Institute for Reactor Safety and Technology
Univ.-Prof. Dr. rer. nat. Hans-Josef Allelein

Institute of Energy- and Climate Research
Nuclear Waste Management and Reactor Safety (IEK-6)

Delayed Neutron Treatment in Dynamic Mode of SERPENT 2

Project: VENE

Mohammad Hessan

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Motivation

- Who are we?
  - RWTH/LRST (Institute for Reactor Safety and Reactor Technology)
  - IEK-6/FzJ (Research Centre Juelich/ Safety Research and Reactor Technology)
- What do we do?
  - Reactor research (HTR simulation)
  - Cotainment phenomena and –processes
  - CFD simulations
- VENE: **Ve**rzögerte **Ne**utronen (german expression for delayed neutrons)
  - Incorporation of delayed neutrons in SERPENT in a close collaboration with SERPENT developer team
  - Coupling with thermal hydraulic Codes

Outline

- Monte Carlo neutron tracking
- Current method of dealing with delayed neutrons
- Limitations of the current method
- Alternative method to deal with delayed neutrons
- Preliminary results
- Open questions

Monte Carlo Neutron Tracking

With random walk the transport of neutrons can be modelled:

1. Sample path length till the next collision
2. Transport the neutron to the collision point
3. Sample interaction
4. Model the chosen interaction

Sampling Interaction

Once the new interaction position is calculated, the interaction type must be determined:

$$P_i = \frac{\Sigma_i}{\Sigma_{total}} \;,\quad \Sigma_{total} = \sum_{i=1}^{n} \Sigma_i$$

The reaction type can be chosen by sampling a uniformly distributed random variable:

$$\xi \in [\sum_{i=1}^{m-1} \Sigma_i \;, \sum_{i=1}^{m} \Sigma_i \;),\; m \in \{1, \ldots, n\}$$

Modelling fission with delayed neutrons (current method)

1. Sample the number of the fission neutrons.
2. For each neutron, sample between prompt ($P(prompt)=1-\beta$) and delayed neutron ($P(delayed)=\beta$).
3. Create neutrons
   - Prompt …..
   - Delayed:
     - Sample precursor group
     - Sample energy of emitted neutron based on precursor group
     - Sample emission time based on precursor group (t=0 in CS-Mode)
     - Sample the direction of emission isotropically

Limitations of the Method for Application in Dynamic Mode

- Population control
- Memory usage
- Initial conditions

Population Control

Population control at each time step: many delayed neutrons emerging from precursors with long half-life can survive several time steps. The accumulation of these neutrons which will be produced in a future time causes some problems for sampling a constant number of neutrons in previous time steps.

Memory problems

The data of each delayed neutron have to be saved through all time steps till the emission time of delayed neutrons. This can increase the amount of required memory especially for the simulations of long time intervals.

Initial Conditions

Currently, neutrons can be modelled in dynamic simulation mode starting from a live neutron source. However, there is no method for storing an initial delayed neutron source.

New Method

Modelling fission with delayed neutrons (new method)

1. Sample the number of prompt fission neutrons
2. Create neutrons
   - Prompt (as in the old method)
   - Delayed:
     - Sample precursor group
     - Sample energy of emitted neutron based on precursor group
     - Sample emission time based on precursor group (t=0 in CS-Mode)
     - Sample the direction of emission isotropically
   - Delayed neutrons will be created separately from fission.

Alternative Method to Deal with Delayed Neutrons in DS-Mode

- One way to deal with the population control of neutrons in simulations with delayed neutrons is to store precursors instead of delayed neutrons.
- The precursor concentrations are stored at the end of each time step.
- At the beginning of the following time step new delayed neutrons can be sampled from precursors.
- Implicit estimators are used for improving the statistical results. Precursors are produced in every interaction with a weight which is equal to the probability of producing a precursor of the i-th group.
- There is also a small probability in every interaction to emit a delayed neutron at the current time interval (producing a precursor that decays at the same time interval).

Calculating the Initial Conditions

- The initialization can be done by using the criticality source mode in order to start from steady state.
- The concentration of precursors from the group „i" in steady state is given by:

$$\frac{dC_i(r,t)}{dt} = -\lambda_i C(r,t) + \beta_i \overline{\nu}_i \Sigma_f \phi(r,t) \xrightarrow{\frac{dC_i}{dt}=0} C_i(r,t) = \frac{\beta_i \overline{\nu}_i \Sigma_f \phi(r,t)}{\lambda_i}$$

- The concentration of live neutrons can be obtained by:

$$C = \frac{1}{V} \int_V \int_E \frac{1}{|v(r,E)|} \phi(r,E) dE dV$$

First Step

- The amount of precursors that decay till the next time step is given by the decay law.
- If we want to sample $N_{tot,s}$ neutrons at each time interval, we should sample

$$N_{del,s}(i) = N_{tot,s}\frac{N_{emit}(i)}{N_{emit}(i)+N_{live}(i)},\ i \in \{1,\ldots,n\}\ \textit{for n time steps}$$

delayed and

$$N_{live,s}(i) = N_{tot,s}\frac{N_{live}(i)}{N_{emit}(i)+N_{live}(i)},\ i \in \{0,\ldots,n\}$$

live neutrons.

Producing Precursors

- The expectancy of producing a precursor of the group „i“ is given by:

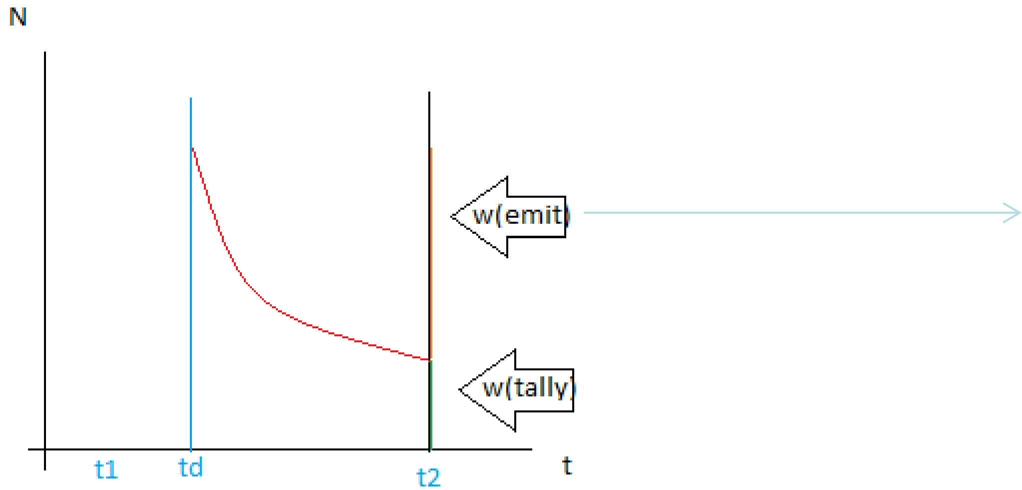
$$P_i = \frac{\Sigma_{fi}}{\Sigma_{tot}} \cdot \bar{\nu}_{tot,del} \cdot \frac{\beta_i}{\beta}$$

- We can produce a precursor from each group in every interaction. In oder to provide consistency, the weight of each produced precursor should be multiplied with the expectancy value of it P_i.

Tallying Precursor

- After a precursor is produced, the weight to be tallied and the weight to decay in $t \in [t_i, t_{i+1}]$ must be determined:

$$w_{tal} = w_{tot} \cdot \exp\left(-\lambda(t_{i+1} - t_d)\right) \qquad w_{em} = w_{tot} - w_{tal}$$



Russian roulette

Sampling Delayed Neutrons

- Delayed neutrons are produced from the share of the precursors which decays till the end of the time step.
- The emission time, the energy and the direction of movement of the delayed neutrons must be sampled.
- The emission time is sampled by inverting the modified cumulative distribution function (CDF)

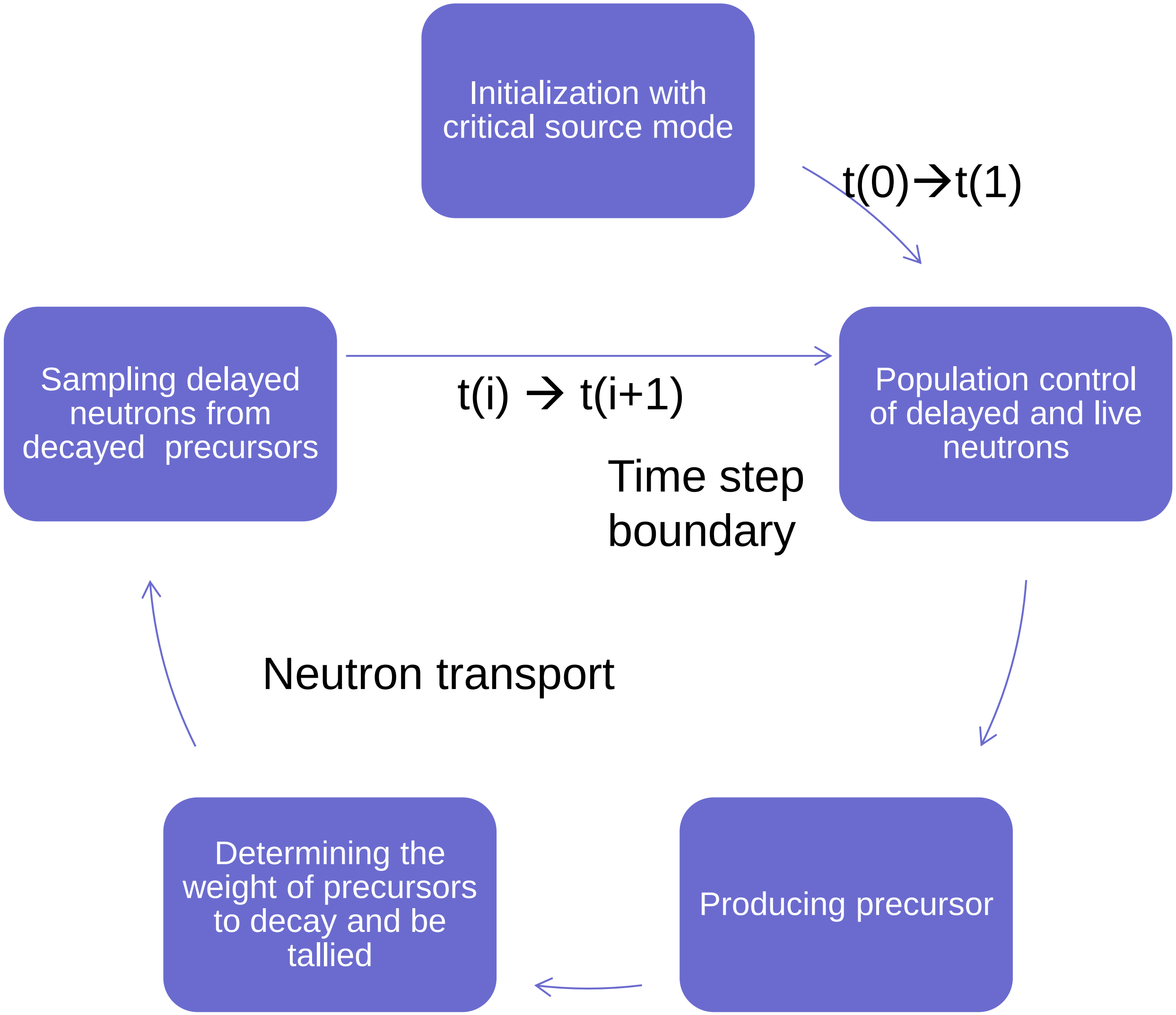
$$\xi = F(t) = \frac{1-\exp\left(-\lambda(t-t_p)\right)}{1-\exp\left(-\lambda(t_{i+1}-t_p)\right)} \in [0,1] \quad for \;\; t \in [t_p, t_{i+1}] \wedge t_p \in [t_i, t_{i+1}]$$

$$t = F^{-1}(\xi) = \frac{-1}{\lambda} \ln\left(1-(1-e^{-\lambda(t_{i+1}-t_p)})\xi\right) + t_p$$

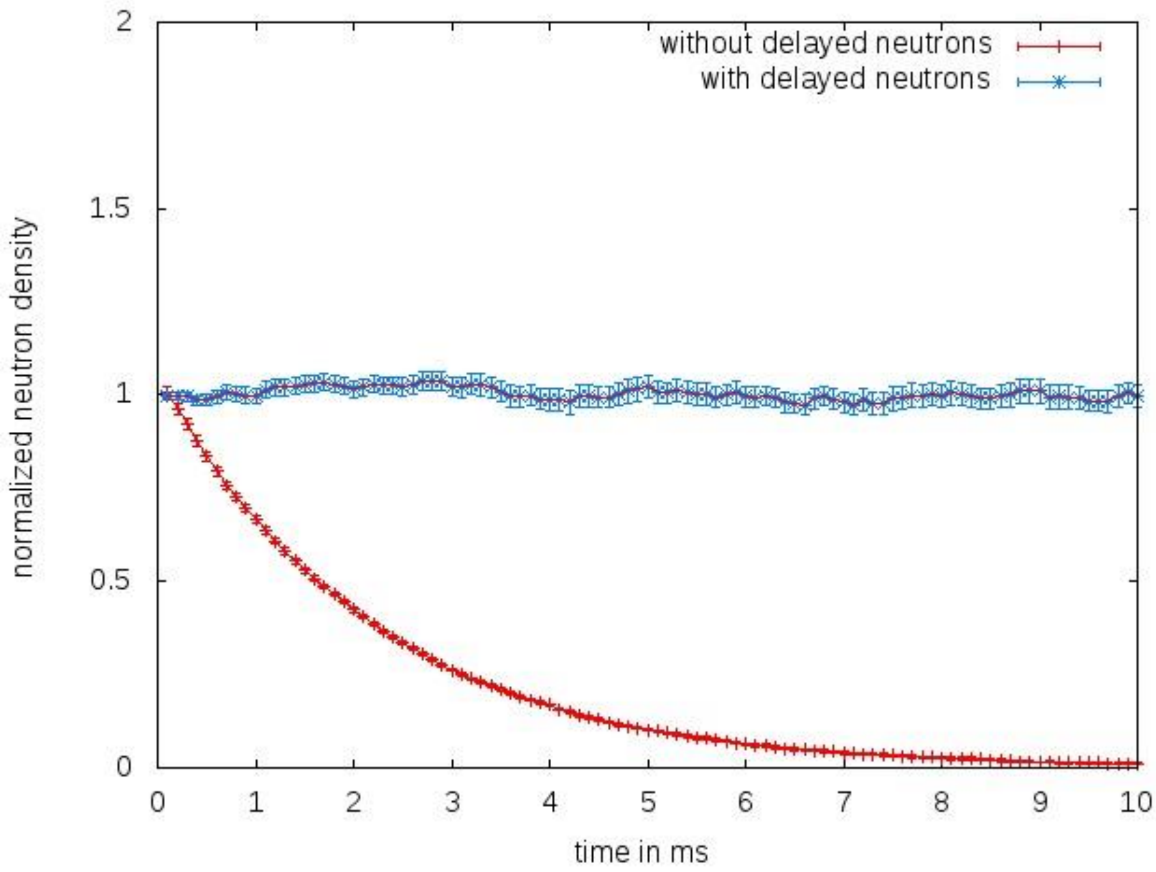
- Direction is sampled isotropically.
- The energy is sampled from the energy distribution of the corresponding precursor group.

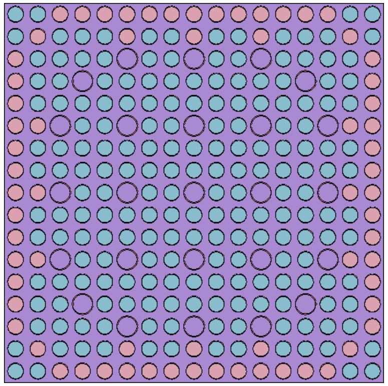
Next Step

- The neutrons which reach the interval boundary t_{i+1} are stored to be used for sampling live neutrons in the next time interval $[t_{i+1}, t_{i+2}]$.
- Precursors which do not decay in the current time interval $[t_i, t_{i+1}]$ are tallied to be used in the next time interval $[t_{i+1}, t_{i+2}]$ as source for delayed neutrons.
- The new $N_{del,s}(i+1)$ and $N_{live,s}(i+1)$ can be obtained from the number of precursors and live neutrons crossed t_{i+1} .

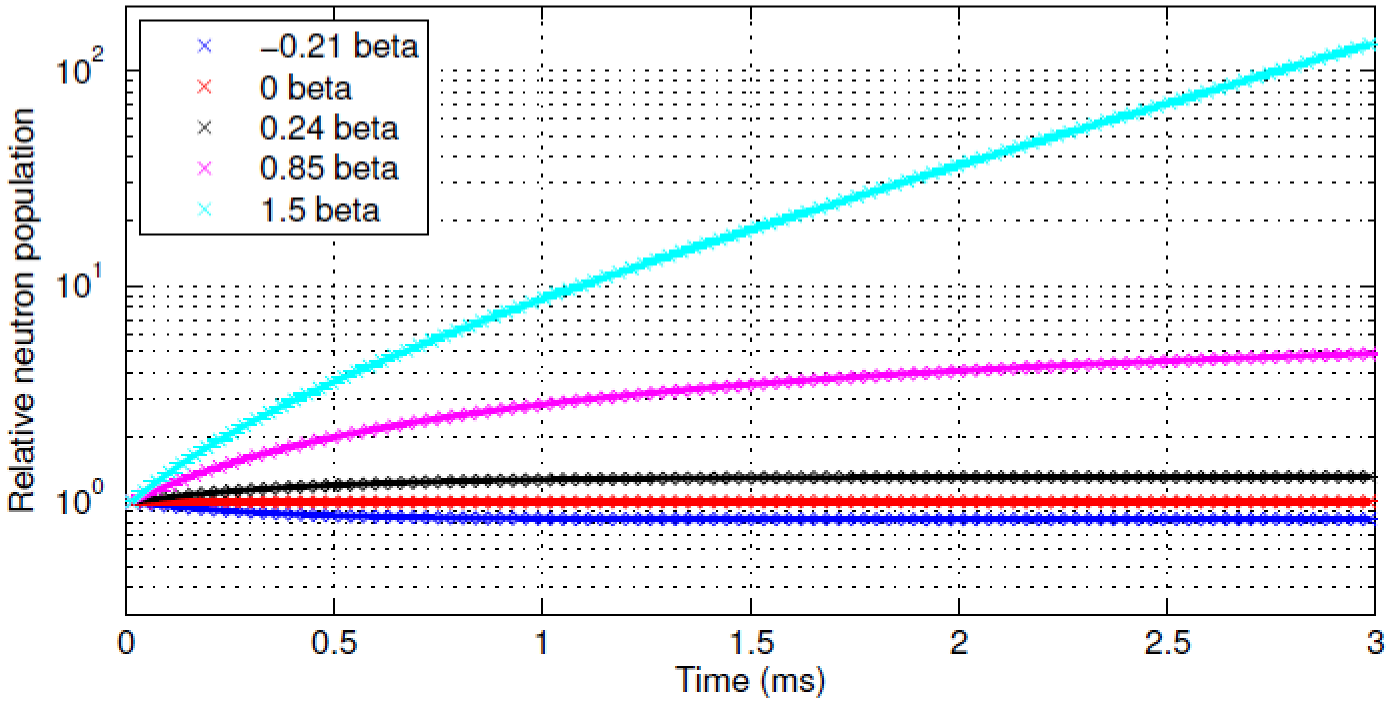

Initialization with critical source mode
t(0)→t(1)
Population control of delayed and live neutrons
Producing precursor
Determining the weight of precursors to decay and be tallied
Sampling delayed neutrons from decayed precursors
t(i) → t(i+1)
Time step boundary
Neutron transport

A Comparison Between Two Simulations with and without Delayed Neutrons in a Critical System.

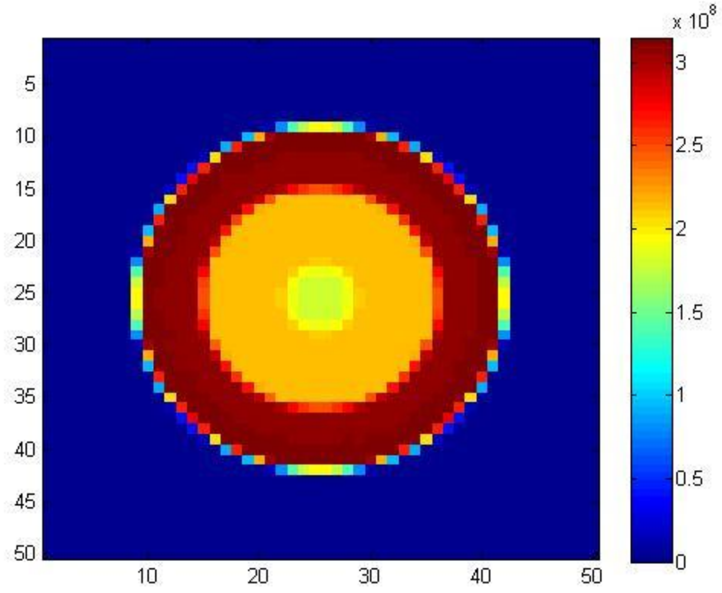




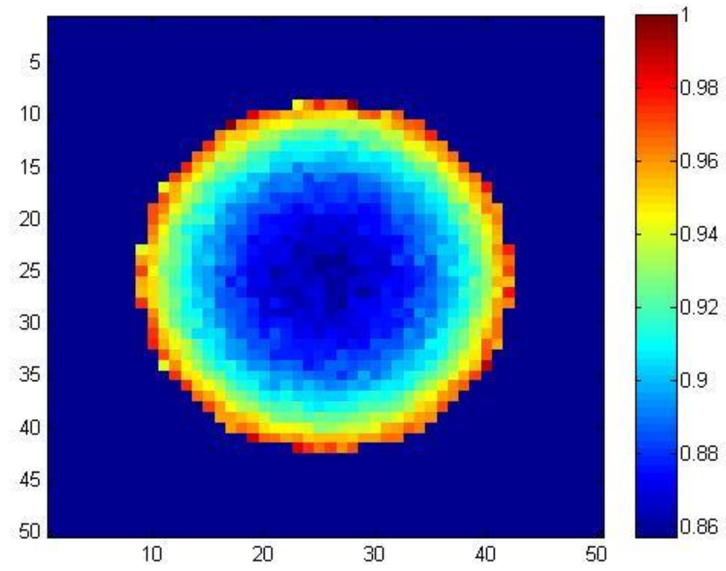
Point Kinetic Comparison



Spatial Distribution



Spatial distribution of precursor concentrations in a fuel rod with concentric structure.



Spatial distribution of precursor concentrations in a fuel rod normalized by initial fuel concentrations in fuel shells.

Open Questions

- Spatial distribution of delayed neutrons / precursors
- Sampling delayed neutrons from inhomogeneous mesh cells
- Group structures
- Variance reduction
- Temperature feedback and coupling with CFD.
- Scalability of dynamic mode with delayed neutrons.

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Thank you for your attention!

Questions?