Karlsruhe Institute of Technology

HIGH-FIDELITY PIN-BY-PIN ANALYSIS OF THE ROSTOV-2 CORE USING SERPENT2/SUBCHANFLOW

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Outline

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- Tools
- Rostov-2 VVER-1000 Core
  - BOC Characteristics
  - Core Loading
- Serpent 2 Pin Level Core Modeling
- Subchanflow Sub-channel Level Core Modelling
- Feedback exchange between Neutronic and Thermal-Hydraulic: Mesh-to-mesh superposition
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- SSS2/SCF Core Analysis
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- Conclusion and Outlook

Objectives

- Provide a reference solution for Rostov-2 Benchmark* Phase I with high-fidelity **pin-by-pin** Serpent2(SSS2)/Subchanflow(SCF)**.

- Perform full-core pin-by-pin **burnup** calculation taking into account local thermal-hydraulic feedback.

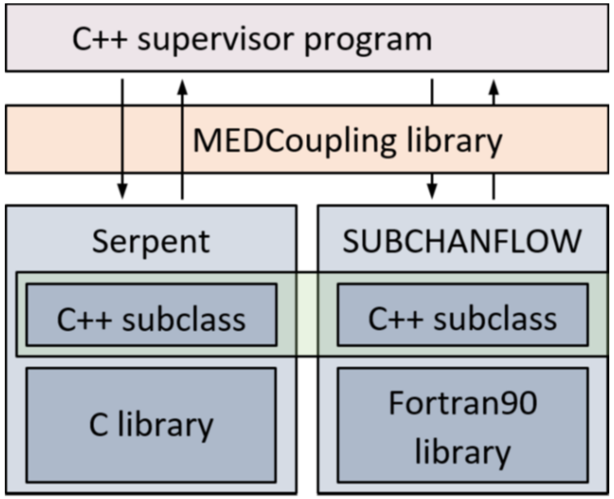
- Detailed model for the begin-of-cycle (BOC) Rostov-2 VVER-1000 **fresh-core** want to be develop.

* M. Avramova, K. Ivanov, K. Velkov, S. Nikonov, P. Gordienko, B. Shumskiy and O. Kavun, "Benchmark on reactivity compensation of boron dilution by stepwise insertion of control rod cluster into the VVER-1000 core, Specifications and Support Data, Version 1.6," OECD/NEA. NEA/EGMPEBV/DOC(2021), Paris, 2021.

** Manuel García, 2021, A high-fidelity multiphysics system for neutronic, thermalhydraulic and fuel-performance analysis of Light Water Reactors. PhD thesis, Karlsruhe Institute of Technologie (KIT), Karlsruhe, GERMANY

Tools (1/2):
ICoCo-based coupling of SSS2/SCF

- SSS2 and SCF modularized as object-oriented approach and coupling scheme implemented in a separate supervisor program.
- The codes are implemented as a C++ solver class derived from a common base class, defining a standard coupling interface and masking the internal calculation methods, data structures and programming languages.
- The base class is defined by Interface for Code coupling (ICoCo).
- The codes are kept completely separate and maintainability is enhanced.
- The coupling through the supervisor is flexible and generic.
- Provide pin-level feedback, fully coupled calculation scheme.
- Mesh-based field exchange of variables with using MEDCoupling library.

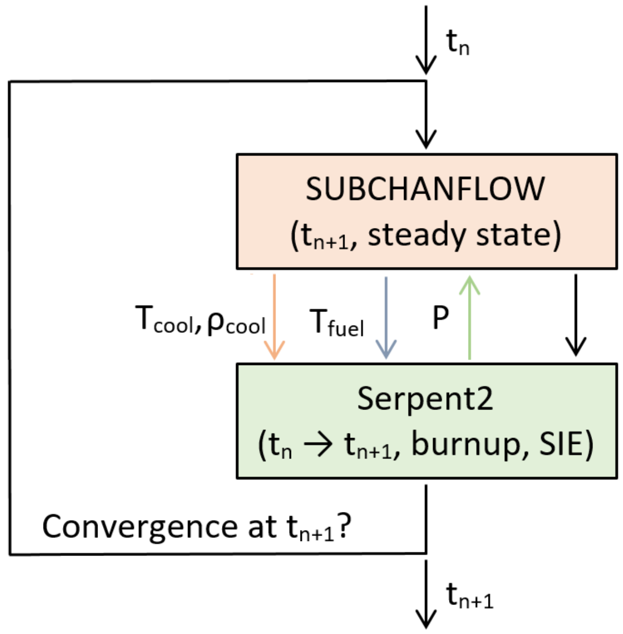


Object-oriented coupling

Manuel García, 2021, A high-fidelity multiphysics system for neutronic, thermalhydraulic and fuel-performance analysis of Light Water Reactors. PhD thesis, Karlsruhe Institute of Technologie (KIT), Karlsruhe, GERMANY

Tools (2/2):
Multiphysics Depletion Scheme

- The algorithm is based on operator-splitting method with a semi-implicit iterative scheme.
- Code-to-code feedback is done using the fields at the end of the step (EOS) and convergence at EOS is achieved iterating each burnup step.
- First, SCF steady-state calculation performed to get the cooling conditions for the SSS2 power distributions at EOS.
- For the first iteration in each burnup step, when the Serpent solution at EOS has not yet been estimated, the power at the beginning of the step (BOS) is utilized in SCF.
- Serpent perform a burnup iteration using the SIE method with the thermal-hydraulic conditions at EOS. The SIE depletion scheme includes on averaging the solutions at EOS for all iterations within each burnup step to accumulate statistics and stabilize the solution.
- The **steady-state solution at t_0=0**, which need to be calculated before the burnup calculation, is obtained with the same iterative scheme starting from an initial guess for the power, typically a uniform distribution or a result from a previous run.



Depletion scheme

- Serpent simulation has massive calculation, therefore it should be carried out with the latest thermal-hydraulic data.

Manuel García, 2021, A high-fidelity multiphysics system for neutronic, thermalhydraulic and fuel-performance analysis of Light Water Reactors. PhD thesis, Karlsruhe Institute of Technologie (KIT), Karlsruhe, GERMANY

Rostov-2 VVER 1000 Core (1/2)

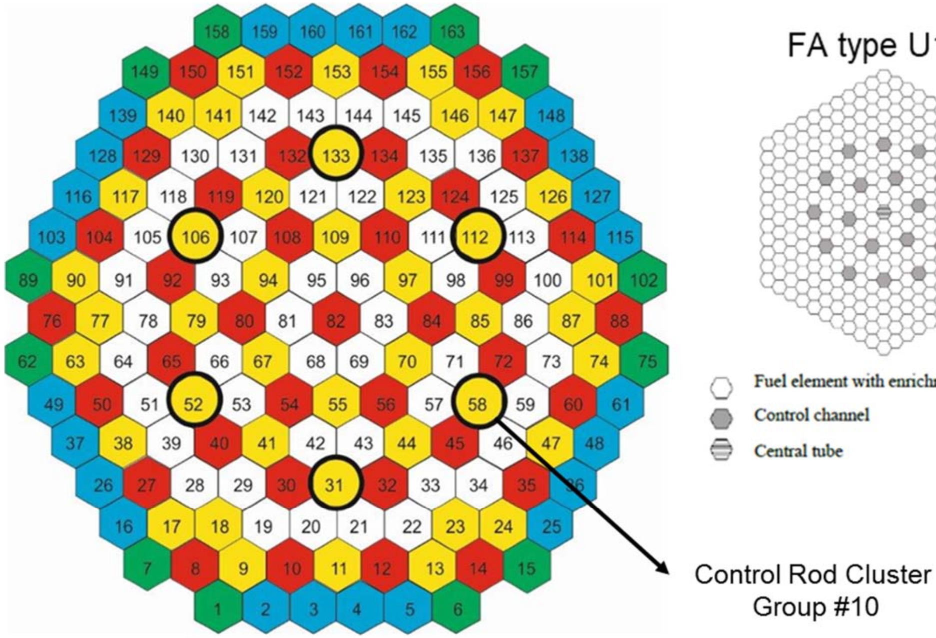
BOC Characteristics

- Core loading at BOC (Date: 20.02.2010)
  - Effective day (TEF)= 0.0
  - Fuel Assemblies: 163 FAs with 5 different types loaded
  - Control Assemblies: 10 CR group banks located in 61 FAs
    - Control Rod position: CR group 1-9 out and only CR group 10 72.9% (from core bottom) inserted
  - Boric Acid concentration: 6.5 g/kg
    - Boric Acid (H_3BO_3) density= 1.435 g/cm^3

- Thermal-hydraulic parameters at BOC
  - Core power= 44.4 MW
  - T_{inlet}= 552.95 K
  - System Pressure= 15.7 MPa
  - Total circuits mass flow rate (100% total flow)=87342.7 m^3/h (18558.29 kg/s)
    - Core mass flow rate (97% of the total mass circuit flow) =18001.53 kg/s

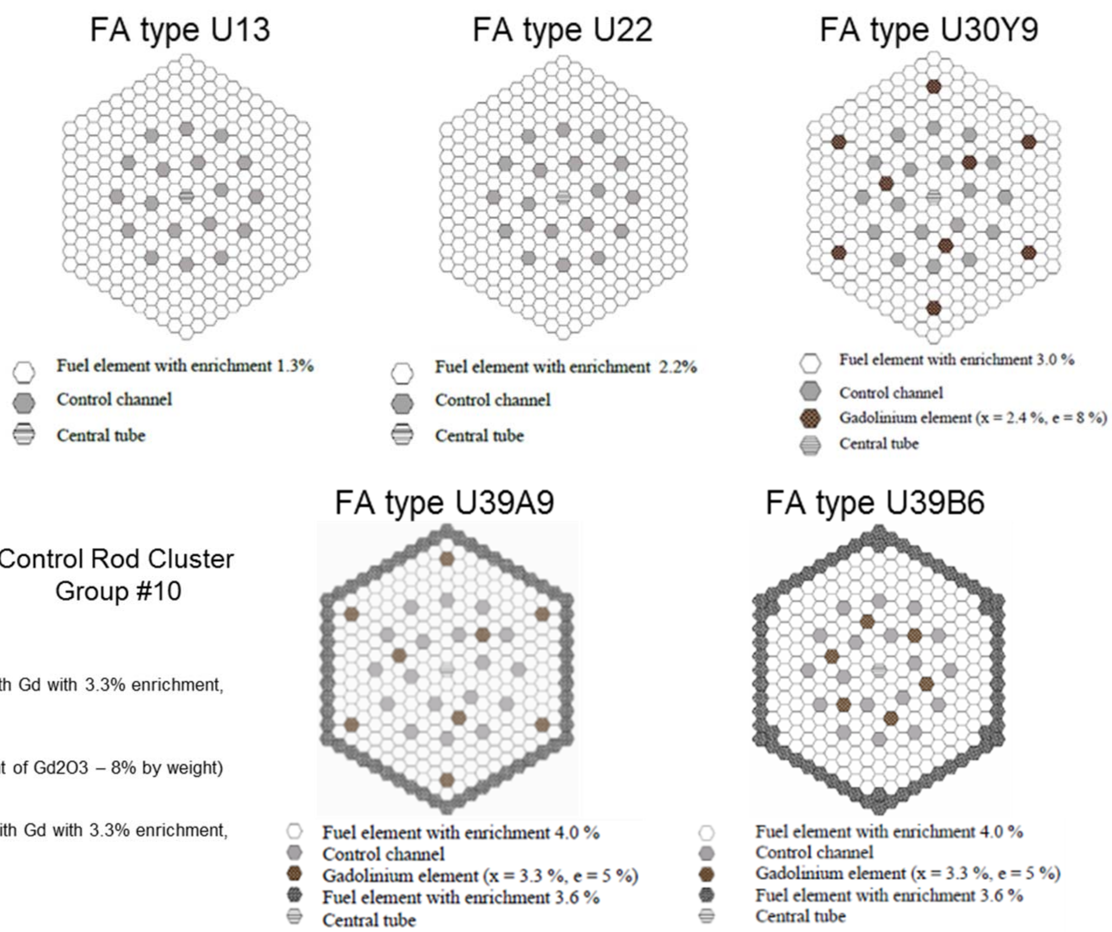
Rostov-2 VVER 1000 Core (2/2)

Core Loading



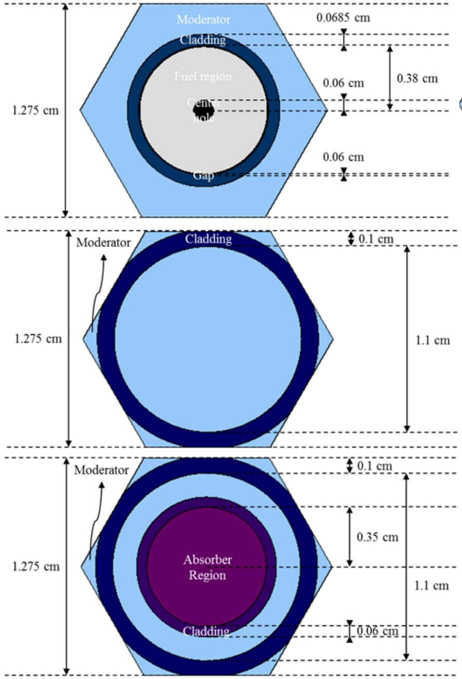
- FA type U39A9 with Uranium-235 3.89% average enrichment (243 fuel rods with 4.0% enrichment, 60 fuel rods with 3.6% enrichment, 9 fuel rods with Gd with 3.3% enrichment, content of Gd2O3 – 5%)
- FA type U30Y9 with Uranium-235 2.98% average enrichment (303 fuel rods with 3.0% enrichment, 9 fuel rods with Gd with 2.4% enrichment, content of Gd2O3 – 8% by weight)
- FA type U39B6 with Uranium-235 3.9 % average enrichment (240 fuel rods with 4.0% enrichment, 66 fuel rods with 3.6 % enrichment, 6 fuel rods with Gd with 3.3% enrichment, content of Gd2O3 – 5%)
- FA type U22 with Uranium-235 2.2% enrichment
- FA type U13 with Uranium-235 1.3% enrichment

Fuel-loading map of the reactor core of Rostov Unit 2, Cycle 1

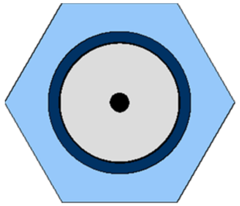


Radial arrangement of elements in the fuel assemblies

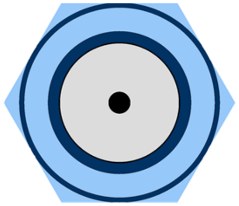
Serpent 2 Pin Level Core Modeling (1/2)



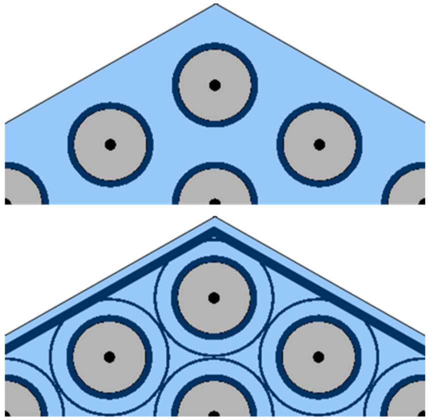
Pin cell models



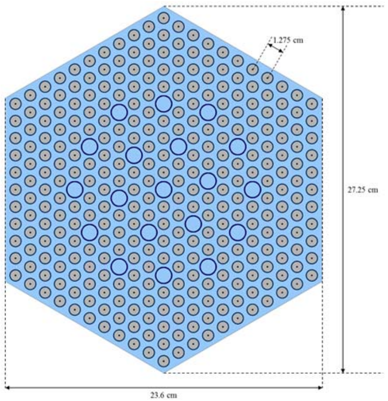
Pin cell model without spacer grid



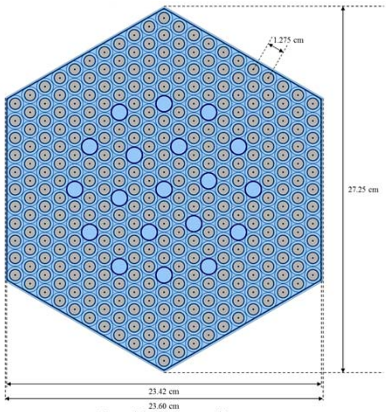
Pin cell model with spacer grid



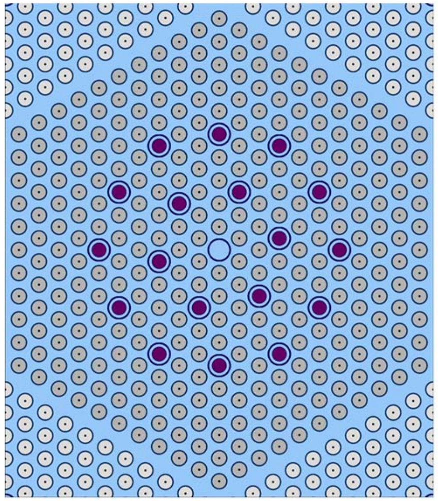
Spacer Grid views



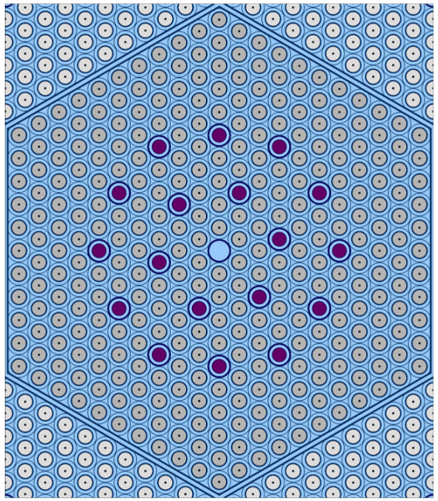
FA model without spacer grid



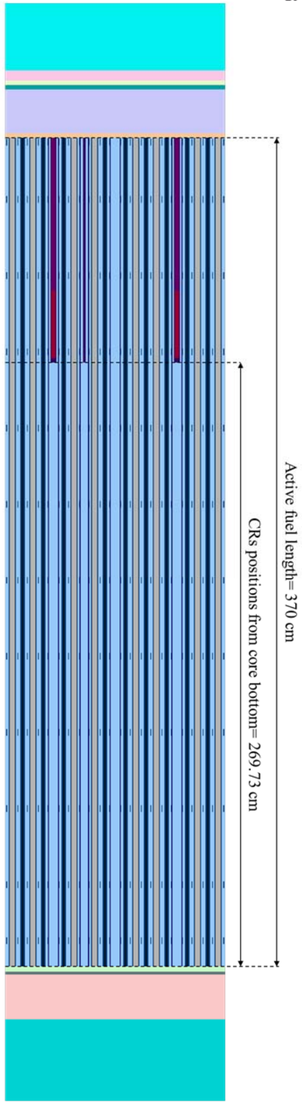
FA model with spacer grid



Radial view of partly CR inserted FA model without spacer grid

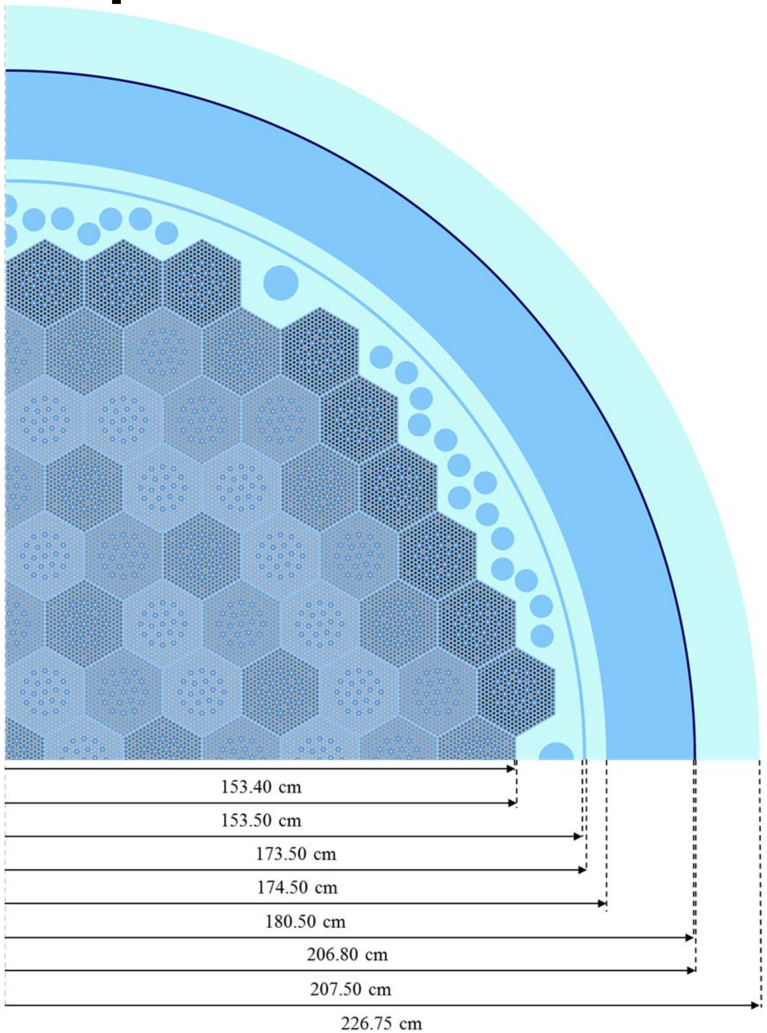


Radial view of partly CR inserted FA model with spacer grid

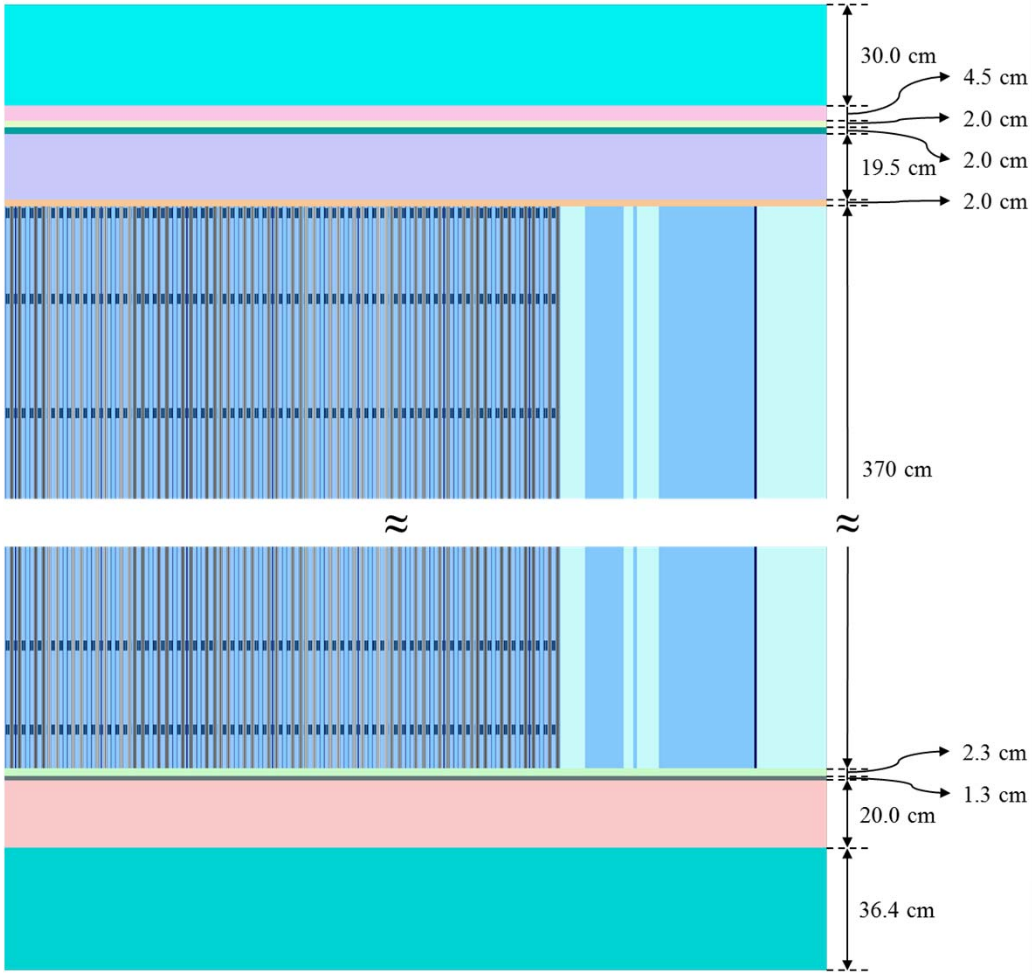


Axial view of partly CR inserted FA model with spacer grid

Serpent 2 Pin Level Core Modeling (2/2)

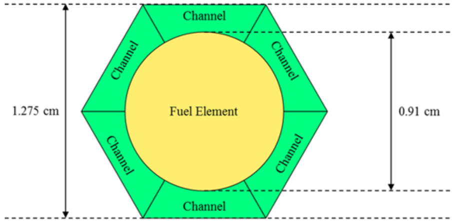


SERPENT2 XY cut figure of ¼ the core
with radial reflectors dimensions

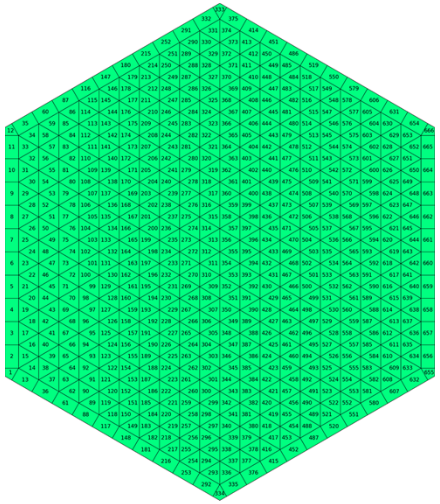


SERPENT2 XZ cut figure of ½ the core
with axial reflectors dimensions

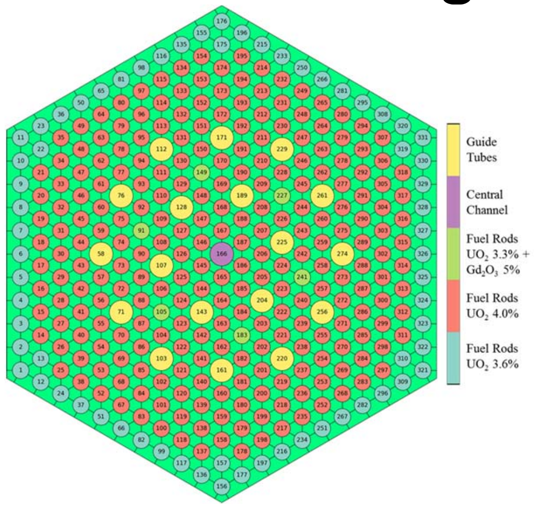
Subchanflow Sub-channel Level Core Modelling



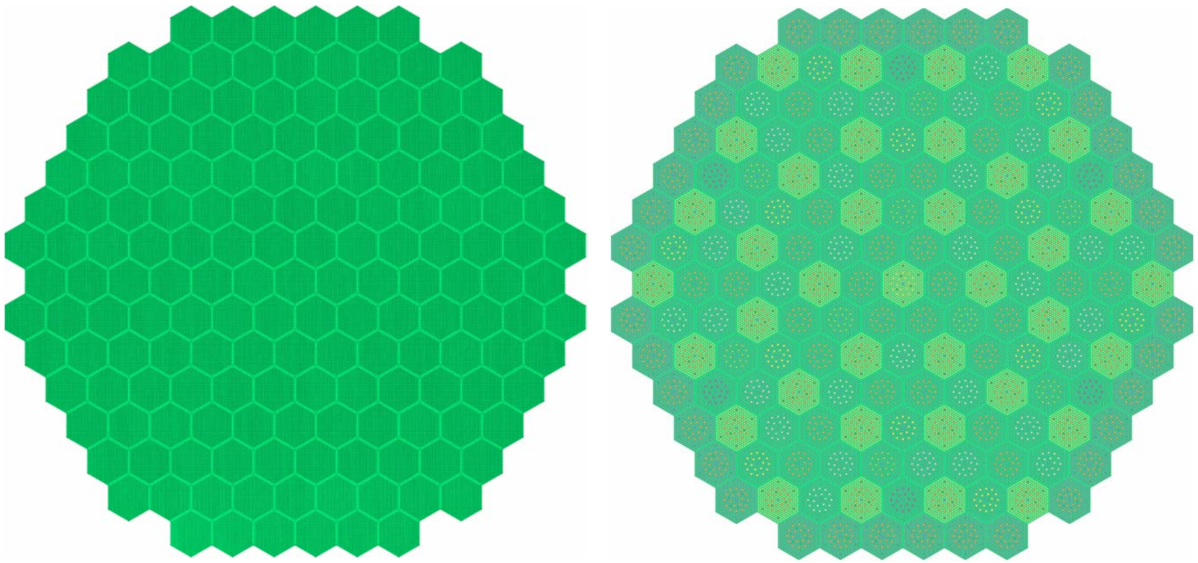
SCF rod centered model



SCF FA model - channel indexing



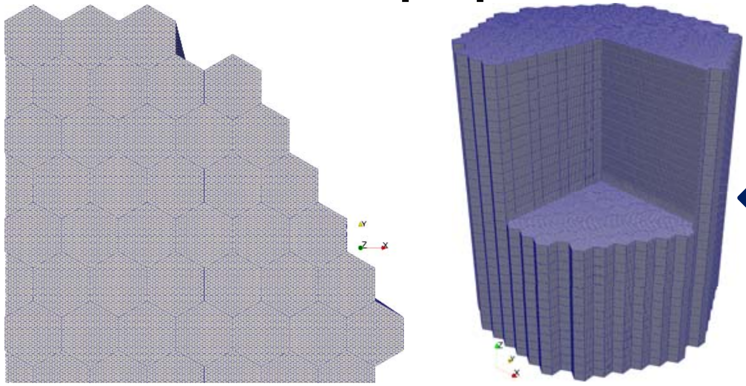
SCF FA model - rod indexing



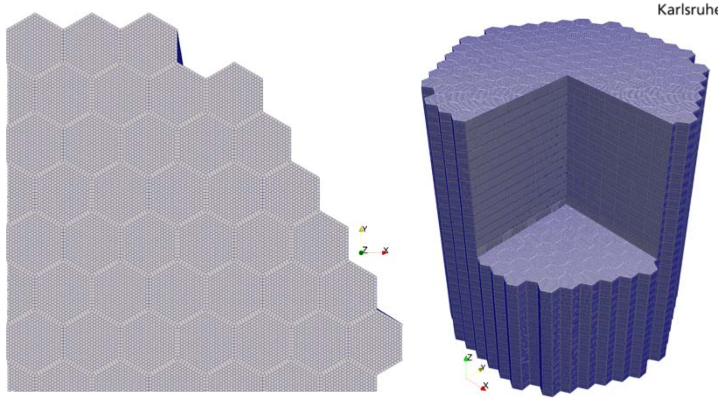
SCF Core model - channel and rod indexing

- Python based preprocessor was used to generate rod and channel layout and connectivity relations.

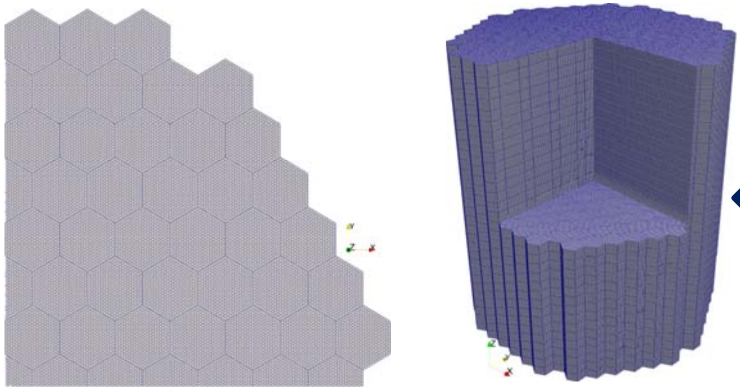
Feedback exchange between Neutronic and Thermal-Hydraulic: Mesh-to-mesh superposition



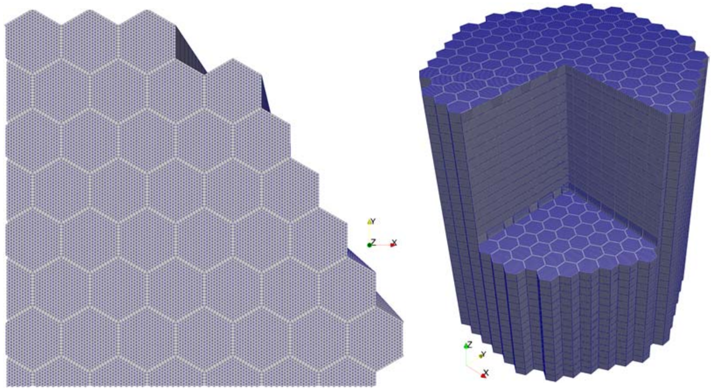
SSS2 **fuel** feedback mesh for the core



SCF **fuel** mesh for the core



SSS2 **coolant** feedback mesh for the core



SCF **coolant** mesh for the core

- SERPENT2 (30 Axial Nodes)
  - 30 nodes*53953 coolant area= 1,618,590 coolant area and 30 nodes*53953 rods= 1,618,590 divided rod
  - Not linked directly to the tracking geometry.
  - Mesh superimposed to the geometry to define densities and temperatures.
- SUBCHANFLOW (30 Axial Nodes)
  - 30 nodes*103512 sub-channels= 3,105,360 channels and 30 nodes*53953 rods= 1,618,590 divided rod
  - Coolant and fuel meshes to define the channel and rod geometry.

SSS2/SCF Criticality Simulation Features

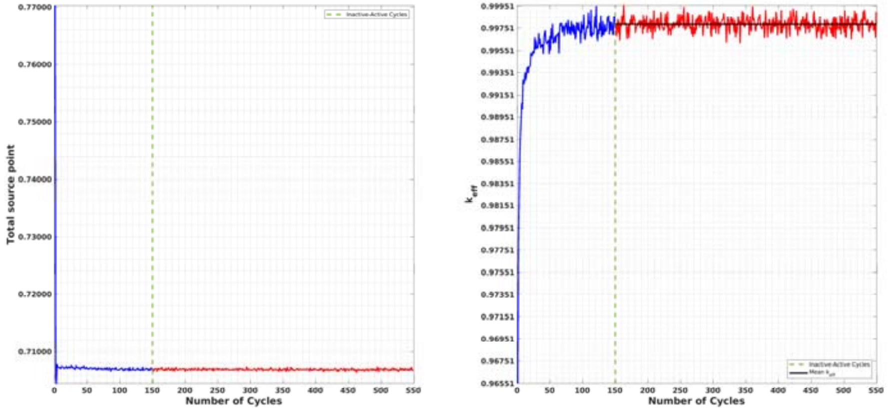
- Serpent 2
  - Serpent 2 Version 2.1.32
  - Active cycle and inactive cycle: **400** and **150**, respectively
  - Particle number: **1,000,000**
  - **tft** temperature card option for the multi-physics calculations
  - **ifc** used files for multi-physics interface
  - ENDF/B-VII neutron library

- Subchanflow
  - SCF Version 3.7.1
  - VVER-specific thermophysical properties in SCF was used.
  - Axially **30** nodes
  - Doppler temperature predicted as in benchmark formulation.

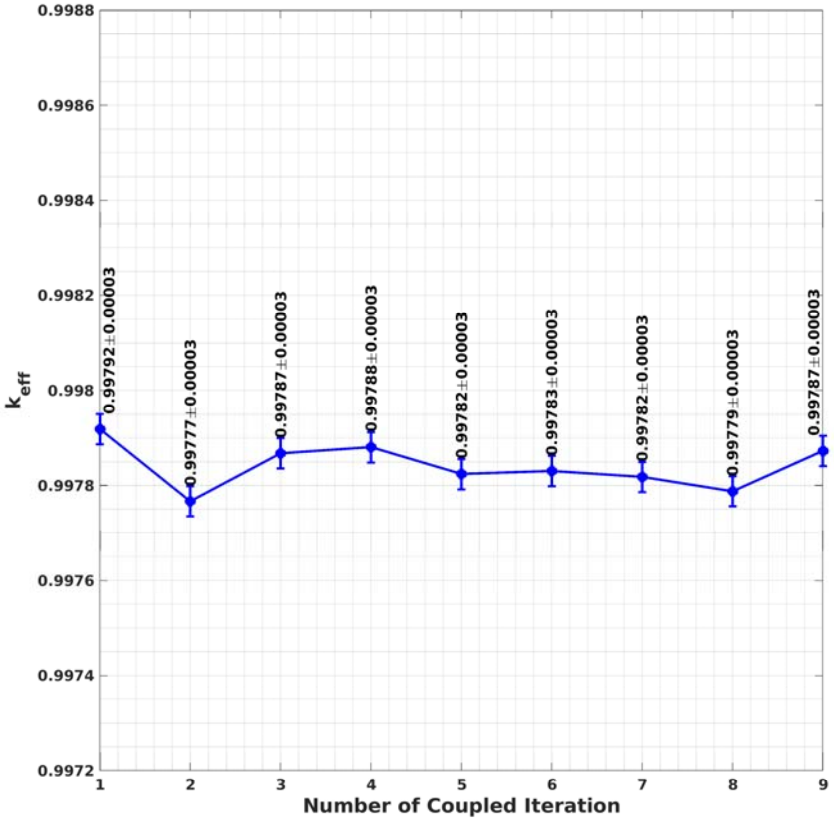
- Simulation Architecture
  - 20 OpenMPI node and 76 OpenMP task for the coupled simulation on HoreKa HPC (KIT/SCC).
    - Intel Xeon Platinum 8368
  - Convergence criteria:
    - $k_{effective}$: **30 pcm**
    - Coolant Density: **0.001 g/cm^3**
    - Fuel Temperature: **10 K**
    - Power: **1% in L2 norm**

SSS2/SCF Core Analysis

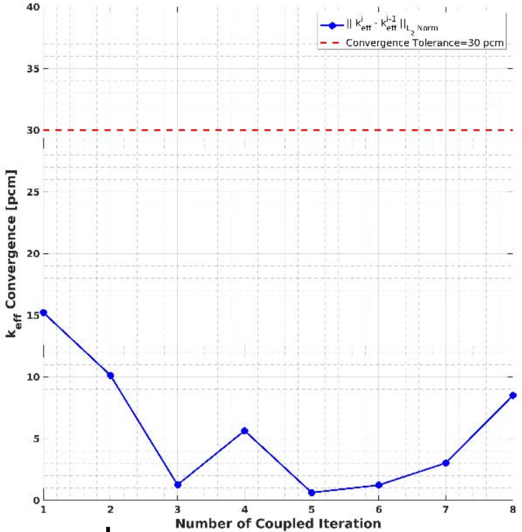
➤ Global Results



Shannon entropy distribution and k_{eff} history



k_{eff} results for iterations



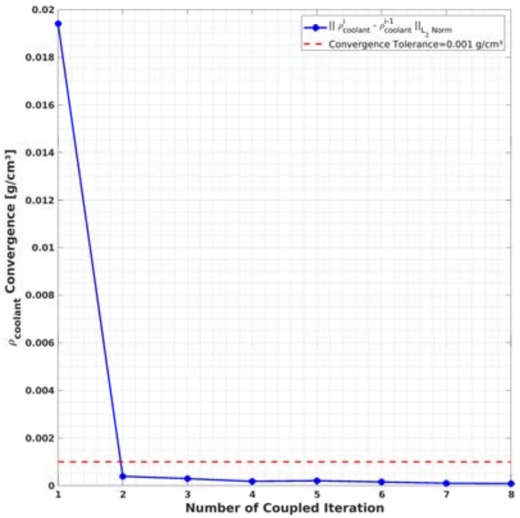
k_{eff} convergence

$k_{effective}$	0.99787 ± 3.0E-05
$\rho_{initial}$	-213 pcm ± 3.0E-05

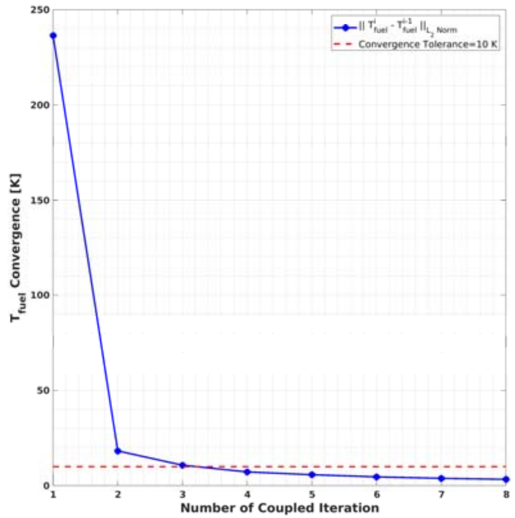
SSS2/SCF Core Analysis

- Convergence Results
  - Convergence tolerance calculation for the multiphysics simulation

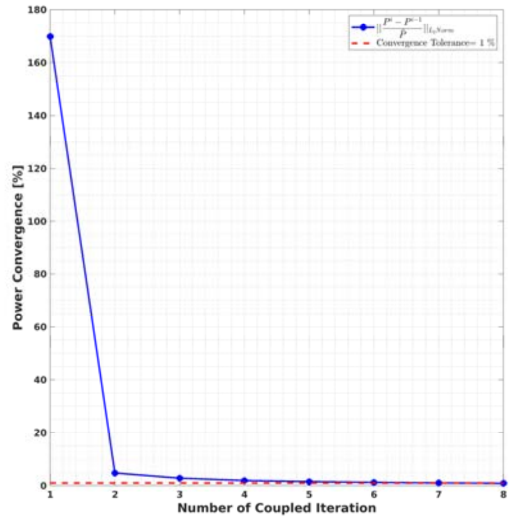
$$||x_i(\vec{r}) - x_{i-1}(\vec{r})||_{L_2} < \epsilon$$



Coolant density convergence



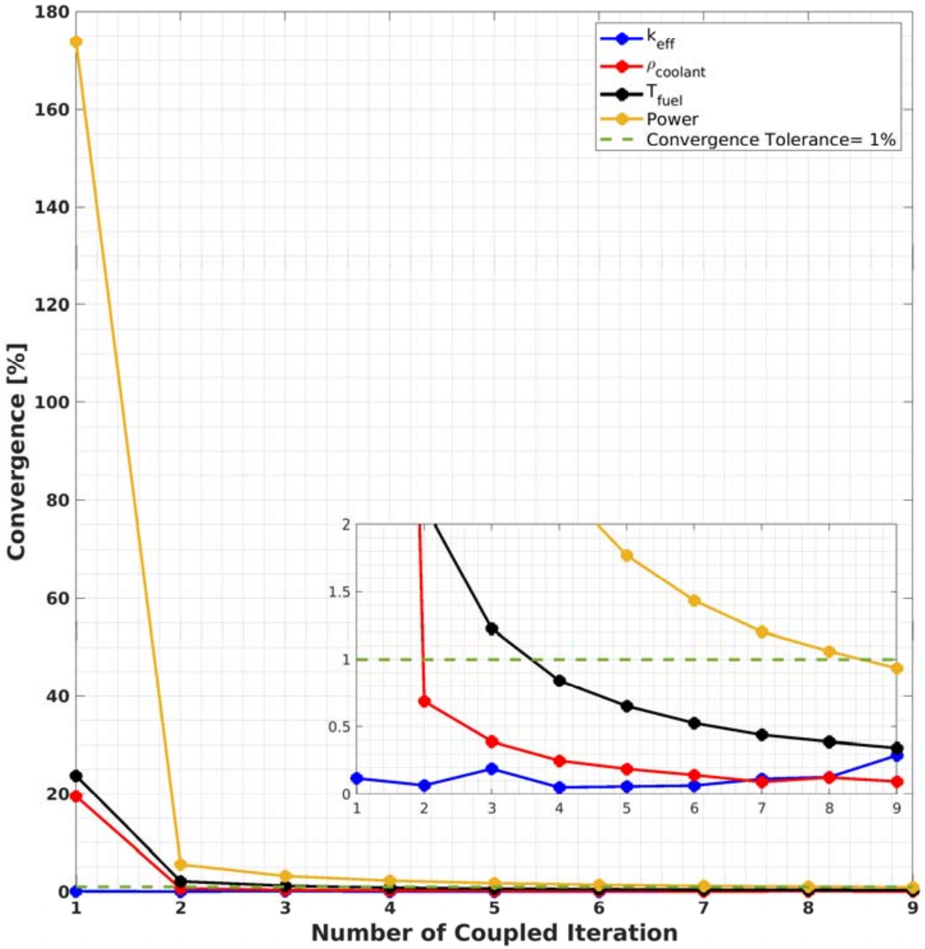
Fuel temperature convergence



Power convergence

SSS2/SCF Core Analysis

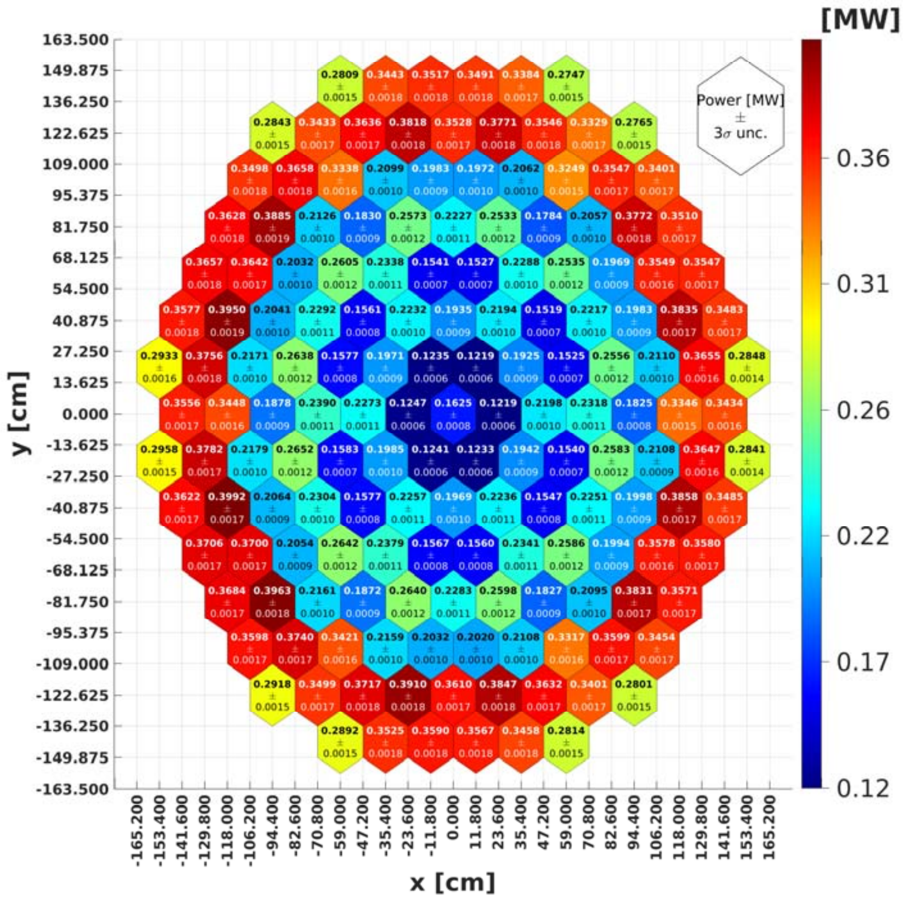
- Convergence Results



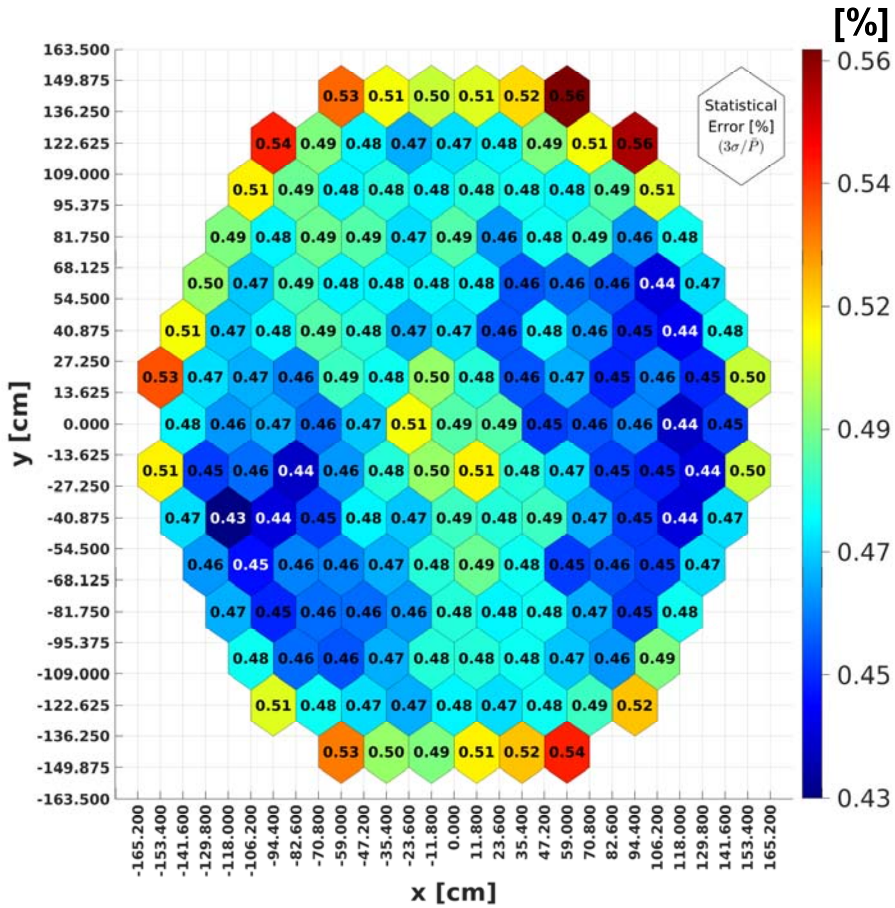
- k_{eff} value converged.
- After all selected convergence parameters, power value converged lastly.
- All selected convergence parameters are less than 1% when simulation finished.

SSS2/SCF Core Analysis

- Fuel assembly-based Neutronic Results



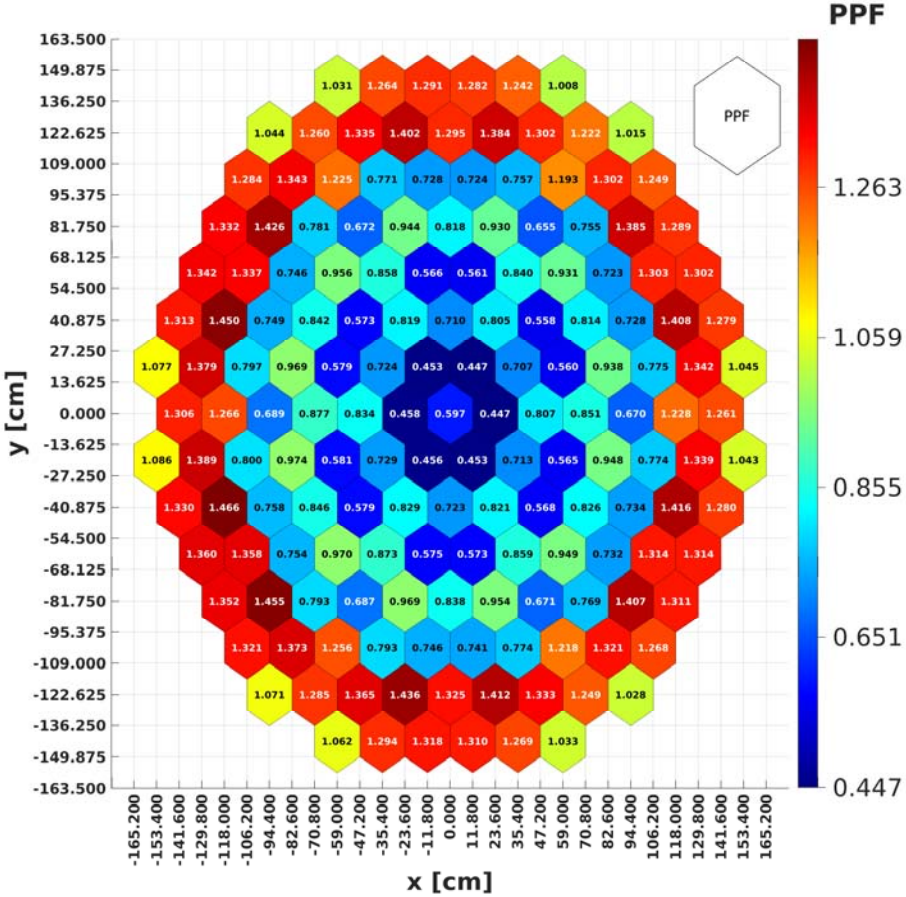
Radial view of FA level average power distribution



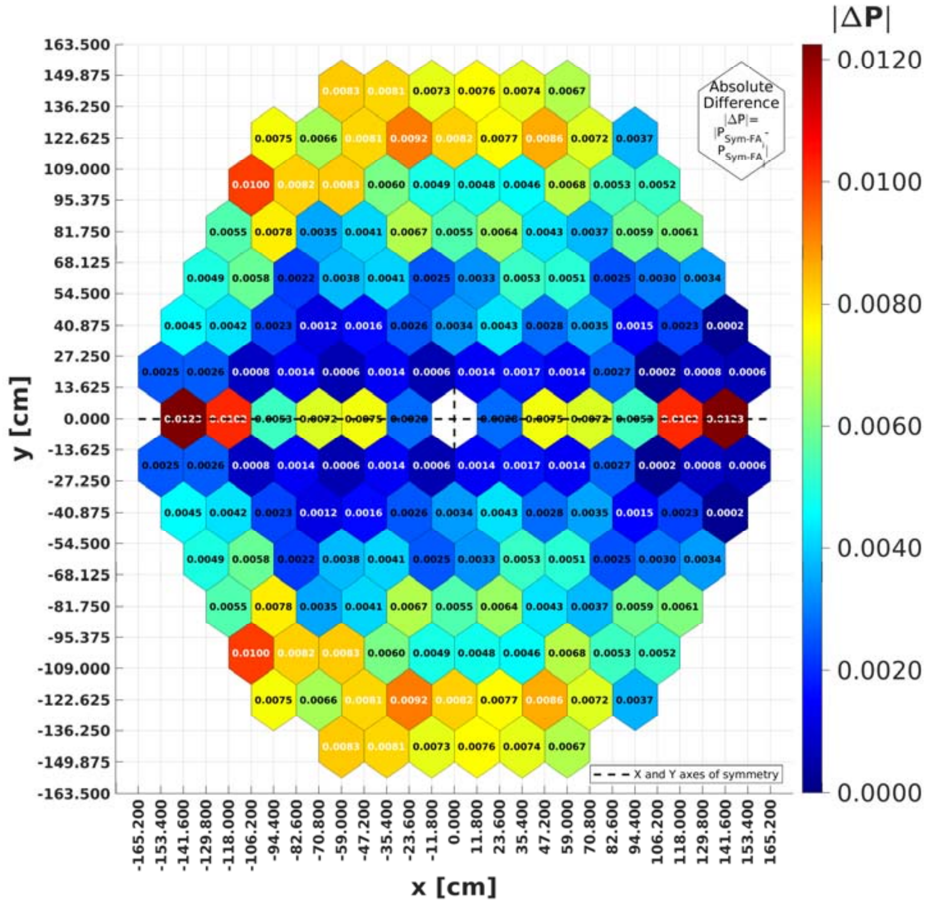
Radial view of FA level average power statistical error

SSS2/SCF Core Analysis

- Fuel assembly-based Neutronic Results



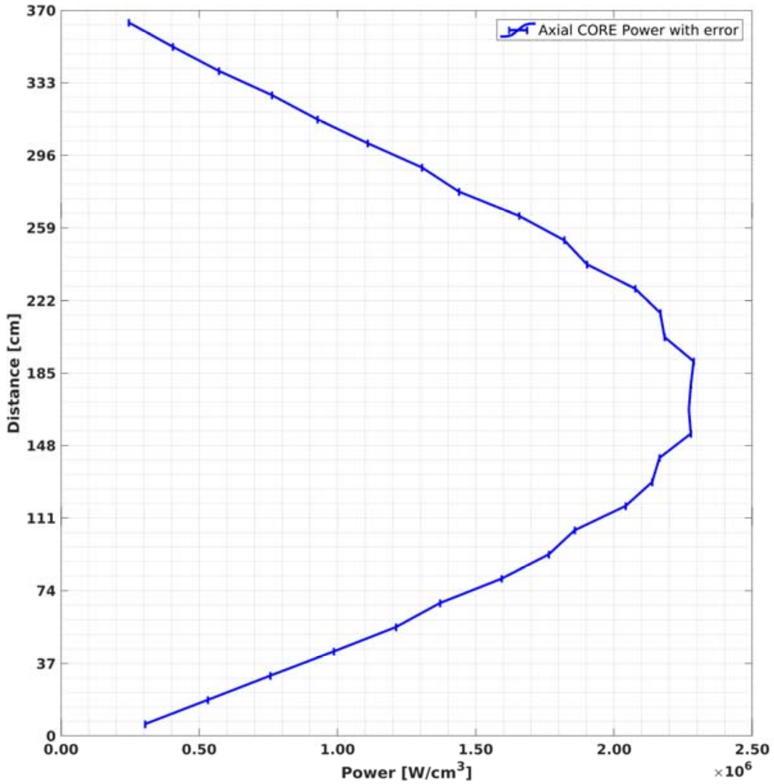
Radial view of FA level power peaking factor



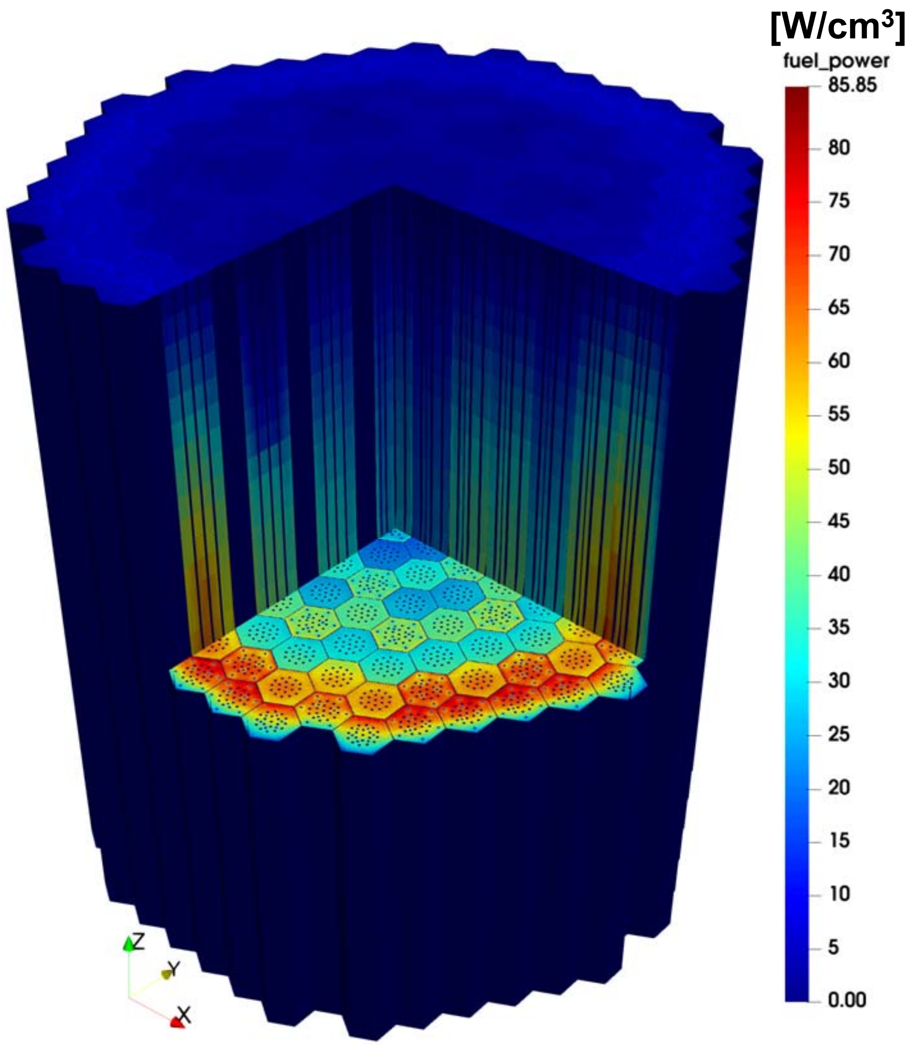
Radial view of power difference for symmetrical FAs

SSS2/SCF Core Analysis

- Neutronic Results



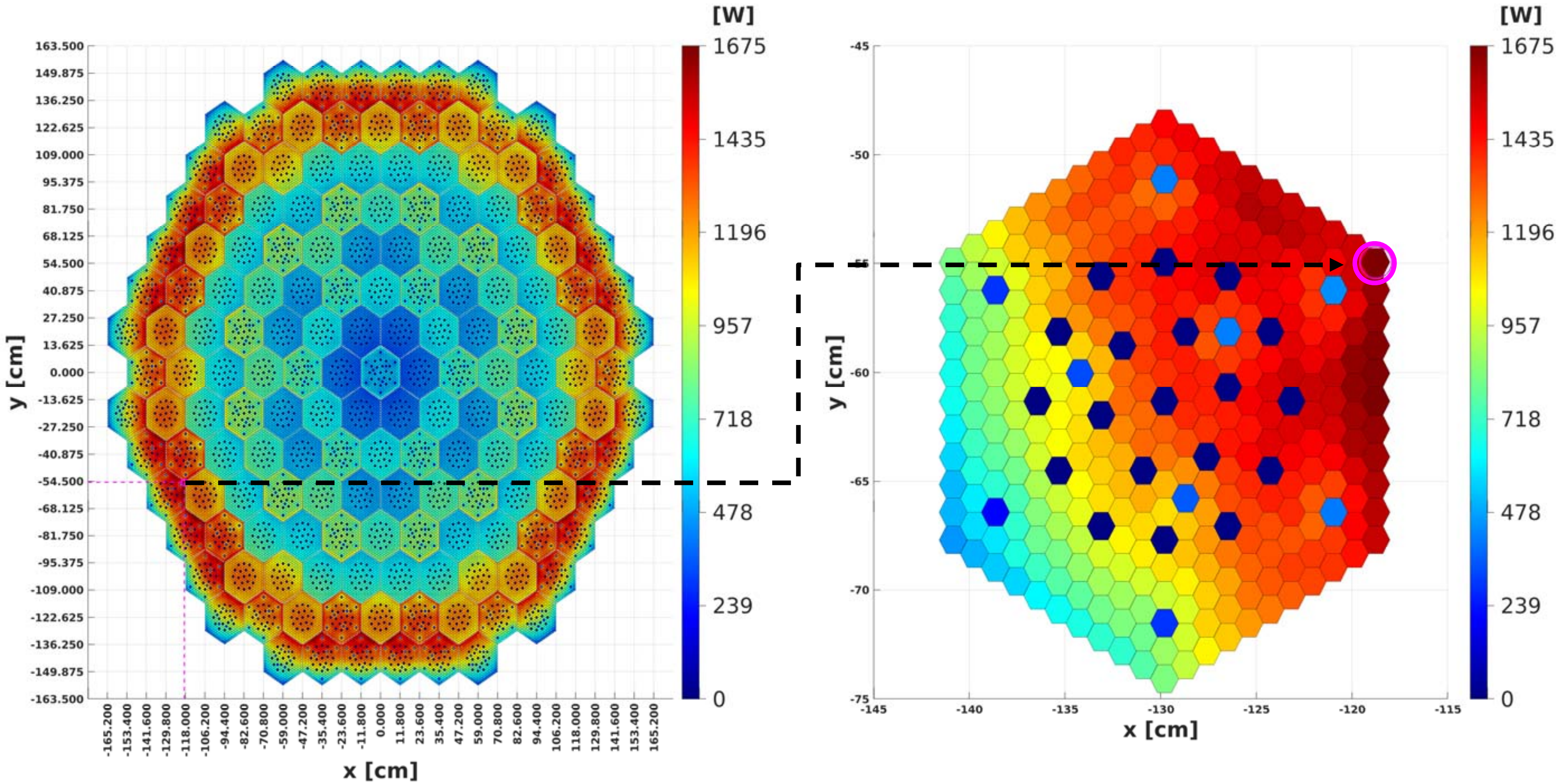
Core average axial power distribution



3D pin power distribution

SSS2/SCF Core Analysis

- Neutronic Results

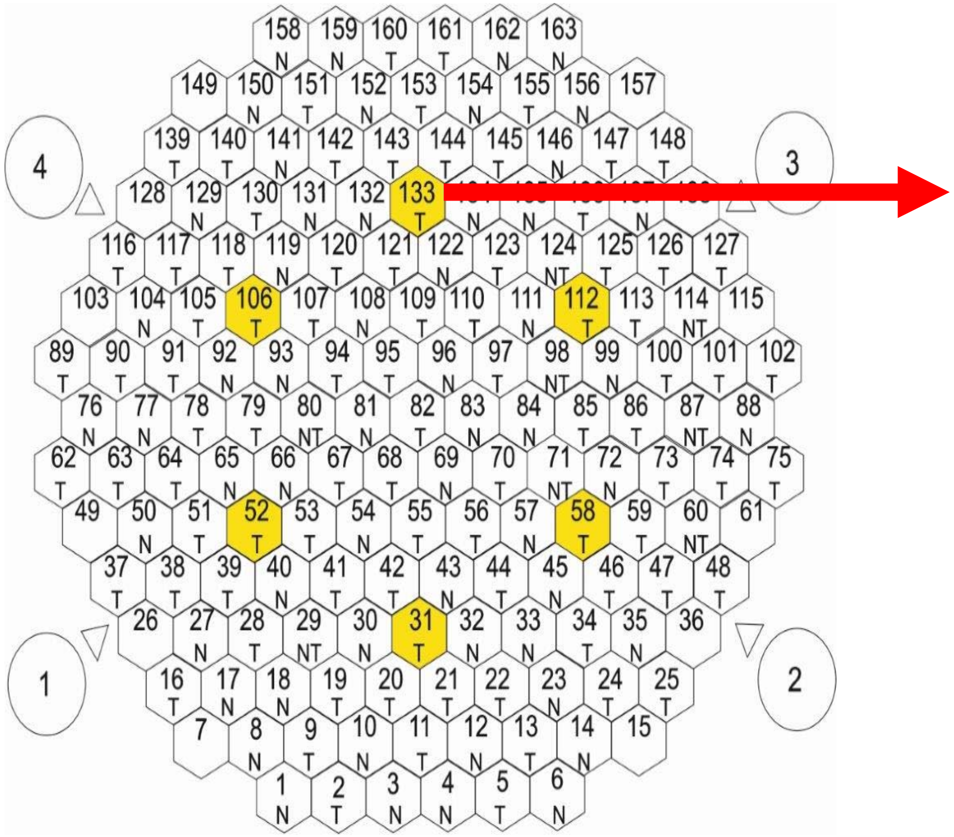


Radial view of pin level average power distribution in core

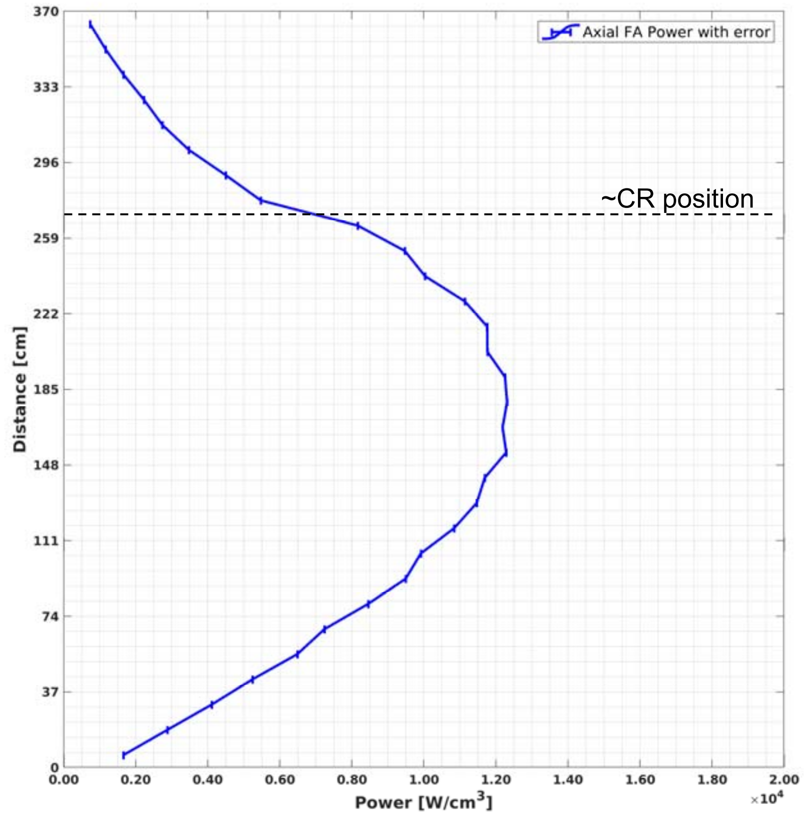
Maximum power generated pin and its located FA

SSS2/SCF Core Analysis

- Neutronic Results



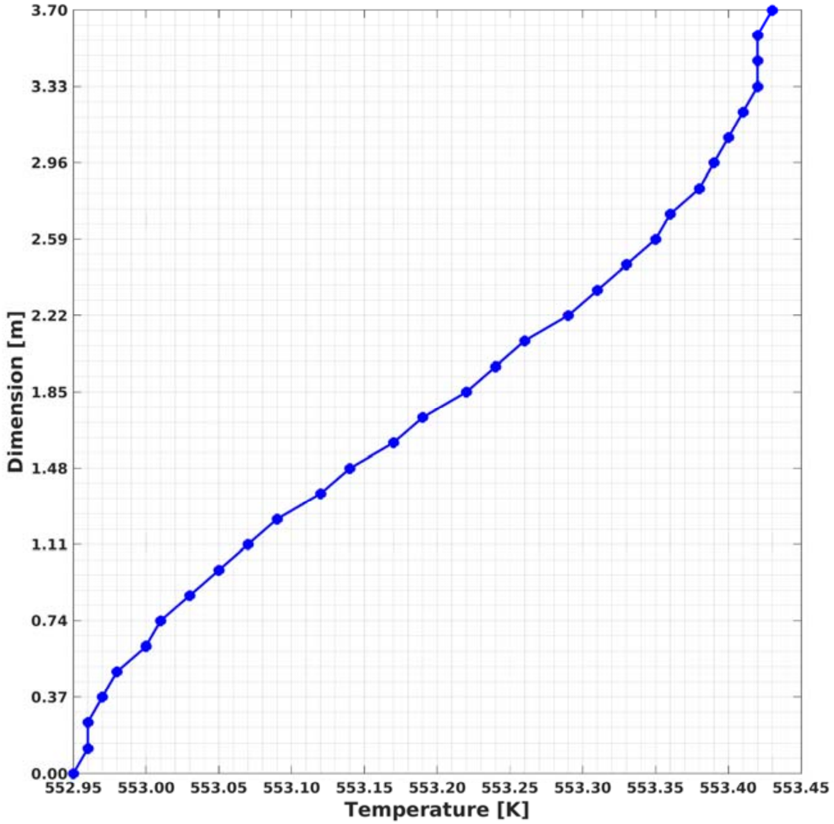
Core layout with numbering of the FA and position of the CRC #10 (yellow)



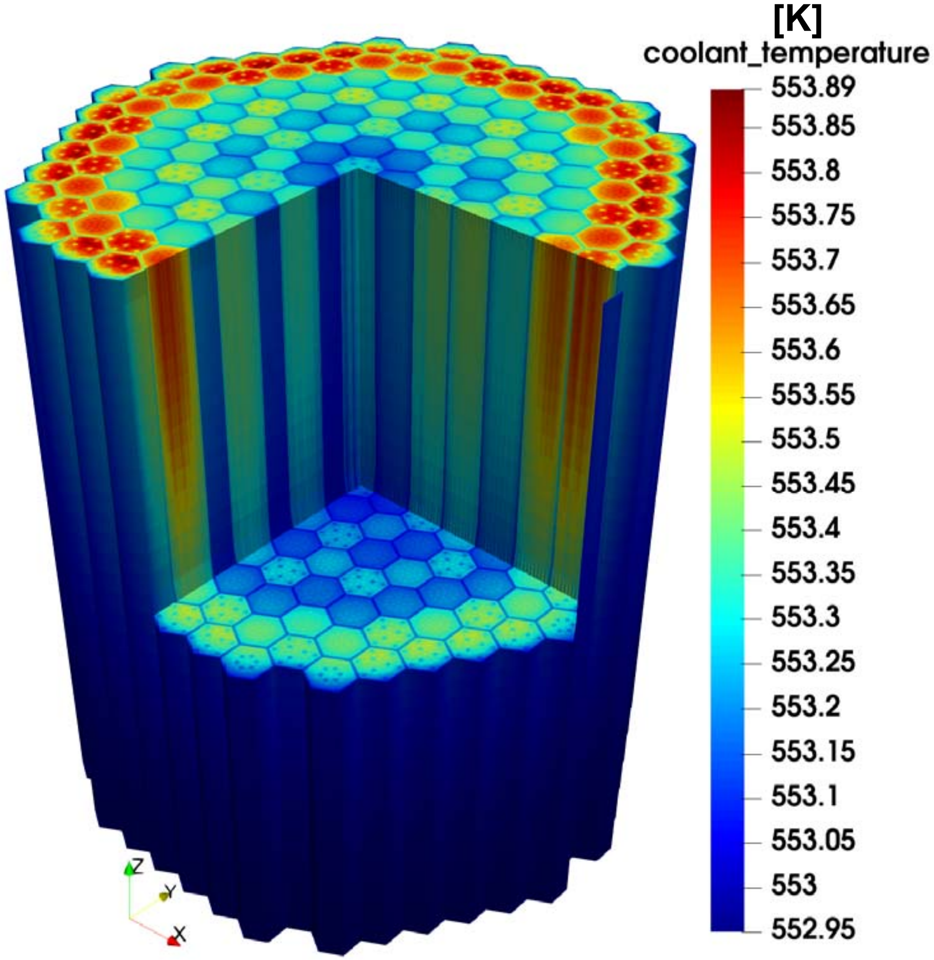
FA #133 (control rod inserted) axial power distribution

SSS2/SCF Core Analysis

- Thermal-Hydraulic Results



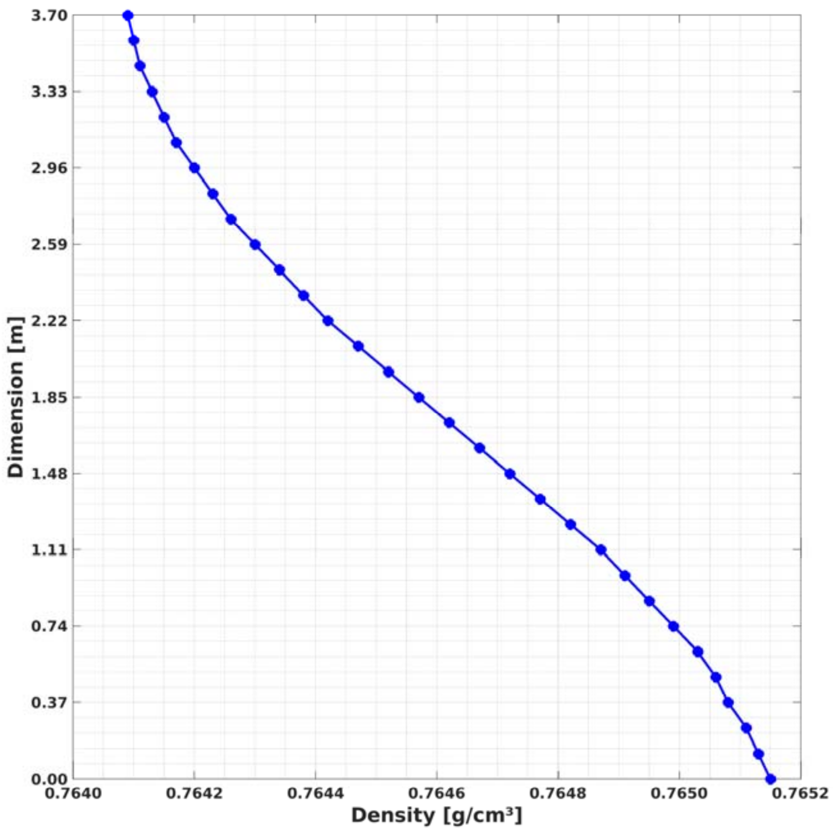
Core average axial coolant temperature distribution



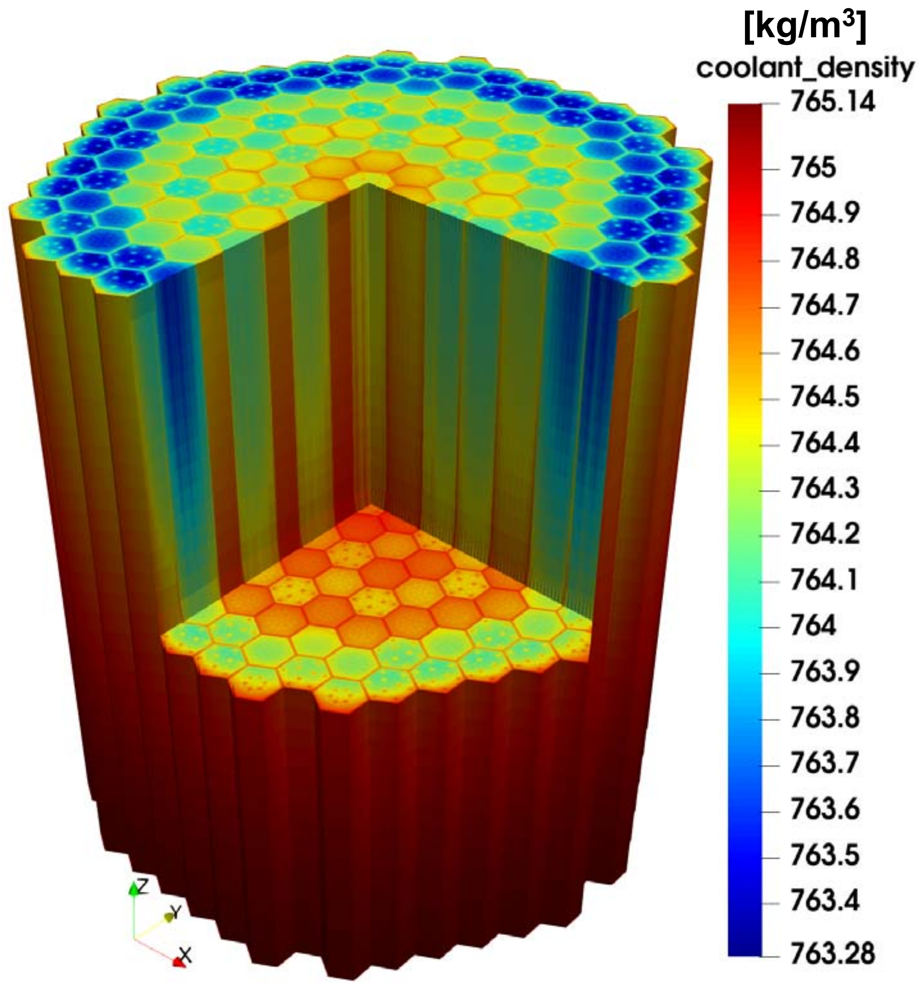
3D coolant temperature per subchannel

SSS2/SCF Core Analysis

- Thermal-Hydraulic Results



Core average axial coolant density distribution



3D coolant density distribution per subchannel

Conclusion and Outlook

- ICoCo-based coupling works fine and stable.

- Successful simulation for fresh core.
  - The coupling simulation time is **12.6** hours.
    - ~110 GB memory utilized.
    - ~40,000 CPU-hours used on HoreKa HPC (KIT/SCC).

- Data sharing in neutronic/thermal-hydraulic meshes are useful for post-processing.

- Next Steps:
  - SSS2/SCF burnup simulation of Rostov-2 first cycle (36.37 effective days)
    - Required inputs of SSS2 for depletion calculation prepared
    - Enable KIT to provide a reference solution for burn core.

Thank you for your attention!