Karlsruhe Institute of Technology

KIT Neutronic Computational Tools for SMR-Core Analysis

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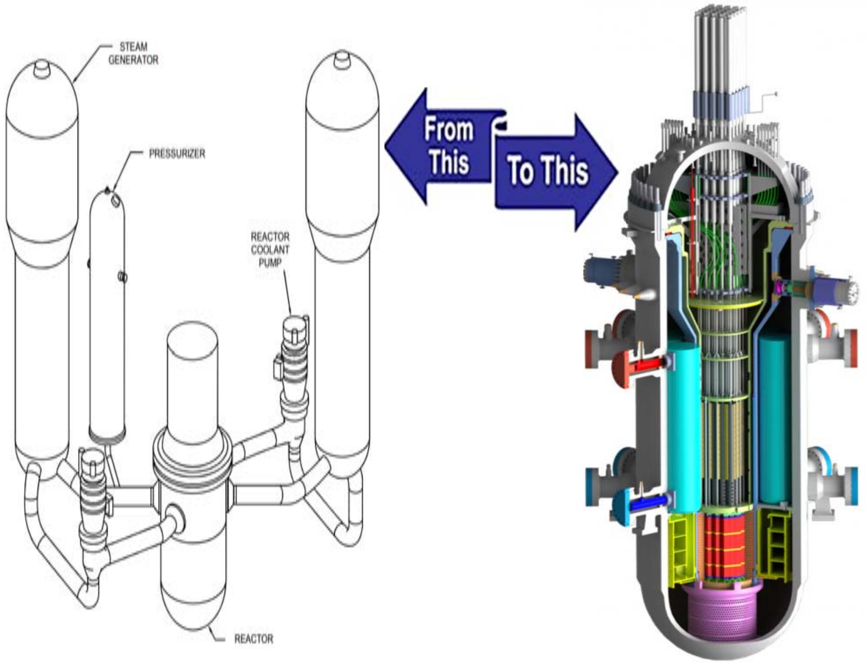
Institute for Neutron Physics and Reactor Technology

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



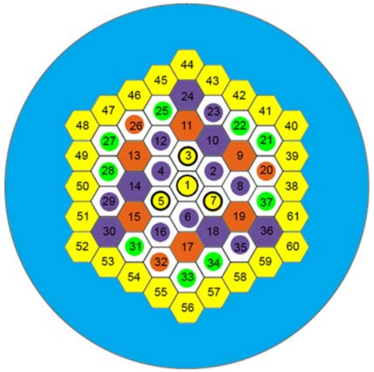
PWR

SMR (SMART)

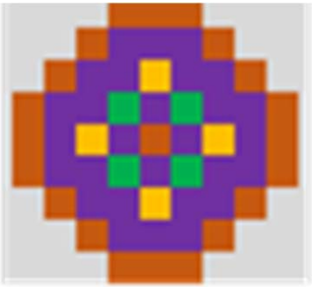
SMR will be build only if economically competitive and safe

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

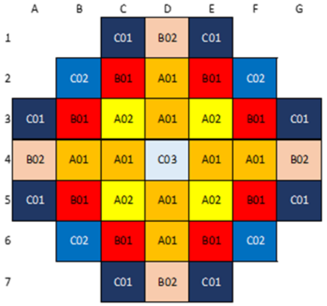
CAREM-Like core



FSMR Core

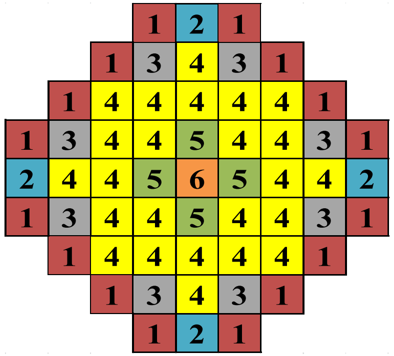


NuScale



	A	B	C	D	E	F	G
1			C01	B02	C01		
2		C02	B01	A01	B01	C02	
3	C01	B01	A02	A01	A02	B01	C01
4	B02	A01	A01	C03	A01	A01	B02
5	C01	B01	A02	A01	A02	B01	C01
6		C02	B01	A01	B01	C02	
7			C01	B02	C01		

KSMR



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		1	3	4	3	1		
	1	4	4	4	4	4	1	
1	3	4	4	5	4	4	3	1
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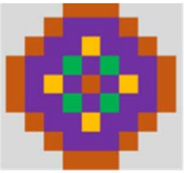
1	3	4	4	5	4	4	3	1
	1	4	4	4	4	4	1	
		1	3	4	3	1		
			1	2	1			

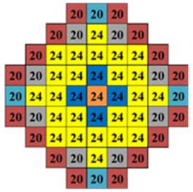
Common Features of Water-cooled SMRs [1]

- 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



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		20	20	24	20	20		
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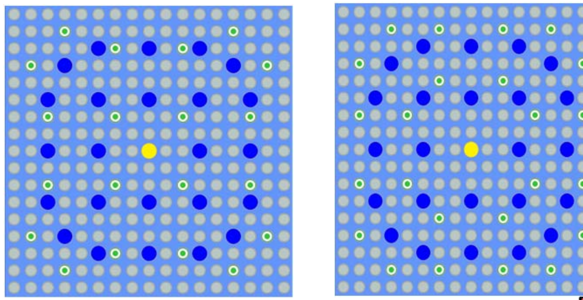
20	20	24	24	24	24	24	20	20
20	24	24	24	24	24	24	24	20
20	20	24	24	24	24	24	20	20
	20	24	24	24	24	24	20	
		20	20	24	20	20		
			20	20	20			

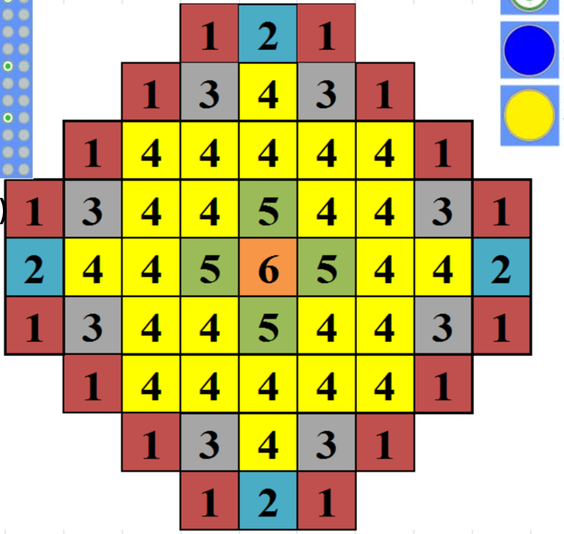
KSMR

→ 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)**



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		1	3	4	3	1		
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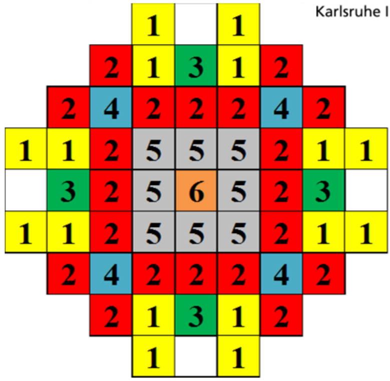
1	3	4	4	5	4	4	3	1
2	4	4	5	6	5	4	4	2
1	3	4	4	5	4	4	3	1
	1	4	4	4	4	4	1	
		1	3	4	3	1		
			1	2	1			

Core Configuration



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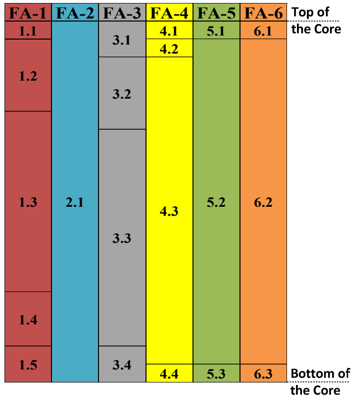
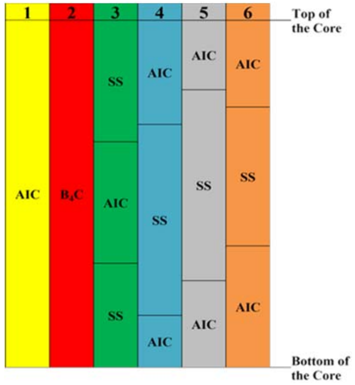
		2	1	3	1	2		
	2	4	2	2	2	4	2	
1	1	2	5	5	5	2	1	1
	3	2	5	6	5	2	3	
1	1	2	5	5	5	2	1	1
	2	4	2	2	2	4	2	
		2	1	3	1	2		
			1		1			

Control Rods Configuration





Ref. [3,4,5]

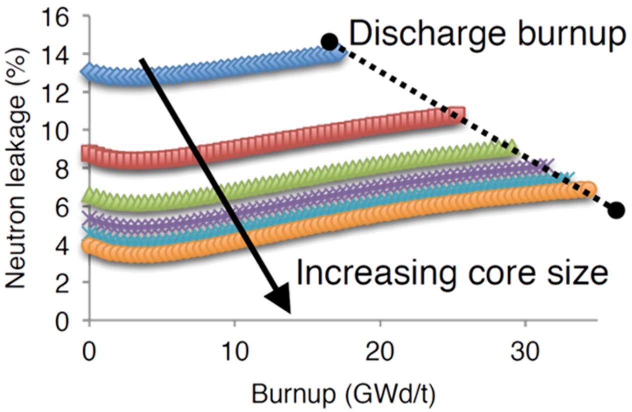
Challenges

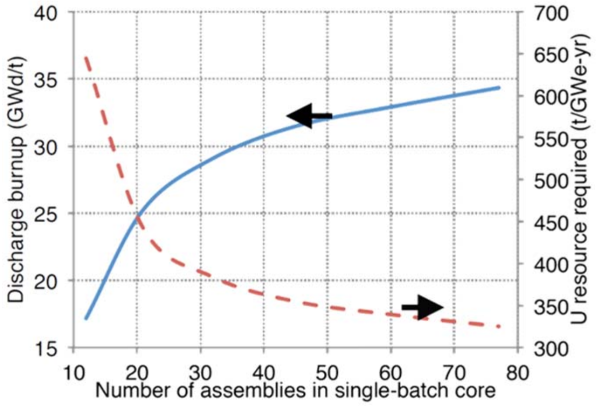
Neutronics: Core Design Challenges [30]

- 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] :

- 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]

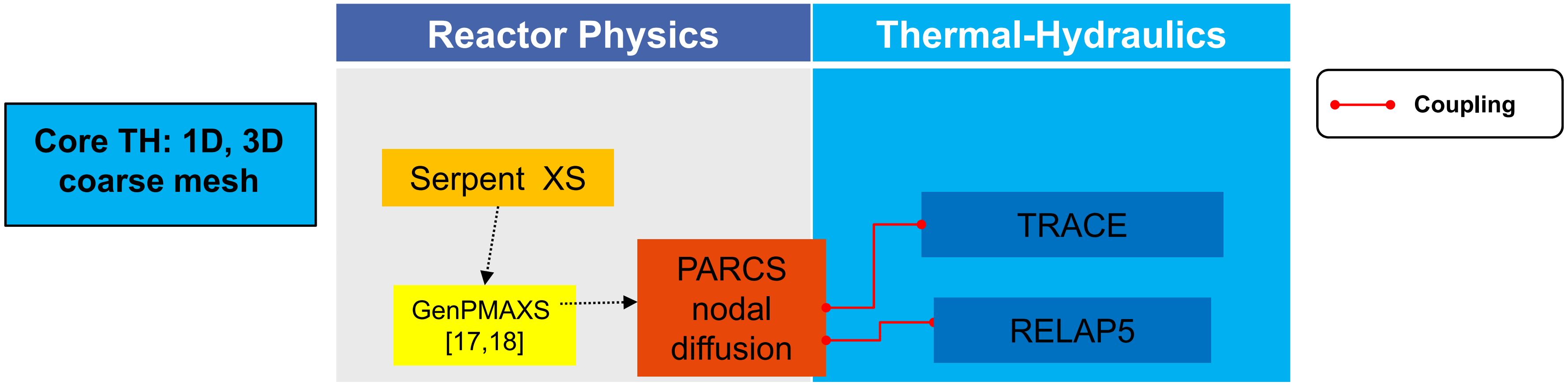
- Improved core thermal hydraulics:
  - Subchannel codes: Subchanflow (in-house) [7,8]
  - Porous-media 3D TH: Twoporflow (in-house) [9]

- 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



Core TH: 1D, 3D coarse mesh

Reactor Physics

Thermal-Hydraulics

Serpent XS

GenPMAXS [17,18]

PARCS nodal diffusion

TRACE

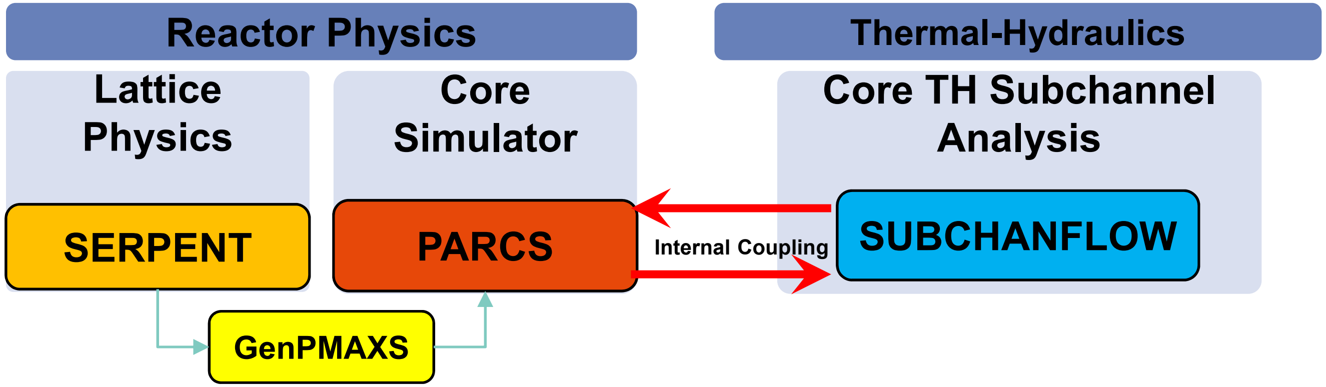
RELAP5

●—● **Coupling**

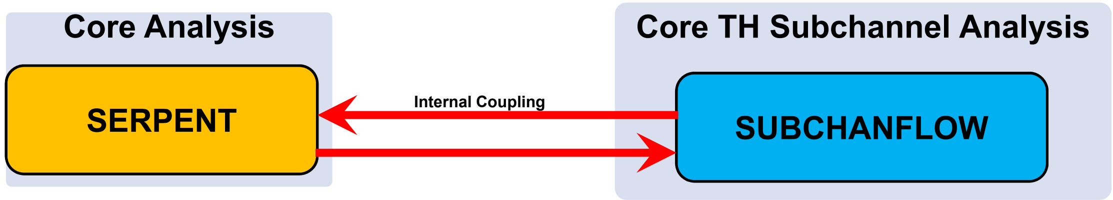
No direct prediction of **local** safety parameters

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

- Core design and core optimization tools:



- 3D core reference solutions:

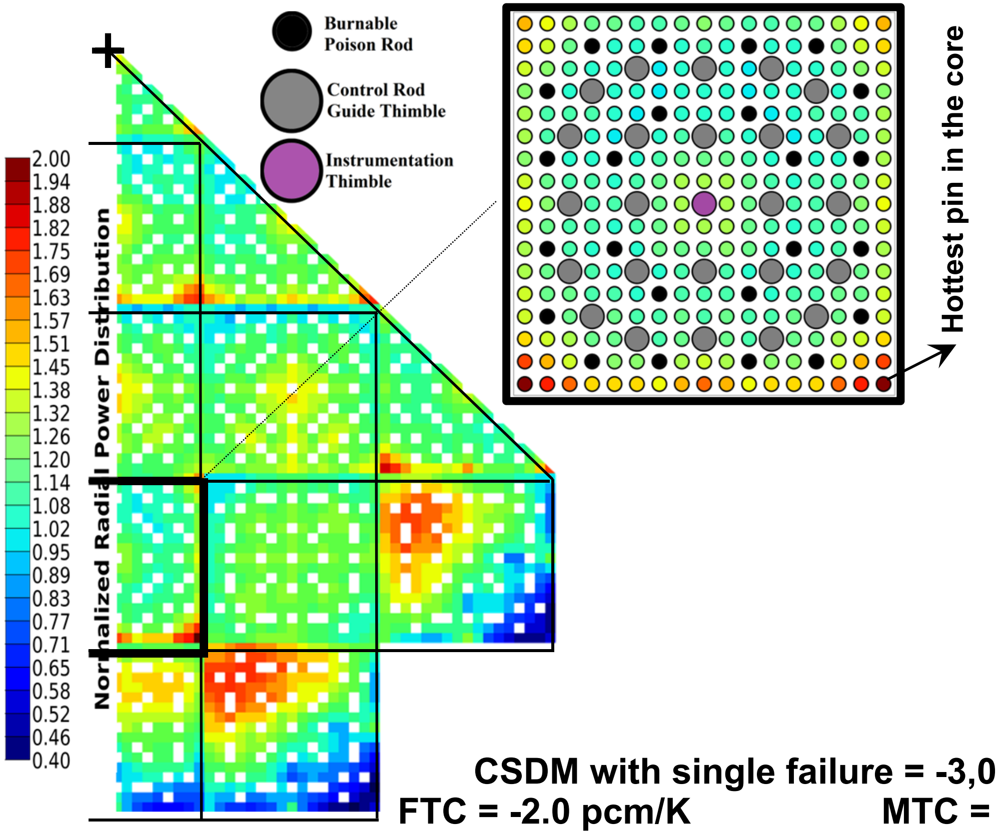


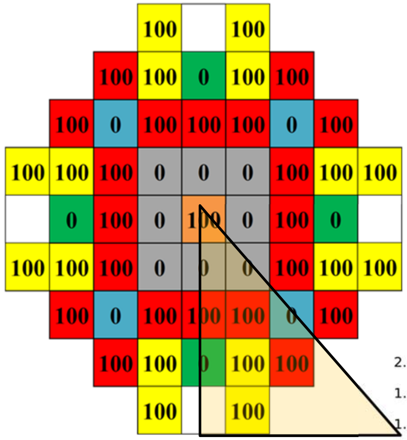
Visualization Tool

ParaView
Parallel Visualization Application

matplotlib

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

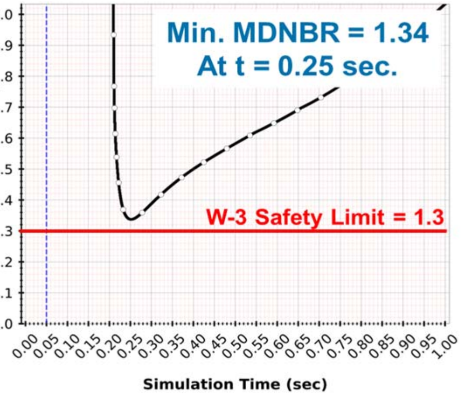




			100		100			
		100	100	0	100	100		
	100	0	100	100	100	0	100	
100	100	100	0	0	0	100	100	100
	0	100	0	100	0	100	0	
100	100	100	0	0	0	100	100	100
	100	0	100	100	100	0	100	
		100	100	0	100	100		
			100		100			

Control Rods Critical Configuration at HFP Condition

Ref. [4,5]

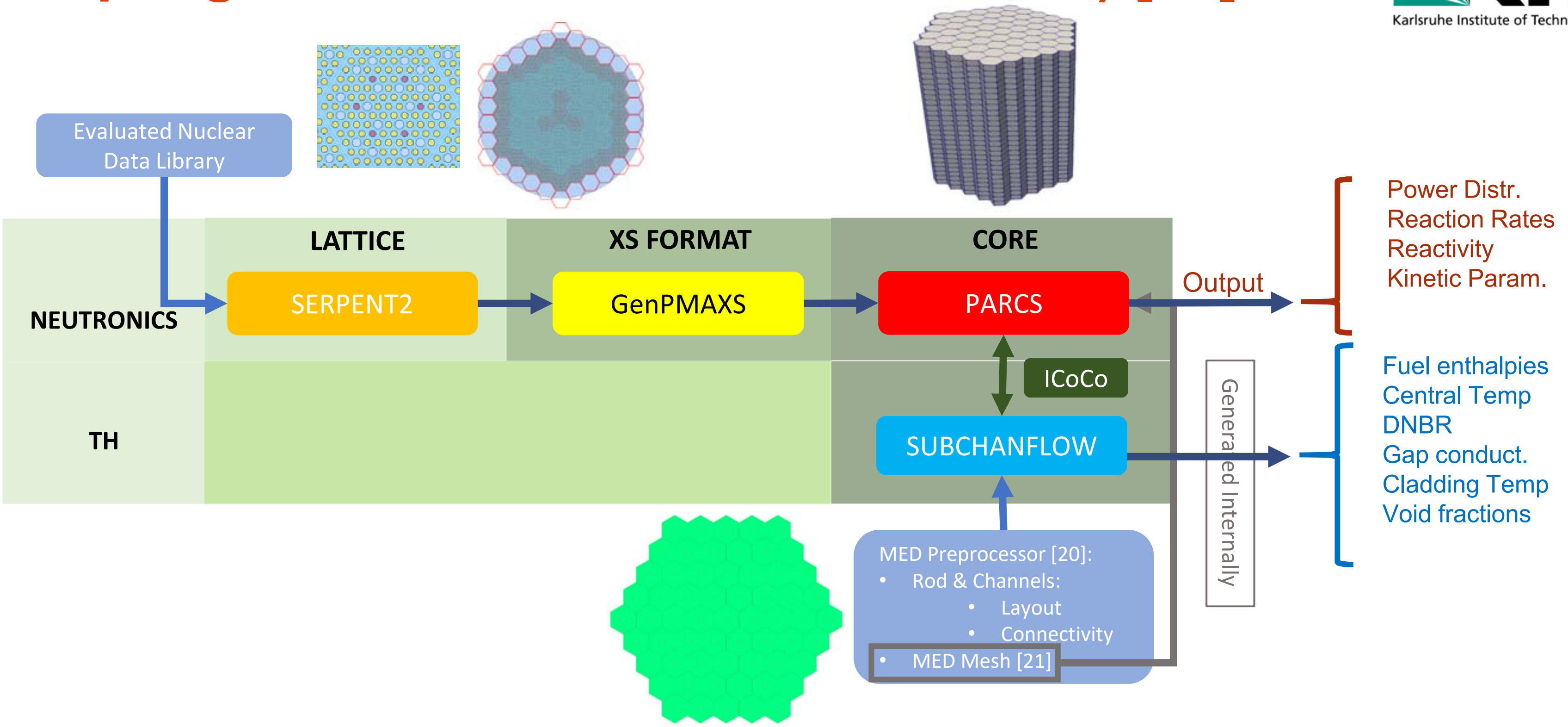


REA: MDNBR

CSDM with single failure = -3,000 pcm

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

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



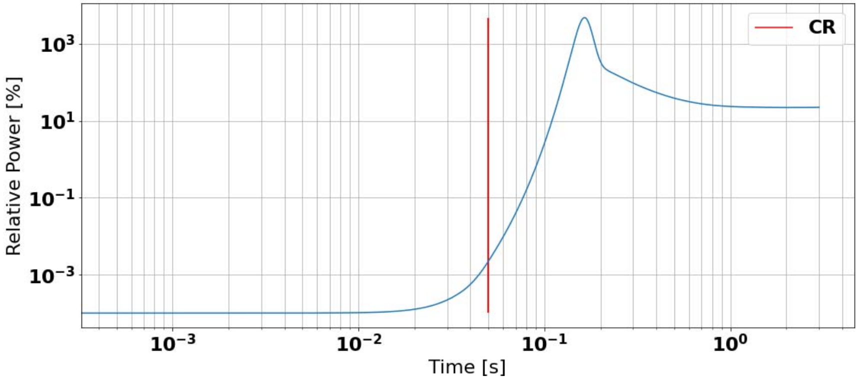
Power Distr.
Reaction Rates
Reactivity
Kinetic Param.

Fuel enthalpies
Central Temp
DNBR
Gap conduct.
Cladding Temp
Void fractions

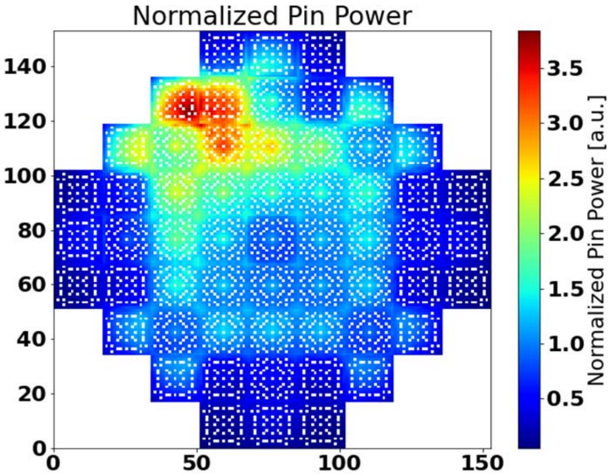
MED Preprocessor [20]:
- Rod & Channels:
  - Layout
  - Connectivity
- MED Mesh [21]

Ref. [18]

KSMR REA: ICoCo PARCS/SCF Analysis [20]



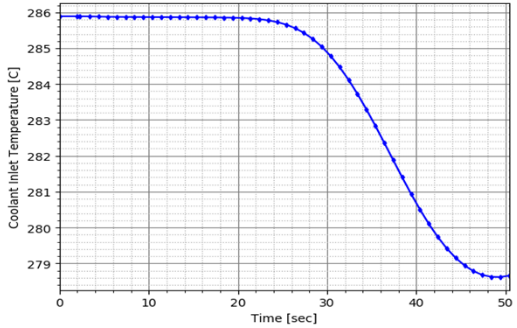
KSMR Rod Ejection Accident with Pin Power Reconstruction at power peak



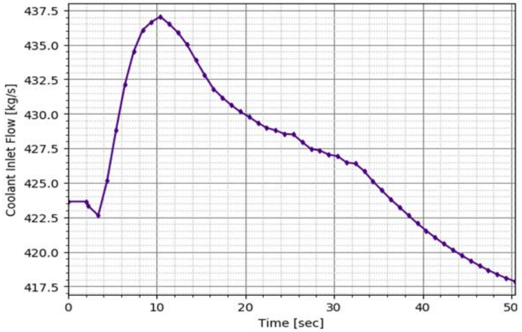
KSMR REA: Relative power [%] at peak power

Ref. [20]

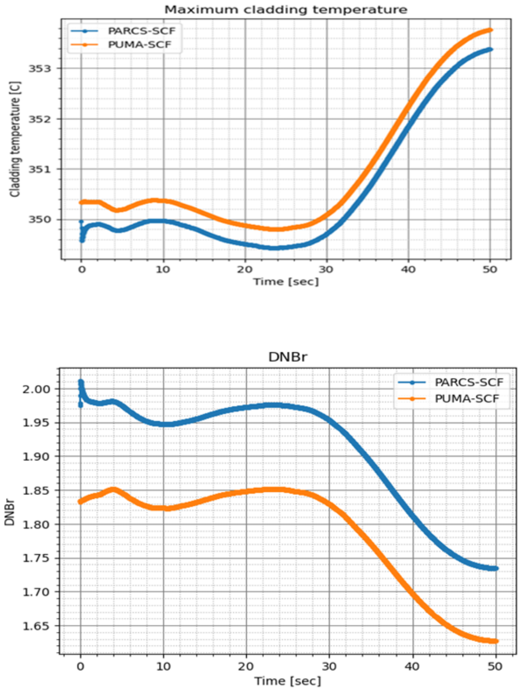
PARCS/SCF/ICoCo:
Analysis of CAREM: Overcooling Transient [20]



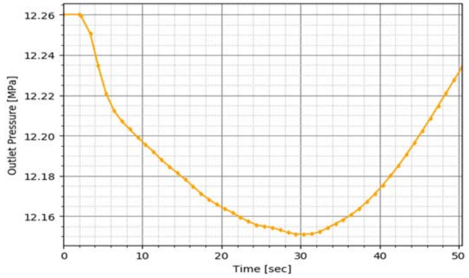
Coolant temperature decrease



Mass flow rate change

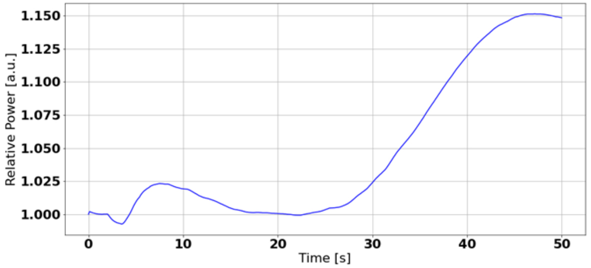


CAREM Overcooling transient: Key-parameters



Outlet pressure evolution

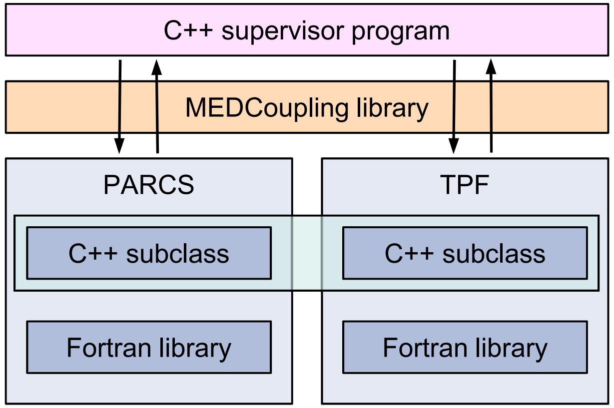
Ref. [20]



Normalized Power [a.u.]

ICoCo-based
coupling of PARCS/Twoporflow (2022)

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


C++ supervisor program

MEDCoupling library

PARCS

C++ subclass

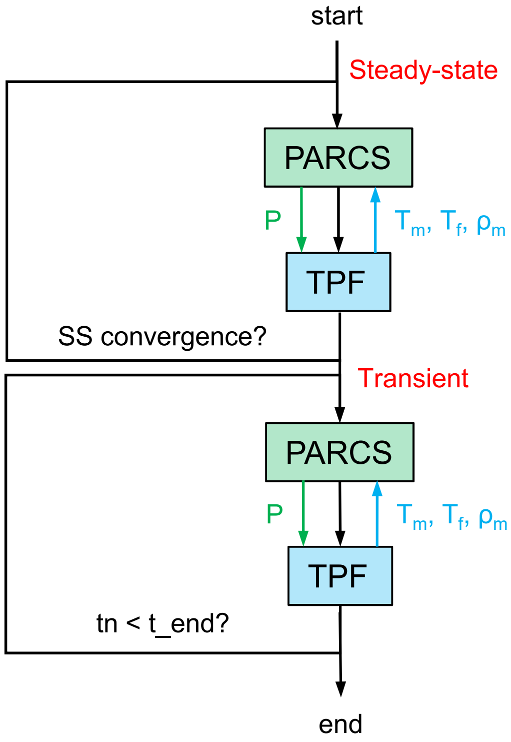
Fortran library

TPF

C++ subclass

Fortran library

Ref. [9]


start

Steady-state

PARCS

P

T_m, T_f, ρ_m

TPF

SS convergence?

Transient

PARCS

P

T_m, T_f, ρ_m

TPF

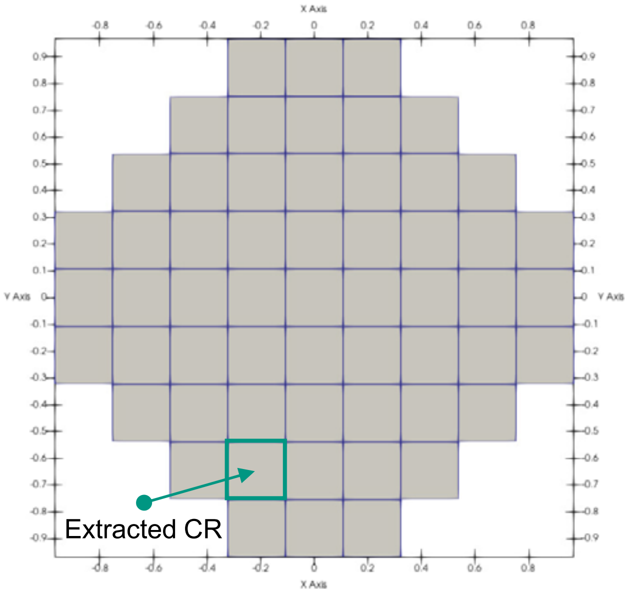
tn < t_end?

end

KSMR: REA Analysis at HZP

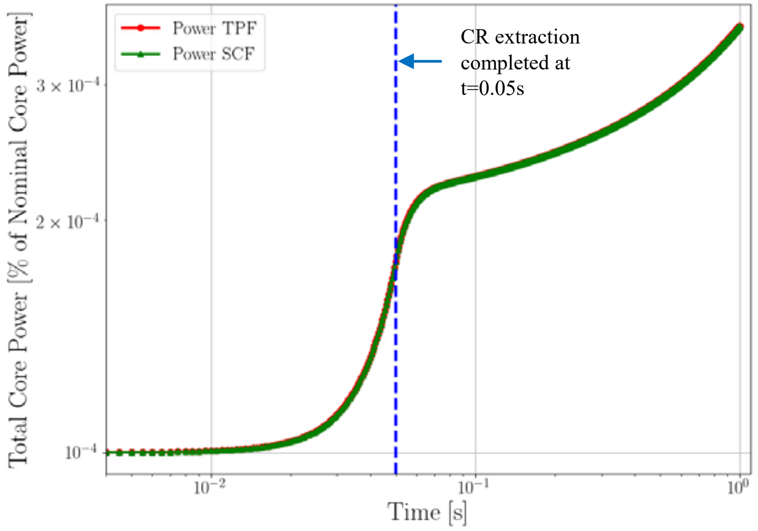
- Half highest CR worth extraction (0.725 $) at the hot zero power (HZP) condition.

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

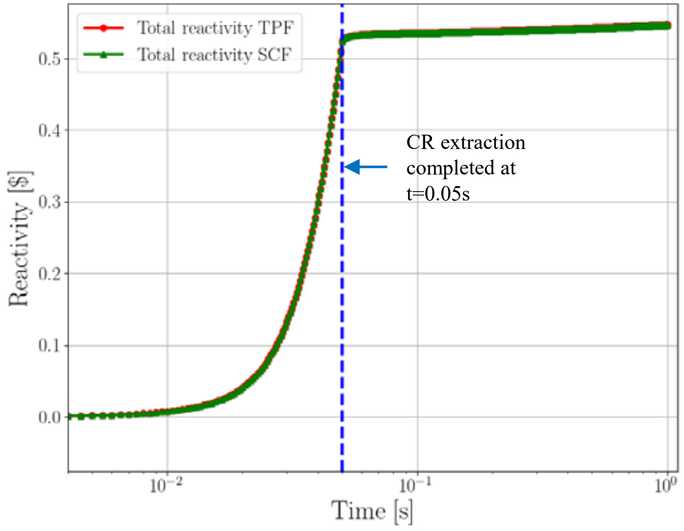


Ref. [9]

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


CR extraction completed at t=0.05s

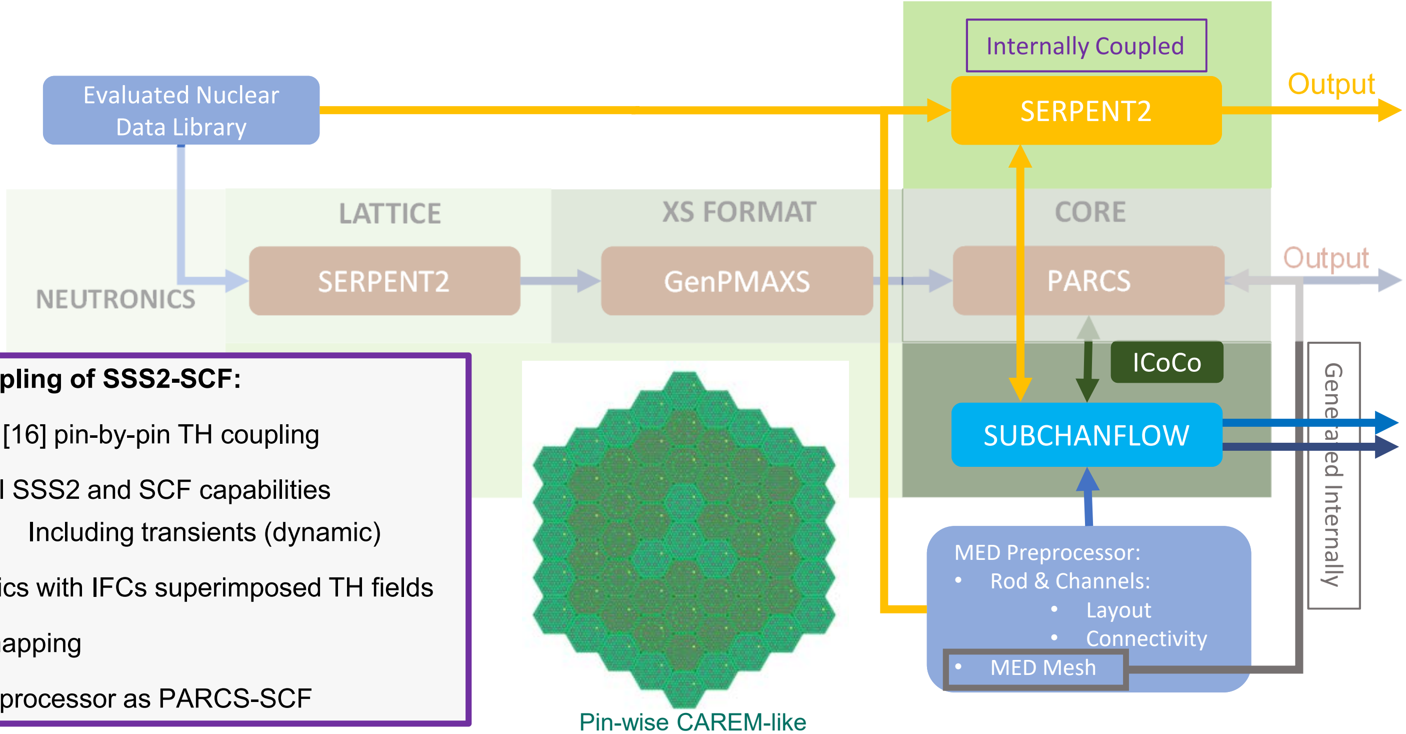
PARCS Total Core Power


CR extraction completed at t=0.05s

PARCS Total Reactivity

Ref. [9]

High Fidelity MC-based Multiphysics: SSS2-SCF



Internal coupling of SSS2-SCF:

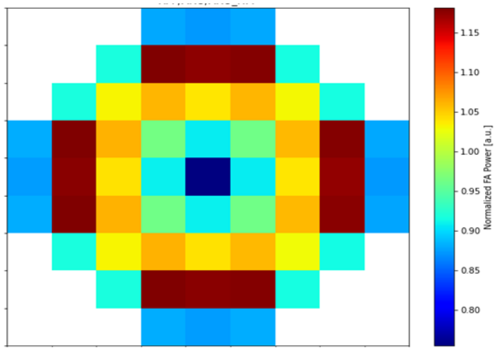
- MCSAFE [16] pin-by-pin TH coupling
- Inherits all SSS2 and SCF capabilities
    - Including transients (dynamic)
- Multiphysics with IFCs superimposed TH fields
- Internal mapping
- Same preprocessor as PARCS-SCF

Pin-wise CAREM-like preprocessor plot

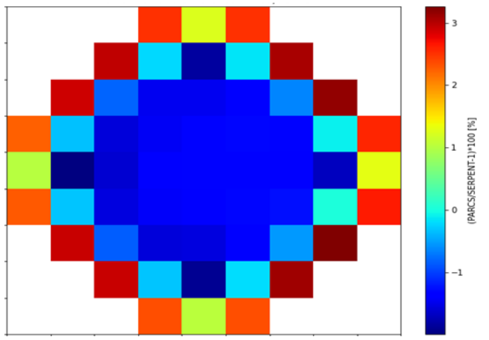
Ref. [20, 13,14,23,24]

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

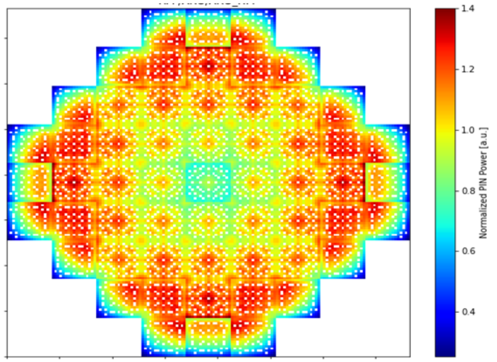
SSS2: axially integrated FA normalized radial power for HFP ARO



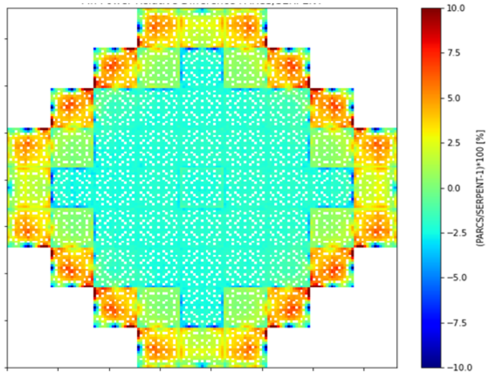
PARCS-SSS2: axially integrated FA normalized radial power relative difference for HFP ARO



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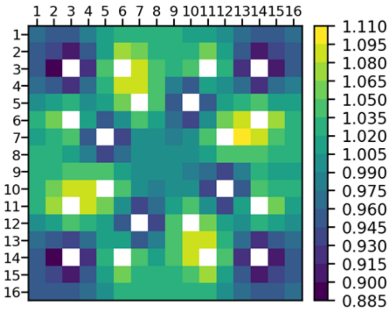
- Motivation: Pin-wise Simulation, XS Optimization, TH Feedback

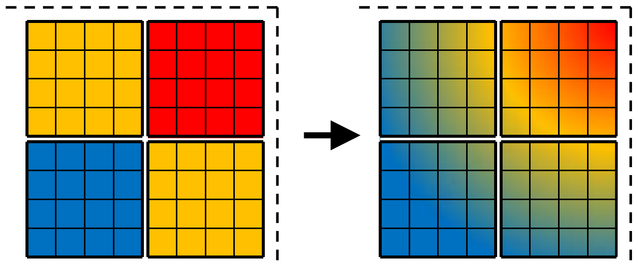
*The discussion in this slide only concern **Cartesian** geometry*



Pin-wise results are important

PARCS V331 has two methods for pin-wise results:

- Nodal + Pin power reconstruction



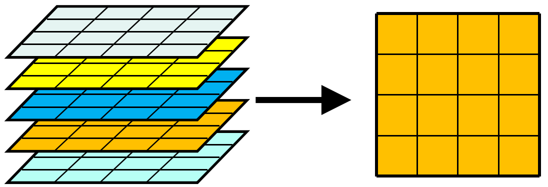
Advantage:

- Fast running.

Limitation:

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

- FMFD (Fine Mesh Finite Difference)



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.

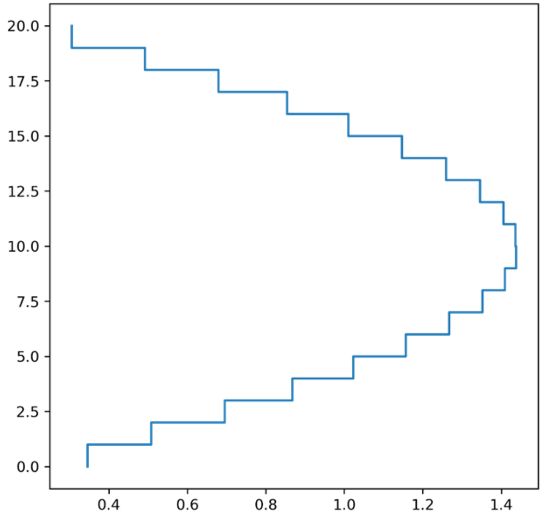
PARCS V331 can not do this

Function extension is required

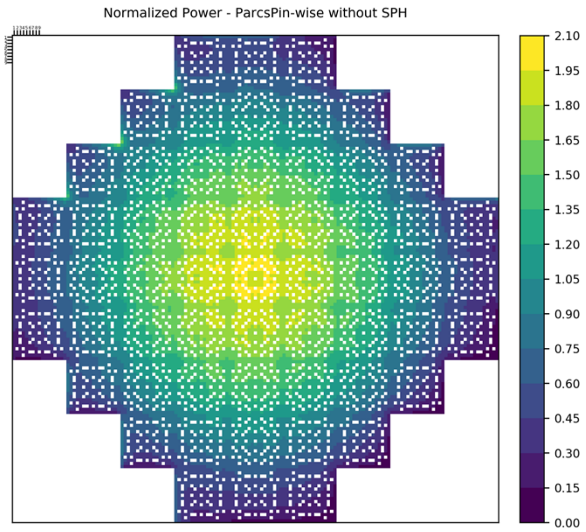
Ref. [22]

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

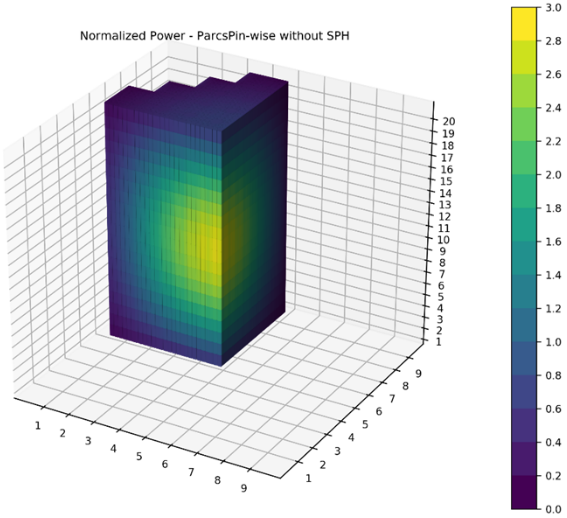
- First Results: KSMR core steady state



Axial power distribution



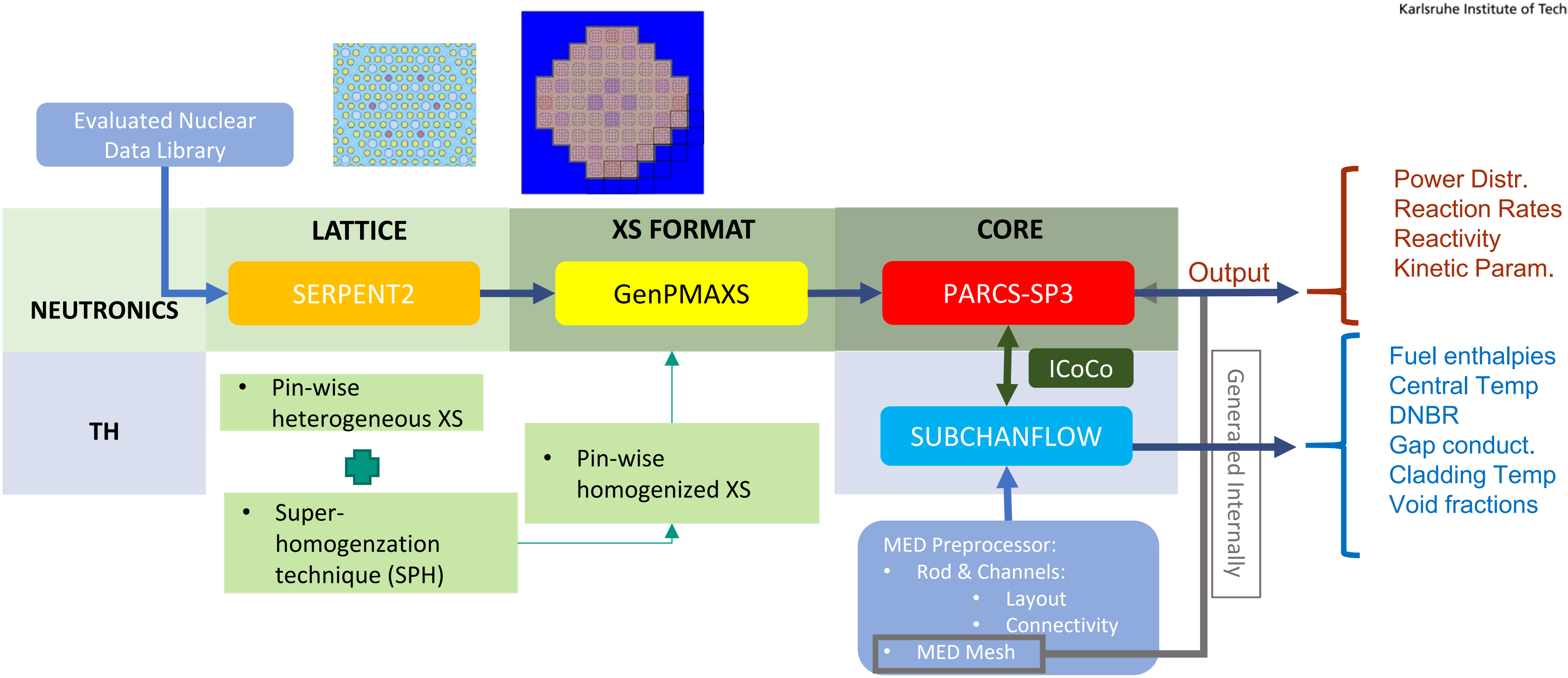
Radial power distribution



Spatial power distribution

Ref. [22]

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



Evaluated Nuclear Data Library

NEUTRONICS

TH

LATTICE

SERPENT2

- Pin-wise heterogeneous XS

✚

- Super-homogenzation technique (SPH)

XS FORMAT

GenPMAXS

- Pin-wise homogenized XS

CORE

PARCS-SP3

ICoCo

SUBCHANFLOW

MED Preprocessor:
- Rod & Channels:
  - Layout
  - Connectivity
- MED Mesh

Generated Internally

Output

Power Distr.
Reaction Rates
Reactivity
Kinetic Param.

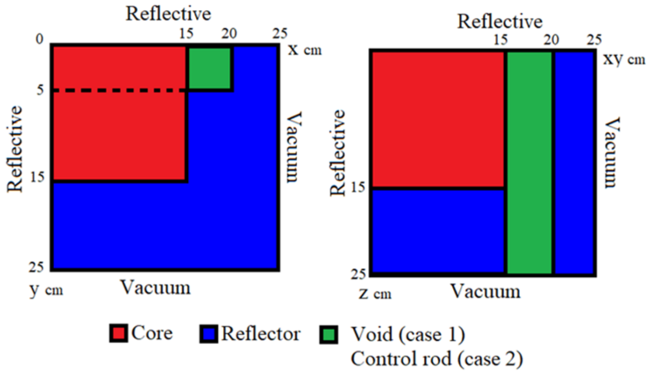
Fuel enthalpies
Central Temp
DNBR
Gap conduct.
Cladding Temp
Void fractions

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)

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