Variance Reduction for Multi-physics Analysis of Moving Systems

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Preliminary Exam

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Shutdown Dose Rate (SDR) Analysis

- Fusion Energy Systems (FES)
  - Burning plasma, D-T fusion
  - ${}_1^2H +_1^3 H \rightarrow_2^4 He +_0^1 n$
- Neutrons penetrate deeply into system components, causing activation
- Radioisotopes persist long after shutdown
- Important to quantify the dose caused by decay photons

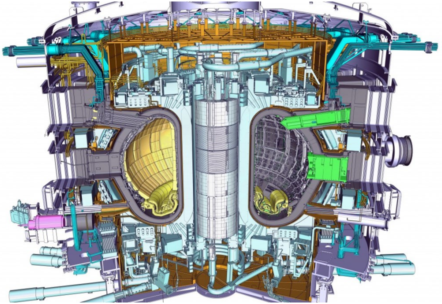
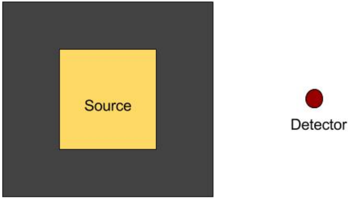


Figure : Cutaway view of ITER drawing.

SDR Analysis: Movement After Shutdown

- Example: 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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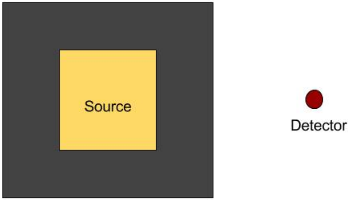

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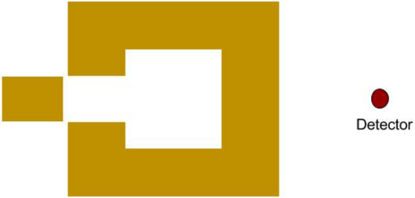

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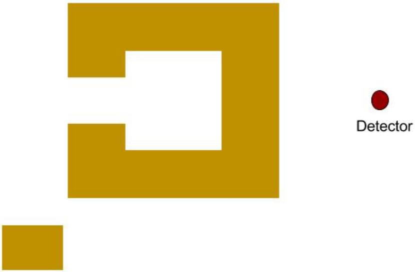

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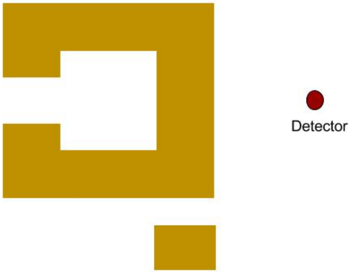

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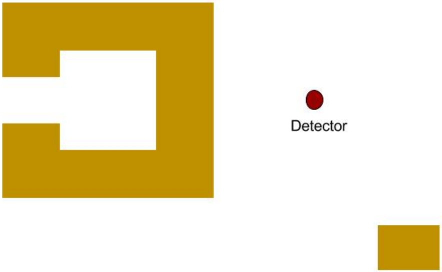

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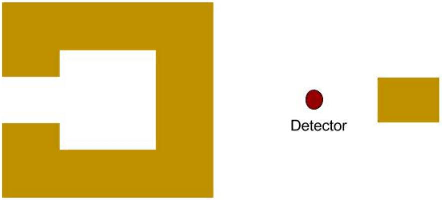

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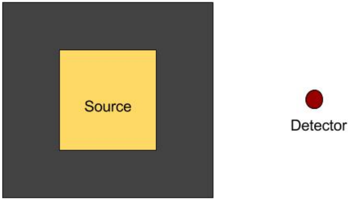


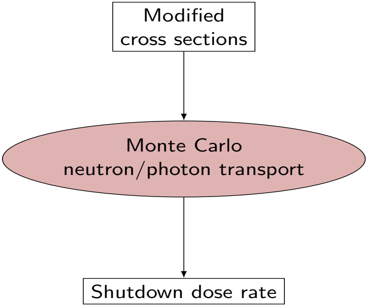
Goal

Optimize the **radiation transport** simulation used to calculate the **shutdown dose rate** at a particular location as activated components are **moving** around the facility.

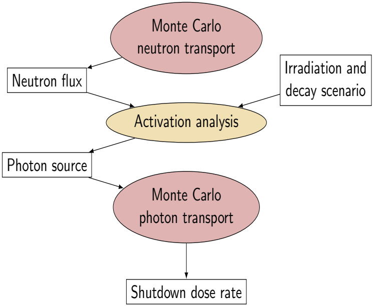
Deterministic vs. MC

SDR Solution Methods

- Direct 1-Step Method (D1S)



- Rigorous 2-Step Method (R2S)



Add pros/cons of D1S, 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

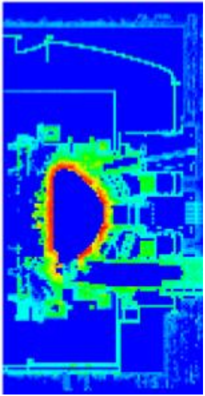


Figure : Photon flux in ITER tokamak building.

Stat error in MC and intro VR

MC Variance Reduction Techniques

- Techniques to modify particle behavior
  - **Goal:** 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)

- Adjoint flux can define the importance of regions of phase space to the detector response
- Use **deterministic** estimate of the adjoint flux, Ψ^+, to generate **Monte Carlo** VR parameters in a **consistent** manner
  - Define detector response function to be the adjoint source

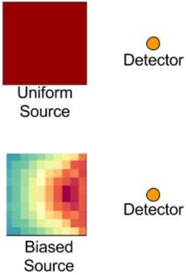
$$H^+\Psi^+ = q^+ \tag{1}$$

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

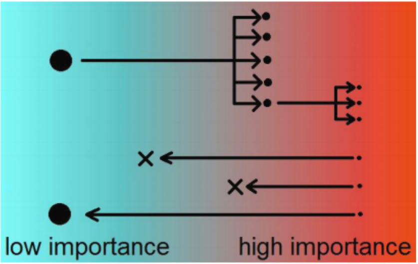
Hybrid Deterministic/MC VR Methods: CADIS

- Use the adjoint flux to generate MC source and transport biasing parameters

Source: sample from biased PDF



Transport: weight windows



Variance Reduction for SDR Analysis

VR for **photon** transport

- **Straightforward**
- Can use CADIS method to direct photons towards detector
  - Flux-to-dose-rate conversion factors define adjoint source

VR for **neutron** transport

- 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
  - Relies upon function that represents importance of particles to final response of interest
- When applied to SDR analysis, MS-CADIS will optimize the neutron transport
  - Use function that represents the importance of the neutrons to the final dose rate

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

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

Variance Reduction for SDR Analysis: MS-CADIS

- Combining these equations:

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

- 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

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

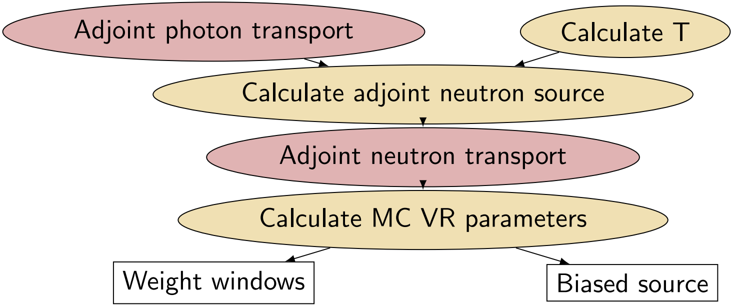
Variance Reduction for SDR Analysis: GT-CADIS

- Use T to solve for adjoint neutron source:

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

Variance Reduction for SDR Analysis: GT-CADIS

- GT-CADIS workflow



GT-CADIS Demonstration

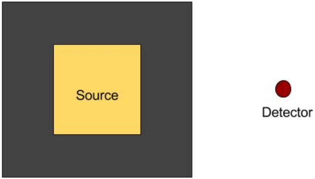


Figure : Demo model. Steel chamber, walls are 2 m thick. 14 MeV neutron source in center. Chamber surrounded by air.

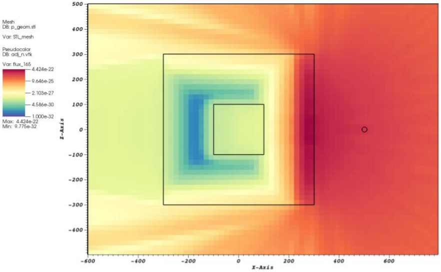
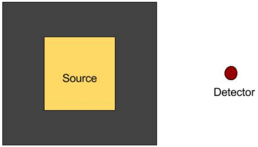


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

GT-CADIS Demonstration

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



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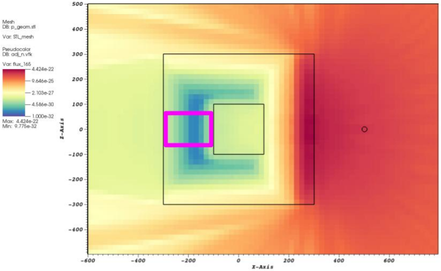

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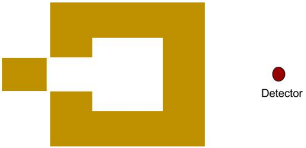

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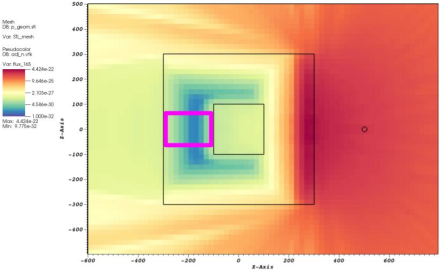

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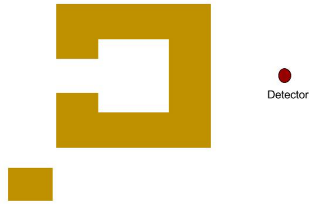

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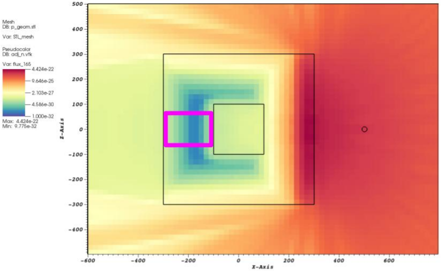

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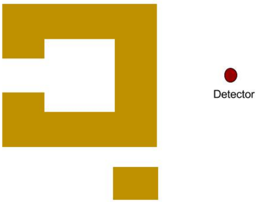

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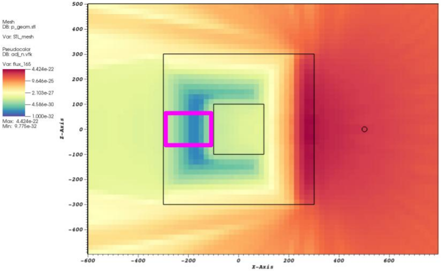

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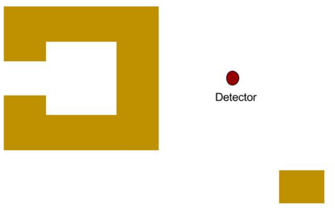

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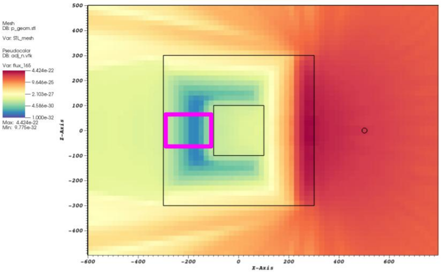

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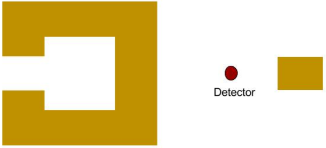

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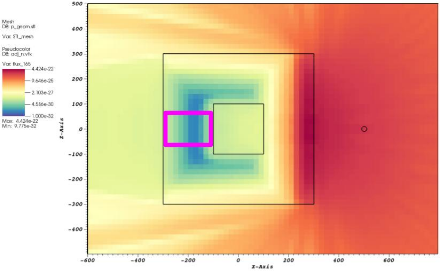

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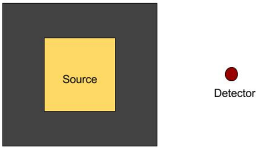

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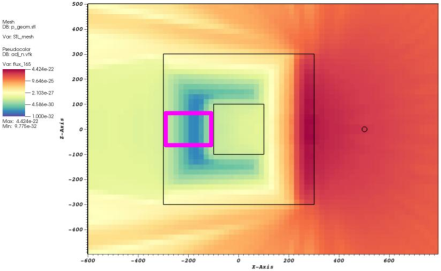

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Derive New Adjoint Neutron Source

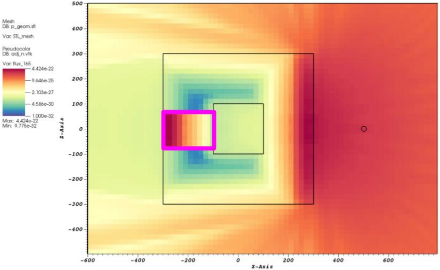
- Geometry movement during photon transport effects the construction of the adjoint neutron source
- Need to:
  1. Perform adjoint photon transport at each time step of geometry movement
  2. Integrate over time

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

- $\phi^{+}_{\gamma}(\overrightarrow{r}_v(t), E_\gamma, t)$ 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

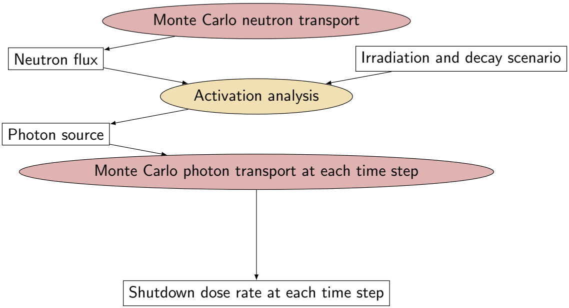
- Perform deterministic adjoint neutron transport using the time-integrated source
- Resultant adjoint neutron flux should look something like this:



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

Time-integrated R2S

- R2S workflow for geometry movement after shutdown



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

Questions?