6th Serpent User Group Meeting

Milano, 27th September, 2016

Serpent activities at PoliMi

Nuclear Reactors Group

Serpent Activities

Serpent used at Nuclear Reactor Group of Politecnico di Milano since 2010

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Serpent is mainly used for:

- Group constant generation and thermal feedback coefficient for reactor simulation codes (COMSOL, OpenFOAM, Point Kinetic model, …)

Simulation & Control, Multiphysics, Reduced Order Modelling

» multiphysics approach: neutronics, fluid dynamics and thermal mechanics in the same simulator

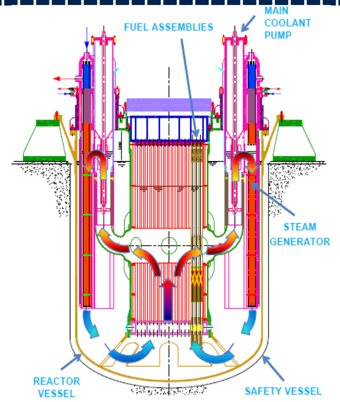
» object-oriented and ROM models for flexible and fast running simulators, for new control strategies

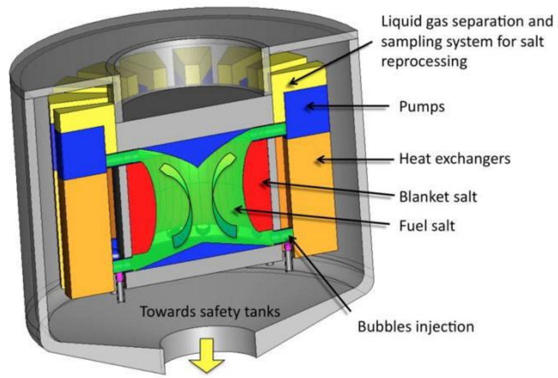
- Burnup calculation

Ongoing new activities with SERPENT:

- Coupling OpenFOAM and SERPENT (collaboration with UC Berkeley)
- Core optimization with Particle Swarm Algorithms
- Educational purpose (starting from this academic year)

Reactor studied with SERPENT



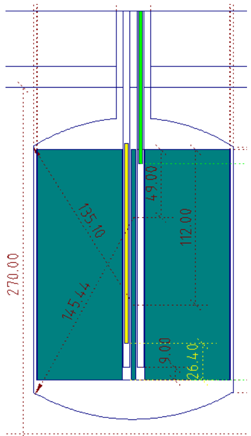


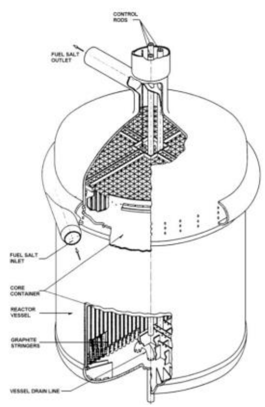
Generation IV (ALFRED, MSFR)

FP7 LEADER Project

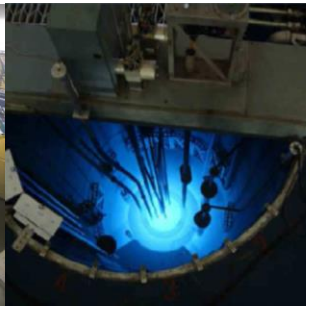
FP7 EVOL Project

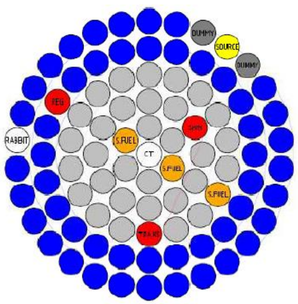
H2020 SAMOFAR Project





Molten Salt Reactor Experiment





Research reactor (TRIGA Mark II Pavia)

ARCO Project

Group constant generation for reactor simulation codes

Generation of group constants
(neutron cross-sections)

Monte Carlo simulation (MC) **SERPENT**

Neutronics (Diffusion equation)
+ Spatial basis calculation

Finite Element software **COMSOL**

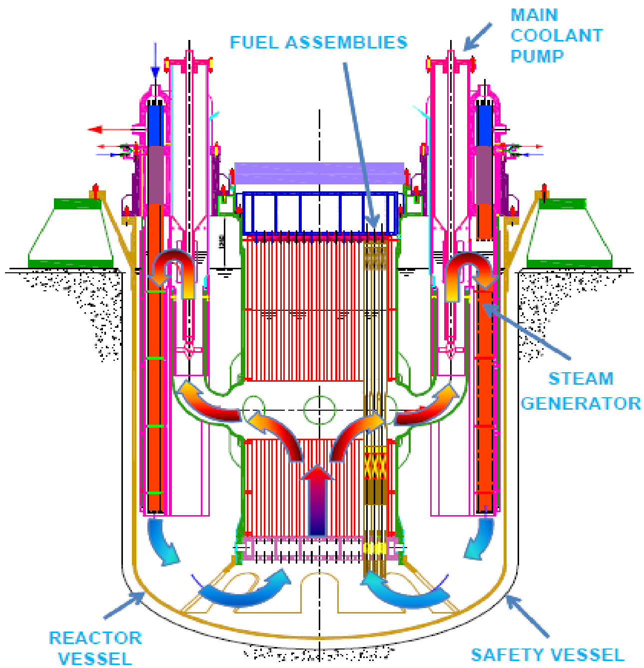
OFFLINE procedure: the computation is made only once

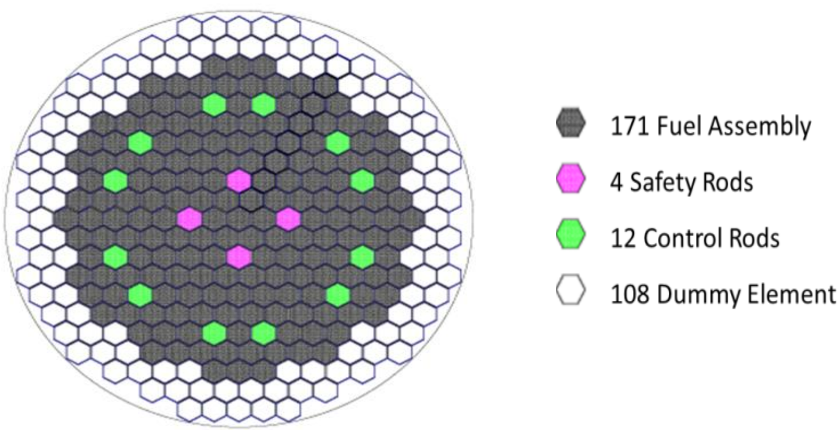
OBJECT-ORIENTED MODEL (OO)
Neutronics (Spatial Neutronics component)
+ Heat transfer (Fuel pin component)

ODE solver **MODELICA**

ONLINE calculation: ODE set can be run as many times as required

ALFRED Reactor





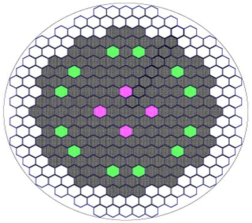
LEADER
Lead-cooled European Advanced DEmonstration Reactor

Fuel pin design parameter	Value
Thermal power, MW	300
Coolant inlet temperature, °C	400
Average coolant outlet temperature, °C	480
Average coolant velocity, m s^{-1}	≈ 1.4
Fuel type	MOX
Average enrichment as Pu/(Pu+U), wt%	25.77
Cladding	Ti-15-15
Fill gas	He
Active length, mm	600
Cladding outer diameter, mm	10.5
Cladding inner diameter, mm	9.3
Fuel pellet outer diameter, mm	9
Fuel pellet inner diameter, mm	2
Pin pitch, mm	13.86

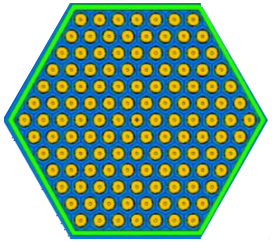
SERPENT Model

ALFRED Case

- Core level
  - *Core_geometry*
  - *Core_cell*
  - *Material*
- FA level
  - *FA_inner_cell, FA_outer_cell, Dummy_cell*
  - *CR_cell, SR_cell*
  - *FA_geometry, CR_geometry, SR_geometry*
  - *Rod_mov*
  - FA_inner
    - *FA_inner_1, …, FA_inner_57*
  - FA_outer
    - *FA_outer_1, …, FA_outer_114*
  - CR
    - *CR_1, …, CR_12*
  - SR
    - *SR_1, …, SR_4*
- Pin level
  - *Pin_geometry*
  - *Pin_inner_cell*
  - *Pin_outer_cell*

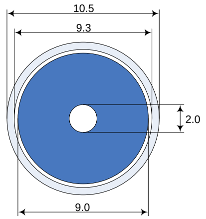


. Different level of nested universes



. Possibility to obtain group constant from each FA

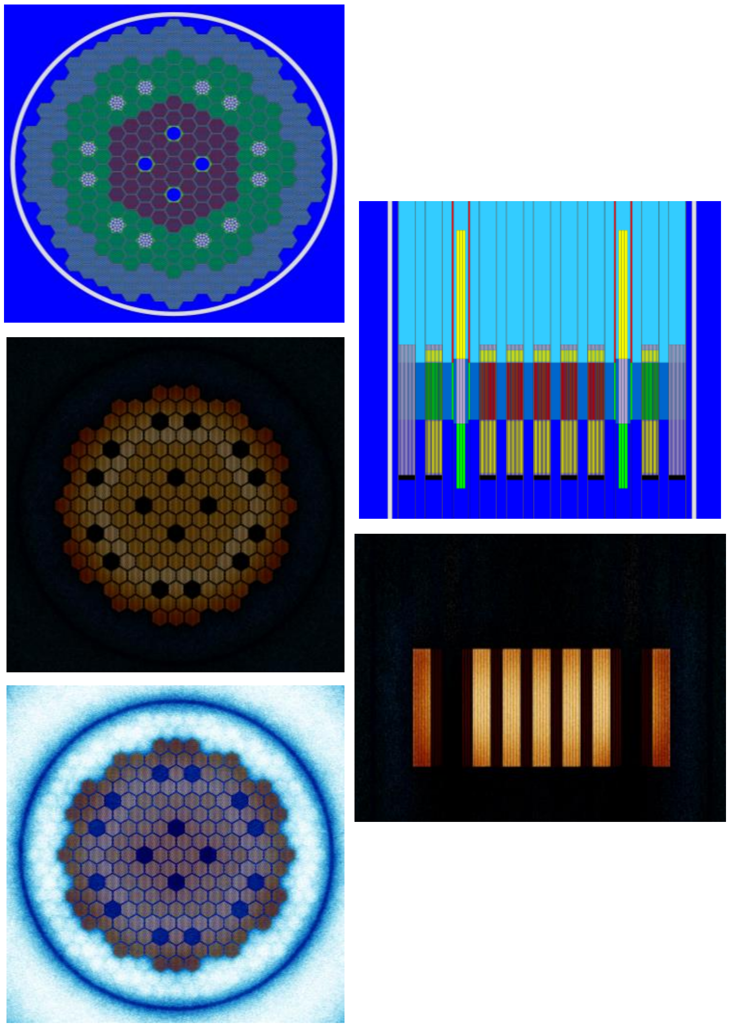
. CR/SR extraction/insertion thanks to the *trans* card

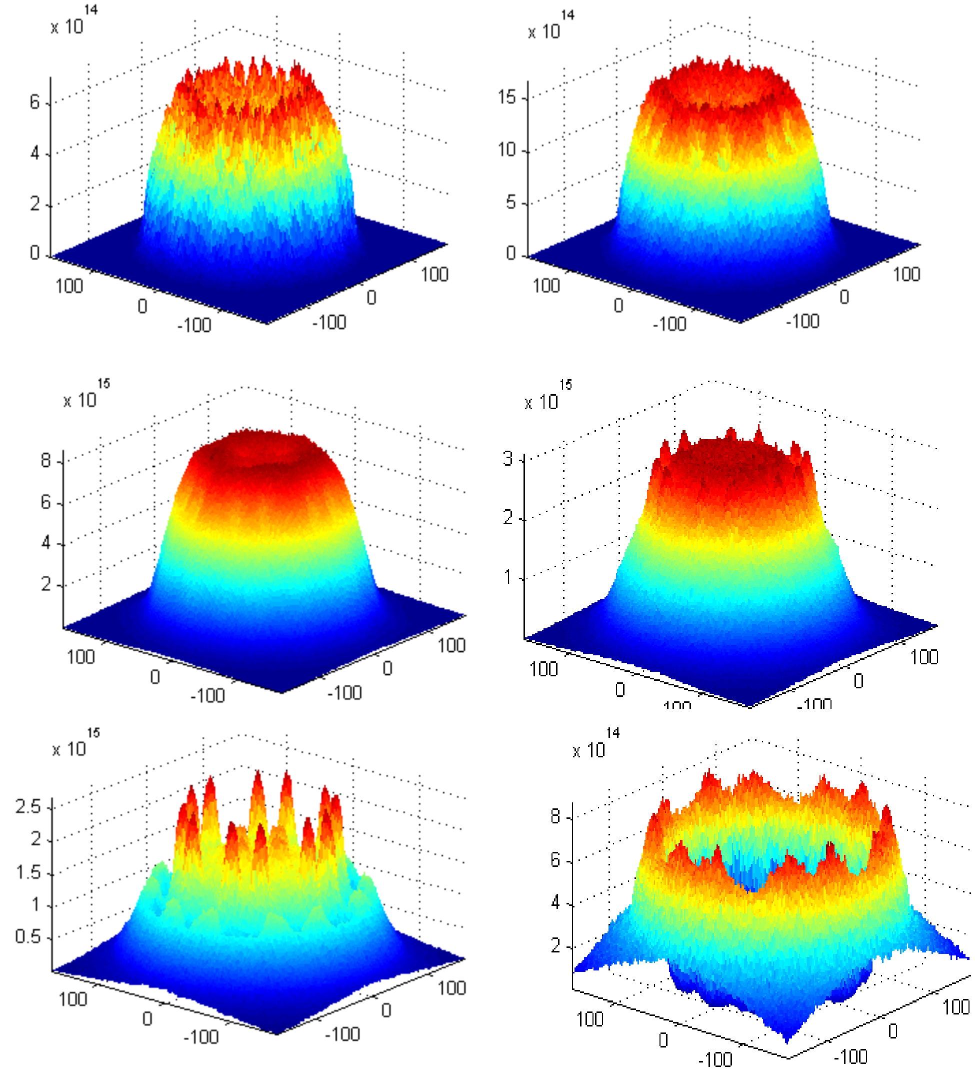


. Flux detector for calculating Albedo coefficients

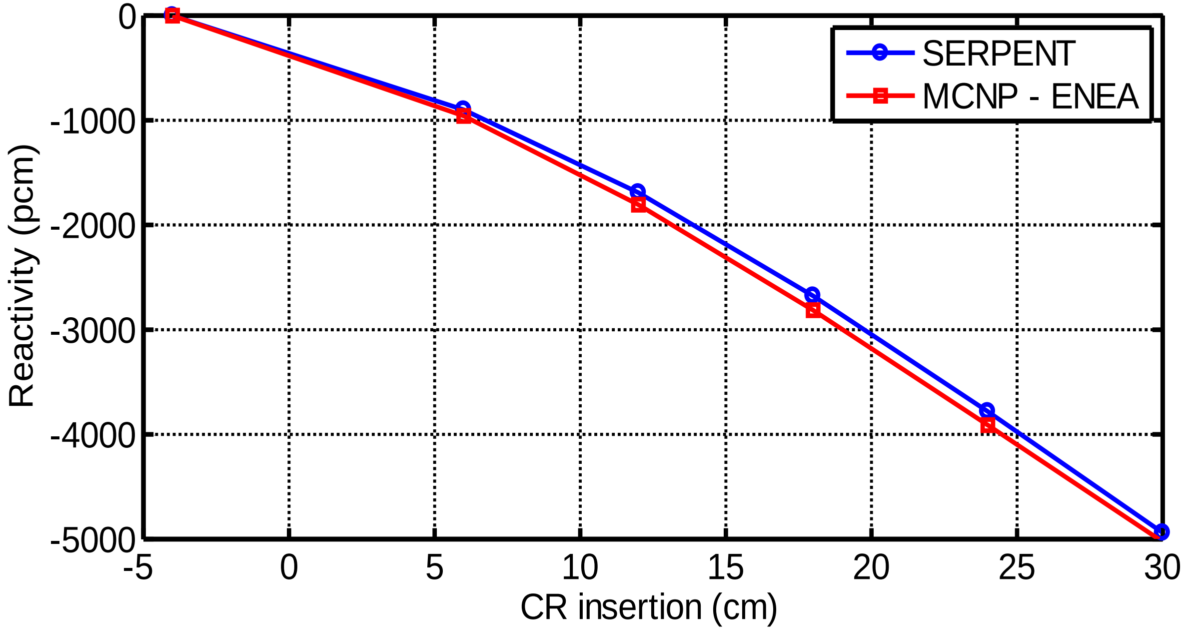
SERPENT Model

SERPENT model of the ALFRED reactor





SERPENT model · comparison



	SERPENT	Uncertainty (σ)	ERANOS[3]
Doppler constant (pcm)	-549	18	-566
Lead expansion coefficient (pcm/K)	-0.327[1]	0.019	-0.268[2]
Axial fuel expansion (pcm/K)	-0.152	0.006	-0.155
Axial cladding expansion (pcm/K)	0.044	0.006	0.037
Grid expansion (pcm/K)	-0.780	0.007	-0.789
Axial wrapper expansion (pcm/K)	0.036	0.006	0.022

[1]Calculated considering all the lead inside the inner vessel. [2]Calculated for the whole height of the fissile subassemblies.

[3]Grasso, G. et al., 2014. The Core Design of ALFRED, a Demonstrator for the European Lead-Cooled Reactors. Nucl. Eng. Des., 278, 287–301

COMSOL model

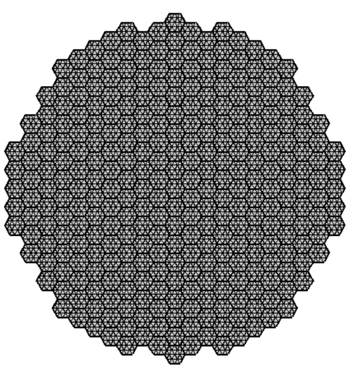
COMSOL model (Finite Element) of the ALFRED reactor (diffusion equation)

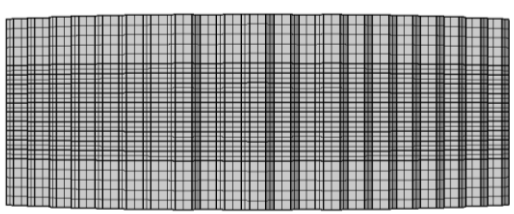
$$\underline{\underline{V}}^{-1}\frac{\partial \underline{\phi}}{\partial t} = \nabla \cdot \left(\underline{\underline{D}}\nabla \underline{\phi}\right) - \underline{\underline{\Sigma_a}}\,\underline{\phi} - \underline{\underline{\Sigma_s}}\,\underline{\phi} + (1-\beta)\underline{\chi_p}\,\underline{F}^T\underline{\phi} + \sum_j \lambda_j \underline{\chi_d} C_j$$

$$\frac{\partial C_j}{\partial t} = -\lambda_j C_j + \beta_j \underline{F}^T \underline{\phi} \qquad\qquad j = 1 \div 8$$

$\underline{\underline{V}}^{-1}$ $\underline{\underline{D}}$ $\underline{\underline{\Sigma_a}}$ $\underline{\underline{\Sigma_s}}$ $\underline{\chi_p}$ $\underline{F}^T$ $\underline{\gamma_a}$ $\underline{\gamma_r}$

Neutronics parameters of seven energy groups calculated by means of the MC transport code SERPENT (included albedo coefficients for the BC)





Group	Upper boundary	Lower boundary
1	20 MeV	2.23 MeV
2	2.23 MeV	0.82 MeV
3	0.82 MeV	0.30 MeV
4	0.30 MeV	67.38 keV
5	67.38 keV	15.03 keV
6	15.03 keV	0.75 keV
7	0.75 keV	0 keV

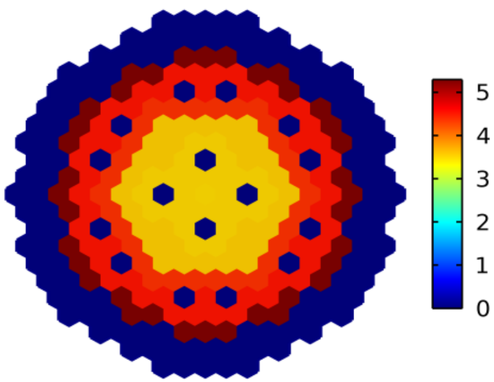
COMSOL model · XS homogenization

XS homogenization zones: 5 for the inner fuel, 5 for the outer fuel, 4 for the SRs, 5 for the CRs and 3 for the dummy elements.

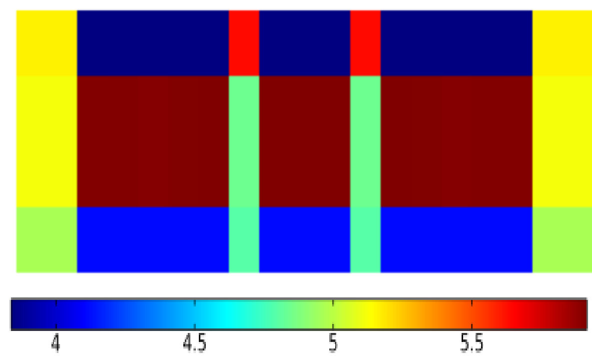
Temperature dependence of the cross sections (from SERPENT) for each coarse zone and slice

$$\Sigma(T) = \Sigma_0 + \alpha \cdot log\left(\frac{T}{T_0}\right)$$

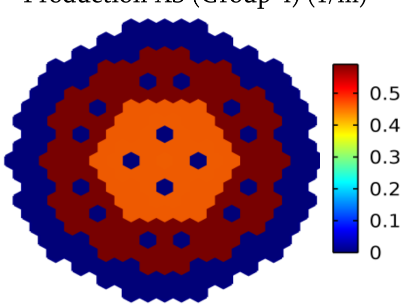
Production XS (Group 7) (1/m)



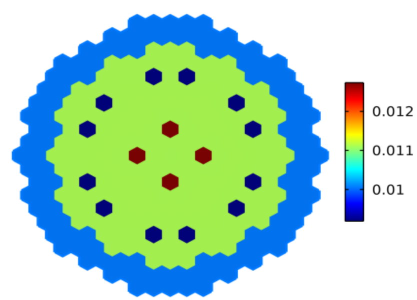
Removal XS (Group 1) (1/m)



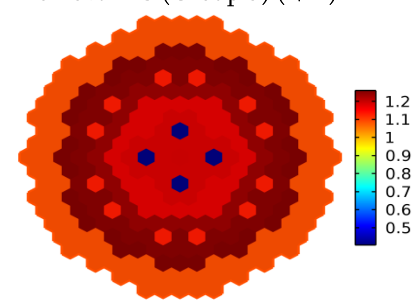
Production XS (Group 4) (1/m)



Diffusion coeff. (Group 4) (1/m)



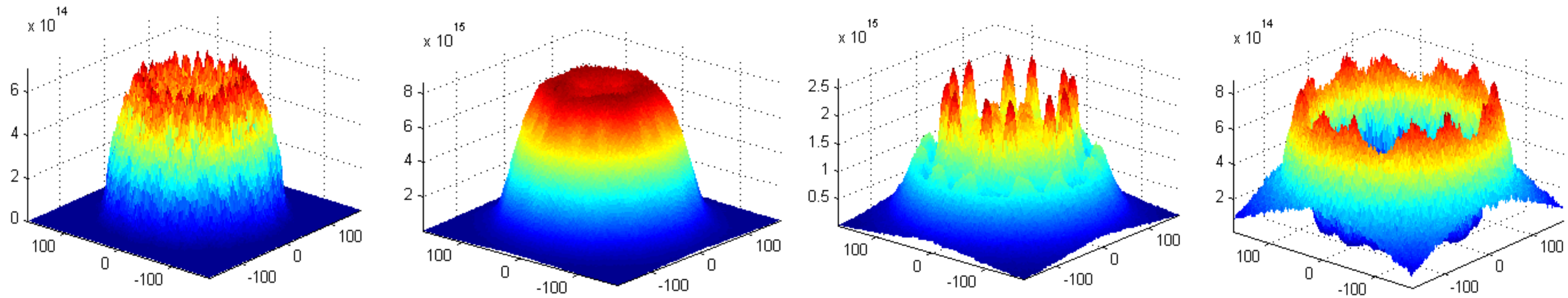
Removal XS (Group 5) (1/m)



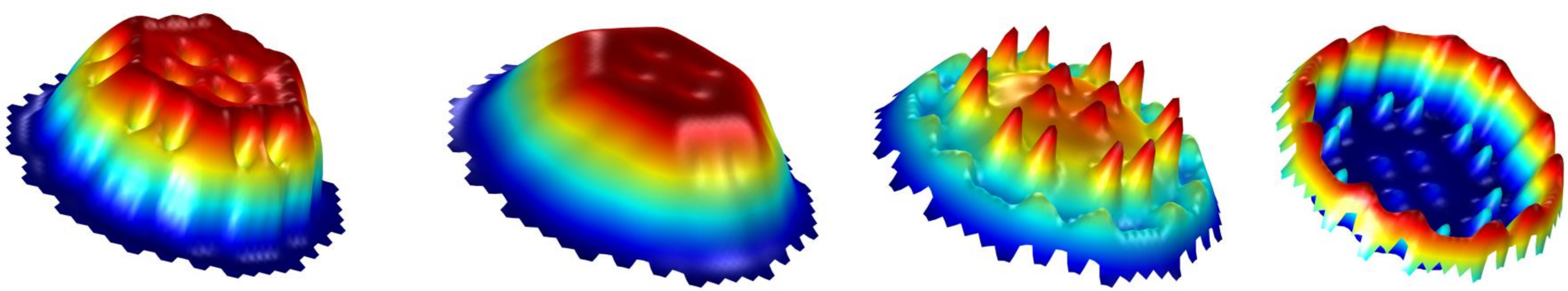
COMSOL model · comparison with SERPENT

Flux distribution in different energy group

SERPENT



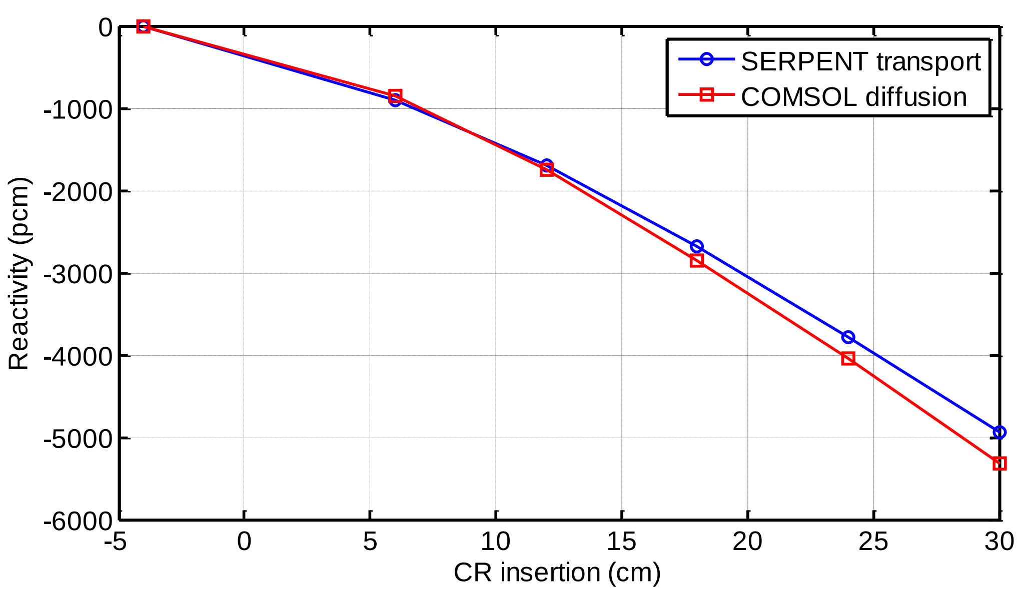
COMSOL



1^{st} group 4^{th} group 6^{th} group 7^{th} group

COMSOL model · comparison with SERPENT

CR insertion (pcm)	SERPENT		COMSOL		Error	
	k	Δρ (pcm)	k	Δρ (pcm)	k	Δρ(pcm)
-4	1.07391	0	1.07387	0	7.4%	-
6	1.06362	-901	1.06409	-856	6.4%	-5.0%
12	1.05474	-1692	1.05405	-1752	5.4%	3.5%
18	1.04390	-2677	1.04201	-2847	4.2%	6.4%
24	1.03201	-3781	1.02911	-4050	2.9%	7.1%
30	1.01982	-4939	1.01584	-5320	1.6%	7.7%



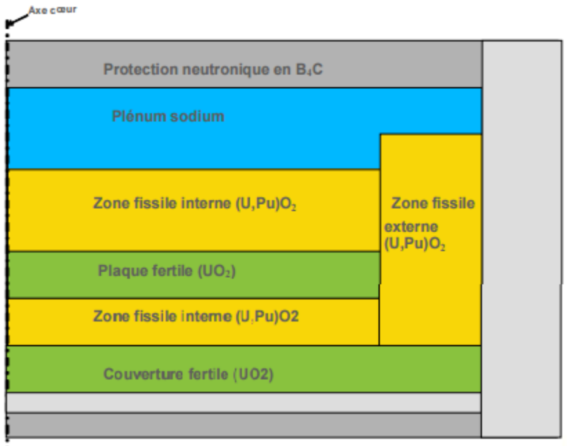
COMSOL model · comparison with SERPENT

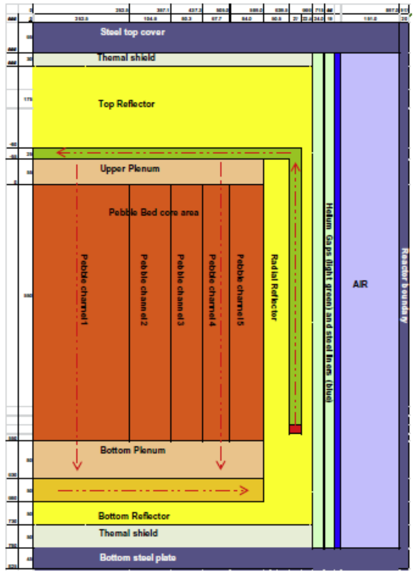
	Fuel temp. (K) (inner/outer)	Lead temp. (K) (below active zone /active zone/ above active zone)	Active length (cm) (inner/outer)	Fuel density (g/cm3) (inner/outer)	FA pitch (cm)
Unperturbed	1500 / 1200	673 / 713 / 753	60 / 60	10.443 / 10.47	17.1
Doppler (inner)	900 / 1200	673 / 713 / 753	60 / 60	10.443 / 10.47	17.1
Doppler (outer)	1500 / 600	673 / 713 / 753	60 / 60	10.443 / 10.47	17.1
Lead density	1500 / 1200	1473 / 1513 / 1573	60 / 60	10.443 / 10.47	17.1
Axial fuel exp. (inner)	1500 / 1200	673 / 713 / 753	61.2245 / 60	10.234 / 10.47	17.1
Axial fuel exp. (outer)	1500 / 1200	673 / 713 / 753	60 / 61.2245	10.443 / 10.261	17.1
Radial grid expansion	1500 / 1200	673 / 713 / 753	60 / 60	10.443 / 10.47	17.1855

	SERPENT (transport)	COMSOL (diffusion)	Error (%)
Doppler (inner)	128.1±7.5	121.1	5.5
Doppler (outer)	206.7±7.5	224.3	8.5
Lead density	-261.7±7.5	-275.3	5.21
Axial fuel expansion (inner)	-101.5±7.5	-105.6	4
Axial fuel expansion (outer)	-154.6±7.5	-139.1	10
Radial grid expansion	-206.8±7.5	-207	0.11

Optimization problem

New reactor concepts can be characterized by an increased number of parameters (different composition, enrichment, fuel materials)





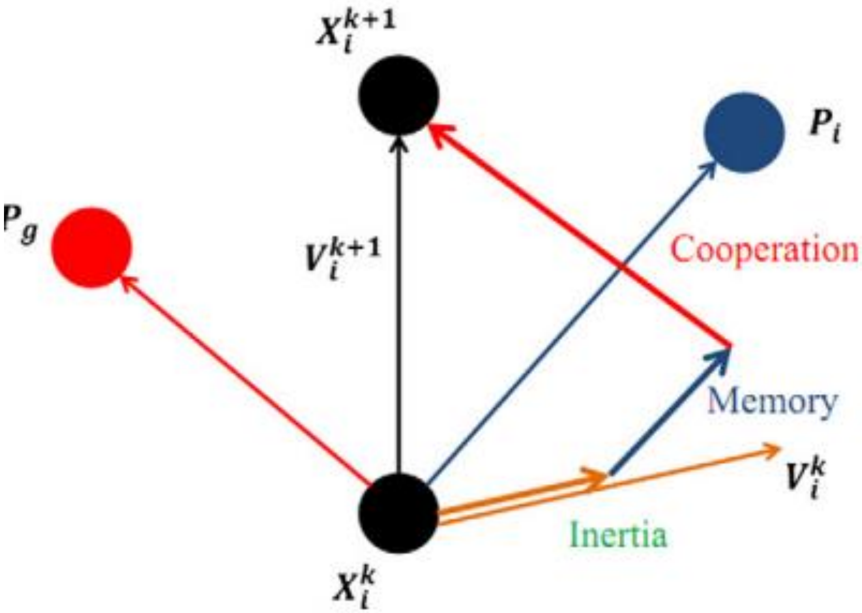
B. Tavron, E. Shwageraus. Nucl. Eng. Des. 307 (2016) 96–105

Optimization problems related to reactor physics cannot be usually tackled with gradient-based optimization algorithm

Develop optimization algorithm based on Genetic Algorithm, **(Quantum) Particle Swarm** or other derivative-free methods

Core reactor design, fuel cycle and incore fuel management optimization are possible application

PSO & QPSO



M. Jamalipour, et al.. Ann. Nucl. Energy, 54 (2013) 134–140.

Particle Swarm Algorithm mimics the interactions between members of biological swarn.

Optimum = Cooperation + Memory + Inertia

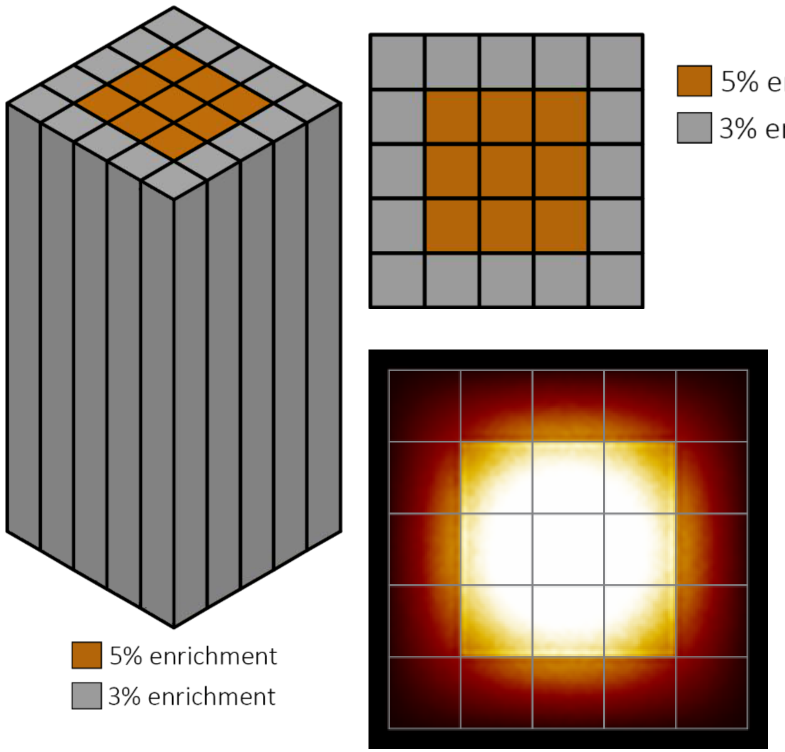
Therefore, Particle Swarm turned out to be less likely to get trapped in local optima with respect to Genetic Algorithms.

PSO = state of a particle given by position x^k_i and velocity v^k_i (Newtonian mechanics)

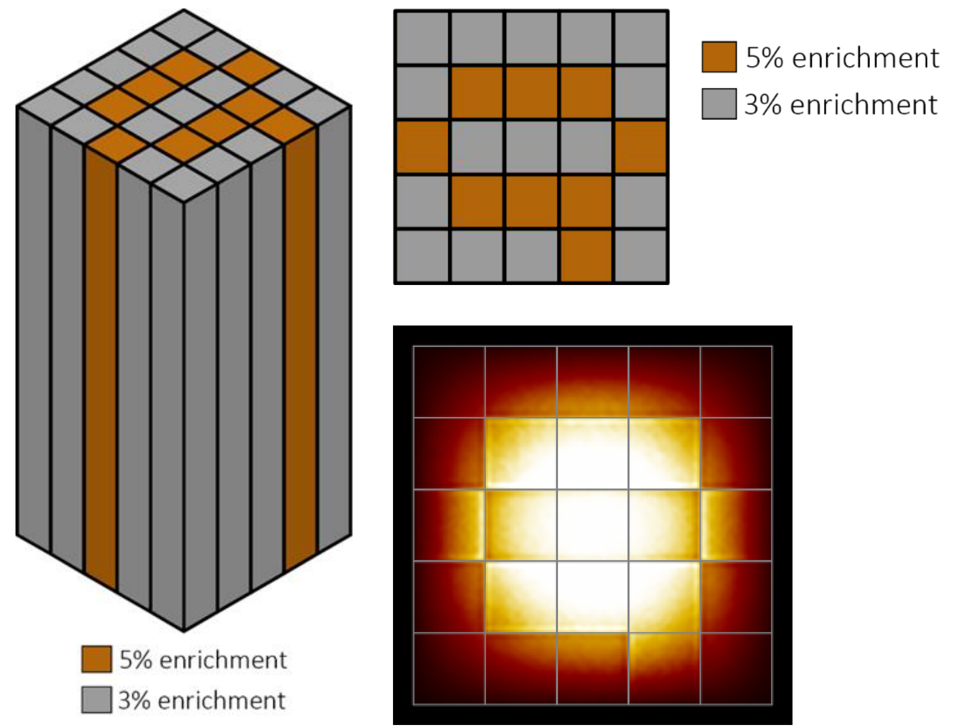
QPSO = state of a particle is given by a probability density / wave function (Quantuum mechanics)

PSO/QPSO with SERPENT

The objective is to optimize the fuel assemblies spatial disposition in order to obtain the highest value of the multiplication factor, k_{eff} using SERPENT runs.



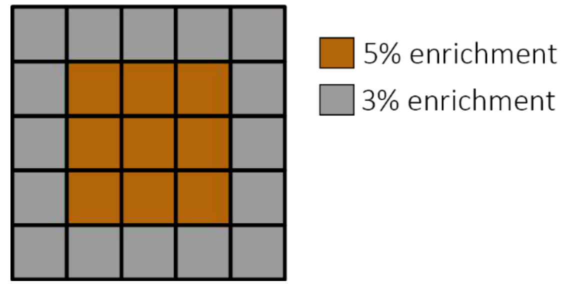
1.06076 ± 15 pcm



1.03745 ± 15 pcm

Optimization task

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

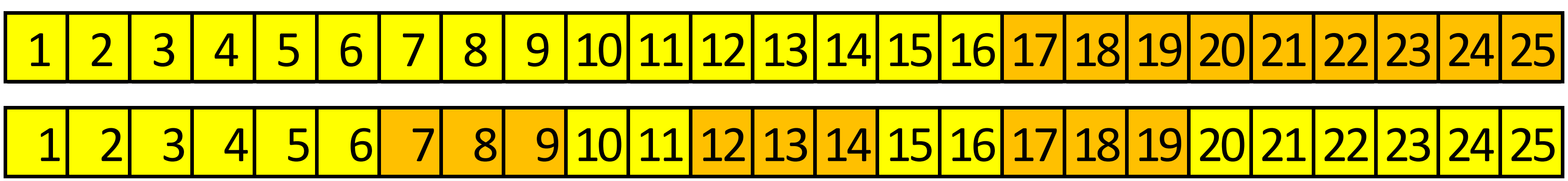


Goal: perform a discrete optimization (max k_{eff}) procedure in a 25-dimensional space in which the possible solutions are permutations of 25 integer numbers

Constraints

i) the same fuel assembly can't be simultaneously loaded into different positions

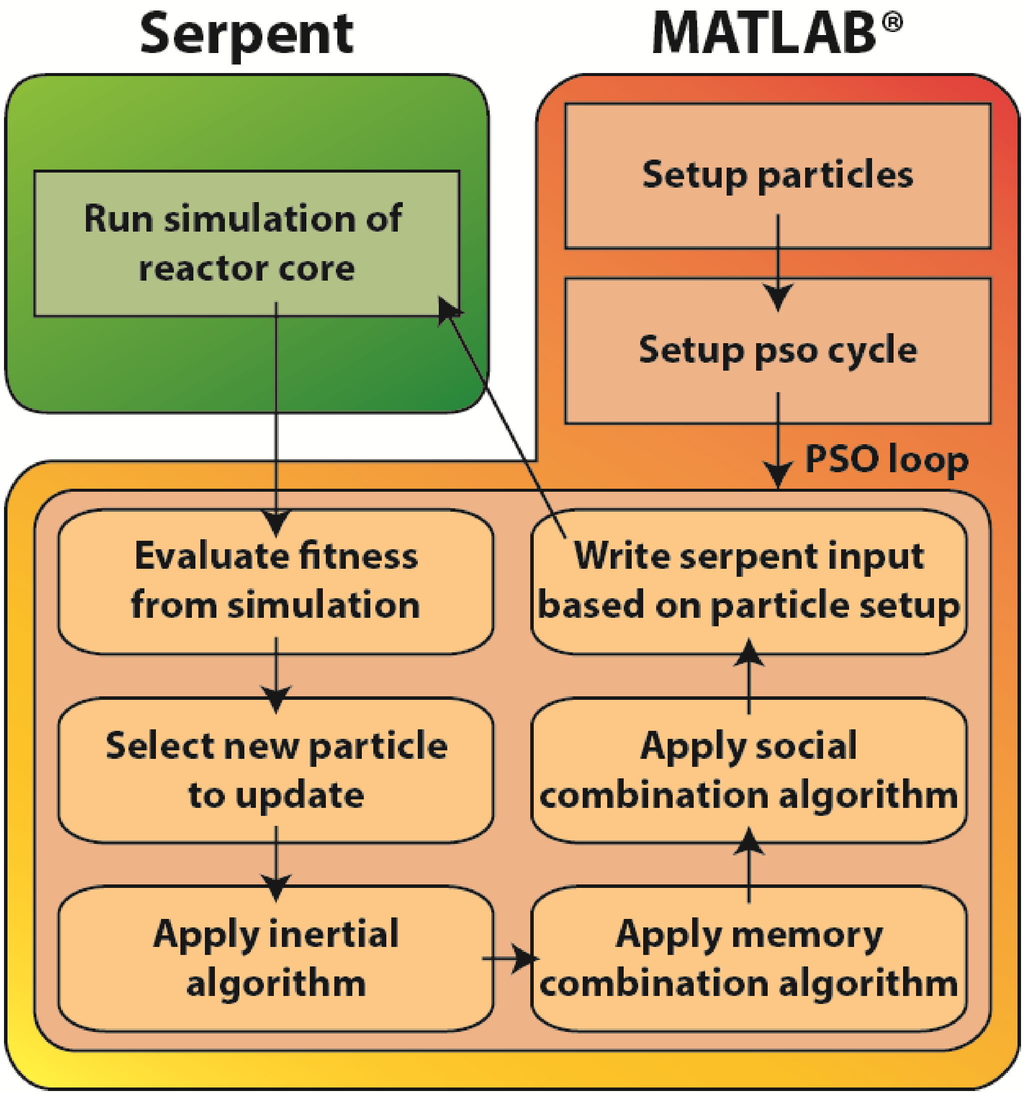
ii) all the 25 fuel assemblies provided for the reactor core must be loaded.



16 fuel assemblies of 3% enrichment

9 fuel assemblies of 5% enrichment

Matlab script



Results

PSO						
Number of Iterations/ Swarms	$\lvert k_{evaluated} - k_{optimum} \rvert$ (pcm)			Time (h)		
	Number of Particles			Number of Particles		
	20	30	40	20	30	40
10	1134	1253	971	16	23	34
20	1134	1097	207	29	41	65
30	971	425	0 (at 26th iteration)	43	63	101
40	207	425		54	102	
50	207	0 (at 43th iteration)		78	105	
60	0 (at 56th iteration)			87		

QPSO						
Number of Iterations/ Swarms	$\lvert k_{evaluated} - k_{optimum} \rvert$ (pcm)			Time (h)		
	Number of Particles			Number of Particles		
	10	20	30	10	20	30
10	225	378	218	5	13.5	22
20	0 (at 13th iteration)	0 (at 18th iteration)	113	6.5	31	46
30			0 (at 27th iteration)			52

G. Tavelli, F. Giacobbo, A. Cammi, M. T. Cauzzi. A Feasibility Study on In-Core Fuel Management via Quantum Particle Swarm Optimization. Proceedings of the 25th International Conference Nuclear Energy for New Europe, Portoroz, Slovenia, 5-8 September 2016.

OpenFOAM and SERPENT

Neutronics–thermohydraulics coupling for criticality and burnup simulations (Master thesis of P. Bianchini in collaboration with UC Berkeley)

.

Goal: Perform burnup calculation on EPR reactor for JUNO (Jiangmen Underground Neutrino Observatory, China) experiment, in order to determine if thermohydraulics feedback on neutronics is significant for burnup

SERPENT + OpenFOAM coupling

Thank you for attention

POLITECNICO
MILANO 1863

Nuclear
Reactors
Group