FISA 2019

9th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems

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Pitesti, Romania

ADVANCED NUMERICAL SIMULATION AND MODELLING FOR REACTOR SAFETY – CONTRIBUTIONS FROM THE CORTEX, HPMC, MCSAFE AND NURESAFE PROJECTS

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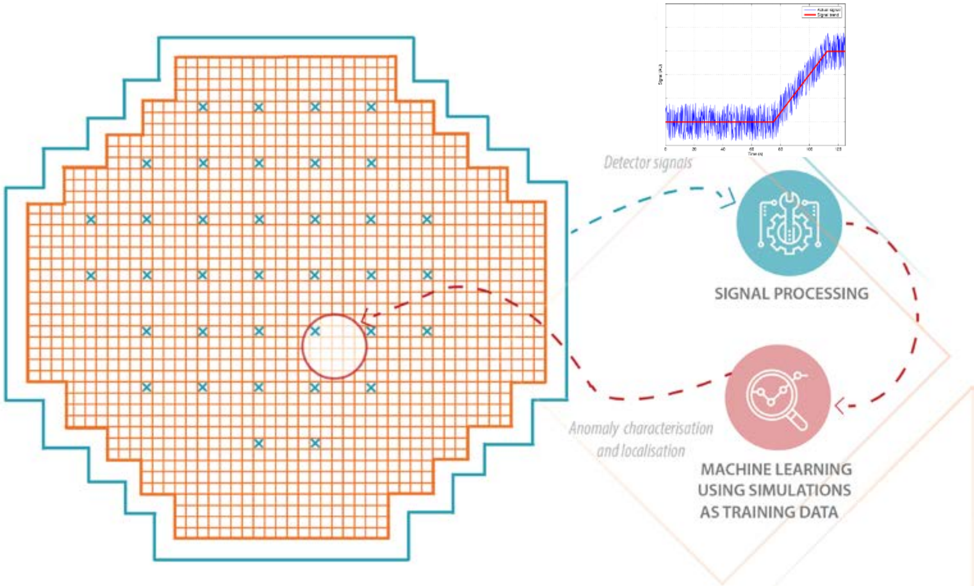
Introduction

- **Predictive simulations** = backbone of nuclear reactor safety
- Most of the tools developed when **computing** resources and capabilities were **limited**
- ➢ Shift towards **high-fidelity methods** taking advantage of progress in computing (hardware/software)
- Reactor **operating closer to their safety limits** due to less conservative safety evaluations
- ➢ Importance of **core monitoring** (+ operational problems more frequent due to ageing fleet)
- Presentation of four projects funded by the European Commission on **advanced numerical simulation and modelling for reactor safety**

Short description of the respective projects

- **CORTEX**: CORe monitoring Techniques and EXperimental validation and demonstration

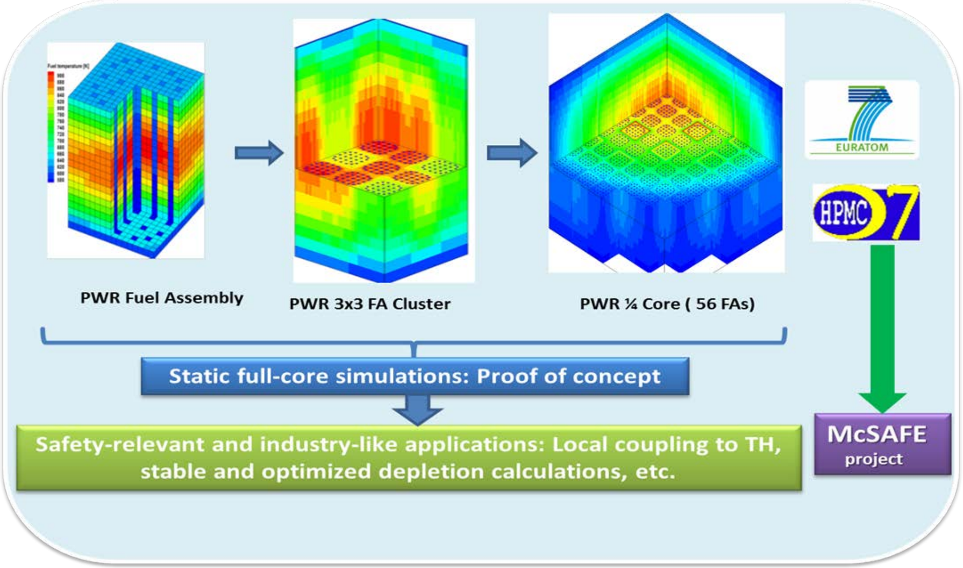
➢ Aim: develop a core monitoring technique for the early detection, localization and characterization of anomalies using **neutron noise**



Short description of the respective projects

- **HPMC**: High Performance Monte Carlo Methods for Core Analysis
  McSAFE: High Performance Monte Carlo Methods for SAFEty Analysis

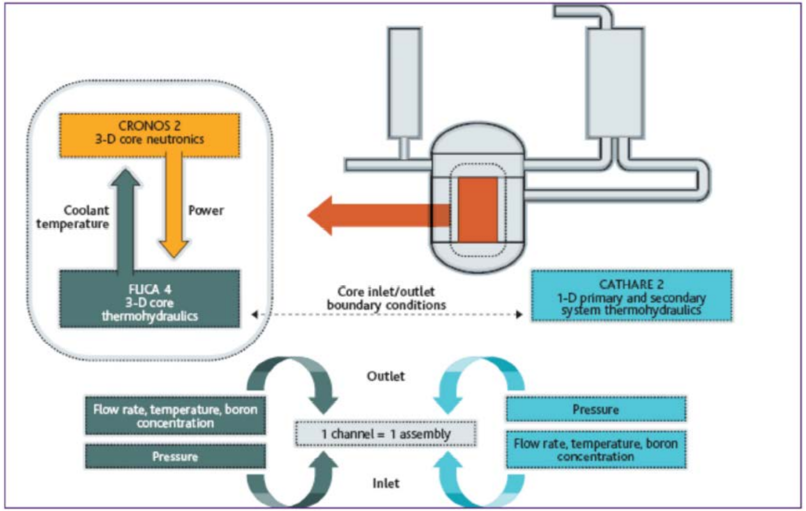
➢ Aim: develop high fidelity multi-physics simulation tools based on Monte-Carlo techniques for neutron transport

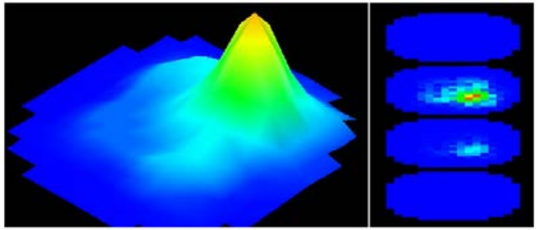


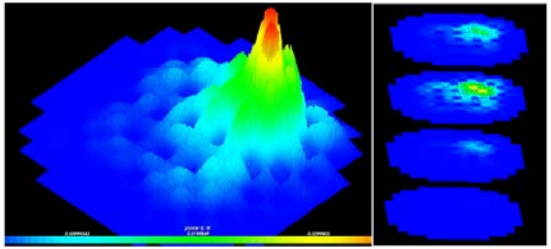
Short description of the respective projects

- **NURESAFE**: NUclear REactor SAFEty simulation platform

➢ Aim: develop a European reference tool for higher fidelity simulation of LWR cores for design and safety assessment



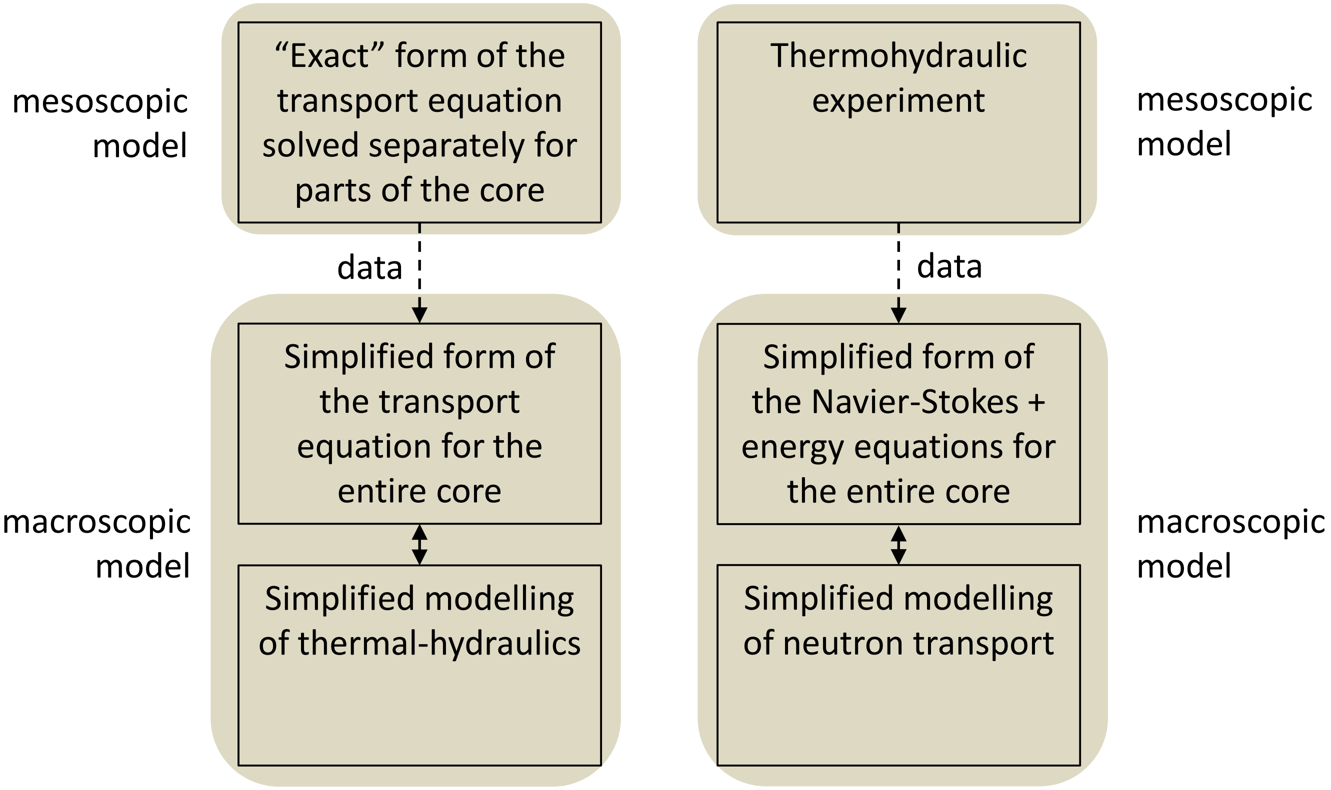




Dynamic 3D coupling of codes : core physics, thermohydraulics, fuel thermomechanics. Release of industry-like applications. Uncertainty quantification

Key objectives and achievements for advanced numerical simulation and modelling

- From "divide-and-conquer"…



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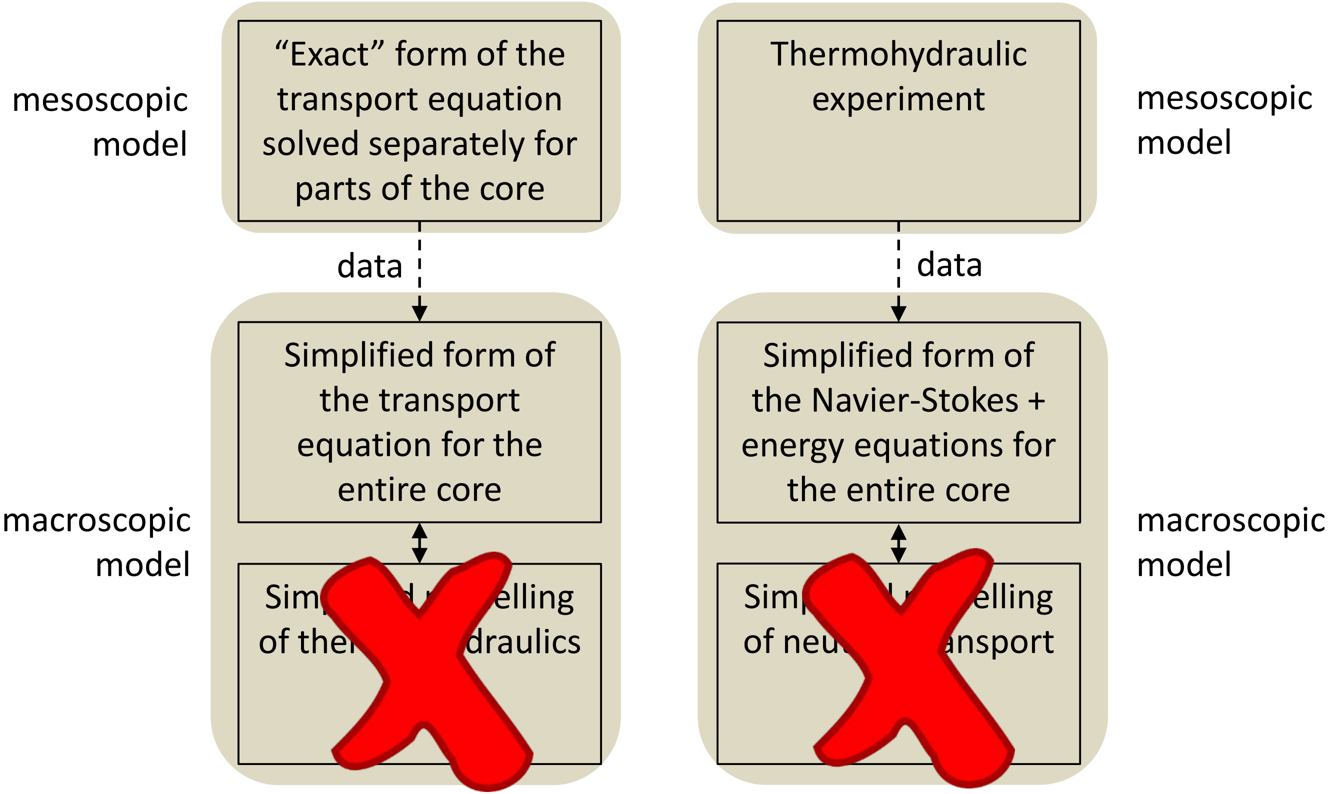

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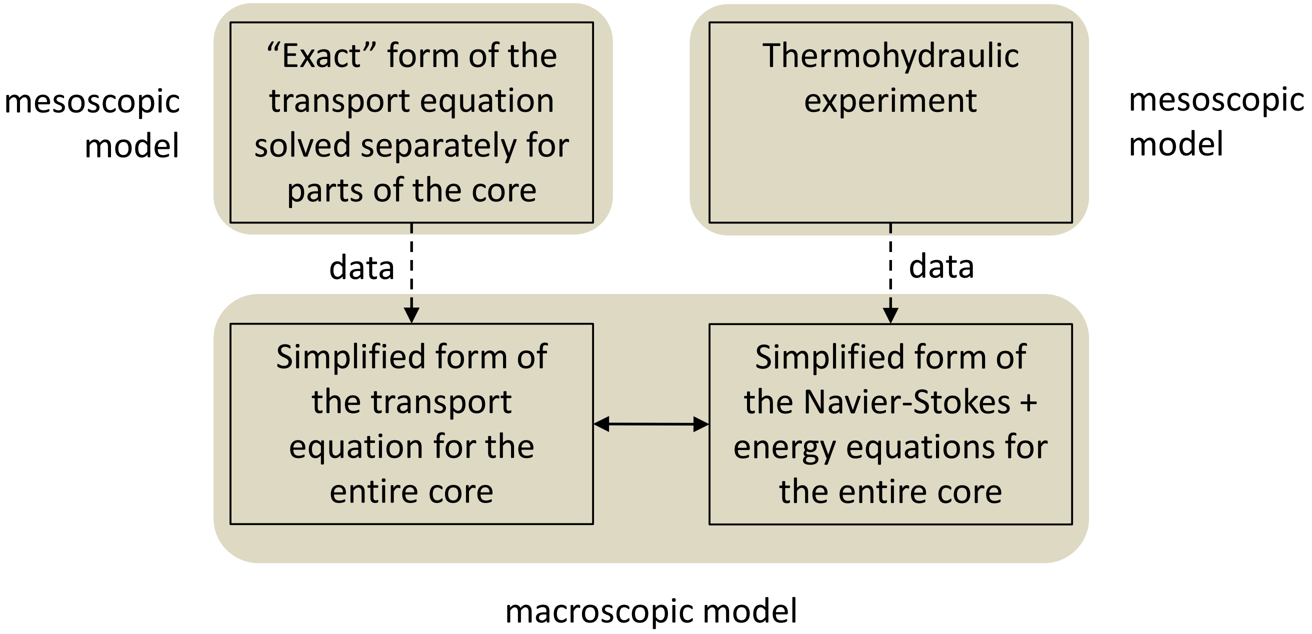

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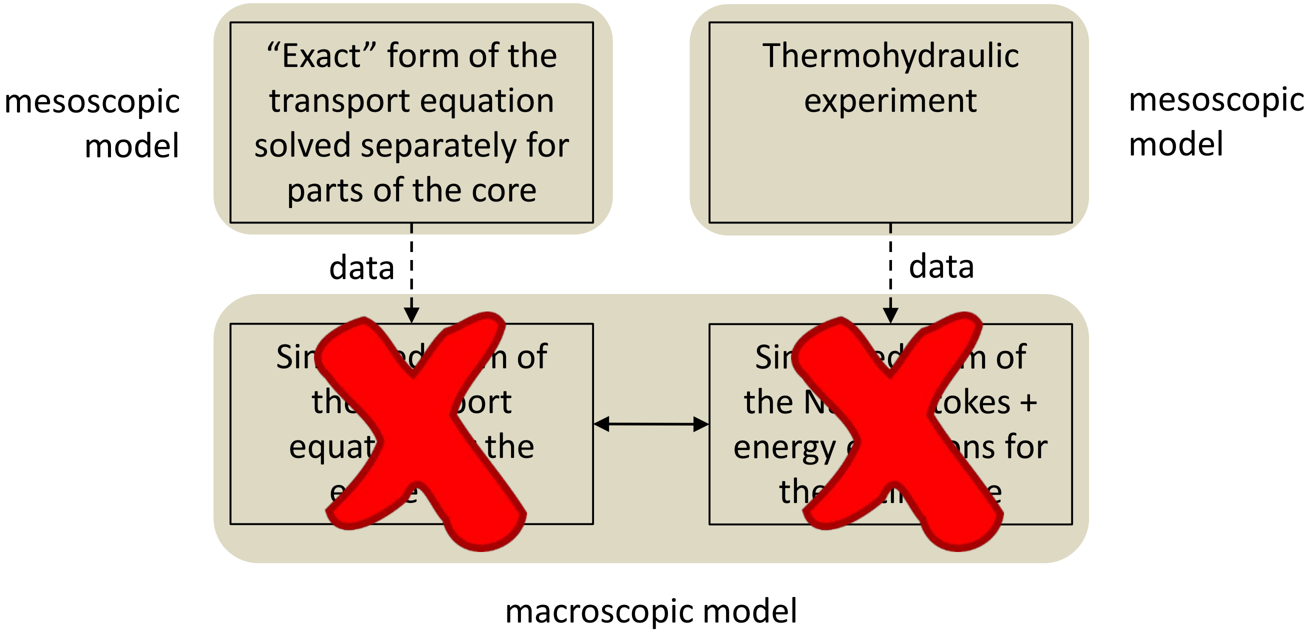


Key objectives and achievements for advanced numerical simulation and modelling

- From "divide-and-conquer" to integrated models

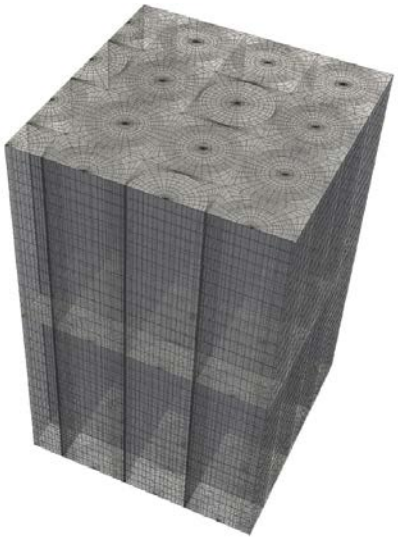
mesoscopic model

"Exact" form of the transport equation solved for the entire core

↔

Navier-Stokes + energy equations solved for the entire core

mesoscopic model



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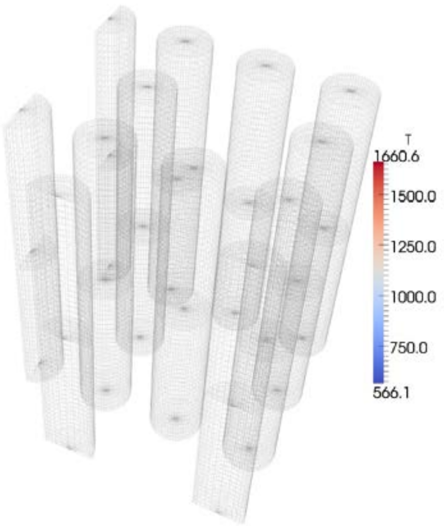

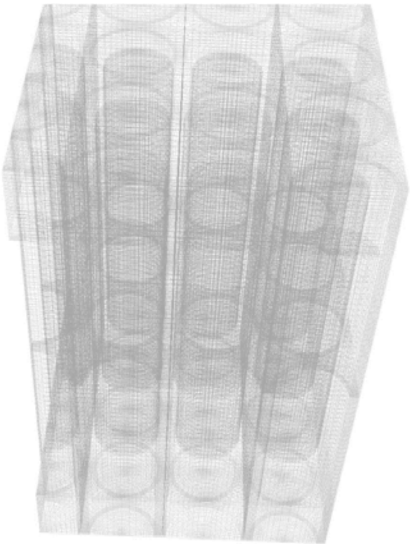

- **CORTEX**:
  - Development of modelling capabilities for estimating the transfer function

    Several complementary approaches:

    - Use of existing codes or codes specifically developed for noise analysis
    - Codes working in either the time- or in the frequency-domain
    - Use of coarse mesh or fine mesh approaches

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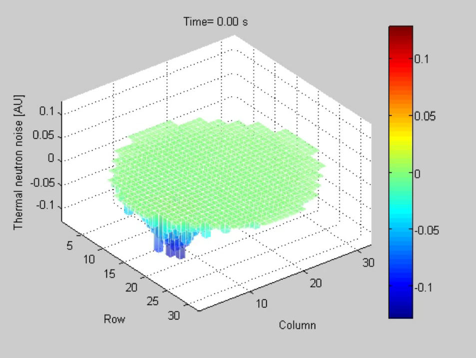

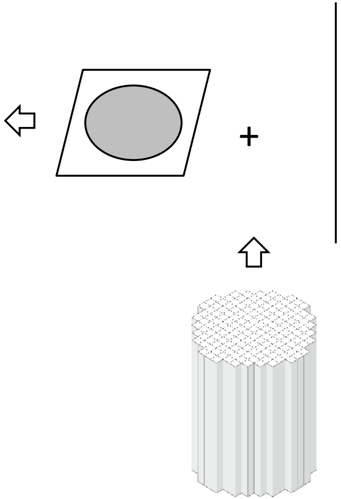

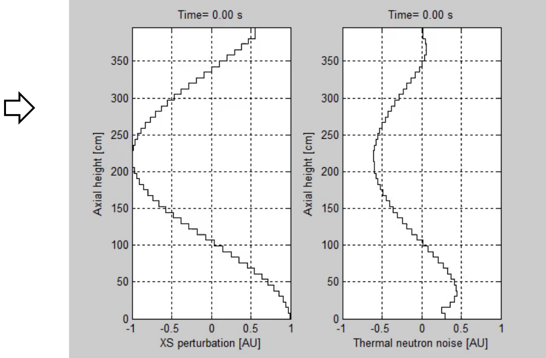

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- **CORTEX**:
  - Validation of the modelling capabilities against experiments:

COLIBRI experiments in CROCUS
(@EPFL, Switzerland)

Key objectives and achievements for advanced numerical simulation and modelling

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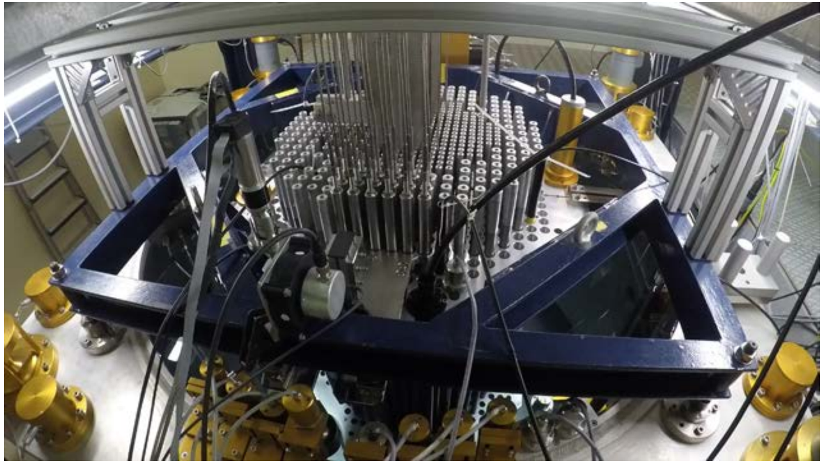
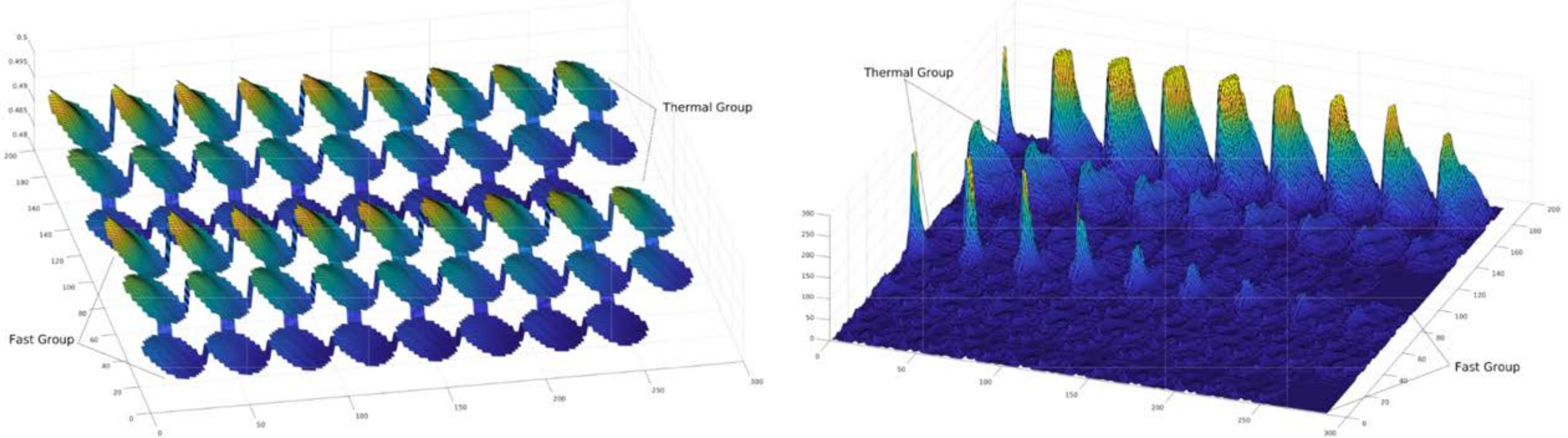


AKR-2 (@TUD, Germany)

Key objectives and achievements for advanced numerical simulation and modelling

- **CORTEX**:
  - Inversion of the reactor transfer function using machine learning:
    - Detection of abnormal fluctuations and their classification
    - Inversion of the reactor transfer function
    - Handling of the scarcity of in-core instrumentation
    - Handling of intermittences



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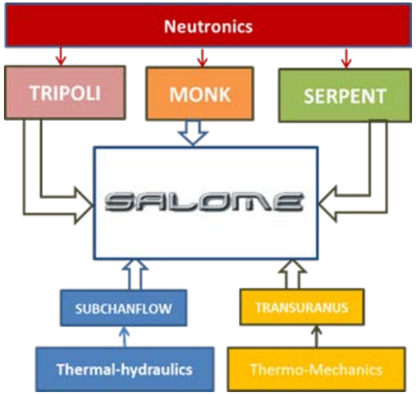
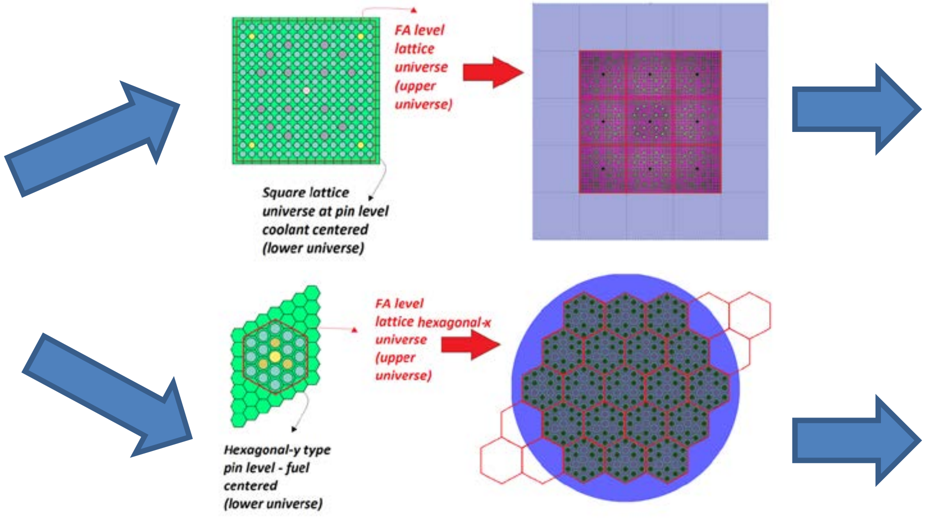
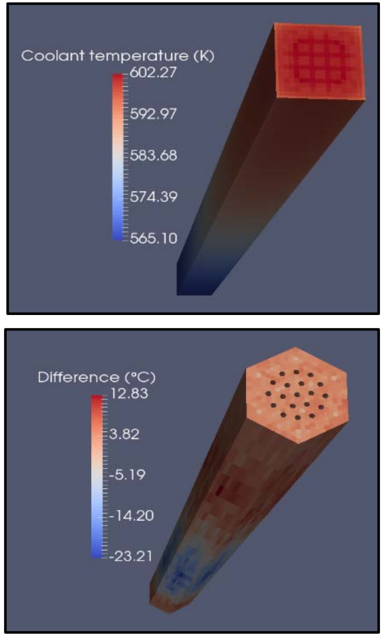
Key objectives and achievements for advanced numerical simulation and modelling

- **HPMC and McSAFE**: Optimal Monte Carlo-thermal-hydraulics coupling:
  - HPMC: Internal/external coupling
  - McSAFE: ICOCO-based coupling and internal master-slave coupling based on Serpent MP-interface with advanced SCF pre-processor, MED coupling library, in-build interpolation (1D, 2D) (SALOME)



McSAFE: Multi-physics Platform tools

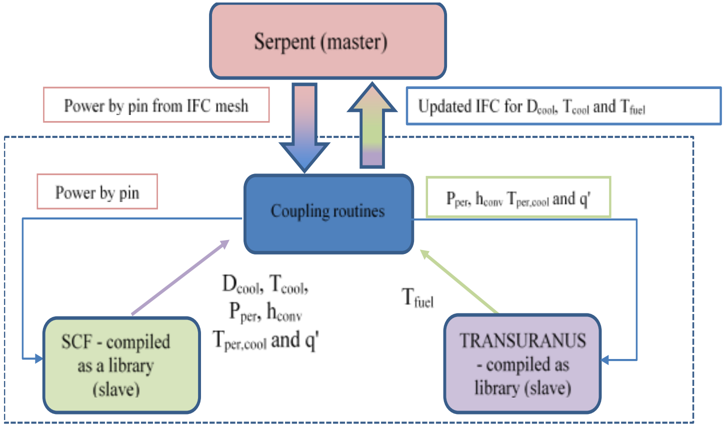




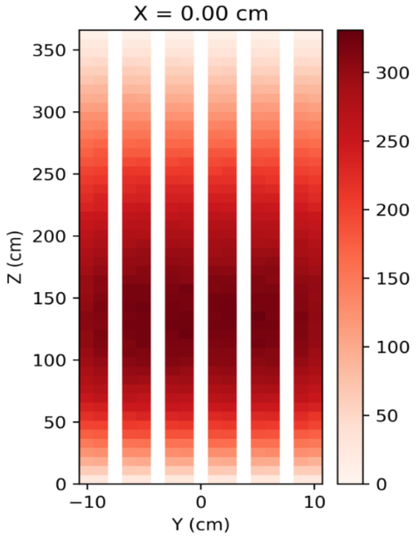
McSAFE: Analysis of cores with square and HEX FAs

Key objectives and achievements for advanced numerical simulation and modelling

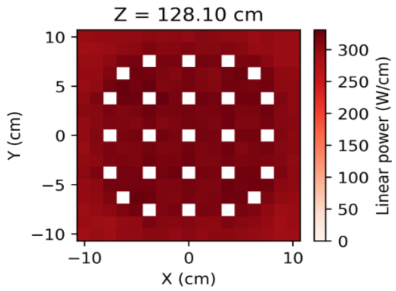
- **McSAFE**: Multiphysics N, TH and TM coupling based on Monte-Carlo:
  - E.g. SERPENT/SUBCHANFLOW/TRANSURANUS: master-slave coupling (one single executable)



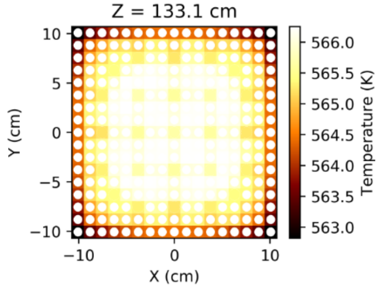
Main coupling Serpent-TU-SCF implementation scheme



FA Vertical Cut: Axial Power



Radial power at max FAX

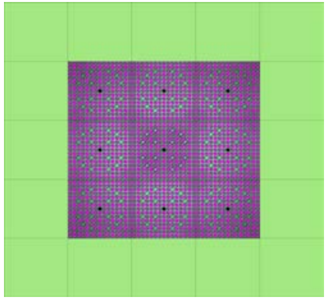


Radial coolant temp at Z=133.1 cm

Test case: PWR FA 17x17: PC Xeon 6132 COZ with 28 cores: 90 min

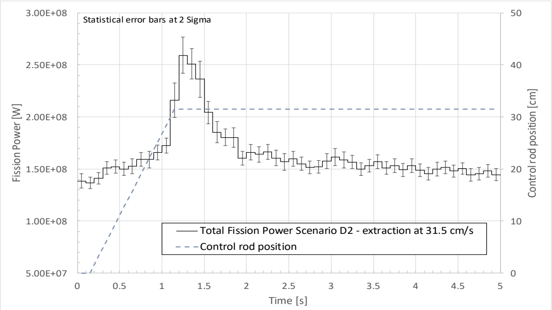
Key objectives and achievements for advanced numerical simulation and modelling

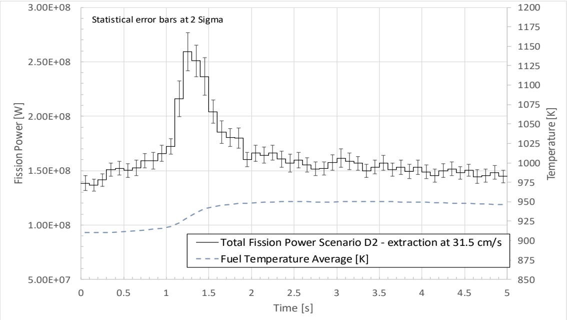
- **McSAFE**: dynamic Monte Carlo capability for transient analysis:
  - New versions of dynSERPENT, dynTRIPOLI, dynMCNP



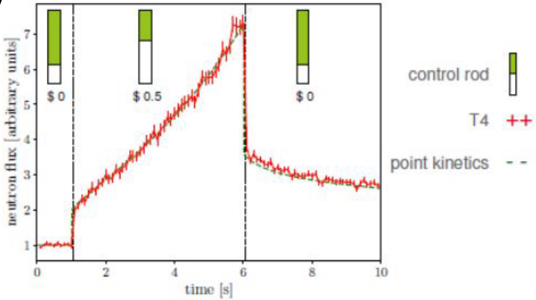
Minicore 3x3 FA - Control rod extraction with 31.5 cm/s

Demonstration

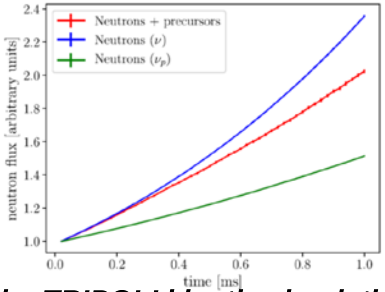




dynSERPENT/SUBCHANFLOW



dynTRIPOLI code (kinetic capability)

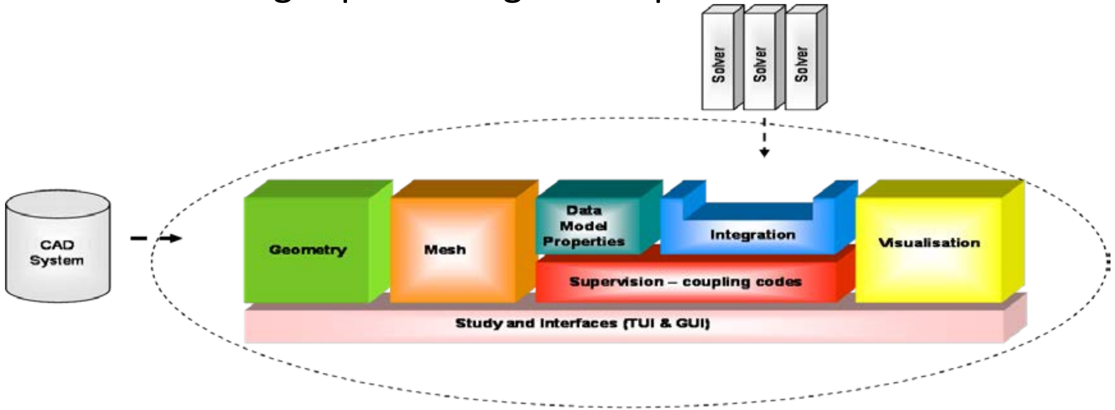


- Red line: TRIPOLI-4 simulation with precursors
- Blue line: TRIPOLI-4 simulation without precursors and ν neutrons created at each fission on average
- Green line: TRIPOLI-4 simulation without precursors and ν_p neutrons created at each fission on average

dynTRIPOLI kinetic simulation: role of precursors

Testing: SPERT-III REA

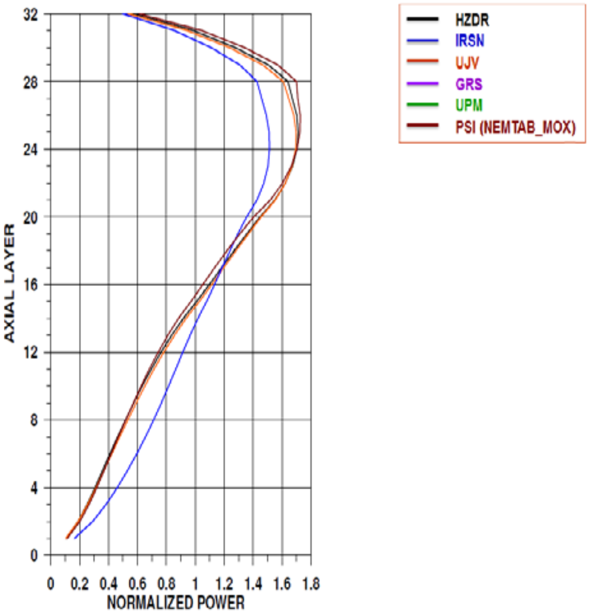
- **NURESAFE**: Enhancement of multi-physics simulation capabilities:
  - Integration of existing codes into the SALOME software platform which provides coupling capacities, uncertainty quantification and standardized users interface
  - Development of advanced 2-phase CFD models in some existing CFD codes
  - Delivery of safety-relevant industry-like applications for LOCA, pressurized thermal shock, MSLB, boron dilution accident, some BWR ATWS
  - Validation of the modelling capacities against experiments



THE SALOME OPEN-SOURCE SOFTWARE PLATFORM

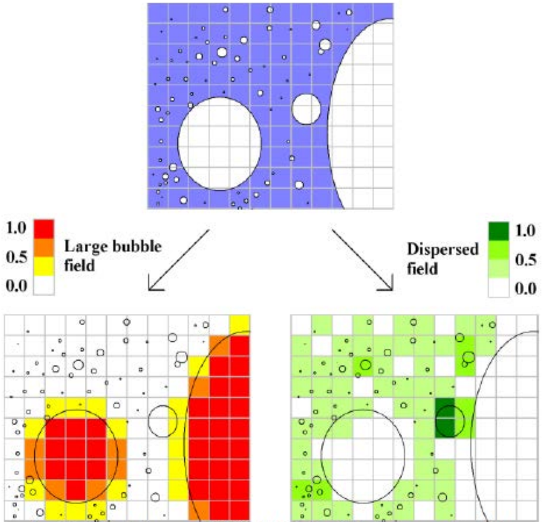
Key objectives and achievements for advanced numerical simulation and modelling

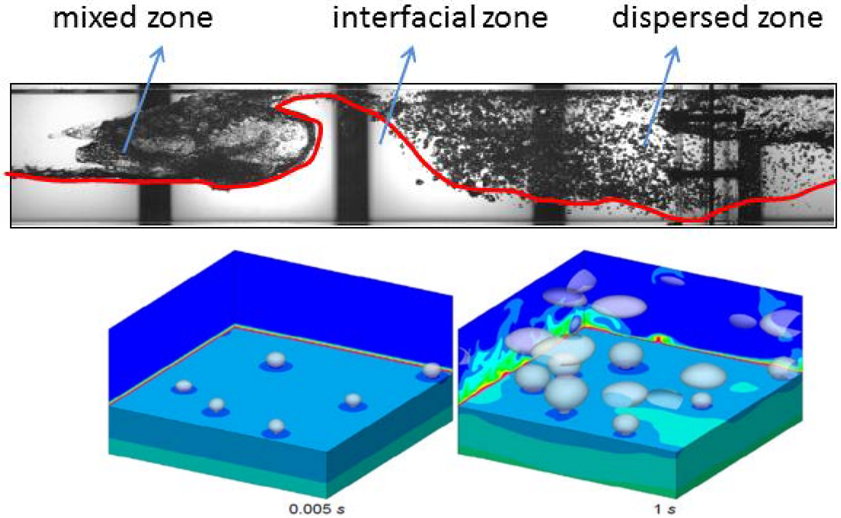
- **NURESAFE**: Development of multi-scale and multi-physics simulation capabilities for safety analyses:
  - 3D code coupling (system, core TH, neutron kinetics), (CFD models, core TH) , (fuel thermomechanics, core TH)
  - MSLB simulation for PWR and VVER (nodal and pin-by-pin modelling)
  - BWR ATWS: simulation of OECD/NEA Benchmark based on the Oskarshamn-2 1999 event
  - Simulation of OECD/NEA BWR Peach Bottom Turbine Trip Benchmark
  - LOCA: coupling system code, CFD and fuel thermomechanics codes for simulation of situations with ballooned fuel rods
  - Pressurized Thermal shock: high fidelity prediction of wall temperature using CFD models
  - BWR TH applications: simulation of steam injection in a pressure suppression pool



Axial power distribution at maximum power

- **NURESAFE**: Advancement of the fundamental knowledge in 2-phase thermal-hydraulics:
  - Coupling Interface Tracking models with phase-average models ➔ all flow regimes models
  - DNS and LES modelling of pool and convective boiling
  - DNS and LES modelling of bubbly flow





Key objectives and achievements for advanced numerical simulation and modelling

- **NURESAFE**: Validation of simulation capabilities against experiments:
  - Validation of core neutron kinetics codes: 3D steady state experiments (ZR-6 at KFKI, V1000-LR0 experiments at REZ)
  - ROCOM (HZDR) tests: coolant mixing during MSLB
  - KOZLODUY-6 vessel mixing experiments (MSLB modelling)
  - TOPFLOW PTS (HZDR) steam-water experiments and KAERI CCSF tests: Pressurized Thermal Shock (prediction of mixing of safety injection flow and wall temperature)
  - LOCA: FEBA, ACHILLES, PERICLES experiments (reflooding with ballooned rods)
  - LOCA: MOBY-DICK tests (CEA) for validation of break-flow critical flow prediction
  - PSBT tests: core boiling flow (validation of void fraction prediction by CFD models)
  - PERSEO experiment (ENEA): validation of coupling CFD and TH system codes techniques
  - CHAPTAL experiments (CEA-EDF): modelling of high pressure bubbly flow in a vertical tube
  - Validation of all regimes flow models against CASTILLEJOS experiment
  - And some other experiments…..

Conclusions

- Advancement in the simulation capabilities for **two-phase flows**
- Maturity of the **Monte Carlo**-based methods for **depletion** and **dynamic calculations**
- Truly **multi-physics** and **multi-scale** calculations for **industrial** applications
- Extension of the capabilities to the modelling of **stationary fluctuations**
- Use of **machine learning** for anomaly backtracking

Conclusions

- **Future trends**:
  - **More and more physics** to be accounted for
  - Use of "**hybrid**" methods
  - Increase use of **machine learning** for **predictive modelling**

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