Variance Reduction for Multiphysics Analysis of Moving Systems

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Dec. 8, 2017

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Shutdown Dose Rate Analysis

- Fusion Energy Systems (FES)
  - Burning plasma, D-T fusion
  - $^2H +^3 H \rightarrow^4_2 He + n$
- Neutrons penetrate deeply into system components, causing activation
- Radioisotopes persist long after shutdown
- Important to quantify the dose caused by decay photons

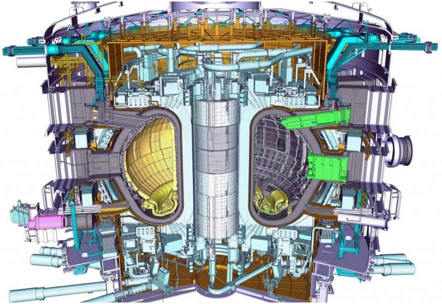


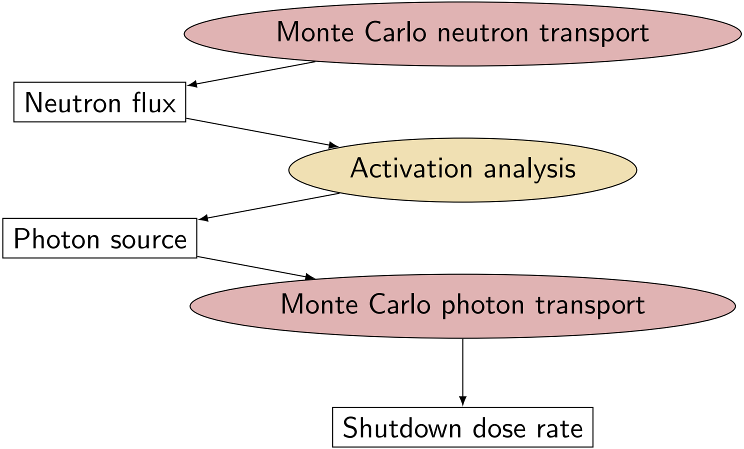
Figure: Cutaway view of ITER drawing.

SDR Analysis: Maintenance Operations

- During a maintenance procedure:
  - Need to move component(s) around facility
  - Interested in SDR at a particular location
  - SDR will change as a function of the activated component's position over time

SDR Solution Method

- Rigorous 2-Step Method (R2S)



Monte Carlo Radiation Transport

- Monte Carlo (MC) analysis of fusion energy systems is challenging due to the highly attenuating structural materials
  - Results scored in regions that have low particle flux, have higher statistical uncertainty
- To decrease statistical uncertainty:
  - Increase number of histories
  - Use variance reduction (VR) techniques

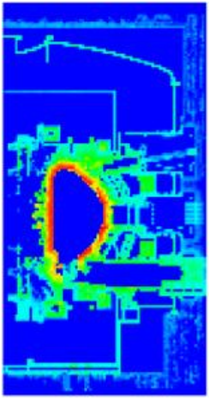


Figure: Photon flux in ITER tokamak building.

MC Variance Reduction Techniques

- Techniques to modify particle behavior
    - Preferentially sample events that will contribute to results of interest
- Statistical weight of particles is adjusted to keep playing a fair game

Hybrid Deterministic/MC VR Methods

- Use **deterministic** estimate of the adjoint flux, Ψ^+, to generate **Monte Carlo** biasing prarameters
- Adjoint flux can define the importance of regions of phase space to the detector response

$$H^+\Psi^+ = q^+ \tag{1}$$

$$H^+ = -\widehat{\Omega}\cdot\nabla + \sigma_t(\overrightarrow{r}, E) - \int_0^\infty dE' \int_{4\pi} d\Omega' \sigma_s(\overrightarrow{r}, E \rightarrow E', \widehat{\Omega} \rightarrow \widehat{\Omega}') \tag{2}$$

Hybrid Deterministic/MC VR Methods

- Consistent Adjoint Driven Importance Sampling (CADIS)
  - Use the adjoint flux to generate source and transport biasing parameters in a consistent manner
    - Source: sample from biased PDF
    - Transport: weight windows to control particle flow

Variance Reduction for SDR Analysis

- VR for photon transport step is straightforward
  - Can use CADIS method
    - Flux-to-dose conversion factors define adjoint source
- VR for neutron transport step is more complicated
  - Biasing function needs to capture
    1. Potential of regions to become activated
    2. Potential to produce photons that will contribute to the SDR

Variance Reduction for SDR Analysis

- Multi-Step (MS)-CADIS
  - VR method to optimize the initial radiation transport step of a coupled, multi-step process
  - When applied to SDR analysis, MS-CADIS will optimize the neutron transport
    - Use a function that represents the importance of the neutrons to the final dose rate

VR for SDR Analysis: GT-CADIS

- Groupwise Transmutation (GT)-CADIS
  - Implementation of MS-CADIS specifically for SDR analysis
  - Provides method to calculate optimal adjoint neutron source, q_n^+
    - This is used as the source in the deterministic calculation of the adjoint neutron flux, ϕ_n^+, used as the importance function

$$q_n^+(E_n) = \int_{E_p} T(E_n, E_p)\phi_p^+(E_p)dE_p$$

VR for SDR Analysis: GT-CADIS

- Coupling term, T, defined by

$$q_p(E_p) = \int_{E_n} T(E_n, E_p)\phi_n(E_n)dE_n$$