CORTEX

Core monitoring techniques and experimental validation and demonstration

Work Package 1
Development of modelling capabilities for reactor noise analysis

CORTEX final workshop, 21-22 June 2021

Paolo Vinai (Chalmers)
vinai@chalmers.se

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754316.

Outline

- Introduction
- Modeling of fluid-induced vibrations in nuclear power reactors
- Simulations of neutron noise in nuclear power reactors
- Stochastic and deterministic higher-order methods
- Uncertainty and Sensitivity analysis

- Introduction

Partners

Joachim Herb
Christoph Bläsius
Jürgen Sievers
Matthias Küntzel
Yann Perin

Abelhamid Dokhane
Vasudha Verma
Dionysios Chionis

Andrea Zoia
Amélie Rouchon
Baptiste Gasse
Simone Santandrea
Igor Zmijarevic
Alberto Brighenti

Carsten Lange
Alexander Knospe
Marco Viebach

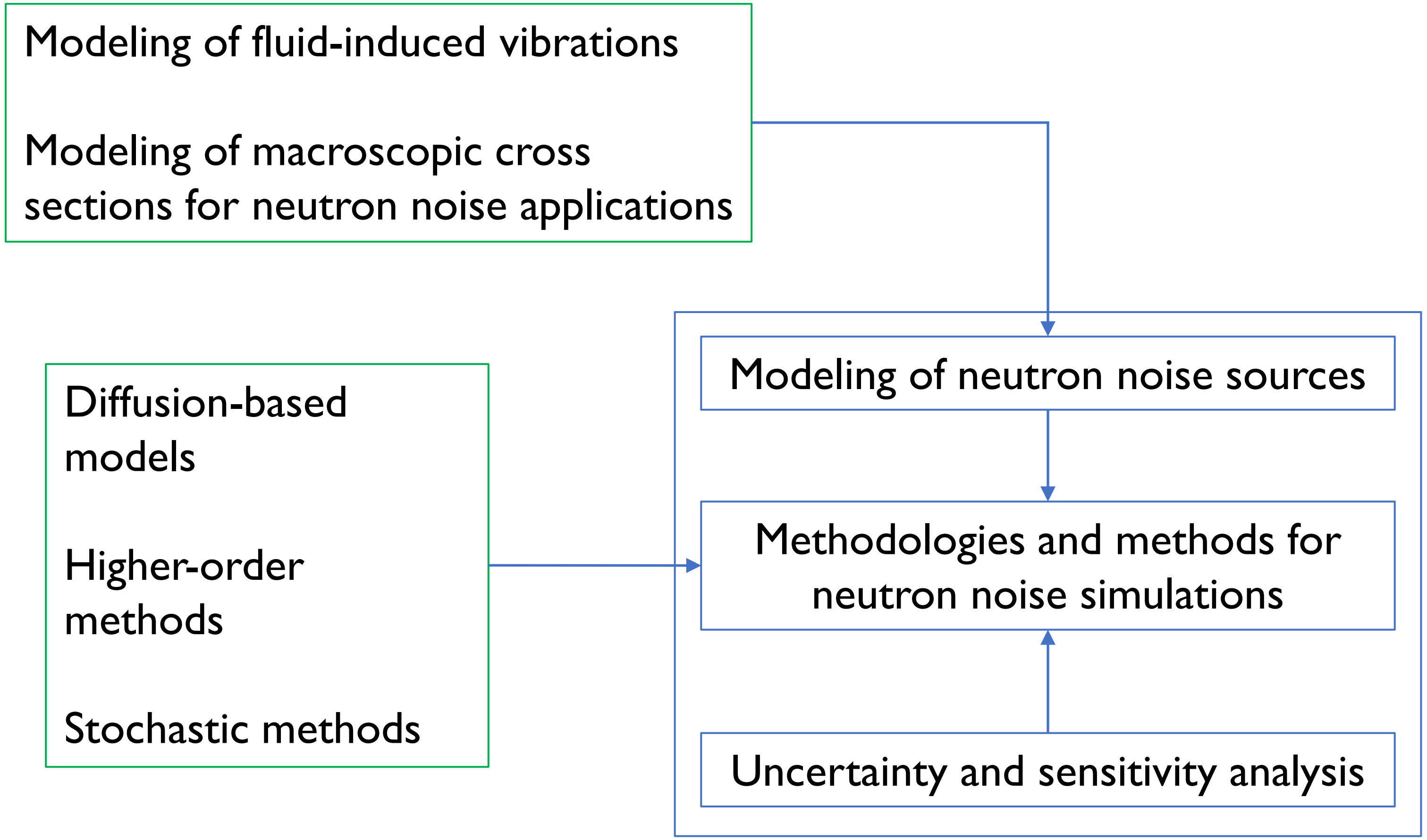
Toni Vidal
Damian Ginestar
Gumersindo Verdú

Toshihiro
Yamamoto

Rafael Macian
Soobeen Yum

Christophe Demazière
Antonios Mylonakis
Huaiqian Yi

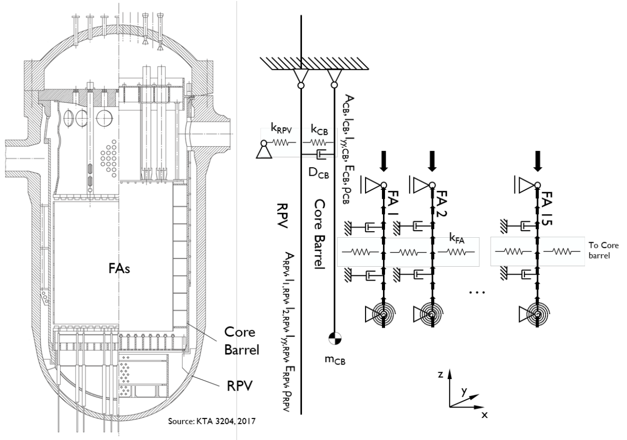
WP1

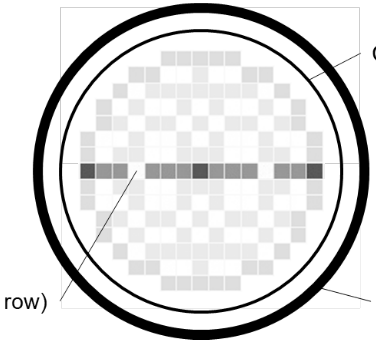

Modeling of fluid-induced vibrations
Modeling of macroscopic cross sections for neutron noise applications
Diffusion-based models
Higher-order methods
Stochastic methods
Modeling of neutron noise sources
Methodologies and methods for neutron noise simulations
Uncertainty and sensitivity analysis

- Modeling of fluid-induced vibrations in nuclear power reactors
- Coupling between mechanical vibrations, TH and NK

Modeling of fluid-induced vibrations

- Oscillating system RPV + Core Barrel + Fuel Assemblies
- Coupling between mechanical vibrations and TH

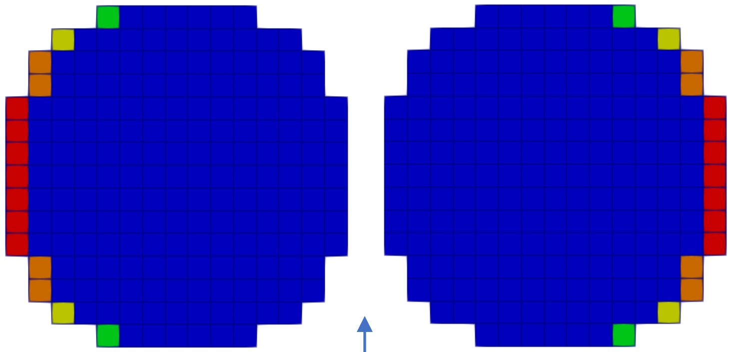




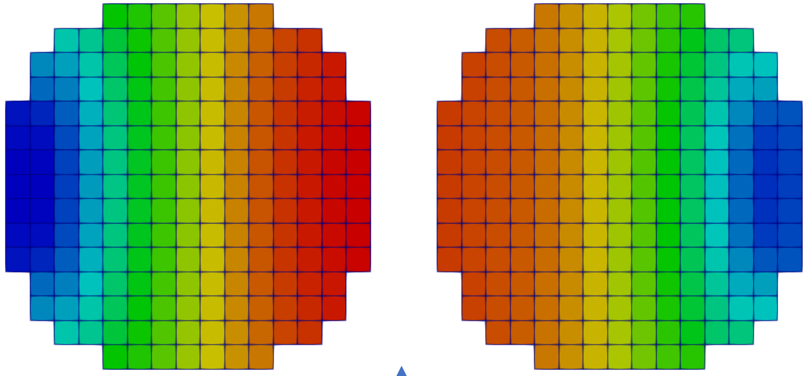
ANSYS model of mechanical vibrations → Variation of fuel assembly cross-sectional area wrt time → Fluid response by added mass/stiffness/damping, quantified by ATHLET → Variation of mass flow rate and enthalpy in the fuel assemblies wrt time → ANSYS model of mechanical vibrations

Modeling of fluid-induced vibrations

- ANSYS – ATHLET simulation of a 4-loop Pre-Konvoi PWR

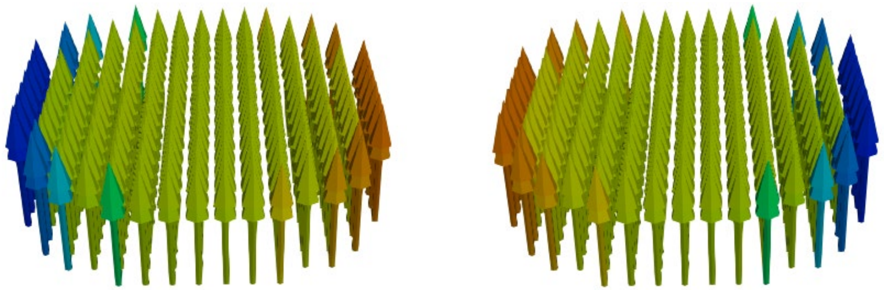


Variation of the cross-sectional area of the fuel assemblies wrt time



Variation of pressure in the fuel assemblies wrt time

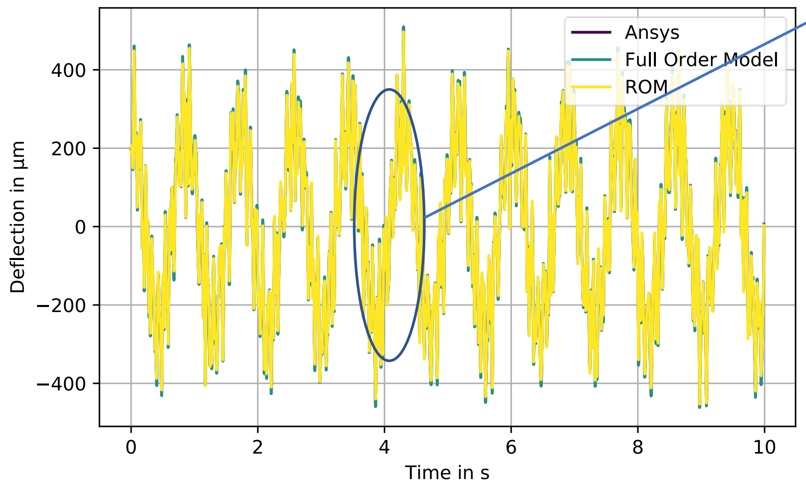
Variation of the coolant velocity in the fuel assemblies wrt time

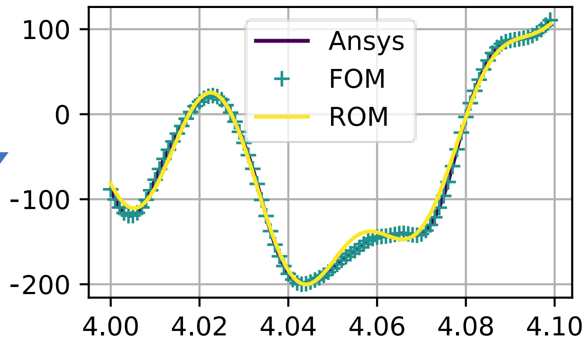


Coupling between mechanical vibrations and NK-TH

- Reduced order models from the full ANSYS model
  - Proper Orthogonal Decomposition – POD
  - Krylov subspace reduction
  - Balanced truncation

System response to a RPV + Core Barrel deflection





Coupling between mechanical vibrations and NK-TH

- POD-based reduced order model for mechanical vibrations of core components
  - RPV, Core Barrel and Fuel Assemblies
- DYN3D for NK-TH calculations

POD-based ROM for mechanical vibrations

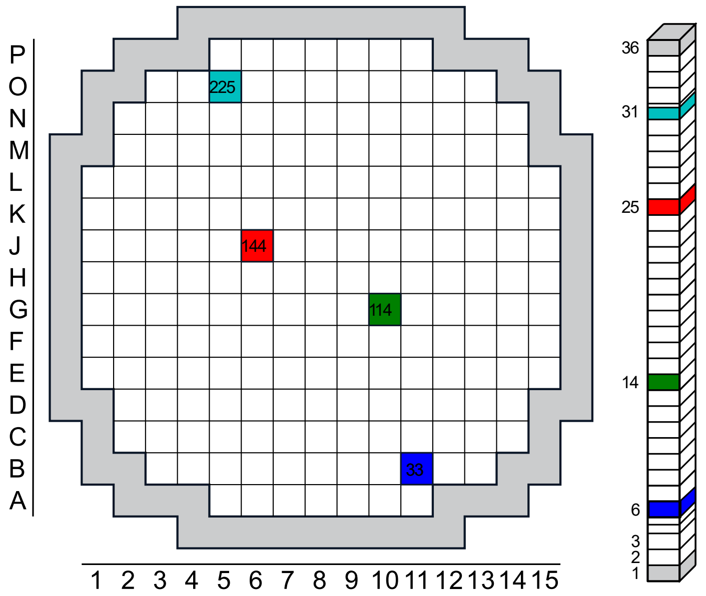
↓

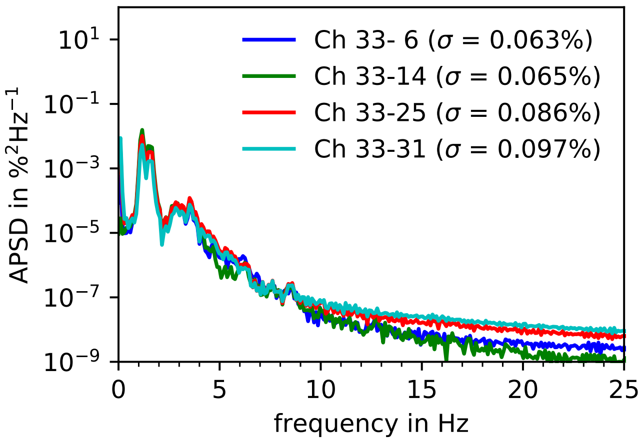
DYN3D steady-state calculation → Mean distances between fuel assemblies and their neighbors → Cross sections from tables prepared with CASMO-5 → DYN3D NK-TH full core calculation

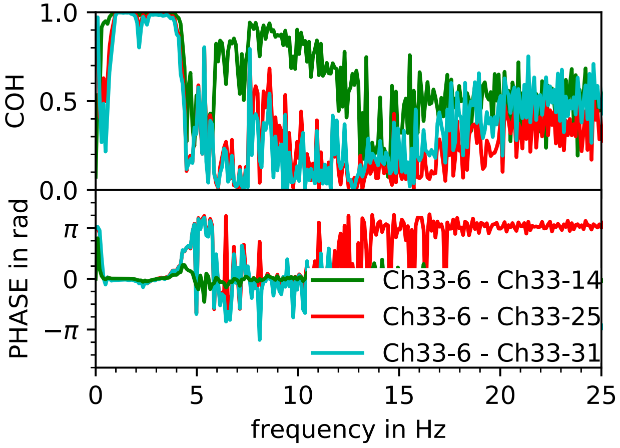
next time step

Coupling between mechanical vibrations and NK-TH

- Simulation of the effect of vibrations of core components on neutron noise
- 4-loop Pre-Konvoi PWR

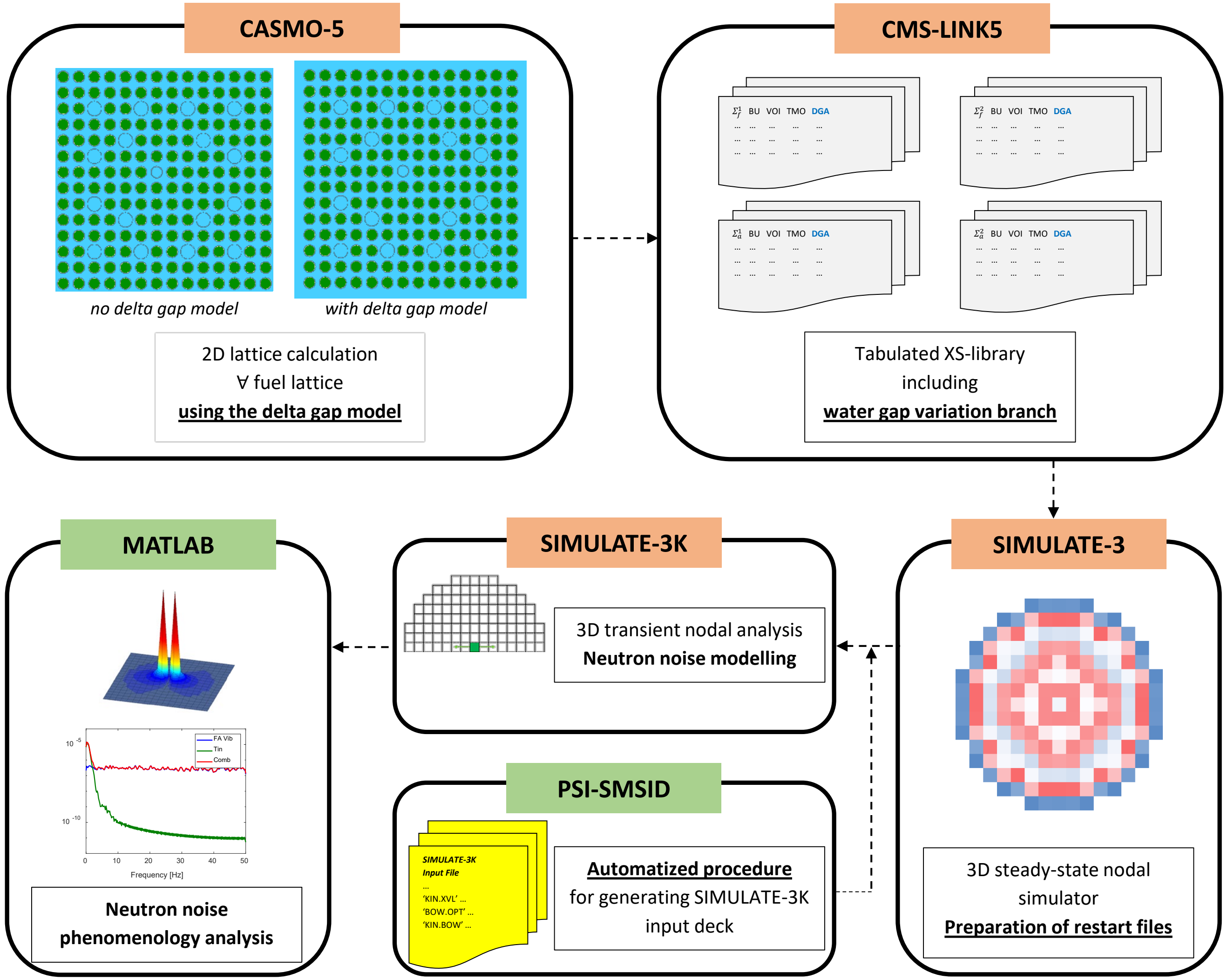






- Methodologies for simulations of neutron noise in nuclear power reactors

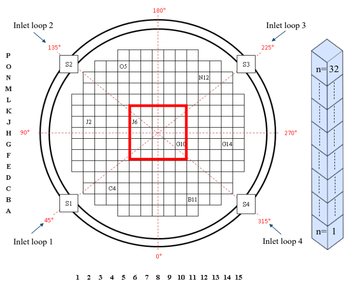
PSI methodology for neutron noise

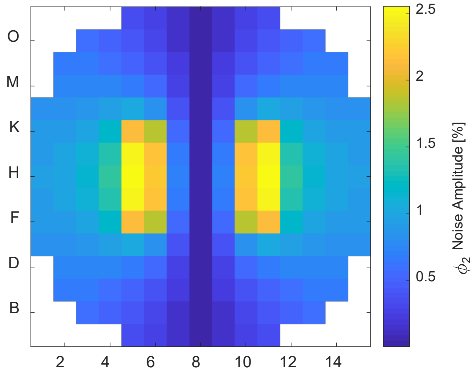


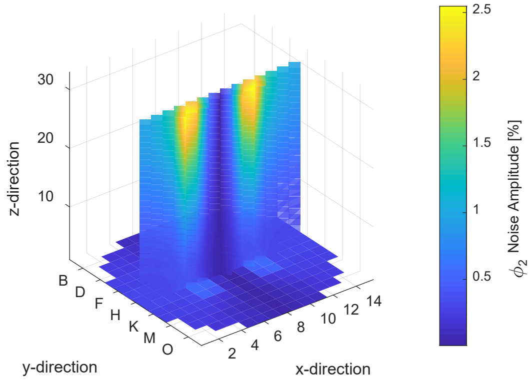
PSI methodology for neutron noise

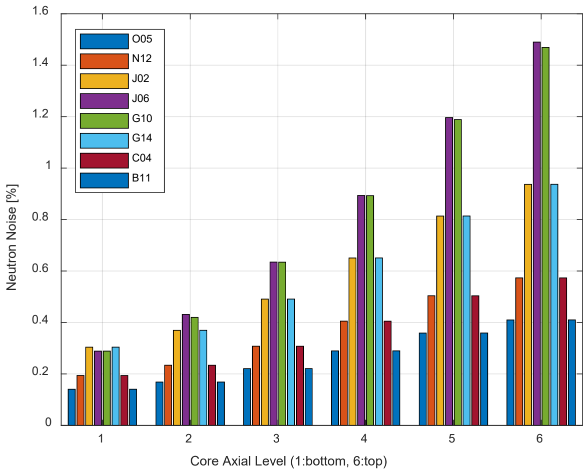
PAUL SCHERRER INSTITUT

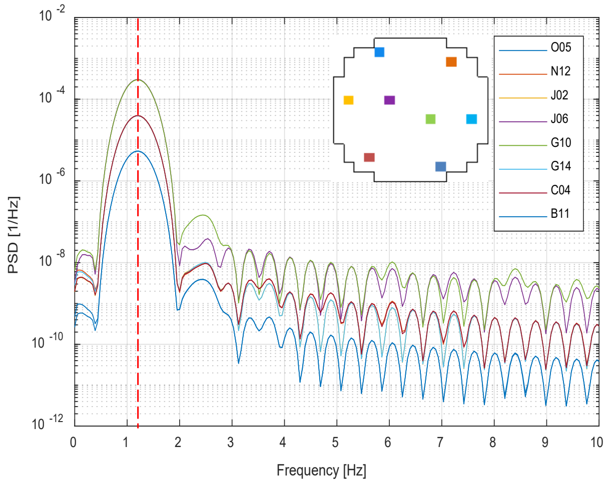
- Vibration of 5x5 cluster of FAs in a PWR
  - Cantilever mode, max amplitude of displacement = 1.0 mm, and f = 1.2 Hz





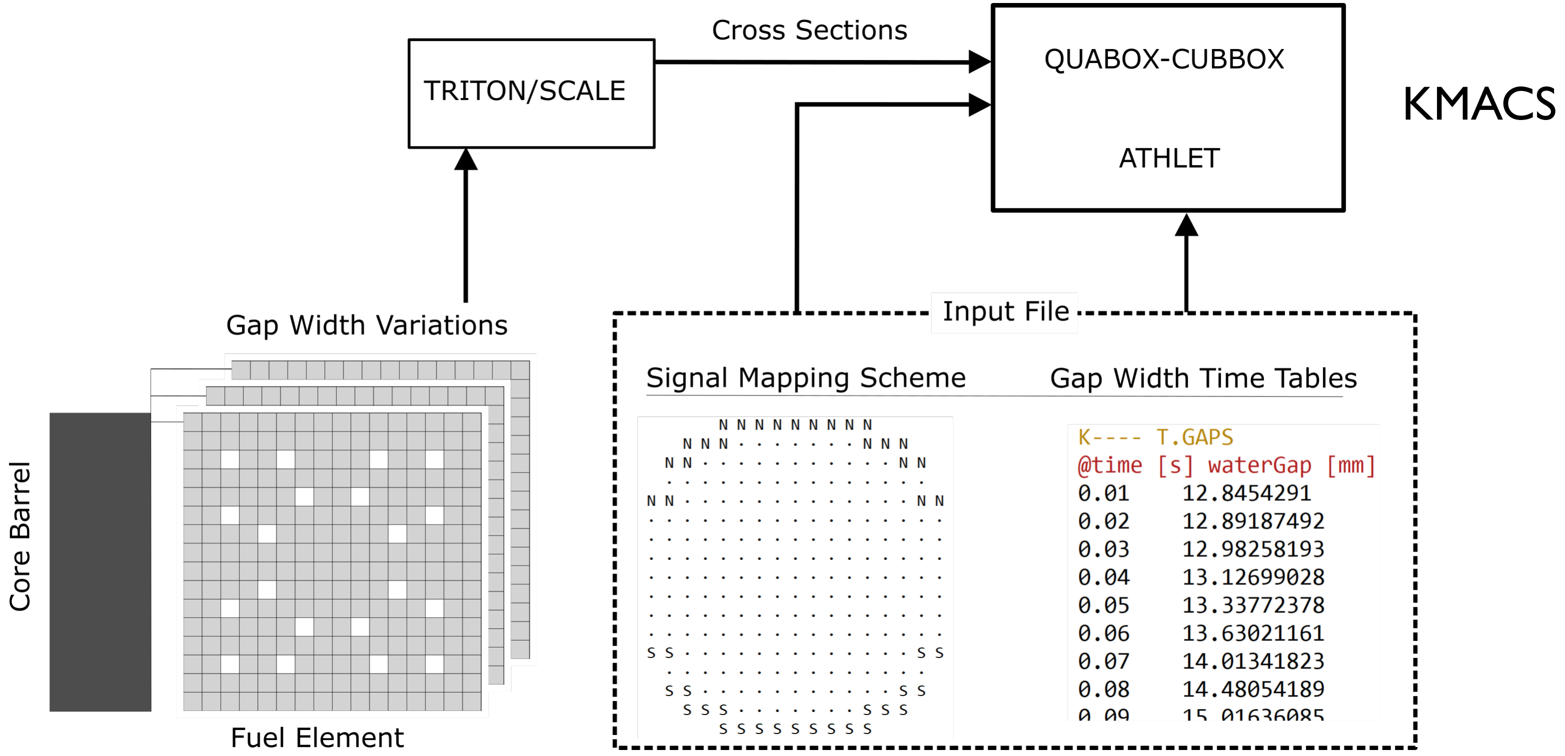






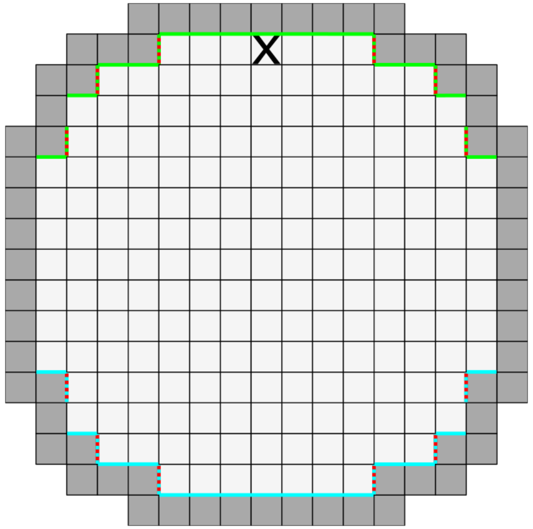
KMACS/QUABOX/CUBBOX

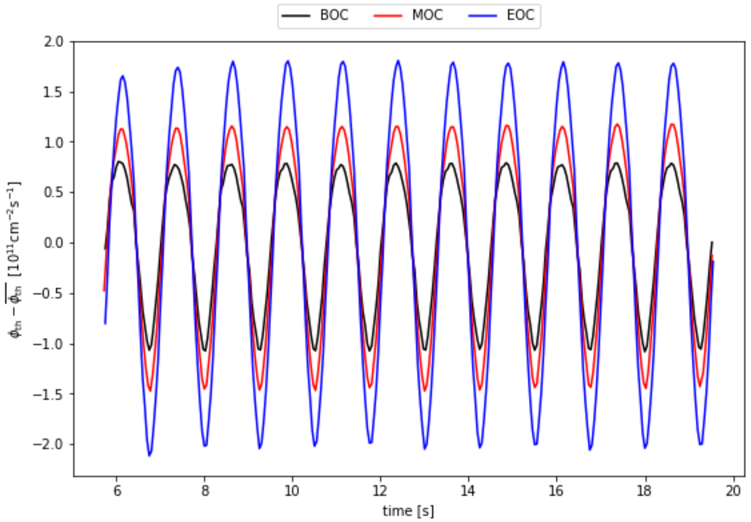
- Modeling of water gap variation between reactor core and core baffle induced by vibrations

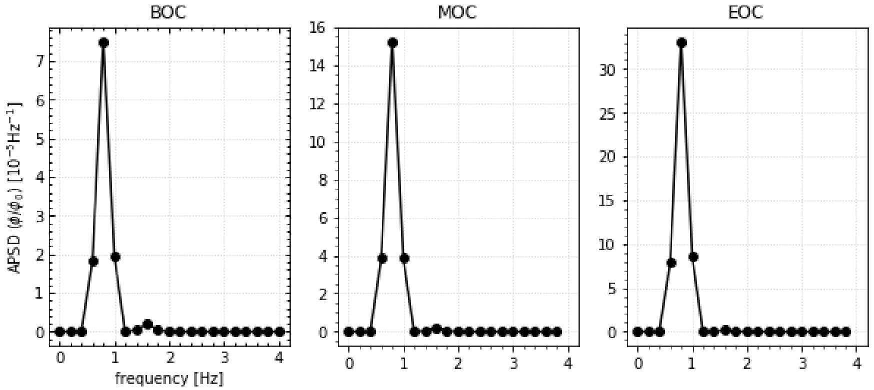


KMACS/QUABOX/CUBBOX

- Neutron noise simulation with water gap variation between reactor core and core baffle in a 4-loop Pre-Konvoi PWR
  - BOC – MOC – EOC

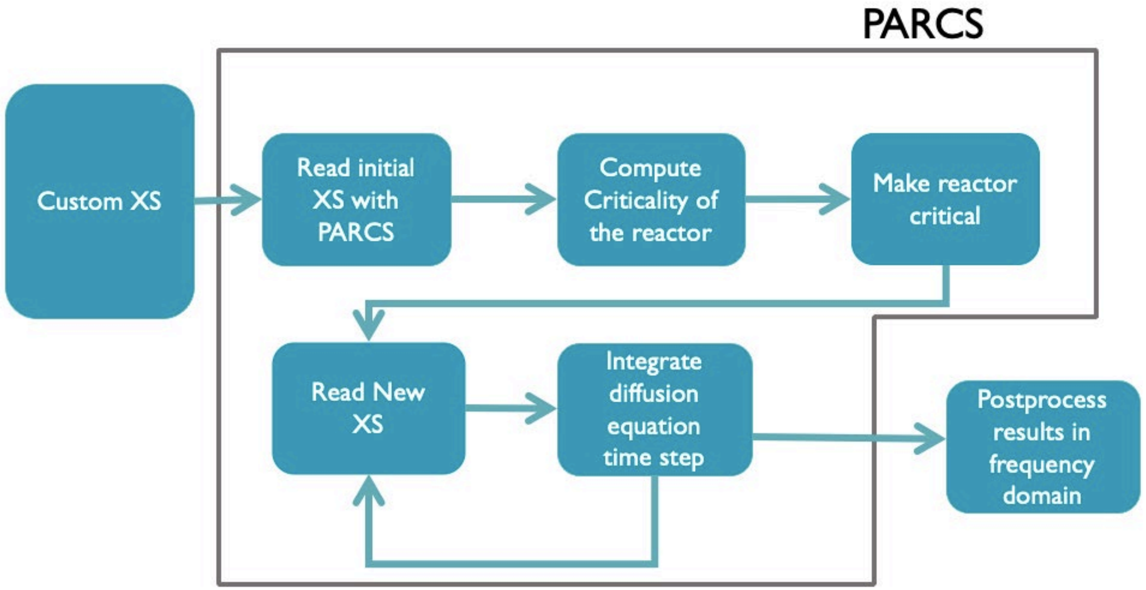






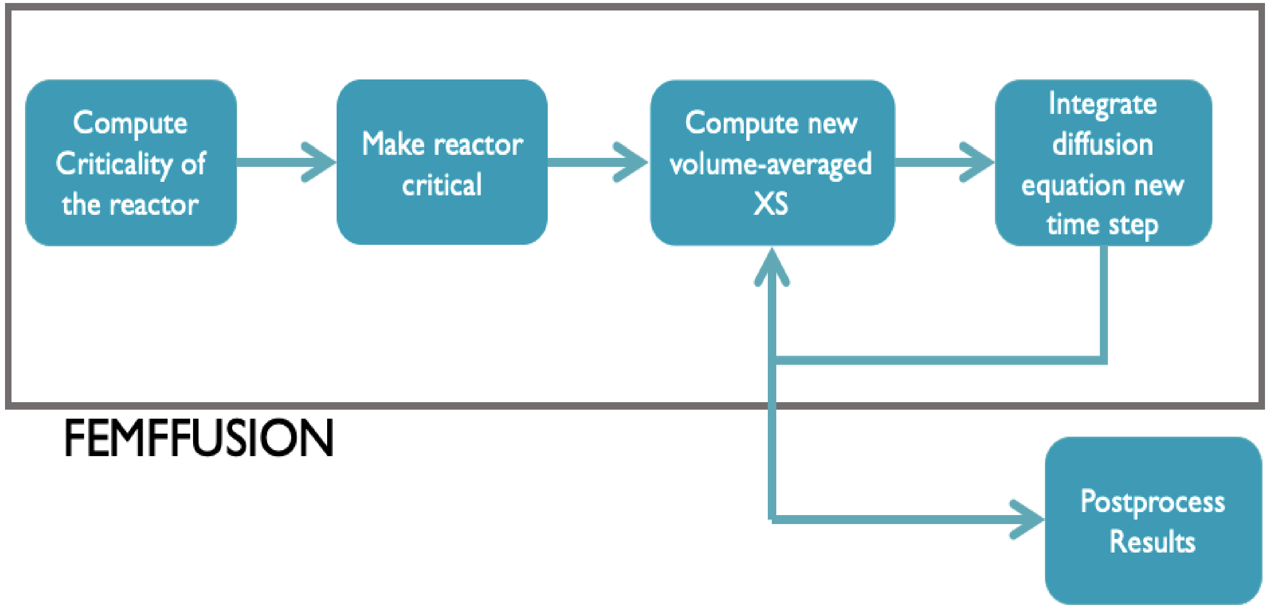
PARCS

- Diffusion theory
- Time-dependent calculations
- Finite difference module
- Modification for neutron noise simulations
  - User-defined time-dependent cross sections



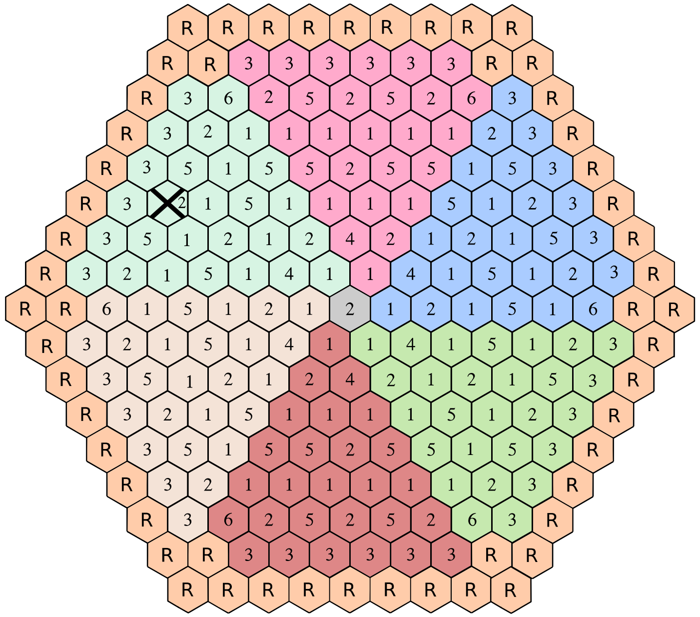
FEMFFUSION

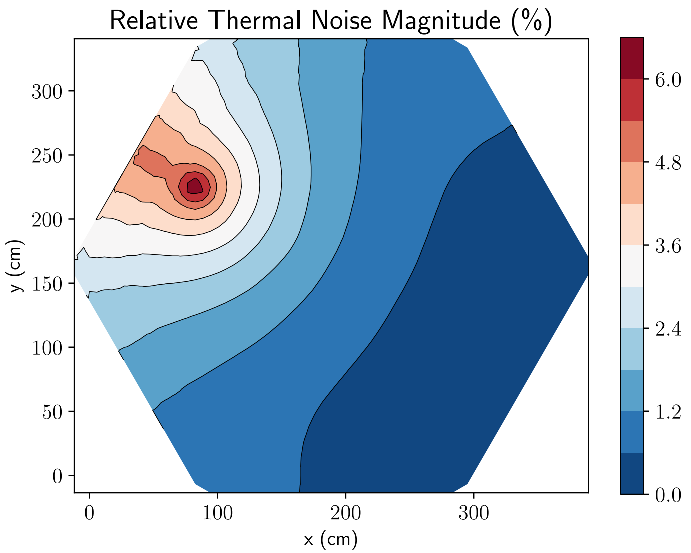
- Diffusion theory
- Finite Element method – FEM
- Time-domain and frequency-domain calculations
  - They provide essentially the same results

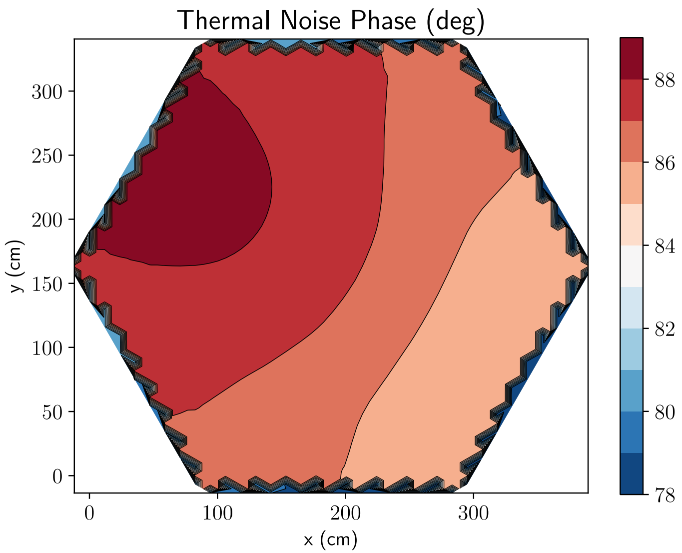


FEMFFUSION

- Frequency-domain simulation of neutron noise in VVER-440 and VVER-1000 reactors.
  - Generic fluctuations of the cross sections in a fuel assembly.
  - Perturbations moving with the coolant flow.

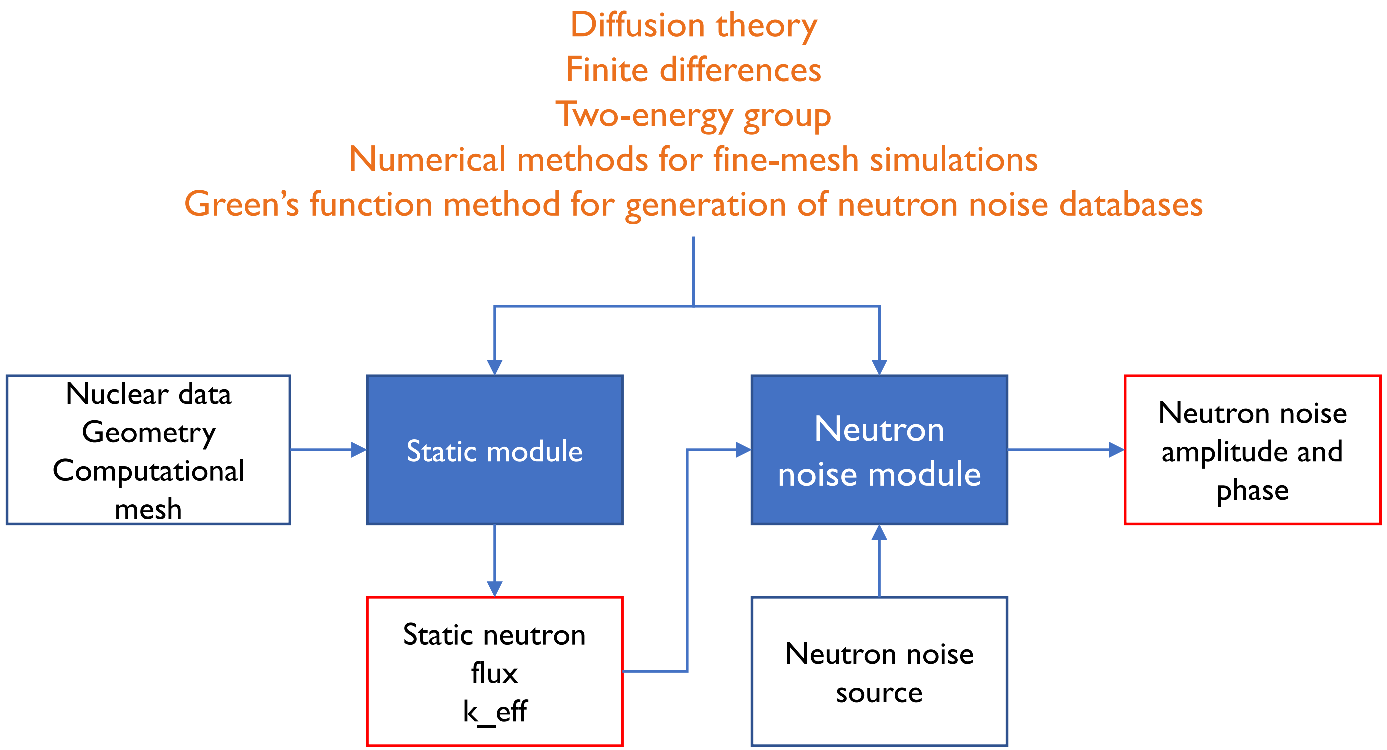






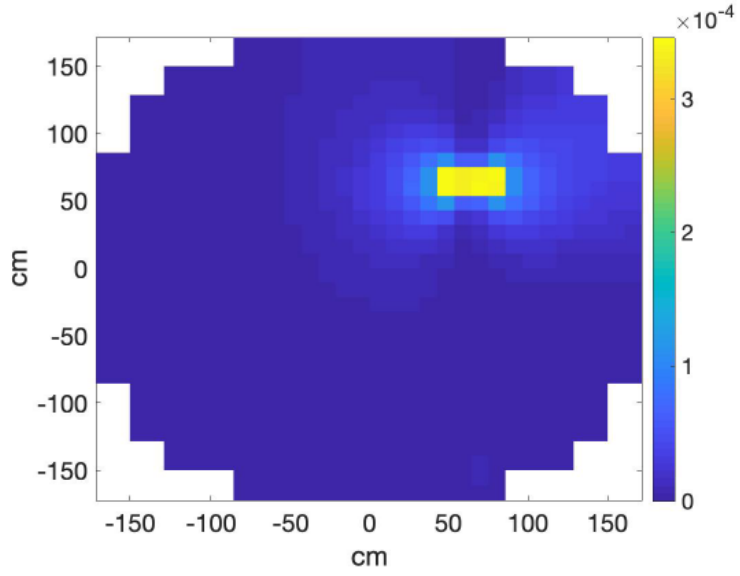
CORE SIM+

- First-order perturbation theory
- Frequency-domain calculations

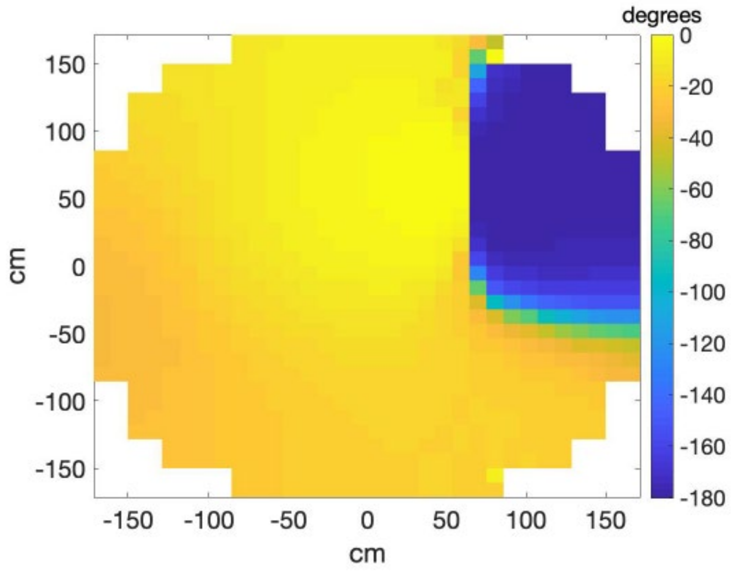


CORE SIM+

- Neutron noise simulations in a nuclear power reactor
  - Vibration of a fuel assembly



(b) Relative amplitude of thermal noise.

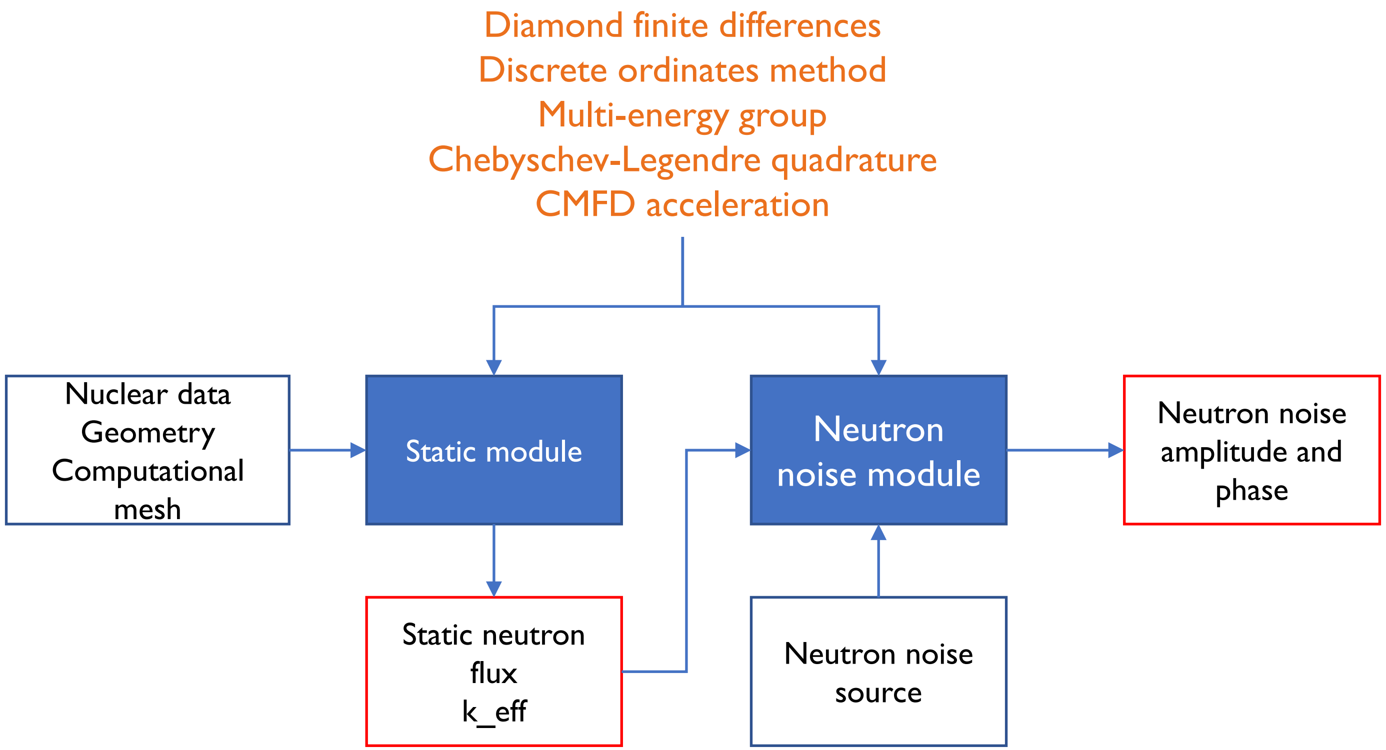


(d) Phase of thermal noise.

- Deterministic higher-order methods
- Monte Carlo methods

NOISE-SN

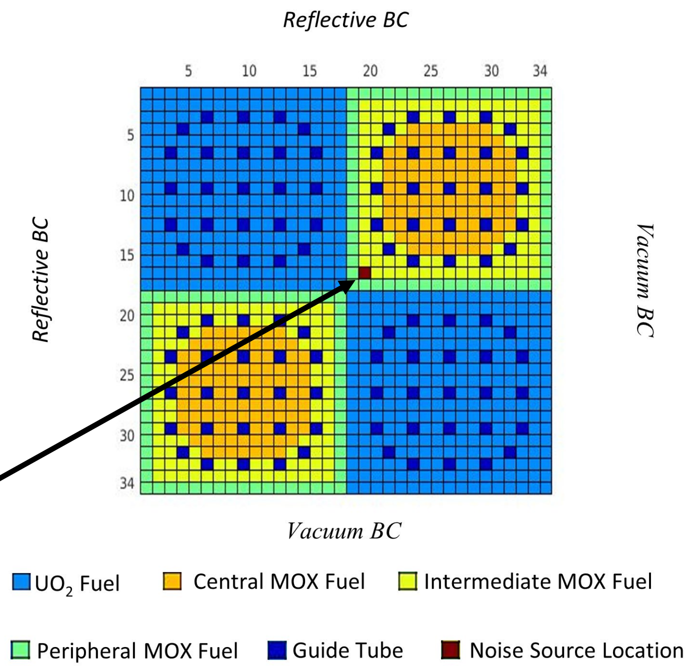
- First-order perturbation theory
- Frequency-domain calculations

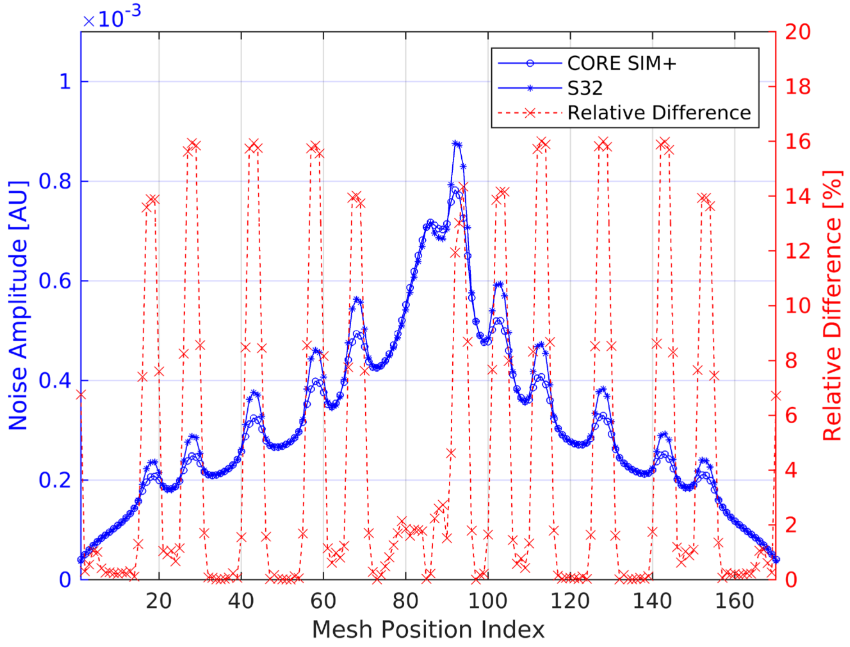


NOISE-SN

- Comparison between NOISE-SN and CORE SIM+
  - Investigation of possible limitations of diffusion theory

Fluctuation of capture cross section in a fuel cell





APOLLO3® – IPK model

- Time-dependent Improved Point-Kinetics scheme

Reactor kinetics multi-group problem

$$\left(\frac{1}{v}\partial_t + \Omega\cdot\nabla + \tilde{\Sigma}_t(\vec{r},E,t)\right)\psi = H\psi + \frac{F_p}{k_{dyn}}\phi + \frac{F_d\vec{C}}{k_{dyn}}$$

$$\partial_t C_i(\vec{r},t) = -\bar{\lambda}_i C_i(\vec{r},t) + \beta_i \int_E dE'\, \nu\Sigma_f(\vec{r},E',t)\phi(\vec{r},E',t)$$

Angular flux factorization

$$\psi(\vec{r},E,\Omega,t) = S(\vec{r},E,\Omega,t)\cdot P(E,t)$$

Fourier interpolation along the period

$$S(\vec{x},t) \cong c_0(\vec{x}) + \sum_{i=1}^{N/2} a_i(\vec{x})\cos\left(\frac{2\pi}{T}t\right) + b_i(\vec{x})\sin\left(\frac{2\pi}{T}t\right)$$

$$\partial_t P + \frac{1}{v}\langle\partial_t S\rangle P + \frac{J^+ - J^-}{\langle S/v\rangle}P + \langle\tilde{\Sigma}_t S\rangle P - \langle HS\rangle P = \frac{1}{k_{dyn}}\langle F_p S\rangle P + \frac{1}{k_{dyn}}\langle F_d\vec{C}\rangle$$

Balance point-kinetics equation

TRIPOLI-4®

- Frequency-domain stochastic calculation scheme

$$B(\omega)\delta\varphi(\omega) + \frac{1}{2\pi}\int \delta B(\omega-\omega')\delta\varphi(\omega')d\omega' = -\delta B(\omega)\varphi_c$$

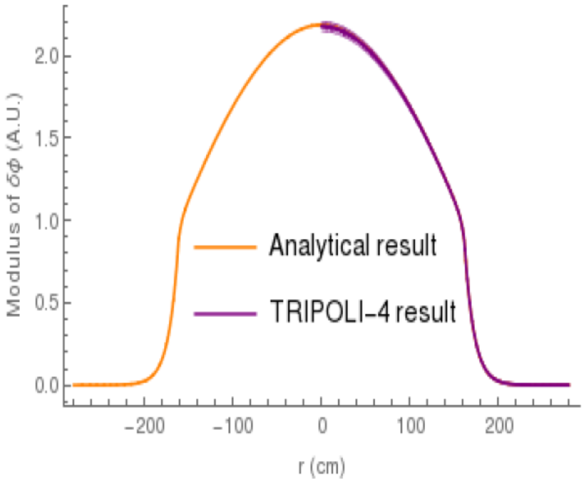
→ Orthodox Linearization → $B(\omega)\delta\varphi(\omega) = -\delta B(\omega)\varphi_c$

Critical flux using a regular power iteration → Sample the noise source $-\delta B(\omega)\varphi_c(\boldsymbol{r},\boldsymbol{\Omega},E)$ → Resulting particle population with weights for the real and imaginary parts

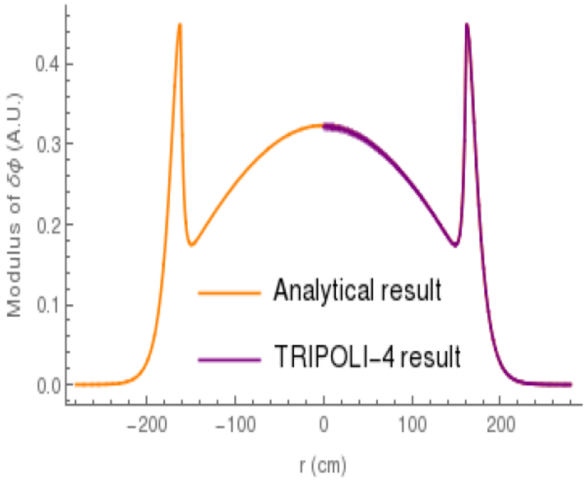
→ Particle population transported according to (collision-based) stochastic rules related to $B(\omega)$ → Independent replicas over a collection of batches

TRIPOLI-4®

- Verification test
  - One-dimensional homogeneous core with reflector and 2 energy groups
  - Neutron noise source at the core/reflector interface; $\omega = 1\ Hz$
    - $S = -3 - 0.5i$ for the fast group
    - $S = -1.2 + 2i$ for the thermal group



(a) Modulus of the fast neutron noise.



(b) Modulus of the thermal neutron noise.

KU Monte Carlo-based solver

京都大学 KYOTO UNIVERSITY

- Solution scheme

$$\mathbf{\Omega}\cdot\nabla\delta\phi_g(\boldsymbol{r},\mathbf{\Omega},\omega)+\Sigma_{t0g}(\boldsymbol{r})\delta\phi_g(\boldsymbol{r},\mathbf{\Omega},\omega)$$
$$+\frac{1}{4\pi}\sum_{\substack{g'=1\\ g\neq g'}}^{G}\Sigma_{s0}^{g\to g'}(\boldsymbol{r})\delta\phi_g(\boldsymbol{r},\mathbf{\Omega},\omega)$$
$$=\frac{\chi_g}{4\pi k_{eff}}\left(1-\frac{i\omega\beta}{i\omega+\lambda}\right)\sum_{g'=1}^{G}\nu\Sigma_{f0g'}(\boldsymbol{r})\delta\phi_{g'}(\boldsymbol{r},\mathbf{\Omega},\omega)$$
$$+\frac{1}{4\pi}\sum_{\substack{g'=1\\ g\neq g'}}^{G}\Sigma_{s0}^{g'\to g}(\boldsymbol{r})\delta\phi_{g'}(\boldsymbol{r},\mathbf{\Omega},\omega)-\frac{i\omega}{v_g}\delta\phi_g(\boldsymbol{r},\mathbf{\Omega},\omega)$$
$$+S_g(\boldsymbol{r},\mathbf{\Omega},\omega)$$

Particle emitted from the noise source position according to $S_g(\boldsymbol{r},\mathbf{\Omega},\omega)$

↓

Particle transported to collision point

↓

Treatment of $\frac{i\omega}{v_g}\delta\phi_g(\boldsymbol{r},\mathbf{\Omega},\omega)$ using particle weight

$$W_{j+1}=W_j\cdot exp\left(-\frac{i\omega}{v_{gj}}s_j\right)$$

↓

At each collision point, weight reduction multiplying by Σ_s/Σ_t

→

Russian roulette game: particle killed when both real and imaginary parts are killed

↓

If the collision is a fission reaction: particles emitted with weights mulitplied by $(1-i\omega\beta/(i\omega+\lambda))$

↓

If the particle and its progenies are killed, a new noise source particle is emitted

↓

Repeat until desired statistics

A procedure for neutron noise calculations using a stochastic code

Frequency-domain neutron noise balance equations based on 2-energy group diffusion

$$\nabla\cdot\left[D_{1,0}(\mathbf{r})\nabla\delta\phi_1(\mathbf{r},\omega)\right]+\left[\frac{\upsilon\Sigma_{f,1}(\mathbf{r},\omega)}{k_{eff}}-\Sigma_1(\mathbf{r},\omega)\right]\delta\phi_1(\mathbf{r},\omega)+\frac{\upsilon\Sigma_{f,2}(\mathbf{r},\omega)}{k_{eff}}\delta\phi_2(\mathbf{r},\omega)=-\delta S_1(\mathbf{r},\omega)$$

$$\nabla\cdot\left[D_{2,0}(\mathbf{r})\nabla\delta\phi_2(\mathbf{r},\omega)\right]+\Sigma_{r,0}(\mathbf{r})\delta\phi_1(\mathbf{r},\omega)-\Sigma_2(\mathbf{r},\omega)\delta\phi_2(\mathbf{r},\omega)=-\delta S_2(\mathbf{r},\omega)$$

$$\mathbf{A}(\mathbf{r},\omega)\times\begin{bmatrix}\delta\phi_1(\mathbf{r},\omega)\\ \delta\phi_2(\mathbf{r},\omega)\end{bmatrix}=-\begin{bmatrix}\delta S_1(\mathbf{r},\omega)\\ \delta S_2(\mathbf{r},\omega)\end{bmatrix}-i\mathbf{B}(\mathbf{r},\omega)\times\begin{bmatrix}\delta\phi_1(\mathbf{r},\omega)\\ \delta\phi_2(\mathbf{r},\omega)\end{bmatrix}$$

$$\begin{bmatrix}\delta\phi_1(\mathbf{r},\omega)\\ \delta\phi_2(\mathbf{r},\omega)\end{bmatrix}=\begin{bmatrix}\int\left[\widetilde{G}_{1\to1}(\mathbf{r},\mathbf{r}',\omega)\widetilde{\delta S}_1(\mathbf{r}',\omega)+\widetilde{G}_{2\to1}(\mathbf{r},\mathbf{r}',\omega)\widetilde{\delta S}_2(\mathbf{r}',\omega)\right]d^3\mathbf{r}'\\ \int\left[\widetilde{G}_{1\to2}(\mathbf{r},\mathbf{r}',\omega)\widetilde{\delta S}_1(\mathbf{r}',\omega)+\widetilde{G}_{2\to2}(\mathbf{r},\mathbf{r}',\omega)\widetilde{\delta S}_2(\mathbf{r}',\omega)\right]d^3\mathbf{r}'\end{bmatrix}$$

$$\mathbf{A}(\mathbf{r},\omega)\times\begin{bmatrix}\widetilde{G}_1(\mathbf{r},\mathbf{r}',\omega)\\ \widetilde{G}_2(\mathbf{r},\mathbf{r}',\omega)\end{bmatrix}=\begin{bmatrix}\delta(\mathbf{r}-\mathbf{r}')\\ 0\end{bmatrix}\text{ or }\begin{bmatrix}0\\ \delta(\mathbf{r}-\mathbf{r}')\end{bmatrix}$$

$\widetilde{G}(\boldsymbol{r},\boldsymbol{r}',\omega)$ is estimated from a stochastic code

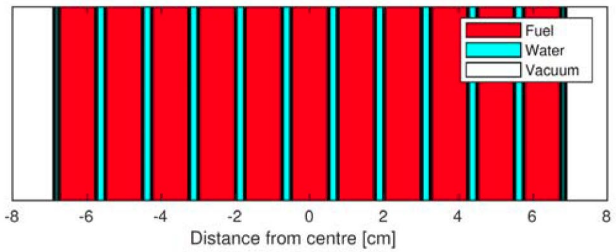
$$\left[\mathbf{I}+i\widetilde{\mathbf{G}}(\omega)\times\mathbf{B}(\omega)\right]\times\delta\boldsymbol{\phi}(\omega)=-\widetilde{\mathbf{G}}(\omega)\times\delta\mathbf{S}(\omega)$$

Linear system to be solved numerically

$$\boxed{\delta\phi}$$

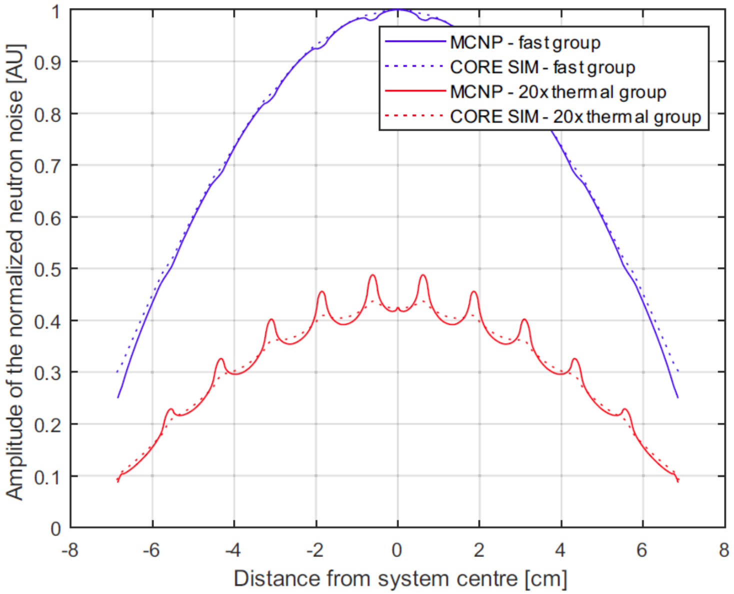
A procedure for neutron noise calculations using a stochastic code

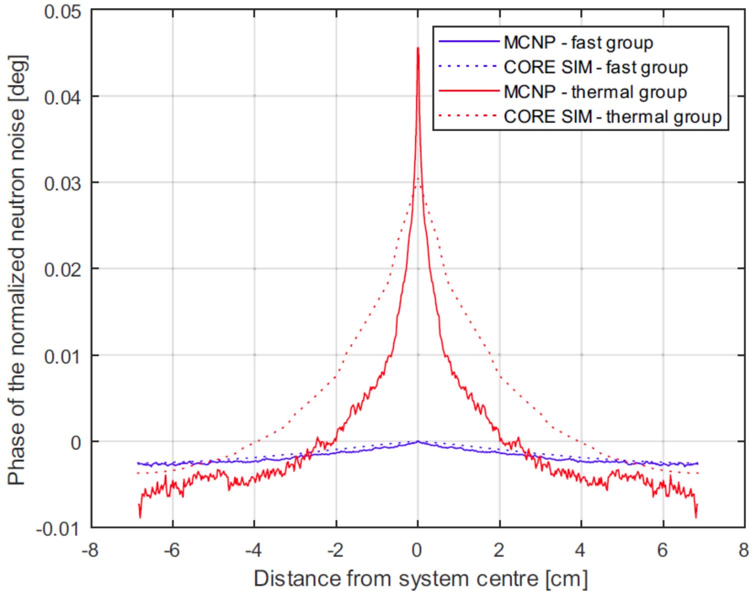
- Verification test



1-D heterogeneous system

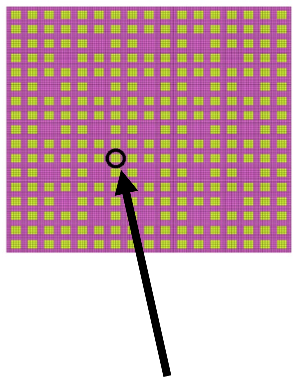
Perturbation of the macroscopic cross sections at $x = 0$ and $f = 0.159\ Hz$



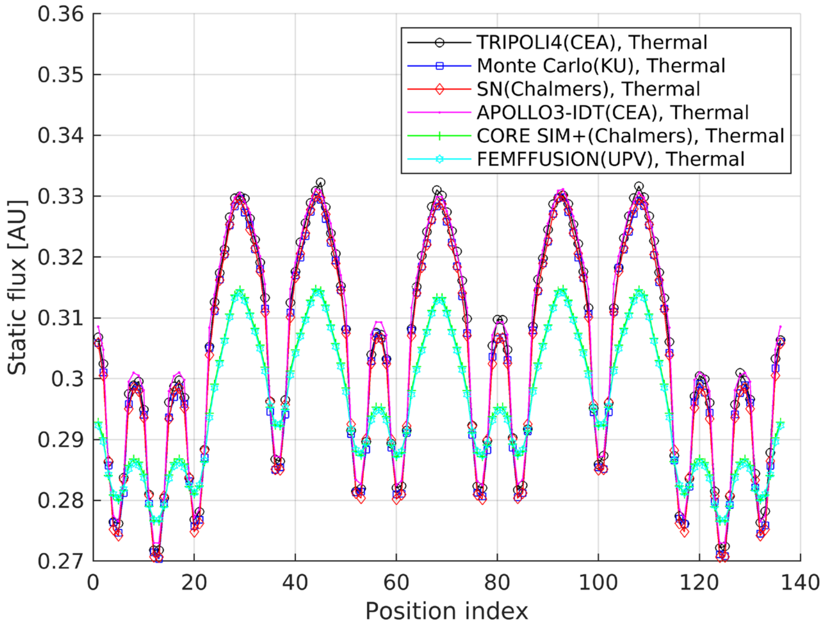


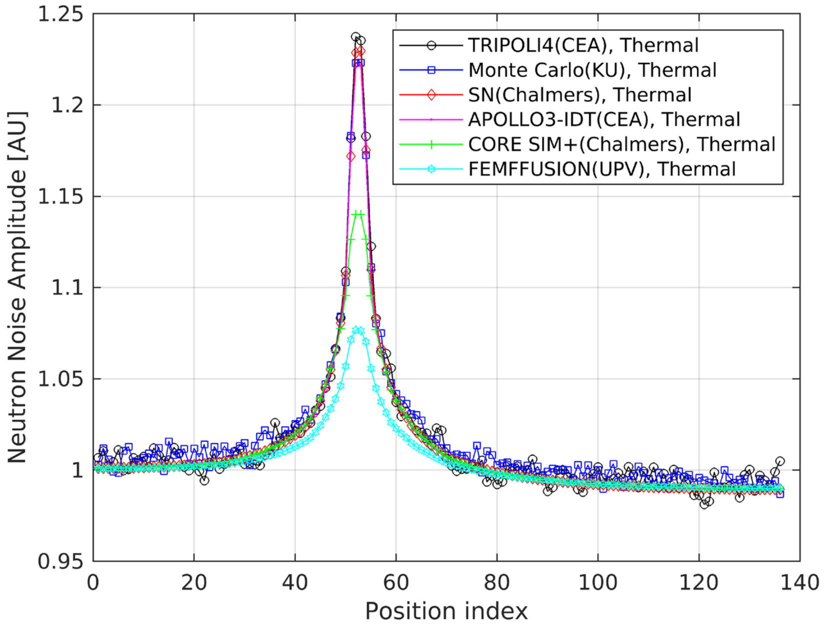
Comparison of codes

Monte Carlo solvers	Deterministic higher-order solvers	Diffusion solvers
TRIPOLI-4®	NOISE-SN	CORE SIM+
KU MC	APOLLO3® - IDT	FEMFFUSION (time-domain)



Combination of fluctuations of cross sections in a fuel pin

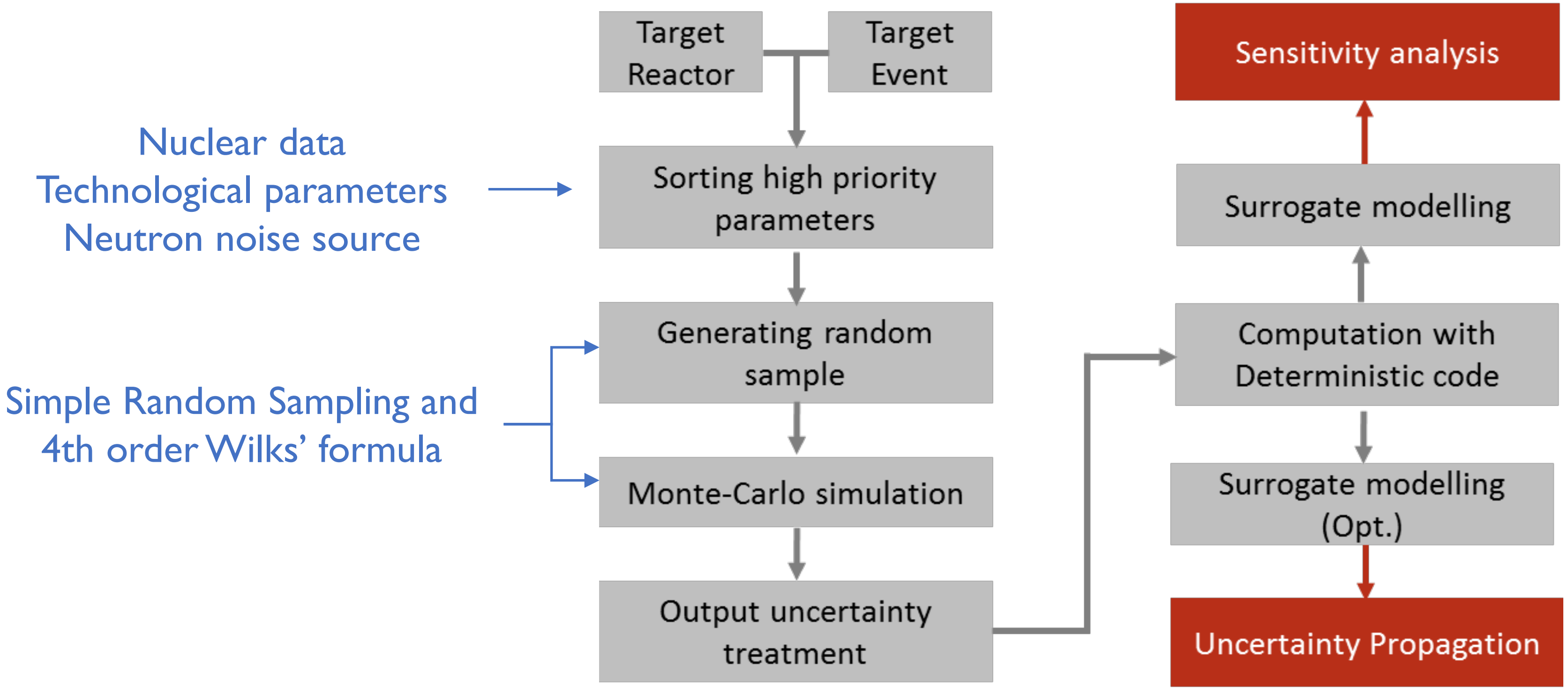




- Uncertainty and sensitivity analysis

Uncertainty and Sensitivity analysis

- Methodology for neutron noise simulations



Conclusions – WP1 within CORTEX

Modeling of mechanical vibrations

Modeling of macroscopic cross sections for neutron noise applications

Diffusion-based solvers

Higher-order methods

Stochastic methods

Modeling of neutron noise sources

Methodologies and methods for neutron noise simulations

Uncertainty and sensitivity analysis

Reference solutions and assessment of low-order methods

Validation using neutron noise experiments
WP2

Training of machine learning algorithm for core monitoring and diagnostics
WP3 and WP4

Thank you!

GRS

Joachim Herb
Christoph Bläsius
Jürgen Sievers
Matthias Küntzel
Yann Perin

PAUL SCHERRER INSTITUT

PSI

Abelhamid Dokhane
Vasudha Verma
Dionysios Chionis

cea

Andrea Zoia
Amélie Rouchon
Baptiste Gasse
Simone Santandrea
Igor Zmijarevic
Alberto Brighenti

TECHNISCHE UNIVERSITÄT DRESDEN

Carsten Lange
Alexander Knospe
Marco Viebach

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Toni Vidal
Damian Ginestar
Gumersindo Verdú

京都大学 KYOTO UNIVERSITY

Toshihiro
Yamamoto

TUM

Rafael Macian
Soobeen Yum

CHALMERS

Christophe Demazière
Antonios Mylonakis
Huaiqian Yi