Variance Reduction for Multi-physics 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
    - ${}^2H + {}^3H \rightarrow {}^4_2He + n$
- Neutrons penetrate deeply into system components, causing activation
- Radioisotopes persist long after shutdown
- Important to quantify the dose caused by decay photons

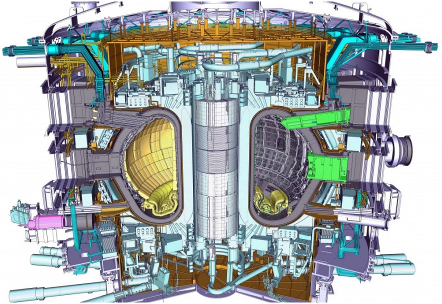
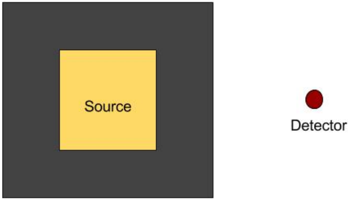


Figure : Cutaway view of ITER drawing.

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



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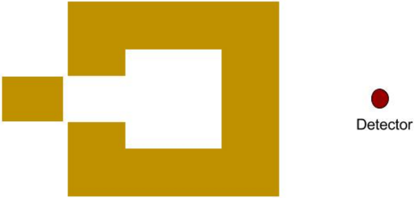

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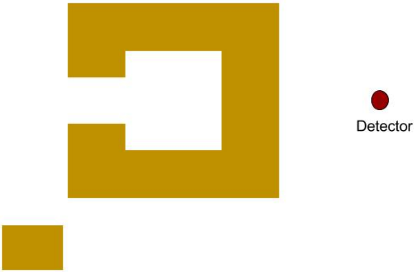

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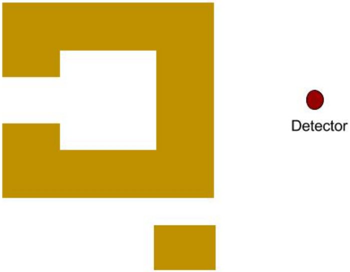

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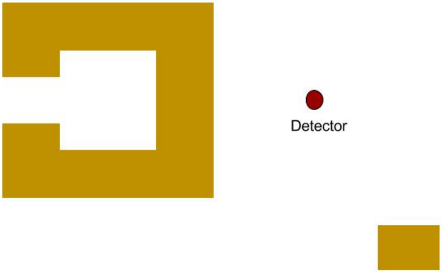

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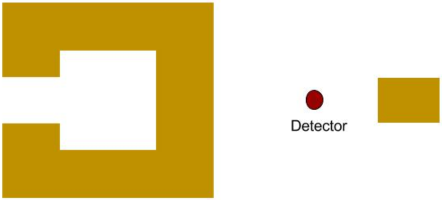
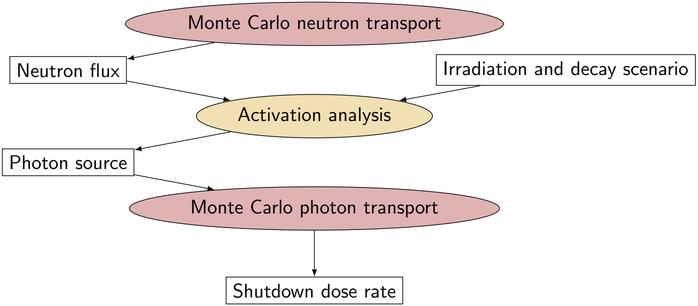


SDR Solution Method

- Rigorous 2-Step Method (R2S)



Monte Carlo Radiation Transport

- Monte Carlo (MC) analysis of fusion energy systems is:
  - Accurate for large, complex models
  - 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

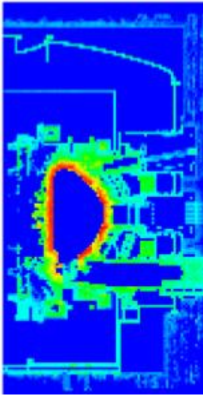


Figure : Photon flux in ITER tokamak building.

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: CADIS

- Consistent Adjoint Driven Importance Sampling (CADIS)
- Use **deterministic** estimate of the adjoint flux, Ψ^+, to generate **Monte Carlo** biasing parameters
- Adjoint flux can define the importance of regions of phase space to the detector response

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

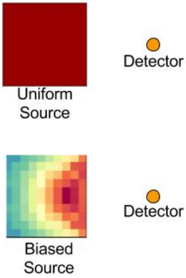
$$H^+ = -\widehat{\Omega}\cdot\nabla + \sigma_t(\overrightarrow{r}, E) - \int_0^\infty dE' \int_{4\pi} d\Omega' \sigma_s(\overrightarrow{r}, E \rightarrow E', \widehat{\Omega} \rightarrow \widehat{\Omega}') \tag{2}$$

- Adjoint transport $\sim$ "backwards" transport
- Detector response function is the adjoint source

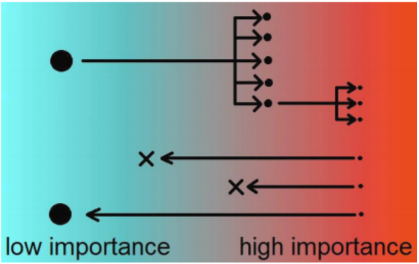
Hybrid Deterministic/MC VR Methods: CADIS

- Use the adjoint flux to generate MC source and transport biasing parameters in a consistent manner
  - Source: sample from biased PDF
  - Transport: weight windows to control particle flow

- Uniform vs. biased source distribution



- Splitting/rouletting with weight windows



Variance Reduction for SDR Analysis

- VR for **photon** transport step is **straightforward**
  - Can use CADIS method to direct photons towards detector
    - Flux-to-dose-rate 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
  - Can use CADIS if we can construct adjoint source that will fulfill these criteria

Variance Reduction for SDR Analysis: MS-CADIS

- 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

$$\int_{\overrightarrow{r}} \int_{E_n} \phi_n(\overrightarrow{r}, E_n) q_n^+(\overrightarrow{r}, E_n) d\overrightarrow{r} dE_n = SDR \tag{3}$$

$$SDR = \int_{\overrightarrow{r}} \int_{E_\gamma} \phi_\gamma^+(\overrightarrow{r}, E_\gamma) q_\gamma(\overrightarrow{r}, E_\gamma) dr dE_\gamma \tag{4}$$

Variance Reduction for SDR Analysis: MS-CADIS

- Combining these equations:

$$\int_{\overrightarrow{r}} \int_{E_n} \phi_n(\overrightarrow{r}, E_n) q_n^+(\overrightarrow{r}, E_n) d\overrightarrow{r} dE_n = \int_{\overrightarrow{r}} \int_{E_\gamma} \phi_\gamma^+(\overrightarrow{r}, E_\gamma) q_\gamma(\overrightarrow{r}, E_\gamma) d\overrightarrow{r} dE_\gamma \tag{5}$$

- To solve for the adjoint neutron source, q_n^+, a relationship between q_γ and ϕ_n is required

$$q_\gamma(E_\gamma) = \int_{E_n} T(E_n, E_\gamma) \phi_n(E_n) dE_n \tag{6}$$

Variance Reduction 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^+, by first calculating, T
  - Calculate T:
    1. Irradiate each material with neutrons from a single energy group, g
    2. Record resulting photon emission in each energy group, h

$$T_{g,h} = \frac{q_{\gamma,h}(\phi_{n,g})}{\phi_{n,g}} \tag{7}$$

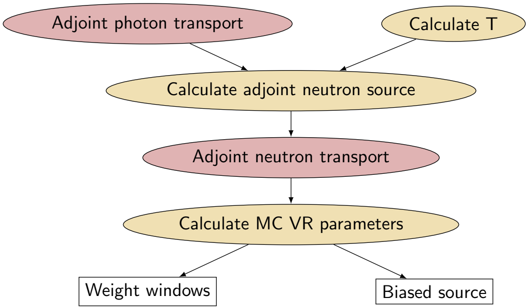
Variance Reduction for SDR Analysis: GT-CADIS

- Use T to solve for adjoint neutron source:

$$q_n^+(E_n) = \int_{E_\gamma} T(E_n, E_\gamma)\phi_\gamma^+(E_\gamma)dE_\gamma \tag{8}$$

- This is used as the source in the deterministic calculation of the adjoint neutron flux, ϕ_n^+

- GT-CADIS workflow



GT-CADIS Demonstration

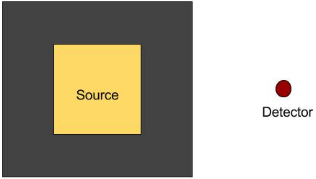


Figure : Demo model. Steel chamber, walls are 2 m thick. 14 MeV neutron source in center. Chamber surrounded by air.

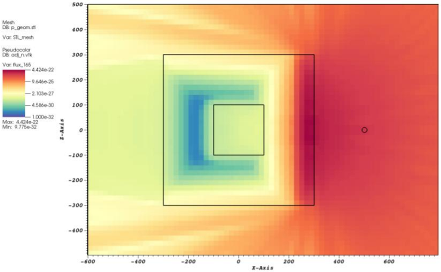
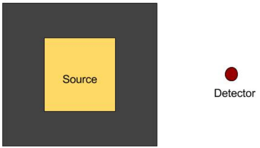


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

GT-CADIS Demonstration

GT-CADIS importance map is **insufficient** for moving systems.



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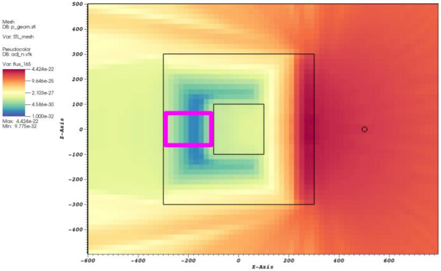

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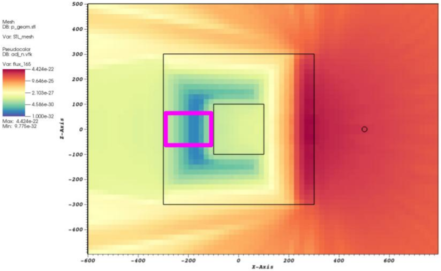

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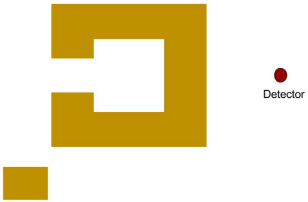

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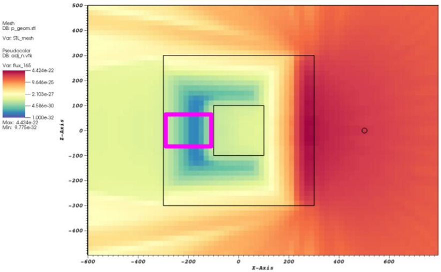

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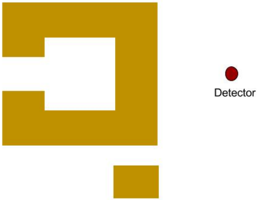

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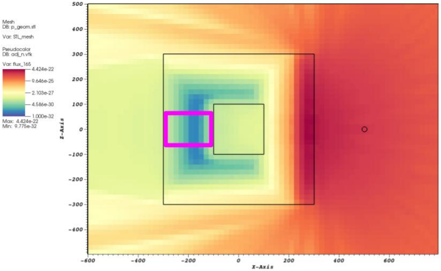

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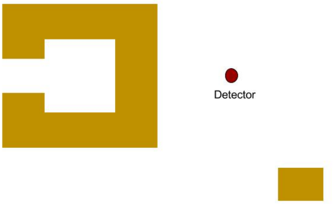

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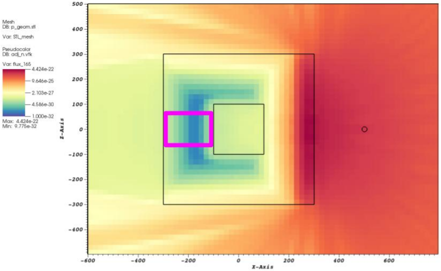

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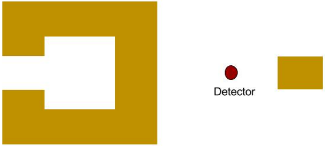

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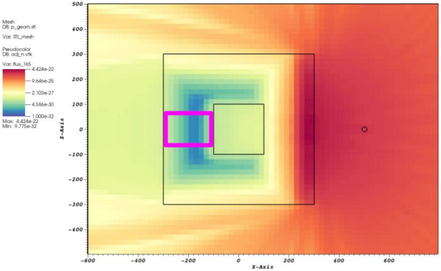

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Derive New Adjoint Neutron Source

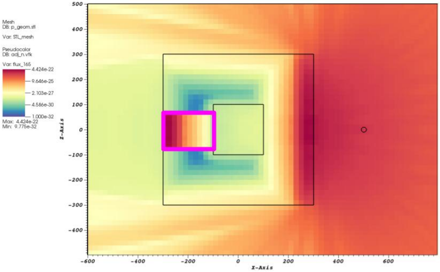
- Geometry movement during photon transport effects the construction of the adjoint neutron source
- Need to:
  1. Perform adjoint photon transport at each time step of geometry movement
  2. Integrate over time

$$q^{+}_{n,v}(E_n) = \int_t \int_{E_\gamma} T_v(E_n, E_\gamma, t)\phi^{+}_{\gamma}(\overrightarrow{r}_v(t), E_\gamma, t)\, dE_\gamma\, dt \tag{9}$$

- $\phi^{+}_{\gamma}(\overrightarrow{r}_v(t), E_\gamma, t)$ is the adjoint flux of photons of energy E_γ, in volume element v, at time t
- $T_v(E_n, E_\gamma, t)$ is the T value of the material in volume element v, at decay time t

Time-integrated GT-CADIS

- Perform deterministic adjoint neutron transport using the time-integrated source
- Resultant adjoint neutron flux should look something like this:



- Use this adjoint neutron flux to generate biasing parameters that will optimize the MC neutron transport step of R2S.

Time-integrated GT-CADIS

- Assumptions
  - Photon transport occurs much faster than geometry movement $\therefore$ reasonable to do quasi-static simulation
  - Period of geometry movement is short enough that the photon source will not change appreciably $\therefore$ can use same photon source for all MC calculations
- Challenges
  - Depending on complexity of model and fidelity of time resolution, can amass large number of CAD geometry files, volume mesh tally files
  - Need to optimize this workflow in order to keep file storage at minimum