Validation calculations for Serpent full-core pin-by-pin burnup in Light Water Reactors

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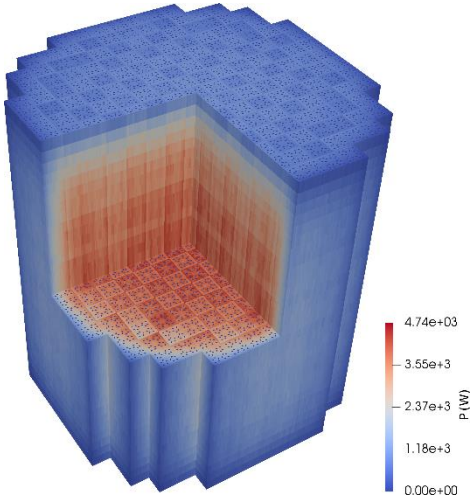
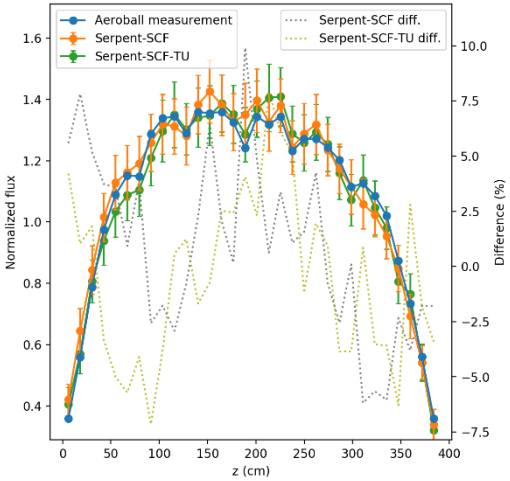
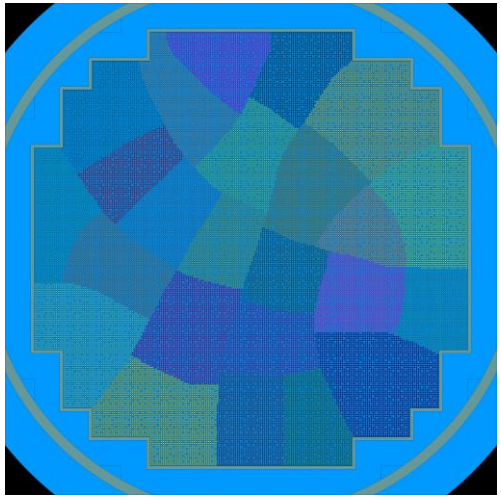




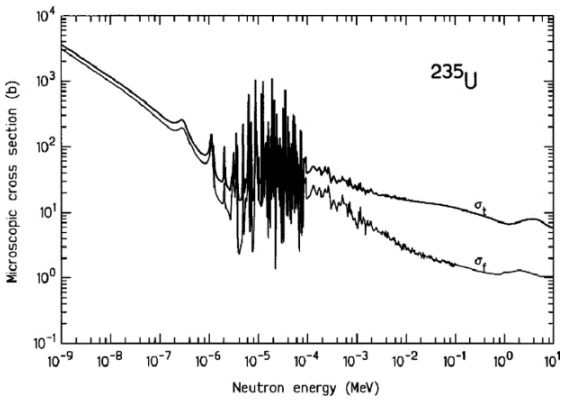


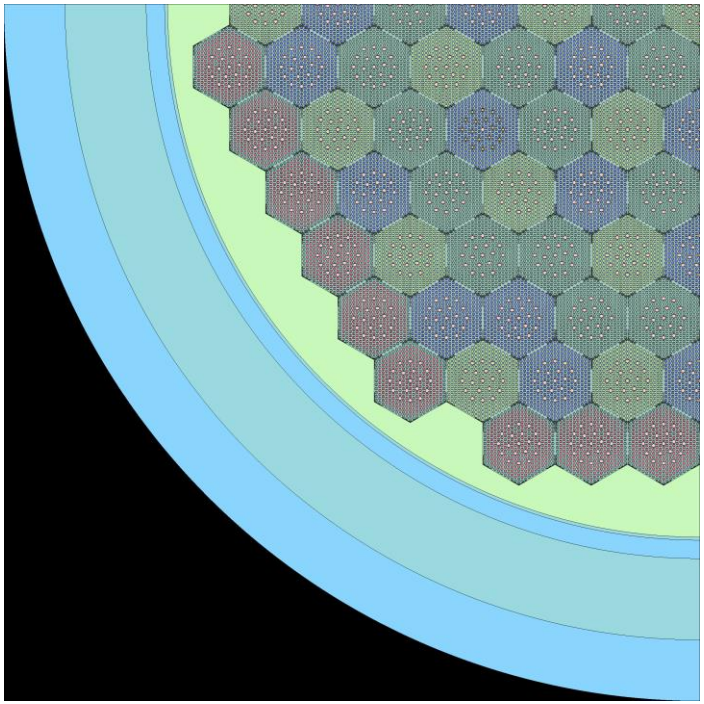
Introduction

- Burnup analysis for Light Water Reactors (McSAFE project):
  - 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 methodology:
  - 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)

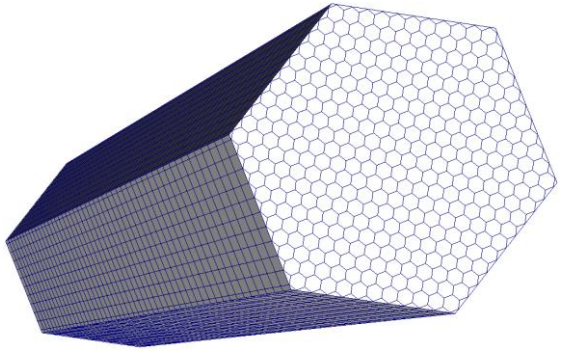
- Neutron transport calculation:
  - Stochastic (not deterministic) method.
  - No inherent approximations:
    - Continuous-energy nuclear data.
    - Arbitrary level of geometrical detail.
    - Explicit angular treatment.
  - Large calculation times.
- Depletion calculation:
  - Direct calculation.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

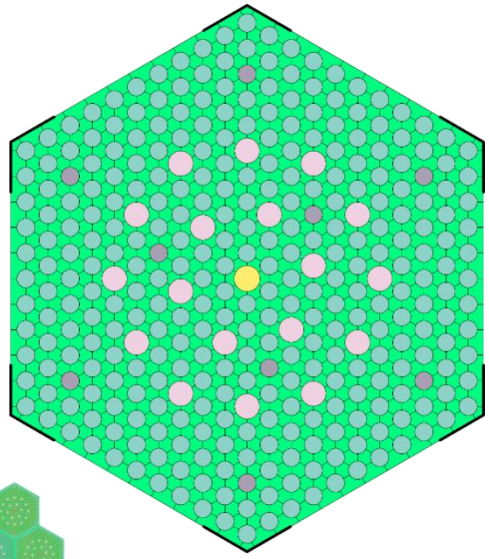


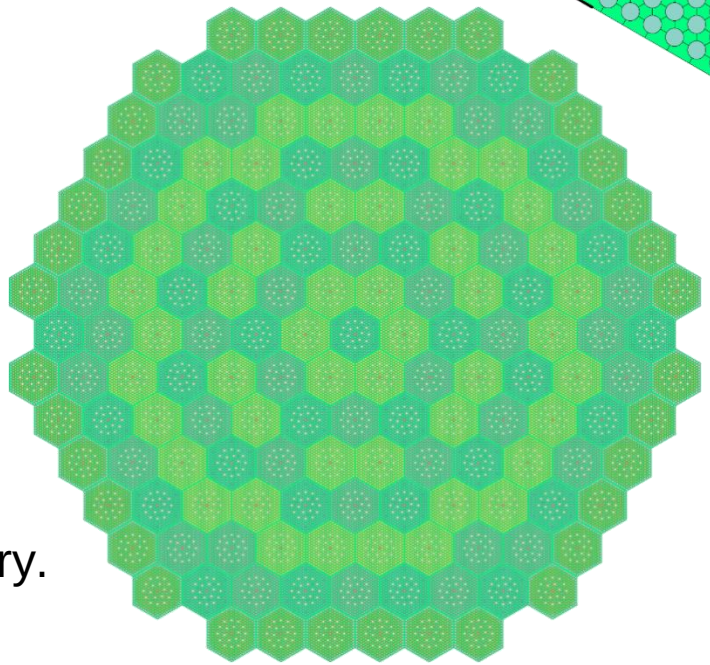


Subchannel thermalhydraulics (SUBCHANFLOW)

- 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.







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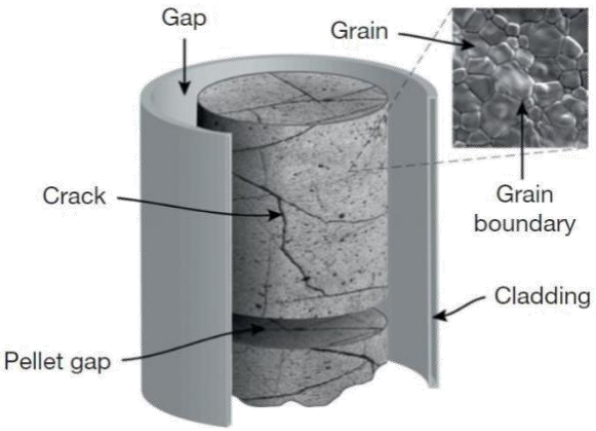
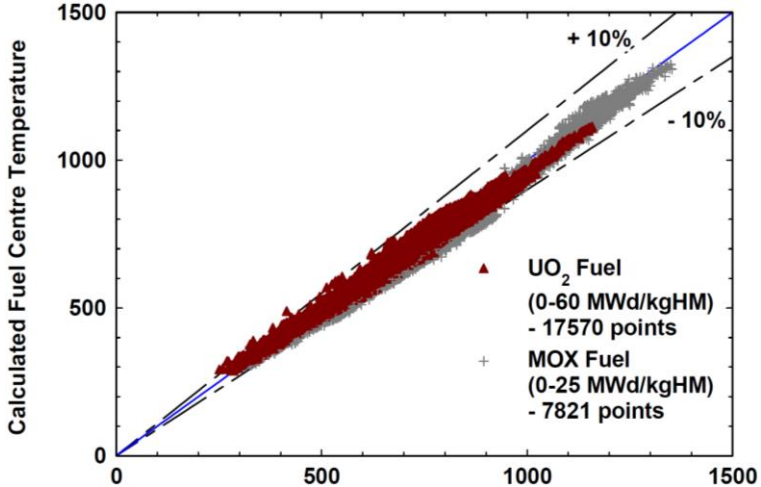
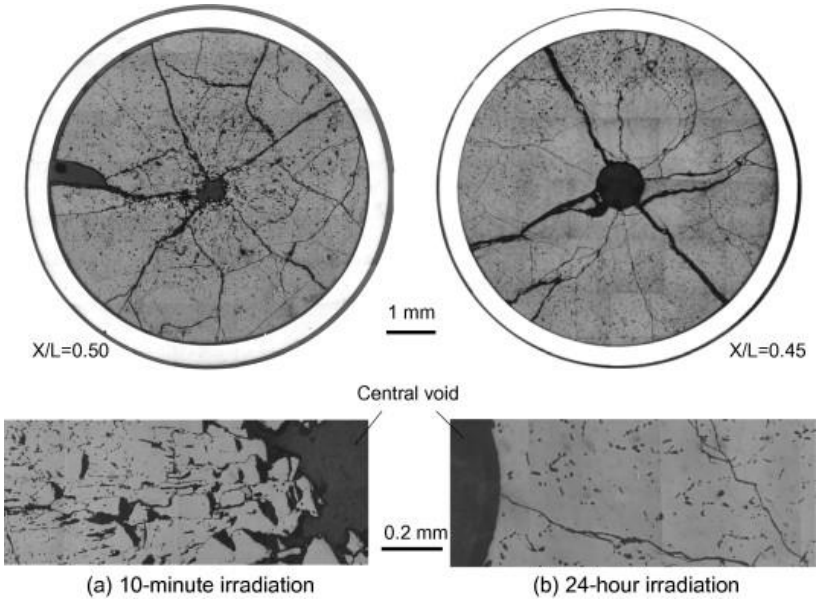
Fuel-performance analysis (TRANSURANUS)

- 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.

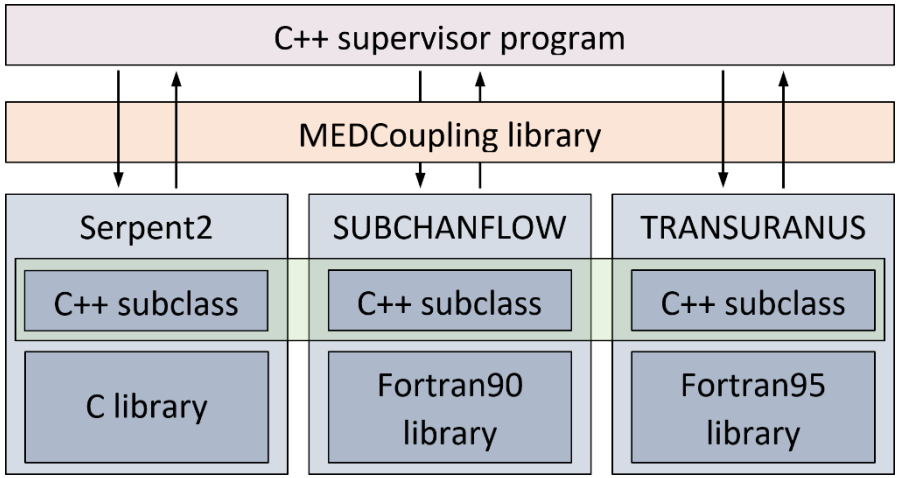


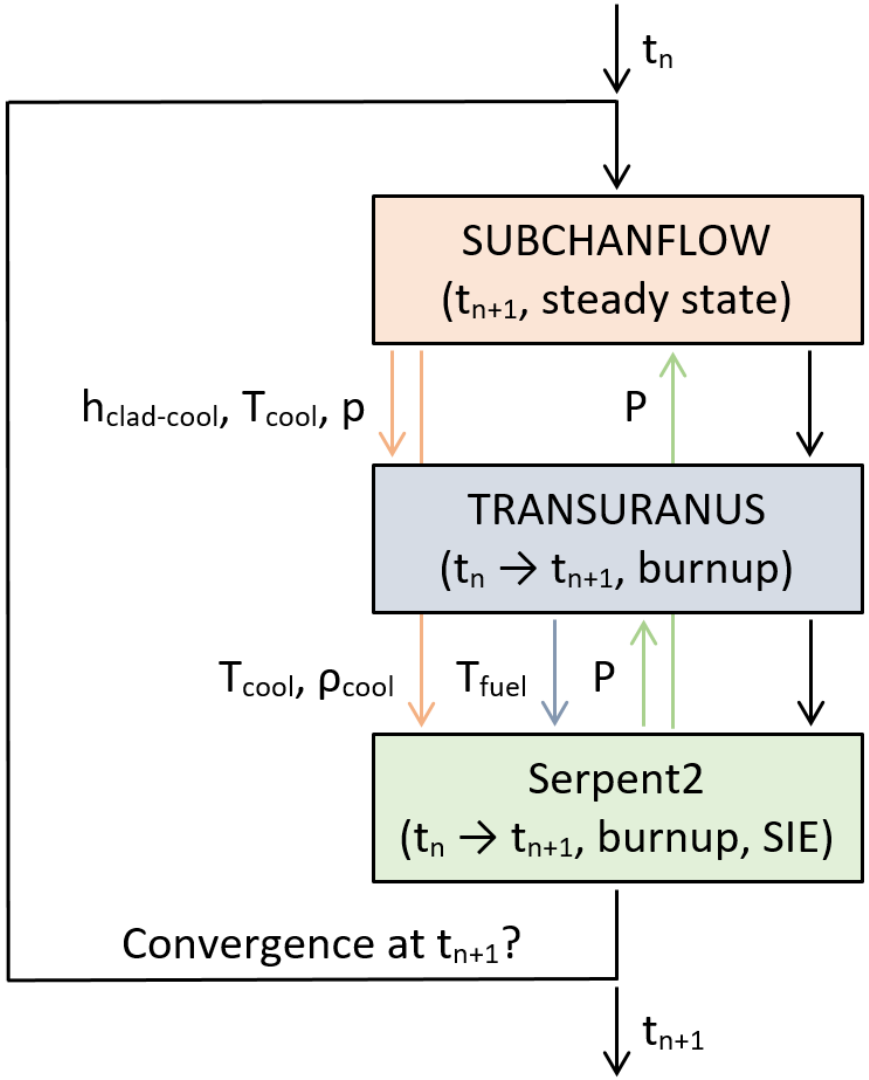




Coupled calculation scheme for depletion

- 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.





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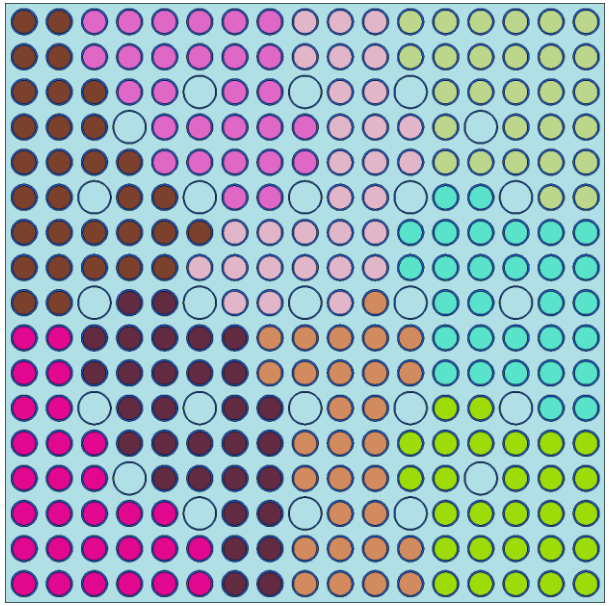
Collision-based Domain Decomposition

- 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.



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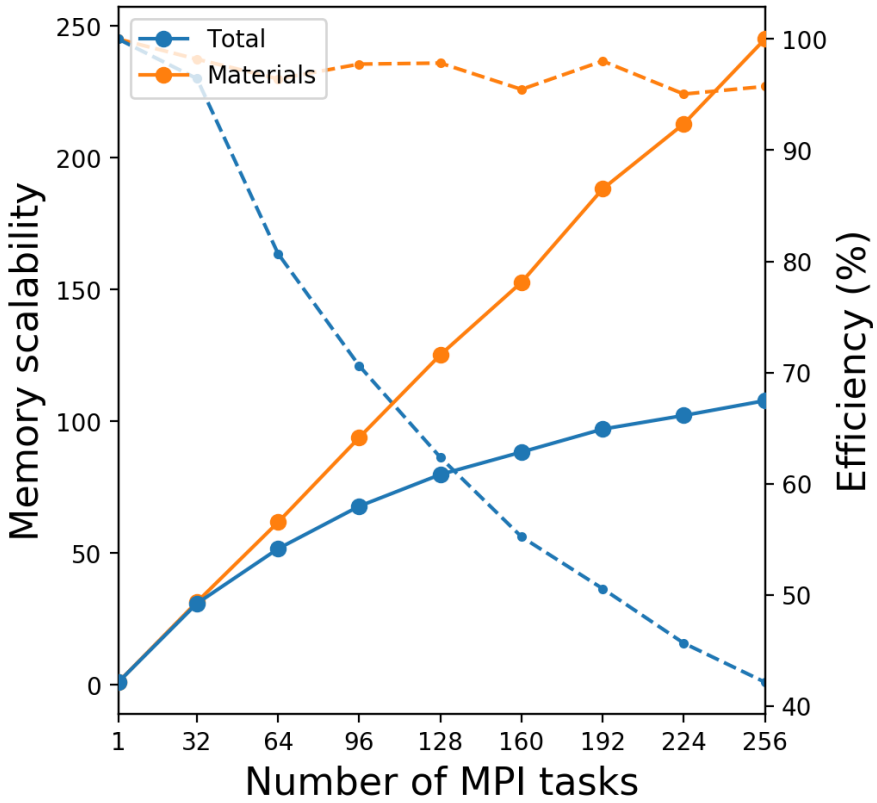
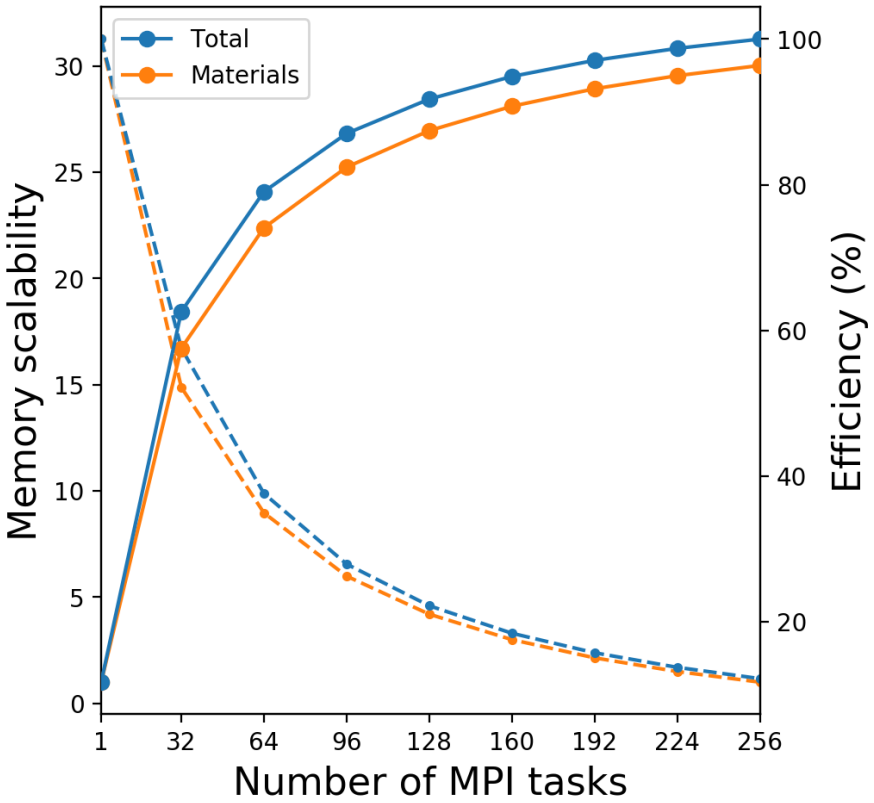
CDD performance in a PWR-like system

- 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).





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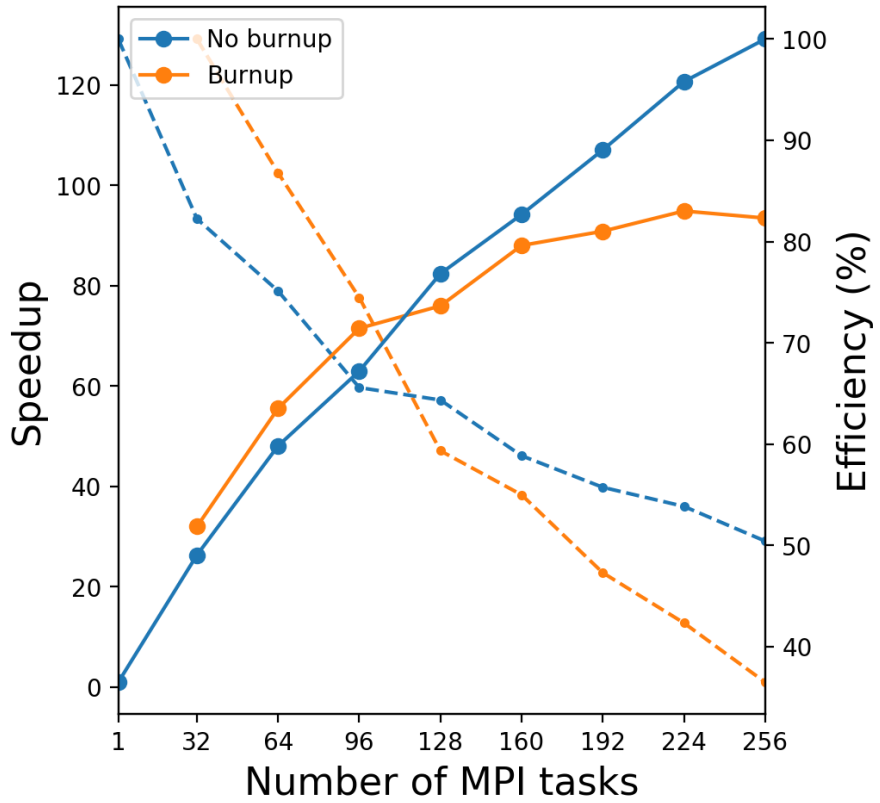
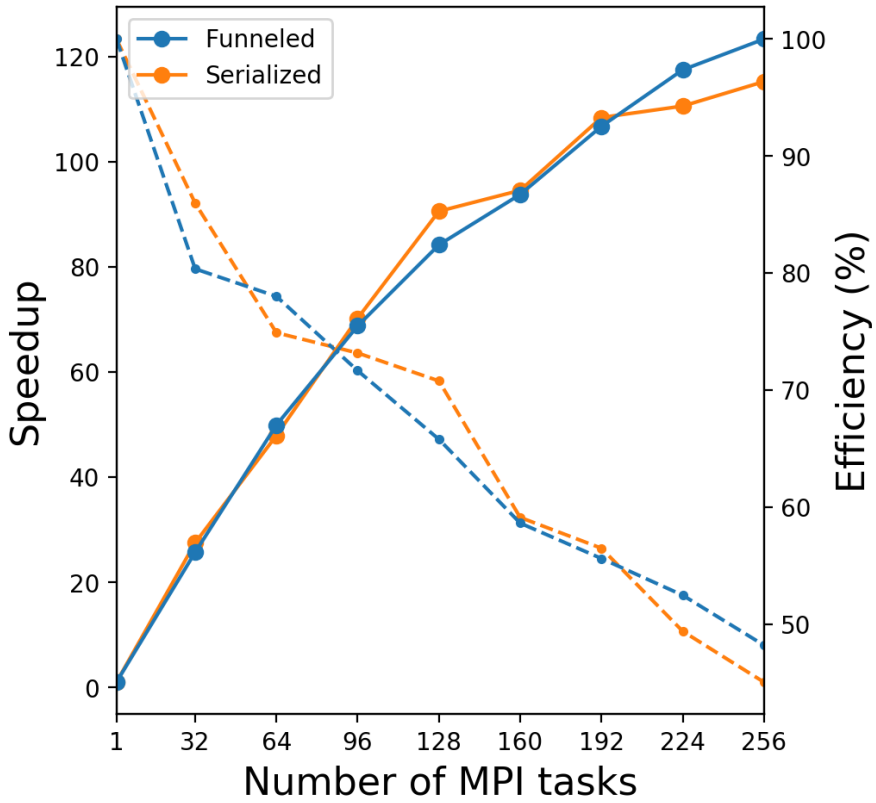
CDD performance in a PWR-like system

- 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.





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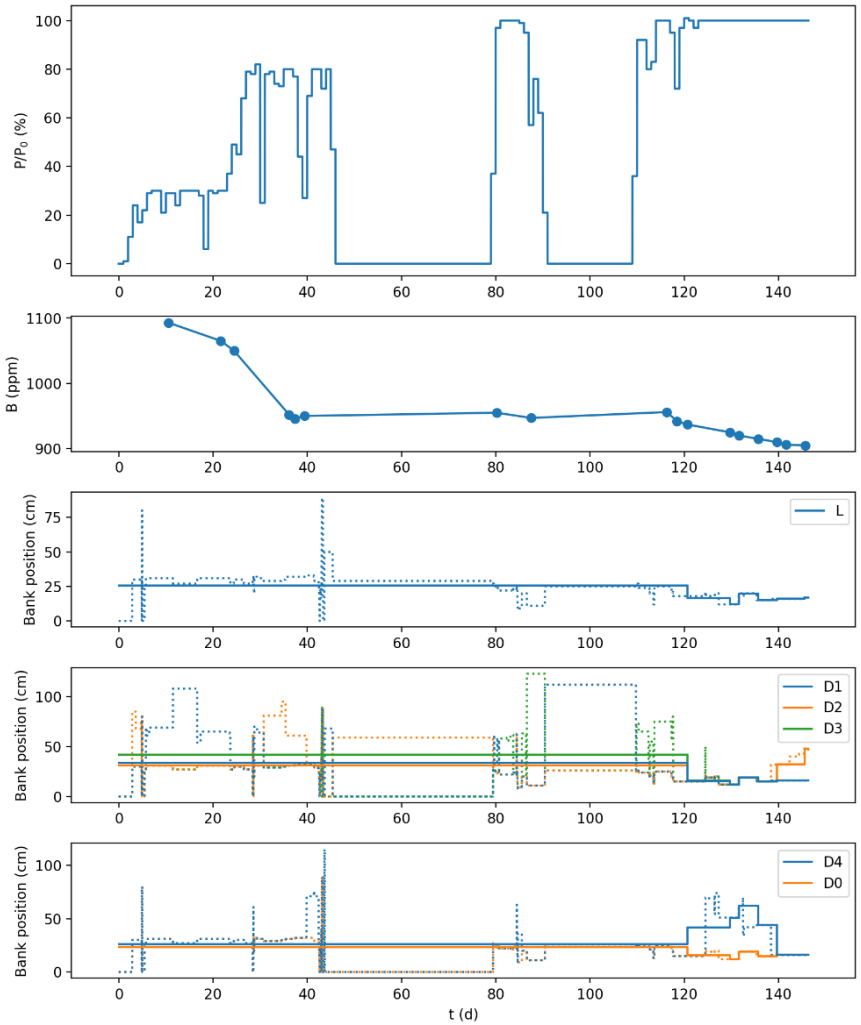
Validation for a Pre-Konvoi PWR reactor

- 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.



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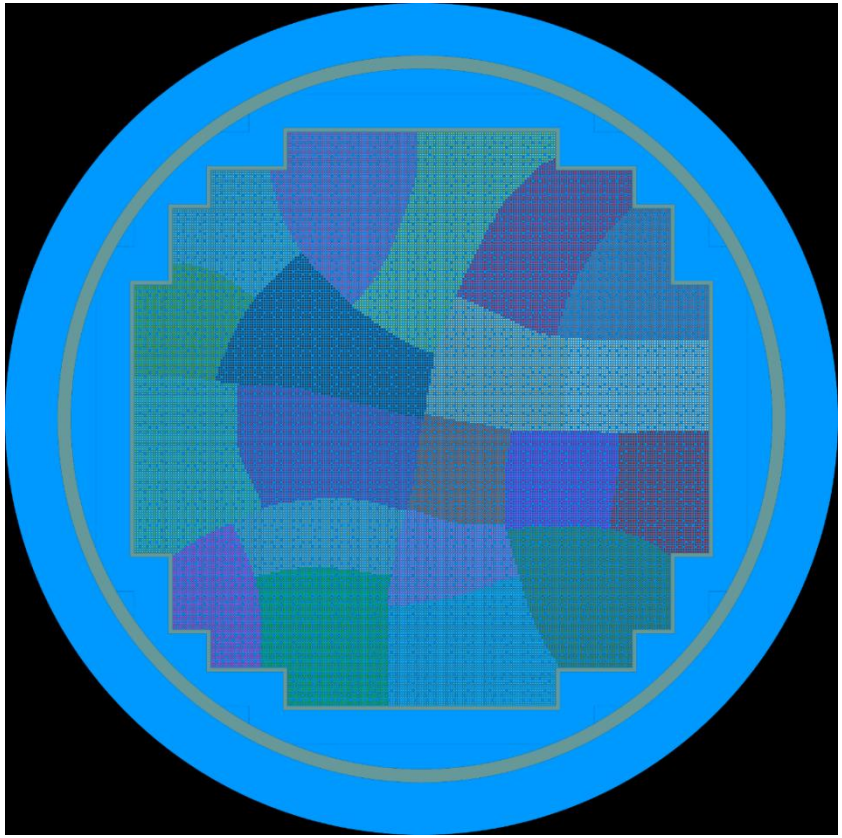
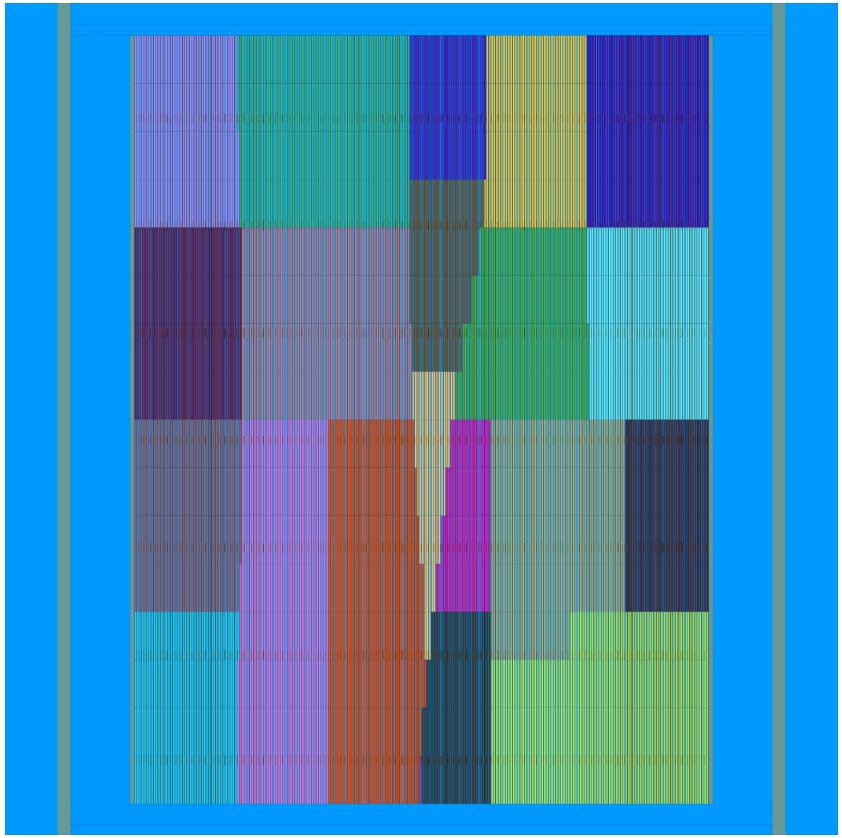
Material decomposition for CDD

- 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).





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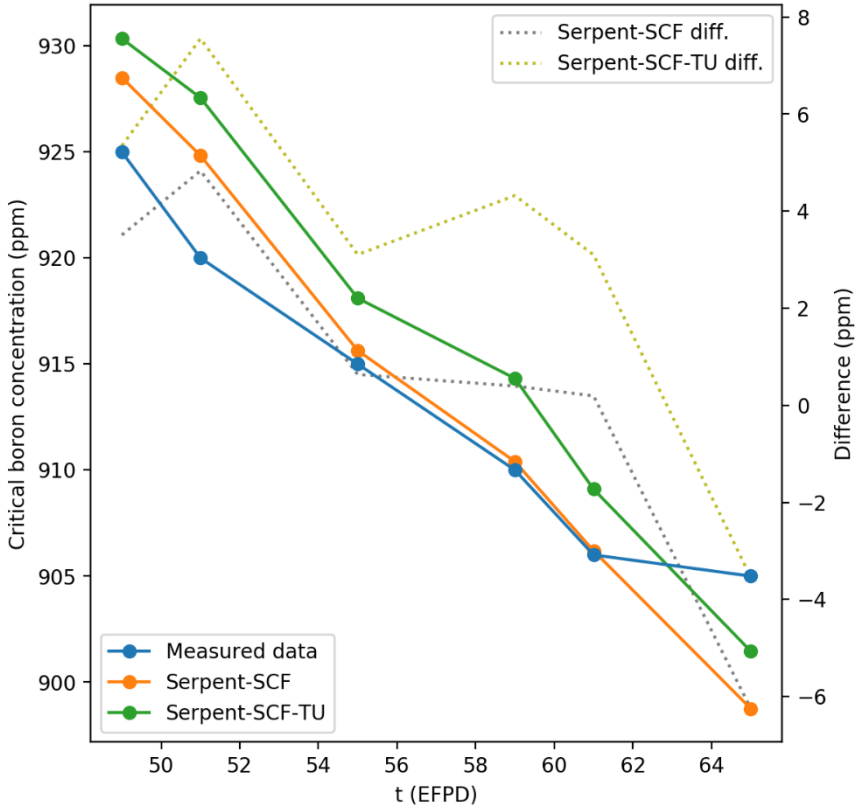
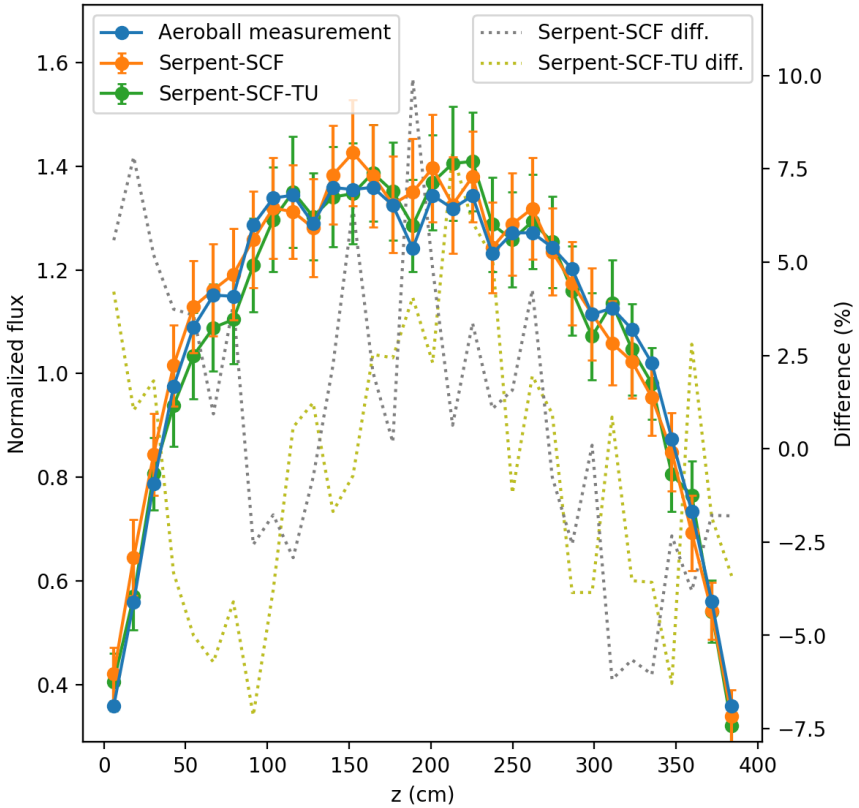
Validation results

- Good agreement between results and experimental measurements.
  - Differences in critical boron concentration within a few ppm.
  - Aeroball neutron flux profiles within the statistical range of the results.





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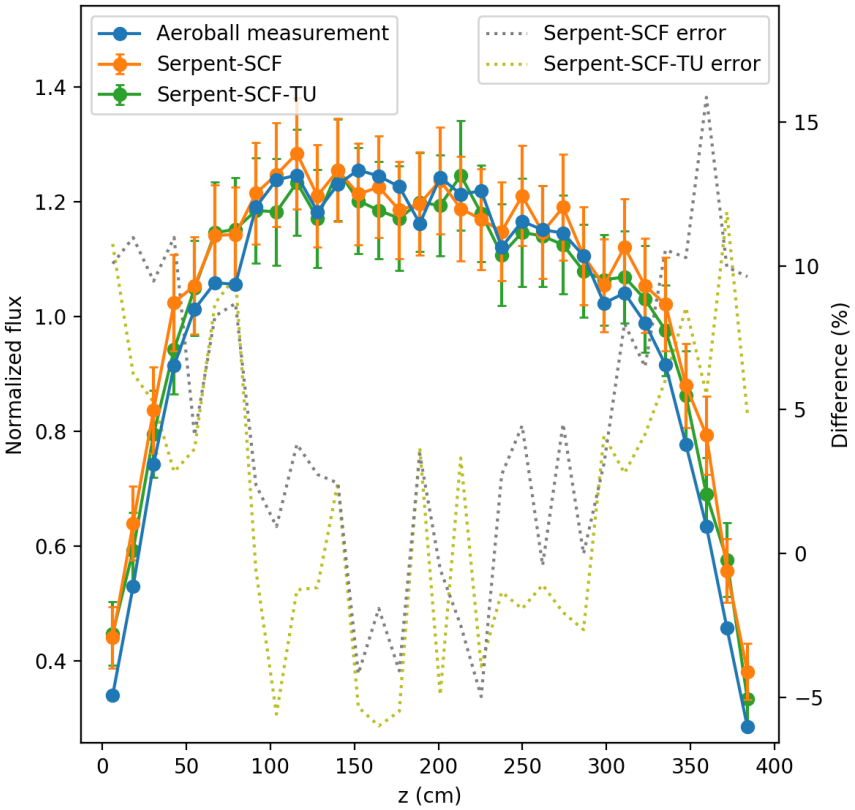
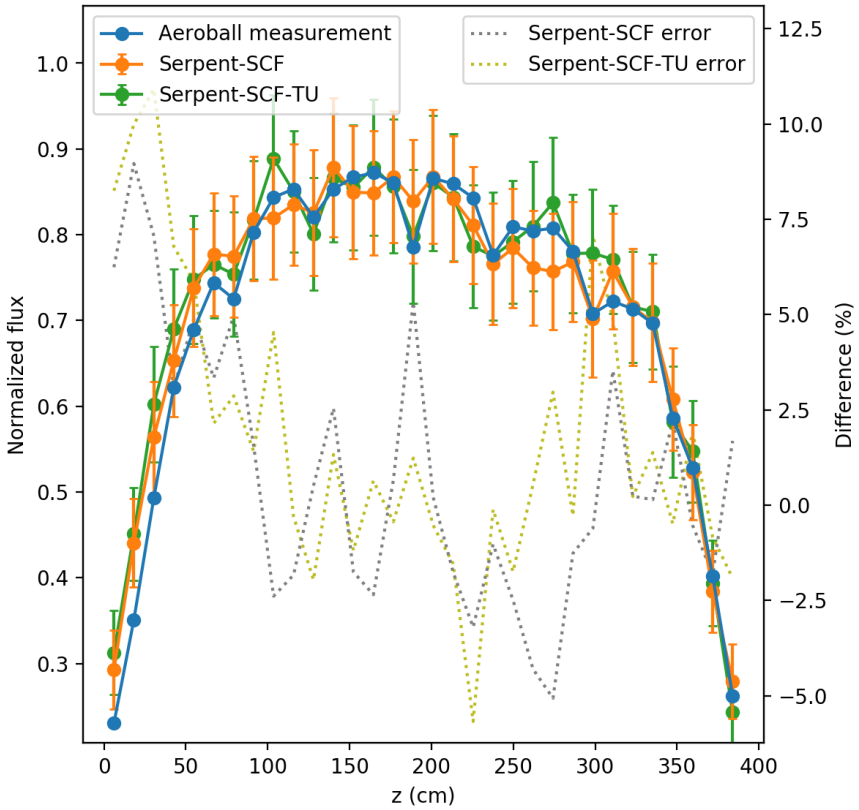
Validation results

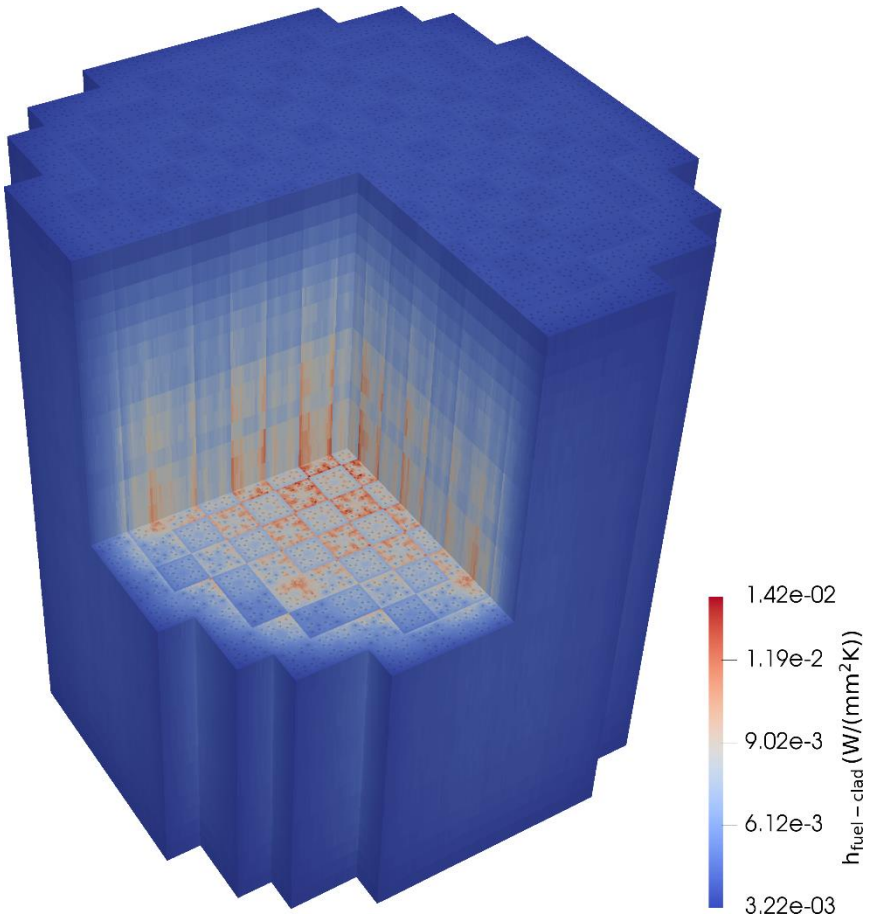
- Some more aeroball results (28 in total):

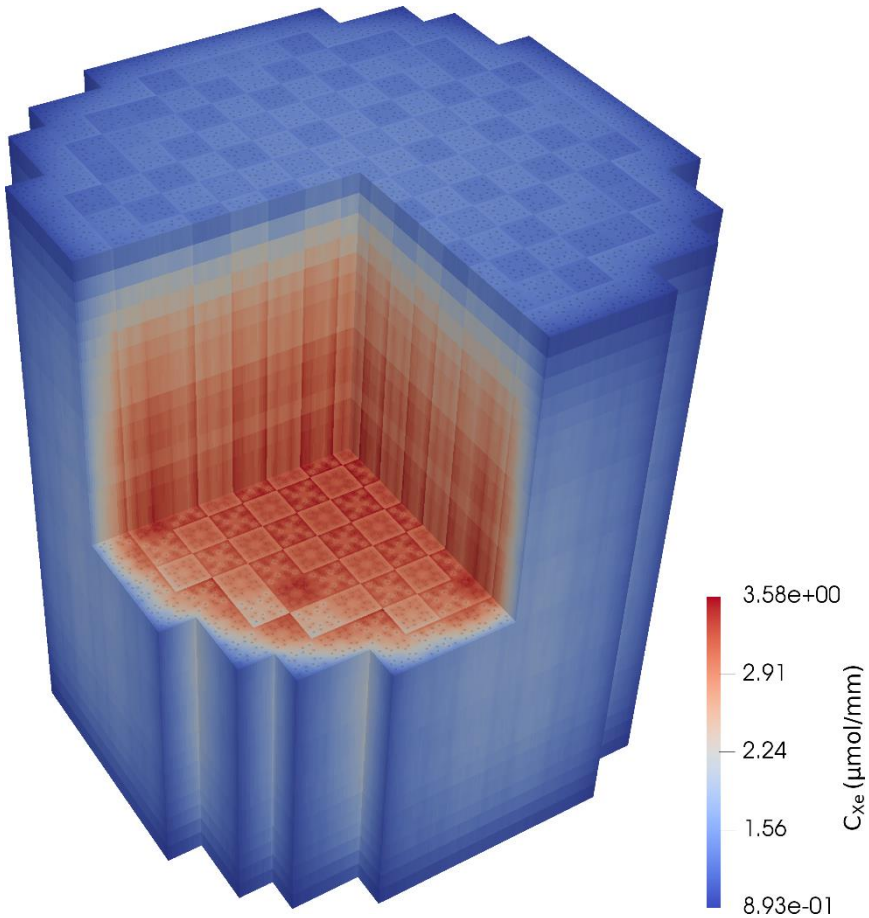




Fuel-performance capabilities

- Fuel-cladding gap conductivity and Xe release at 2.35 MWd/kg:





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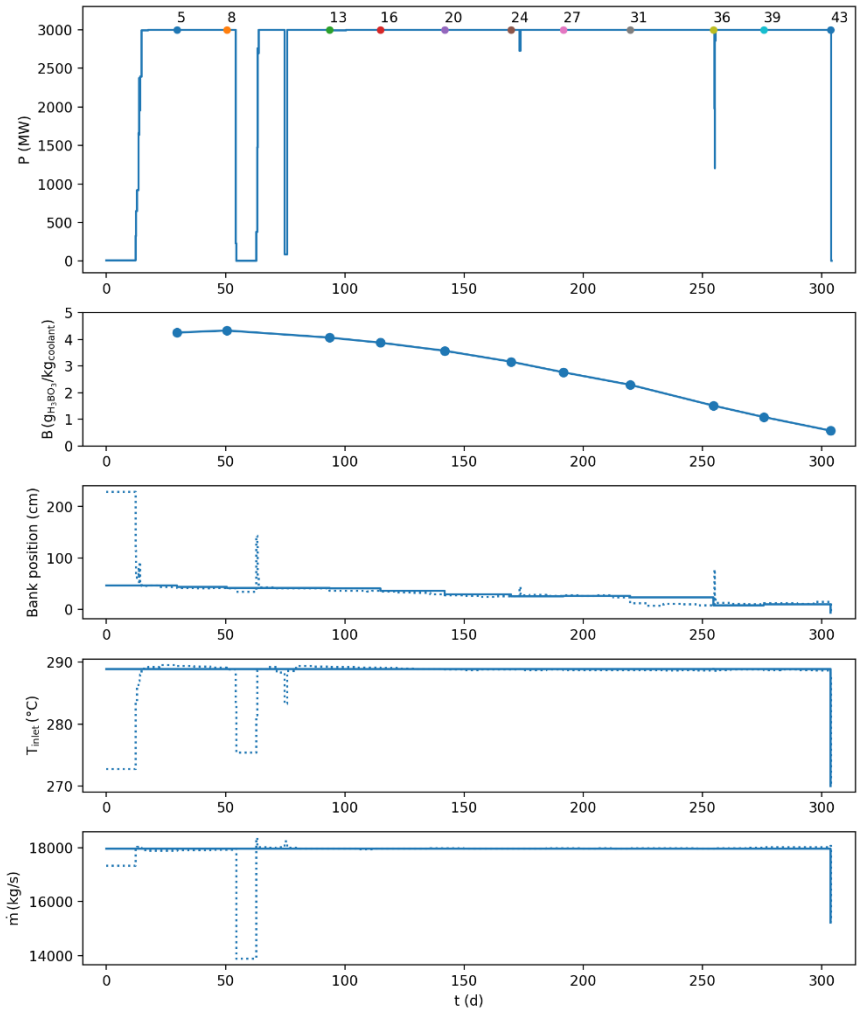
Validation for a VVER-1000 reactor

- 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.



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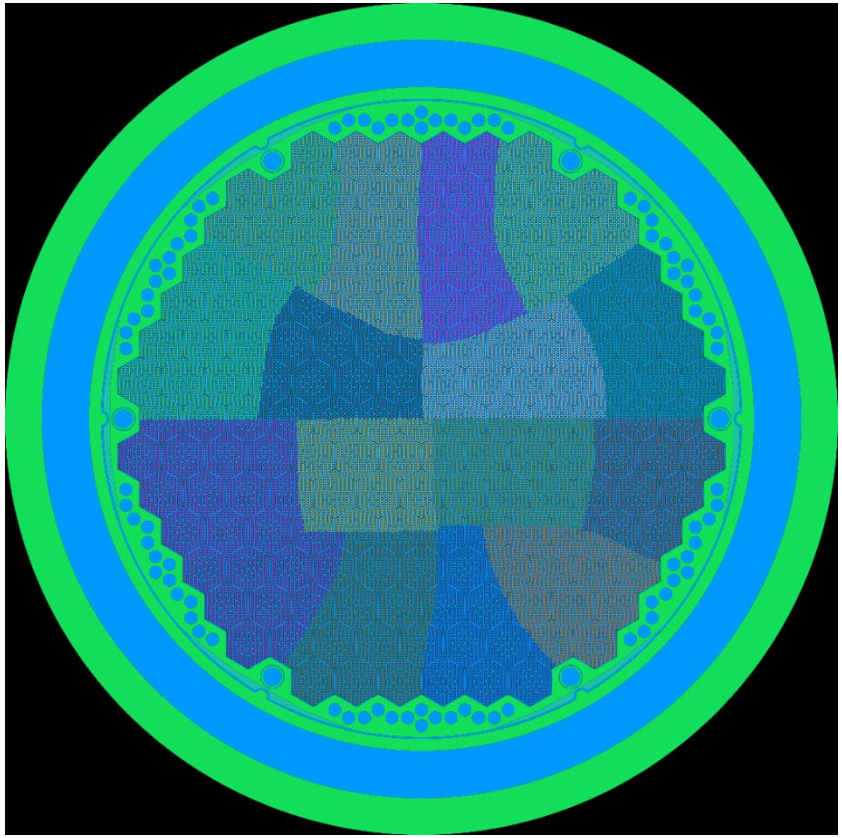

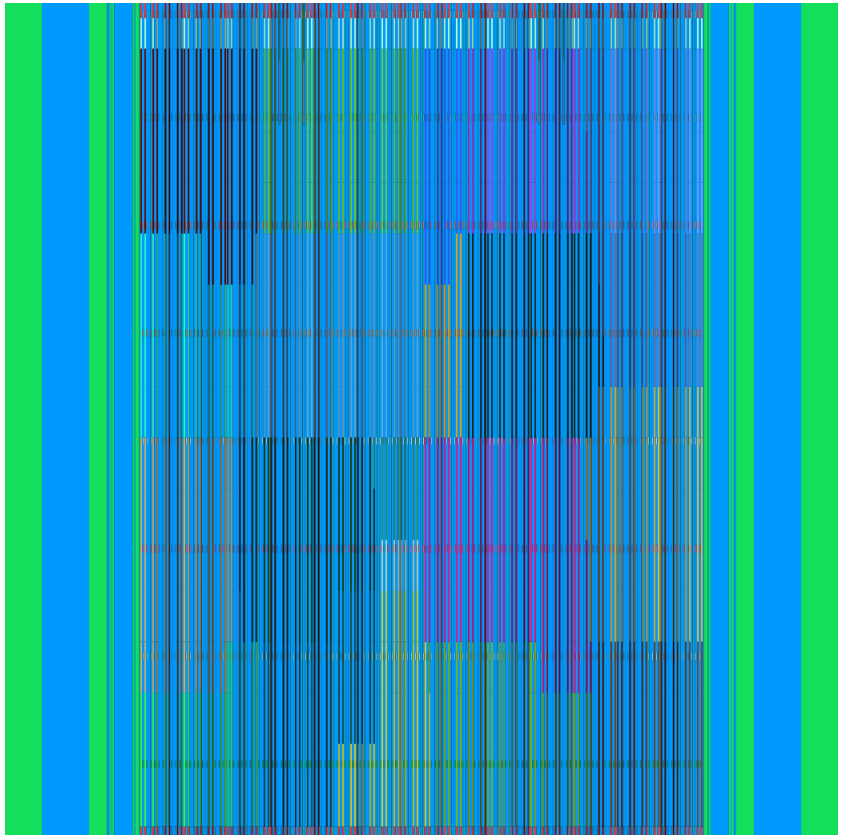

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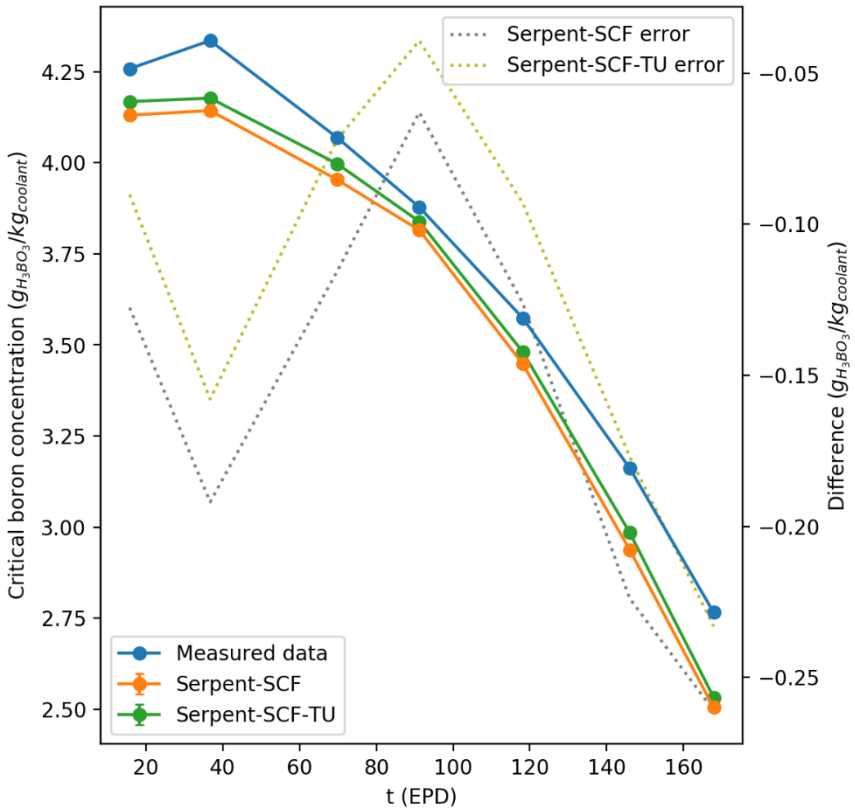
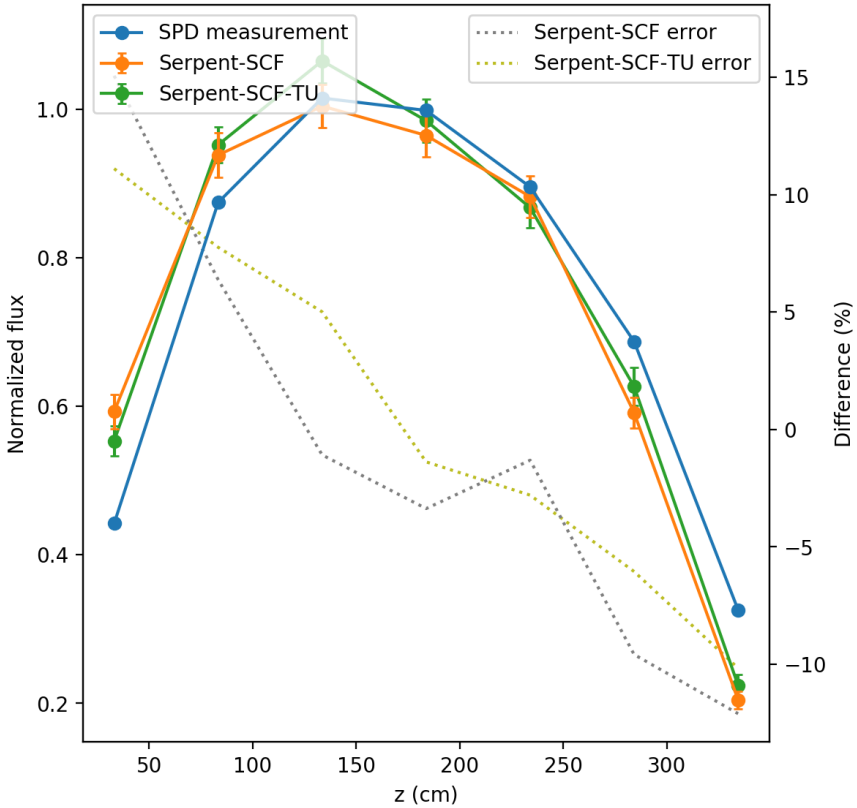
Validation results

- Good agreement between results and experimental measurements.
  - Differences in critical boron concentration within a few ppm.
  - Some good SPD results, some bad (some SPDs are up to 70% burnt).





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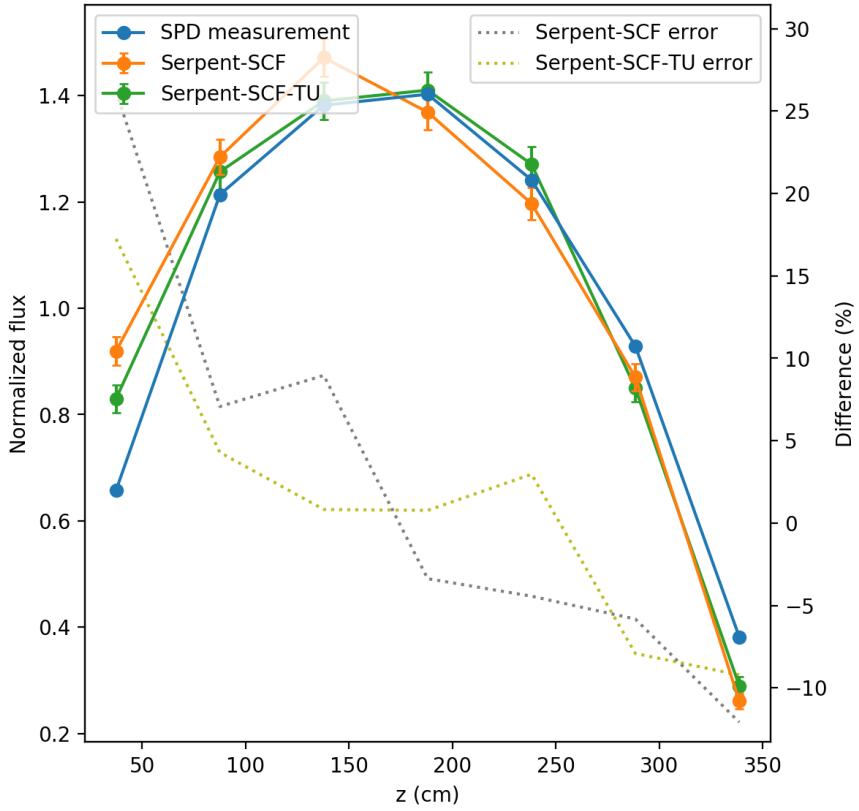
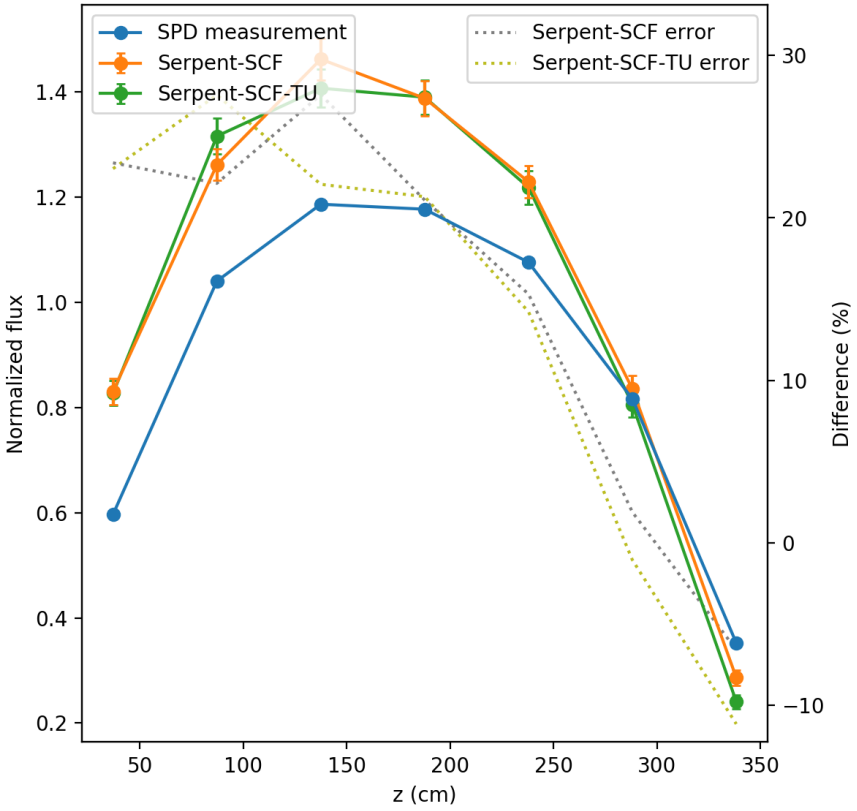
Validation results

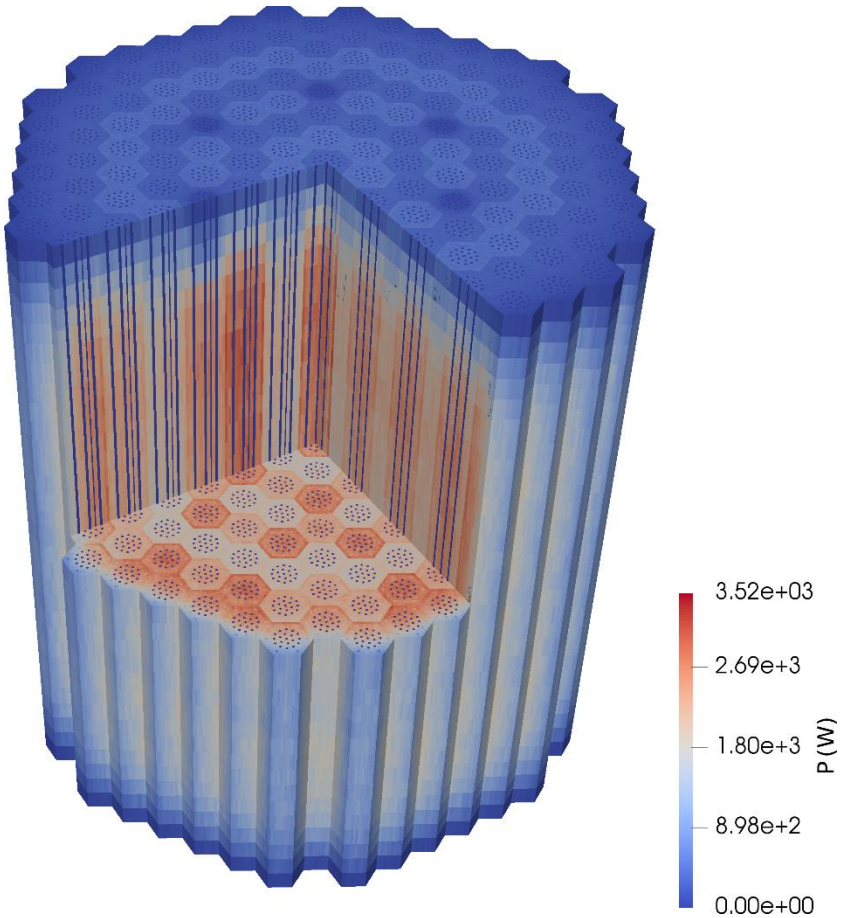
- Some more SPD results (64 in total):

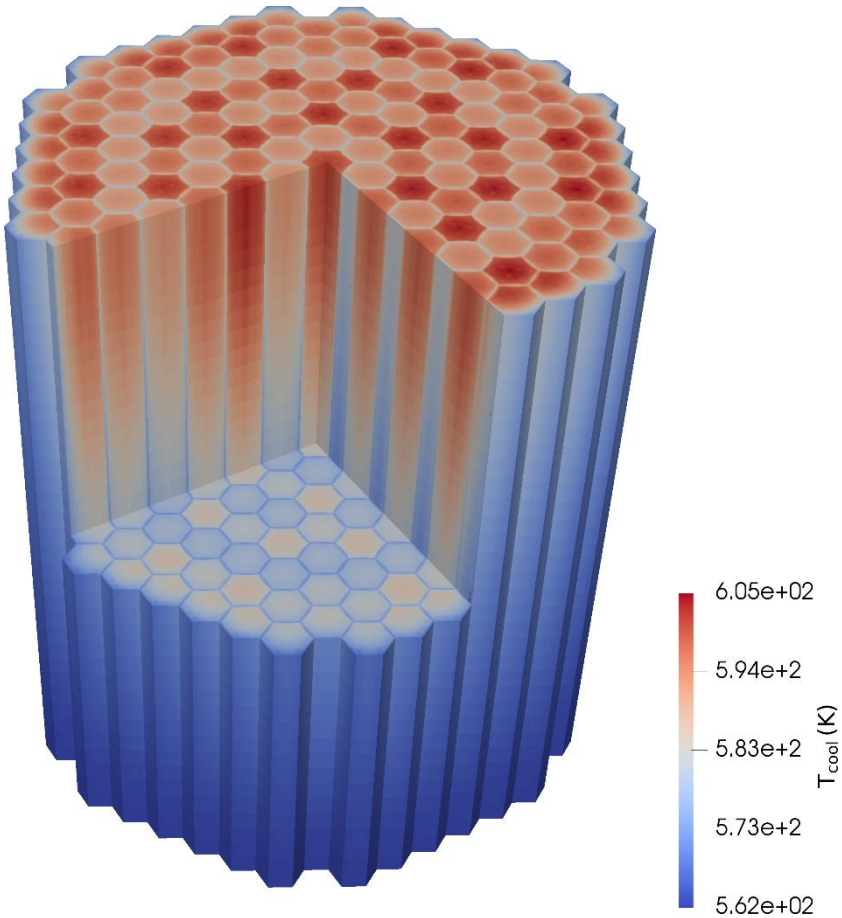




Power and coolant temperature (EOC)

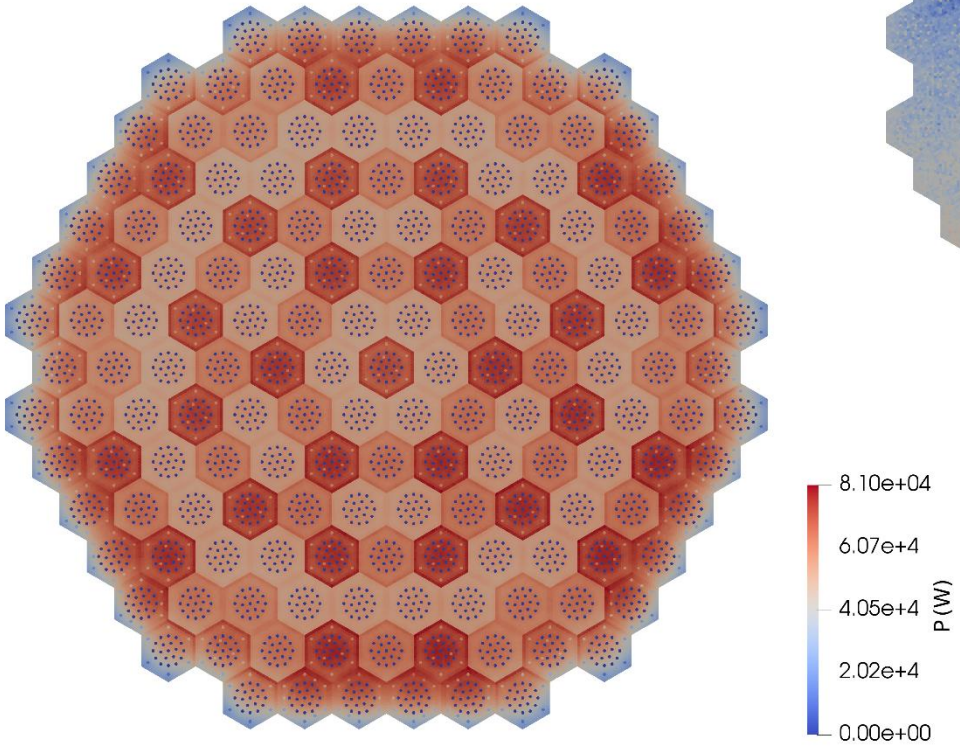
- Serpent-SCF-TU solution:

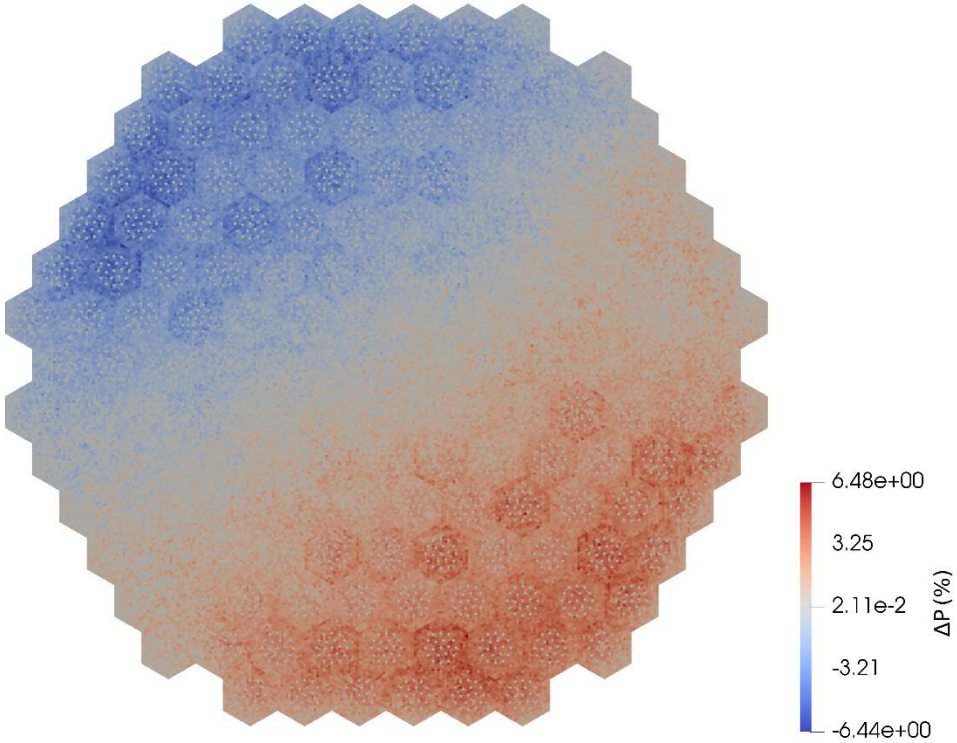




Power oscilations (EOC)

- Serpent-SCF-TU solution:





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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 (done).
  - VVER-1000 up to 280 EFPD (more challenging due to calculation time).
  - 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
ARIGATO
SHUKURIA
BOLZÏN
MERCI
BÏYAN
SHUKRIA
TINGKI
DANKSCHEEN
SPASSIBO
SNACHALHUYA
NUHUN
CHALTU
YAQHANYELAY
TASHAKKUR ATU
YUSPAGARÁTAM
WABEEJA
MAITEKA
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SUKSAMA
EKHMET
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EKOJU
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MEHRBANI
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SANCO
MERASTAWHY
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