# Improvements in heat flux calculations for water-cooled plasma-facing components in W7-X

Progress report

Sebastian Thiede

Max Planck Institute for Plasma Physics

University of Greifswald

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# Motivation - New divertor structure

OP 2.1 divertor overview

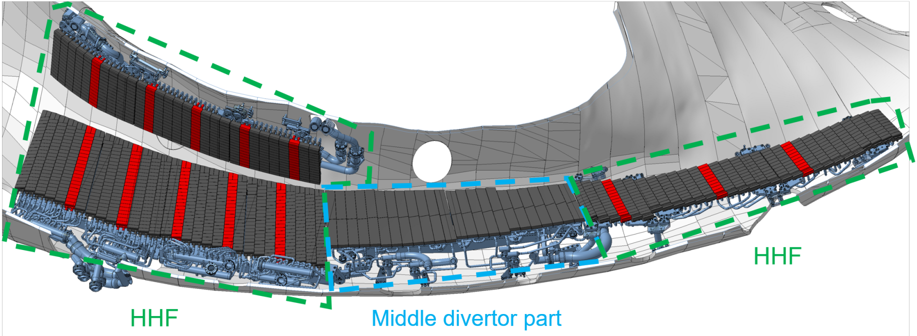



Figure: 3D model of the divertors. For the red regions there are thermocouples measuring the cooling water temperature [1].

# Motivation - New divertor structure

HHF (high heat flux) divertor structure

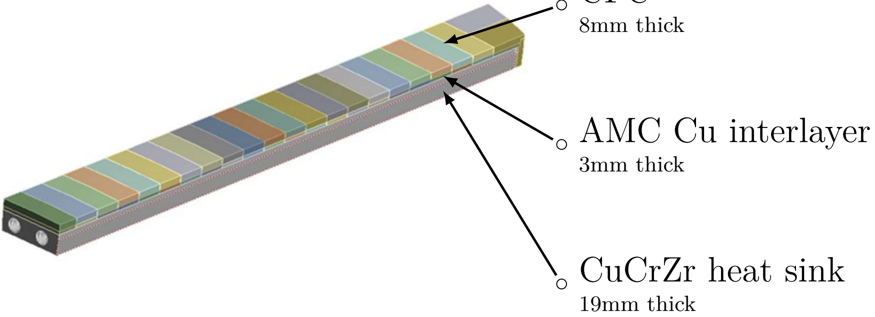



Figure: 3D model of a divertor finger. CFC (Carbon Fiber Composite) is facing the plasma

*AMC = Active Metal Casting, a bonding technique [2]

# Motivation - New divertor structure

middle divertor structure

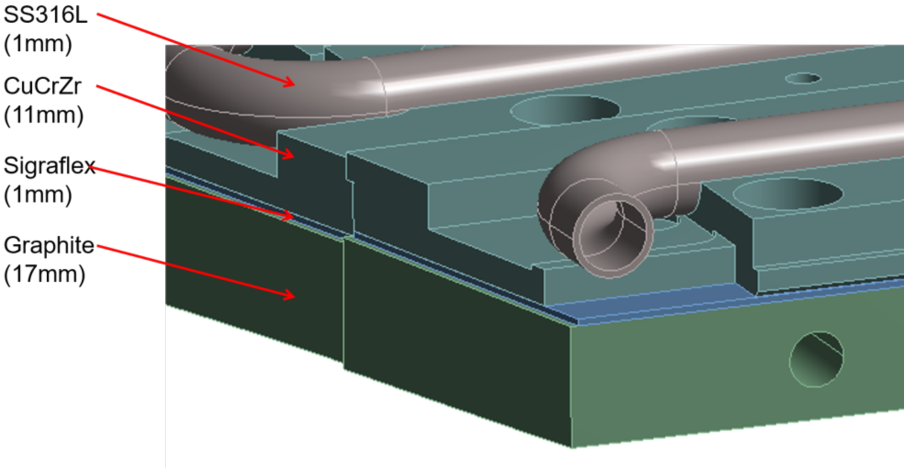


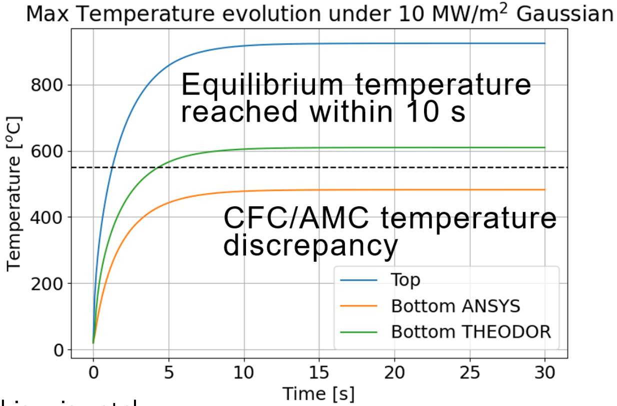

Figure: middle divertor - low heat flux region. (Sigraflex is a carbon based material) [3]

# Motivation - New divertor structure

- OP 2 specification: max. $10\,\mathrm{MW\,m^{-2}}$ on HHF (high heat flux) divertors, max. $1\,\mathrm{MW\,m^{-2}}$ on middle divertors
- measurement of top surface temperature with IR thermography $\Rightarrow$ no issue with plasma facing layers
- material limitations: $T \leq 550\,^{\circ}\mathrm{C}$ for the Cu interlayer, $T \leq 450\,^{\circ}\mathrm{C}$ for the CuCrZr heat sink
  *how to get the maximum temperature in those layers?*
  Thermocouples are very sparsely distributed $\rightarrow$ not enough information.
- accurate knowledge of heat flux from plasma is needed (to know the deposited power, further physics studies)

# Motivation - Simulation with THEODOR

Insufficiencies of THEODOR - comparison with ANSYS simulation [1]




Reasons for this mismatch:

- watercooled divertor layers have different material properties, but THEODOR can only model one
- the bottom heat transfer coefficient was adjusted "by hand" ⇒ doesn't model the actual divertor well

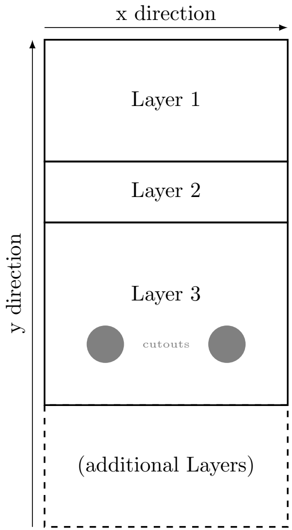
# Motivation - Improvement potential

Possible improvements:

- **multiple layers**
- use the experimental data of thermocouples at the heatsink (model water cooling pipes as boundary conditions)
- THEODOR only allows one predefined expression for the material properties as functions of temperature $\rightarrow$ allow lookup tables and other functions
- better execution times $\rightarrow$ full C++ implementation
- provide documentation on how to use the software and how it works

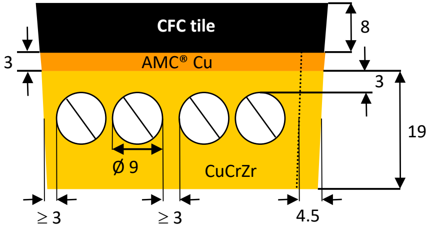
# LayerTHEODOR - 2D divertor model

Defining a goal:




(a) initial model for LayerTHEODOR

$\Longrightarrow$




(b) target geometry (image from divertor specification)

# LayerTHEODOR - Heat diffusion equation

Heat diffusion equation for temperature dependent material properties:

$$c_p(T)\,\rho(T)\,\frac{\partial T}{\partial t} = \vec{\nabla}\cdot(\underbrace{\boldsymbol{\kappa}(T)\,\vec{\nabla}T}_{=\vec{\phi}}) + \dot{q} \tag{1}$$

where

- $T$ ... temperature
- $c_p(T)$ ... specific heat capacity
- $\rho(T)$ ... mass density
- $\boldsymbol{\kappa}(T)$ ... (anisotropic) heat conductivity
- $\vec{\phi}$ ... heat flux
- $\dot{q}$ ... additional volumetric energy sources

here, $\boldsymbol{\kappa}$ can only be of the form (2D !):

$$\boldsymbol{\kappa}(T) = \begin{pmatrix} \kappa_x(T) & 0 \\ 0 & \kappa_y(T) \end{pmatrix} \tag{2}$$

$\longrightarrow$ no hope for analytical solution

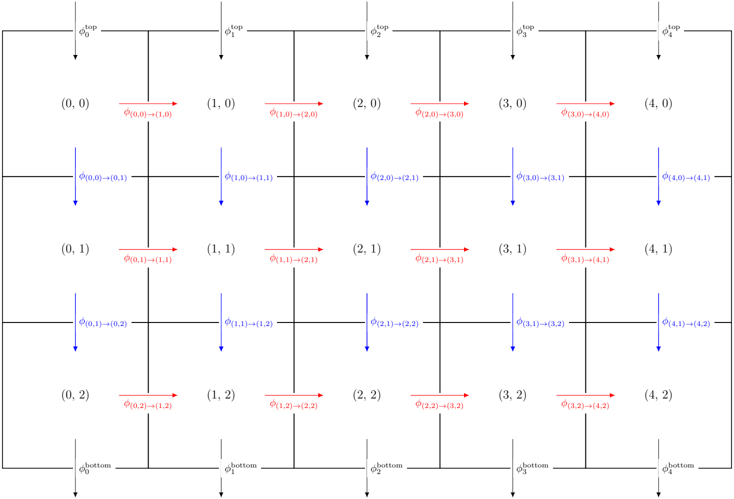
# LayerTHEODOR - Heat diffusion equation

numerical solution required $\Rightarrow$ (e.g.) finite difference method (FDM) meaning:

$$
\begin{aligned}
x = i \cdot \triangle x \text{ for } i \in \{0, ..., N_x\} \subseteq \mathbb{N} \\
y = j \cdot \triangle y \text{ for } j \in \{0, ..., N_y\} \subseteq \mathbb{N} \\
t = n \cdot \triangle t \text{ for } n \in \{0, ..., N_t\} \subseteq \mathbb{N} \\
T(x, y, t) &\Rightarrow T_{i,j}^{n} \\
\frac{\partial T(x, y, t)}{\partial x} &\Rightarrow \frac{T_{i+1,j}^{n} - T_{i,j}^{n}}{\triangle x} \text{ (analogous for y)} \\
\frac{\partial T(x, y, t)}{\partial t} &\Rightarrow \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\triangle t}
\end{aligned} \tag{3}
$$

# LayerTHEODOR - Heat diffusion equation

LayerTHEODOR approach: heat flux matricies **per layer** of the divertor




$$\phi_{(i,j)\to(k,l)} = -\phi_{(k,l)\to(i,j)}$$

# LayerTHEODOR - Heat diffusion equation

heat flux:

$$\phi^n_{(i,j)\to(k,l)} = \kappa_{x/y}\left(\frac{T^n_{i,j}+T^n_{k,l}}{2}\right)\cdot \underbrace{\frac{T^n_{i,j}-T^n_{k,l}}{\triangle x/\triangle y}}_{\text{discrete T derivative}} \tag{4}$$

(discretized Fourier's law, $(k = i \pm 1)\dot{\vee}(l = j \pm 1)$, $x$ or $y$ chosen accordingly)
used in heat flux equation:

$$\begin{aligned} c_p(T^n_{i,j})\rho(T^n_{i,j})\frac{\color{red}{T^{n+1}_{i,j}} - T^n_{i,j}}{\triangle t} =& \frac{\phi^n_{(i-1,j)\to(i,j)} - \phi^n_{(i,j)\to(i+1,j)}}{\triangle x} \\ &+ \frac{\phi^n_{(i,j-1)\to(i,j)} - \phi^n_{(i,j)\to(i,j+1)}}{\triangle y} + \dot{q} \end{aligned} \tag{5}$$

# LayerTHEODOR - Heat diffusion equation

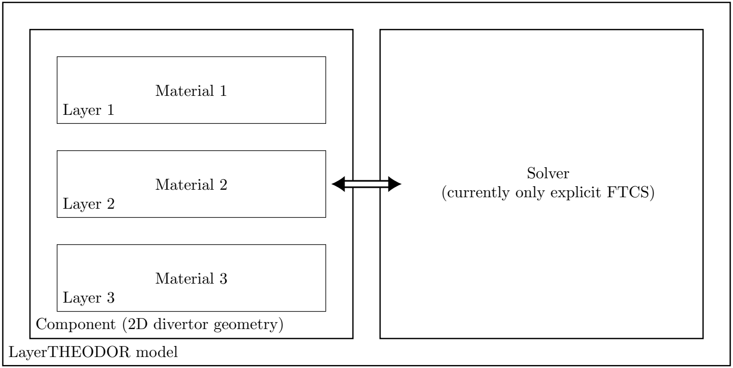
- FDM are not unconditionally stable
- important quantity: thermal diffusivity $D_{x/y} = \frac{\kappa_{x/y}}{\rho c_p}$
- Stability criterion:

$$\frac{\max\left(D_x, D_y\right) \cdot \triangle t}{\min\left(\triangle x^2, \triangle y^2\right)} \leq \frac{1}{2} \tag{6}$$

- choosing smaller timestep might require finer spatial resolution and vice-versa

# LayerTHEODOR - Code structure

Model framework:

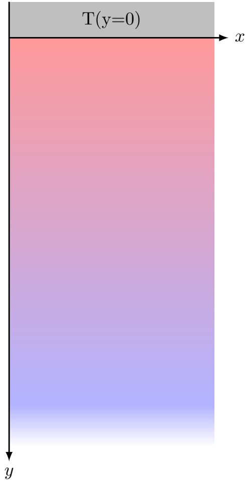



Used external C++ libraries:

(a) Eigen [4] for parallelized matrix operations

(b) pybind11 [5] to create a Python interface

# Preliminary results - 1D semi-infinite solid model




- $\phi^{\text{top}} = \text{const.}$
- solve heat diffusion equation on $y \geq 0$

$$c_p \rho \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial y^2}$$

for $\kappa, \rho, c_p$ constant and isotropic, $T(y, t = 0) = T_0$

- Solution:

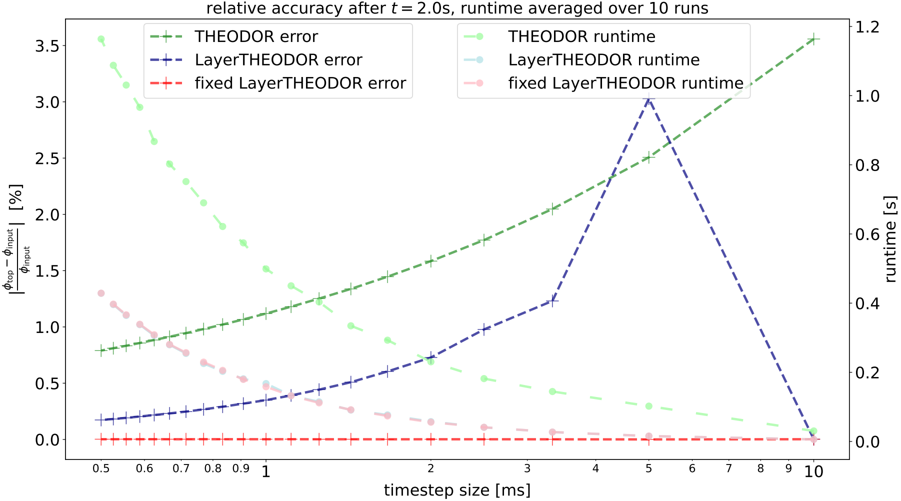
$$T(y \geq 0, t) = T_0 + 2\,\phi^{\text{top}} \sqrt{\frac{t}{\pi \kappa \rho c_p}} \exp\left(\frac{-y^2 \rho c_p}{4 \kappa t}\right) - \frac{\phi^{\text{top}}}{\kappa} \operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\rho c_p}{\kappa t}}\right)$$

- input for THEODOR and LayerTHEODOR:

$$T(y = 0, t) = T_0 + 2\,\phi^{\text{top}} \sqrt{\frac{t}{\pi \kappa \rho c_p}}$$

# Preliminary results - 1D semi-infinite solid model

## Comparison THEODOR and LayerTHEODOR input data each 10 ms



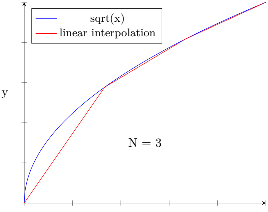
# Preliminary results - 1D semi-infinite solid model

THEODOR and LayerTHEODOR have vastly different accuracy and runtime
→ we don't know yet why THEODOR is less accurate. Possible reasons:

- artifact of interpolating the inputted temperature data (figure below)
- THEODOR uses the so-called heat flux potential, while LayerTHEODOR operates on temperatures directly (different discretized equations)
- fixing error in how output flux is calculated removes most of the error for LayerTHEODOR (red line, averaging over the "microsteps" between new data input instead of just outputting the last)

In any case choosing smaller timesteps decreases error.
Why is it also faster? (for small timesteps $\sim$ 2.8 times)

- internally 100% C++ code, less passing data Python ↔ C(++)
- "Eigen" library parallelization → speed improvement is heavily dependent on architecture



# Summary

- THEODOR was improved to handle multiple layers of the divertor
- the accuracy and runtime was also improved
- first tests suggest that it works correctly for simple materials

next steps:

- find out why it is more accurate than THEODOR
- check if anisotropic materials are handeled correctly
- test with ANSYS (heat flux $\rightarrow$ temperature) simulation
- check against experimental data

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