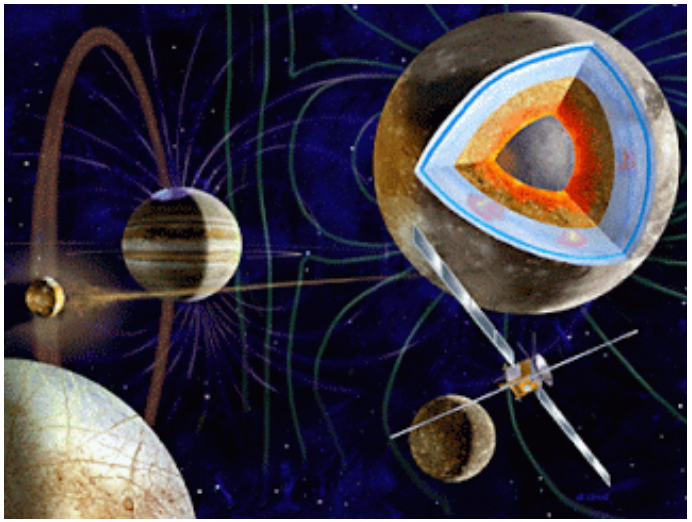
"Matryoshka": Variance Reduction Using Multi-Stage Simulations – Some Lessons From the CIRSOS Project



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(Prime contractor RadMod Research Ltd)

Sorry!

This is not really a talk about conventional "Biasing"…

… Neither is it a talk about Geant4 toolkit development …

… It's a ESA GRAS tool development …

(GRAS = Geant4 Radiation Analysis for Space)

… But the techniques may possibly have some application to Geant4 variance reduction as well as analysis & persistency

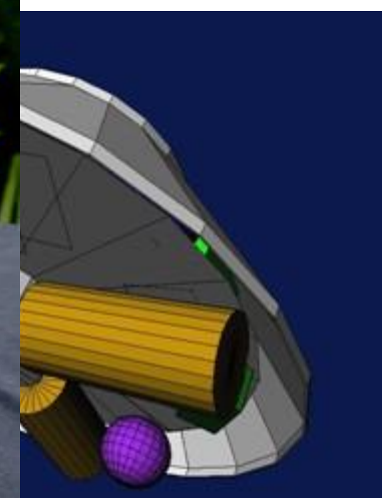
Status of GRAS "Matryoshka" Enhancement

There was no established method in Geant4 to do this easily

- Radiation effects analysis still does not regularly involve the use of Monte Carlo radiation simulation

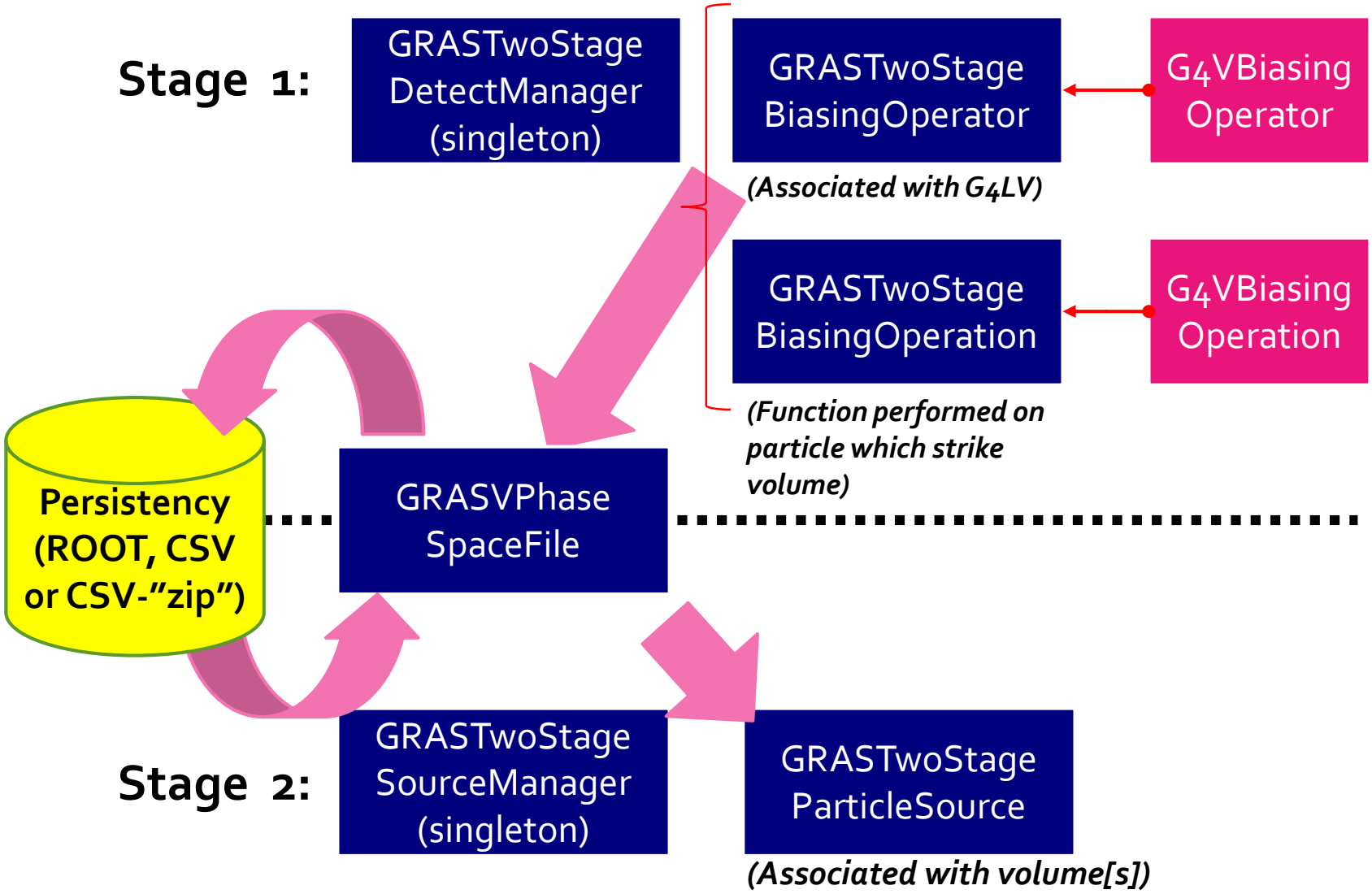
…"Boxes within boxes within boxes"

- Spacecraft comprise collections of systems, each containing sub systems, …
- A straight… improve s… to:
  - Transp… equipm…
  - Store t…
  - Use sub… resamp… box/bo…



…t: Lindberg & Santin, ESA

Basic Modules for 2-Stage Analysis



Key Features

Stage 1:

- Several Bias Operators can be created and allocated to one or more Phase-space files
- Each Bias Operator associated with one or more detection G4Logical volumes
- Particles are killed outright at surface (may introduce Russian Roulette in future developments)
- ROOT, CSV or compressed-CSV file outputs

Specify by PV, but bias operation applied to LV

```
/gras/twoStage/detect/addModule mod1
/gras/twoStage/detect/mod1/selectVolume v1_out_PV
/gras/twoStage/detect/mod1/selectVolume v2_out_PV 1
/gras/twoStage/detect/addPSFile PSFile1 test_mod1.csv CSV
/gras/twoStage/detect/mod1/setPSFile PSFile1
/gras/twoStage/detect/PSFile1/dumpInterval 1000

/gras/twoStage/detect/addModule mod2
/gras/twoStage/detect/mod2/selectVolume v3_out_PV
```

Key Features

Stage 2:

- Can apply splitting to each event in the 1st stage simulation
- To augment splitting there, there are options to "dither" position and angle of particles
- Can record events striking sub-volumes: 3-stage analysis, *etc*
- Full management of normalisation back to original number of events in Stage 1

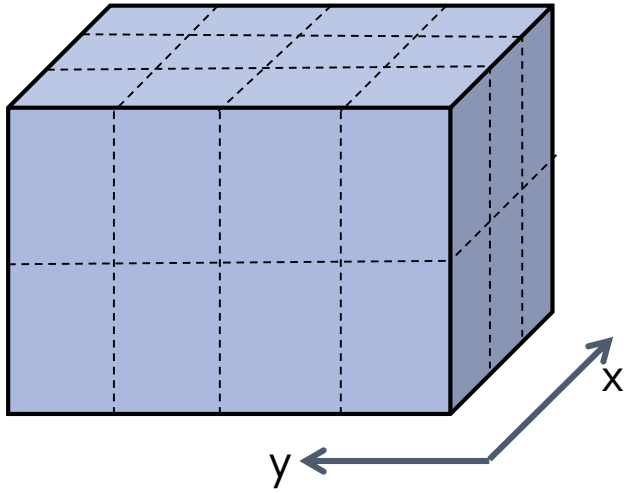
/gras/twoStage/source/selectPSFile ***PSFile1*** *test_mod1.csv CSV*
/gras/twoStage/source/selectPSFile ***PSFile2*** *test_mod2.root ROOT*
/gras/twoStage/source/addSource ***sourceVol1*** ***PSFile1*** ***v1_out_PV*** *0*
*/gras/twoStage/source/****PSFile1****/split 10 1 true true 1*
*/gras/twoStage/source/****sourceVol1****/resample/position UNIFORM 1.0 cm*

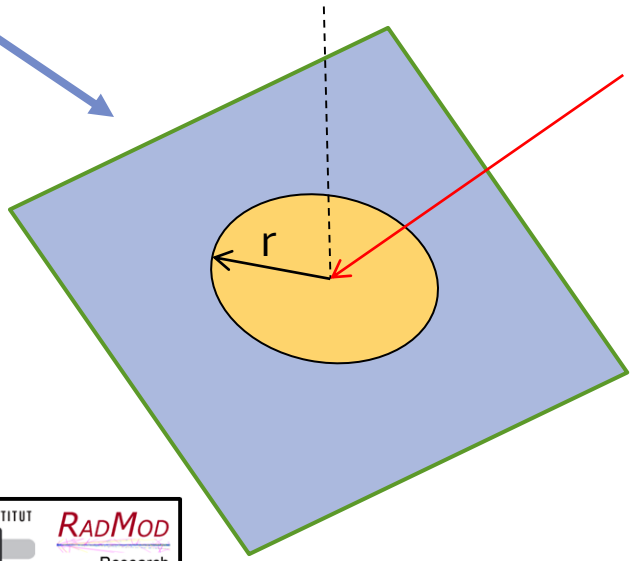
/gras/twoStage/source/addSource ***sourceVol2*** ***PSFile2*** ***v3_out_PV*** *0*
*/gras/twoStage/source/****sourceVol2****/targetVolume* ***v2_out_PV*** *0*
*/gras/twoStage/source/****sourceVol2****/resample/angle uniform 5.0 deg*
*/gras/twoStage/source/****sourceVol2****/resample/grid 5 5 5*

"Dithering" Options for Position and Angle (1)

/gras/twoStage/source/<source_module>/resample/grid 3 4 2

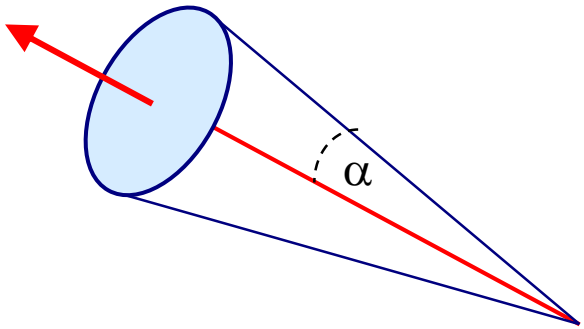
- Position "dither" on grid:
  - G4Box, segmented evenly in x, y and z
  - G4Tubs, segmented evenly in r, θ and z
  - G4Sphere, segmented evenly in θ and ϕ
- Alternatively, position may be "dithered" by sampling as a function of radius, r, from the original point of intersection with the PV surface
  - UNIFORM: radius sampled evenly over area up to user-defined maximum radius
  - GAUSS: radius sampled with radial-Gaussian probability function (user-defined StdDev radius)
  - Evenly sampled in azimuth



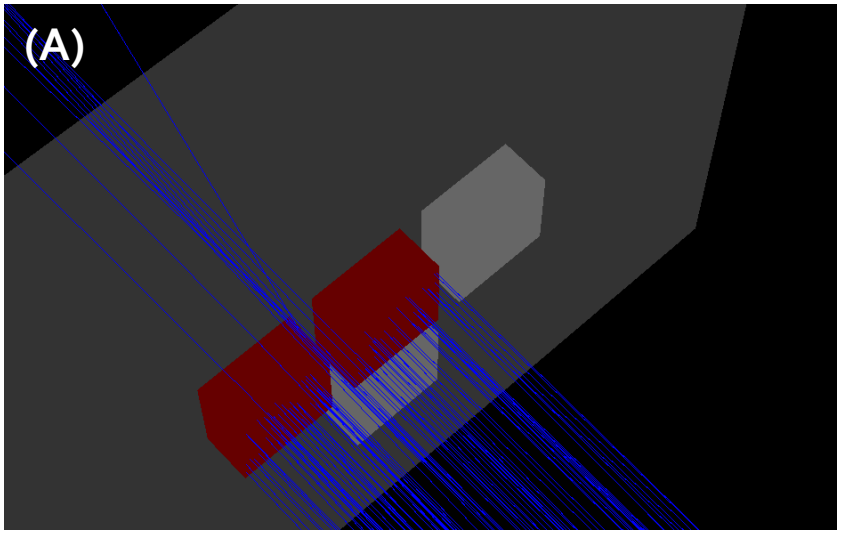


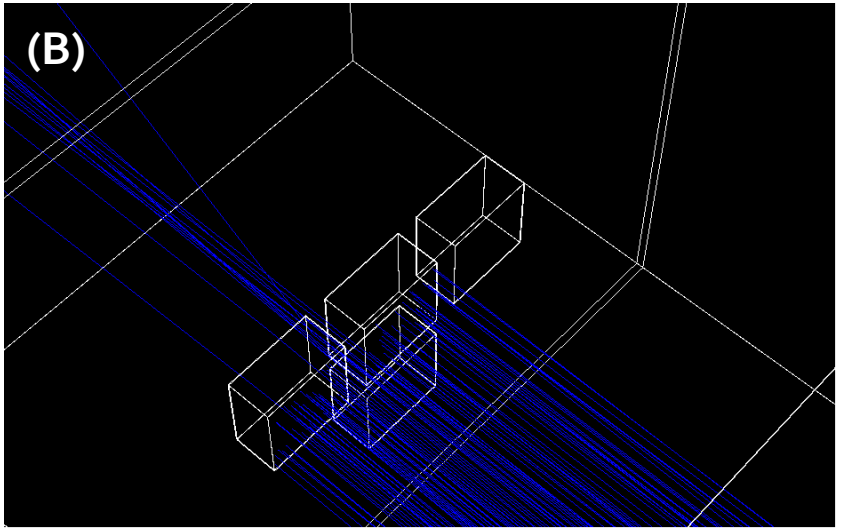
"Dithering" Options for Position and Angle (2)

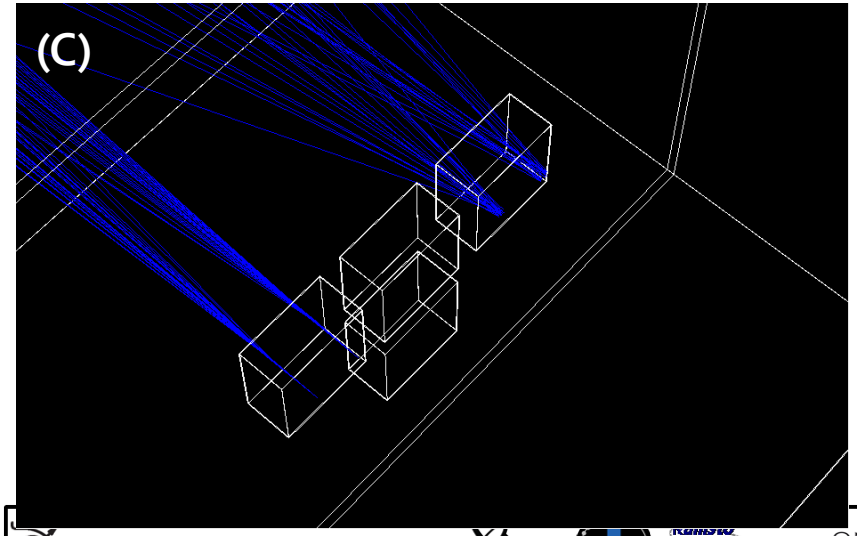
- NOTE: When using grid sampling, the external surface of the volume (G4VSolid) must be a complete box, cylinder or sphere without any cut-out, section, restrictions in the range of θ and/or ϕ (such as a hemisphere) otherwise the gridding will not work
- Once position is resampled and new point on surface located, the angle of incidence can be resampled:
- Uniformly sampled in solid angle within a cone of half-angle, α, defined by the user



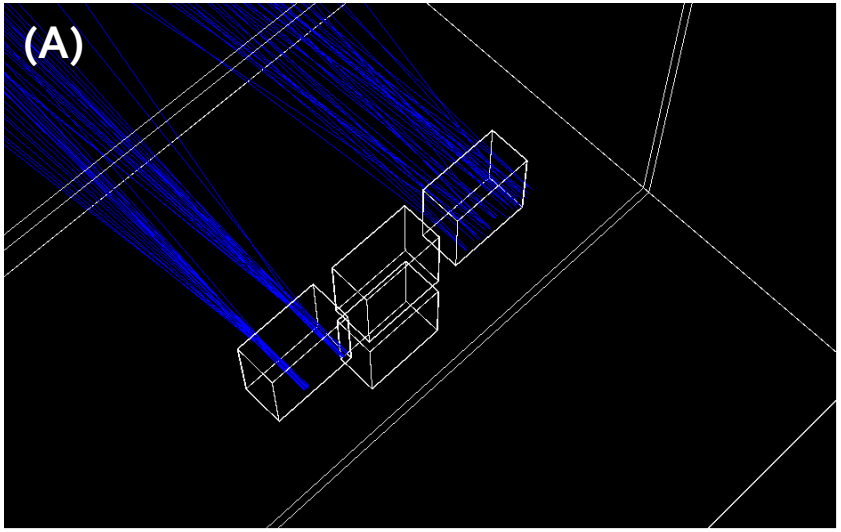
Example 1st Stage simulation: Four electronics boxes (200mm × 200mm × 100mm) mounted on plate in satellite. Two of these (in red) are irradiated. In solid (A) and wireframe representation (B).

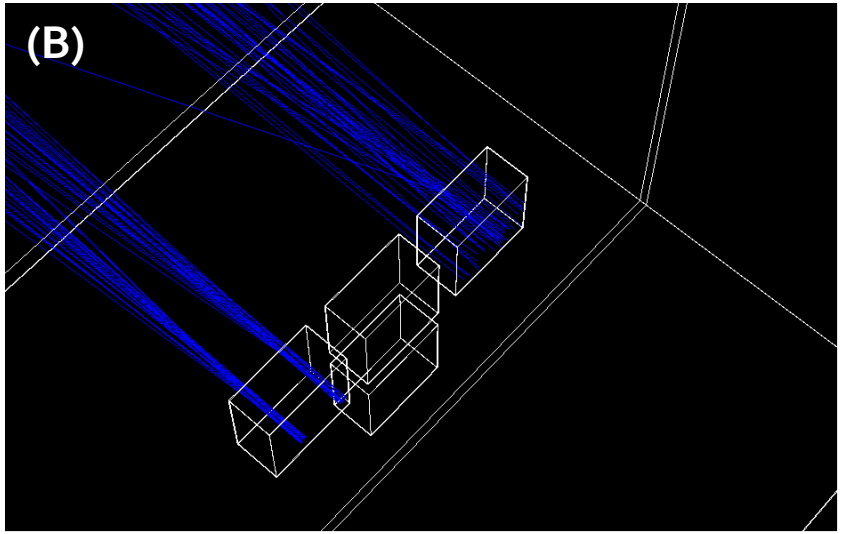






(C): Example 2nd Stage simulation: The source is generated on one of the original red volumes with no position nor angular "dithering", but split (***samples***=20). The source is also used for one of the PVs irradiated in the first stage: grid resampling (gridded in 10x10x10), and angular dither with α=15°, ***samples***=20. Only 2 of the original 1st stage events are used for each PV

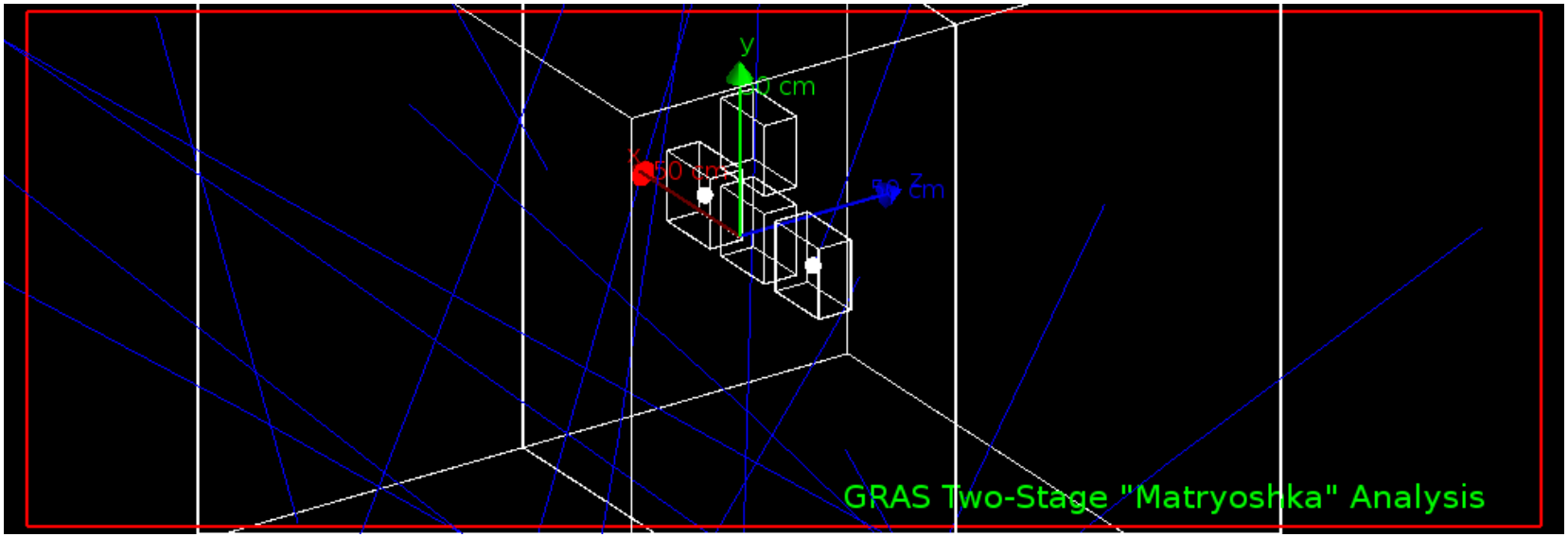


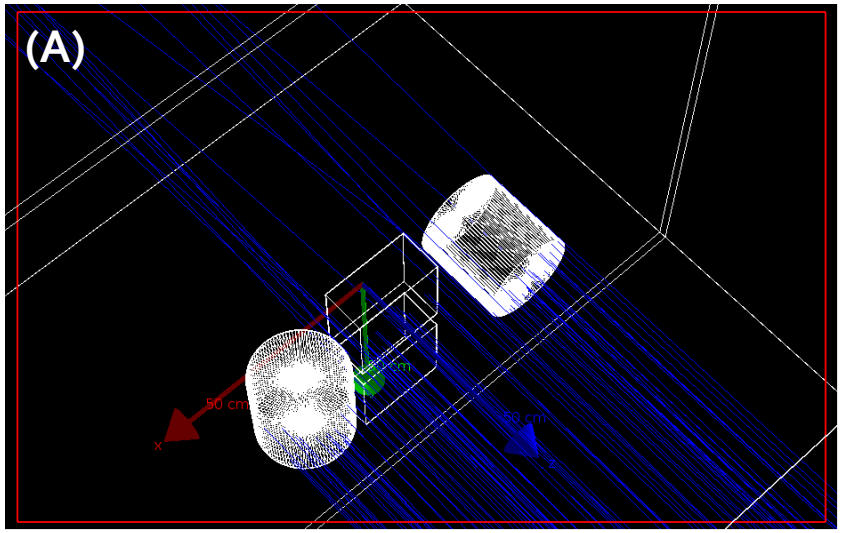


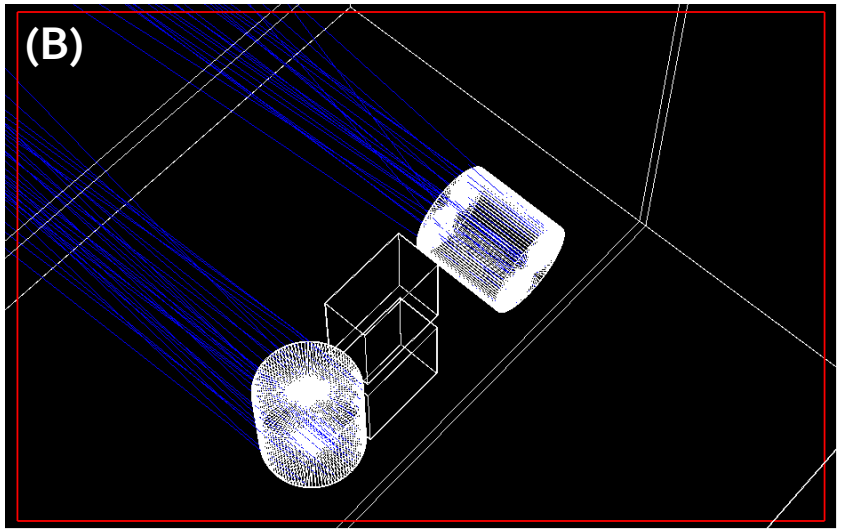
Example of 2nd stage simulation: 2 1st-stage events are sampled 20 times (***samples***=20). For left box , events are sampled uniformly over disc radius 1cm, no angular dithering. Right box, events are sampled uniformly over disc radius 7cm, with α=5° angular dithering. Sampling conditions and acceptance/ rejection criteria for the sampled particle are different

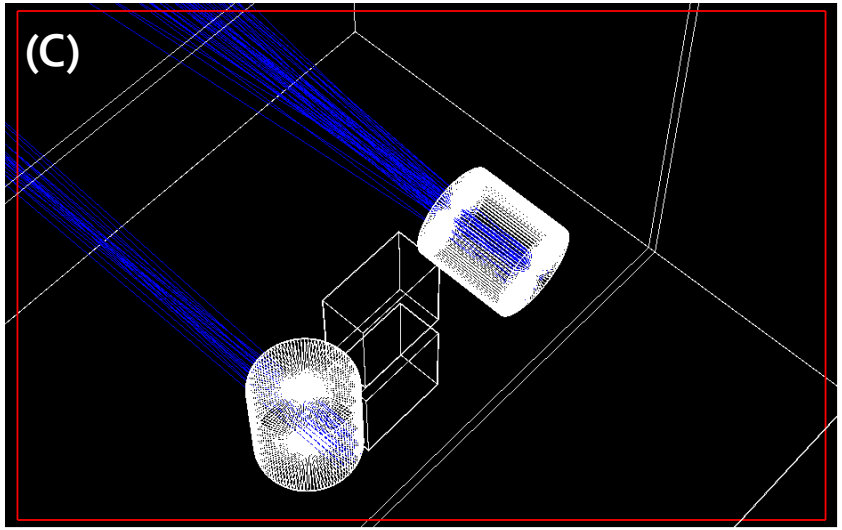
Example

- Test case with 2cm radius Si spheres, 50 MeV protons isotropic
  - (1.44 ± 0.10) x10^{-12} rad(Si)/event (conventional)
  - (1.41 ± 0.02) x10^{-12} rad(Si)/event (2-stage with splitting)



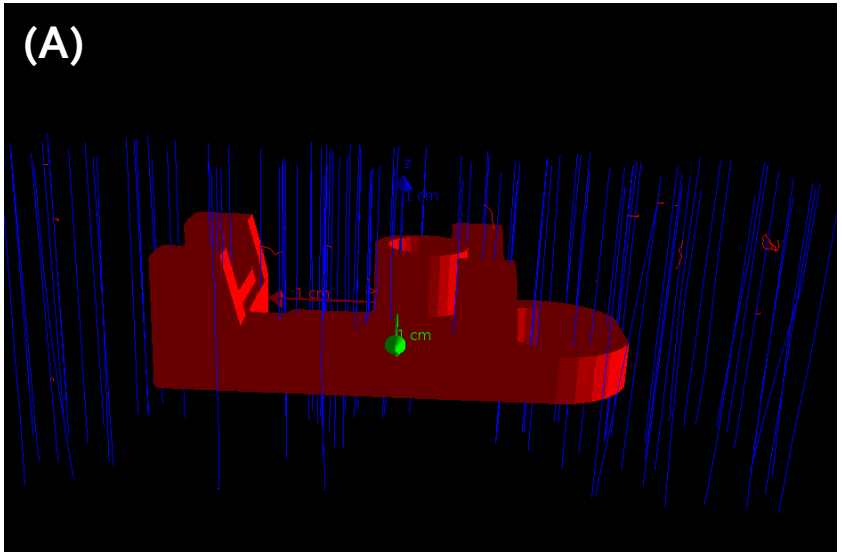


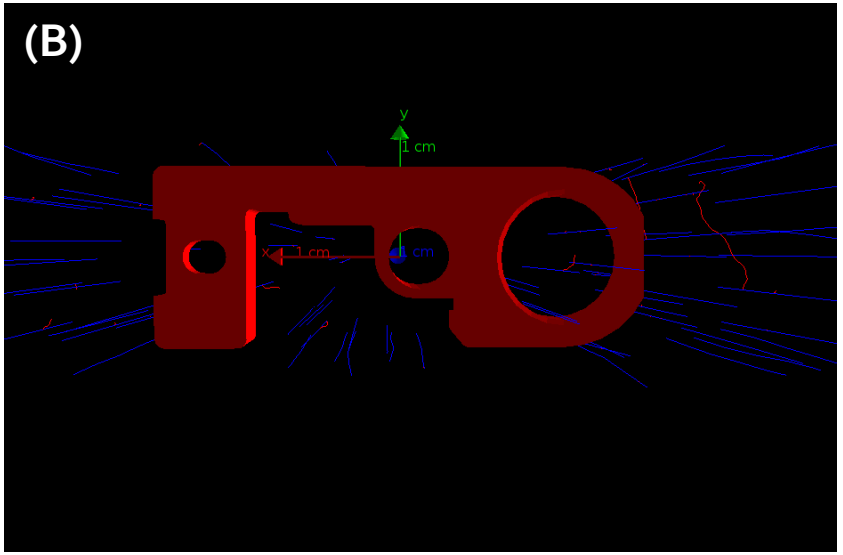


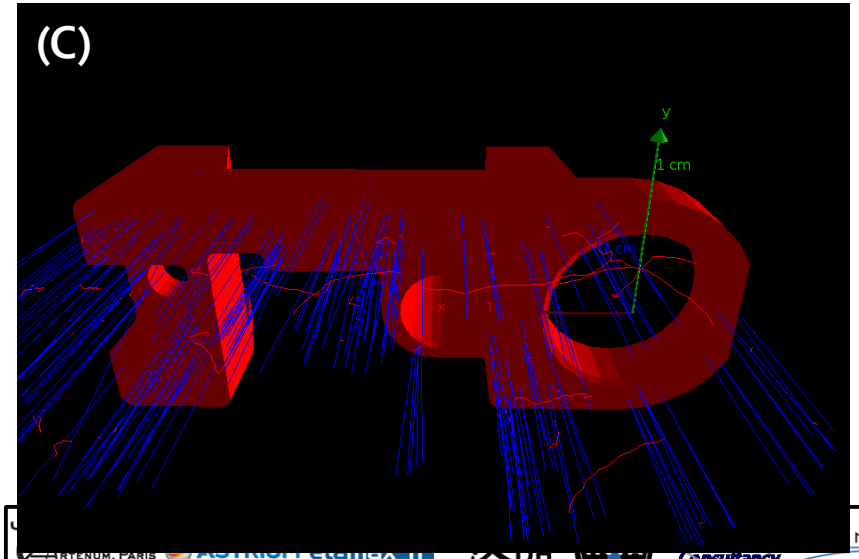


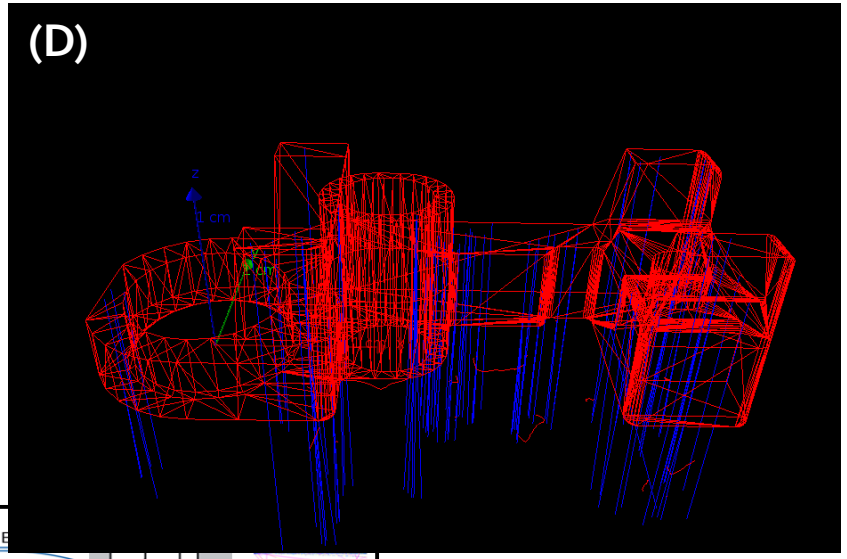
As with previous examples, but systems two enclosures are cylindrical.
(A) 1st stage simulation with particle stopping on enclosures.
(B) 2nd stage simulation, no splitting (***samples***=1) and position resampled on uniform disc radius 4cm (left cyl) and using grid resampling (right cyl). Right cyl also includes α=5° angular dithering
(C) Same as for (B), but with ***samples***=20, and only first 3 events from 1st stage simulation shown.

Example Two Stage simulation for arbitrary Al geometry in air irradiated in –z-direction by protons. (A) & (B) 1st stage simulation. (C) and (D) 2nd stage simulation, with each 1st-stage event split into 5, and uniform repositioning within a disc radius 2mm.









Phase Space Files (1)

- The PS file has four types of PS records in the following order:
  - Header records: including date, time and any comments added by user
  - Run record: minimum and maximum eventID, and the number of events at which PS data should be dumped (eventModulo)
    - Note there is a "total events" number field in the Run PS record, and this will probably be removed as it's misleading and I don't think it's needed any more
  - Volume PS record includes:
    - Solid types
    - Parent volumes/volume hierarchy
    - Extent
    - Transformations (rotation + translation) of PV with respect to parents
  - Particle records

Phase Space Files (2)

- Particle records stored in blocks of ***eventModulo*** events
  - One consequence is, if ***eventModule*** = 1000 and the simulation fails at eventID = 5275, then the last eventID to be treated for the file will be 4999
- Information in particle PS record:
  - eventID, trackID, isAPrimary
  - particleName, pdgEncoding, A, Z, Q, excitation
  - Weight
  - KE
  - Time, global position, global direction, local position, local direction
  - Distance since last interaction (not used yet and set to zero)
  - PV name, PV copy#, PV instance ID
- 2-Stage is intended as a *variance reduction technique*, not scoring/analysis - particles are killed

However phase-space information could be used for postprocessing analysis – similar PS ROOT files produced for ESA AREMBES Project

Summary

- 2-Stage Analysis developed for ESA CIRSOS Project in GRAS application
- Easily to:
  - Record boundary-crossing events from one simulation
  - Retrieve the events
  - Displace to the same or another volume(s)
  - Split and/or perturb ("dither") in space and angle
- Phase-space information useful for post-processing event analysis

- Are some of these techniques/principles useful within Geant4 toolkit?