

Variance Reduction for Multiphysics Analysis of Moving Systems

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

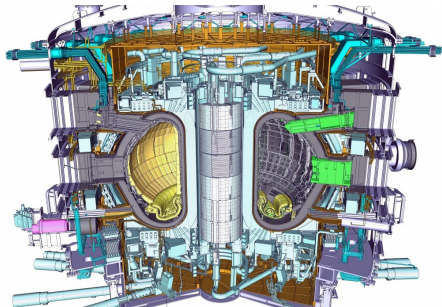
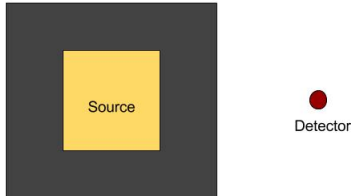


Figure : Cutaway view of ITER drawing.

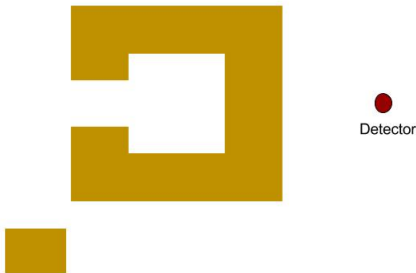
- During a maintenance procedure:
 - Need to move component(s) around facility
 - Interested in SDR at a particular location
 - SDR will change as a function of the activated component's position over time



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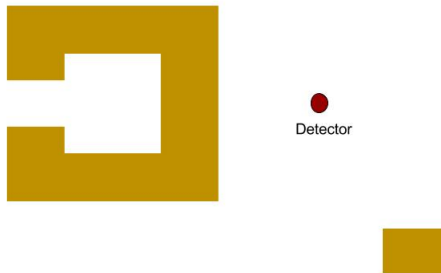
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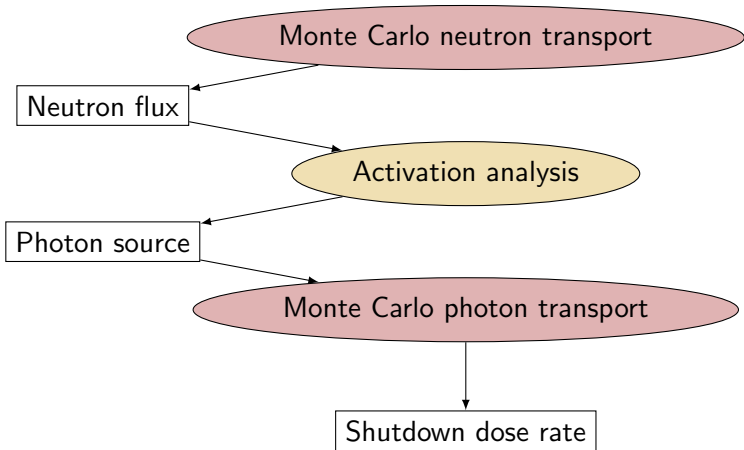
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- Rigorous 2-Step Method (R2S)



- 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

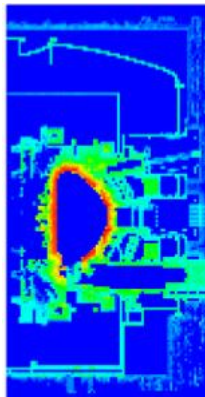


Figure : Photon flux in ITER tokamak building.



- 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

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

$$H^+ \Psi^+ = q^+ \quad (1)$$

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



- 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
 - *Particles are born within weight windows
- weight window pic
- biased source pic

- 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
 - Can use CADIS if an adjoint source that will fulfill these criteria is found

- 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

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

$$SDR = \int_{\vec{r}} \int_{E_p} \phi_p^+(\vec{r}, E_p) q_p(\vec{r}, E_p) dr dE_p \quad (4)$$

Combining these equations:

$$\int_{\vec{r}} \int_{E_n} \phi_n(\vec{r}, E_n) q_n^+(\vec{r}, E_n) d\vec{r} dE_n = \int_{\vec{r}} \int_{E_p} \phi_p^+(\vec{r}, E_p) q_p(\vec{r}, E_p) d\vec{r} dE_p \quad (5)$$

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

$$q_p(E_p) = \int_{E_n} T(E_n, E_p) \phi_n(E_n) dE_n \quad (6)$$

- 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

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



- Use T to solve for adjoint neutron source:

$$q_n^+(E_n) = \int_{E_p} T(E_n, E_p) \phi_p^+(E_p) dE_p \quad (8)$$

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

GT-CADIS workflow

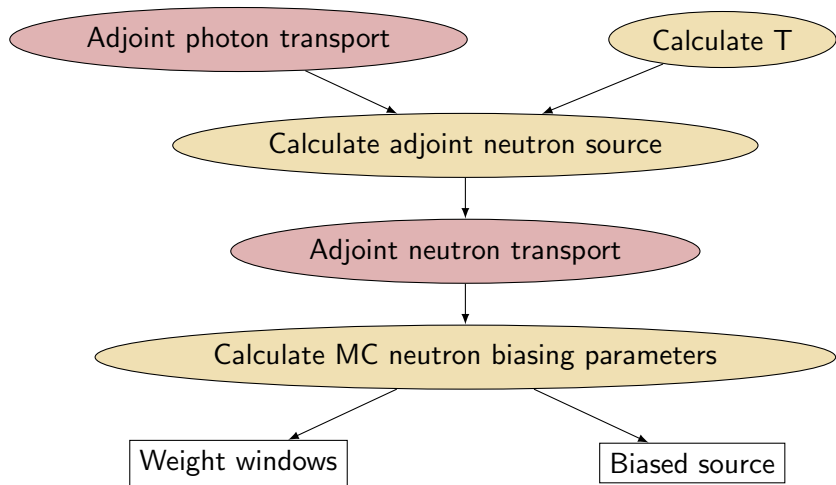




Figure : Demo model. Steel chamber, walls are 2 m thick. 14 MeV neutron source in center. Chamber surrounded by air.

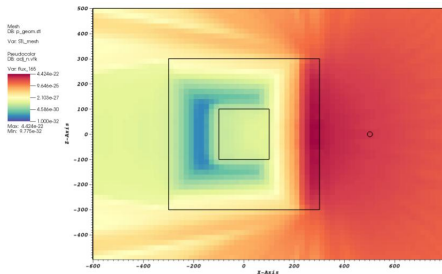


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

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



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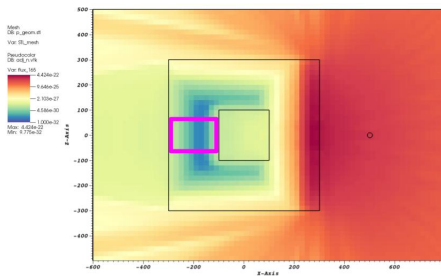


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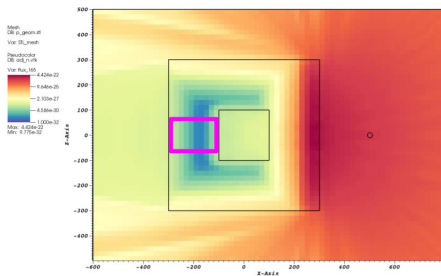


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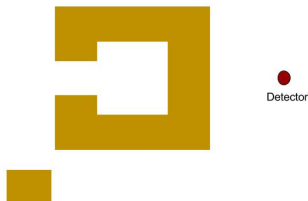


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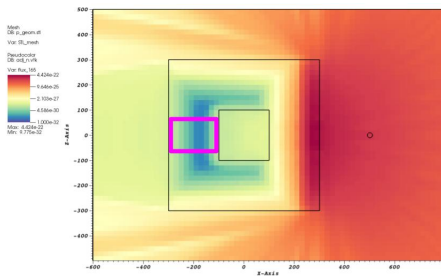


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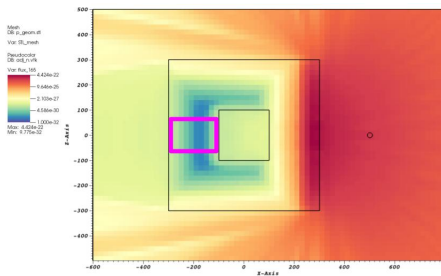


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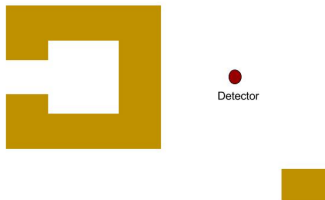


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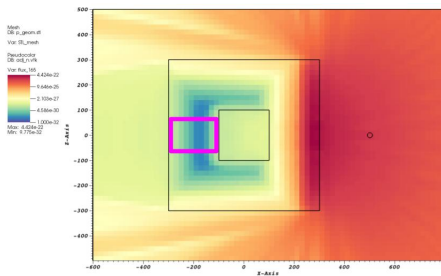


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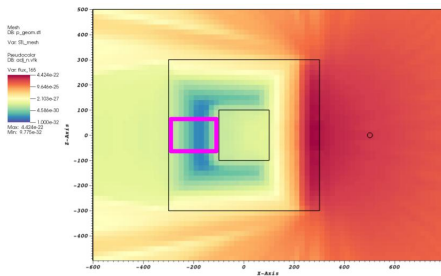


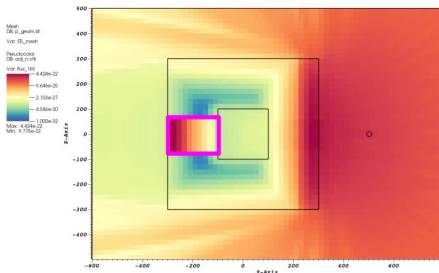
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- Geometry movement during photon transport effects the construction of the adjoint neutron source
- Need to:
 - ① Perform adjoint photon transport at each time step of geometry movement
 - ② Integrate the adjoint photon flux over time

$$q_{n,v}^+(E_n) = \int_t \int_{E_\gamma} T_v(E_n, E_\gamma, t) \phi_\gamma^+(\vec{r}_v(t), E_\gamma, t) dE_\gamma dt \quad (9)$$

- $\phi_\gamma^+(\vec{r}_v(t), E_\gamma, t)$ 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

- 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.