Neutron/Gamma Discrimination in Nuclear Reactors

Mounia Laassiri

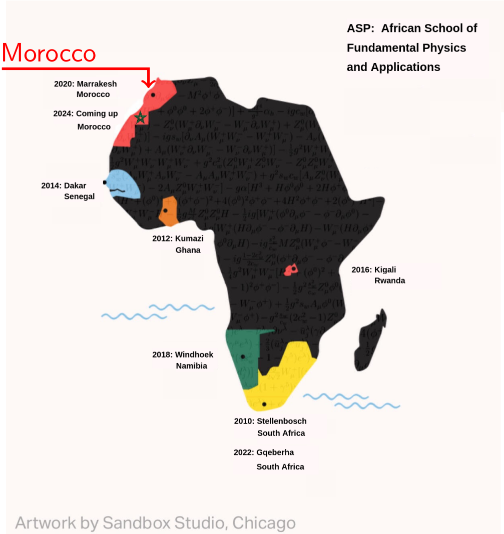
Science Team of Matter and Radiation (ESMaR)
Department of Physics, Faculty of Sciences
Mohammed V University

African School of Physics Seminar Series

April 27, 2021

Université Mohammed V Faculté des Sciences Rabat
CNESTEN
BROOKHAVEN NATIONAL LABORATORY
UNIVERSITY OF JOHANNESBURG

Born & Raised (in Morocco).



Building up the African physics community—By Meredith Fore

BSc in physics

Bachelor's thesis: Ionizing Radiation and Radioprotection

Bachelor's Supervisor: **Prof. R. Cherkaoui El Moursli**

MSc in Security of Computer Networks and Embedded Systems (Sécu.RISE)

Master's thesis: Development of Wavelet Based Tools for Processing and Characterising the γ-ray Spectrometry

Master's Supervisor: **Prof. M. Jedra & Dr. E. M. Hamzaoui**

Ph.D. in Physics and Nuclear Instrumentation

Ph.D. thesis: Neutron Signals Nonnegative Tensor Blind Source Separation: Application to Neutron/Gamma Discrimination

Master's Supervisor: **Prof. R. Cherkaoui El Moursli & Dr. E. M. Hamzaoui**

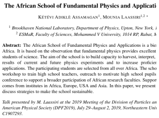
ASP2016 - A Moroccan in Rwanda

- My flight from Morocco (Casablanca) to Rwanda (Kigali)
- Kigali, Rwanda's capital (Africa's cleanest city)
- ASP has opened my mind in so many ways; academically, socially, morally...
- ASP Mentorship Program (***Dr. Mario Campanelli*** & ***Dr. Kate Shaw***)
- This school meant a lot for my Ph.D research (Thanks to **Dr. K. A. Assamagan** (BNL), **Dr. L. Elouadrhiri** (JLab)) & ASP Committee
- Internship at BNL for summer 2019 (5 & a half months)

I will forever be grateful for this privileged scientific adventure.

ASP IMPACT

- Scientific Activities
  - DPF2019, Northeastern University, Boston, USA
  - BF2019, BNL, Upton, NY, USA
  - NSBP2019, Providence, Rhode Island, USA
  - ...
- BNL, Nuclear Reactors Seminar
  - M. laassiri et al., Monte Carlo (MC) modelling of a nuclear reactor core using the Geant4 framework, BNL, Nuclear Science and Technology Department, Bldg. 817



The African School of Fundamental Physics and Applicati

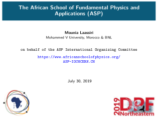
Kétévi Adiklè Assamagan[1], Mounia Laassiri[1,2] *

[1] Brookhaven National Laboratory, Department of Physics, Upton, New York,
[2] ESMaR, Faculty of Sciences, Mohammed V University, 1014 RP, Rabat,

Abstract: The African School of Fundamental Physics and Applications is a bie Africa. It is based on the observation that fundamental physics provides excellent students of science. The aim of the school is to build capacity to harvest, interpret, results of current and future physics experiments and to increase proficier applications. The participating students are selected from all over Africa. The scho workshop to train high school teachers, outreach to motivate high school pupils conference to support a broader participation of African research faculties. Suppor comes from institutes in Africa, Europe, USA and Asia. In this paper, we present discuss strategies to make the school sustainable.

Talk presented by M. Laassiri at the 2019 Meeting of the Division of Particles an American Physical Society (DPF2019), July 29–August 2, 2019, Northeastern Uni C1907293.

arXiv:1909.06309



The African School of Fundamental Physics and Applications (ASP)

Mounia Laassiri
Mohammed V University, Morocco & BNL

on behalf of the ASP International Organizing Committee
https://www.africanschoolofphysics.org/
ASP-IOC@CERN.CH

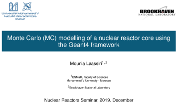
July 30, 2019

Neutron Signals Nonnegative Tensor Blind Source Separation:
Application to neutron/gamma discrimination

Mounia Laassiri[1,2]

[1] ESMaR, Faculty of Sciences, Mohammed V University - Morocco
[2] Brookhaven National Laboratory

NSBP Conference, 2019. November



Monte Carlo (MC) modelling of a nuclear reactor core using the Geant4 framework

Mounia Laassiri[1,2]

[1] ESMaR, Faculty of Sciences, Mohammed V University - Morocco
[2] Brookhaven National Laboratory

Nuclear Reactors Seminar, 2019. December

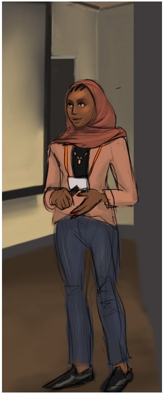


Illustration by: S. Savannah

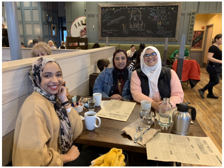
ASP2016 - Memories

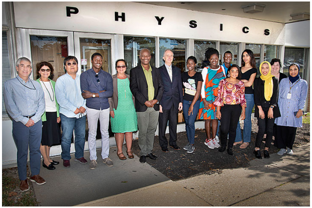
Alumni from ASP at BNLab

thelaassiri
The All Star

Liked by **iman.laaroussi** and **others**

thelaassiri What's meant for you will happen for you in a way which you would never expect of explain. Nothing can get in the way of it and how it will enter your life. just be in a constant state of gratitude and focus your mindset on your vesion. Belive in it. it's all happening for you.





thelaassiri
Patchogue, New York

Liked by **iman.laaroussi** and **others**

thelaassiri Just call me Chaïbia 🎨 🤣

thelaassiri
Mashomack Preserve

Liked by **iman.laaroussi** and **others**

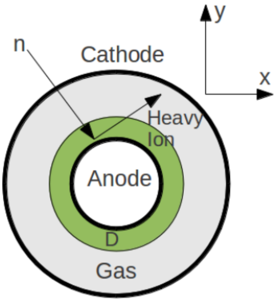
thelaassiri Hiking is absolutely not my thing 😅. Here's To trying something different.

palesa.assam 😊

October 13, 2019

Neutron flux monitoring

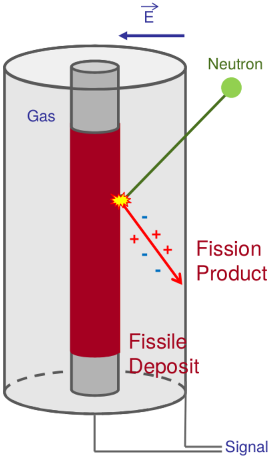
- Online flux measurement in CNESTEN: WL-7657 fission chamber
- Stochastic electric signal on the electrodes (Using Geant4/Garfield++ interface)
- 3 different processing modes (and **different electronics**)
  - Pulse mode (low flux)
  - Campbelling mode (medium flux)
  - Current mode (high flux)
- Nonnegative Tensor Factorisation (NTF) to achieve n/γ discrimination



D: fissile deposit

Fission chamber

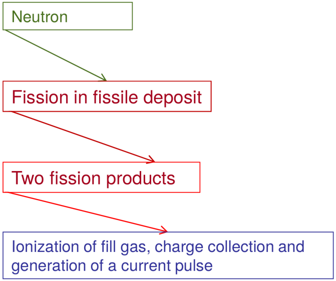
Detection principle



A two-step Signal Forming:

Converter: fissile deposit

Ionization Chamber: electrodes, field and gas



Simulation tools

Simulation of the pulse creation - Geant4/Garfield++

Geant4 ➔ Used to simulate the interactions and passage of particles through matter.

Garfield++ ➔ Simulation of particle detectors that use a gas mixture or a semiconductor material as sensitive medium.

Interfacing Geant4/Garfield++

Simulation tools

The main parts of a gas detector simulation program are:

1. Primary high energy particle ionization; } Geant4
2. Forming of ionization clusters in gas (Heed software);
3. Electron and Ion drift properties in electric and magnetic fields (Magboltz software);
4. Amplification/creation of additional ionization via avalanche;
5. Forming of electronic signal at read out.

(Items 2–5: } Garfield++)

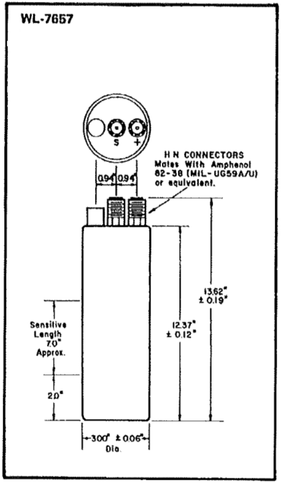
Simulation tools

Program architecture

- Required packages: Geant4.10.02.p02, Garfield++ (version 2015,1), root5.34
- Geant4 /Garfield++ interface:
  - Geant4 part to the interface
    G4Region
    G4VFastSimulationModel
    G4VUserPhysicsList
  - Garfield++ part to the interface)
    DoIt() method
  - Compilation & linking
    CMakeLists.txt
- Neutron source: Cf252NeutronVertex.gps

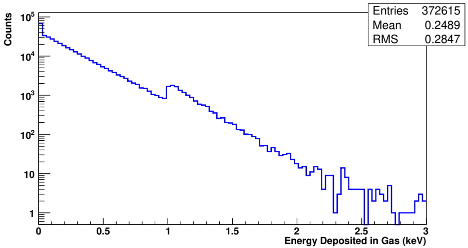
Technical characteristics of the WL-7657

Mechanical	
O.D. nominal	3.00 Inches
Length nominal	13.62 Inches
Sensitive Length nominal	7.00 Inches
Materials	
Structures	Aluminum
Insulation	AL_2O_3
Fissile deposit (mass, thickness)	90 % enriched ^{235}U in U_3O_8 (1.68 g, 2.00 mg/cm^2)
Filling gas (pressure)	Argon 96 % Nitrogen 4 % (76 cm of Hg)

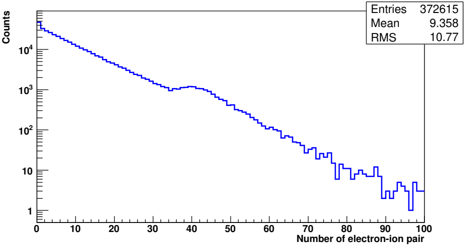


Simulation results

Energy deposited in gas vs. count



Number of created pairs vs. count

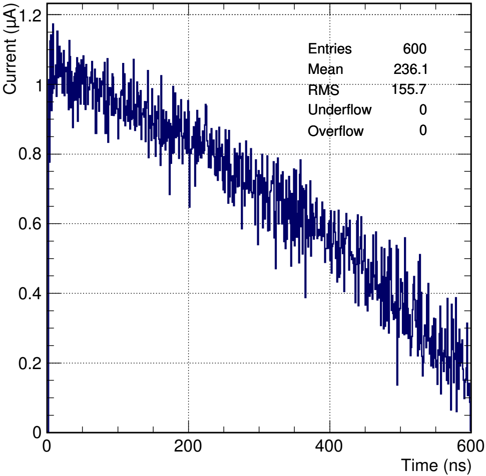


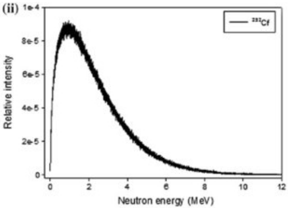
rinp-2017

MeanNumberOfIonsAlongStep() $\xrightarrow{\text{electron-ion pairs}}$ ***G4ElectronIonPair***

Simulation results

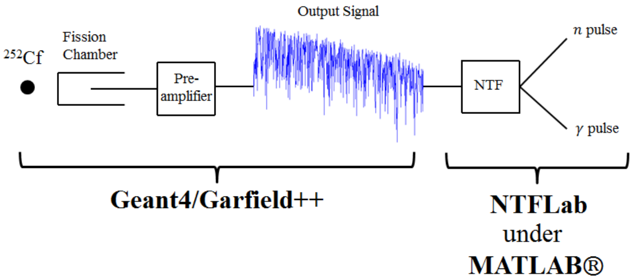
Electric signal inside the WL-7657 FC as a function of time.





Motivation

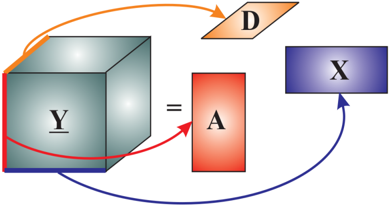
Goal: n, γ discrimination



Nonnegative Tensor Factorisation

Nonnegative Tensor Factorisation (NTF)

- Generalization of Nonnegative Matrix Factorization (NMF)
- Directional information can be derived from the result of NTF
- NTF is also known as multichannel NMF



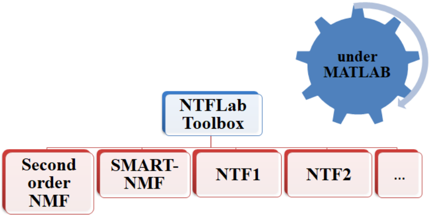
$$Y_k = AD_kX + E_k, \quad (k = 1,2, \dots , K)$$

Nonnegative Tensor Factorisation

Algorithm choice → Performance Index of Separability (PI)

$$PI = \frac{1}{n(n-1)} \sum_{i=1}^{n} \left\{ \left(\sum_{k=1}^{n} \frac{|g_{ik}|}{max_j |g_{ij}|} - 1 \right) + \left(\sum_{k=1}^{n} \frac{|g_{ki}|}{max_j |g_{ji}|} - 1 \right) \right\}$$

- Algorithms are classified according to their lowest PI values.
- In practice, PI $\sim 10^{-1}$ → Good performance



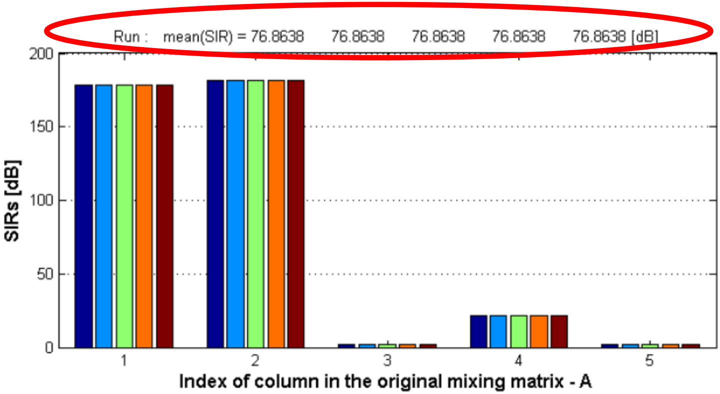
NMF/ NTF Application

- Simulated FC output signals $= \sum$ of pulses with exponentially disctributed arrival times;
- Simulated FC output signals + random noise = Observations;
- 5 Observations processed at once;
- 5 Slices processed at once;
- ^{252}Cf neutron sources.

	Algorithm	PI Value
NMF	Fixed-Point NMF algorithms	0.6723
	Second order NMF	0.6761
	SMART-NMF	0.5032
NTF	NTF1	0.3927
	NTF2	0.3022

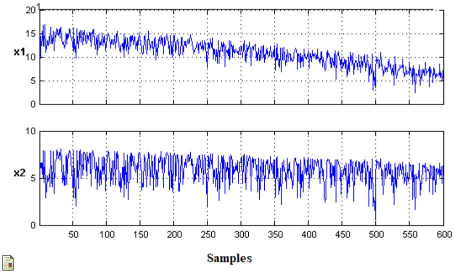
NTF2 Application

SIR evaluation according to the mixing matrix A.

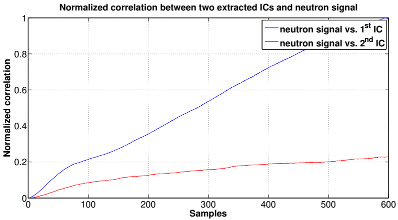


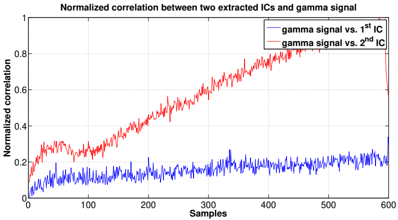
NTF2 Application

Estimated sources (NTF2)



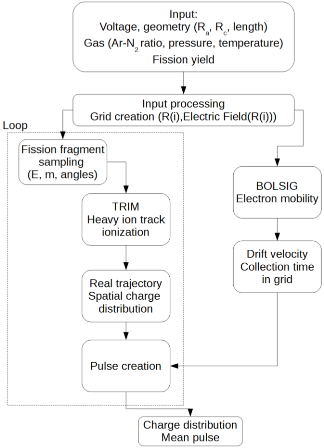
IOP Conf. Series: Journal of Physics



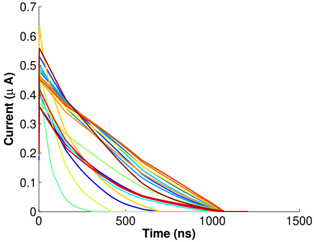


pyFC (python-based simulation of Fission Chambers)

The structure of the pyFC suite code



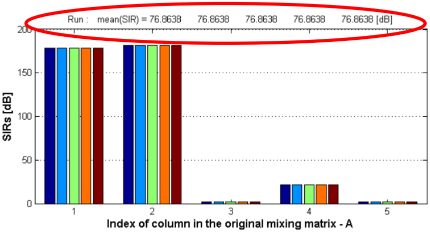
Current signlas

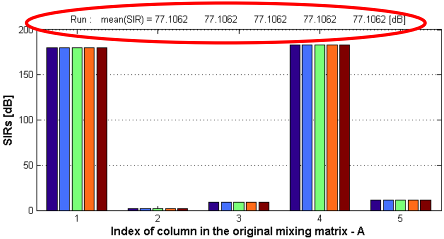


Geant4/Garfield++ *vs.* pyFC

Verification & comparison

SIR evaluation according to the mixing matrix A from: (left) Geant4/Garfield++ (right) pyFC.



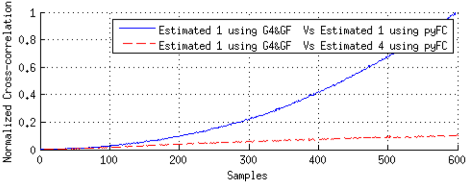


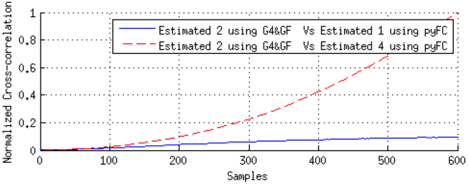
APhysPolBSupp.11.73

Geant4/Garfield++ *vs.* pyFC

Verification & comparison

Normalized cross-correlation function between estimated sources in both the Geant4/Garfield++ and pyFC simulations.

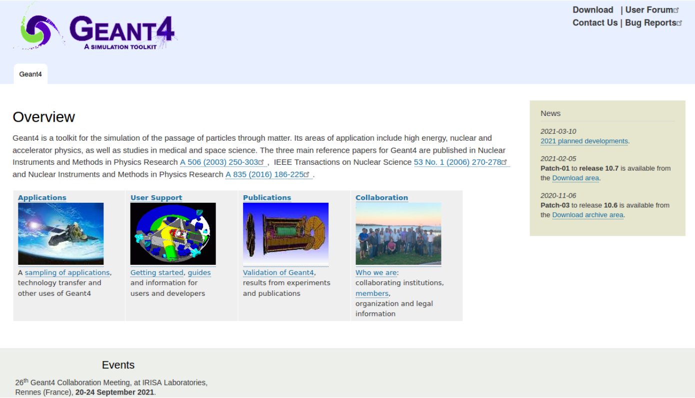




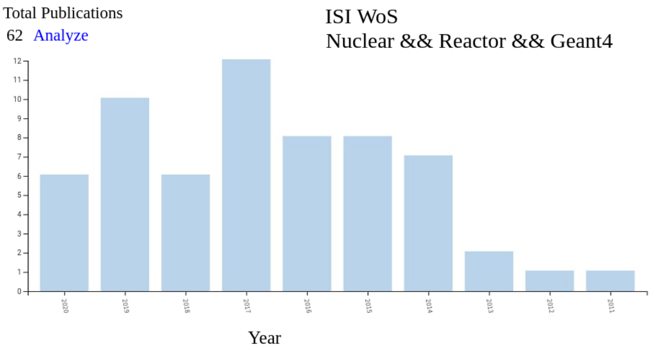
APhysPolBSupp.11.73

Why GEANT4? Because:

- It's there;
- Traditional MC's work with cycles and generations. The concept of time is lost because some neutrons live longer than others;
- Geant4 tracks particles in "real" time.



geant4 web cern



Number of publications per year from a web of science search for articles with topics of Nuclear & Reactor & Geant4, taken March 25, 2021. The average number of citations per item is 6.76.

Active Teams: ADS, Fast neutron studies, G4-STORK, CNL-Geant4, Criticality studies ...

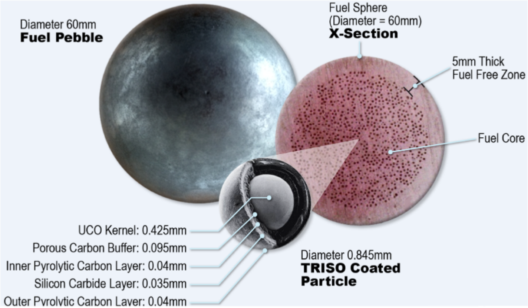
Geant4 – Space Physics

Grand vision: "Ubuntu reactor"

Simulate the entire reactor, using only open source code;
Allow anyone to innovate, verify, improve on reactor modelling.

Lower hanging fruit

Simulate a particular piece within a reactor code.



Geant4 - Monte Carlo Transport code - Databases

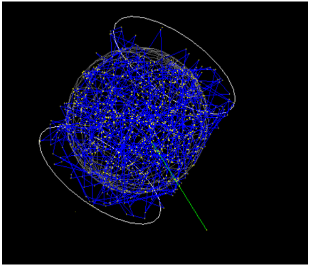
Download	G4NDL4.6, Neutron data files (with thermal cross-sections) - version 4.6 (572.1Mb, 599862135 bytes)
Download	G4EMLOW7.13, data files for low energy electromagnetic processes - version 7.13 (284.8Mb, 298636910 bytes) NEW
Download	G4PhotonEvaporation5.7, data files for photon evaporation - version 5.7 (9.6Mb, 10089240 bytes) NEW
Download	G4RadioactiveDecay5.6, data files for radioactive decay hadronic processes - version 5.6 (1.0Mb, 1059792 bytes) NEW
Download	G4SAIDDATA2.0, data files from evaluated cross-sections in SAID data-base - version 2.0 (37.6kb, 38502 bytes)
Download	G4PARTICLEXS3.1.1, data files for evaluated particle cross-sections on natural composition of elements - version 3.1.1 (8.2Mb, 8613102 bytes) NEW
Download	G4ABLA3.1, data files for nuclear shell effects in INCL/ABLA hadronic mode - version 3.1 (104.8kb, 107286 bytes)
Download	G4INCL1.0, data files for proton and neutron density profiles in INCL - version 1.0 (93.6kb, 95840 bytes)
Download	G4PII1.3, data files for shell ionisation cross-sections - version 1.3 (4.1Mb, 4293607 bytes)
Download	G4ENSDFSTATE2.3, data files for nuclides properties - version 2.3 (283.9kb, 290745 bytes) NEW
Download	G4RealSurface2.2, Optional - data files for measured optical surface reflectance - version 2.2 (126.4Mb, 132506346 bytes) NEW
Download	G4TENDL1.3.2, Optional - data files for incident particles - version 1.3.2 (558.0Mb, 585100935 bytes)

C++, modular architecture, multi-threaded, trivially parallel on multi-nodes, source available User modifies + extends User Classes, even System Classes, not input card driven Engines for geometry, materials, physics, tracking, history recording, visualisation, analaysis.

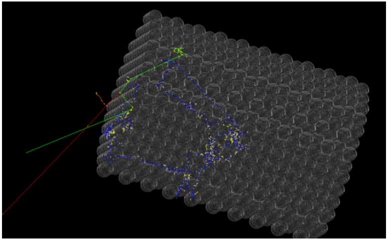
Geant4 – Nuclear Reactors – Proof of Concept

Some new "physics"

1. New Physics Class to reflect neutron at outer boundary with adjustable albedo to allow modelling of small systems.



Following one neutron at two different system scales



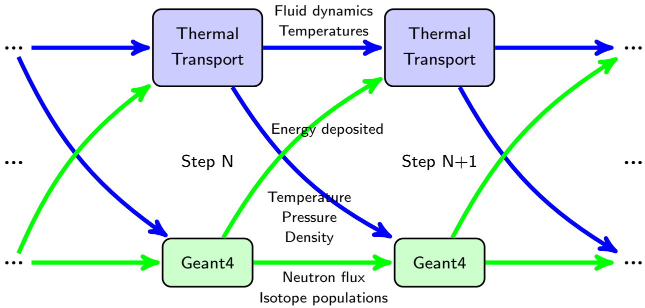
2. Later also introduce a New Physics Class to do nuanced treatment particle inventory for end of time at global wall clock time slice. Modify how Geant4 prioritises decay vs killing of particles in order to capture history snapshot at end of time slice accurately.

Geant4 – Nuclear Reactors – Proof of Concept

Dual Neutronics and Thermal Hydraulics

Time stepped in time slices

Neutronics has persistence and continuity between steps with updates on thermal properties, leading to updates on macroscopic cross sections and densities.



Geant4 – Nuclear Reactors – Proof of Concept

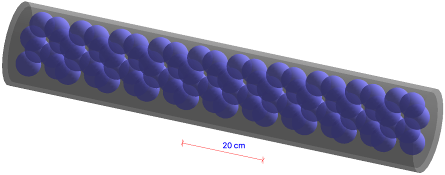
Physics model:

- Accurate simulation of fission:
  - (temp dependent) cross-section,
  - fission fragments,
  - prompt and delayed neutron production
- Accurate simulation of neutron capture:
  - (temp dependent) cross-section
- Other reactions, like inelastic scattering;
- Fast and thermal neutron tracking;
- Neutron decay;
- Fission fragment decay;
- Modelling for energy deposition from gammas, electrons, positrons etc.

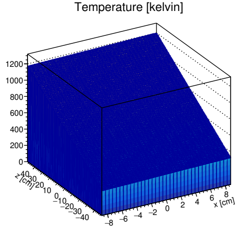
Geant4 – Nuclear Reactors – Proof of Concept

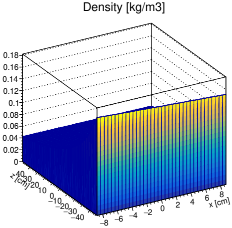
Proof of Principle

1m long $\times 0.18$m diameter, "reactor" with 80×6 cm diameter hcp pebbles



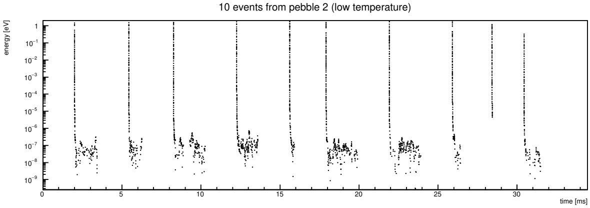
$$T = 300K + 900K \cdot \frac{6(z - z_0) + (x - x_0}{6Z + X}$$



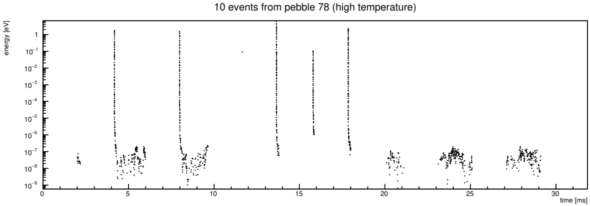


Geant4 – Nuclear Reactors – Proof of Concept

Proof of Principle
Following single neutrons. 2 MeV, low temperature side 2 MeV, high temperature side



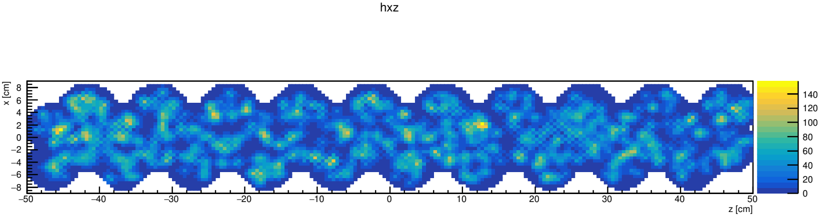
Neutrons explore entire space, final temperature has small memory of original location



Geant4 – Nuclear Reactors – Proof of Concept

Energy deposition map

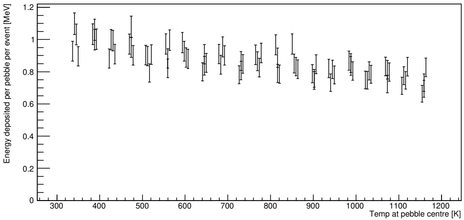
Energy deposits within pebbles [MeV], for 50k neutrons, shown in a x-z slice for y=0.

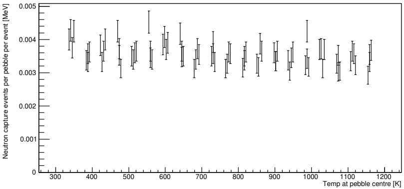


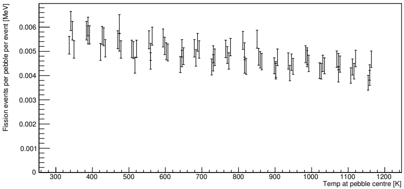
Geant4 – Nuclear Reactors – Proof of Concept

Energy deposition map analysis

Temperature higher on left than right







Geant4 – Nuclear Reactors – Proof of Concept

Fission Fragment history

- 50k primary neutrons
- 14k new nuclei, ff + other
- 16 unique isotopes
- 8 stable
- 8 unstable

Table: Top 16 most abundant isotopes created, for 50,000 primary 2 MeV neutrons.

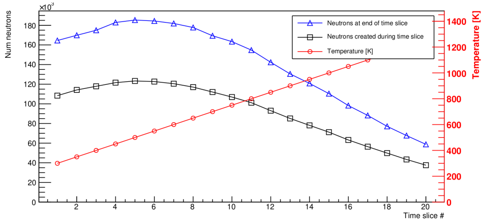
Isotope	#created
^{239}U	4599
^{13}C	3628
^{236}U	3068
^{29}Si	1334
^{12}C	598
^{238}U	243
^{28}Si	193
^{14}C	60

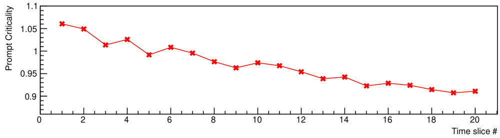
Isotope	#created
^{30}Si	58
^{9}Be	51
^{31}Si	37
^{235}U	26
^{28}Al	4
^{25}Mg	1
^{237}U	1
^{26}Mg	1

Geant4 – Nuclear Reactors – Proof of Concept

Criticality Core Follow

- Measured per time slice for 20 slices (20 $\times$ 1 ms)
- Start at 300K, artificially step by 50k per slice He at 100 atm
- He at 100 atm
- 18% enrichment to start near "critical" reactor for this condition.





Numbers of neutrons per generation (top) and prompt criticality (bottom) for 20 time slices

Summary

- First application of the NTF/BSS in neutron signal processing;
- New approach to discriminate neutron and γ-ray;
  - Correlation (Time domain)
  - Power spectral density (Frequency domain) — Not mentioned in this talk!
- The verification of the code through comparison with the results of pyFC;

- Geant4 — Nuclear Reactors
  - Time slicing and adaption of Geant4 for correct persistence
  - Energy depositions
  - Fission Fragment history
  - Criticality
  - Core follow