JUNO meeting 2022 @ Polimi

A Monte Carlo model for reactor antineutrino prediction

POLITECNICO
MILANO 1863

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Lorenzo Loi

Objective

Propose a model for the reactor antineutrino spectrum prediction, adopting the summation method and identifying some features which increase the output's reliability

Reactor antineutrino model: summation method

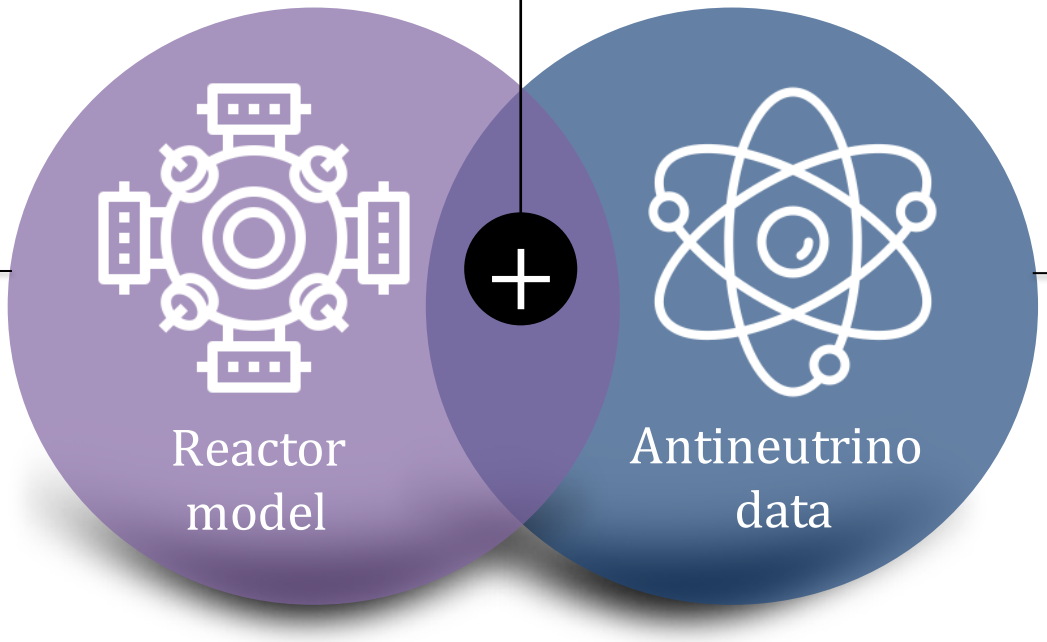
$$S_{\bar{\nu}}^{tot}(E,t) = \sum a_i(t)\, S_{\bar{\nu}}^{i}(E)$$

$$a_i(t) = \frac{A_{\beta,i}}{A_{\beta,tot}}$$

$$S_{\bar{\nu}}^{i}(E)$$

Serpent

Through an assembly Monte Carlo simulation it is possible to know the beta emission intensity for each nuclide in the system



BetaShape

Through a numerical solution of the Dirac equation, it allows to build a library which contains all the antineutrino spectra under exam

Which features increase the robustness of the neutronic model?

$$S_{\bar{\nu}}^{tot}(E,t) = \sum a_i(t)\, S_{\bar{\nu}}^{i}(E)$$

Post Irradiation Experiments (PIE)

The isotopic concentration of a given nuclides' set are measured after an irradiation time

Legend

- $S_{\bar{\nu}}^{tot}$: total spectrum
- i : isotope
- a_i : isotopic activity
- $S_{\bar{\nu}}^{i}$: isotopic spectrum

② Reactor model: Takahama-3 experiment

Takahama-3
Main features

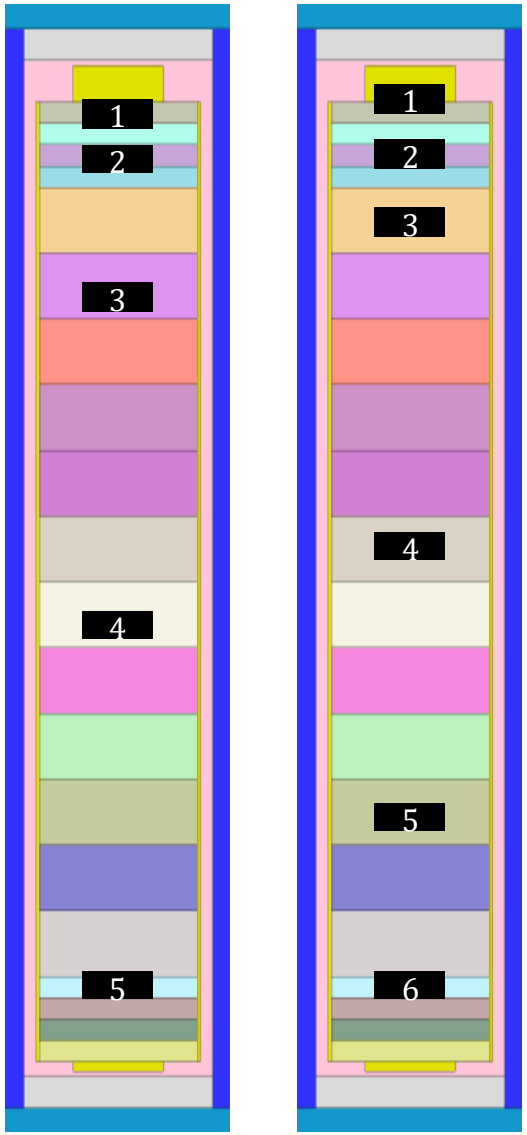
- 17x17 PWR fuel assembly design;
- Data were collected from sampling two rods at the end of an irradiation period;
- It measures more than 35 nuclides' species;

Z	Isotope
U	234, 235, 236, 238
Pu	238, 239, 240, 241, 242
Am	241, 242m, 243
Cm	242, 243, 244, 245, 246, 247
Nd	143, 144, 145, 146, 148, 150
Sm	147, 148, 149, 150, 151, 152, 154
Cs	134, 137
Ce	144
Eu	154
Sb	125
Ru	106

Isotope	Measurement Technique	Maximum standard deviation
^{234}U	IDMS	1 %
^{235}U, ^{238}U	IDMS	0.1 %
^{236}U	IDMS	2 %
^{238}Pu	IDMS	0.5 %
^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu	IDMS	0.3 %
Nd, Sm isotopes	IDMS	0.1 %
^{241}Am, ^{243}Cm, ^{244}Cm	αs, MS	2 %
^{243}Am, ^{246}Cm	αs, MS	5 %
^{242m}Am, ^{242}Cm, ^{247}Cm	αs, MS	10 %
Gd isotopes	MS	0.1 %
^{237}Np	αs	10 %
^{134}Cs, ^{137}Cs, ^{154}Eu	γs	3 %
^{106}Ru	γs	5 %
^{125}Sb , ^{144}Ce	γs	10 %

② Reactor model: rod geometry

SF95 SF97



Assembly	Sample ID	Enrichment (wt % ^{235}U)	Axial location [cm]	Local Burnup [MWd/kg]
SF95	SF95-1	4.11	4.12	14.30
	SF95-2		20.2	24.35
	SF95-3		72.2	35.53
	SF95-4		200.2	36.69
	SF95-5		340.2	30.40
SF97	SF97-1	4.11	0.40	17.69
	SF97-2		19.1	30.73
	SF97-3		46.8	42.16
	SF97-4		168	47.03
	SF97-5		276.7	47.25
	SF97-6		339.7	40.79

Reactor model: validation results

- i = isotopic concentration
- j = axial sampling position
- C = calculated concentration
- E = experimentally measured concentration

Calculated-to-experimental ratio

$$R_j^i = \frac{C_j^i}{E_j^i}$$

$$\sigma_{j,i}$$

Monte Carlo

Adopting $n = 4 \cdot 10^5$, $c_{in} = 100$, $c_{ac} = 100$, the r.s.d. remains at a subpercent level

Known
Negligible

Experimental

The measurement techniques report a relative standard deviation which vary in the range 0.1% - 10%

Known
Not negligible

Systematic

Missing geometric and operational informations

- Reflector's data
- Shuffling procedure

Unknown
Not negligible

Reactor model: validation results

- i = isotopic concentration
- j = axial sampling position
- C = calculated concentration
- E = experimentally measured concentration

Calculated-to-experimental ratio

$$R_j^i = \frac{C_j^i}{E_j^i} \pm \sigma_{j,i}$$

$\sigma_{j,i}$ → consequences

- The C/E's uncertainty coincides with the experimental standard deviation:

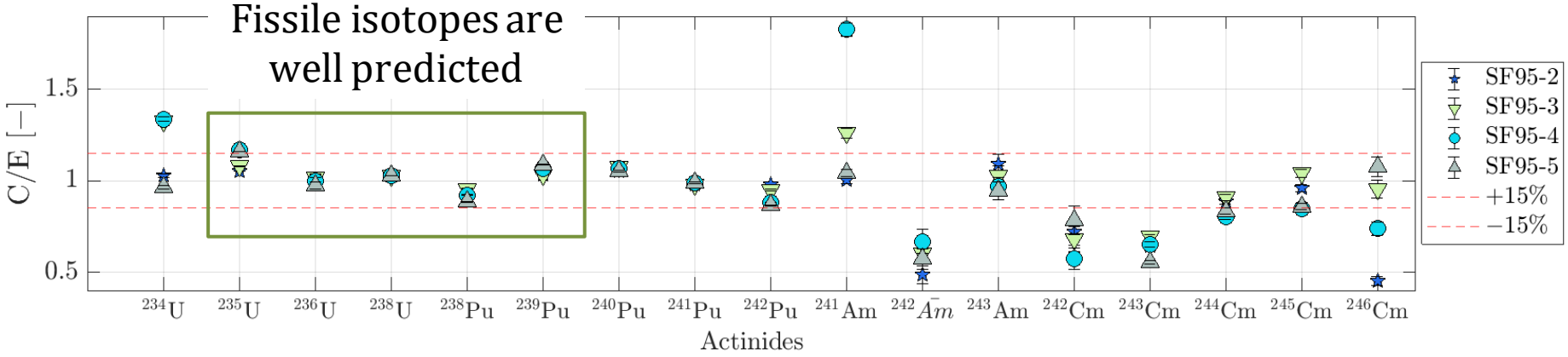
$$\sigma_{j,i} \triangleq \sigma_{exp}$$

- The systematic contribution is taken into account placing an *acceptance band* at $\pm$ 15% from the unity. Also, the outermost samples (SF95-1, SF97-1) are not considered.

Reactor model: validation results

$$\text{Success Rate} = \frac{\text{N° of C/E inside the band}}{\text{Total number of C/E}}$$

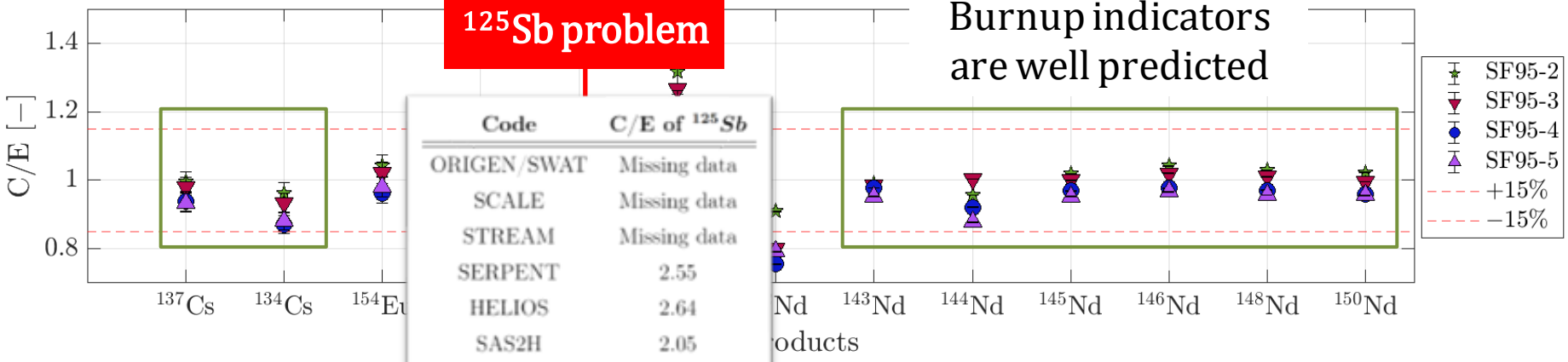
Fissile isotopes are well predicted



^{125}Sb problem

Code	C/E of ^{125}Sb
ORIGEN/SWAT	Missing data
SCALE	Missing data
STREAM	Missing data
SERPENT	2.55
HELIOS	2.64
SAS2H	2.05
This work	2.5

Burnup indicators are well predicted

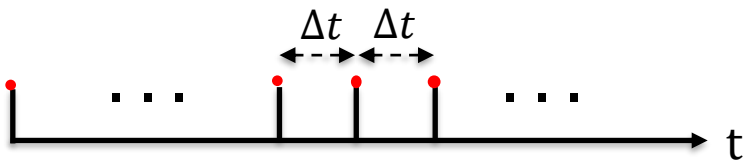


② Reactor model: sensitivity analysis

Neutronic library

Two different libraries are compared looking at which is the most viable

- ENDF/B-VII.0
- JEFF-3.1.1



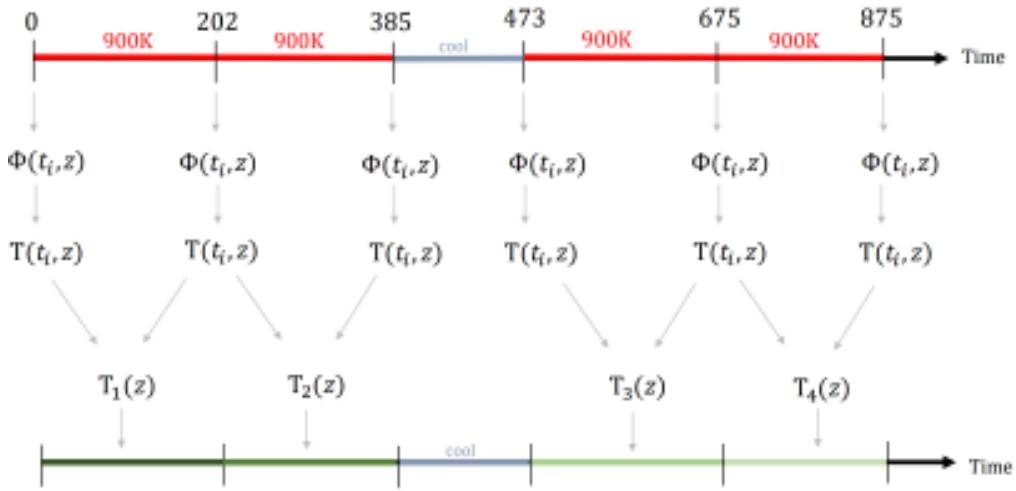
Time sensitivity

During a burnup cycle, the Boltzmann/Bateman equation is solved at discrete time instants.
This work compares three discretization patterns:
$\Delta t = 25$ [d], $\Delta t = 50$ [d] and $\Delta t = 100$ [d]

Temperature sensitivity

The temperature plays a very imporant role for the microscopic cross section value.
This work adopts two temperature treaments:

- T const @ 900 [K] in space and time
- T(t,z) tailored on the former case



Reactor model: success rate comparison

Sensitivity	SF95
ENDF/B-VII.0 : JEFF-3.1.1	0.758 : 0.708
$\Delta t_1 : \Delta t_2 : \Delta t_3$	0.7 : 0.7 : 0.68
$T\|_{900K} : T(z,t)$	0.68 : 0.76

Sensitivity	SF97
$T\|_{900K} : T(z,t)$	0.753 : 0.726

ENDF > JEFF

$\Delta t_1 = 25$ and $\Delta t_2 = 50$ share the same SR

The temperature imposition increases the SR by +8%

The temperature imposition decreases the SR by -2.5%

Antineutrino data: BetaShape

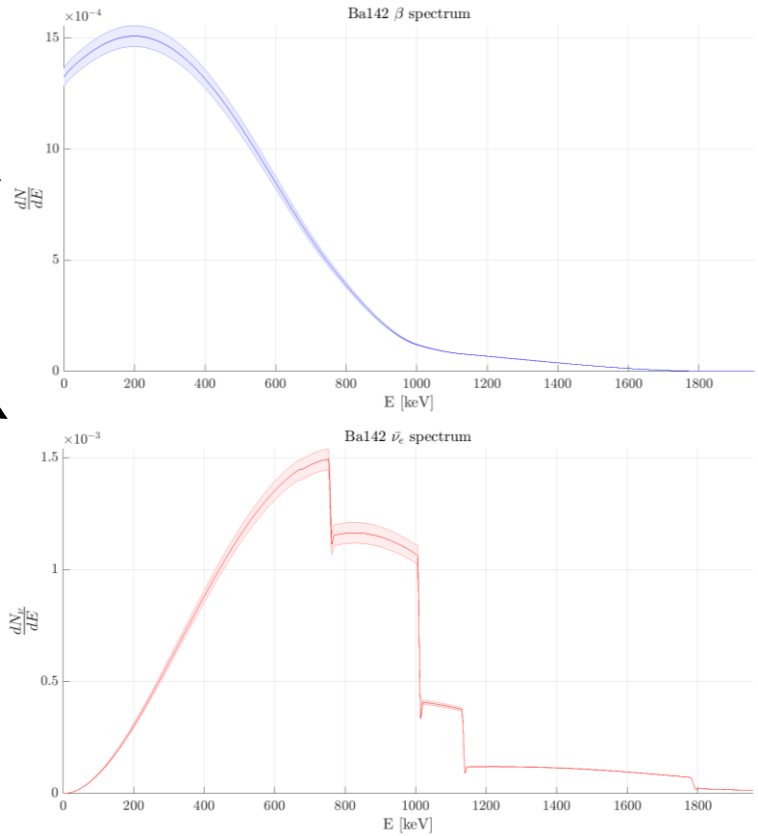
$$S_{\bar{\nu}}^{tot}(E,t) = \sum a_i(t)\, S_{\bar{\nu}}^{i}(E)$$

ENSDF file → BetaShape

For β^-, β^+, EC processes

[Nuclear structure and decay data]

- Rose/Büring screening
- Radiative corrections
- Availability to use experimental/theoretical shape factors
- Add the (anti)neutrino distribution
- Manual choice of energy binning



Antineutrino library

How many and which nuclides buildup the antineutrino spectrum for a PWR?

Total number of isotopes in the fuel
~ 1500 isotopes

Check the radioactive decay process

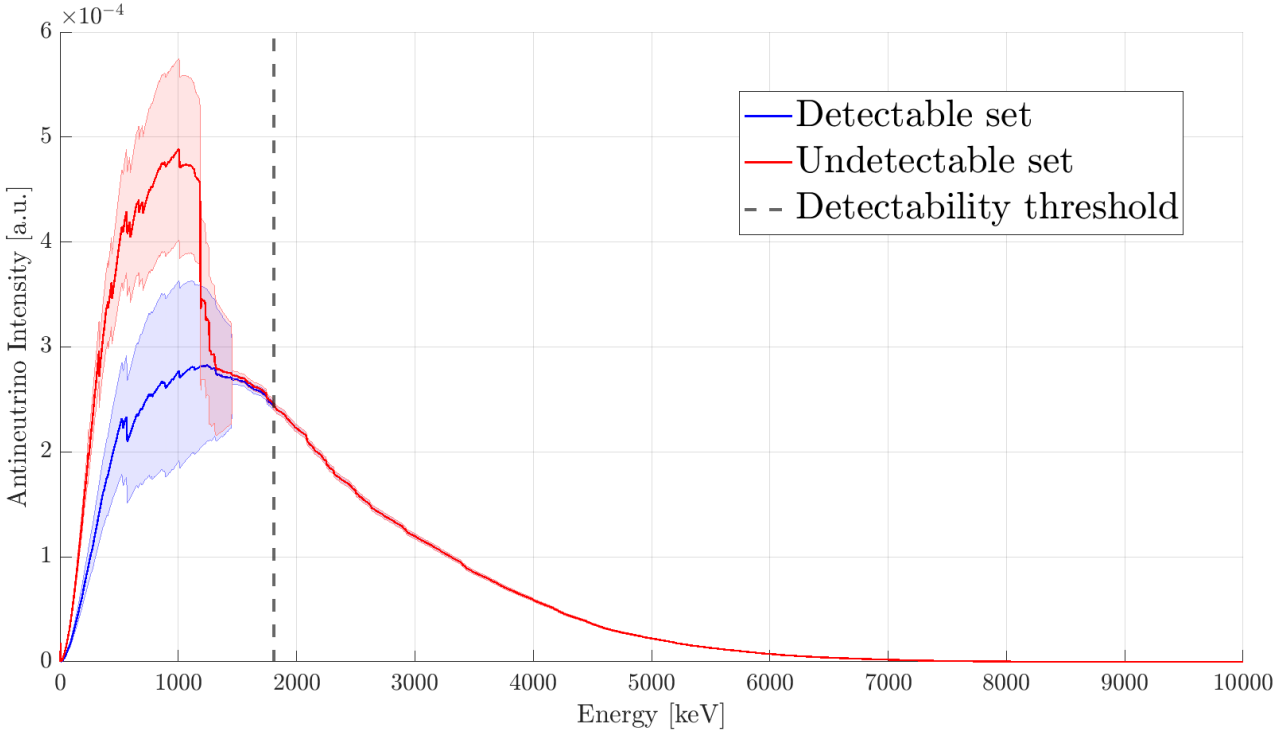
Total number of beta emitters
~ 1000 isotopes

Threhsold at 0.1%

Important isotpes
182 isotopes

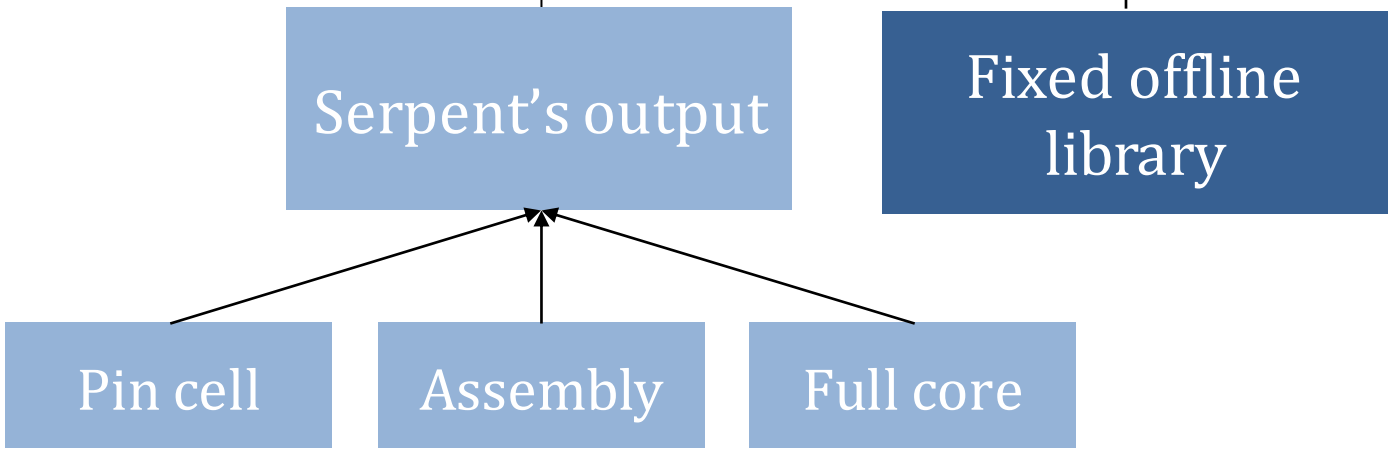
1.806 [MeV] discrimination

Detectable important isotopes
144 isotopes



Scalability of the model

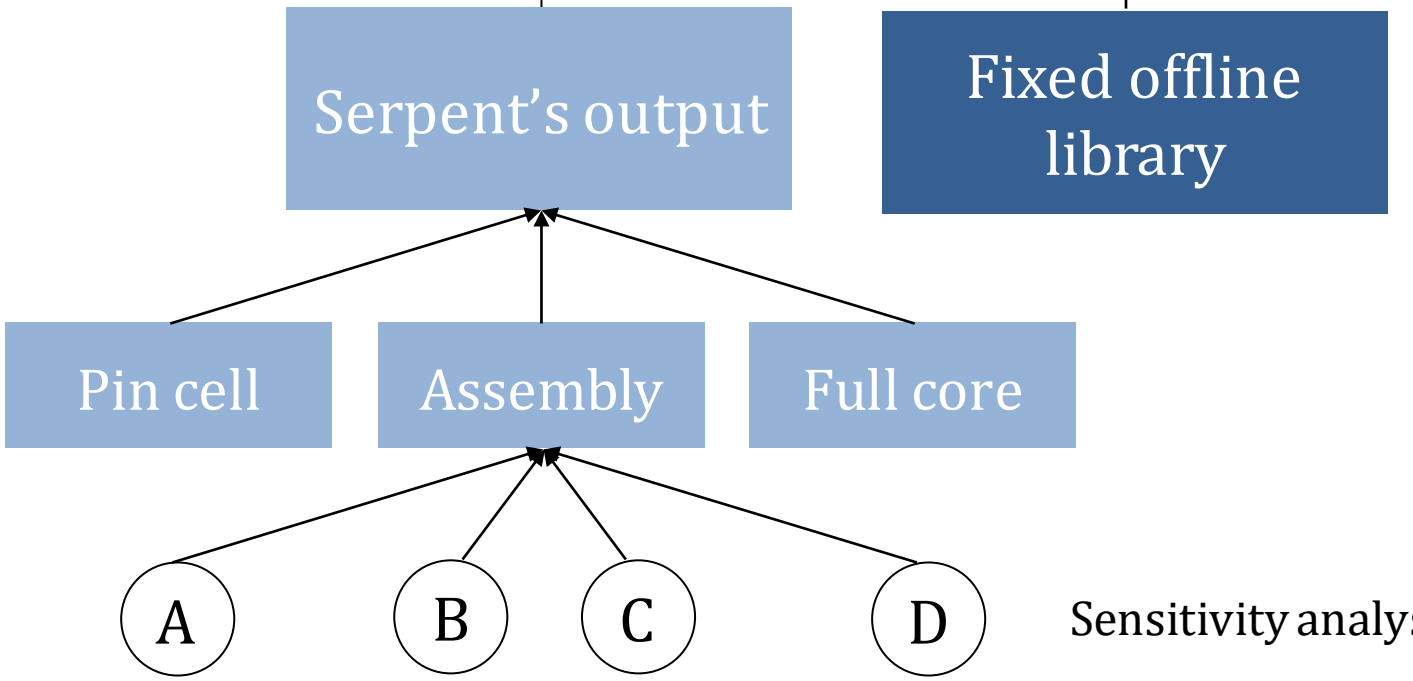
$$S_{\bar{\nu}}^{tot}(E,t) = \sum a_i(t)\, S_{\bar{\nu}}^{i}(E)$$



Adopting this structure it's easy to evaluate the total spectrum from different reactor's models

Scalability of the model

$$S_{\bar{\nu}}^{tot}(E,t) = \sum a_i(t)\, S_{\bar{\nu}}^{i}(E)$$



Sensitivity analysis

Total spectrum: sensitivity analysis

In order to test the internal coherence of the model, a series of perturbations were considered

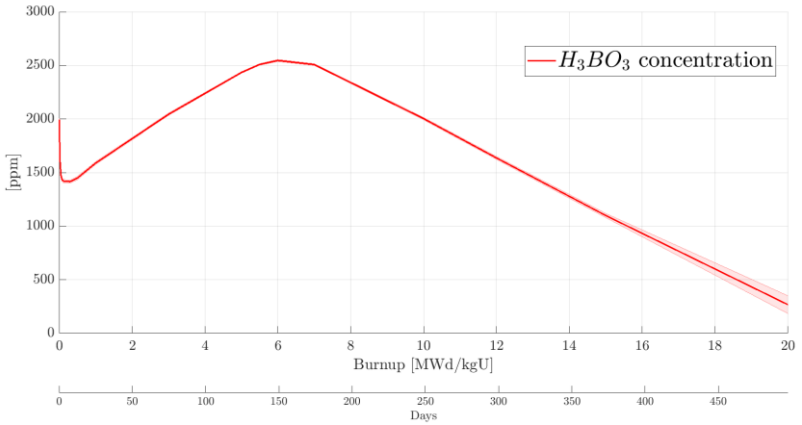
Solver's figure of merit

A

K-eigenvalue

B

Critical boron density



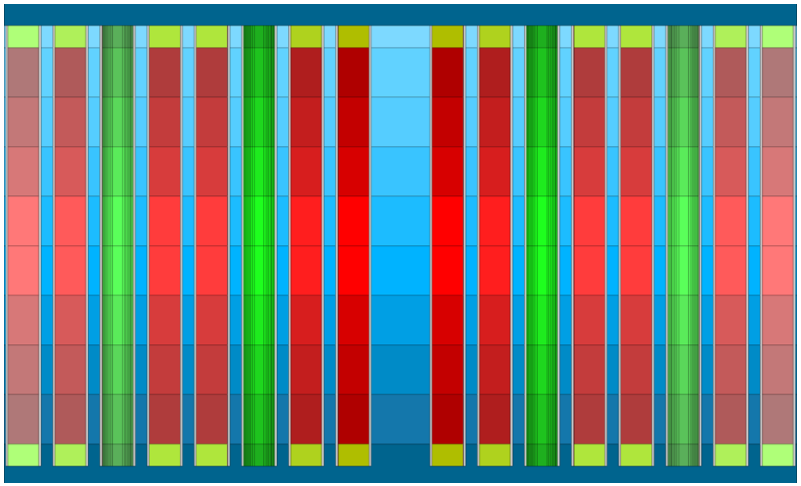
Temperature treatment

C

Constant temperature

D

Axial and radial temperature profile



Total spectrum: principal results

	k-eigenvalue	Critical Density Iteration
Uniform Temperature	A	B
Temperature Mesh	C	D

→ AB, AC, AD, BC, BD, CD

Total spectrum: principal results

	k-eigenvalue	Critical Density Iteration
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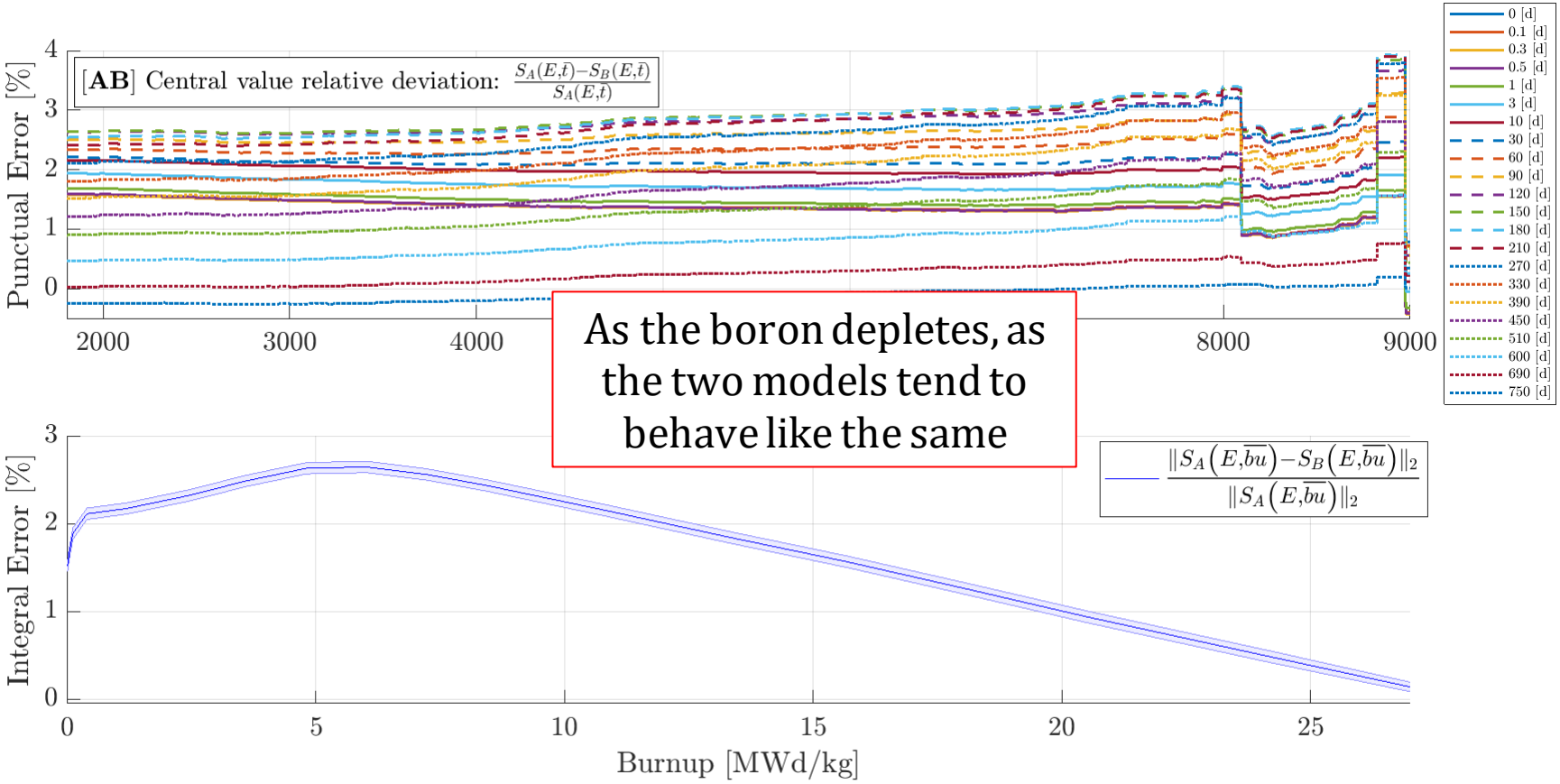

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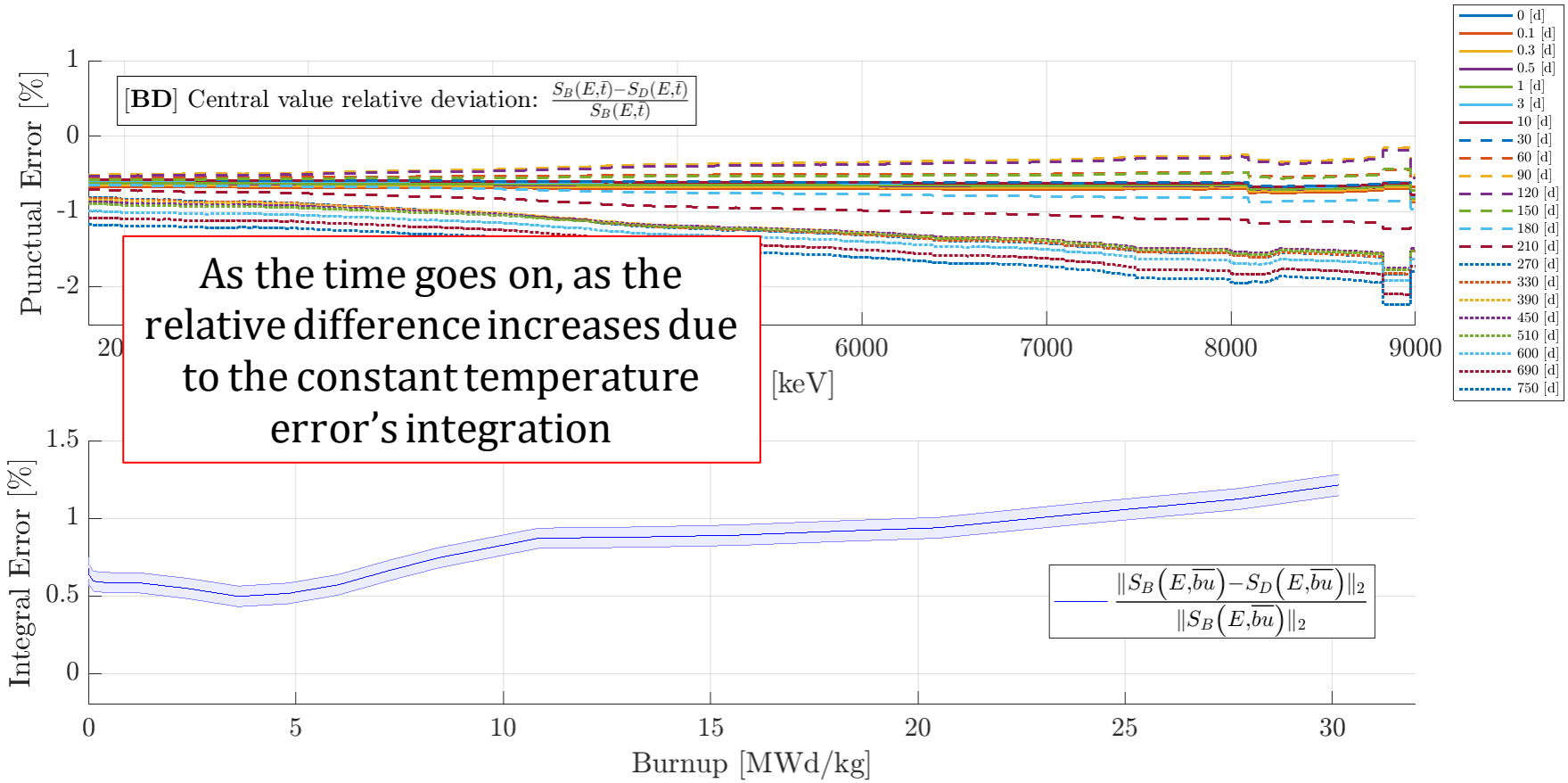

5 Conclusions and future developments

The internal coherence of an antineutrino prediction model based on the coupling of Serpent and BetaShape has been verified for what concern the boron control and the temperature treament

1

The validation process against a PIE's dataset shows how the choice of neutronic library (+5%) and temperature mesh (+8%) play a macroscopic role in the benchmark

2

3

In the future:

- A full core simulation should be considered
- A validation of the model agains total antineutrino spectrum will be performed

Thank you!

Q&A