Variance Reduction for Multi-physics Analysis of Moving Systems

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Preliminary Exam

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Introduction

Shutdown Dose Rate (SDR) Analysis

- Fusion Energy Systems (FES)
  - Burning plasma, D-T fusion
  - ${}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n$
- Neutrons penetrate deeply into system components, causing activation
- Radioisotopes persist long after shutdown
- Important to quantify the dose caused by decay photons

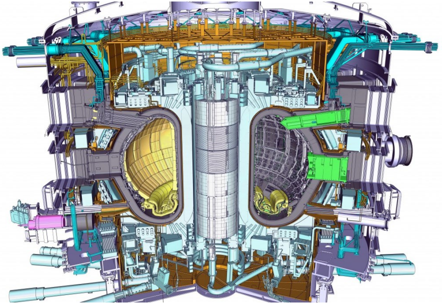
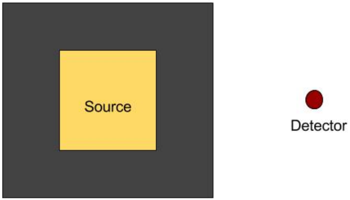


Figure : Cutaway view of ITER drawing.

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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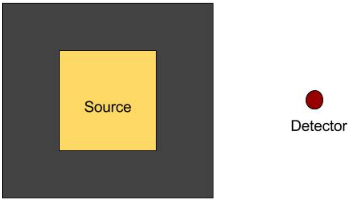

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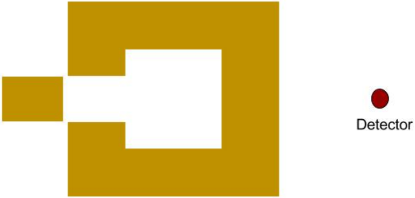

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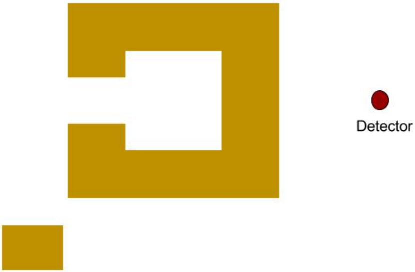

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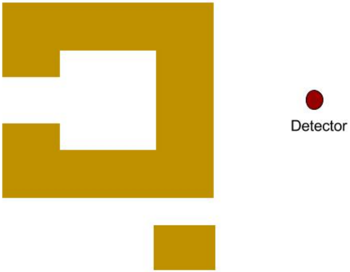

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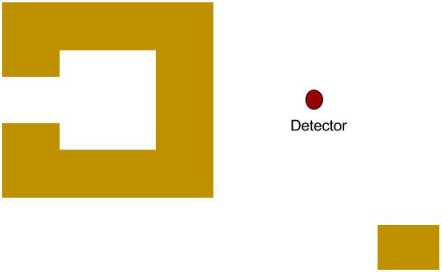

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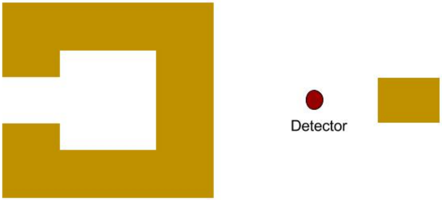

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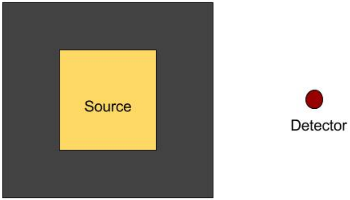


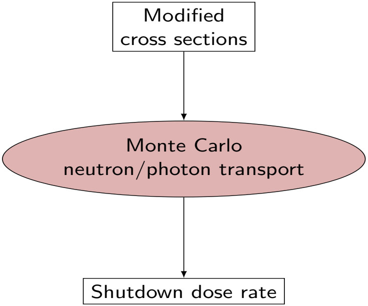
Goal

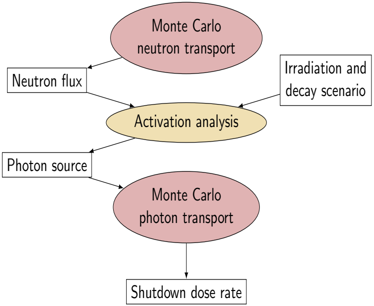
Optimize the **radiation transport** simulation used to calculate the **shutdown dose rate** at a particular location as activated components are **moving** around the facility.

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

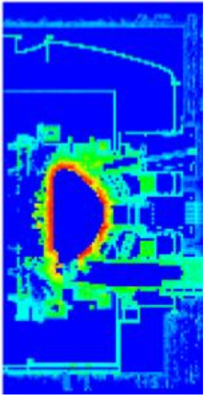


Figure : Photon flux in ITER tokamak building.

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

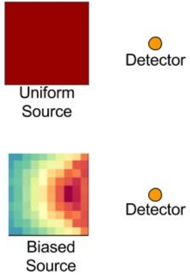
$$H^+\Psi^+ = q^+ \tag{1}$$

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

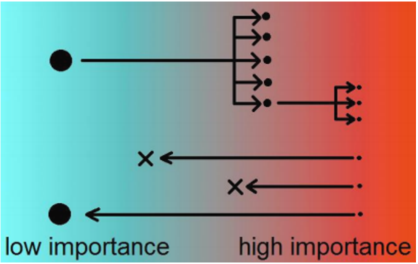
Hybrid Deterministic/MC VR Methods: CADIS

- 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-**S**tep (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

- **G**roupwise **T**ransmutation (GT)-CADIS
  - Implementation of MS-CADIS specifically for SDR analysis
  - Provides method to calculate optimal adjoint neutron source, q_n^+, by first calculating, T, a term that relates the neutron flux to photon source
  - Calculate T: (move this to later slide)
    1. Irradiate each material with neutrons from a single energy group, g
    2. Record resulting photon emission in each energy group, h

$$T_{g,h} = \frac{q_{\gamma,h}(\phi_{n,g})}{\phi_{n,g}} \tag{3}$$

Variance Reduction for SDR Analysis: GT-CADIS

- MOVE:Use T to solve for adjoint neutron source:

$$q_n^+(E_n) = \int_{E_\gamma} T(E_n, E_\gamma)\phi_\gamma^+(E_\gamma)dE_\gamma \quad (4)$$

Moving Geometries and Sources

MCNP6 Moving Objects

- Update in future version of MCNP6
- Allows movement of objects, sources, delayed particles during single simulation
- Available for native MCNP geometry descriptions (not mesh)

Mesh Coupled implementation of R2S (MCR2S)

- Capability that allows components to move before photon transport step
- Transformations are applied to copies of moving components
- Original component still in original location, set to void material

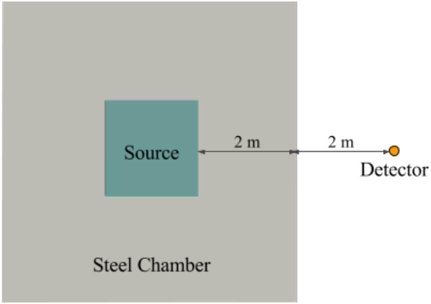
Review

- MC method is most accurate way to obtain detailed particle flux distributions
    - Use MC codes for both neutron and photon transport steps of R2S
    - Need to use VR methods to optimize the transport calculations
- GT-CADIS, an implementation of MS-CADIS, has proven to optimize the neutron transport step of R2S
- MCNP6 and MCR2S have developed some capabilities for performing transport on moving geometries

Demonstration

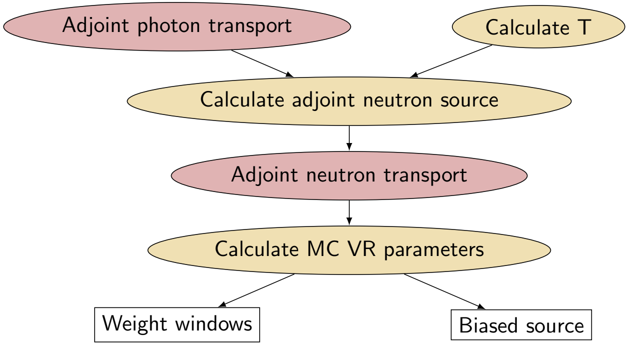
GT-CADIS Demonstration

- Geometry
  - Steel chamber
  - 2m x 2m x 2m central cavity
- Source
  - Volume source in central cavity
  - 13.8-14.2 MeV neutrons



Variance Reduction for SDR Analysis: GT-CADIS

- GT-CADIS workflow



GT-CADIS Demonstration

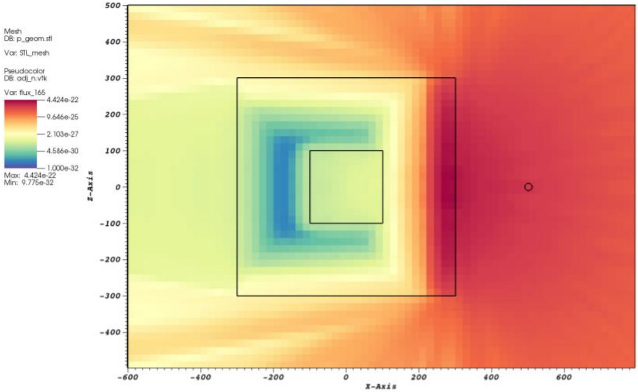


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

GT-CADIS Demonstration

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

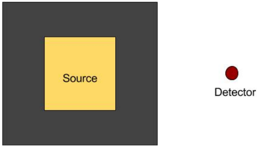
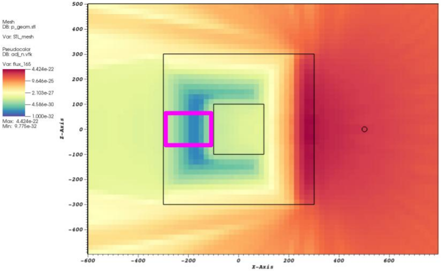


Figure : Demo model. Steel chamber, walls are 2 m thick. 14 MeV neutron source in center. Chamber surrounded by air.



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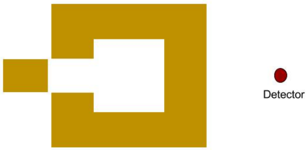

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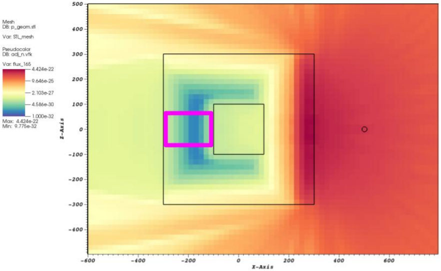

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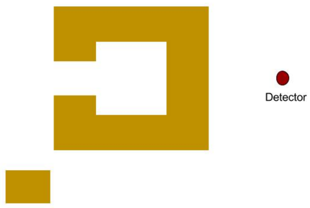

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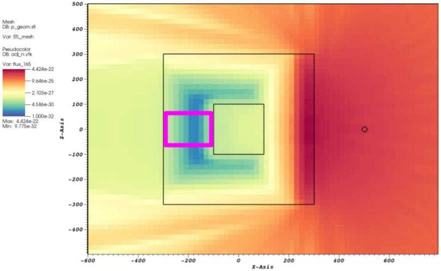

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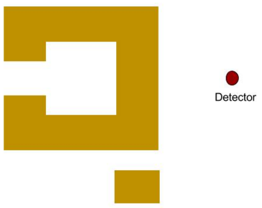

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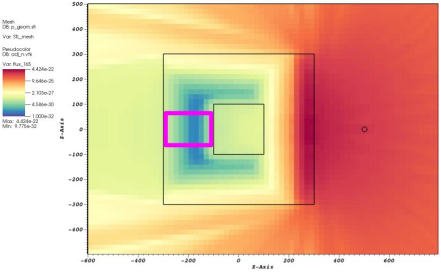

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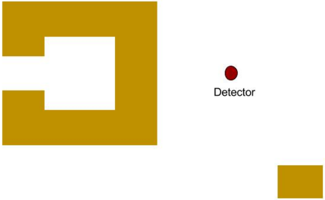

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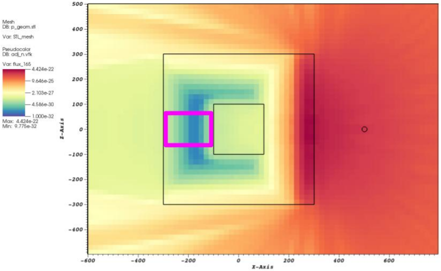

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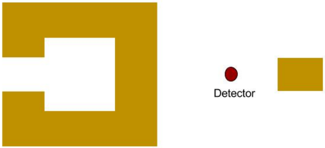

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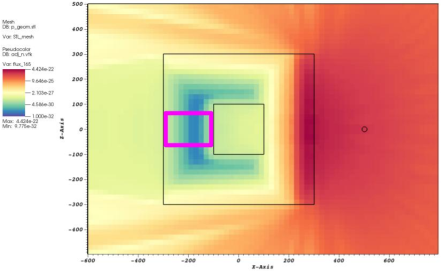

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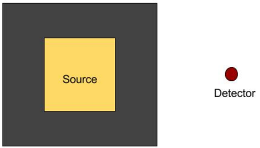

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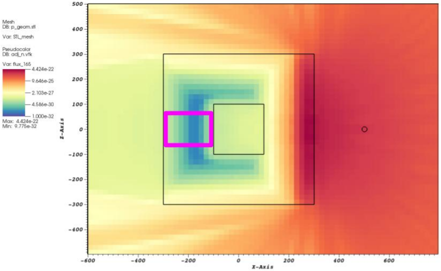

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Proposal

VR for Time-integrated Multi-physics Analysis

- MS-CADIS optimizes initial radiation transport step in a coupled, multi-step process
- Need to derive new adj neutron source

Generalized MS-CADIS

- System of coupled, multi-physics:

$$Primary : H\phi(u) = q(u) \tag{5}$$

$$Secondary : L\Psi(v) = b(v) \tag{6}$$

- Adjoint identities:

$$\langle \phi^{+}, q \rangle = \langle \phi, q^{+} \rangle \tag{7}$$

$$\langle \Psi^{+}, b \rangle = \langle \Psi, b^{+} \rangle \tag{8}$$

- MS-CADIS requires a representation of the relationship between primary and secondary physics:

$$b(v) = \langle \sigma_b(u, v), \phi(u) \rangle, \tag{9}$$

Solving for the Adjoint Primary Source

- Response to secondary physics:

$$R_{final} = \langle \omega_R(v), \psi(v) \rangle \tag{10}$$

- Set ω_R as adjoint source and invoke adjoint identity:

$$R_{final} = \langle \omega_R, \psi \rangle = \langle b, \psi_R^+ \rangle \tag{11}$$

- Substitute Eq. 9 :

$$R_{final} = \Big\langle \ \langle \sigma_b(u,v), \phi(u) \rangle, \ \psi_R^+(v) \ \Big\rangle \tag{12}$$

Solving for the Adjoint Primary Source

- Switch the order of integration

$$R_{final} = \Big\langle\ \langle \sigma_b(u,v), \psi_R^+(v) \rangle,\ \phi(u)\ \Big\rangle \tag{13}$$

- Set response of primary physics equal to final response of the system and invoke the adjoint identity to solve for q^+:

$$R_{final} = \Big\langle\ \langle \sigma_b(u,v), \psi_R^+(v) \rangle,\ \phi(u)\ \Big\rangle = \langle q(u), \phi_R^+(u) \rangle, \tag{14}$$

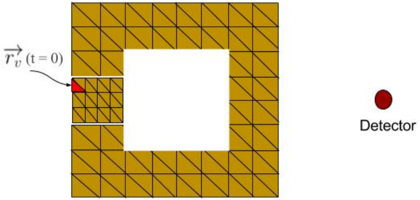
$$q^+(u) \equiv \langle \sigma_b(u,v), \psi_R^+(v) \rangle. \tag{15}$$

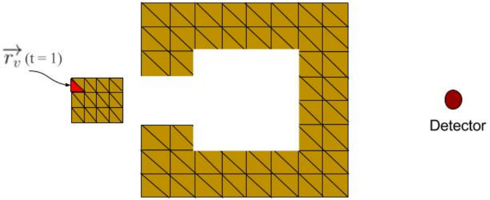
Time-integrated Adjoint Neutron Source

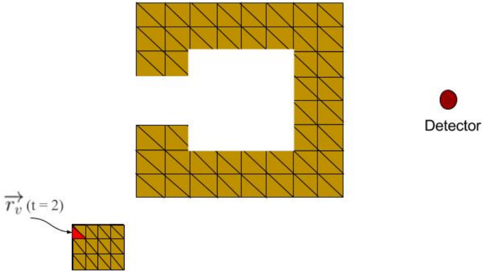
- Geometry movement during secondary physics effects the construction of the adjoint neutron source

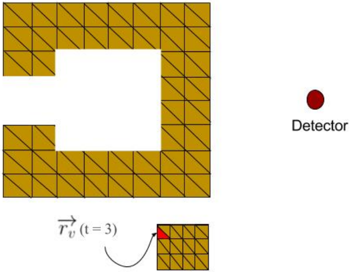
$$q_v^+ = \int_t \Psi^+(\overrightarrow{r}_v(t), t)\sigma_{c,v}(t)\, dt \tag{16}$$

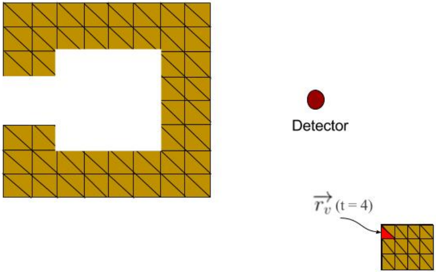
- Adjoint flux in volume element v at time t: $\Psi^+(\overrightarrow{r}_v(t), t)$
- Position of volume element v at time t: $\overrightarrow{r}_v(t)$

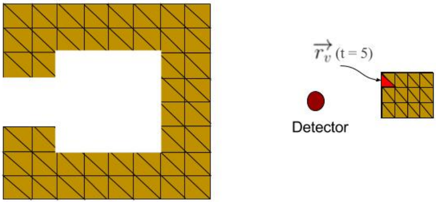

$\overrightarrow{r_v}$ (t = 0)
Detector


$\overrightarrow{r_v}$ (t = 1)
Detector


$\overrightarrow{r_v}$ (t = 2)
Detector


Detector
$\overrightarrow{r'_v}$ (t = 3)


Detector
$\overrightarrow{r_v}$ (t = 4)



$\overrightarrow{r_v}$ (t = 5)
Detector

Time-integrated GT-CADIS

- To apply time-integration to GT-CADIS:
  1. Perform adjoint photon transport at each time step of geometry movement
  2. Integrate over time

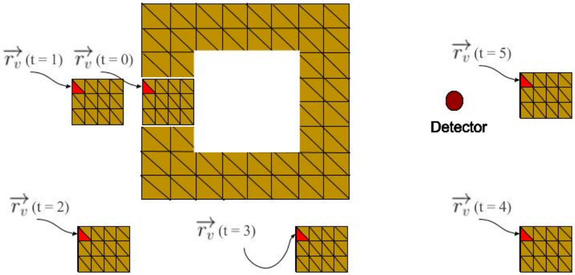
$$q^+_{n,v}(E_n) = \int_t \int_{E_\gamma} T_v(E_n, E_\gamma, t)\phi^+_\gamma(\overrightarrow{r}_v(t), E_\gamma, t)\, dE_\gamma\, dt \tag{17}$$

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

- Average the adjoint photon flux calculated at each time step

$$\phi^{+}_{\gamma,v,h} = \frac{\sum_{t_{mov}} \phi^{+}_{\gamma,v,h,t_{mov}} \Delta t_{mov}}{t_{tot}} \tag{18}$$



Time-integrated Adjoint Neutron Source

- Calculate T for each voxel

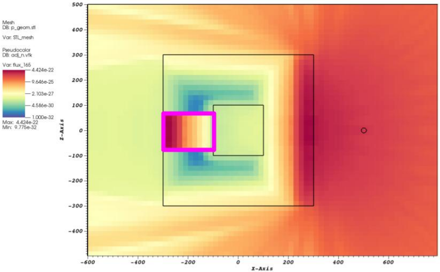
$$T_{v,g,h} = \frac{q_{\gamma,v,h}(\phi_{n,v,g})}{\phi_{n,v,g}} \tag{19}$$

- Combine with adjoint photon flux in each voxel

$$q^{+}_{n,v,g} = \frac{\sum_{t_{mov}} \left(\sum_{h} T_{v,g,h} \phi^{+}_{\gamma,v,h,t_{mov}} \right) \Delta t_{mov}}{t_{tot}} \tag{20}$$

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.

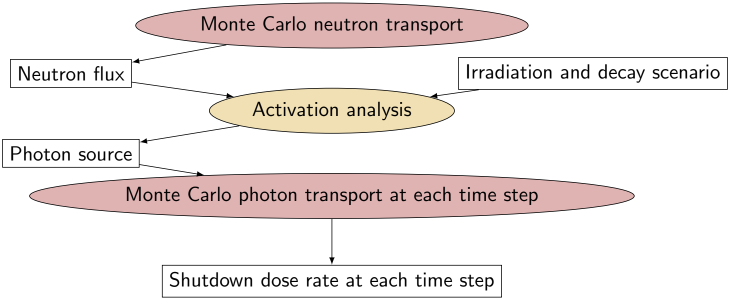
Progress: MC Moving Geometry Simulations

- Tools to update position of geometry based on user-defined motion data
  1. Tool to produce step-wise geometry files
  2. DAGMC update to facilitate on-the-fly geometry transformations
- Common functionality:
  -

Implementation plan

Time-integrated R2S: Analog

- R2S workflow for geometry movement after shutdown



TGT-CADIS: Generate VR Parameters

-

Time-integrated R2S: Neutron and Photon VR

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

Summary

Questions?