Reactor and $\bar{\nu}_e$ spectrum prediction for the DC experiment

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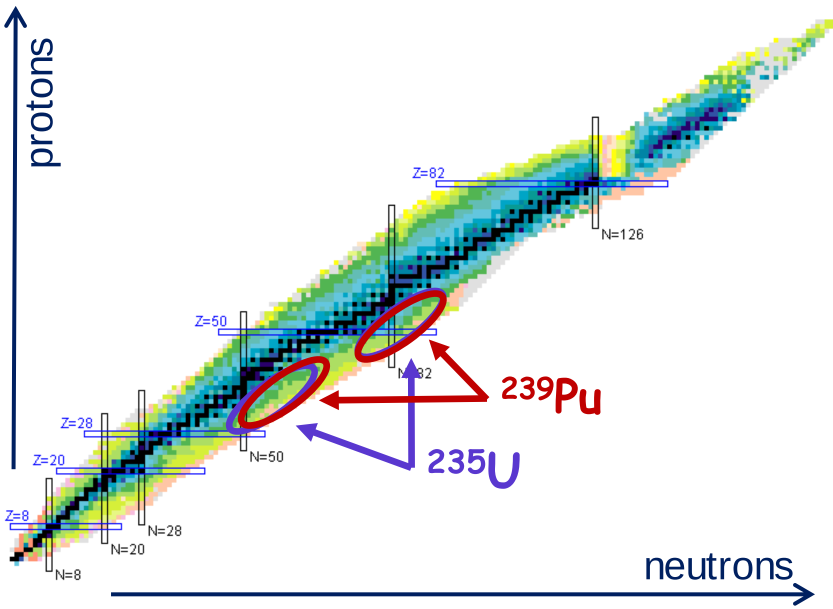
the Double Chooz Collaboration

Outline

- *Reactor antineutrinos & the Chooz nuclear power plant*
- *Reactor core simulation: - reactor codes*
  - method
  - results
- *Fission rate error estimates*
- *Prediction of antineutrino flux and shape*
- *Conclusion & outlooks*

Reactor antineutrinos

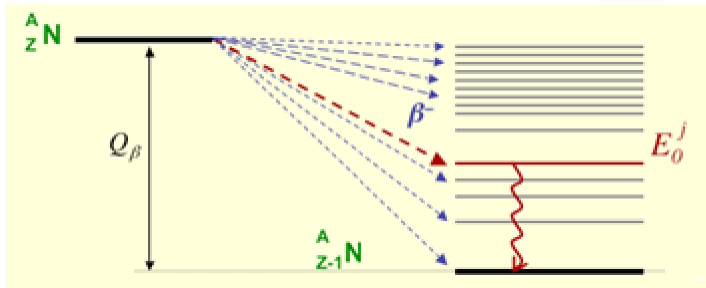
PWReactor : Thermal power mainly induced by fission of 4 nuclei : **^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu**



The fission products (FP) after the fissions are neutron-rich nuclei

undergoing successive β^- decays to reach stability:

$$\beta^- \text{ decay: } \; {}^A_Z X \rightarrow {}_{Z+1}{}^{A}Y + e^- + \bar{\nu}_e$$



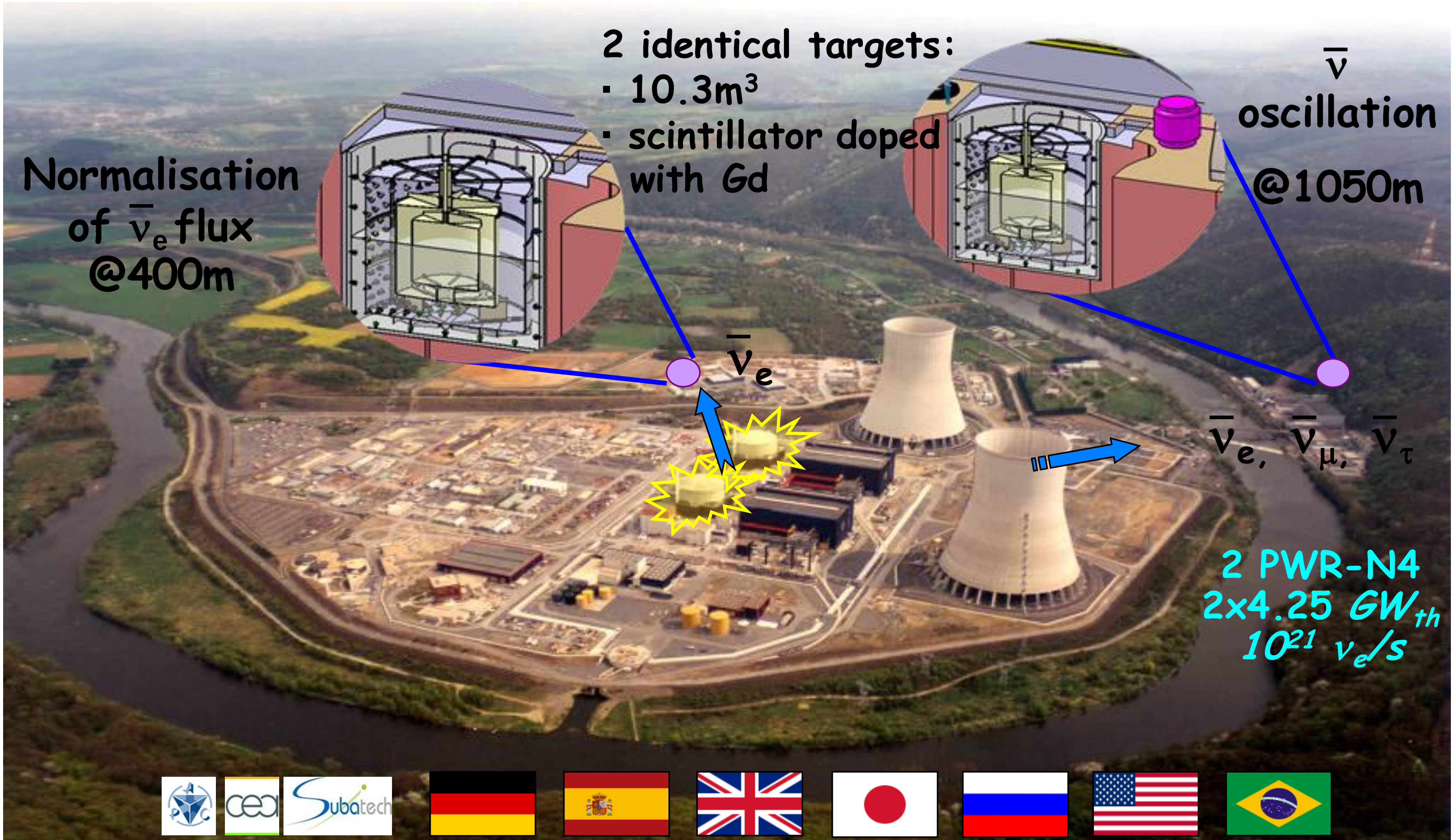
	^{235}U	^{239}Pu	^{238}U	^{241}Pu
<E$_\nu$> (MeV)	1.46	1.32	1.56	1.44
<N$_\nu$> *(E>1.8MeV)*	5.58 (1.92)	5.09 (1.45)	6.69 (2.38)	5.89 (1.83)

Standard PWR-N4@4.25GW$_{th}$:

$$\frac{4250\ MW_{th}}{200\ MeV} \times 6\,\bar{\nu}_e \ \sim 1.10^{21}\,\bar{\nu}_e/s$$

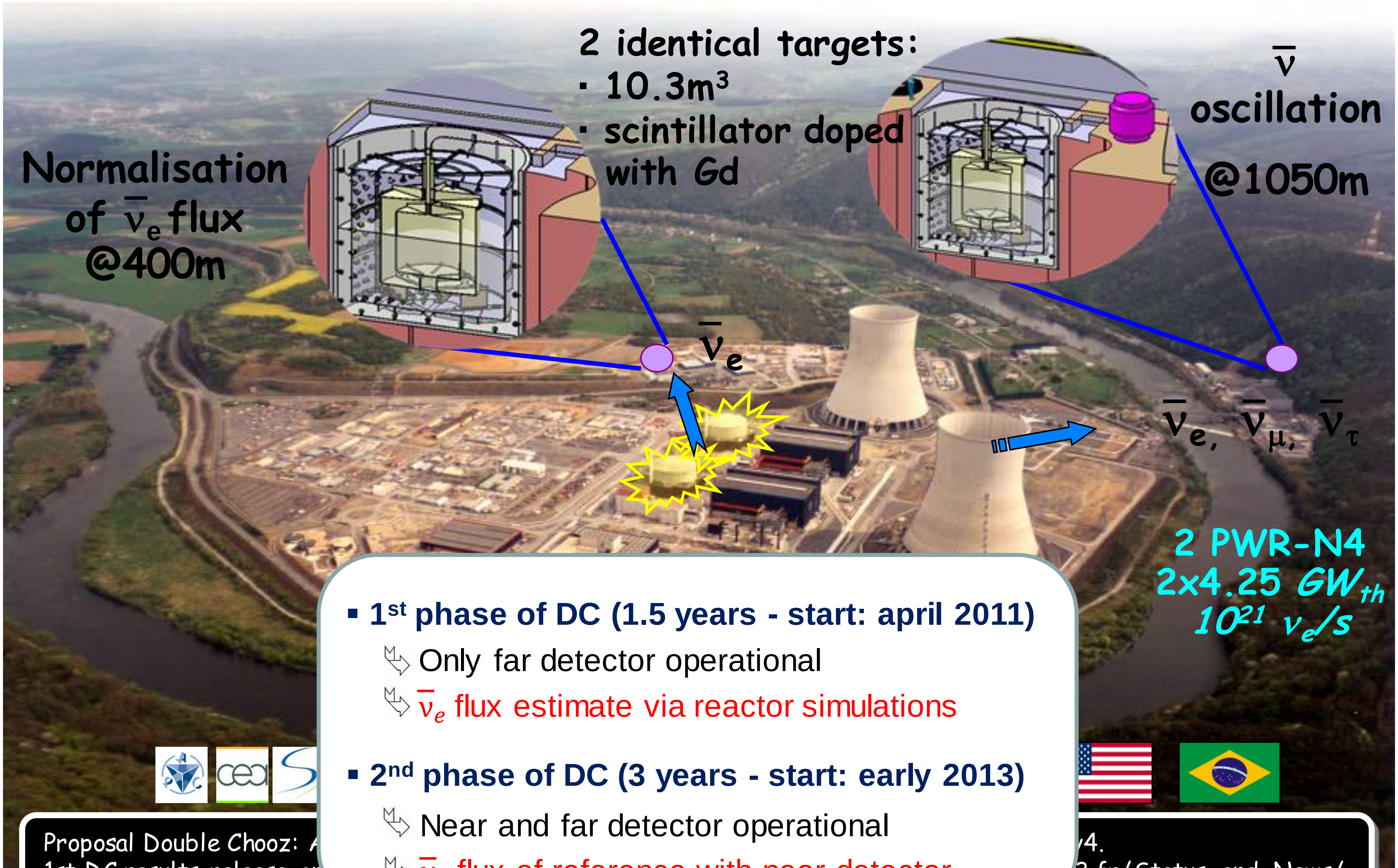
$\langle N_\nu \rangle_k$: *Average number of $\bar{\nu}_e$ resulting of fission of isotope k*

The Chooz nuclear power plant



Proposal Double Chooz: A search for the Neutrino Mixing Angle Θ_{13}, arXiv:hep-ex/0606025v4,
1st DC results release on Nov. 9. @LowNu11 Conf., Seoul, by H. de Kerret : doublechooz.in2p3.fr/Status_and_News/

The Chooz nuclear power plant



- **1st phase of DC (1.5 years - start: april 2011)**
  - Only far detector operational
  - $\bar{\nu}_e$ flux estimate via reactor simulations
- **2nd phase of DC (3 years - start: early 2013)**
  - Near and far detector operational
  - $\bar{\nu}_e$ flux of reference with near detector

Proposal Double Chooz: A ... v4.
1st DC results release on ... 3.fr/Status_and_News/

Two reactor codes

- **Experiment needs:** The most accurate as possible calculation of the fission rates of the two cores and their associated errors during the period of data taking

- **Use of 2 codes already (validated reactor code for PWR simulations):**

MURE (Subatech) :

- Probabilistic code *(neutron tracked event-by-event)*
- Nuclear databases: continuous in energy
- 3D code (allow full core simulations)

=> Important CPU resources needed not to be affected by statistical errors but most predictive method

DRAGON (MIT) :

- Deterministic code *(Boltzmann equation lattice resolution)*
- Nuclear databases: multigroup energy
- 2D code / simulation @assembly level

=> Fast computation crosschecks

- Validation of our own simulations and discrepancies assessment: DRAGON and MURE benchmark
  + **Takahama benchmark containing measured inventories** :

  ↳ **C. Jones et al. *arxiv***.*org/pdf/1109.5379* ⇒ *good agreement on code*

⇒ **First DC publication: reactor fission rates & associated errors provided by MURE simulations**

The MURE code

- **The MURE Code** (***MCNP** utility for Reactor Evolution*) **:**

  - (developed by CNRS labs): C++ interface to the Monte Carlo code MCNP (static particle transport code)

Definition of system: geometry, materials, sources … → Static computation t = 0 (**MCNP**) $\xrightarrow{\frac{dN}{dT} = AN}$ Static computation t = Δt_1 (**MCNP**) $\xrightarrow{\frac{dN}{dT} = AN}$ - - → Static computation t = Δt_x (**MCNP**)

⟨σ⟩, ⟨ϕ⟩   ⟨σ⟩, ⟨ϕ⟩

+ evolution's condition (power …)   + evolution's condition (power …)

Material evolution: Resolution of Bateman differential equations

$$\frac{\partial N_i}{\partial t} = \underbrace{-\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j}_{\textit{decays}} + \underbrace{\sum_{j'} N_{j'} \langle\sigma_{j'}\rangle^{j'\to i}\langle\phi\rangle - N_i \sum_{\forall r}\langle\sigma_i\rangle^{(r)}\langle\phi\rangle}_{\textit{reactions induced by neutron}}$$

⇒ Outputs provided: k_{eff}, neutron flux, **inventory, reaction rates (fission, capture, …)**

⇒ **Development of a complete core simulation with a follow up of core operating parameters**

- Confidentiality agreement with EDF company: design data, operating parameters, instrumental core measurement (neutron flux map), simulation results ...
- Development of interfaces MURE code / operating parameters :
  - **- thermal power**
  - **- boron concentration**
  - - position of control rods (not yet implemented, in progress)

Short description of the Chooz Core

Exemple of one core plan

➢ ***Summary of the core geometry in a few figures :***

- 205 assemblies, each composed of 264 fuel rods
- 4 assembly types with different :
  - geometrical characteristics
  - initial fuel composition & enrichments
- ~ 1/3 of the assemblies with fresh fuel
- ~ 100 assemblies with gadolinium & 100 without

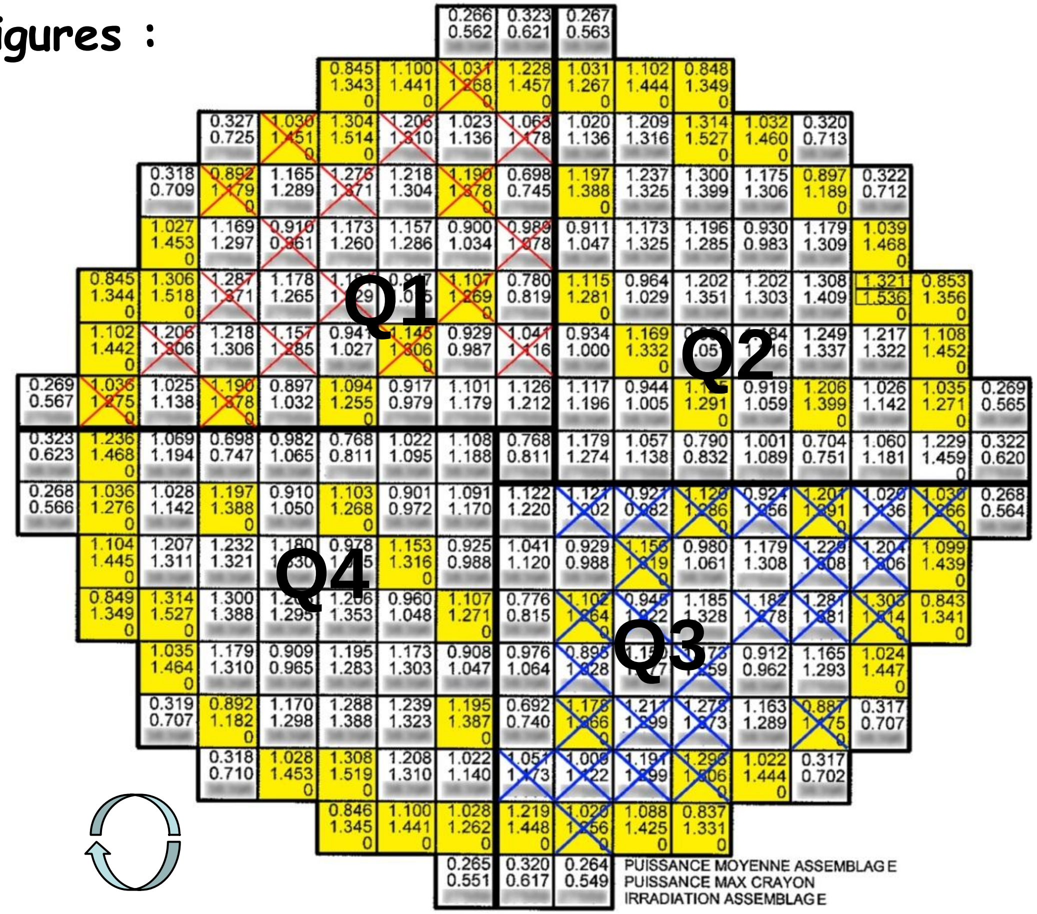
x x x → **Burnup at the start of the cycle**

: Fresh fuel

: Control rod position (first quadrant)

: Gadolinum assemblies (third quadrant)

↳ *High neutron absorber*



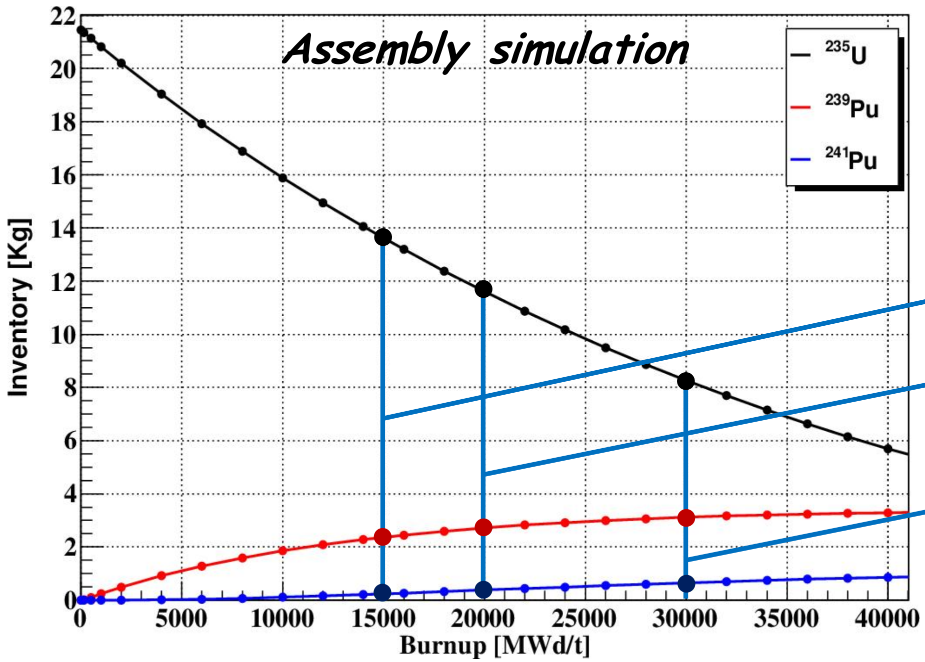
Each assembly is loaded in the core with a different burnup (burnup = level of irradiation).

⇒ **Different initial fuel composition for each assembly at the start of a new cycle.**

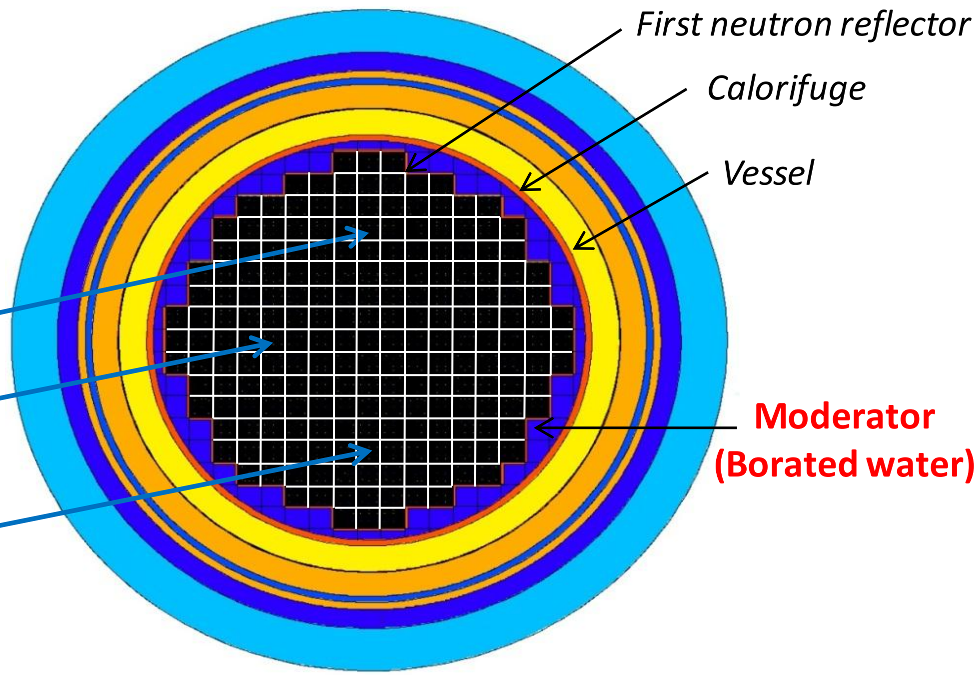
Initial core inventories :

- **For the two cores**: Extraction of all **initial assembly burnups from EDF fuel loading map.** (EDF prediction, computed with last flux map of previous cycles and assembly simulations)

- **Simulation of the 4 assembly types** with MURE: **Extraction of each assembly fuel composition at their loading burnup** (Heavy nuclei & fission products) => **Input of core simulations**.

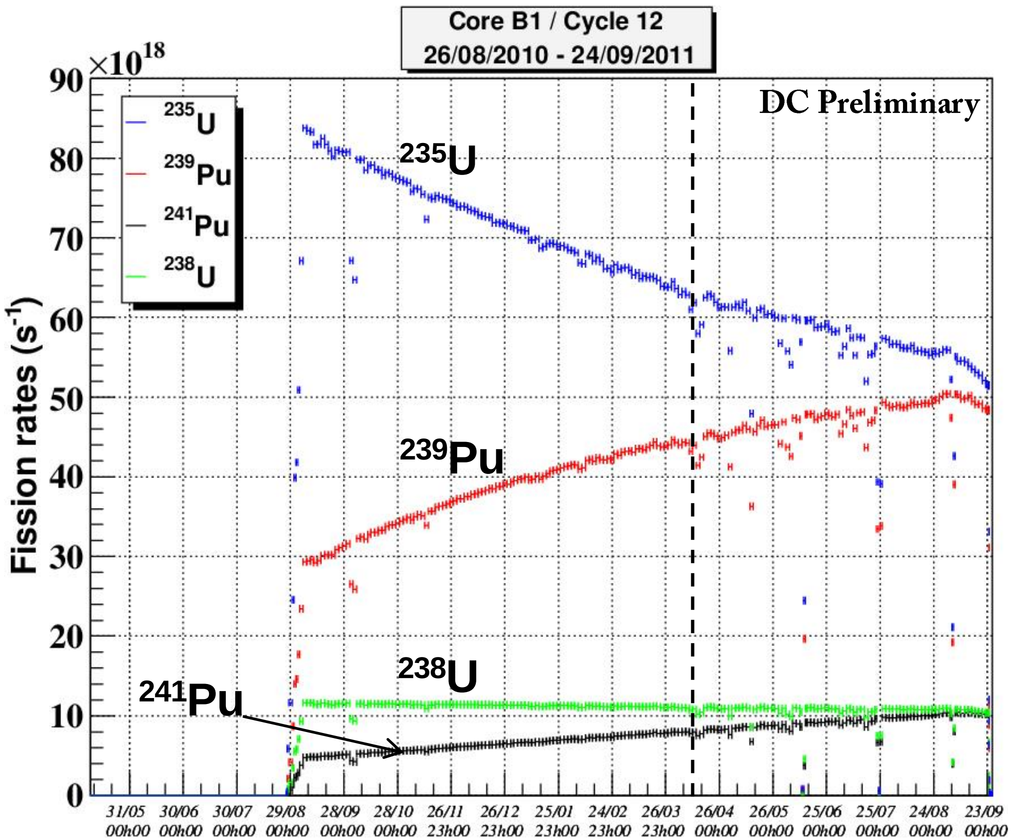


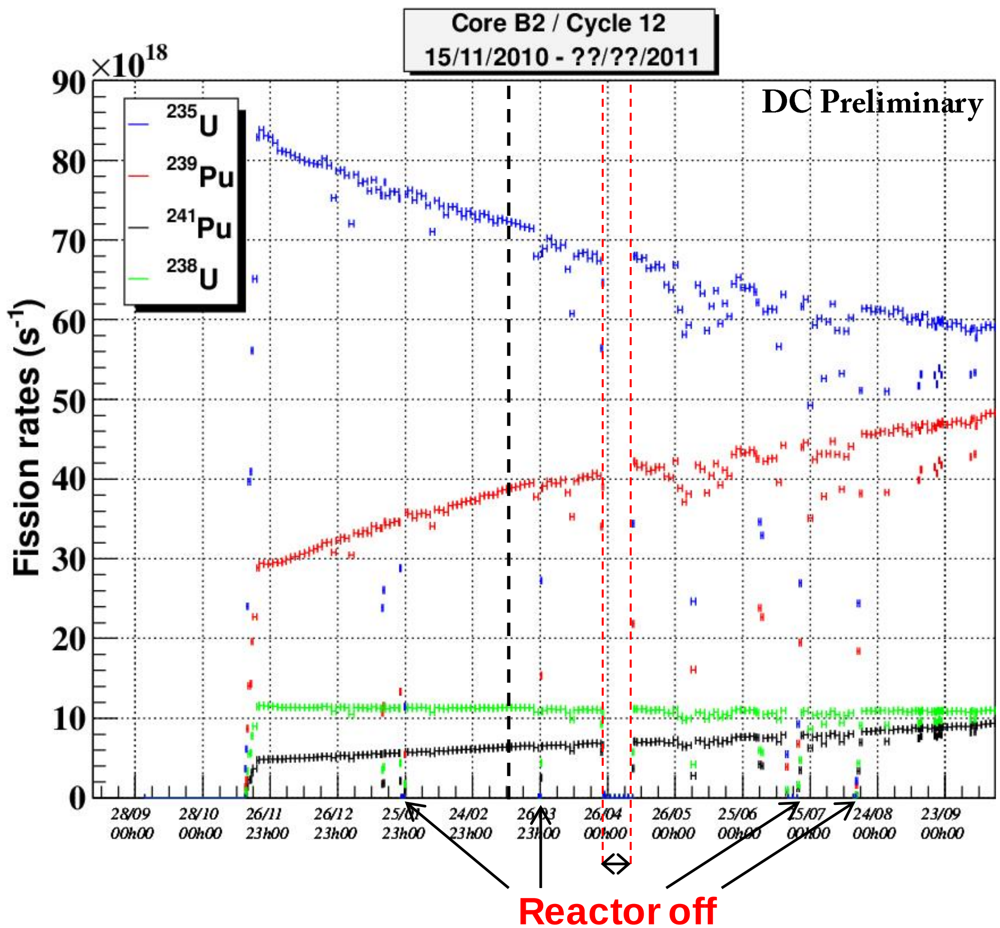
$$Burnup = \sum_i \langle P_{therm} \rangle_i \times time_i / Mass_{initial}$$



MCNP display of core geometry

Fission rates results

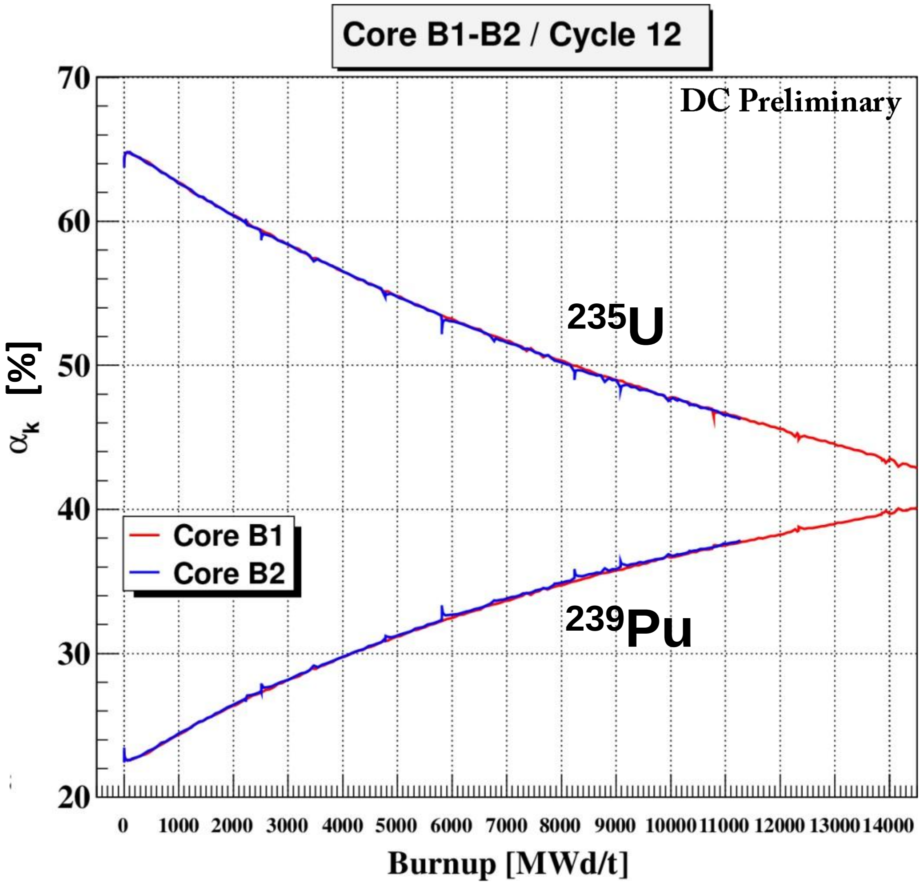


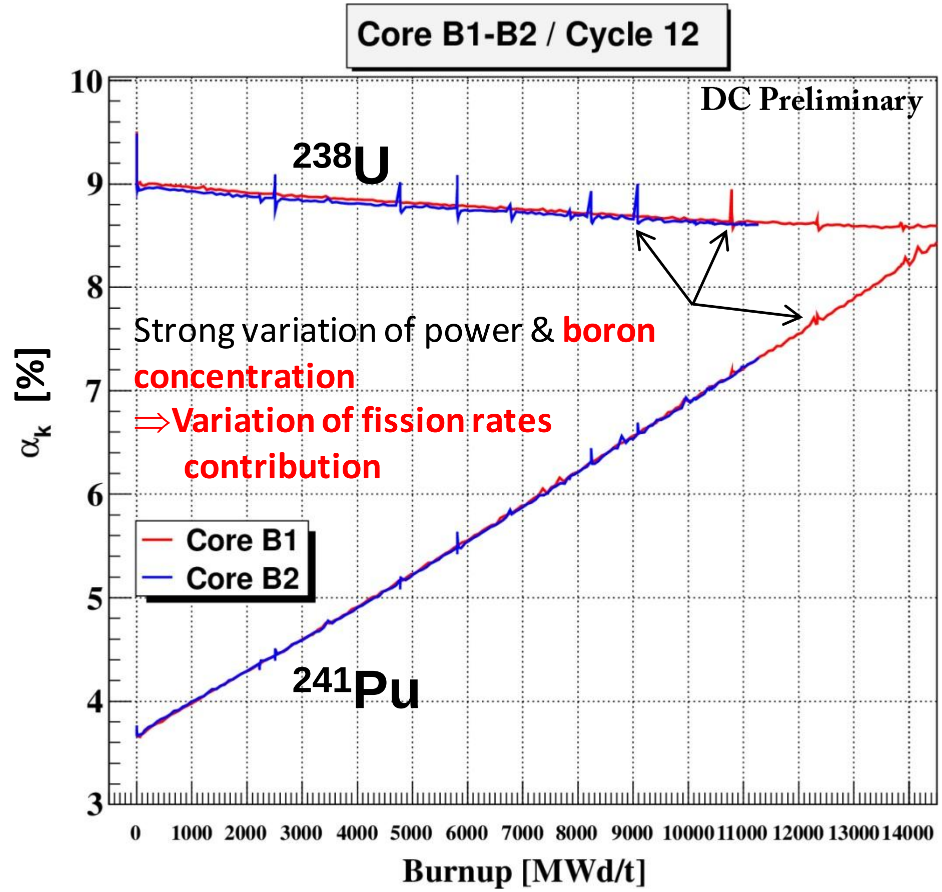


- - - - **Start of data taking (April 13, 2011)**

⇒ Fission rate fluctuations induced by the variation of the thermal power

For a complete cycle simulation: ~700h of cpu time needed with 12 processors …





α_k coefficients : $\alpha_k = 100 * \frac{FR_k}{\sum_i FR_i}$

For a typical PWR N4 core cycle:

$\alpha_{U5} + \alpha_{U8} + \alpha_{Pu9} + \alpha_{Pu41} \cong 99.7\%$

⇒ Small contribution of other fissile nuclei (^{236}U, ^{240}Pu, ^{238}Pu, ^{234}U, ^{237}Np …)

⇒ **Same behavior in average for the two cores**

⇒ **Variation of α_k with core inventory**

Knowledge of $\alpha_k(t)$ coefficient : $\bar{\nu}_e$ flux normalize with $\langle\sigma_f\rangle^{Bugey}$ anchor point (see slide 13)

Fission rate errors estimates

⇒ A systematic error is associated to each computed fission rate and this error evolves with the core history

- Numerical computation of σ_{f_i} $(i = U^5, Pu^9, U^8, Pu^{41})$ associated to each fission rate with MURE
- **Independent evaluation of the errors associated to the main input parameters** of the core simulation that have an impact on the fission rates: variation of each input parameter over a large range of values in order to determine the corresponding fission rate sensibility.
- **The relationship between the fission rates as a function of these variations is then deduced by fitting the simulation results.**

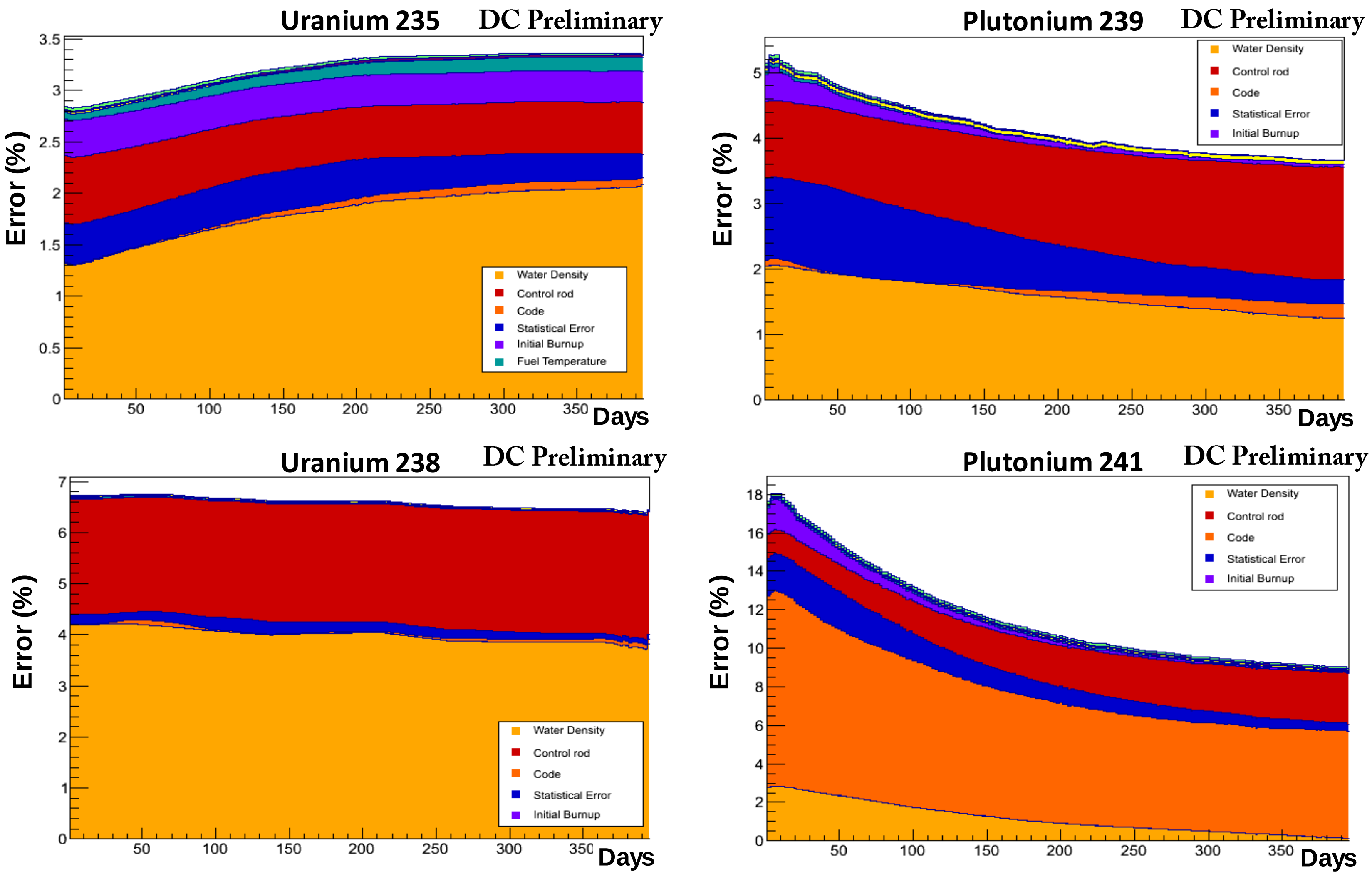
⇒Each σ_{f_i} are then deduced by a quadratic sum of each error:

$$\sigma_{f_i}^2 = \boldsymbol{\sigma_{P_{th}}^2} + \sigma_{C_B}^2 + \sigma_{nuclear\ data}^2 + \sigma_{e_i}^2 + \sigma_{T_{fuel}}^2 + \sigma_{\rho_{fuel}}^2 + \sigma_{\rho_{water}}^2 + \sigma_{code}^2 + \sigma_{Burnup}^2$$

P_{th}: thermal power $\Rightarrow \boldsymbol{\delta P_{th}/P_{th} = 0.46\ \%}$
C_B: boron concentration $\Rightarrow \boldsymbol{\delta CB/C_B = 1.4\ \% \times C_{B\_max}}$
T_{fuel}, T_{Water}, ρ_{fuel}, ρ_{Water}: water and fuel temperatures and densities
Code: systematics arising from the computational method (M-C vs deterministic)
Nuclear data: Nuclear database choice
e_i: energy released per fission
Burnup: initial inventories of loaded assembly (in the cores 2/3 of assemblies with 5% error on initial burnup + 1/3 fresh fuel with very small error)

⇒ Computation of the α_k correlation matrix

Fission rate errors: results for one typical reactor cycle



Average error over the 101 days of data taking :

^{235}U : 3.3%
^{239}Pu : 4.0%
^{238}U : 6.5%
^{241}Pu : 11%

⇒ Most dominant errors on computed fission rates come from errors on: **Water density, reactor code, initial burnup of loaded assemblies, effect of not following the control rod positions.**

- **Expected detector neutrino rate:**

$$N_\nu^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

With the mean energy released per fission :

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k$$

$k = U^5, Pu^9, U^8, Pu^{41}$

Bugey4 measurement is used as an anchor point for the mean cross-section per fission $\langle \boldsymbol{\sigma_f} \rangle$

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^{DC} - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k$$

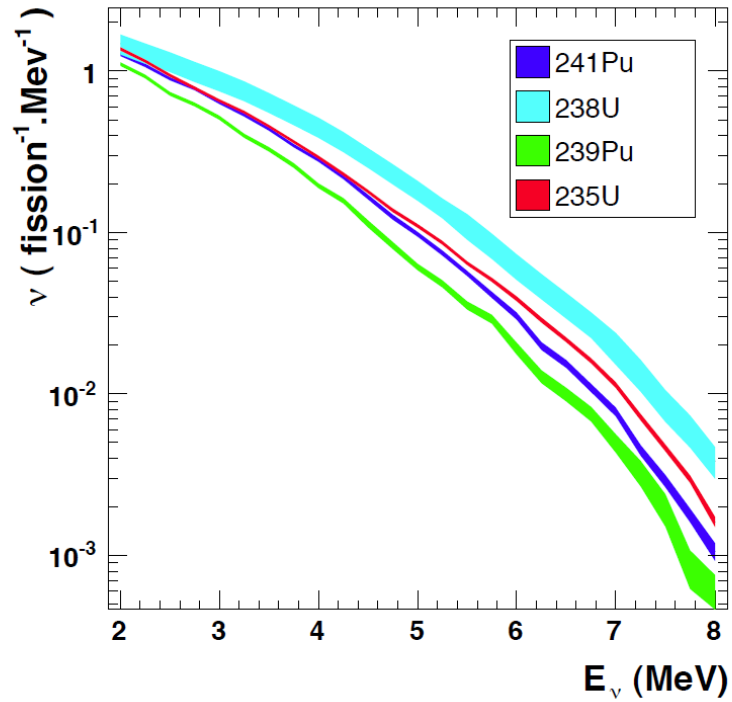
$$\langle \sigma_f \rangle^{Bugey} = 5.752^{\pm 0.081} 10^{-43} cm^2/fission$$

$$\langle \sigma_f \rangle_k = \int_0^x dE \;\; S_k(E) \; \sigma_{IBD}(E)$$

Inverse beta-decay cross section Includes latest neutron life time: $\tau_n = 881.4\, s\, , PDG2011$

Reference antineutrino spectrum

Reference ν spectra

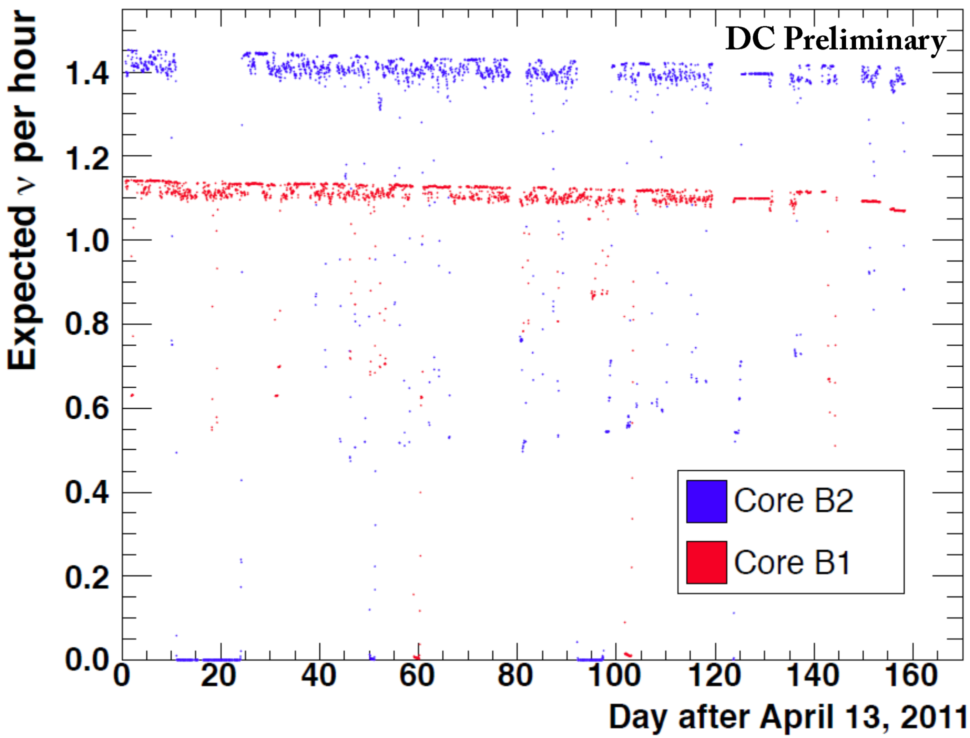


- Recent re-evaluations by

- Th.A Mueller et al, Phys.Rev. C83 (2011) 054615
- P. Huber, Phys.Rev. C84 (2011) 024617

- Off-equilibrium corrections included

(from Th. Mueller et al. @ 100days)

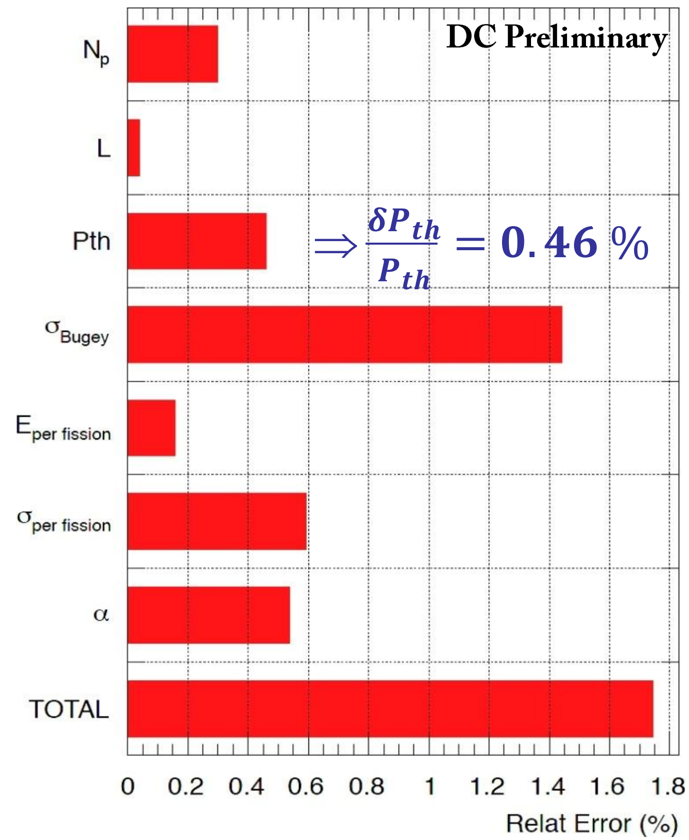


Expected $\bar{\nu}_e$ (101 days): 2583.5 (B1), 2751.2 (B2)

$\Rightarrow$ Total = 5334.7 ± 93

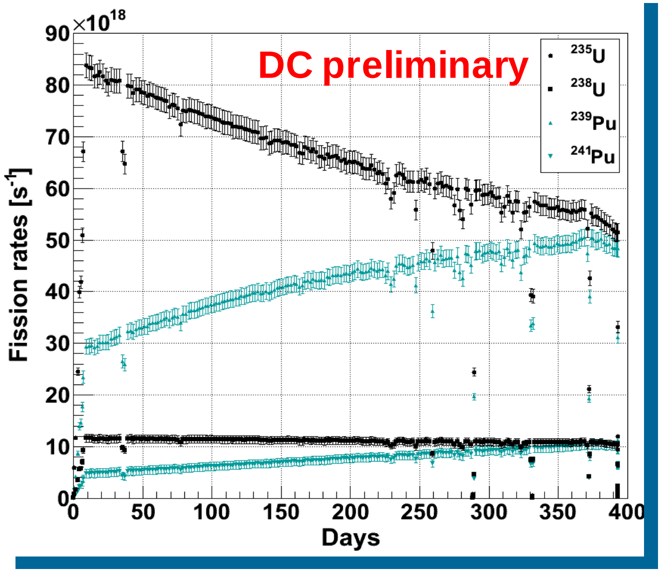
~2.5% reduction of neutrino rate during data taking due to accumulation of ^{239}Pu in the core **(Burnup effect)**

Errors of reactor predictions



$\Rightarrow$ Total error = 1.74%

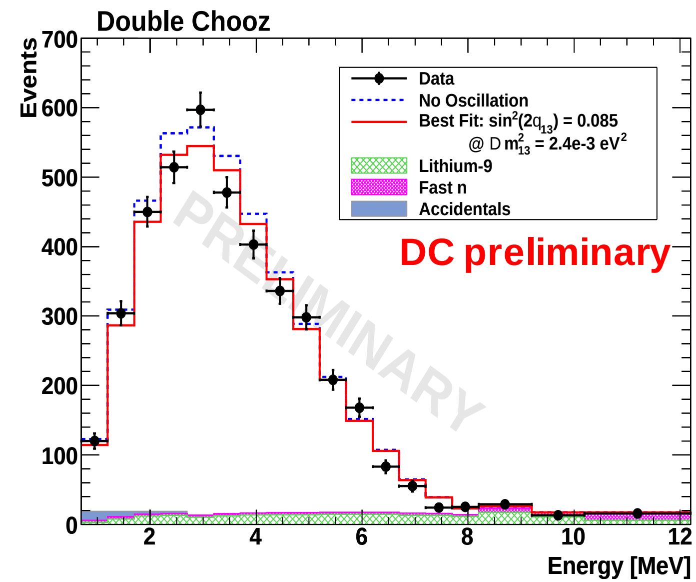
- σ_{N_ν} dominated by error on $\langle\sigma_f\rangle^{Bugey}$
- Accurate reactor simulation keep contribution of the uncertainty on α_k low



- Far detector data only

- No-Oscillation $\Rightarrow$ reactor flux prediction via core simulations
Normalisation to the Bugey-4 cross-section with far detector only

$\Rightarrow$ Reduced reactor systematics: $\frac{\delta N_\nu^{exp}}{N_\nu} = 1.74\ \%$



First DC neutrino oscillation data release at LowNu11 @ Seoul (Korea) by H. de Kerret: ***(doublechooz.in2p3.fr/Status_and_News/)***

Hint for a positive value of θ_{13}

Rate + Shape Analysis: $\sin^2(2\theta_{13}) = 0.085 \pm 0.051$

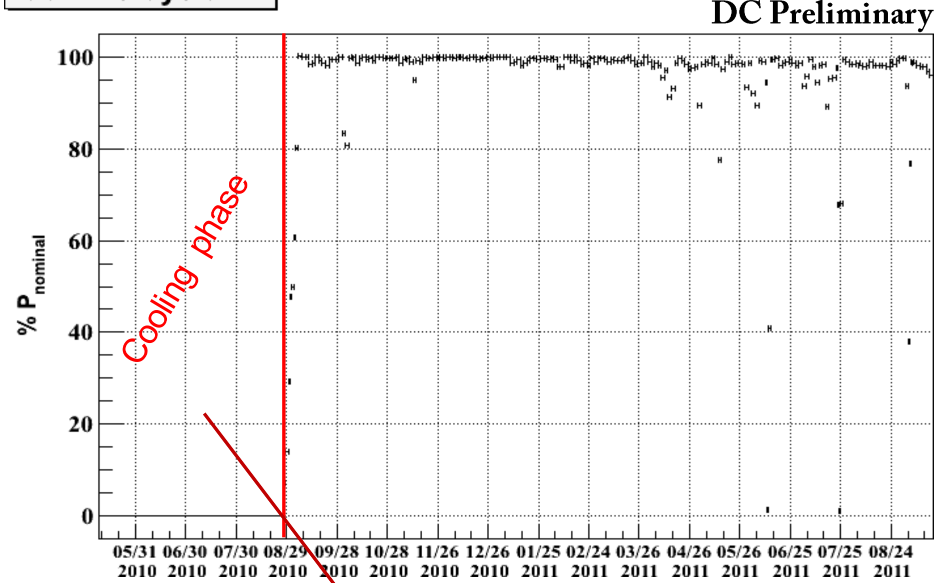
No-Oscillation Excluded at 92.9 %

$\Rightarrow$ **Double chooz results are consistent with T2K & Minos results: combined effect: $\sin^2(2\theta_{13})>0$ @ 3σ**

Backup

Reactor simulation: follow-up of operating parameters

Core 1 / Cycle 12



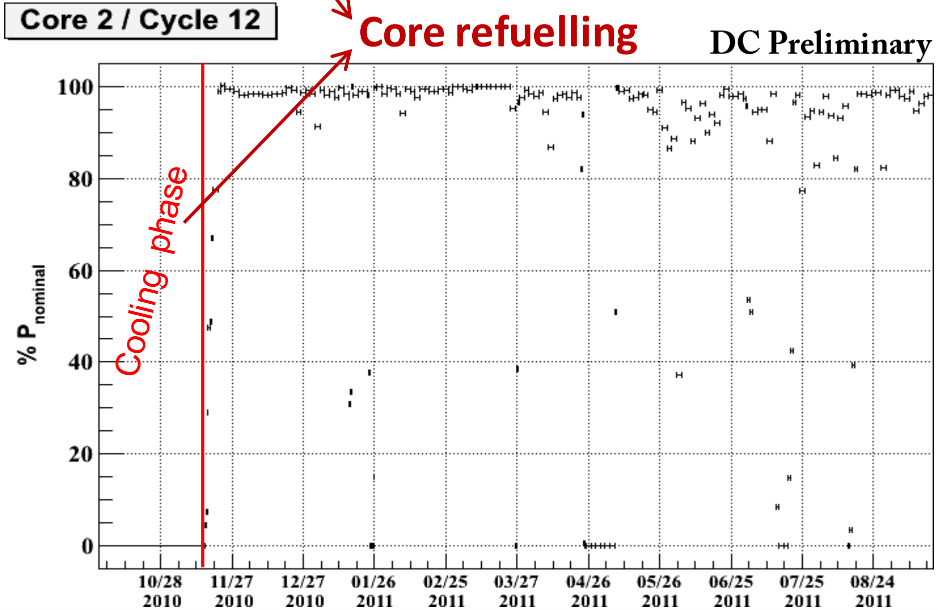
Thermal power & boron concentration values available each minute (EDF data / EXALT database)

Averaged over 12/24/48h and used as input parameters

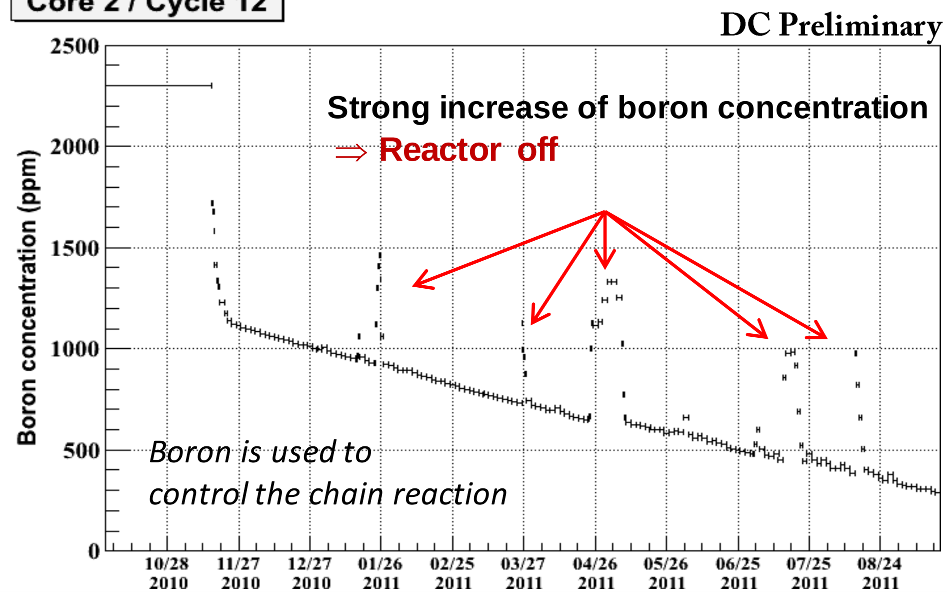
Principal other MURE input parameters:

- Database : JEFF 3.1
- Energy per fission : Kopeikin *(Kopeikin, V. et al., 2004. A comment on Pandemonium, Phys. Atom. Nucl. 67 1963.)*
- Statistic : 2.2×10^{7} neutrons per run

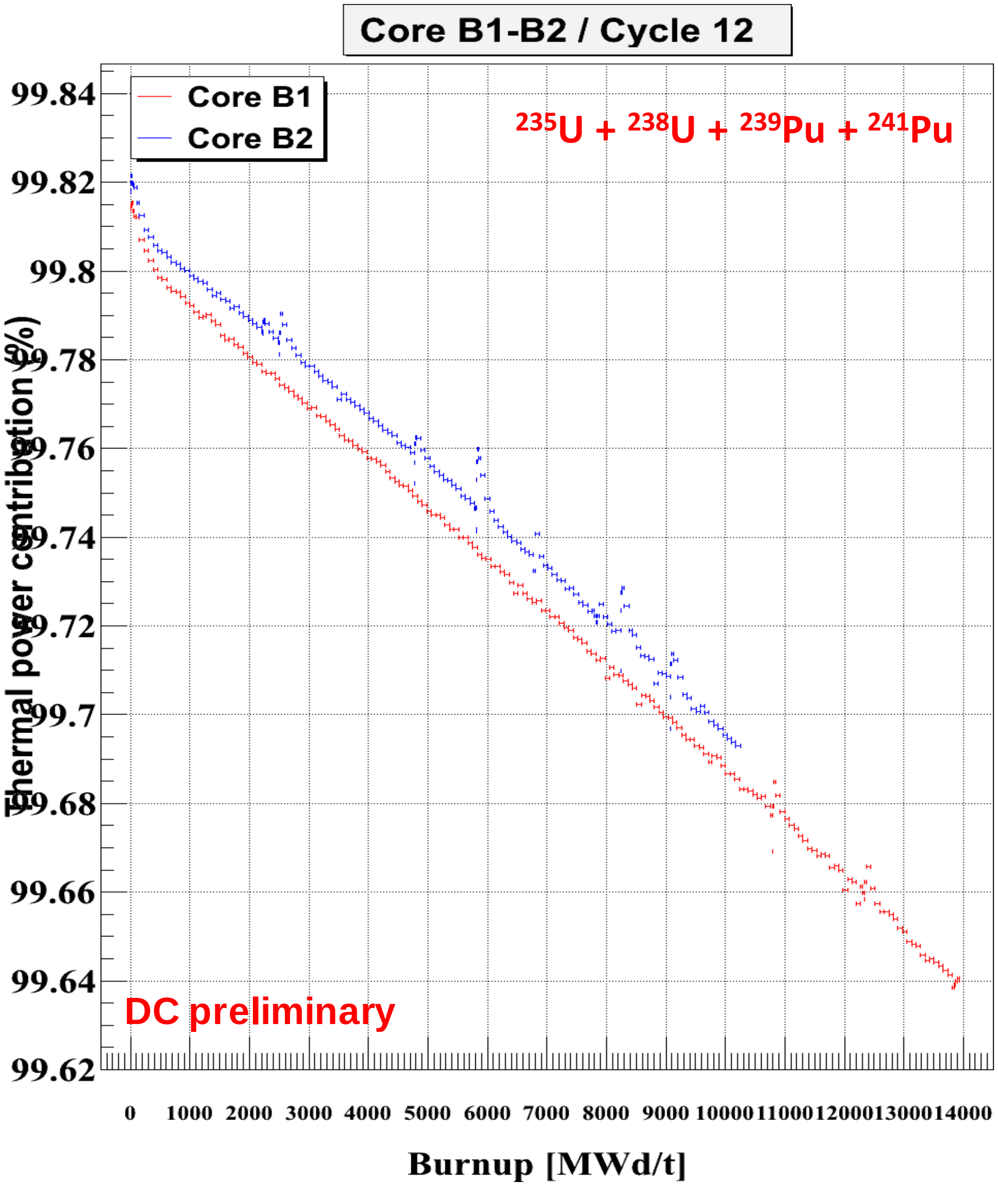
Core 2 / Cycle 12

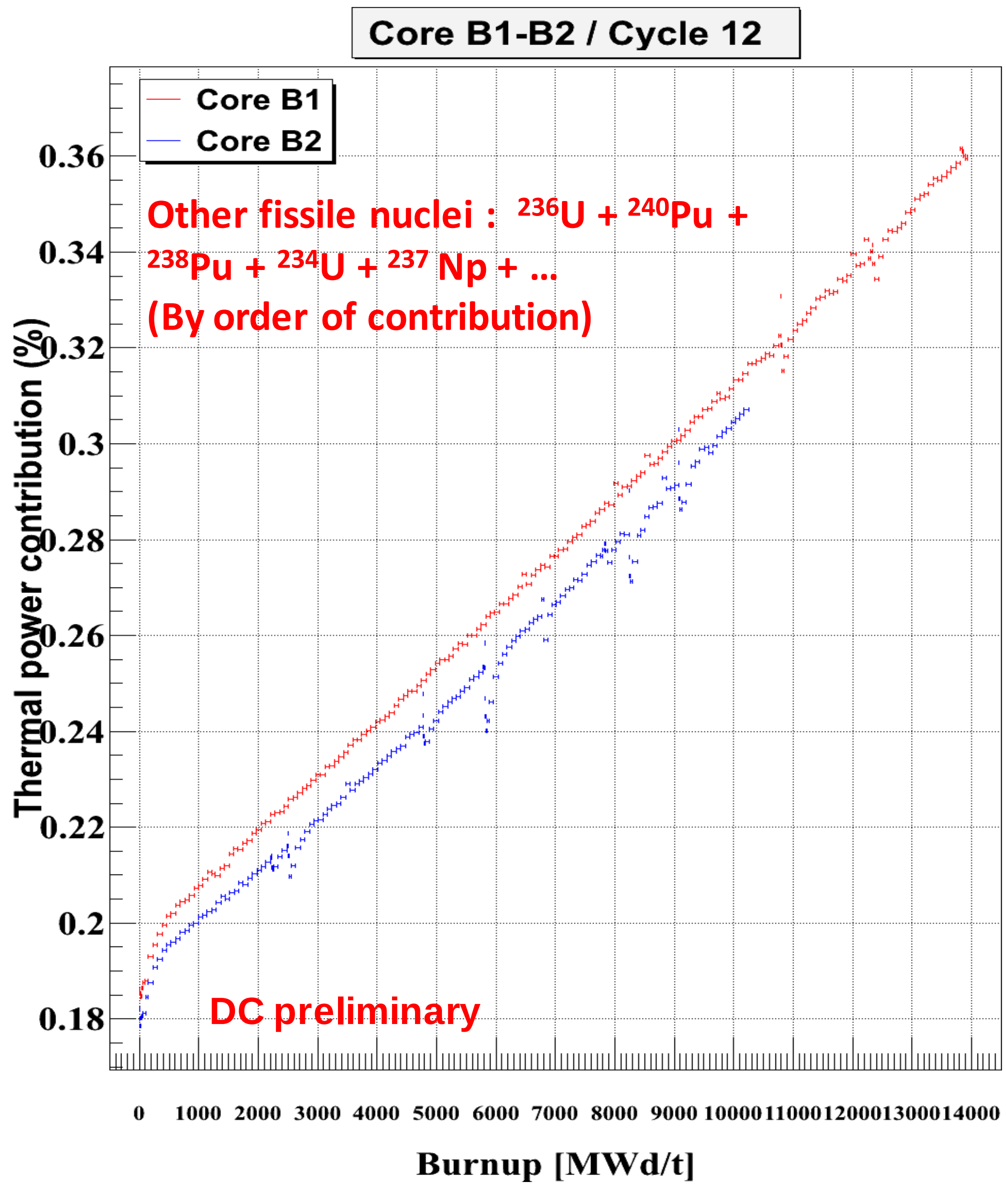


Core 2 / Cycle 12

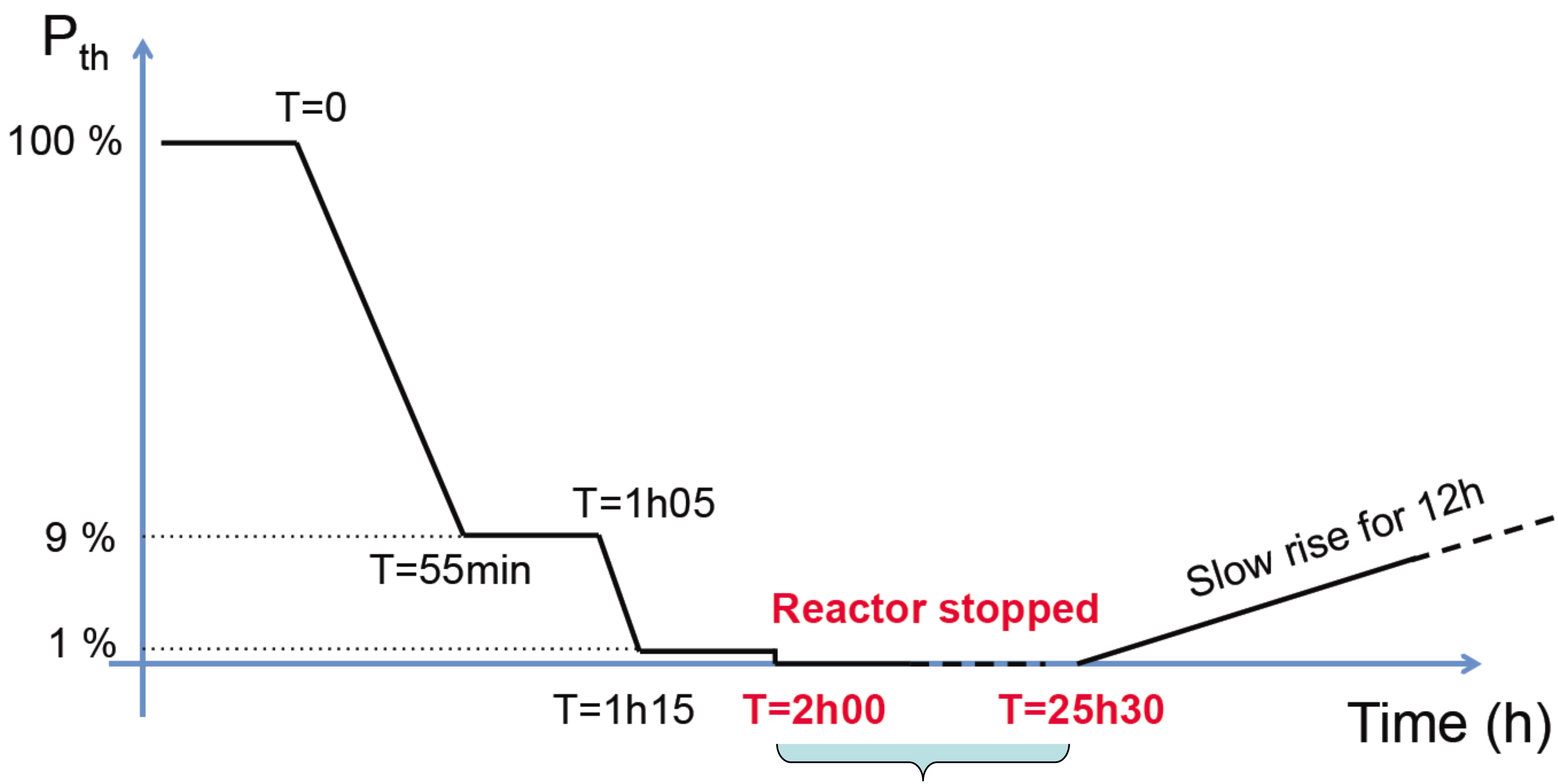


Isotope contributions to the thermal power





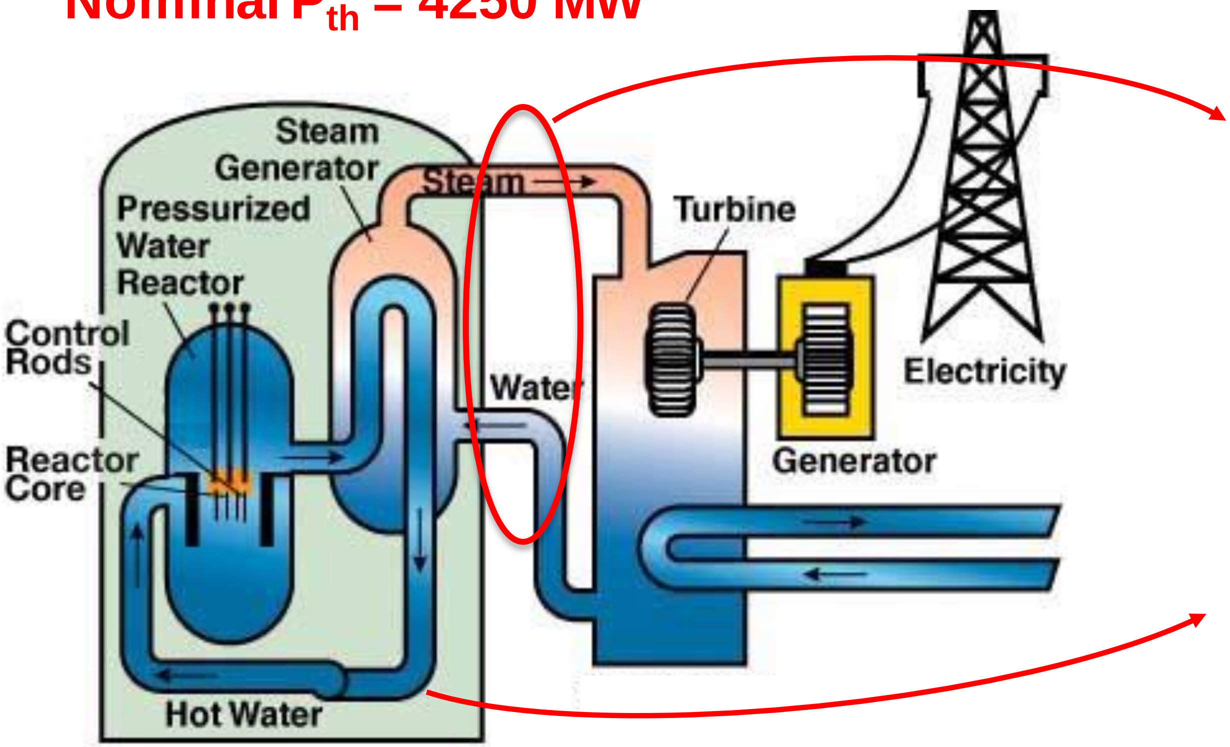
1 day of reactor off-off



$\Rightarrow$ **3 events detected**

Thermal power

Nominal P_{th} = 4250 MW



Absolute anchor point

- "BIL100"
- Once per week
- Enthalpic balance at Steam Generator

Monitoring

- "BILSPIN"
- Mean temperature and flow in the 4 primary loops

Dedicated study done at EDF R&D Chatou, based on the analysis of 14 EDF notes:
Ref: HP1C-2011-2007-FR, Y. Caffari, J.M. Favennec

Errors at Nominal Power (95% C.L.)

One measurement ever minute from Exalt

$$\sigma_{TOTAL} = \sigma_{SPIN} + \left|\varepsilon_{SPIN}\right| + \Delta_{REC}$$

σ_{SPIN} = 0.43%, random error from BILSPIN

$\left|\varepsilon_{SPIN}\right|$: syst. offset from BILSPIN, zeroed by BIL100 calibration

Δ_{REC} = 0.48 remaining syst. offset inherent to the BIL100 recalibration

$$\rightarrow \sigma_{TOTAL} = 0.91\%$$

Mean Power

$$\sigma_{TOTAL} = \sigma_{SPIN} + \left|\varepsilon_{SPIN}\right| + \Delta_{REC}$$

- **Average of Exalt points:**

  Assume 100% correlated errors between 2 Exalt points (although σ_{SPIN} should converge as $1/\sqrt{N_{pt}}$)

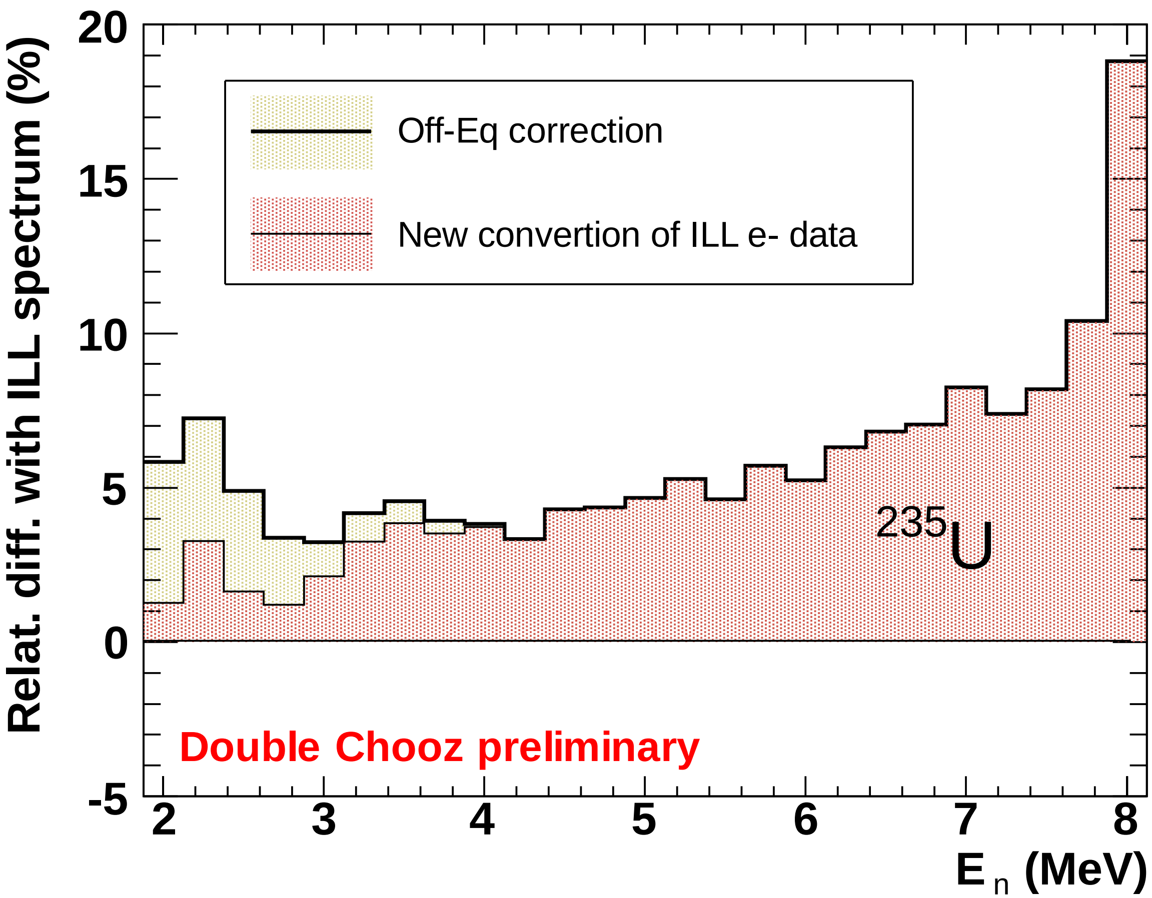
  → $\delta Mean\_P_{th}/Mean\_P_{th}$ = 0.91%

- **Sum two reactors:**
  - Δ_{REC} dominated by discharge coeff of orifice plate
  - σ_{SPIN} dominated by temperature profile in pipes of primary loops

  → Errors on B1 and B2 power are independent but $1/\sqrt{2}$ scaling is not valid for Δ_{REC}

Global relative error $\delta P_{th}/P_{th}$ = 0.91% (0.46% at 1σ)

ν spectra



+2.4% in emitted flux

+3.7% in detected flux

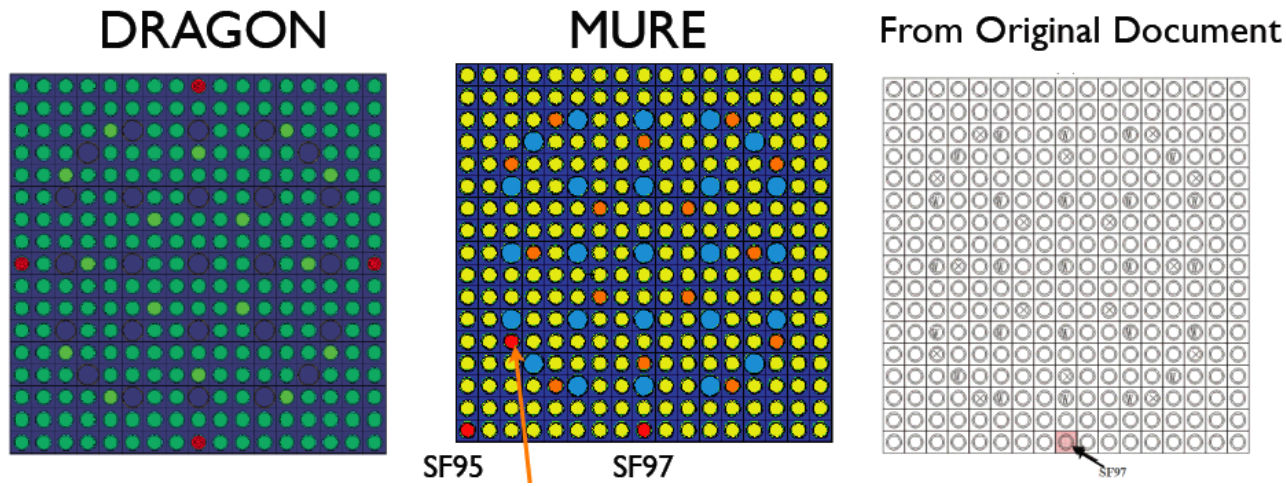
Off-Eq

from Th. Mueller et al. (calc. At 100days).

+4.9% in emitted flux

+3.7% in detected flux

Takahama Benchmark



- Takahama-3 reactor: 17x17 PWR close to the Chooz ones

- 2 fuel rods destructive assays from 2 of the assemblies

- Comparison to mass measurements in these 2 rods (from 0.1% to 0.3 % relative standard deviation for ^{235,238}U and ^{239}Pu), burnups comparable to Chooz case
- Comparison to reactor codes: Apollo2-Pépin2 (Darwin), KENO, Origen2, MONTEBURN (MCNP + Origen2), … + sensitivity study to main reactor inputs