Experimental Reactor Physics at IN2P3

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A Bailly (2019-2022)[1], T Chevret (2013-2016)[1]

With the support of the technical staff of the laboratories

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Conseil Scientifique de l'IN2P3, Feb. 3rd-4th, 2022

1. ADS Physics at IN2P3: achievements
2. Remaining work on ADS monitoring (SPATIAL project)
3. A possible application: core loading monitoring (SALMON project)

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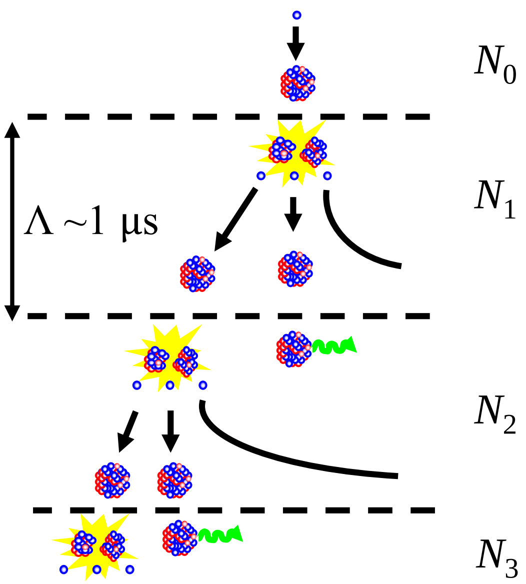
Accelerator Driven Subcritical Reactors (ADS)



$$k_{eff} = N_{i+1}/N_i$$

ADS: $k_{\mathrm{eff}} < 1$ or $\rho = \frac{k_{\mathrm{eff}}-1}{k_{\mathrm{eff}}} < 0$ or $\frac{\rho}{\beta_{\mathrm{eff}}} < 0$

⇨ Chain reaction not self-sustained: $N_3 < N_2 < N_1 < N_0$

⇨ An external neutron source S is needed to maintain constant power

⇨ Coupling with a proton accelerator via a spallation source

$$P_W \propto S \times k_{eff} + S \times k_{eff}^2 + S \times k_{eff}^3 \ldots = S \frac{k_{eff}}{1-k_{eff}} \Rightarrow \boxed{P_W \propto \frac{S}{-\rho}}$$

⇨ Delayed neutrons (β_{eff}) do not play any role for reactor control

⇨ Large amount of Minor Actinides (with low β_{eff}) can be loaded

TABLEAU 5 : ORDRE DE GRANDEUR DE LA CAPACITÉ DE TRANSMUTATION DES DIFFÉRENTS MODES DE TRANSMUTATION

MODE DE TRANSMUTATION	Homogène			Hétérogène (CCAM)		ADS
Teneur AM	1 %	2 %	4 %	10 %	20 %	55 %
Capacité de transmutation AM (kg/TWhe)	0*	5*	14*	3,5 (-0,5*)	6 à 8 (2 à 4*)	95*

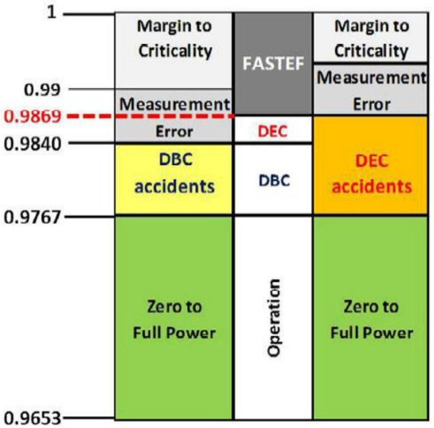
* capacité de transmutation d'actinides mineurs exogènes au réacteur

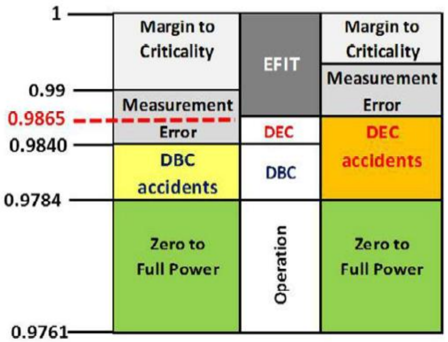
Need for ADS reactivity monitoring

Advantages of the ADS hold only if they remain subcritical in any circumstance

$$k_{eff}(t) < 1 - \Delta k_{eff}^{+} = k_{eff}^{max}$$

Maximum positive reactivity insertion possible





Sarotto, Ann. Nuc. En. 102 (2017) 440

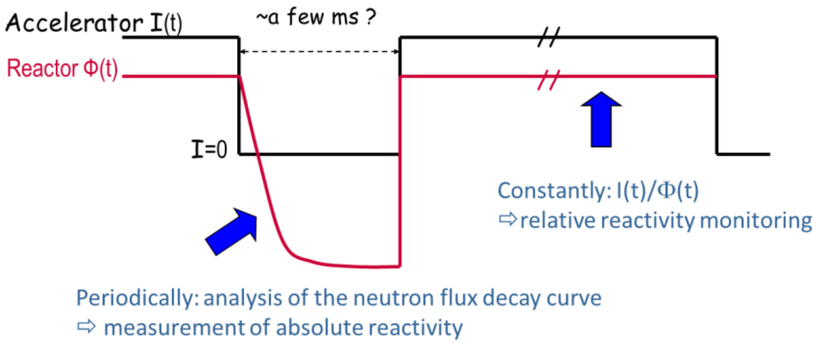
It must be checked constantly that k_{eff} remains below $k_{\mathrm{eff}}^{\mathrm{max}}$

⇨ k_{eff} (or $\rho = 1\text{-}1/k_{eff}$) must be regularly measured

⇨ The uncertainty on reactivity measurement must be added to the safety margins

Issues:

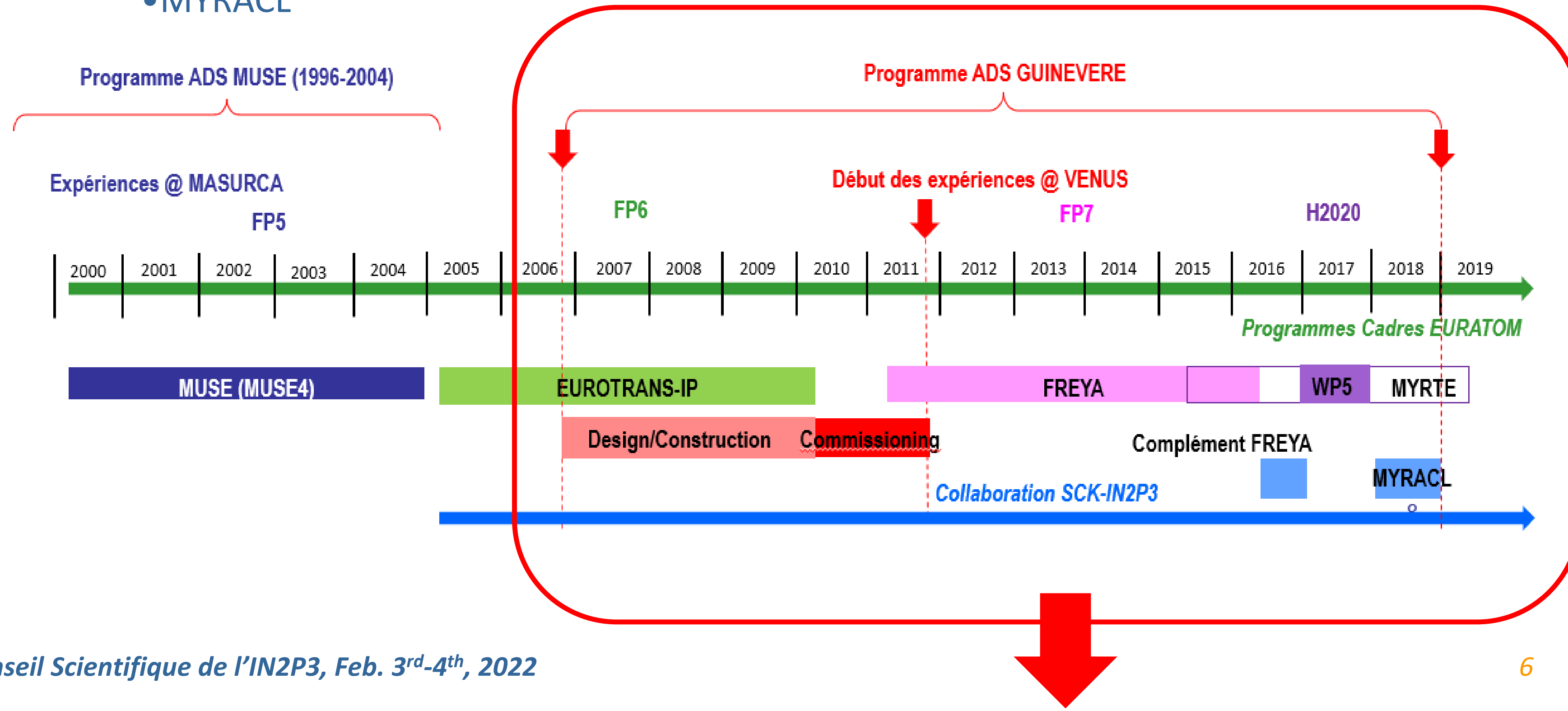
- Is it possible to constantly measure the ADS reactivity (monitoring)? In what conditions?
- What are the precision and accuracy?



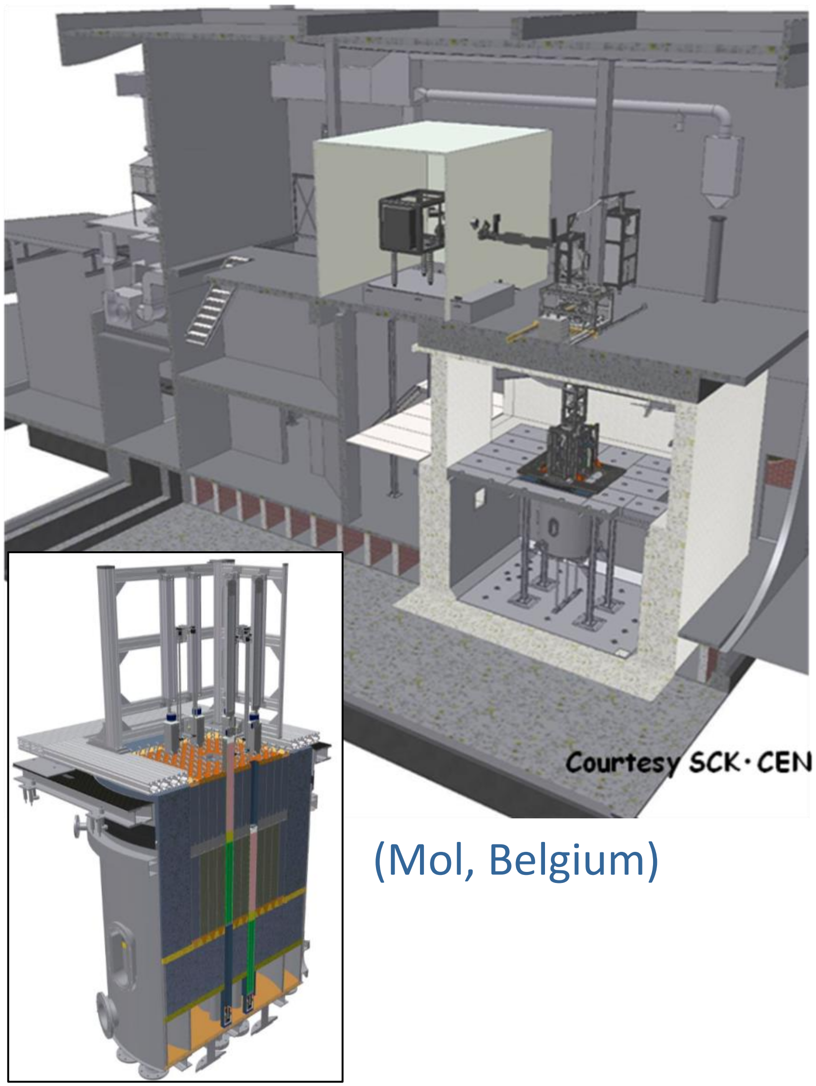
A long story at IN2P3

- **Work on ADS physics by the experimental approach on mock-up / zero power reactor:**

- MUSE @ MASURCA (FP5)
- GUINEVERE @ VENUS
  - EUROTRANS-IP (FP6)
  - FREYA (FP7)
  - MYRTE (H2020)
  - MYRACL



The GUINEVERE Facility at SCK·CEN



(Mol, Belgium)

- **VENUS-F**: A zero-power sub-critical fast reactor with enriched U (30%, **CEA**), with solid Pb(-Bi) « coolant » at **SCK CEN**

+

- **GENEPI-3C**: A 220-keV deuteron accelerator + TiT target located at core center (**CNRS/IN2P3**)

⇨ production of 14-MeV neutrons by fusion reaction T(D,n)α

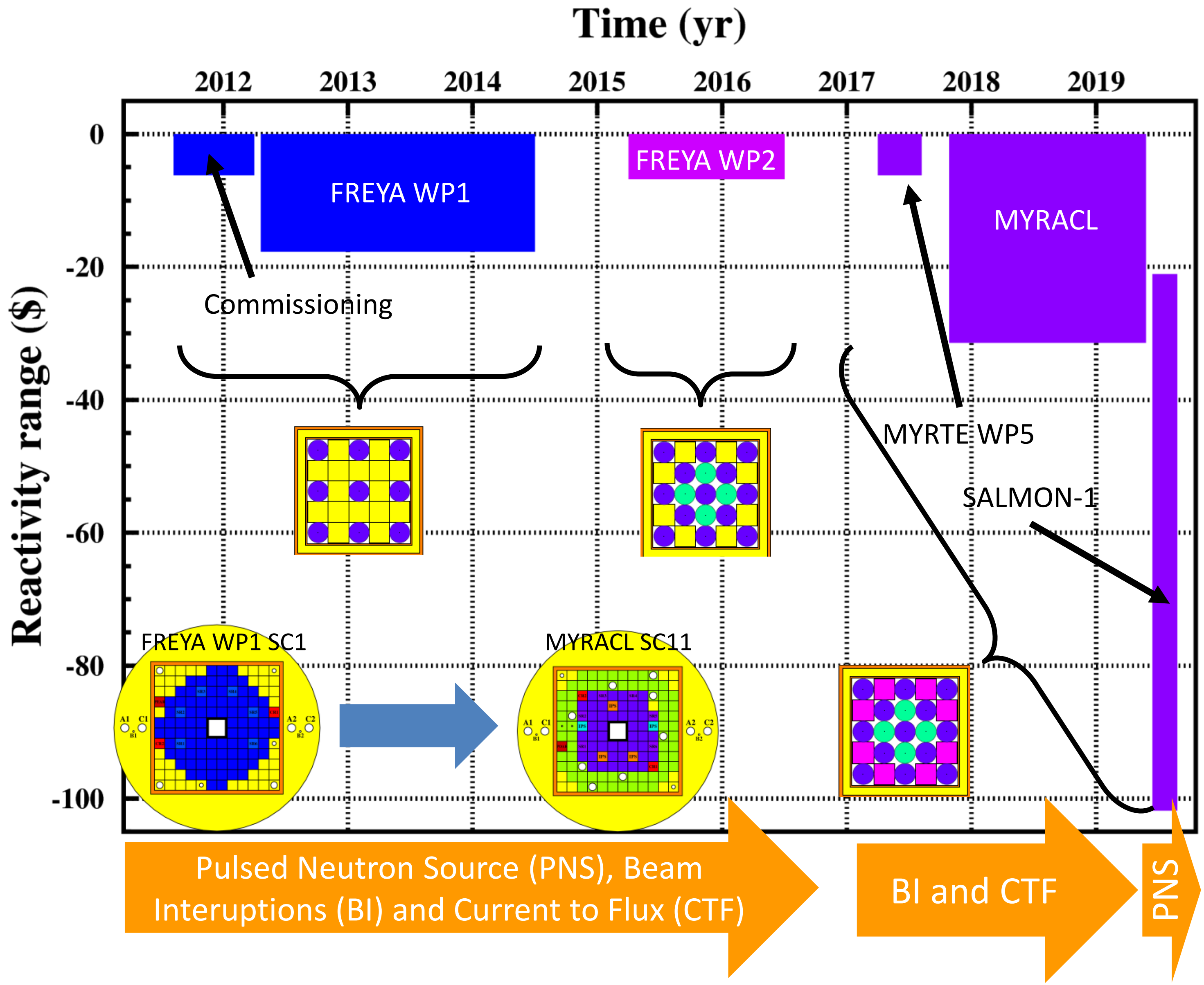
⇨ Pulsed and continuous beam (with interruptions)

Mode	Pulsed	Continuous w/ interruptions
I (mA)	20 (peak)	1
f (Hz)	10 - 5000	0 - 250
t_{on} (ms)	7×10^{-4} (σ_{pulse})	2 - 98
Number of neutrons	10^6 pulse^{-1}	10^{10} s^{-1}

=

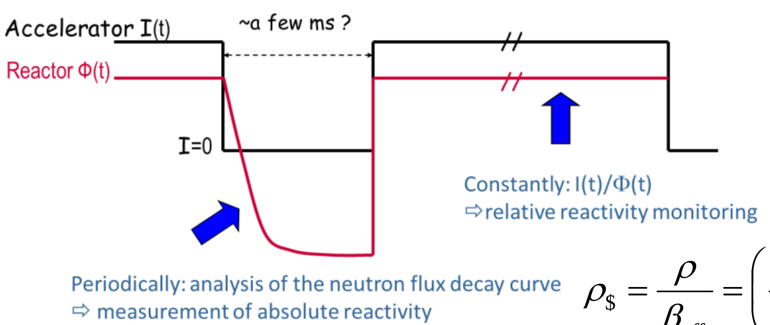
A unique « mock-up » of a LBE-cooled Power ADS

Experiments @ GUINEVERE

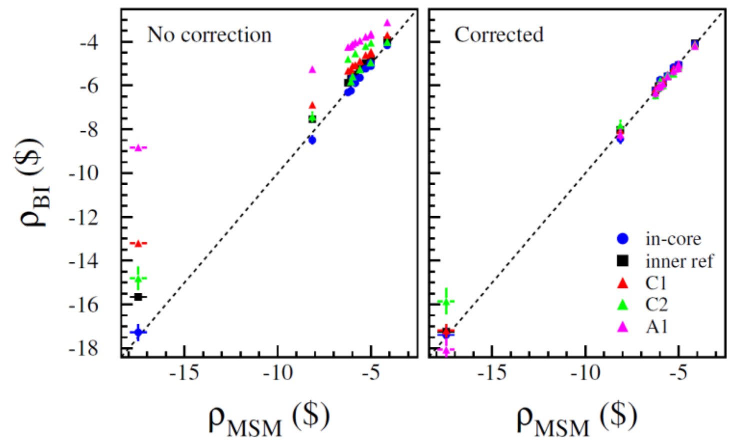


Reactivity measurement: where do we stand?

Outcomes of FREYA (2011-2016) and MYRTE (2016-2019) Euratom projects:



$$\rho_\$ = \frac{\rho}{\beta_{eff}} = \left(\frac{t_{on}}{T}\right)\left(\frac{n_1 - n_0}{n_1}\right)$$



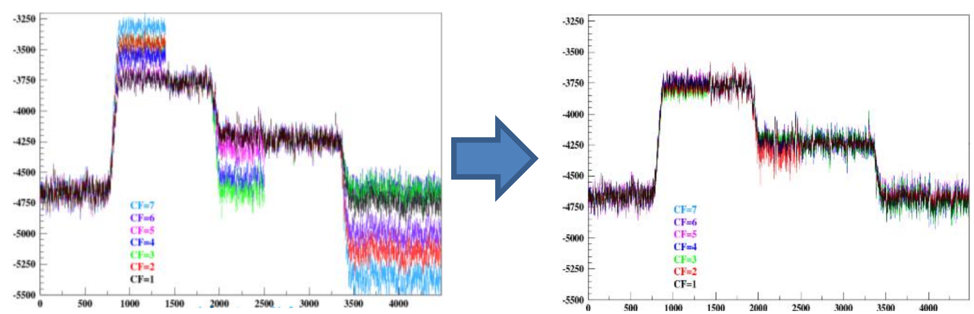
Chevret et al. 2014, 2016

Space-energy effects beyond Point Kinetics ⇨ $\rho_{measured} \geq \rho_{real}$

⇨ Monte Carlo Simulations ⇨ Space-energy factors f_{SE} ⇨ $\rho_{final} = f_{SE} \times \rho_{meas.} \cong \rho_{real}$

Current-to-Flux ratio:

$$-\rho = C\left(\frac{I_{beam}}{P_W}\right) \Rightarrow -\rho = C'\left(\frac{S}{R_{det}}\right)$$



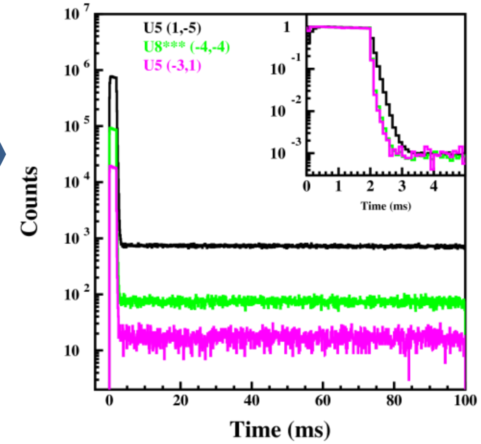
Marie et al. 2019

+ PNS experiments: Area method (Marie et al. 2013, Lehaut et al. 2016) and kp method (Chabod et al. 2014)

Reactivity measurement: where do we stand?

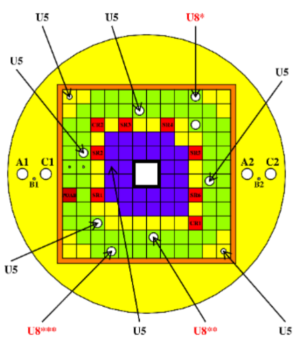
	FREYA WP1	FREYA WP2	MYRTE WP5
MYRRHA-like core	☒	☑	☑
U5 FCs in MYRRHA-like positions	☑	☑	☑
High source duty cycle	☑	☑	☑
U8 FCs in MYRRHA-like positions	☒	☒	☑
Large reactivity range tested	☑	☒	☒
Low source duty cycle	☒	☒	☒
Effects of random beam trips	☒	☒	☒

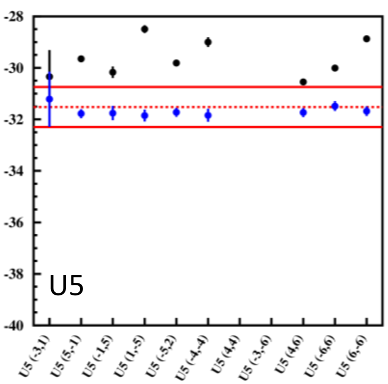
MYRACL

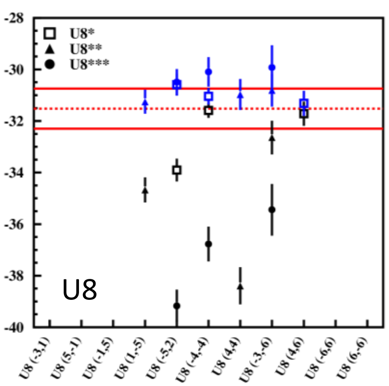


(Some) outcomes of MYRACL (2017-2020):

$$\rho_{final} = f_{SE} \times \rho_{meas.} \cong \rho_{real}$$







A. Bailly et al., LPCC report, 2020

With SEF ⇨ good estimate of ρ

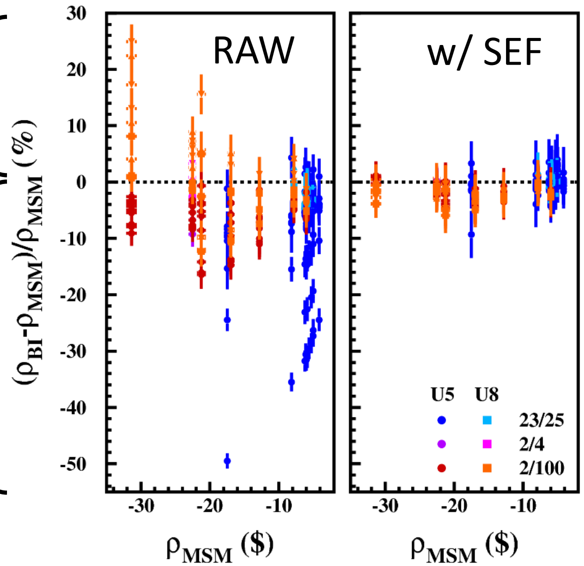
Without SEF, ρ is underestimated !

Shortcomings of past experiments at GUINEVERE

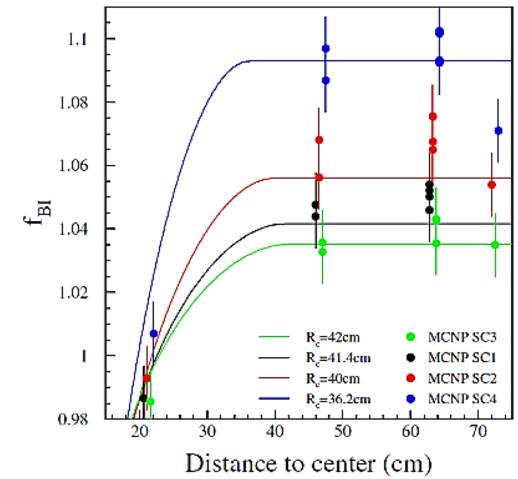
All configurations, all detectors

Underestimation of ρ

Overestimation of ρ



In FREYA, effects beyond PK are almost purely spatial



- Space-energy effects hindering reactivity measurements seem under control, but:

- Space-wise:
  - most detectors in similar locations
  - almost no detector in the fuel zone
- Energy-wise, it is even worse:
  - no threshold FC in fuel zone
  - only one threshold nuclide used (^{238}U)

- Full space-energy effects probed mostly in MYRACL

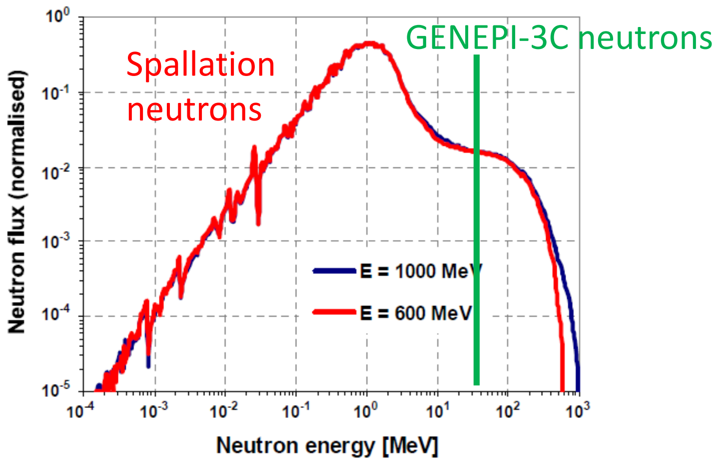
⇨ Complex interplay between absorbent, graphite and ^{238}U as FC deposit

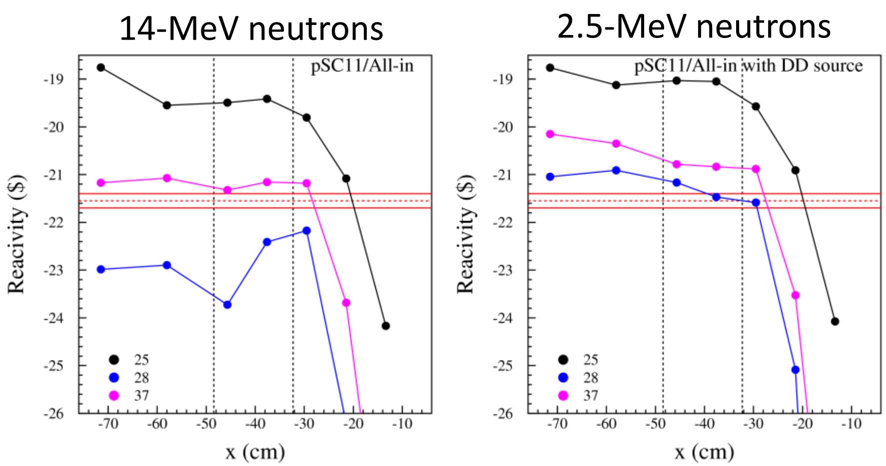
- Important case because ^{238}U is envisioned for MYRRHA
- Worrisome: reactivity underestimation **never seen before**, **not expected** and **not understood in details yet**

⇨ If space-energy effects are not fully understood in VENUS-F, the reliability of transposition of the results to power ADS is doubtful

Other shortcomings of past programs

- Although the overall impact of neutron source energy is ≈ 0 in the core, simulations show that it might not be true for reactivity measurements with threshold detectors, **especially for ^{238}U!**





no alternative threshold detectors ever tested

- Obviously there is no fuel evolution in VENUS-F (≈15 W) ≠ power ADS (≈100 MW)

The impact of spallation energy spectrum, fuel burn-up, specific designs in power ADS on reactivity measurement remain to be studied using simulations

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SPATIAL project, axis 1: Traverses during transients at GUINEVERE

- **Comprehensive experimental study of space-energy effects beyond Point Kinetics during reactor transients**

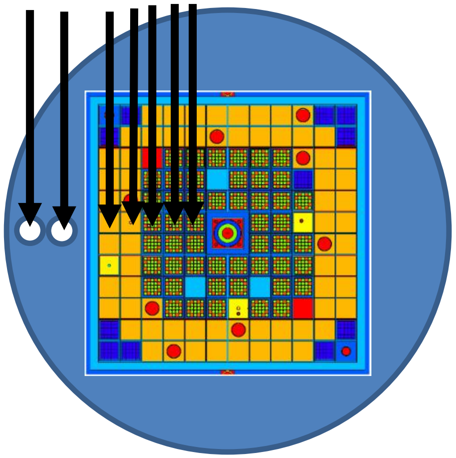
⇨ Ideally: measurement of $\phi(\vec{r},\vec{\Omega},E,t) \quad \forall\, \vec{r},\vec{\Omega},E,t$!

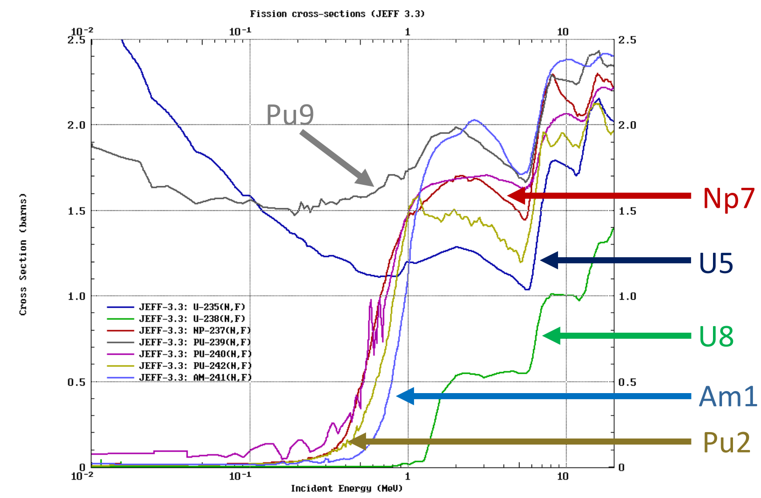
⇨ Impossible!

⇨ In practice, we can:
  - reduce the positions to a traverse thanks to reactor symmetries
  - use spectral indices with various threshold deposits to probe indirectly energy spectrum variations:

$$\frac{F\mathbf{za}}{F\mathbf{25}}(\vec{r},t) = \frac{\int dE\, \sigma_f\left({}^{AA\mathbf{a}}_{ZZ\mathbf{z}}X\right)\phi(\vec{r},E,t)}{\int dE\, \sigma_f\left({}^{23\mathbf{5}}_{9\mathbf{2}}U\right)\phi(\vec{r},E,t)}$$

⇨ Measurement of fission rates of various deposits in calibrated FCs as a function of time during transients, in a few positions in the core and in the reflector, in a few VENUS-F configurations



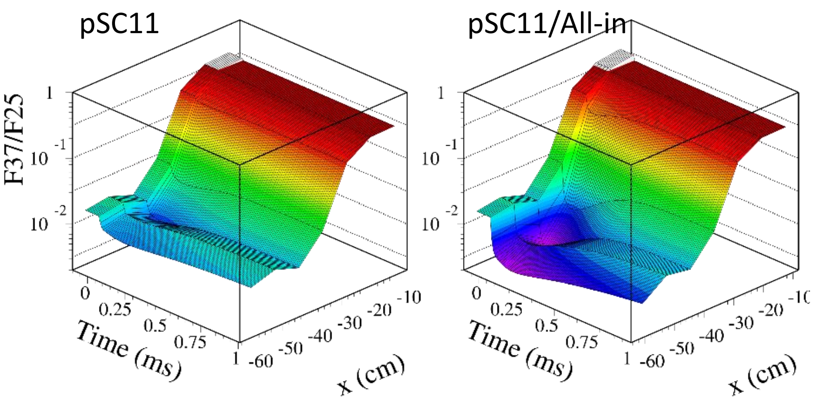


Fission thresholds: Np7 < Pu2 < Am1 < U8

Expected outcome

Transients: 100-Hz periodic beam interruptions

$$\frac{F\mathbf{37}}{F\mathbf{25}}(\vec{r},t) = \frac{\int dE\ \sigma_f\left({}^{237}_{93}Np\right)\phi(\vec{r},E,t)}{\int dE\ \sigma_f\left({}^{235}_{92}U\right)\phi(\vec{r},E,t)}$$



New data on space energy effects with much more emphasis on energy spectrum variations

⇨ unfolding of the various spatial effects at work

⇨ data analysis using « smart » approaches like modal approaches

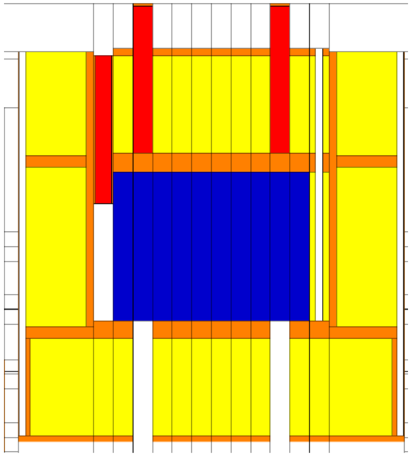
⇨ by-product:

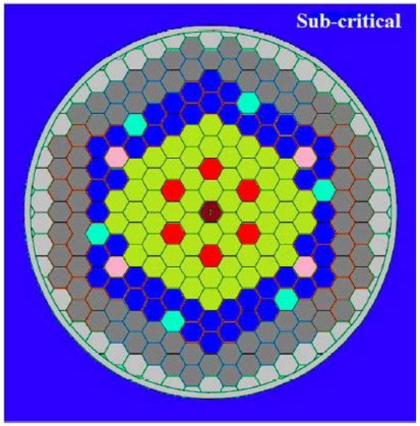
- modal basis: faster re-calculations of space-energy factors after reactor operation changes

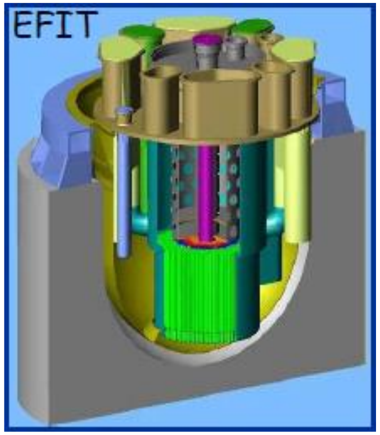
$$\Phi(\mathbf{r},E,\mathbf{\Omega},t>t_{BI}) = \sum_i T_i(t_{BI})\exp(\alpha_i t)\varphi_{\alpha_i}(\mathbf{r},E,\mathbf{\Omega})$$

- test of other threshold deposits as potential detector deposits (^{237}Np)
- A new, complete set of data for constraining kinetic models more accurate than Point Kinetics, ultimately needed for reactor transients in ADS and critical reactors!

SPATIAL project, axis 2: transposition







GUINEVERE : **P ≈ 15 Wth**
- No MA
- 10^{10} 14-MeV neutrons/s

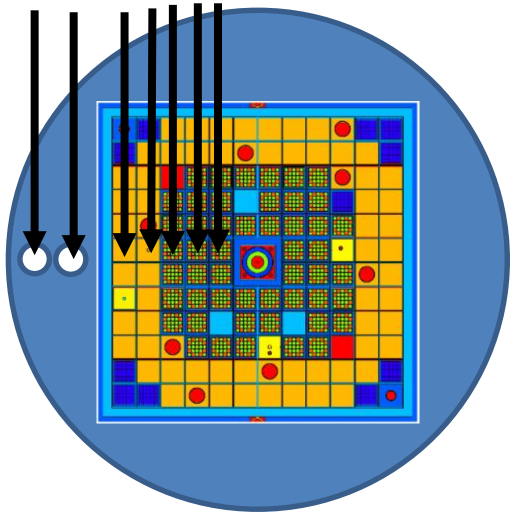
MYRRHA : **P ≈ 100 MWth**
- No MA
- 10^{17} spallation neutrons/s

EFIT : **P ≈ 400 MWth**
- Core loaded with MA
- 10^{17} spallation neutrons/s

Heavy simulation work needed to study, in the light of the experiments performed at the zero-power GUINEVERE facility, the impact of:
- spallation energy spectrum
- fuel evolution and reactor cycle

on space-energy effects and reactivity monitoring
⇨ Quantification of precision and accuracy of reactivity measurement in future power ADSs

SPATIAL in practical



- Measuring Spectral Indices along a traverse
  ⇨ small FCs
  ⇨ Very intense and stable external neutron source
  ⇨ The GENEPI-3C must be modified to meet these requirements

Duoplasmatron source:
Pulsed, continuous with interruptions

⇨

Continuous ECR source
+ beam chopper

⇨ Modification of target cooling + beam diagnostic

- Very ambitious program

⇨ Project submitted in Nov. 2021 to « Banque Publique d'Investissement », in the framework of a call partially devoted to « Search for alternatives to deep geological storage », to get 4-year funding (2022-2026)

⇨ Project currently under scrutiny by BPI

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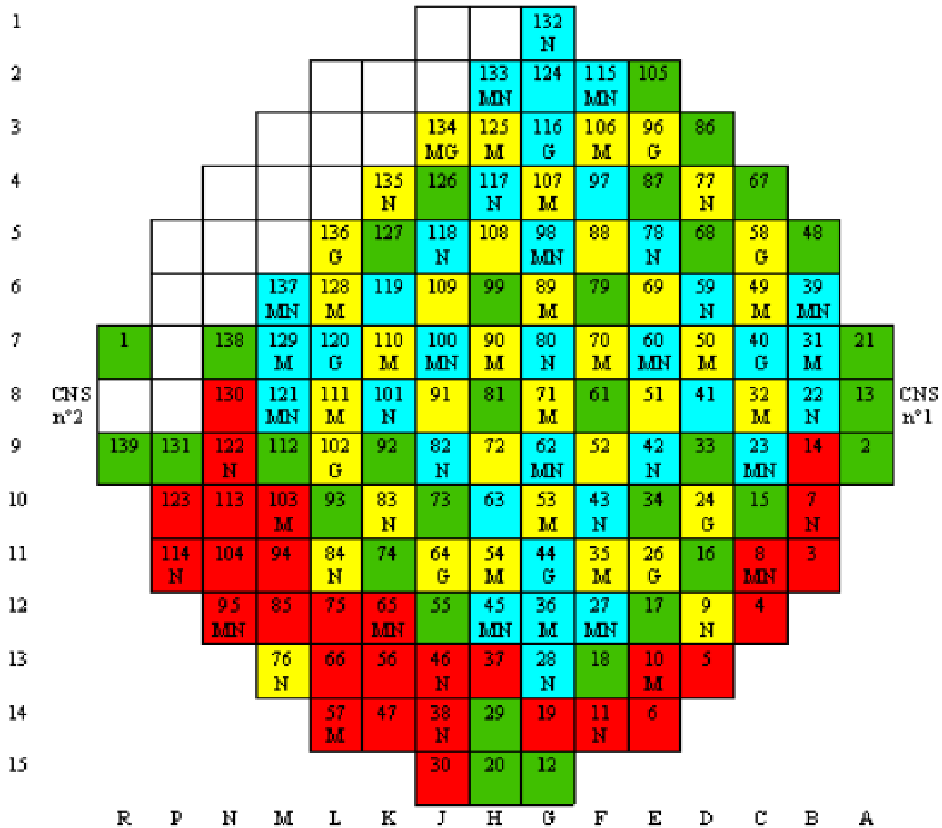
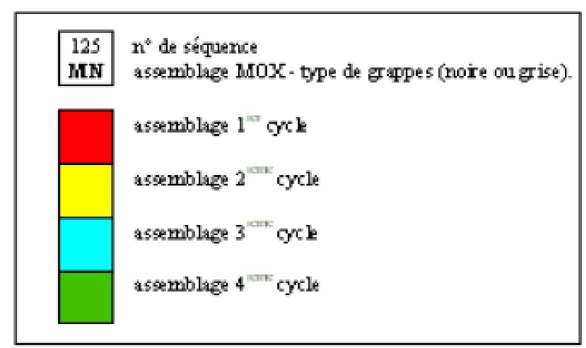
Fuel loading incident at Dampierre





Wrong loading pattern for a 900 MWe PWR (April 2001):

- Fuel Assembly #25 forgotten
- Accumulation of very reactive FAs
- Problem discovered only when loading FA #138

A. Verdier, « Evaluation de la sous-criticité lors des opérations de chargement d'un réacteur REP », thèse 2005

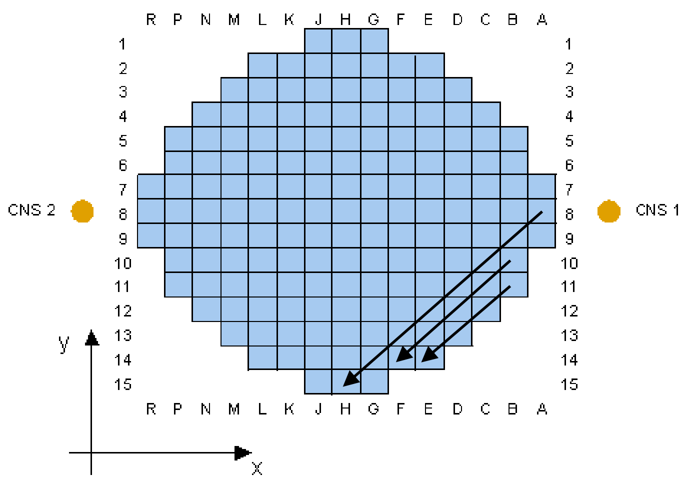
Measurement procedure for loading PWRs

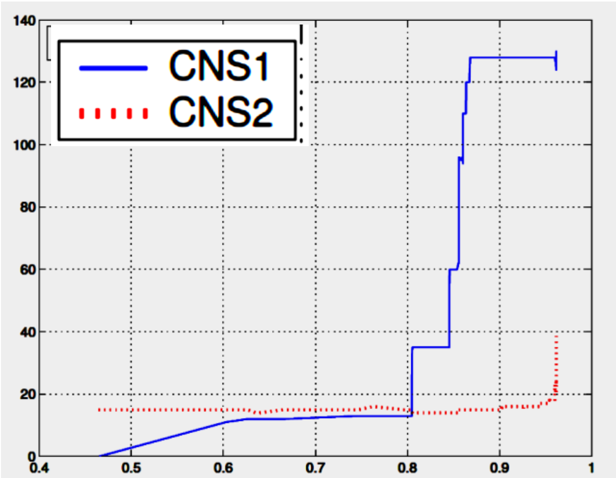
- Two ex-core proportional counters with enriched boron

⇨ Evolution of detector count rates is monitored during loading

⇨ Mixture of independent neutron sources and multiplication neutrons

⇨ Lack of correlation between count rates and sub-criticality





A. Verdier, PhD thesis 2005

⇨ Much more information expected with the use of a known time-dependent (pulsed) neutron source

⇨ Can correlation between Area method's reactivity and actual reactor reactivity be expected to hold for detectors located in the outer reflector, during loading?

⇨ Can safety of core loading be improved?

The SALMON project

The SALMON (Subcritical Approach for core Loading MONitoring) project: test in VENUS of a subcritical approach with reactivity measurement at several steps thanks to GENEPi-3C in pulsed mode.

1. Small fast SALMON phase at VENUS-F:
   - Taking advantage of VENUS-F unloading at the end of MYRACL
   - Few unloading steps of VENUS-F with GENEPI-3C in pulsed mode

   ⇨ ***done 2019***

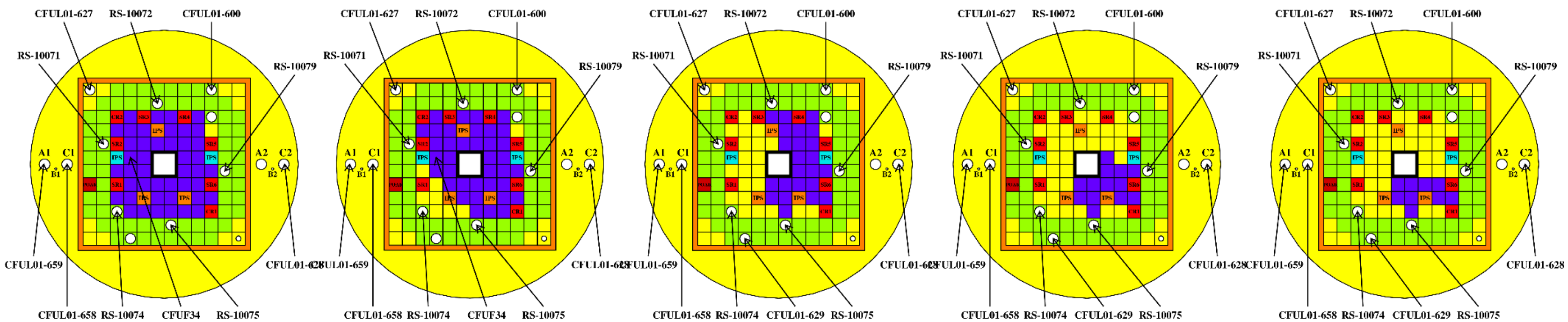
2. Small thermal SALMON phase at VENUS-T (water-cooled thermal VENUS)
   - integrated in the more general, innovative project SUCRE (CNRS-CEA-IRSN) within the framework of NEEDS-V2 (French CNRS program for nuclear energy and related topics)
   - any thermal core at use for SCK customers as a starting point
   - short experimental program with GENEPI in pulsed mode

   ⇨ ***originally planned 2021-2022***

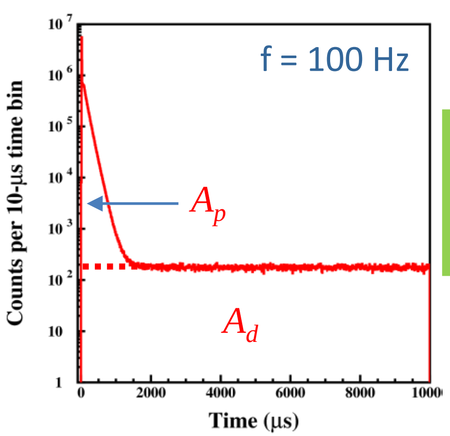
3. Results of these two exploratory phases would help:
   - building a larger scale project in VENUS-T
   - convincing potential funders
   - (and help involving miniature neutron source manufacturers)

   ⇨ ***Not programmed yet***

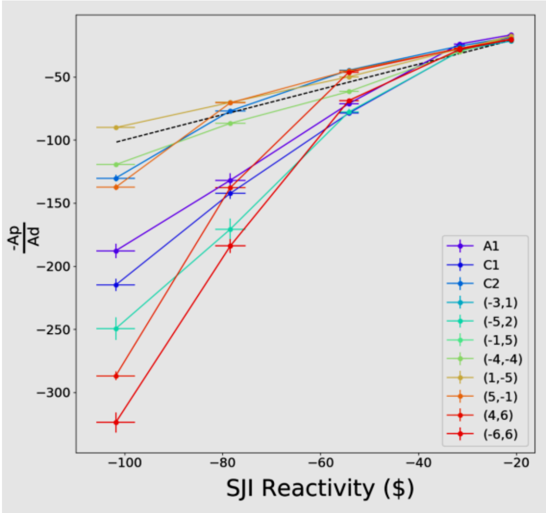
SALMON phase one: unloading of SC11



Config	SC11/All-rods in	SC11-7FAs	SC11-21FAs	SC11-31FAs	SC11-35FAs
SJ k_{eff}	0.866(3)	0.806(5)	0.711(8)	0.624(9)	0.557(10)
SJ ρ/β ($)	-21.1(6)	-32.6(1.1)	-54.2(2.0)	-78.4(3.1)	-101.8(3.9)



$$\rho_\$ = \frac{\rho}{\beta_{eff}} = -\frac{A_p}{A_d}$$



A. Bailly, submitted to PHYSOR'22

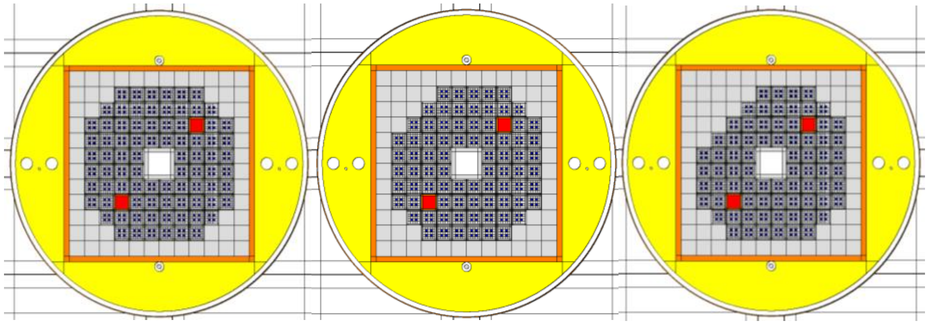
➔ Strong correlation between area result and reactivity kept throughout unloading for all detectors

Area method:

Feasibility of next phases

Phases 2 and 3 need to turn VENUS-F back to thermal, water-cooled VENUS-T
⇨ initially planned in 2020-2021, thermal VENUS-T has been postponed indefinitely
⇨ two alternatives to be studied:

- Test experiment with a neutron generator at another facility
- « Thermal VENUS-F » with Pb-Bi replaced by polythene in assemblies (SUCRE)



SALMON Phases 2 and 3 at VENUS are obviously incompatible with the SPATIAL project
⇨ Ideally, SPATIAL first, then SALMON-2 and 3, could be performed at VENUS

Conclusion

GUINEVERE is a unique facility for studying fast lead (and Pb-Bi) ADS, which exists thanks to SCK CEN, CNRS and CEA

- Large set of reactor experiments performed in 15 years
- Research programs mostly funded by external resources (Euratom, SCK,…)
- Strong involvement of CNRS/IN2P3 teams in reactivity measurement studies (know-how, leadership and initiatives)

  ⇨ ρ can be measured in a « MYRRHA-like zero-power ADS at start-up and in operation » within ≈ 4%

A strong and fruitful collaboration between SCK CEN and CNRS/IN2P3 for the last 15 years

⇨ Despite difficulties specific to the nuclear reactor field, the CNRS/IN2P3 teams feel encouraged to propose new ambitious projects to take advantage of the GUINEVERE facility:

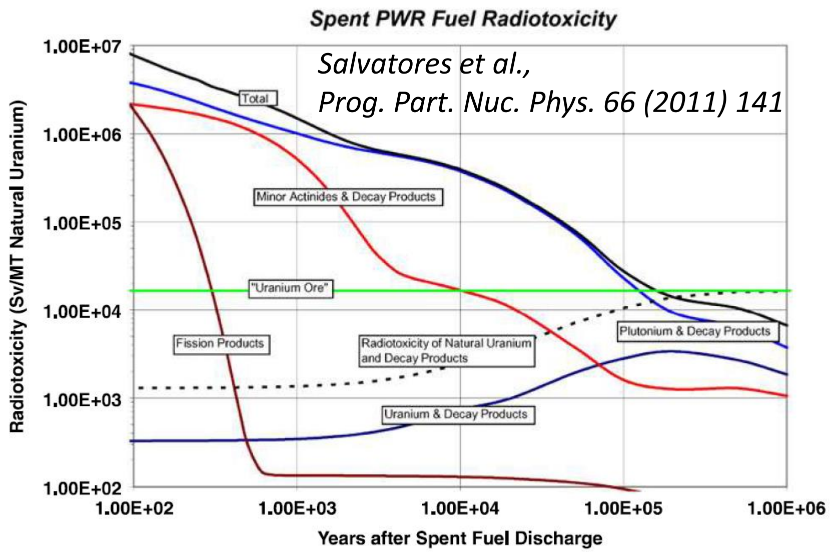
- SPATIAL: a comprehensive and thorough study of space-energy effects during reactor transients and their impact on reactivity monitoring, especially in power ADS
- SALMON: study of reactor core (re)loading monitoring

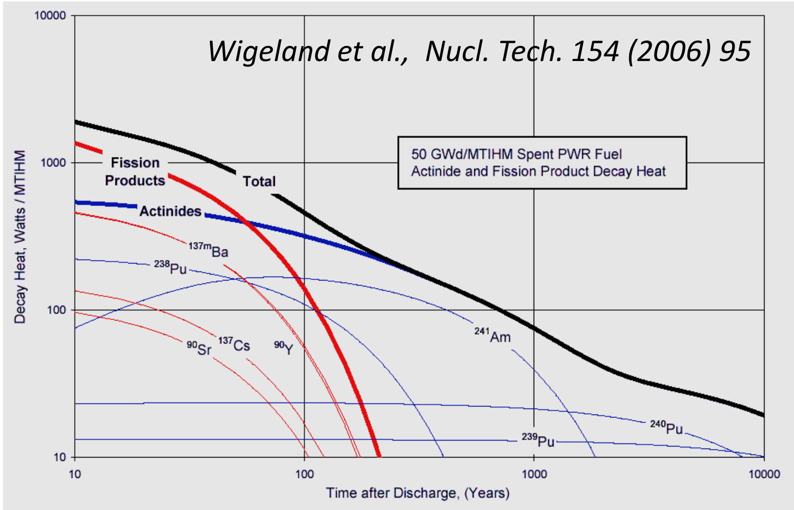
⇨ Both projects bear interests beyond pure ADS studies

⇨ Both projects would deliver new data of interest for the CNRS project of « common digital framework »

Presentation ends here

L'incinération des Actinides Mineurs





A long terme (t > 100 ans), les AM contribuent le plus à la radiotoxicité du combustible usé (une fois le Pu recyclé…)

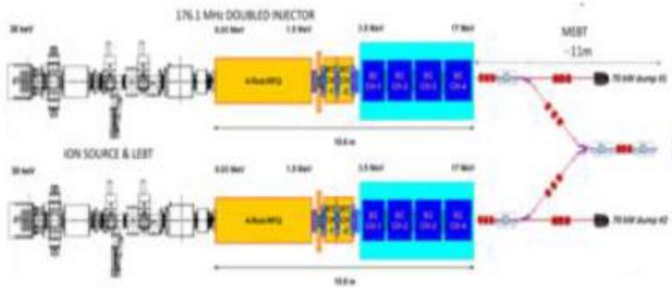
A long terme (t > 100 ans), l'américium est responsable de la majeure partie de la chaleur émise

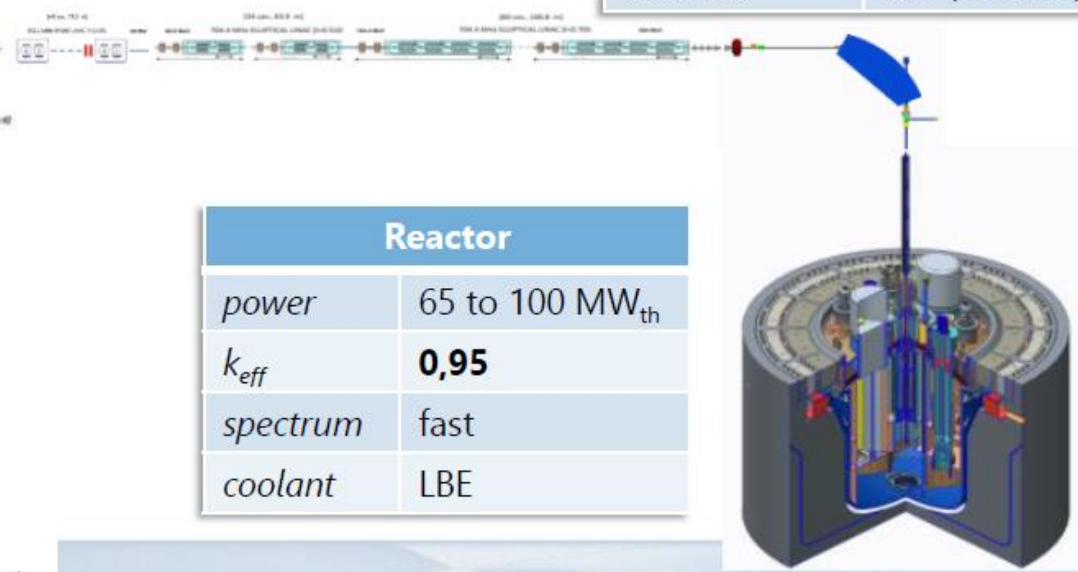
⇨ Incinération (fission) des AM dans un réacteur nucléaire

⇨ Réduction de la radiotoxicité des entreposages et augmentation de la capacité de stockage

The MYRRHA project

Power ADS driven by p accelerator
MOX fuel + Lead Bismuth Eutectic (LBE) as coolant

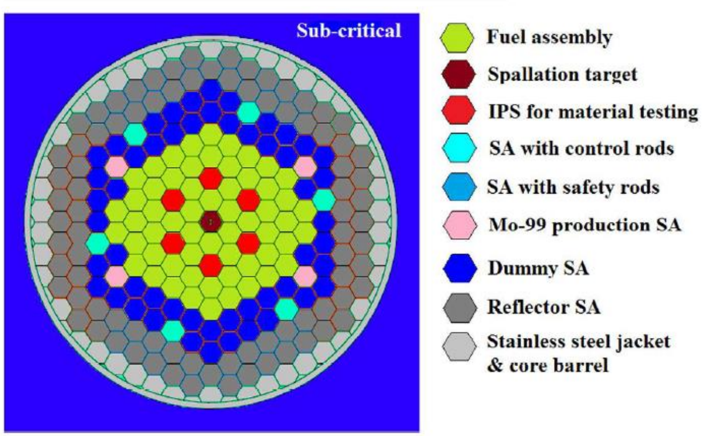




Target	
main reaction	spallation
output	$2{\cdot}10^{17}$ n/s
material	LBE (coolant)

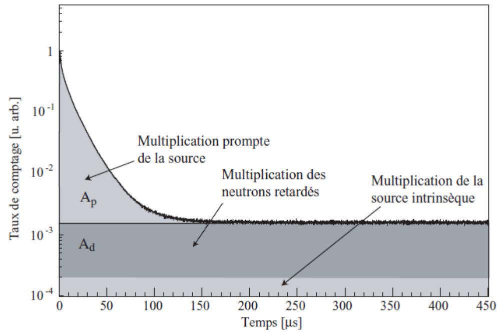
Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Reactor	
power	65 to 100 MW_{th}
k_{eff}	**0,95**
spectrum	fast
coolant	LBE



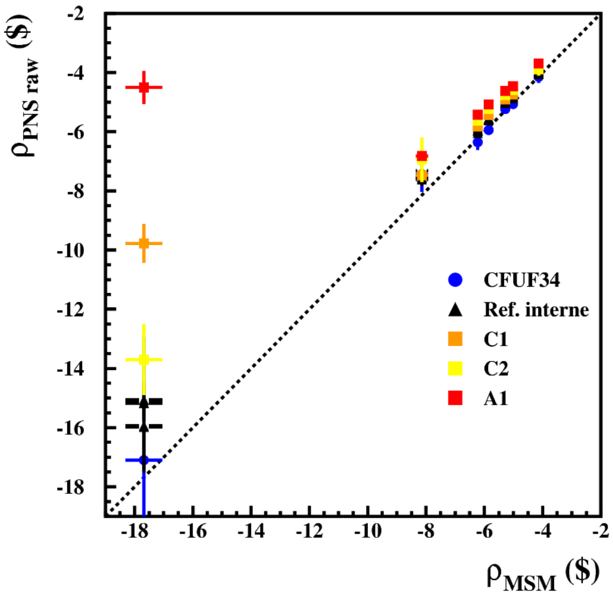
G. Van den Ende, TC-ADS 4 (2019)

Reactivity measurement in PNS experiments

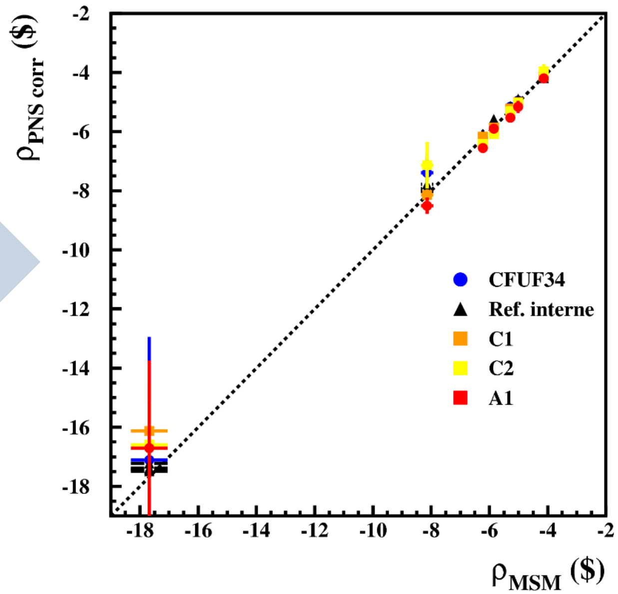


Area method: $$\frac{\rho}{\beta} = \frac{-A_p}{A_d}$$

Without space-energy factors



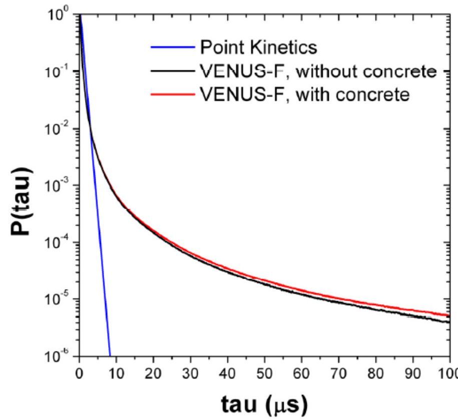
Space-energy factors included



N. Marie et al., en préparation

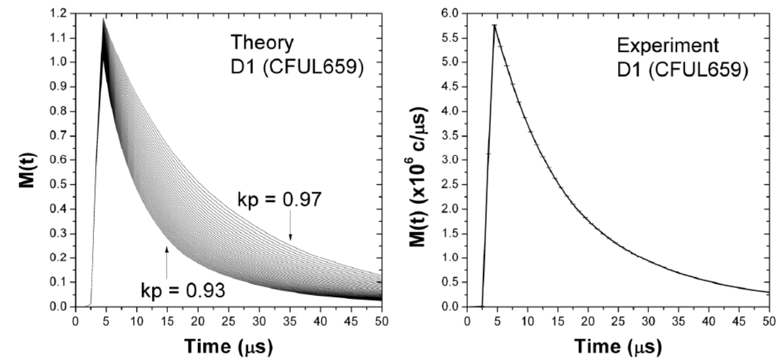
Very good agreement between reference values and Area results

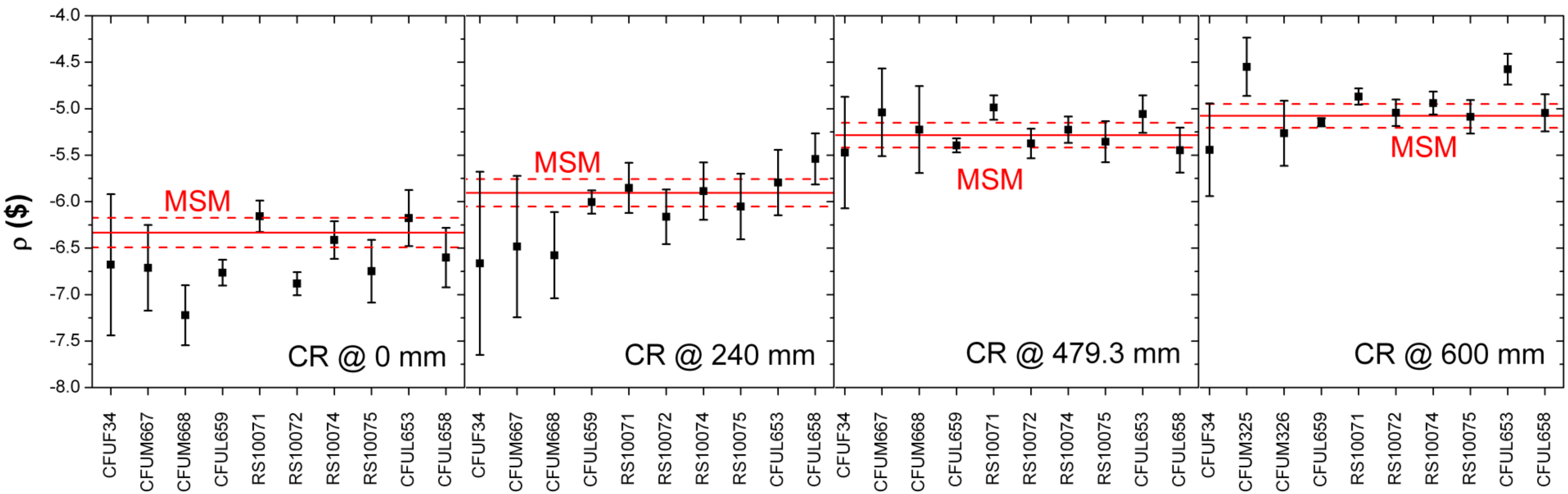
Méthode kp



$$W_{exp}(t) = \frac{\int_{t'=t_{min}}^{t} M_{exp}^{2}(t')dt'}{\left(\int_{t'=t_{min}}^{t} M_{exp}(t')dt'\right)^{2}}$$

Gros avantage : n'utilise que la décroissance prompte !





Chabod et al., PHYSOR 2014

Robustesse des facteurs spatio-énergétiques

Une estimation de réactivité robuste requiert :

- FSE peu sensibles à la géométrie du modèle
- Un moyen d'annuler la dépendance des FSE à la réactivité du modèle

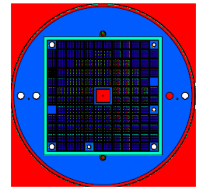
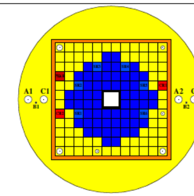
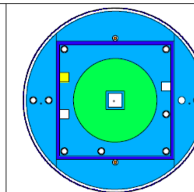
⇨ Double test :

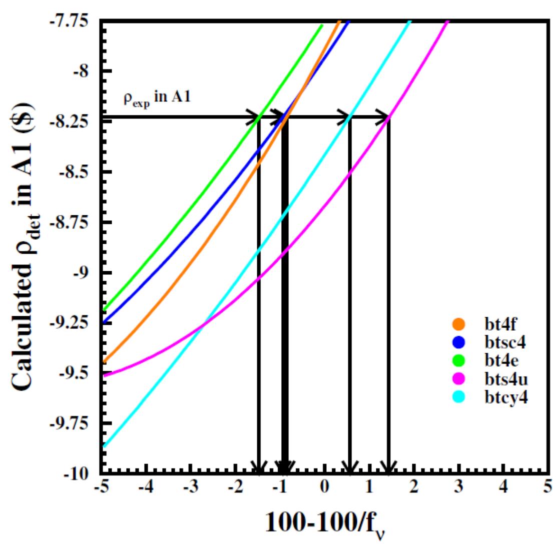
- Variations de géométrie
- Variations de réactivité du modèle

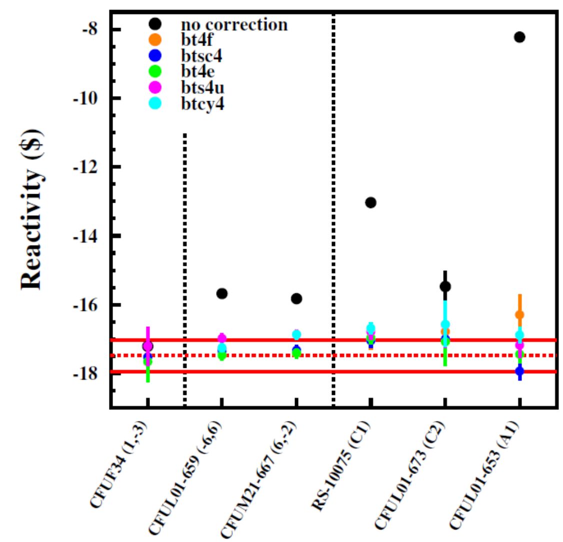
⇨ Bootstrapping

⇨ Propagation correcte des erreurs expérimentales

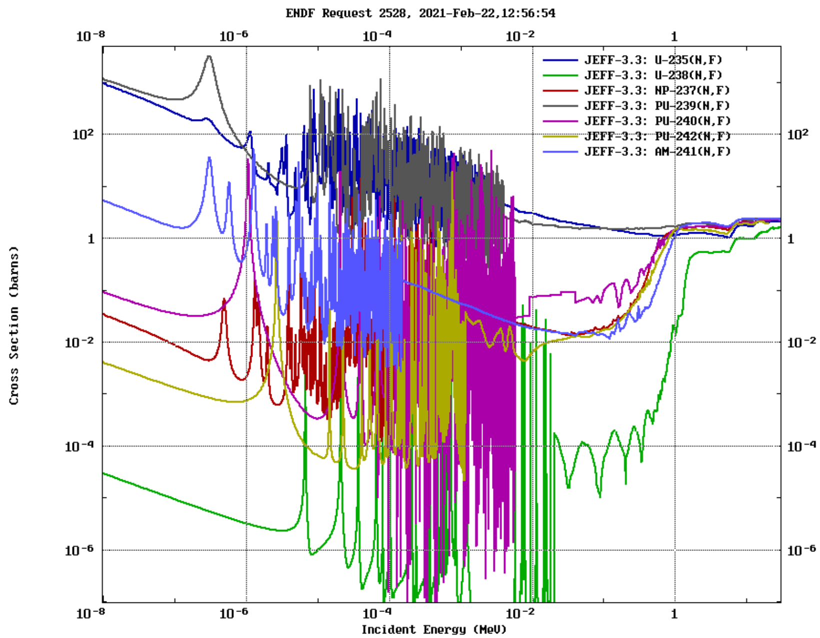
⇨ Tous les modèles donnent des FSE compatibles

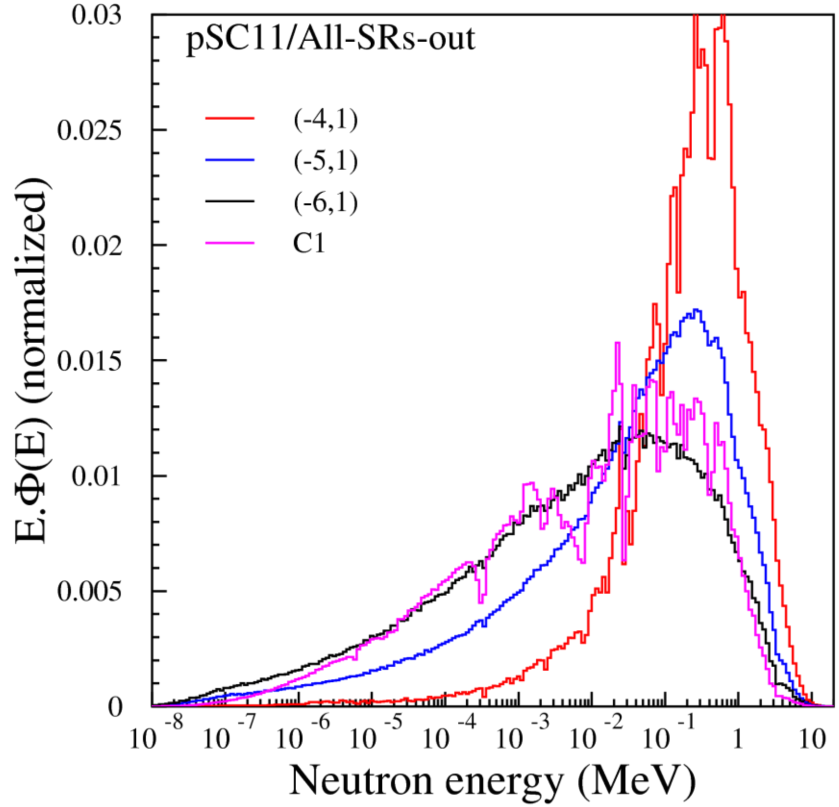
					
MCNP model	bt4f	btsc4	bt4e	bts4u	btcy4
Core geometry	heterogeneous		homogeneous		homogeneous
Data libraries	JEFF 3.1	JEFF 3.1	ENDF-B/VI	JEFF 3.1	JEFF 3.1
U enrichment (%)	30	30	30	28.8	30
Model β_{eff} (pcm)	742(4)	742(4)	746(4)	745(4)	748(4)
Model ρ (\$)	-15.0(1)	-16.5(1)	-15.2(1)	-19.4(1)	-17.7(1)





Fission cross-sections vs SC11 spectrum





Strong variations of energy spectrum in the SC11-like configuration of VENUS-F
⇨ strong variations of spectral indices as a function of position expected