BEAM TRANSPORT AND ENVIRONMENT SIMULATION, A (Geant4) BIASED VIEW

EuPRAXIA Workshop

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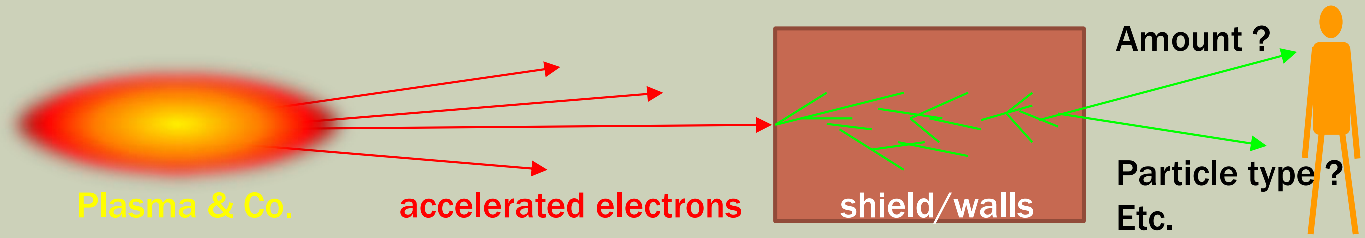
USING "STANDARD" HEP TOOLS

- EuPRAXIA will implement an innovative technique for accelerating electrons

- But once accelerated, these e^- are just "regular" electrons in the GeV range
- "Standard" simulation tools of particle transport in matter used in HEP are hence well suited to simulate transport of these electrons in beam lines and interactions of these e^- (and subsequent daughters) in the environment



- Limitations of HEP transport codes:
  - Acceleration phase in plasma involves collective effects
    - In the plasma
    - In the beam
  - that are beyond the scope of the HEP particle transport codes
  - These transport codes assume:
    - Independent particles
    - Immutable materials
  - This, by default.
    - With a toolkit like Geant4, it is always possible to work +/- hard to move +/- away from these assumptions… (if very needed).

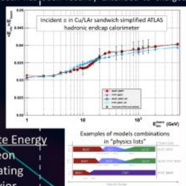
Geant4 Physics & Applications

Projectile Kinetic Energy (GeV)

A toolkit for Monte Carlo simulation of passage of particles in matter

Geant4 Hadronic Physics

Hadronic interaction modeling involves three main regimes : high energy, with string models (Quark Gluon String [QGS], Fritiof [FTF]), intermediate energy, with intra-nuclear cascade models (Bertini [BERT], Binary [BIC], Liège [INCL++]), and low energy, with precompound, Fermi break-up, fission/evaporation, capture at rest models and radioactive decays. Below 20 MeV down to thermal energy neutrons are handled by means of cross-section databases, with the High Precision [HP] package. This approach has been recently extended to charged particles.



High Energy
Quark/gluon dominating behavior

Intermediate Energy
Nucleon dominating behavior

Low Energy
Nucleus dominating behavior

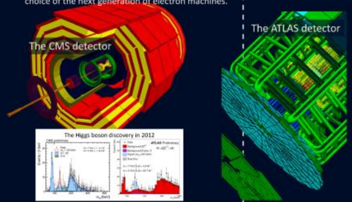
Very Low Energy
Atom and molecule dominating behavior

Neutron simulation down to thermal energies:

Geant4 can use the same neutron data library than MCNPX. Verification spectra of MCNP and Geant4 output of outgoing neutrons produced in neutron collision.

HEP Applications

High Energy Physics has been the first domain to utilize Geant4 in production, with the BaBar experiment at SLAC. The CERN LHC experiments used Geant4 for detector design and now for physics analysis. Geant4 is also the simulation engine choice of the next generation of electron machines.

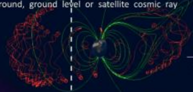


Responding to the simulation needs of the LHC era was the initial motivation for the creation of the Research & Development project, RD44, in 1994, to assess the interest of OO technologies for detector simulation. RD44 became Geant4 in 1999.

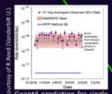
Space Applications

Applications of Geant4 in space cover planetary scale simulation for soil level media activation studies, soil composition through X-ray re-emission, space ship simulation for radioprotection and electronic single event upset predictions, electronic chip scale simulation for accurate understanding of single event upset generation. It includes also underground, ground level or satellite cosmic ray experiments simulation.

XMM-Newton X-ray telescope, launched in 1999
Radiation effects on its instruments were modeled with Geant4 prior to its launch.



Planetocosmics : a simulation tool for planetary scale particle transport. The red curve is a proton trajectory in the Earth magnetic field. Irradiation level around a planet, at ground level, and with related activated isotopes can then be predicted.

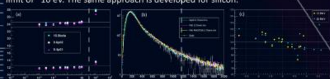


Geant4 prediction for single upset rate is more accurate than standard software of the domain.

Nucleon Size
Uranium Nucleus Size
Water Molecule Size
Proton, Neutron
Carbon Ion
Electron
Gamma

Geant4 Electromagnetic Physics

The electromagnetic physics covers interactions of gammas, muons and electrons, and ionisation of all charged particles. A "standard" package offers an implementation suited for applications disregarding effects below a few ~10 keV, and a "low energy" one provides approaches (Livermore, Penelope) for more accurate modeling of atomic shell effects allowing simulation down to ~250 eV. A very low extension, Geant4-DNA, includes particle-molecule effects for an energy limit of ~10 eV. The same approach is developed for silicon.



(a) The simulation energy resolution (in %) in two sampling calorimeters compared with one standard deviation measurement (ZEUS calorimeter : E. Bernardi E *et al.*, NIM A, 262, 229-242, (1987); G. D'Agostini *et al.*, NIM A, 274, 134, (1989))).
(b) Comparison of Geant4 energy loss models with ALICE test-beam data (D. Antonchyk *et al.*, NIM A, 565, 551-560 (2006); P. Christiansen *et al.*, Int. J. Mod. Phys. E, 16, 2457-2462 (2007)).
(c) Comparison of angular distribution width (Data/MC in %) for various materials after traversing various material thicknesses, data from electron scattering benchmark (C. Ross et al., Med. Phys., 35, 4121, 2008).

Medical Applications

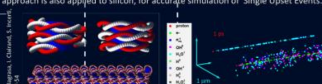
Medical Applications interest in Monte Carlo is the accuracy capability in complex structures. Geant4 is used in radio-, proto- & carbo-therapy medical research fields. It is also utilized in optimization of brachytherapy devices, radioprotection and nuclear imaging. Large users communities exist in US, Europe and Japan. CPU performance boost allowed by Geant4 MT or by GPU prototype versions open the possibility for routine usage in treatment planning.

Proton beam line, range shifter and dose deposit simulations at HIBMC (Japan).

A gMocren dose display in DICOM geometry http://geant4.kek.jp/gMocren/

DNA Scale Level Simulation

The ESA initiated a DNA scale level simulation, in view of manned mission to Mars. A bottom-up approach of dosimetry is adopted. Physics processes are extended down to a few eV, based on particle – molecule cross-sections. The approach is also applied to silicon, for accurate simulation of Single Upset Events.



DNA geometry model simulated : 46 chromosomes, 332k chromatine pieces, 30 millions nucleosomes, 6 billions base pairs...

Simulation of water chemical species migration accounting for electrical mutual interaction after a 50 MeV proton irradiation. Post irradiation chemical attacks amount for ~60% of total damages on DNA.

Homeland Security Applications

Homeland security applications of Geant4 are rather new, with the simulation of X-ray scanning systems developed for airports or the simulation of systems for large devices like cargos, trucks...

Projectile de Broglie λ(fm)

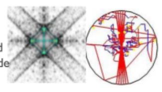
Geant4 Software

Introduction

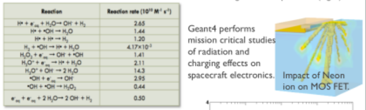
Geant4 is being used in many different fields where simulation of radiation passing through and interacting with matter is critical. User domains include: high energy and nuclear physics, medical physics and space engineering, shielding protection and more.
Its abstract layers based on robust OO design enables flexibility and extendibility of the code, and its open-source code and open collaboration have allowed substantial extensions of the code.
New features are constantly added to the code, while increasing attention is paid to improving software performance and robustness by employing cutting-edge software engineering technologies.

New physics

The flexibility and extendibility of Geant4 design allows it to be applied to new physics domains. These include the physics of condensed matter (phonon transportation in crystals, drift of electrons and holes in semiconductors) and processes for bio-chemical substances and DNA.

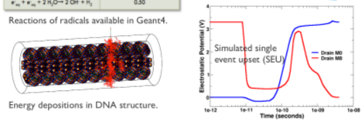


SuperCDMS Cryogenic Dark Matter Search seeks to directly detect dark matter. Geant4 models the caustic pattern in a Ge crystal (left) by tracking individual phonons (right)



Reactions of radicals available in Geant4.

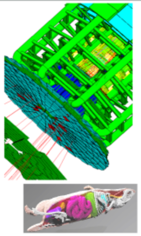
Geant4 performs mission critical studies of radiation and charging effects on spacecraft electronics.



Energy depositions in DNA structure.

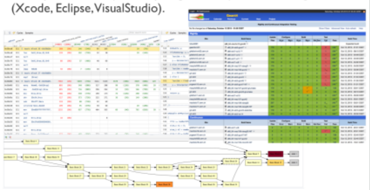
Geometry

The flexibility and extendibility of Geant4 design also enables handling rich collection of shapes including CSG (Constructed Solid Geometry), Boolean operation, Tessellated solid, etc. and the user can easily add new shapes. Geant4 geometry navigation can deal with setups up to billions of volumes with automatic optimization. In addition, geometry models can be 'dynamic', i.e. changing the setup at run-time, e.g. "moving objects".



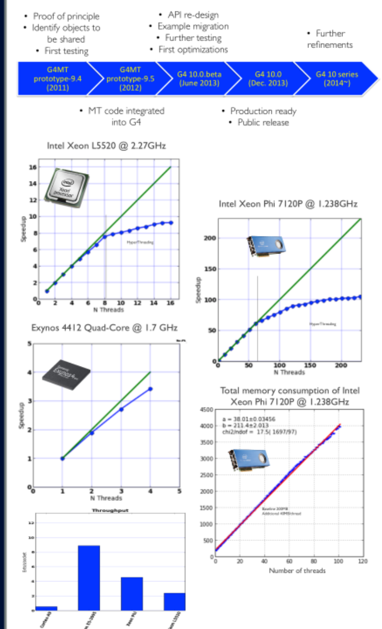
Software quality assurance

Geant4 uses modern tools to manage the code and improve code quality: from handling issues with JIRA to continuous testing integration with CTest/CDash, profiler based optimizations, Quality/Assurance (Coverity, Valgrind, etc.), and IDE integration (Xcode, Eclipse, VisualStudio).



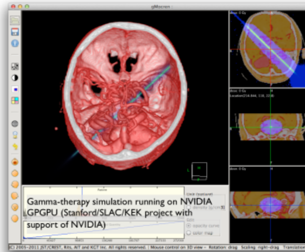
New era - Geant4 version 10 series

The new release of Geant4 – Version 10.0 (December 2013) include event-level parallelism via multi-threading. To efficiently use new computing architectures the workload of a single job is sub-divided to many worker threads each responsible for the simulation of one or more events. Version 10.0 has already shown good scalability on a number of different architectures: Intel Xeon servers, Intel Xeon Phi co-processors and low-power ARM processors

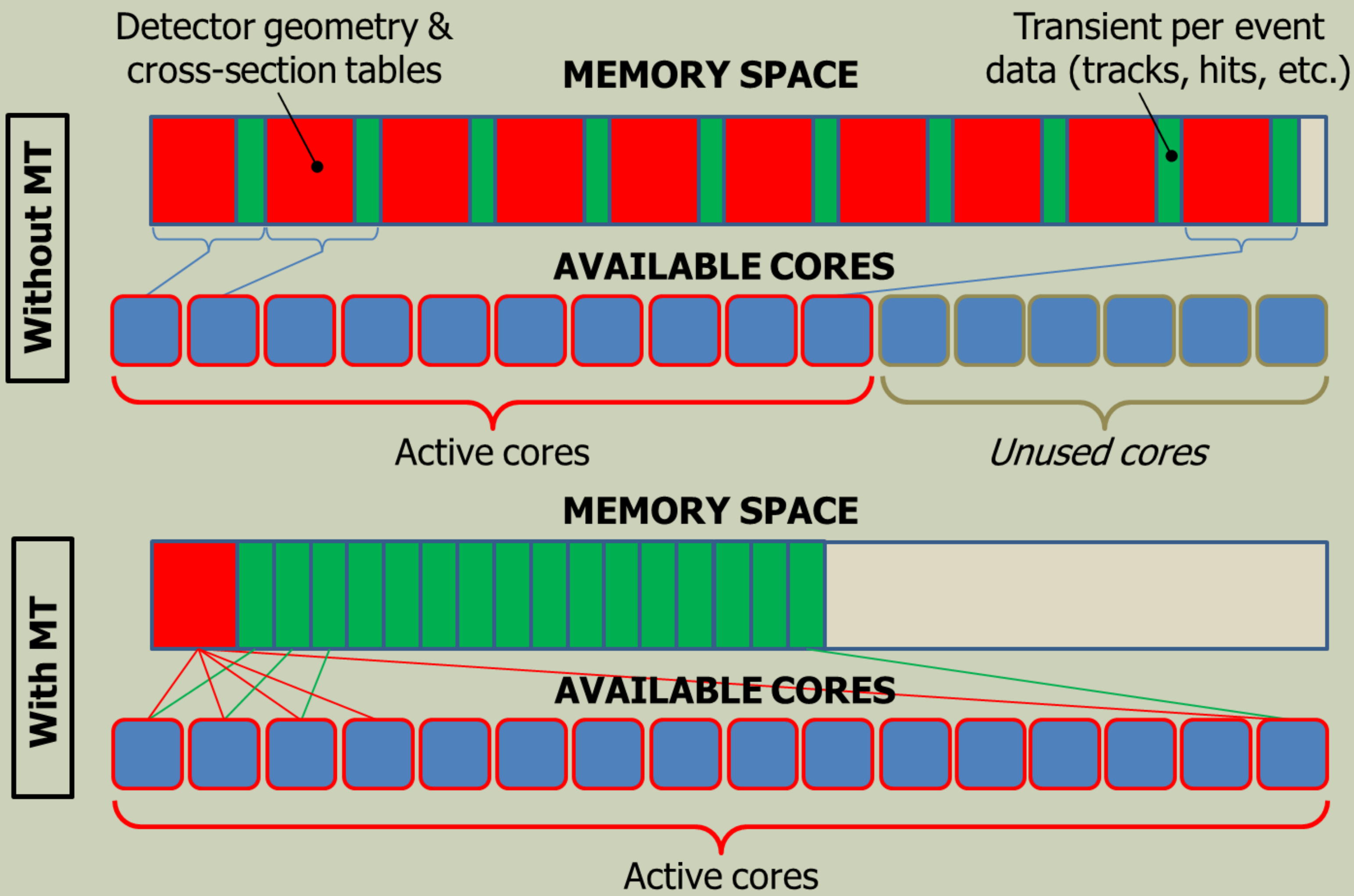


Investments for the future

Geant4 collaboration members are participating in various explorations of emerging technologies. These technologies include GPU/CUDA, OpenCL, OpenACC, vectorization, DSL, etc.



MULTI-THREADING : THE INTEREST FOR BIG APPLICATIONS



BEAM TRANSPORT SOFTWARES

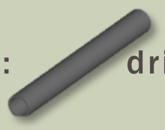
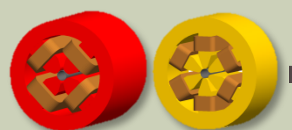
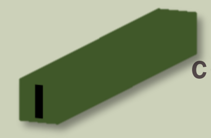
- Tools based on Geant4 like BDSIM or G4Beamline provide functionalities to transport beams
  - Provide a layer of functionalities built on top of Geant4 libraries
  - Meaning the physics interactions are the Geant4 ones

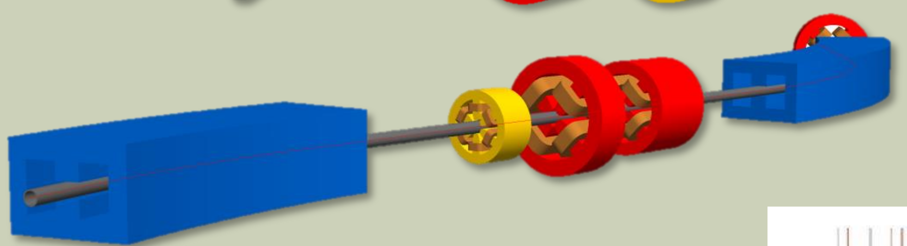
- These beam line simulation tools can be found at:
  - https://twiki.ph.rhul.ac.uk/twiki/bin/view/PP/JAI/BdSim
  - http://www.muonsinternal.com/muons3/G4beamline

- G4beamline more oriented to muons transport
- BDSIM used by ILC, CLIC, XFEL, etc.
  - Certainly a good candidate to consider for EuPRAXIA

BDSIM
Beam Delivery SIMulation

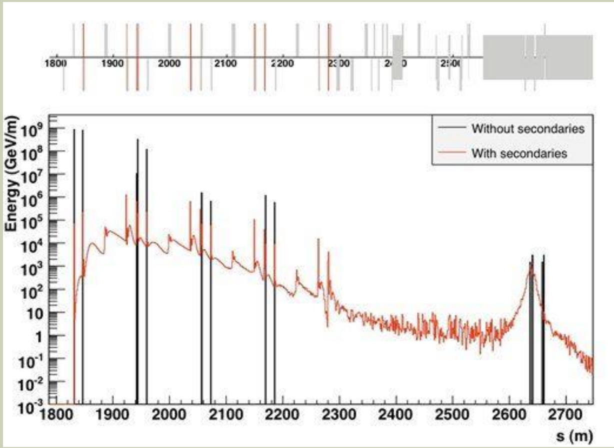
- Transport particles through accelerators and detectors
- Provides:
  - Single particle Monte-Carlo simulations of particle accelerators
  - Simulation of beam loss in a particle accelerator
  - Simulation of detector backgrounds from halo and machine background sources

- Beam line described
  - Using pre-defined elements :  drift  magnets…  collimators…



  - … or user-defined ones…
  - … or imported from other tools such as MAD-X (MAD8) .

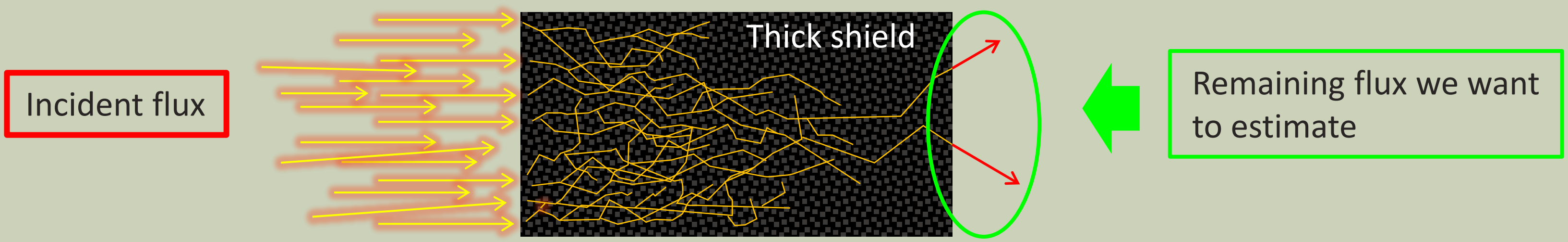
- Interfaced with ROOT for analysis (histograms, etc.)



ENVIRONMENT SIMULATION

- Mainly regarding radioprotection issues
  - With in particular the case of shielding

- In itself, this does not involve special physics
  - But the setup makes the simulation of the problem very slow, sometimes impracticable…



- There are techniques to overcome such difficulties
  - Called "biased simulation", "variance reduction", "event biasing"…
  - They are aiming at boosting the simulation of "rare events"
- In the case of the shielding, several techniques exist
  - Let's illustrate with one

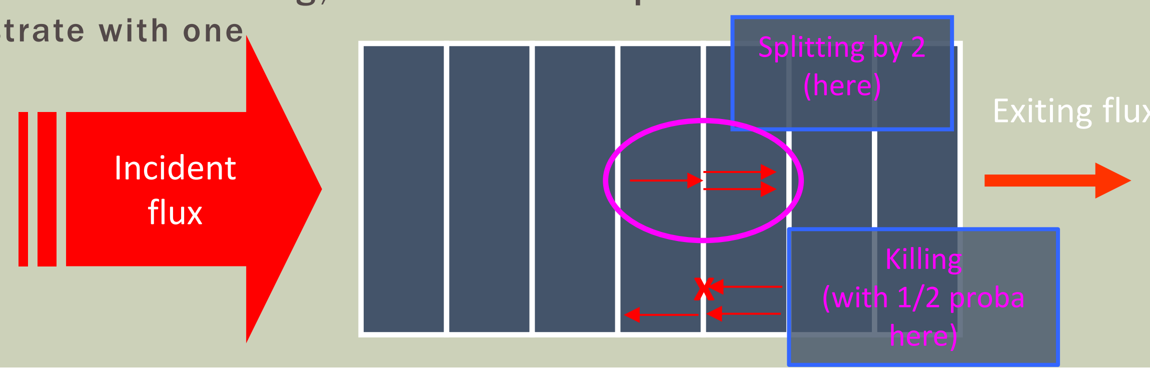
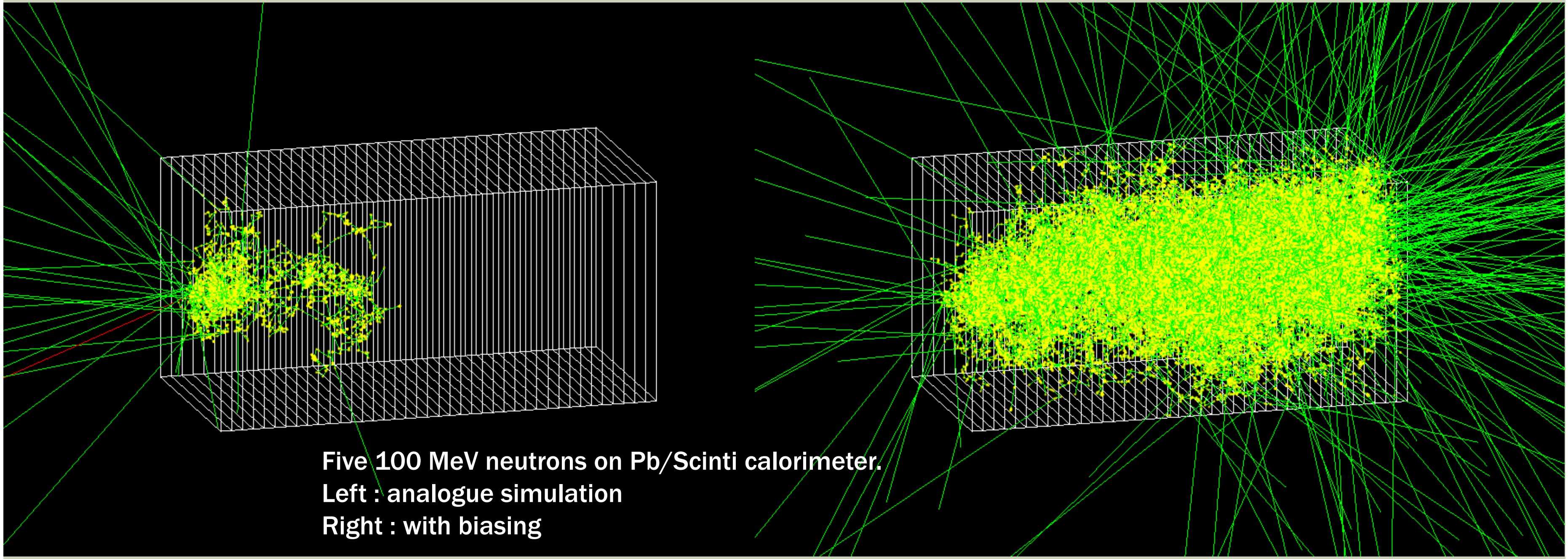


ILLUSTRATION WITH NEUTRONS



- This is one example, but several techniques exist
  - In addition, Geant4 allows you to create your own.
- One comment though:
  - These are powerful techniques, but delicate to handle

CONCLUSION

- Beam transport and environment simulations at EuPRAXIA do not seem to face difficulties at the level of principles
- Existing HEP tools look well adapted
- Geant4 is well suited
  - Both for functionalities and physics coverage
- Beam transport can be tried with BDSIM
  - Good candidate to start with
- Acceleration techniques also exist to treat problems like the radioprotection one
- Of course, this does not mean that practical work is straightforward !
- Note : as Geant4 member I underlined Geant4, but other tools exist : FLUKA, MCNP, etc.