Verification of Ants time-dependent nodal neutronics model

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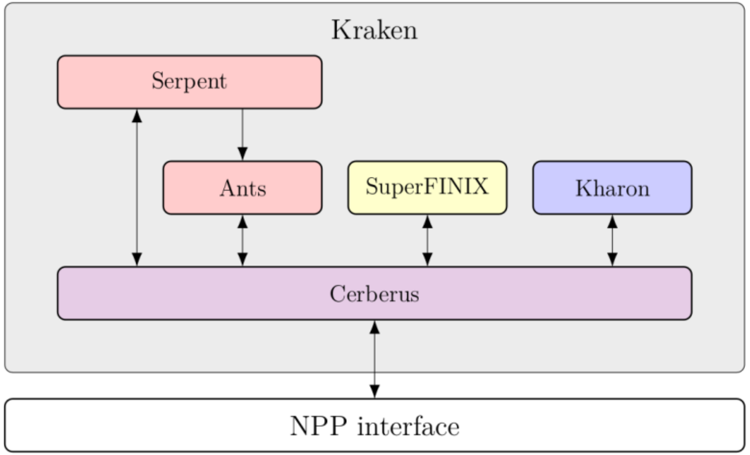
Outline

- Background
- Benchmark descriptions and results
- Conclusions

Background

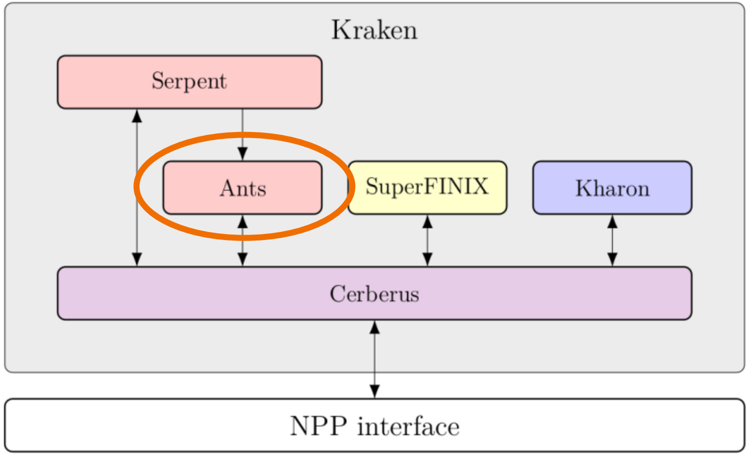
VTT is developing a new framework for reactor modeling

- Kraken is a new computational framework for coupled calculations
  - Consists of modular solvers of neutronics, fuel behaviour and thermal hydraulics
  - Data transfer between the solvers is committed with a multiphysics driver
- Current work includes coupled calculations with Kraken and system level codes, e.g. TRACE



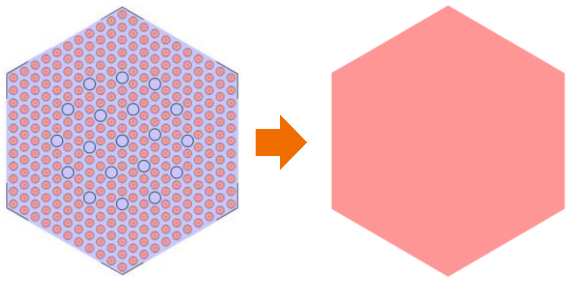
Ants – nodal neutronics solver

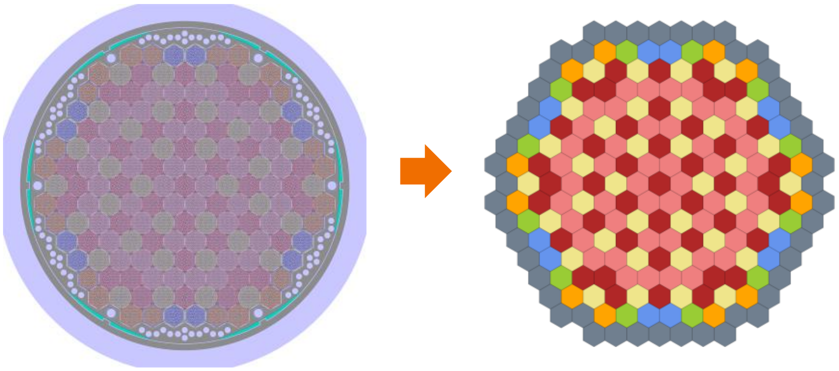
- Developed at VTT since 2017
- Object: Reduced-order core-level routine calculations with low computational cost
- Steady-state calculations have been verified for
  - Different geometries (rectangular, hexagonal and triangular)
  - Different energy group structures (two-group and multi-group)
- Time-dependent model still required verification



Nodal neutronics

- High-fidelity heterogeneous methods are not feasible for routine calculations → reduced-order methods
- Nodal methods are based on averaging fuel assemblies to homogeneous blocks, nodes
- The neutron flux is solved separately within each node and the node-wise flux solutions are coupled together with boundary conditions





Neutron diffusion equation

- The behaviour of neutrons in a reactor core is often characterized with the time-dependent neutron diffusion equation:

$$\frac{1}{v_g(\mathbf{r})}\frac{\partial \phi_g(\mathbf{r},t)}{\partial t} = \nabla \cdot D_g(\mathbf{r})\nabla\phi_g(\mathbf{r},t) - \Sigma_{\mathrm{r},g}(\mathbf{r})\phi_g(\mathbf{r},t)$$

$$+ \sum_{g'=1}^{G} \Sigma_{g'\to g}(\mathbf{r})\phi_{g'}(\mathbf{r},t) + \chi_{\mathrm{d},g}(\mathbf{r}) \sum_{k=1}^{m} \lambda_k(\mathbf{r})C_k(\mathbf{r},t)$$

$$+ \big(1-\beta(\mathbf{r})\big)\chi_{\mathrm{p},g}(\mathbf{r}) \sum_{g'=1}^{G} \nu\Sigma_{\mathrm{f},g'}(\mathbf{r})\phi_{g'}(\mathbf{r},t),$$

$$\frac{\partial C_k(\mathbf{r},t)}{\partial t} = \beta_k(\mathbf{r}) \sum_{g'=1}^{G} \nu\Sigma_{\mathrm{f},g'}(\mathbf{r})\phi_{g'}(\mathbf{r},t) - \lambda_k(\mathbf{r})C_k(\mathbf{r},t), \;\; k = 1,2,\ldots,m,$$

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Time rate of change in neutron density

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Neutron leakage

Neutron diffusion equation

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$$
\begin{aligned}
\frac{1}{v_g(\mathbf{r})}\frac{\partial \phi_g(\mathbf{r},t)}{\partial t} = {} & \nabla \cdot D_g(\mathbf{r})\nabla\phi_g(\mathbf{r},t) - \Sigma_{\mathrm{r},g}(\mathbf{r})\phi_g(\mathbf{r},t) \\
& + \sum_{g'=1}^{G} \Sigma_{g'\to g}(\mathbf{r})\phi_{g'}(\mathbf{r},t) + \chi_{\mathrm{d},g}(\mathbf{r}) \sum_{k=1}^{m} \lambda_k(\mathbf{r})C_k(\mathbf{r},t) \\
& + \big(1-\beta(\mathbf{r})\big)\chi_{\mathrm{p},g}(\mathbf{r}) \sum_{g'=1}^{G} \nu\Sigma_{\mathrm{f},g'}(\mathbf{r})\phi_{g'}(\mathbf{r},t),
\end{aligned}
$$

$$
\frac{\partial C_k(\mathbf{r},t)}{\partial t} = \beta_k(\mathbf{r}) \sum_{g'=1}^{G} \nu\Sigma_{\mathrm{f},g'}(\mathbf{r})\phi_{g'}(\mathbf{r},t) - \lambda_k(\mathbf{r})C_k(\mathbf{r},t), \;\; k = 1, 2, \ldots, m,
$$

Removal of neutrons due to nuclear reactions

Neutron diffusion equation

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New neutrons via scattering

Neutron diffusion equation

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Delayed neutrons born from precursor decay

Neutron diffusion equation

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Prompt neutrons from fission

Neutron diffusion equation

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Delayed neutron precursor concentration time rate of change

Neutron diffusion equation

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New delayed neutron precursors from fission

Neutron diffusion equation

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Decay of precursors

Neutron diffusion equation

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- Ants uses AFEN and FENM methods to solve the time-dependent diffusion equation in each node separately

Benchmark descriptions and results

VTT

All verification cases in a nutshell

1. One-point kinetics problem:
   - One-point one-group core with no delayed neutrons with a step absorption cross section change.
   - Analytical solution available for time-integration method verification
2. TWIGL problem:
   - 2D core with a ramp and a step change of absorption cross section.
3. LMW problem:
   - 3D simplified PWR core with moderate control rod movements.
4. AER-DYN-001 problem:
   - Rod ejection transient with SCRAM in a VVER-440 hexagonal core.
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   - Rod drop transient in a BWR core with a simple Doppler feedback mechanism.

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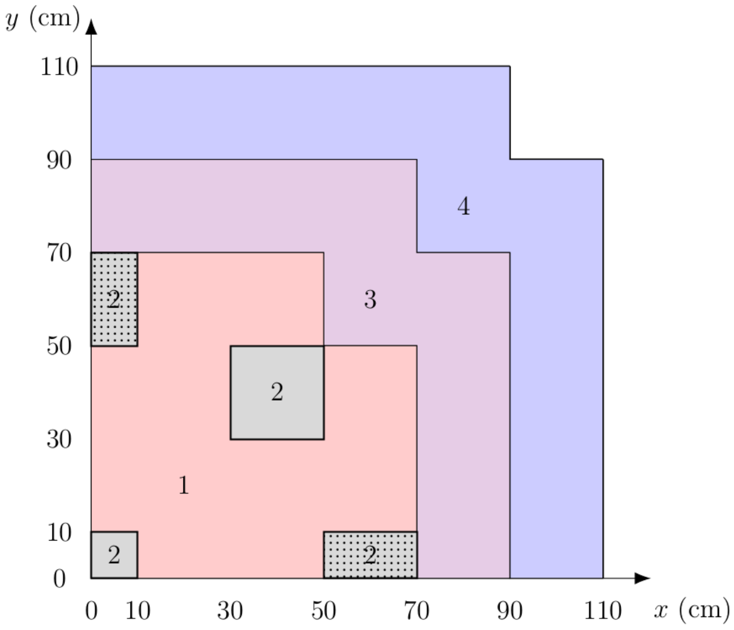
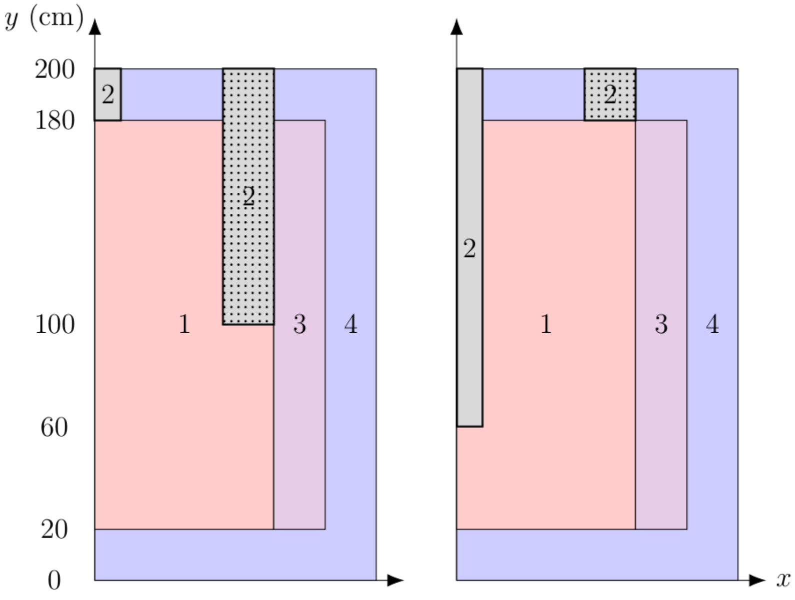
The LMW problem geometry

Fuel materials 1 and 3
Control rod material 2
Reflector material 4



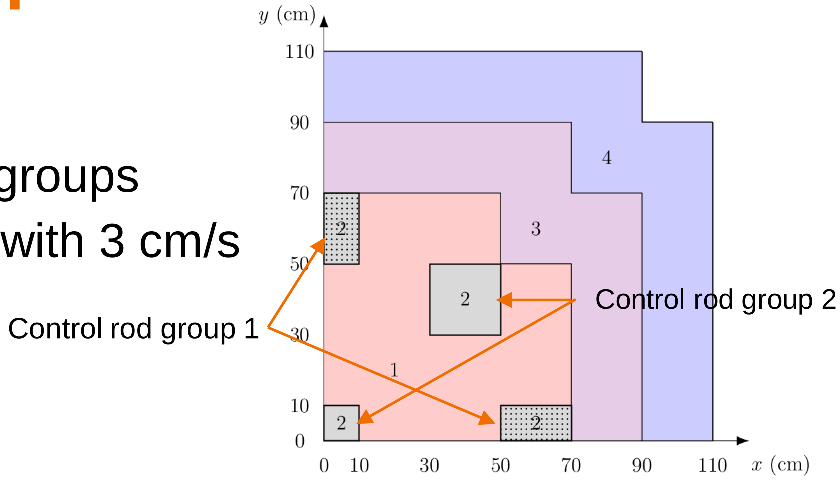
Radial geometry of the quarter-core model



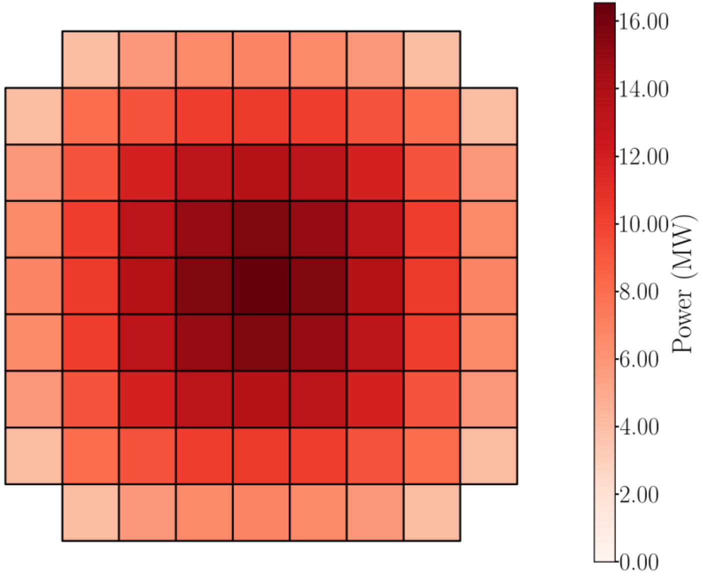
Axial geometry of the quarter-core model in the initial state (left) and final state (right)

The LMW transient problem

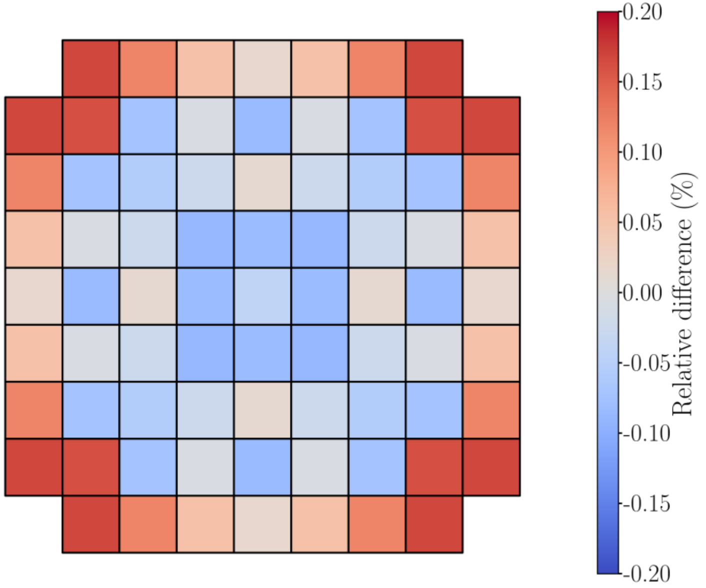
- Includes movements of two control rod groups
- At 0 s, control rod group 1 is withdrawn with 3 cm/s velocity
- At 7.5 s, control rod group 2 is inserted at 3 cm/s velocity and stopped at 60 cm elevation from the bottom of the core



The LMW initial power distribution

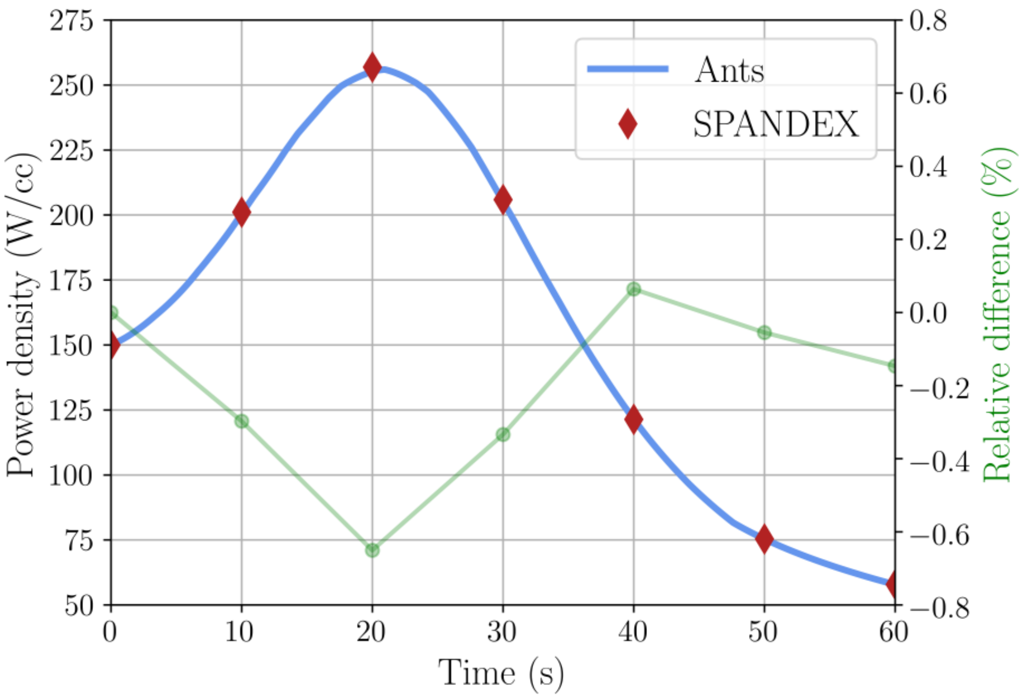


Ants power distribution

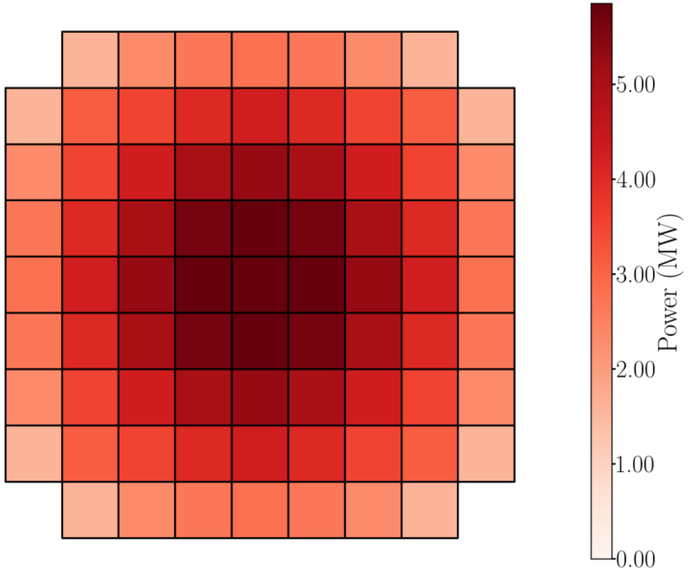


Relative difference between Ants and MGRAC

The LMW transient results



The LMW final power distribution



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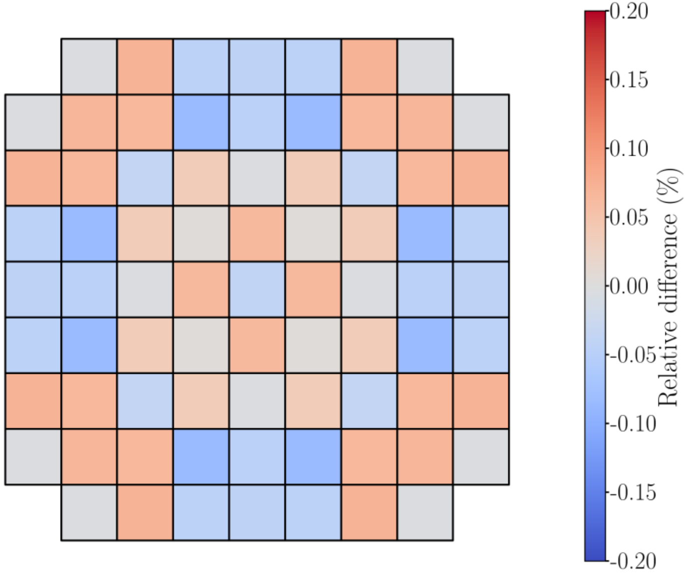

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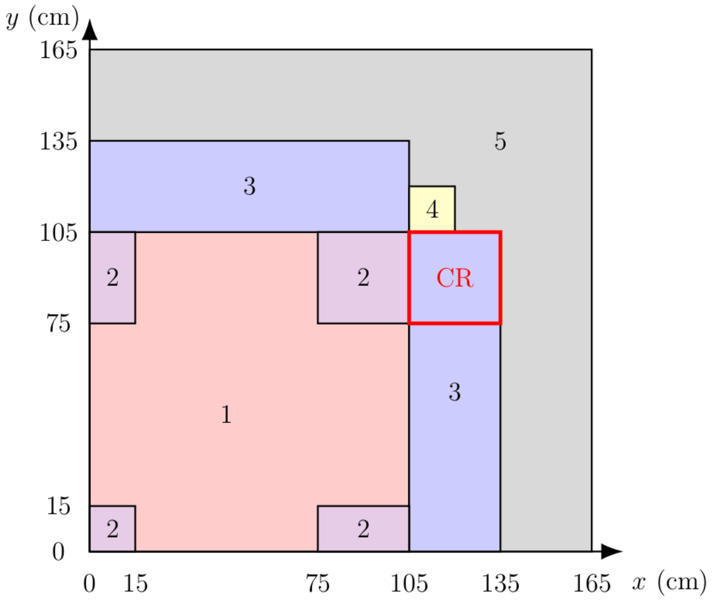
The LRA BWR rod-drop problem

Fuel materials 1, 2 and 4
Control rod material 3
Reflector material 5



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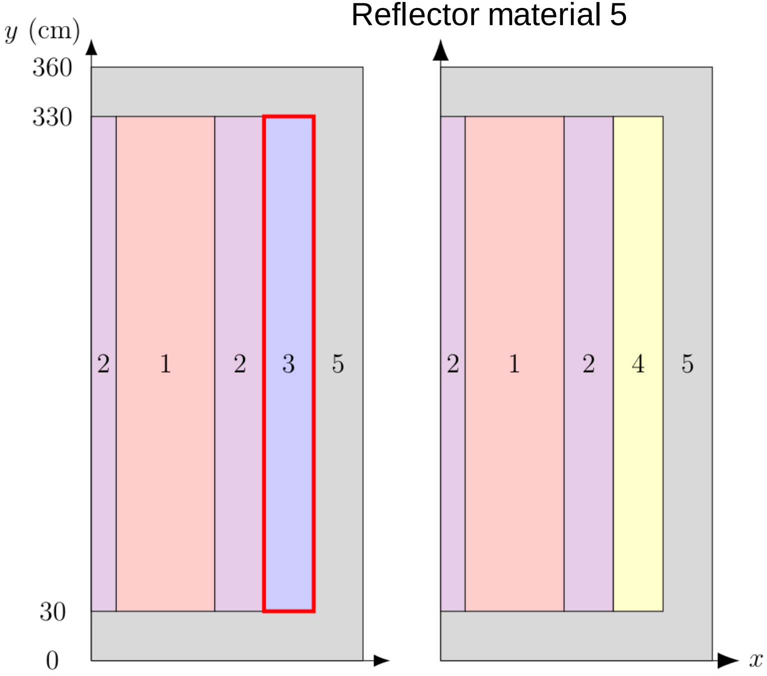
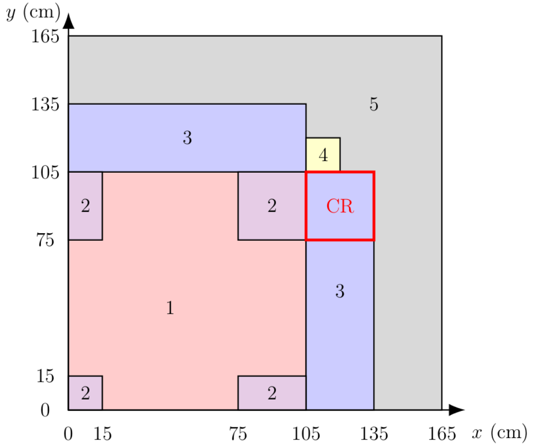


Axial geometry of the quarter-core model in the initial state (left) and final state (right)

The LRA BWR rod-drop problem

- Rod indicated by CR drops with 150 cm/s velocity
- Fuel temperature obeys equation

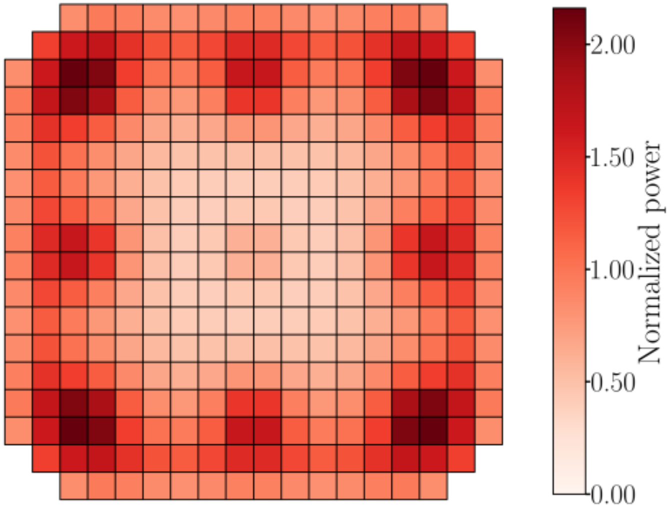
$$\frac{\partial T_\mathrm{f}^k(t)}{\partial t} = \alpha \sum_{g=1}^{2} \Sigma_{\mathrm{f},g}^k \phi_g^k(\mathbf{r}, t)$$



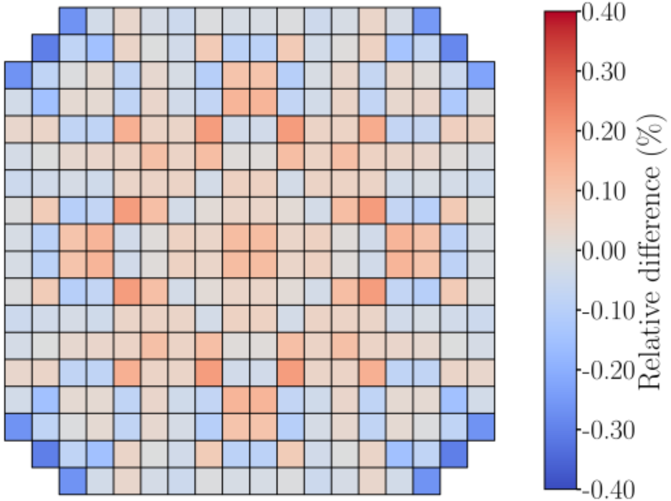
- Doppler feedback effect based on fuel temperature changes is given as

$$\Sigma_{\mathrm{a},1}^k(t) = \Sigma_{\mathrm{a},1}^{k,0}\left[1 + \gamma_\mathrm{d}\left(\sqrt{T_\mathrm{f}^k(t)} - \sqrt{T_\mathrm{f}^0}\right)\right]$$

The LRA problem – initial power distribution

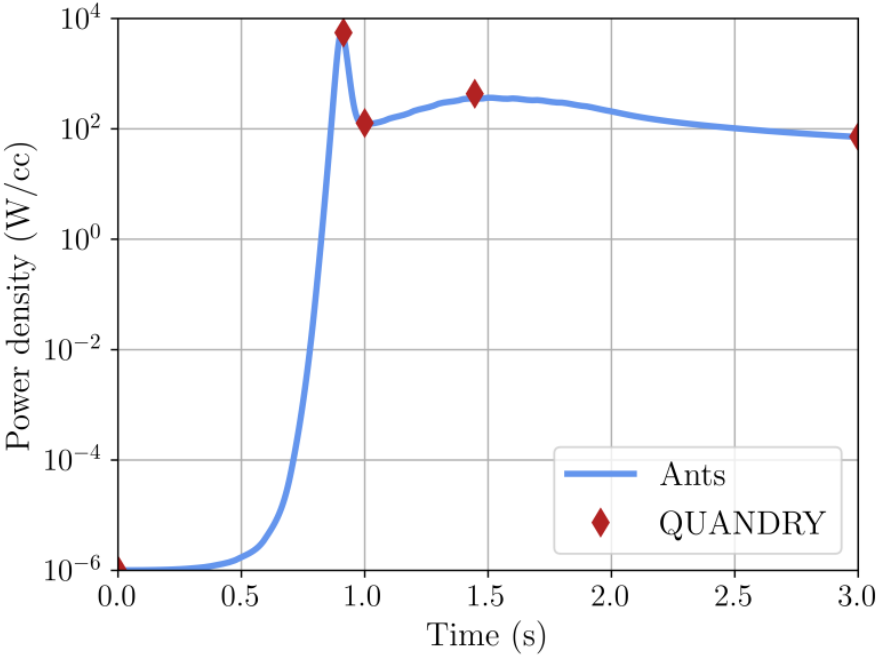


Ants power distribution

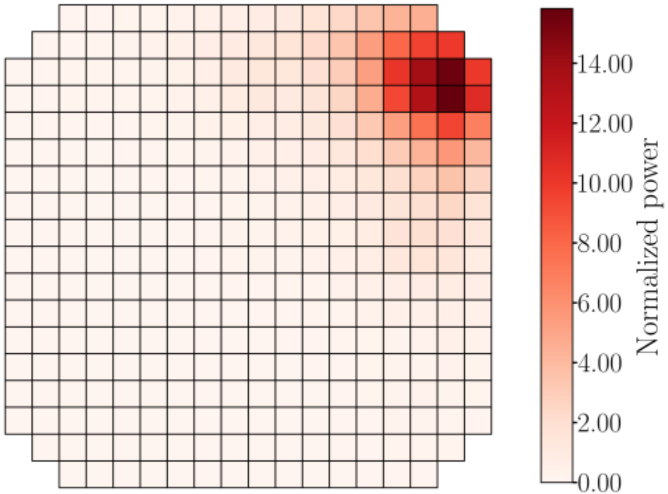


Relative difference between Ants and QUANDRY

The LRA problem – transient



The LRA problem – final power distribution



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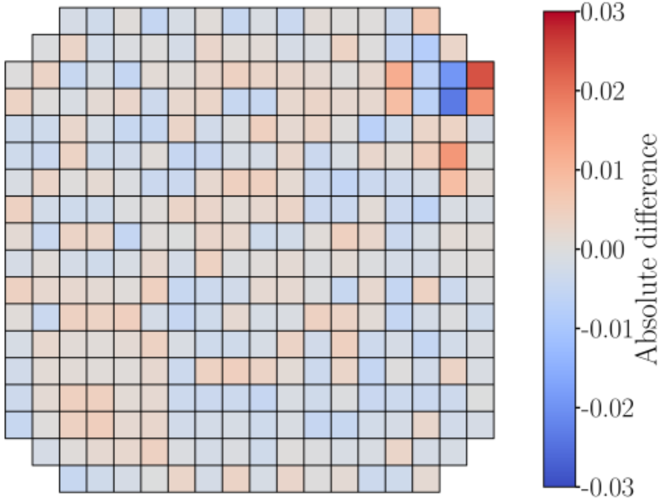
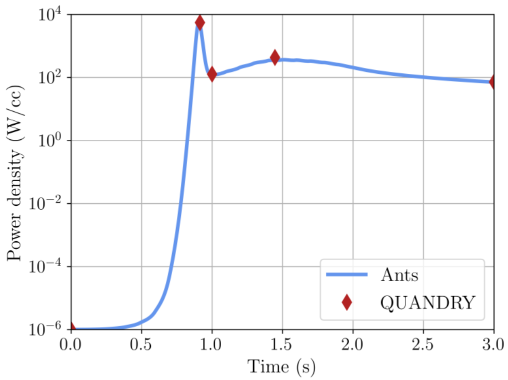


Absolute difference between
Ants and POLCA-T

The LRA problem – transient

Code	Ants	QUANDRY	CONQUEST
Mesh size (cm^3)	15×15×15	15(30)×15(30)×30	15×15×30
Number of time steps	410	410	410
Time at first peak (s)	0.907	0.907	0.905
Power at first peak (W/cm^3)	5550	5739	5390
Time at first minimum (s)	1.00	0.988	~1.0
Power at first minimum (W/cm^3)	120	109	~100
Time at second peak (s)	1.42	1.44	1.44
Power at second peak (W/cm^3)	353	412	431



Conclusions

Ants performs well in the transient problems considered in this work

- Six different transient benchmark cases were conducted

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  - Less than 1 % relative difference of total power in all reference points
- The more difficult problems exhibited larger differences

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- Current work includes coupled time-dependent calculation with other Kraken-solvers

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