

Variance Reduction for Multi-physics Analysis of Moving Systems

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Preliminary Exam

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Introduction

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

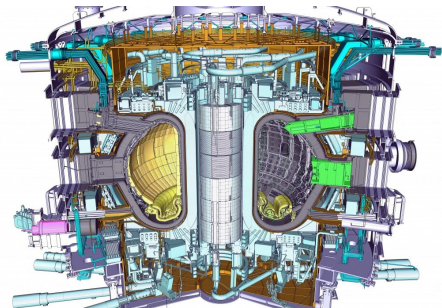
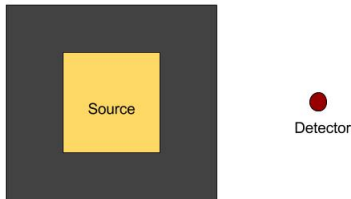


Figure : Cutaway view of ITER drawing.

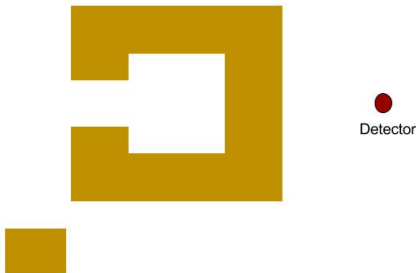
- FES are designed with modular components
 - Can move during maintenance procedure
- Interested in SDR at a particular location
- SDR will change as a function of the activated component's position over time



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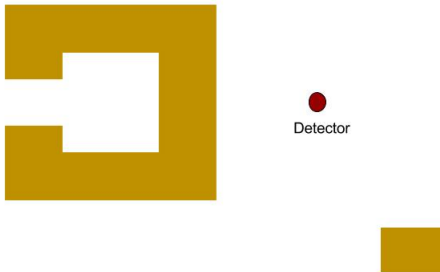
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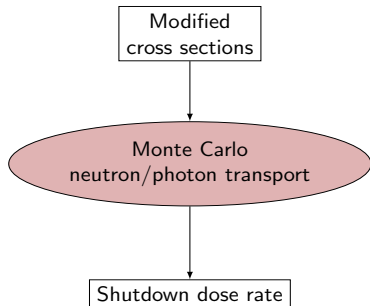
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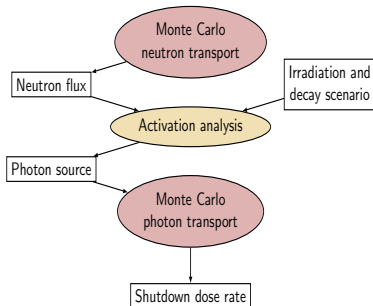


Optimize the calculation of the **shutdown dose rate** at a particular location as activated components are **moving** around the facility.

Direct 1-Step Method (D1S)



Rigorous 2-Step Method (R2S)



- Monte Carlo (MC) analysis of FES 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

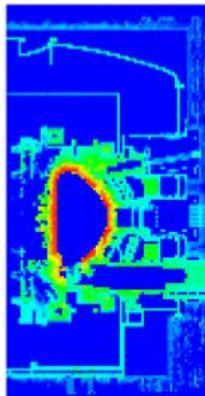


Figure : Photon source in ITER tokamak building.

- Uncertainty in MC calculations:

$$\Re = \frac{\sigma_{\bar{X}}}{\bar{X}} \quad (1)$$

$$\sigma_{\bar{X}} \propto \frac{1}{\sqrt{N}}$$

- To decrease statistical uncertainty:
 - Increase number of histories, N
 - Use variance reduction (VR) 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
- Types
 - **Modified Sampling:** source direction and energy biasing
 - **Population Control:** geometry and energy splitting/rouletteing

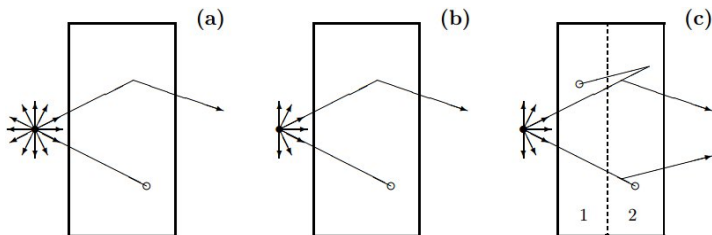


Figure : a) Analog b) Source biasing c) Splitting/rouletteing

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

Forward:

$$H\Psi(\vec{r}, E, \hat{\Omega}) = q(\vec{r}, E, \hat{\Omega}) \quad (2)$$

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

Adjoint:

$$\langle \Psi^+, q \rangle = \langle \Psi, q^+ \rangle \quad (3)$$

$$H^+\Psi^+(\vec{r}, E, \hat{\Omega}) = q^+(\vec{r}, E, \hat{\Omega}) \quad (4)$$

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

Consistent Adjoint Driven Importance Sampling (CADIS)

- Use the adjoint flux, Ψ^+ , to generate MC source and transport biasing parameters
- Biased source:

$$\hat{q}(\vec{r}, E, \hat{\Omega}) = \frac{\Psi^+(\vec{r}, E, \hat{\Omega}) q(\vec{r}, E, \hat{\Omega})}{R} \quad (5)$$

- Weight window lower bounds:

$$w_l(\vec{r}, E, \hat{\Omega}) = \frac{R}{\Psi^+(\vec{r}, E, \hat{\Omega})^{\left(\frac{\alpha+1}{2}\right)}} \quad (6)$$



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



Multi-Step (MS)-CADIS

- VR method to optimize the initial radiation transport step of a coupled, multi-step process
 - Relies upon biasing function that represents importance of particles to final response of interest
- When applied to SDR analysis, MS-CADIS will optimize the neutron transport step of R2S

- System of coupled, multi-physics:

$$\textit{Primary} : H\phi(u) = q(u) \quad (7)$$

$$\textit{Secondary} : L\psi(v) = b(v) \quad (8)$$

$$b(v) = f(\phi(u))$$

- Adjoint identities:

$$\langle \phi^+, q \rangle = \langle \phi, q^+ \rangle \quad (9)$$

$$\langle \psi^+, b \rangle = \langle \psi, b^+ \rangle \quad (10)$$

- Response to secondary physics:

$$R_{final} = \langle \omega_R(v), \psi(v) \rangle \quad (11)$$

- Define $b^+ \equiv \omega_R$ and apply adjoint identity:

$$R_{final} = \langle \omega_R, \psi \rangle = \langle b, \psi_R^+ \rangle \quad (12)$$

- ψ_R^+ represents importance function for R_{final}

- Set primary response to final response and apply adjoint identity:

$$R_{final} = \langle q^+, \phi \rangle = \langle q, \phi_R^+ \rangle \quad (13)$$

- Solving for q^+ requires this unique relationship:

$$b(v) = \langle \sigma_b(u, v), \phi(u) \rangle \quad (14)$$

- Substitute Eq. 14 and set primary response equal to secondary :

$$R_{final} = \langle q^+(u), \phi(u) \rangle = \langle \langle \sigma_b(u, v), \phi(u) \rangle, \psi_R^+(v) \rangle \quad (15)$$

- Switch the order of integration

$$R_{final} = \langle q^+(u), \phi(u) \rangle = \langle \langle \sigma_b(u, v), \psi_R^+(v) \rangle, \phi(u) \rangle \quad (16)$$

- MS-CADIS adjoint primary source:

$$q^+(u) \equiv \langle \sigma_b(u, v), \psi_R^+(v) \rangle \quad (17)$$

- Prompt photon production: $\sigma_b(u, v) \equiv \sigma_{n,\gamma}(E_n, E_\gamma)$

- MS-CADIS adjoint primary source:

$$q^+(u) \equiv \langle \sigma_b(u, \nu), \psi_R^+(\nu) \rangle \quad (18)$$

- Apply MS-CADIS to coupled neutron-photon physics:
 - $q^+(u) \equiv q_n^+(E_n)$
 - $\psi^+(\nu) \equiv \phi_\gamma^+$
 - Prompt photon production: $\sigma_b(u, \nu) \equiv \sigma_{n,\gamma}(E_n, E_\gamma)$
 - Delayed photon production: $\sigma_b(u, \nu) \equiv T_{n,\gamma}(E_n, E_\gamma)$

Groupwise Transmutation (GT)-CADIS

- Implementation of MS-CADIS specifically for SDR analysis
- Provides method to calculate optimal adjoint neutron source, q_n^+ :

$$q_n^+(E_n) = \langle T(E_n, E_\gamma), \phi_\gamma^+(E_\gamma) \rangle \quad (19)$$

- $T(E_n, E_\gamma)$
 - Approximation of the transmutation process
 - Solution exits when SNILB criteria are met
 - Defined by this relationship:

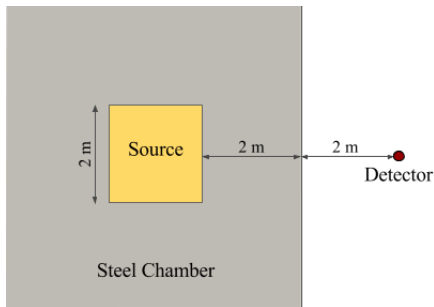
$$q_\gamma(E_\gamma) = \langle T(E_n, E_\gamma), \phi_n(E_n) \rangle \quad (20)$$

- Calculate by performing single-energy-group irradiations of each material and recording the resultant photon emission densities

$$T_{g,h} = \frac{q_{\gamma,h}(\phi_{n,g})}{\phi_{n,g}} \quad (21)$$

Demonstration

- Geometry
 - Steel chamber
 - $2\text{ m} \times 2\text{ m} \times 2\text{ m}$ central cavity
- Source
 - Volume source in central cavity
 - 13.8-14.2 MeV neutrons
- Detector
- Calculate SDR
- 2m away from chamber



GT-CADIS workflow

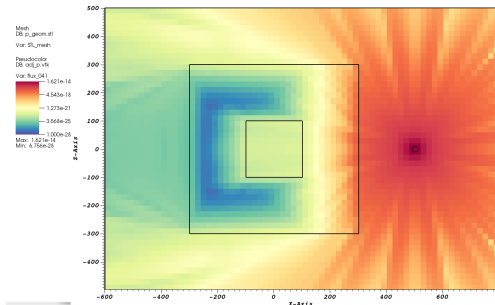
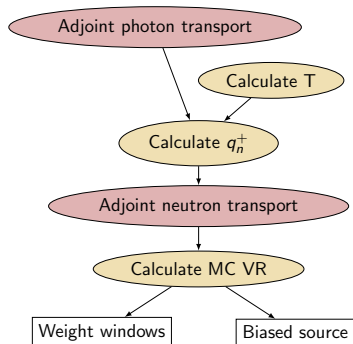


Figure : Adjoint photon flux used to generate adjoint neutron source according to the GT-CADIS method.

GT-CADIS workflow

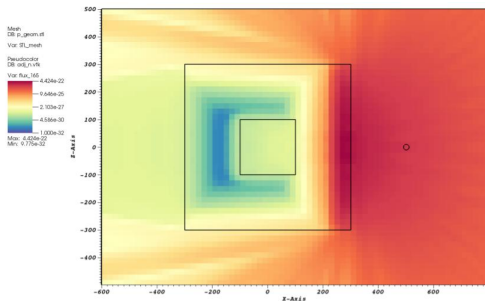
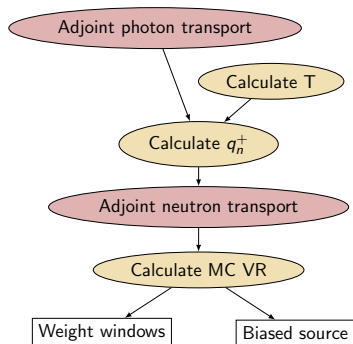


Figure : GT-CADIS adjoint neutron flux.
Functions as importance map.

GT-CADIS workflow

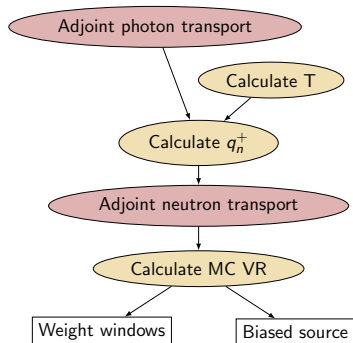
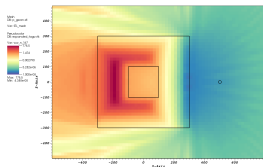
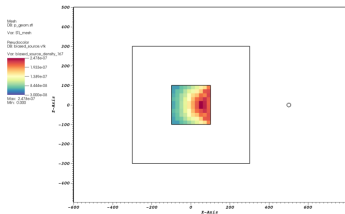


Figure : Biased neutron source generated with GT-CADIS method.





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



Figure : Demo model.

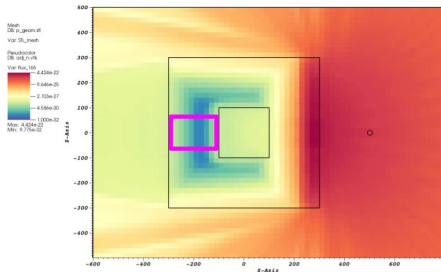


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

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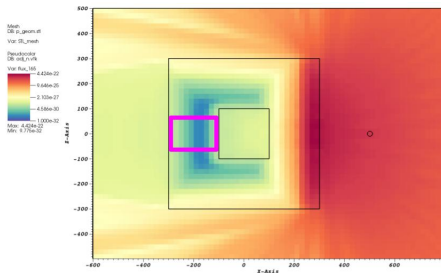


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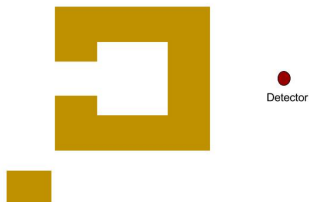


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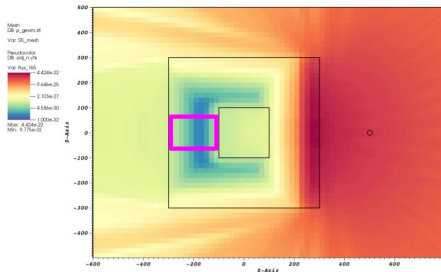


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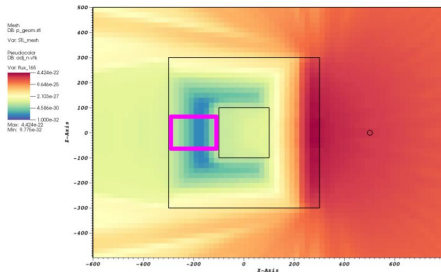


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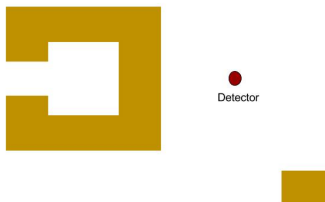


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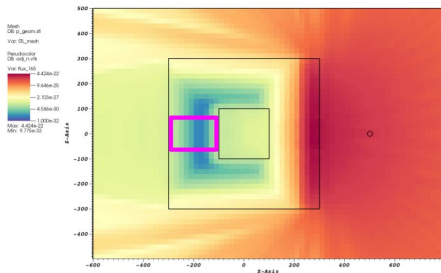


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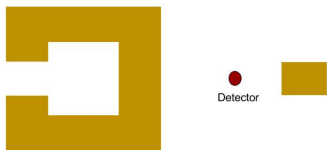


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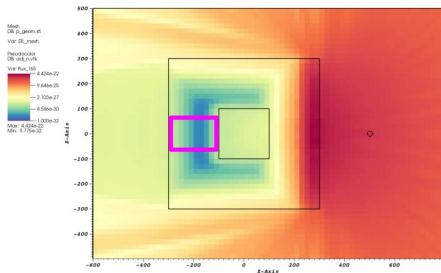


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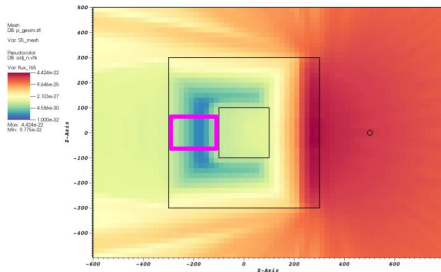


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.



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 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



- 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

Proposal



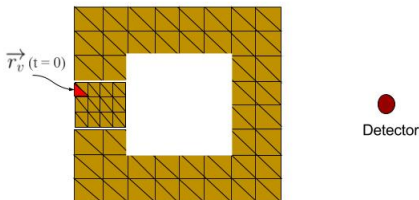
- MS-CADIS optimizes initial radiation transport step in a coupled, multi-step process
- Movement during secondary step changes the construction of the adjoint primary source

Need to derive new adjoint source

Time-integrated Adjoint Primary Source



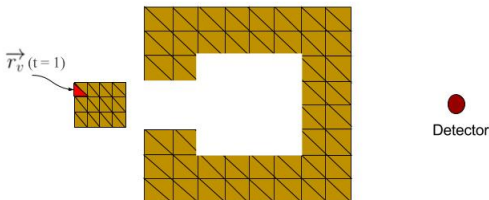
- Geometry movement during secondary physics effects the construction of the adjoint primary source
 - Score adjoint secondary flux in discrete volume elements
 - Adjoint flux in volume element v at time t : $\psi^+(\vec{r}_v(t), t)$
 - Position of volume element v at time t : $\vec{r}_v(t)$
- Integrate over time



Time-integrated Adjoint Primary Source



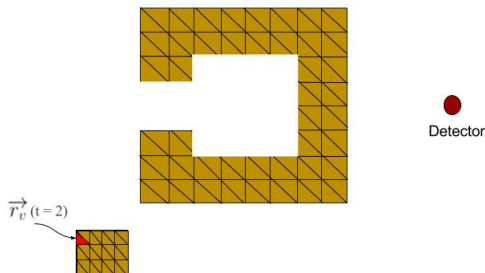
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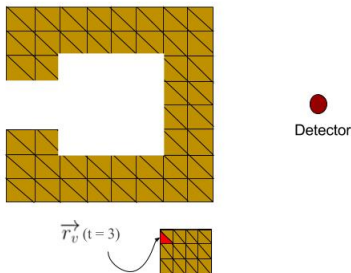
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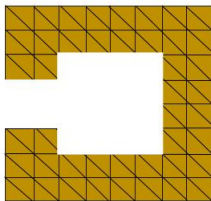
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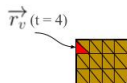
Time-integrated Adjoint Primary Source



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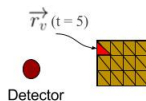
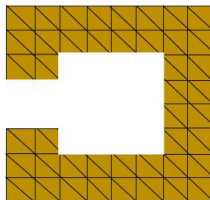
Detector



Time-integrated Adjoint Primary Source



- Geometry movement during secondary physics effects the construction of the adjoint primary source
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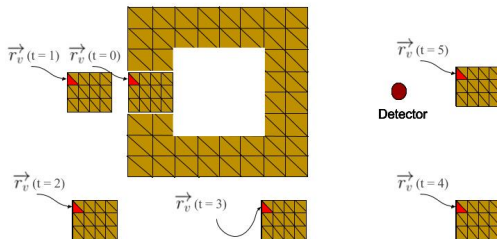
- To apply time-integration to GT-CADIS:
 - ① Perform adjoint photon transport at each time step of geometry movement
 - ② Score adjoint photon flux in each volume element, v
 - ③ Integrate over time

- Calculate coupling term, T , for each volume element

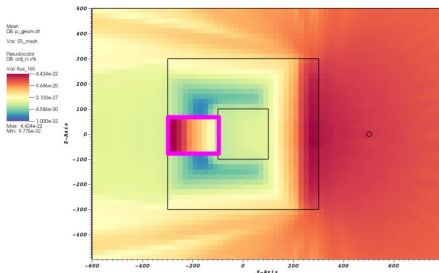
$$T_{v,g,h} = \frac{q_{\gamma,v,h}(\phi_{n,v,g})}{\phi_{n,v,g}} \quad (22)$$

- Combine with adjoint photon flux in each volume element

$$q_{n,v,g}^+ = \frac{\sum_{t_{mov}} (\sum_h T_{v,g,h} \phi_{\gamma,v,h,t_{mov}}^+) \Delta t_{mov}}{t_{tot}} \quad (23)$$



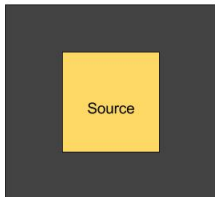
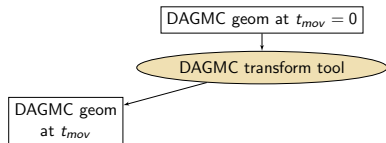
- Perform deterministic adjoint neutron transport using the time-integrated source
- Resultant adjoint neutron flux should look something like this:



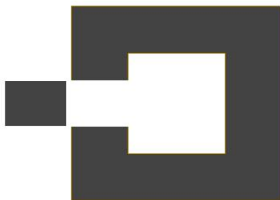
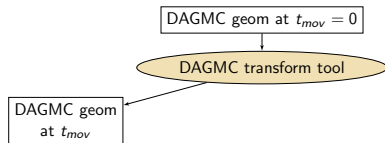
- Use this adjoint neutron flux to generate biasing parameters that will optimize the MC neutron transport step of R2S

Implementation Plan

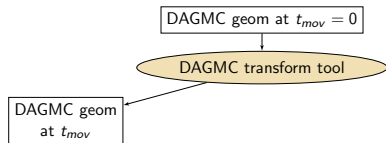
- Generate geometry files at each time step of movement after shutdown



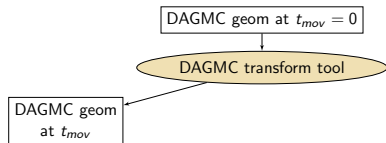
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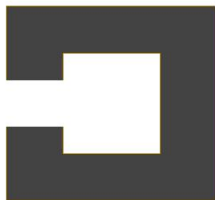
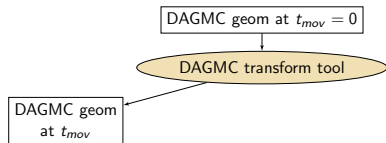
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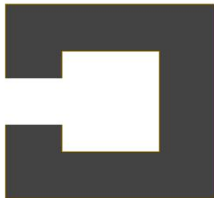
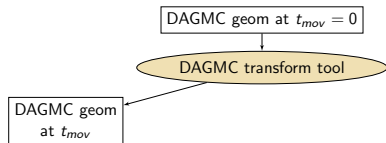
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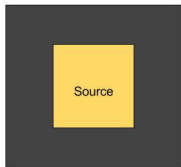

Detector



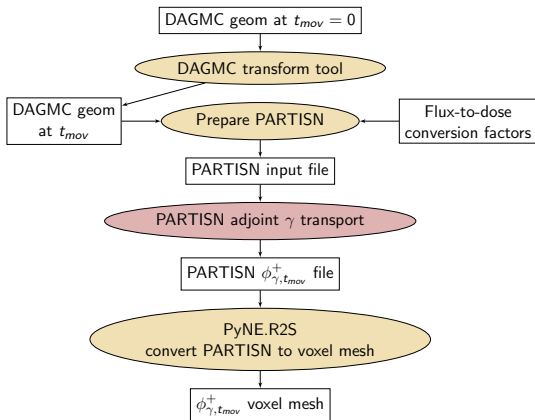
- Generate geometry files at each time step of movement after shutdown



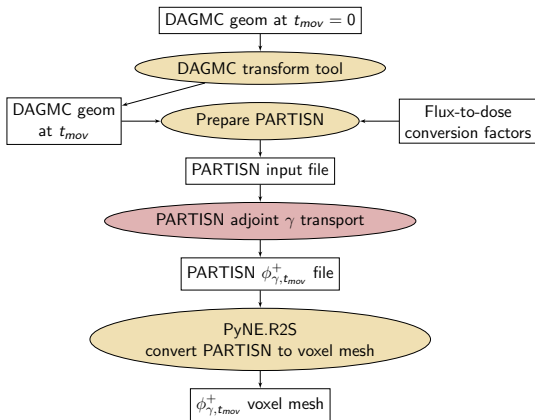
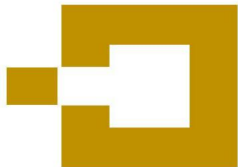
- Perform adjoint photon transport at each time step



Detector



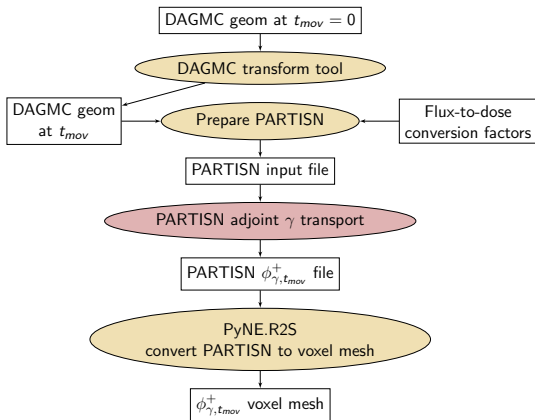
- Perform adjoint photon transport at each time step



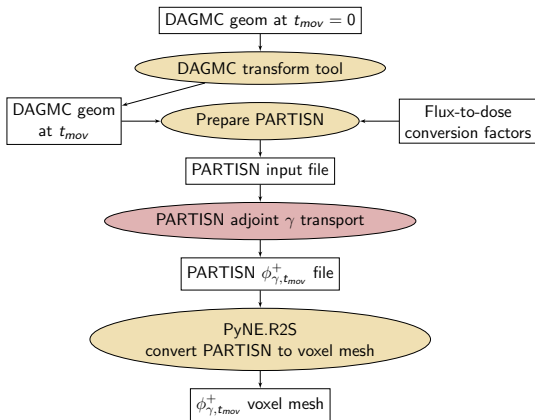
- Perform adjoint photon transport at each time step



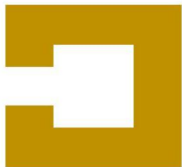

Detector



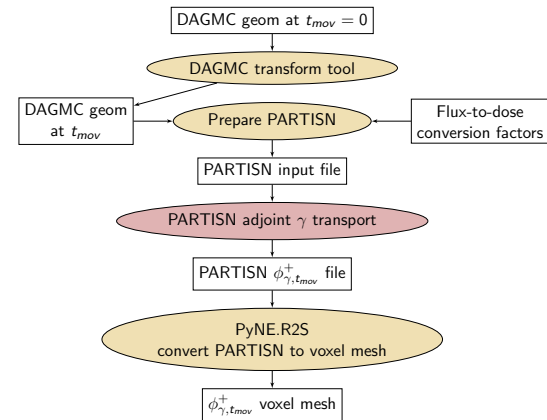
- Perform adjoint photon transport at each time step



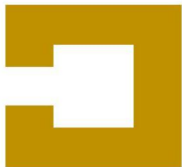
- Perform adjoint photon transport at each time step



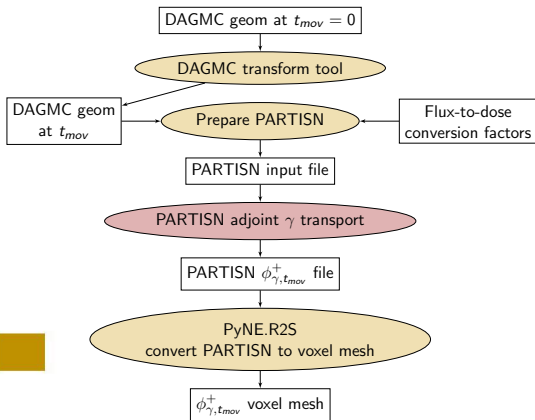
●
Detector



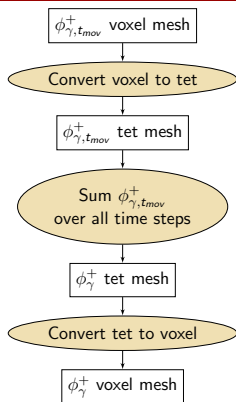
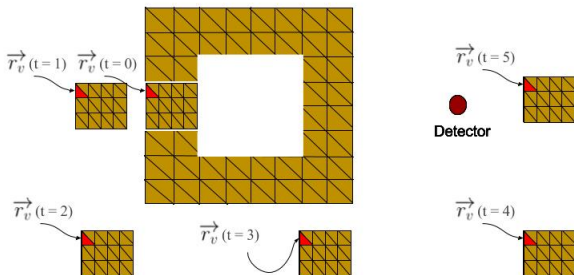
- Perform adjoint photon transport at each time step



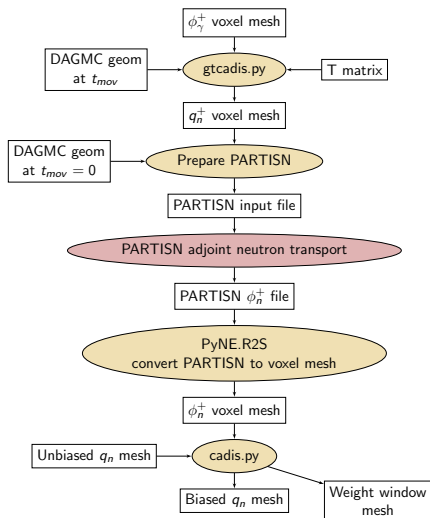
Detector



- Map the voxel mesh to a tetrahedral mesh
- Average the adjoint photon flux calculated at each time step



- Calculate T of each voxel
- Calculate adjoint neutron source
- Perform adjoint neutron transport
- Generate biased source and weight window mesh

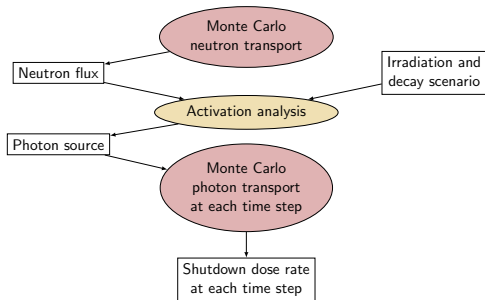


Experiment

- Toy problem
 - Steel chamber with moving component
 - Incrementally add optimization
 - Calculate figure of merit (FOM) to assess utility of TGT-CADIS method
- Full-scale FES demonstration

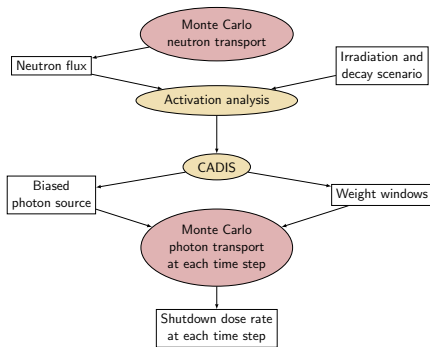
Experimental Steps:

1 No VR



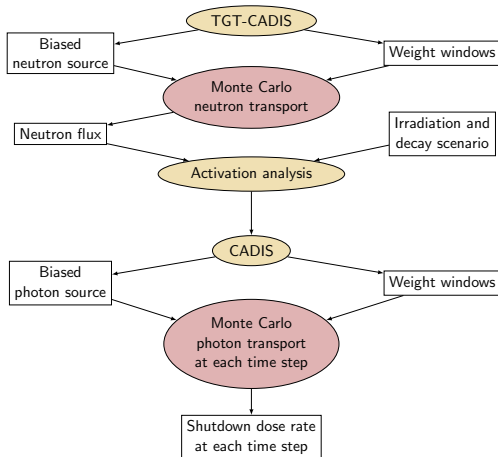
Experimental Steps:

- 1 No VR
- 2 Photon VR:
CADIS



Experimental Steps:

- 1 No VR
- 2 Photon VR:
CADIS
- 3 Neutron and
Photon VR:
TGT-CADIS



Progress

- Tools to update position of geometry based on user-defined motion data
 - ① Production of step-wise geometry files
 - ② DAGMC update to facilitate on-the-fly geometry transformations
- Motion data:
 - Time-dependent translation or rotation vector, total length of time, number or desired time steps
 - Relocation transform
- Common functionality:
 - Read tag data that specifies type of transformation
 - Identify starting position of each component
 - Update position according to transformation

Conclusions

- 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

- 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

- Accurate quantification of the SDR during maintenance procedures is crucial to the design and operation of FES
- GT-CADIS has proven to accurately quantify the SDR in static FES
- TGT-CADIS aims to provide the capabilities necessary to calculate the SDR at various time points during operations that involve activated components moving around the facility

Questions?

- REFERENCES
- Fig numbers
- FW-CADIS
- Pros/cons deterministic/MC
- Intro DAGMC, MOAB
- Too much detail in Gen. MS-CADIS?
- labels on tet mesh time slices
- Overall alignment/sizing/spacing
- Error propagation
- Add more on moving geom progress, movie
- OBB tree optimization