Hyper-fidelity depletion coupled with discrete pebble motion in pebble bed reactors

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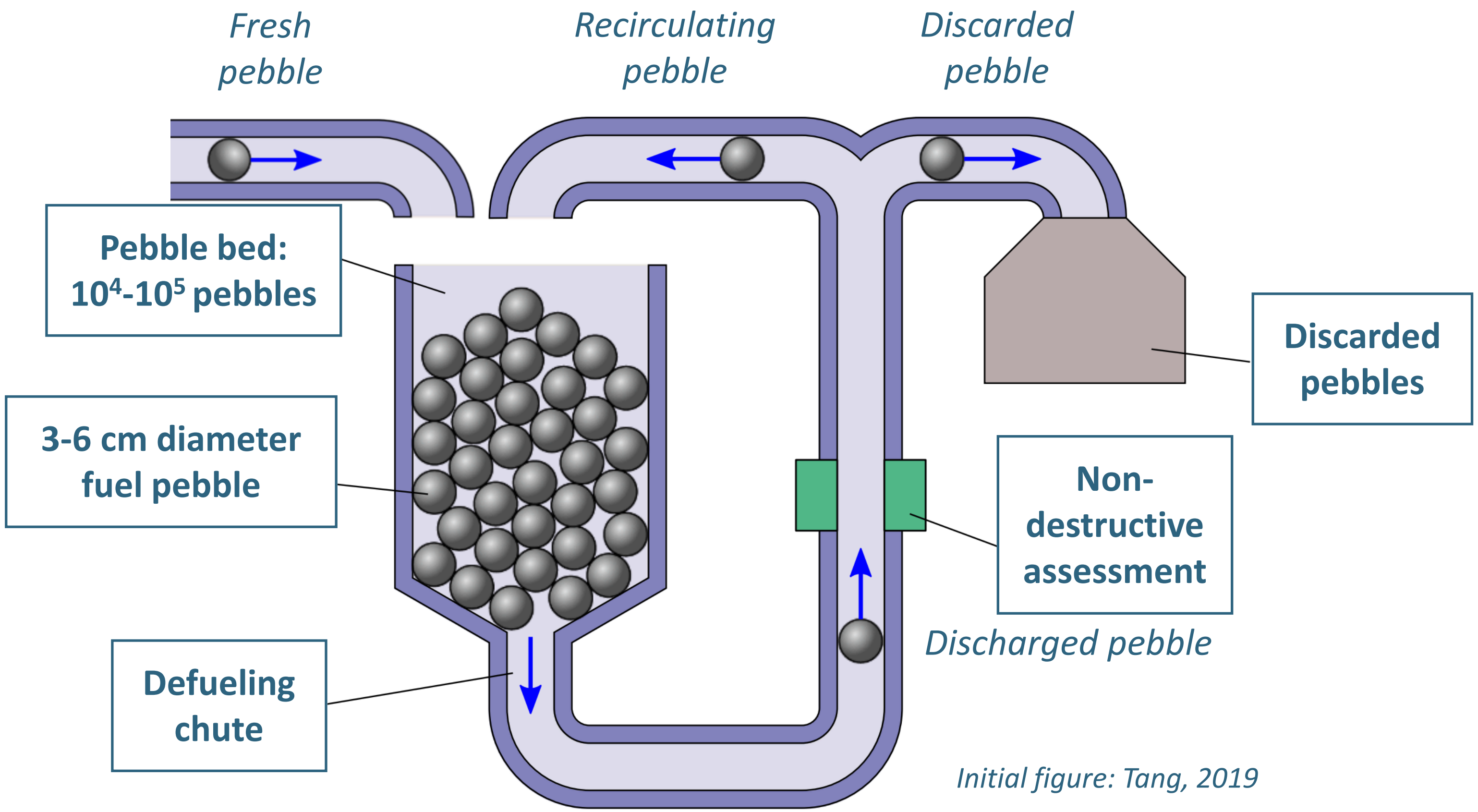
Pebble bed reactors operation is unique



Schematic view of multipass PBR operation

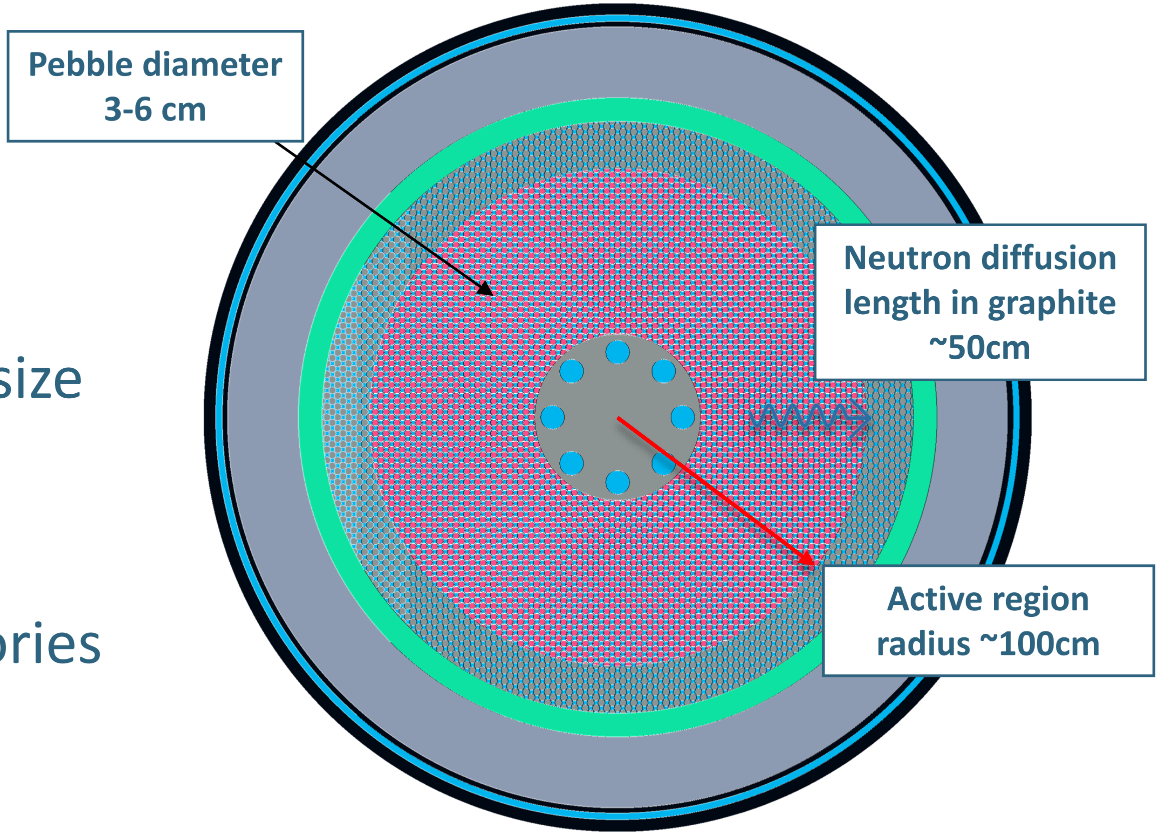
Note: Motion is inverted for FHRs

High burnup, plant availability, low excess reactivity

Simulation challenges arise from the design and operation

Main challenges

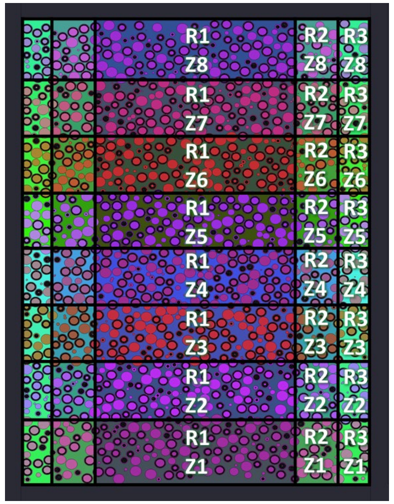
- Double-heterogeneous geometry
- Graphite moderator and small pebbles size
- Numerous, different evolving pebbles
- Pebble bed motion with unique trajectories
- Pebbles recirculation/refueling



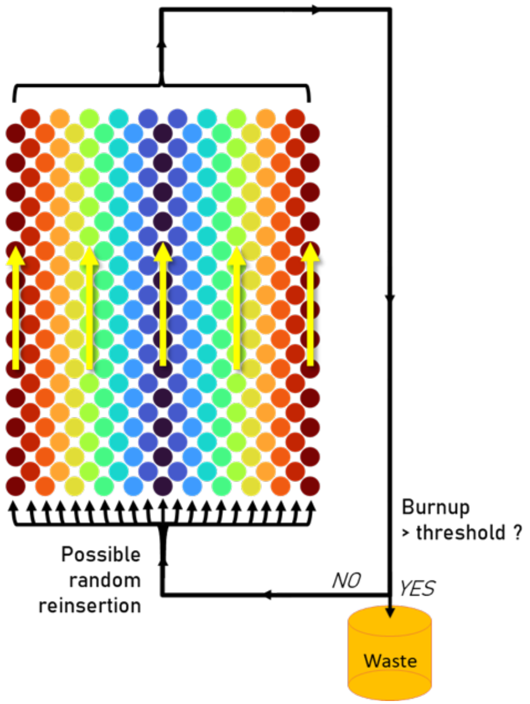
Mark-I FHR core and typical sizes

Hyper-fidelity can provide a resolution never reached before in PBR depletion calculations

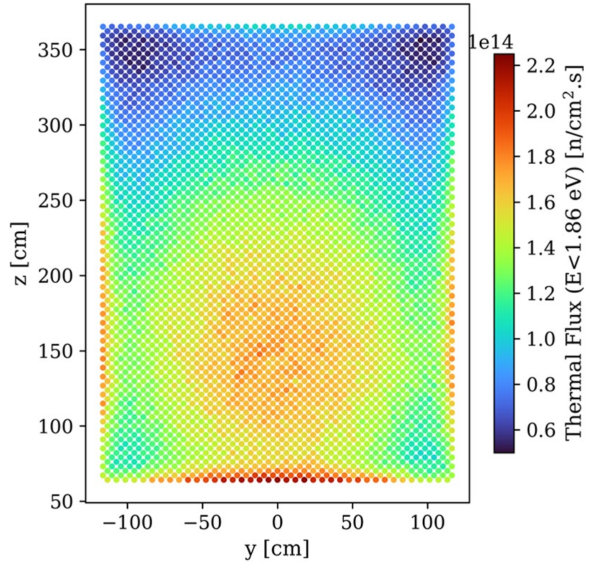
1. Review of current methods



2. Methodology for hyper-fidelity (pebble-by-pebble) depletion with discrete motion



3. Application to the gFHR equilibrium and obtained results



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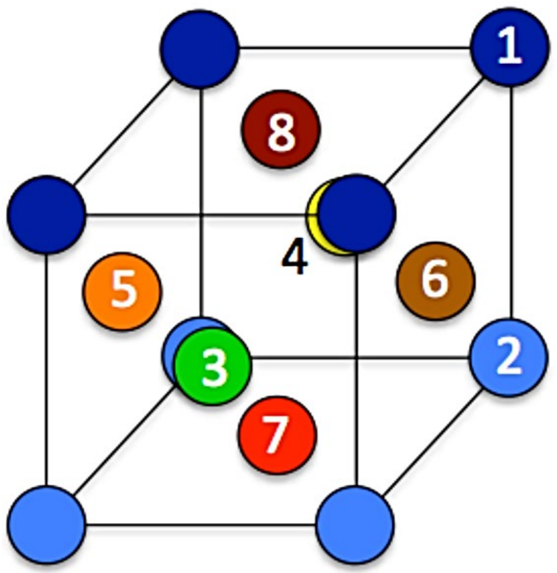
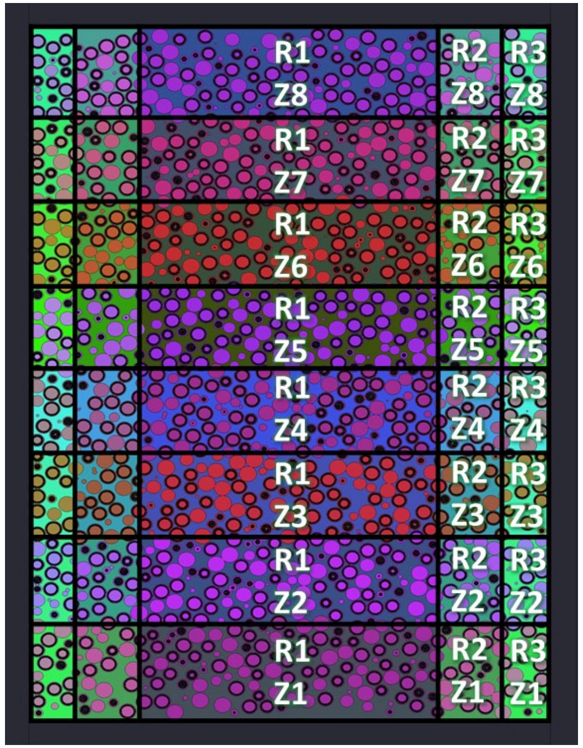
Most common tools for pebble-bed depletion only provide coarse, averaged data

Current methods: coarse approaches, equilibrium concentrations



Source: Cisneros, 2013

Representative unit cell with various compositions



Full-scale with coarse uniform depletion regions

Previous work on static core showed that hyper-fidelity is feasible

- **Hyper-fidelity depletion**: track pebbles individually in full-core simulations
- Feasibility demonstrated with a cluster with common resources using Serpent

RAM usage and number of nodes needed

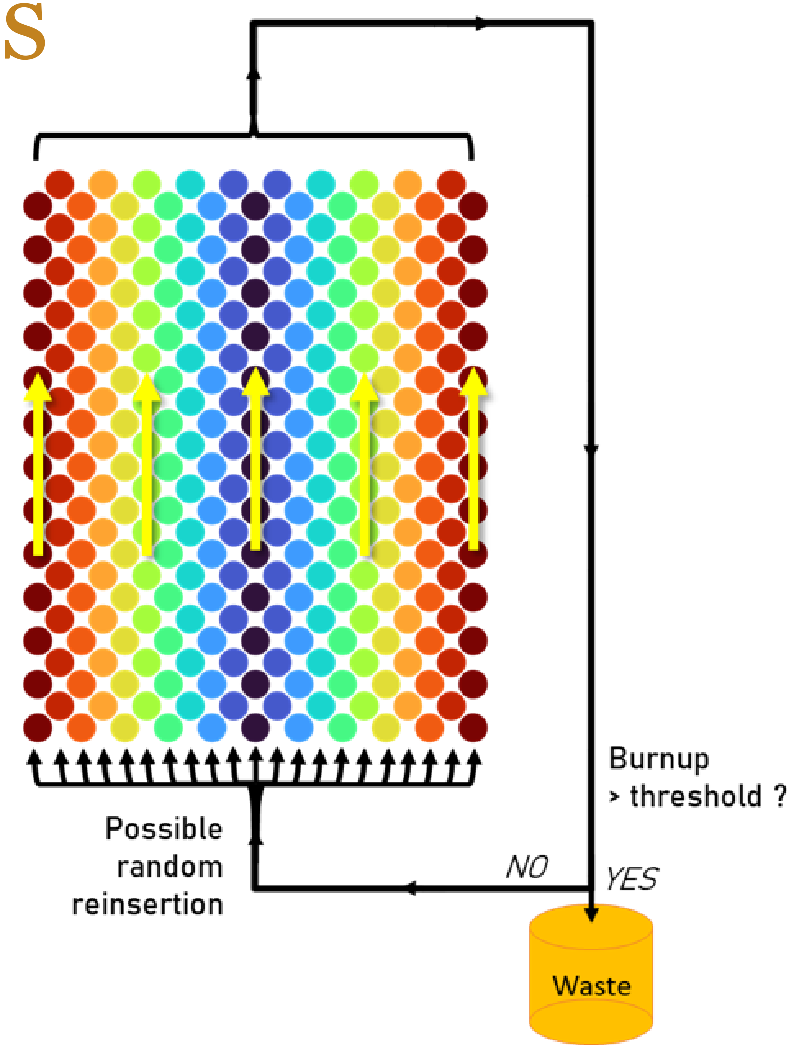
RAM/node for 50,000 pebbles (GB)	31
RAM/node for 500,000 pebbles (GB)	244
Max. number of pebbles with 90 GB and 1 node	174,899
Nodes needed for 50,000 pebbles with Domain Decomposition	1
Nodes needed for 500,000 pebbles with Domain Decomposition	3

Total simulation time (hours) vs number of BU steps and pebbles

# pebbles	**# nodes**	**# burnup steps**		
		1	**5**	**10**
50,000	**1**	1.2	6	12
	12	0.5	2.5	4.9
100,000	**1**	2.5	11.7	23.3
	1	2.4	11.5	22.9
	12	1	4.5	8.9
500,000	**12**	6.8	21.5	39.9

Discrete motion utilizes a static pebble bed with moving compositions

- Goal: internally couple Serpent and motion with recirculation handling
- **Discrete motion:** Move the compositions in Serpent, not the pebbles
- First step towards fully couple hyper-fidelity and pebble motion



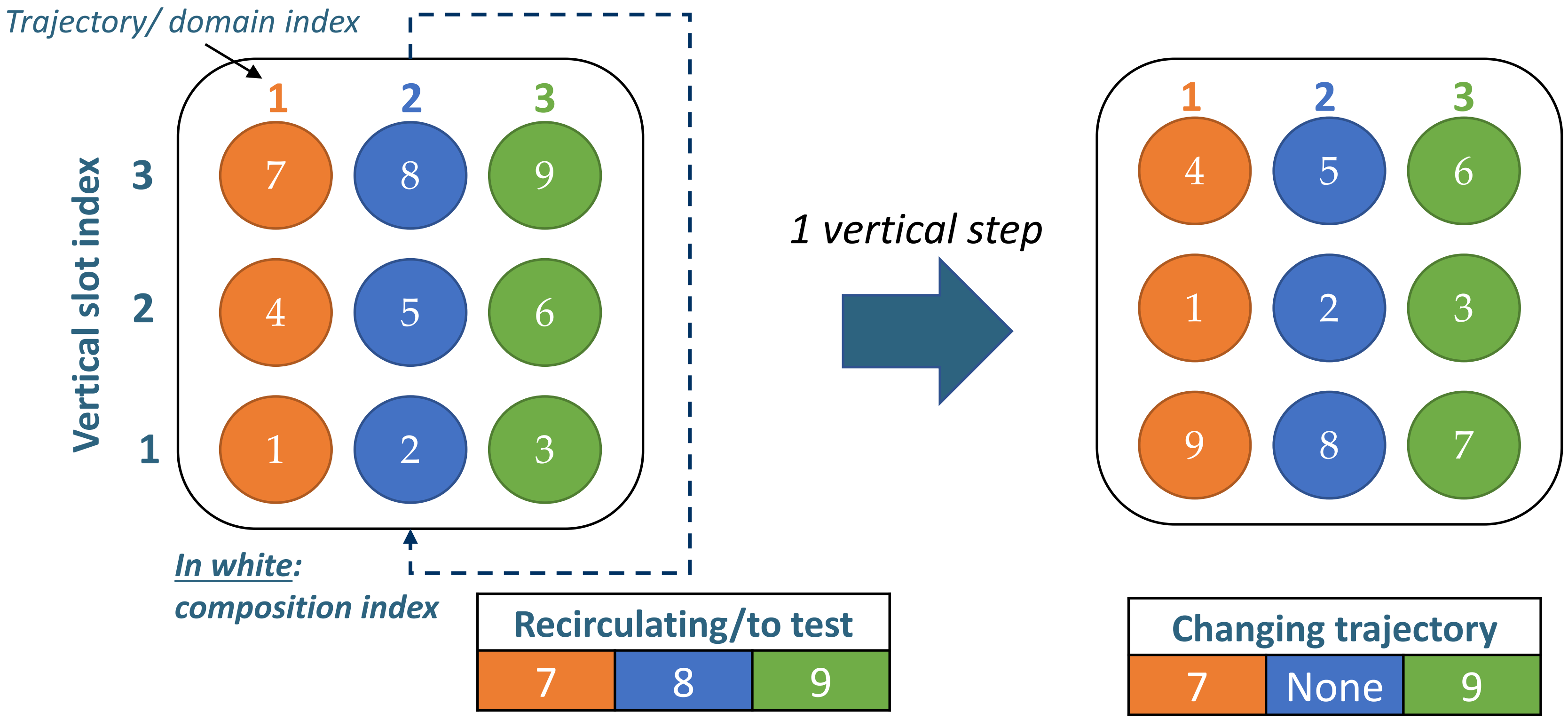
Schematic description of discrete motion method

Discrete motion was implemented in Serpent

Compositions move from pebble slot to another

Compositions reaching the top recirculate

Recirculating compositions tested for burnup (e.g., Cs-137): discarded/replaced by fresh fuel



Explanation of discrete motion with a small 2D core

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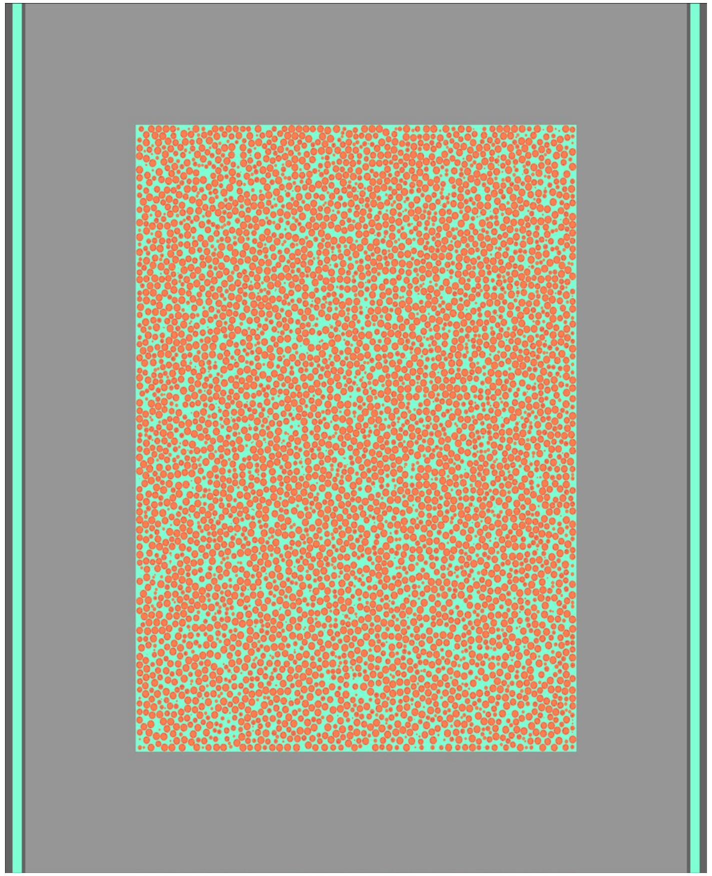
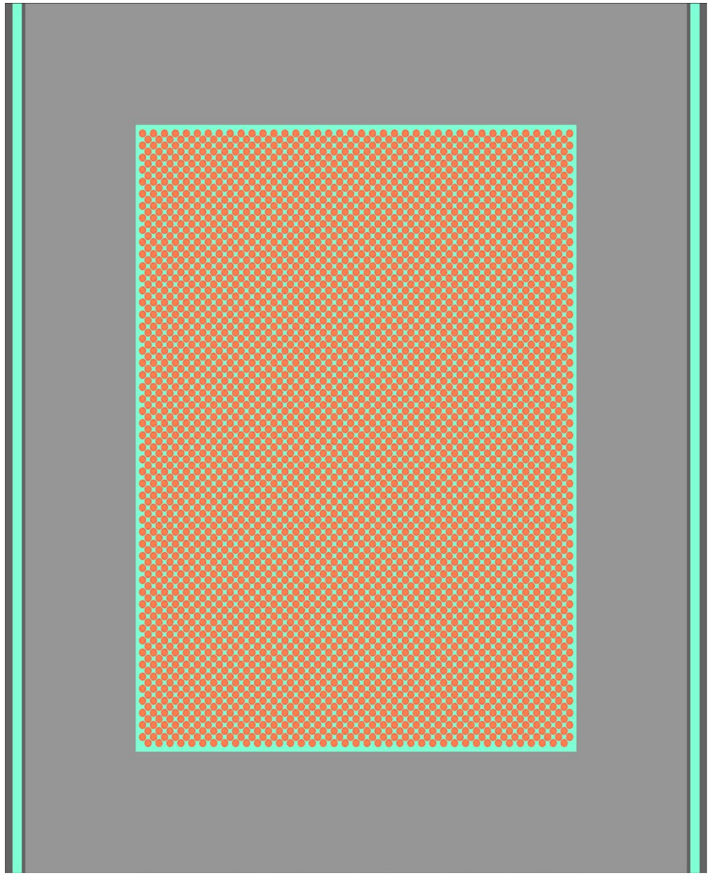
Hyperfidelity depletion with discrete motion was applied to the generic FHR model

CORE PARAMETERS	
POWER(MW_{TH})	280
CORE RADIUS (CM)	120
CORE HEIGHT (CM)	310
NUMBER OF PEBBLES	250,190
PACKING FRACTION (%)	60
DOWNCOMER WIDTH (CM)	5
CORE BARREL THICKNESS (CM)	2
VESSEL THICKNESS (CM)	4
REFLECTOR THICKNESS (CM)	60
FLIBE ENRICHMENT (PPM LI-6)	50



gFHR model from the benchmark (PF = 60%)



gFHR model used with discrete motion (PF = 60%)

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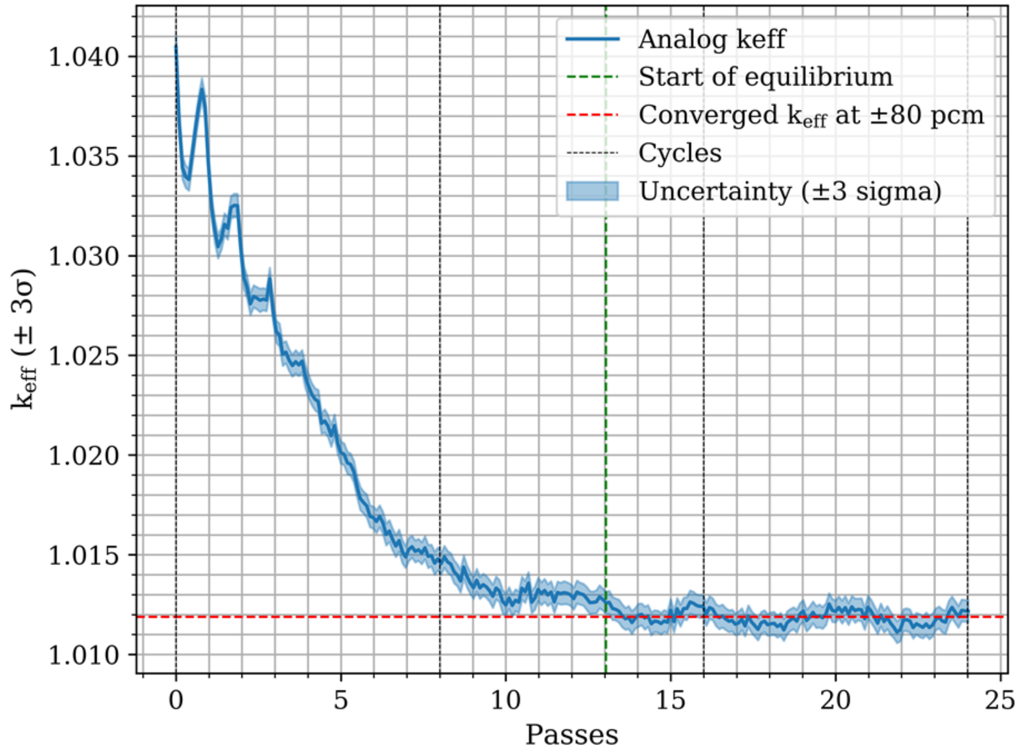
An equilibrium state with the gFHR was found with discrete motion

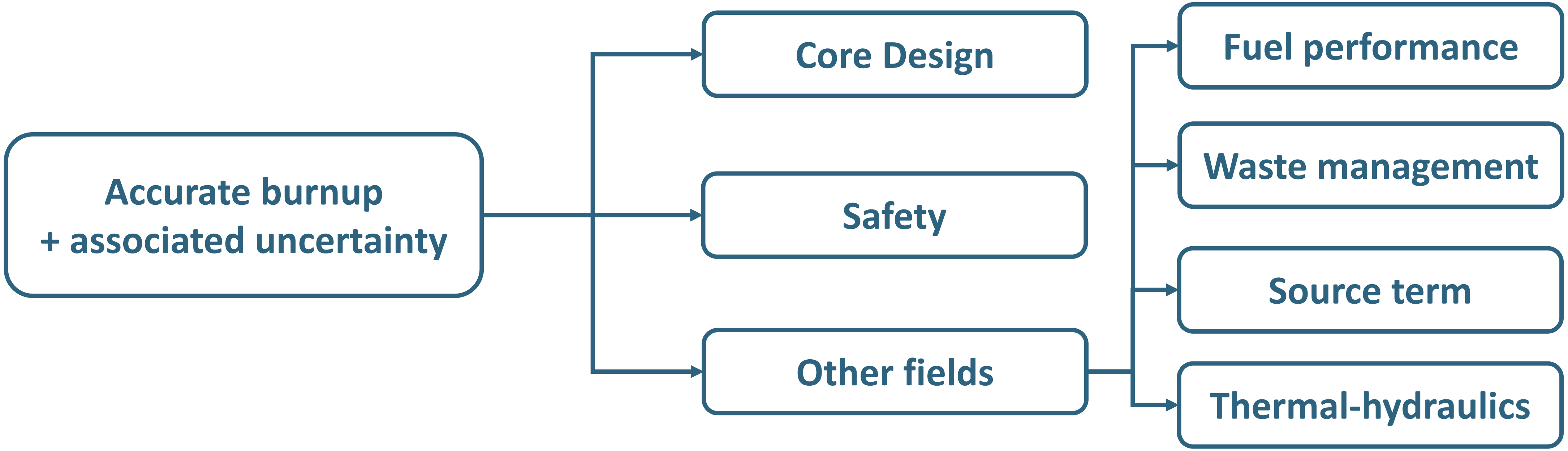
FUEL/OPERATION PARAMETERS	
PEBBLES RADIUS (CM)	2
SHELL LAYER THICKNESS (CM)	0.2
FUEL LAYER THICKNESS (CM)	0.42
(AGR-5/6/7) TRISOS	9022
U-235 ENRICHMENT (% WT)	19.55
RESIDENCE TIME (DAYS)	522
DISCARDING CRITERION (PASSES)	8
TEMPERATURE (K)	900

SIMULATION PARAMETERS	
NEUTRONS PER CYCLE	50,000
INACTIVE CYCLES	100
ACTIVE CYCLES	1,000
BURNUP STEP (DAYS)	6.4



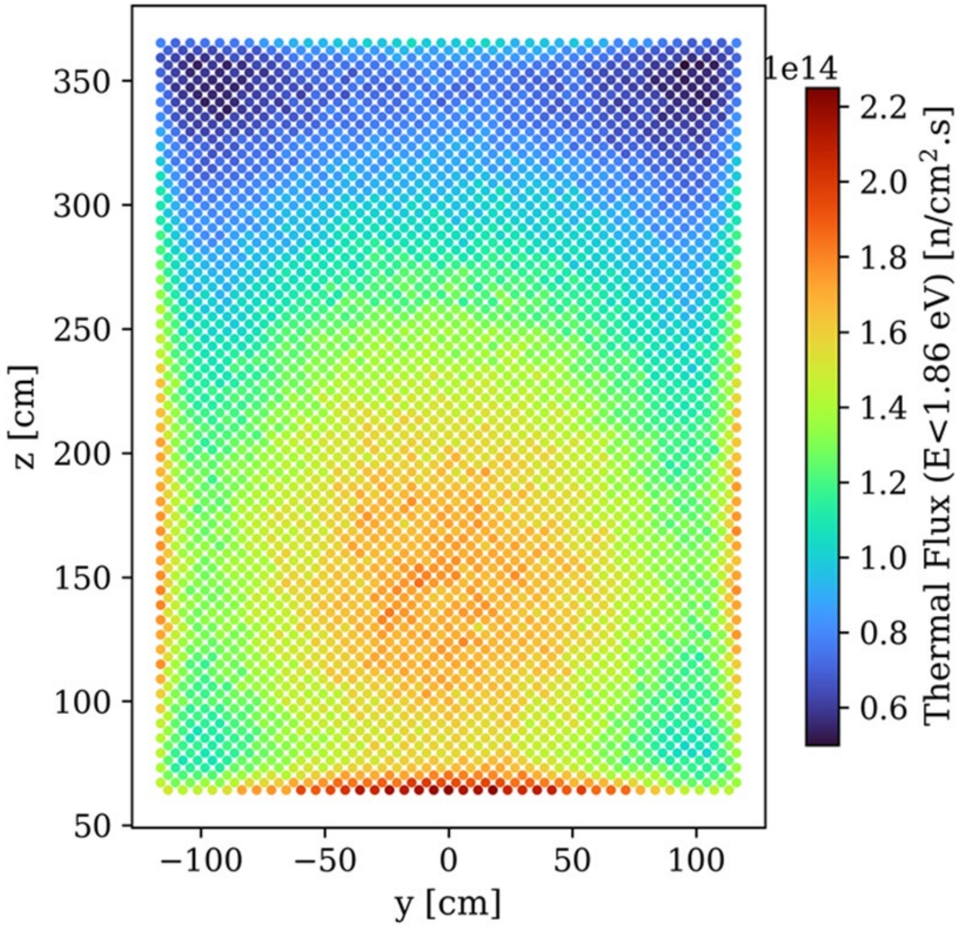
COMPARISON KEFF			
HYPER-FIDELITY	1.01188	±	19 pcm
KPACS (KAIROS)	1.01230	±	68 pcm
DIFFERENCE	42 pcm		
STANDARD DEVIATION	35 pcm		

Burnup simulations represent an upstream source of error that needs to be minimized

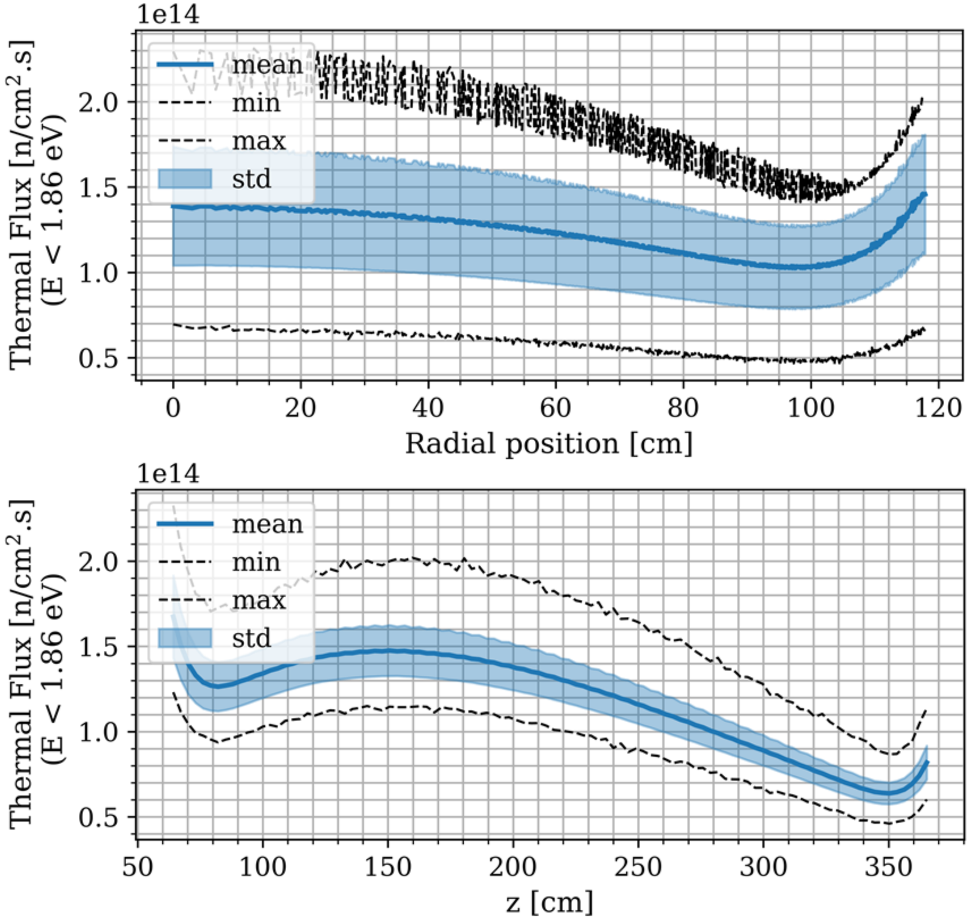


Errors and uncertainties propagate, high accuracy is crucial

The equilibrium state shows a downward shift for the thermal flux

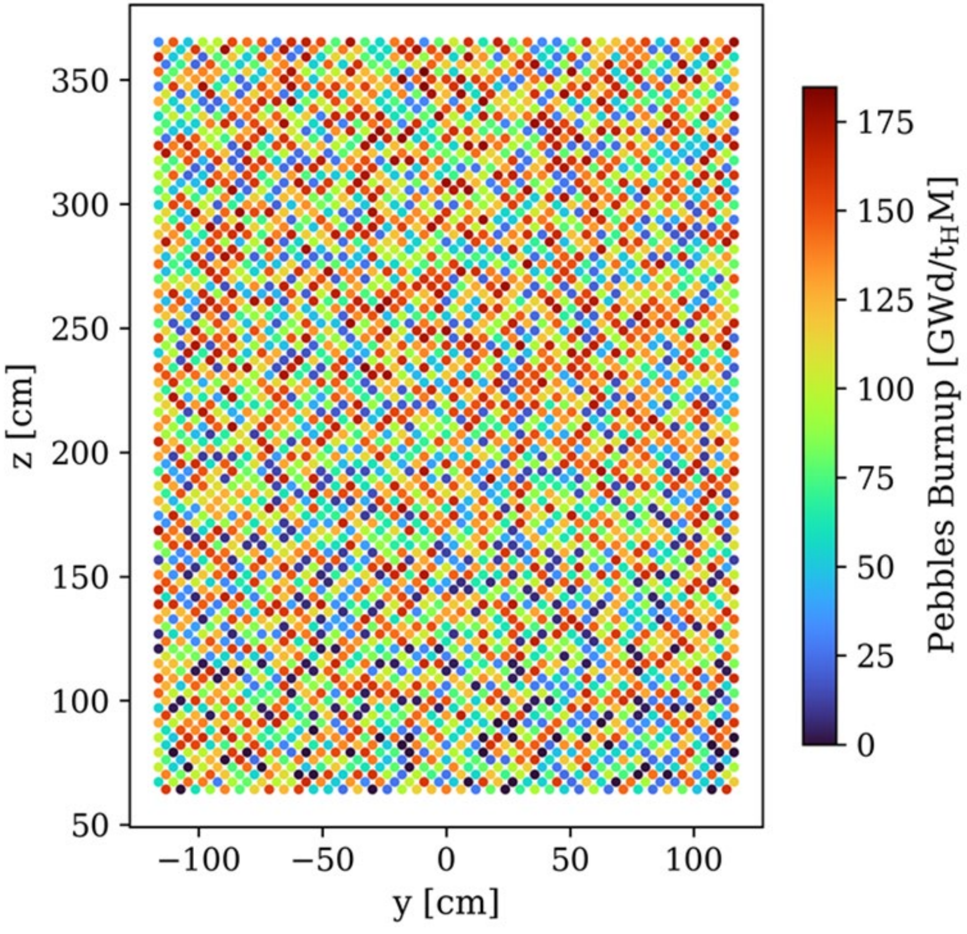


Thermal flux distribution for equilibrium core

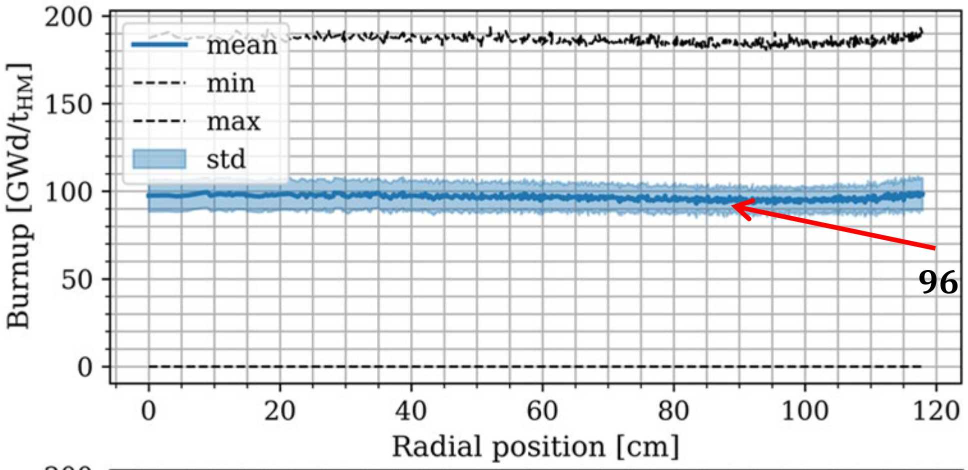


Averaged equilibrium core in 1D

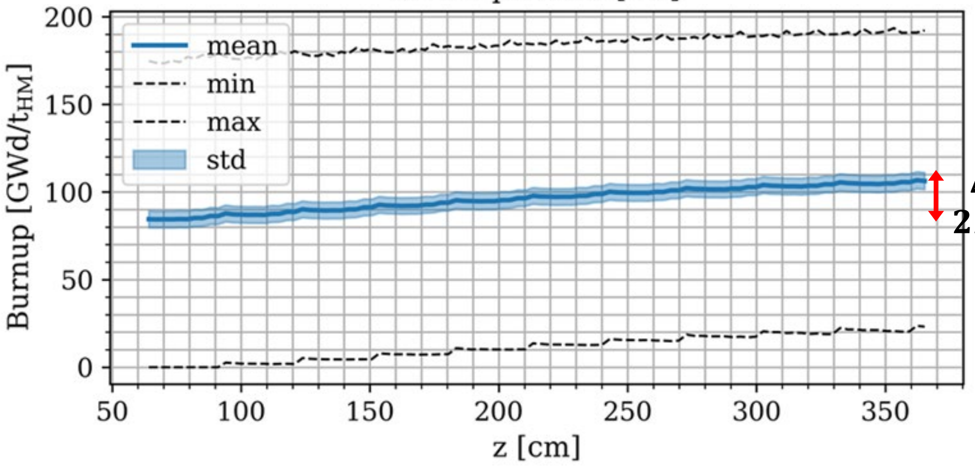
The burnup distribution shows random radial burnup mixing and axial increase



Burnup distribution for equilibrium core



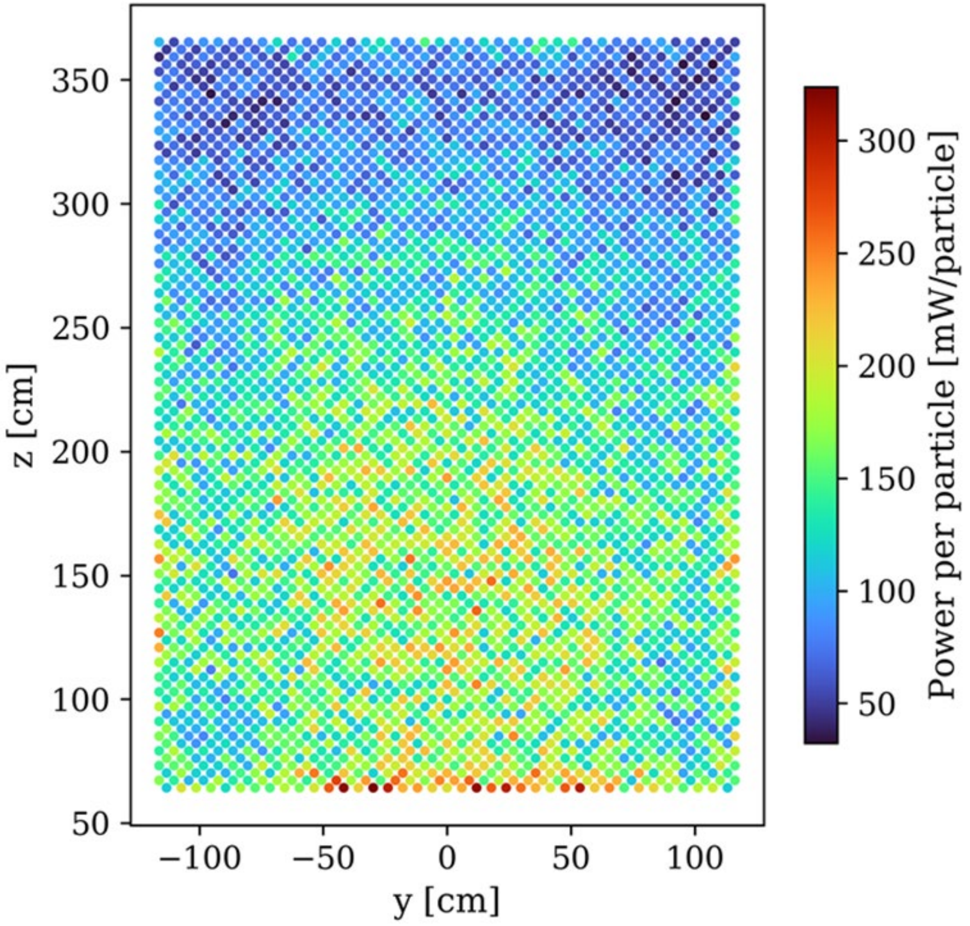
$\overline{\mathbf{BU}} =$ **96 GWd/t$_{HM}$**



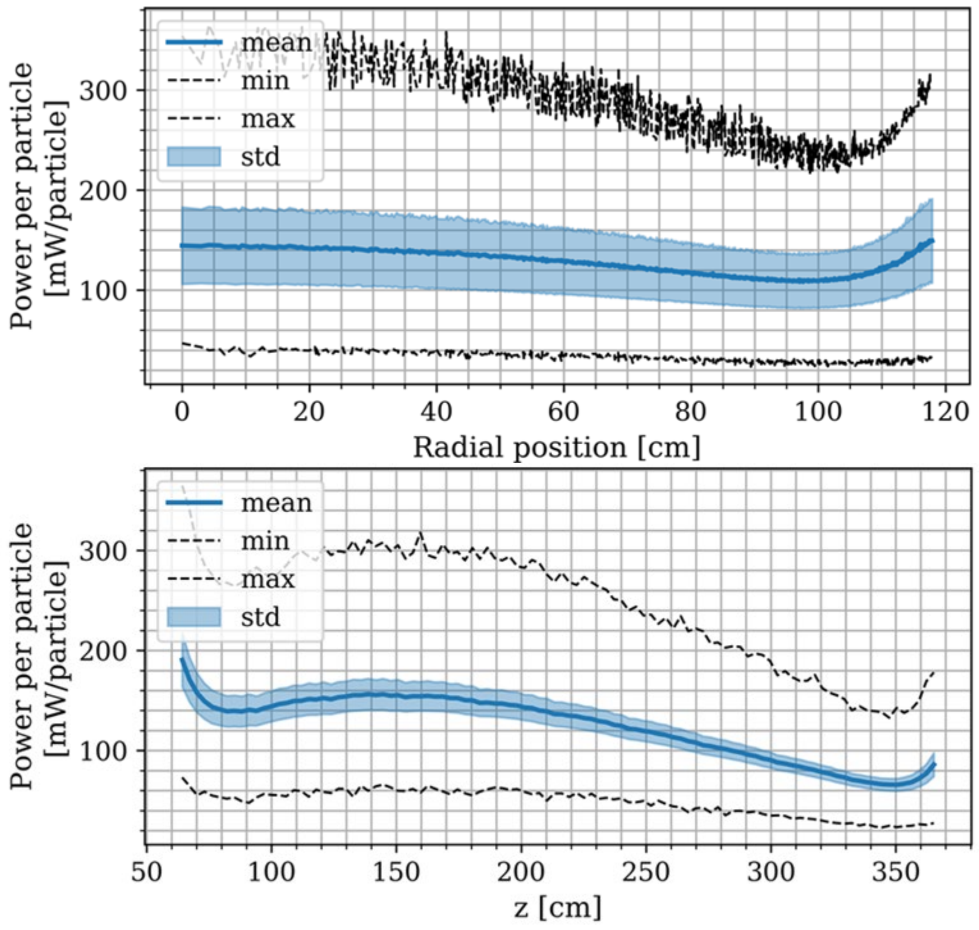
$\Delta \mathbf{BU}_{axial} =$ **22 GWd/t$_{HM}$**

Averaged equilibrium core in 1D

The power profile is peaked close to reflectors and results from the burnup and thermal flux

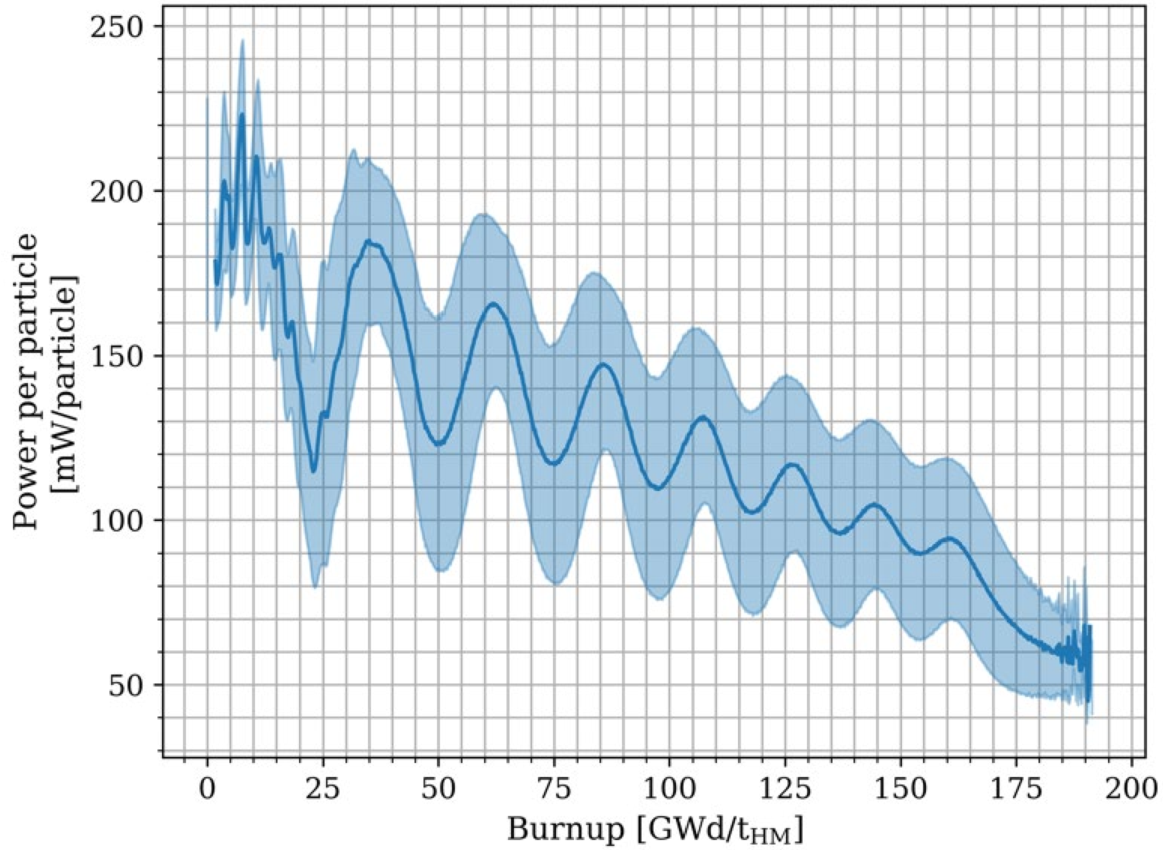


Power distribution for equilibrium core



Averaged equilibrium core in 1D

Power and burnup are strongly linked, with dependences on flux and pass number



Average power per particle in pebbles as a function of the pebbles' burnup

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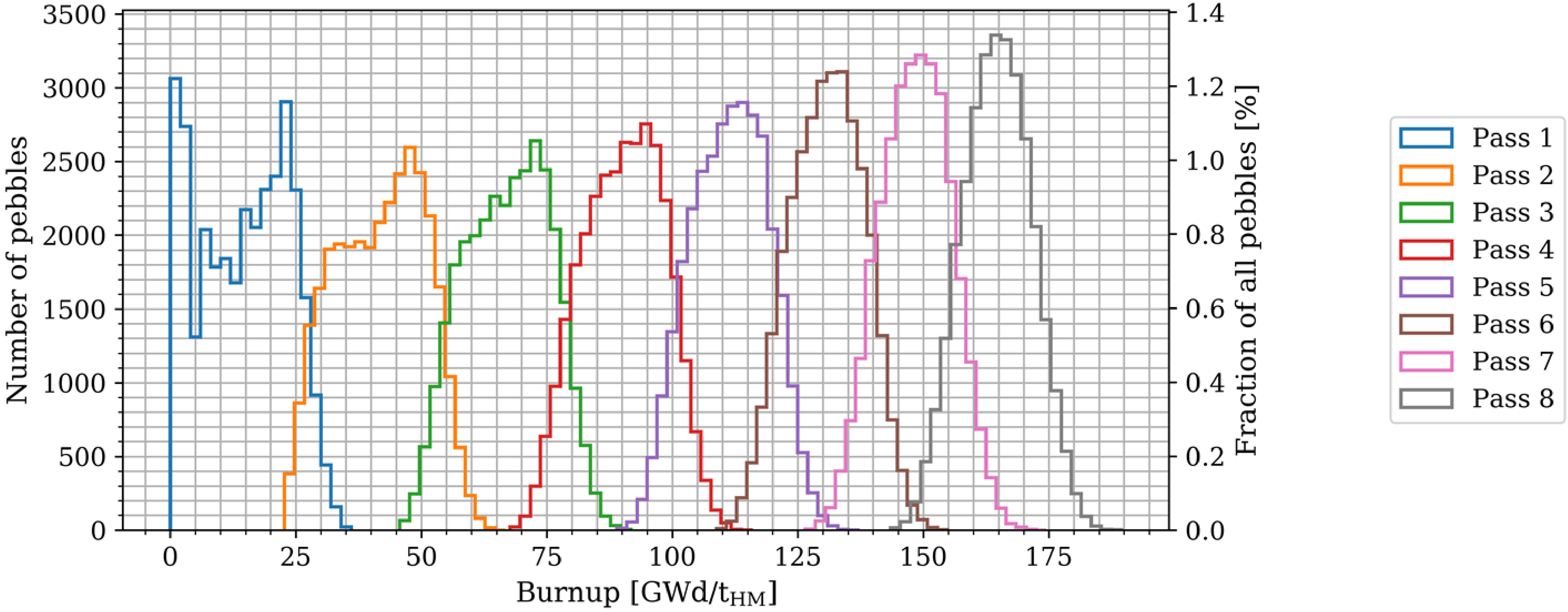
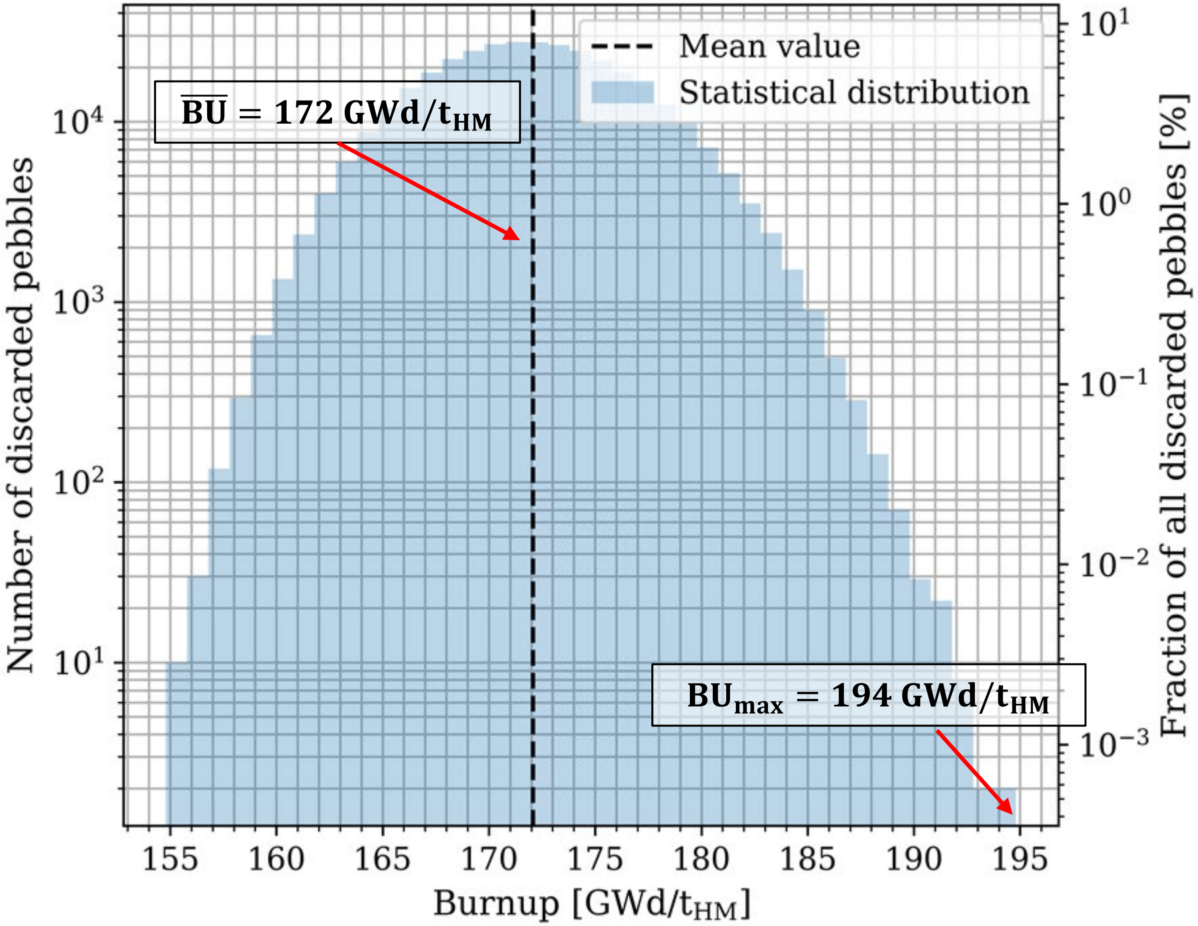
The burnup distribution becomes closer to a normal distribution with passes



Burnup statistical distribution for each passes number at equilibrium

Hyper-fidelity provides a statistical distribution for discarded pebbles

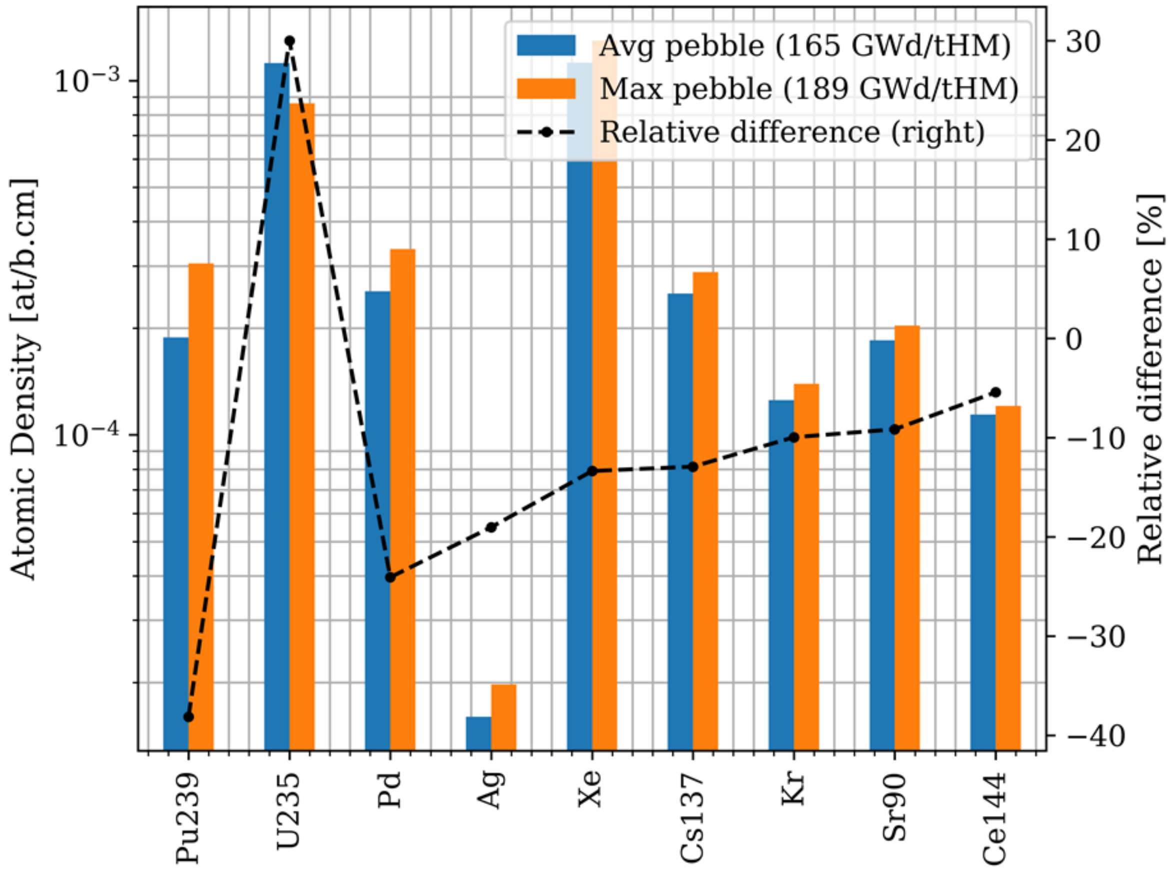


Burnup statistical distribution among discarded pebbles during equilibrium

- 368,377 analyzed discarded pebbles
- Significant discrepancy on pass-dependent discarding criterion (ΔBU=38 GWd/t_{HM})
- Maximum to average burnup ratio: 1.13

Hyper-fidelity determines distributions and outliers to inform other physics models

PEAKING FACTORS INFORMATION	
AVERAGE POWER (mW/particle)	120
MAXIMUM POWER (mW/particle)	340
POWER PEAKING FACTOR	**2.76**
AVERAGE BURNUP (GWd/t_{HM})	96
MAXIMUM BURNUP (GWd/t_{HM})	189
BURNUP PEAKING FACTOR	**1.97**



Comparison of concentrations between maximum BU pebble with a pebble having an average BU at pass 8

Conclusions

- Previous work demonstrated that tracking depletion of >10^5 pebbles individually is possible
- This work couples hyper-fidelity depletion with fuel motion
  - Implicit coupling based on discrete motion
  - Regular lattice bed model
- The methodology was applied to model the generic FHR benchmark
  - Extracted equilibrium core, envelope/outliers, pebble-wise data, discarded pebbles distribution
- Ongoing/future work
  - Improve discrete motion to model more realistic geometries (i.e., conic regions) and pebble speed profile
  - Model actual fuel motion using Discrete Element Method, coupling with Cerberus
  - Some coupling with thermal-hydraulics (Goose, GenFOAM, Pronghorn, …)

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Thank you
Do you have any questions?

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