KIT Neutronic Computational Tools for SMR-Core Analysis

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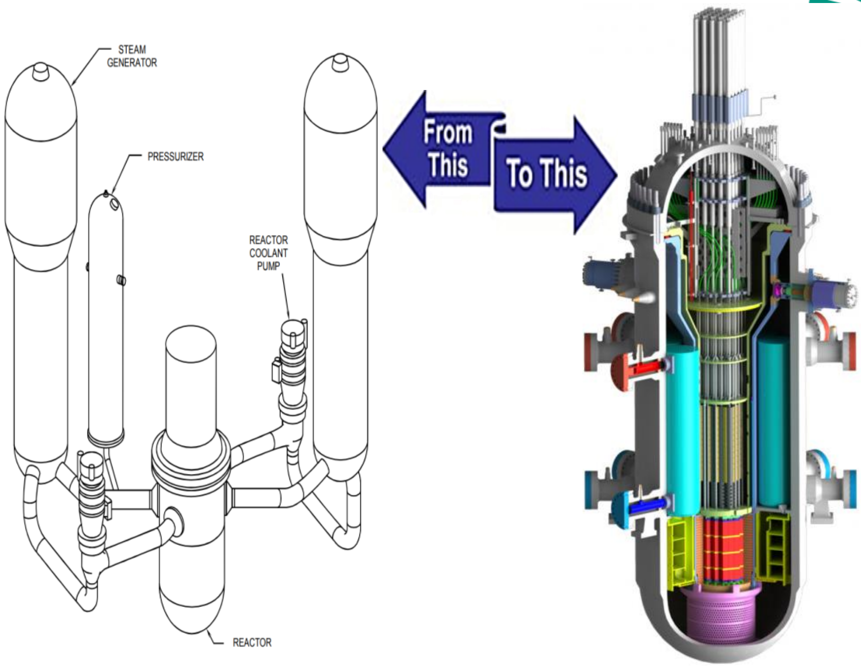
Content

- Background
- Challenges
  - Neutronics
  - Thermal hydraulics
- KIT approach
- Outlook

Background [1]

- Increase interest on SMR
  - Water cooled
  - Gas-cooled
  - Liquid-metal cooled
  - Etc.
- Multiple-use
  - Electricity, heat
  - Water desalination
  - Hydrogen production
- Attractiveness:
  - Module factory fabrication
  - Pursuing economies of series production and
  - Short construction times



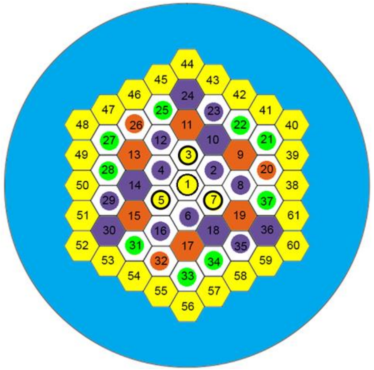
PWR

SMR (SMART)

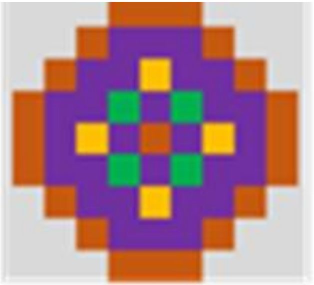
SMR will be build only if economically competitive and safe

Water Cooled SMR-Cores: Different designs [1,2]

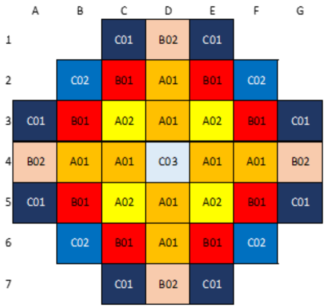
CAREM-Like core



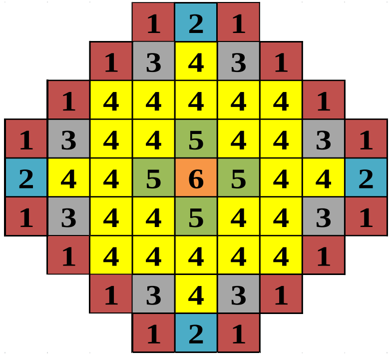
FSMR Core



NuScale



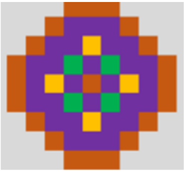
KIT KSMR-Core



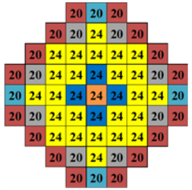
Common Features of Water-cooled SMRs [1]

- Compactness
- Small size (H and D)
- Heterogeneity (radial, axial)
- High leakage
- Harder spectrum
- Complex control rod designs
  - Different types
  - Axial heterogeneity
- Increased role of reflector

- Boron free cores:
  - Need innovative control rod design
  - Optimized shutdown reactivity
  - Reduced reactivity swing over the cycle
  - Etc.



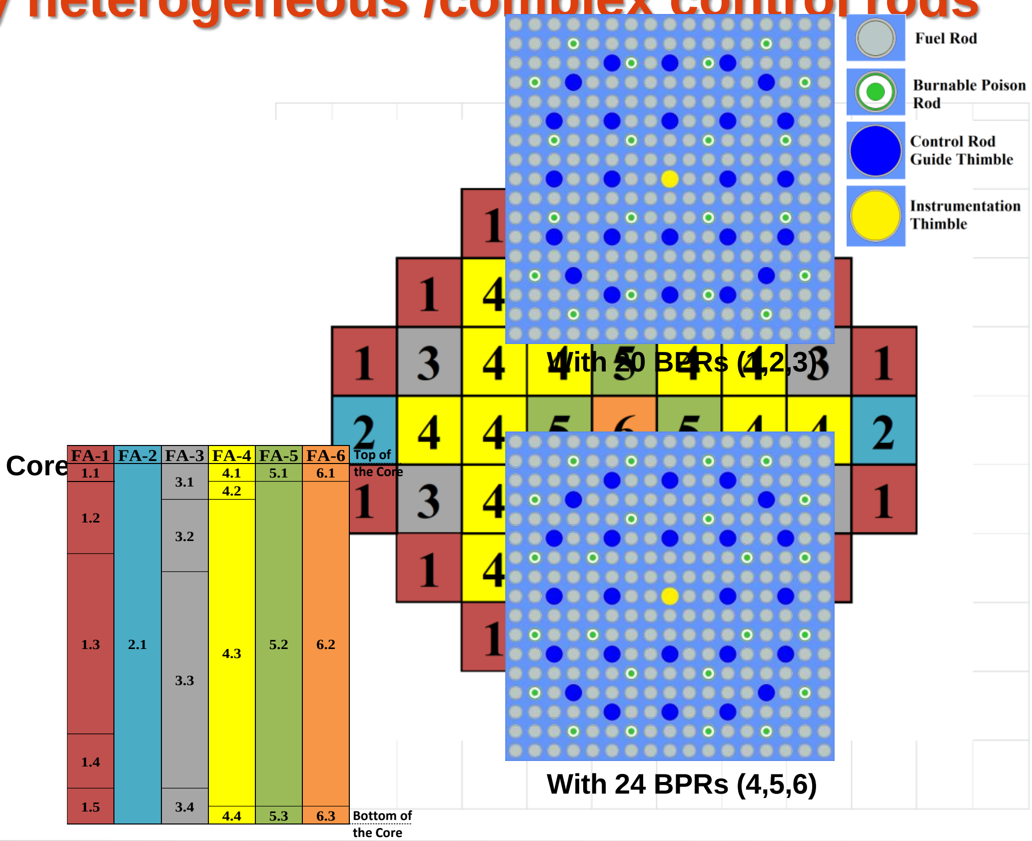
F-SMR



KSMR

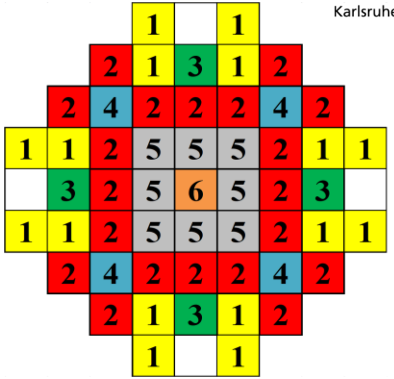
→ Innovations needed to improve economics and keep high safety

KSMR Design: Example [3,4,5]
Highly heterogeneous /complex control rods

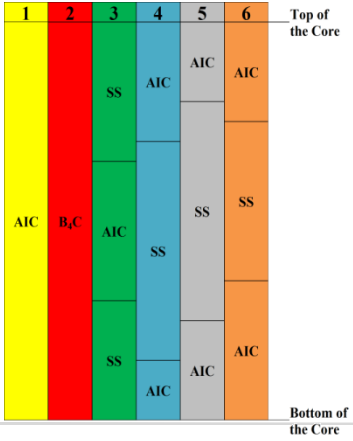


With 20 BPRs (1,2,3)

With 24 BPRs (4,5,6)



Control Rods Configuration



Ref. [3,4,5]

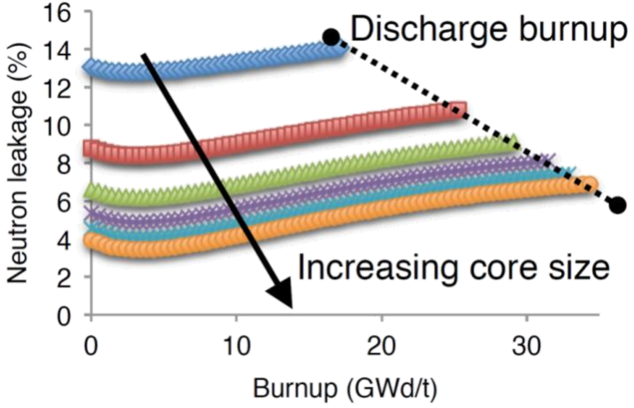
Challenges

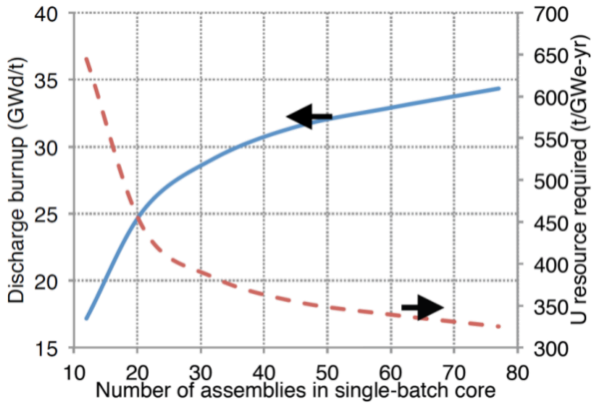
Neutronics: Core Design Challenges [30]

- Typical SMR core size is 37 – 89 FAs
  - NuScale: 37 FAs, SMART: 57 FAs,
  - CAREM-25: 61 FAs
  - mPower: 69 FAs
- Core height is almost half of large LWR

- Increased neutron leakage
- Less degree of freedom

Lower fuel utilization





Ref [30]

Safety-related Thermal Hydraulics [1] :

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- Experimental data exist but proprietary (SMR developers)
- Public SMR-specific data for research community needed e.g.
  - Cross flow in the core
  - Helical HX
  - Transition from
    - Forced to natural convection
    - Natural to forced convection
  - Safety parameters like
    - CHF
  - 3D flow inside the RPV
  - Effectiveness of PRHRS
  - Stability of natural convection flow
- Data need for code validation

McSAFER Solution Approach:

- COSMOS-H experimental program:
  - Fundamental HT, boiling, CHF
- HWAT experimental program`:
  - System behavior under natural circulation
  - Transition to forced convection
  - Transition to natural convection
- MOTEL experimental program:
  - Helical HX heat transfer, pressure drop
  - Cross flow in the core

KIT Approach for SMR Core Analysis: Multiphysics

KIT Approach: Multiphysics

- Industry-like approach: Nodal diffusion / 1D system TH
  - PARCS / TRACE or PARCS/ RELAP5 [6]

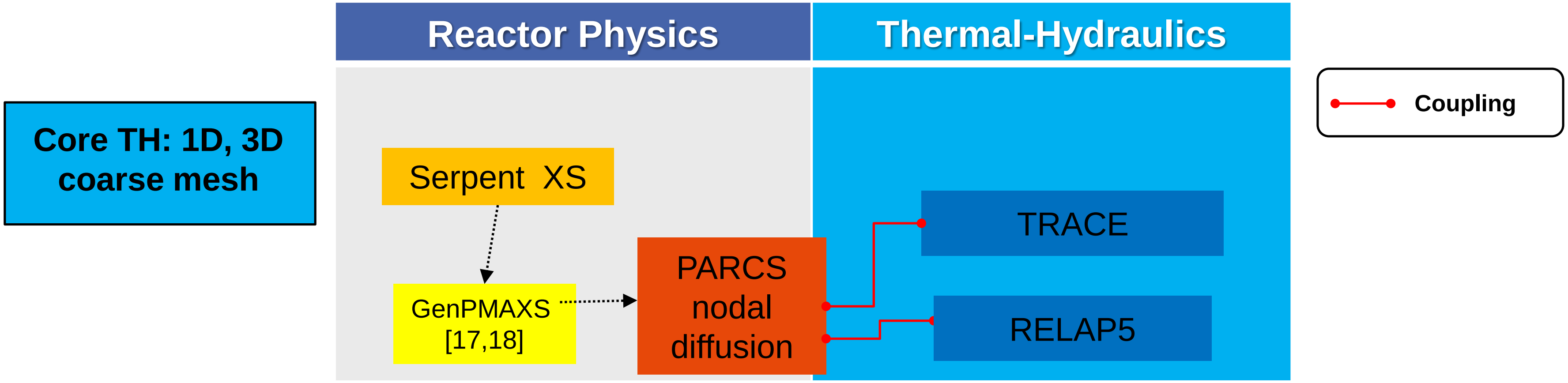
- Improved core thermal hydraulics:
  - Subchannel codes: Subchanflow (in-house) [7,8]
  - Porous-media 3D TH: Twoporflow (in-house) [9]

- Improved neutronics:
  - Simplified transport solvers at pin level:
    - PARCS-SP3

  - Monte Carlo codes:
    - Static simulations: Serpent2 [10]/Subchanflow/ICoCo [11]
    - Dynamic simulations: internal coupled Serpent2/Subchanflow [13,14,15]

  - Deterministic transport solvers e.g. PARAFISH (in-house) [12]

KIT Core Analysis Tools: Internal Coupling



No direct prediction of **local** safety parameters

Internal coupling: PARCS/SCF & SERPENT2/SCF (2019)

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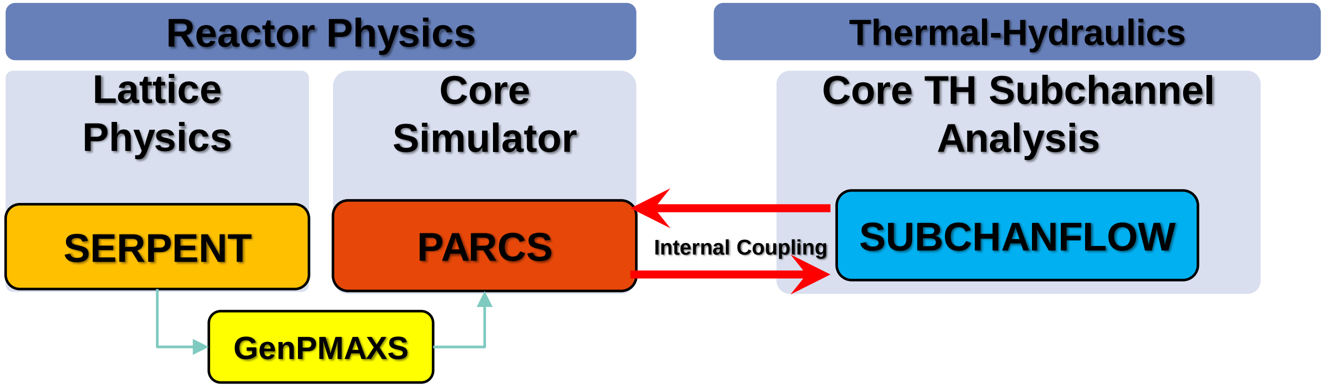
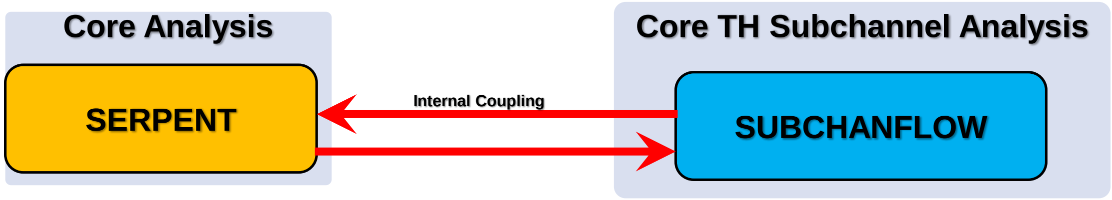
- Core design and core optimization tools:



- 3D core reference solutions:

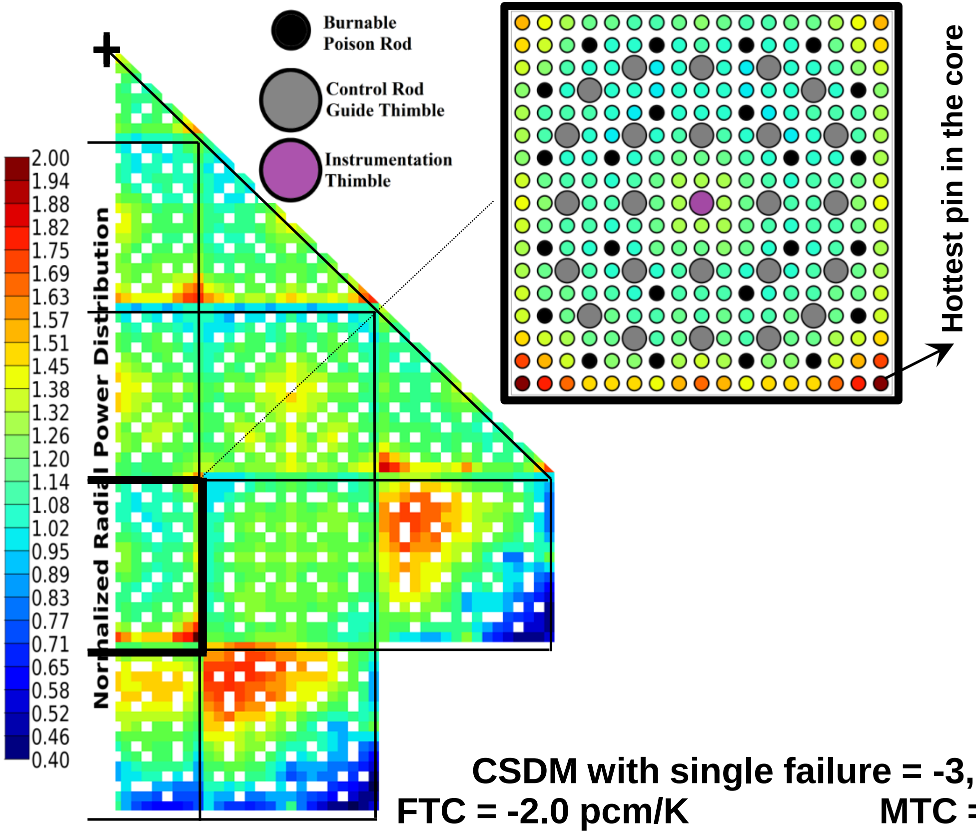


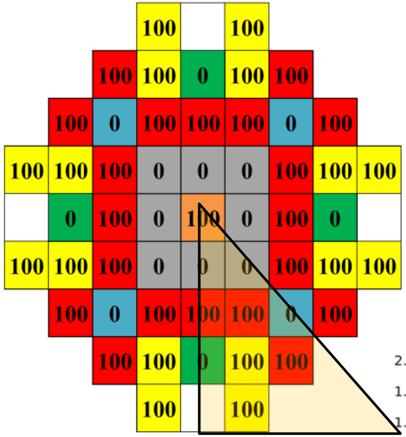
Visualization Tool

ParaView
Parallel Visualization Application

matplotlib

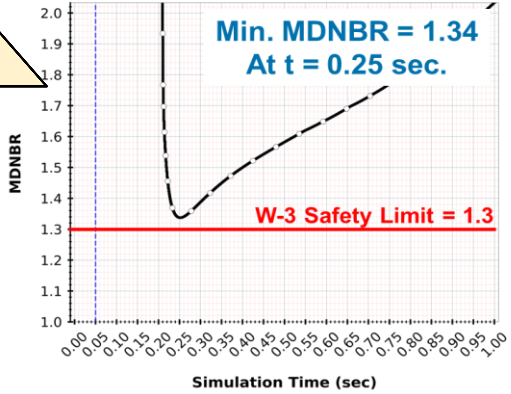
KSMR:
rel. radial pin Power Distribution at HFP [3,4,5]





Ref. [4,5]

Control Rods Critical Configuration at HFP Condition

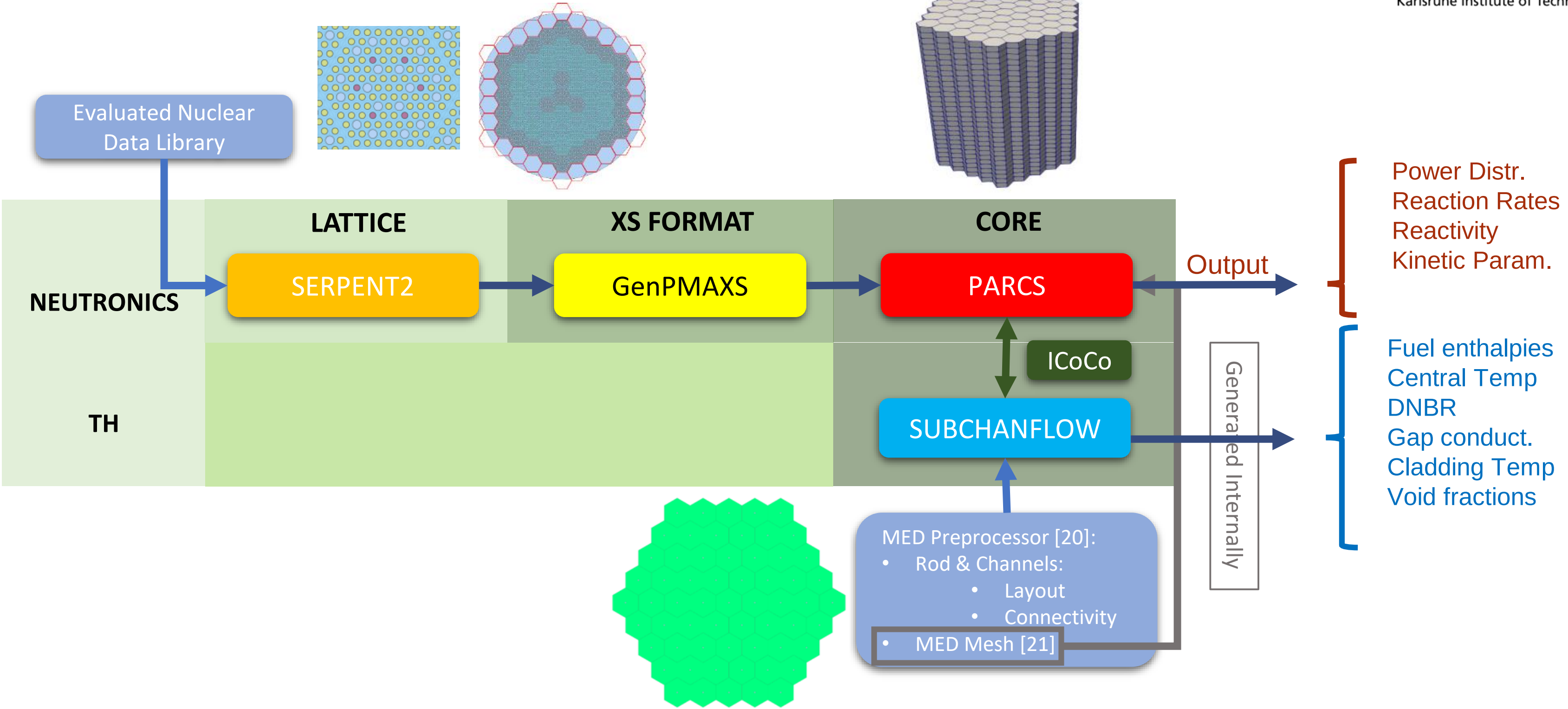


CSDM with single failure = -3,000 pcm

FTC = -2.0 pcm/K MTC = -76.0 pcm/K

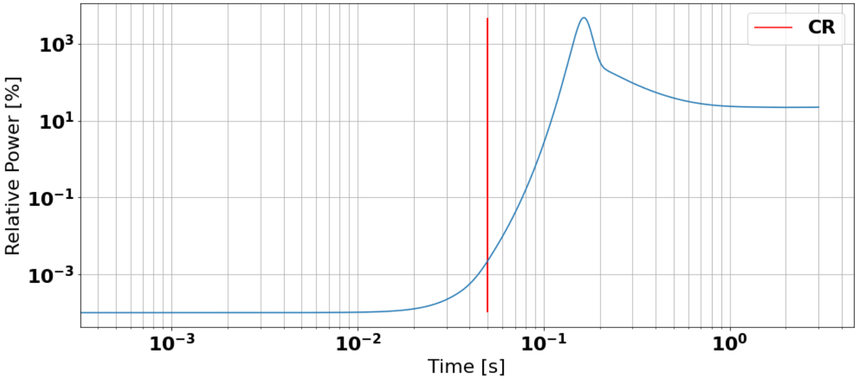
REA: MDNBR

ICoCo-based
Coupling of PARCS/ Subchanflow (2021) [18]

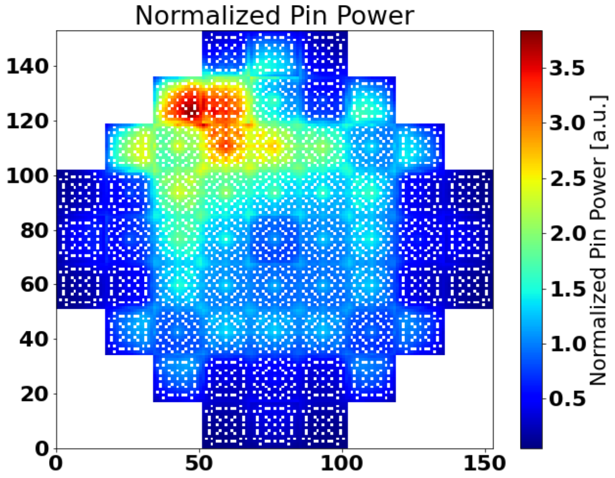


Ref. [18]

KSMR REA: ICoCo PARCS/SCF Analysis [20]



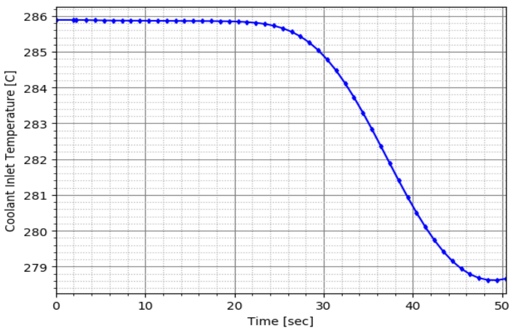
KSMR Rod Ejection Accident with Pin Power Reconstruction at power peak



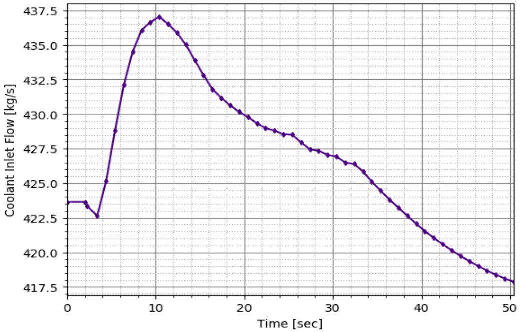
KSMR REA: Relative power [%] at peak power

Ref. [20]

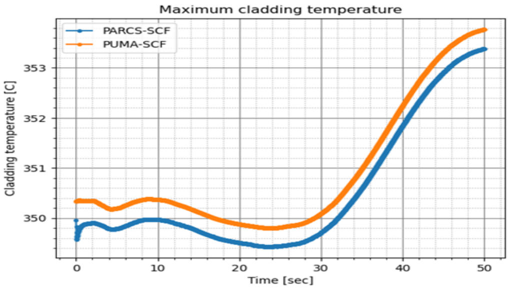
PARCS/SCF/ICoCo: Analysis of CAREM: Overcooling Transient [20]

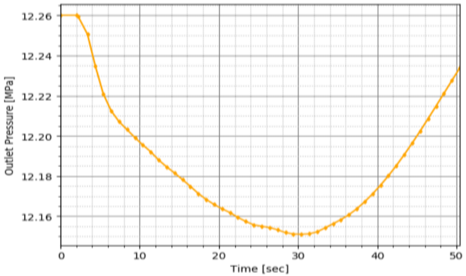


Coolant temperature decrease

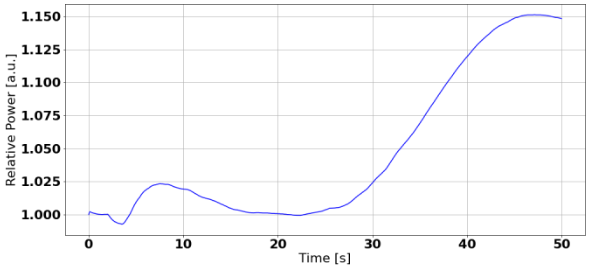


Mass flow rate change



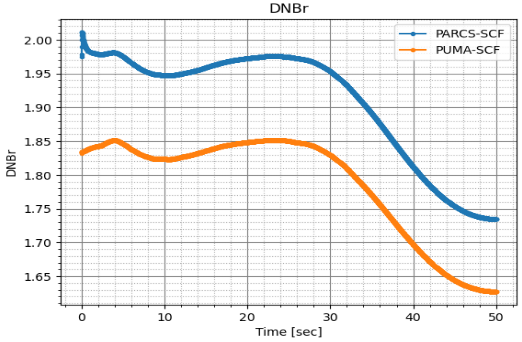


Outlet pressure evolution



Ref. [20]

Normalized Power [a.u.]



CAREM Overcooling transient: Key-parameters

ICoCo-based coupling of PARCS/Twoporflow (2022)

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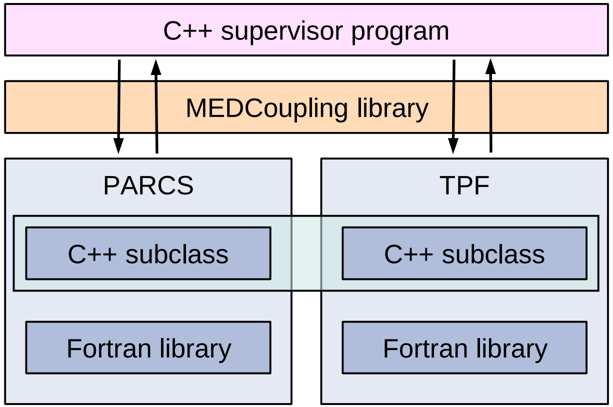
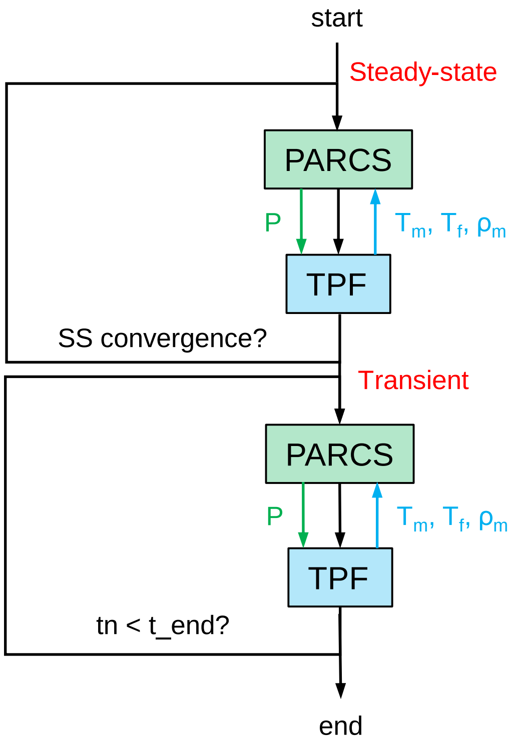
- External coupling.
- Serial execution.
- Domain overlapping.
- Fields mapping via MEDCoupling library.
- Explicit iterative scheme.
- Node-wise feedback.



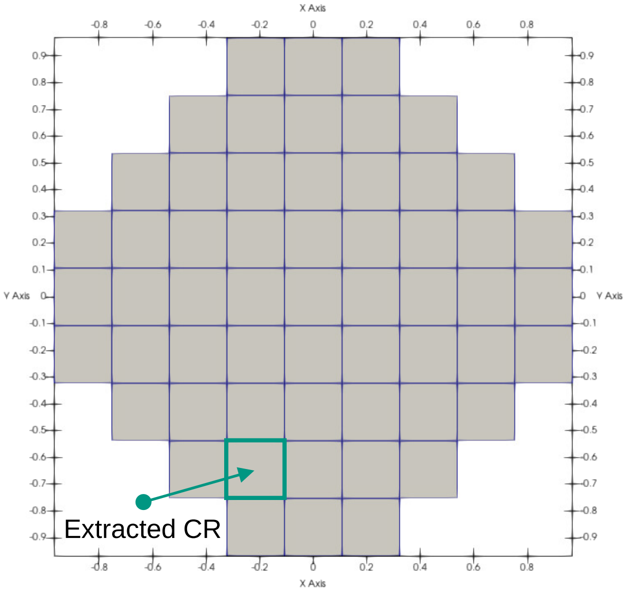
Ref. [9]



KSMR: REA Analysis at HZP

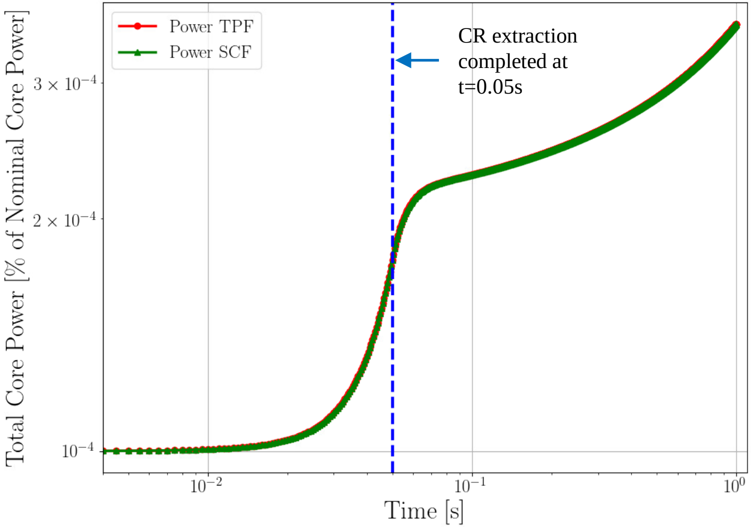
- Half highest CR worth extraction (0.725 $) at the hot zero power (HZP) condition.

Parameter	Value
Initial core power	1.0E-4 %
Highest CR worth	1.45 $
Ejection duration	0.05 s
End of transient simulation	1.0 s

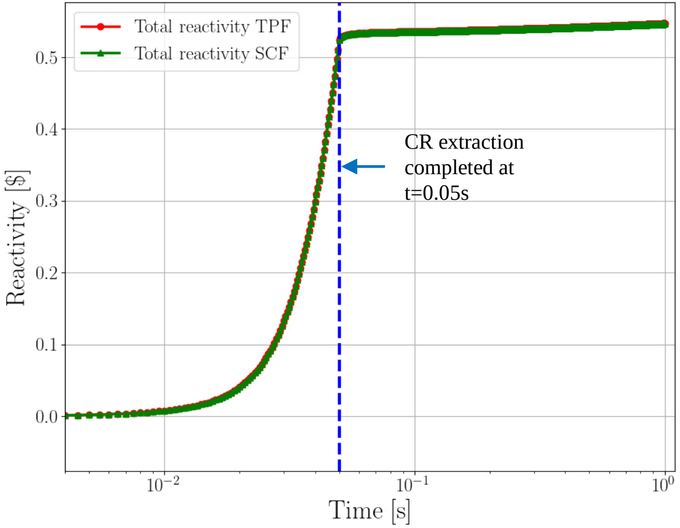


Ref. [9]

SMART REA Analysis: PARCS/SCF vs. PARCS/TFP



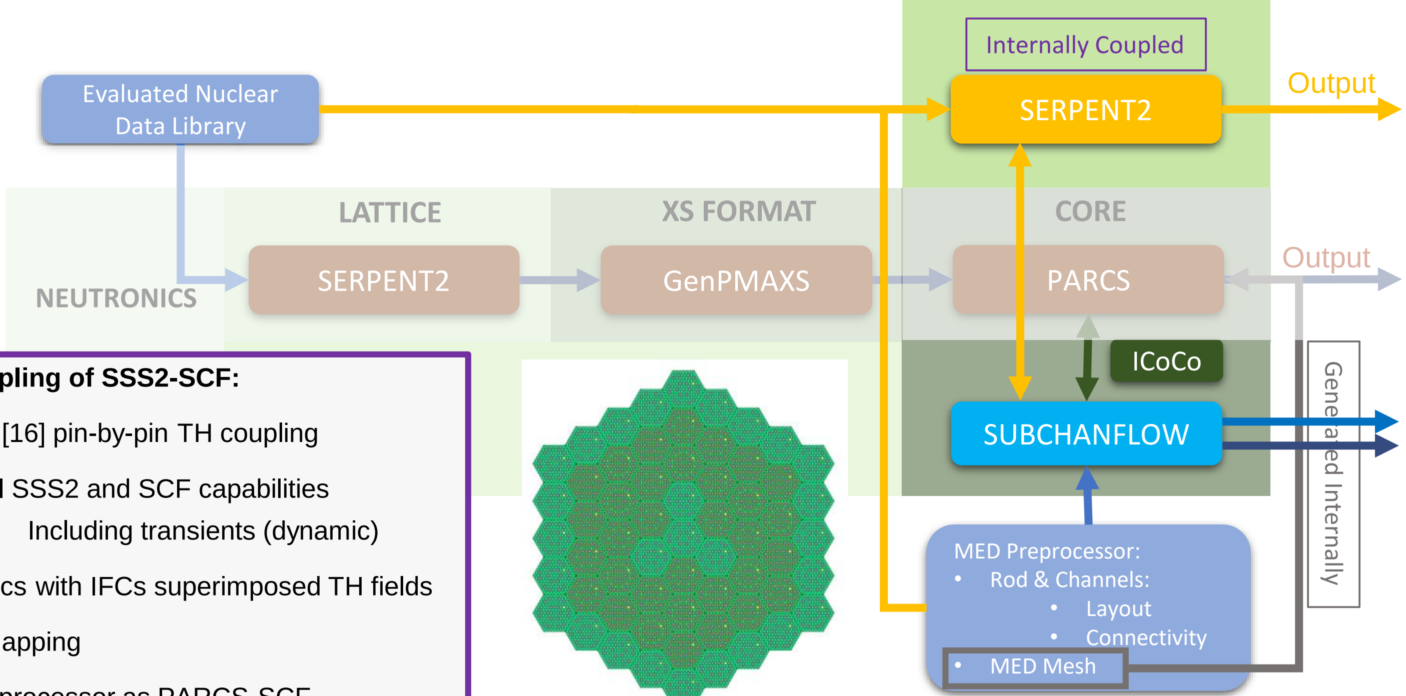
PARCS Total Core Power



PARCS Total Reactivity

Ref. [9]

High Fidelity MC-based Multiphysics: SSS2-SCF



Internal coupling of SSS2-SCF:

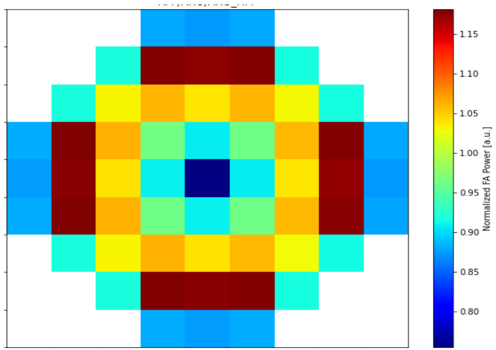
- MCSAFE [16] pin-by-pin TH coupling
- Inherits all SSS2 and SCF capabilities
  - Including transients (dynamic)
- Multiphysics with IFCs superimposed TH fields
- Internal mapping
- Same preprocessor as PARCS-SCF

Pin-wise CAREM-like preprocessor plot

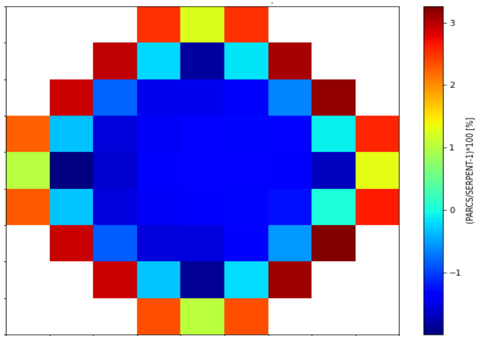
Ref. [20, 13,14,23,24]

KSMR: Comparison of PARCS/SCF and SSS2/SCF Solutions [22]

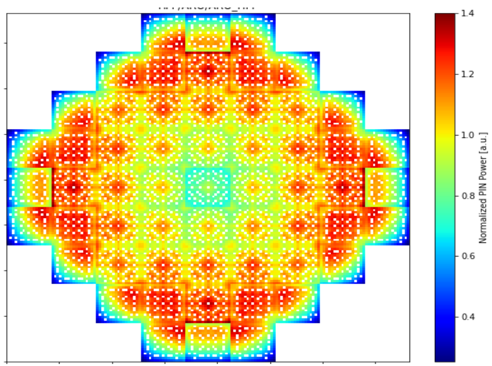
SSS2: axially integrated FA normalized radial power for HFP ARO



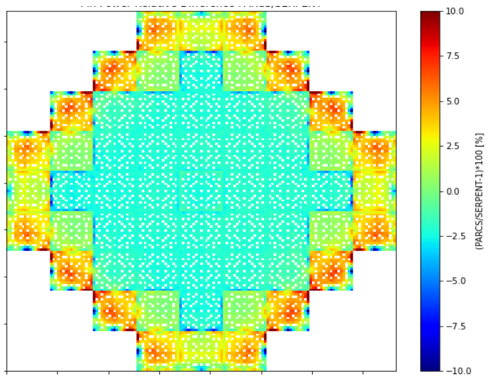
PARCS-SSS2: axially integrated FA normalized radial power relative difference for HFP ARO



SSS2: axially integrated pin normalized radial power for HFP ARO



PARCS- SSS2: axially integrated pin normalized radial power relative difference for HFP ARO. Values are truncated in the interval [-10; 10] %



Ref. [20]

Outlook

Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (1/2)

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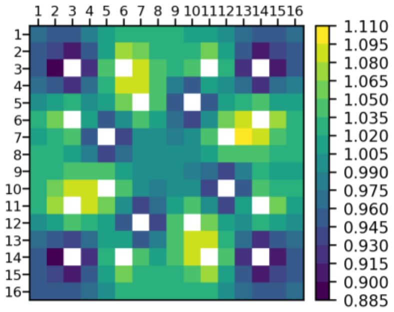
- Motivation: Pin-wise Simulation, XS Optimization, TH Feedback

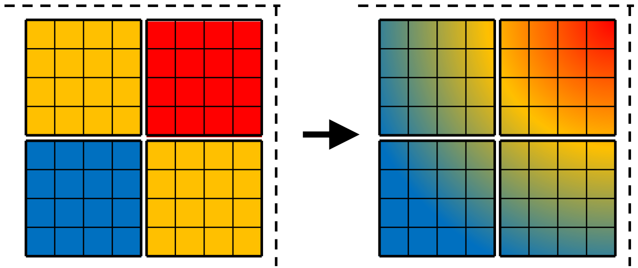
*The discussion in this slide only concern **Cartesian** geometry*



Pin-wise results are important

PARCS V331 has two methods for pin-wise results:

- Nodal + Pin power reconstruction



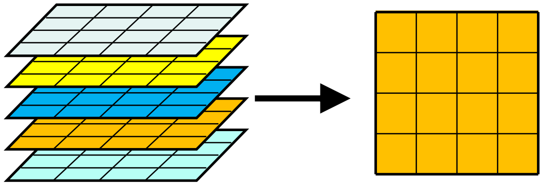
Advantage:

- Fast running.

Limitation:

- No Pin-wise TH coupling.
- No Pin-wise XS optimization.

- FMFD (Fine Mesh Finite Difference)



PLANAR_REG PLANAR_LAT

Advantage:

- SP3 Pin-wise simulation.

Limitation:

- Use “PLANAR_REG”, no “ASSY_TYPE”.

In KIT, we would like to do:

- Pin-by-pin simulation in core-scale with “ASSY_TYPE”.
- Enable pin-wise XS optimization and TH feedback.

PARCS V331 can not do this

Function extension is required

Ref. [22]

Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (2/2)

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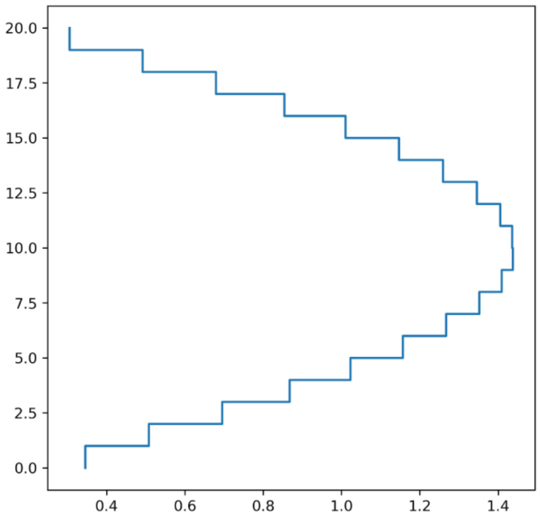
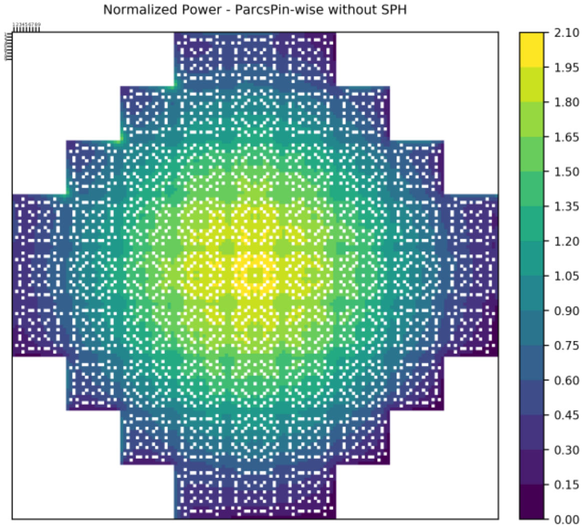
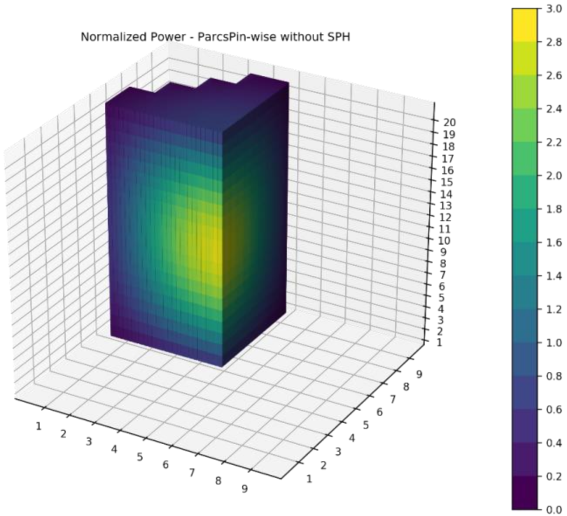
- First Results: KSMR core steady state



Axial power distribution



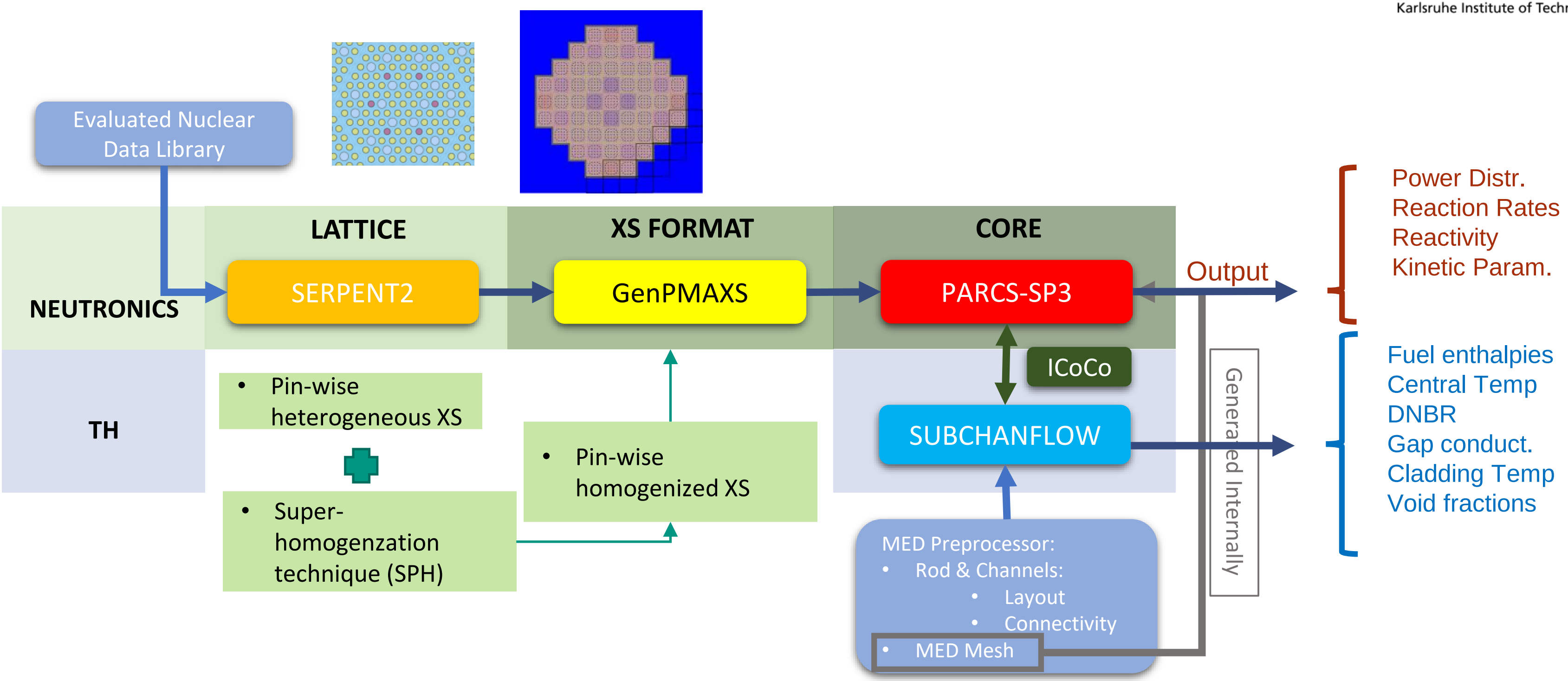
Radial power distribution



Spatial power distribution

Ref. [22]

Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (2/2)

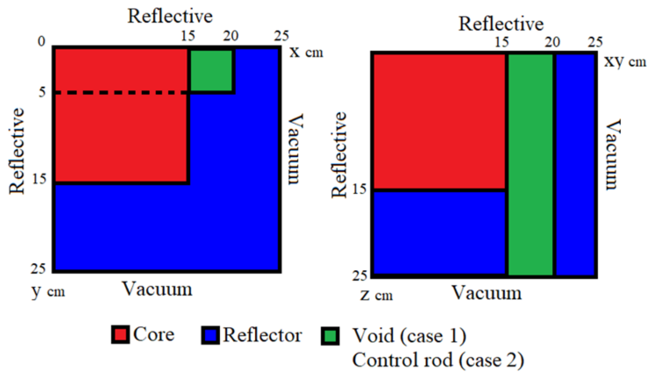


Pin /subchannel coupling based on same ICoCo-Interface FA-based Coupling

Next steps: High fidelity Transport Solver

- PARAFISH code development
  - Finite element spherical harmonic neutron transport solver
  - Written in C++
  - Domain decomposition

- At present: steady state solver
- Next steps:
  - Time-dependent solver
  - Coupling with TH e.g. SCF
  - Pin-by-pin analysis of SMR-core transients
  - Code-to-code comparisons
    - E.g. SSS2/SCF



Code	Case 1	Case 2	CR-worth
Monte-Carlo	0.97780	0.96240	1.64×10^{-02}
Parafish (P_{11})	0.97686 Error= 96 pcm	0.96249 Error= 9 pcm	1.52×10^{-02} Error= 7.3 %

Small PWR: LWR based on the Kyoto University Critical Assembly (KUCA)

Ref. [12]

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