pressure of saturated vapor, M is the molecular mass, R is the gas constant, ρ is the density of material.

Typical results of calculations

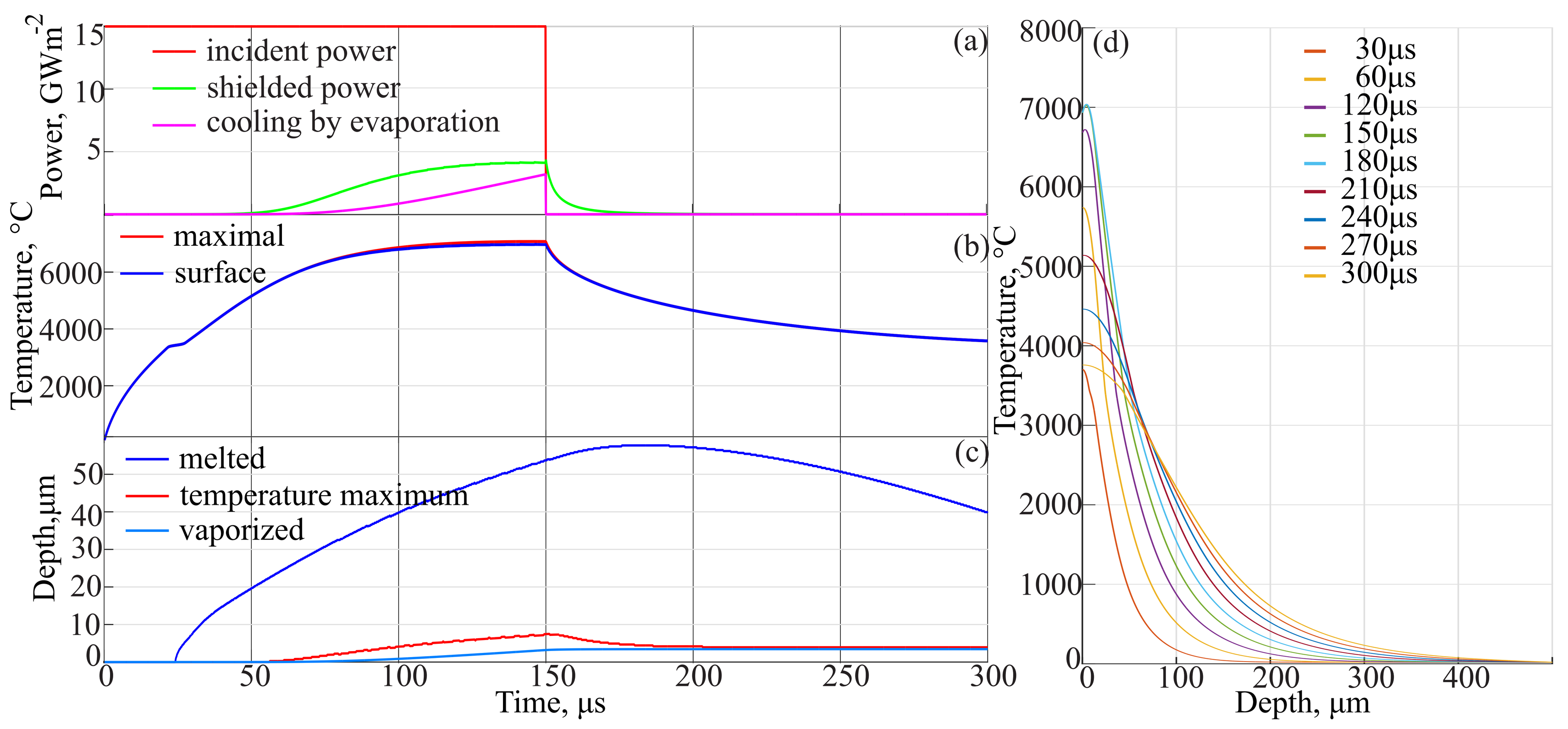


Figure 1: The results of tungsten heating with parameters 100keV energy electron beam with released power 15GWm^{-2} and during 100μs. (a)power of heating, shielding and cooling (b)surface and maximal temperature (c)depth of melted, evaporated layers and depth of maximal temperature (d)temperature distribution at different moments with 30μs steeps.

Shielding development duration.

Duration of vapor shielding development for different heating sources (with different depth of heating) were calculated.

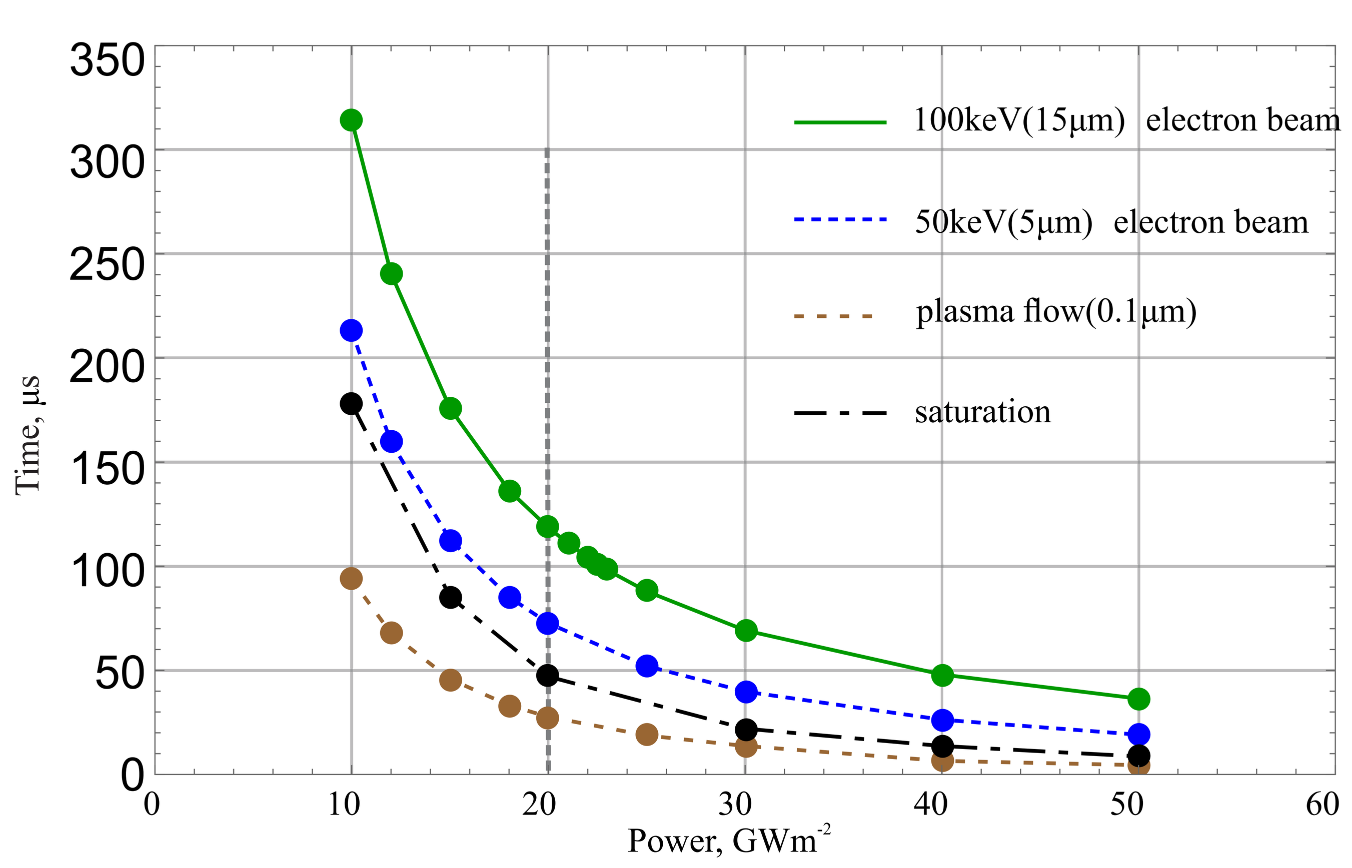


Figure 2: Time needed to evaporate 30% of shielding layer for 50keV, 100keV electron beams and plasma flow heating. Lengths in brackets is considered stopping ranges. Dash-doted curve is time needed to heat surface to temperature at that cooling by evaporation becomes 30% of incident power in flow.

The ratios of the calculated durations of the shielding developments for the sorts of particles do not differ as dramatically as stoping range ratios. The reason is dash-doted curve separates plasma and electron beam heating shielding developing durations. There is significant differences in heating process in case of electron beam and plasma flow heating.

Process of shielding development

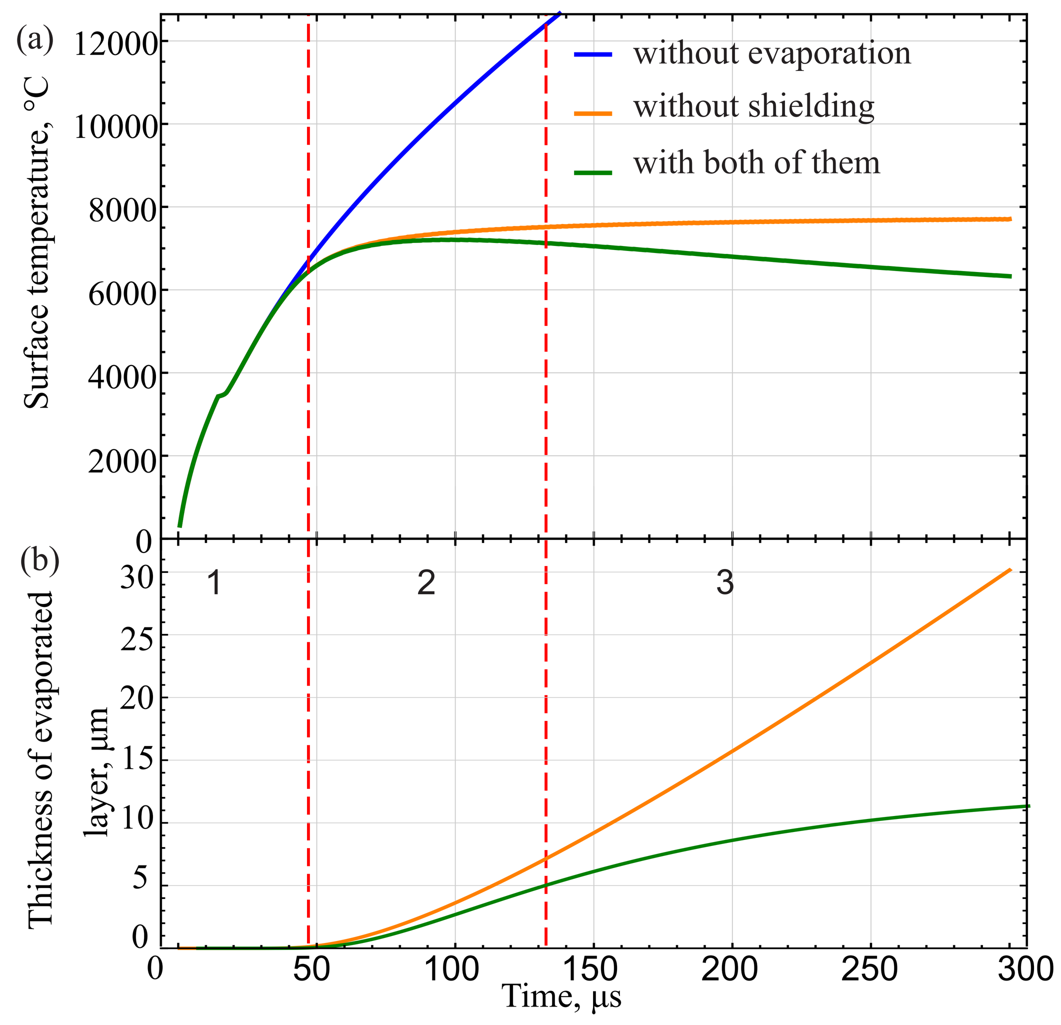


Figure 3: Surface temperature(a) and depth of evaporated material (b) time dependence for 3 different simulations: for switched off evaporation, switched off vapor shielding and for taking into account all of them. In addition, vertical dashed lines show moments at witch evaporation takes away 30% of incident power and at witch evaporated layer starts to shield 30%. Parameters of simulation: 15μm stopping range (100keV), 20GWm^{-2} heating power with heating duration 300μs.

There are can be divided 3 different stages in vapor shielding development:

1. Stage of uncovered heating
   - Almost full incident power heat surface
   - Temperature grows fast, roughly as $\sqrt{t}$
   - Evaporation rate increases fast, but this doesn't significant yet.
2. Stage of stable temperature
   - Power taken away by evaporation becomes comparable with incident.
   - Temperature grows slow, roughly is stable. It's has upper limit.
   - Evaporation rate is roughly constant, so depth of vapor layer increases proportional to t.
3. Stage of vapor shielding
   - Power taken by vapor becomes significant.
   - Temperature reduces because of heating power achieved surface decreases.
   - Evaporated mass becomes comparable with shielding mass, evaporation rate decreases.

At 2 stage cooling by evaporation comparable with incident power.

Superheated liquid

- At stage 2 temperature grows up to

$$\delta T \simeq \frac{P_{surf}\lambda\beta^2}{2\chi} \qquad (4)$$

where P_{surf} is power achieved surface through vapor layer; β is ratio of power that lost by evaporation to P_{surf}; λ is stopping range.

- This estimation gives additional pressure up to 20% of the pressure at the surface. So, the liquid under the surface is superheated and the melt may boil.
- The boiling may be a reason of the splashing with ejection of droplets.

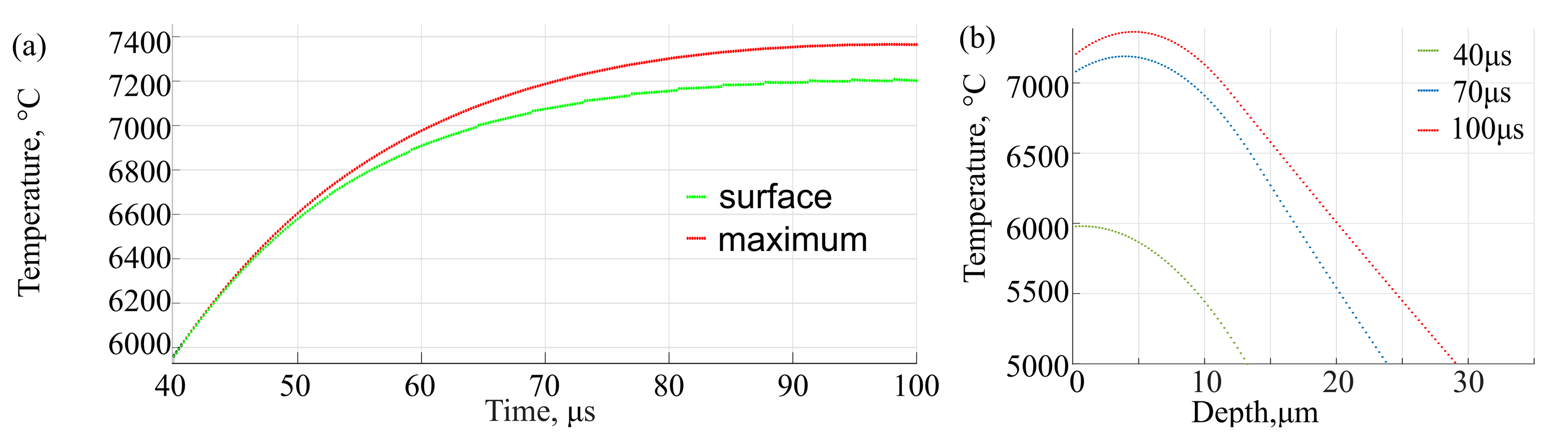


Figure 4: At this figures temperature distribution shown for heating by 100keV electron beam (15μm) with 20GWm^{-2} heating power during $100\mu s$

Conclusions

- Vapor shielding development duration was calculated for electron beam and plasma flow transient heating.
- Cooling by evaporation takes effect before the vapor shielding development in case of electron beam heating
- Temperature of surface is mostly stabile at the intermediate stage. The shift of the maximum temperature beneath the surface results in boiling and splashing.