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ETSON EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

# Analysis of the RCF experiments dedicated to spatial correlations measurements

NUCLEAR CRITICALITY SAFETY PROGRAM
U.S. DEPARTMENT OF ENERGY

*E. Dumonteil*

*On behalf of the*
*IRSN-LANL collaboration*

*Contact: eric.dumonteil@irsn.fr*

*IRSN PSN-EXP/SNC*
*France*

# Collaboration

- IRSN PSN-EXP/SNC/LN :

  N. Thompson, W. Monange, B. Dechenaux, E. Dumonteil

- LANL NEN-2 group:

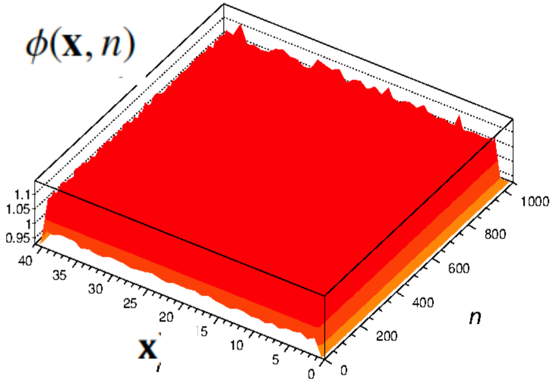
  J. Hutchinson, R. Bahran, G. McKenzie, M. Nelson, A. McSpaden

- RCF staff @ RPI led by P. Caracappa

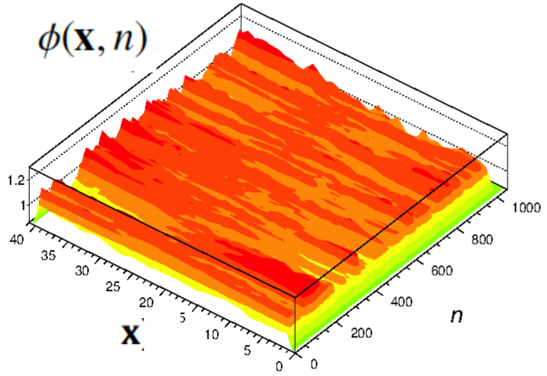
- Experiments at RPI performed in mid-2017

- Analysis: N. Thompson (1 year postdoc at LANL+1 year postdoc at IRSN)

# Clustering & Spatial correlations



L = 10 cm



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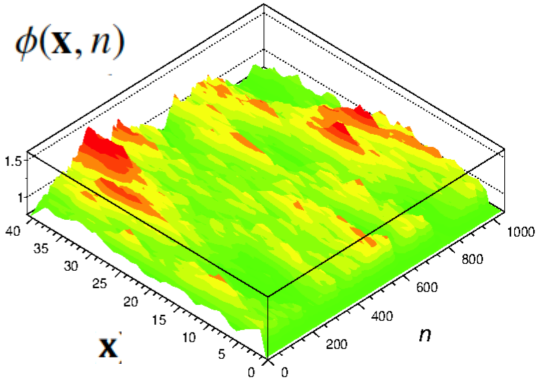
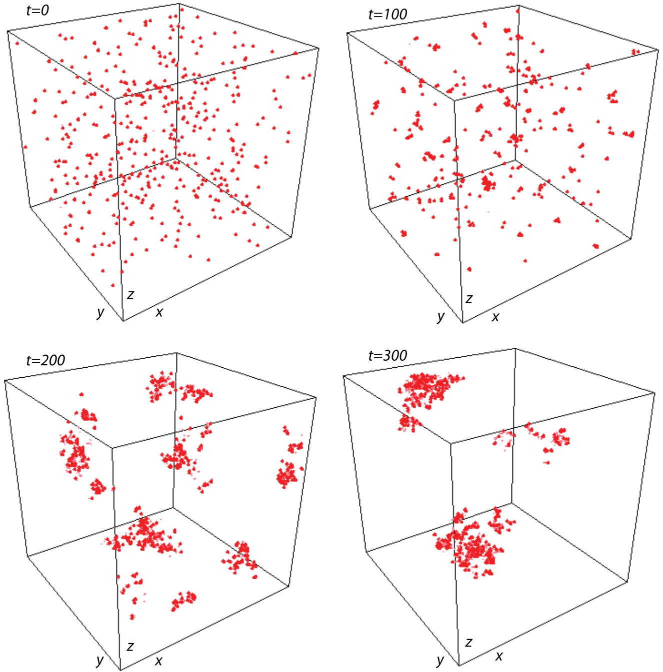
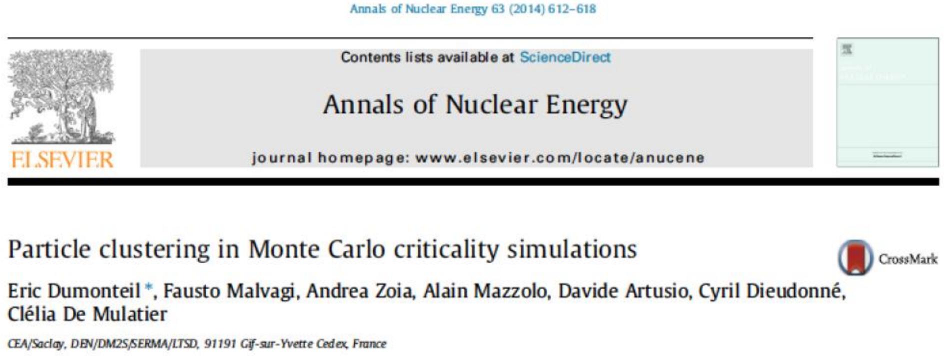


L = 400 cm



$$\boxed{\frac{\partial}{\partial t} g_t(r) = 2D\nabla_r^2 g_t(r) + \frac{\lambda \nu_2}{c_t}\delta(r)}$$



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Particle clustering in Monte Carlo criticality simulations

Eric Dumonteil *, Fausto Malvagi, Andrea Zoia, Alain Mazzolo, Davide Artusio, Cyril Dieudonné, Clélia De Mulatier

CEA/Saclay, DEN/DM2S/SERMA/LTSD, 91191 Gif-sur-Yvette Cedex, France

# Motivations to study spatial correlations

- Spatial correlations generalize the notion of stochastic noise

- Monte Carlo criticality codes :
  - "artificial" sampling of the fission pdf width (2 or 3 neutrons)
  - "artificial" spatial correlations and stochastic noise
  - prevent to correctly estimate error bars when simulating large systems
  - => generalized central limit theorems could be used is correlations/noise could be properly characterized

- Correlated physics Monte Carlo codes :
  - use for homeland security applications, noise-based detectors (ex: fuel reloading), systems with low sources levels (ex: start-up of reactors), …
  - these codes use specific nuclear data: nubar => mean number of pairs
  - qualification of these codes needs specific benchmarks/experiments

- Research reactors / industry / etc.
  - Understanding fundamental principles of stochastic fluctuations at the startup of sub-critical / critical experiments
  - Feynman & Rossi curves behavior vs reactivity, dominance ratio, etc. ?

# Measurements to characterize clustering / spatial correlations ?

- Should be measurable, if certain conditions are gathered:

$$\frac{\tau_D}{\tau_E} \simeq \left(\frac{L^2}{D}\right) / \left(\frac{N}{\lambda}\right) = \frac{1}{N}\frac{L^2}{\ell_m^2}$$

$$\boxed{\ell_m^2 = \frac{D}{\lambda}}$$

Neutron **migration area**

- Ideal conditions for an experiment that could characterize clustering?
  - Zero power reactor
  - Fresh fuel, no burn-up effects
  - As big as possible

**RCF@RPI**

- Find a way to do spatial measurements

**NOMAD detectors & He3 tubes**

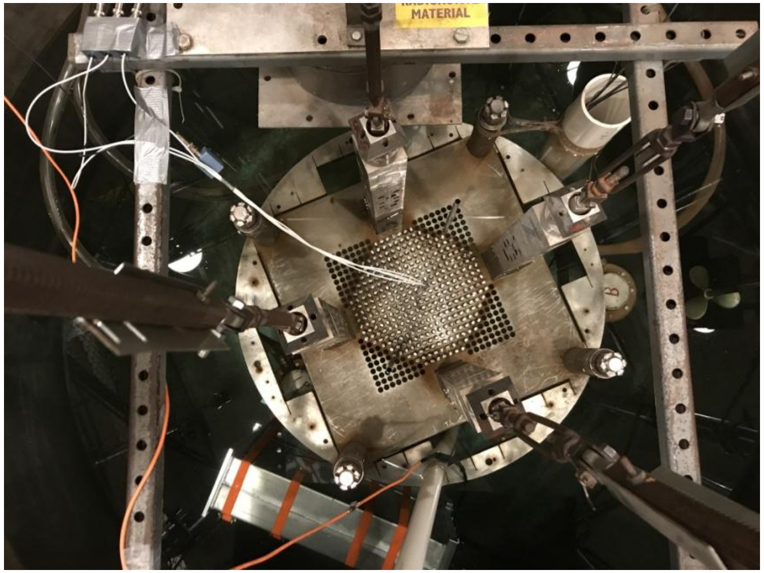
# RPI RCF

- "Zero power" reactor (maximum operating power = 15 W)
  - Fuel is essentially "fresh", not activated
  - Makes it very easy to set up and perform experiments

- $UO_2$ ceramic fuel, 4.81 wt. % $^{235}U$, 335 fuel pins for measurements
  - Fuel is 36 inches active length

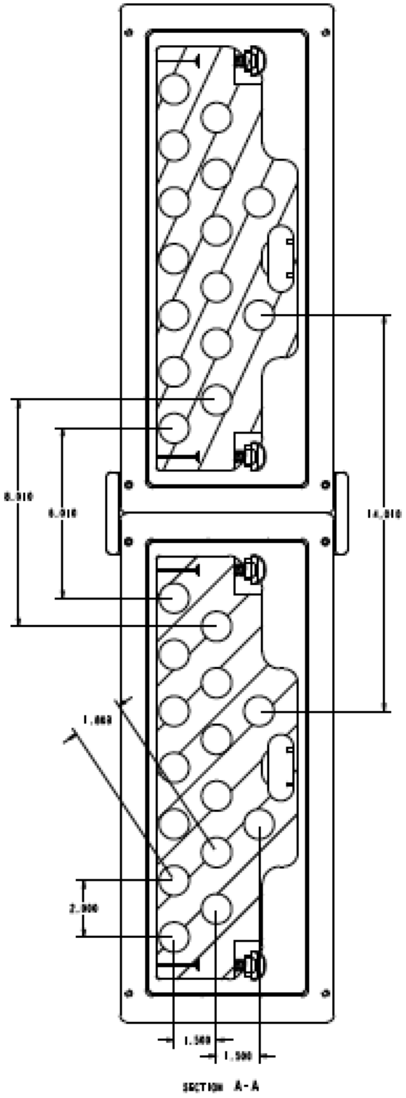
- Water moderated

- Four boron control rods surrounding the core



# Measurements at RPI

- Were able to complete 3 full days of experiments
- Experiments used two NOMAD detectors
- Also used $^3$He tubes in the core



# Measurements at RPI

# Measurements at RPI

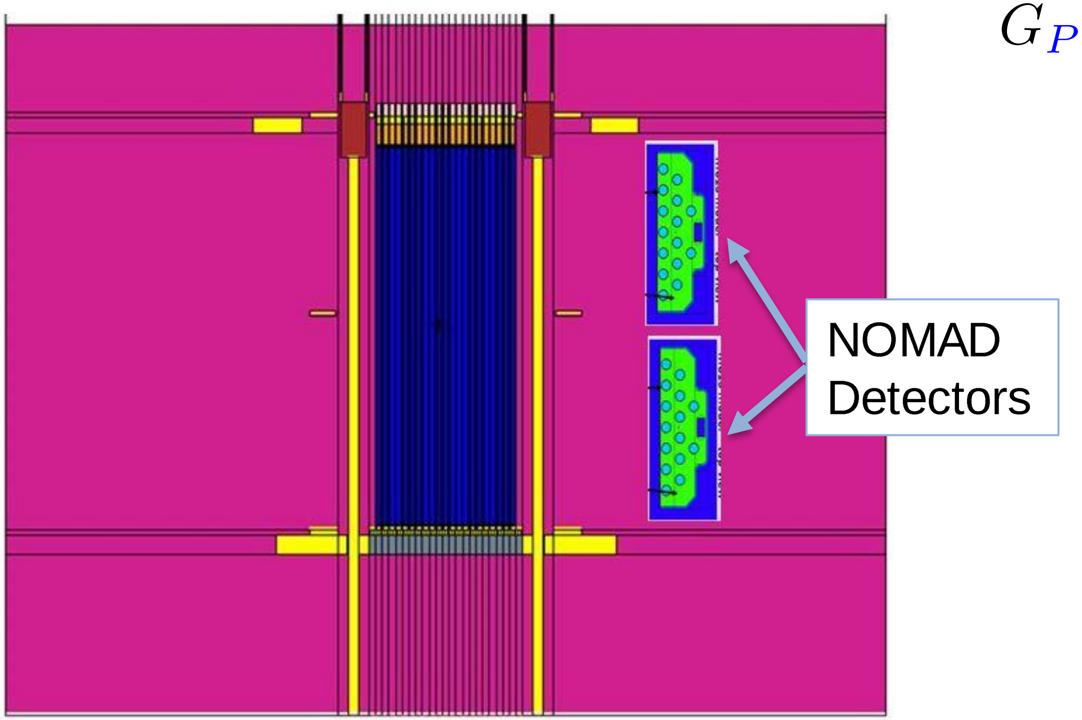
- Made over a dozen critical measurements at different reactor powers, from less than 1 mW to 0.85 W
  - 0.93 mW, 1 mW, 1.4 mW, 1.7 mW, 4.1 mW, 4.6 mW, 7.0 mW, 43 mW, 85 mW, 90 mW, 90 mW, 0.47 W, 0.85 W
  - Measurement times varied from 30 seconds to 2 hours long
- During the measurements, we did not adjust control rod positions
  - Because of this, some measurements were slightly above or below critical
- Measurements with the in core $^{3}$He detectors, NOMAD detectors, and RCF detectors (uncompensated ion chambers)
  - In core $^{3}$He detectors tended to saturate at fairly low power levels
  - => $^{3}$He detectors were used to calculate correlations vs distance in the core
  - => NOMAD detectors were used in the analysis to calculate spatial correlations vs power outside the core

# Simulations of the RCF Measurements

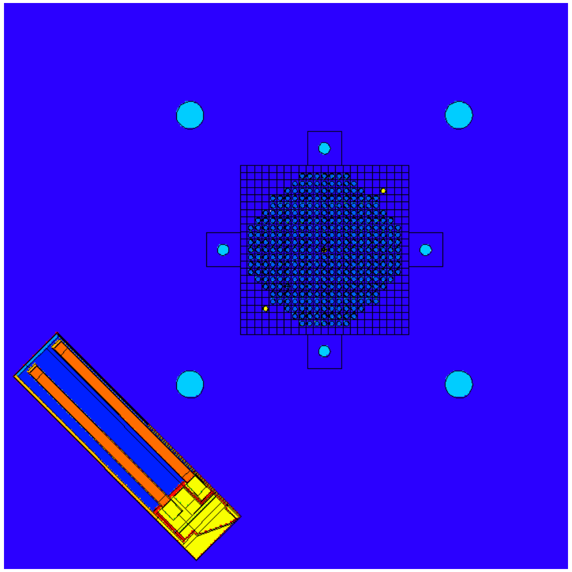
- Simulations of the experiment showed it might be possible to measure clustering / spatial correlations at the RCF

- Experiments were designed with two NOMAD detectors

$$G_P(n,m) = \left.\frac{\langle nm\rangle - \langle n\rangle\langle m\rangle}{\langle n\rangle\langle m\rangle}\right|_P$$



NOMAD Detectors



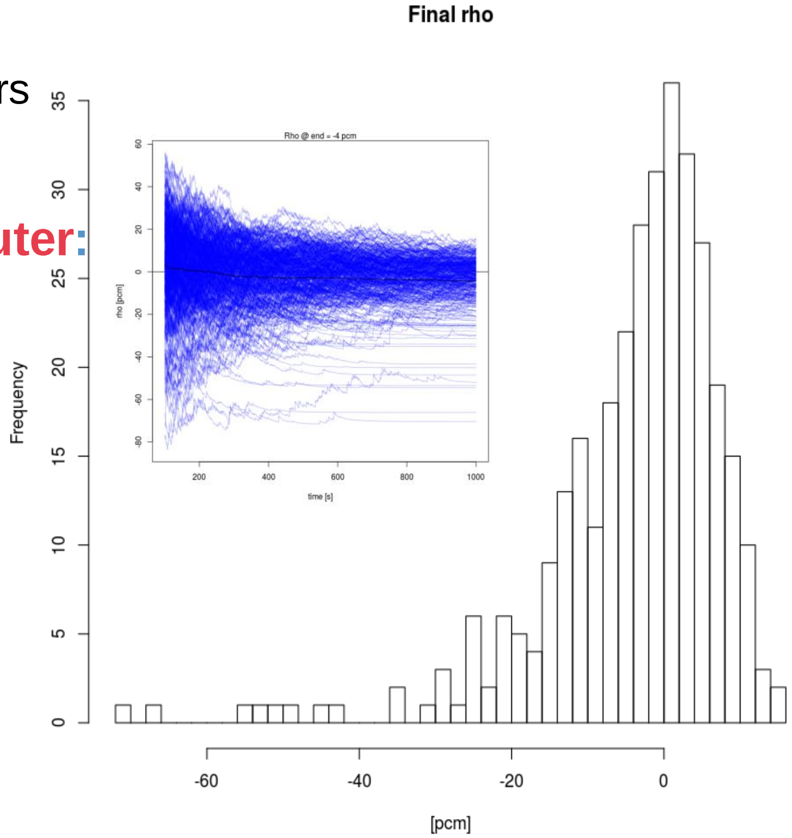
# Design of the experiment using MORET 5

## ❑ MORET 5 code with all Random Noise options activated:

- ❑ Data library: Endfb71
- ❑ Fission sampling:
  - ✓ Freya
  - ✓ discrete Zucker and Holden tabulated
  - ✓ Pn distributions and corresponding nubars
  - ✓ Only Spontaneous fissions

## ❑ Simulations run on the CCRT supercomputer:

- ❑ Simulated signal = 1000 s (prompt+delayed)
- ❑ Number of independent simulations = 330
- ❑ Number of neutrons per simulation = $2.4\ 10^4$



**Excellent reactivity: Rho = -4 pcm**

**+**

**Up to 10 mW of simulated power!**

# Analysis of the experiment using MORET 5

- Goal was to simulate the actual number of events in the core

- To make the simulations as accurate as possible, a first set of simulations was done, and fission sites were tallied
  - These fission sites were used as the starting neutron positions for the next set of simualtions
  - Instead of simulating fission neutrons as the starting particles, delayed neutrons with the accurate proportion of delayed neutron groups were used as starting particles

- Over three months of simulations, using >32 cores

- Almost 8 TB of data (gzipped!)

- 2500 simulations, each with 1000 starting neutrons
  - Most simulations died immediately, some multiplied and continued
  - Simulations were for 2000 seconds live time

# Systematic Uncertainty in Power

- Since the RCF is “zero” power (produces no heat from fission), reactor power is inferred indirectly

- Normal procedure for calculating power:
  - Bring the reactor critical with gold foils attached to a fuel pin
  - Irradiate gold foils, measure the radioactivity after irradiation
  - Counts are compared to an MCNP simulation of the reactor

- Many small sources of error:
  - Detector calibration, ROI on data acquisition software, error on the number of counts

- Added complication – RCF detectors are not accurate at extremely low powers (under 5 mW) and also detect gamma background.

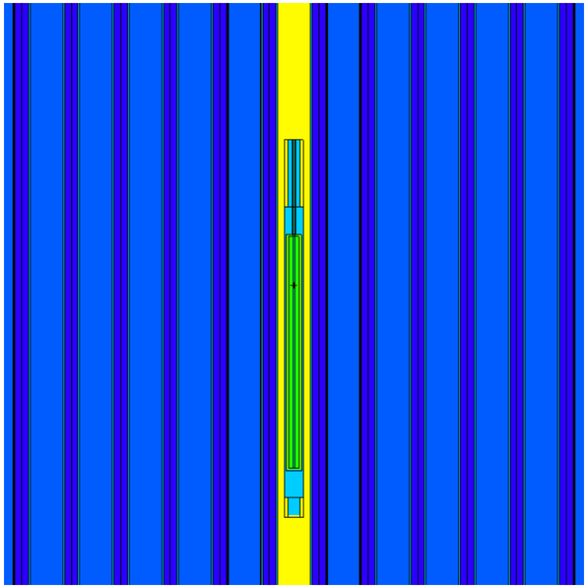
- Currently working on a estimate of power solely based on the NOMAD detector responses to reduce uncertainty in power.

# Systematic Uncertainty in Position

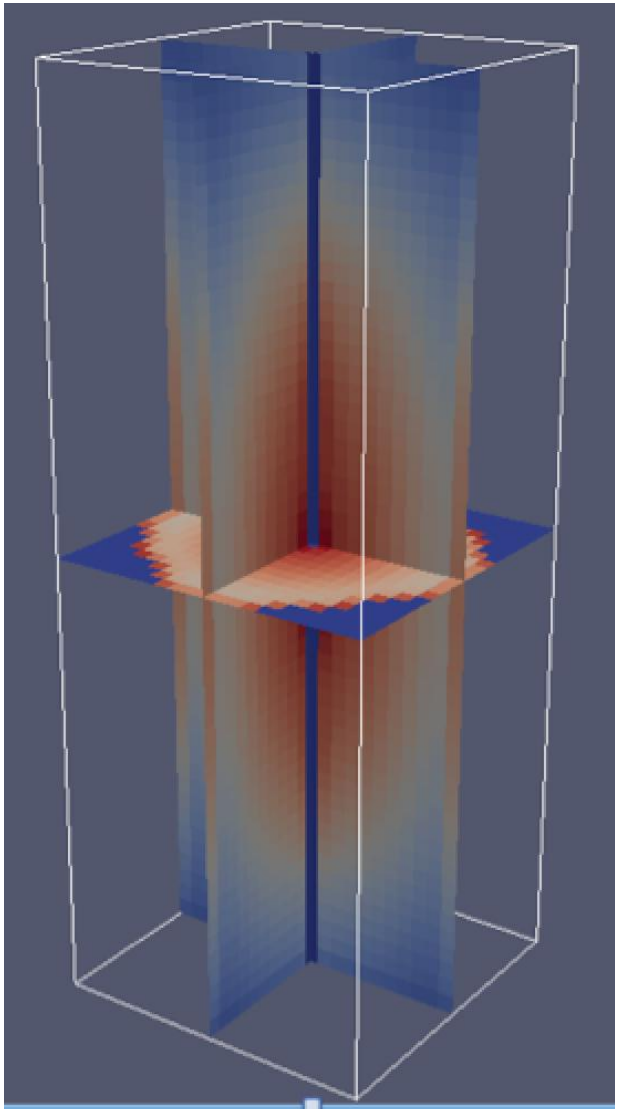
- Should be constant and ~1 cm

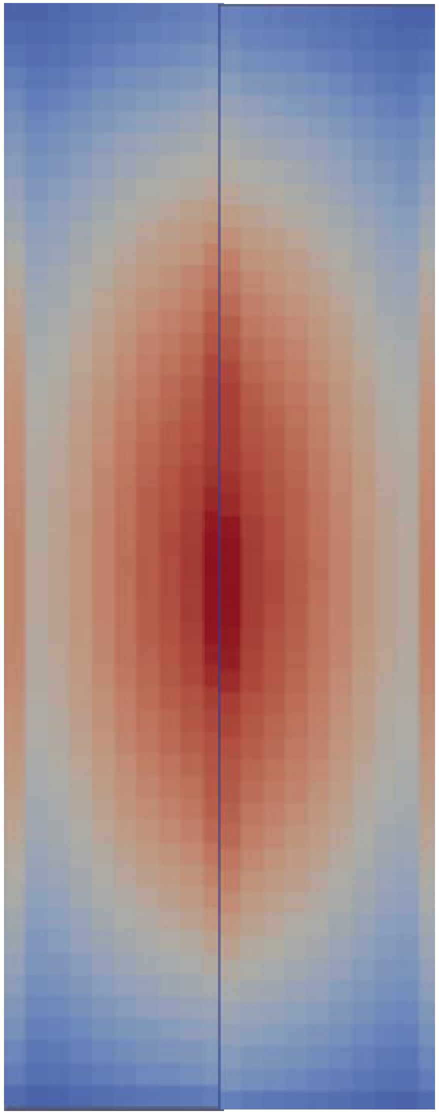
- An alignment procedure could be employed to correct the positions once for all the runs ?

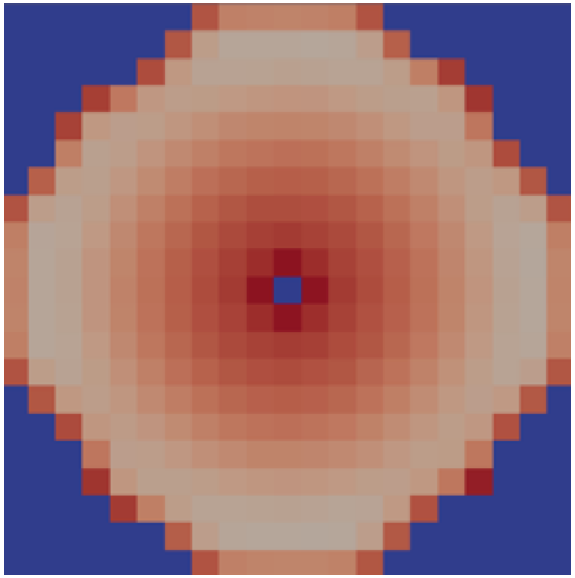
- ☐ He3 tube: 4 inches & 30 atm
- ☐ 4 He3 tubes fit in the pin-cell !



# Simulated data results for power spatial distribution

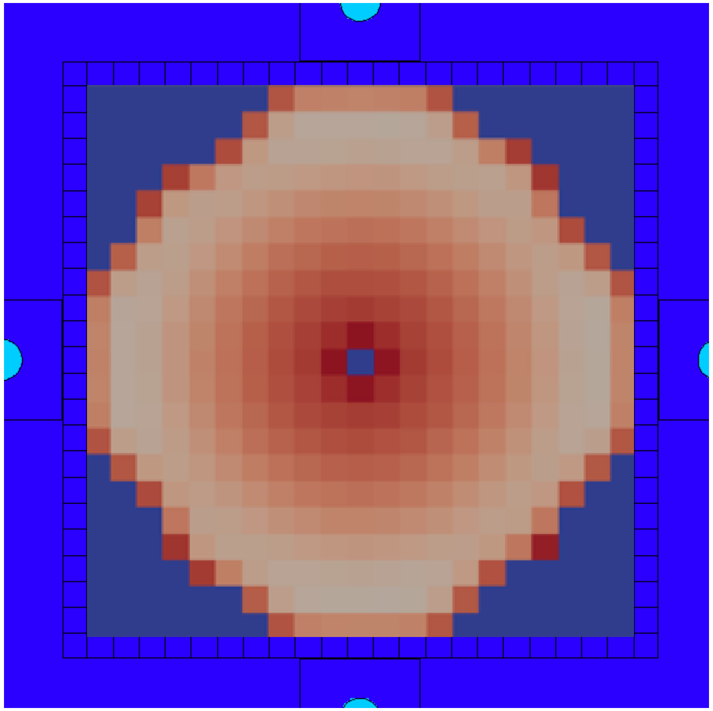




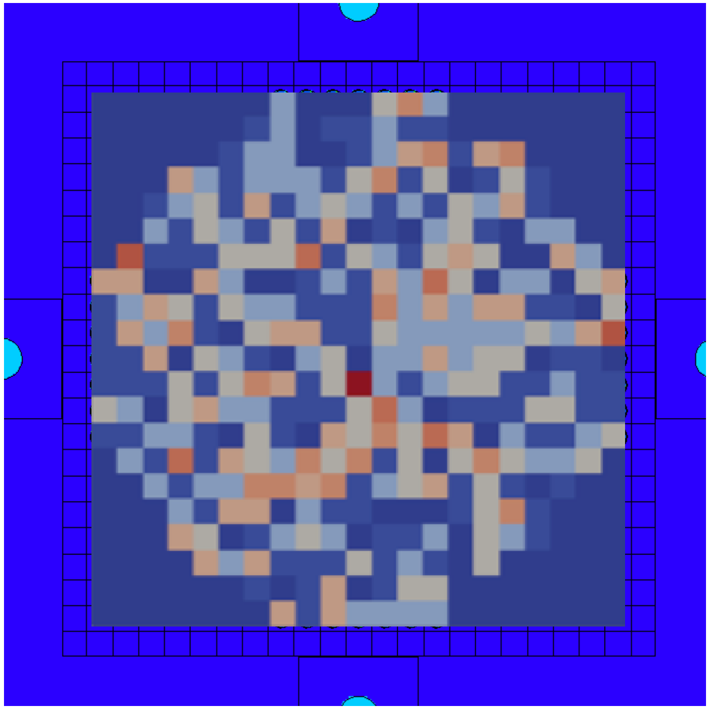


- Time-integrated power for the 1.8 mW run
- 3D view and 2D cuts
- Distributions are converged

# Simulated radial spatial power distribution



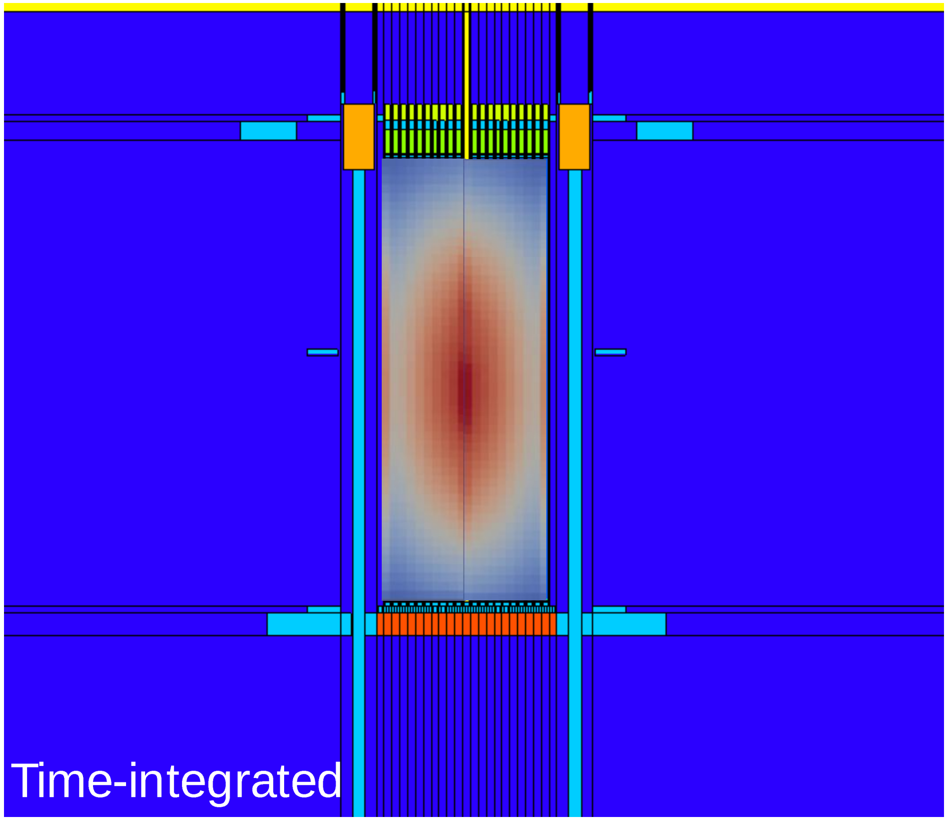
Time-integrated

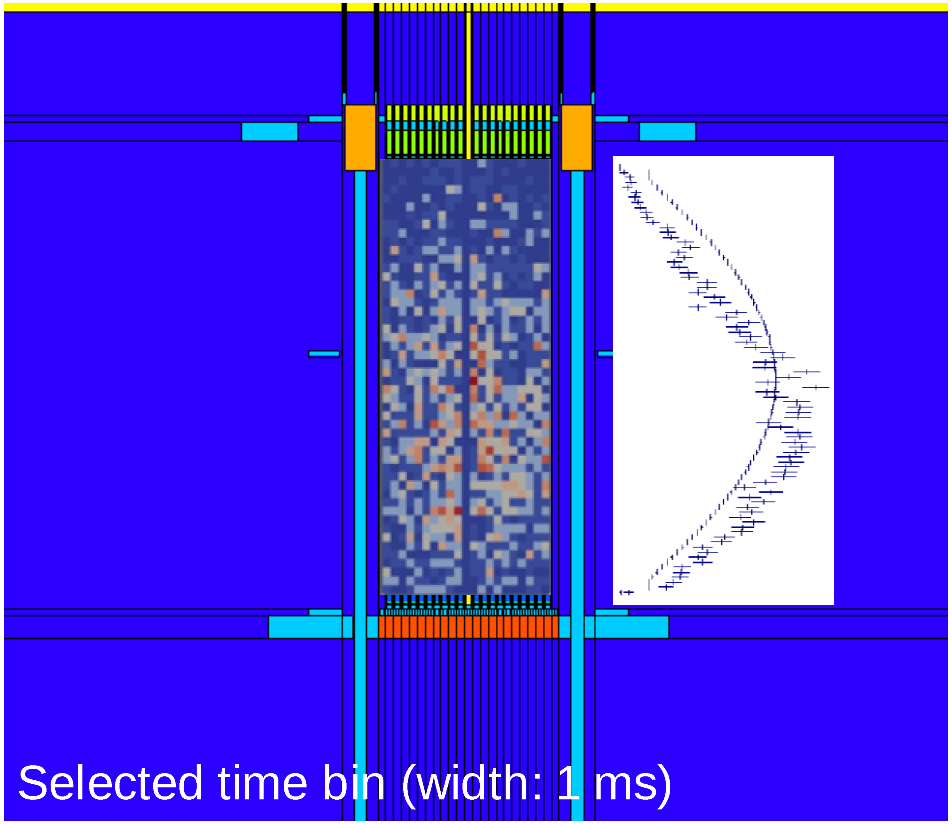


Selected time bin (width: 1 ms)

- Radial power view for the 1.8 mW run
- The different time bins exhibit a spatial Poissonian statistics
- Coherent with the $\frac{L^2}{\ell_m^2}$ theoretical prediction

# Simulated axial spatial power distribution





- Axial power view for the 1.8 mW run

- The different time bins exhibit spatially correlated patterns

- Coherent with the $\frac{L^2}{\ell_m^2}$ theoretical prediction

# Comparison between simulated & experimental data

Theoretical prediction :

$$g_t(r) = \frac{\lambda \nu_2}{8Dc_0\pi^{3/2}r}\Gamma\left(\frac{1}{2}, \frac{r^2}{8Dt}\right)$$

$$\Rightarrow g_t(r) \propto \frac{1}{c_0} = \frac{1}{P}$$

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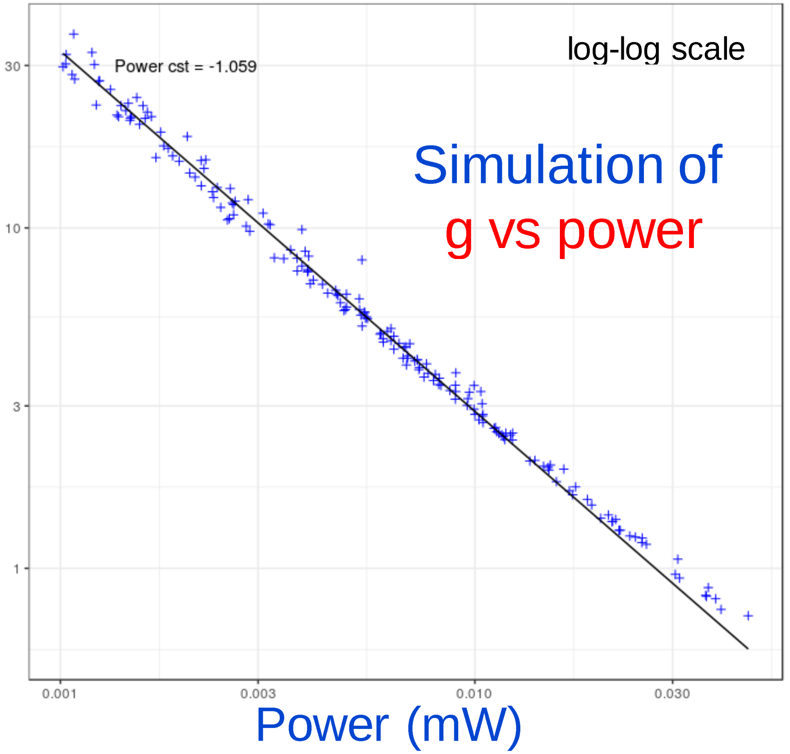
- Experimental data: 1.8 mW run + NOMAD
- Theoretical, simulated and experimental data for g vs P are in perfect accordance

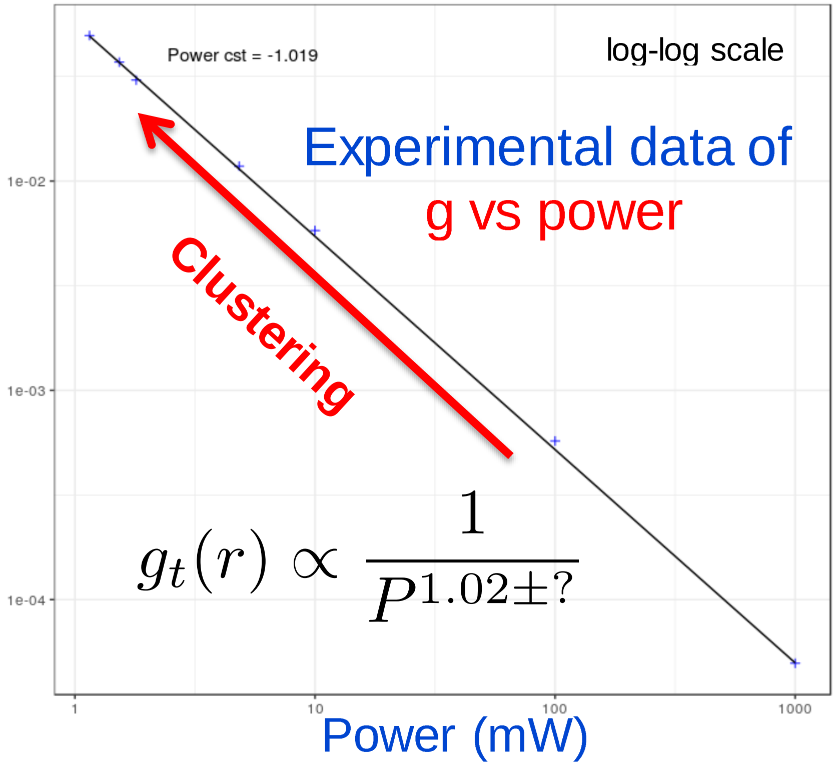


log-log scale

Power cst = -1.059

Simulation of g vs power

Power (mW)



log-log scale

Power cst = -1.019

Experimental data of g vs power

Clustering

$$g_t(r) \propto \frac{1}{P^{1.02\pm?}}$$

Power (mW)

# Comparison between simulated & experimental data

Theoretical prediction :

$$g_t(r) = \frac{\lambda \nu_2}{8 D c_0 \pi^{3/2} r} \Gamma\left(\frac{1}{2}, \frac{r^2}{8Dt}\right)$$

$$\Rightarrow \quad g_t(r) \propto \frac{1}{r}$$

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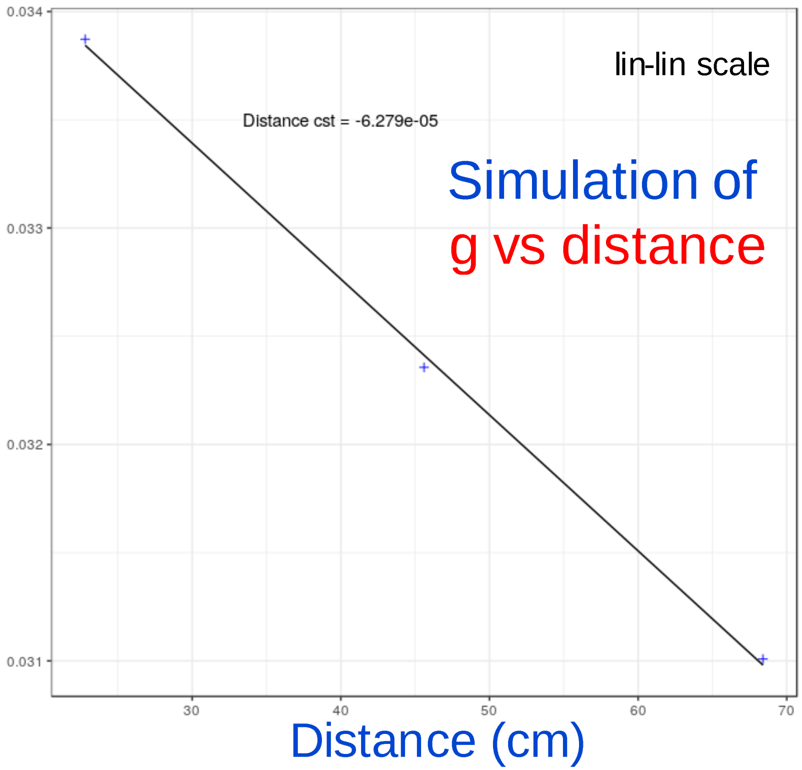
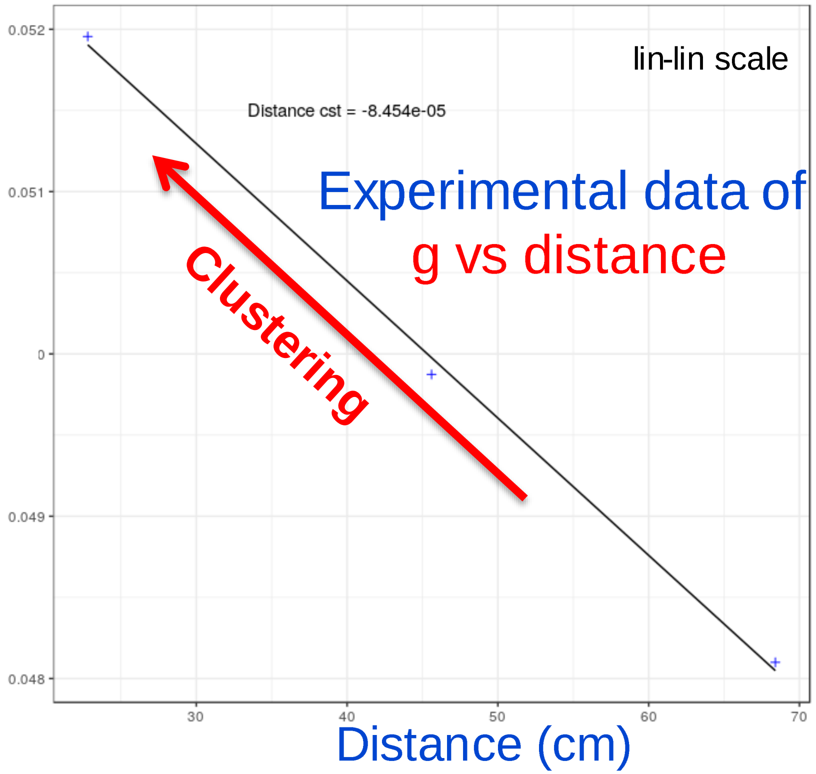
- Experimental data: 1.8 mW run + 3He
- Theoretical, simulated and experimental data for g vs distance are in good qualitative accordance
- Only 3 points but linear fit strangely good



Simulation of g vs distance



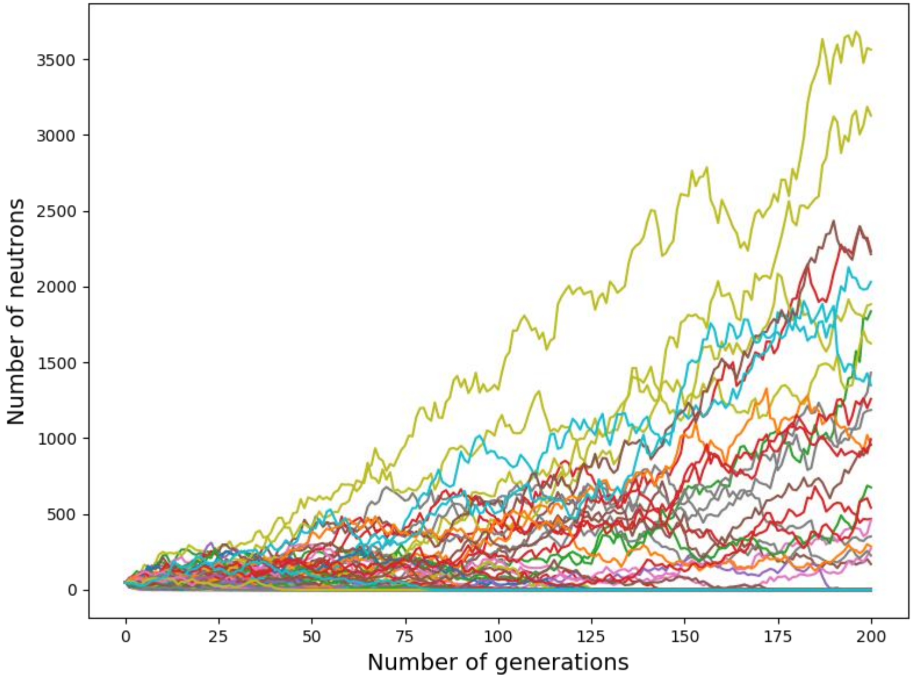
Experimental data of g vs distance

Clustering

# Critical catastrophe : what did we expect ?

- Stochastic modelling of the neutron population for the following events
  - **Capture**, inducing transitions **n -> n-1** with rate $\lambda_C$
  - **Fission**, inducing transitions **n -> n – 1 + ν** with rate $\lambda_F$

- We should observe increasing fluctuations

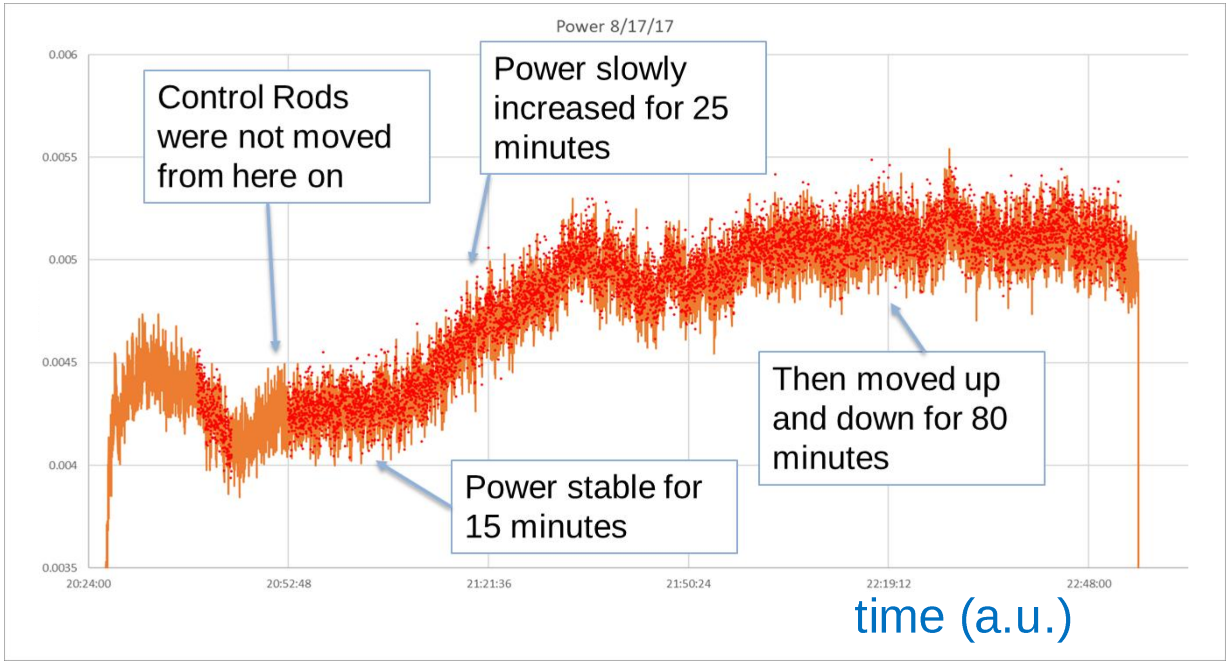


$$\langle n \rangle = n(0)$$

$$\mathrm{Var}(n,t) = C\, n(0)\, t$$

# Critical catastrophe : what did we observe ?

- 2 long runs with similar behavior : analysis of the 5 mW run (2h / 500MB / $10^7$ cts)
- Observation #1 : re-ajustment of the neutron power level
- Observation #2 : fluctuations are not diverging linearly but stayed bounded



Control Rods were not moved from here on

Power slowly increased for 25 minutes

Power stable for 15 minutes

Then moved up and down for 80 minutes

$$\cancel{\langle n\rangle = n(0)}$$

$$\cancel{\mathrm{Var}(n,t) = C\, n(0)\, t}$$

# Critical catastrophe : what did we conclude ?

- Stochastic modelling of the neutron population for the following events
  - **Capture**, inducing transitions **n -> n-1** with rate $\lambda_C$
  - **Fission**, inducing transitions **n -> n – 1 + ν** with rate $\lambda_F$
  - **Spontaneous fission**, inducing transitions **n -> n + $\nu_{SF}$** with rate ?

# Stochastic modeling of the effect of intrinsec sources

- Forward equation for probability of having n neutrons at time t

$$\frac{\partial P(n,t)}{\partial t} = -\lambda_C\, n\, P(n,t) + \lambda_C\,(n+1)P(n+1,t) + \lambda_F \sum_{\nu} p_\nu\,(n+1-\nu)P(n+1-\nu,t)$$
$$-\lambda_F \sum_{\nu} p_\nu n P(n,t) + \lambda_{SF} \sum_{\nu_{SF}} p_{\nu_{SF}} P(n-\nu_{SF},t) - \lambda_{SF} \sum_{\nu_{SF}} p_{\nu_{SF}} P(n,t)$$

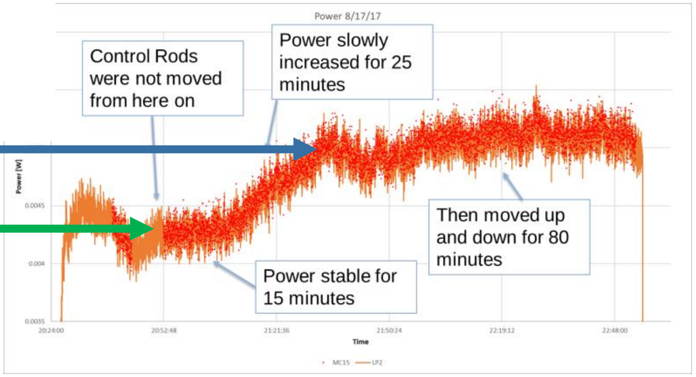
- From which we can derive the equations for **mean** and **variance**

$$\frac{\partial}{\partial t}\langle n\rangle = \underbrace{\left[\lambda_F\,(\bar{\nu}-1) - \lambda_C\right]}_{\rho}\langle n\rangle + \lambda_{SF}\bar{\nu}_{SF}$$

$$\frac{\partial}{\partial t}\mathrm{Var}(n,t) = 2\rho\mathrm{Var}(n,t) + \left[\lambda_F\,\overline{\nu(\nu-1)}\right]\langle n\rangle + \lambda_{SF}\left[\overline{\nu_{SF}(\nu_{SF}-1)} + \bar{\nu}_{SF}\right]$$

# Mean and variance

- We obtain $\langle n \rangle = n(0)\, e^{\rho\, t} + \dfrac{\lambda_{SF}\, \bar{\nu}_{SF}}{\rho}\left(e^{\rho t} - 1\right)$



Control Rods were not moved from here on

Power slowly increased for 25 minutes

Power stable for 15 minutes

Then moved up and down for 80 minutes

- To maintain a constant neutron population at late times we must have ρ < 0

$$\mathrm{Var}(n,t) = C e^{2\rho t} + \left(\frac{\rho - a_F}{\rho}\right)\langle n \rangle + \frac{\lambda_{SF}\bar{\nu}_{SF}}{2\rho}\left(\frac{\rho - a_F}{\rho}\right) - \frac{b_{SF}}{2\rho}$$

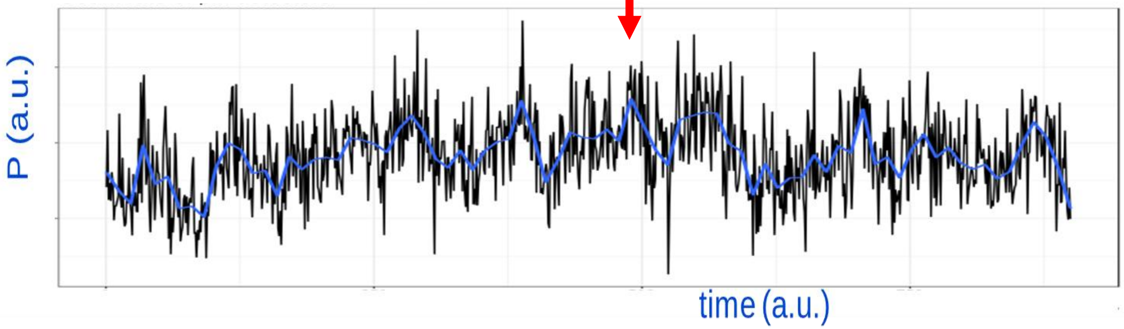
$$\frac{\mathrm{Var}(n_\infty,\infty)}{n_\infty} = 1 + \frac{\lambda_F\, \overline{\nu(\nu-1)}}{2\,|\lambda_F(\bar{\nu}-1) - \lambda_C|} + \frac{\overline{\nu_{SF}(\nu_{SF}-1)}}{2\,\bar{\nu}_{SF}}$$

is kept constant

with:

$$a_F = \lambda_F\, \overline{\nu(\nu-1)}$$

$$b_{SF} = \lambda_{SF}\left[\overline{\nu_{SF}(\nu_{SF}-1)} + \bar{\nu}_{SF}\right]$$



# Conclusions

- Spatial correlations & clustering in theory/simulations/measurements match very well

- Theoretical framework to understand the absence of critical catastrophe => due to intrinsic sources

- This work should help understanding noise, fluctuations and correlations of systems with small power

- Might help to qualify correlated physics codes

# Remaining work

- Difficulties arising whenever simulating configurations with raising power
- Check of the ergodic assumption to calculate statistical error bars
- Re-run simulations on a supercomputer to reach 10 mW
- Systematic error bars on power & positions
- Design of an experiment to measure the same quantities for different dominance ratio, and with different reactivities

Questions ?