Advanced divertor heat flux analysis for alternative divertor concepts and non-trivial tile geometries with the updated open source code THEODOR

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ABSTRACT

THEODOR (Thermal Energy Onto DivertOR) solver for the non-linear heat diffusion equation for physics analysis. [1]

Heat load density distributions on divertor tile is linked to

- deposition from electrons, ions, neutrals, radiation (more general than Langmuir probes)
- Scrape-off layer (SOL) physics like λ_q
- Intermittency (e.g. ELMs 1 Hz to 1 kHz, 0.5 ms duration)
- Machine safety (melting, recrystallization, fatigue)

MOST ESSENTIAL UPDATES

- Implicit Solver – unconditionally stable, less “lag" (3)
- 1D, 2D, and 3D Geometries
- Irregular grid spacing (FD → orthogonal grid).
- Adjustable material parameters for different section
  - Model voids in tile
  - Model different materials and their interfaces
- Git repository with testing and versioning
- Ongoing work to make THEODOR open source!

CONCLUSION

- After 30 years there is still a need for THEODOR.
- Updates make its use easier and more general.
- Higher accuracy and reliability through implicit solver.
- Less constrains from geometry and material composition.
- 3D solver allows evaluation of toroidal asymmetries
- Versioning for comparability

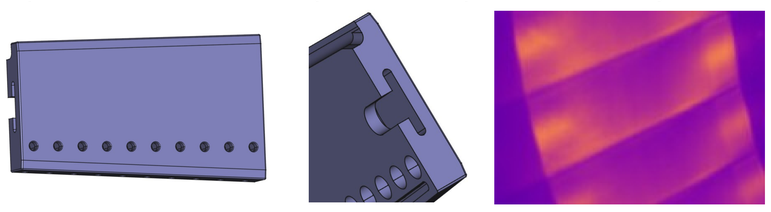
1) AUG INFRARED DIAGNOSTIC

IR camera sensitive at (4 to 5) µm

Adaptive Integration time from (2 to 200) µs

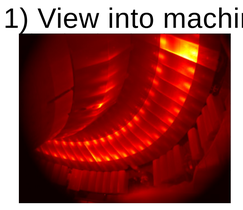
Frame-rate up to 3 kHz or 300 Hz full-frame

Up to 15 bit resolution (25 mK temperature noise)

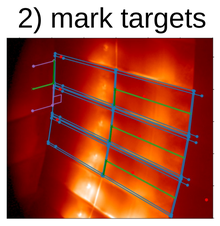


Workflow

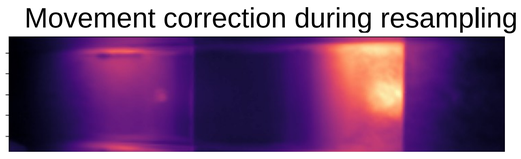
1) View into machine



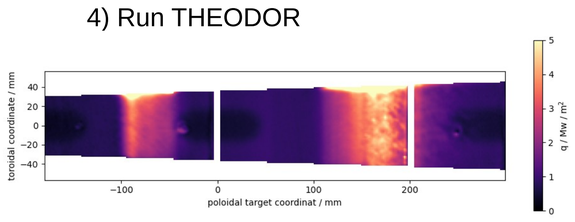
2) mark targets



3) Extract view on target.
Movement correction during resampling



4) Run THEODOR

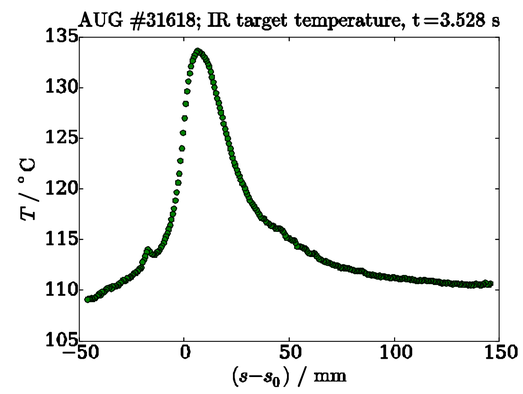


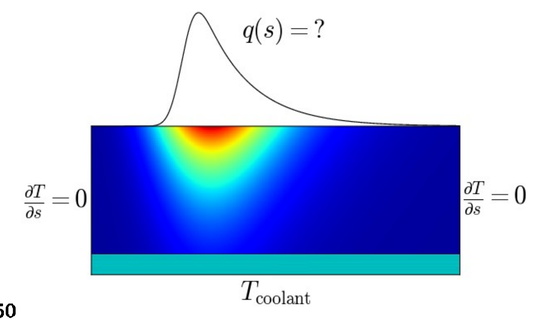
5) post-processing as needed

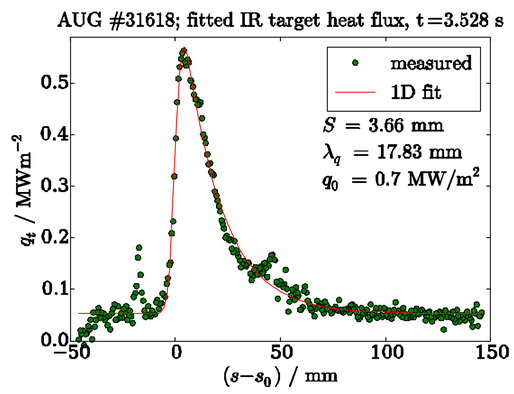
- toroidal averaging on tile coordinates (x,y,z)
- quantify toroidal variation (std, skewness, ...)
- map from tile to machine coordinates (R,z,ϕ)
- evaluate in-tile-temperatures see (6)

2) THEODOR BASICS

Use surface temperature as boundary condition when solving the Heat Diffusion Equation (HDE) to determine the heat flux onto the surface. Keep track of temperature distribution inside the tile: 1D Surface information → 2D System







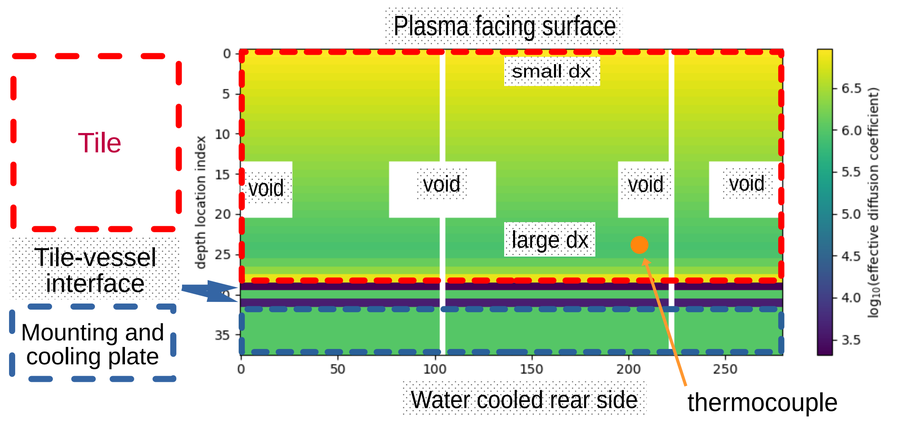
4) TILE GEOMETRY & MATERIALS

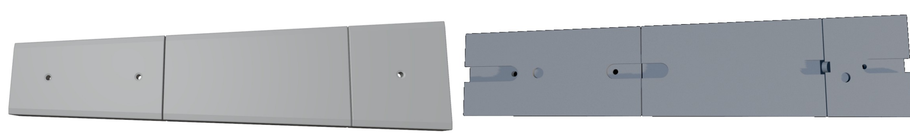
3D Extension & Material parameter variation

- Less restrains on tile geometry.
- Less assumptions on toroidal symmetry.
- Better SNR by toroidal averaging (mean and std).

Tiles are not always toroidally symmetric & not homogeneous (on long time scales) and larger structures use material combinations:

- Local scaling of conductivity/diffusivity/heat capacity
- Including zero conductivity ↔ voids
- Approximate differing wall material (e.g. W → Steel)
- New approach to surface layers (not shown)

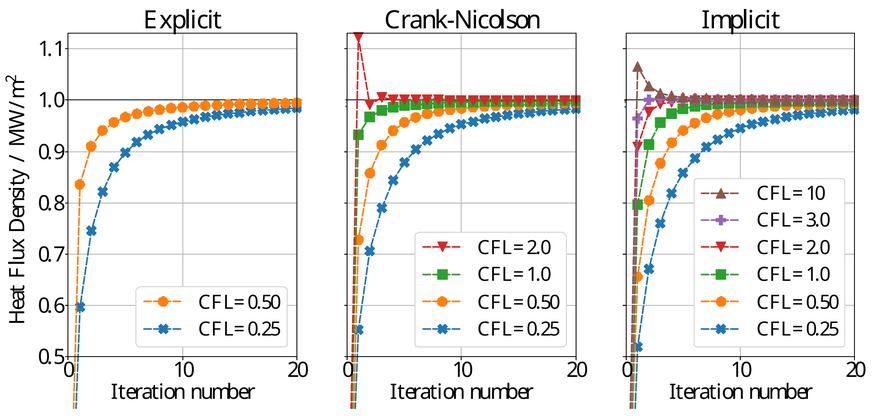




3) IMPLICIT SOLVER

Higher depths resolution → better heat load resolution

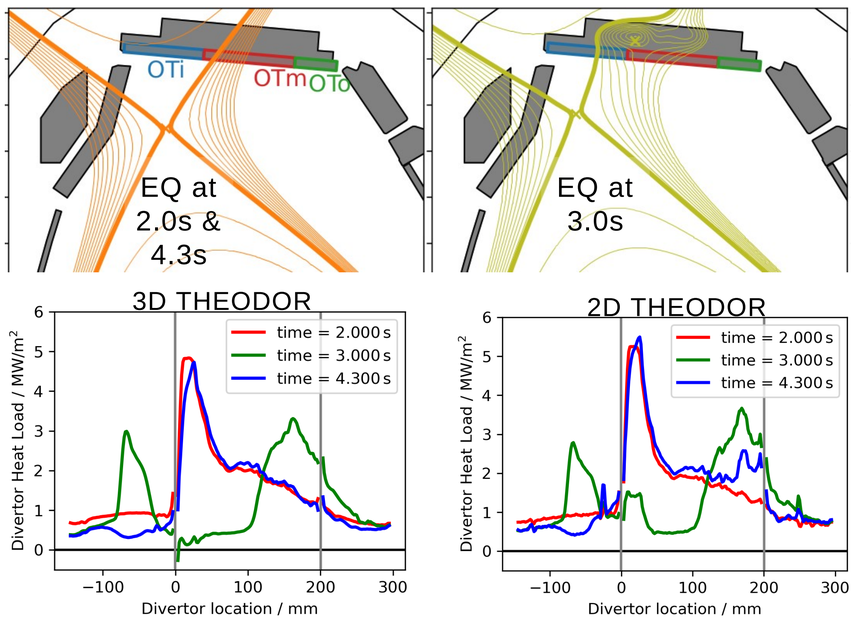
- Explicit solver limited in resolution → limited gradient
- Implicit: no time step limit, but still only first order
- Crank-Nicolson second order, but: introduces spurious ringing through changing boundary condition



$$q = -\kappa \nabla T \approx \kappa \frac{T_1 - T_2}{\Delta x}$$

5) ADCs [2]

Changing magnetic configuration changes strike line position → time dependent bias easy to spot



6) CALORIMETRY [3]

Compare tile temperatures as estimated by THEODOR with Thermocouple (TC) measurements.

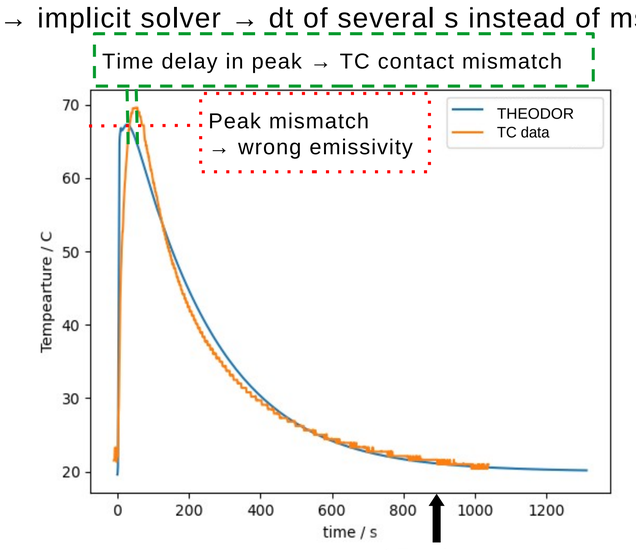
→ Reduced uncertainty in surface emissivity

→ Ensure volume radiation is not introducing issues

→ Validate toroidal symmetry / estimate asymmetry

→ Validate thermal model of tile-wall coupling

→ implicit solver → dt of several s instead of ms



[1] D. Nille et al. “Probabilistic Inference of Surface Heat Flux Densities from Infrared Thermography”. Bayesian Inference and Maximum Entropy Methods in Science and Engineering.

[2] A. Herrmann et al. “A new upper divertor with internal coils for ASDEX upgrade – Status of the project”. In: Fusion Engineering and Design 146 (2019)

[3] A Redl et al. “The global energy balance of the ASDEX Upgrade tokamak determined with the revised cooling water calorimetry”. Plasma Physics and Controlled Fusion 65.11 (2023)

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