Business from technology

Serpent Monte Carlo code as a modeling tool for Gen-IV reactors

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Outline

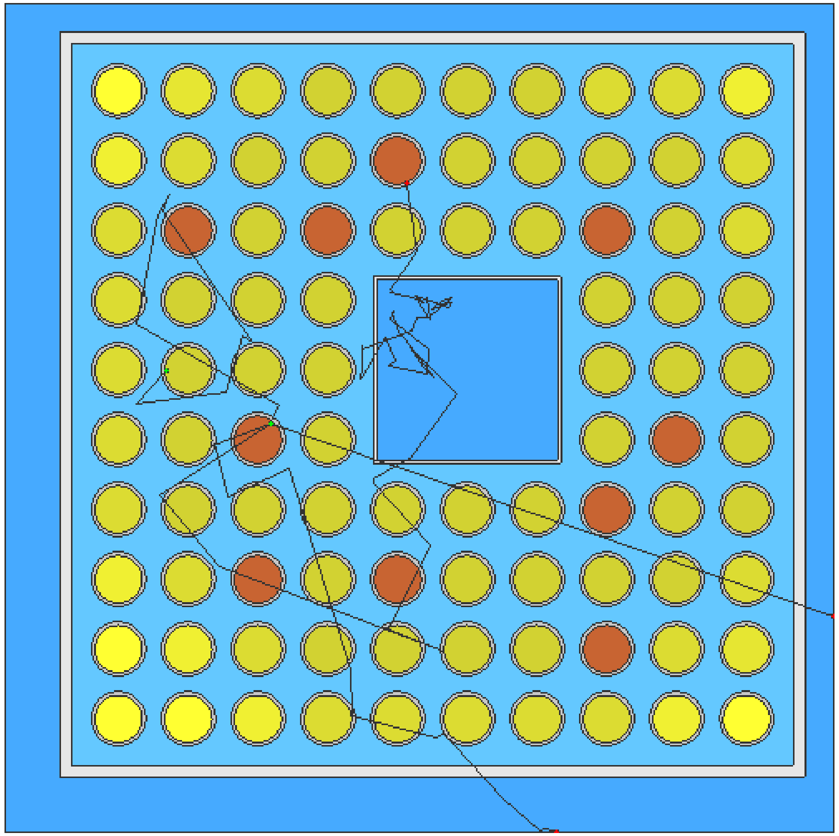
Monte Carlo method in neutron transport

- Advantages and limitations
- Monte Carlo codes and Gen-IV applications

Serpent Monte Carlo code

- Methods, capabilities and applications
- Two practical Gen-IV examples:
  1. High-temperature gas cooled reactors
  2. Liquid metal cooled fast reactors
- Future plans

Summary



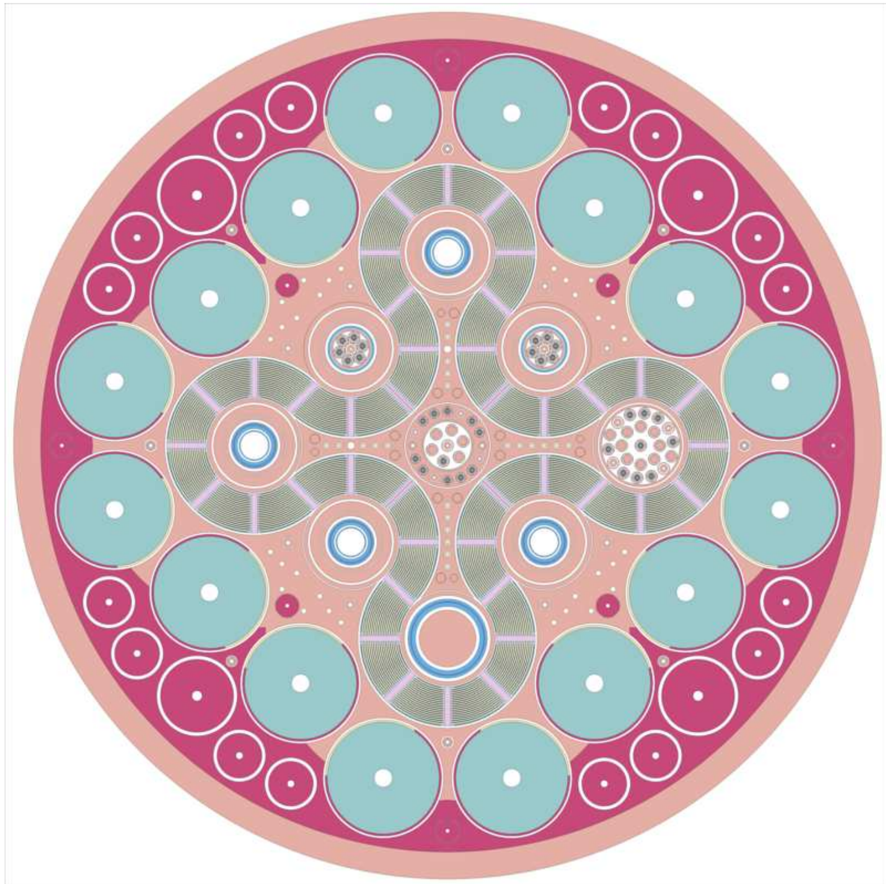
Advantages and limitations of Monte Carlo

Geometry description

- Geometry can be modeled at an arbitrary level of detail without spatial discretization
- Inherently three-dimensional simulation

Physics

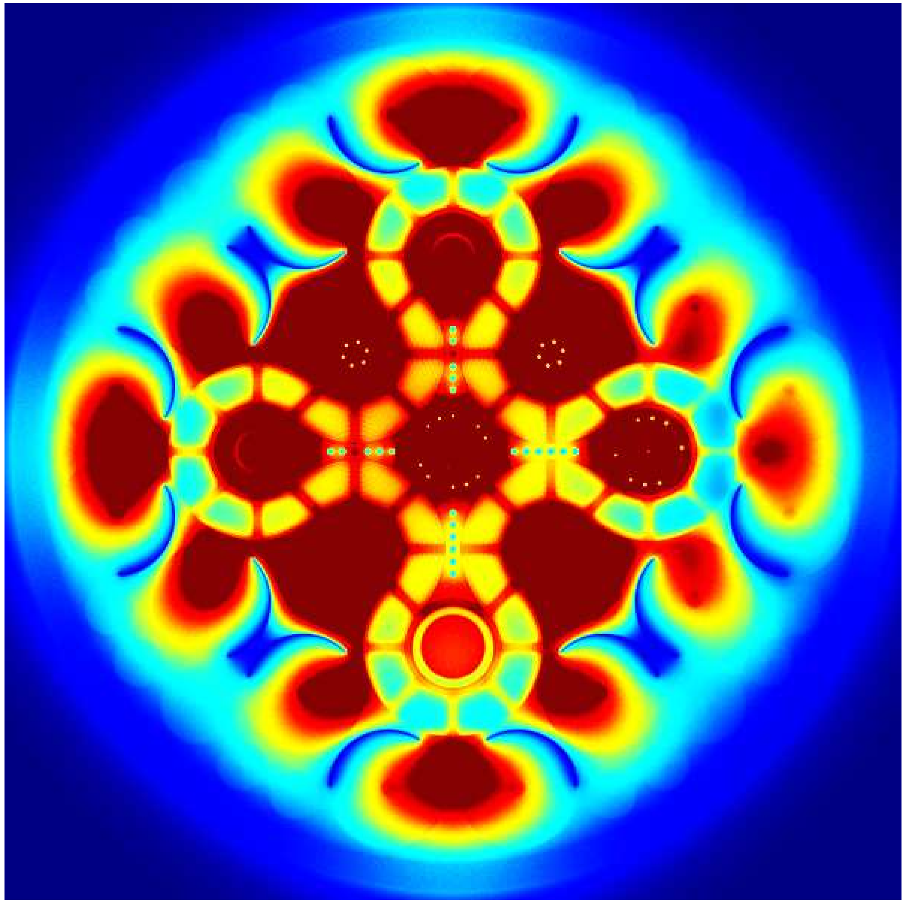
- Energy and angular dependence can be handled without discretization or functional expansions
- Continuous-energy cross sections are not subject to self-shielding effects
- Time dependence can be handled without separation of variables and other approximations



Advantages and limitations of Monte Carlo

Limitations

- Simulation requires a lot of CPU time
- All results are random variables, statistical accuracy is a function of running time
- Calculation always involves integration over energy, space and time – differential quantities are not easy to calculate
- Combination of Monte Carlo and deterministic transport methods is not always straightforward
- Possibilities to simplify calculations by making approximations on geometry and physics are quite limited



Advantages and limitations of Monte Carlo

Why use continuous-energy Monte Carlo for Gen-IV applications?

- Best available knowledge on neutron interactions can be used almost directly in the simulation
- The same code and cross section data can be used for modeling any fuel or reactor type without compromising the reliability of the calculation scheme
- Monte Carlo codes can be used for full-scale simulations or for producing multi-group constants for deterministic full-scale simulations (or both)
- Anything that happens to neutrons during the transport process can (at least in principle) be simulated in Monte Carlo
- Development in computer capacity and parallel calculation constantly broadens the field of applications for Monte Carlo codes
- Several hot research topics in reactor physics involve the use and development of Monte Carlo codes: coupling to CFD codes, adjoint Monte Carlo simulation, etc.

Brief introduction to Serpent

History

- Development started in 2004 under working title “PSG”
- Motivation: *to develop a lattice physics code based on the continuous- energy Monte Carlo method, capable of generating homogenized multi-group constants for deterministic reactor simulator codes*
- The field of applications has considerably diversified since then

User community

- Public distribution in 2009 (OECD/NEA Data Bank) and 2010 (RSICC)
- Current status: 200 users in 82 universities and research organizations in 27 countries around the world

Development of Serpent 2 started in October 2010

Brief introduction to Serpent

Methods

- Three-dimensional universe-based CSG geometry model (similar to MCNP and KENO-VI)
- “Laws of physics” from on ACE format cross section libraries (also used by MCNP)
- Transport routine for neutrons, optimized for (but not limited to) lattice physics applications

Capabilities

- Automated generation of homogenized multi-group constants for simulator codes
- Semi-deterministic B1 fundamental mode calculation for homogenization in critical spectrum
- Fully automated built-in burnup calculation routine
- Tally capabilities similar to other Monte Carlo codes

Brief introduction to Serpent

Applications

- Typical Serpent user is a graduate or undergraduate student, using the code in his/her thesis work
- A few example applications:[a]
  1. Group constant generation for axially heterogeneous RBWR fuel assemblies
  2. Group constant generation and burnup calculation for SFR's
  3. Full-core LWR burnup calculations
  4. Modeling of continuous reprocessing for MSR's
  5. Inventory calculations for a Triga Mark II reactor
- Serpent is used more and more as a platform for developing new features and capabilities

[a] Presented at the 2nd International Serpent User Group Meeting in Madrid, Spain, September 19-21, 2012. http://montecarlo.vtt.fi/mtg/2012_Madrid/index.htm

Practical Gen-IV example: HTGR modeling

Characteristic features of High-temperature gas cooled reactors:

- What the neutrons see: microscopic high-absorbing fuel particles randomly distributed in low-absorbing graphite
- Long neutron histories, especially in reflector regions
- Extremely small geometry dimensions compared to neutron mfp

Modeling challenges:

- Continuous-energy Monte Carlo simulation does not allow many approximations for geometry and physics $\longrightarrow$ fuel particles must be modeled explicitly
- Modeling random particle distributions as a regular lattice of equivalent packing fraction results in unrealistic streaming paths and particle clipping at the boundary
- Generation of pebble distributions for pebble-bed type reactors is not a trivial task (not to mention continuous refueling)
- Surface-tracking is slow when neutron mfp is long compared to geometry dimensions

Practical Gen-IV example: HTGR modeling

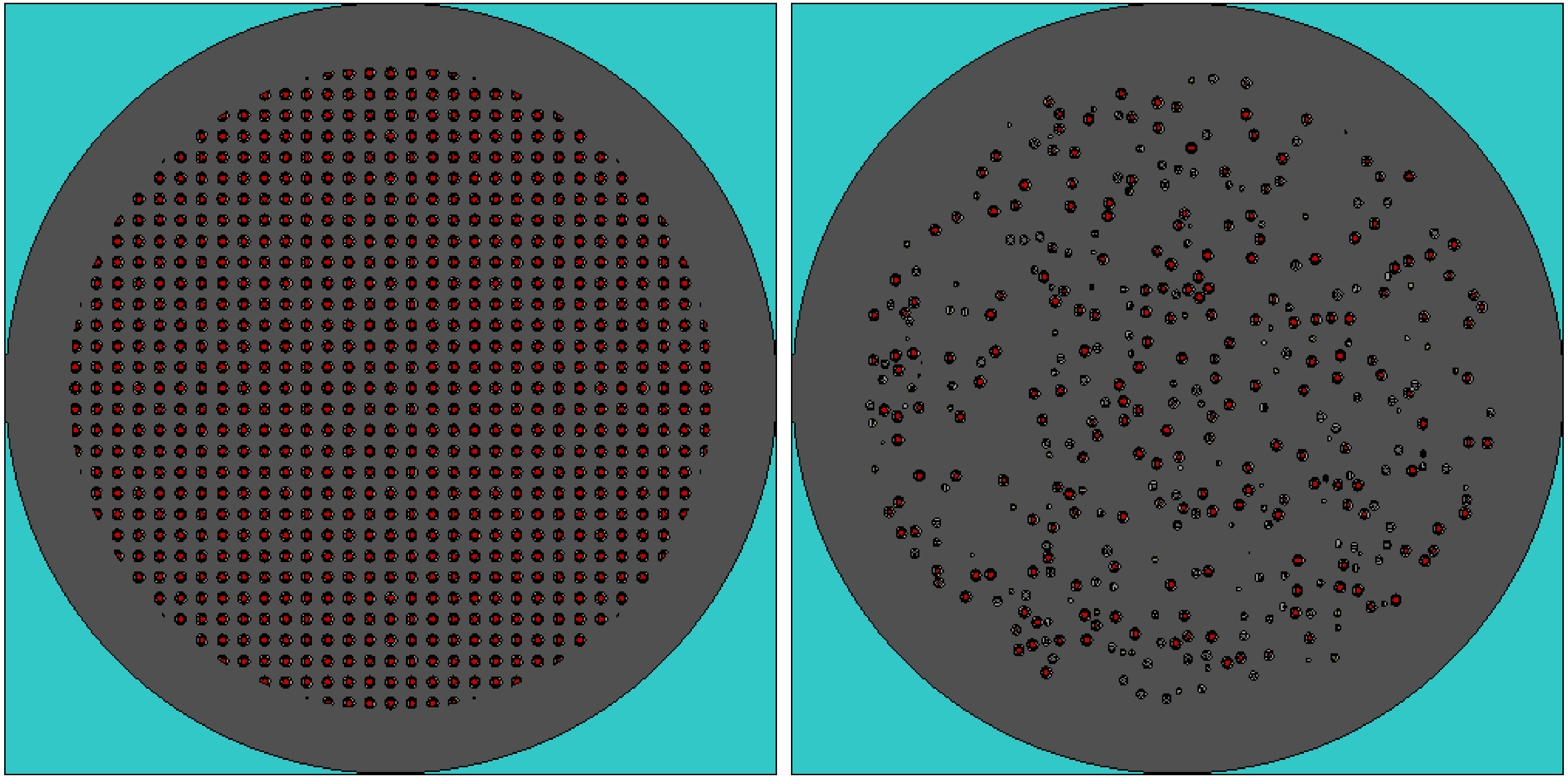
Explicit HTGR geometry model in Serpent:

- Special universe type, in which the coordinates of spherical objects are read from a separate input file and placed in a Cartesian search/tracking mesh
- Works at multiple levels: particle distributions inside pebbles or compacts and pebble distributions inside core
- Explicit geometry description – no approximations, no unrealistic streaming paths, no particle clipping (as long as the distribution is appropriately defined)
- No major increase in running time compared to the regular lattice model
- Successfully used for: HTTR, ASTRA, KAHTER, HTR-10

Serpent tracking routine based on Woodcock delta-tracking:

- Efficient alternative to surface-tracking when neutron mfp is long compared to geometry dimensions
- Speed-up of a factor of 10 in HTGR particle fuels

Practical Gen-IV example: HTGR modeling



Left: PBMR fuel pebble with regular lattice model for particle distribution.

Right: Same geometry with explicit particle fuel model.

Practical Gen-IV example: Fast reactor modeling

Characteristic features of fast reactors:

- What the neutrons see: relatively uniform geometry (at least compared to thermal reactors), no sharp changes in material properties
- No major differences between the neutronics of sodium-, lead- or even gas-cooled fast reactors
- High leakage rate
- Time constants considerably shorter compared to thermal reactors

Modeling challenges:

- More inelastic reactions (complicated interaction physics) compared to thermal reactors
- Energy dependence of fission yields and isomeric branching ratios in burnup calculation
- Uncertainties in minor actinide cross sections are pronounced in fuel cycle studies
- Higher eigenmodes become significant in fast reactivity transients (???)

Practical Gen-IV example: Fast reactor modeling

Serpent experience:

- Fast reactor modeling does not significantly differ from thermal reactors (same cross sections, similar geometries)
- Users seem to be less familiar with the methodology used for group constant generation
- Validation of results is less straightforward (lack of experimental data and deterministic reference codes)
- Applications often involve calculation of reactivity coefficients (problem for the Monte Carlo method) and time constants (Serpent methodology not fully developed)
- Group constant generation requires special tricks to get sufficient statistics to low energy groups (combination of several groups or variance reduction)
- Serpent has been succesfully used for both full-core calculations (JOYO, ELECTRA) and group constant generation (ESFR)

Near-future plans for Serpent development

New code version: Serpent 2

- Development started in October 2010, beta-testing phase in January 2012, public distribution in 2013-2014
- Improved capabilities for burnup calculation and parallelization
- Photon and coupled neutron/photon transport mode
- Dynamic Monte Carlo simulation

Multi-physics applications

- Internal temperature feedback module for simulating fast reactivity transients
- External coupling to CFD and system codes
- External coupling to fuel performance codes

Applications not limited to any particular reactor technology

Summary

- Continuous-energy Monte Carlo codes offer several significant advantages over deterministic transport codes, many of which are emphasized in Gen-IV applications.
- Monte Carlo codes can be used for full-scale neutronics simulations, as well as group constant generation for deterministic codes. The overall CPU time required for the calculation is still a limiting factor, but no longer a reason to reject the method altogether.
- Serpent Monte Carlo code has been developed for reactor physcis applications at VTT since 2004. The code has an international user community of about 200 users, most of which are young professionals performing calculations for their M.Sc. and Ph.D. work.
- Serpent is currently used for group constant generation, fuel cycle analysis, research reactor modeling, etc. The applications involve both Gen-III and Gen-IV technology.
- Next version of Serpent will extend the field of applications to gamma transport, dynamic Monte Carlo simulation and multi-physics coupling to CFD, system and fuel performance codes.

Thank you for your attention!

Questions?

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