Karlsruhe Institute of Technology

Numerical Studies of Axial Fuel Shuffling

Dalin Zhang, Xue-Nong Chen, Fabrizio Gabrielli, Andrei Rineiski, Werner Maschek

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KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT), INSTITUT für KERN UND ENERGETIK (IKET)

Outline

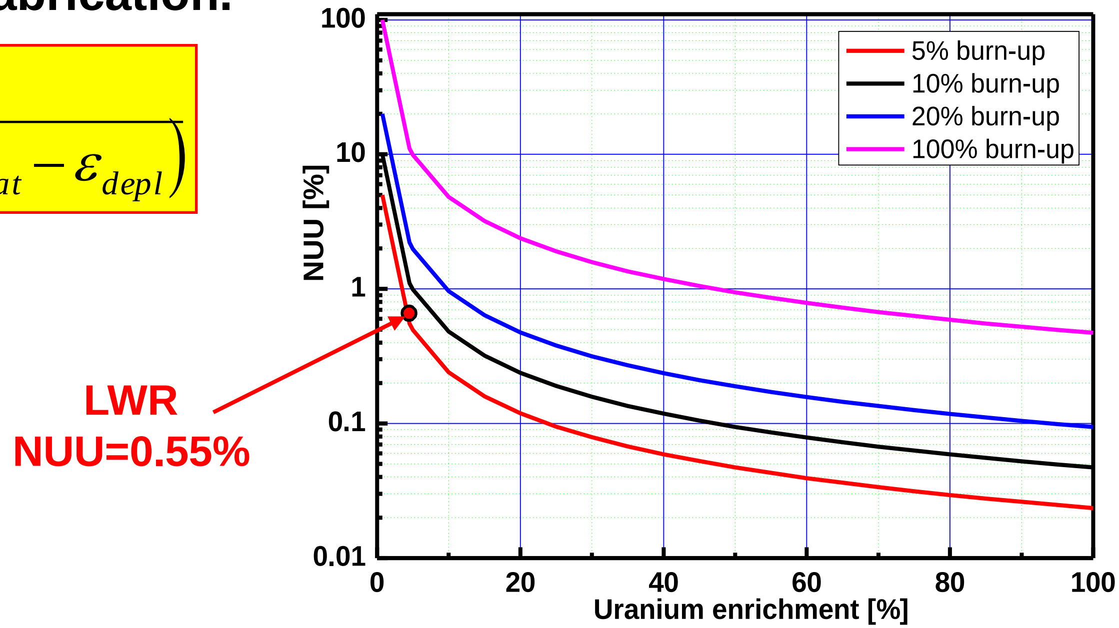
- ❑ **Introduction**
- ❑ **Axial Fuel Shuffling Strategy and Calculation Scheme**
  - Basic idea
  - Calculation scheme and tools
  - Calculation conditions
- ❑ **Results and Discussion**
  - Burn-up benchmark calculation
  - 1-D axial shuffling calculation of SFR
  - 2-D calculation
- ❑ **Conclusions**

❑ Introduction (1/2)

- **Natural uranium utilization (NUU) = the burned heavy metals (HMs) / total nature uranium for fuel fabrication.**

$$NUU = \frac{Burnup}{\left(\varepsilon_{fuel} - \varepsilon_{depl}\right) / \left(\varepsilon_{nat} - \varepsilon_{depl}\right)}$$

LWR[1]	
Burn-up	5%
ε_{fuel}	4.5%
ε_{depl}	0.25%
ε_{nat}	0.72%



- **High burn-up and low enrichment is favorable to improve NUU.**
- **Traveling wave reactor (TWR): very high burn-up, while using no enriched uranium, instead burning fuel made from natural uranium, depleted uranium, thorium, spent fuel removed from LWRs …**

[1] from E. Greespan and F. Heidet, INES-3, Oct.31-Nov.3 2010, Tokyo, Japan.

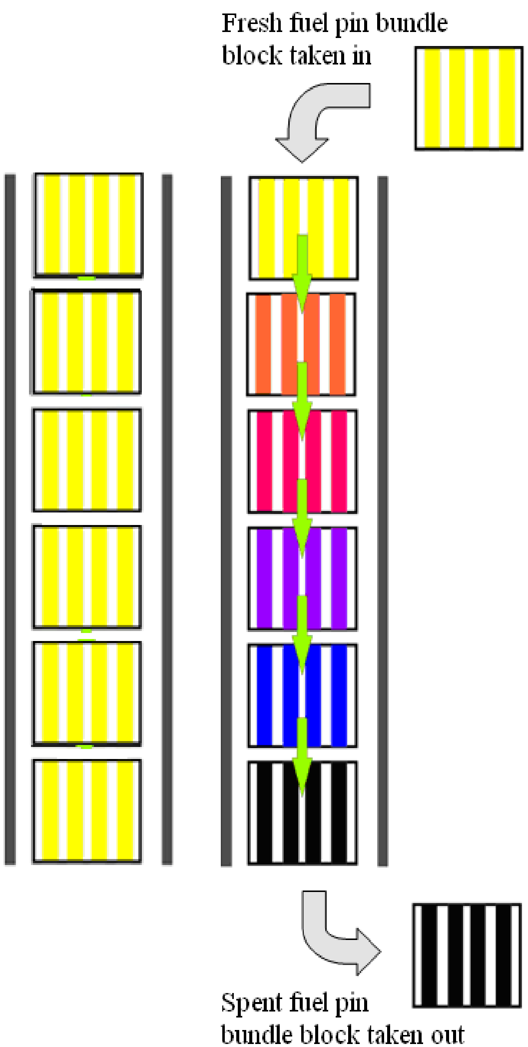
❑ Introduction (2/2)

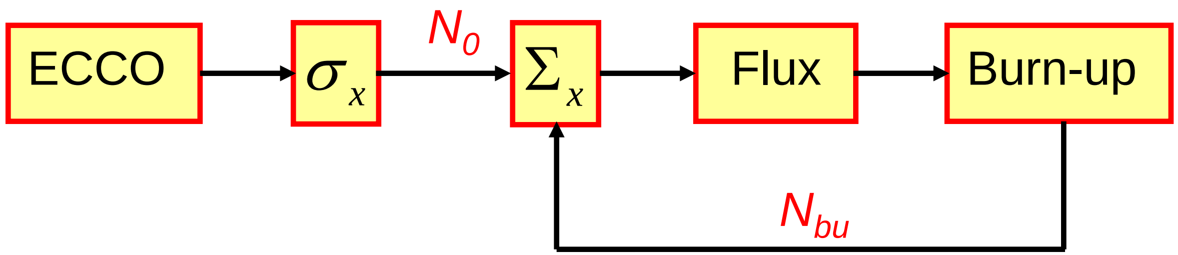
- **Strict requirements for traveling wave reactor (TWR) application:**
  - **Very long active core**
  - **Asymptotic criticality condition**
- **Truncated traveling wave mechanism:**
  - **Relative motion principle: fuel motion, rather than power profile motion.**
  - **Asymptotic nuclear fission traveling wave in a finitely long core by fuel shuffling.**
- **Application in SCWFR for Th-U and U-Pu conversions (INES-3)**
  - **Very high burn-up is obtained but need initial enrichment for fresh fuel.**

  √ X

- **Axial shuffling strategy is applied to SFR with metallic fuel.**
- **1-D and 2-D calculations are performed.**
- **ERANOS code is used.**

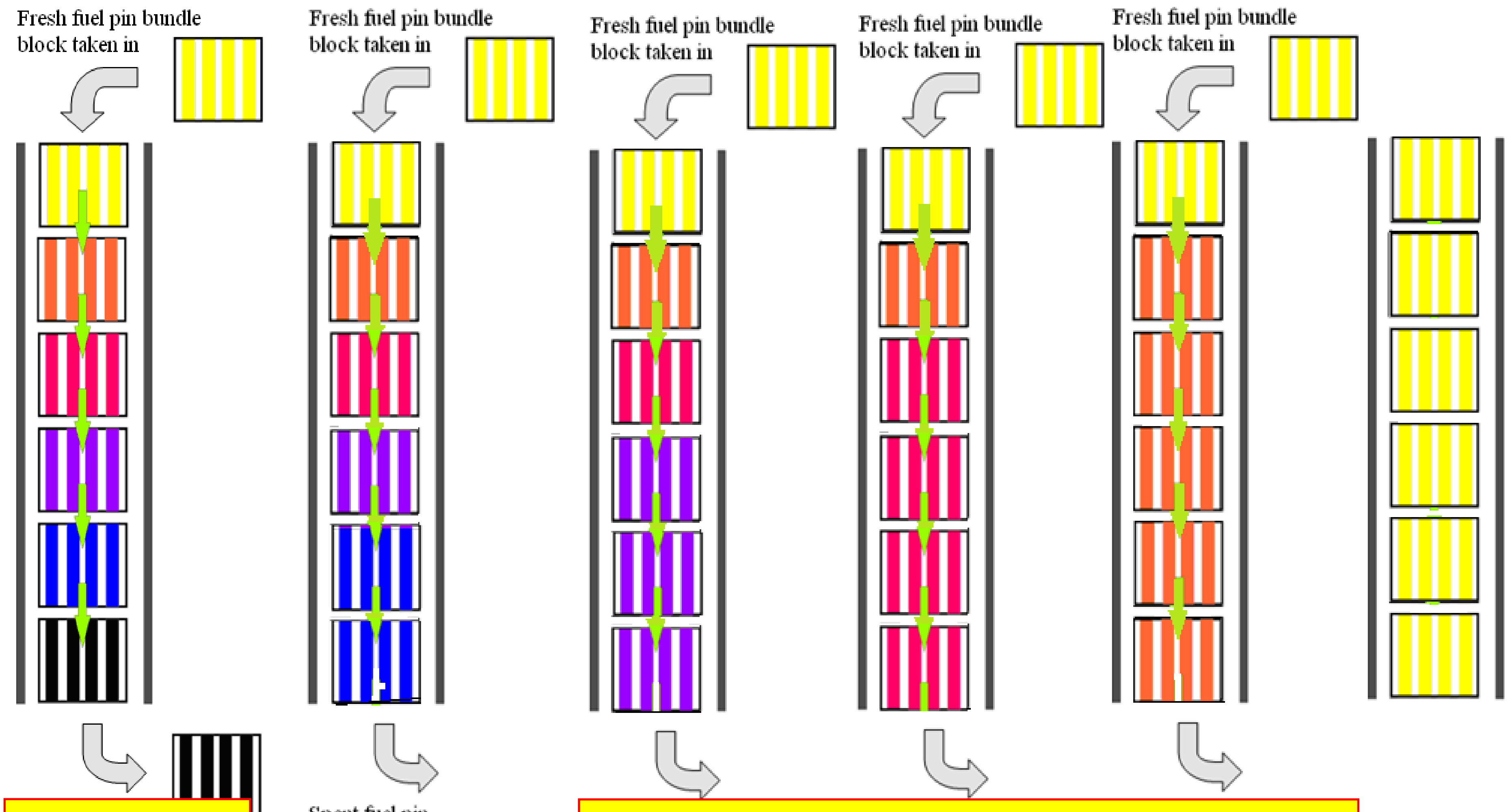
❑ Axial Fuel Shuffling Strategy and Calculation Scheme (1/3)



- **Basic idea:**
  - **Pin bundle in an SA is divided into *n* movable blocks**
  - **Fuel frog-leap = Fuel axial shuffling**
- **Simulation tools:**
  - **ECCO with JEFF3.1 data library → micro-xs**
  - **ERANOS → burn-up and flux calculation**
- **Calculation scheme:**
  - 

- **Calculation conditions:**
  - **Typical SFR design: α_f = 50 %, α_c = 30 %, α_s = 20 %**
  - **Metallic ^{238}U fuel**

❑ Axial Fuel Shuffling Strategy and Calculation Scheme (2/3)

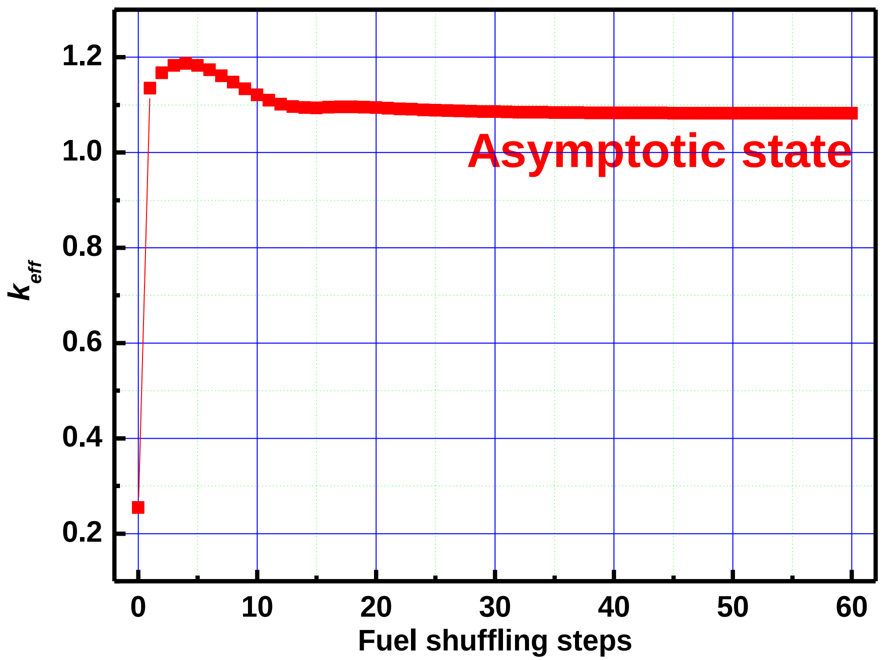


Asymptotic state

Each color represents the same burn-up time

❑ Axial Fuel Shuffling Strategy and Calculation Scheme (3/3)

➢ **k_{eff} converging process with shuffling steps**



- ❖ The asymptotic state will be reached after several shuffling steps.
- ❖ At asymptotic state, k_{eff}, power shape and nuclides distributions are constant.
- ❖ Every shuffling period approaches an asymptotic state.
- ❖ Just shuffling period is adjusted to obtain different asymptotic states.
- ❖ Only asymptotic state is studied.

- ❖ Fuel moving speed is inversely proportional to shuffling period.

$$\upsilon = \frac{\Delta z}{\Delta t}$$

$$\sigma_{\upsilon} = \frac{\upsilon}{\phi L}$$

❑ Results and Discussion (1/6)

➢ Burn-up benchmark calculation

- ***F* function**

$$F(\psi) = \nu\Sigma_f(\psi) - \Sigma_a(\psi)$$

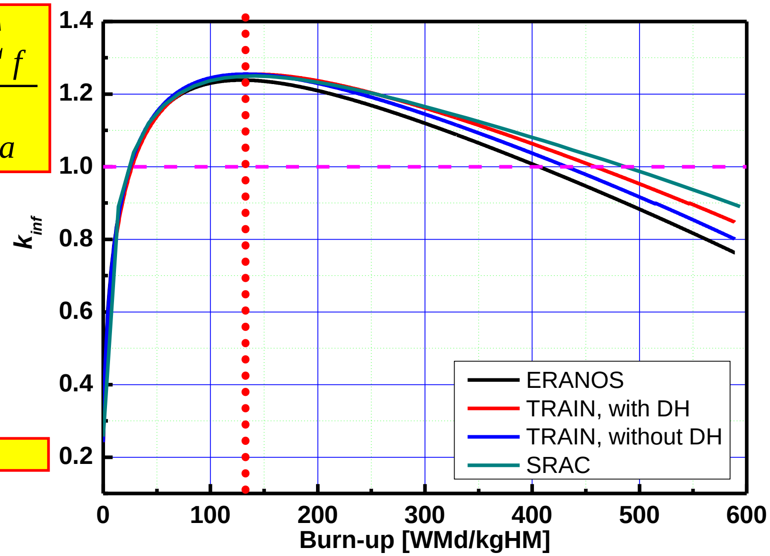
- ❖ Net neutron generation (macro-) cross section.
- ❖ It is only material composition dependent. If the fresh fuel is made of certain actinides, e.g. ^{238}U, the fuel composition is irradiation dependent, i.e. mostly on neutron fluence.

- ***G* function**

$$G(\psi) = \int_0^t F(\psi)\phi dt = \int_0^\psi F(\psi) d\psi$$

- ❖ Net generated neutron density by certain neutron fluence.
- ❖ Total generated neutrons per unit volume by certain irradiation time.

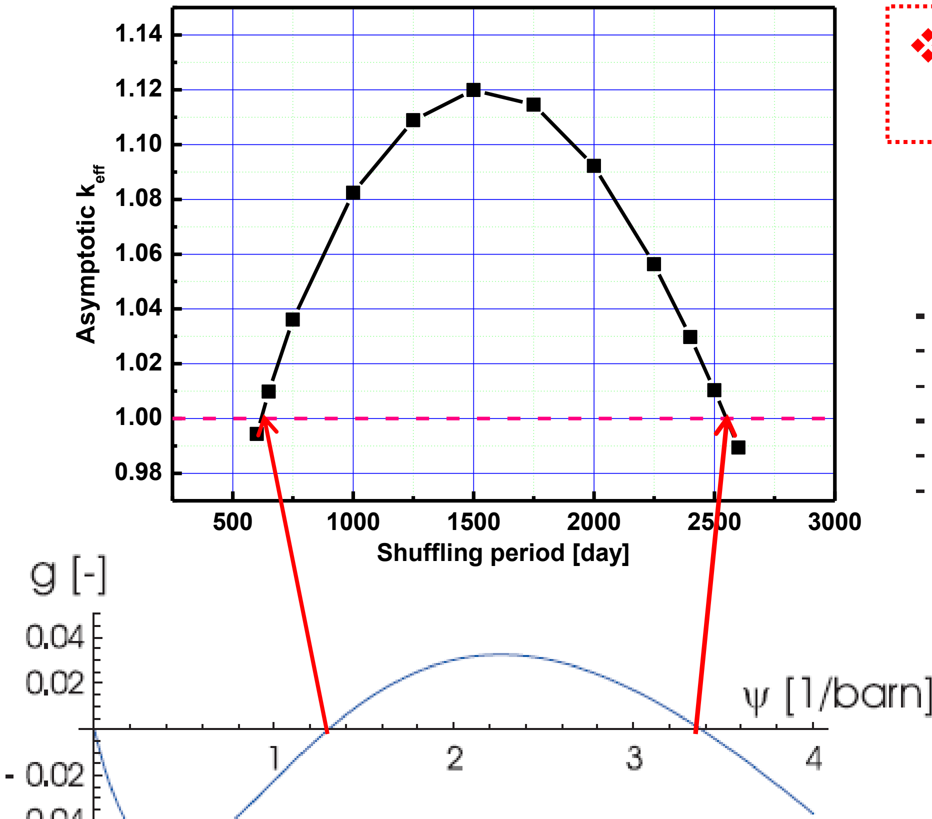
$$k_\infty = \frac{\nu\Sigma_f}{\Sigma_a}$$



- ❖ The FP treatment, nuclear data, soft wares must be improved for TWR accurate calculation with high burn-up.

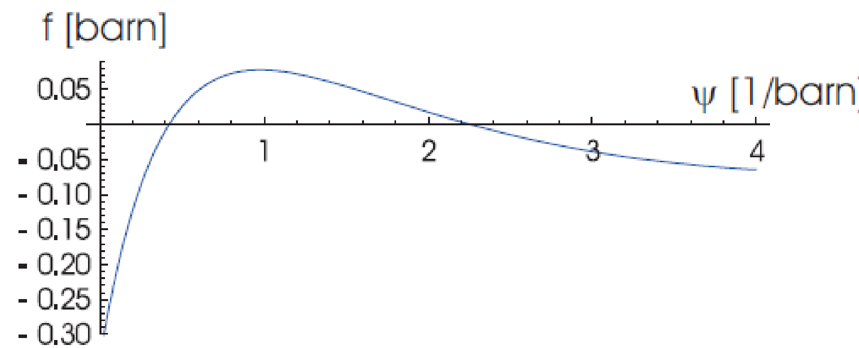
❑ Results and Discussion (2/6)

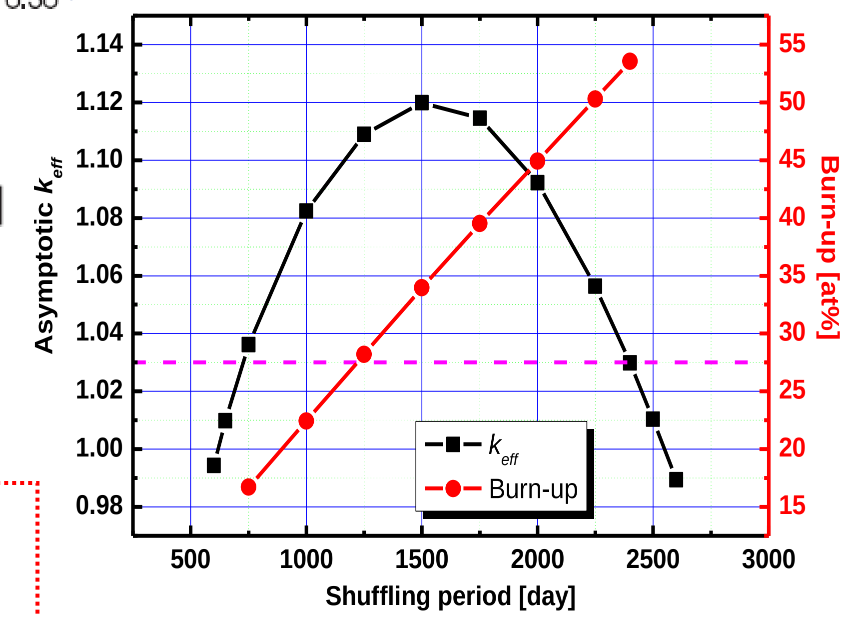
➢ **1-D axial shuffling calculation**



$$g(\psi) = \int_0^t f(\psi)\phi dt = \int_0^{\psi} f(\psi) d\psi$$

❖ The asymptotic k_{eff} varies with the shuffling period parabolically.

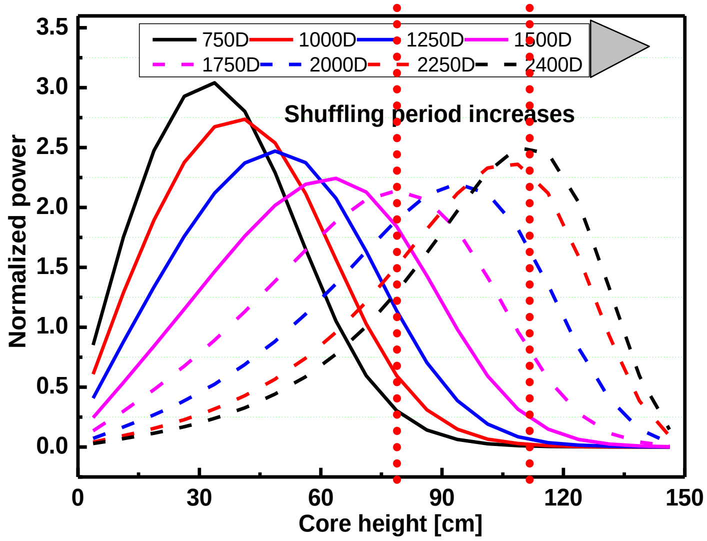




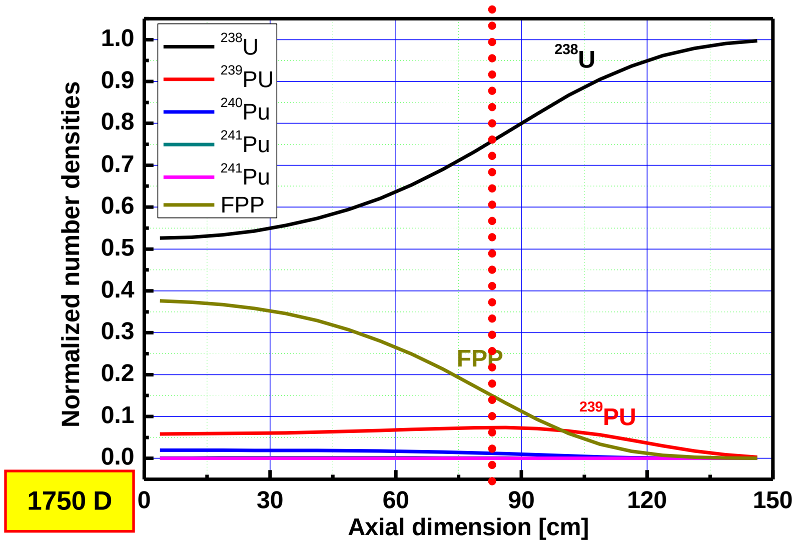
❖ The asymptotic burn-up linearly increases with the shuffling period.

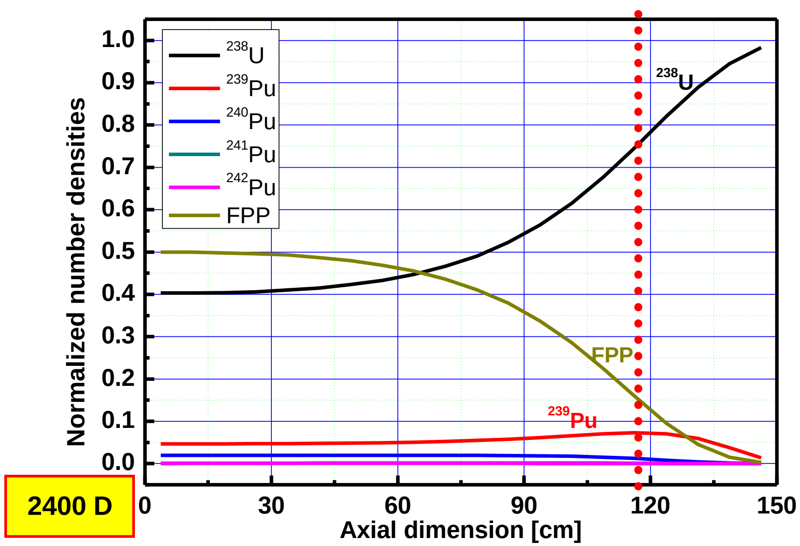
❑ Results and Discussion (3/6)

➢ 1-D axial shuffling calculation



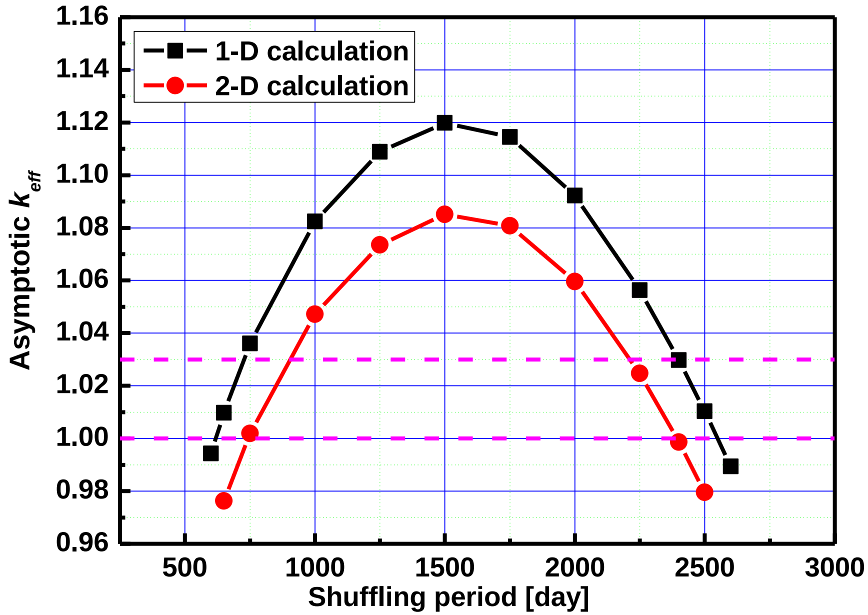
- Power peak shifts from the fuel outlet side to inlet side with the fuel shuffling period increasing.
- The peaking factor firstly decreases from 3.02 to 2.13 and then increases to 2.48.
- The peak of ^{239}Pu shifts to the fuel inlet side, and determines the location of the power peak.





❑ Results and Discussion (4/6)

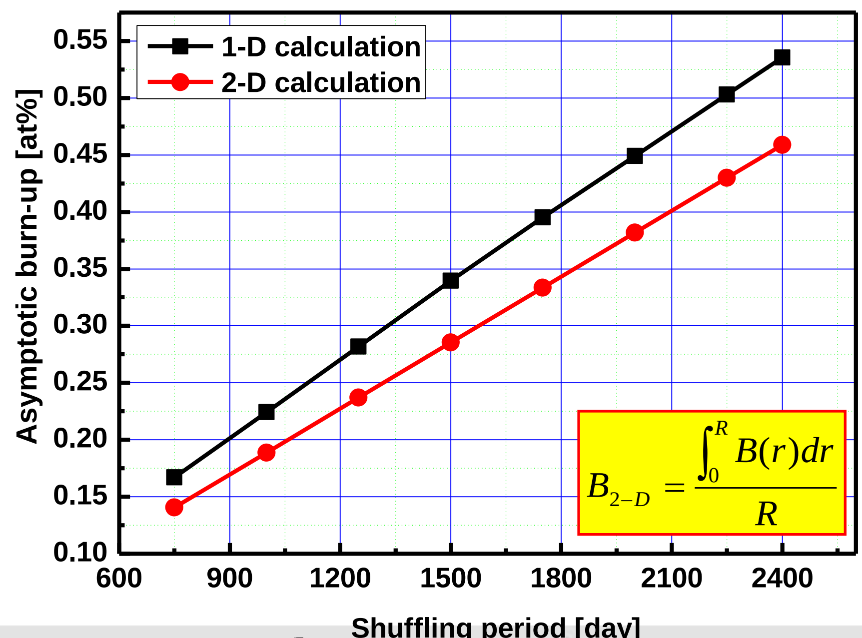
➢ 2-D axial shuffling calculation



$$k_{eff,2-D} = \frac{1+L^2 B^2_{g,1-D}}{1+L^2 B^2_{g,2-D}} k_{eff,1-D}$$

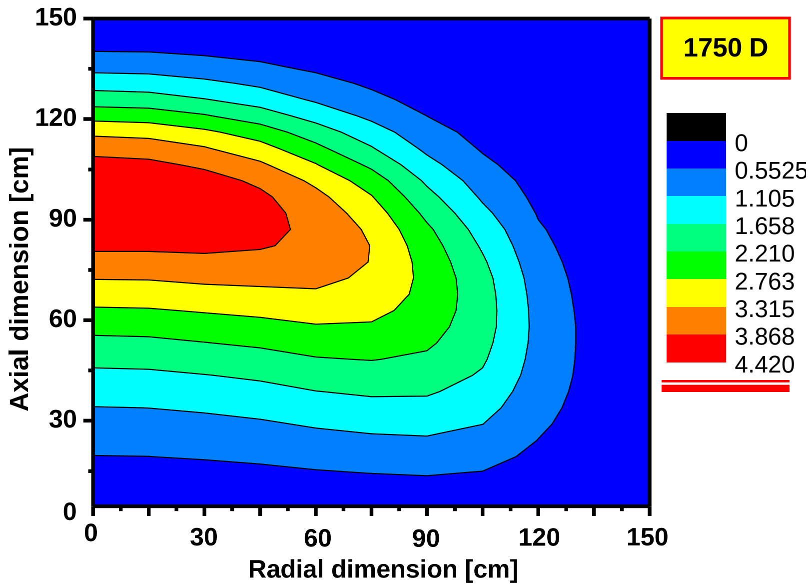
- ❖ The asymptotic k_{eff} decreases about 3% from 1-D case to 2-D case.
- ❖ The shuffling period between 750 and 2400 days can make core critical.

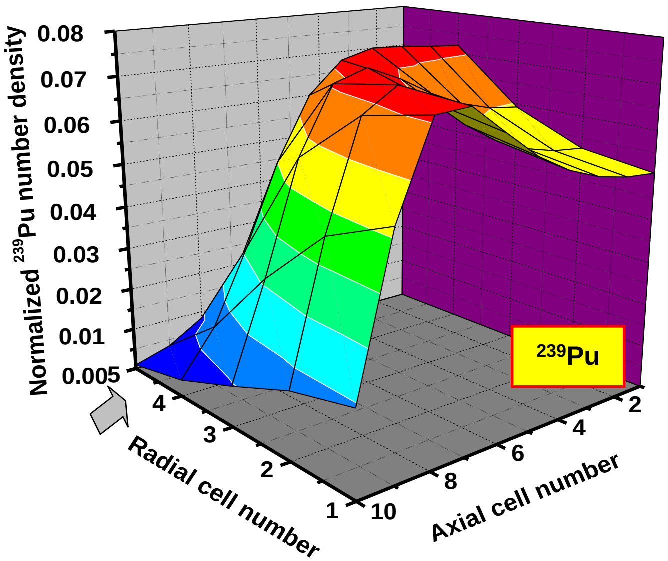
- ❖ The asymptotic burn-up still linearly increases with the shuffling period, but decreases about 15% from 1-D case to 2-D case.
- ❖ The maximal burn-up is 46at% in 2-D cases.

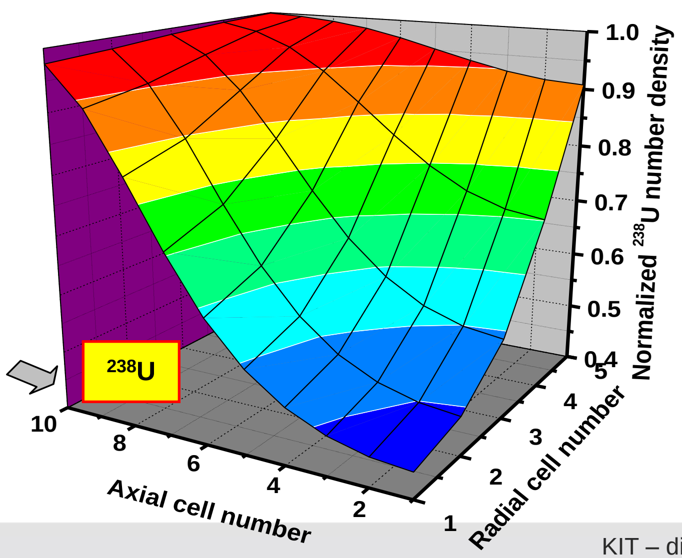


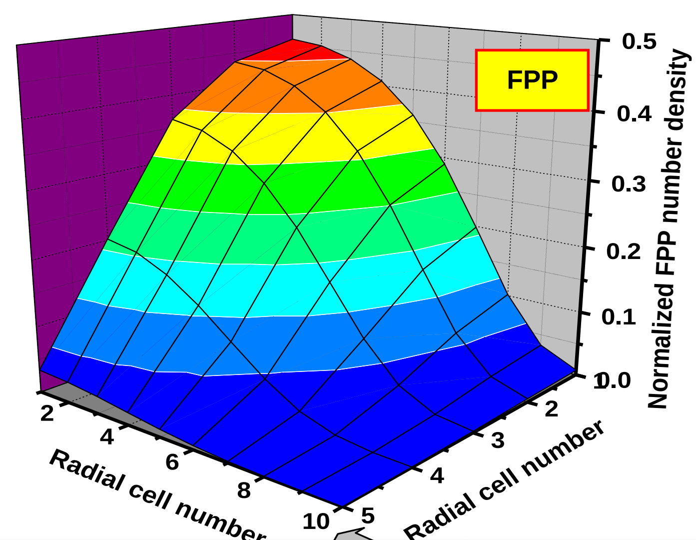
❑ Results and Discussion (5/6)

➢ 2-D axial shuffling calculation



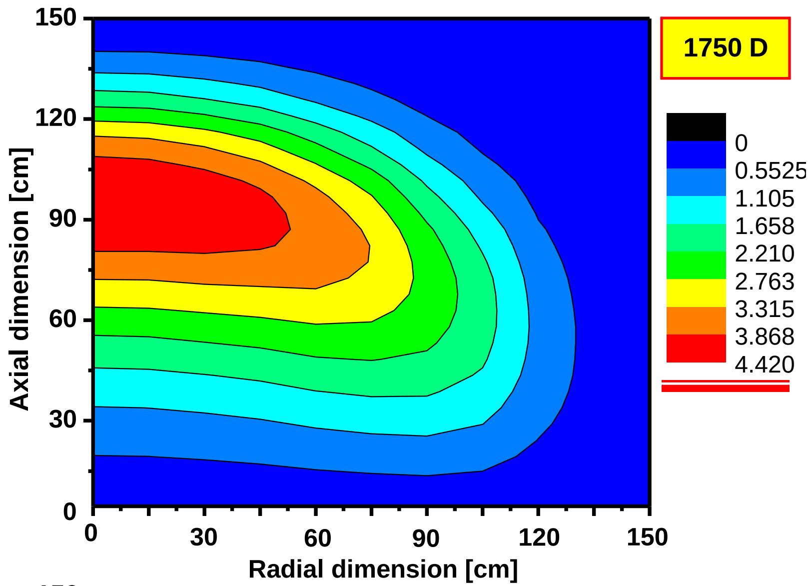


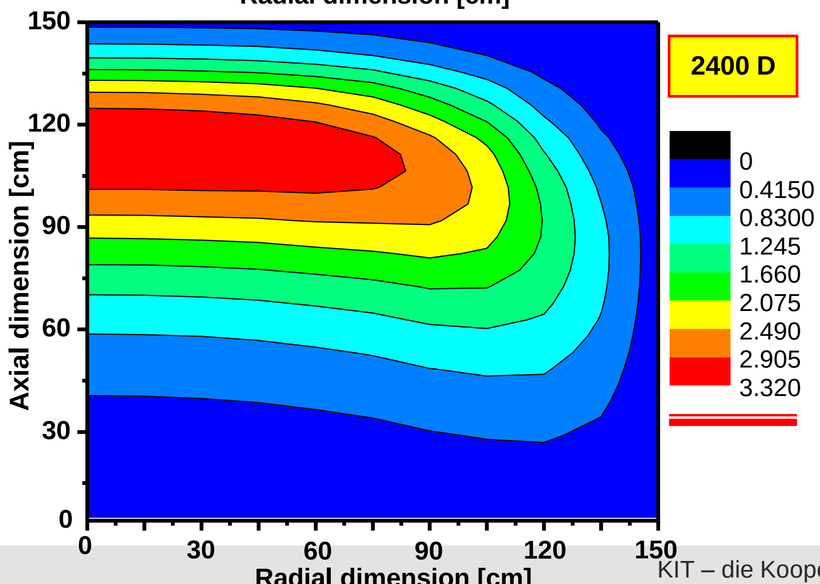




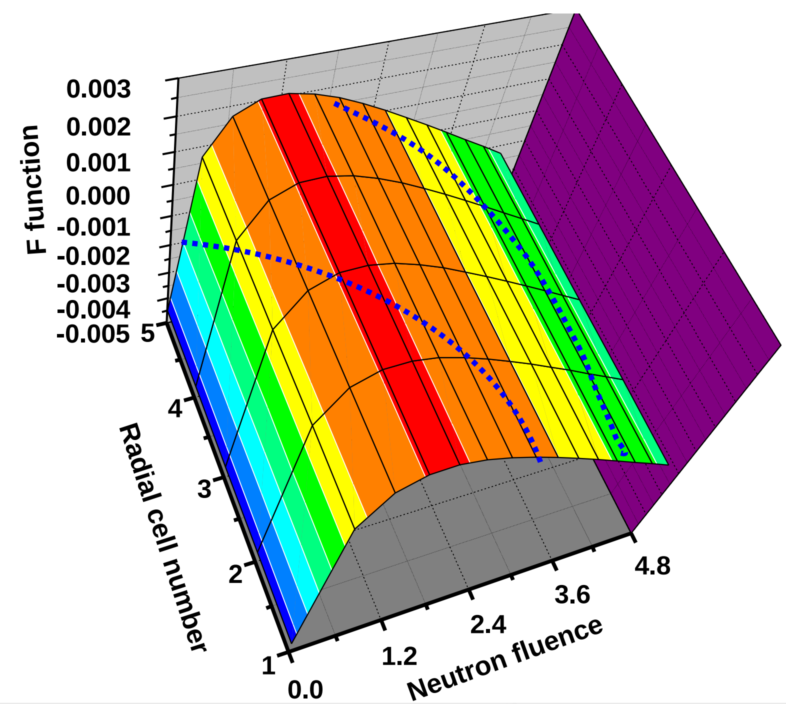
❑ Results and Discussion (6/6)

➢ 2-D axial shuffling calculation





- Power peak shifts from the fuel outlet side to inlet side with the fuel shuffling period increasing.
- The peaking factor decreases from 4.42 to 3.32 when the shuffling period increases from 1750 to 2400D.



Conclusions

- Axial shuffling calculation is set up for SFR with metallic ^{238}U fuel in 1-D and 2-D cases.
- The asymptotic k_{eff} parabolically varies with the shuffling period, while the burn-up increases linearly in both 1-D and 2-D cases.
- The asymptotic k_{eff} decreases about 3% from the 1-D case to 2-D case due to the radial buckling effects.
- The asymptotic burn-up decreases about 15% from 1-D case to 2-D case with the same shuffling period, and the highest burn-up achieved in 2-D case is 46at%.
- The power peak shifts from the fuel outlet side to the fuel inlet side in both 1-D and 2-D cases.
- The power shape distortion in 2-D case is observed, and the power peaking factor is much higher than that in 1-D case, but it decreases with the shuffling period increasing.

Thank you very much for your attention!

By: Dalin Zhang, Xue-Nong Chen, Fabrizio Gabrielli, Andrei Rineiski, Werner Maschek