Validation of Serpent-SCF-TU pin-by-pin depletion for PWR and VVER reactors

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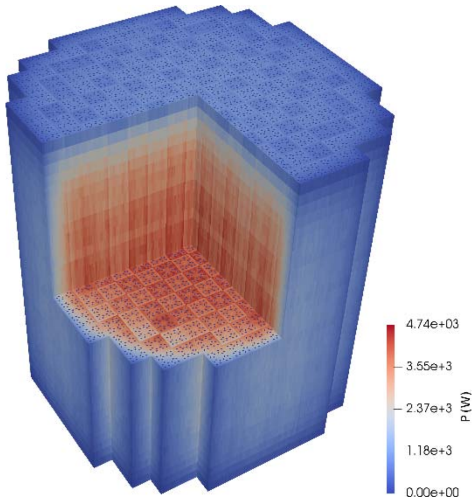
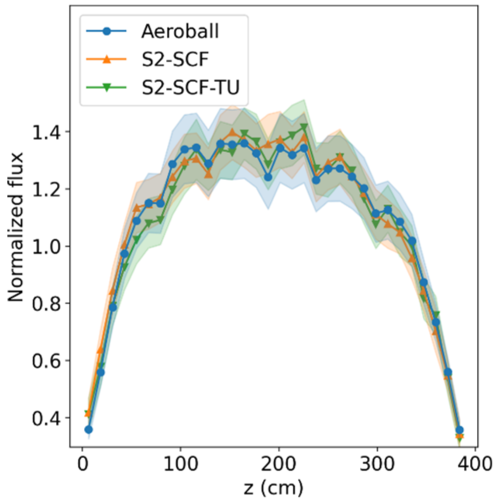
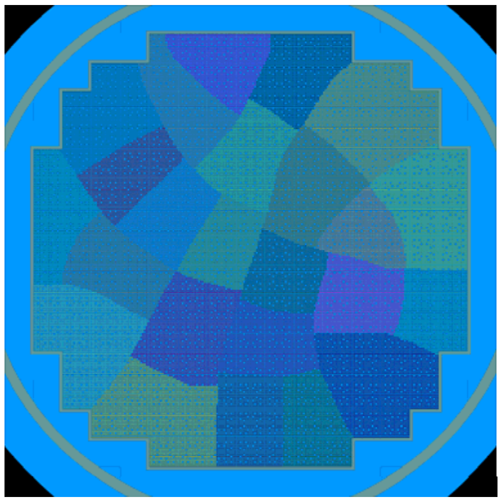




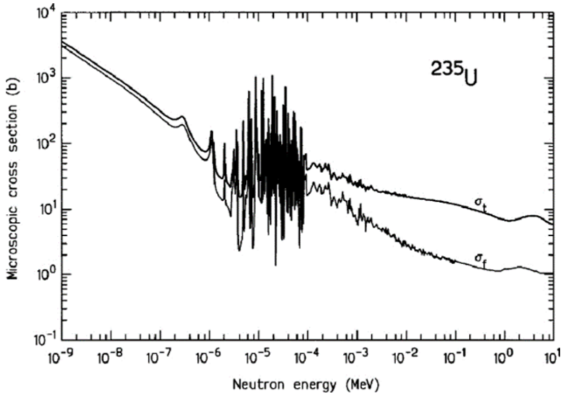


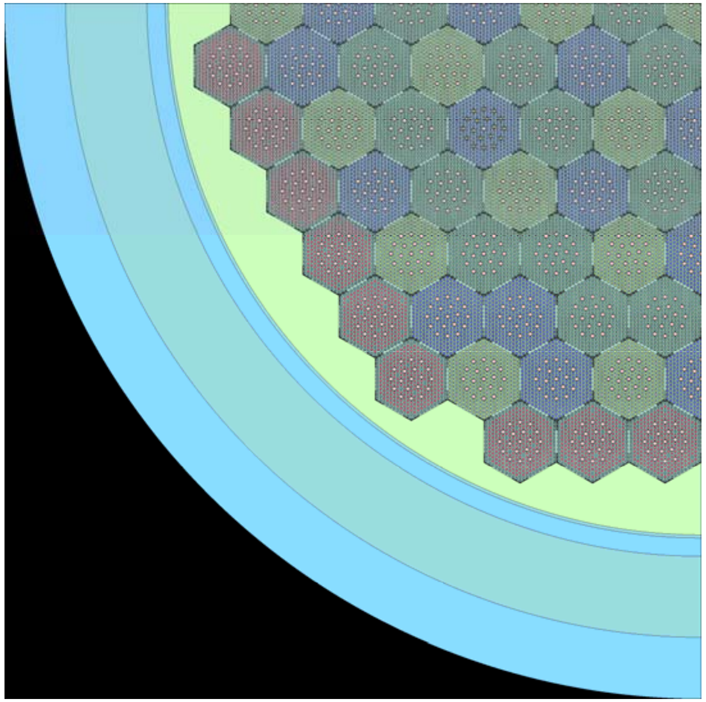
Introduction

- Burnup analysis for Light Water Reactors (LWRs):
  - Multiphysics:
    - Monte Carlo neutron transport (criticality, power, burnup).
    - Subchannel thermalhydraulics (cooling conditions, safety parameters).
    - Fuel-performance analysis (thermomechanics, burnup, safety parameters).
  - High-fidelity methods:
    - Less approximations compared to industry standards.
    - Higher resolution (geometry, neutron direction and energy).
  - High Performance Computing (HPC).
- Proposed depletion methodology (McSAFE EU project):
  - Serpent-SCF-TU full-core pin-by-pin depletion.
  - Objectives:
    - Burnup calculation with fuel-performance analysis for realistic core states.
    - Potential improvement of the calculation of local safety parameters.
    - Proof of concept for industry-like (?) applications.
  - Validation for PWR and VVER reactors using experimental data.

Monte Carlo neutron transport (Serpent 2)

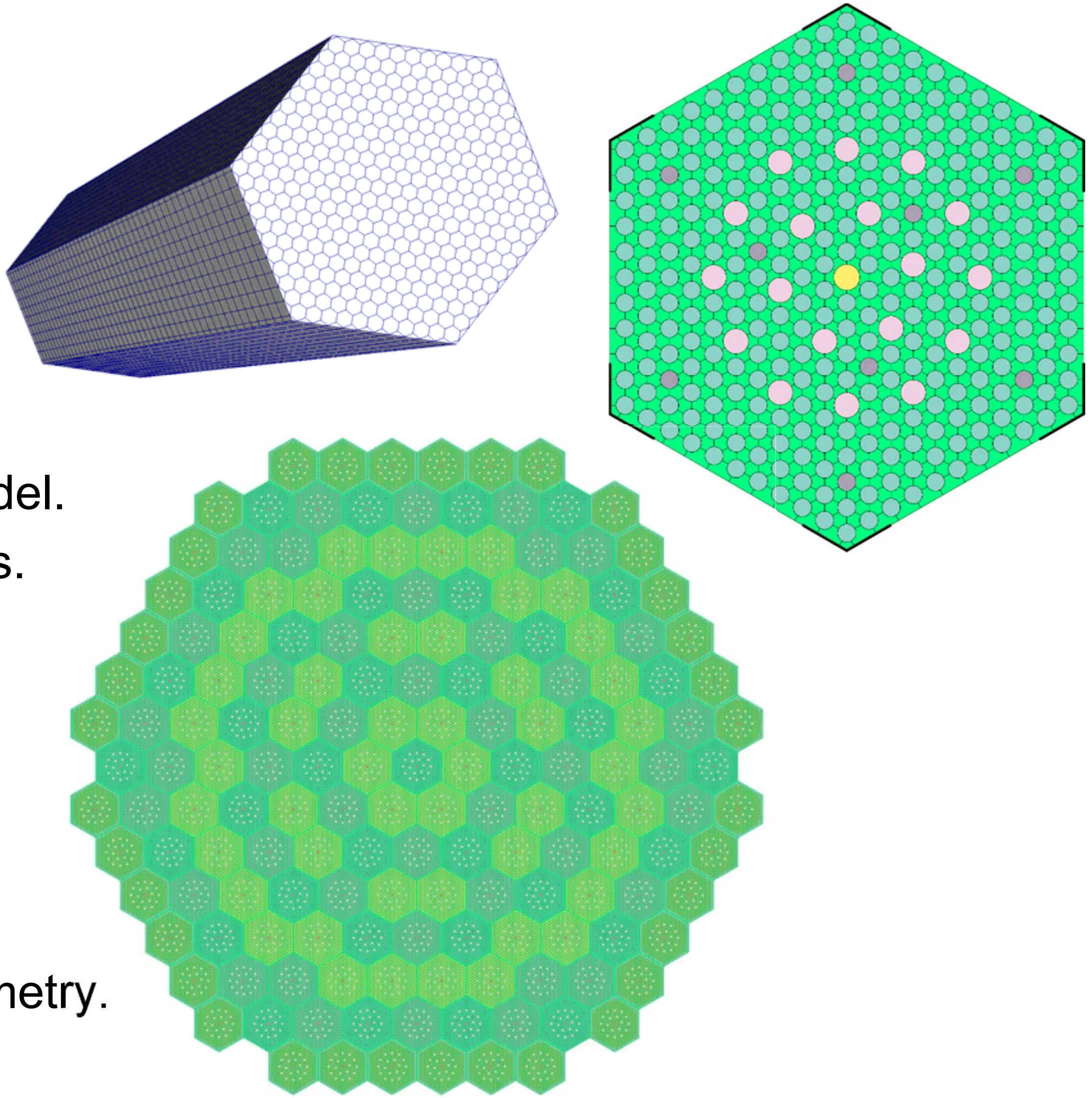
- Neutron transport calculation:
  - Stochastic (not deterministic) method.
  - No inherent approximations:
    - Continuous-energy nuclear data.
    - Arbitrary level of geometrical detail.
    - Explicit angular treatment.
  - Large calculation times.
- Depletion calculation:
  - Direct calculation.
  - ~1700 nuclides.
  - Huge memory demand.
- Modelling approach:
  - Full-core pin-by-pin geometry.
  - Pin-level thermalhydraulic feedback.
  - Pin-by-pin burnup.





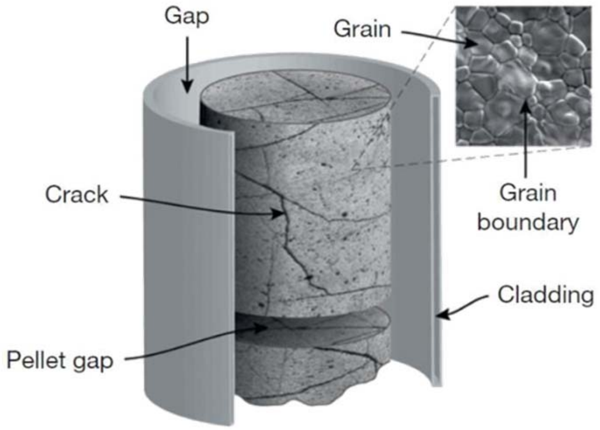
Subchannel thermalhydraulics (SUBCHANFLOW)

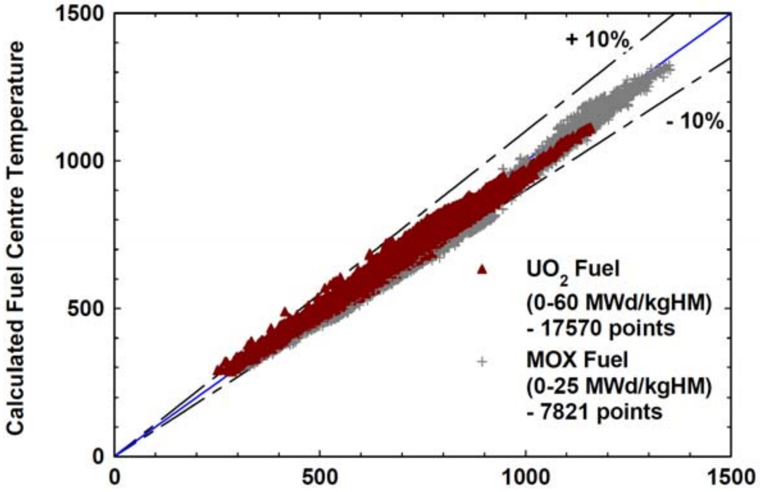
- Coolant flow calculation:
  - Subchannel approach.
  - Turbulent mixing.
  - Empirical correlations.
- Fuel rod calculation:
  - Radial scheme.
  - Simple fuel-clad gap model.
  - Simple thermomechanics.
- Safety parameters:
  - DNBR.
  - Fuel temperature.
  - Clad temperature.
- Modelling approach:
  - Full-core pin-by-pin geometry.
  - Subchannel-level model.

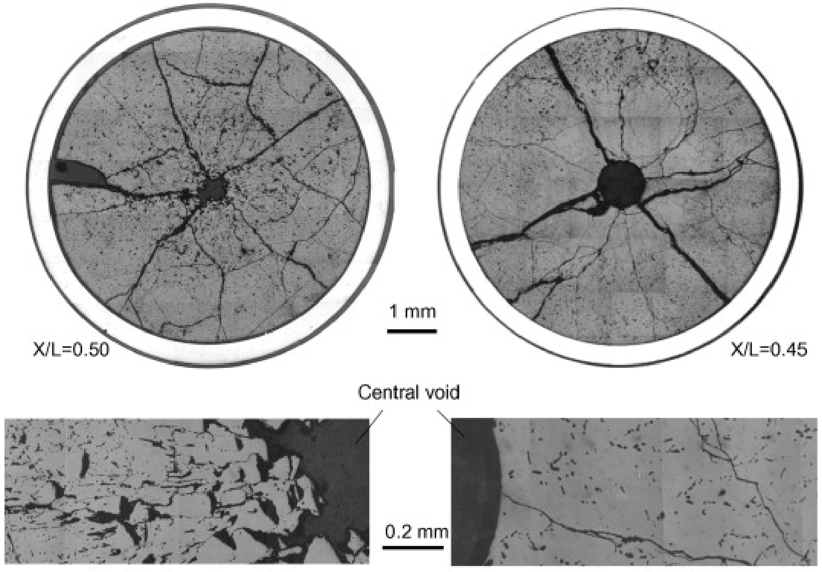


Fuel-performance analysis (TRANSURANUS)

- Main thermomechanical phenomena:
  - Fuel-cladding gap conductance and width.
  - Fission gas release, filling gap pressure.
  - Pellet-cladding mechanical interaction.
  - Thermal and irradiation-induced densification.
  - Swelling, creep, plasticity, cracking, relocation.
- Modelling approach:
  - Fuel-performance analysis of all rods.





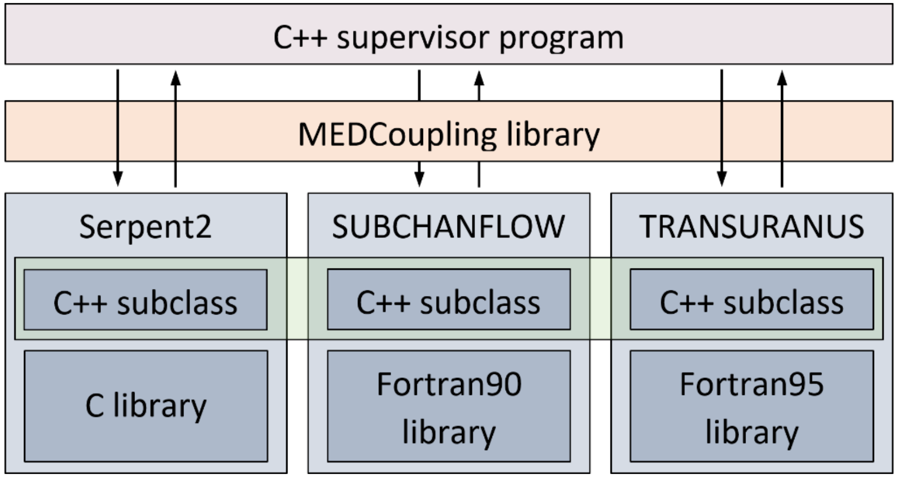


(a) 10-minute irradiation

(b) 24-hour irradiation

Coupled calculation scheme for depletion

- Semi-implicit (?) iterative scheme.
- Pin-level feedback.
- Burnup in Serpent and TU.
- Potential improvements in TU:
  - Radial power distributions.
  - Fast flux feedback.
  - Serpent burnup calculation.



C++ supervisor program

MEDCoupling library

Serpent2

C++ subclass

C library

SUBCHANFLOW

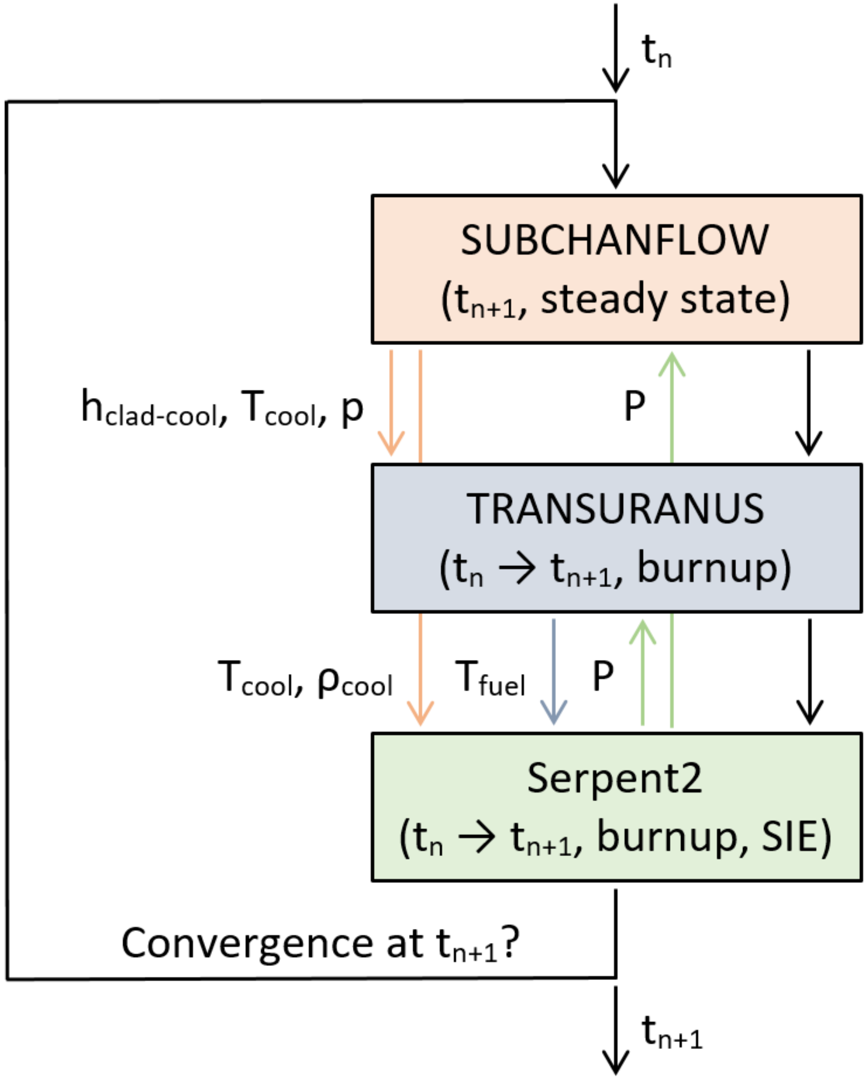
C++ subclass

Fortran90 library

TRANSURANUS

C++ subclass

Fortran95 library



t_n

SUBCHANFLOW (t_{n+1}, steady state)

$h_{clad\text{-}cool}$, T_{cool}, p

P

TRANSURANUS ($t_n \rightarrow t_{n+1}$, burnup)

T_{cool}, ρ_{cool}

T_{fuel}

P

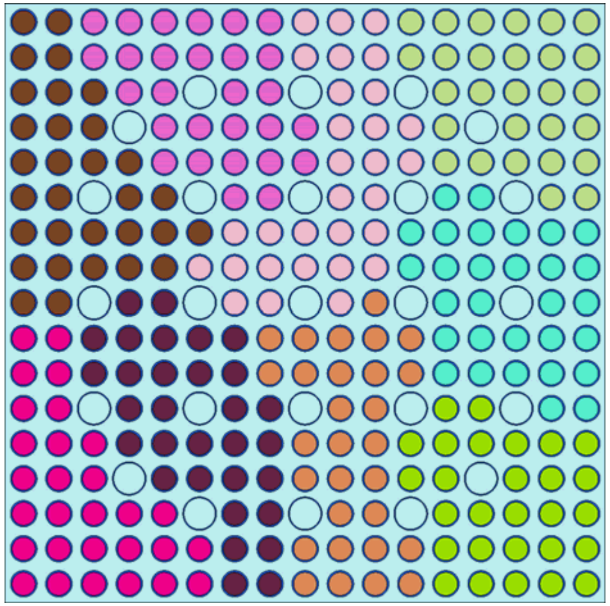
Serpent2 ($t_n \rightarrow t_{n+1}$, burnup, SIE)

Convergence at t_{n+1}?

t_{n+1}

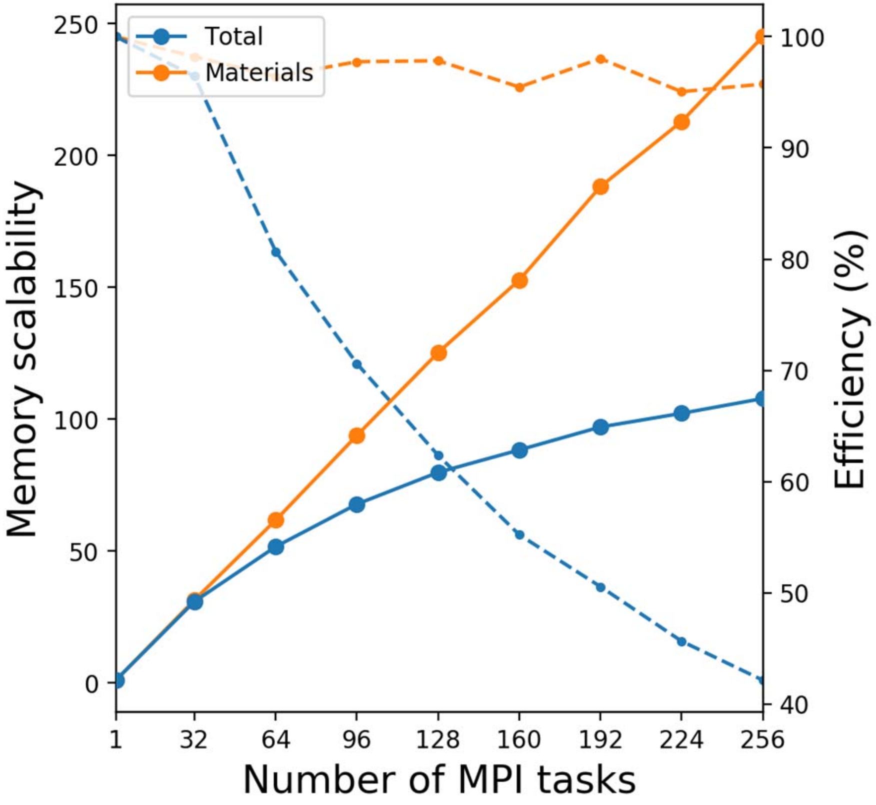
Collision-based Domain Decomposition

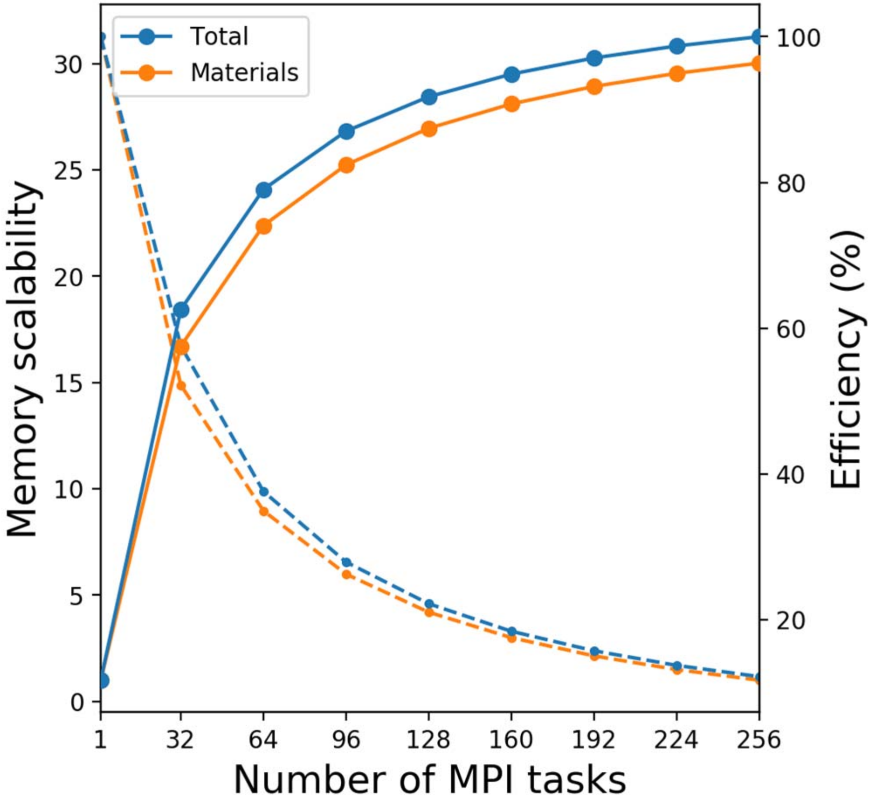
- Full-core pin-by-pin burnup:
  - Hugh runtimes (~10^9 neutron histories per transport calculation).
  - Massive memory demand (~TB, larger than the in-node memory in HPC).
- Collision-based Domain Decomposition (CDD):
  - Memory scalability in burnup calculations:
    - Burnup materials decomposed in domains (MPI tasks).
    - All other data replicated across domains.
  - Tracking scheme:
    - Particle transfers across domains.
    - Asynchronous MPI communications.
    - Optimized tracking termination control.
    - No physical or numerical approximations.



CDD performance in a PWR-like system

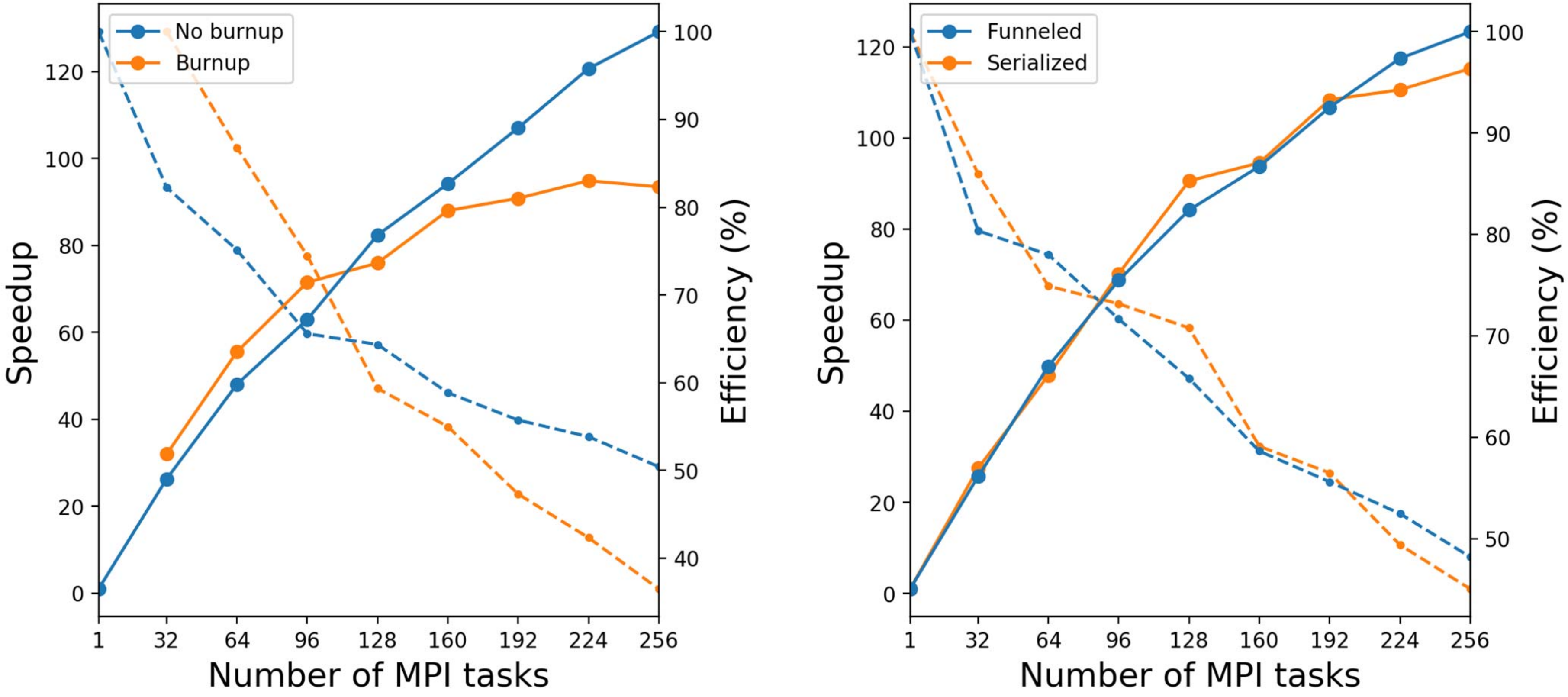
- Memory scalability:
  - Tests done in the ForHLR II cluster (KIT/SCC) up to 5,120 cores.
  - Much better scalability for opti mode 4 (left) than for mode 2 (right).



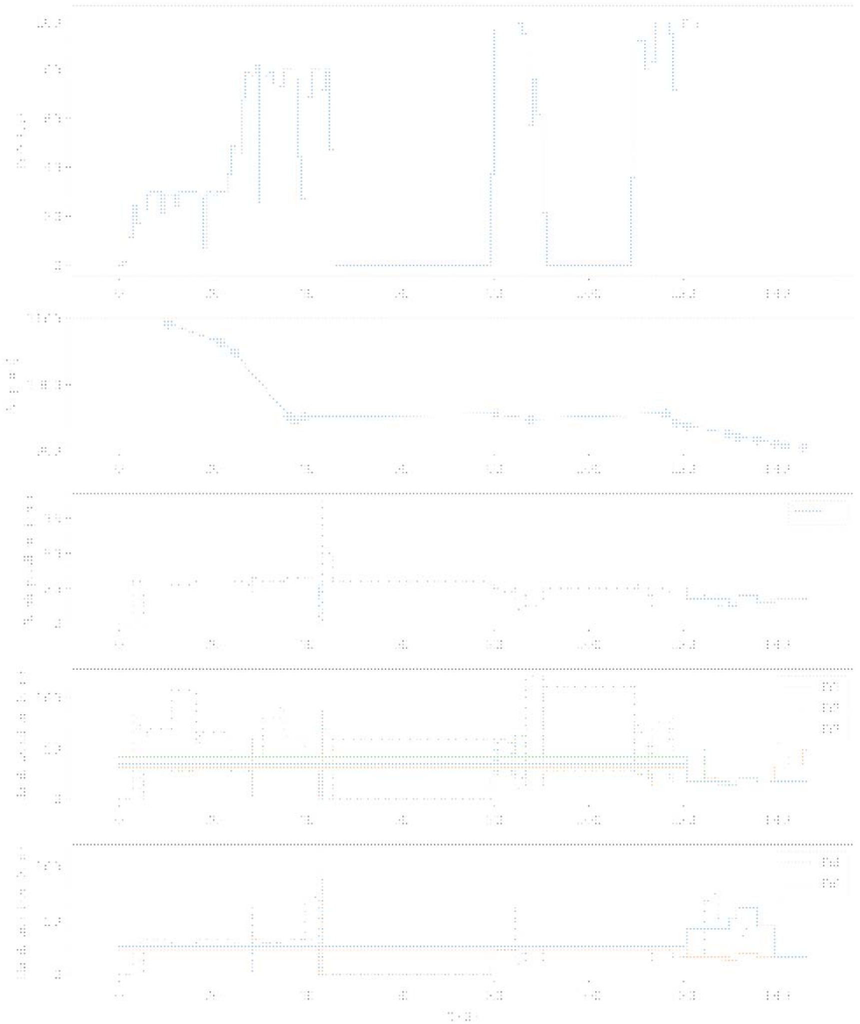


CDD performance in a PWR-like system

- Speedup (~10^6 particles per cycle):
  - Tests done in the ForHLR II cluster (KIT/SCC) up to 5,120 cores.
  - Acceptable speedup, some penalty from CDD.



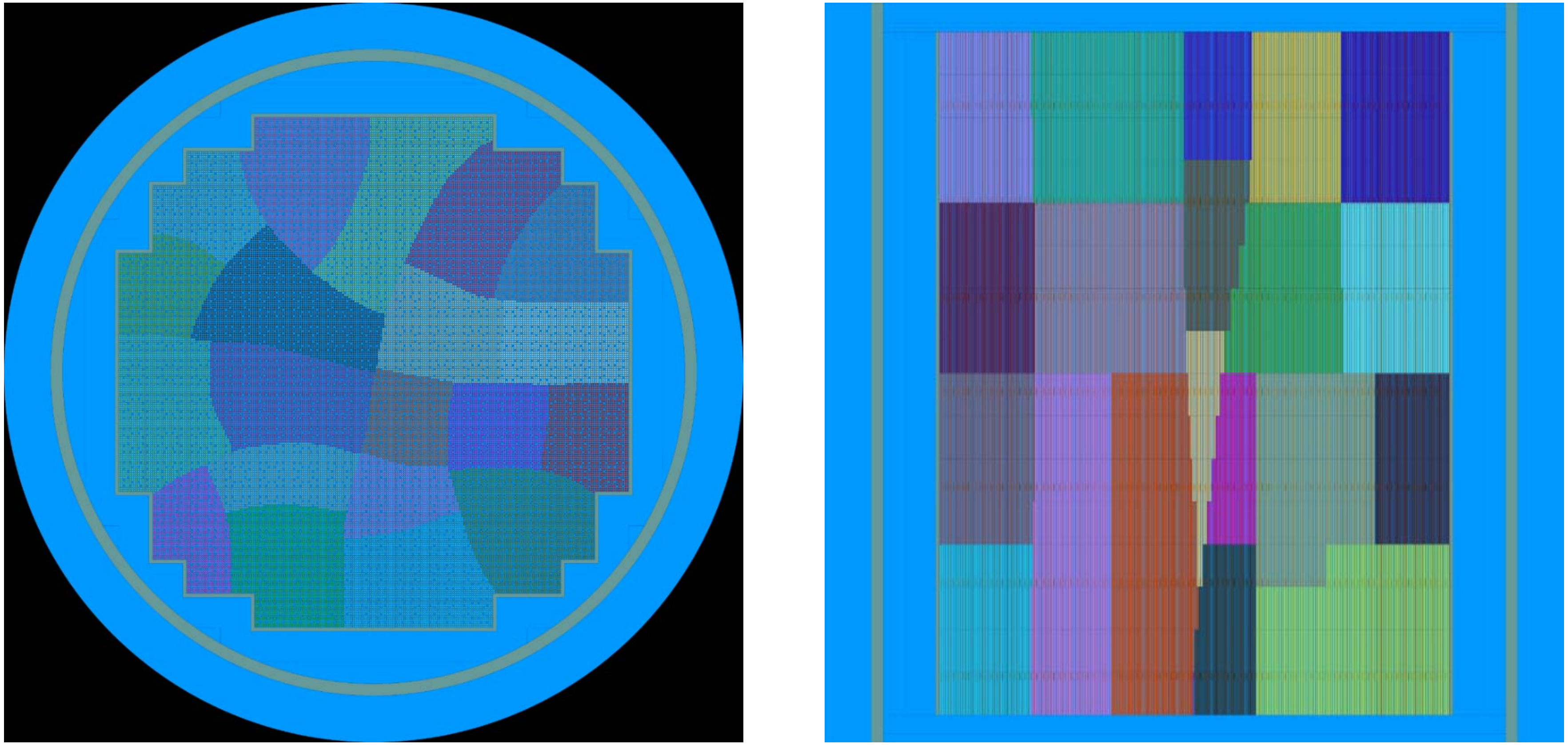
Validation for a Pre-Konvoi PWR reactor



- Burnup history:
  - Nominal power (3765MW).
  - Measured point:
    - 64.9 effective power days.
    - Full power.
    - Equilibrium xenon.
    - Experimental data:
      - Critical boron concentration.
      - Neutron flux (aeroballs).
  - Critical boron iteration.
  - Control rod movements:
    - Constant for each burnup step.
    - Power-weighted averaged.
- HPC resources (ForHLR II):
  - 64 nodes, 20 CPU/node.
  - 7 day runtime limit.

Material decomposition for CDD

- Material decomposition:
  - 728,768 burnable materials, 64 nodes, 68GB per node, opti mode 1.
  - Graph-based method using Metis (not available in the official release).



Validation results: critical boron concentration

- Differences in critical boron within a few ppm (< 50-100 ppm).
- No significant differences between S2-SCF and S2-SCF-TU.

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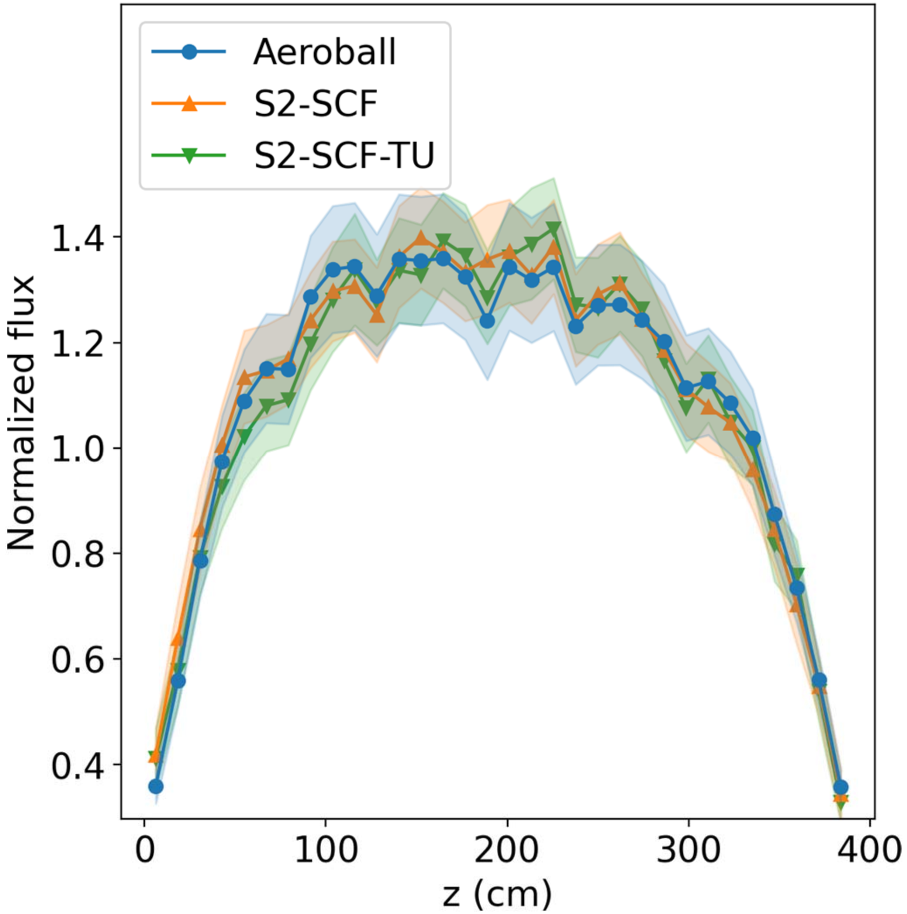
Validation results: neutron flux profiles

- Aeroball positions with the smallest deviations (M07 and L04):



Validation results: neutron flux profiles

- Aeroball positions with the largest deviations (C14 and K01):

Fuel solution at 2.35 MWd/kg

- Fuel-cladding gap conductance using TU and differences against SCF:

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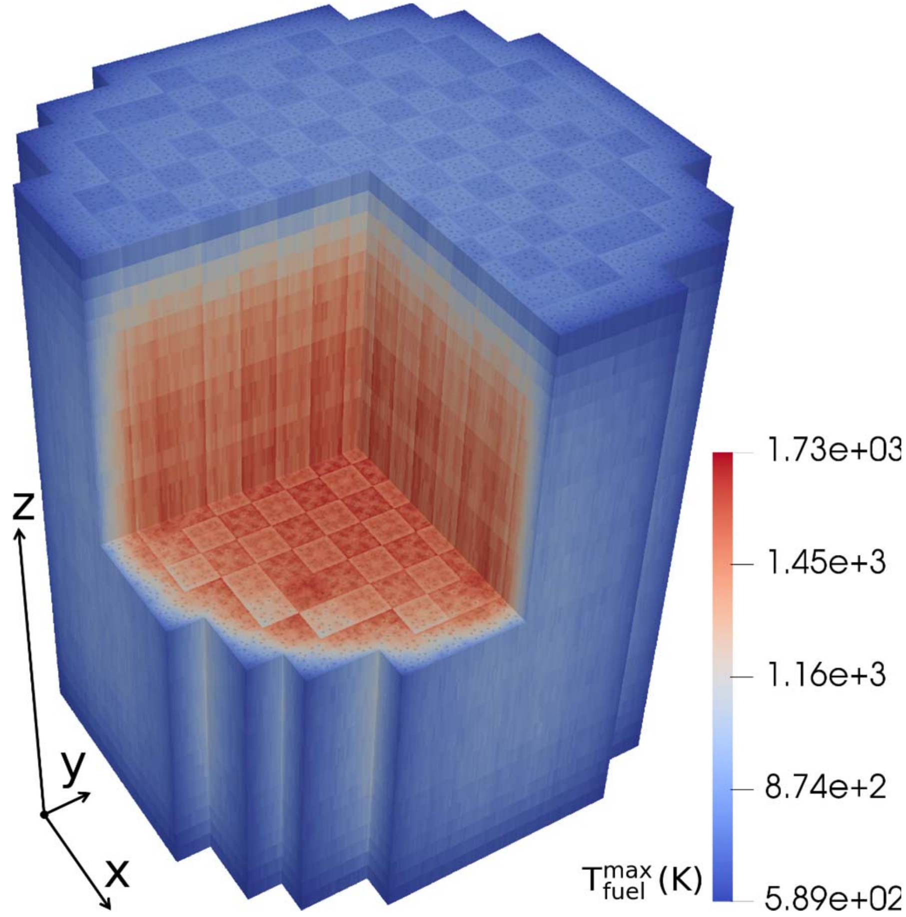
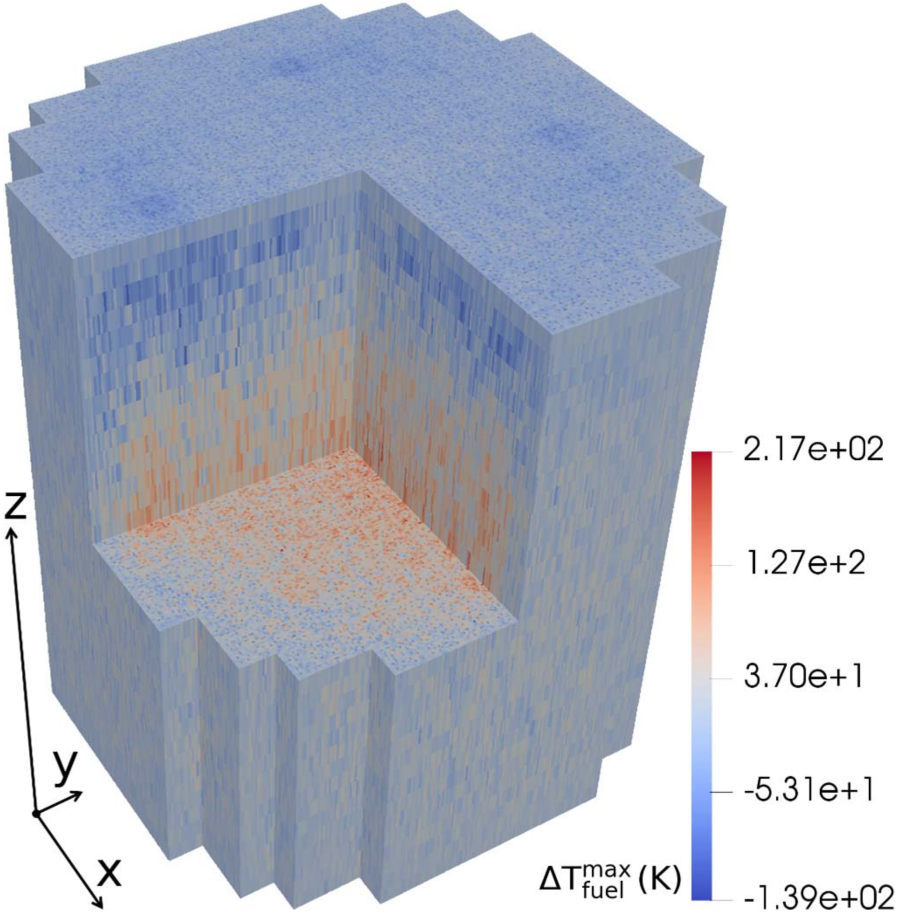
Fuel solution at 2.35 MWd/kg

- Fuel-cladding gap width using TU and differences against SCF:

Fuel solution at 2.35 MWd/kg

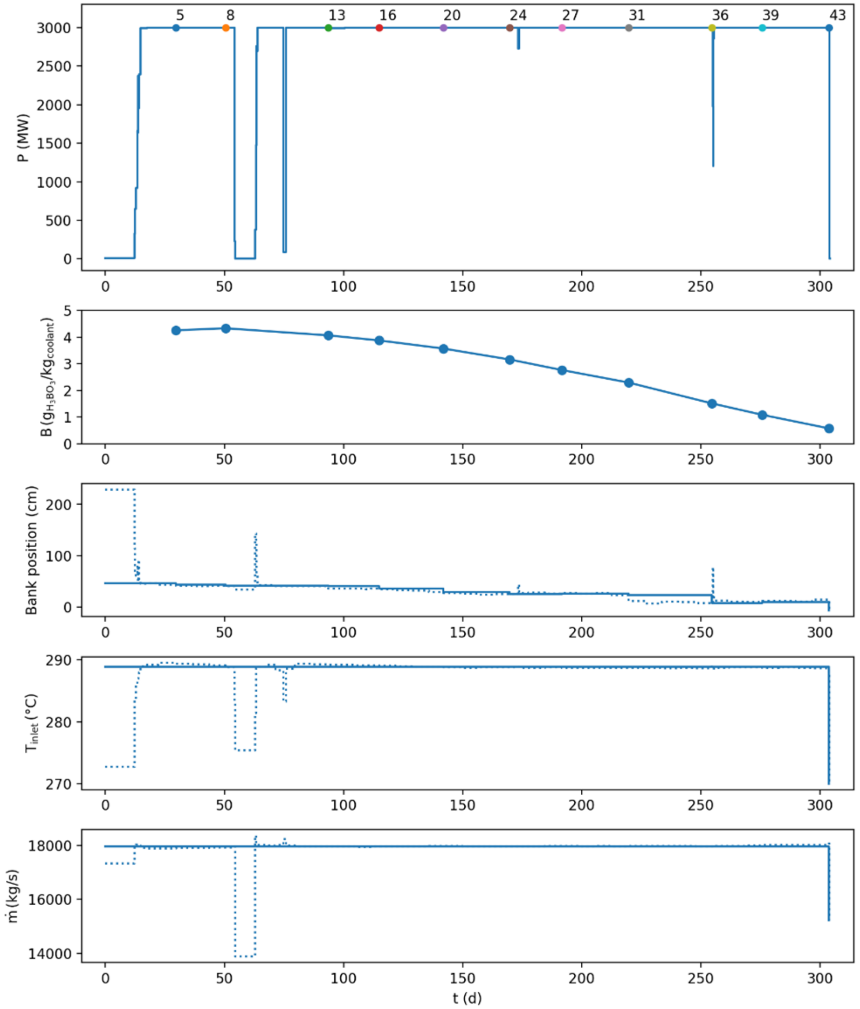
- Fuel centerline temperature using TU and differences against SCF:





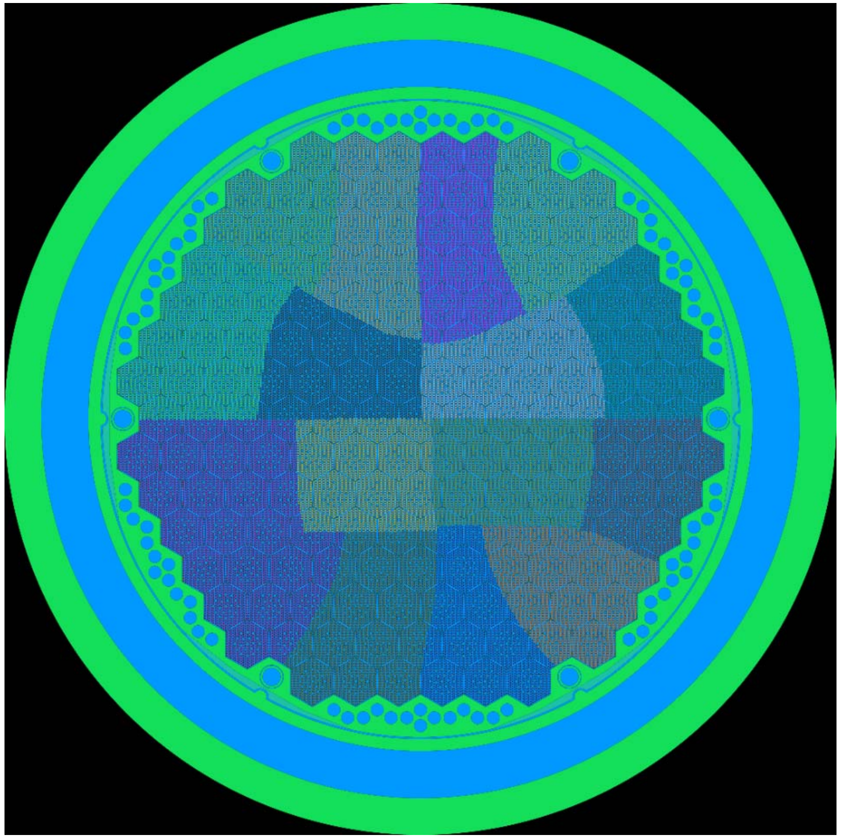
Validation for the Temelín II VVER-1000 reactor

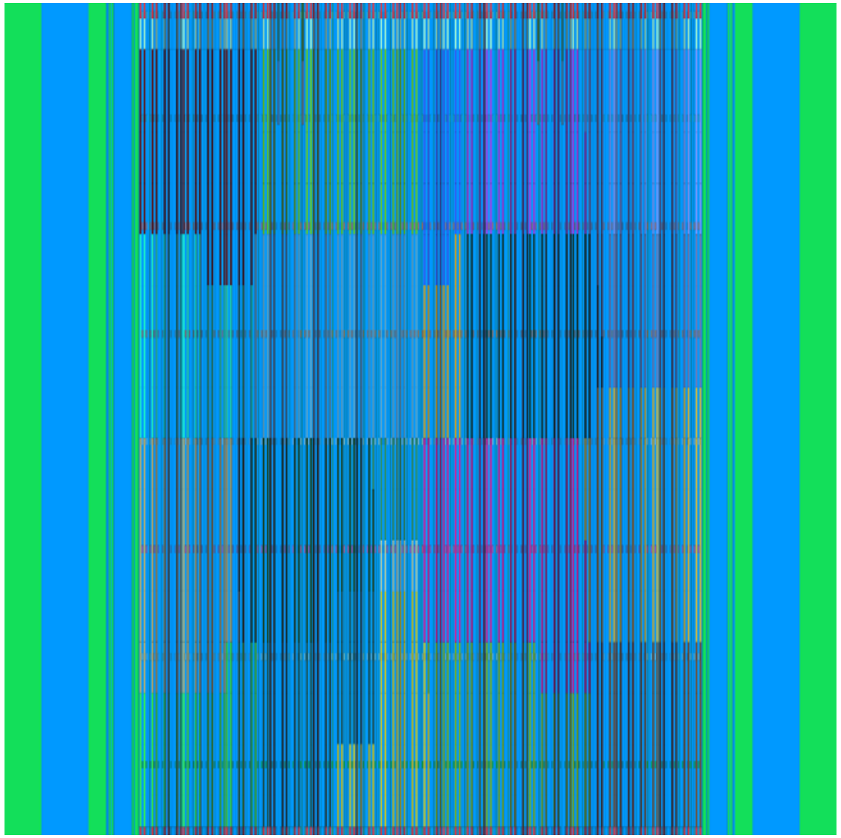
- Burnup history:
  - Nominal power (3000MW).
  - Measured points:
    - Full power.
    - Equilibrium xenon.
    - Experimental data:
      - Critical boron concentration.
      - Power (CMS).
      - Neutron flux (SPNDs).
  - Critical boron iteration.
  - Control rod movements:
    - Constant for each burnup step.
    - Power-weighted averaged.
- HPC resources (ForHLR II):
  - 64 nodes, 20 CPU/node.
  - 7 day runtime limit.



Material decomposition for CDD

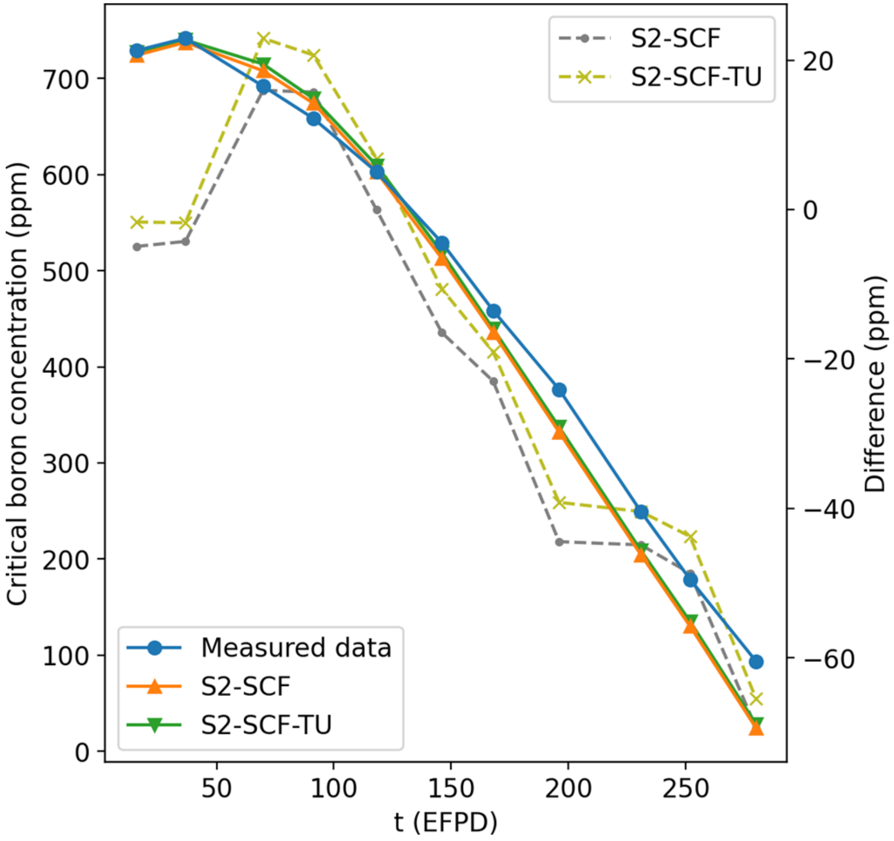
- Material decomposition:
  - 813,696 burnable materials, 64 nodes, 68GB per node, opti mode 1.
  - Graph-based method using Metis (not available in the official release).





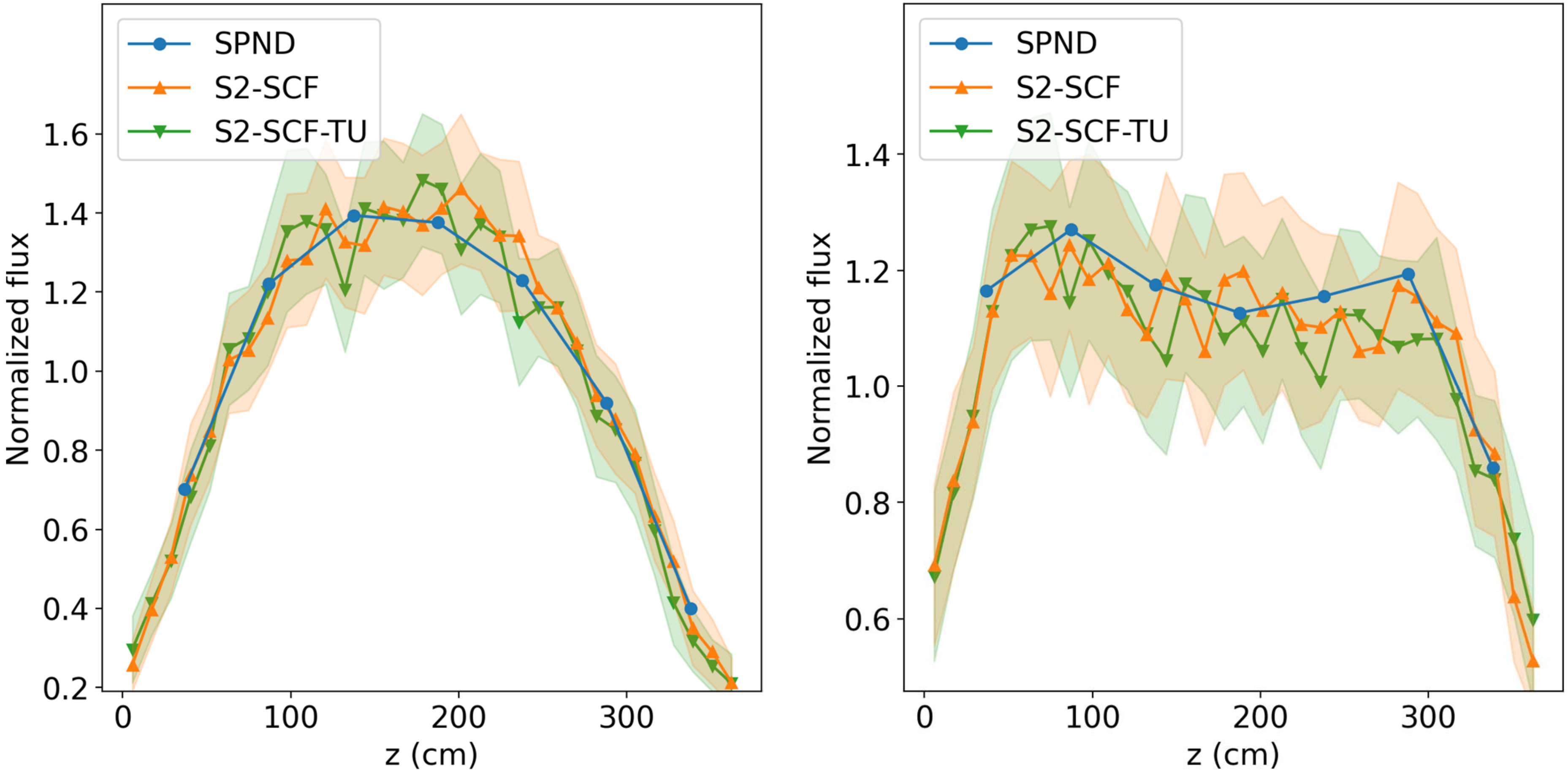
Validation results: critical boron concentration

- Differences in critical boron within the acceptance criteria (< 100 ppm).
- No significant differences between S2-SCF and S2-SCF-TU.



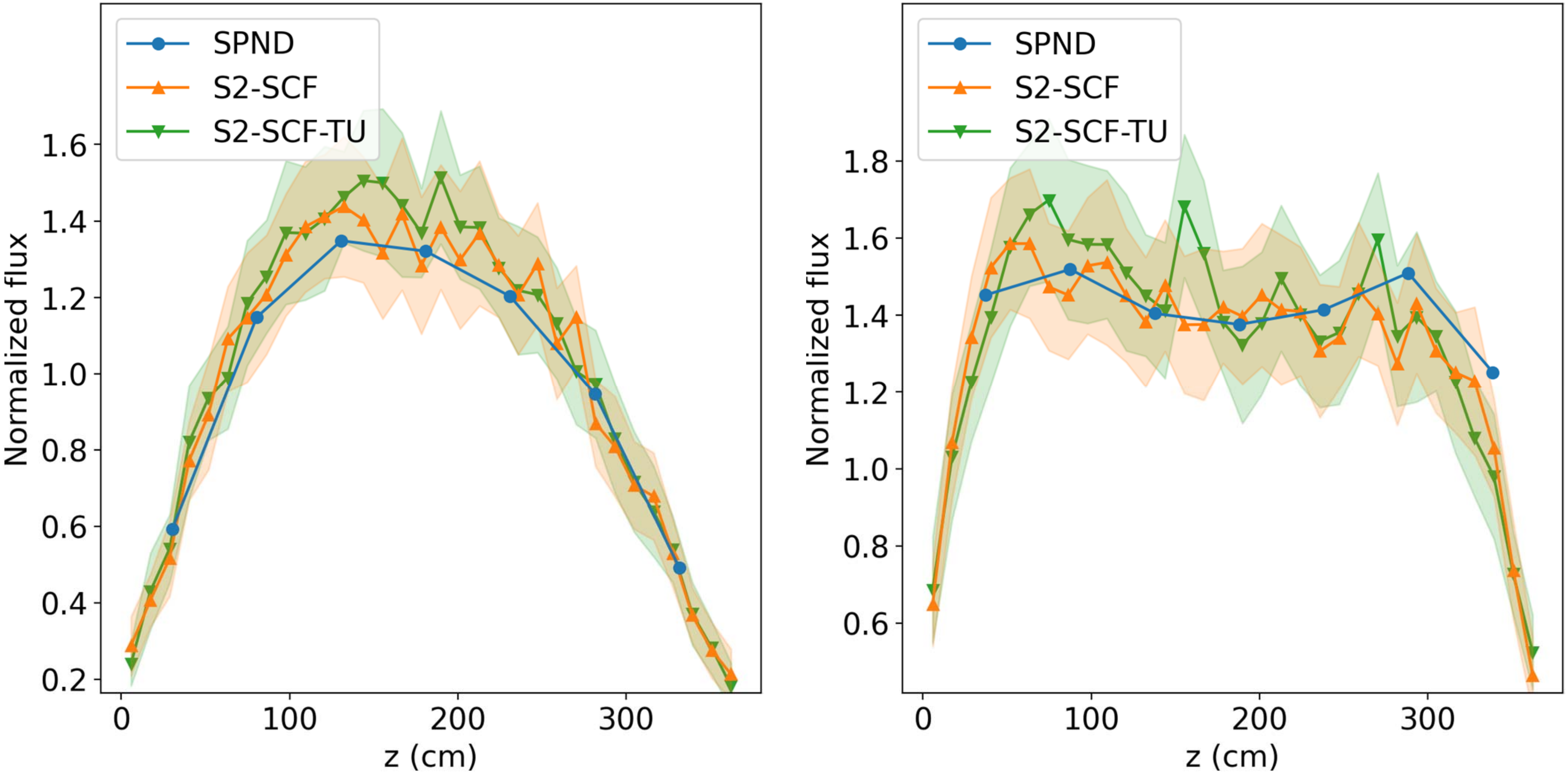
Validation results: neutron flux profiles

- SPND positions with the smallest deviations (BOC: 98, EOC: 128):



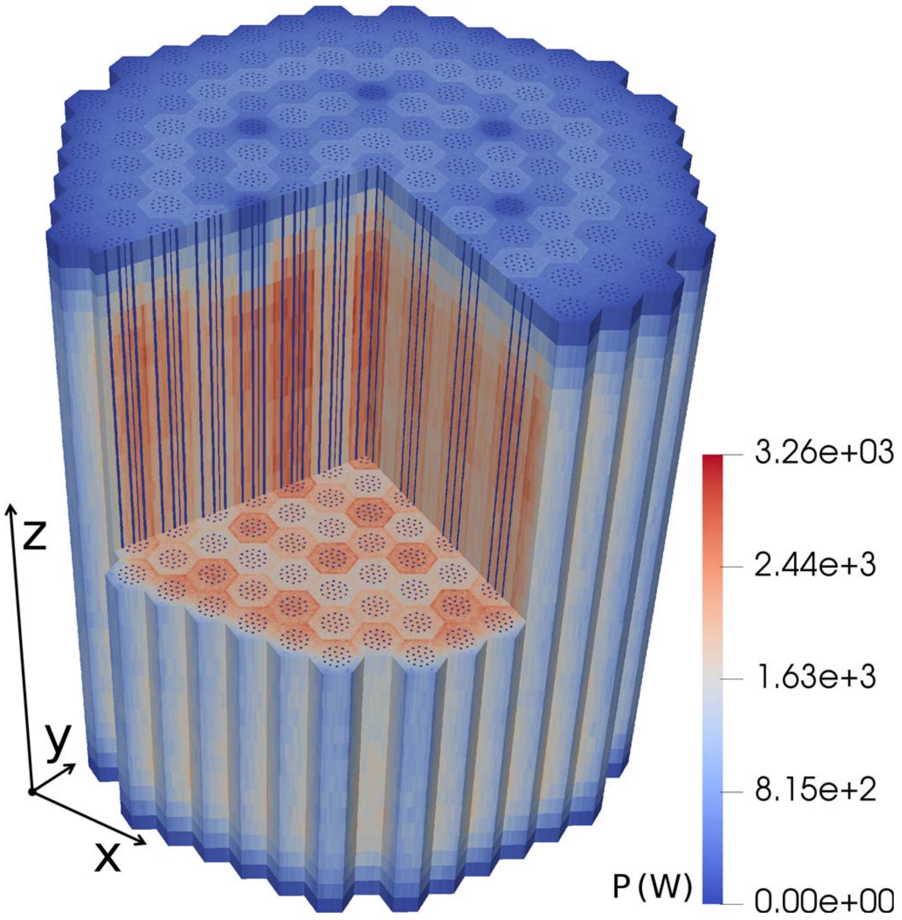
Validation results: neutron flux profiles

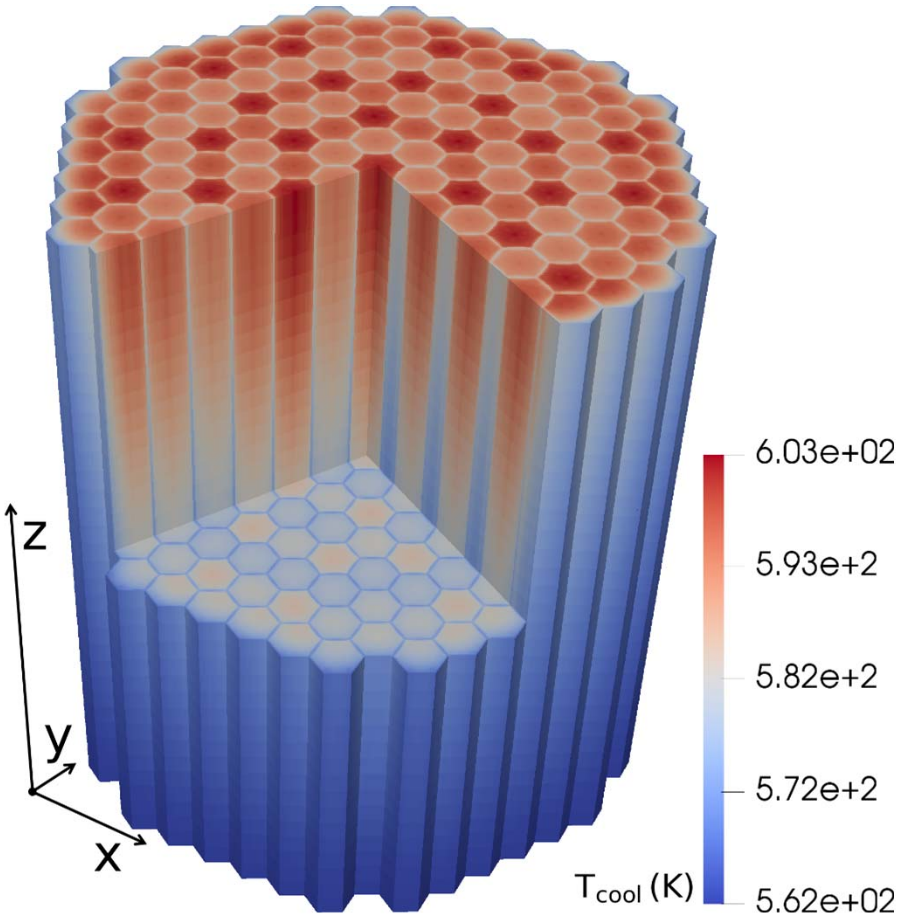
- SPND positions with the largest deviations (BOC: 151, EOC: 92):



Serpent-SCF-TU solution at 11.08 MWd/kg (EOC)

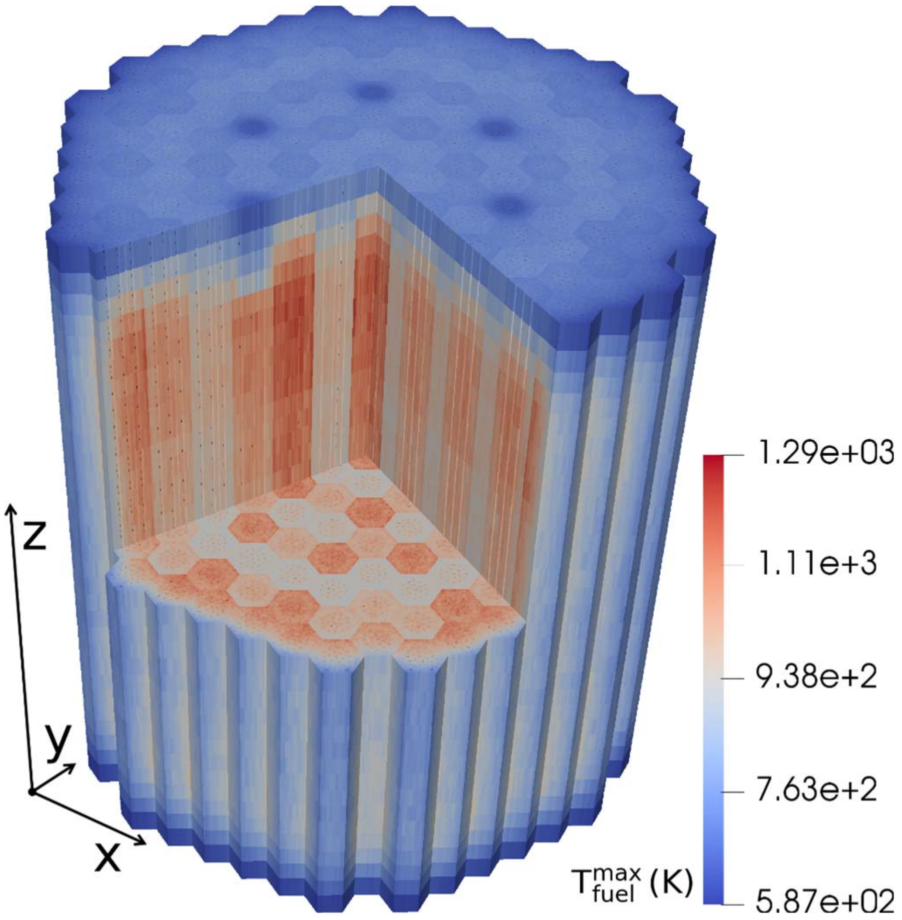
- Serpent power and SCF coolant temperature:

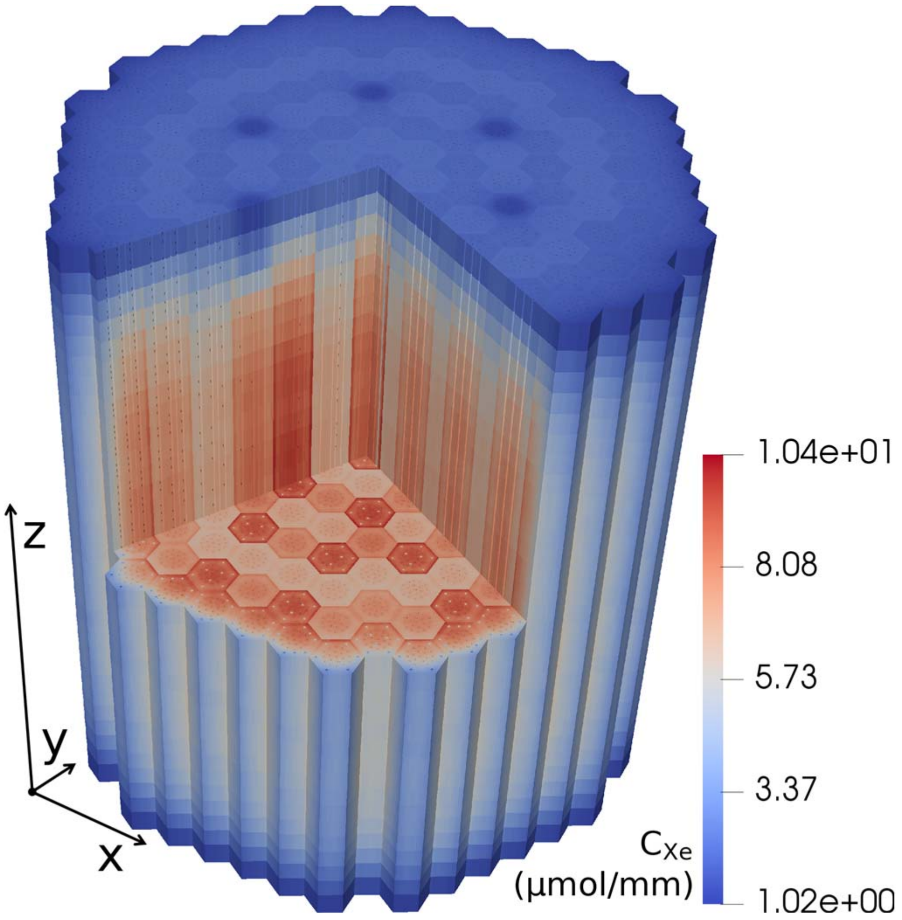




Serpent-SCF-TU solution at 11.08 MWd/kg (EOC)

- TU peak fuel temperature and Xe release:





Conclusions

- Developed calculation system:
  - Coupled neutronic-thermalhydraulic-thermomechanic depletion scheme.
  - CDD method for memory scalability.
  - Full-core pin-by-pin burnup capabilities.
- Validation:
  - Pre-Konvoi PWR up to 65 EFPD.
  - Temelín II VVER-1000 up to 280 EFPD.
  - Runtime up to 7 days in 64 computing nodes (1,280 cores).
- Fully coupled burnup calculations:
  - Improvement in the modelling of the fuel during irradiation.
  - Minor impact on the neutronic solution.
  - Large impact on fuel parameters such as gap behavior and fuel temperature.

Questions?


THANK
YOU
GRACIAS
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TINGKI
YAQHANYELAY
CHALTU
NUHUN
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SPASSIBO
TASHAKKUR ATU
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