A Study on Reconstruction of Intra Fuel Pin Power and Flux Distributions with the iDTMC method in the Monte Carlo Reactor Analyses

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Introduction

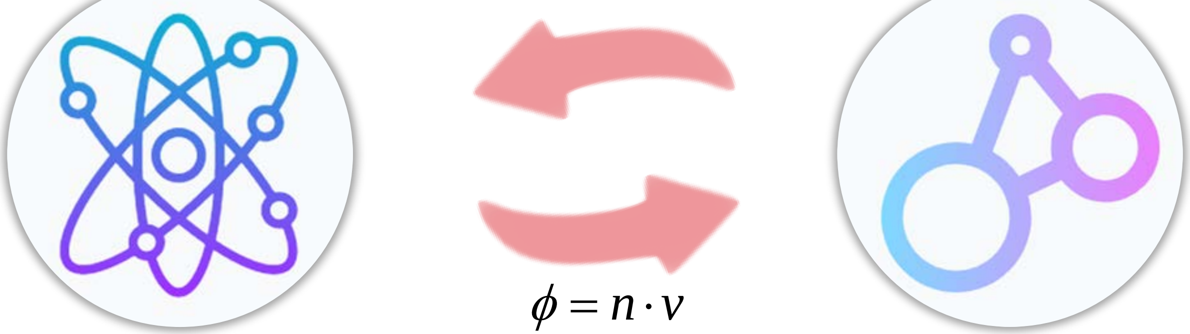
- **Depletion calculation in reactor problems**
  - **Economy** (core life time, excess reactivity…)
  - **Safety** (decay heat, spent fuel processing, …)

- **Monte Carlo method for the depletion calculation**
  - **Numerically expensive**
    - Time-consuming
      - » Sub-pin tallies (fuel pin should be axially and radially divided for exact evaluation)
      - » At least 3 rings for thermal reactors
      - » Even more than 5 rings for burnable absorbers
    - Large memory requirement
      - » Nuclear data for an amount of isotopes (> 100 isotopes)

Depletion calculation of a nuclear reactor

– **Nuclide property changes during a nuclear reactor operation**

$$\Sigma = N \cdot \sigma$$



$$\phi = n \cdot v$$

Transport

- ✓ Boltzmann equation
- ✓ Monte Carlo method
- ✓ Neutron flux calculation

Depletion

- ✓ Bateman equation
- ✓ CRAM method
- ✓ Materials & cross sections (number density, composition …)

Introduction

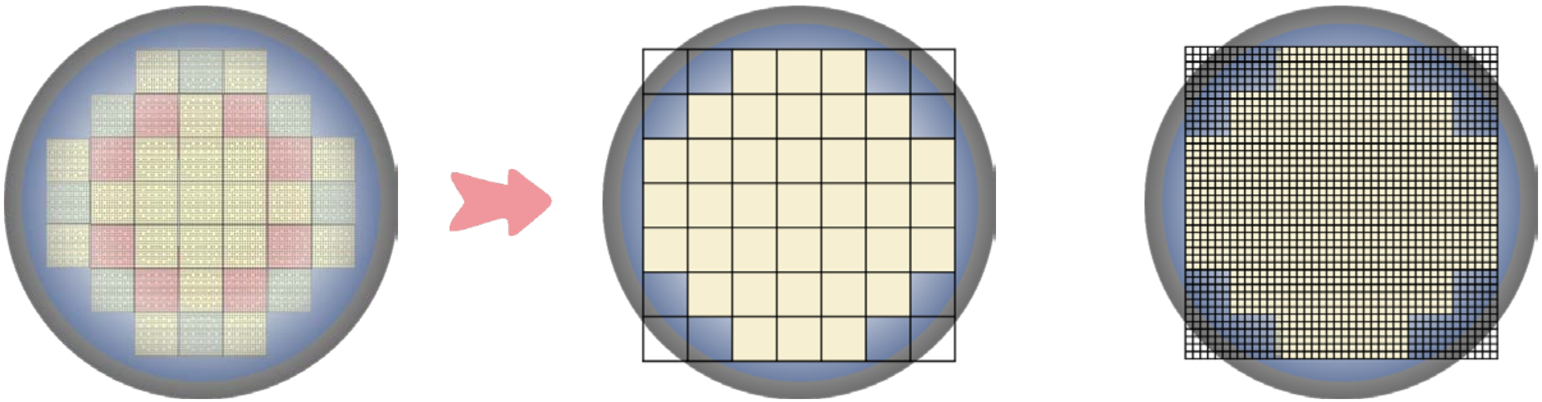
Coarse mesh finite difference (CMFD) method

– Solving the lower-order diffusion-like equation with the surface current correction
  - Fast and efficient deterministic calculation
  - MC-equivalent accuracy based on the generalized equivalent theory (GET)

– Unavailable to produce the detailed power distribution → radial direction : assembly size (~ 20 cm)

Pin-wise CMFD

– **Fine mesh grid to generate the detailed pin-wise homogenized power distribution**
  - Radial direction : pin size (~ 1 cm)
  - Axial direction : 10 – 15 cm

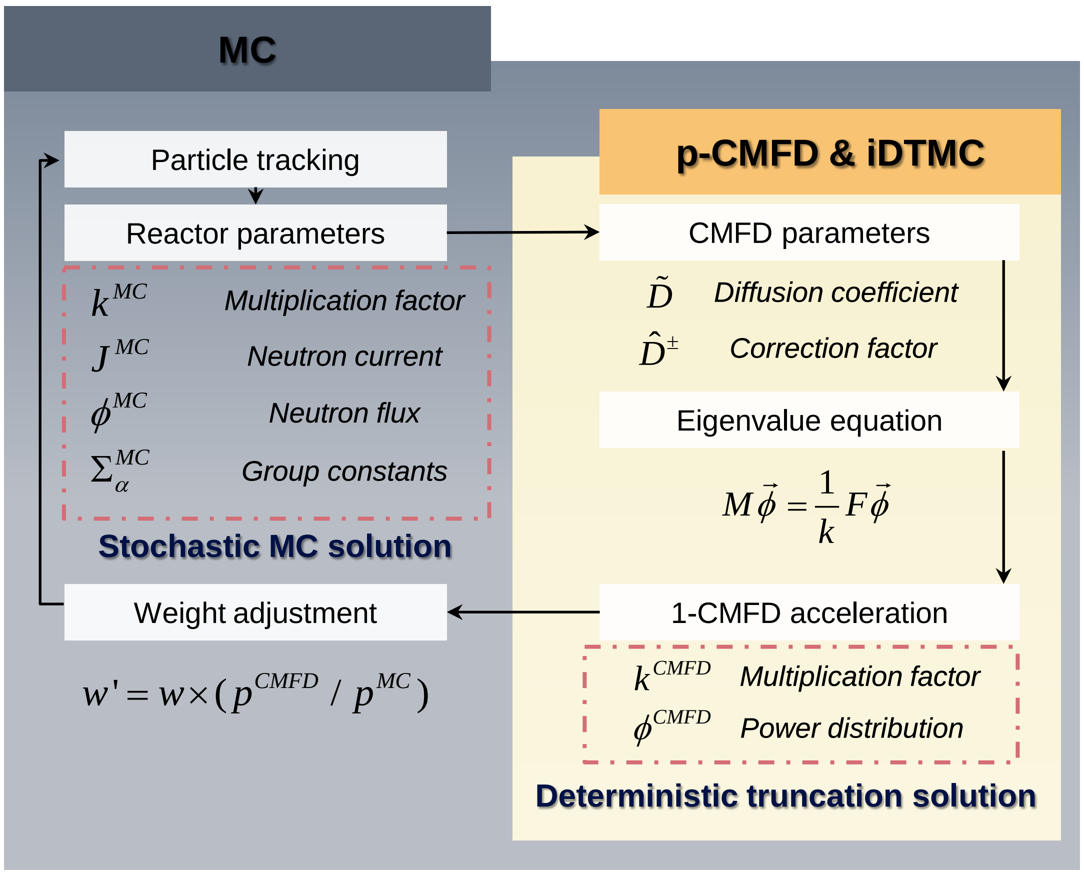


MC　　CMFD grid　　FMFD grid

Improved Deterministic Truncation of Monte Carlo solution method

– **A statistic treatment of deterministic solutions determined by CMFD-assisted MC**

- To accelerate the convergence of the fission source distribution by adjusting particles’ weight
- To provide a subset of solutions to the original MC approach



Deterministic solutions
truncated by MC simulation

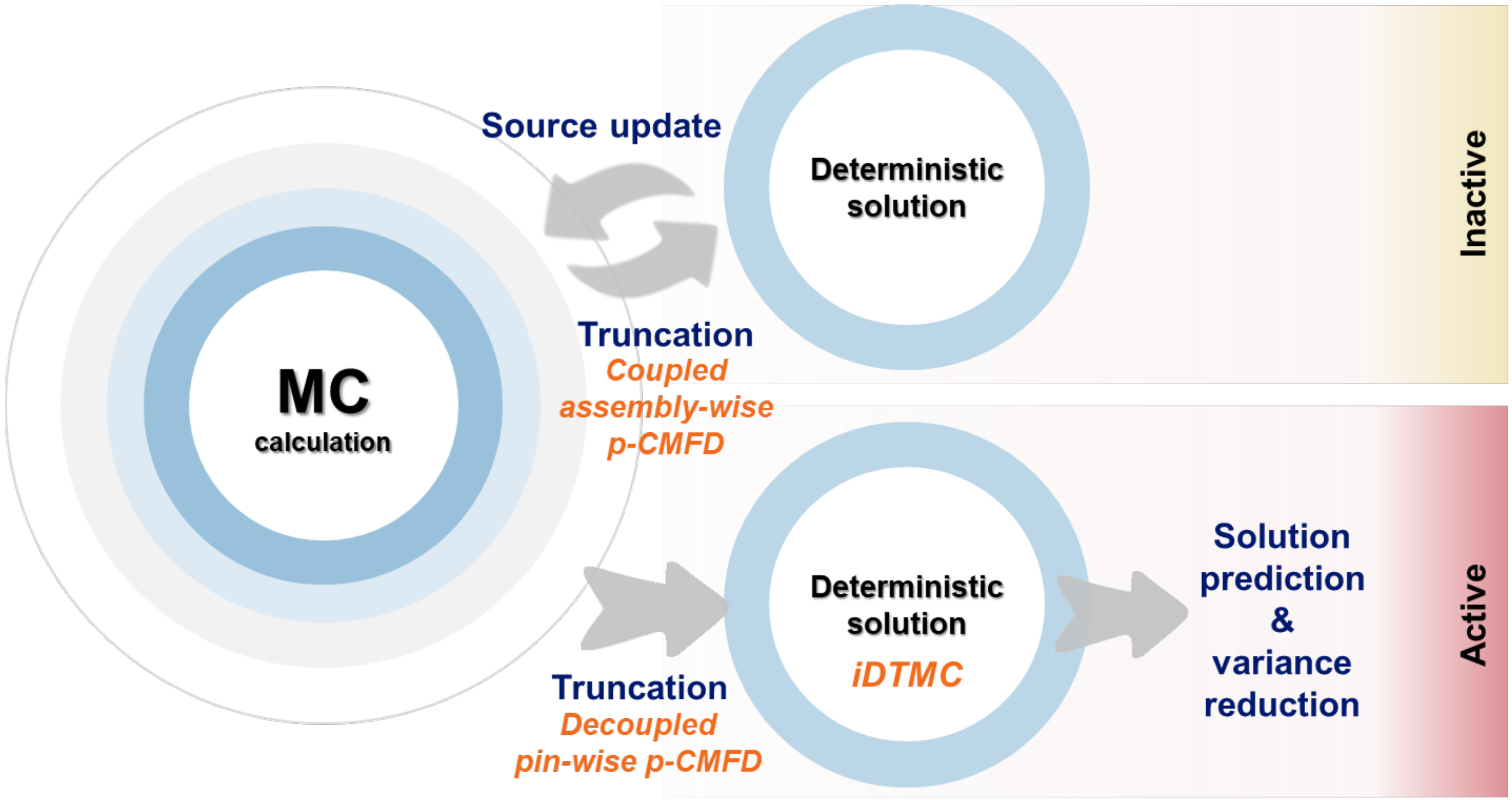
- ✓ *Short computing time*
- ✓ *Fast convergence of FSD*
- ✓ *Low uncertainty*
- ✓ *MC-equivalent solution*
  (High fidelity solution)

*CMFD : Coarse mesh difference method

iDTMC method

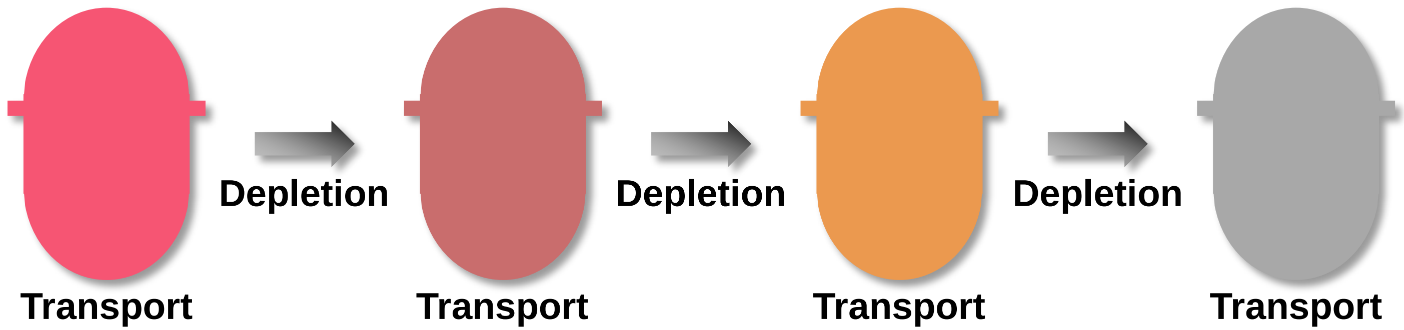
– **A statistic treatment of deterministic solutions determined by CMFD-assisted MC**

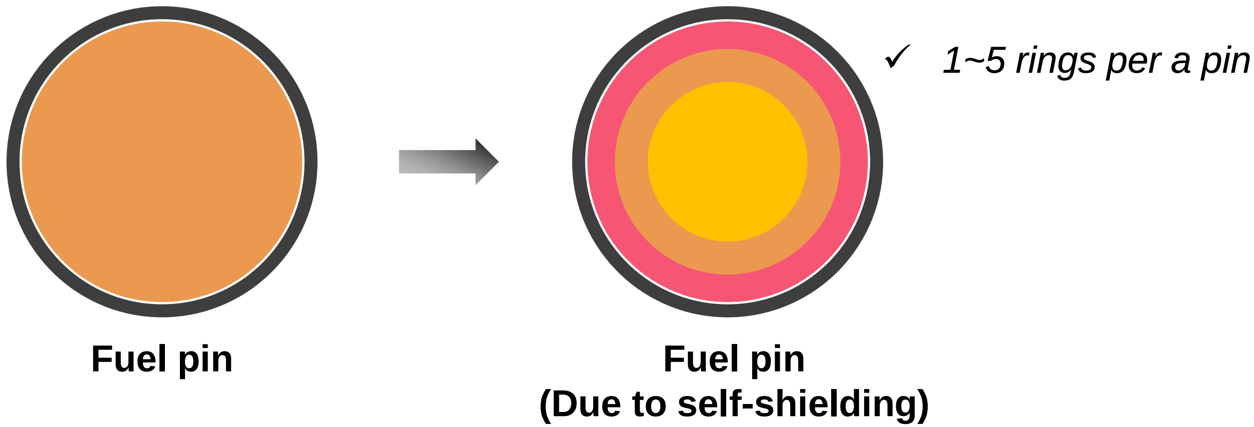
- To accelerate the convergence of the fission source distribution by adjusting particles' weight
- To provide a subset of solutions to the original MC approach



Depletion calculation of a nuclear reactor

– Eigenvalue calculation with intra pin-level tally calculation
  → Time-consuming & large memory

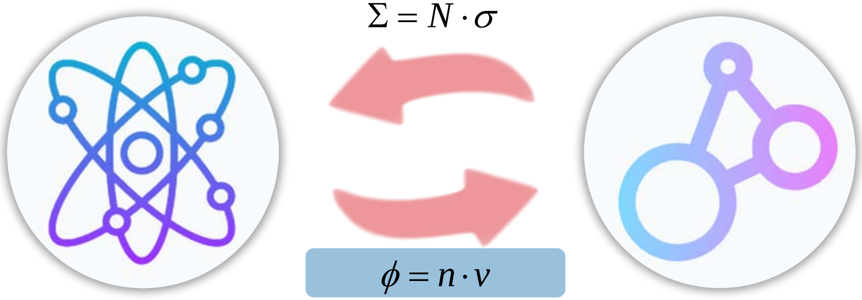




iDTMC application in the depletion calculation

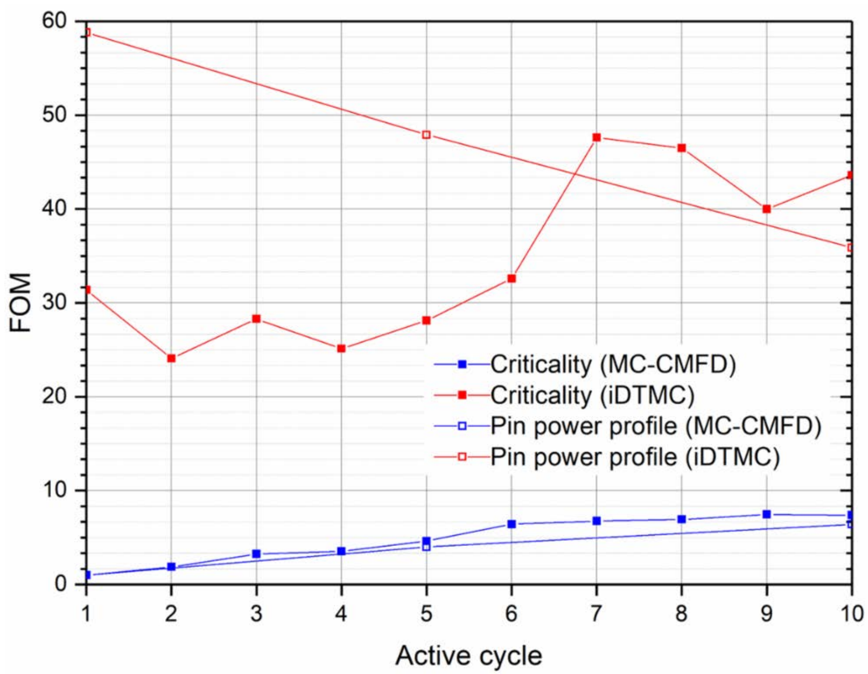
– **iDTMC method is very efficient for calculation of pin-resolved power distribution**

$$\Sigma = N \cdot \sigma$$



$$\phi = n \cdot v$$

Transport **iDTMC** **Depletion**



APR1400 problem (*Inhyung Kim, Doctoral thesis 2021*)

- 30 times higher FOM in k_{eff}
- 40 – 60 times higher FOM in pin power

than conventional p-CMFD accelerated MC method

Introduction

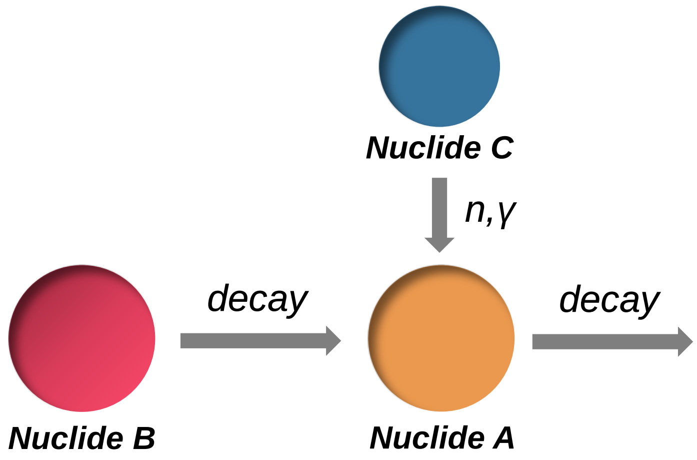
Depletion calculation of a nuclear reactor

– **Neutron transport equation**

$$\hat{\Omega}\cdot\nabla\phi(\vec{r},E,\hat{\Omega})+\Sigma_t(\vec{r},E)\phi(\vec{r},E,\hat{\Omega})=\frac{1}{4\pi}S_f(\vec{r},E)+\int_{\hat{\Omega}'}\int_{E'}\Sigma_s(\vec{r},E'\rightarrow E,\hat{\Omega}'\rightarrow\hat{\Omega})dE'd\hat{\Omega}'$$

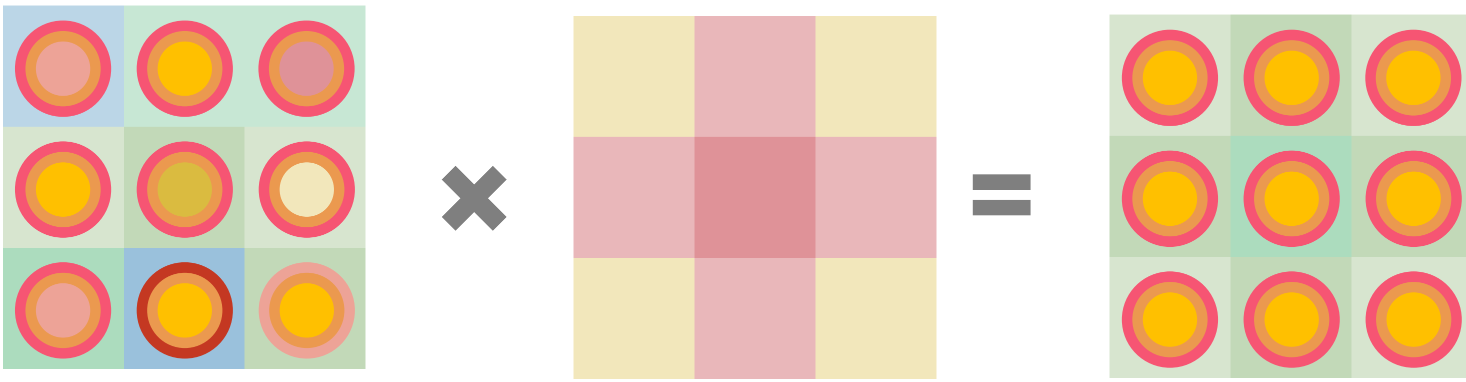
– **Bateman equation**

$$\frac{dN_A(t)}{dt}=-(\underbrace{\sigma_A^a\phi}_{\text{Reaction}}+\underbrace{\lambda_A}_{\text{Decay}})N_A(t)+\underbrace{\sigma_C^\gamma\phi N_c(t)}_{\text{Reaction}}+\underbrace{\lambda_B N_B(t)}_{\text{Decay}}$$



iDTMC application in the depletion calculation

– **iDTMC method : square-lattice based calculation**



Intra-pin MC tally iDTMC solution Flux distribution

iDTMC application in the depletion calculation

– **Form function (MC)**

*Normalized for average to be unity

$$ff_{i,r} = \frac{p_{i,r}^{MC}}{\sum_{r}^{N_r} p_{i,r}^{MC} / N_r}$$

where
i : pin node index
r : ring node index
$p^{MC} = \kappa\Sigma_f \phi V$
N_r : No. of rings

– **Flux distribution (iDTMC)**

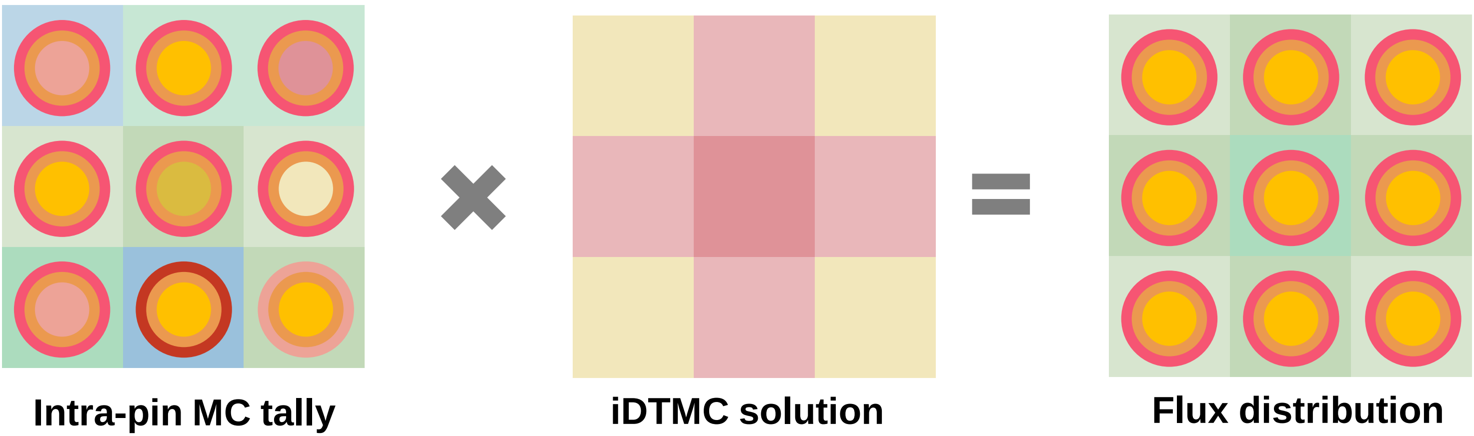
Total reactor power $$P = C \cdot \sum_i \kappa\Sigma_f^i \phi_i^{DTMC} V_i$$

Normalization factor $$C = \frac{P\ [MW]}{\sum_i \kappa\Sigma_f^i \phi_i^{DTMC} V_i\ [MeV]} / 1.602E-19$$

$$\phi_i^{DTMC'} = C \cdot \phi_i^{DTMC}$$

iDTMC application in the depletion calculation

– **Intra-pin power reconstruction**

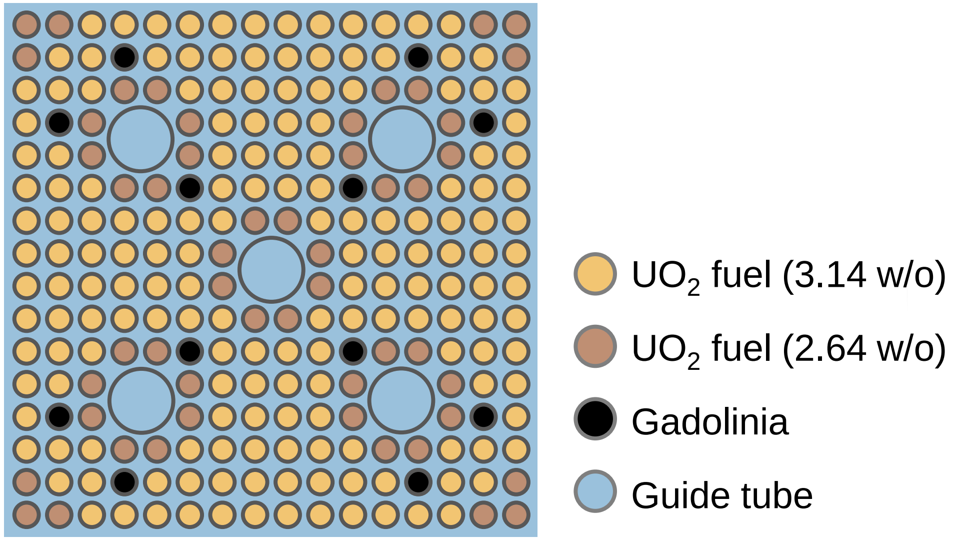


$$ff_{i,r} \times \phi_i^{DTMC'} = \phi_{i,r}$$

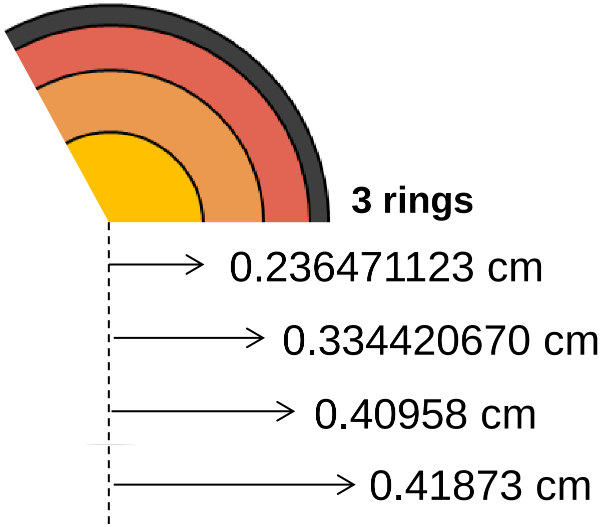
Numerical Results

APR1400 fuel assembly

- 16 x 16 array (fuel, zoned fuel, burnable absorber, guide tube, instrumentation tube)
- 3 rings per a pin cell
- All reflective BC
- FMFD (iDTMC) mesh : 16 X 16 X 1
- Power : 10 MW
- 10 inactive cycles
- 10 active cycles
- 10,000 histories per cycle

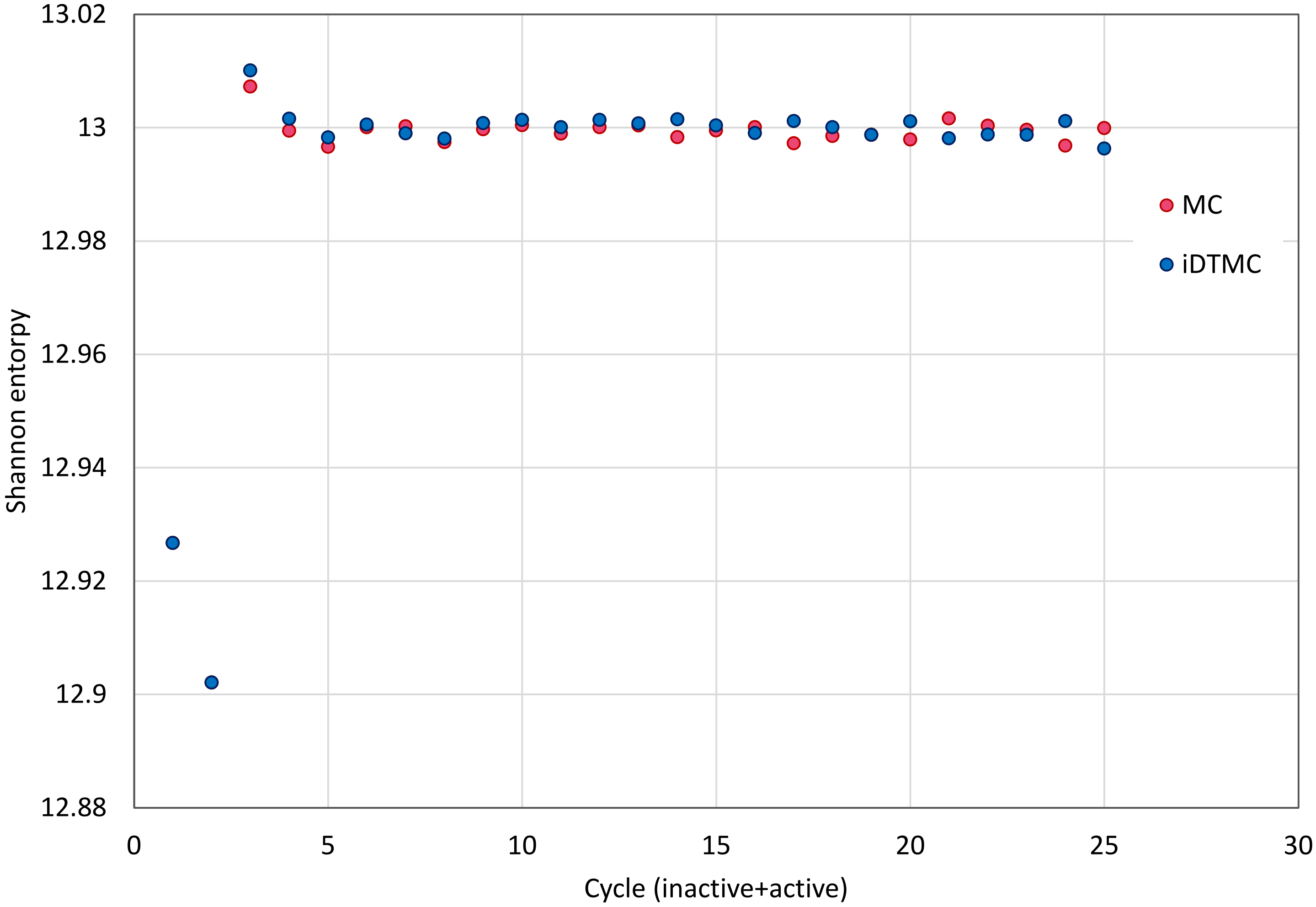


Type B1 fuel assembly



Numerical Results

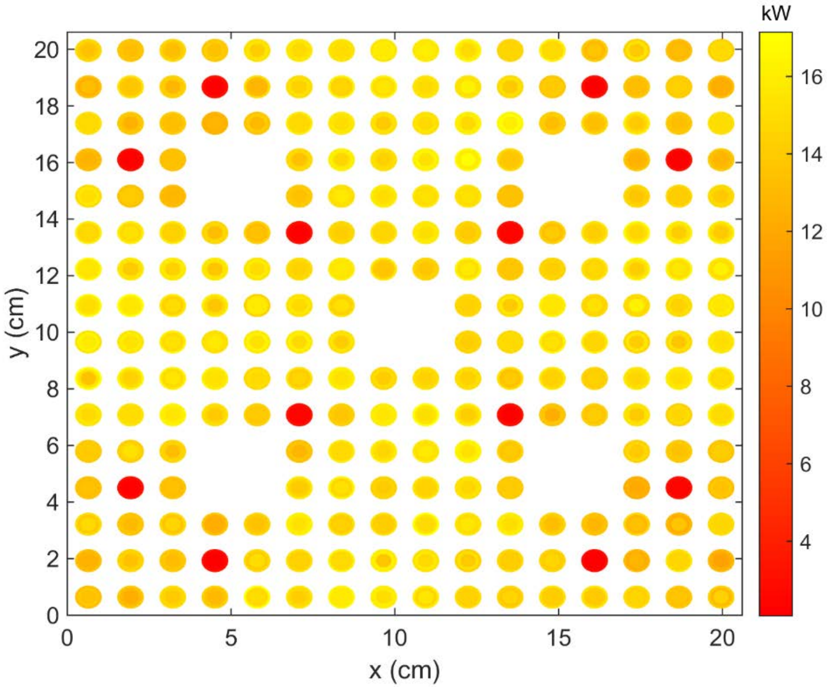
FSD convergence



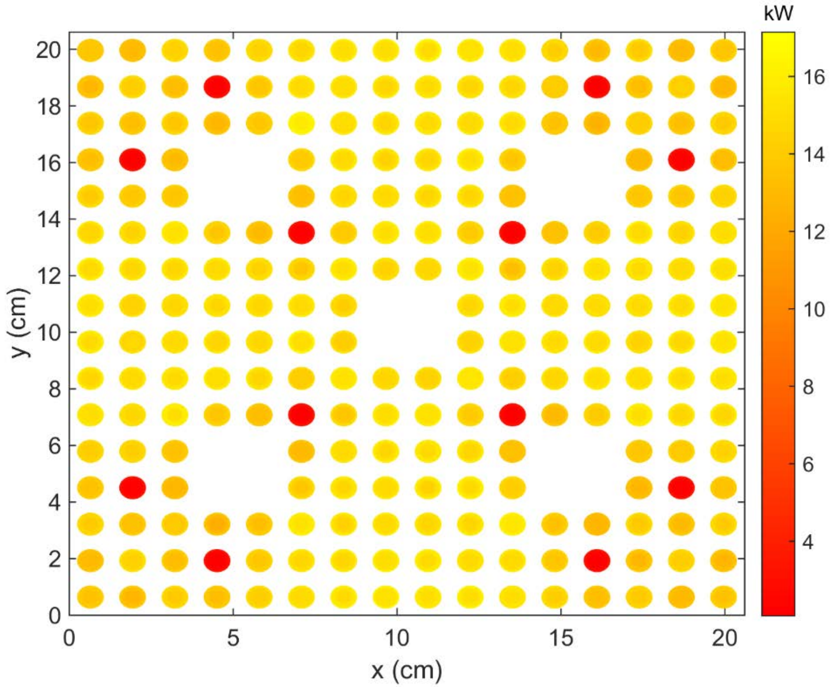
Numerical Results

Pin power distribution

– **Cycle 1**



MC

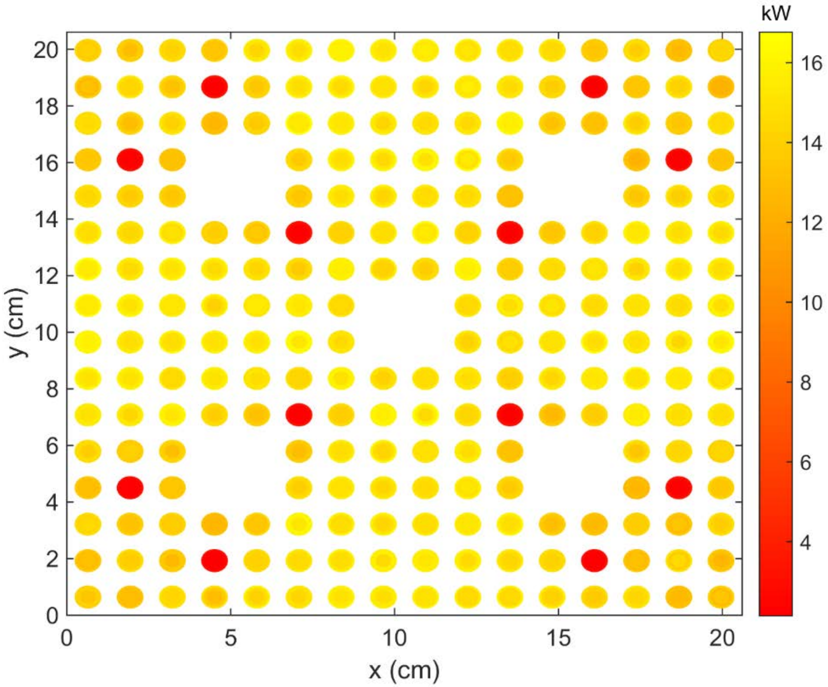


iDTMC

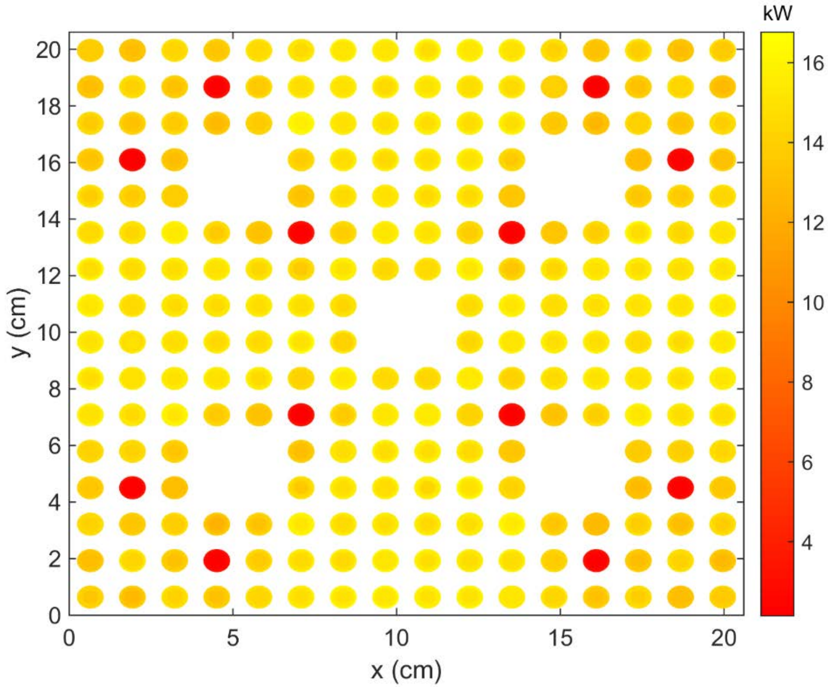
Numerical Results

Pin power distribution

– **Cycle 3**



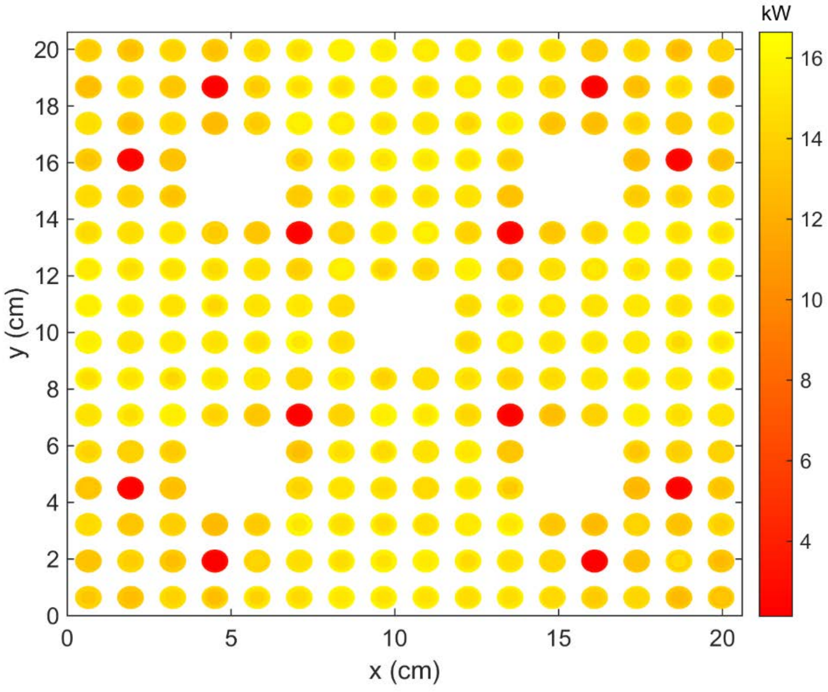
MC



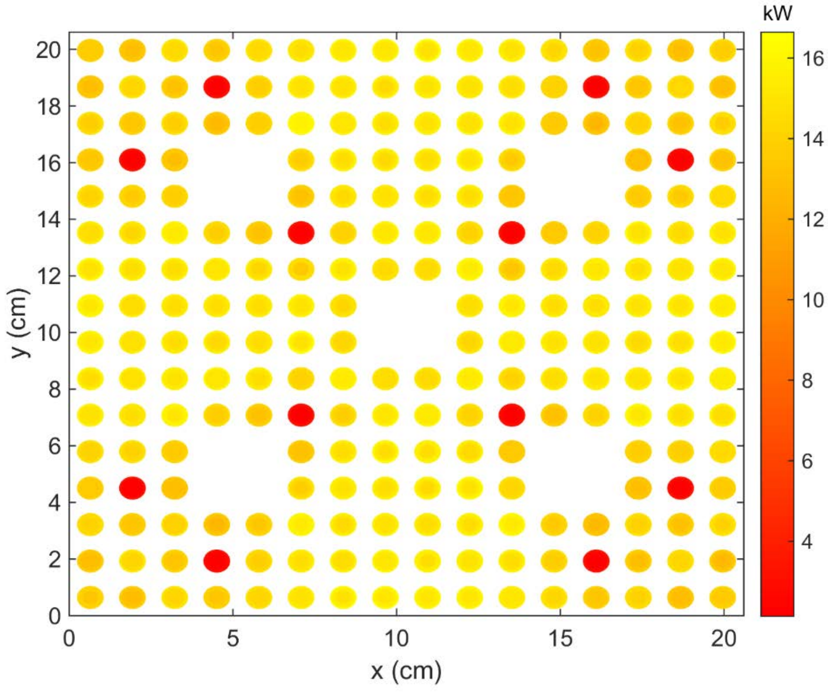
iDTMC

Pin power distribution

– **Cycle 5**



MC

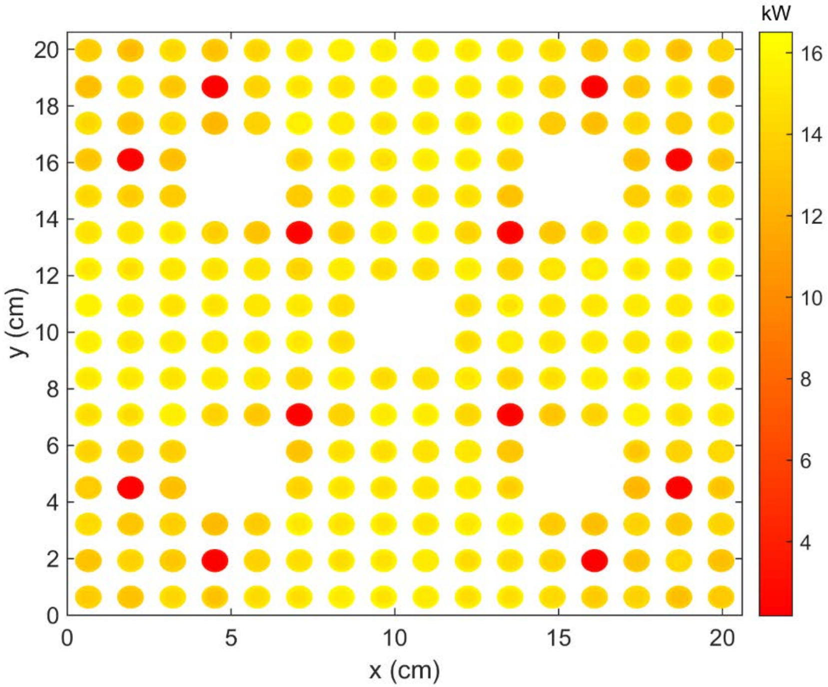


iDTMC

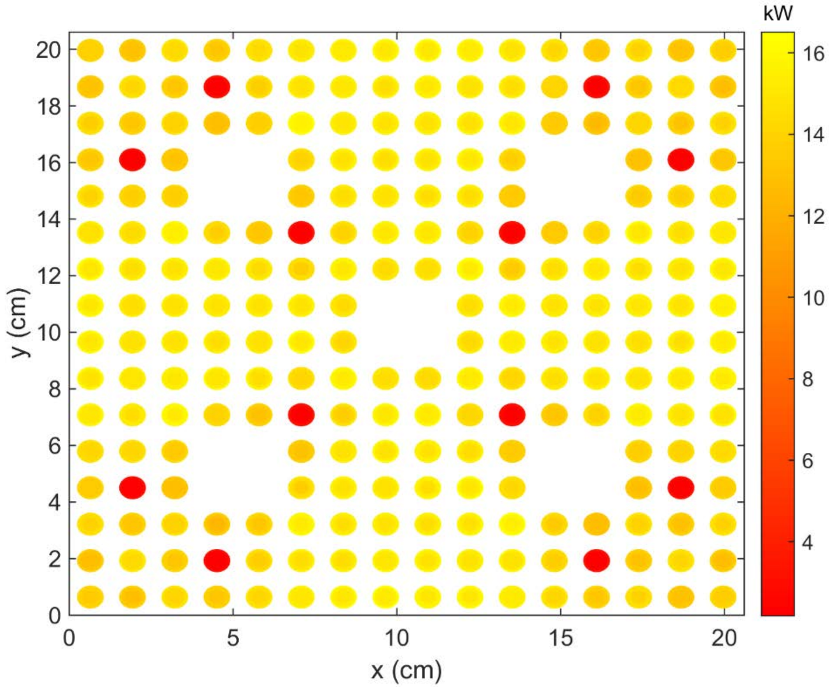
Numerical Results

Pin power distribution

– **Cycle 10**



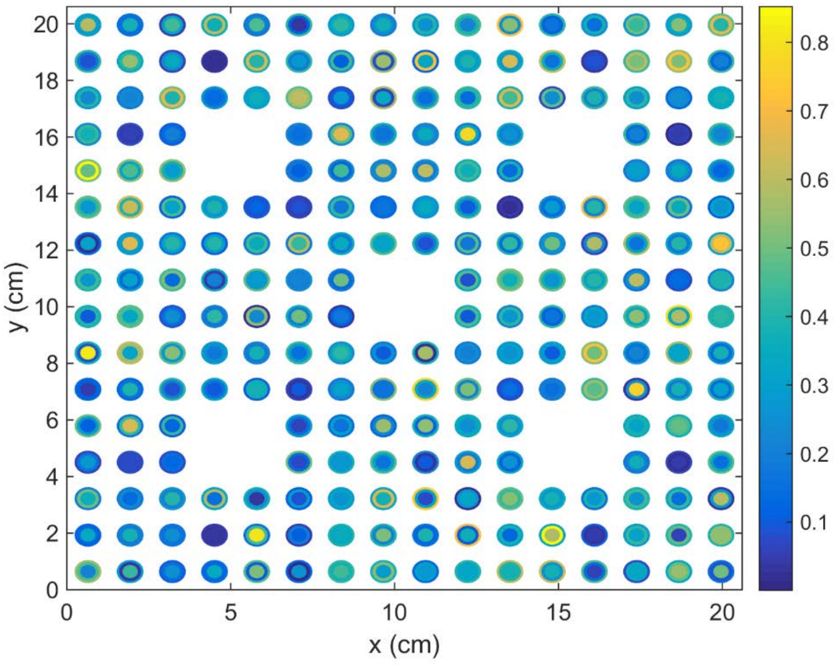
MC



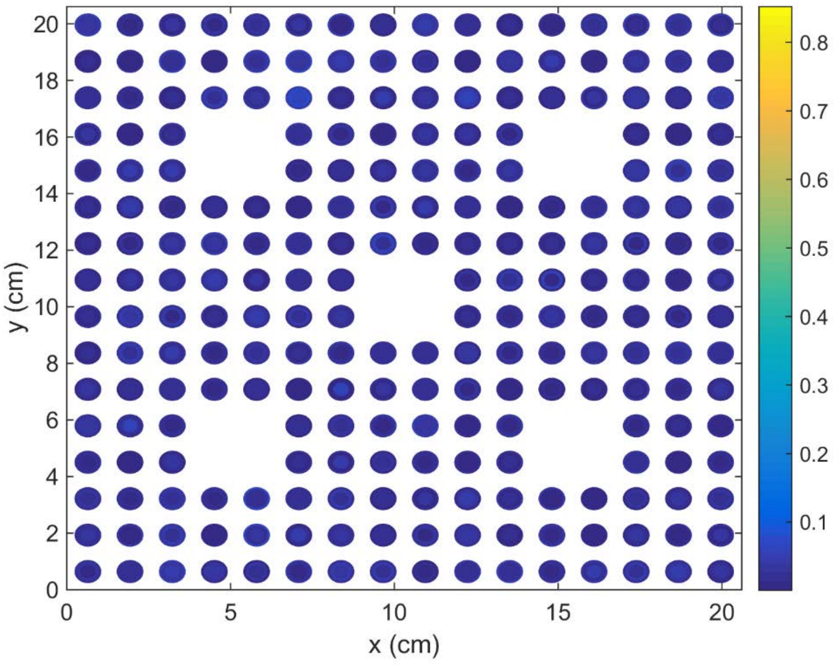
iDTMC

SD of Pin power distribution

– **Cycle 3**



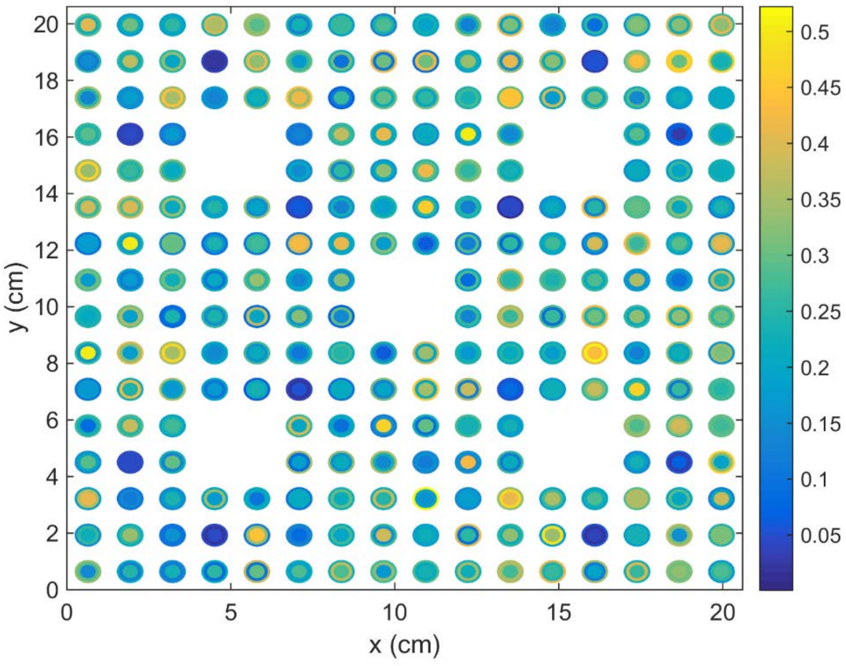
MC



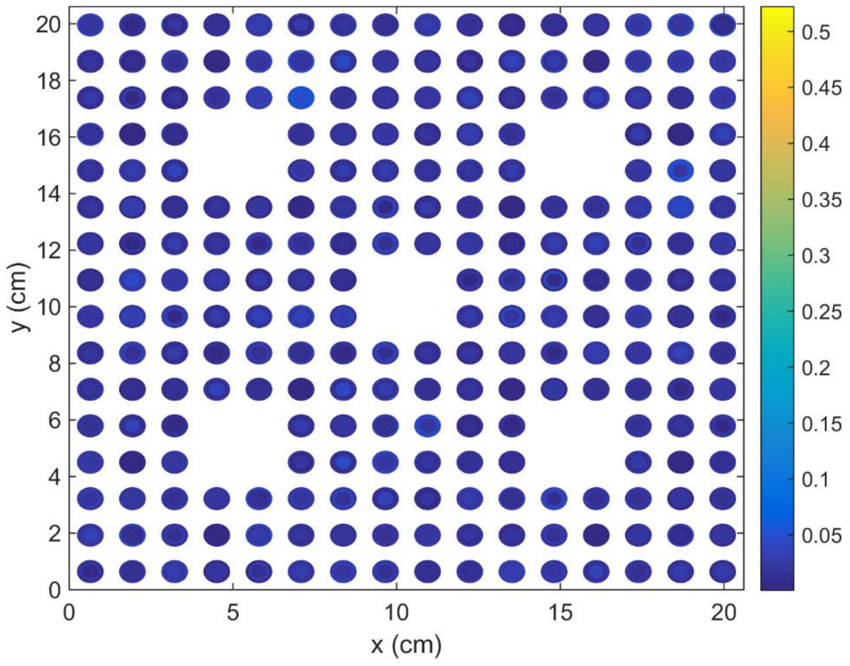
iDTMC

SD of Pin power distribution

– **Cycle 5**



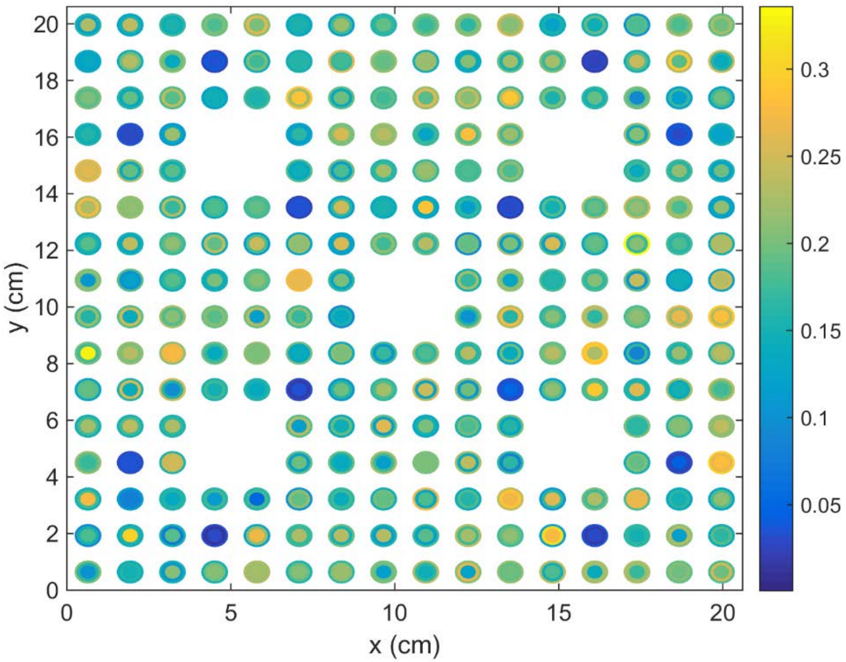
MC



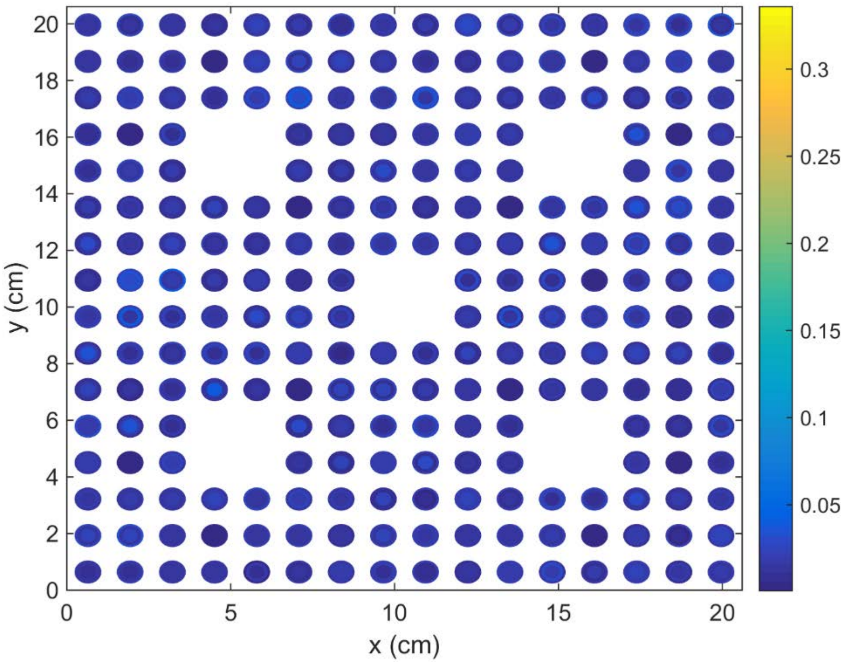
iDTMC

SD of Pin power distribution

– **Cycle 10**



MC

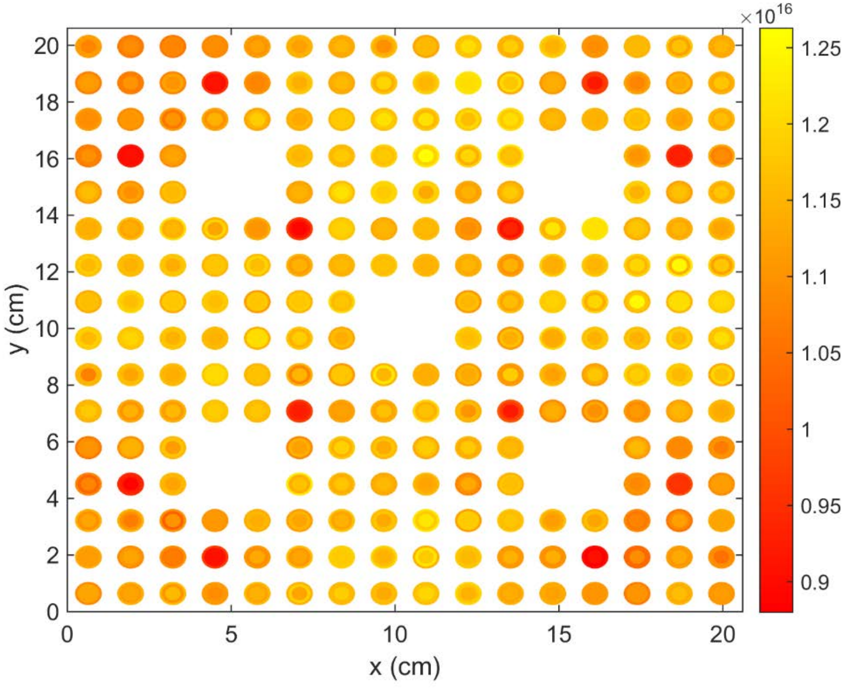


iDTMC

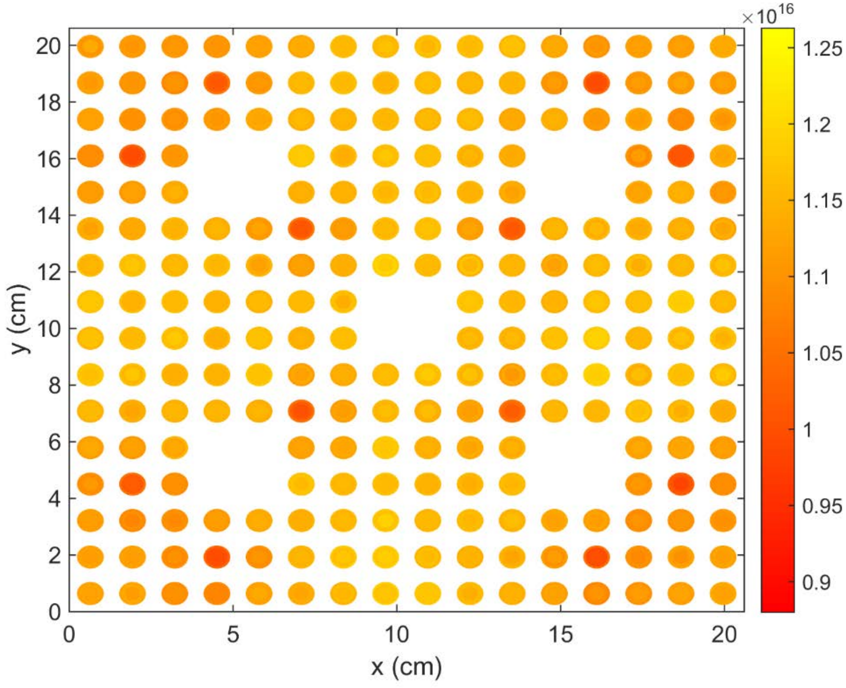
Numerical Results

Flux distribution

– **Cycle 1**



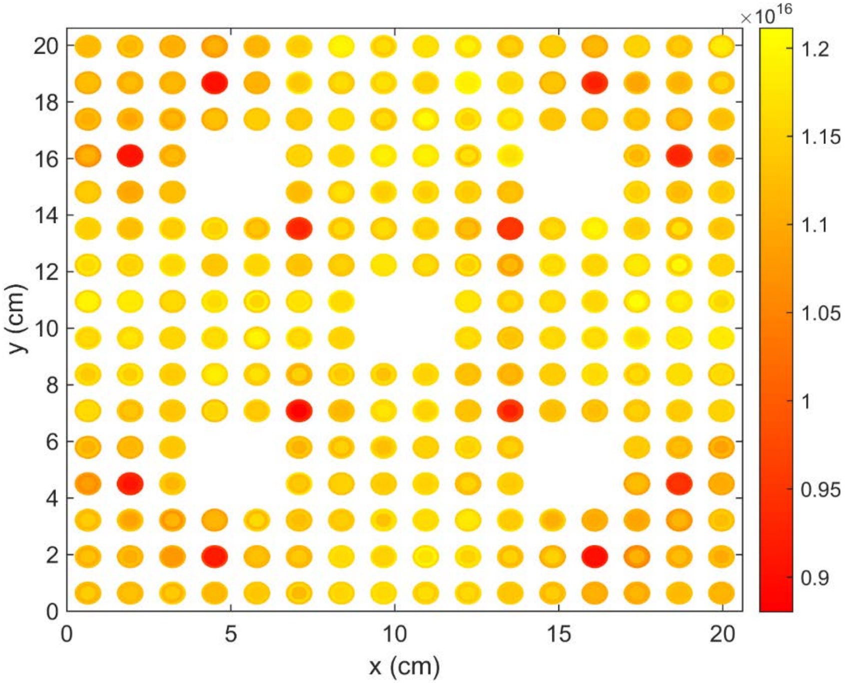
MC



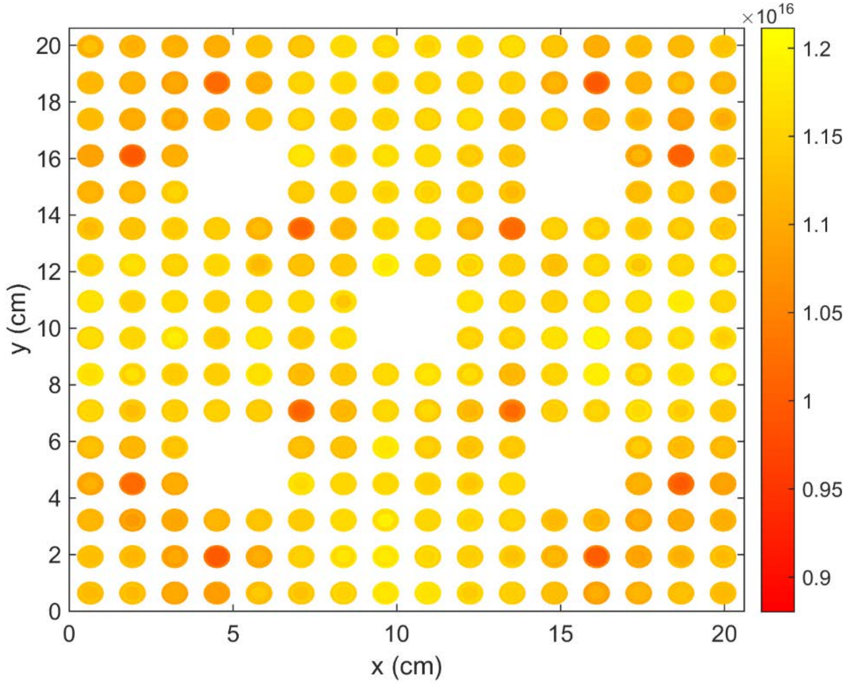
iDTMC

Flux distribution

– **Cycle 3**



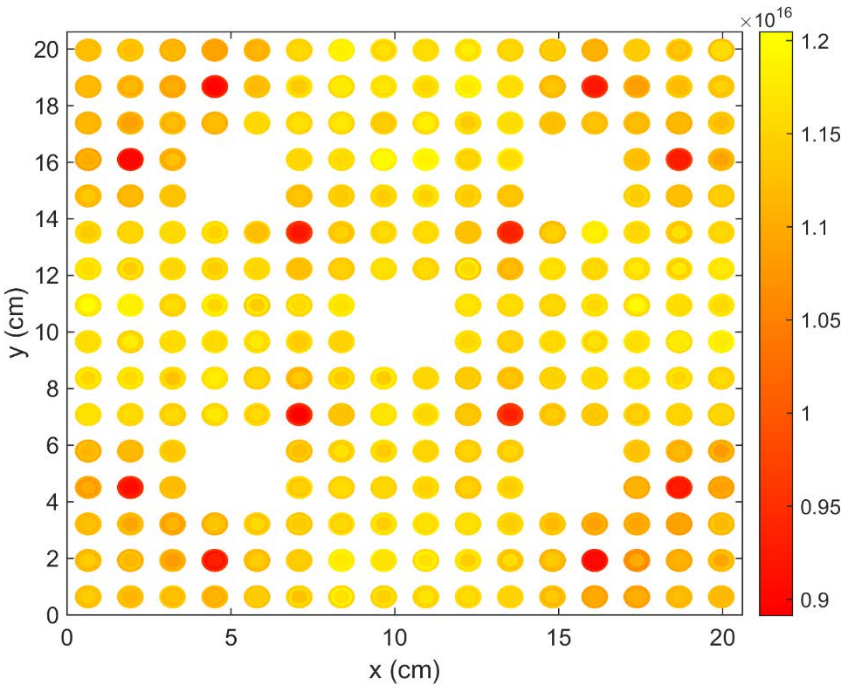
MC



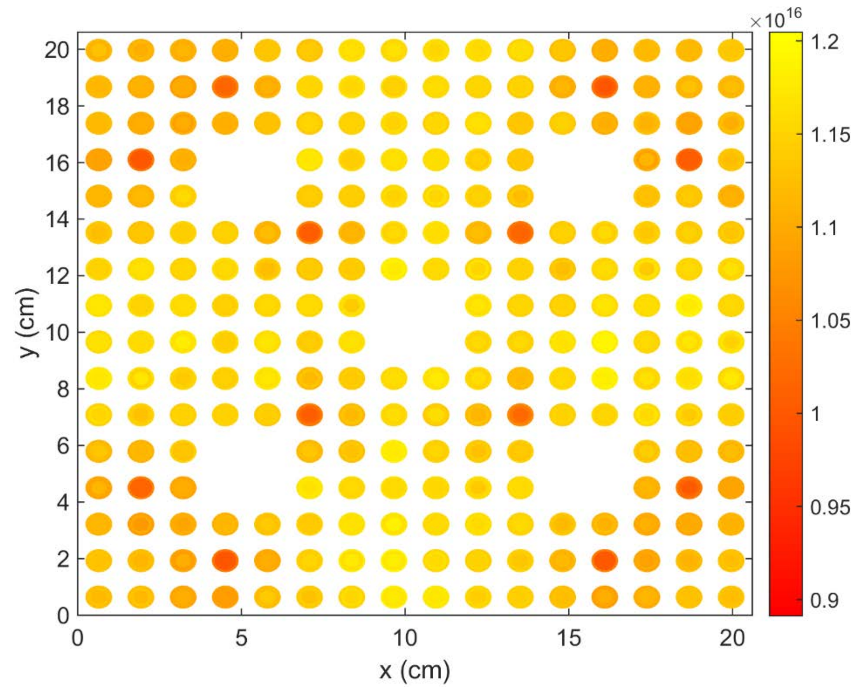
iDTMC

Flux distribution

– **Cycle 5**



MC

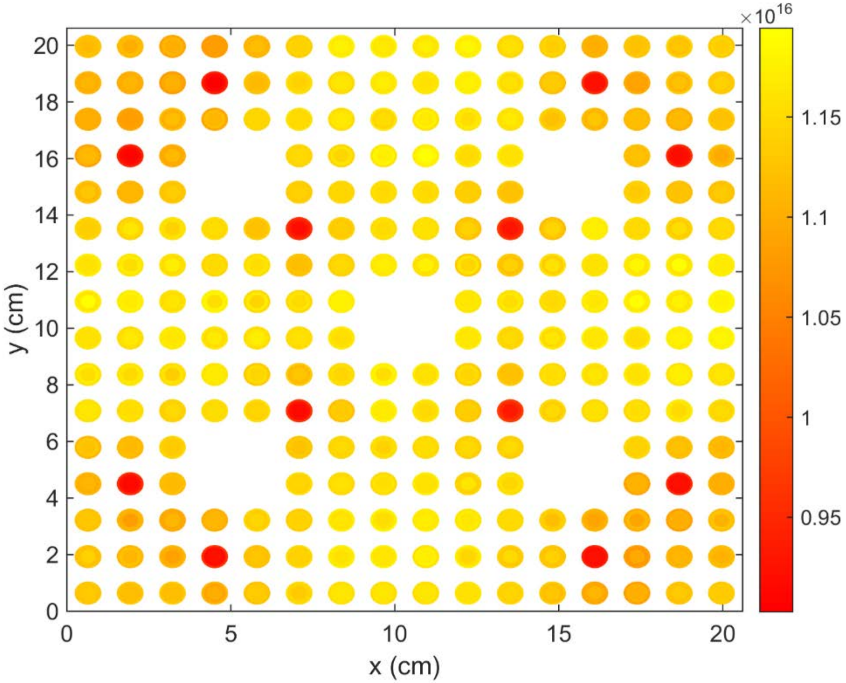


iDTMC

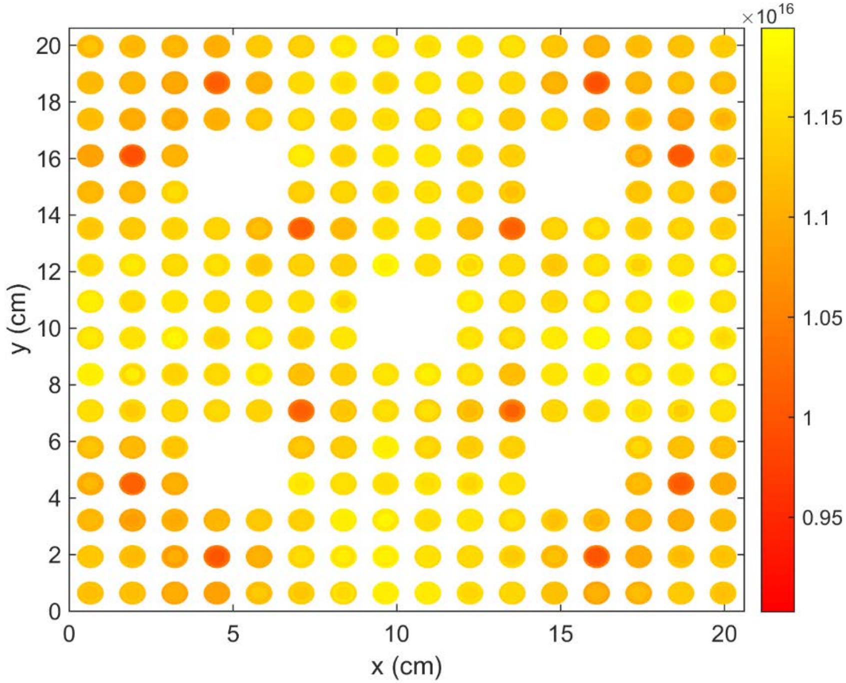
Numerical Results

Flux distribution

– **Cycle 10**



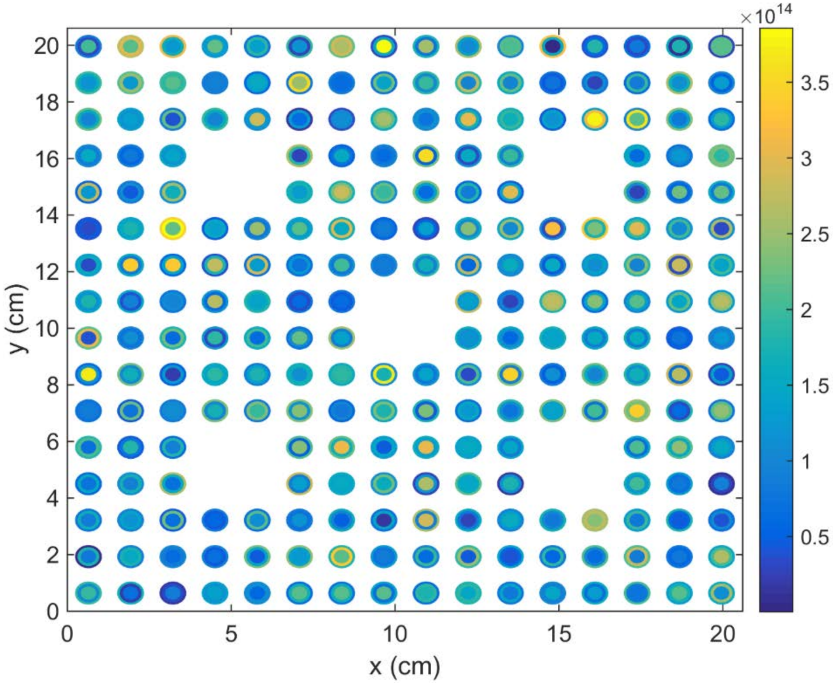
MC



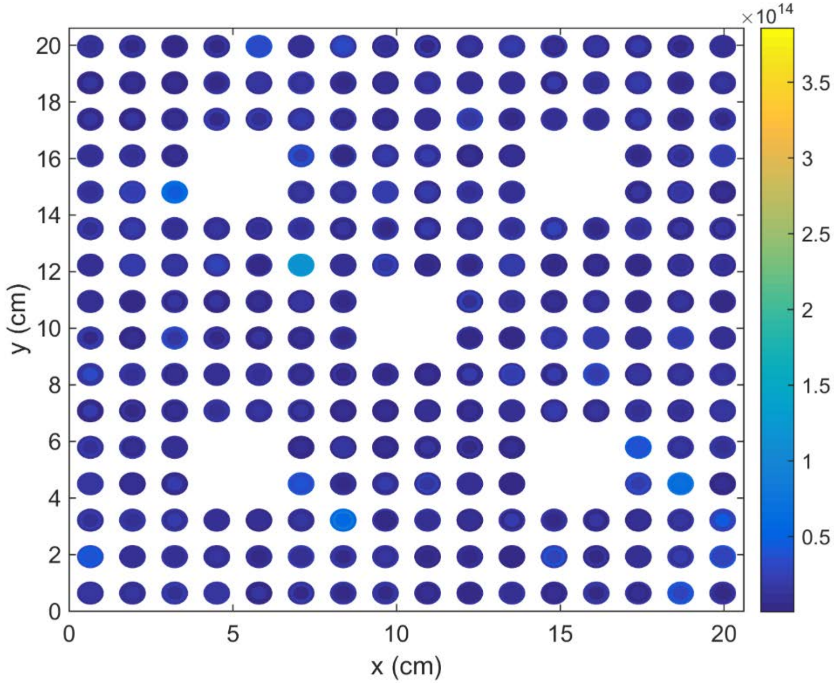
iDTMC

SD of flux distribution

– **Cycle 3**



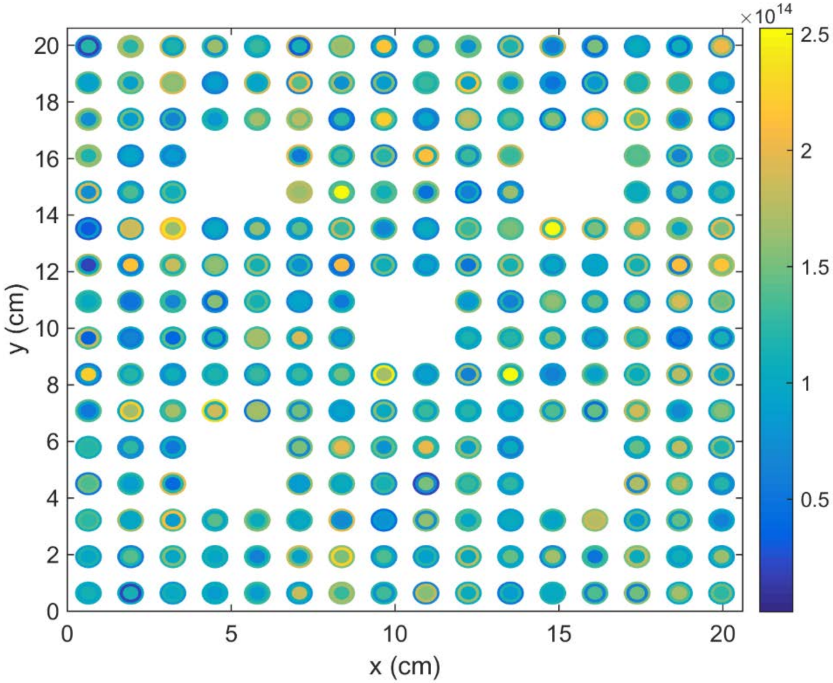
MC



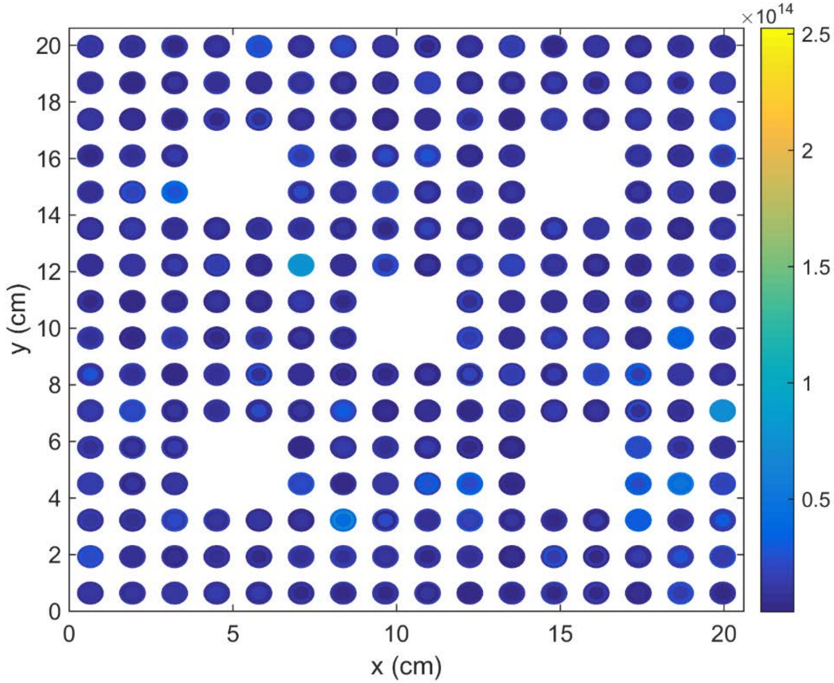
iDTMC

SD of flux distribution

– **Cycle 5**



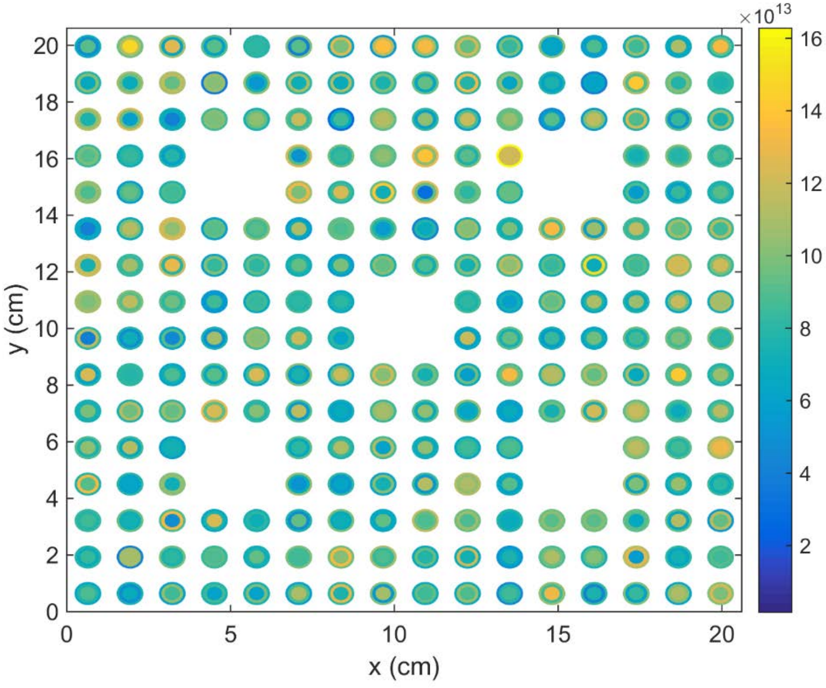
MC



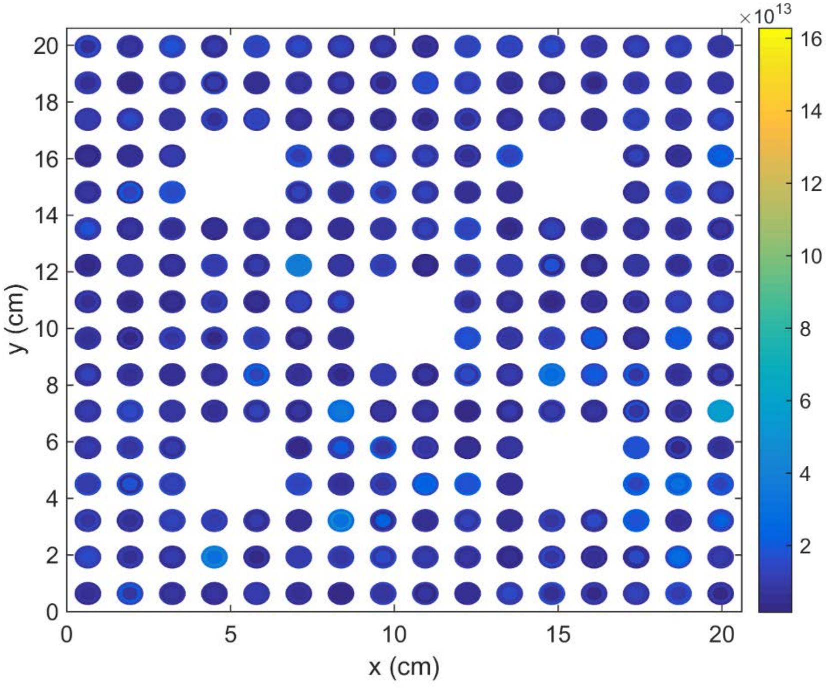
iDTMC

SD of flux distribution

– **Cycle 10**



MC



iDTMC

Numerical Results

Average of standard deviation of intra pin power

Cycle	Power		Flux	
	MC	iDTMC	MC	iDTMC
3	0.181	0.013	8.2E+13	1.2E+13
5	0.115	0.010	5.1E+13	9.8E+12
10	0.071	0.008	3.1E+13	6.9E+12

Concluding Remarks

Conclusions

– **Intra pin power profile has been generated with MC tallies corrected by iDTMC solutions**

– **The iDTMC method can provide accurate pin homogenized solutions**

– **The iDTMC method shows more reliable solutions for both the power and flux distribution compared to the conventional MC method**

  - The average standard deviation of the intra pin power distribution was about 10 times smaller in the iDTMC method
  - The average standard deviation of the intra pin flux distribution was about 5 times smaller in the iDTMC method

Future works

– **Depletion calculation with the pin-reconstruction scheme**

Thank you for your attention