US-Japan Workshop on Fusion Power Plants and Related Advanced Technologies
March 13-14, 2014. UCSD. San Diego, USA

Divertor physics and related safety issues

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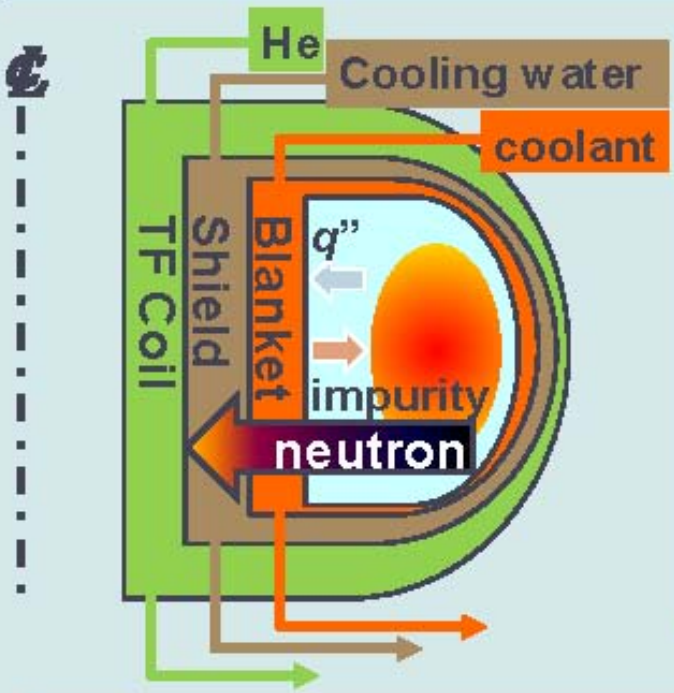
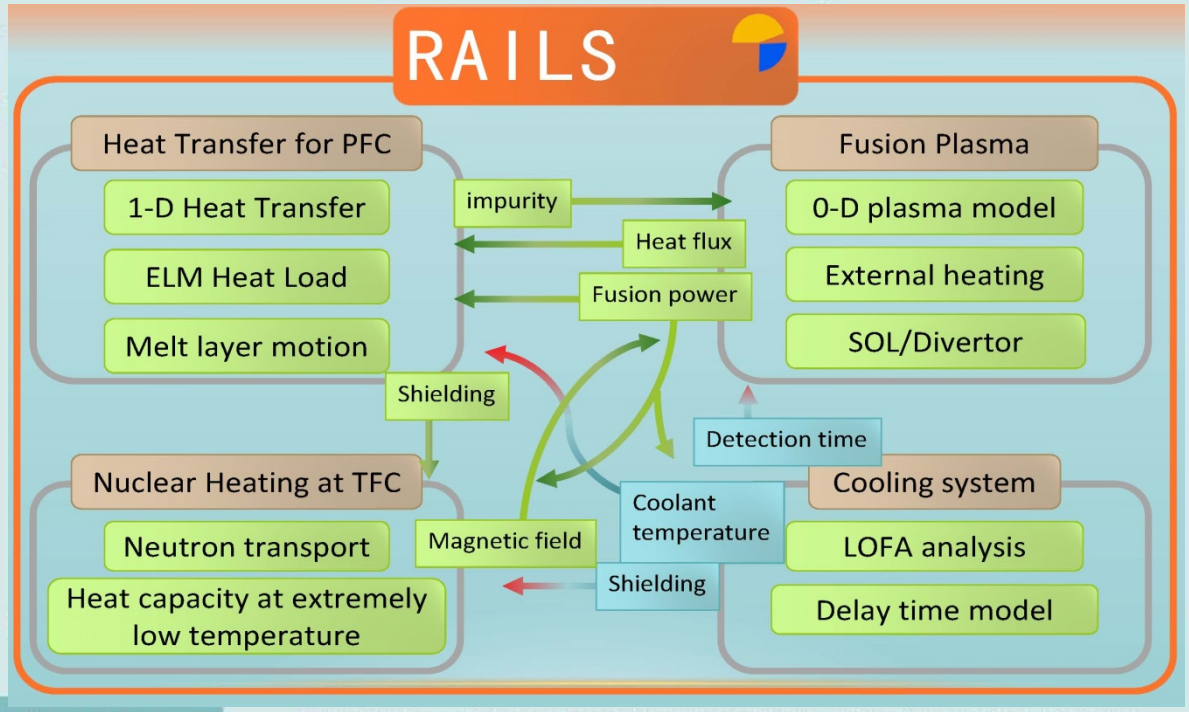
Introduction

transient fusion ReActor safety analysIs codes on plasma anomaLy eventS

How the fusion reactor passively shutdown?





Safety analysis for DEMO.

Termination by impurity contamination.
by quench of the TF coil.

Reference studies for ITER consisted of Plasma + Wall.

Nuclear and cooling system models should be added.

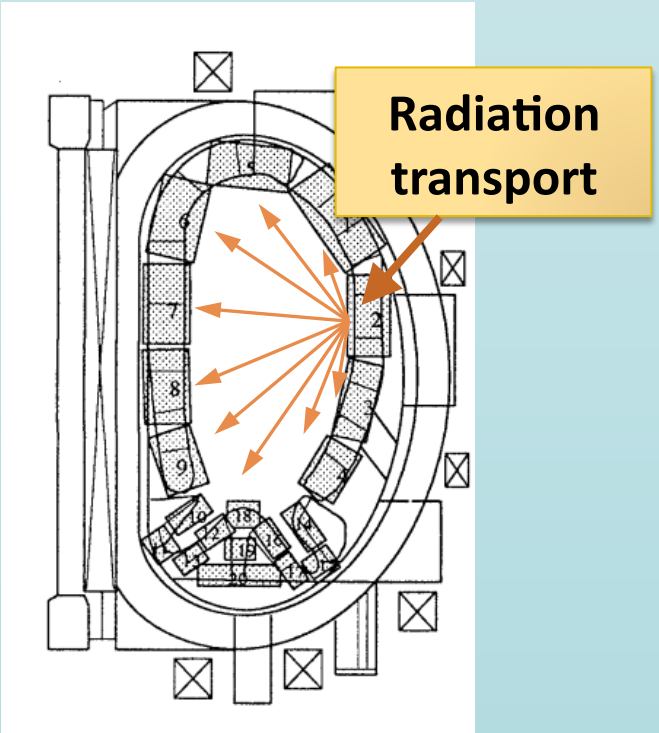
Topics

@ Passive shutdown of burning plasmas

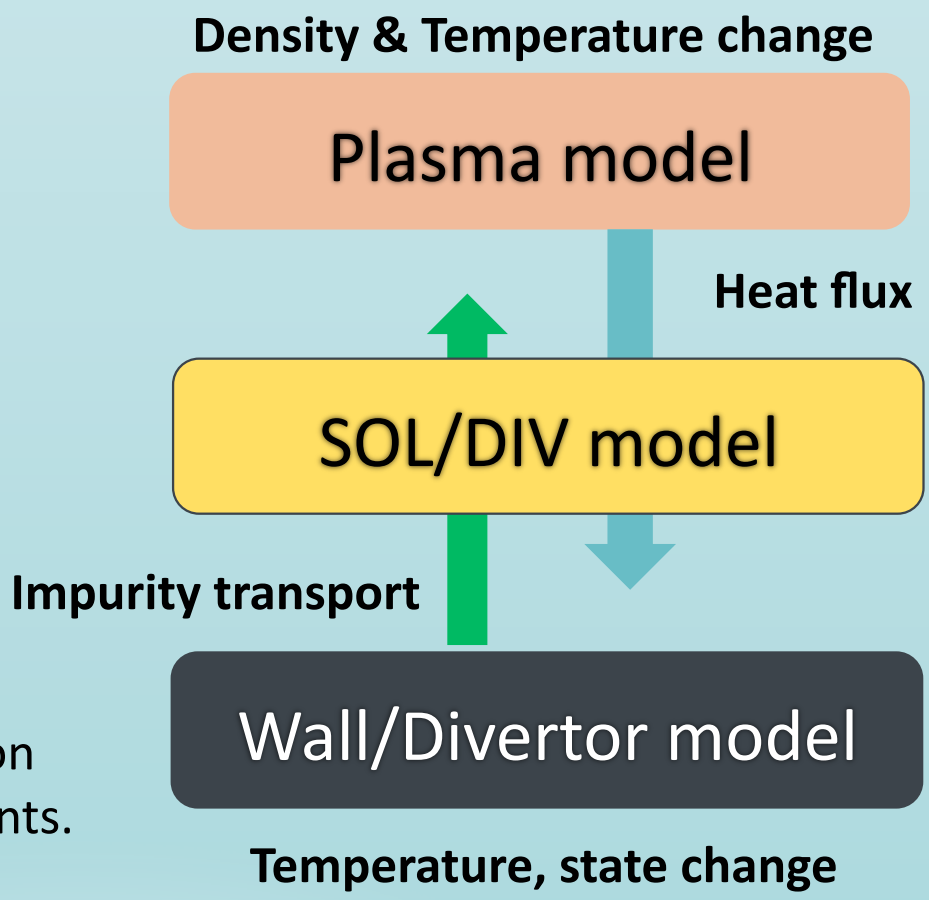
@ Possibility of TF coil quench at the ex-VV LOCA

RAILS code
Transient plasma analysis for safety Operation

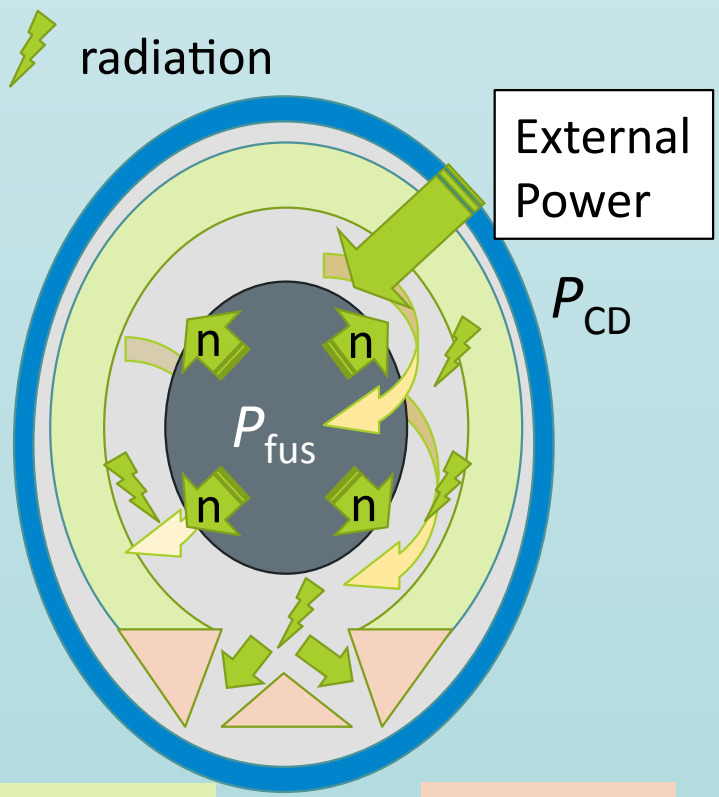
What happens to the reactor before its "inherent" shut-down?



Evaluating interaction between Fusion Plasma and Plasma Facing Components.
* Similar with SAFALY, AINA codes.



RAILS Plasma model (0-D Power balance)



Blanket

Neutron heating
Radiated power

Divertor

External heating
α heating

Plasma model

$$\frac{3}{2}\cdot\frac{d}{dt}(n_e T_e) = (1-f_{\alpha i})P_\alpha + (1-f_{auxi})P_{aux} + P_{ie} + P_{oh} - P_{br} - P_{sy} - \frac{3}{2}\cdot\frac{nT_e}{\tau_e}$$

Radiation power goes to Blanket.

Confined power goes to Divertor.

Details of the Plasma model

$$\frac{3}{2}\cdot\frac{d}{dt}(nT_i) = f_{\alpha i}P_\alpha + f_{auxi}P_{aux} - P_{ie} - \frac{3}{2}\cdot\frac{nT_i}{\tau_{Ei}}$$

Ions power balance

$$\frac{3}{2}\cdot\frac{d}{dt}(n_eT_e) = (1-f_{\alpha i})P_\alpha + (1-f_{auxi})P_{aux} + P_{ie} + P_{oh} - P_{br} - P_{sy} - \frac{3}{2}\cdot\frac{nT_e}{\tau_e}$$

Electrons power balance

$$\frac{d}{dt}n_i = S_i - \frac{1}{2}f_p n_i^2 < \sigma v >_{DT} - \frac{n_i}{\tau_{pi}}$$

D & T continuity

$$\frac{d}{dt}n_\alpha = \frac{1}{4}f_p {n_i}^2 < \sigma v >_{DT} - \frac{n_\alpha}{\tau_{p\alpha}}$$

α continuity

$$\frac{d}{dt}n_{imp} = S_{imp}f_{Z1} - \frac{n_{imp}}{\tau_{pimp}}$$

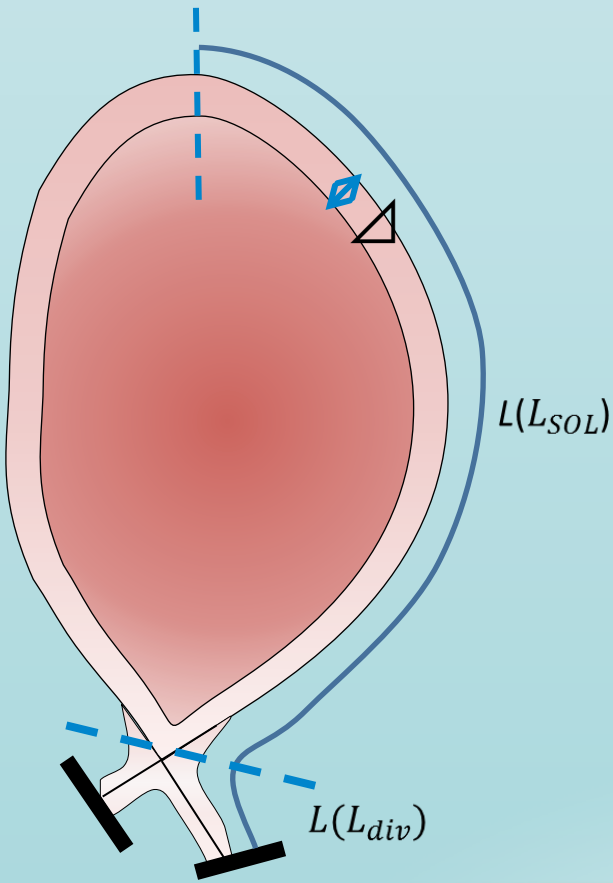
Impurity continuity

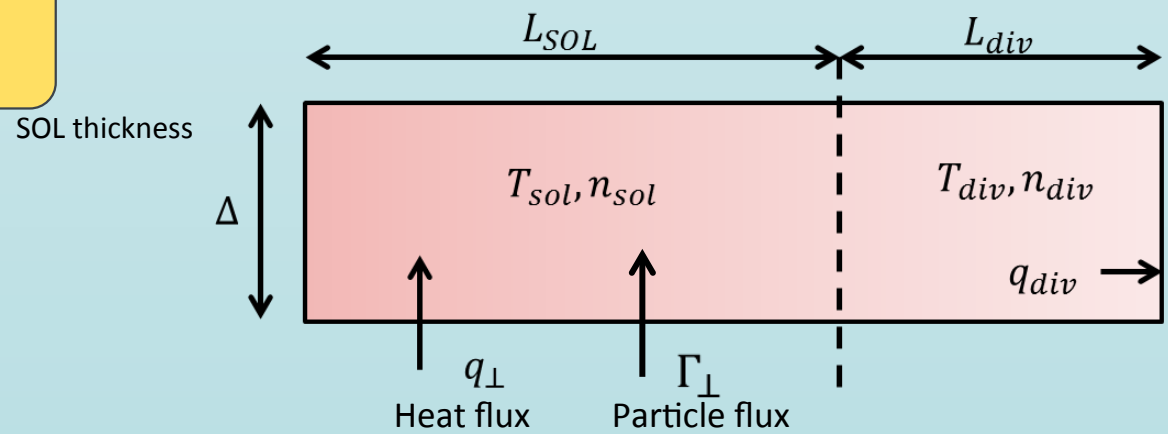
$$n_e = n_i + 2n_\alpha + \sum_z (Zn_z)$$

Electrons continuity

RAILS　SOL/DIV model（Point model + impurity）

SOL/DIV model





$$q_\perp L_s^2 = \frac{4\Delta\kappa_0}{49}\left[T_s^{\frac{7}{2}} - T_d^{\frac{7}{2}}\right]$$

Energy balance at SOL-DIV

$$2n_s T_s = m_p n_d M_d^2 C_s^2 + 2n_d T_d$$

Momentum balance at SOL-DIV

$$\left(1 - f_{imp}^{div}\right) q_\perp L_s = \gamma n_d T_d M_d C_s \Delta_E$$

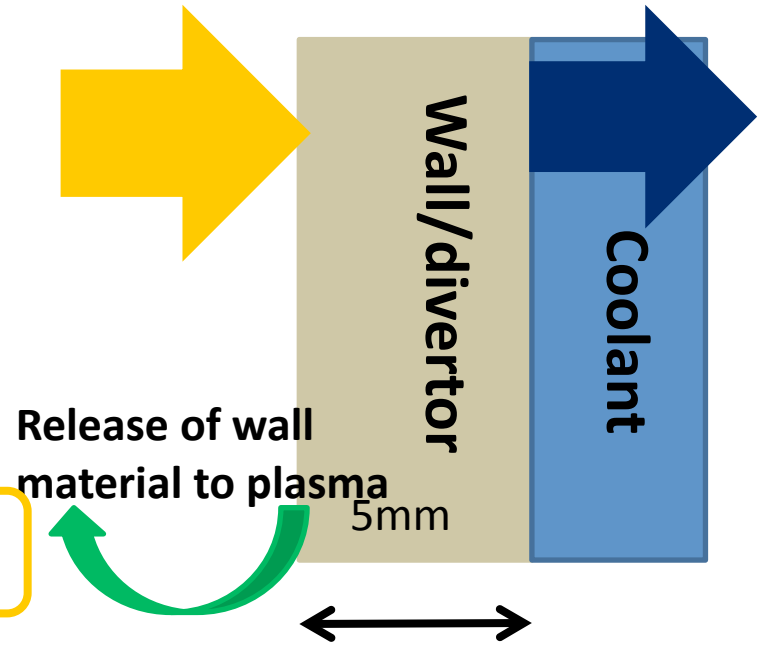
Power balance at CORE-DIV

$$\Gamma_\perp L_s + \eta n_d M_d C_s h \Delta_n + N_{puff} = n_d M_d C_s$$

Particle balance at SOL-DIV

Plasma – Wall modeling

$$\rho c \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial X^2}$$



Boundary condition

$$-\kappa \frac{\partial T}{\partial X} = \dot{q}_p - \dot{q}_{ev} \quad \text{(Plasma - Wall)}$$

Heat flux from plasma

Evaporation

$$-\kappa \frac{\partial T}{\partial X} = \alpha (T - T_W) \quad \text{(Wall - Coolant)}$$

Heat transfer coefficient

Coolant Temperature

RAILS wall impurity model

Wall model

Generation of impurity

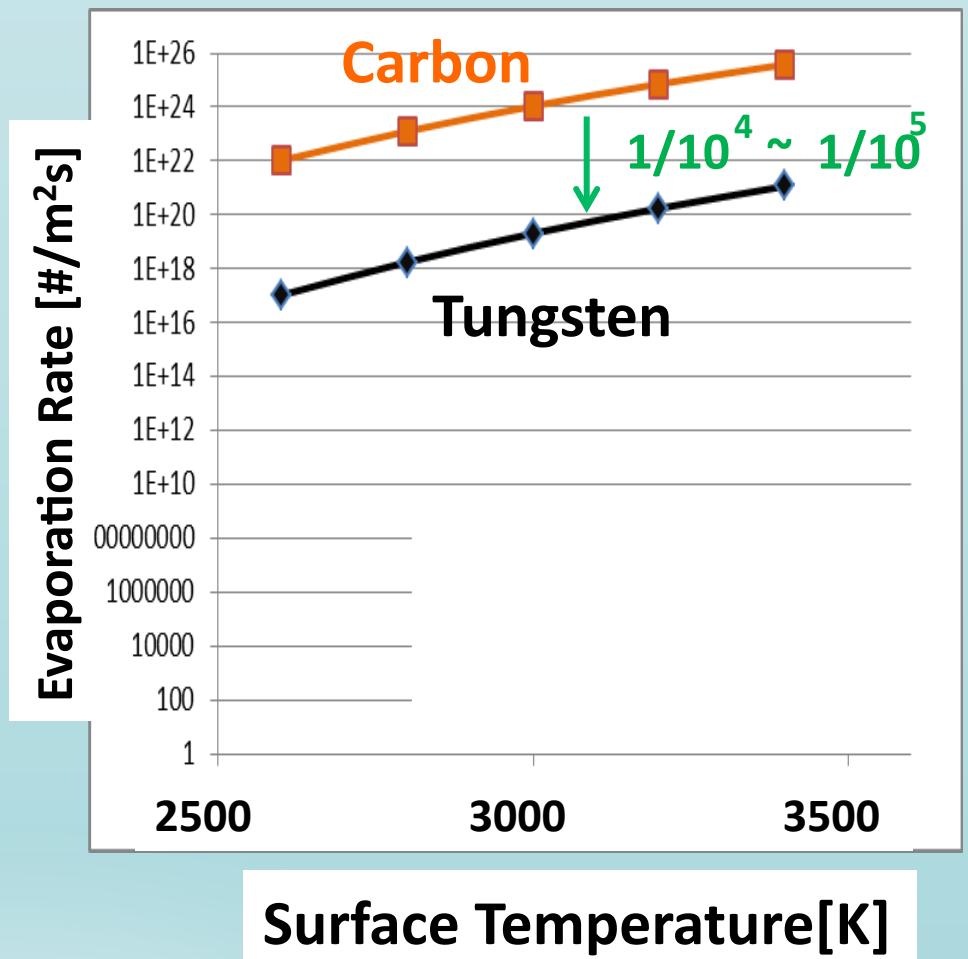
Surface evaporation rate

$$Y[/s] = N_A \rho A_0 \dot{\delta} / m_0$$

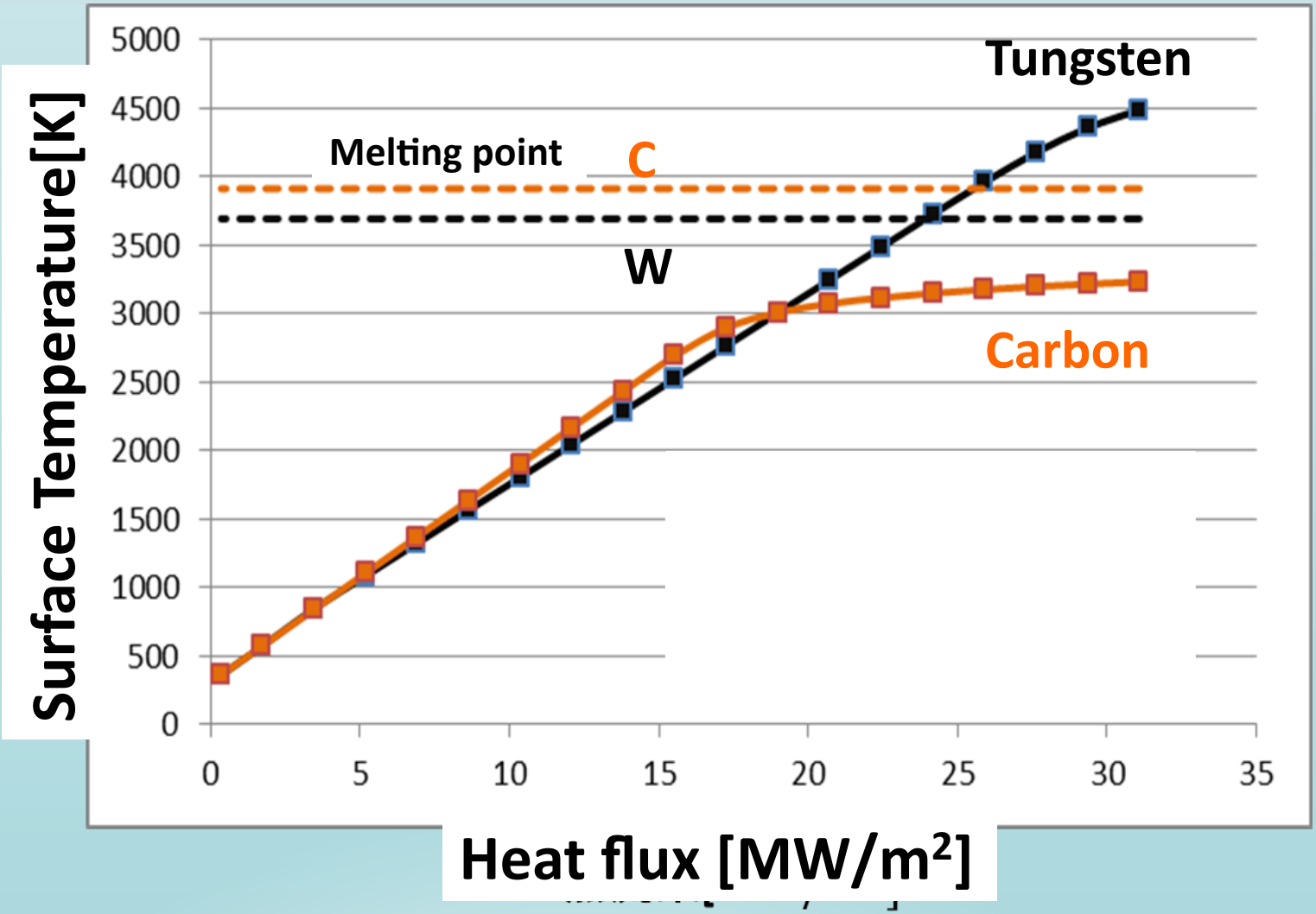
$$\dot{\delta}[m/s] = \alpha_0 C \frac{1}{\sqrt{T}} \exp\left(-\frac{\Delta H}{\kappa T}\right)$$

$\frac{\Delta H}{k}$ Activation energy

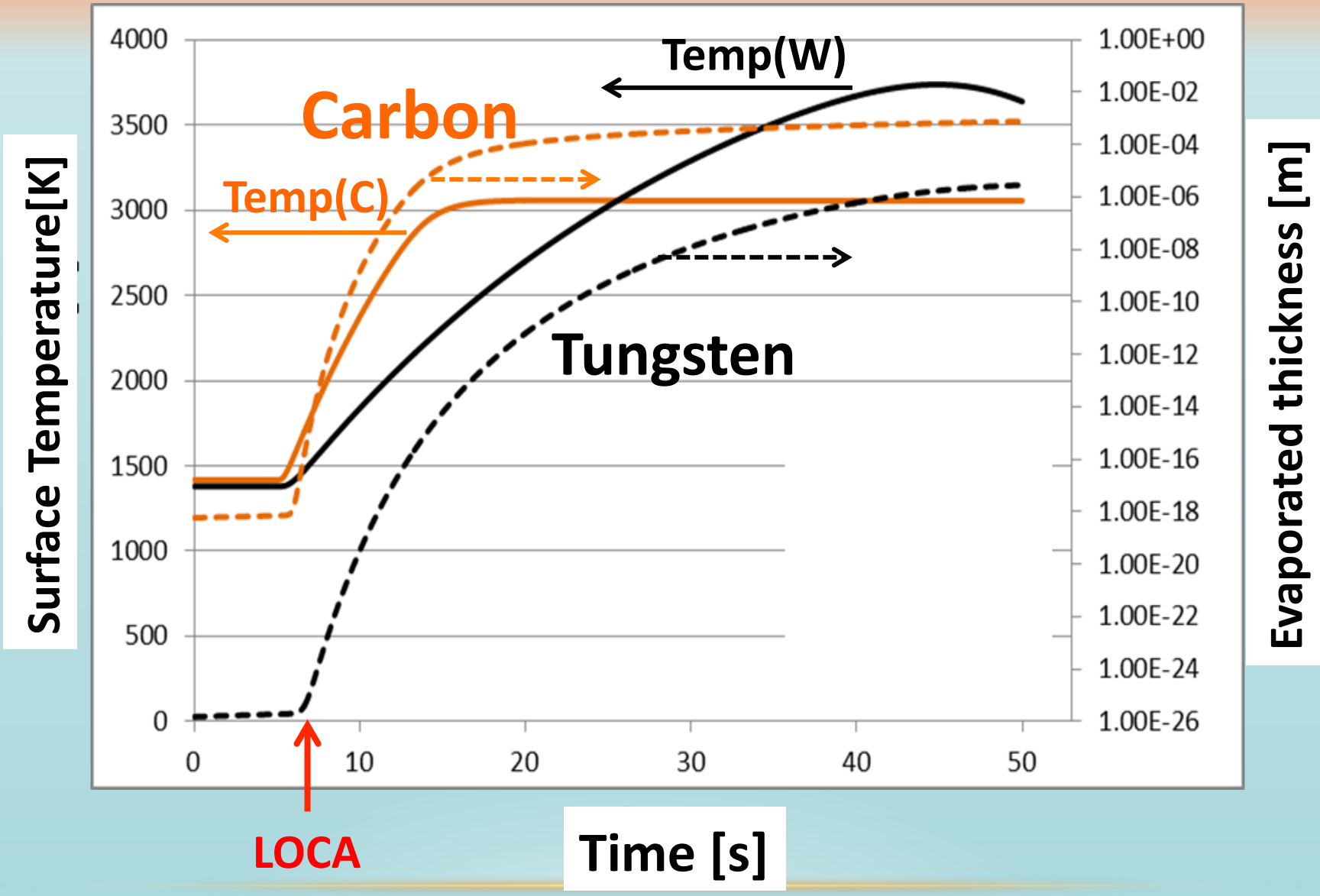
N_A Avogadro's #
ρ Density
m_0 Mass
A_0 Surface area



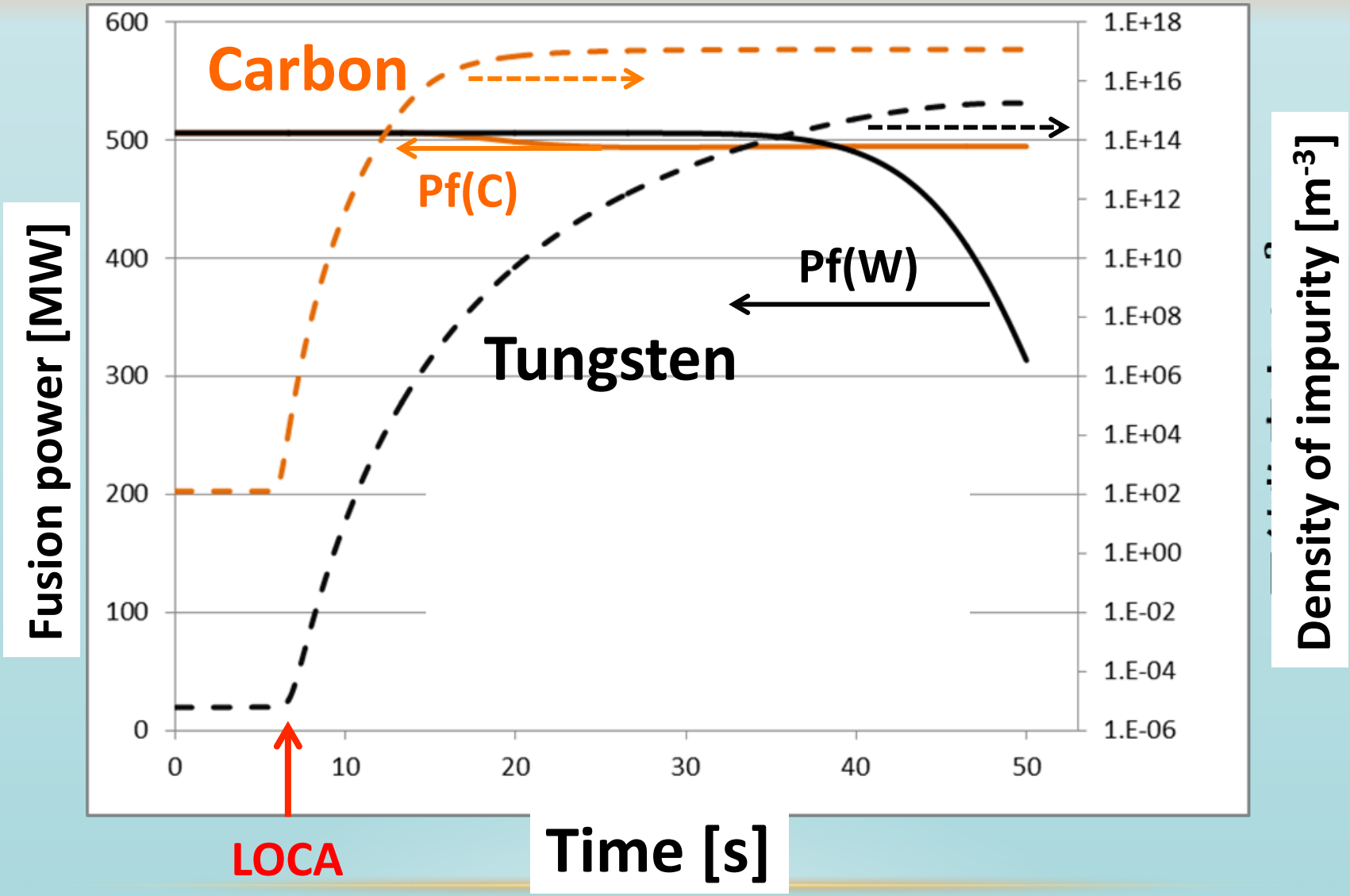
Comparison between Carbon and Tungsten



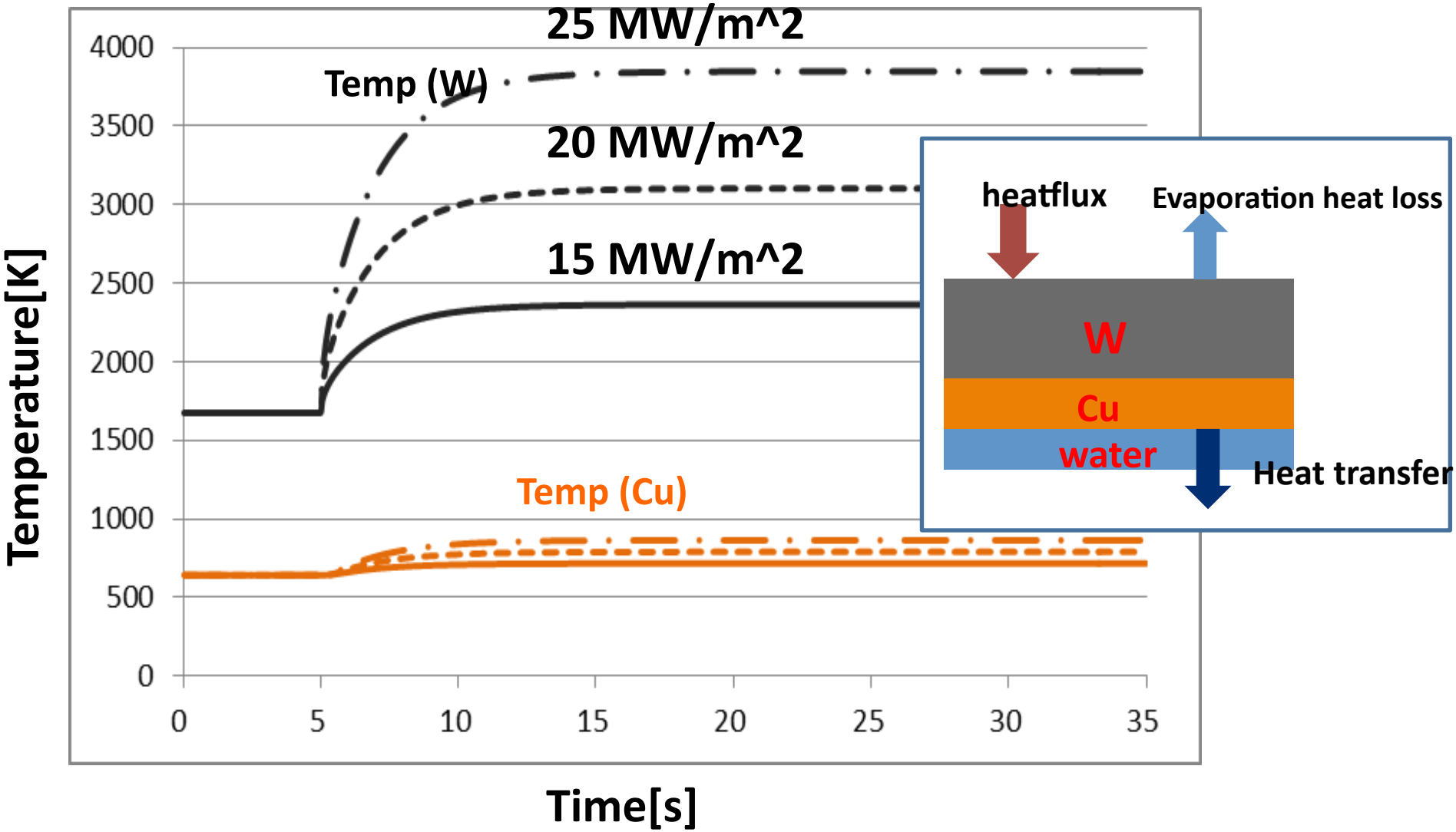
Behavior of Divertor wall (C and W) at LOCA



Behavior of Divertor wall (C and W) at LOCA(2)

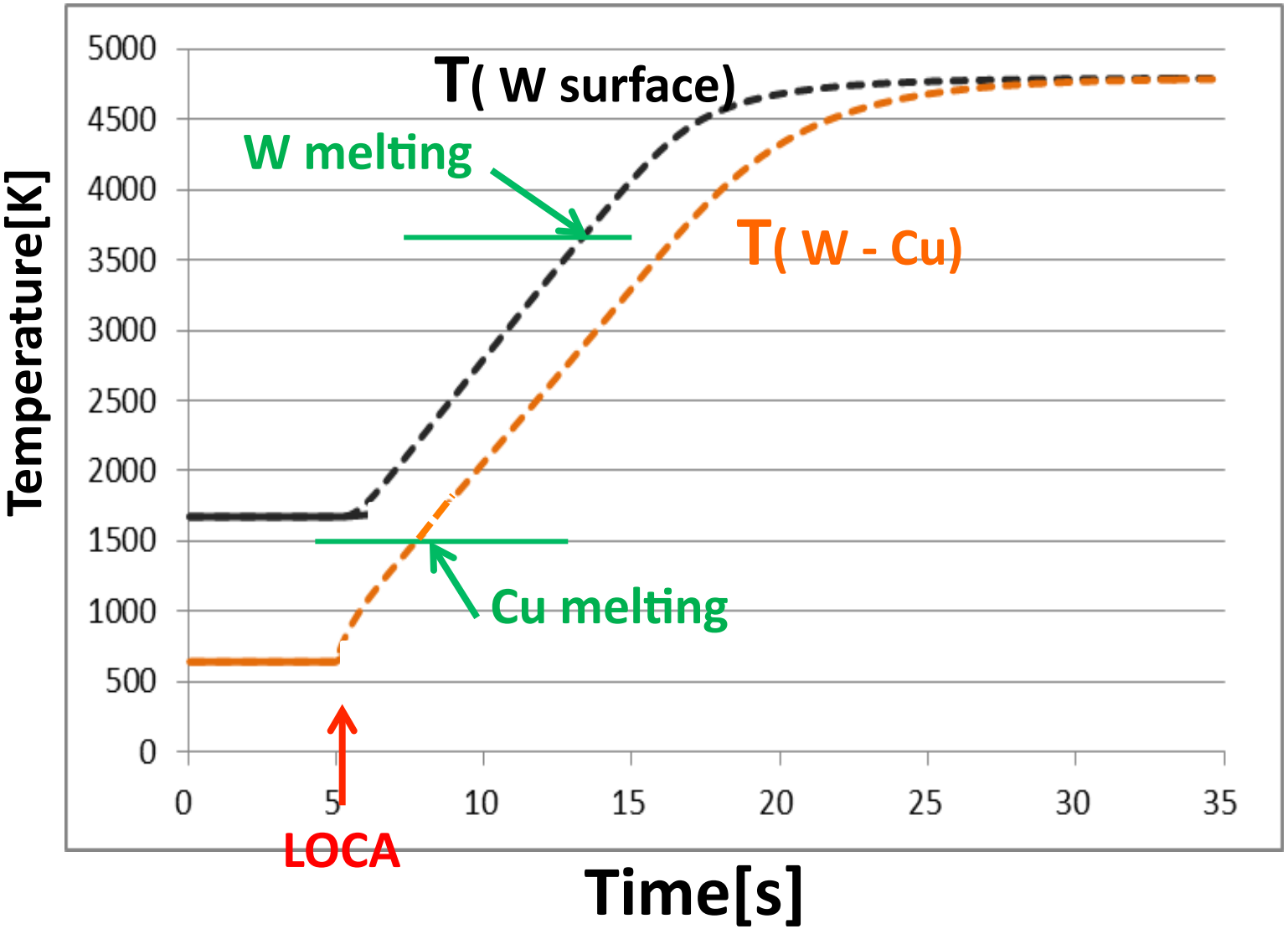


Cooling tube temperature (increase of heat flux)



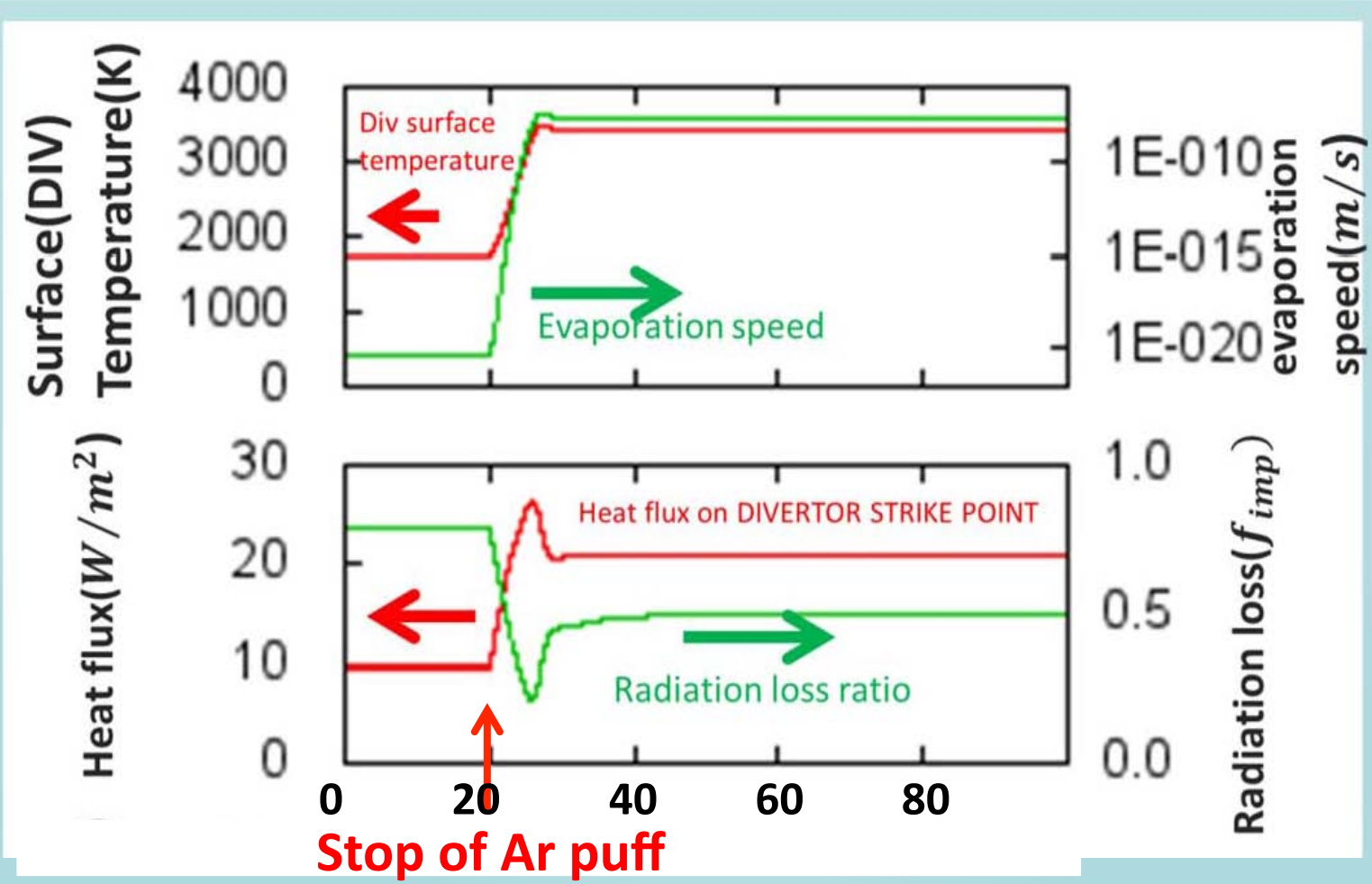
Melting of tungsten surface at > 25 MW/m^2, while copper is sound.

Cooling tube temperature (LOCA)



Cupper coolant tube reached melting point faster than tungsten surface reached melting point.

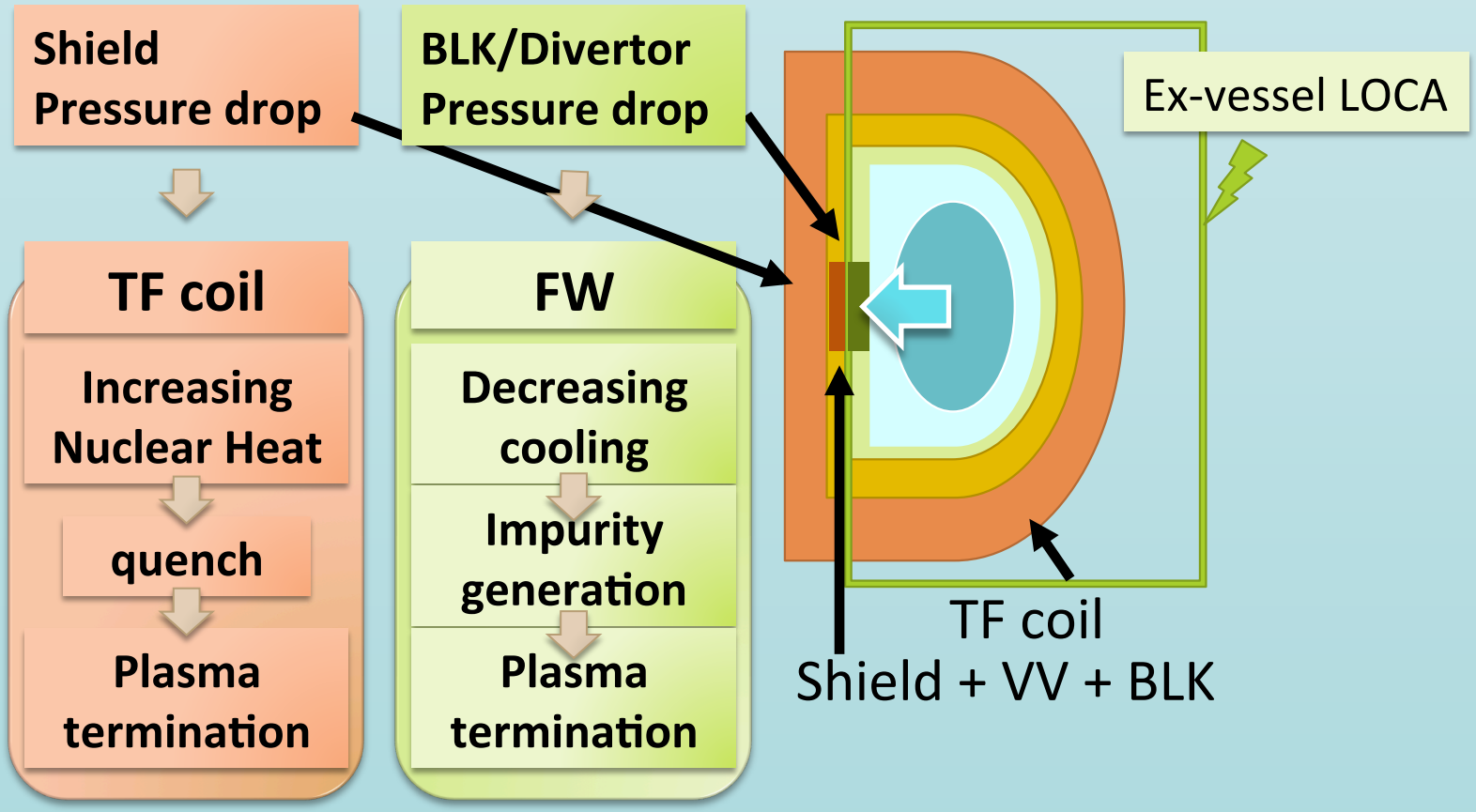
Loss of impurity gas puff at divertor region



Loss of impurity gas puff => Wall temperature increase
=> Radiation by impurity gas => New thermal equilibrium.

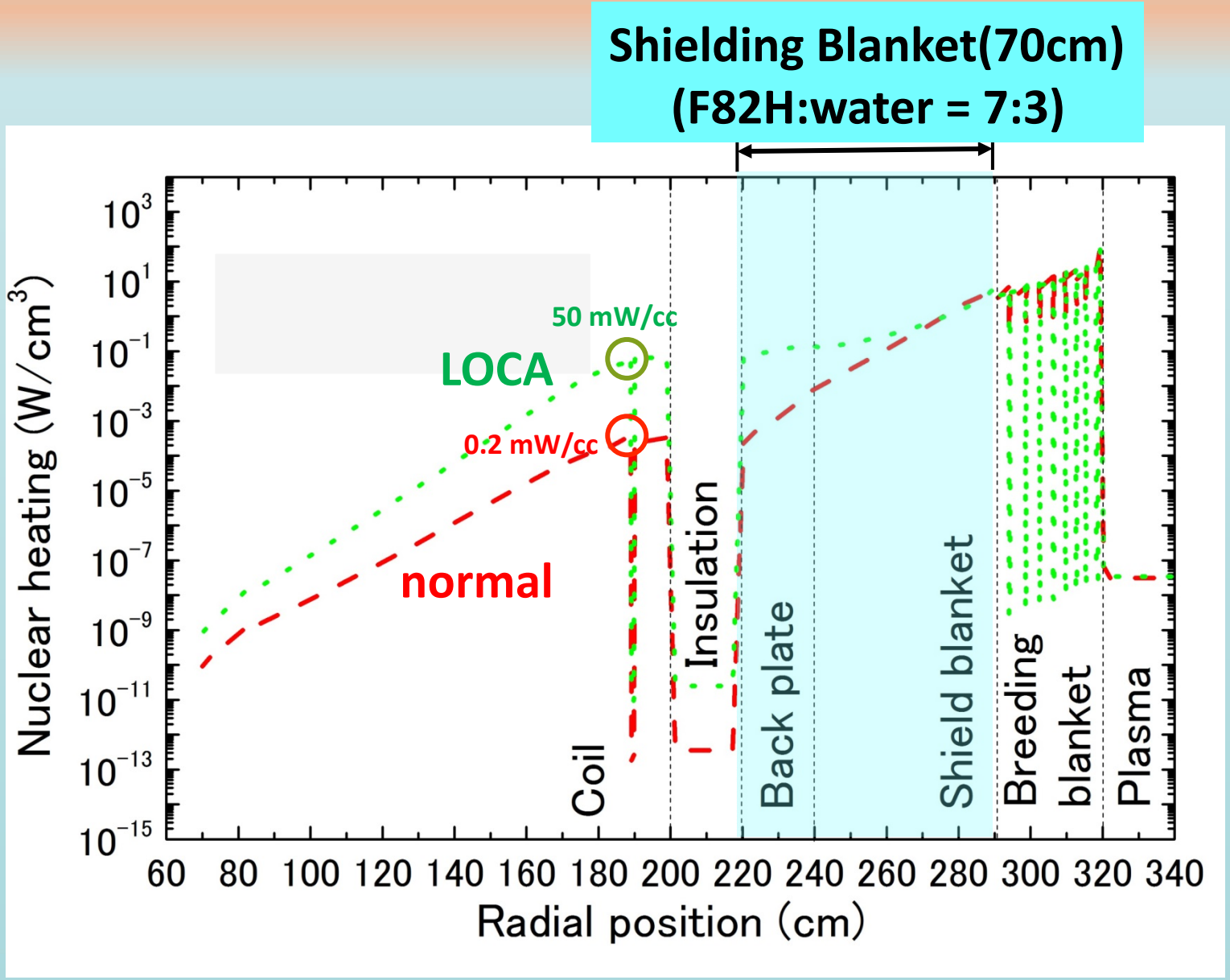
Ex-VV LOCA only at the shielding blanket

What is the difference between LOCA at BLK/DIV and LOCA at Shield?

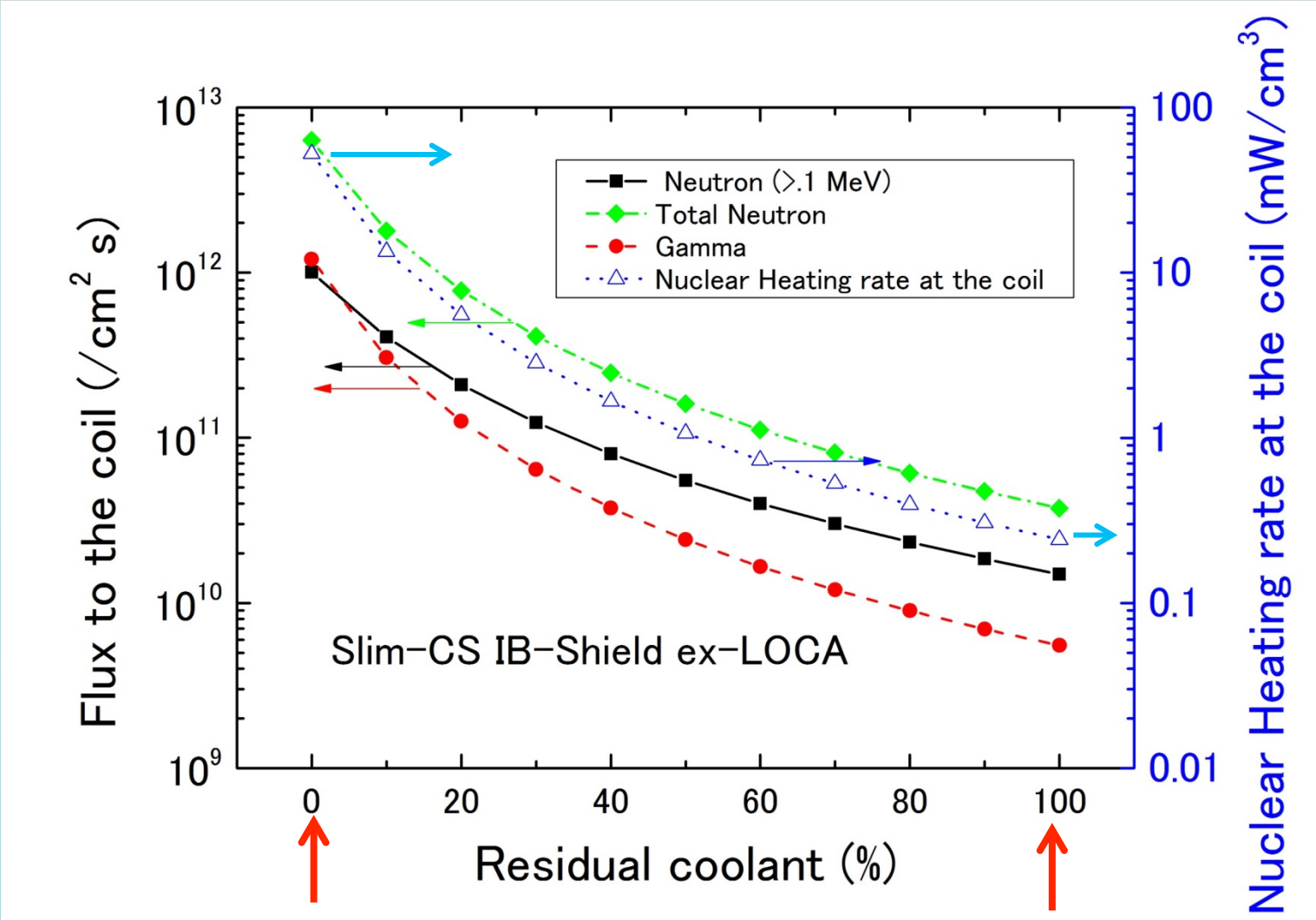


Loss of coolant from shield blanket may trigger the quench at the TF coil. The quench can be a *wide-area* quench not local.

Nuclear heating rate with and without water at the shield blanket of Slim-CS



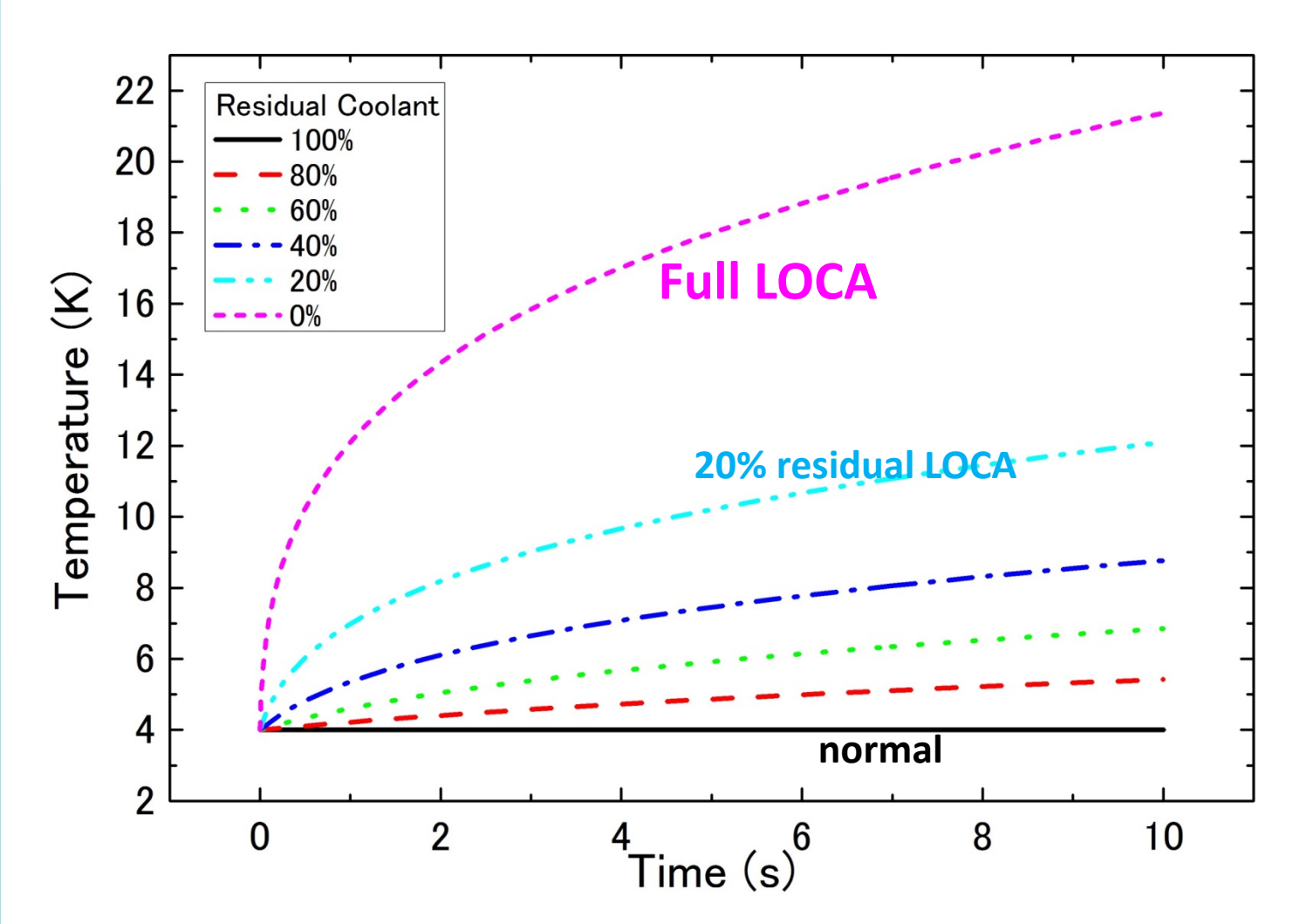
Nuclear heating rate at the TF coil as a function of residual coolant at the shield blanket



LOCA

normal

Temperature change of the TF coil as a function of residual coolant at the shield blanket



Summary

@ A new code system RAILS is under development for the safety analysis related with plasma and PFCs.

@ Safety features have been compared between carbon and tungsten. In the carbon case the sublimation might be dominant, and in the tungsten case the melting might occur.

@ In the LOCA the melting of the cooling pipe might take place within a few seconds, while it takes > 10 seconds for the melting of the tungsten surface.

@ In the case of the LOCA only at the shielding blanket, the remarkable reduction of the neutron shielding performance might raise a problem of the TF coil quench.