My view on the vapor shielding issues

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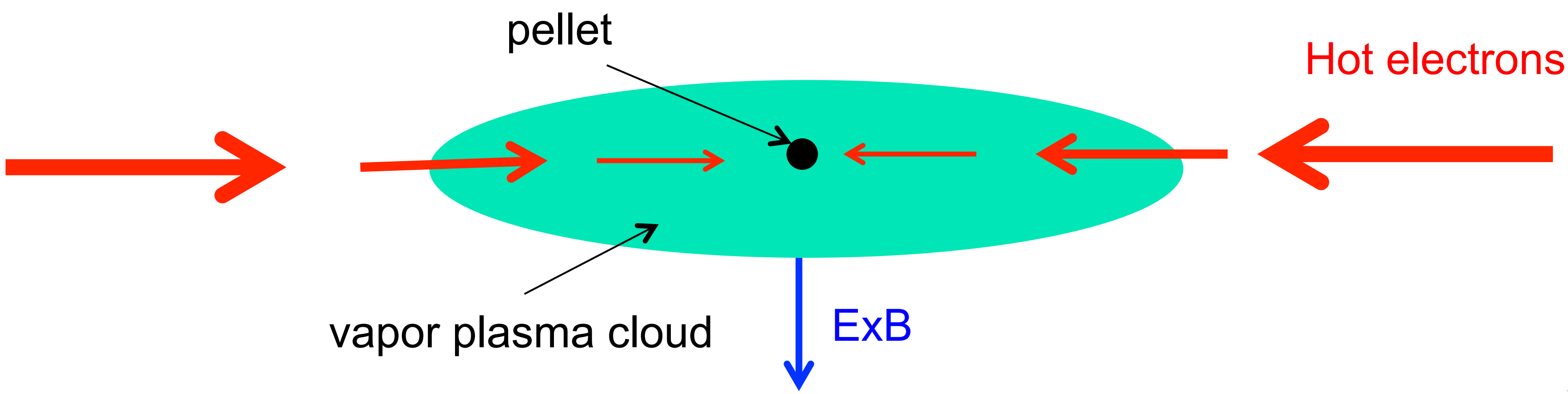
Introduction

- There are different models of the vapor shielding. In a ballpark they could be divided on two major categories:
  - i) inertial models, and
  - ii) dissipative models
- The first one is relying on inertial heating of the vapor cloud (ablated material) by incoming heat flux, which is carried by plasma particles. The amount of energy reaching the surface is determined by the stopping power of the vapor. No dissipation of energy from the vapor is accounted for.
- The second one, in addition to the heating of the vapor cloud, involves also dissipation of incoming heat flux by the radiation loss.
- As a result, atomic physics data used in these models are very different

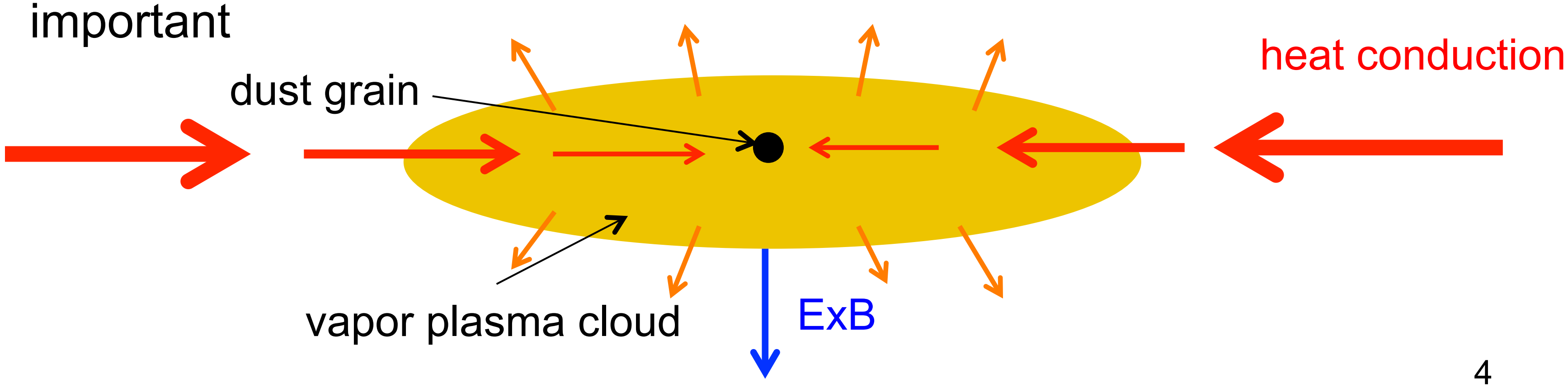
Introduction (con-ed)

- As an example of the first, inertial, models one could refer to the shielding of pellets (both H and impurity) in a hot core tokamak plasmas
- Shielding effect of the plasma vapor cloud is caused by stopping of hot (~10 keV) electrons due to elastic collisions
- However, some of these models account for dynamic effects of the vapor plasma cloud (e.g. parallel flow and ExB drift)
  - P. B. Parks and R. J. Turnbull Phys. Fluids **21** (1979) 1735.
  - S. L. Milora et al., Nucl. Fusion **35** (1995) 657.
  - V. A. Rozhansky and I. Yu. Senichenkov Plasma Phys. Rep. **31** (2005) 993.
  - Cseh, et al., Nucl. Fusion **57** (2017) 016022.



Introduction (con-ed)

- The second one, in addition to the heating of the vapor cloud, involves also dissipation of incoming heat flux by the radiation loss.
- Examples are: shielding of dust particles in tokamak edge plasma, an impact of large ELMs and disruption on divertor targets, and, finally, effective "impurity and hydrogen shield" of divertor targets in detached regimes
  - S. Krasheninnikov and E. D. Marenkov, J. Nucl. Mater. 463 (2015) 869
  - S. Pestchanyi et al., J. Nucl. Mater. **438** (2013) S. 459.
  - S. I. Krasheninnikov and A. S. Kukushkin, J. Plasma Phys. **83** (2017) 155830501
- Shielding effect of the plasma vapor cloud in these cases is mainly caused by radiation losses, although plasma dynamic effects are still important



Introduction (con-ed)

- As a result, “dissipative” shielding models could be subjected to the radiation trapping effects
- This is indeed the case for high density detached divertor regime, where there is a strong trapping of hydrogenic lines (e.g. Ly_{α}, Ly_{β}, …)
- However, under an impact of large ELMs and disruption, strong ablation of divertor targets could result in impurity line trapping
  - S. I. Krasheninnikov, A. Yu. Pigarov, Nucl. Fusion Suppl. **3** (1987) 387
  - R. Marchand, and J. Lauzon, Phys. Fluids **4** (1992) 924-933
  - H. A. Scott, J. Quant. Spectrosc. Radiat. Transfer. **71** (2001) 689.
  - D. Reiter, V. Kotov, P. Börner, K. Sawada, R. K. Janev, B. Küpers, J. Nucl. Mater. **363-365** (2007) 649-657
  - V. Sizyuk and A. Hassanein, Phys. Plasmas **22** (2015) 013301.
- As a result, atomic physics included, or which should be included, into these models is by far more complex than that we could be dealing with in “inertial” models of vapor shielding!

What AD are used in vapor shielding models

- "Inertial" models are relying on electron stopping in vapor cloud caused by elastic collisions of energetic electrons with both free and bound electrons. Both these collisions in many cases described by modified coulomb collisions.

- "Dissipative" models use a wide range of different approximations for the radiation losses ranging from:
  - MC simulation of photon transport (only for few hydrogen lines) and impact on the atomic rate constants following from the CR models
    - D. Reiter, V. Kotov, P. Börner, K. Sawada, R. K. Janev, B. Küpers, J. Nucl. Mater. **363-365** (2007) 649-657
  - To the LTE approximation for the population of excited and ionization states and radiation losses accounted with escape probability factor (e.g. Zeldovich, Raizer, "Physics of shock waves…") or even with diffusive approximation
    - S. I. Krasheninnikov, A. Yu. Pigarov, Nucl. Fusion Suppl. **3** (1987) 387
    - V. Sizyuk and A. Hassanein, Phys. Plasmas **22** (2015) 013301

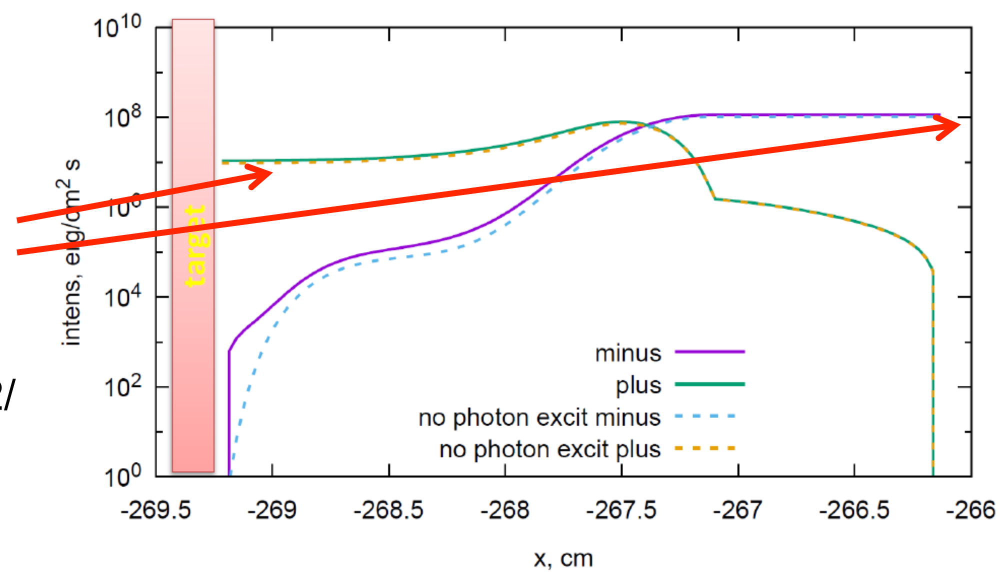
- However, even for hydrogen there is only very limited number of simulations accounting for both MC transport of photons and an impact of photon absorption on AD from CR calculations

What could be done to improve AD for vapor shielding models

- “Inertial” models: is any way to improve the description of stopping power of energetic electrons in vapor cloud (including both neutrals and ions) for the case of high-Z pellets? How to account for the ionization states of high-Z ions while keeping the models tractable?
- “Dissipative” models for high-Z radiators for the case where impurity radiation of trapped: What could be done to go beyond the LTE approximation?
  - Is it feasible to create the database assessing radiation trapping for impurity (e.g. W) lines in the simplest possible way (e.g. as some function of plasma density, temperatures, and typical scale length of the problem of interest)? In case where the number of trapped lines lines is not too large their photons could treated with MC simulation and feed back to the results of atomic rate constants following from CR models. Moreover, in zero order approximation “trapped lines” could be treated in CR models as “forbidden” transitions.
  - However, what to do for the case where the number of trapped impurity lines is large and MC treatment of all these lines becomes, in practical applications, not feasible?

Verification of vapor shielding models

- The most uncertain issue affecting AD is related to the photon transport of trapped lines
- For example, on my best knowledge, the EIRENE's part dealing with radiation transport was not verified so far!
- Whereas, radiation transport on the wings of deeply trapped lines (e.g. Ly_α line for detached divertor conditions in ITER) could be rather tricky
- For example, for particular conditions radiation transport on the wings of the lines could divert energy flux away from the target
  - E. D. Marenkov, et al., Contr. Plasma Phys. 2017, DOI: 10.1002/ctpp.201700132



Verification of vapor shielding models

- However, recently it was suggested a model allowing semi-analytical solutions of the radiation transport in inhomogeneous conditions for arbitrary line shape but having a self-similar dependence of both the characteristic line width, , and radiator density, n(x).
  - P. A. Sdvizhenskii, S. I. Krasheninnikov , and A. B. Kukushkin, Contr. Plasma Phys. **56** (2016) 669.
- Self-similar conditions correspond to:

$$a(\omega) \equiv \omega_w^{-1}(x)\, a\left\{\frac{\omega}{\omega_w(x)}\right\} \qquad n(x) \propto \frac{n_0(x)}{\{\omega_w(x)\}^{\alpha}}$$

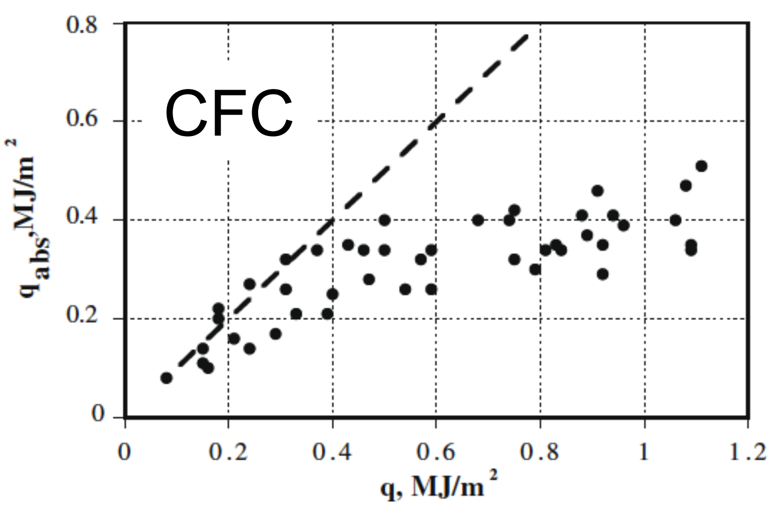
α is an adjustable parameter

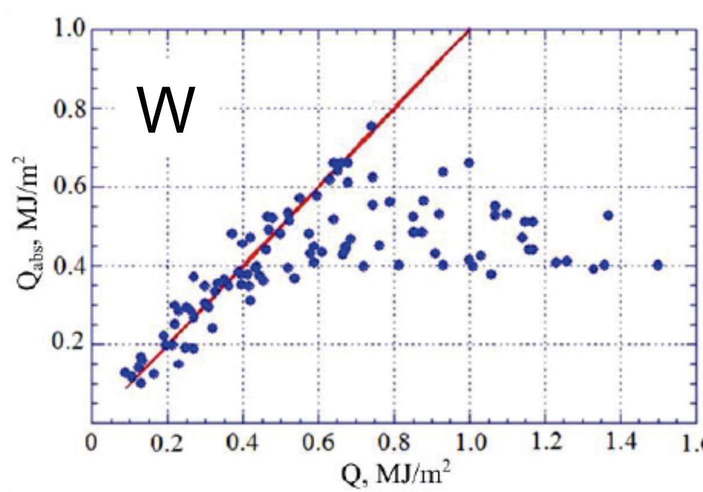
$$\frac{\omega_w(x)}{n_0(x)} \frac{d\ell n\{\omega_w(x)\}}{dx} \equiv \gamma = \text{const.}$$

- Comparison of EIRENE simulation results with such semi-analytical model(-s) would be a good verification test of the accuracy of the MC radiation transport used for ITER simulations

Validation of vapor shielding codes

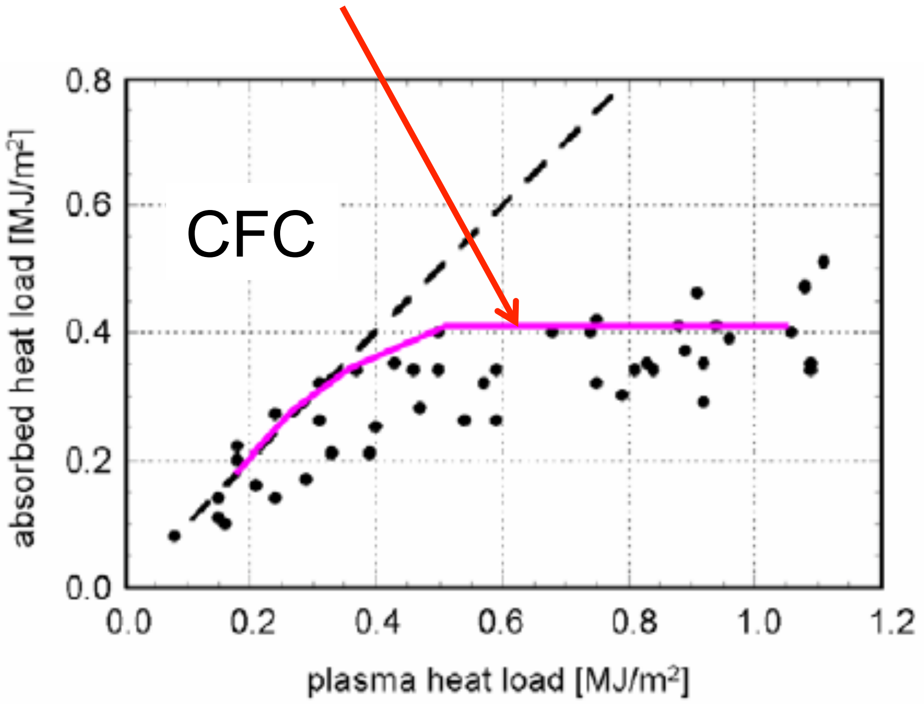
- We should be careful with the validation of the vapor shielding codes
- For example, experimental data on CFC and W vapor shielding effects show very similar dependencies of the energy absorbed by the target, E_{abs}, vs total energy pulse E_{tot}, even though the radiation capabilities of CFC and W are very different
  - V. M. Safronov, et al., J. Nucl. Mater. **386-388** (2009) 744
  - I. M. Poznyak, et al., AIP Conf. Proceedings **1771** (2016) 060006





Validation of vapor shielding codes (con-ed)

- Numerical simulation of the CFC shielding effects have shown a good agreement with experimental data
- This agreement could be interpreted as a "code validation"
  - S. Pestchaniy and I. Landman, J. Nucl. Mater.**390-391** (2009) 822



Validation of vapor shielding codes (con-ed)

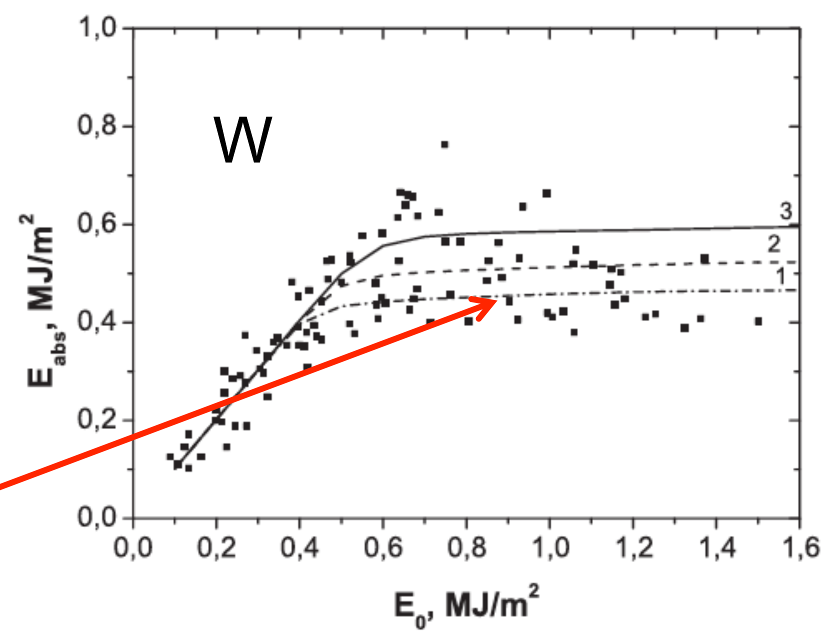
- However, recently three vastly different, from the physics point of view, shielding models were considered
  - D. I. Skovorodin, et al., Phys. Plasmas **23** (2016) 022501

$$\frac{dN}{dt} = j_0 e^{-E_{ev}/kT_s} \qquad T_s = \frac{1}{\sqrt{\pi C_p \rho \varkappa}} \int_0^t \frac{q(t')}{\sqrt{t-t'}} dt'$$

(1) $q = q_0 e^{-N\sigma}$

(2) $q(t) = q_0 - \dot{E}_{rad} N(t)$

(3) $q(t) = q_0 - \frac{\langle Z \rangle L_{rad}}{U_v t} (N(t))^2$



- Surprisingly, all of them have shown very good agreement with experimental data

Validation of vapor shielding codes (con-ed)

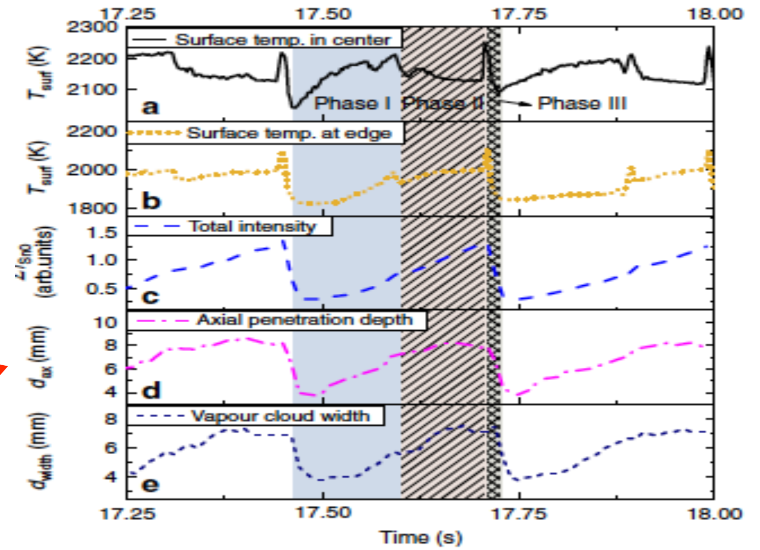
- It appears that the reason for such insensitivity of E_{abs} to the details of shielding models is a very rapid increase of the vapor density for the case where surface temperature becomes too high, $T_S \gtrsim T_{max}$
- Therefore, E_{abs} depends largely on the material heat conduction and evaporation energy and have logarithmically weak dependence on the details of shielding model
- As a result, E_{abs} , virtually saturates at the level E_{max} for $T_S \gtrsim T_{max}$:

$$E_{max} \approx \sqrt{t_{pulse} C_p \rho \kappa} \frac{E_{ev}}{k\Lambda} \qquad T_{max} \sim E_{ev} / (2k\Lambda) \qquad \text{(Eq. I)}$$

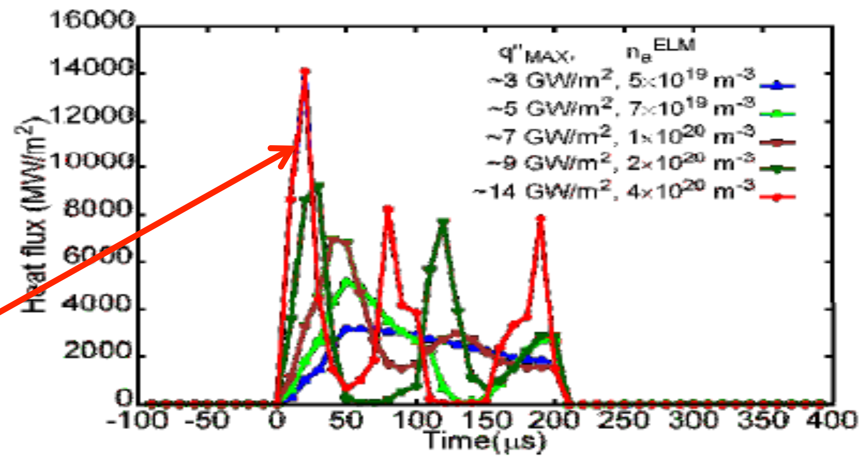
- This finding show that:
  - It is virtually impossible to do code validation based only on the magnitude of E_{abs}
  - On the other hand, to evaluate E_{abs} for practical applications one could just use (Eq.I) and do not worry about the details of the shielding physics
- However, we notice that (Eq.I) is unable to describe target erosion and this should be a real goal of more comprehensive shielding models!

Validation of vapor shielding codes (con-ed)

- Another option for the vapor shielding code validation is the benchmarking against experimental data for the case of self-sustained oscillating regimes observed in experiments with liquid metals at Pilot-PSI and FTU (?)
    - G. G. van Eden, et al., Phys. Rev. Lett. **116** (2016) 135002; Nature Communications, DOI: 10.1038/s41467-017-00288-y

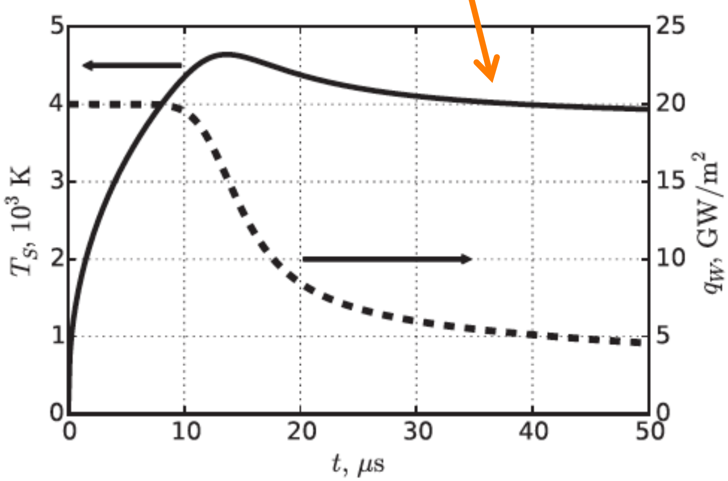


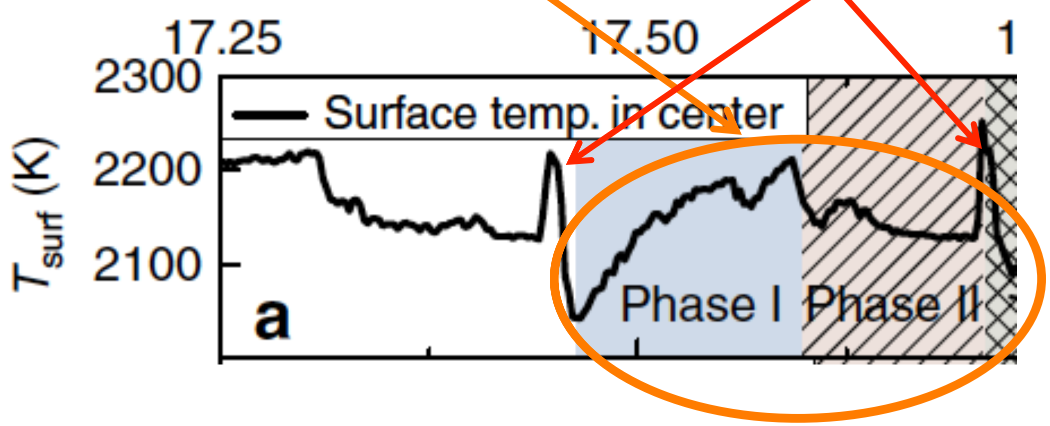
- We notice that somewhat similar relaxation oscillations were also observed in numerical simulations of vapor shielding for the case of solid Be target
    - K. Ibano, et al., Contr. Plasma Phys. 2018



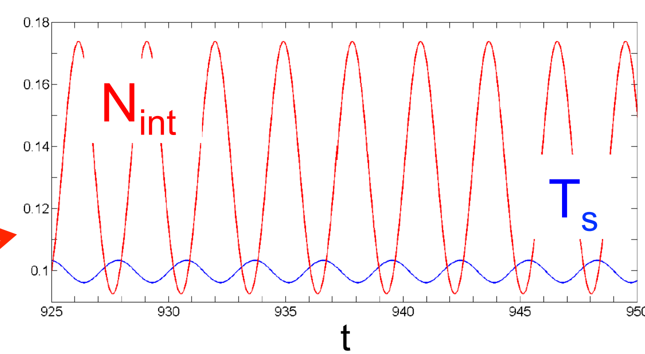
Validation of vapor shielding codes (con-ed)

- We notice that temperature evolution observed in experiments with liquid metals at Pilot-PSI (G. G. van Eden, et al., Nature Communications, DOI: 10.1038/s41467-017-00288-y) resembles $T_s(t)$ found from semi-analytic models discussed above (D. I. Skovorodin, et al., Phys. Plasmas **23** (2016) 022501). Although, the physics of temperature spikes in experimental data is not clear!





- However, it is also plausible that self-sustained oscillations observed in Pilot-PSI are not related to the vapor shielding *per se* but to some peculiarity of the CP system used, which are observed in the models when heat loading exceeds some threshold
  - S. Krasheninnikov, et al., 2018



Conclusions

- The need for AD for vapor shielding effects is closely linked to plasma physics models under consideration!
- Whereas "inertial" models need better description for stopping power of energetic electrons in vapor cloud
- The models relying on the energy "dissipation" via radiation loss require:
  - Better assessment of the condition for trapping of different lines (this is in particular true for high-Z impurity lines)
  - Verification of radiation transport codes
  - Incorporation of trapping effects into CR models for impurities
  - Some new approaches to coupled CR models and radiation transport effects are needed for the cases where the are large number of trapped impurity lines and the LTE approximation is not valid
- Validation of the shielding models should be appropriate. E.g. validation of such experimental data as:
  - Amount of eroded material,
  - Absolute intensities of line radiation ,
  - Plasma/neutral gas parameters in the vapor cloud, …
- If code does not reproduce experimental data it does not necessarily mean that AD are incorrect/incomplete! It is very plausible that something else is wrong!