PETALE@CROCUS

Analysis and feedback on INDEN

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EPFL
cea

Laboratory for Reactor Physics and Systems Behaviour

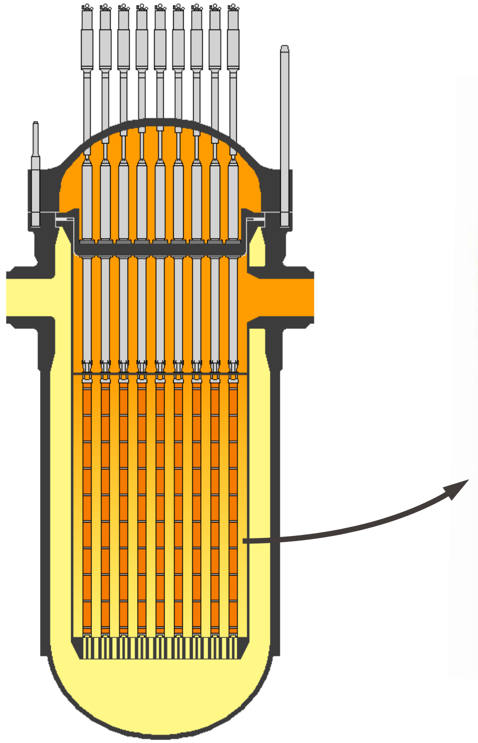
**INDEN Consultancy meeting
December 2024**

Objective: stainless steel nuclear data

Provide new constraints in the MeV-range and above for stainless steel nuclear data

- Fission: heavy reflectors (GEN-III PWR)
- Fusion: 14 MeV neutrons
- Accelerators: structures activation

Collaboration between CEA & EPFL



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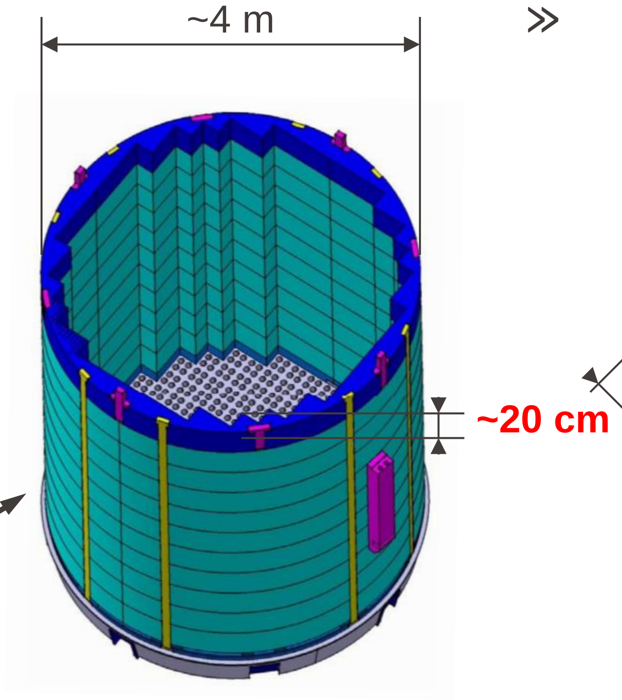

EPR heavy reflector

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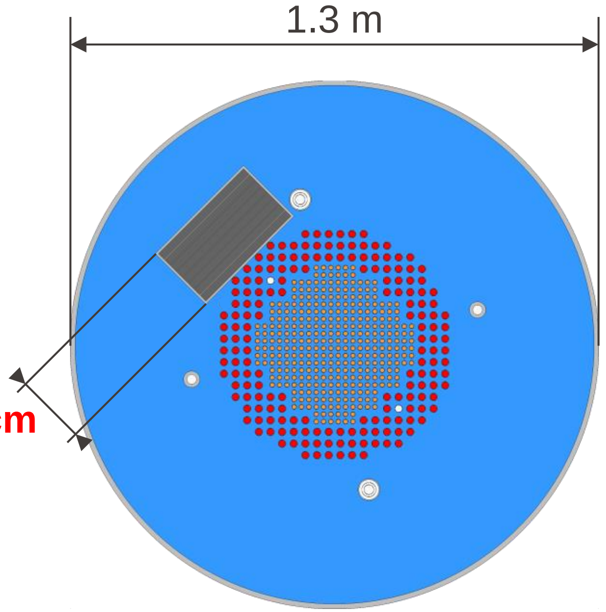


Cross section of the CROCUS reactor core for PETALE

The CROCUS reactor

Reactor type

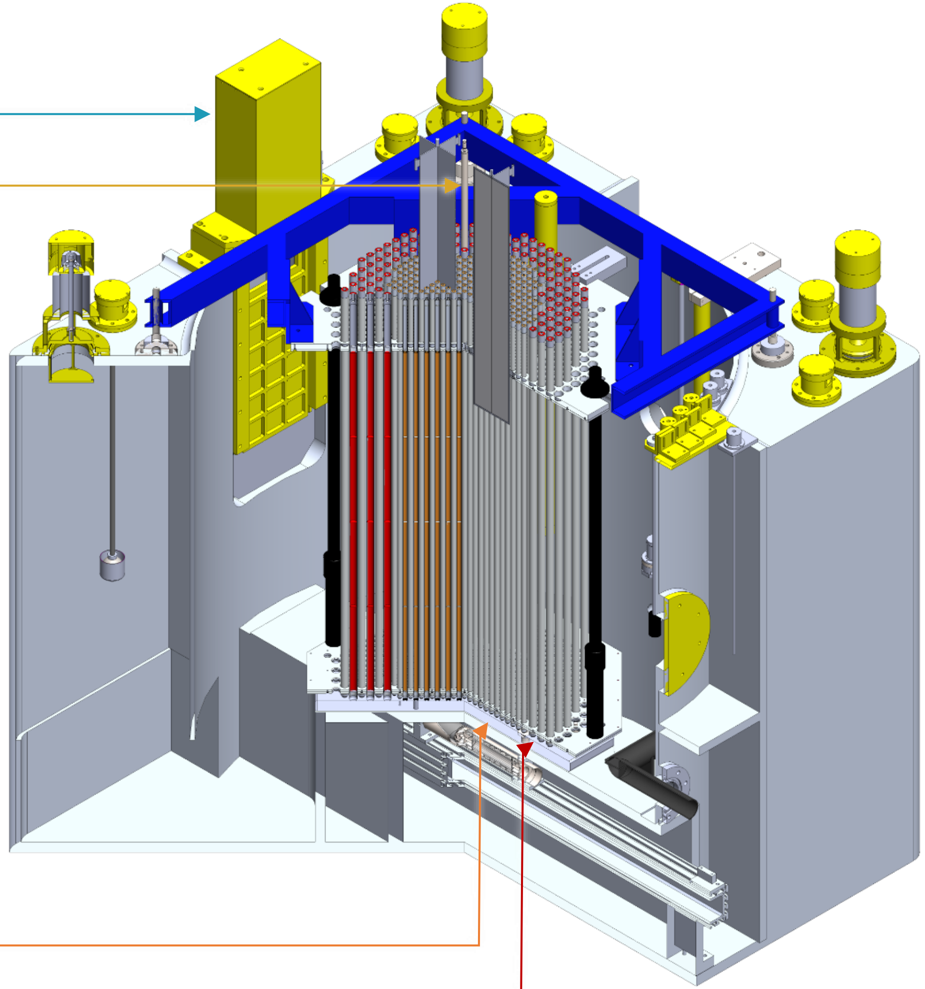
- LWR with partially submerged core
- Room T (controlled) and atmospheric P
- Forced water flow (160 $l.min^{-1}$)

Operation

- 100 W (zero-power reactor)
- i.e., maximum 2.5×10^{9} $cm^{-2}.s^{-1}$
- Control: B_4C rods and spillway

Core

- ⌀60 cm/100 cm, 2-zone
- Inner: 336 UO_2 1.806 wt% 1.837 cm
- Outer: 176 U_{met} 0.947 wt% 2.917 cm

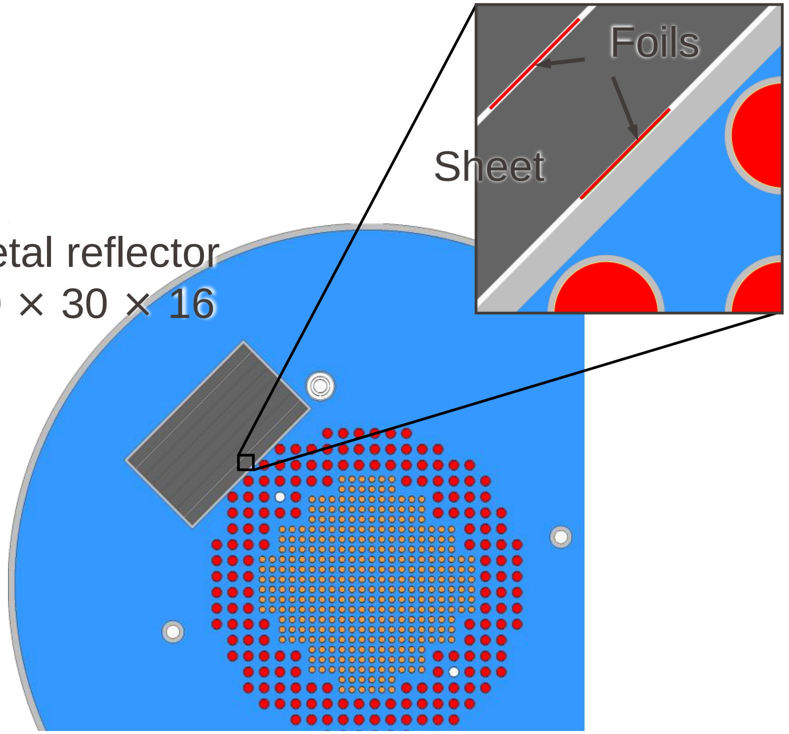


U. Kasemeyer *et al.*, "Benchmark on Kinetic Parameters in the CROCUS Reactor," in IRPhE, no. 4440, OECD, Ed. 2007, p. 94
J. M. Paratte *et al.*, "A benchmark on the calculation of kinetic parameters based on reactivity…," Ann. Nucl. Energy, vol. 33, no. 8, pp. 739–748, May 2006

The PETALE program in CROCUS

CEA-EPFL program on stainless-steel heavy reflectors carried out **from Sep. to Dec. 2020**

- 4 selected materials:
  - Stainless steel 304 L, iron, nickel, and chromium
  - Strong emphasis on estimation of covariances

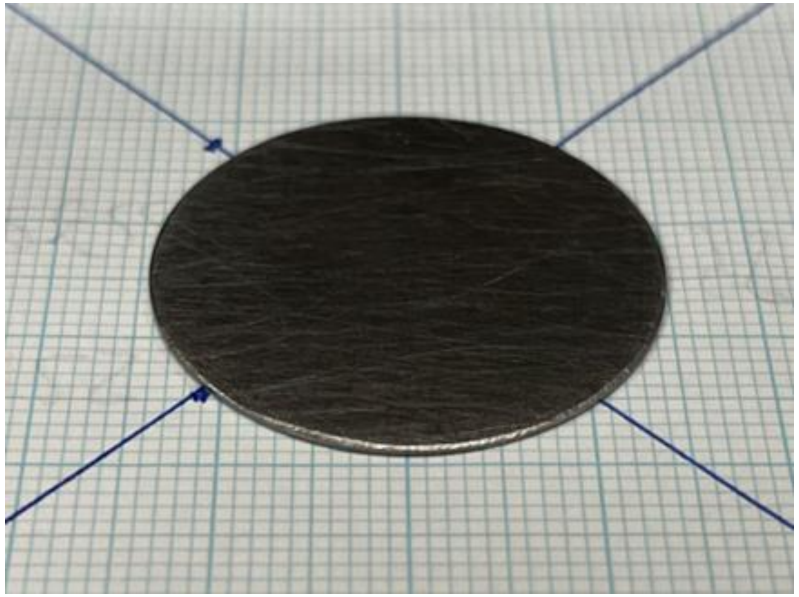


- **Neutron transmission** experiments
  - 21 experiments (one repetition)
  - Activation dosimeters between reflector sheets
  - Output: **dosimeters reaction rates**

- **Reactivity worth** experiments
  - 5 dedicated experiments: full water, then each material
  - Output: **effect on criticality** of the metallic sheets

- **Analysis status**
  - High-fidelity analysis reaching its end
  - Collaboration work for **benchmarking** in **ICSBEP** is starting (US DOE funding)
    - with Prof. Siefman @Berkley and C. Percher @LLNL

Analysis of Spectrometry Data : Dosimetry Setup



- CERVIN platform: 4 HPGe spectrometers
  - Dosimetry platform developed by the CEA for usage at EPFL
  - One fully shielded reference HPGe: Fürggen
  - 3 partially shielded HPGe: Hörnli, Lion & Zmutt
- 7 types of activation dosimeters
  - With different energy ranges
- More than 400 dosimeters measured

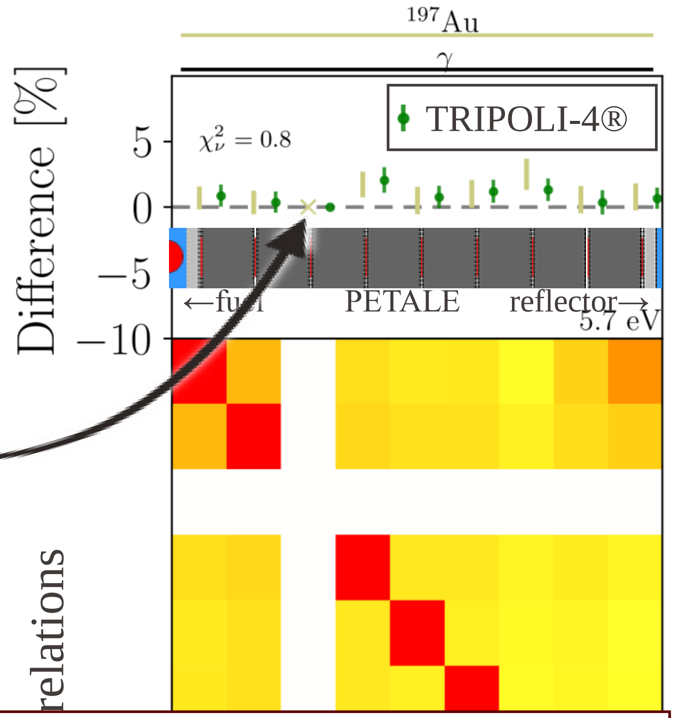
High experimental uncertainties

Material	^{115}In	^{197}Au	^{115}In	^{58}Ni	^{54}Fe	^{56}Fe	^{27}Al
Reaction	n, γ	n, γ	n, n’	n, p	n, p	n, p	n, α
Median Energy of Activation	1.7 eV	5.7 eV	2.0 MeV	3.6 MeV	4.1 MeV	7.6 MeV	8.7 MeV

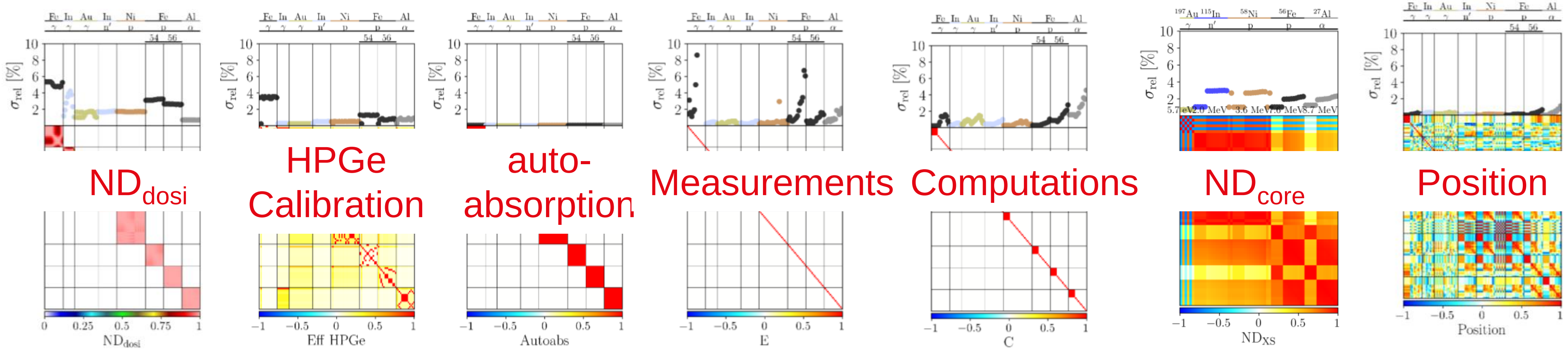
Computational Methods

Monte Carlo neutron transport simulation

- Serpent2 and Tripoli-4® in agreement
  - For readability only Serpent2 presented
- Dosimetry using the IRDFF-II library
- Normalization by the 3rd dosimeter (default)
- Reduced χ^2 statistic in preparation of future work
  - $\chi^2_\nu = Res^T \underline{\underline{Cov}}^{-1} Res / \nu$
- Covariances propagation



Main uncertainties included



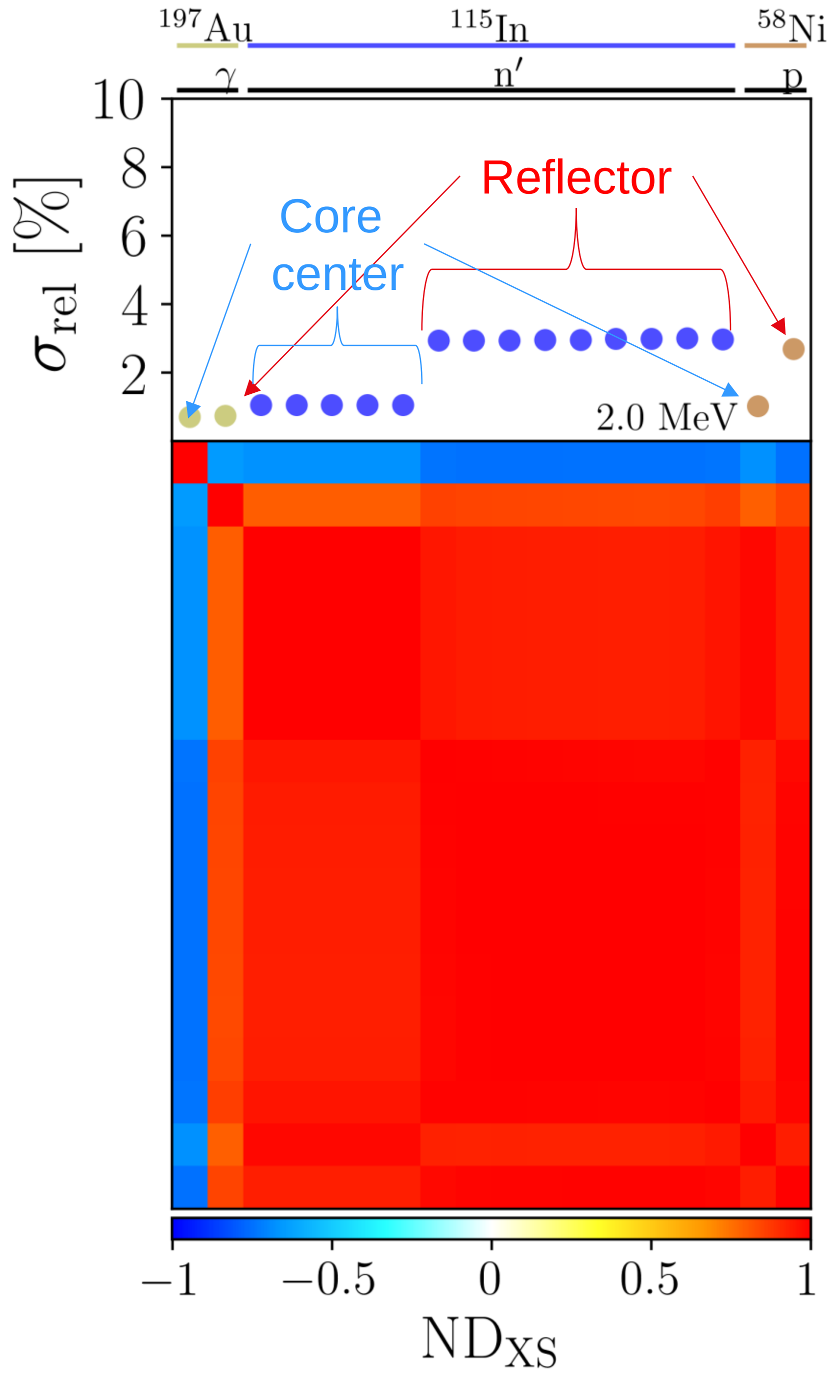
Core XS uncertainty

Monte Carlo neutron transport simulation

- Perturbed XS:
  - Isotopes: ^{27}Al, ^{1}H, ^{16}O, ^{235}U, ^{238}U
  - Mt: 2, 4, 18, 102
  - Multiplicity
- Estimated with 66 Serpent2 simulations
- Dosimetry using the IRDFF-II library
- Use larger virtual dosimeters in the reflector
  - Increase in convergence speed

Results

- Strong positive correlations in the reflector
  - Expected results
- Negative correlations between core center thermal dosimeters and other dosimeters
  - Mild with core center fast dosimeters
  - Strong with reflector dosimeters

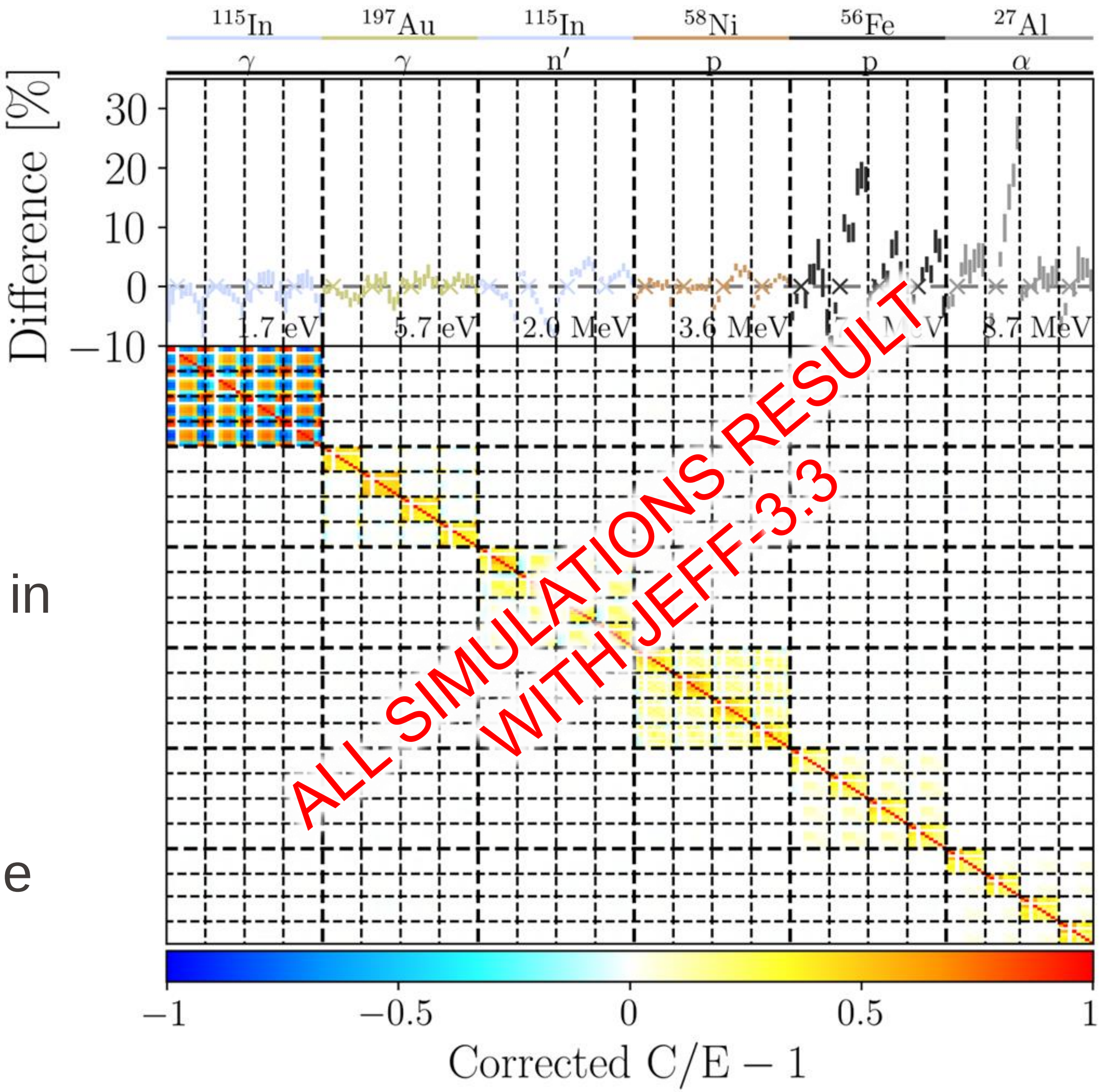


PETALE Results:

Simulations of the transmission experiments

- All cases performed with JEFF-3.3
- All mean values
- Position and core XS uncertainties in progress

- Additional simulations with cross-sections of JEFF-4T3/INDEN for the reflector



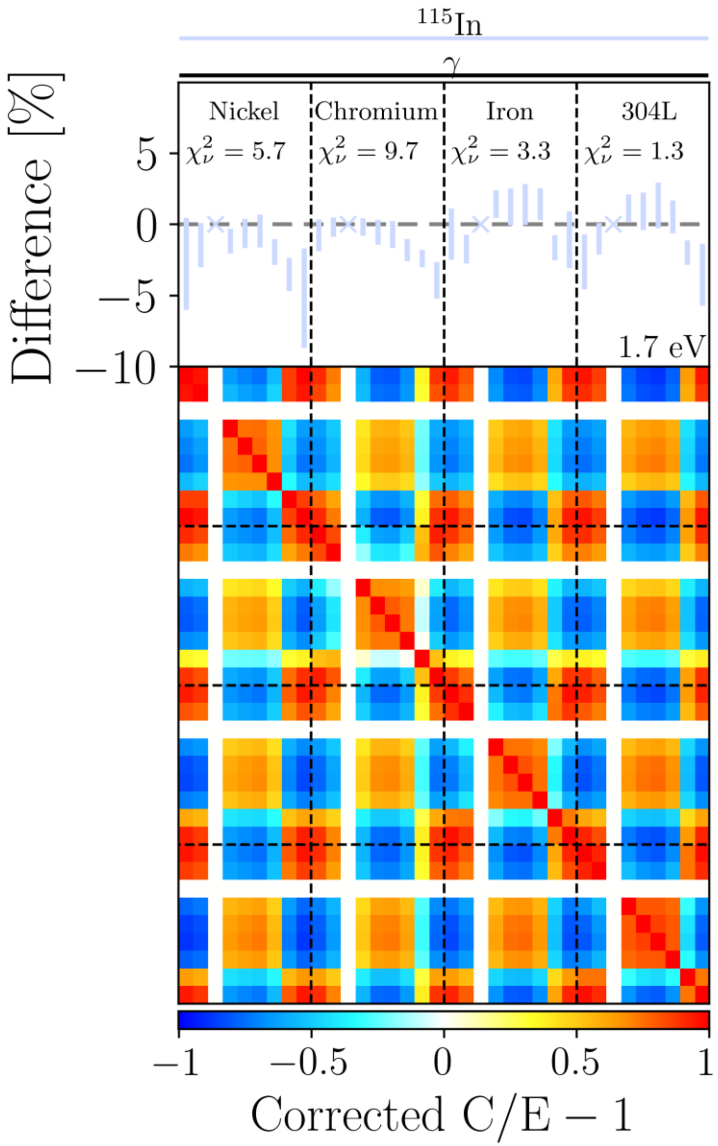
Results : All Reflectors

Same as April

Simulations of the transmission experiments

- XS from JEFF-3.3
- $^{115}In(n,g)$ dosimeters
  - Median energy of activation ~1.7 eV
- Decreasing trends for nickel and chromium
- No clear trends for iron and steel
- Pattern due to the spectrum hardening and dosimetry XS covariances

"Near thermal" range



Results : All Reflectors

Same as April

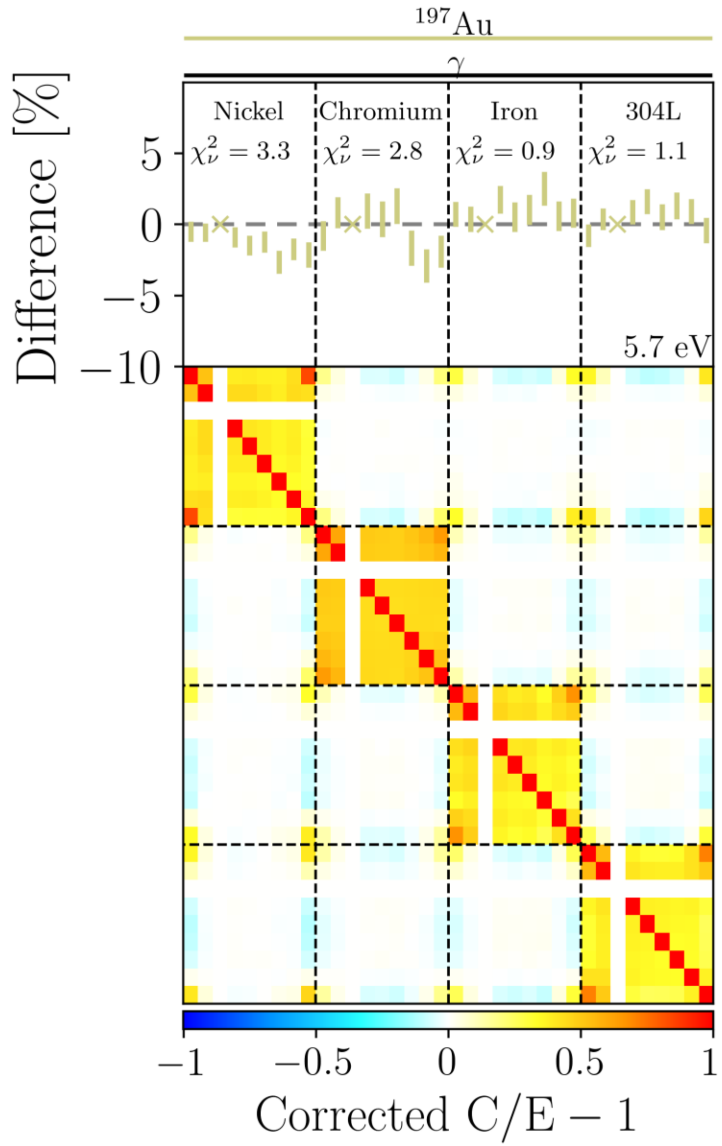
Simulations of the transmission experiments

- XS from JEFF-3.3

- ^{197}Au(n,g) dosimeters
  - Median energy of activation ~5.7 eV

- Decreasing trends for nickel
- Thickness effect for chromium
- Good agreement for iron and steel

"Near thermal" range



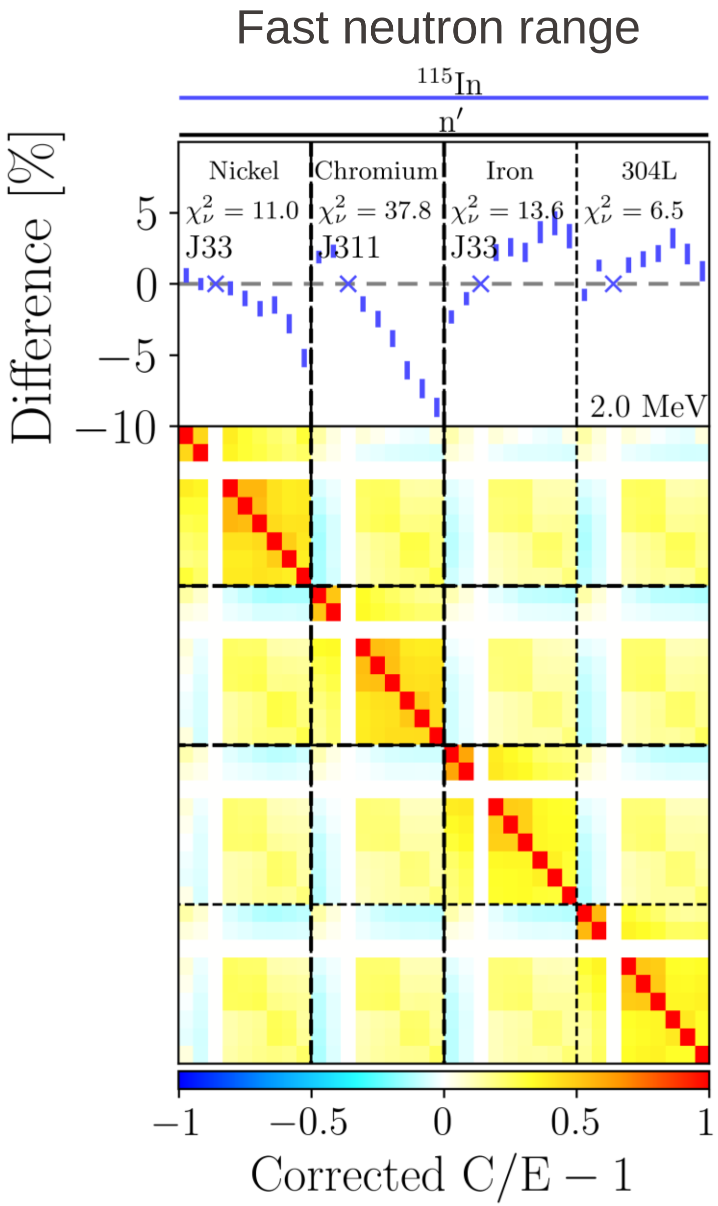
Results : All Reflectors

Simulations of the transmission experiments

- XS from JEFF-3.3

- ^{115}In(n,n') dosimeters
  - Median energy of activation ~2 MeV

- Opposing trend between iron and the other alloy component
  - Over-reflection of the neutron for nickel and chromium
  - Over-transparency of the iron
  - Mild over-transparency for stainless steel (304L)



Results : All Reflectors

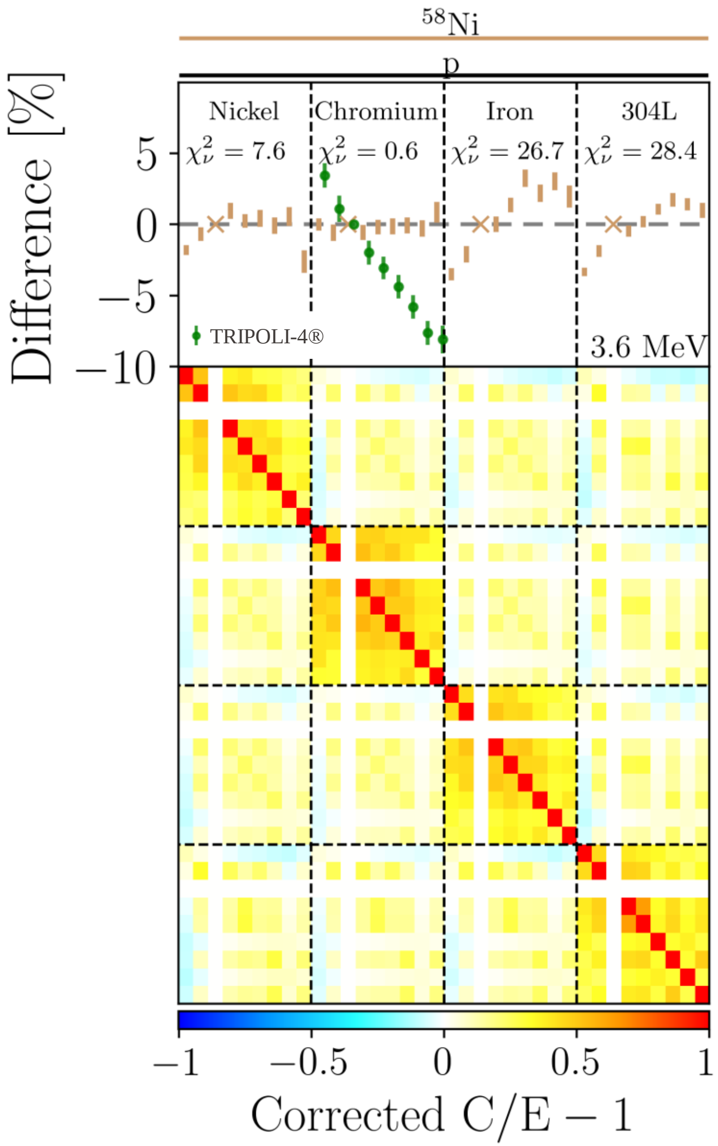
Simulations of the transmission experiments

- XS from JEFF-3.3

- ^{58}Ni(n,p) dosimeters
  - Median energy of activation ~3.6 MeV

- Discrepancy between Serpent2 and Tripoli4®
  - Serpent 2.1.21 has an issue interpreting some unexpectedly defined XS
  - Corrected in later release

Fast neutron range



Results : All Reflectors

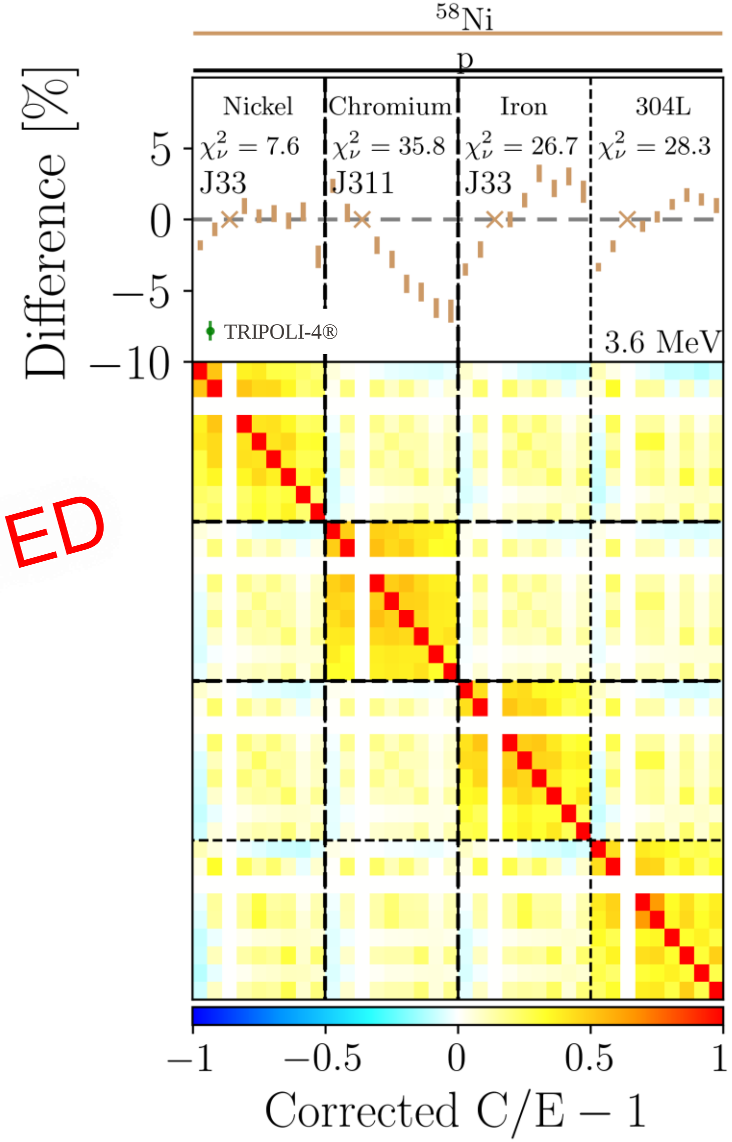
Simulations of the transmission experiments

- XS from JEFF-3.3

- $^{58}Ni(n,p)$ dosimeters
  - Median energy of activation ~3.6 MeV

- Discrepancy between Serpent2 and Tripoli4® SOLVED
- Border effect for nickel
- Over-transparency of iron and steel 304L
- Strong over-reflection for chromium

Fast neutron range



Results : All Reflectors

Simulations of the transmission experiments

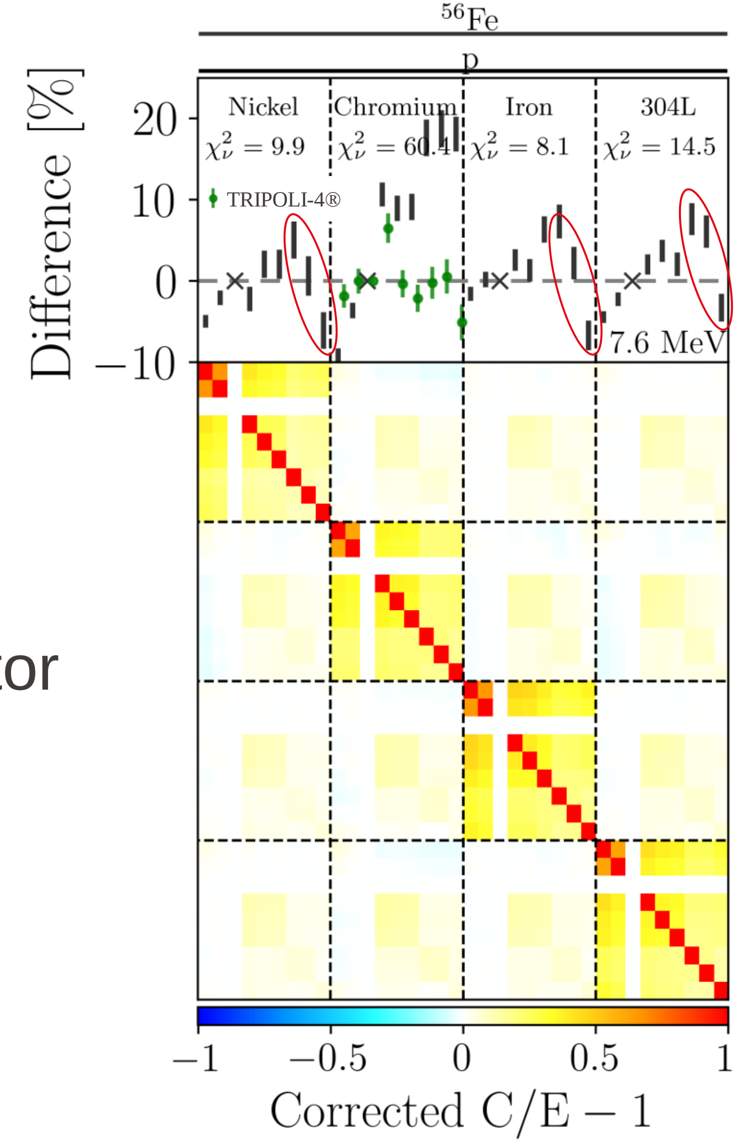
- XS from JEFF-3.3

- $^{56}Fe(n,p)$ dosimeters
  - Median energy of activation ~7.6 MeV

Unexpected behaviour

- Sudden drop of the C/E at the end of the reflector

Fast neutron range



Results : All Reflectors

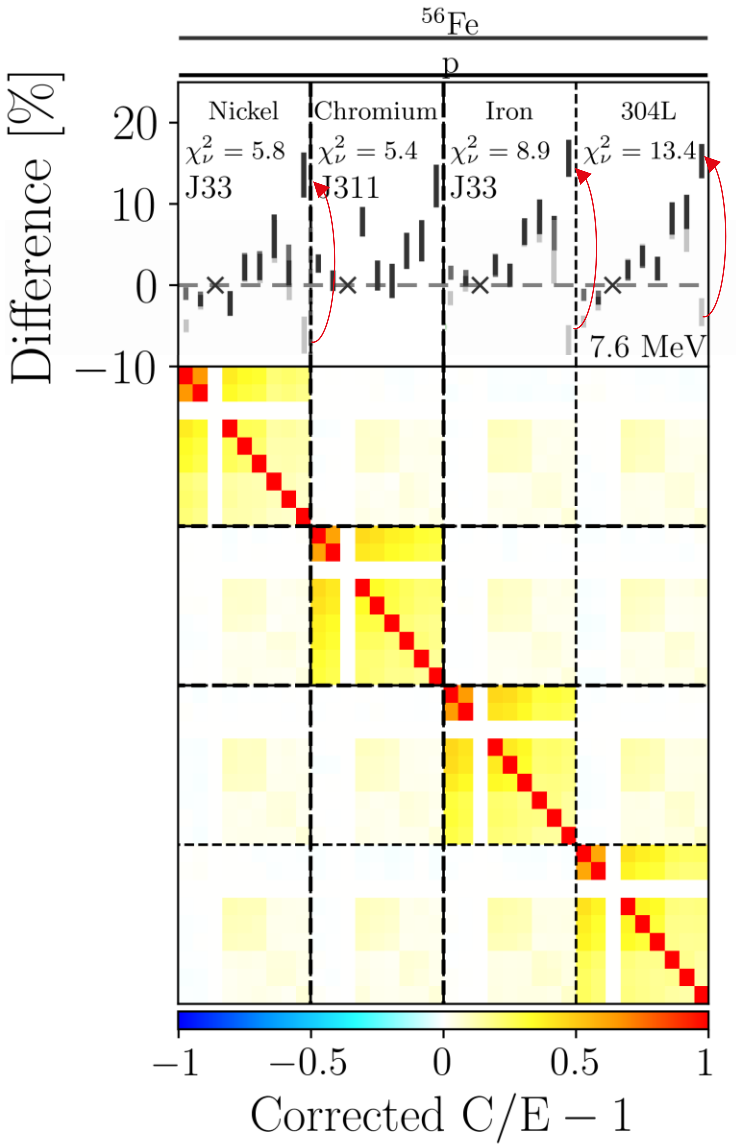
Simulations of the transmission experiments

- XS from JEFF-3.3
- ^{56}Fe(n,p) dosimeters
  - Median energy of activation ~7.6 MeV
- Unexpected behaviour SOLVED

➡ Effect of ^{55}Mn impurities (5.8 ppm)

  - Overestimation of the experimental reaction rates
  - **Up to 20% difference at the end of the block!**

Fast neutron range

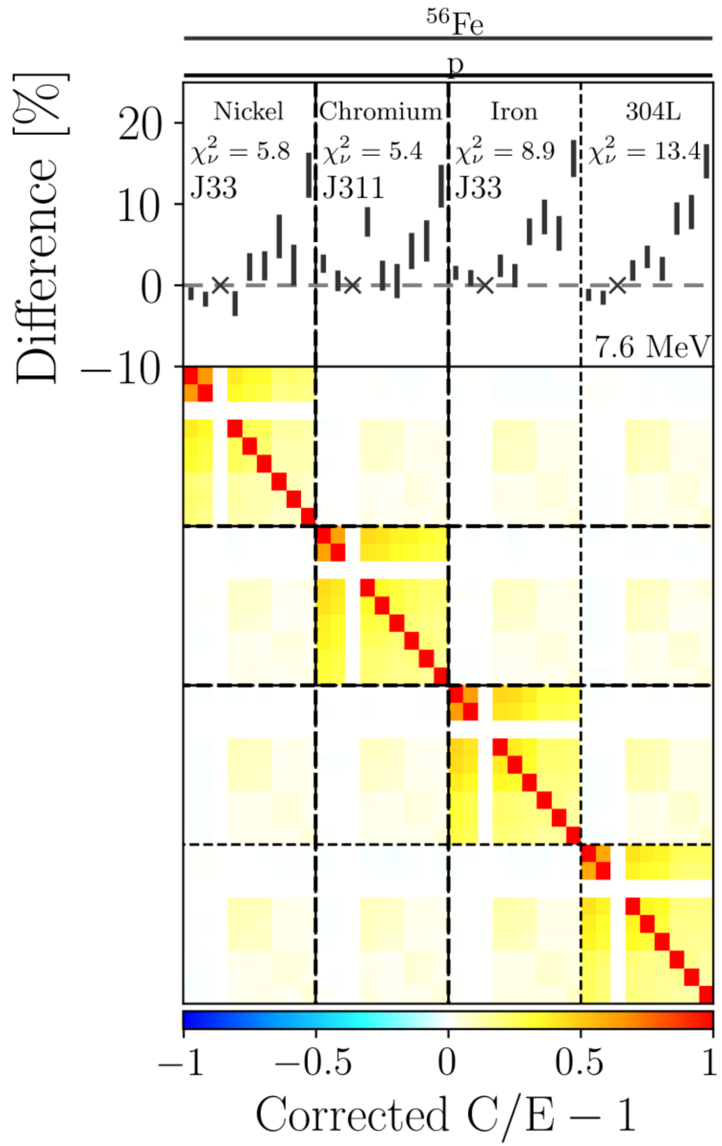


Results : All Reflectors

Simulations of the transmission experiments

- XS from JEFF-3.3
- $^{56}Fe(n,p)$ dosimeters
  - Median energy of activation ~7.6 MeV
- Unexpected behaviour due to ^{55}Mn SOLVED
- Nickel, chromium, iron and steel
  - Over-transparency
  - And thickness effect
  - Steel shows the strongest trend

Fast neutron range

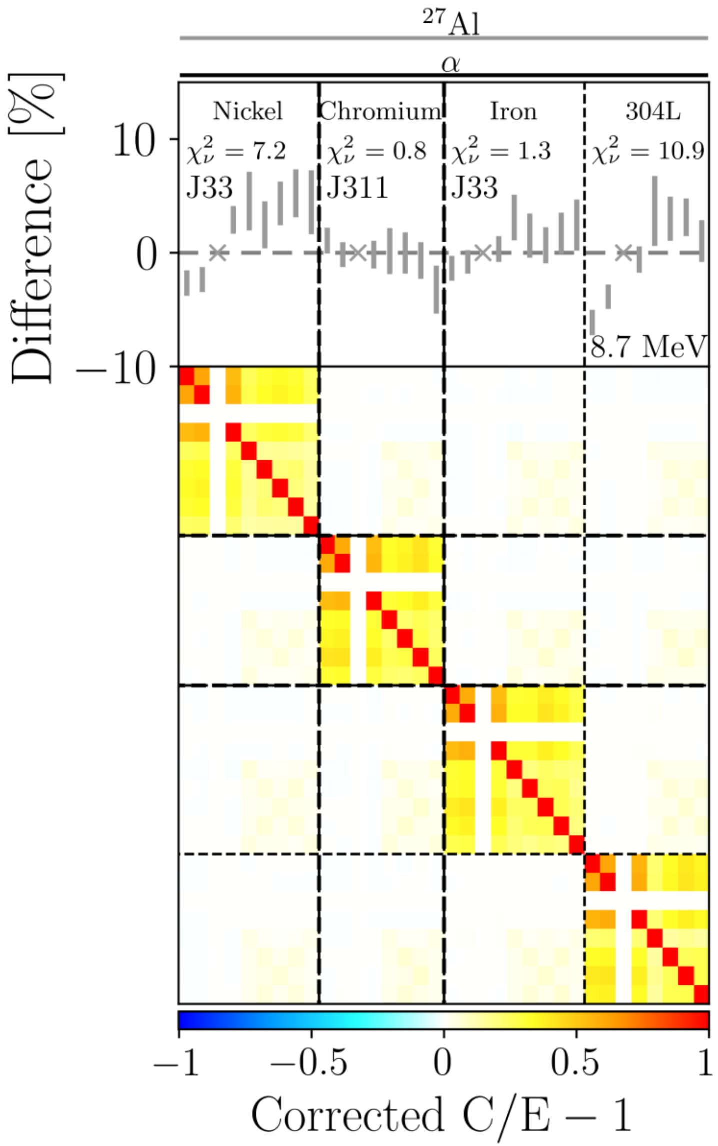


Results : All Reflectors

Simulations of the transmission experiments

- XS from JEFF-3.3
- $^{27}Al(n,a)$ dosimeters
  - Median energy of activation ~8.7 MeV
- Nickel and steel
  - Over-transparency
  - And thickness effect
- Good agreement of the iron and chromium

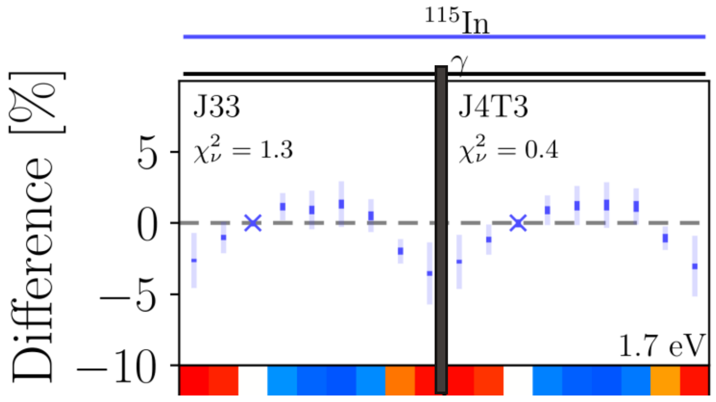
Fast neutron range

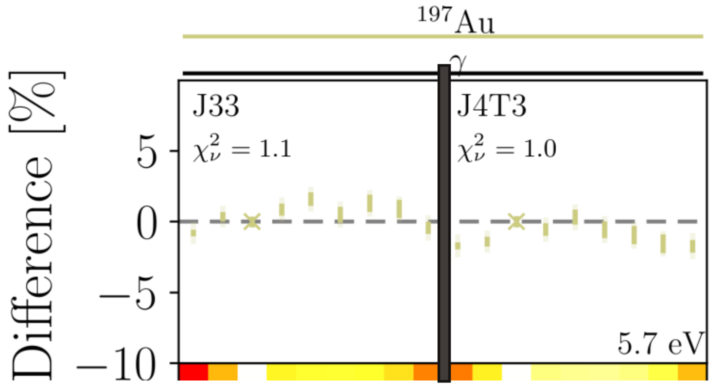


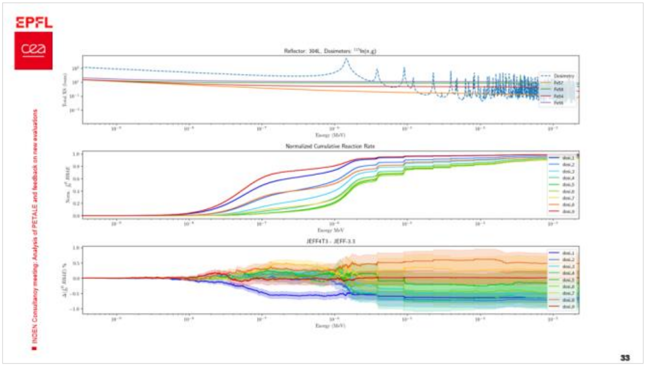
Feedback on JEFF-4T3: 304L Reflectors

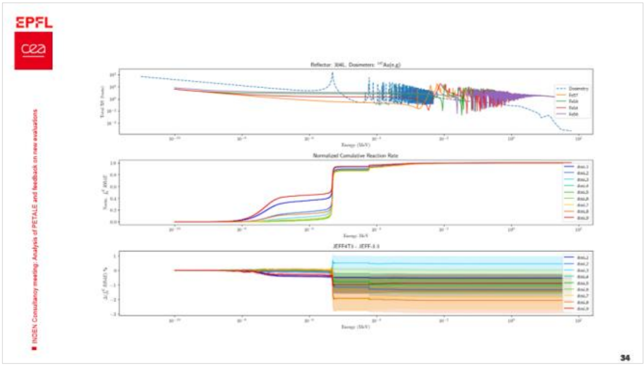
Simulations of the stainless steel 304L transmission experiments

- XS from JEFF-3.3 and JEFF-4T3
  - Minor alloy elements and impurities included
- Both evaluations are in agreement with the experiments
  - Flat C/E
  - χ^2_ν also in agreement







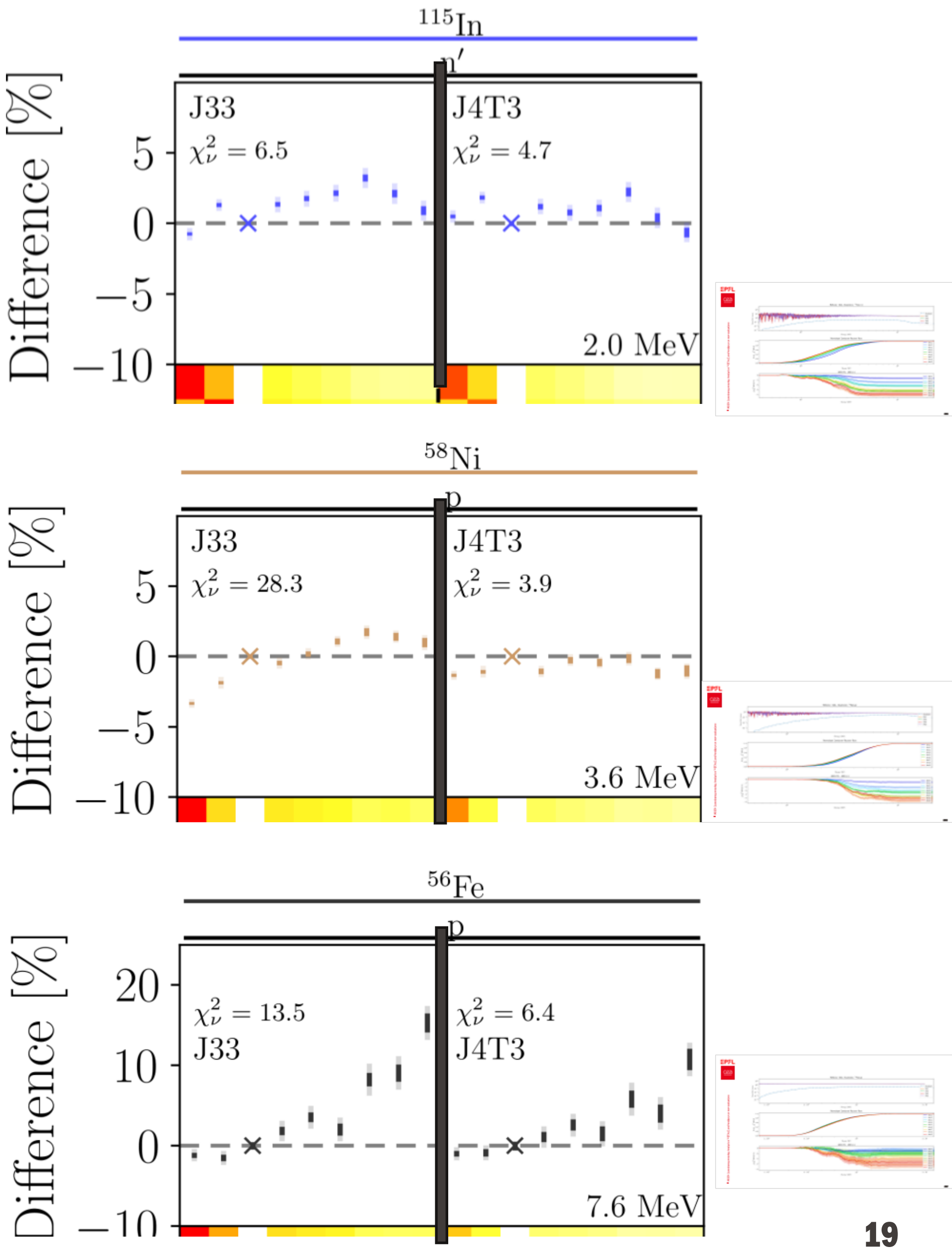


Feedback on JEFF-4T3: 304L Reflectors

Simulations of the stainless steel 304L transmission experiments

- XS from JEFF-3.3 and JEFF-4T3
  - Minor alloy elements and impurities included

- JEFF-4T3 flattens the previous trends in the fast neutron range
  - Especially for ^{115}In(n,n') and ^{58}Ni(n,p) dosimeters
  - Some over-transparency still visible at higher energy



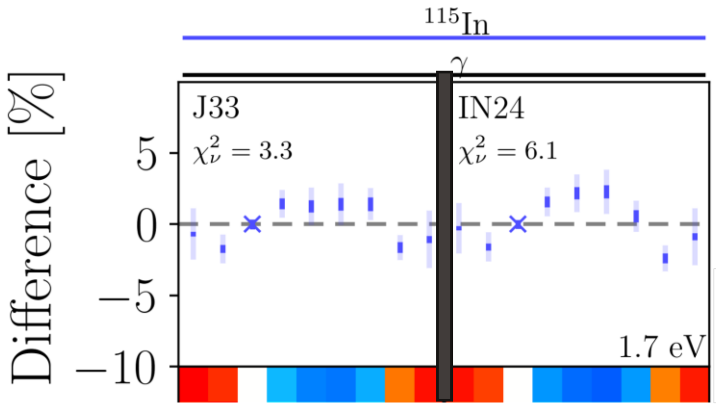
Feedback on INDEN: Iron Reflectors

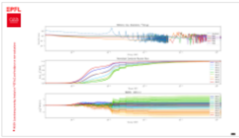
Simulations of the iron transmission experiments

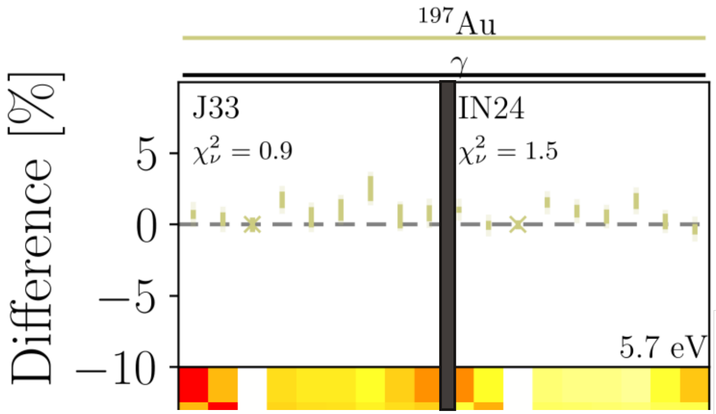
- XS from JEFF-3.3 and INDEN
  - All available isotopes

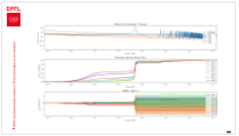
- ^{115}In(n,g) is slightly less consistent
  - χ^2_ν from 3.3 to 6.1

- ^{197}Au(n,g) in agreement with the experimental data
  - Flat C/E







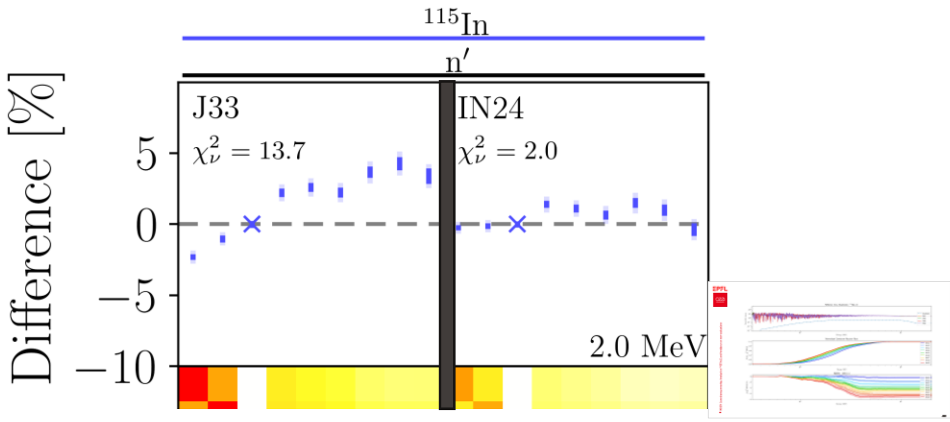


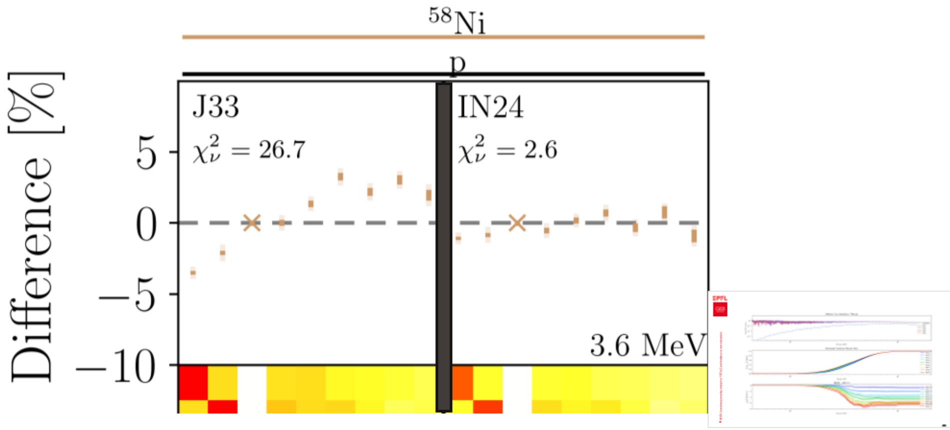
Feedback on INDEN: Iron Reflectors

Simulations of the iron transmission experiments

- XS from JEFF-3.3 and INDEN
  - All available isotopes

- The INDEN evaluation is in good agreement with the experiments around 2 MeV and 3.6 MeV
  - The previous trend is flattened

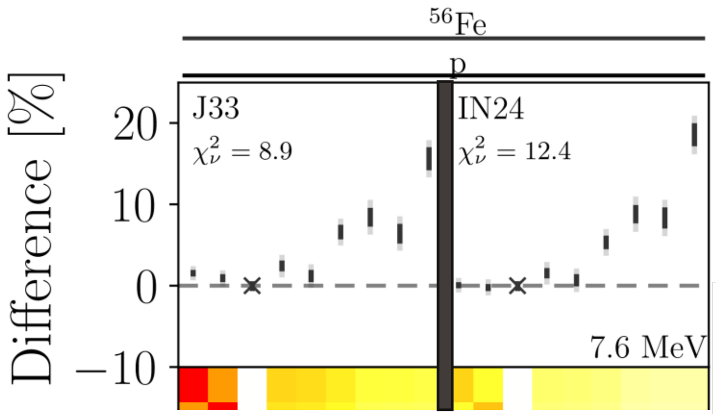


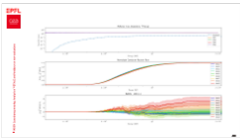


Feedback on INDEN: Iron Reflectors

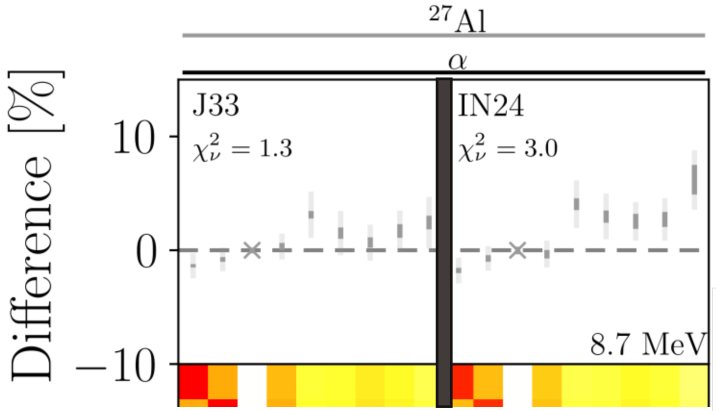
Simulations of the iron transmission experiments

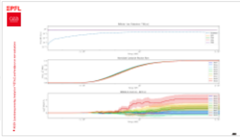
- XS from JEFF-3.3 and INDEN
  - All available isotopes





- At higher energy the trend is slightly stronger than before
  - Slight increase in trend (statistically significant)

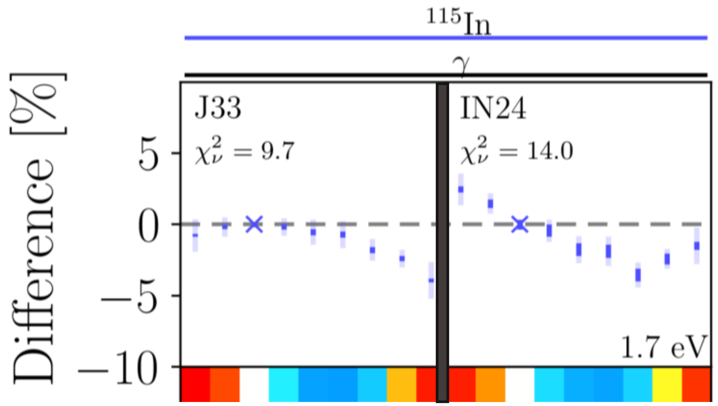


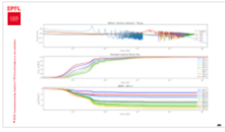


Feedback on INDEN: Chromium Reflectors

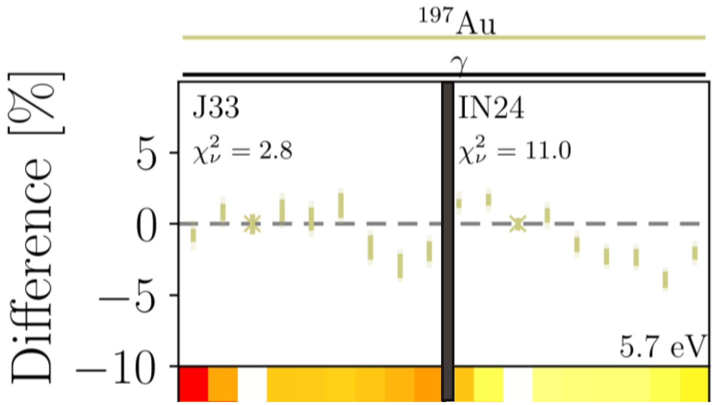
Simulations of the chromium transmission experiments

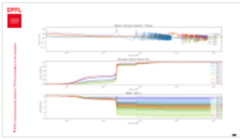
- XS from JEFF-3.3 and INDEN
  - Here the older INDEN only includes Cr-52





- A trend appeared in the near thermal range for chromium
  - Visible with both experiments
  - Degraded χ^2_ν

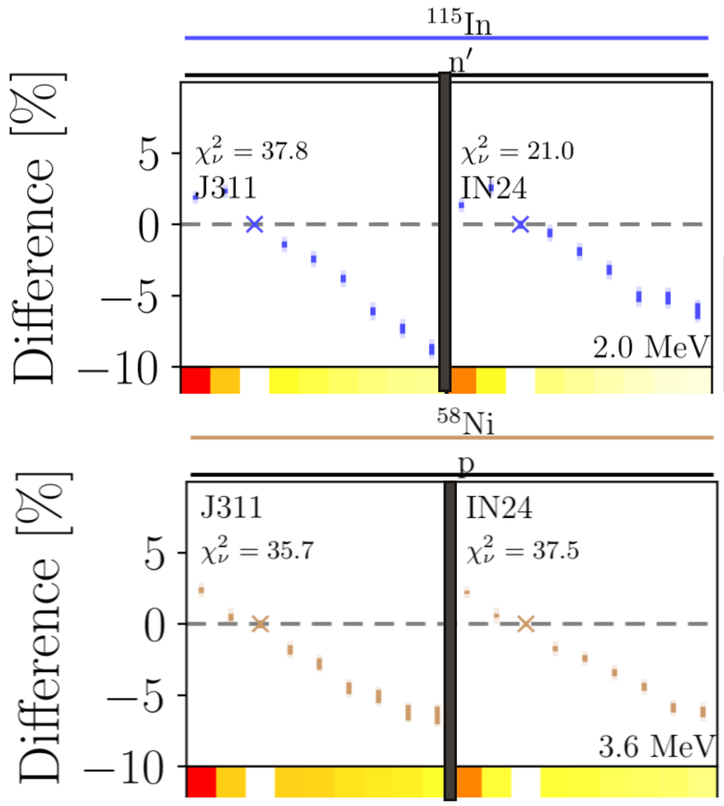


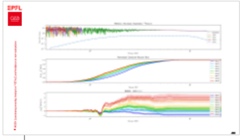


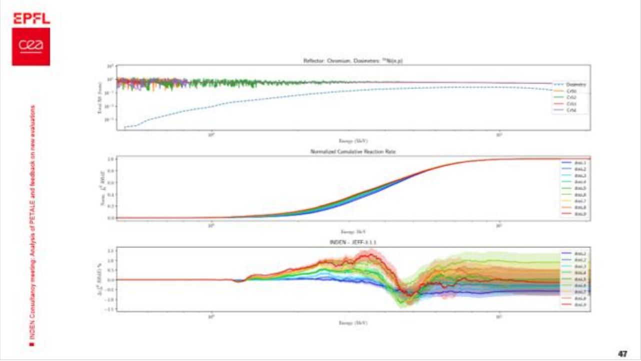
Feedback on INDEN: Chromium Reflectors

Simulations of the chromium transmission experiments

- XS from JEFF-3.3 and INDEN
  - Here the older INDEN only includes Cr-52
- The discrepancies around 2 MeV are reduced with INDEN
  - A clear trend is still visible
- The Ni dosimeter trend is preserved
  - But the activation profile is different



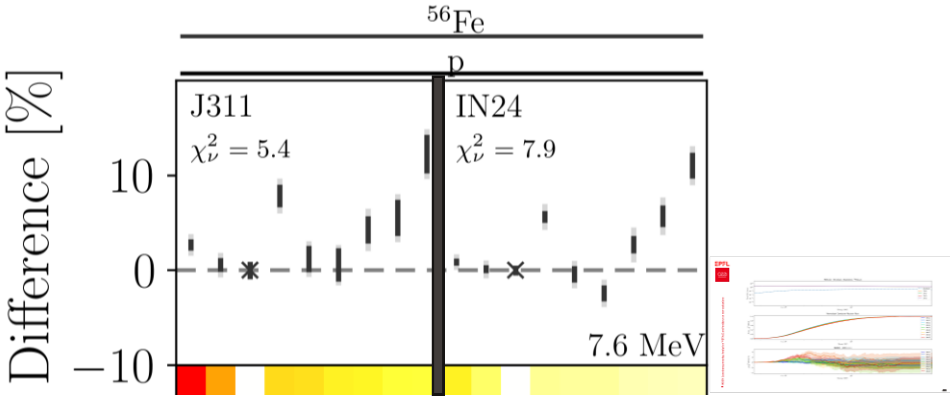




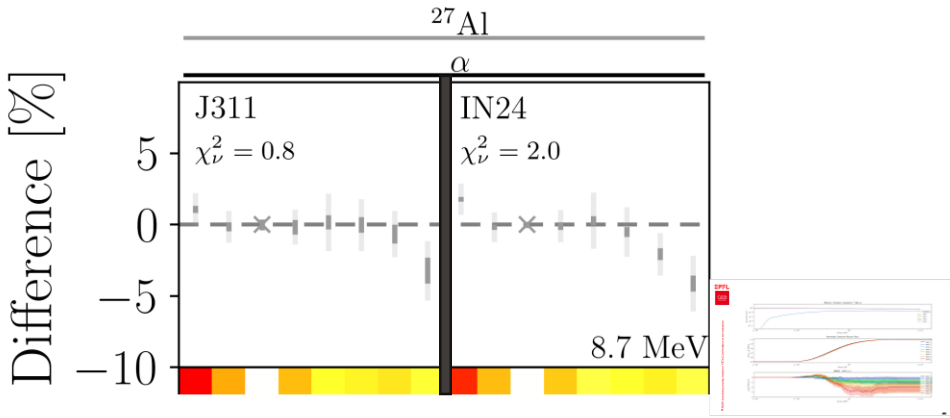
Feedback on INDEN: Chromium Reflectors

Simulations of the chromium transmission experiments

- XS from JEFF-3.3 and INDEN
  - Here the older INDEN only includes Cr-52



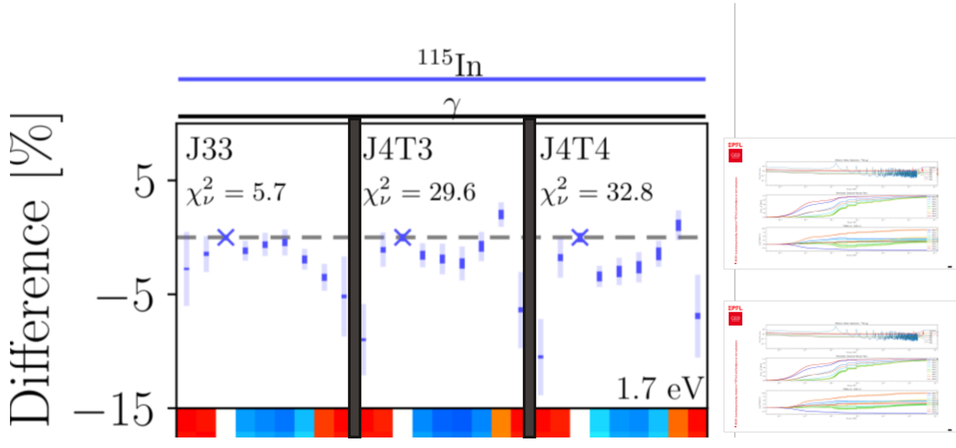
- The trends at higher energy (^{56}Fe(n,p) and ^{27}Al(n,α) dosimeters) are mostly preserved
  - No significant differences are observed in the C/E observed
  - Observed small differences maybe from calculation statistics



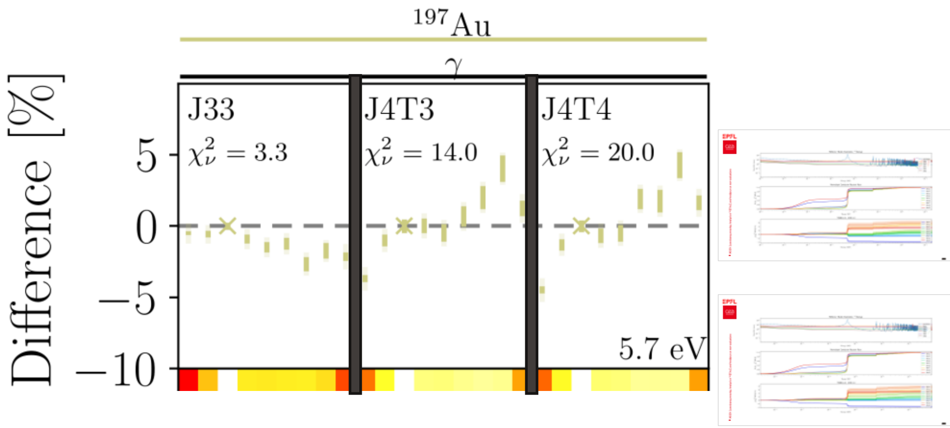
Feedback on TENDL: Nickel Reflectors

Simulations of the nickel transmission experiments

- XS from JEFF-3.3 and Tendl-23/24
  - Tendl-23 from JEFF-4T3 ace files
  - Tendl-24 from JEFF-4T4 ace files



- Magnified drops at the edges of the reflectors
- A gradual increases of the C/E appears after a few sheets

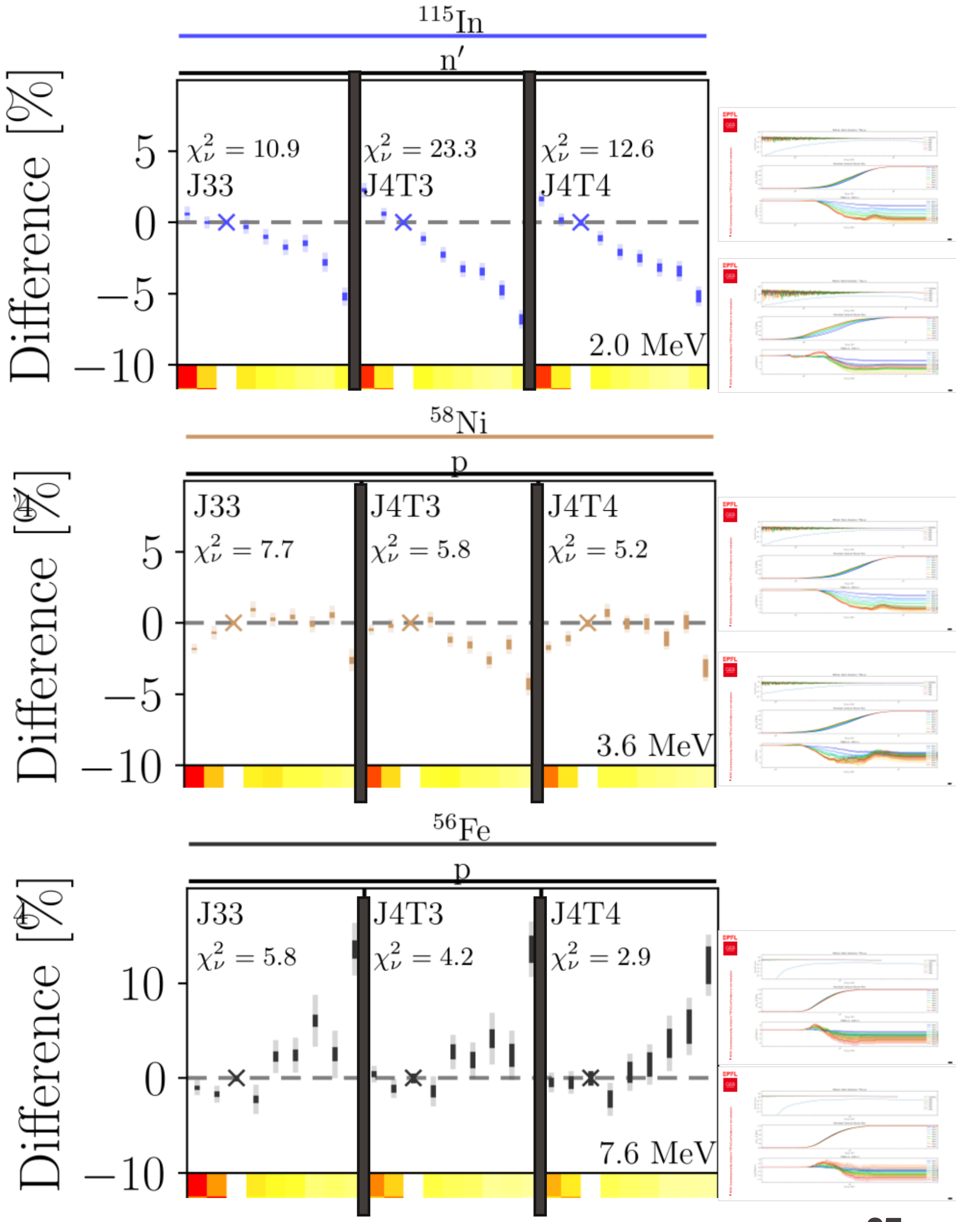


Feedback on TENDL: Nickel Reflectors

Simulations of the nickel transmission experiments

- XS from JEFF-3.3 and Tendl-23/24
  - Tendl-23 from JEFF-4T3 ace files
  - Tendl-24 from JEFF-4T4 ace files

- Tendl-24 close to JEFF-3.3
  - Tendl-23 has slightly stronger trend with In(n,n’) and Ni(n,p)



Comparison to JEFF-4T3

- Simulation with INDEN/JEFF-4T3 shows mixed results with respect to JEFF-3.3
  - Reduced χ^2 are lower and trends are flattened in most cases for iron and stainless steel
  - New trends and effect appeared for nickel and chromium

	JEFF-3.3 (JEFF-3.1.1 for Cr fast neutron dosimeters)						INDEN/Tendl-24					
	$^{115}In(n,\gamma)$	$^{197}Au(n,\gamma)$	$^{115}In(n,n')$	$^{58}Ni(n,p)$	$^{56}Fe(n,p)$	$^{27}Al(n,a)$	$^{115}In(n,\gamma)$	$^{197}Au(n,\gamma)$	$^{115}In(n,n')$	$^{58}Ni(n,p)$	$^{56}Fe(n,p)$	$^{27}Al(n,a)$
	1.7 eV	5.7 eV	2.0 MeV	3.6 MeV	7.6 MeV	8.7 MeV	1.7 eV	5.7 eV	2.0 MeV	3.6 MeV	7.6 MeV	8.7 MeV
Cr	9.7	2.81	37.8	35.7	5.4	0.8	14	11	21	37.5	7.9	2
Ni	5.7	3.3	10.9	7.7	5.8	7.2	32.8	20	23.5	5.2	2.9	-
Fe	3.25	0.88	13.7	26.7	8.9	1.3	6.1	1.5	2	2.6	12.4	3
304L	1.3	1.1	6.5	28.3	13.5	10.9	0.4	1	4.7	3.9	6.4	-

Conclusion

- The PETALE experiment was conducted end of 2020
  - The high-fidelity analysis is nearing its end
  - The benchmarking work is starting

- High-fidelity analysis for the transmission experiments is nearing completion
  - All C/E with JEFF-3.3
  - C/E and EPFL agree on the observed trend
    - Cr reflector discrepancies source is identified and resolved using JEFF-3.1.1
  - The reasons for the drop in ^{56}Fe dosimeter was due to ^{55}Mn impurities
  - Core XS-related uncertainties are being added

- Comparison of C/E between INDEN and JEFF-3.3 evaluations
  - INDEN shows overall better results for iron
    - Especially in the range of ^{58}Ni and $^{115}In(n,n')$ dosimeters
  - INDEN shows better results for chromium around 2 MeV
    - Higer energies are not affected on average
    - Different trends appeared at lower energy
  - JEFF-4T3 shows overall better results for stainless-steel 304L
  - Different trends appeared in the thermal range for the nickel reflector

Contacts:
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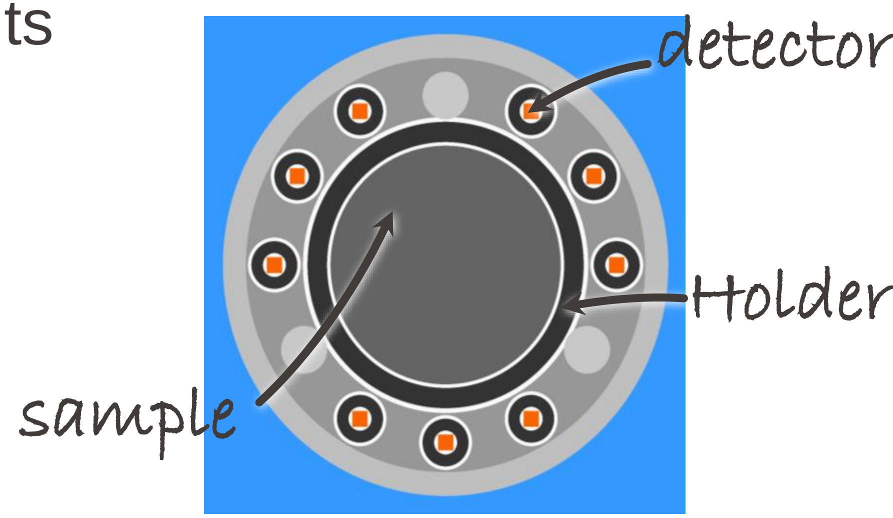
CEA: Tangi.NICOL@cea.fr

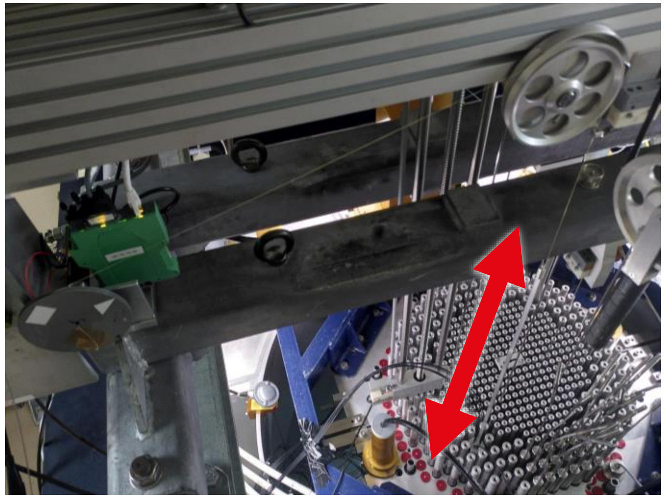
OUTLOOK: HARVEST-X reproducibility

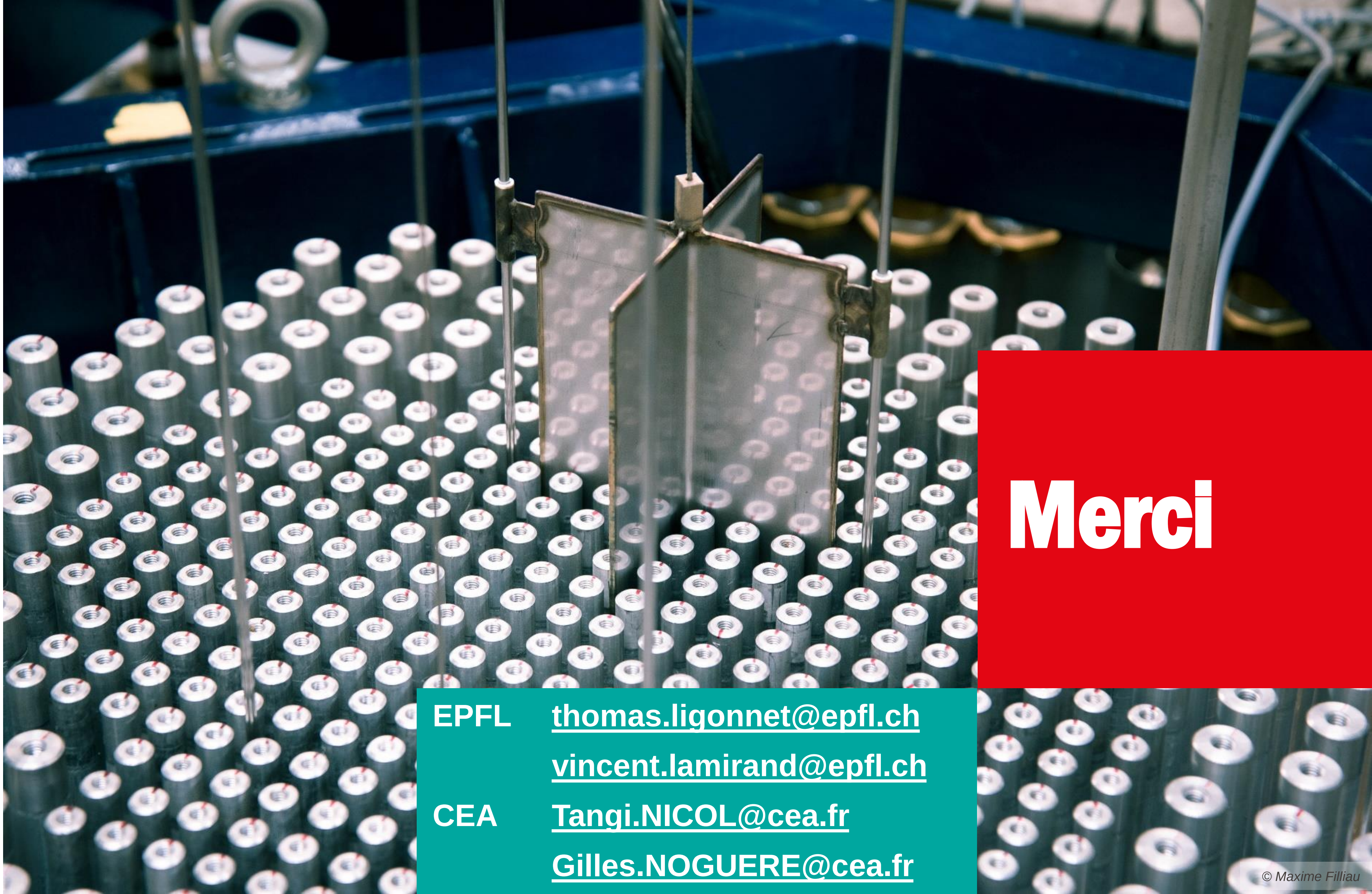
Production and analysis of new experimental results allowing to tackle biases

- Reproduction with other systems
  - Experiments in **accelerator facility**
  - Experiments in **reference fields**
- Reproduction with other methods
  - **Pile-oscillation experiments in CROCUS: BLOOM**
- **BLOOM**
  - Running since Fall 2024 up to February 2025
  - 25 materials (with samples directly cut from PETALE spares)
  - **Local and Global Flux measurement**

SAFFRON
Global & **local** measurements



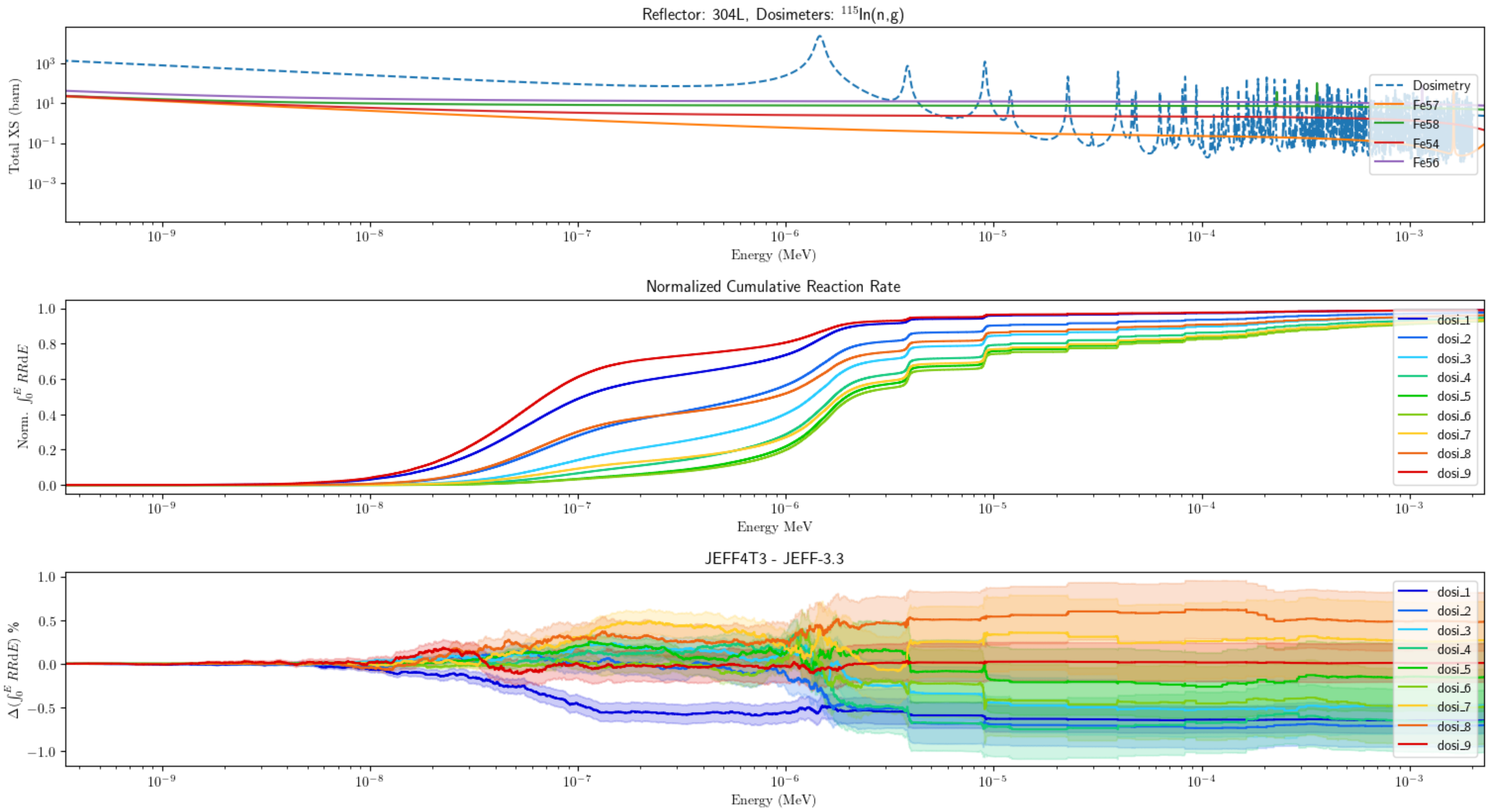


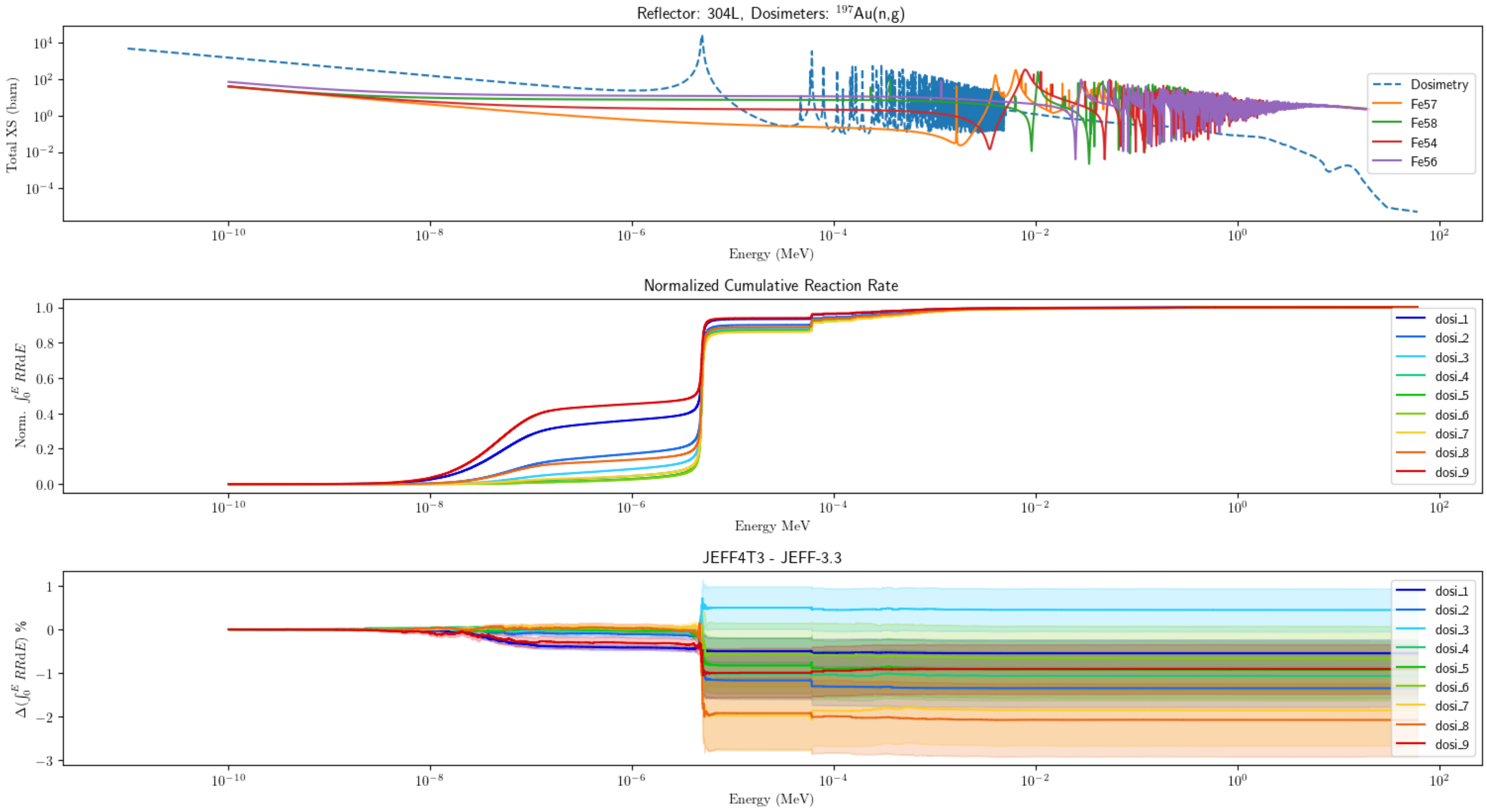


Merci

EPFL thomas.ligonnet@epfl.ch
vincent.lamirand@epfl.ch
CEA Tangi.NICOL@cea.fr
Gilles.NOGUERE@cea.fr

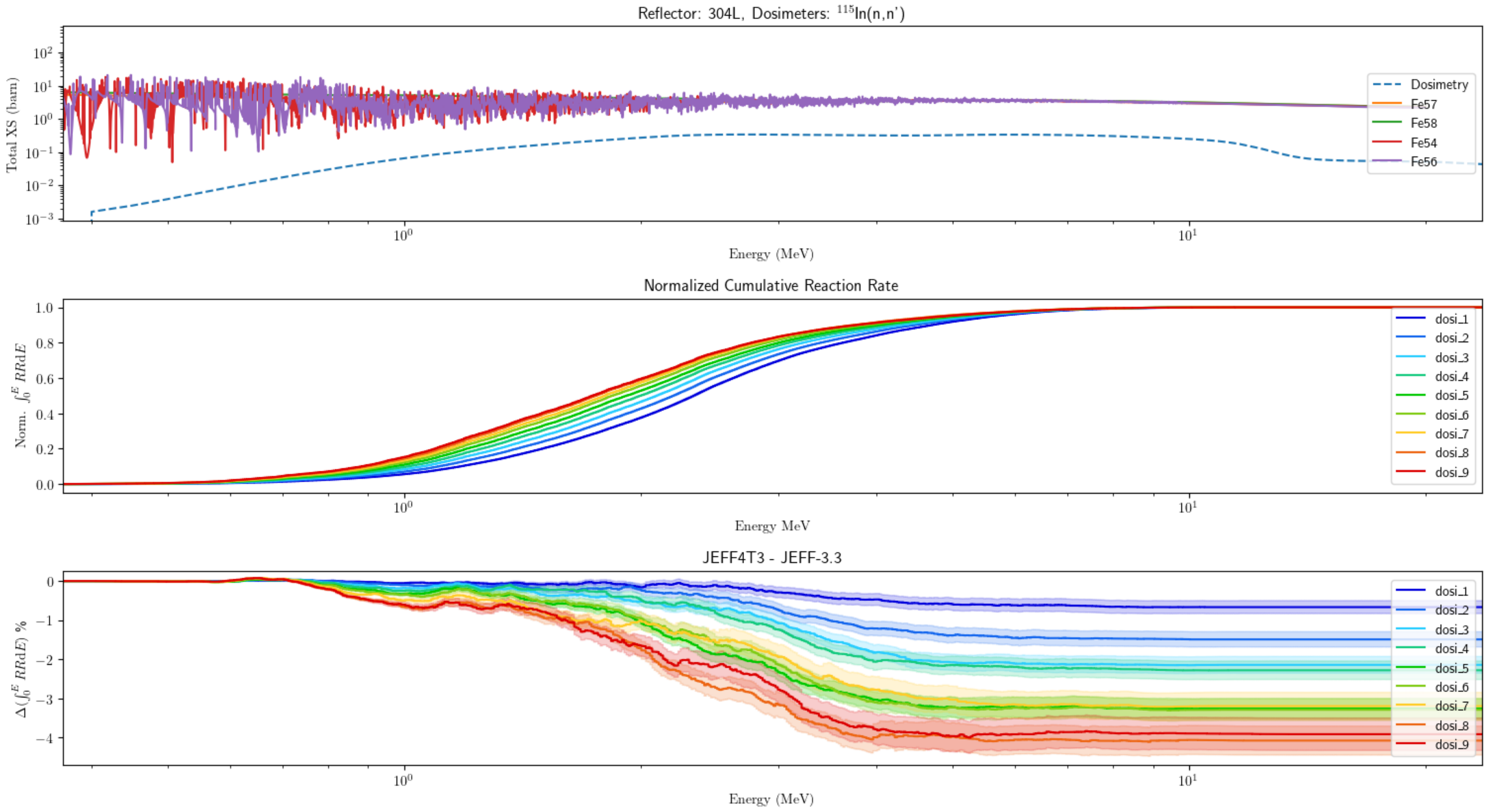
Questions ?


Reflector: 304L, Dosimeters: ^{115}In(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
JEFF4T3 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

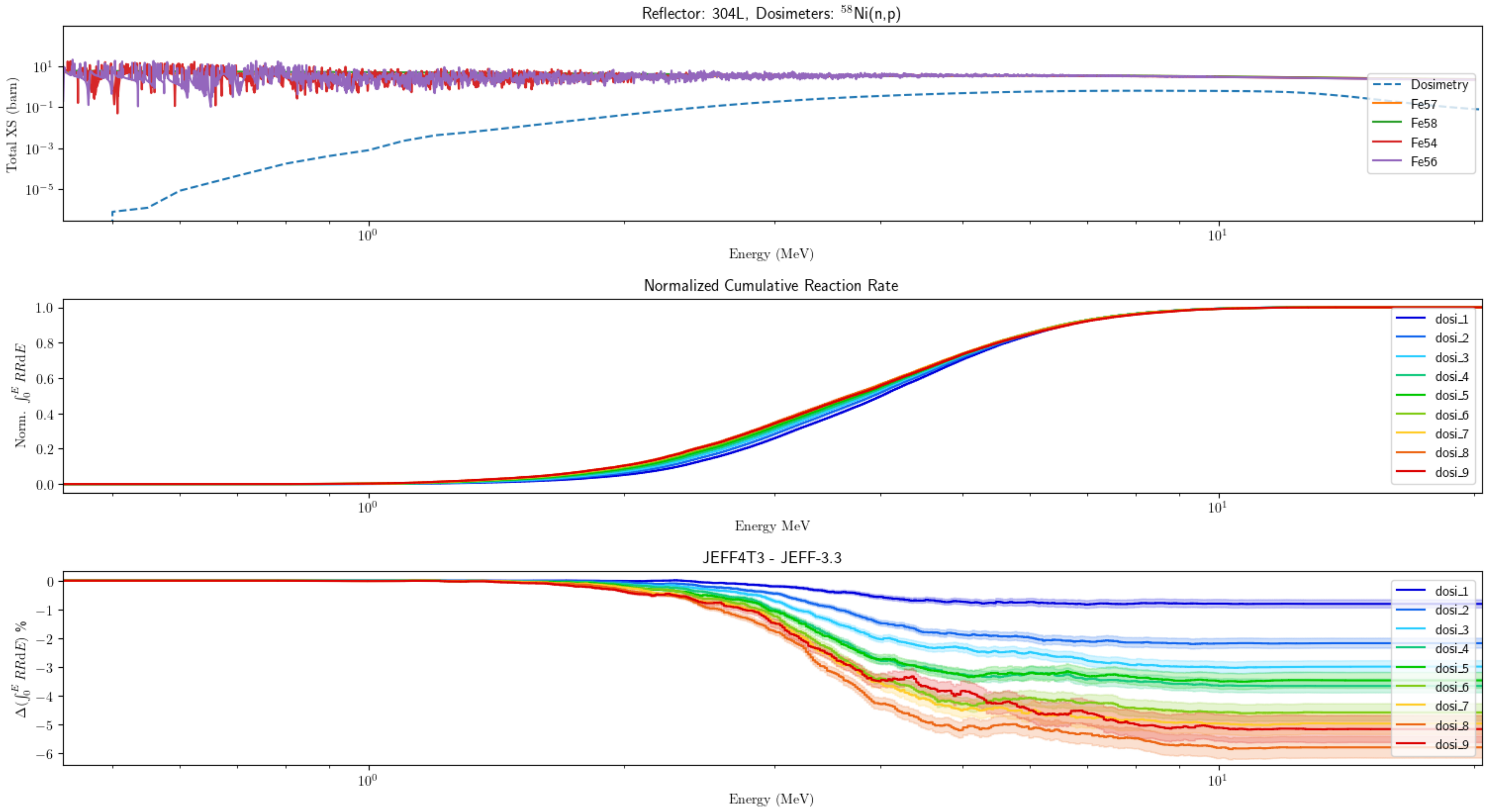

Reflector: 304L, Dosimeters: 197Au(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
JEFF4T3 - JEFF-3.3
Energy (MeV)

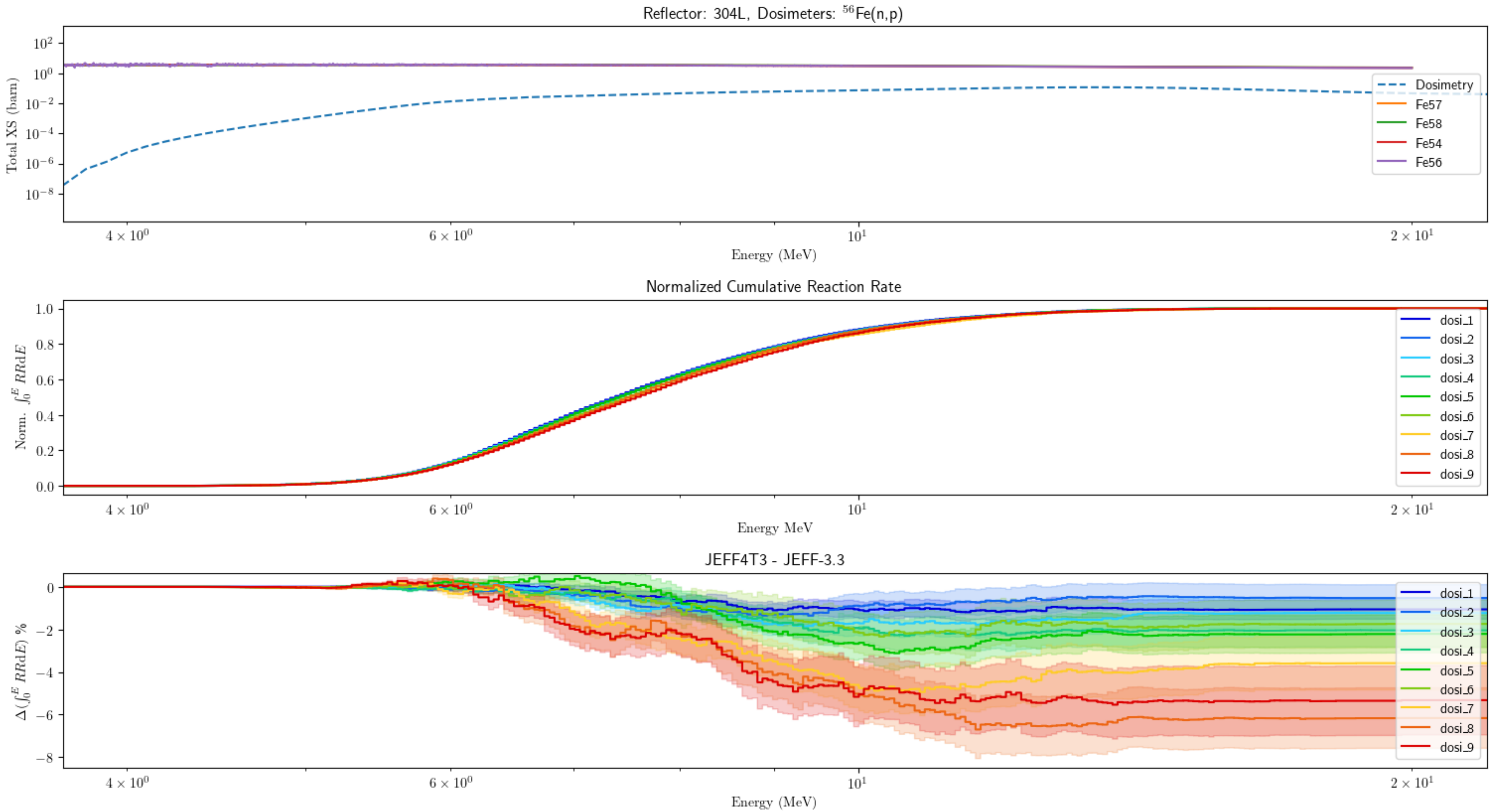
EPFL

cea

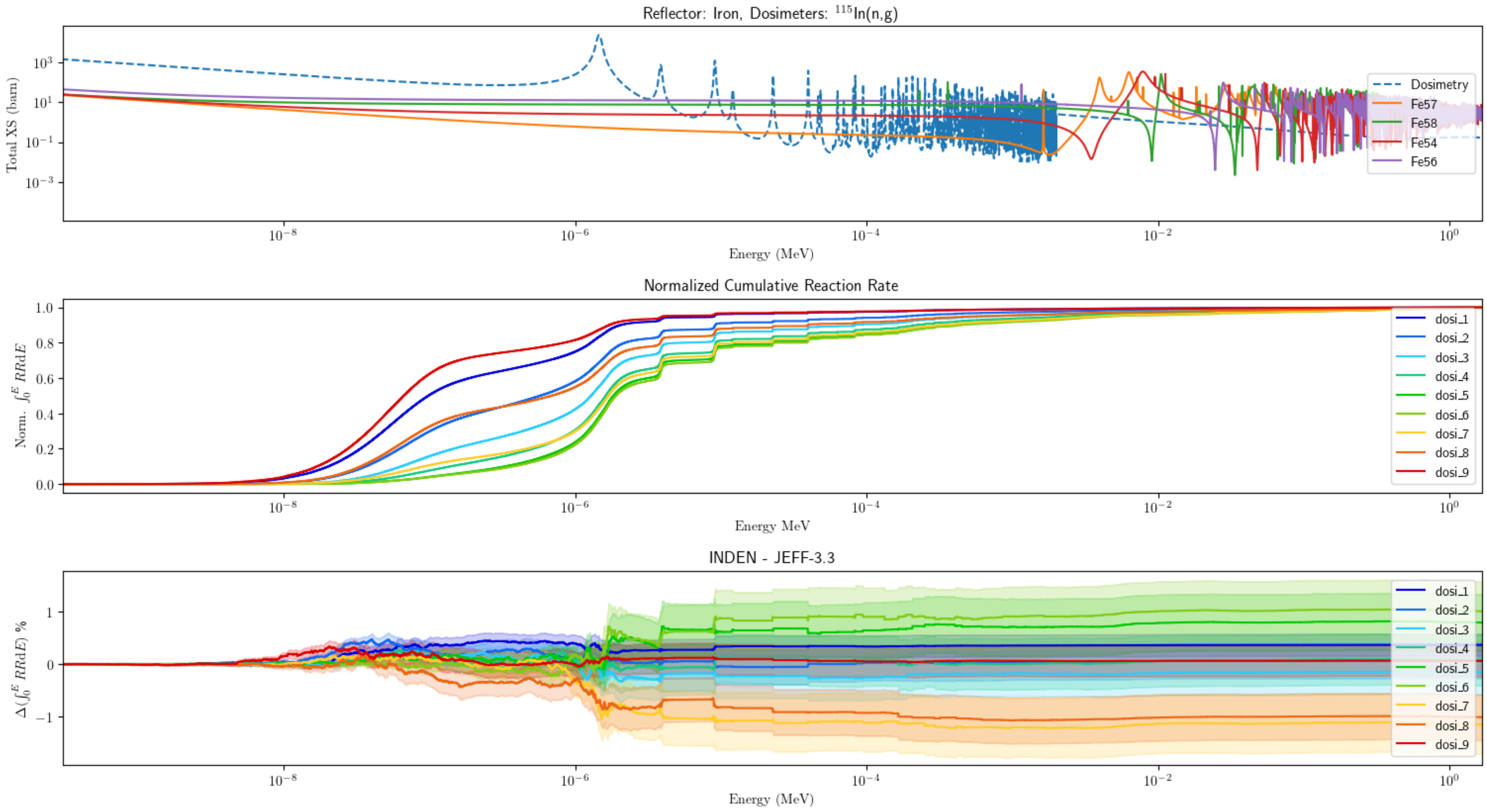


Reflector: 304L, Dosimeters: ^{115}In(n,n')
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
JEFF4T3 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

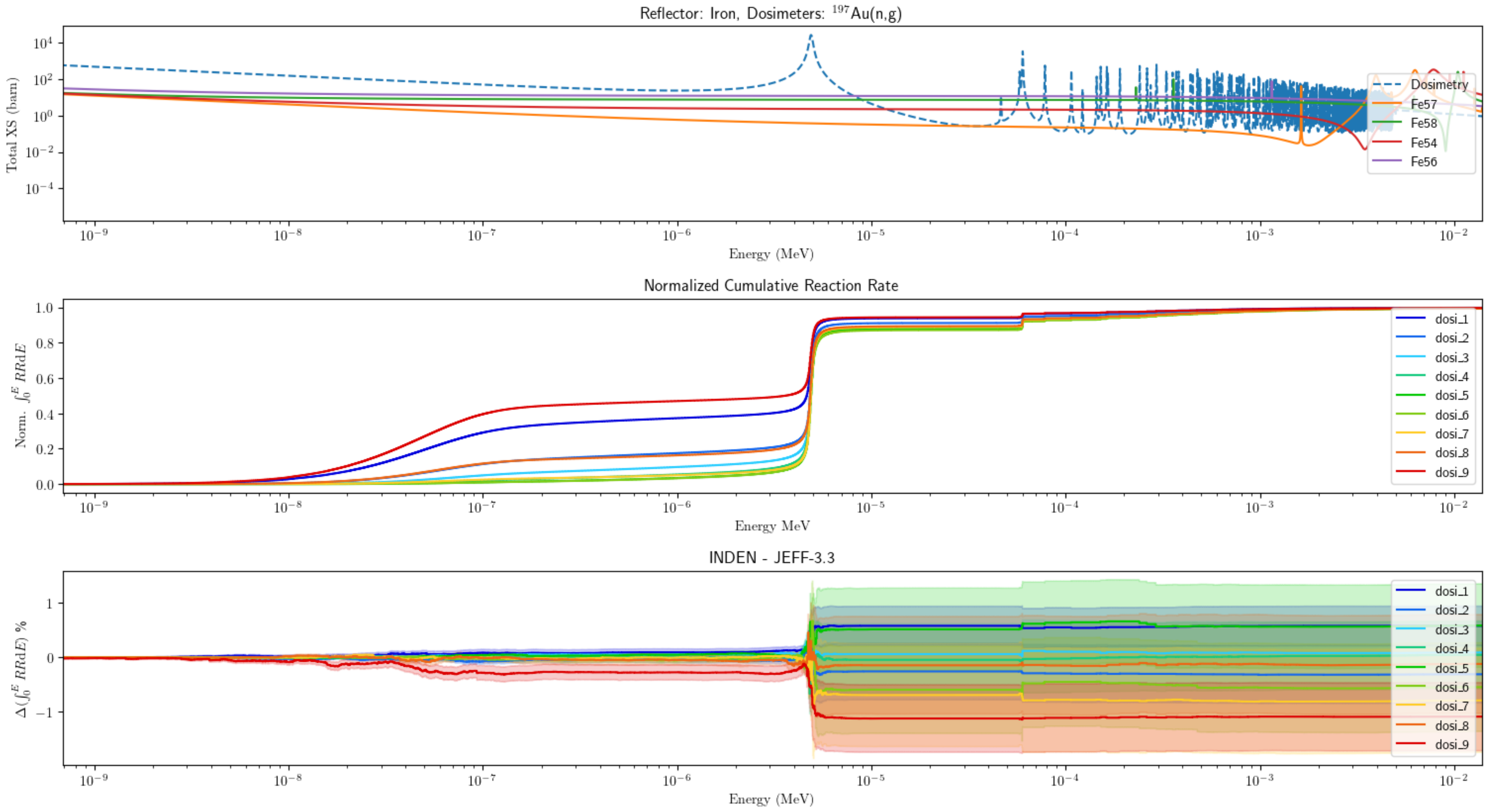

Reflector: 304L, Dosimeters: ^{58}Ni(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
JEFF4T3 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)



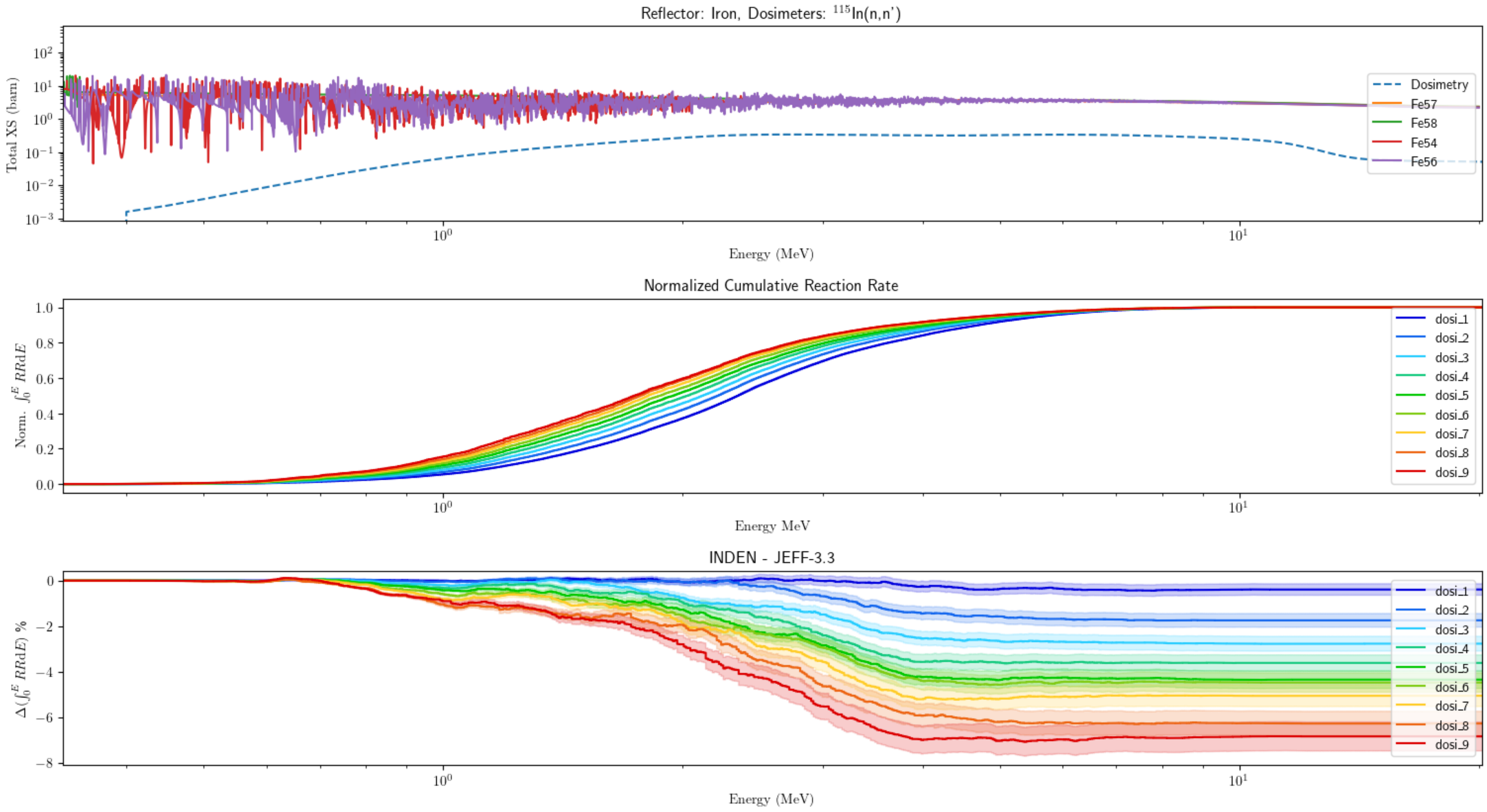
Reflector: 304L, Dosimeters: 56Fe(n,p)
Total XS (barn)
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Dosimetry
Fe57
Fe58
Fe54
Fe56
4×10^{0}
6×10^{0}
10^{1}
2×10^{1}
Energy (MeV)
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
1.0
0.8
0.6
0.4
0.2
0.0
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
Energy MeV
JEFF4T3 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
0
−2
−4
−6
−8
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
Energy (MeV)

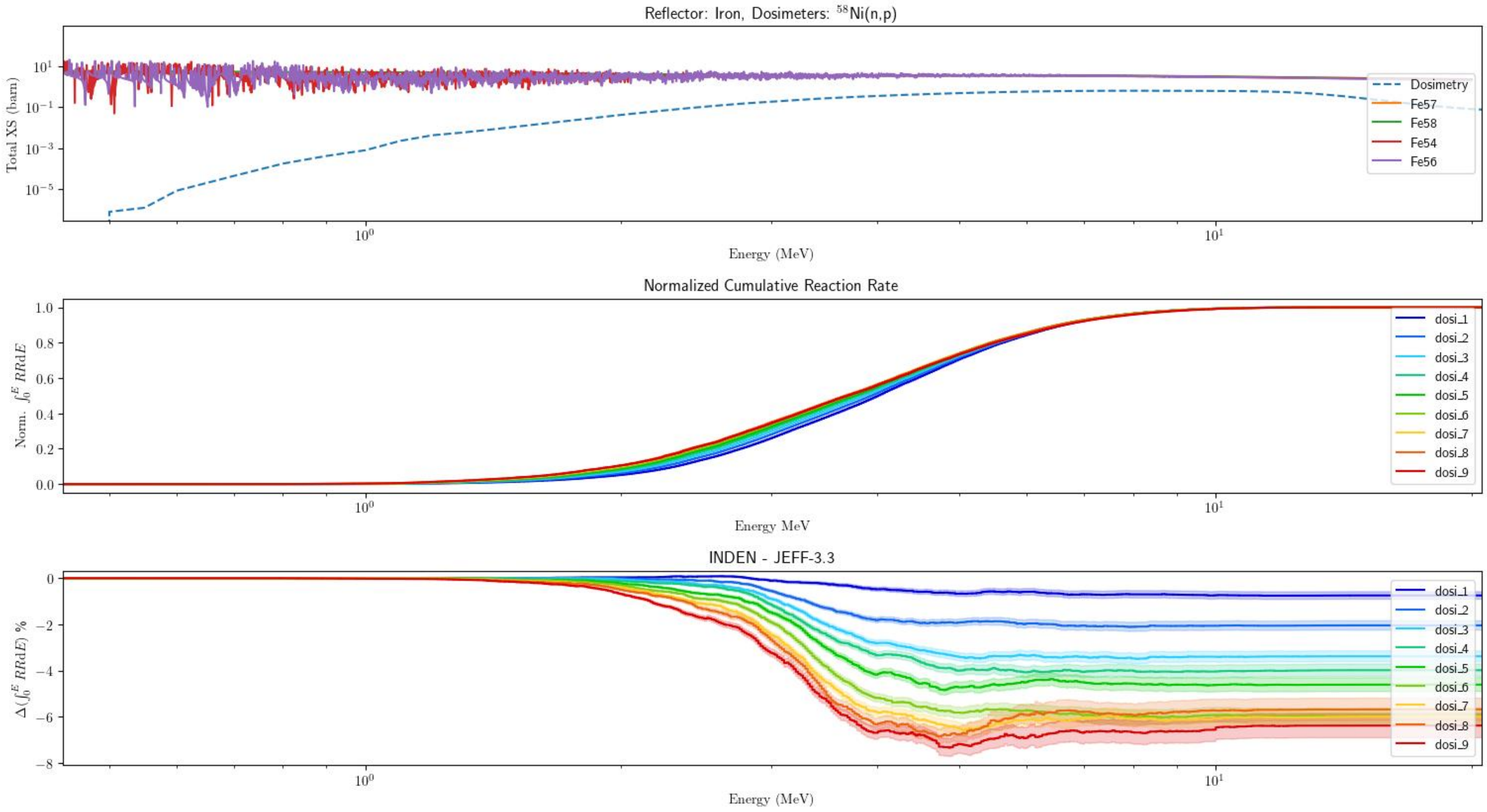


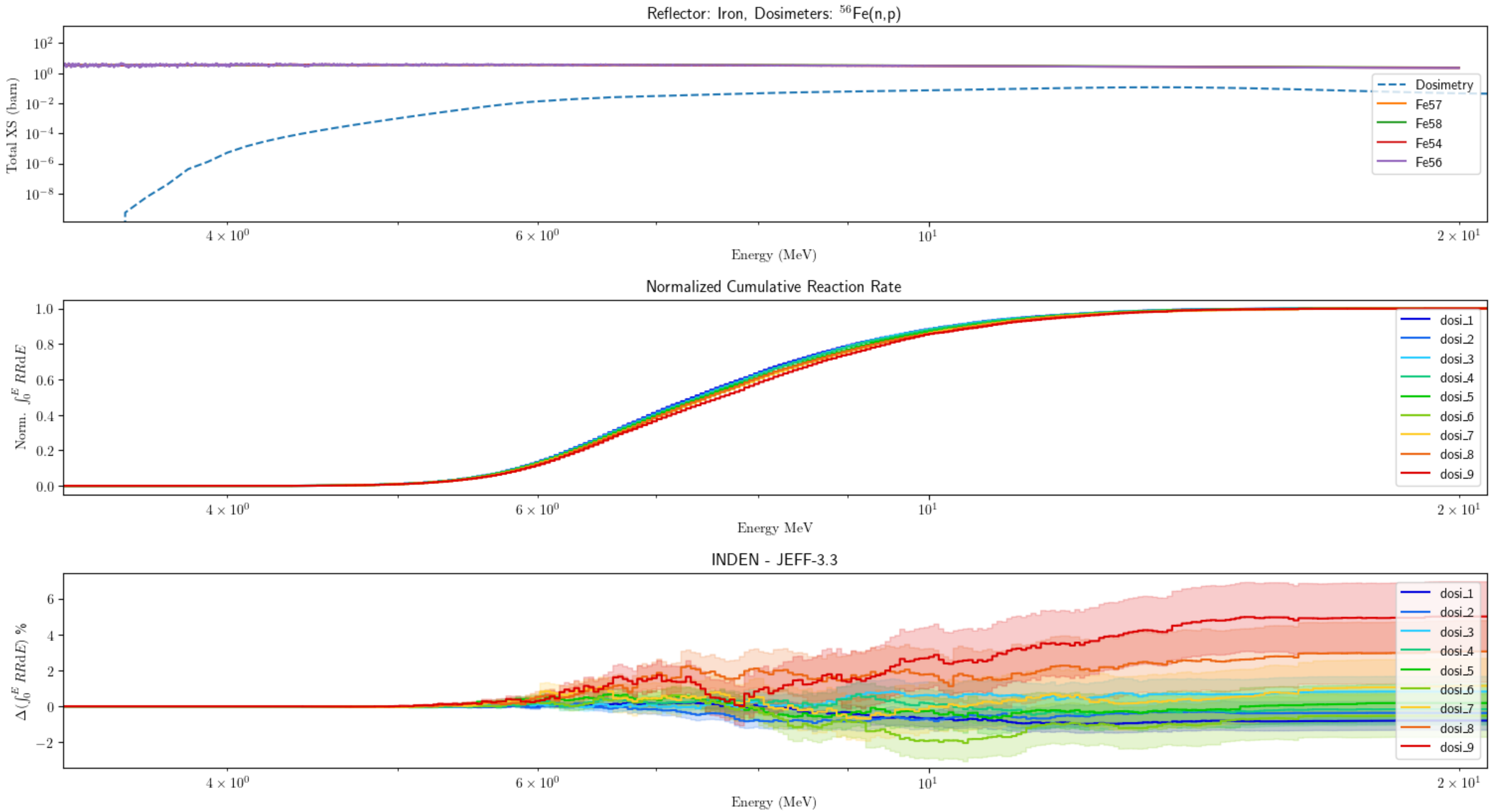
Reflector: Iron, Dosimeters: 115In(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
Energy (MeV)

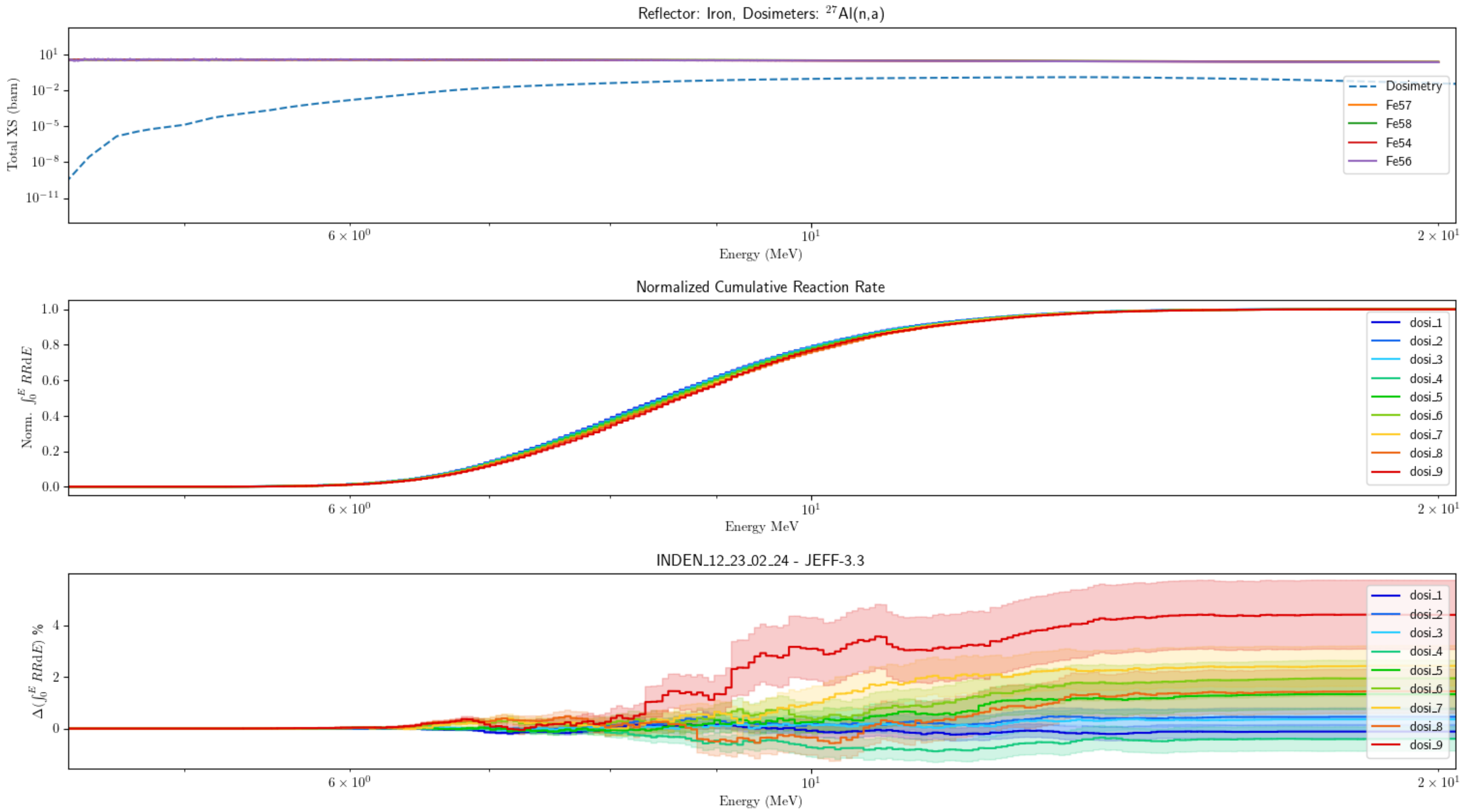

Reflector: Iron, Dosimeters: ^{197}Au(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

INDEN Consultancy meeting: Analysis of PETALE and feedback on new evaluations

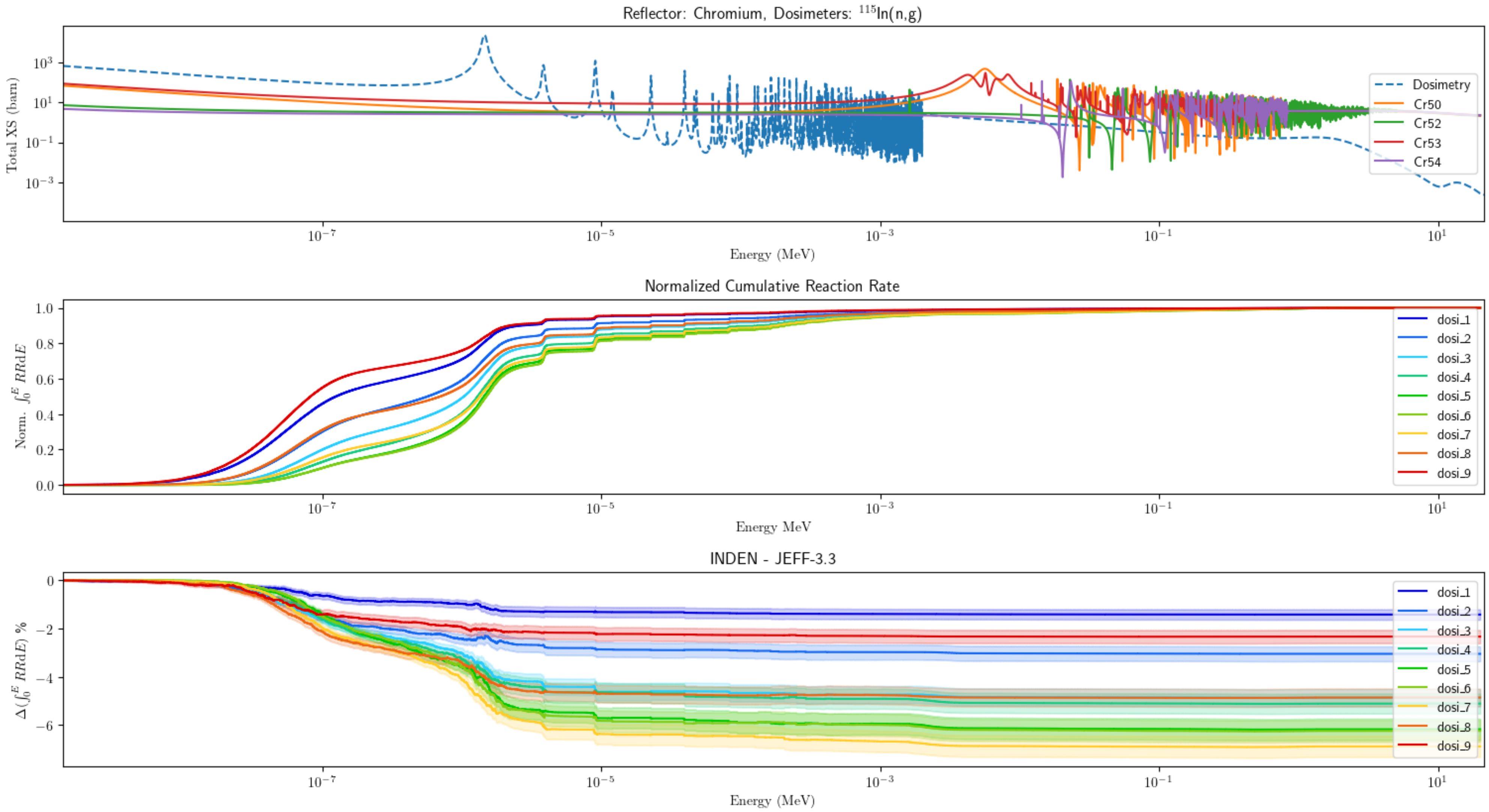


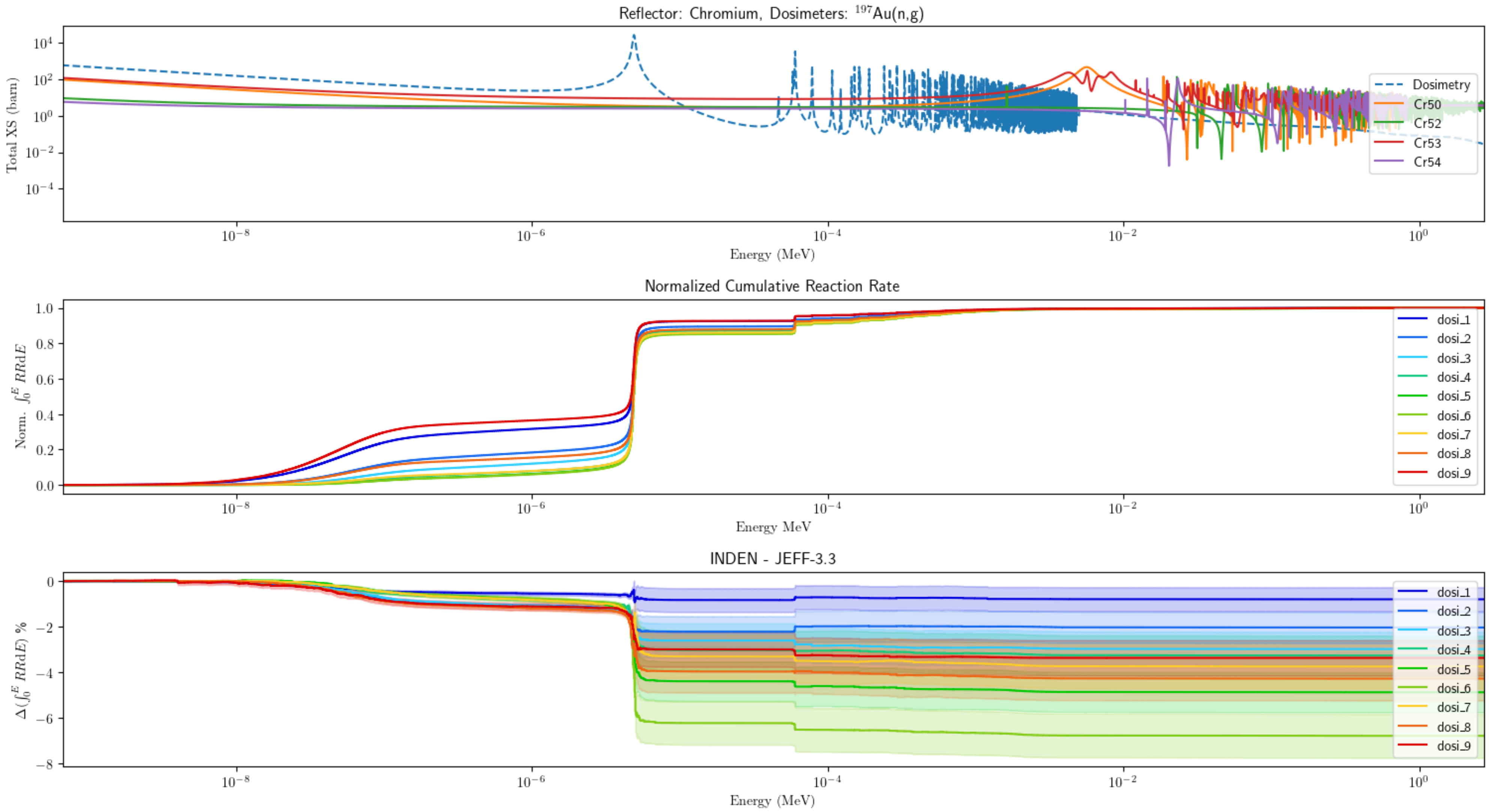

Reflector: Iron, Dosimeters: ^{58}Ni(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)


Reflector: Iron, Dosimeters: ^{56}Fe(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

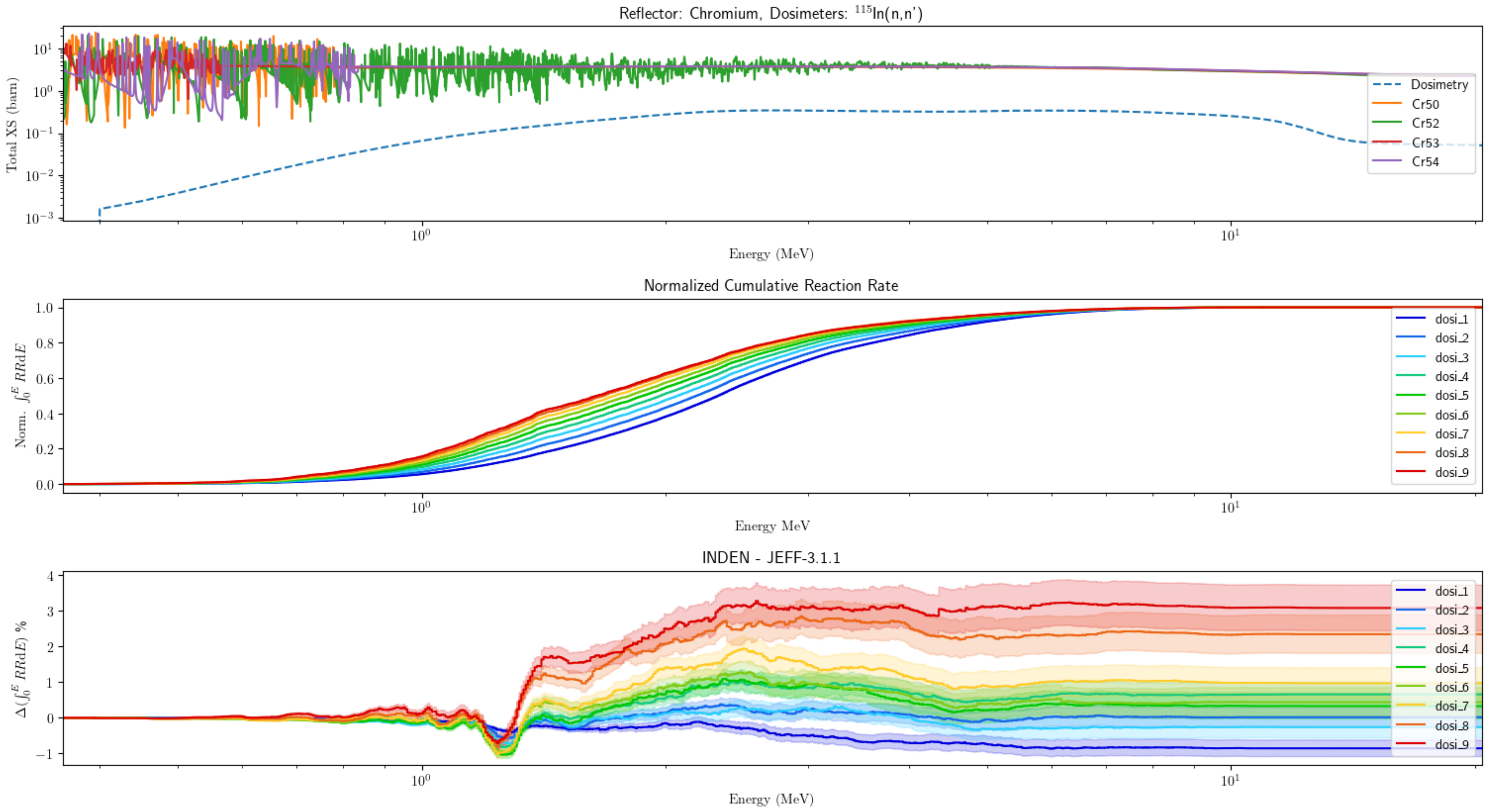


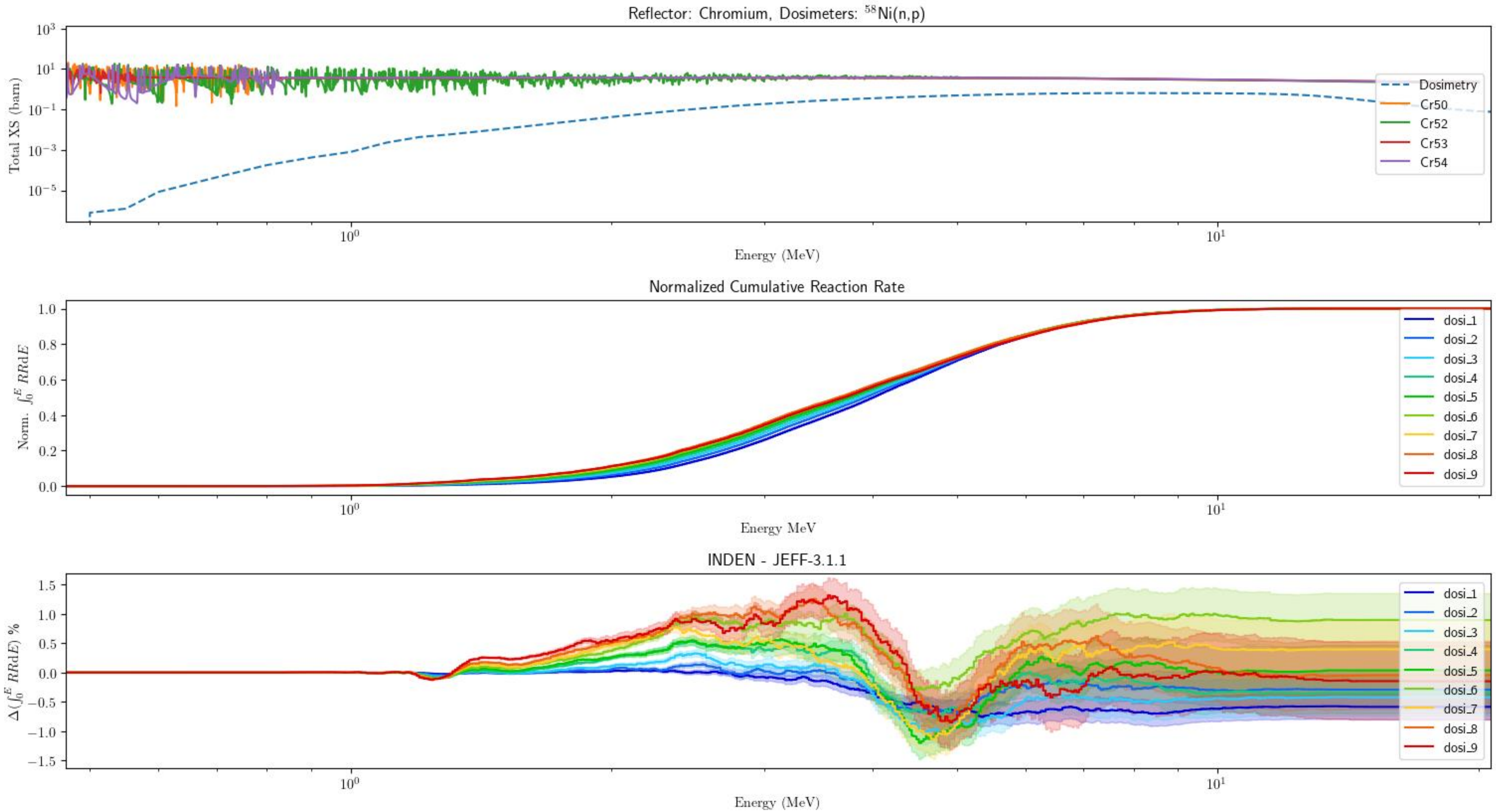
Reflector: Iron, Dosimeters: 27Al(n,a)
Total XS (barn)
Dosimetry
Fe57
Fe58
Fe54
Fe56
Energy (MeV)
Normalized Cumulative Reaction Rate
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
Energy MeV
INDEN_12_23_02_24 - JEFF-3.3
Energy (MeV)


Reflector: Chromium, Dosimeters: ^{115}In(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

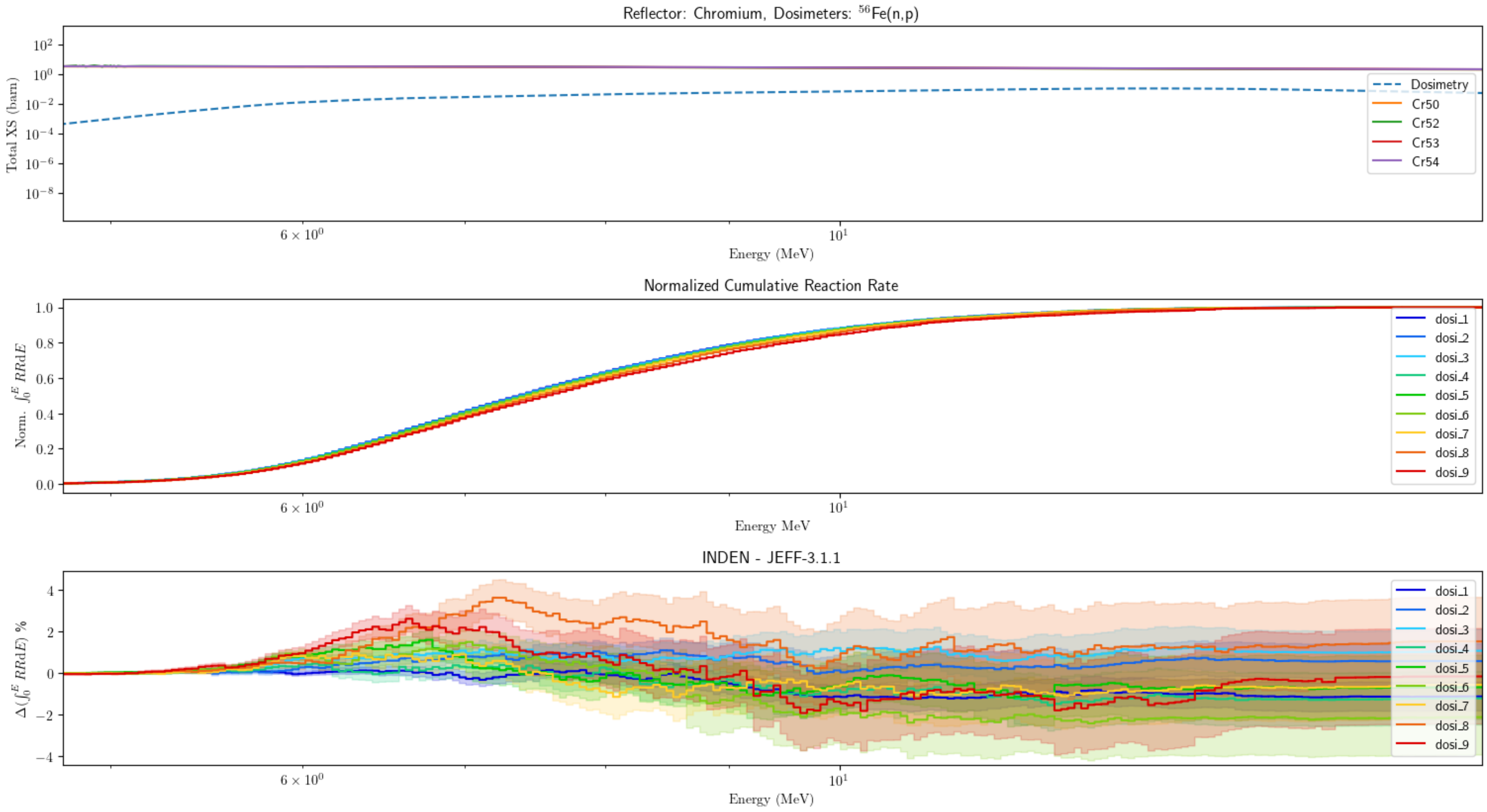


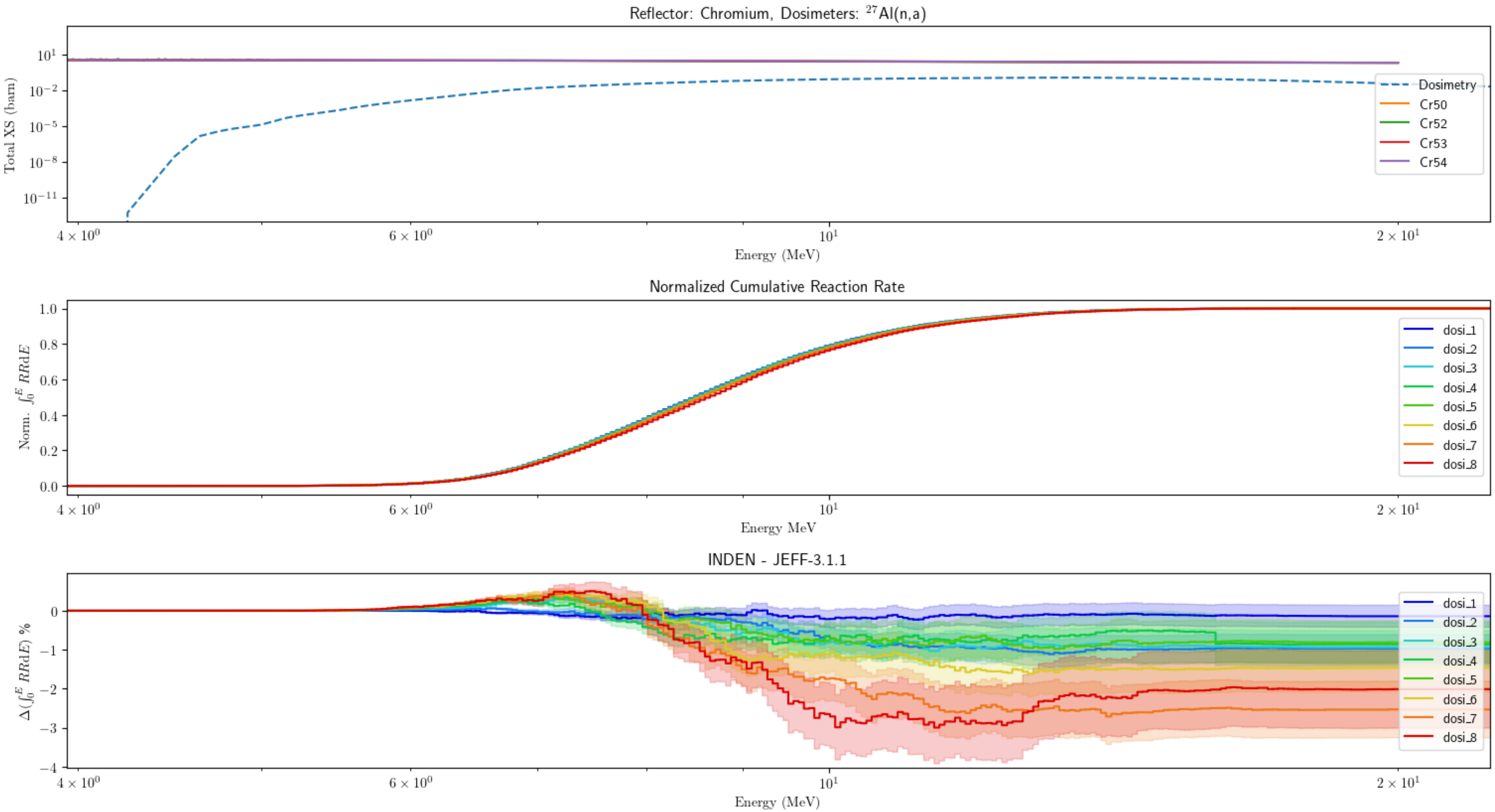
Reflector: Chromium, Dosimeters: ^{197}Au(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)


Reflector: Chromium, Dosimeters: ^{115}In(n,n')
Total XS (barn)
Energy (MeV)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.1.1
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

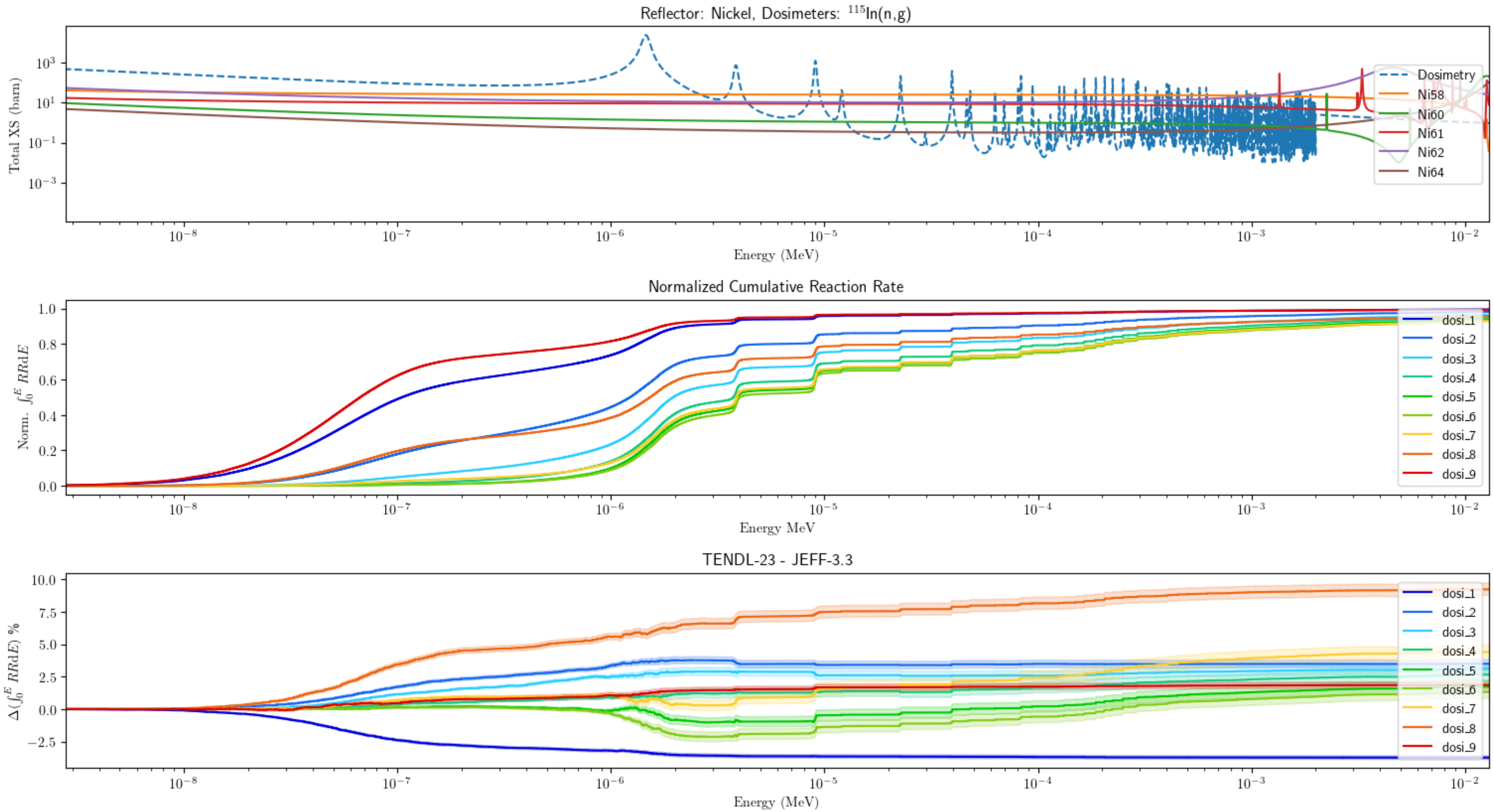


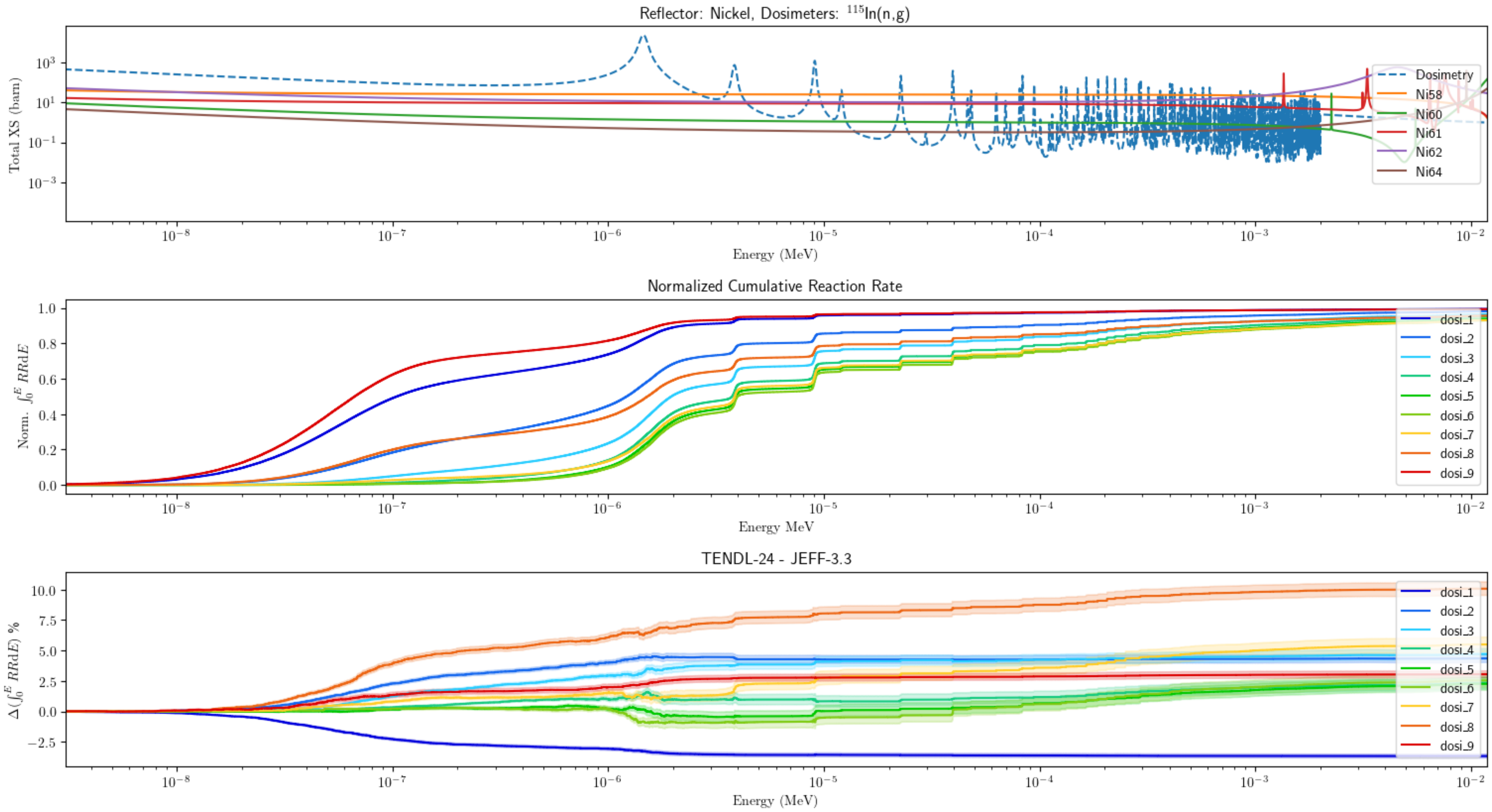
Reflector: Chromium, Dosimeters: ^{58}Ni(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
INDEN - JEFF-3.1.1
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

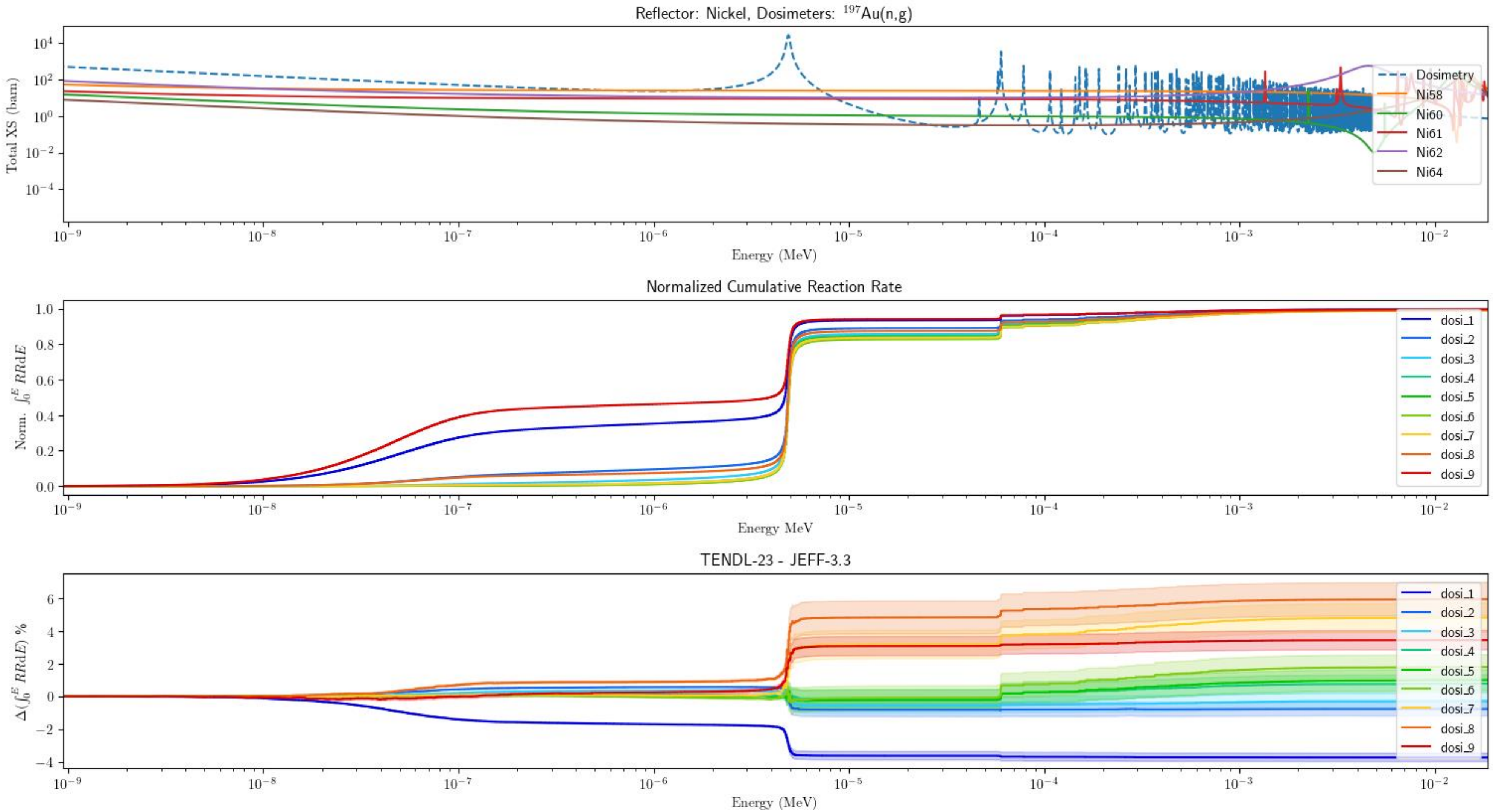

Reflector: Chromium, Dosimeters: ^{56}Fe(n,p)
Total XS (barn)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Energy (MeV)
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
Energy MeV
INDEN - JEFF-3.1.1
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

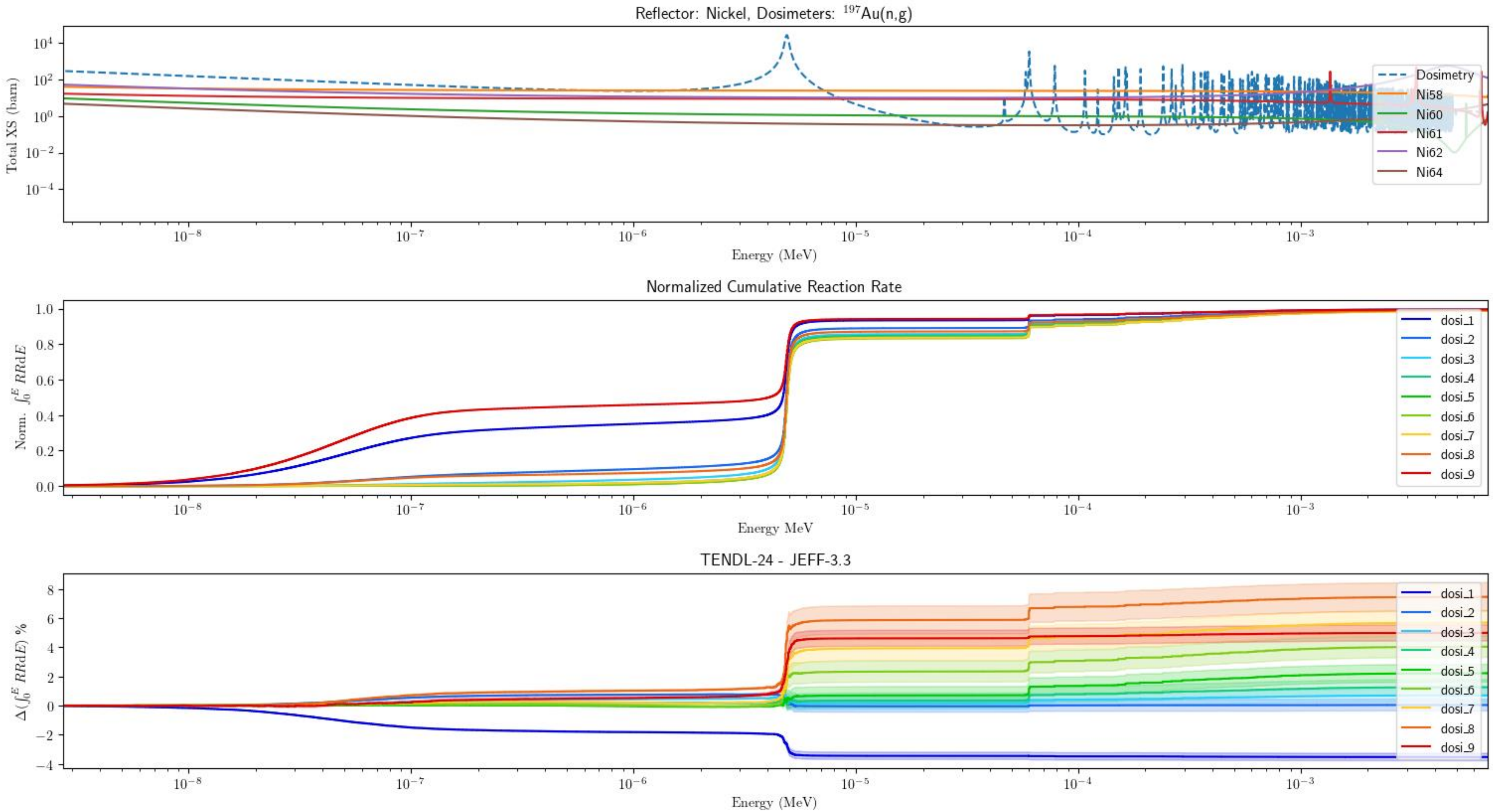


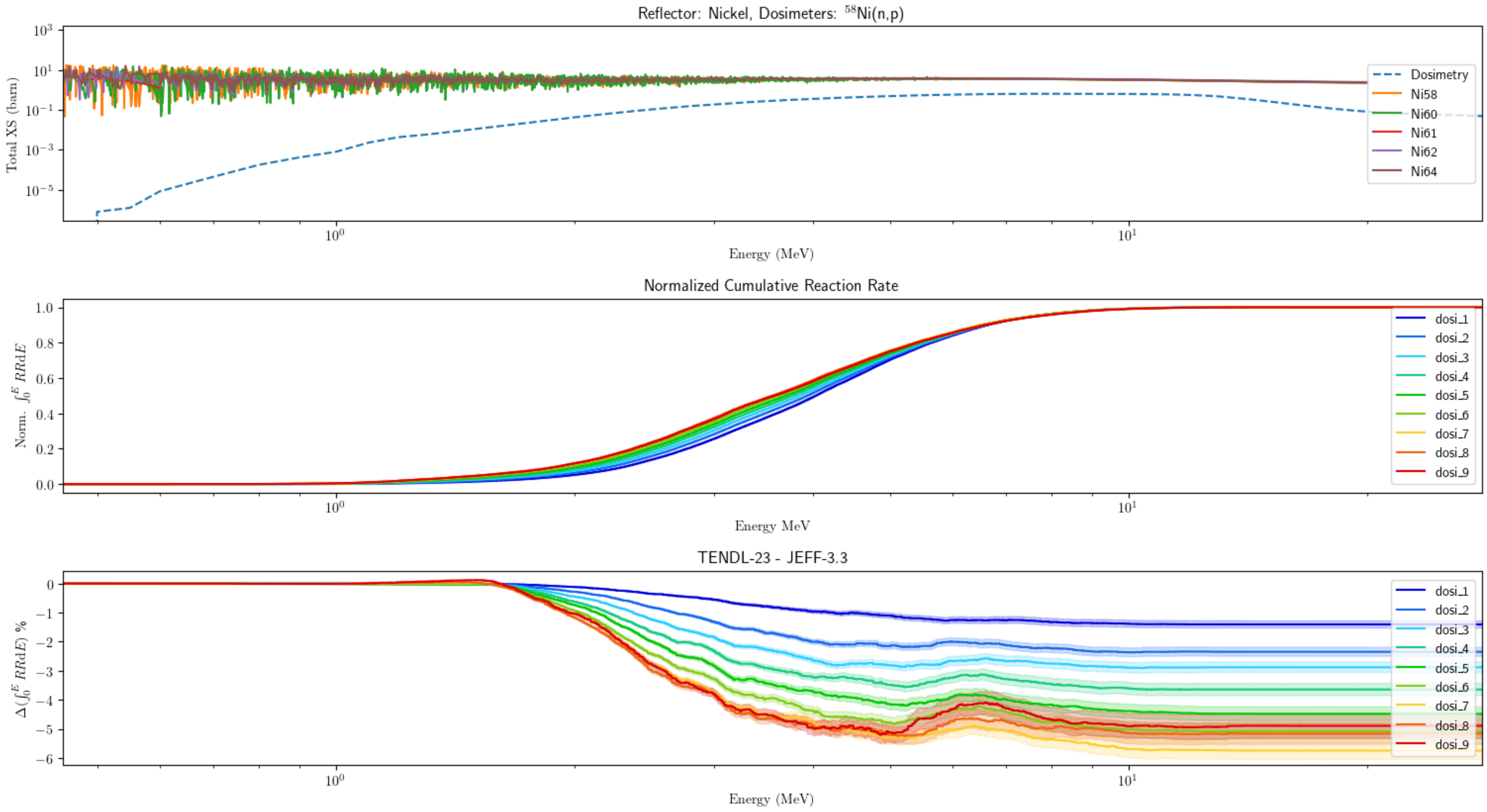
Reflector: Chromium, Dosimeters: ^{27}Al(n,a)
Total XS (barn)
Energy (MeV)
Dosimetry
Cr50
Cr52
Cr53
Cr54
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
INDEN - JEFF-3.1.1
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

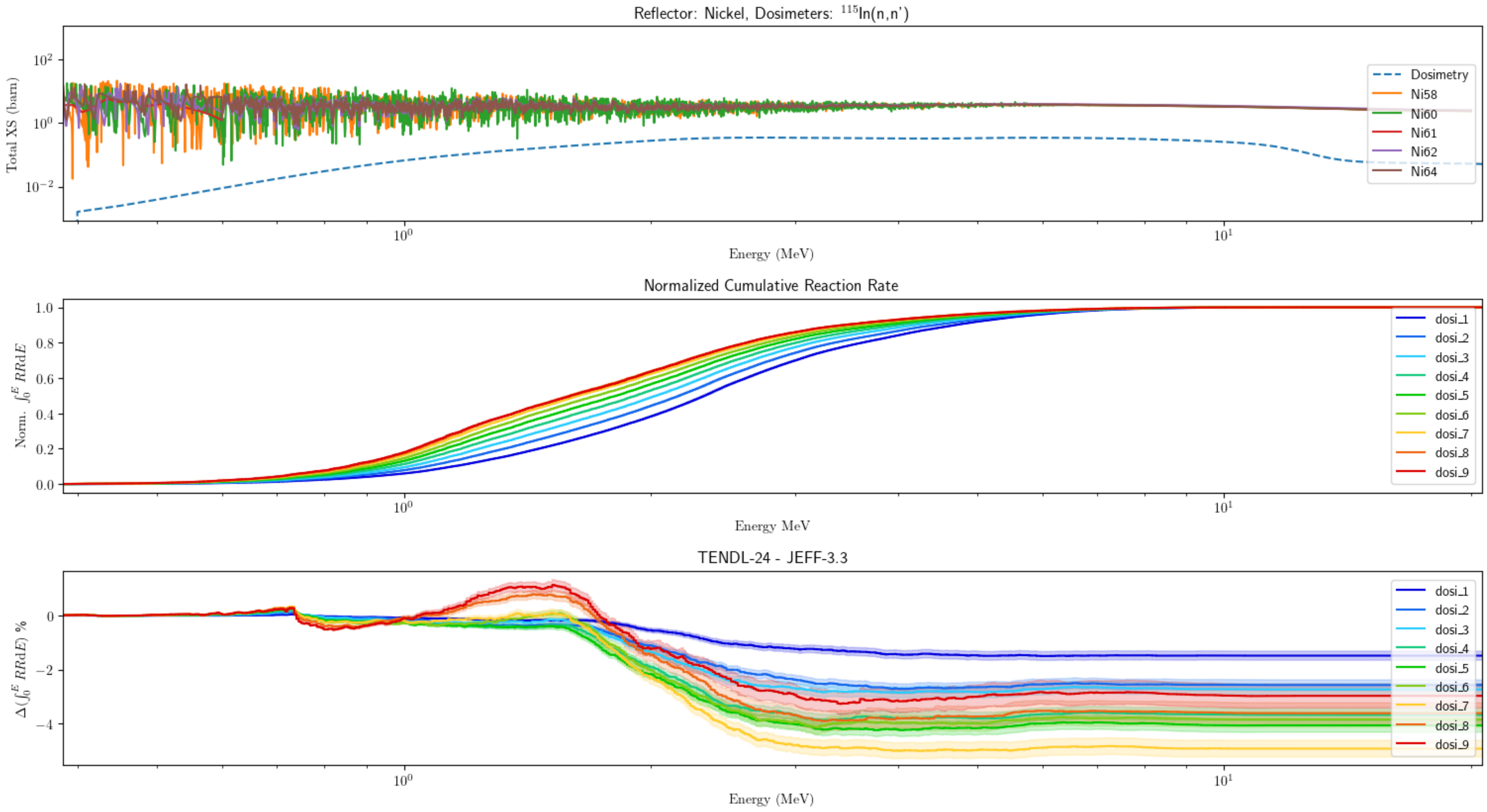

Reflector: Nickel, Dosimeters: 115In(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-23 - JEFF-3.3
Energy (MeV)

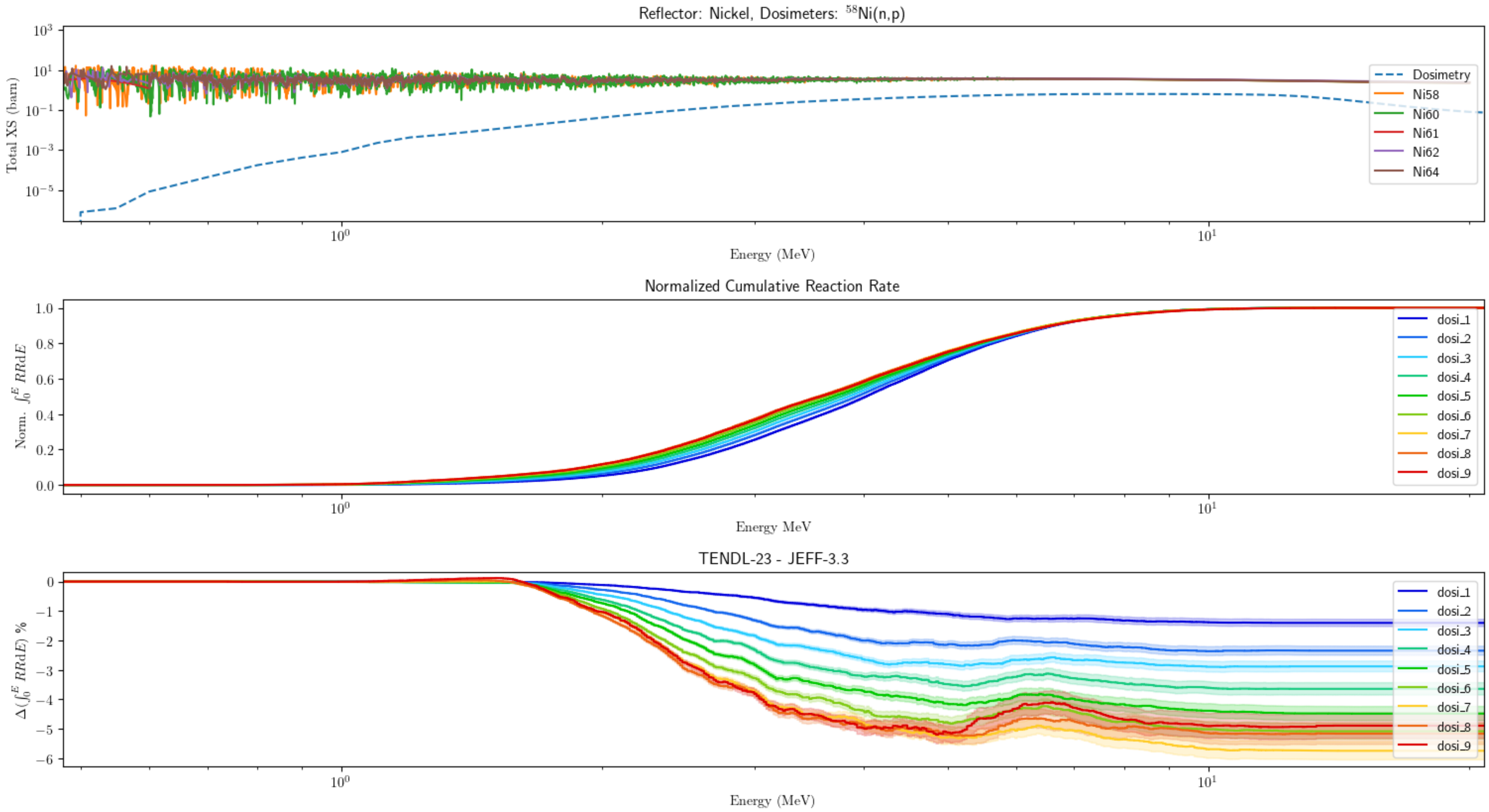

Reflector: Nickel, Dosimeters: ^{115}In(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-24 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)


Reflector: Nickel, Dosimeters: ^{197}Au(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-23 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

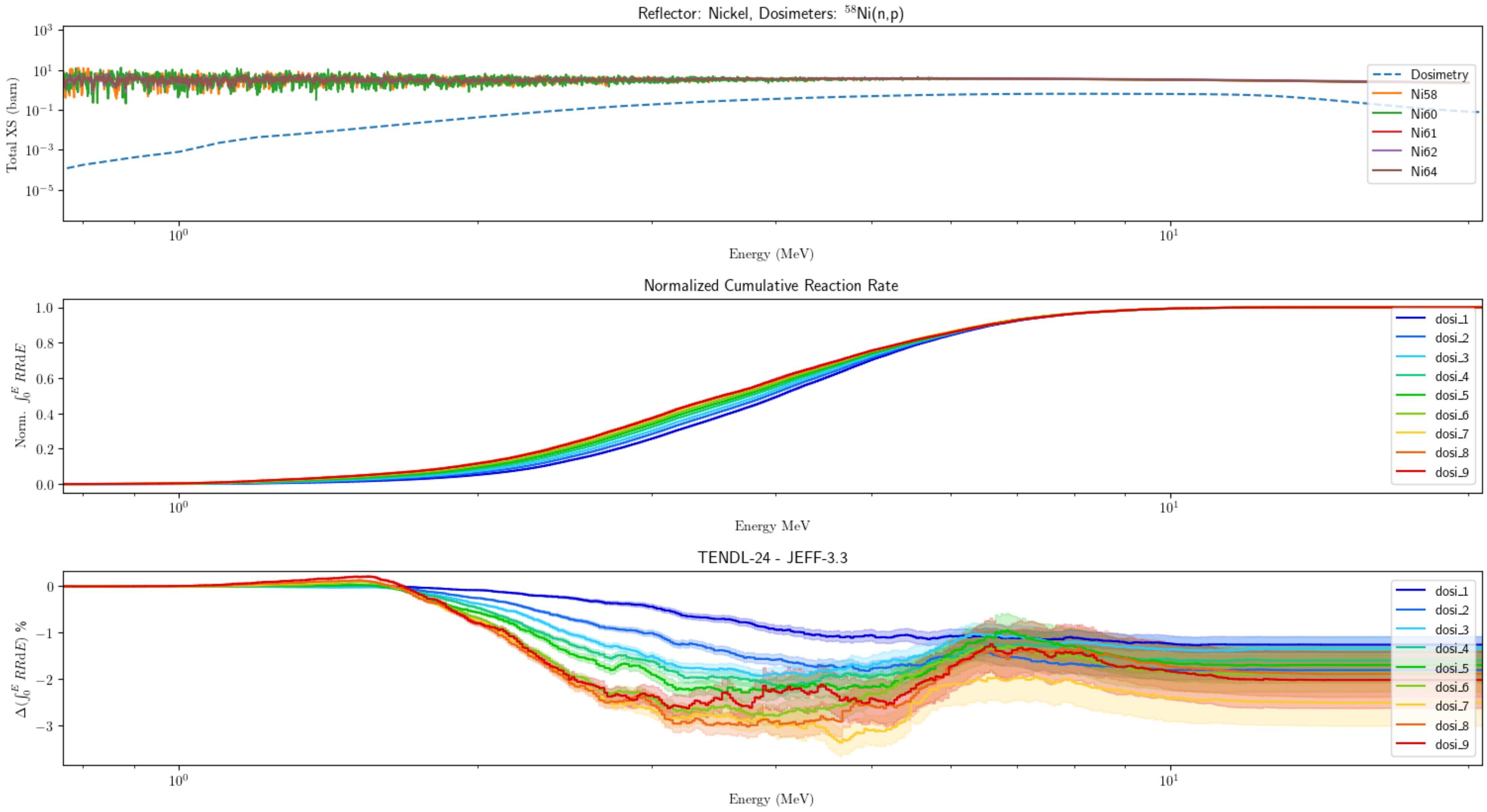

Reflector: Nickel, Dosimeters: ^{197}Au(n,g)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-24 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)


Reflector: Nickel, Dosimeters: 58Ni(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-23 - JEFF-3.3
Energy (MeV)

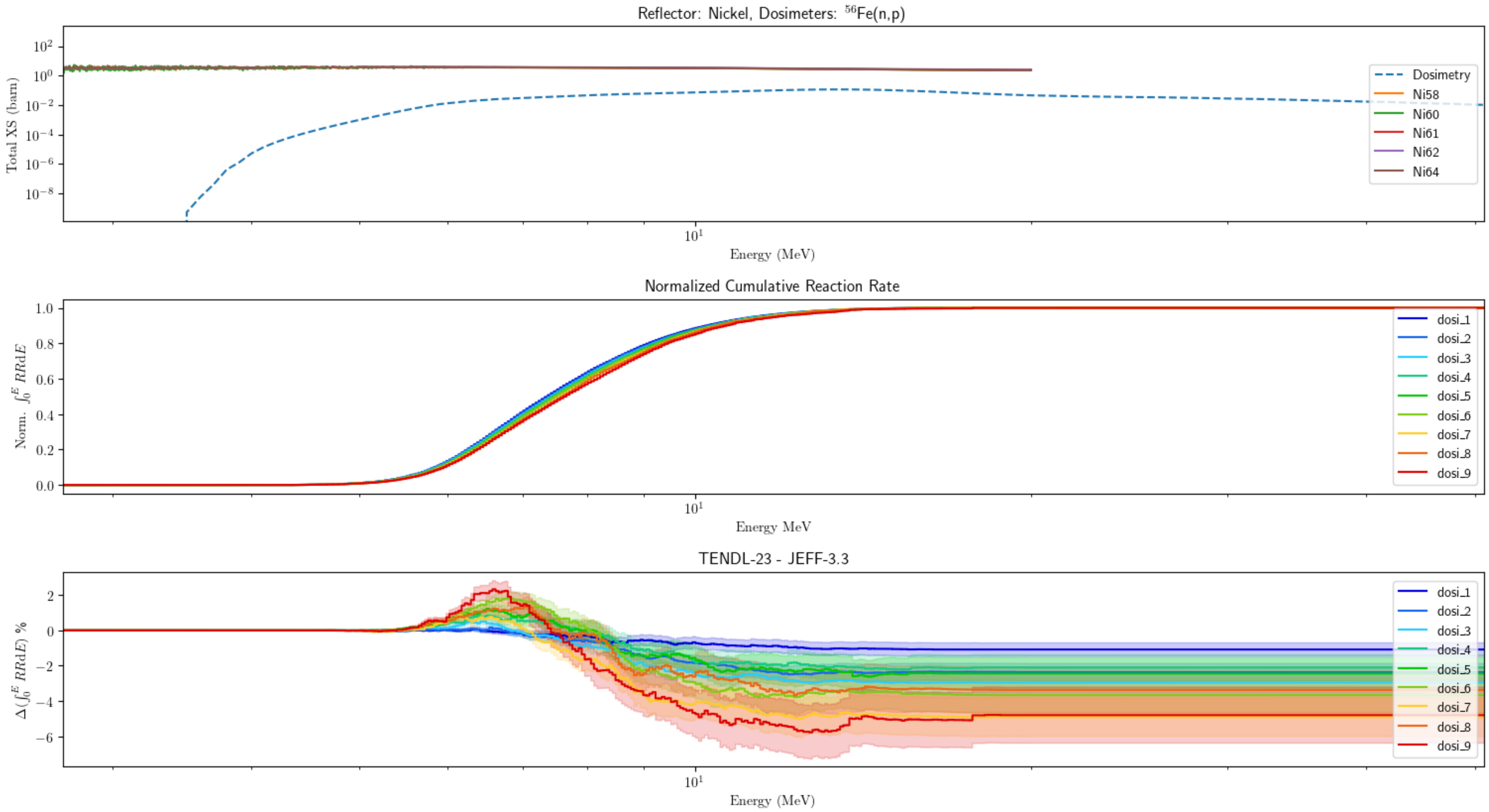

Reflector: Nickel, Dosimeters: 115In(n,n')
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-24 - JEFF-3.3
Energy (MeV)



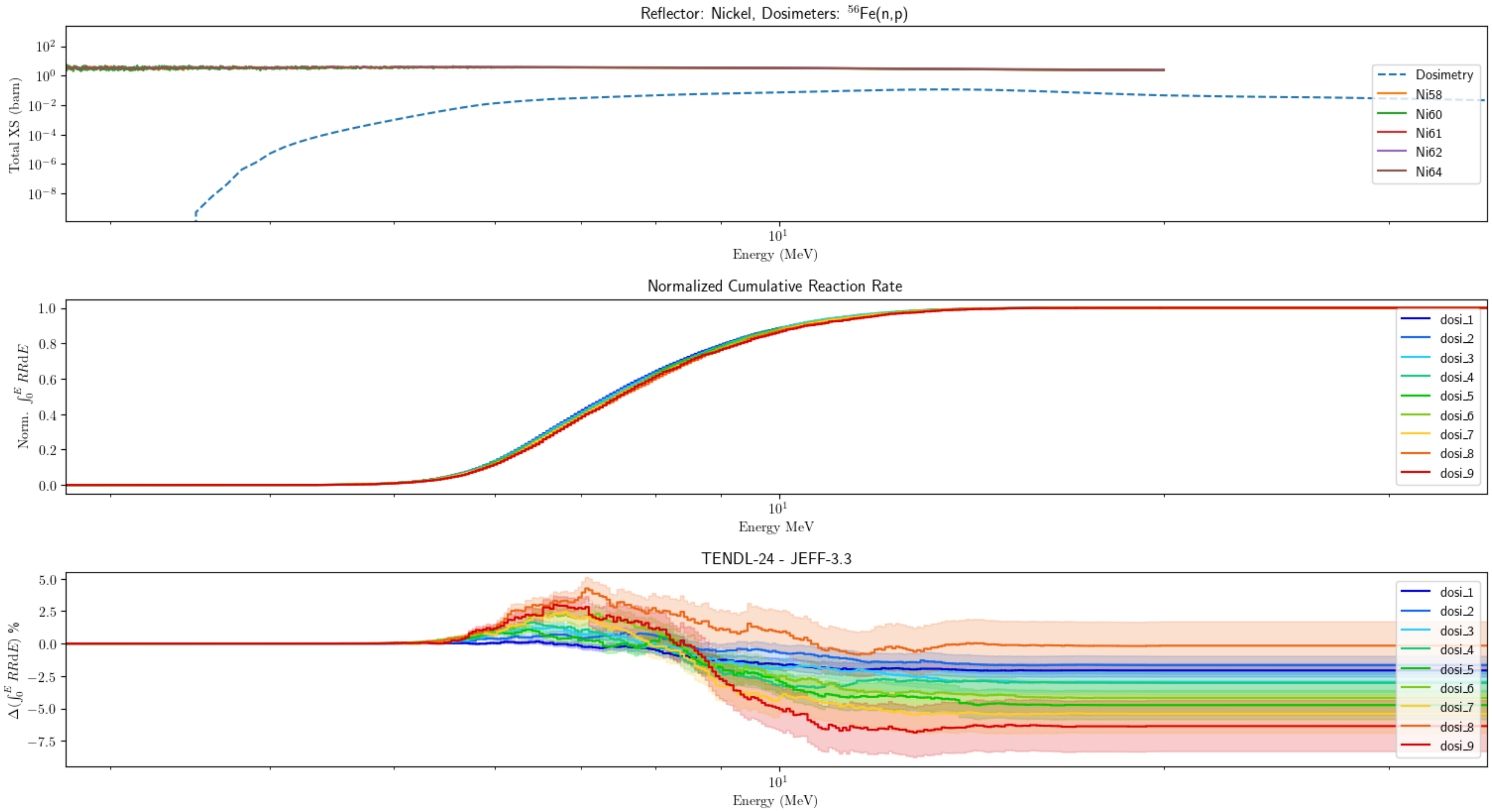
Reflector: Nickel, Dosimeters: ^{58}Ni(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-23 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)



Reflector: Nickel, Dosimeters: ^{58}Ni(n,p)
Total XS (barn)
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^0
10^1
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
1.0
0.8
0.6
0.4
0.2
0.0
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-24 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
0
−1
−2
−3
Energy (MeV)


Reflector: Nickel, Dosimeters: ^{56}Fe(n,p)
Total XS (barn)
Energy (MeV)
Dosimetry
Ni58
Ni60
Ni61
Ni62
Ni64
Normalized Cumulative Reaction Rate
Norm. $\int_0^E RRdE$
Energy MeV
dosi_1
dosi_2
dosi_3
dosi_4
dosi_5
dosi_6
dosi_7
dosi_8
dosi_9
TENDL-23 - JEFF-3.3
$\Delta(\int_0^E RRdE)$ %
Energy (MeV)

■ INDEN Consultancy meeting: Analysis of PETALE and feedback on new evaluations

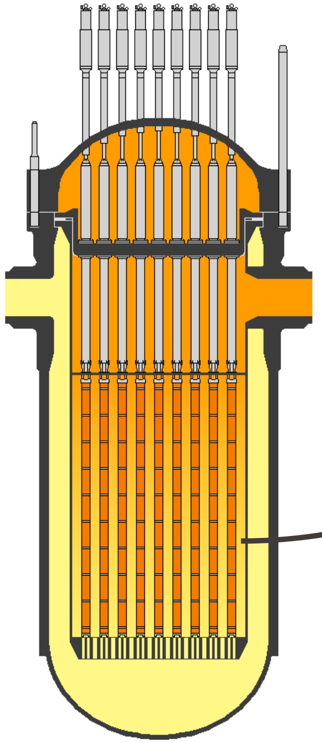


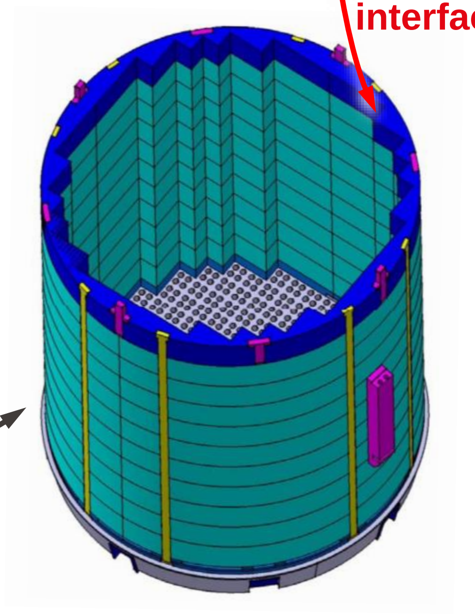
Objective: stainless steel nuclear data

Provide new constraints in the MeV-range and above for stainless steel nuclear data

- Fission: heavy reflectors (GEN-III PWR)
- Fusion: 14 MeV neutrons
- Accelerators: activation

Collaboration between CEA & EPFL

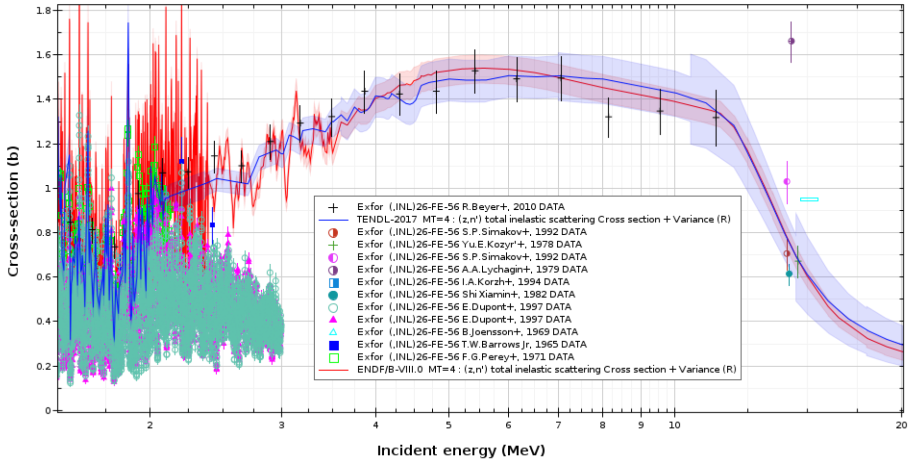




Flux tilt at interface?

EPR heavy reflector

By ChNPP at English Wikipedia, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=22017751



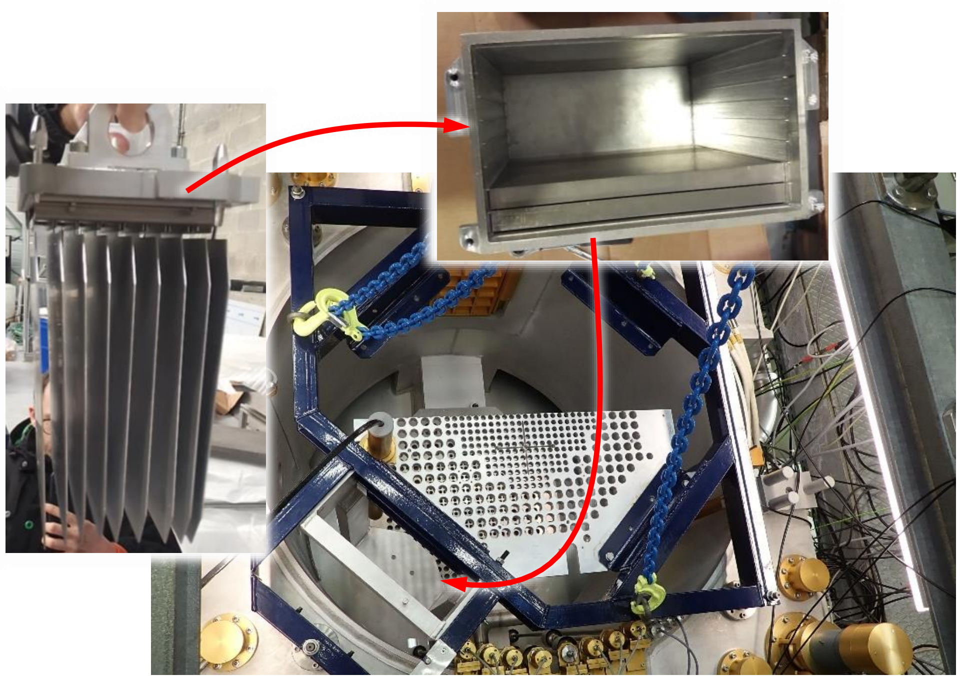
Iron inelastic scattering cross section data (JANIS)

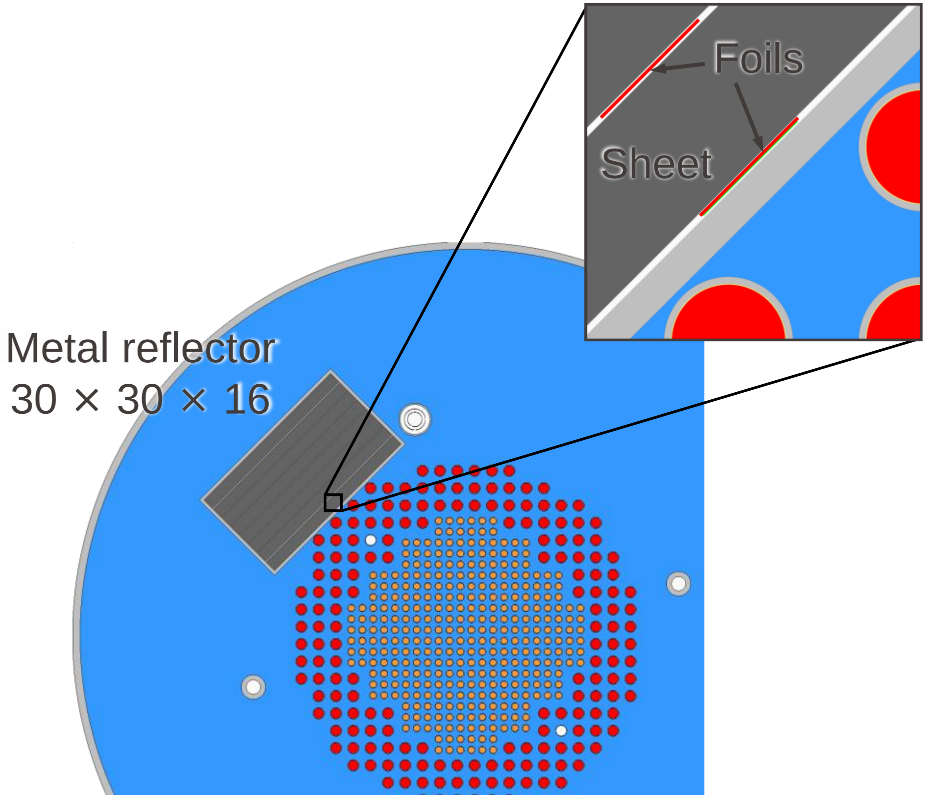
Experimental design

Program in CROCUS* on elemental-type reflector experiments, for new constraints in the MeV-range on stainless steel nuclear data

- Separate study of s. steel (304L), Fe, Ni and Cr
  - Reactivity worth of reflectors
  - **Transmission using activation dosimetry**

Collaboration between CEA & EPFL





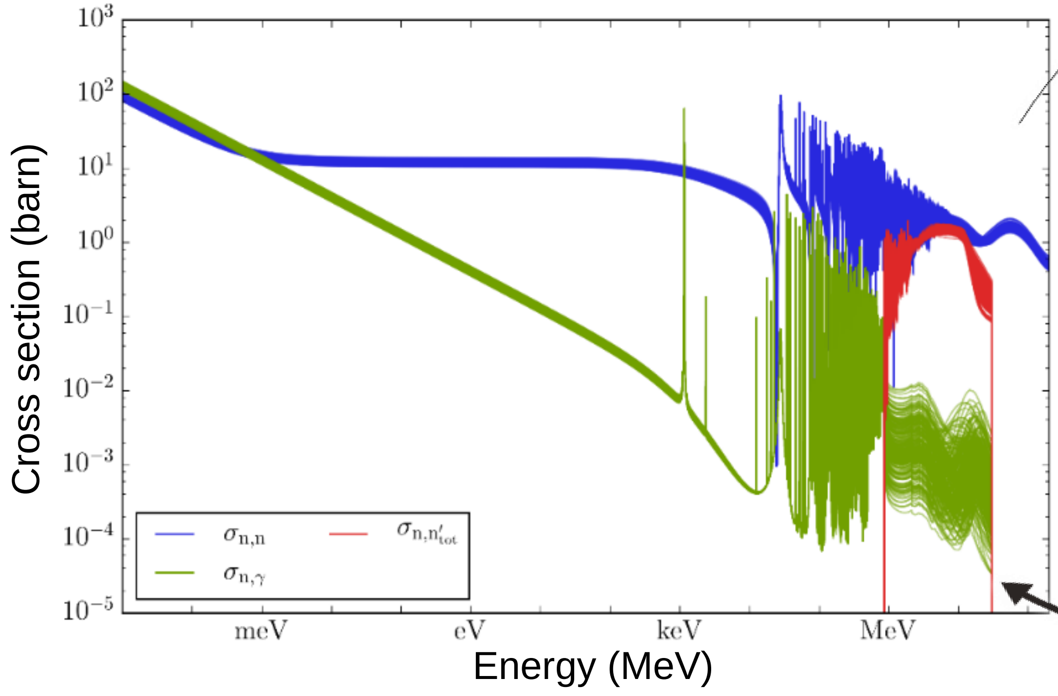
* V. Lamirand et al., "Design of separated element reflector experiments in CROCUS: PETALE," React. Dosim. 16th Int. Symp. ASTM STP1608, p. 7, 2018.

Vincent Lamirand

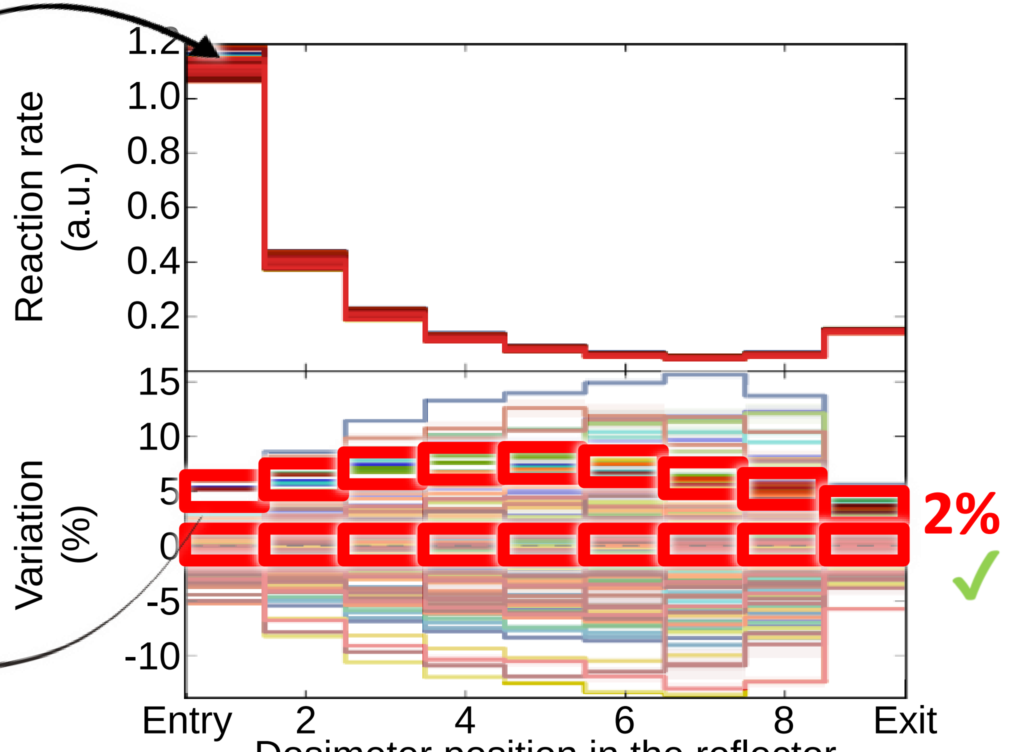
Experimental design by uncertainty propagation

Relating XS uncertainty distribution with measured reaction rates using Total Monte Carlo and Correlated Sampling[1,2]

× N full core Monte Carlo calculations
⇔ 1 node week



^{56}Fe cross sections dispersion in TENDL 2017

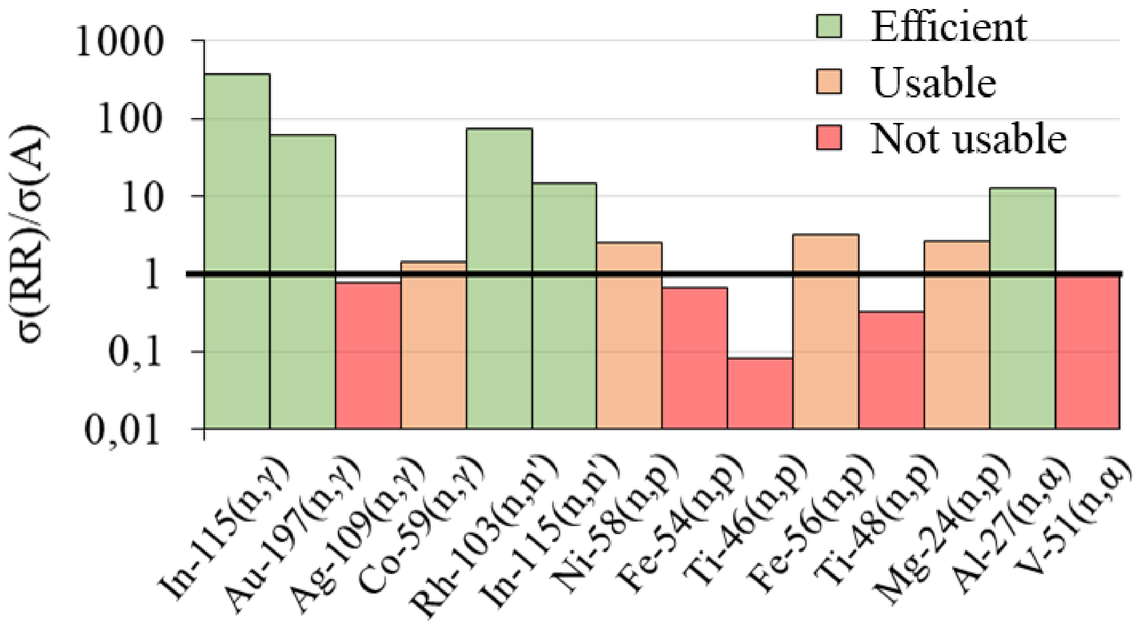


Reaction rate distributions with In(n,γ) in the iron metal reflector (128 ACE files)

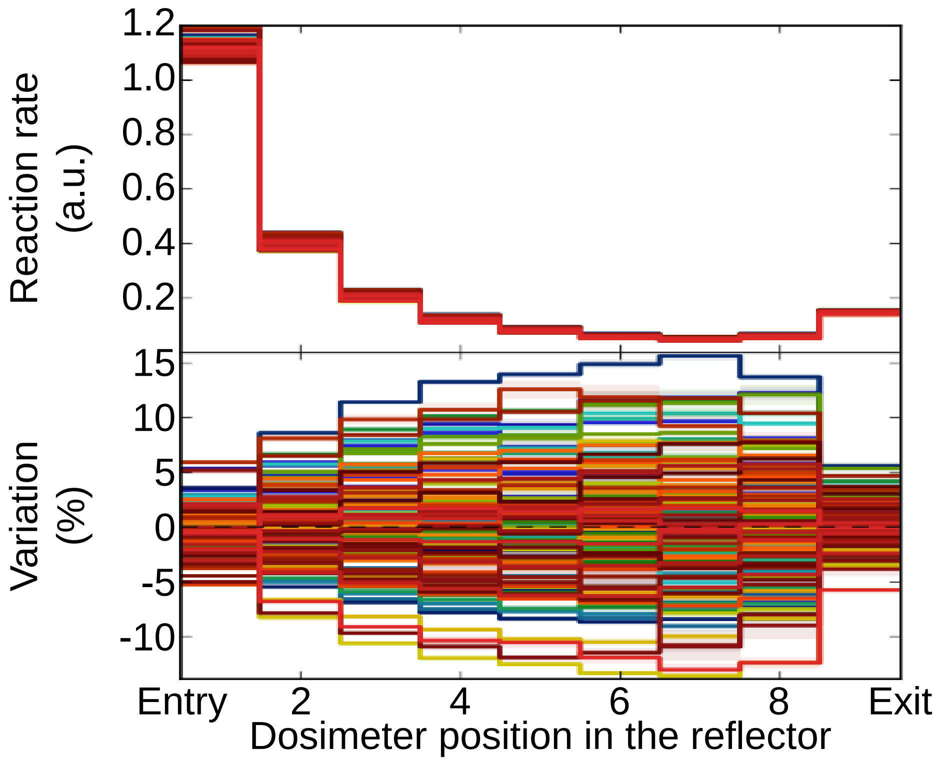
[1] A. Laureau et al., "Uncertainty propagation for the design study of the PETALE experimental programme in the CROCUS reactor," *EPJ Nucl. Sci. Technol.*, vol. 6, p. 9, 2020.
[2] V. Lamirand *et al.*, "An Experimental Programme optimized with Uncertainty Propagation: PETALE in the CROCUS Reactor," *EPJ Web Conf.*, vol. 211, p. 03003, Jun. 2019

Experimental design by uncertainty propagation

Relating XS uncertainty distribution with measured reaction rates using Total Monte Carlo and Correlated Sampling[1,2]



× N full core Monte Carlo calculations
⇔ 1 node week



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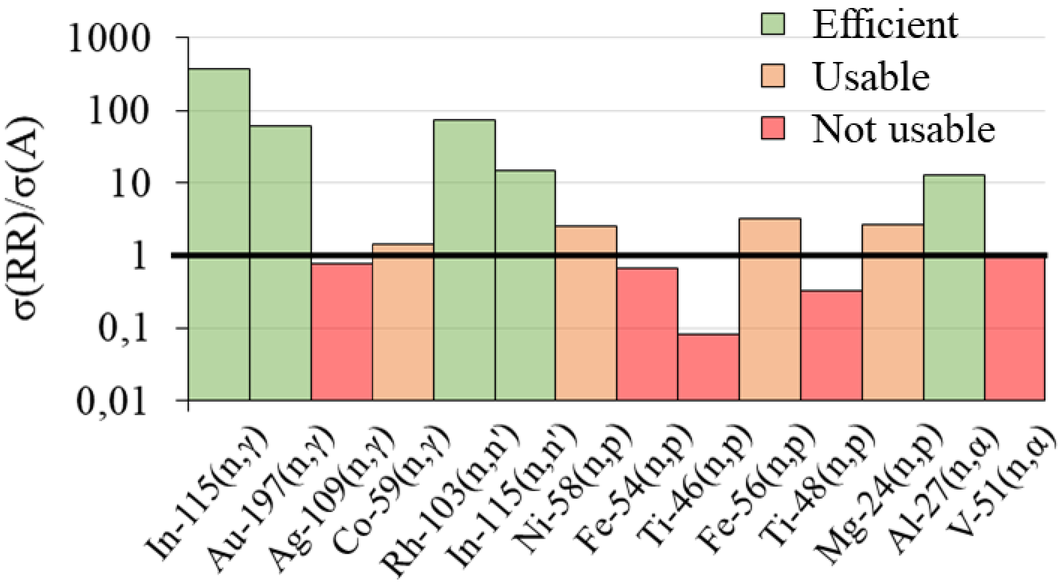
Experimental design by uncertainty propagation

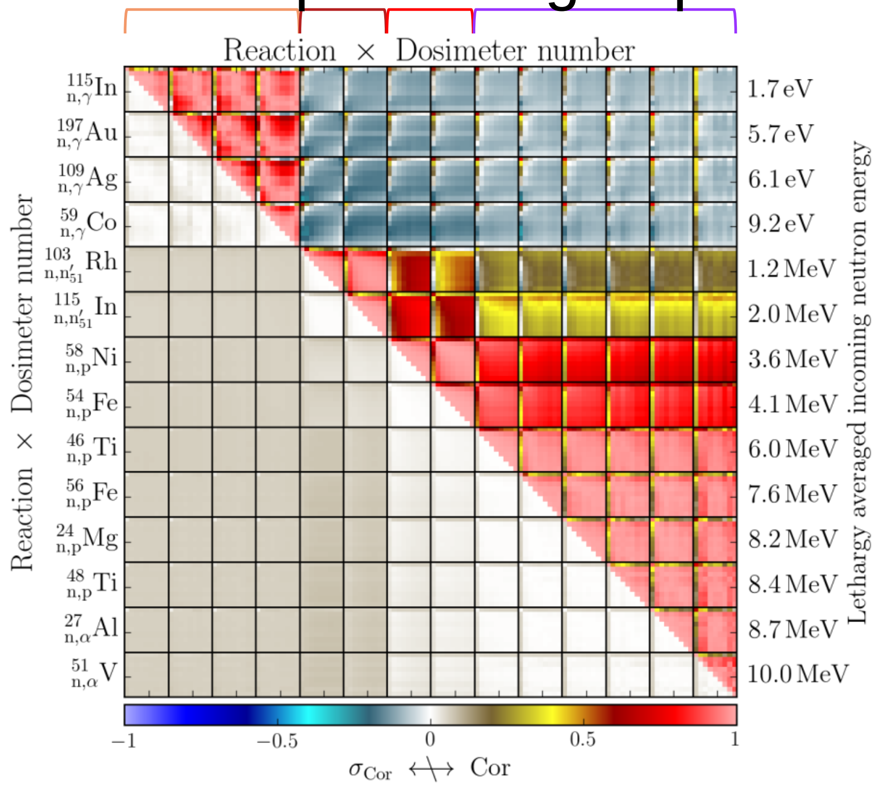
Relating XS uncertainty distribution with measured reaction rates using Total Monte Carlo and Correlated Sampling[1]

Dosimeters selection + target uncertainty



Ratios between RR distributions and activity uncertainties for the iron reflector

4 independent groups

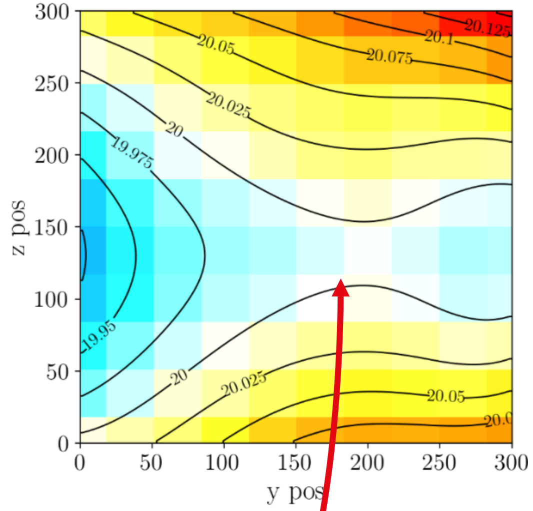


Correlations between reactions for each dosimeters' locations, in the case of the iron reflector

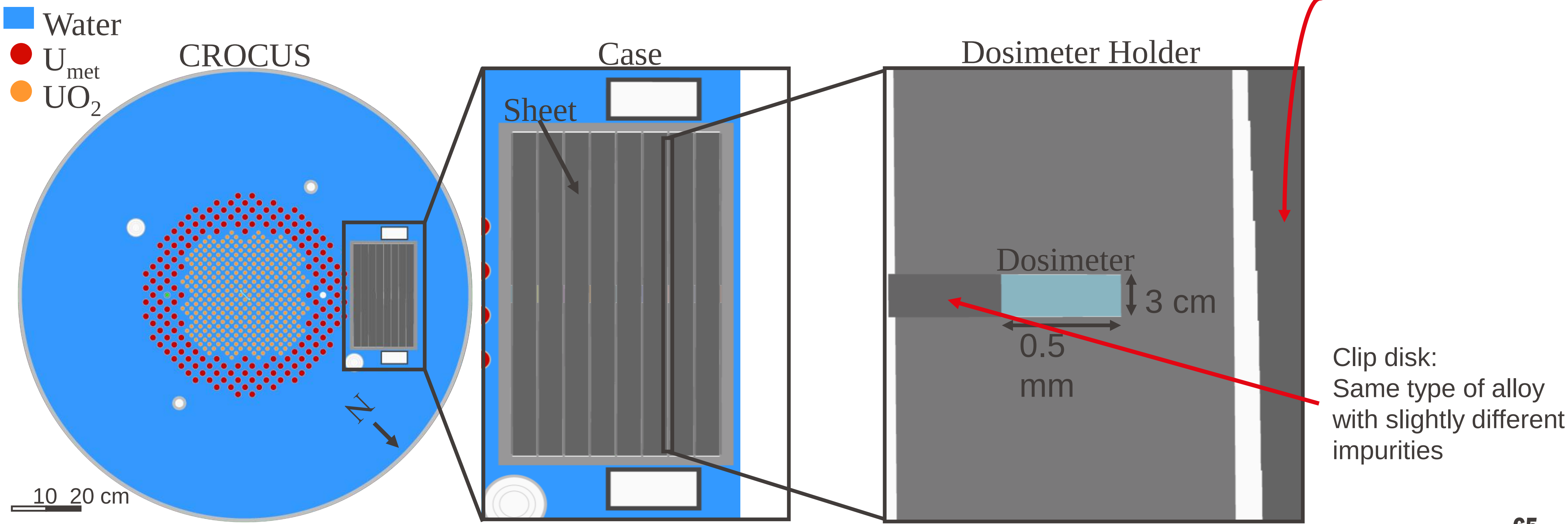
[1] V. Lamirand *et al.*, "An Experimental Programme optimized with Uncertainty Propagation: PETALE in the CROCUS Reactor," *EPJ Web Conf.*, vol. 211, p. 03003, Jun. 2019.

High resolution model

- From design model to high resolution
  - Model with structural elements
  - Fully voxelated reflectors
- Estimation of correction factors and uncertainties
  - **Preparation for the benchmark**
- Simulation with Serpent2 (EPFL)…



Topology of a Fe sheet



Simulation with custom SERPENT2 solver

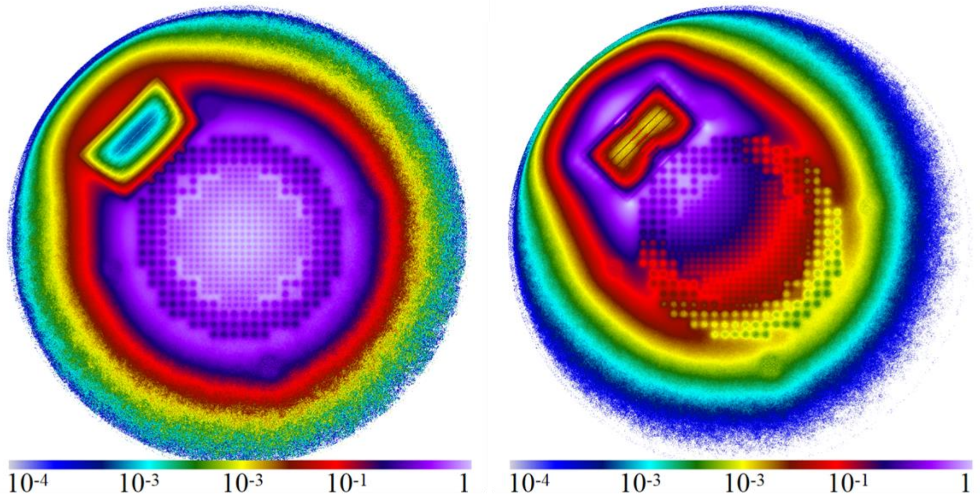
3D Monte-Carlo transport code

- Modified build of Serpent 2.1.21[1, 2]
  - Dosimeter tally with IRDFF-II library[3]
  - Variance reduction method
  - Correlated sampling
    - ND uncertainty propagation
      - Sampled XS: neutrons with multiple weights
      - Multiple results at once
    - More information tomorrow at 10:54 with Axel Laureau in Session Tu2T2
      - With openMC

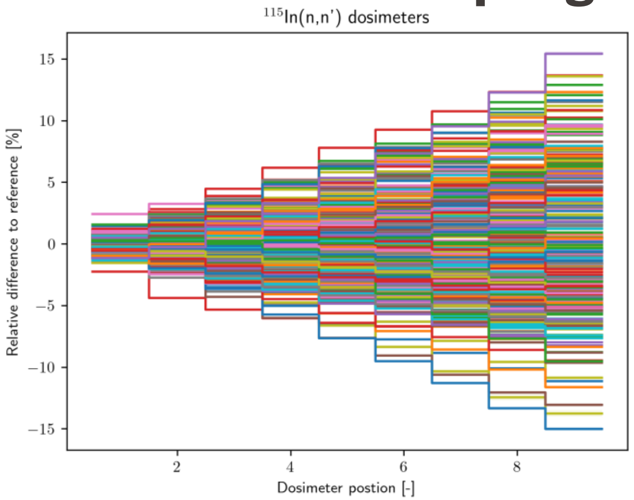
  - **Works with surface tracking**
    - **Not implemented in delta tracking**
    - **Better convergence of thin surfaces**

Variance reduction

Thermal neutron flux　　Biased neutron flux



Correlated sampling

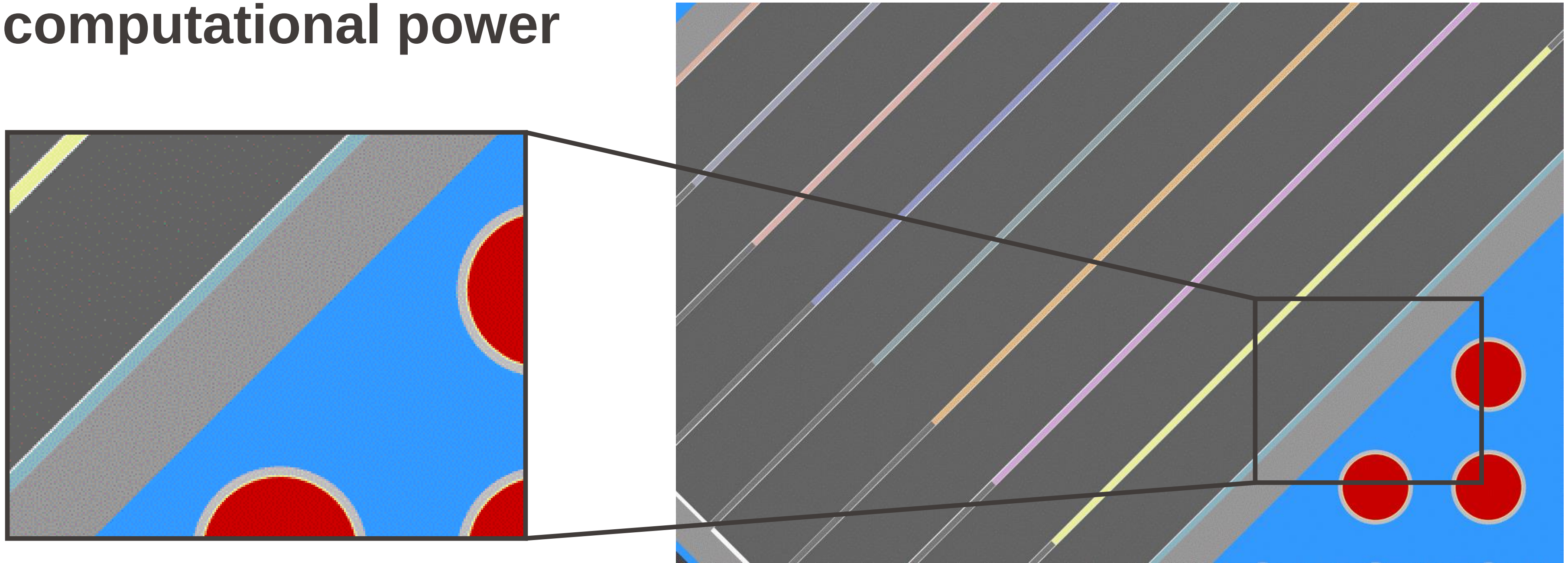


1. J. Leppänen, et al., "The serpent monte carlo code: Status, development and applications in 2013,"
2. A. Laureau, et al., "Monte-carlo development for ND assimilation and experiment optimisation.".
3. A. Trkov, et al., "IRDFF-II: A New Neutron Metrology Library. Special issue of Nuclear Data Sheets", Vol. 163, pp. 1-108 (2020)

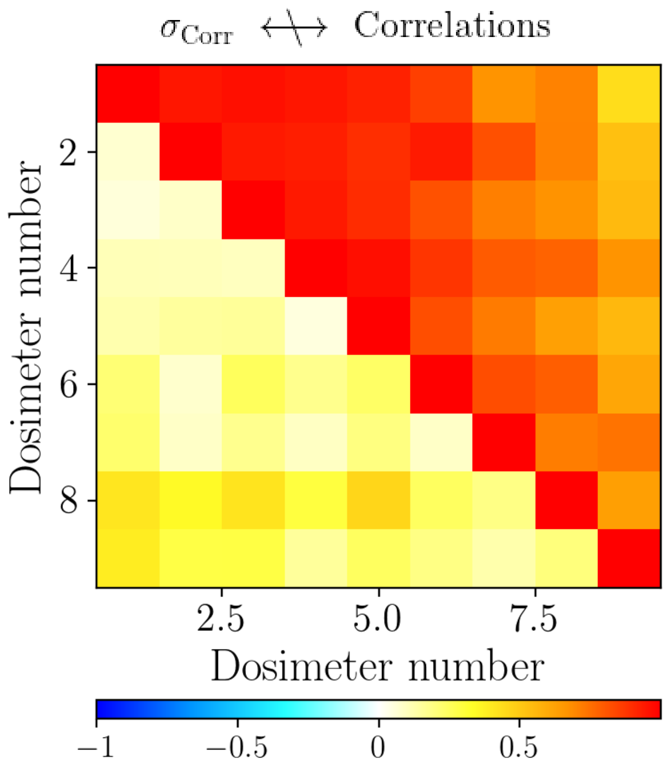
Model constraint: uncertainties on position

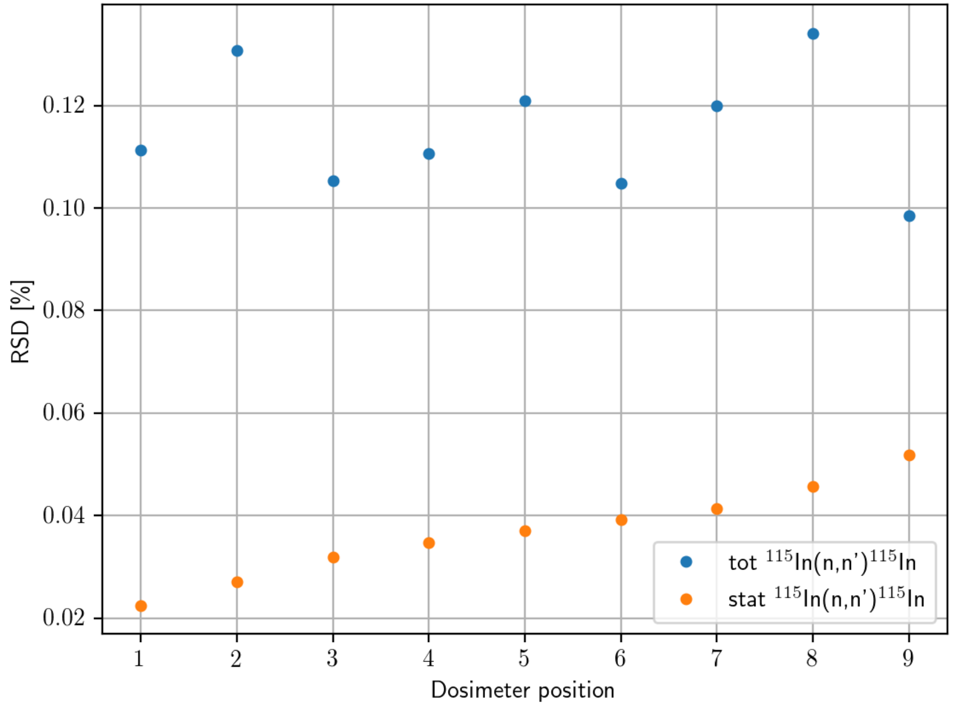
Monte Carlo estimation of position uncertainties

- Results obtained through perturbed geometries calculation
- All elements can move with respect to their mechanical clearance
- The box itself can move with respect to position uncertainties
- Uncertainties and correlations included in the final C/E
- **Expensive in computational power**



Model constraint: uncertainties on position





Backup Computational Methods

Monte Carlo neutron transport simulation

- Core uncertainties

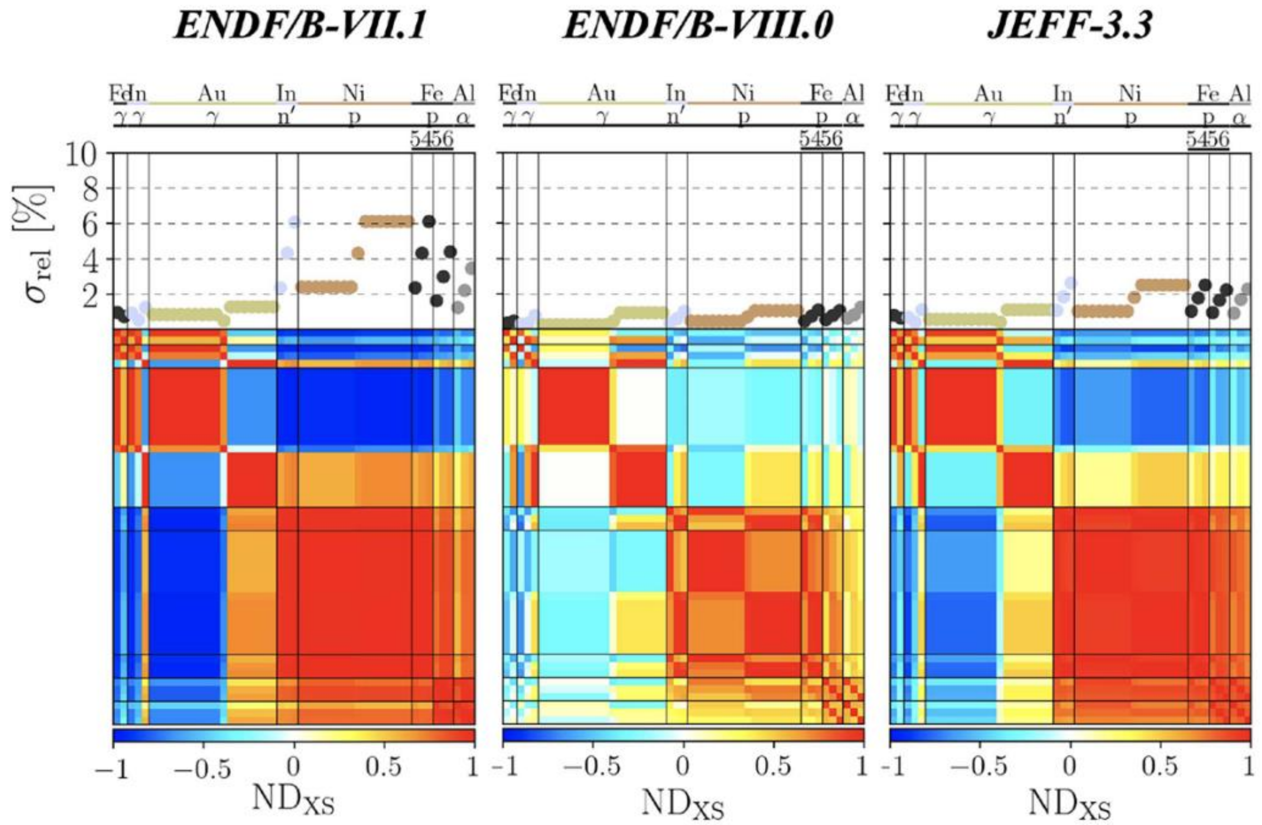


Fig. 9. Propagated nuclear data uncertainty on the dosimeter reaction rate using ENDF/B-VII.1 (left), ENDF/B-VIII.0 (middle) and JEFF-3.3 (right). The top plots are the standard deviation (1σ) for the different dosimeters and reactions on the x-axis. The bottom matrices are the correlation matrices associated with the standard deviation.

A. Laureau *et al.*, "Analysis of the preliminary campaign for the PETALE program" EPJ N, vol. 9, no. 8, p 25, 2023

Backup: TMC

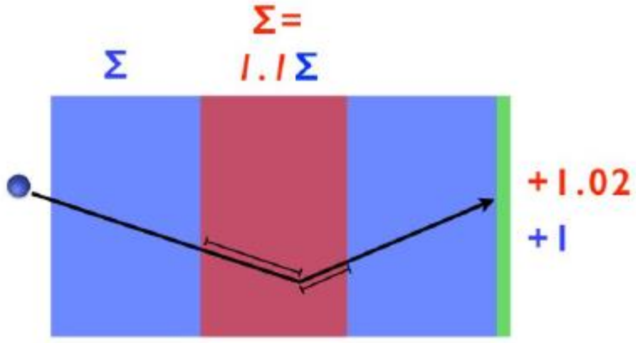
Correlated Sampling technics?

Principle

- Objective: replace 2 “close” calculations by a single one
  → *calculation speed-up - only 1 run*
  → *variance reduction - same neutron path*
  → *no first order assumption*
- Neutron weight modification
  → *ratio of probabilities between the two systems*
- Different application fields
  → *surface displacement*
  → *element concentration / density modification*
  → *Doppler effect*
  → *... nuclear data uncertainty*

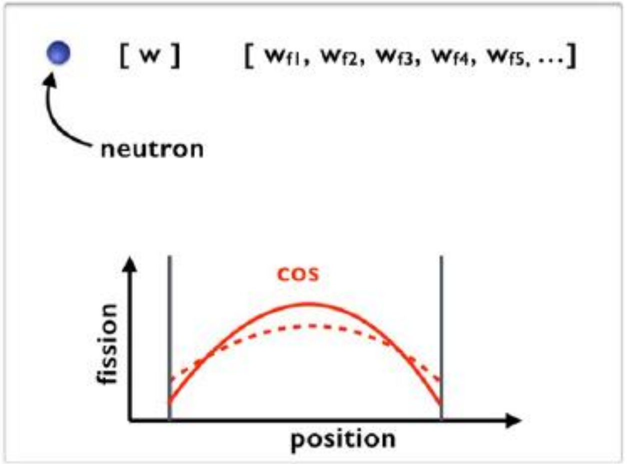
Drawbacks

- Needs probabilities different from zero and infinity
  → *can not make isotope appears from scratch*
- If the systems are too different the neutron weight is too different
  → *bad convergence*



Ratio of probability for a distance d sampling: $\dfrac{\Sigma_{tot}^{pert}\exp(-d\cdot\Sigma_{tot}^{pert})}{\Sigma_{tot}\exp(-d\cdot\Sigma_{tot})}$

Ratio of probability for the reaction sampling: $\dfrac{\Sigma_{n,r}\cdot\Sigma_{tot}^{pert}}{\Sigma_{tot}\cdot\Sigma_{n,r}^{pert}}$



Backup: TMC

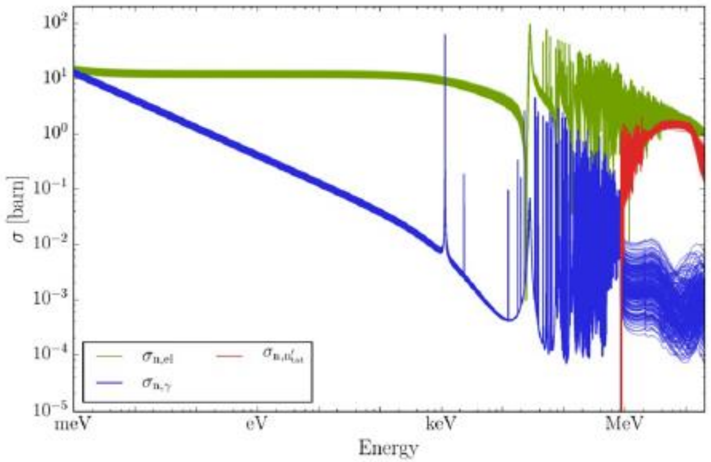
Correlated Sampling with multiple Cross Sections: TMC-CS

Principle

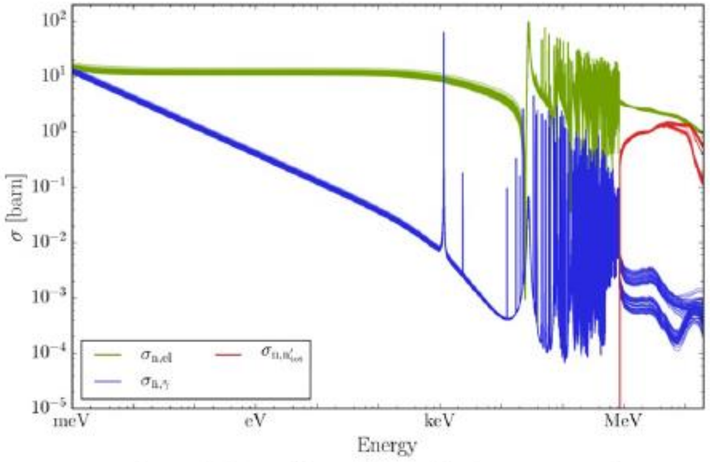
- Each set of cross sections corresponds to a different system
  → *different probabilities during the transport*
- Neutron weight modification for each XS set
- Multiple "isotopes" and "mt" all together
  → *ratio of probabilities between the two systems*

Nuclear Data cross sections

- "Classic" TENDL cross section
  → *sampling on the nuclear data parameters*
- "Extended" TENDL - EUROfusion ("to fill the gap")
  → *sampling on the nuclear models themselves (more challenging)*



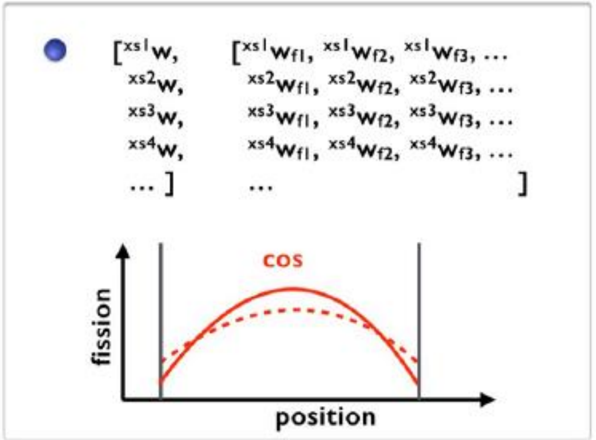
256 random TENDL ^{56}Fe cross sections



2 models x 40 random ^{56}Fe cross sections

→ *discontinuities*

→ *non linearity?*

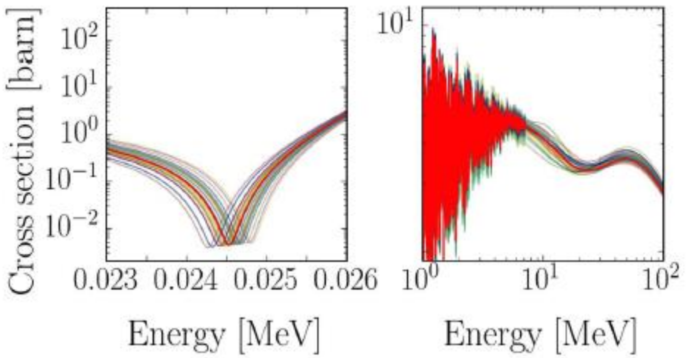


Backup: TMC

Long term objective: constrain nuclear data

Principle of the Bayesian Monte Carlo (BMC)

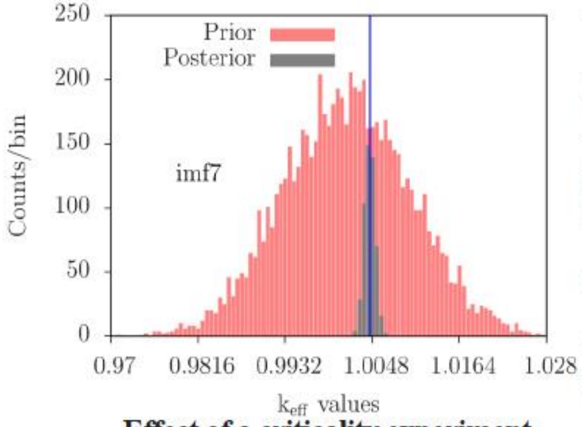
- Step 1: generation of random cross sections (XS) in agreement with the prior experimental knowledge
  ➙ *e.g. TENDL, JEFF+NUSS*
- Step 2: Total Monte Carlo (TMC) uncertainty propagation
  ➙ *prior calculated "C" value for each set of cross sections*
- Step 3: Comparison with experimental "*E*" results and XS-weighting in the BMC process
  ➙ *reduced posterior uncertainty using* $w_x = \exp\left(-\frac{\mathrm{Res}^T \mathrm{Cov}^{-1} \mathrm{Res}}{2}\right)$ → C-E



TENDL - ^{56}Fe random XS_{tot}

Hypothesis : ther is no slope in the C/E

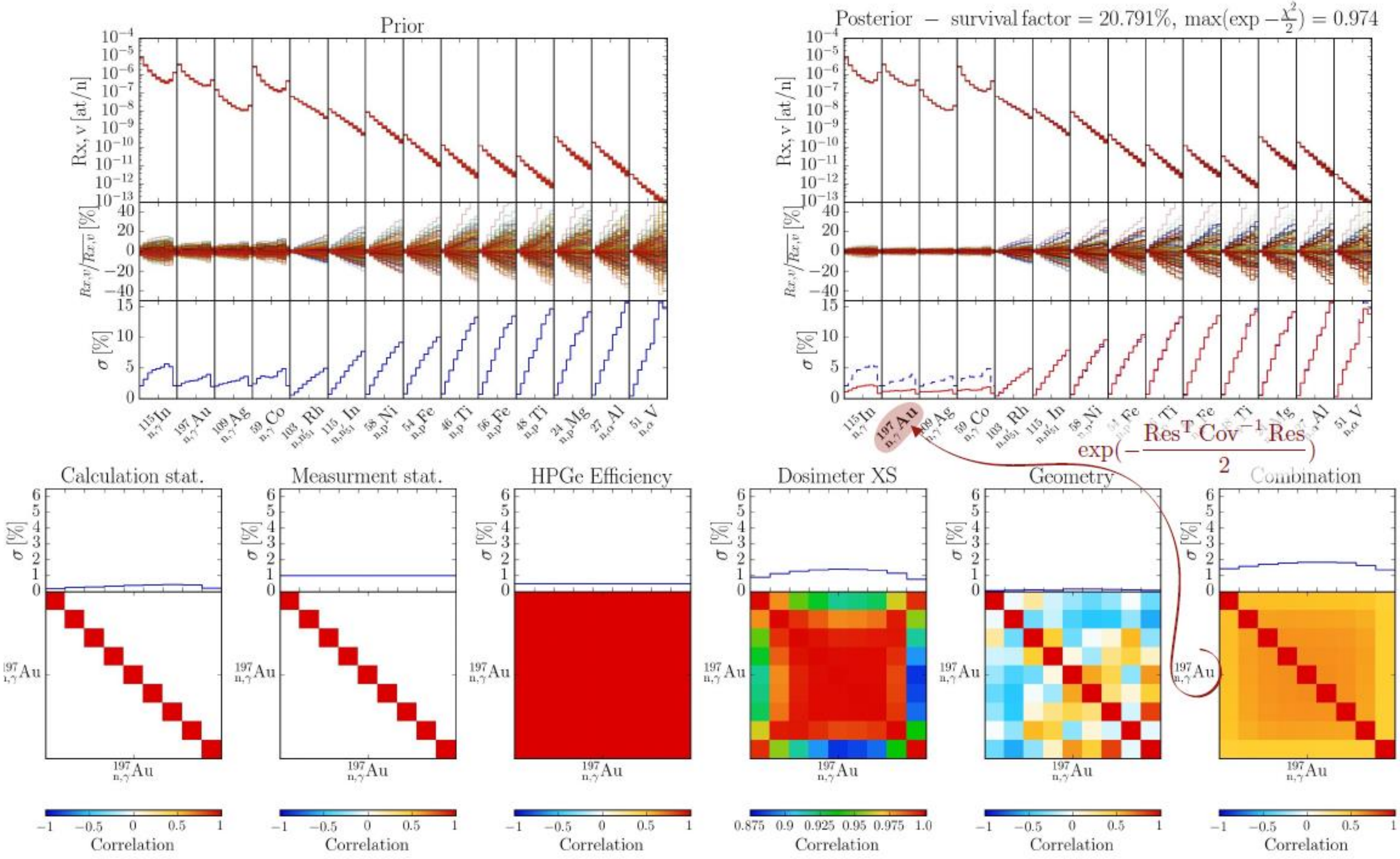
$$\chi^2 = ResTCov^{-1}Res$$



*[Rochman, D. *et al.* EPJ Nuclear Sciences & Technologies, 4, 7]

Effect of a criticality experiment assimilation in the ND on the observable

Backup: BMC



'Res' is supposed to be the 'Calculation' vs 'Experiment' difference → average C value used instead for BMC testing