DE LA RECHERCHE À L'INDUSTRIE

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Recent Developments in the TRIPOLI-4® Monte-Carlo Code for Shielding and Radiation Protection Applications

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Journées "Codes de calcul en radioprotection et radiophysique et dosimétrie"
1-2 février 2018, Sochaux, France

OUTLINE

I - General presentation of TRIPOLI-4®

II - New features of TRIPOLI-4® version 10

III – Main ongoing developments in TRIPOLI-4® for shielding and radiation protection applications

TRIPOLI-4® is a registered trademark of CEA, we gratefully acknowledge EDF long time support of TRIPOLI-4®

I - GENERAL PRESENTATION OF THE TRIPOLI-4® CODE

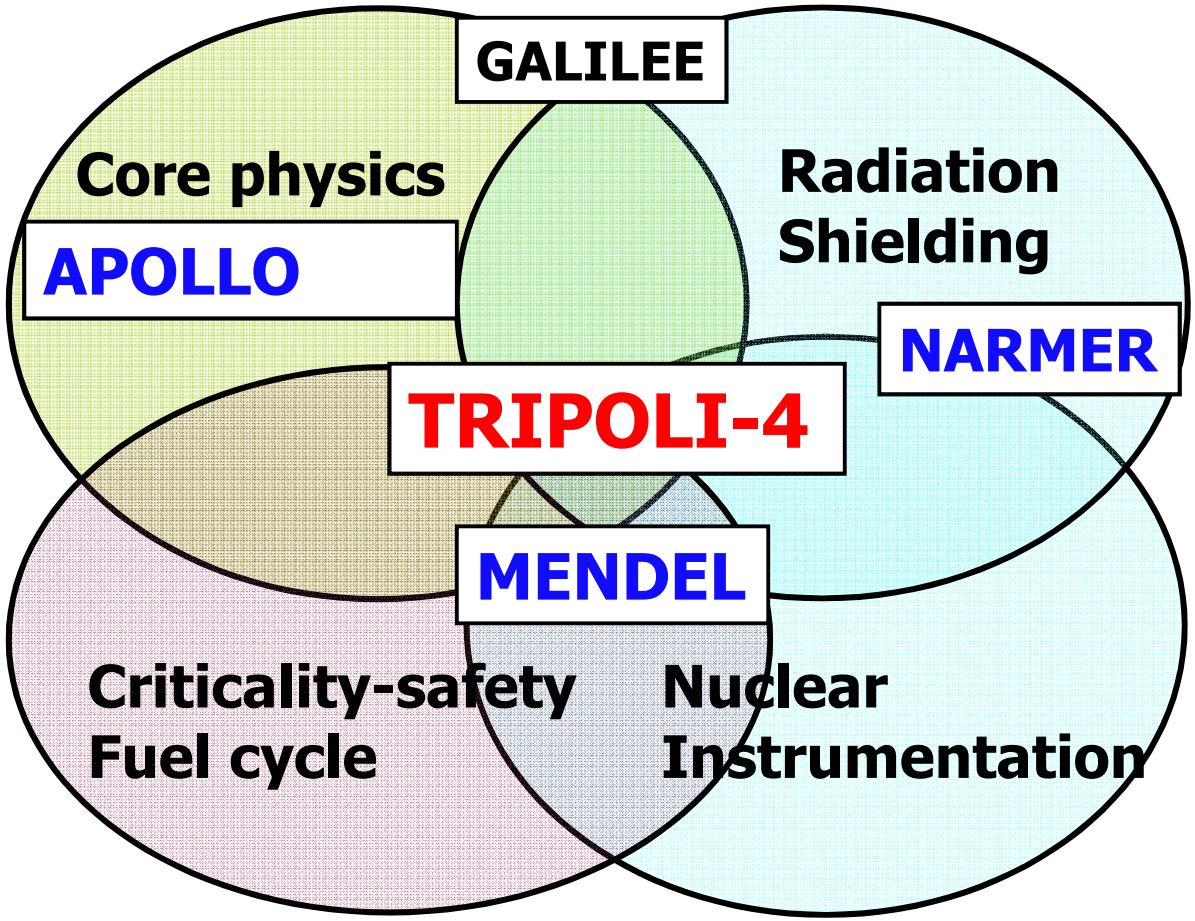
TRIPOLI-4 MONTE CARLO CODE

/. **TRIPOLI-4 is a general purpose radiation transport code. It uses the continuous-energy Monte Carlo method to simulate neutron, photon, electron and positron transport in 3D geometry.**

/. **TRIPOLI-4 application fields include radiation shielding, criticality safety, fission reactor physics, fusion reactor design, and nuclear instrumentation.**

/. **Basic features of TRIPOLI-4 and main ongoing developments for radiation shielding and radiation protection applications will be presented in this talk.**

TRIPOLI-4 MONTE CARLO CODE & NUCLEAR ENGINEERING CALCULATIONS



/. GALILEE

JEFF, ENDF/B, ENDL

/. APOLLO

DETERMINISTIC

CELL / CORE CODES

/. MENDEL

BATEMAN

EQUATIONS SOLVER

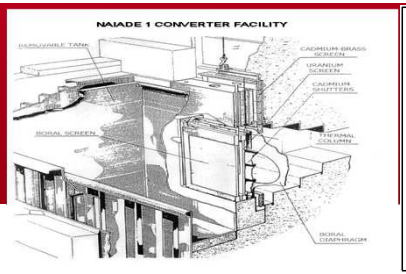
/. NARMER

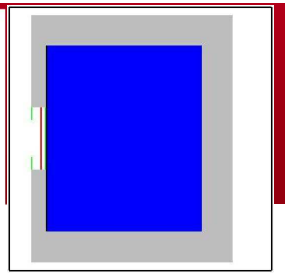
POINT KERNEL CODE

TRIPOLI-4® GENERIC FEATURES

- **Based on previous versions TRIPOLI-2 (1980) & TRIPOLI-3 (1990)**
  - Developed from the mid of 1990s
  - **~500 000** code lines of C++
  - **Geometry, Data Library, Perturbation, Parallel mode,** T4G, Burnup,
  - Variance Reduction – INIPOND, AUTO, DATA, AMS …
- **Tracked particles**
  - Neutrons from 20 MeV down to 10^{-5} eV
  - Photons from 50 MeV down to 1 keV
  - Electrons and positrons from 100 MeV down to 1 keV
  - ***N, P, E, N+P, P+N, E+P+N, P+E cascades ..***
- **Three simulation modes**
  - "Criticality" mode: Kinf, Keff, power map, rod worth …
  - "Shielding" mode: fixed-source simulation
  - "Fixed-sources sub-criticality" mode: factor M
- **Tallies**
  - volume, surface, point **flux**es, mesh tallies, current
  - reaction rates, dose equivalent **rate**, KERMA , deposited energy
  - dpa & gas production, gamma **spectrometry**

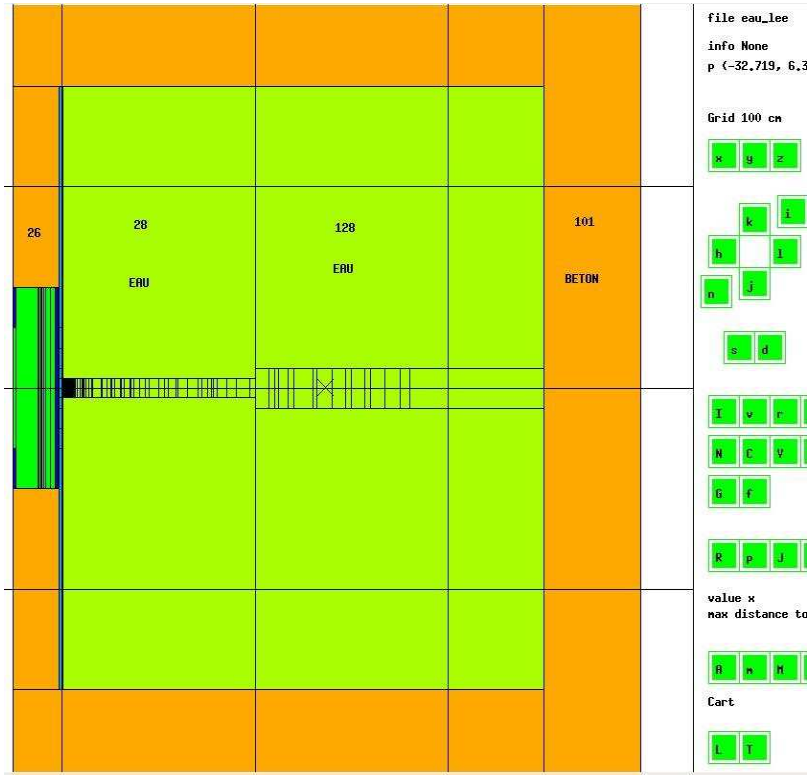
TRIPOLI-4® GEOMETRY MODULE



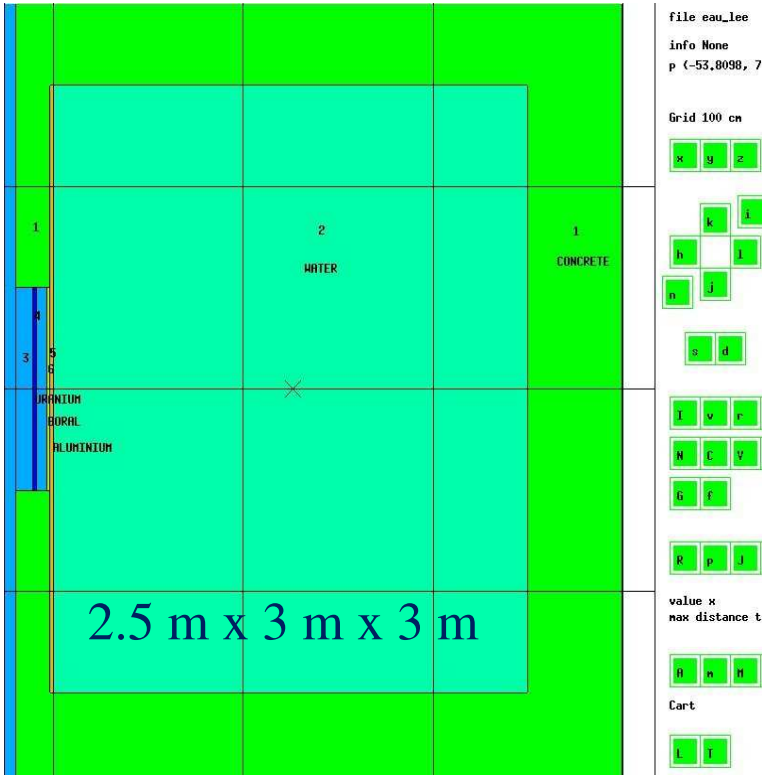


Geometry module – (NAIADE light water shielding experiment)

Surface-based geometry

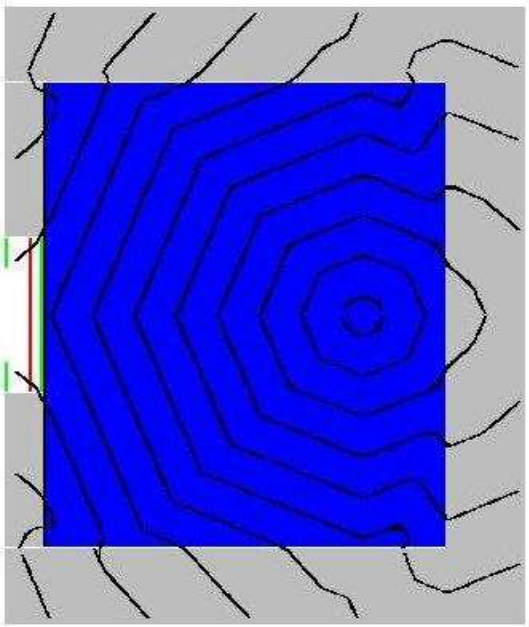


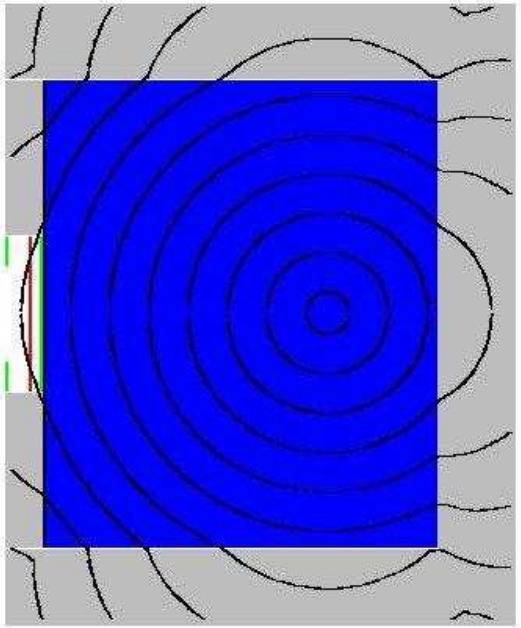
Combinatorial geometry



TRIPOLI-4® VARIANCE REDUCTION - 1

- Standard techniques: implicit capture, particle splitting and Russian roulette
- INIPOND module (Exponential Transform Method):
  - with an automatic pre-calculation of the importance map
  - with possible adjustment of the input parameters of INIPOND in order to adjust the global strength of the biasing)

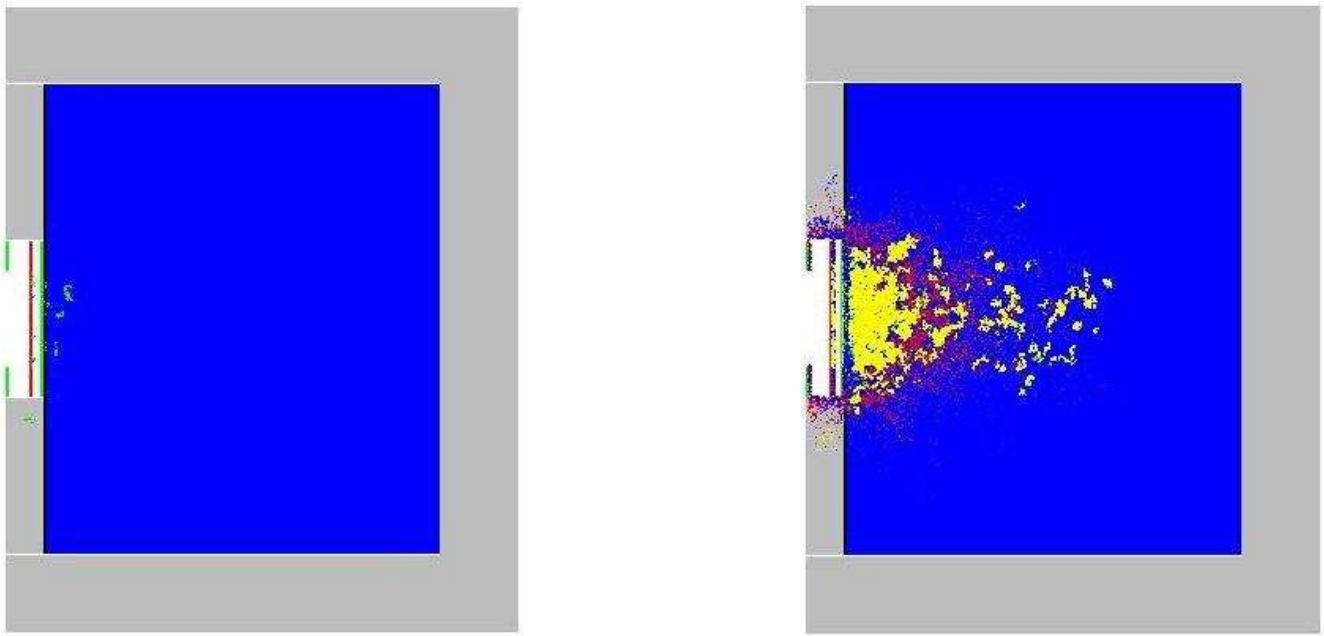




Iso-importance curves of the importance map produced by TRIPOLI-4
The fission source is on the left side and the **detector on the right side**

TRIPOLI-4® VARIANCE REDUCTION - 2

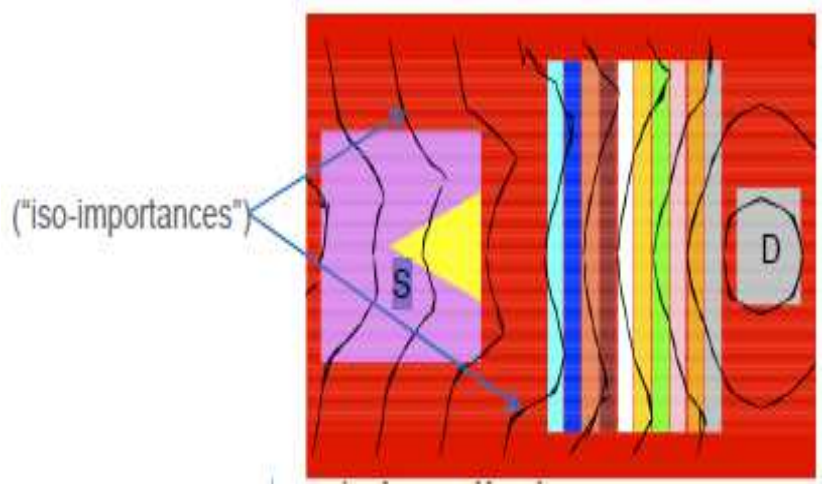
- Standard techniques: implicit capture, particle splitting and Russian roulette
- INIPOND module (Exponential Transform Method):
  - with an automatic pre-calculation of the importance map
  - with possible adjustment of the input parameters of INIPOND in order to adjust the global strength of the biasing)

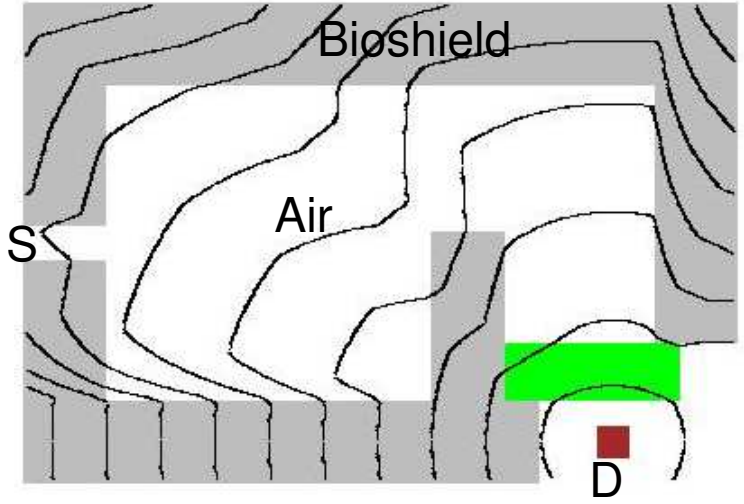


Neutron collisions sites produced by TRIPOLI-4

Analog run on the left side **INIPOND run on the right side**

TRIPOLI-4® VARIANCE REDUCTION - 3





O. Petit, Y.-K. Lee, C. Diop, "Variance reduction adjustment in Monte Carlo TRIPOLI-4® neutron gamma coupled calculations", Progress in Nuclear Science and Technology Volume 4 (2014) pp. 408-412.

Y.-K. Lee, "Neutron Deep Penetration Calculations in Light Water with Monte Carlo TRIPOLI-4® Variance Reduction Techniques", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

TRIPOLI-4 CODE - VERIFICATION & VALIDATION

/. More than 1,000 benchmark cases from OECD/NEA are available in the TRIPOLI-4 validation database.
- SINBAD database for fission & fusion shielding
- ICSBEP handbook for criticality safety & shielding
- IRPhE database for reactor physics applications.

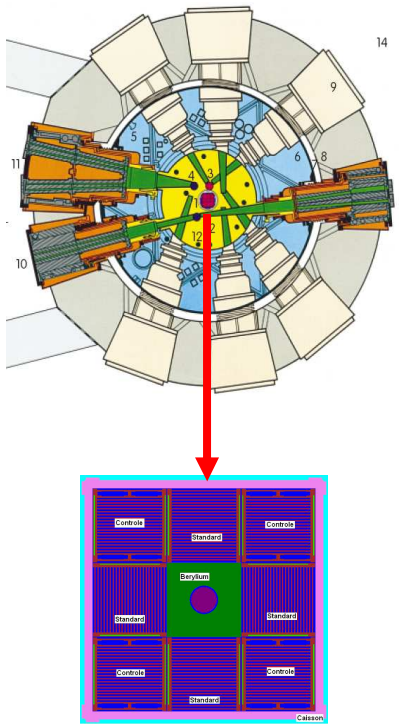
/. TRIPOLI-4 – V&V other benchmarks

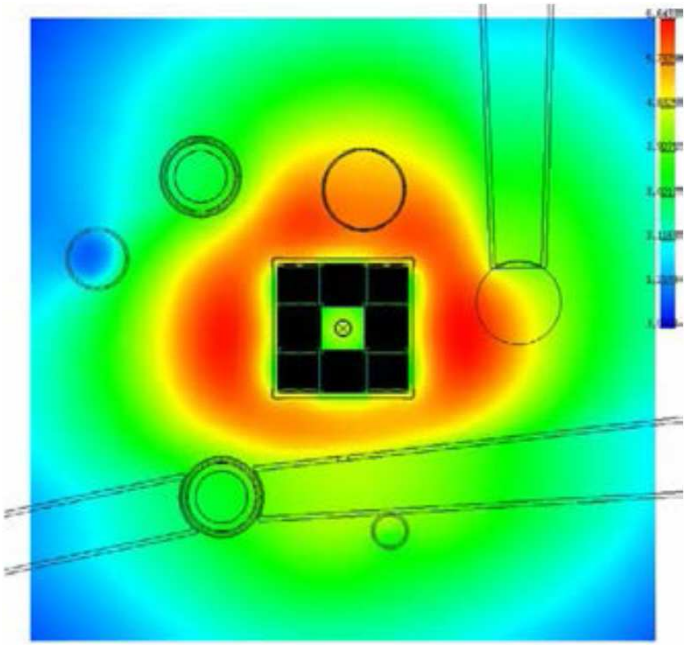
C/T, C/E, C/C, Vn/Vn+1 => PENELOPE, MCNP ..
Component & Integral results
Code (options) => Neutron, Photon & Electron
Data lib. (element, interaction)
Modeling
User

II – NEW FEATURES OF TRIPOLI-4® VERSION 10

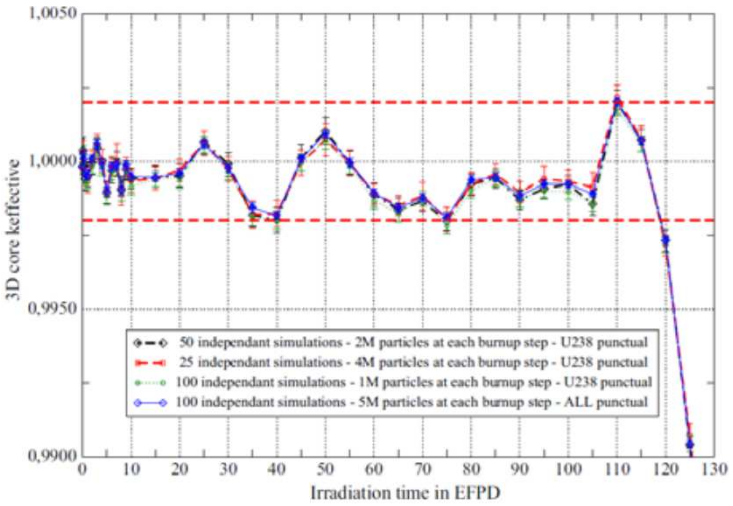
TRIPOLI-4® V10: MONTE-CARLO DEPLETION CODE

ORPHEE reactor 3D core-depletion analysis performed with TRIPOLI-4® v10





Radial thermal flux distribution of the ORPHEE reactor calculated by TRIPOLI-4® (3D core-depletion analysis)



Evolution of the keff during irradiation. Time is expressed in effective full-power days (EFPD). Controls rods insertion is adjusted during irradiation

F. Damian and E. Brun, "ORPHEE research reactor: 3D core depletion calculation using Monte-Carlo code TRIPOLI-4®". Annals of Nuclear Energy 82 (2015) 203–216.

TRIPOLI-4® V10 NEW FEATURES

Asymptotic Reactor period calculation

- Inverse of the dominant eigenvalue (i.e. the fundamental α eigenvalue of the Boltzmann operator)
- Algorithm based on a modified α-k power iteration scheme

> A. Zoia, E. Brun, F. Damian, F. Malvagi, "Monte Carlo methods for period calculations", Annals of Nuclear Energy, Volume 75, 2015, Pages 627–634

Kinetics parameters computing

- Iterated Fission Probability method (IFP)
- Adjoint-weighted kinetics parameters: β_{eff}, Λ_{eff}, α_{Rossi}

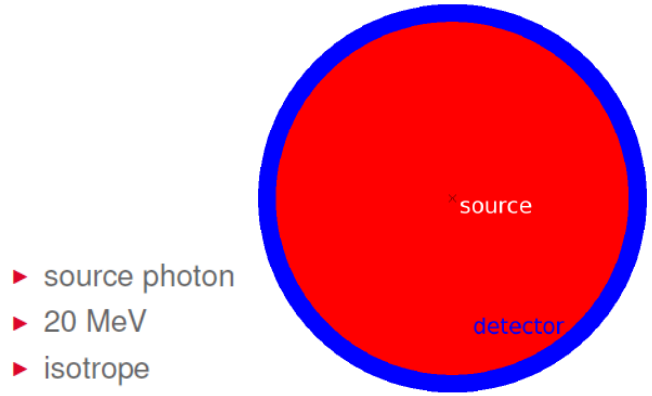
> G. Truchet, P. Leconte, A. Santamarina, E. Brun, F. Damian, A. Zoia, "Computing adjoint-weighted kinetics parameters in TRIPOLI-4® by the Iterated Fission Probability method", Annals of Nuclear Energy, Volume 85, 2015, Pages 17–26

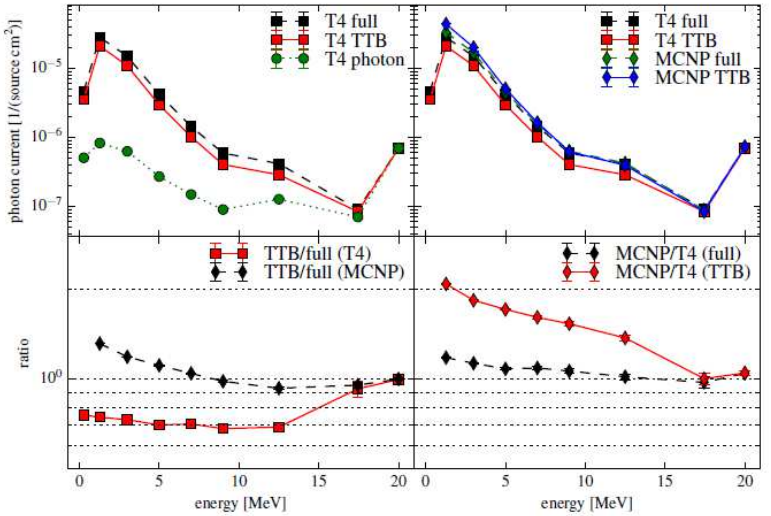
Deposited charge

- Calculation of the spectrum of the charge deposited in a given volume by charged particles (electrons and positrons)
- useful for nuclear instrumentation in the interpretation of signal of sensors irradiated in nuclear reactors

Thick-Target Bremsstrahlung for electromagnetic shower simulation

- Secondary e^- and e^+ produced by photon collisions are not transported, but a part of their energy is converted into new bremsstrahlung photons
- Simplified simulation mode for the electromagnetic shower:
  - TTB vs full calculation: a maximum difference of 30%
- Speed up coupled photon-electron-positron calculations:
  - TTB vs full: acceleration up 10 times



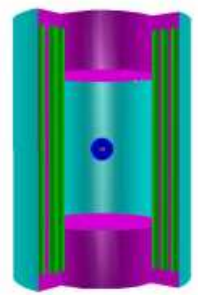


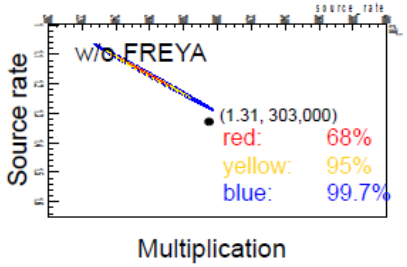
Riz et al.
PHYSOR-2000 proceedings

Courtesy of D. Mancusi
CEA, Saclay, SERMA

Analog simulation with analog fission sampling

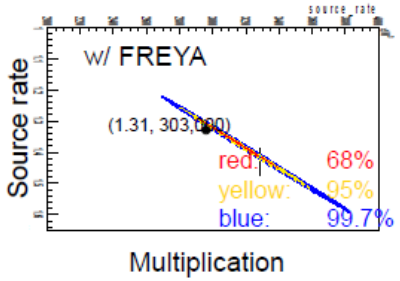
- Fully analog simulation for neutron and photon transport:
  - concerning both collisions and transport between collisions
- Analog fission simulation by sampling a full fission neutron multiplicity distribution
- Coupling between TRIPOLI-4® and an external fission model providing fission sampling data:
  - FREYA (Fission Reaction Event Yield Algorithm, LLNL):
  - Example of application: NMC (Neutron Multiplicity Counting) properly simulated by reconstructing the mass and multiplication of two objects by analyzing the measured signal from ^{3}He tubes in a well counter.





← TRIPOLI-4®

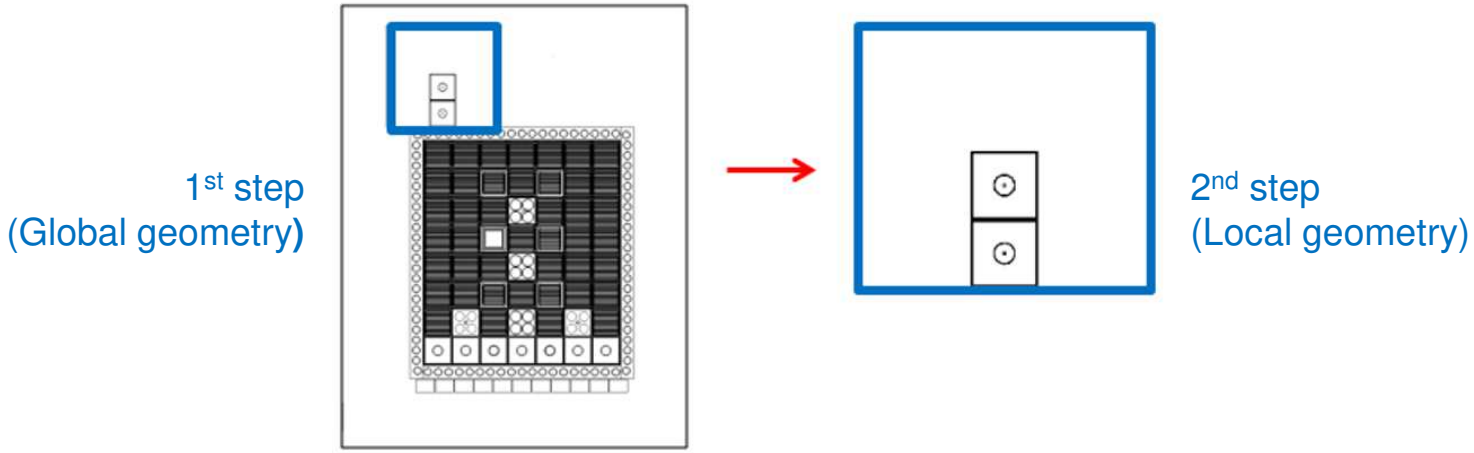
TRIPOLI-4® + FREYA →



J. M. Verbeke, O. Petit, "Stochastic Analog Neutron Transport with TRIPOLI-4 and FREYA: Bayesian Uncertainty Quantification for Neutron Multiplicity Counting", Nuclear Science and Engineering, Vol. 183, Nb 2, June 2016, p. 214-228

"Replicate" option upgrading for two-step calculation

- Technique of variance reduction for two-step calculation
- Global geometry used first to store the properties of particles crossing a given surface
  - Energy, position, direction, weight
- Stored particles used as surface sources for new simulation on a local geometry
- REPLICATE option activates the particle splitting at the second-step simulation



Example of a two-step calculation: Global geometry + Local geometry

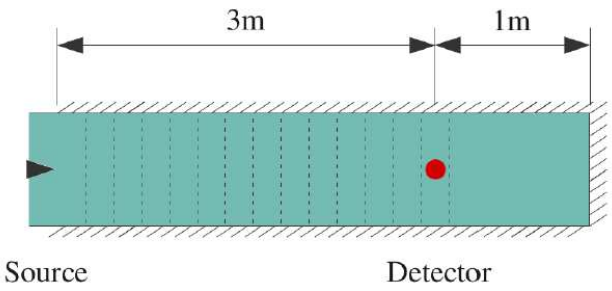
F. Malouch, F. Lopez, L. Barbot, D. Fourmentel, "Calculation of neutron and gamma fluxes in support to the interpretation of measuring devices irradiated in the core periphery of the OSIRIS Material Testing Reactor", ANIMMA2015, Lisbon Portugal, April, 20-24, 2015.

III - MAIN ONGOING DEVELOPMENTS IN TRIPOLI-4® FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS

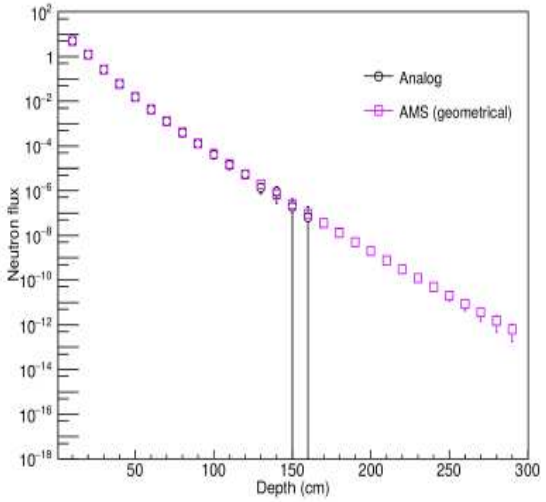
TRIPOLI-4® FEATURES FOR SHIELDING APPLICATIONS

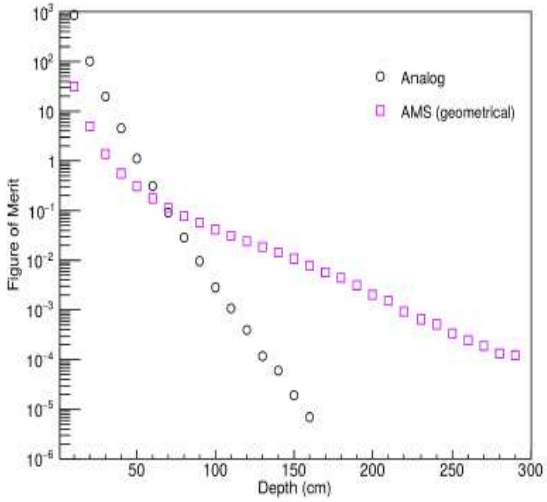
User friendly variance reduction using the method of Adaptive Multilevel Splitting (AMS)

- Iterative algorithm to help simulate rare events
  - Classify simulated particle tracks and define a splitting level
  - Remove the particles that have not reach the threshold
  - Re-sample removed particles by splitting remaining ones



Deep penetration problem (in water)



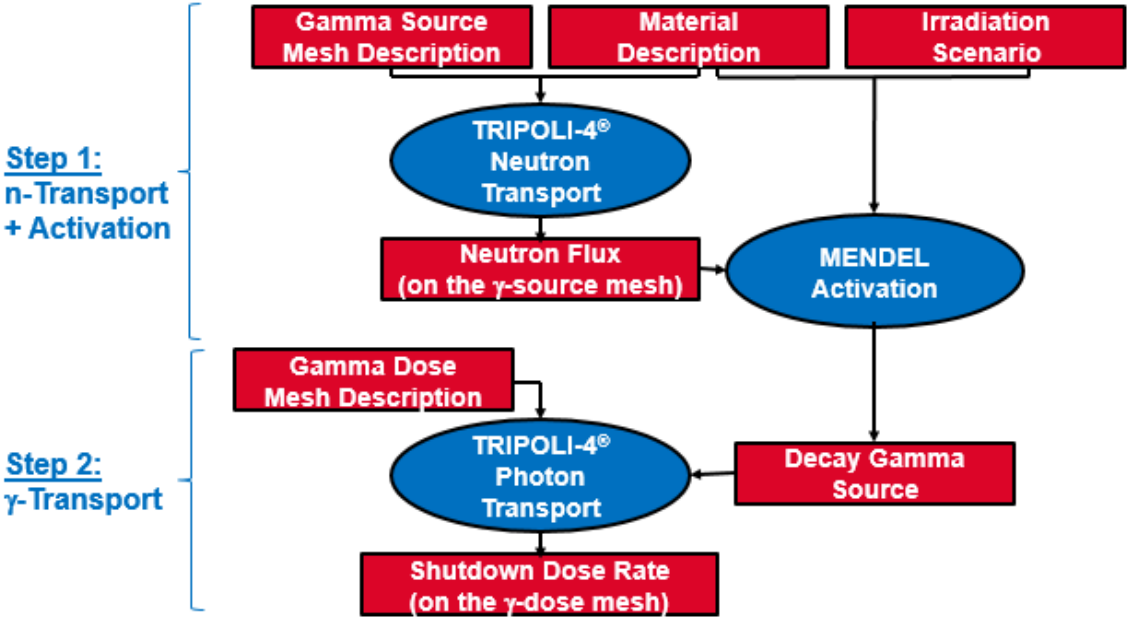


H. Louvin, C. Diop, E. Dumonteil, T. Lelièvre, M. Rousset, "Adaptive Multilevel Splitting for Monte Carlo particle transport", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

TRIPOLI-4® FEATURES FOR SHIELDING APPLICATIONS

Rigorous two-step scheme for shutdown dose rate calculation

- Development of an activation calculation scheme based on the two codes developed by CEA (Saclay, SERMA):
  - the transport code TRIPOLI-4®
  - and the depletion code MENDEL

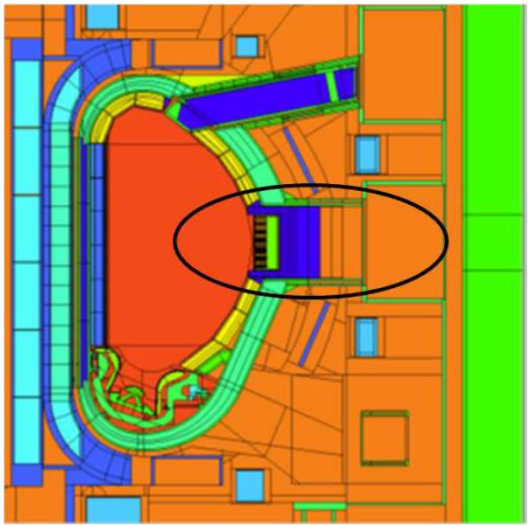


F. Malouch et al., "Recent development in the TRIPOLI-4® Monte-Carlo code for fusion applications", 29th SOFT, Prague, Czech, September 5-9, 2016

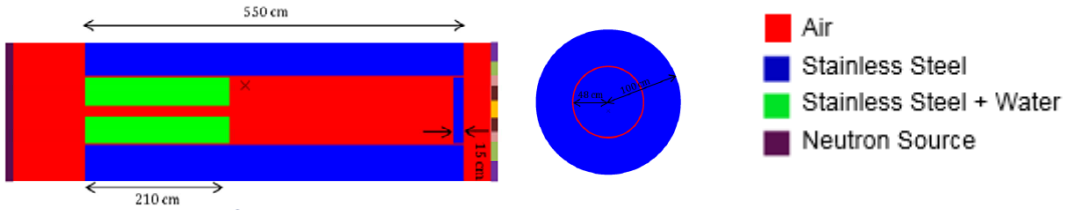
TRIPOLI-4® FEATURES FOR SHIELDING APPLICATIONS

Rigorous two-step scheme for shutdown dose rate calculation

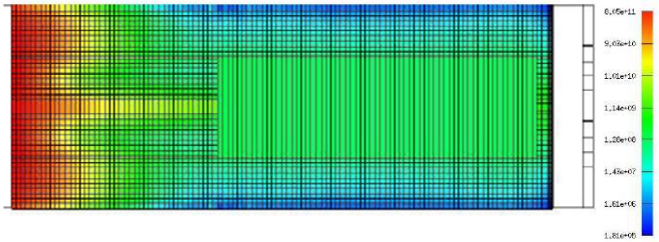
- Comparison with the different SDR calculation schemes (based on MCNP)
- Typical configuration of a port plug in ITER
- Focusing on a streaming path that contributes to activate a steel chamber



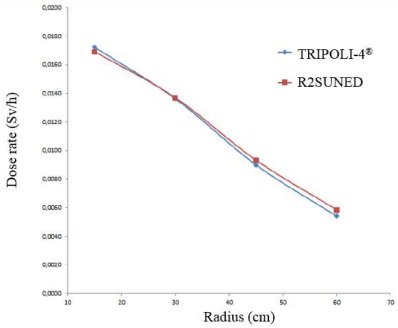
ITER Equatorial Port Plug



TRIPOLI-4® Geometry Model for ITER SDR Benchmark



Distribution of the total neutron flux calculated by TRIPOLI-4®



Shutdown dose rate at the rear face

J.C. Jaboulay, "Rigorous-two-Step scheme of TRIPOLI-4® Monte Carlo code validation for shutdown dose rate calculation", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

SUMMARY AND PERSPECTIVES

- Several recent Developments in the TRIPOLI-4® Monte-Carlo code for Shielding and Radiation Protection applications

- TRIPOLI-4 v10 :
  - Thick-Target Bremsstrahlung for electromagnetic shower simulation
  - Analog simulation with analog fission sampling (FREYA coupling)
  - “Replicate” option upgrading for two-step transport calculations

- Main ongoing developments
  - Variance Reduction using the Adaptive Multilevel Splitting (AMS) method
  - Analog simulation with analog fission sampling (FIFRELIN coupling)
  - TRIPOLI-4® - Geant4 Coupling
  - Rigorous two-step scheme for shutdown dose rate calculation

TRIPOLI-4® DISTRIBUTION AND LICENSING

From the OECD/NEA Data Bank and RSICC

- License covering code evaluation, teaching and R&D (fusion activities included).
- TRIPOLI-4® versions 8 and 9 are currently available
- TRIPOLI-4® version 10 soon available

From CEA

- For countries outside the OECD/NEA Data Bank and RSICC
- For companies requesting a business license
- In both cases following an specific Licence agreement with CEA.

Contact at CEA, Saclay, SERMA

- Andrea ZOIA : andrea.zoia@cea.fr (TRIPOLI-4® Project Leader)

Thank you for attention