High Flux Reactor conversion to LEU: Uncertainties by design with Generalized Perturbation Theory

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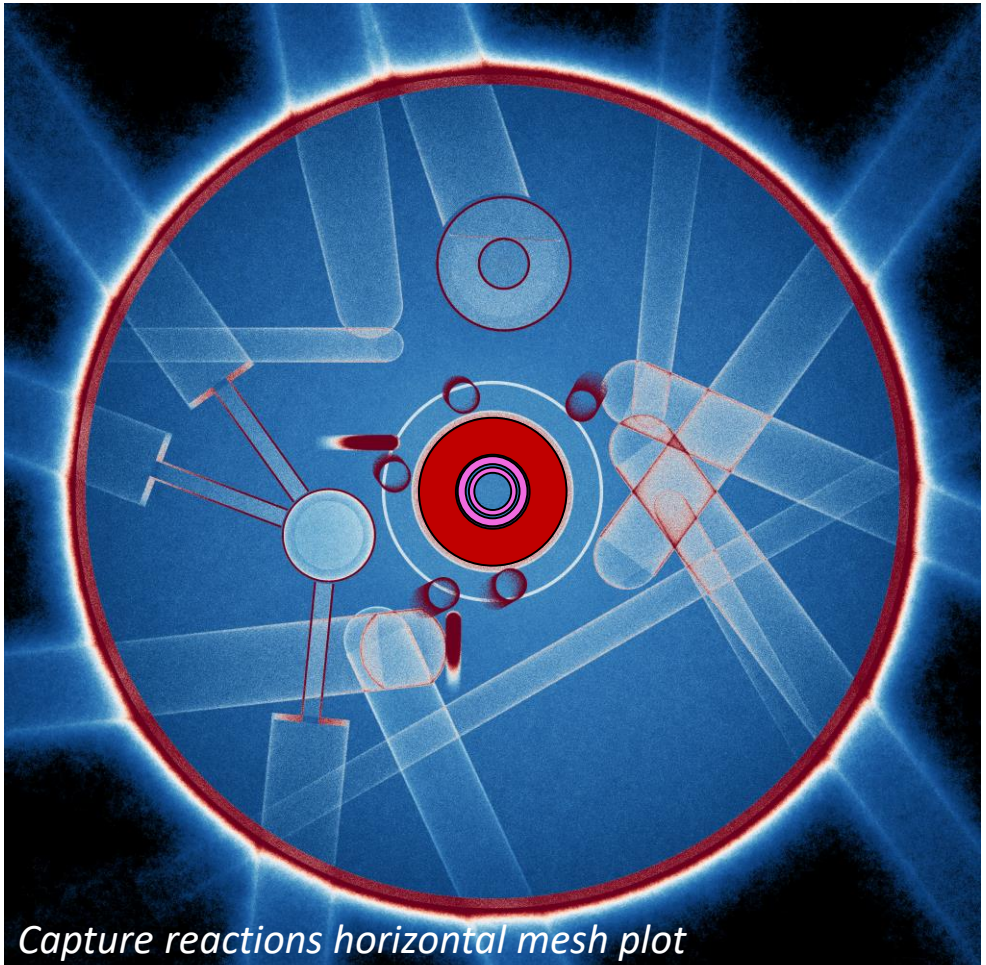
The High Flux Reactor (RHF)



Capture reactions horizontal mesh plot

Reactor design:

- 58 MWth Power
- **D_2O** Moderator and Reflector
- **93% Enrichment** Fuel U-Alx
- 1 Control Rod
- 5 Safety Rods
- Over 40 experiments
- $1.5 \cdot 10^{15}$ n/cm^{2}s max Flux
- 17 beams
- 45 days cycles
- Cold Source at 24K
- Hot Source at 2400K

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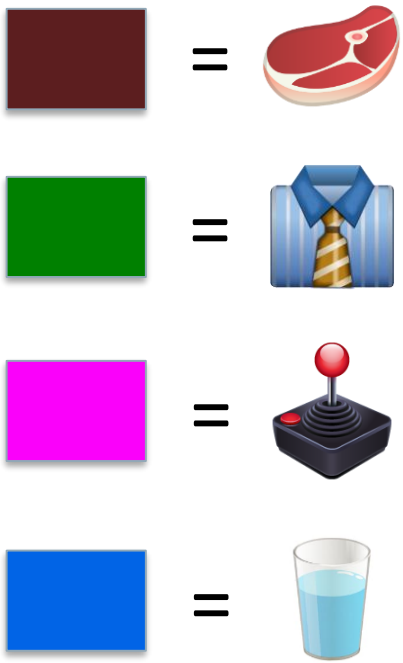
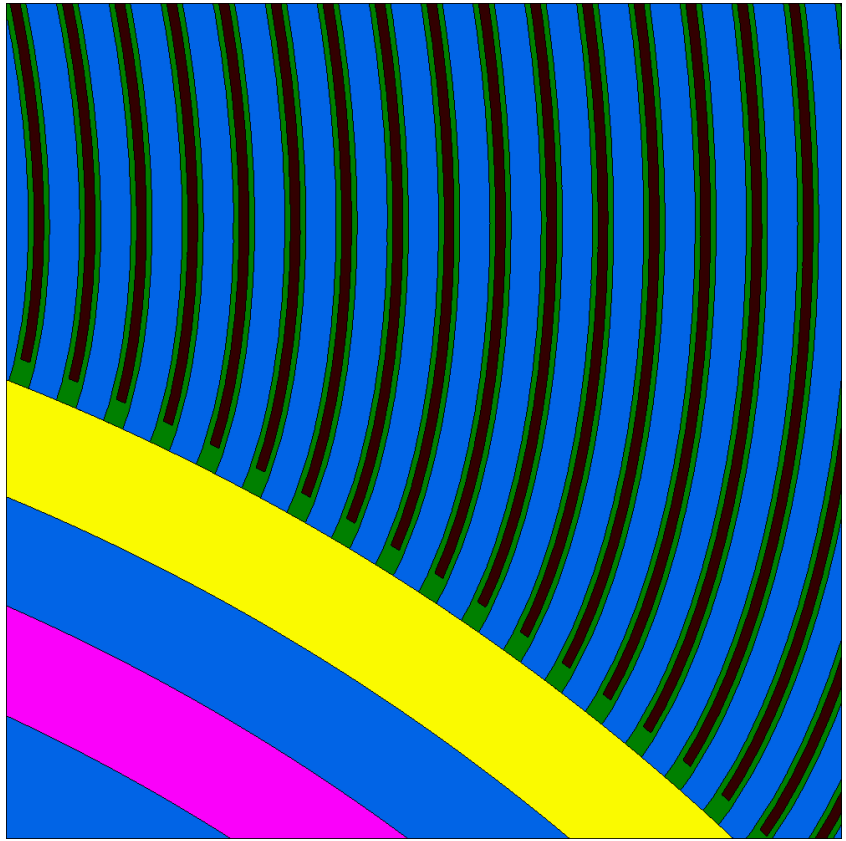
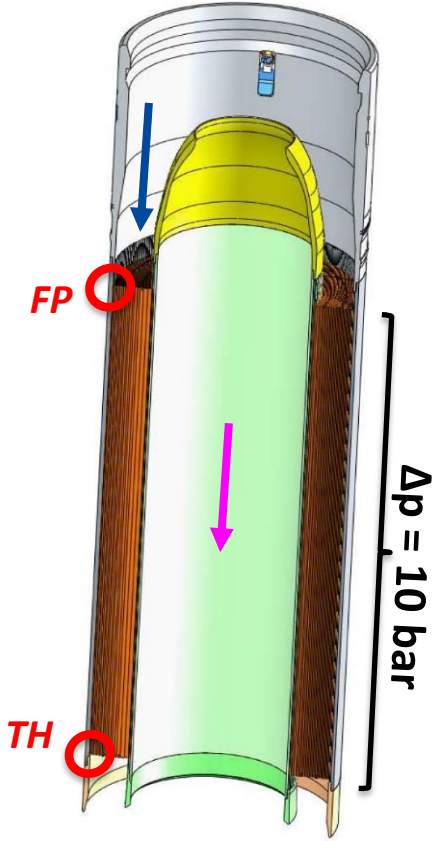




Fuel plates detail



Fuel assembly

Safety parameters: Heat flux peaking

Reduced Fuel Enrichment

Increase in fuel density (U_3Si_2)

Increase in meat thickness, length, width

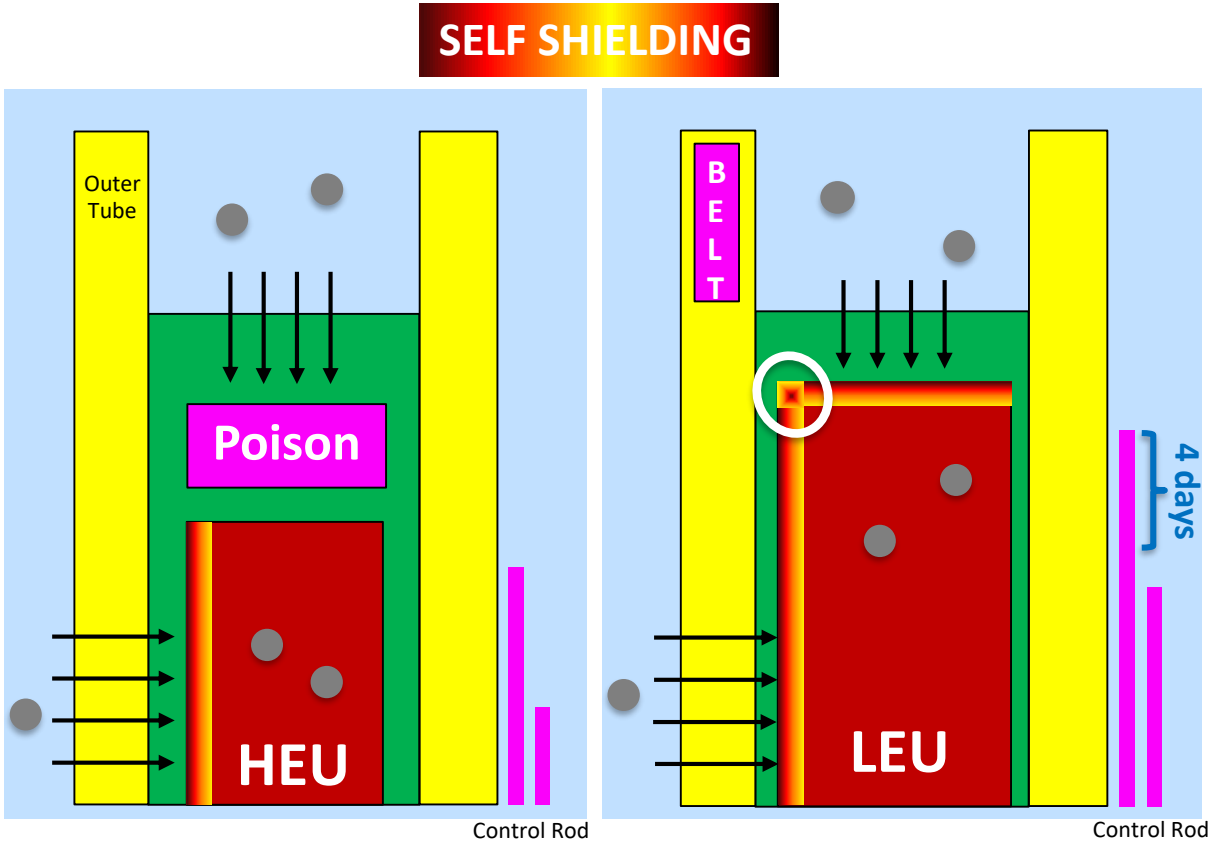
No more cap in the plates:

Hot Channel

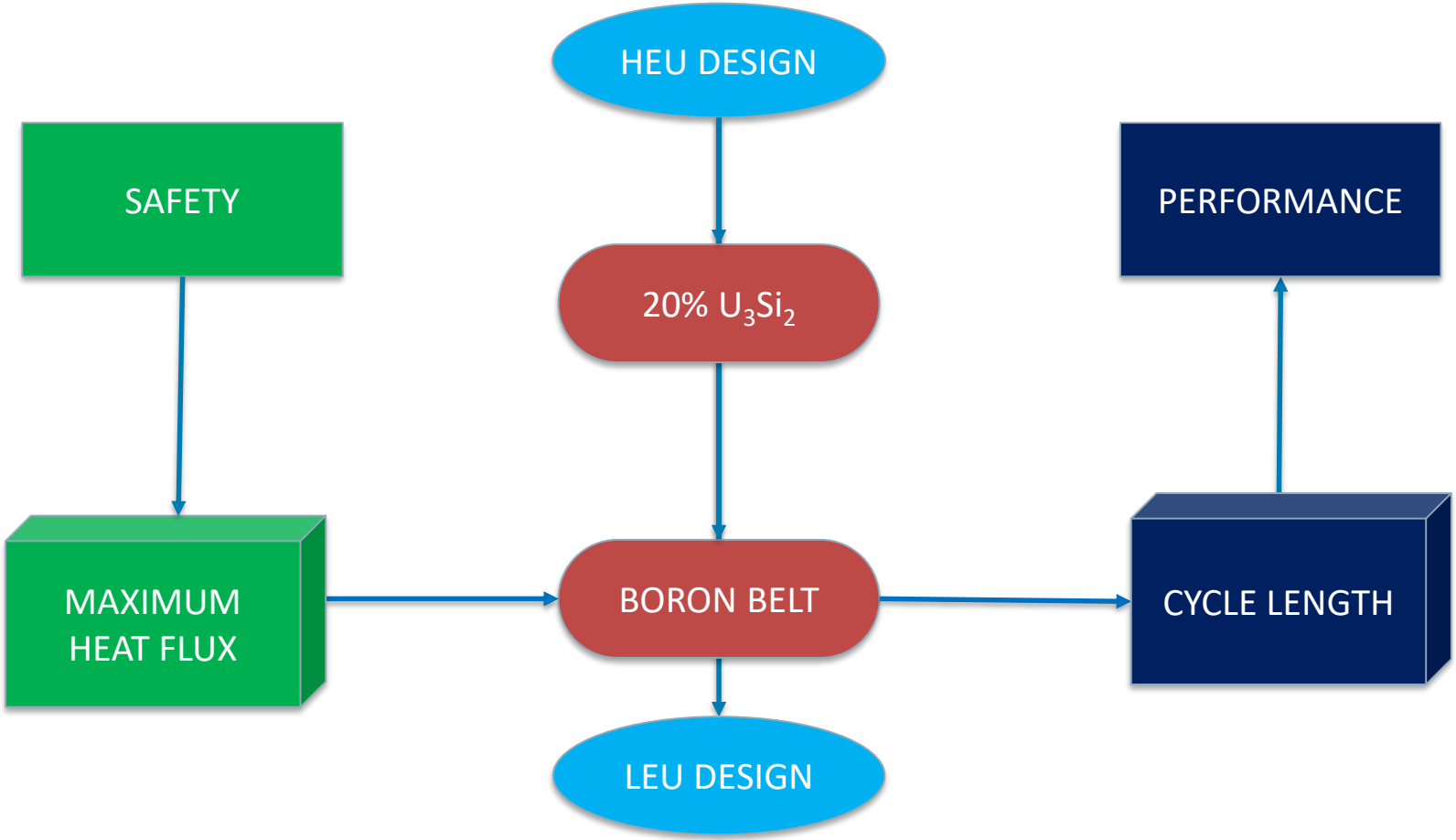
Hot Spot

Poison BELT

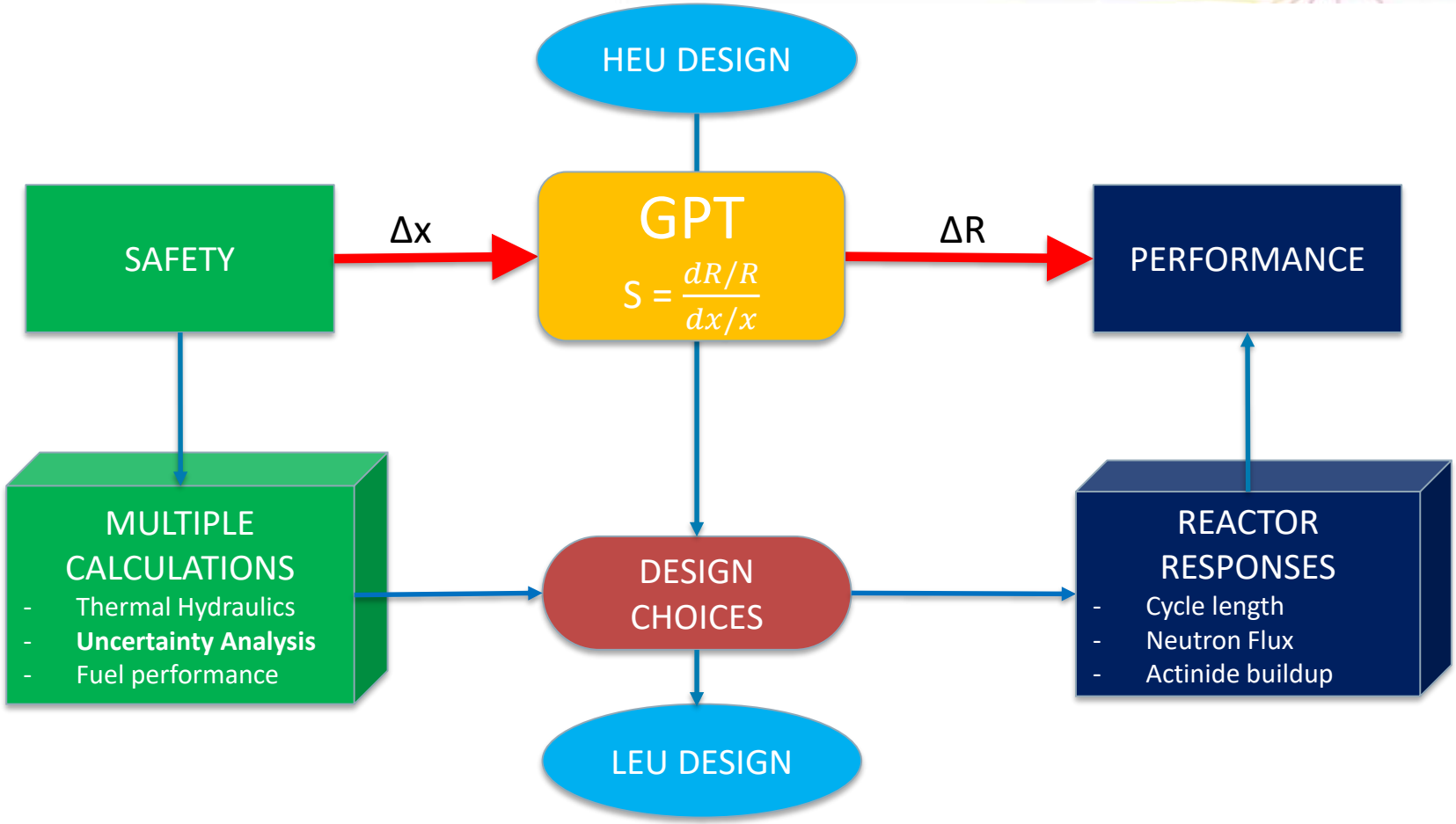
Longer cycle



Uncertainties by design



Uncertainties by design



k_{eff} Uncertainty Analysis

Each term is calculated with the Monte Carlo code SERPENT2:

$$S_{D_2O} = S_D + S_H + S_O = \frac{\frac{dk}{k}}{\frac{d\Sigma_D^{tot}}{\Sigma_D^{tot}}} + \frac{\frac{dk}{k}}{\frac{d\Sigma_H^{tot}}{\Sigma_H^{tot}}} + \frac{\frac{dk}{k}}{\frac{d\Sigma_O^{tot}}{\Sigma_O^{tot}}}$$

It is used to find the reactivity change due to impurities of H_2O in D_2O:

$$\Delta\rho = -S_D \frac{\Delta N_D}{N_D} + S_H \frac{\Delta N_H}{N_H}$$

GPT can estimate k_{eff} uncertainties without running multiple calculations:

Experimental uncertainties	SERPENT direct	MCNP direct	SERPENT GPT
Coolant channel thickness*	+1847/-1812 ± 8	+1856/-1776 ±8	+/- 1786 ± 12
Heavy water composition	**+114/-110 ± 8**	**+119/-116 ±8**	**+/- 127 ± 8**
Fissile mass*	+150/-176 ± 8	+157/-168 ±8	+/- 170 ±1
Cladding density	+70/-58 ±8	+85/-76 ±8	71 ±3

** Results before normalization due to plates independence*

Nuclear Data

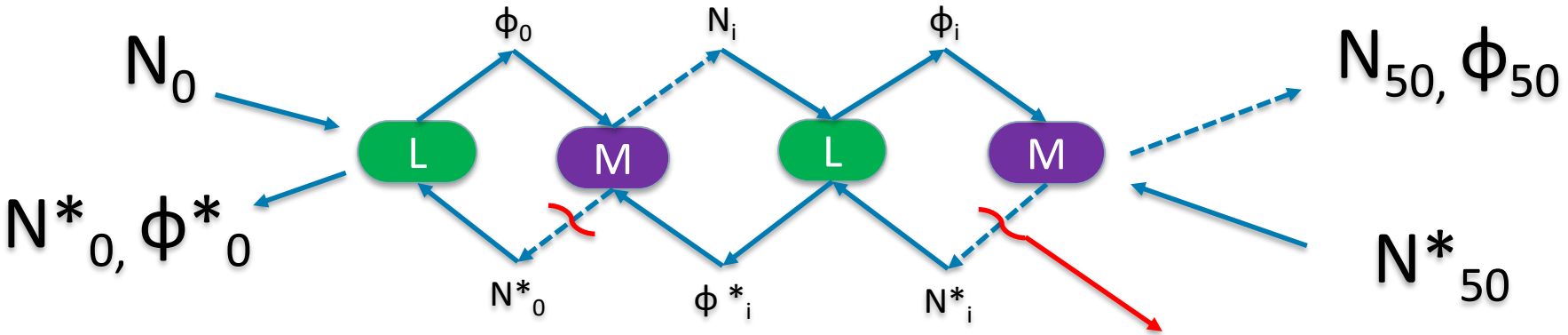
If the covariance matrix for the perturbed parameter x is available, sensitivity vectors allow to estimate the keff uncertainty employing the **sandwich rule**:

$$\sigma_k^2 = S_x^k \times COV_x \times S_x^{k\prime}$$

Nuclear Data	Sensitivity coefficient	k_{eff} Uncertainty
^{235}U ν_t	0.9997	277 pcm
^{235}U fission	0.3009	177 pcm
^{235}U capture	-0.1528	96 pcm
D scattering	0.2895	**477 pcm**
^{16}O scattering	0.1142	110 pcm
Total		**597 pcm**

RHF Nuclear Data uncertainties, 44 groups covariance matrices (SCALE6)

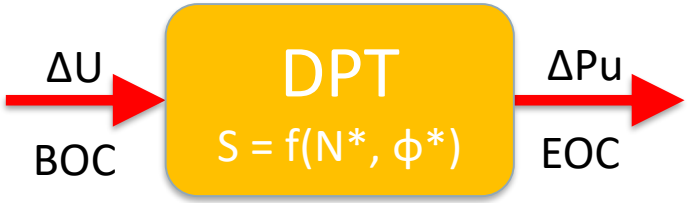
Depletion Perturbation Theory



Step condition on N* dependent on other adjoint quantities (Williams 1978)
Proportional to flux coupling

L Diffusion Matrix $L = B - \lambda F$ $[L^* = L^T]$

M Evolution Matrix $M = R - D$ $[M^* = R^T]$



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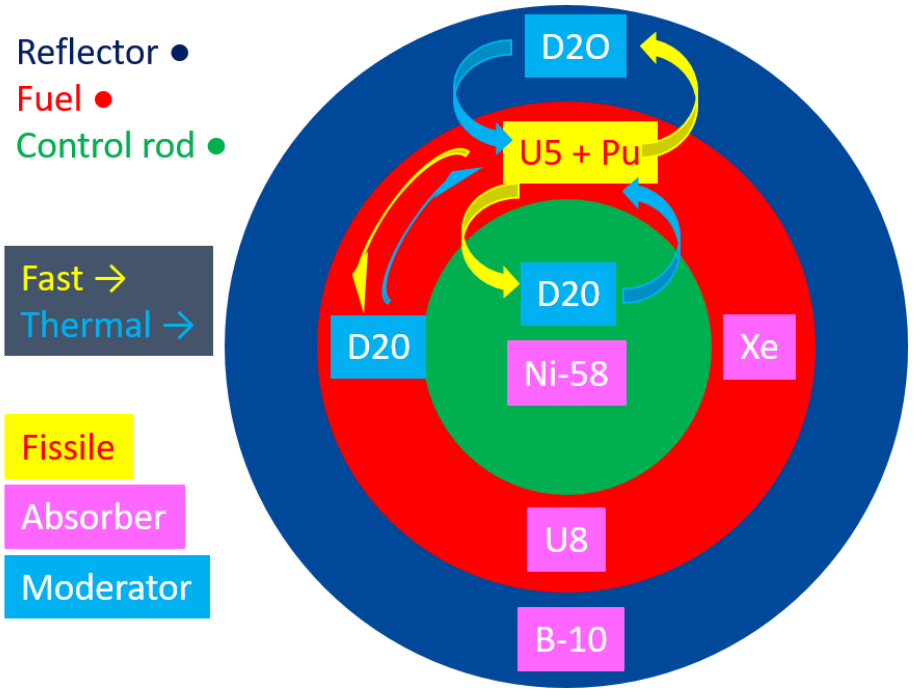
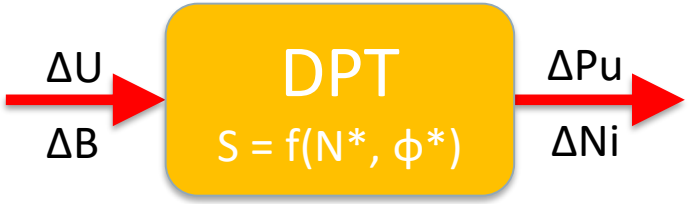


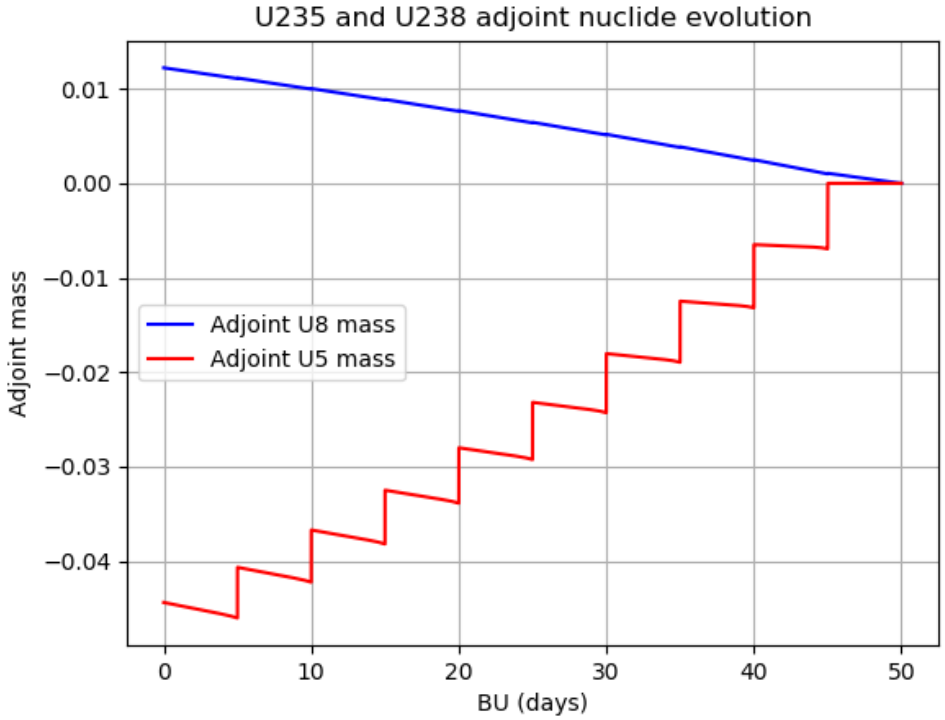
RHF point diffusion model (python):

- 3 regions
- 2 energy groups
- 5 burning nuclides
- Tunable concentration in Ni-58 (control rod) drives criticality and allows for k-reset



Depletion Perturbation Theory

Define a final condition $^{Pu}N^*$(day 50)=1, $^{U}N^*$(day 50)=0. Solve Bateman eq. backwards:

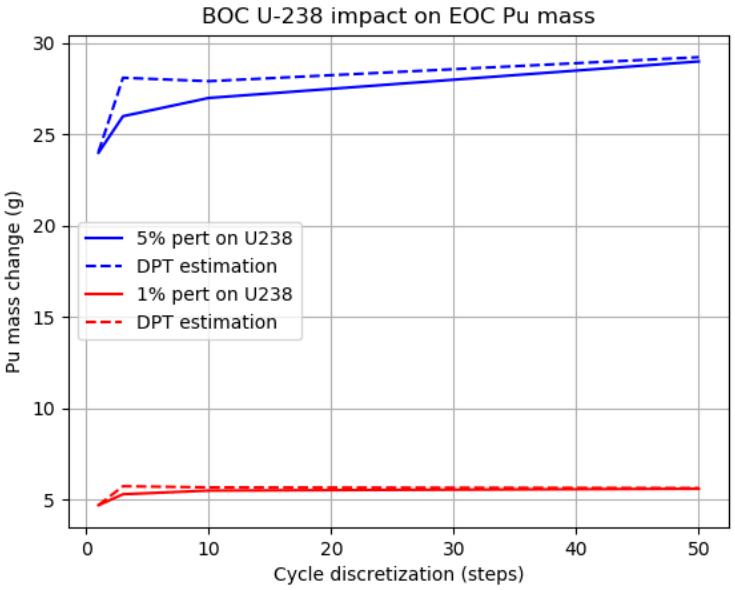


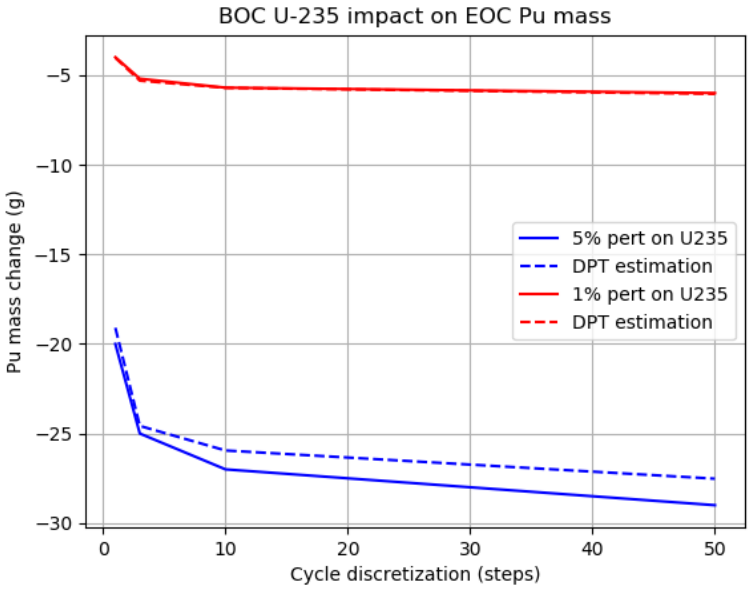
The adjoint nuclide fields define the time dependent sensitivities:

- U238 adjoint field is continuous: resonance captures directly create Pu, no coupling with flux
- U235 field is discontinuous: DPT defines a step condition to couple adjoint flux and adjoint flux field (at P=const more U5 means less flux, less U8 captures, less Pu)
- The U235 indirect effect is 4x bigger then the U238 direct one (it compensates with different enrichments)

Depletion Perturbation Theory

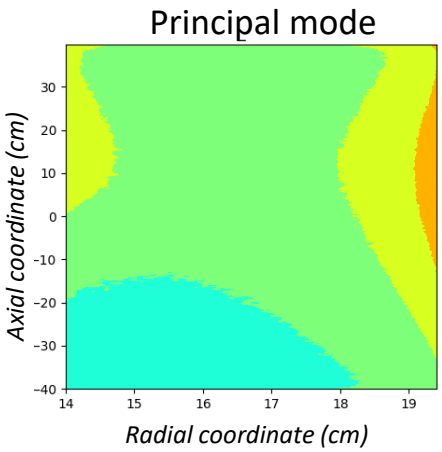
How does a perturbation in the BOC Uranium mass affect the EOC Plutonium mass (500 g) ?

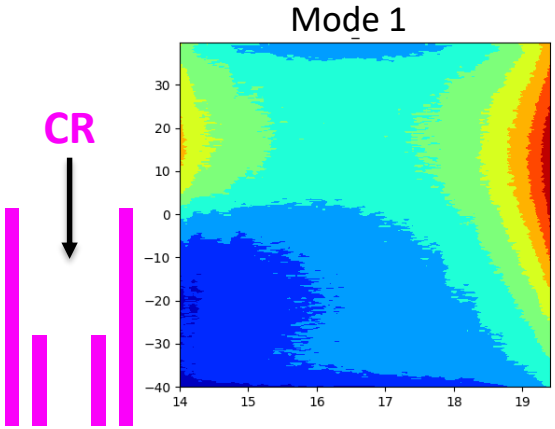


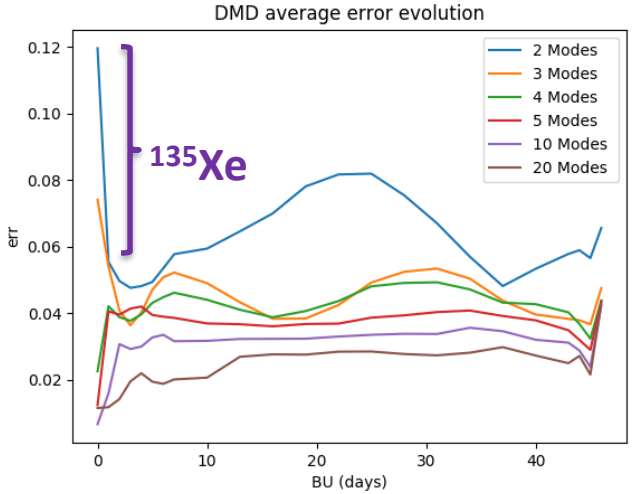


Dynamic mode decomposition

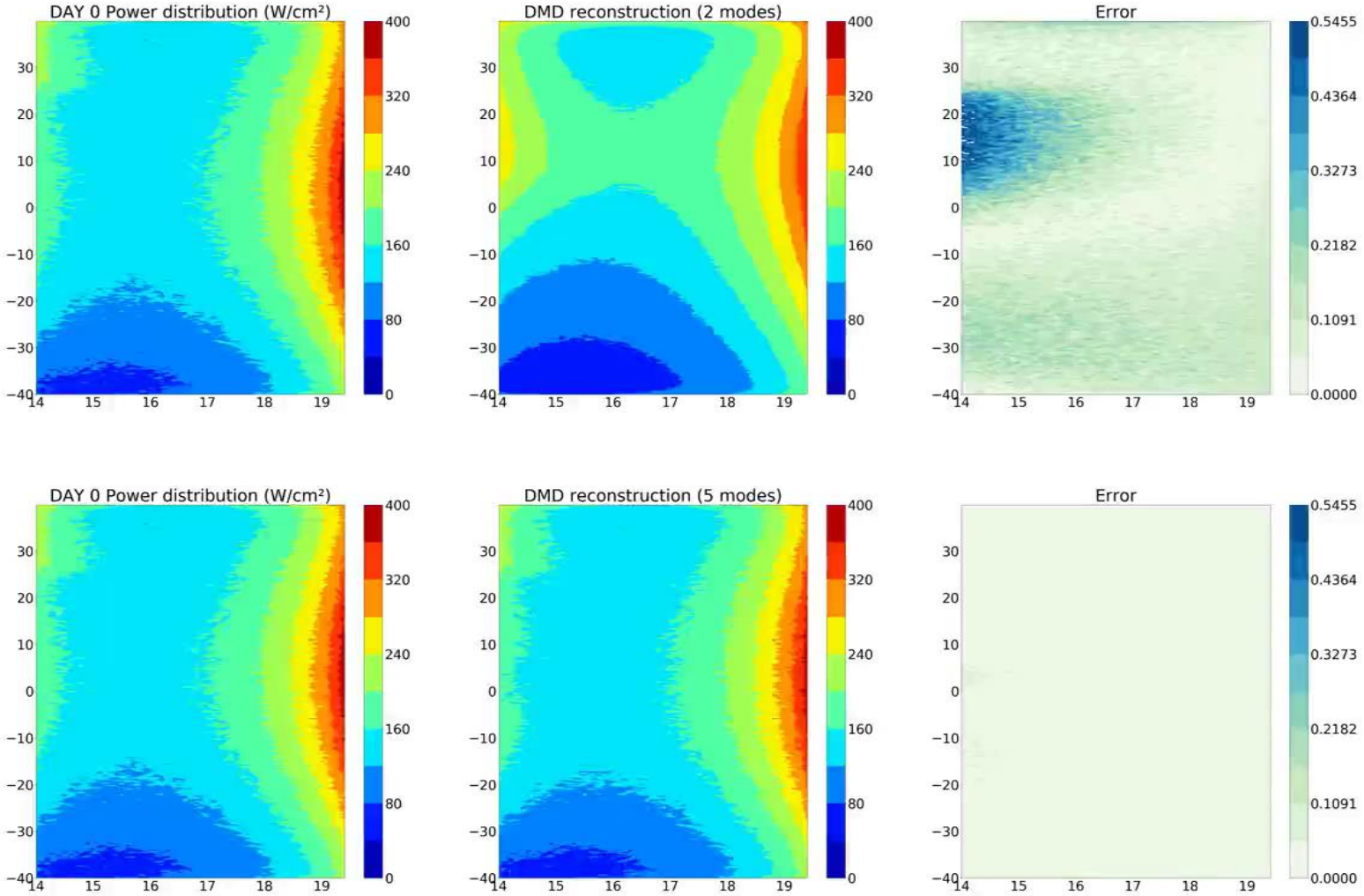
Data analysis technique based on proper orthogonal decomposition (POD)
Describe the behavior of the power distribution by decomposing it in a finite set of basis:







At least 4 modes are necessary to model the steep control rod jump due to Xenon.
With 20 modes employed, the error starts to converge to a minimum value


DAY 0 Power distribution (W/cm²)
DMD reconstruction (2 modes)
Error
DAY 0 Power distribution (W/cm²)
DMD reconstruction (5 modes)
Error
400
320
240
160
80
0
0.5455
0.4364
0.3273
0.2182
0.1091
0.0000
30
20
10
0
−10
−20
−30
−40
14
15
16
17
18
19

Planning

- While cross sections and scattering matrices for migrations to different energy groups were calculated, migrations from one region to the other weren't obtained from Serpent (**Albedos** ?)
- Once the DPT algorithm will be finalised, future Monte Carlo couplings could be performed on some pin/assembly configurations before moving to the RHF. The DPT solver already developed in SMURE will be used as a guideline for further development in python.
- XGPT f(E) perturbations in SERPENT could be used to study the effect of **Doppler feedback**. The presence of U-238 could in fact increase the margin on the "best estimate" reactivity injection transient (beam flooding).
- DMD analysis of rank >5 can suggest "on the fly" applications that could be implemented in the **predictor-corrector** BU solver, or for uncertainty propagation via surrogate models.

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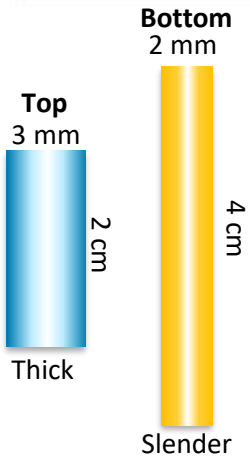
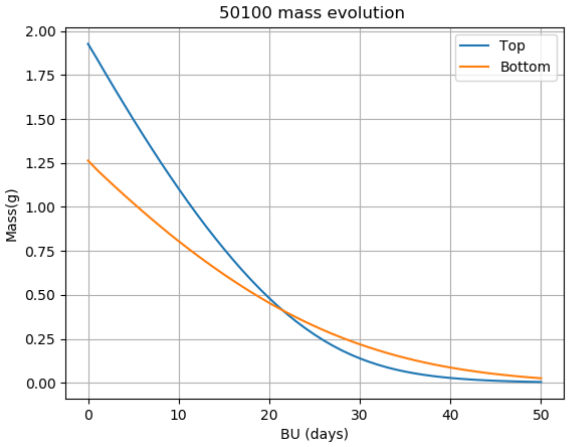
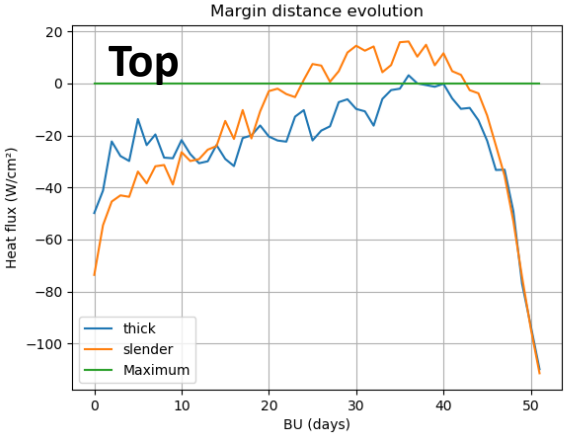
Boron belt design

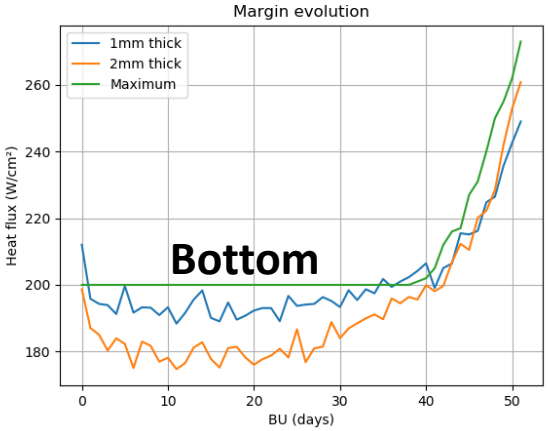
Sensitivity analysis (135 MC) :

Position (0.5-1.5 cm)
Length (2-4 cm)
Thickness (1-2 mm)
Composition (0.8-10 % at.)







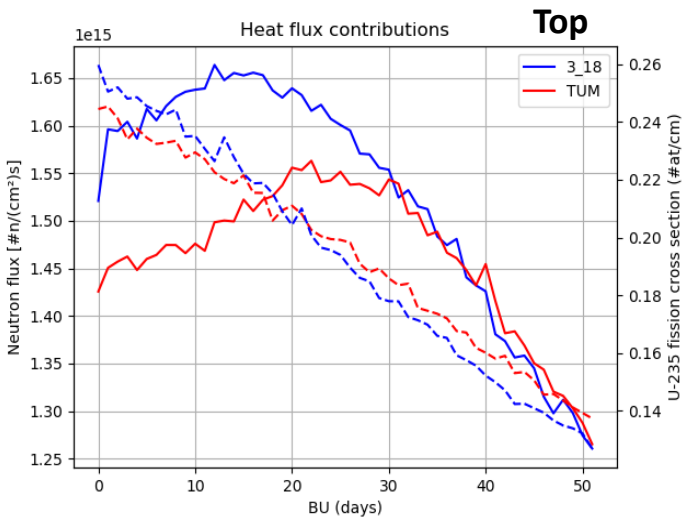


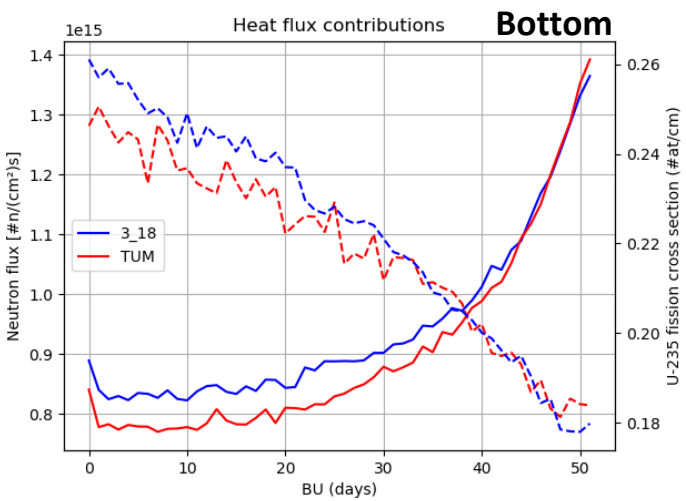
THE SELF-SHIELDING EFFECT CAN BE EXPLOITED TO ACCOMMODATE TWO DIFFERENT FLUX REGIMES

Boron belt design

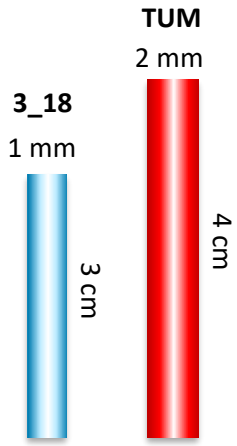
Top corner: Inversion point due to boron / control rod is shifted.
Promoting captures at the beginning of the cycle degrades U5 cross section, leaving more margin for the second half of the cycle

Bottom corner: Burnup has no inversion. Objective is to maximize captures



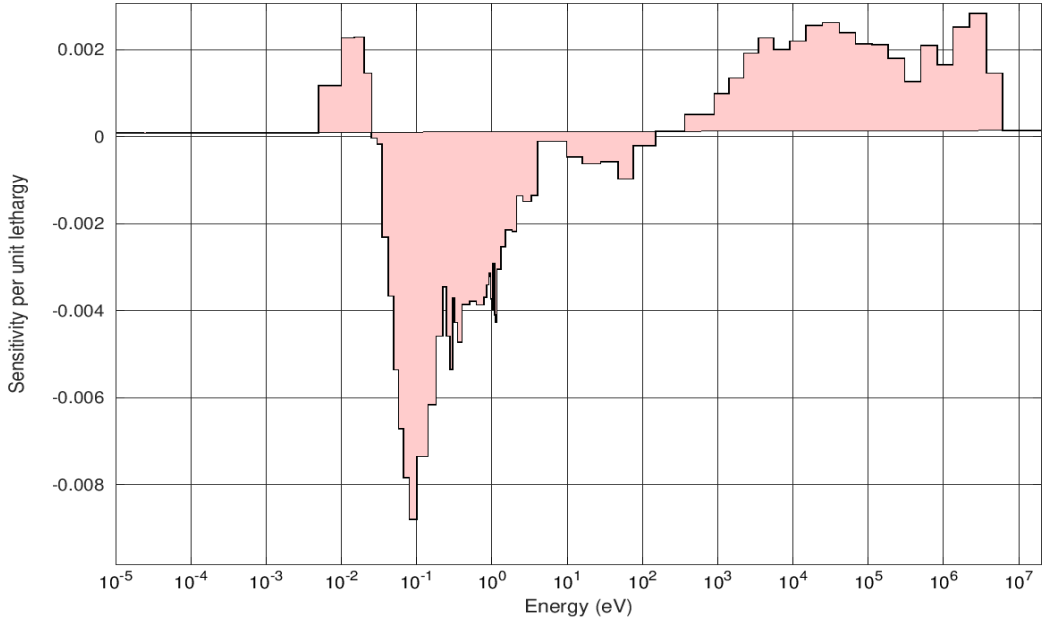
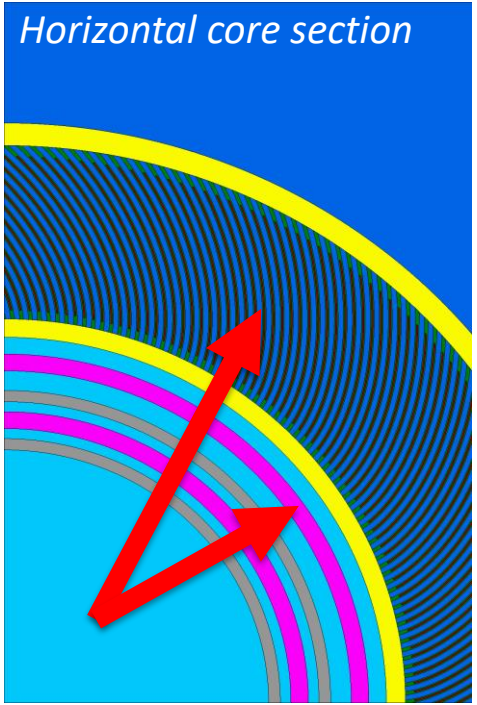


Neutron flux (full line) and macroscopic cross section (dotted line)



FUEL ELEMENT CUTTING
4 → 3.5 cm

Sensitivity vectors

In addition to integral values of k_{eff}, β_{eff}, λ_{eff} and void coefficient sensitivities, **energy dependent** sensitivity vectors can be calculated (M. Aufiero, 2015):

k_{eff} Sensitivity to D_2O around the Control Rod