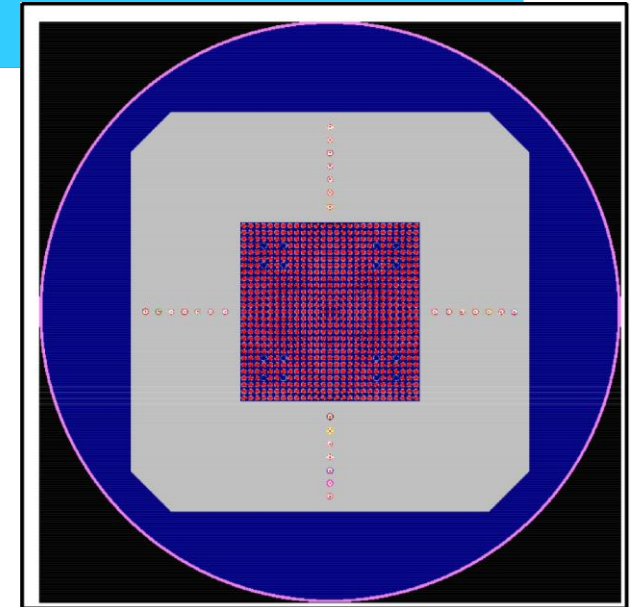


JEFF-4.0 γ -production evaluations and integral validation of γ -heating in ZPR/EOLE

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Outline



1. **JEFF-4.0**/GP capture- γ overall analysis
2. New **JEFF-4.0** Prompt Fission & Capture Gamma Spectra & Multiplicities
3. Benchmarking and Validation of γ -heating in ZPR/LWR/EOLE core using **JEFF-3.1.1** and **JEFF-4.0**
4. Conclusions & perspectives

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JEFF-4.0/GP capture- γ overall analysis



Q_(n,γ) Values

(n,γ)	AME03	JEFF-3.1.1	J311/AME03	Inc: AME03
²³⁴ U	5.29749 ± 0.00023	5.298	0.008%	0.004%
²³⁵ U	6.54545 ± 0.00026	6.545	-0.004%	0.004%
²³⁸ U	5.12577 ± 0.00046	5.126	0.001%	0.009%
²³⁷ Np	5.48832 ± 0.00020	5.482	-0.115%	0.004%
²³⁸ Pu	5.64619 ± 0.00031	5.647	0.021%	0.005%
²³⁹ Pu	6.53420 ± 0.00023	6.533	-0.018%	0.004%
²⁴⁰ Pu	5.24152 ± 0.00003	5.242	0.007%	0.001%
²⁴¹ Pu	6.30972 ± 0.00069	1.110	82.408%	0.011%
²⁴² Pu	5.03420 ± 0.00261	5.032	-0.046%	0.052%
²⁴¹ Am	5.53764 ± 0.00010	5.541	0.061%	0.002%
²⁴³ Am	5.36640 ± 0.00173	5.160	-3.848%	0.032%
²⁴⁴ Cm	5.52026 ± 0.00100	6.451	16.860%	0.018%
²⁴⁵ Cm	6.45758 ± 0.00150	6.460	0.117%	0.023%
¹⁵⁵ Gd	8.53639 ± 0.00007	1.890	77.859%	0.001%
¹³⁵ Xe	8.07942 ± 0.00023	7.000	-2.468%	0.102%
¹⁰³ Rh	6.99896 ± 0.00008	6.999	0.001%	0.001%
¹⁴⁰ Nd	7.81703 ± 0.00005	7.829	0.157%	0.001%
¹³³ Cs	6.89154 ± 0.00001	6.704	-2.718%	0.000%
¹³¹ Xe	8.93659 ± 0.00022	8.936	-0.003%	0.002%
¹⁴⁸ Sm	7.96673 ± 0.00036	7.962	-0.054%	0.005%
⁹⁹ Tc	6.76440 ± 0.00010	6.764	0.000%	0.001%
¹⁵² Eu	6.33968 ± 0.00536	6.490	2.371%	0.084%
¹⁵¹ Sm	8.25760 ± 0.00062	8.223	-0.417%	0.008%
¹⁵² Eu	6.44223 ± 0.00024	6.441	-0.013%	0.004%
¹⁵⁰ Sm	6.86840 ± 0.00013	6.867	-0.024%	0.002%
¹⁵⁴ Eu	8.15140 ± 0.00040	8.167	0.191%	0.005%
¹⁴² Nd	7.56523 ± 0.00009	7.564	-0.016%	0.001%
¹⁴⁷ Pm	5.89528 ± 0.00566	5.901	0.104%	0.096%
¹⁰⁹ Ag	6.80820 ± 0.00010	6.805	-0.082%	0.001%
¹⁰⁷ Ru	9.21964 ± 0.00005	9.220	0.007%	0.001%
⁸⁵ Mn	9.15432 ± 0.00005	9.154	-0.003%	0.001%
¹⁵⁶ Sm	6.59646 ± 0.00011	6.596	-0.008%	0.002%
¹⁰³ Pd	9.56097 ± 0.00028	9.548	-0.138%	0.003%
^{140m} Pm	7.27066 ± 0.00668	7.266	-0.064%	0.091%
¹³⁴ Cs	8.78199 ± 0.00100	8.800	0.434%	0.011%
¹⁰⁶ Pd	6.15360 ± 0.00015	6.154	0.007%	0.002%
¹⁴⁷ Sm	8.14141 ± 0.00028	8.141	-0.005%	0.003%
¹⁵⁷ Gd	7.93739 ± 0.00006	7.937	-0.005%	0.001%
¹⁰⁷ Pd	9.22803 ± 0.00522	9.223	-0.055%	0.057%
¹⁴³ Pr	5.84315 ± 0.00006	5.843	-0.003%	0.001%
⁹¹ Zr	8.22111 ± 0.00195	8.219	-0.031%	0.024%
¹³⁴ Cs	6.62818 ± 0.00215	6.764	0.934%	0.031%
¹⁰² Ru	8.90141 ± 0.00283	8.904	0.028%	0.032%

AME03 = Atomic Mass Evaluation 03
JEFF-3.1.1 = MF3/MT102

← Has to be corrected ! JEFDOC-1362, C. Jouanne

← Has to be corrected !

← JEFF-3.1.1/Feedback page: C. Dean, July 2009

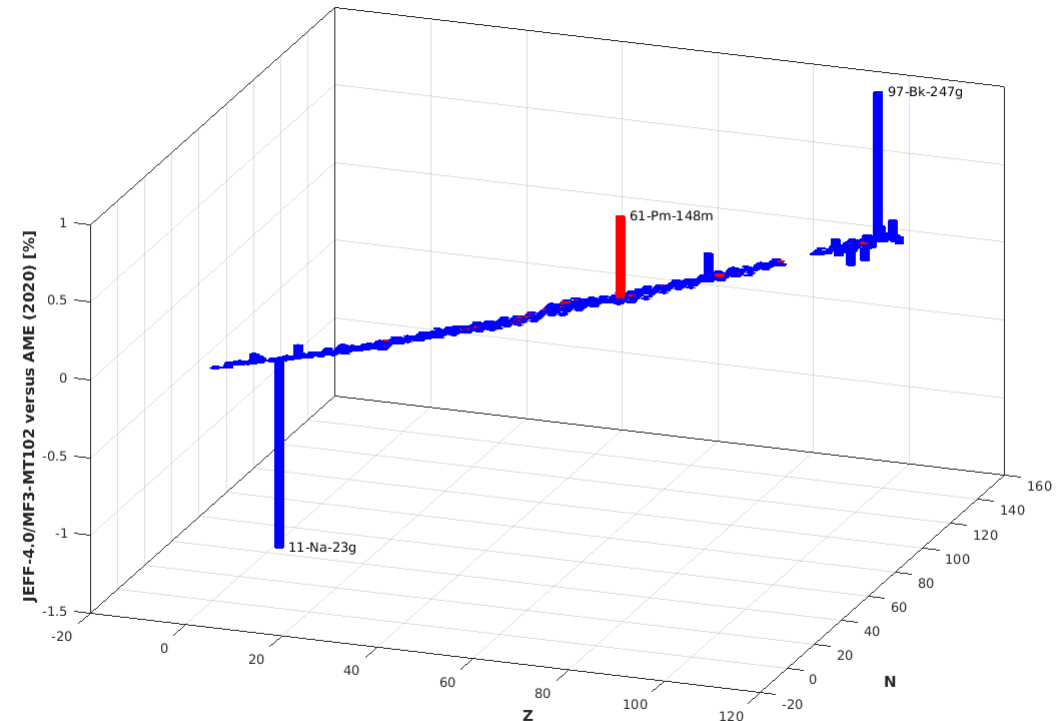
← PWR-UOX@40GWit:

- JEFF-3.1.1 underestimate by 0.40% the prompt gamma energy released by neutron capture of these 29 first FP (representing 90% of the FP absorption rate)
- A priori uncertainty (AME03) is less than 0.02%.

JEFF Meeting 1-3 December 2010, Issy-les-Moulineaux

2010 (!): many MF3-MT102/Q-value were not correct in JEFF-3.1.1

JEFF-4.0 (593 files) corrected almost all of them (<1%):

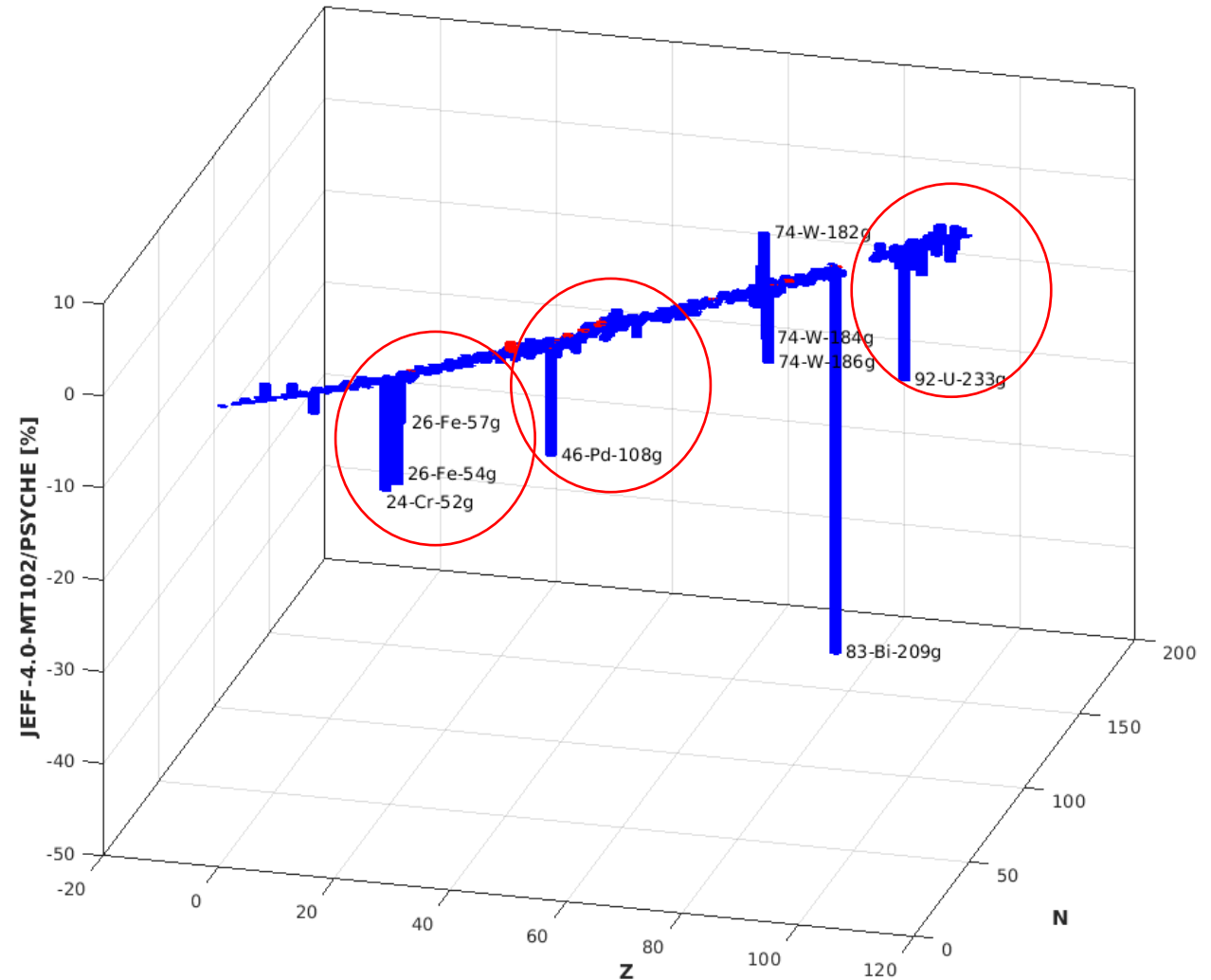


JEFF-4.0/GP capture- γ overall analysis

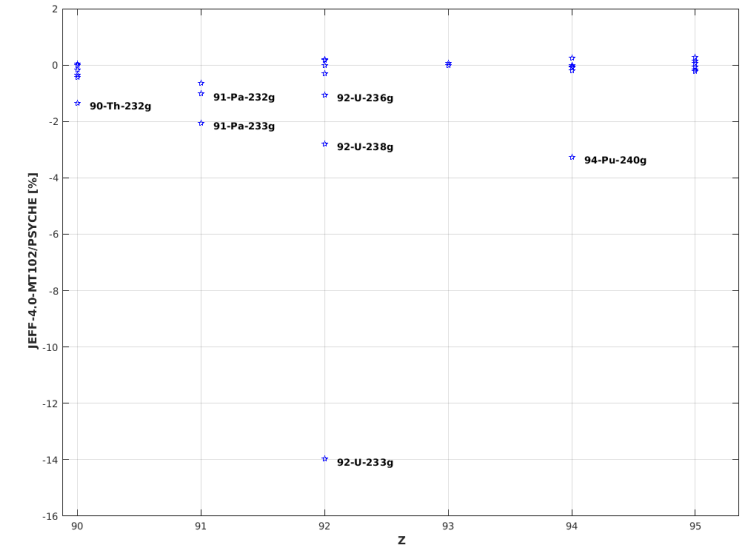
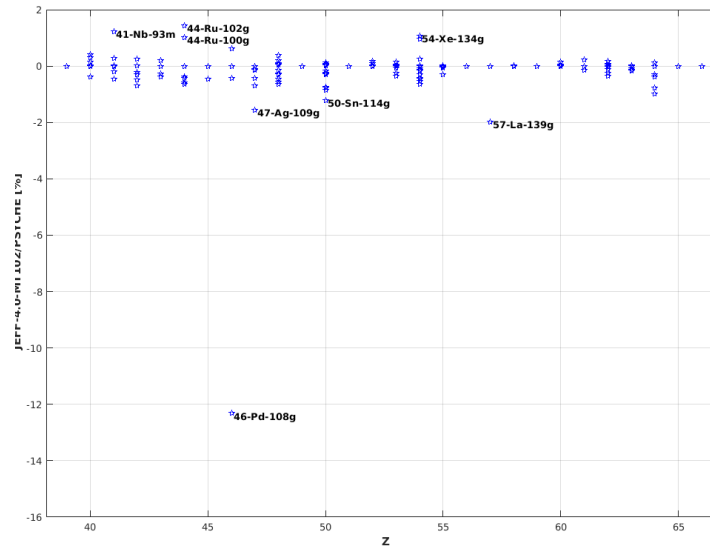
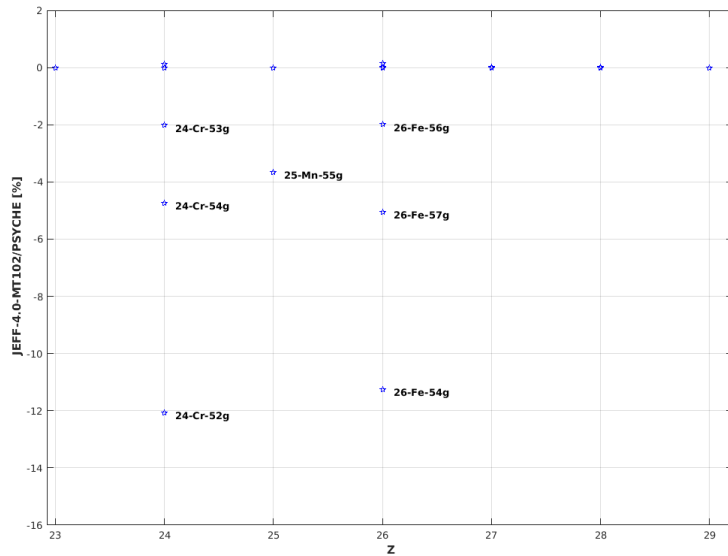
Since **JEFF-4.0/MF3-MT102/Qvalues** are correct,

the completeness of γ -spectra+multiplicities is tested by **PSYCHE** tool (thanks to NEA processing Docker files):

- **MF6 discrete (527 files):** 29 041 γ -lines@thermal
- **MF6 continuum only (37 files)**
- **or composite files MF5-12-13-15 (22 files)**
- No γ -production files (7 files: $^{113,115}\text{In}$, ^{18}O , ^{13}C ...)



JEFF-4.0/GP capture- γ overall analysis



Incomplete MT102 γ -production files

^{52,53,54}Cr: -12.1%, -2.0%, -4.7% resp.
⁵⁵Mn: -3.7%
^{54,56,57}Fe: -11.2%, -2.0%, -5.1% resp.

¹⁰⁸Pd: -12.3%
¹⁰⁹Ag: -1.6%
¹¹⁴Sn: -1.2%
¹³⁹La: -2.0%
^{93m}Nb: +1.2%
^{100,102}Ru: +1.0%, +1.4%
¹³⁴Xe: +1.1%

²³²Th: -1.3%
^{233, 236, 238}U: -14.0%, -1.1%, -2.8% resp.
²⁴⁰Pu: -3.3%

JEFF-3.1.1/⁵⁶Fe(MF12-14-15): -1.3%
 JEFF-3.2/⁵⁶Fe(MF6): -4.3% (ICC corrected)

Outline

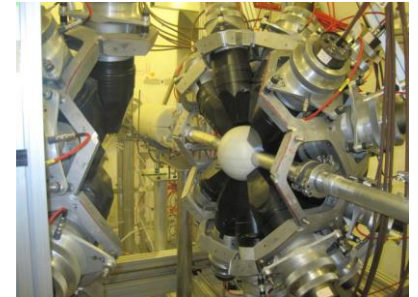
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JEFF-4.0 Prompt Capture Gamma Spectra & Multiplicities

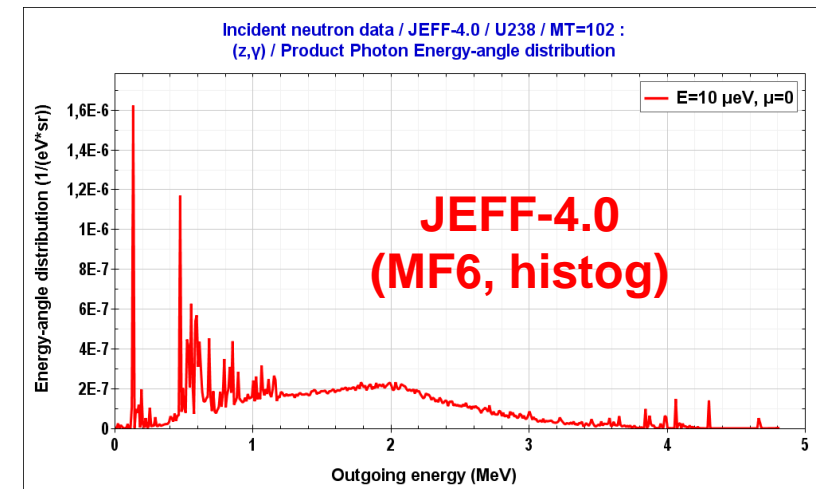
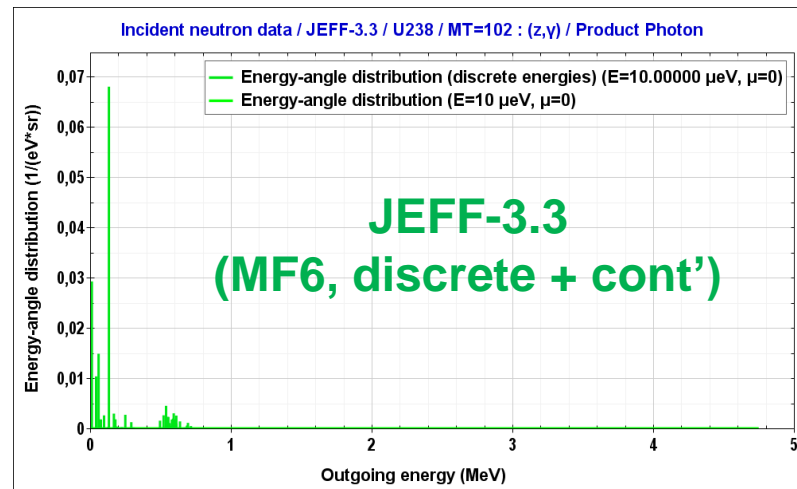
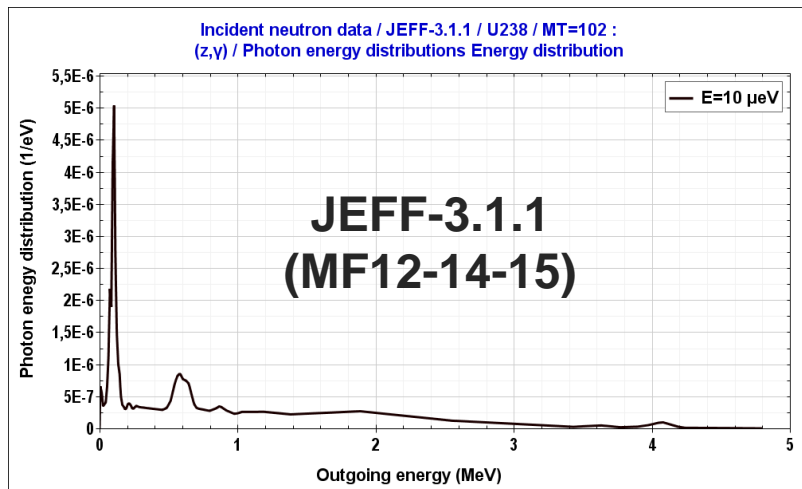


FIFRELIN calculations in decay mode at thermal point and 150 keV

- U238 : LDM (CTM), PSF (MGLO 2xE1 + 3xM1 + 1xE2) adapted to better reproduce $\langle \Gamma_\gamma \rangle$, $\langle D_0 \rangle$ and multi-step gamma-ray energy spectra measured at nTOF. [J. Moreno-Soto et al., Phys. Rev. C 105, 024618 \(2022\)](#)
- Pu240 : LDM, PSF from default models (CGCM/EGLO)

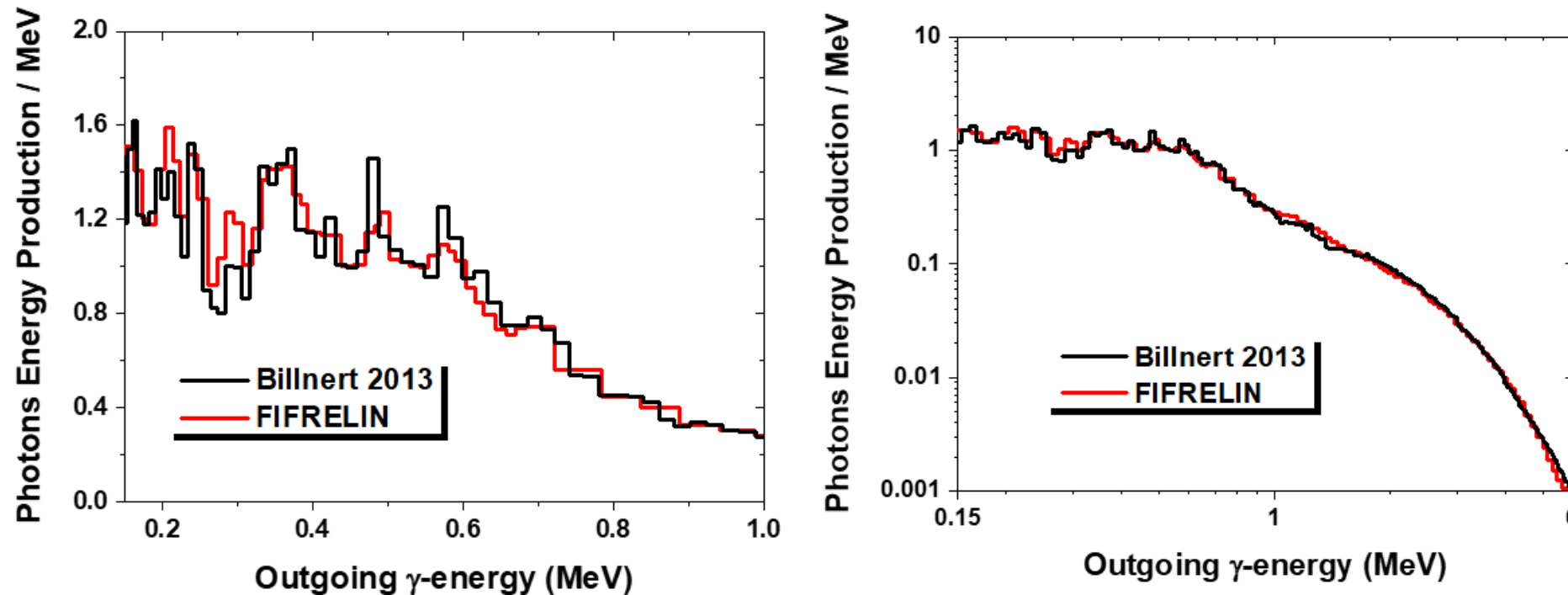


Conversion electrons accounted for but not stored in the γ -section of the evaluation (slight Q value difference, ~ 100 keV)



JEFF-4.0 Prompt Fission Gamma Spectra & Multiplicities

FIFRELIN calculation validated on PFGS and PFGM of $^{252}\text{Cf}(\text{sf})$ measured by Billnert



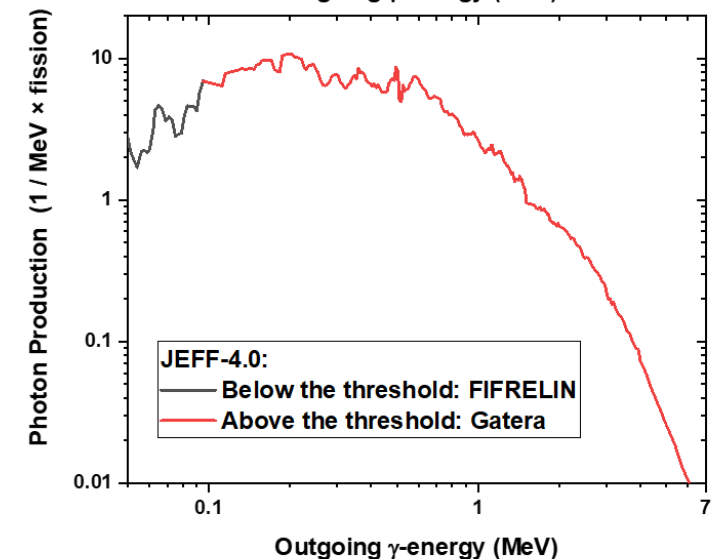
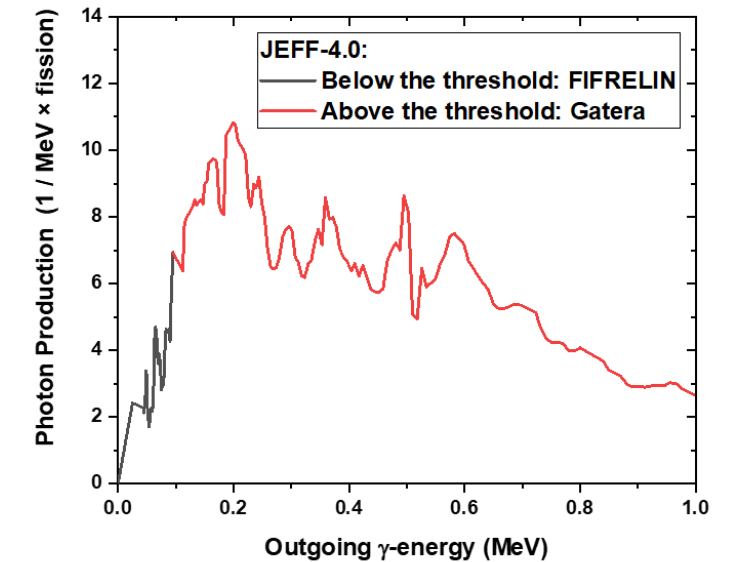
R. Billnert et al., Phys. Rev. C87, 024601 (2013)

JEFF-4.0 Prompt Fission Gamma Spectra & Multiplicities

Example $^{239}\text{Pu}(n_{\text{th}},f)$ reaction

	γ -multiplicity	$\langle \varepsilon_{\gamma} \rangle$	$\langle E_{\gamma} \rangle$
Gatera et al. 2017 with $E_{\text{Thres}} = 100 \text{ keV}$ and $T_{\text{Coinc}} = 3 \text{ ns}$	7.35 ± 0.12	0.85 ± 0.02	6.27 ± 0.11
FIFRELIN simulation : with $E_{\text{Thres}} = 100 \text{ keV}$ and $T_{\text{Coinc}} = 3 \text{ ns}$	7.24	0.93	6.69
FIFRELIN simulation: with $E_{\text{Thres}} = 0 \text{ keV}$ and $T_{\text{Coinc}} = \infty$	8.40	0.86	6.99

A. Gatera et al. PRC 95, 064609 (2017)

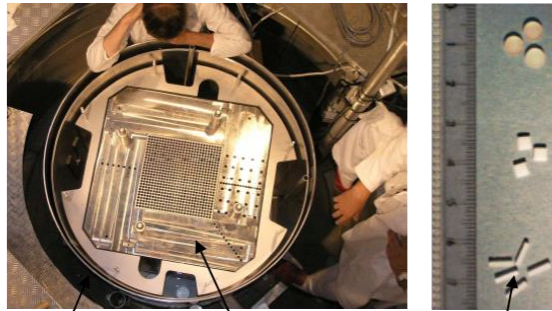


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Experimental set-up



EOLE core
Stainless steel reflector



TLD
ThermoLuminescent
Detector

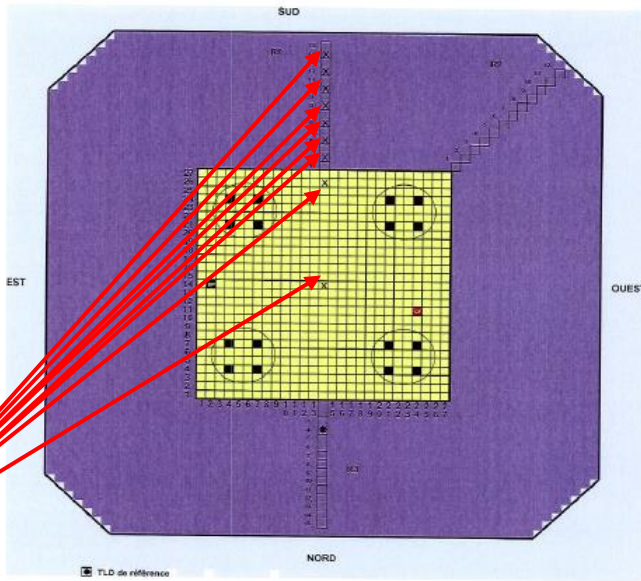
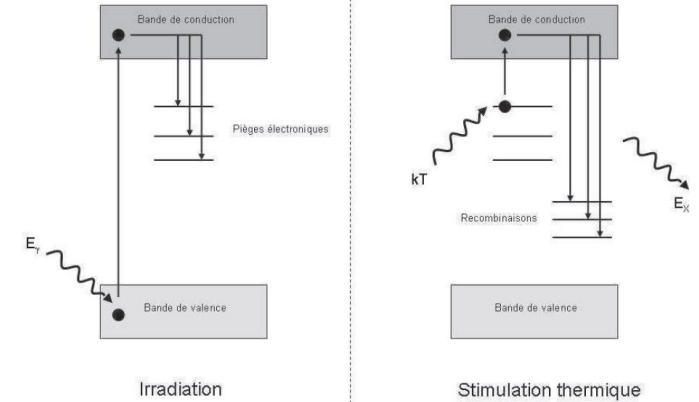
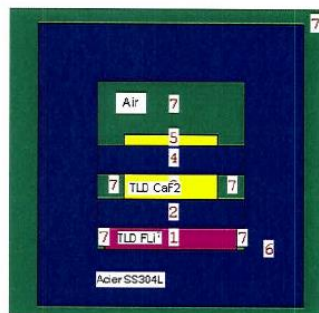


Figure 12 : Carte globale des mesures par TLD



Sub-critical approach
10 W x 604s critical and
few minutes of cooling



Neutron dose correction (ASTM)

TRIPOLI-4® Calculation scheme



$k_{\text{eff}}(\text{JEFF-3.1.1}) = 1.00222$
 $k_{\text{eff}}(\text{JEFF-4.0}) = 1.00077$
 $\sigma \sim 0.4 \text{ pcm}$

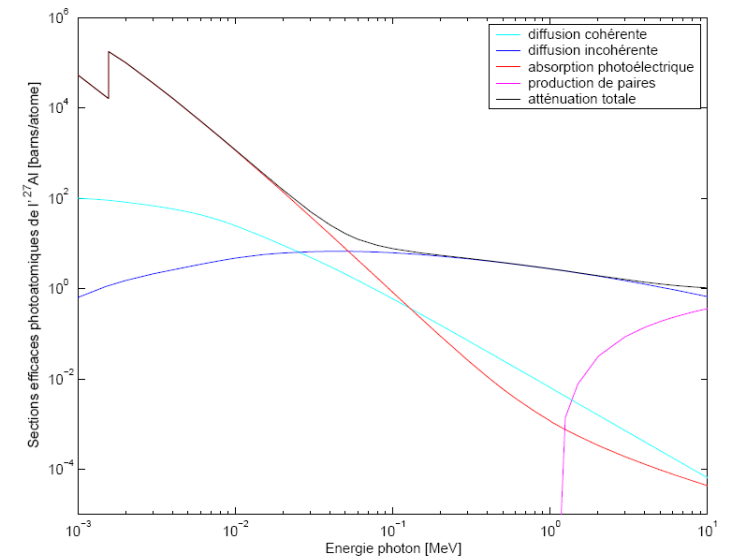
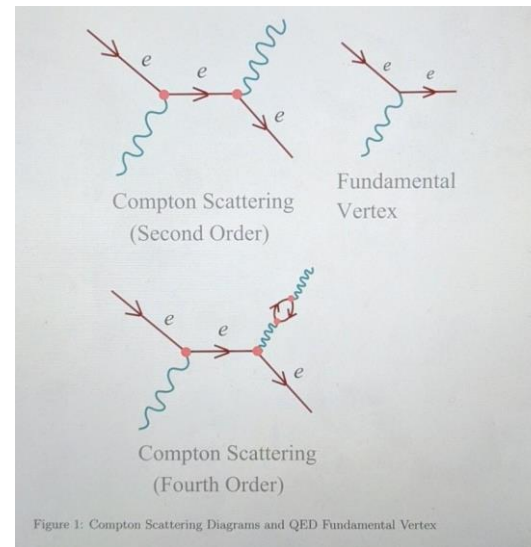
Neutron+photon+electron+positron

~100,000 h.cpu

EPDL-97 (photon transport)

EEDL&Mott (electron transport) + EADL (atomic relaxation)...

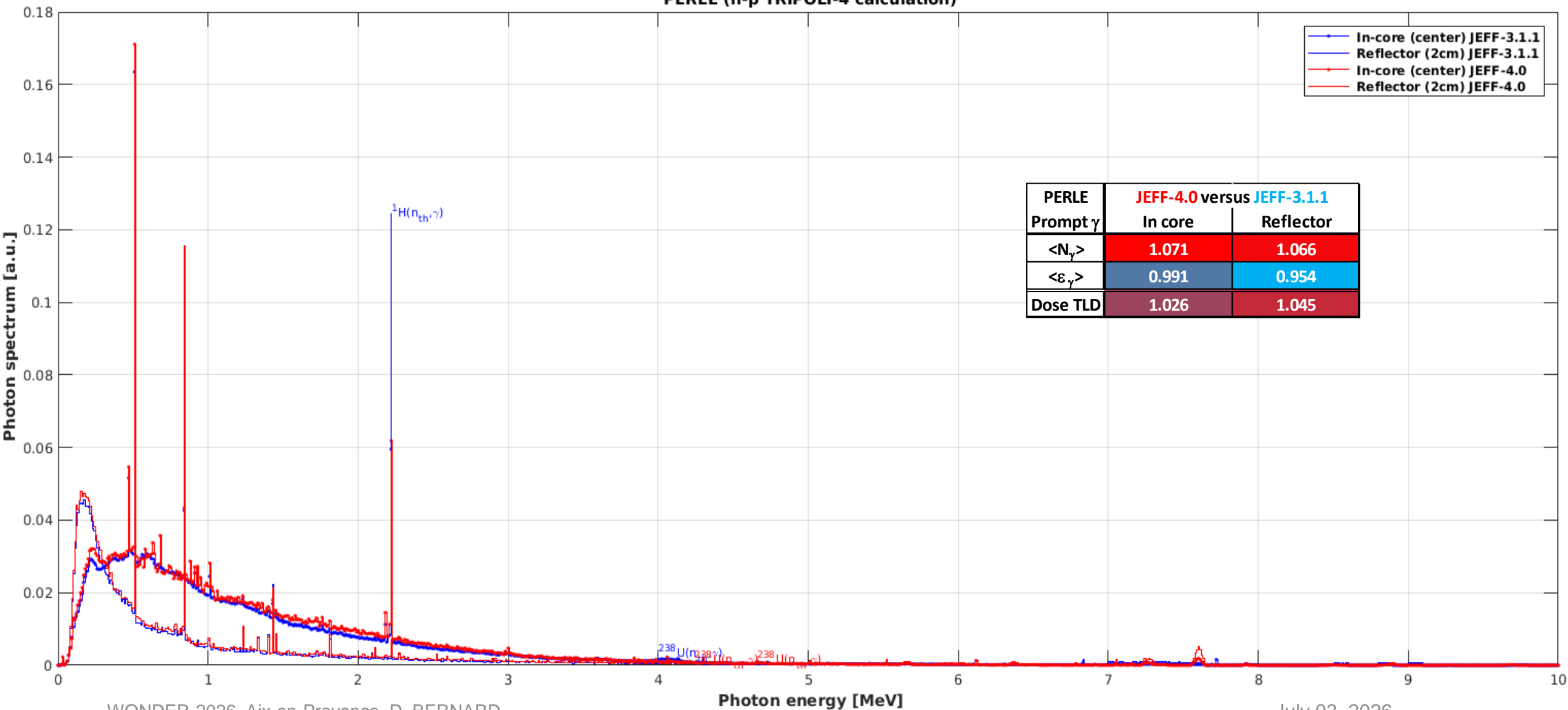
Step 1
VOLENERCUT e [±] 25 keV (PILULIER)
NORM N=7.7724E+11
PHOTO_NUCLEAR
ONLY_PROMPT_GAMMA_ENERGY
Step 2
EXTENDED MESH CARTESIAN 3 3 3
burnupsteps_3x3_steps
All material depleted
Step 3
VOLENERCUT e [±] 25 keV (PILULIER)
Temporal scheme : histogram



PERLE prompt- γ -spectra

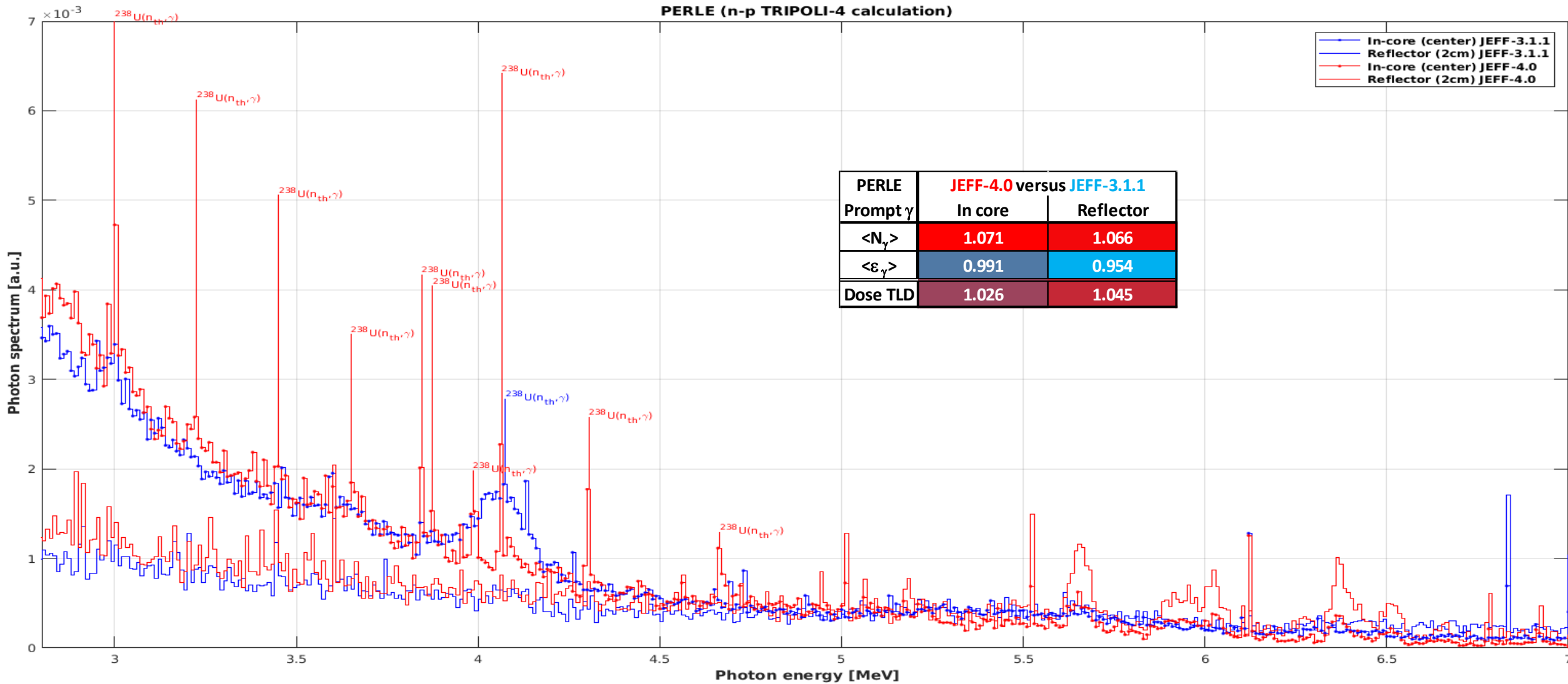


PERLE (n-p TRIPOLI-4 calculation)



PERLE Prompt γ	JEFF-4.0 versus JEFF-3.1.1	
	In core	Reflector
$\langle N_\gamma \rangle$	1.071	1.066
$\langle \varepsilon_\gamma \rangle$	0.991	0.954
Dose TLD	1.026	1.045

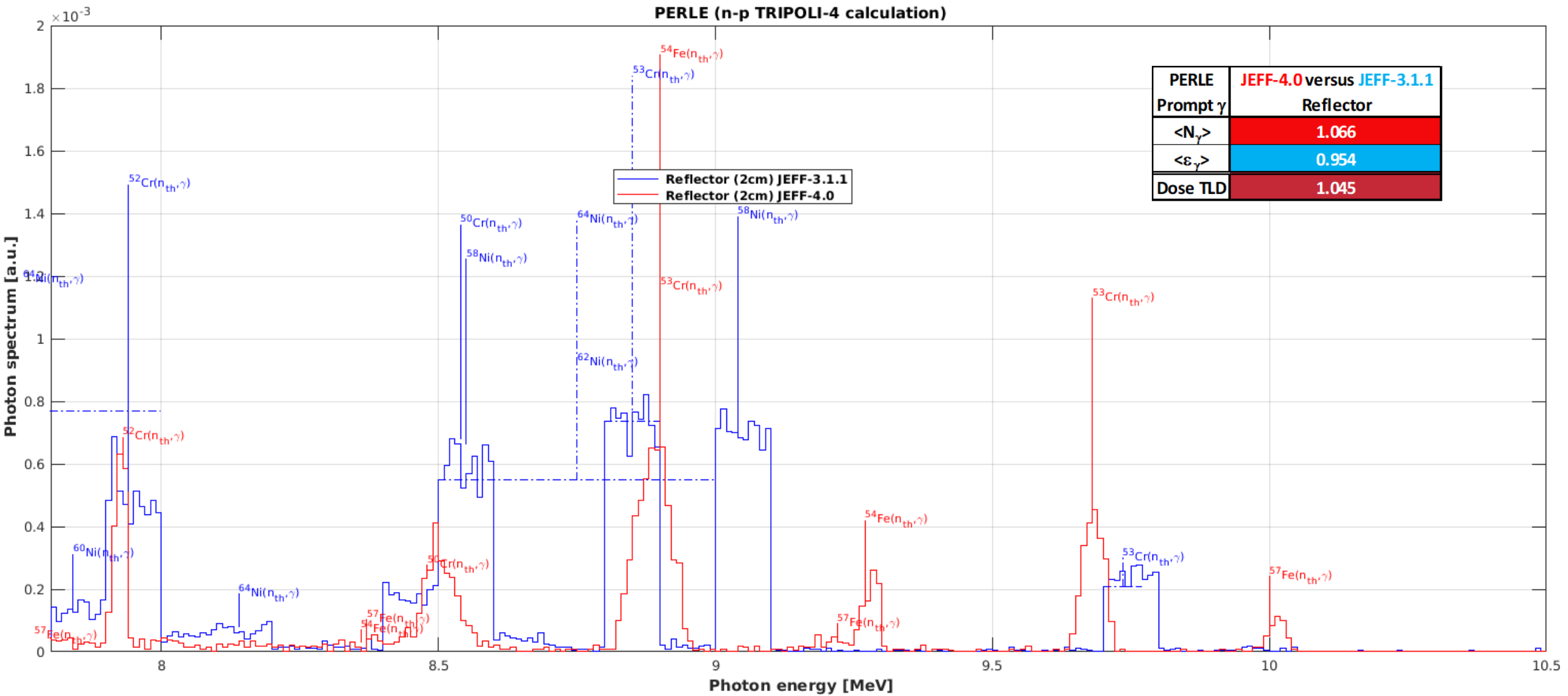
PERLE prompt- γ -spectra



PERLE γ -spectra



th γ)



PERLE Prompt γ	JEFF-4.0 versus JEFF-3.1.1 Reflector
$\langle N_\gamma \rangle$	1.066
$\langle \varepsilon_\gamma \rangle$	0.954
Dose TLD	1.045

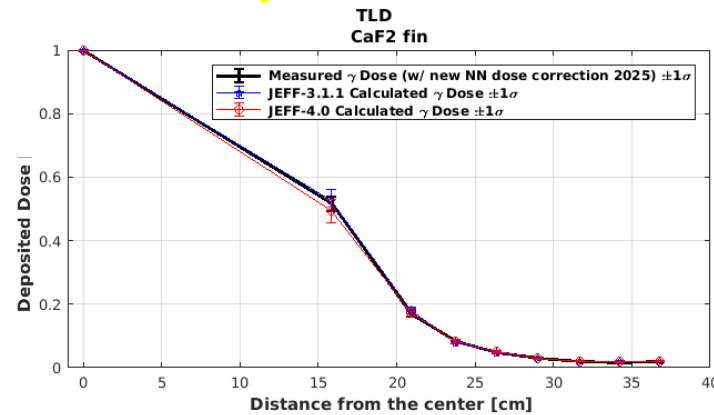
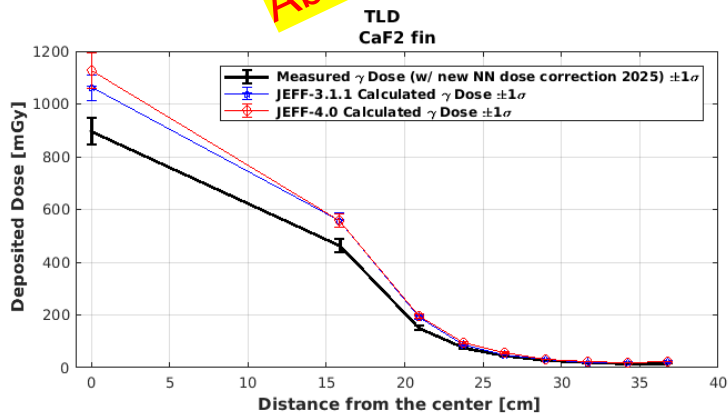
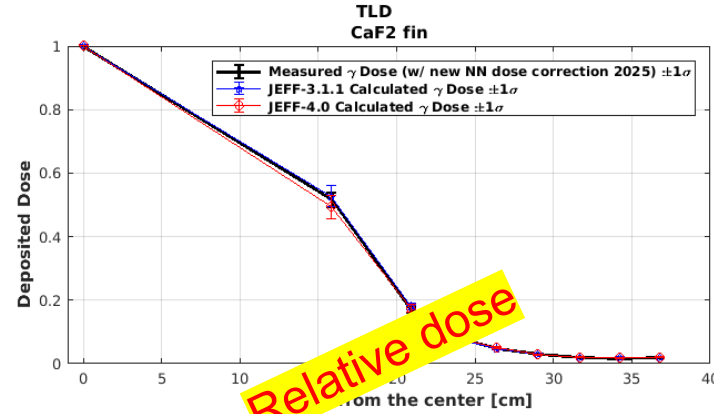
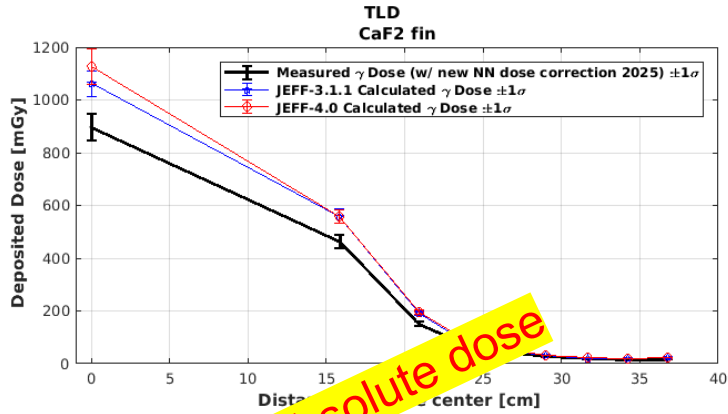
Complete scoring TRIPOLI-4.12.1® (JEFF-3.1.1)



	Dose PROMPTE [μGy]						Dose SCA + DELAYED [μGy]						Dose TOTALE [μGy]	
	γ	e ⁻	e ⁺	NN Therm	NN Fast	TOT	γ	e ⁻	e ⁺	NN Therm	NN Fast	TOT	γ+e ⁺	TOT
FLi centre	43 ± 2	770 005 ± 5 543	18 842 ± 695	52 978 ± 2 564	98 611 ± 71 000	940 479 ± 71 266	21 ± 15	134 389 ± 34 924	0 ± 0	3 306 ± 727	6 153 ± 4 430	143 869 ± 35 211	923 300 ± 35 368	1 084 348 ± 79 490
FLi périph	26 ± 1	441 554 ± 4 128	13 203 ± 530	30 643 ± 1 483	56 848 ± 40 930	542 274 ± 41 168	21 ± 15	91 289 ± 27 884	0 ± 0	1 912 ± 421	3 547 ± 2 554	96 770 ± 28 004	546 093 ± 28 193	639 044 ± 49 790
CaF ₂ EPAIS centre	314 ± 43	832 537 ± 6 357	18 954 ± 766	17 093 ± 17 093	33 100 ± 16 550	901 998 ± 24 639	40 ± 19	142 487 ± 28 513	0 ± 0	1 067 ± 1 067	2 065 ± 1 033	145 660 ± 28 551	994 332 ± 29 223	1 047 657 ± 37 713
CaF ₂ EPAIS périph	167 ± 25	468 313 ± 4 593	13 517 ± 603	9 882 ± 9 882	17 399 ± 8 699	509 278 ± 13 957	0 ± 0	102 083 ± 31 137	0 ± 0	617 ± 617	1 086 ± 543	103 785 ± 31 148	584 080 ± 31 480	613 063 ± 34 132
CaF ₂ FIN centre	316 ± 51	842 983 ± 8 072	22 072 ± 1 041	17 154 ± 17 154	33 584 ± 16 792	916 109 ± 25 347	0 ± 0	181 991 ± 45 664	0 ± 0	1 070 ± 1 070	2 096 ± 1 048	185 157 ± 45 689	1 047 362 ± 46 384	1 101 267 ± 52 249
CaF ₂ FIN périph	222 ± 90	463 505 ± 5 743	16 311 ± 841	9 959 ± 9 959	17 522 ± 8 761	507 519 ± 14 479	21 ± 21	72 241 ± 25 184	0 ± 0	621 ± 621	1 093 ± 547	73 977 ± 25 197	552 300 ± 25 844	581 496 ± 29 061

	Dose PROMPTE [μGy]						Dose SCA + DELAYED [μGy]						Dose TOTALE [μGy]	
	γ	e ⁻	e ⁺	NN Therm	NN Fast	TOT	γ	e ⁻	e ⁺	NN Therm	NN Fast	TOT	γ+e ⁺	TOT
FLi R1-2	9 ± 0	143 353 ± 996	6 976 ± 64	2 496 ± 549	18 792 ± 13 530	171 627 ± 13 578	3 ± 3	16 090 ± 5 018	753 ± 231	195 ± 43	1 471 ± 1 059	18 512 ± 5 134	167 184 ± 5 121	190 139 ± 14 516
FLi R1-4	5 ± 0	72 675 ± 670	3 724 ± 45	644 ± 142	9 550 ± 6 876	86 599 ± 6 911	0 ± 0	1 855 ± 1 207	0 ± 0	50 ± 11	748 ± 538	2 653 ± 1 322	78 259 ± 1 382	89 252 ± 7 036
FLi R1-6	3 ± 0	41 966 ± 492	2 397 ± 36	223 ± 49	5 546 ± 3 993	50 134 ± 4 024	0 ± 0	364 ± 268	0 ± 0	17 ± 4	434 ± 313	815 ± 412	44 729 ± 561	50 949 ± 4 045
FLi R1-8	2 ± 0	26 189 ± 366	1 829 ± 34	97 ± 21	3 503 ± 2 522	31 620 ± 2 549	0 ± 0	0 ± 0	0 ± 0	8 ± 2	274 ± 197	282 ± 197	28 020 ± 368	31 902 ± 2 556
FLi R1-10	1 ± 0	18 536 ± 311	1 246 ± 27	72 ± 16	2 473 ± 1 781	22 329 ± 1 808	0 ± 0	0 ± 0	0 ± 0	6 ± 1	194 ± 139	199 ± 139	19 783 ± 312	22 528 ± 1 813
FLi R1-12	1 ± 0	15 618 ± 278	1 226 ± 28	146 ± 32	2 106 ± 1 516	19 097 ± 1 542	0 ± 0	0 ± 0	0 ± 0	11 ± 3	165 ± 119	176 ± 119	16 845 ± 280	19 273 ± 1 547
FLi R1-14	1 ± 0	17 996 ± 296	1 610 ± 35	563 ± 124	2 451 ± 1 765	22 621 ± 1 794	0 ± 0	0 ± 0	0 ± 0	44 ± 10	192 ± 138	236 ± 138	19 608 ± 298	22 857 ± 1 799
CaF ₂ EPAIS R1-2	105 ± 11	153 739 ± 1 125	7 694 ± 195	814 ± 814	5 741 ± 2 871	168 092 ± 3 195	6 ± 3	15 035 ± 3 367	4 088 ± 4 088	64 ± 64	449 ± 225	19 641 ± 9 821	180 666 ± 5 418	187 734 ± 10 327
CaF ₂ EPAIS R1-4	57 ± 9	79 021 ± 756	4 334 ± 147	211 ± 211	3 065 ± 1 532	86 687 ± 1 728	2 ± 2	8 349 ± 3 090	0 ± 0	17 ± 17	240 ± 120	8 607 ± 4 304	91 762 ± 3 184	95 294 ± 4 638
CaF ₂ EPAIS R1-6	28 ± 3	45 844 ± 572	2 479 ± 101	72 ± 72	1 763 ± 881	50 187 ± 1 058	0 ± 0	2 690 ± 2 480	0 ± 0	6 ± 6	138 ± 69	2 834 ± 1 417	51 041 ± 2 547	53 020 ± 1 768
CaF ₂ EPAIS R1-8	16 ± 2	27 913 ± 416	1 872 ± 89	32 ± 32	1 071 ± 536	30 904 ± 685	0 ± 0	1 930 ± 1 217	0 ± 0	2 ± 2	84 ± 42	2 016 ± 1 008	31 731 ± 1 290	32 921 ± 1 219
CaF ₂ EPAIS R1-10	14 ± 3	20 067 ± 357	1 414 ± 79	24 ± 24	636 ± 318	22 155 ± 485	0 ± 0	1 912 ± 1 912	0 ± 0	2 ± 2	50 ± 25	1 963 ± 982	23 408 ± 1 947	24 119 ± 1 095
CaF ₂ EPAIS R1-12	13 ± 3	16 959 ± 320	1 237 ± 71	47 ± 47	401 ± 200	18 656 ± 387	0 ± 0	0 ± 0	0 ± 0	4 ± 4	31 ± 16	35 ± 18	18 208 ± 328	18 691 ± 388
CaF ₂ EPAIS R1-14	15 ± 3	19 351 ± 344	1 590 ± 78	182 ± 182	251 ± 126	21 389 ± 416	0 ± 0	0 ± 0	0 ± 0	14 ± 14	20 ± 10	34 ± 17	20 956 ± 353	21 423 ± 417
CaF ₂ FINS R1-2	109 ± 17	154 370 ± 1 412	7 837 ± 209	815 ± 815	5 787 ± 2 894	168 919 ± 3 328	5 ± 5	27 204 ± 8 344	0 ± 0	64 ± 64	453 ± 227	27 727 ± 13 863	189 526 ± 8 465	196 646 ± 14 257
CaF ₂ FINS R1-4	59 ± 14	77 847 ± 934	4 242 ± 156	208 ± 208	3 069 ± 1 535	85 424 ± 1 815	0 ± 0	2 037 ± 1 465	0 ± 0	16 ± 16	240 ± 120	2 294 ± 1 147	84 185 ± 1 744	87 718 ± 2 147
CaF ₂ FINS R1-6	17 ± 2	45 281 ± 687	2 838 ± 129	71 ± 71	1 765 ± 882	49 973 ± 1 128	0 ± 0	1 161 ± 632	0 ± 0	6 ± 6	138 ± 69	1 305 ± 653	49 298 ± 942	51 278 ± 1 303
CaF ₂ FINS R1-8	12 ± 2	28 764 ± 530	1 876 ± 100	32 ± 32	1 072 ± 536	31 756 ± 762	0 ± 0	465 ± 465	0 ± 0	3 ± 3	84 ± 42	552 ± 276	31 117 ± 713	32 308 ± 810
CaF ₂ FINS R1-10	12 ± 3	19 336 ± 411	1 414 ± 85	24 ± 24	646 ± 323	21 432 ± 531	0 ± 0	0 ± 0	0 ± 0	2 ± 2	51 ± 25	52 ± 26	20 762 ± 420	21 485 ± 531
CaF ₂ FINS R1-12	12 ± 5	17 062 ± 385	1 467 ± 90	48 ± 48	404 ± 202	18 993 ± 446	0 ± 0	763 ± 763	0 ± 0	4 ± 4	32 ± 16	798 ± 399	19 304 ± 859	19 791 ± 599
CaF ₂ FINS R1-14	6 ± 1	19 233 ± 414	1 585 ± 89	183 ± 183	239 ± 120	21 246 ± 476	0 ± 0	0 ± 0	0 ± 0	14 ± 14	19 ± 9	33 ± 17	20 824 ± 424	21 279 ± 477

Detailed Results:



Absolute γ dose : JEFF-4.0 versus JEFF-3.1.1			
All TLD	Prompt	Delayed	Total
Core	2.6% \pm 1.0%	-15.3% \pm 30.6%	-0.7% \pm 4.6%
Reflector	4.5% \pm 0.9%	43.5% \pm 62.4%	6.6% \pm 4.1%
Core+reflector	3.5% \pm 0.8%	-6.1% \pm 23.5%	2.1% \pm 3.1%

The Stainless-Steel prompt heating is increasing by (+4.5 \pm 0.9)% !

Probably due to:

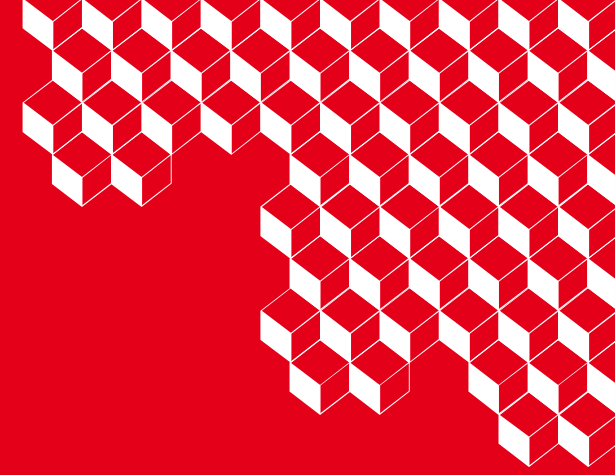
- The increase of the total capture rates by +1.5% : $^{53}\text{Cr}(n,\gamma)$ responsible for +1.1% (only 1/3rd on the \sim 5 keV multiplet), ^{55}Mn for +0.6%, ^{52}Cr for +0.4%, ^{56}Fe for -0.4%, $^{58+60}\text{Ni}$ for -0.5%...with respect of total capture in the reflector
- The modification of γ -production files for probably 3%...

Outline

1. **JEFF-4.0/GP capture- γ overall analysis**
2. New **JEFF-4.0** Prompt Fission & Capture Gamma Spectra & Multiplicities
3. Benchmarking and Validation of γ -heating in ZPR/LWR/EOLE core using **JEFF-3.1.1** and **JEFF-4.0**
4. **Conclusions & perspectives**

Conclusion

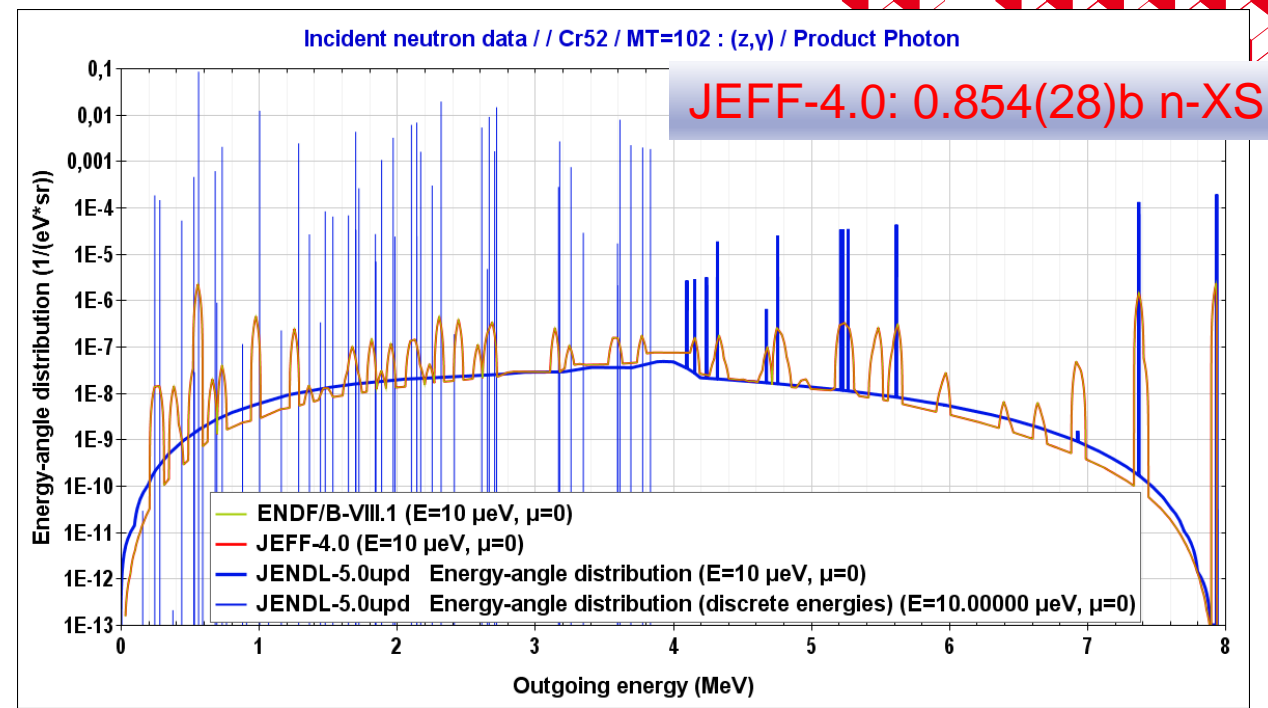
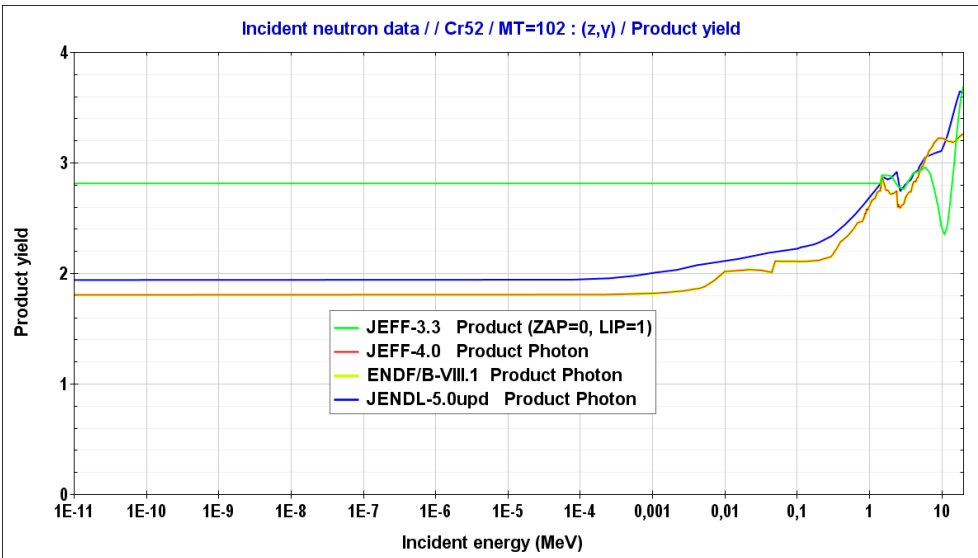
- **JEFF-4.0**/prompt γ -production **at thermal** (29 041 discrete lines!) seems correct for most of nuclides (Atomic Mass Evaluation + PSYCHE), **except**:
 - Qvalues: ^{23}Na , $^{148\text{m}}\text{Pm}$, ^{247}Bk
 - Spectra & Multiplicities: Ag- 113,115 In-Cd, Fe-Cr-Ni, Mn, Gd..., fission products, actinides...
- **JEFF-4.1**:
 - How to manage low nrj conversion emission ? And consecutive X-rays+Auger... (GNDS ?)
 - Account for IAEA/EGAF and extend the incident energy range (cf. the IAEA initiative).
- EOLE/PERLE interpretation shows a clear increase in γ -heating in ZPR. This partially **addresses the OECD/NEA/HPRL requests #4&5** that were submitted exactly 20 years ago (May, 12, 2006) !
- All these results will guarantee the **reliability of JEFF-4.0 γ -heating calculations** for the nuclear industry.



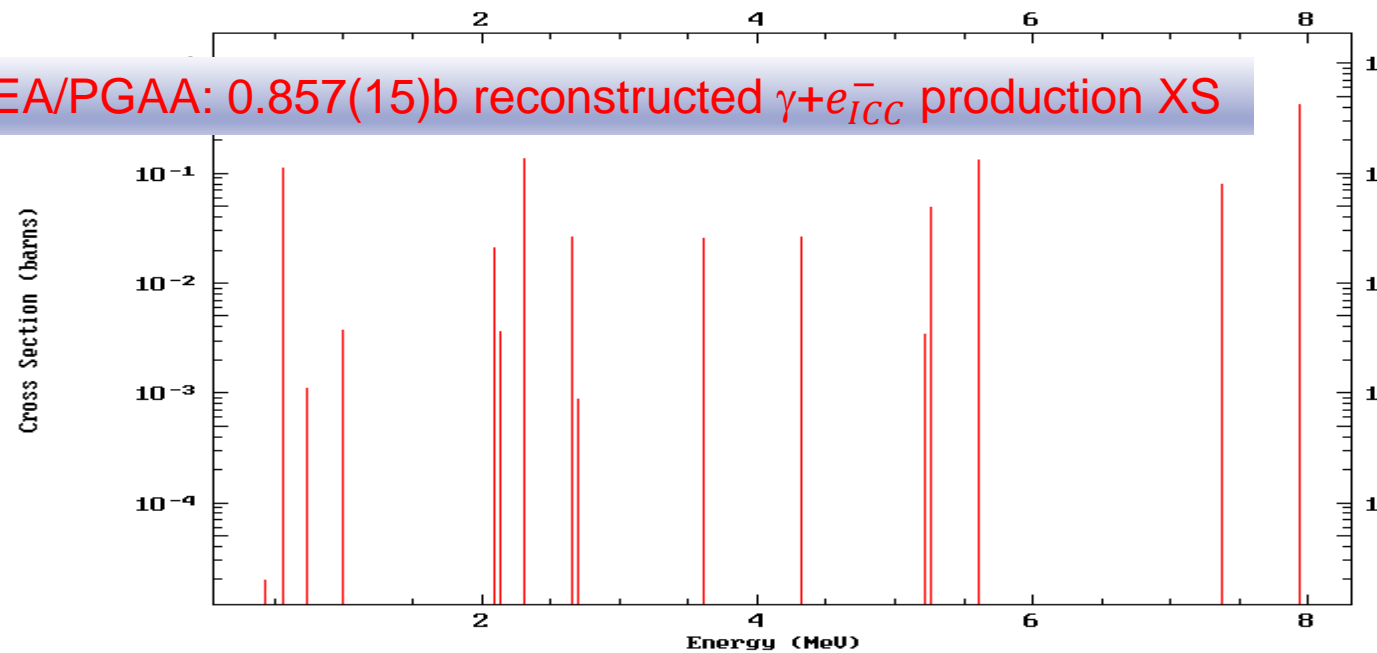
MERCI !

Questions ?

$^{52}\text{Cr}(n_{\text{th}},\gamma)$

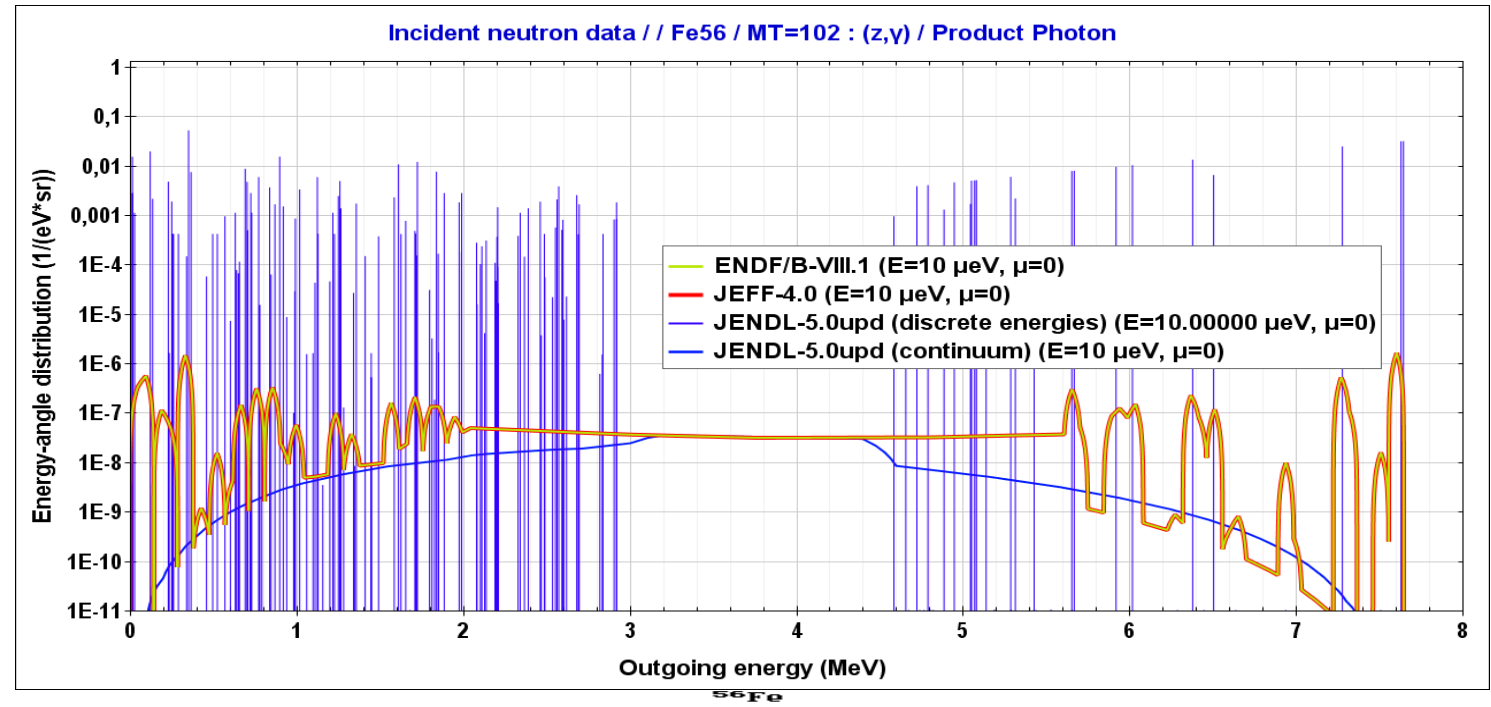
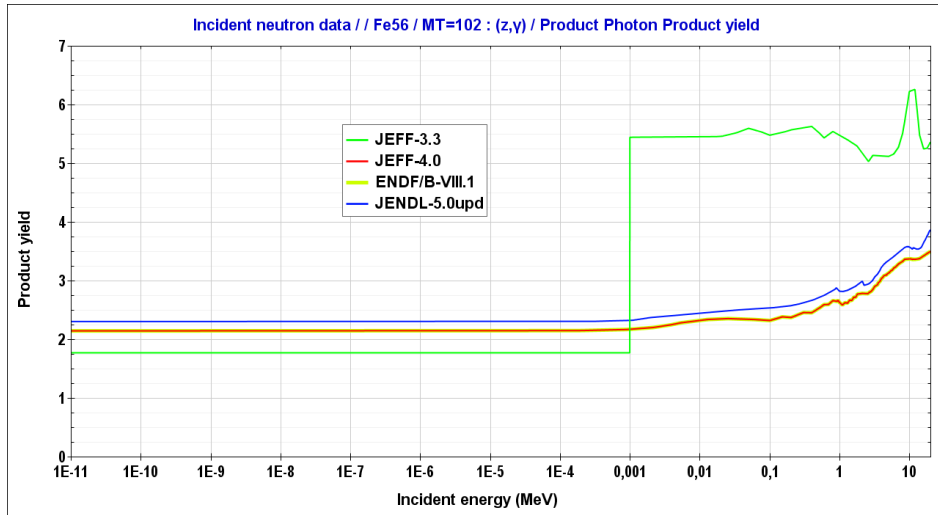


IAEA/PGAA: 0.857(15)b reconstructed $\gamma+e_{\text{IC}}^-$ production XS

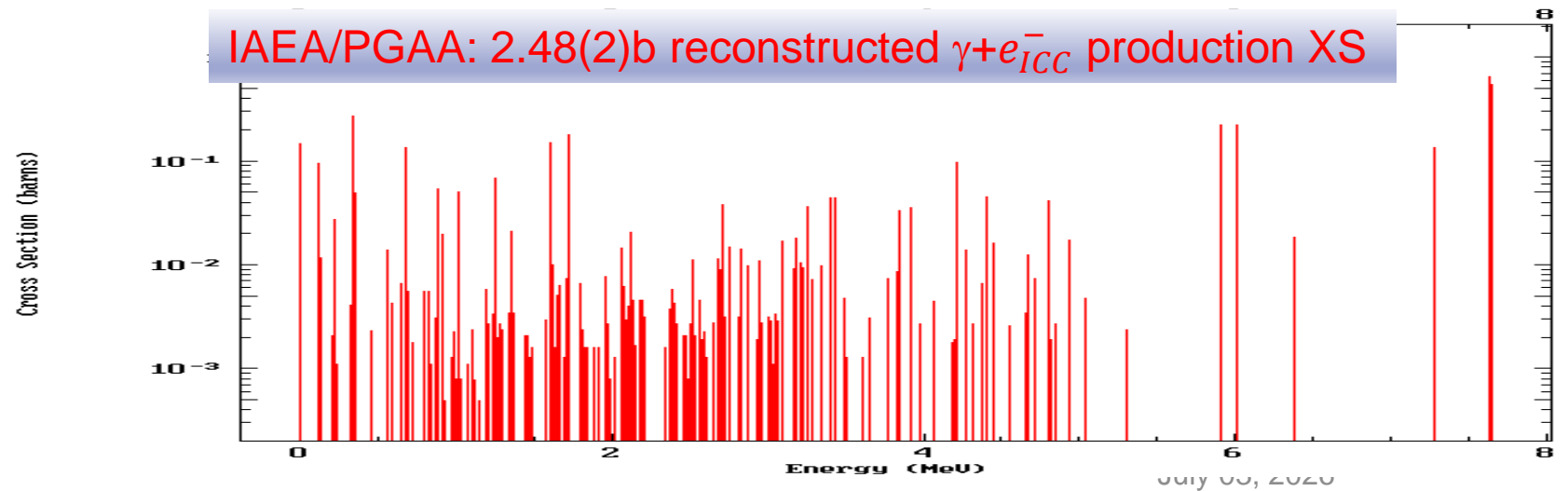


$^{56}\text{Fe}(n_{\text{th}},\gamma)$

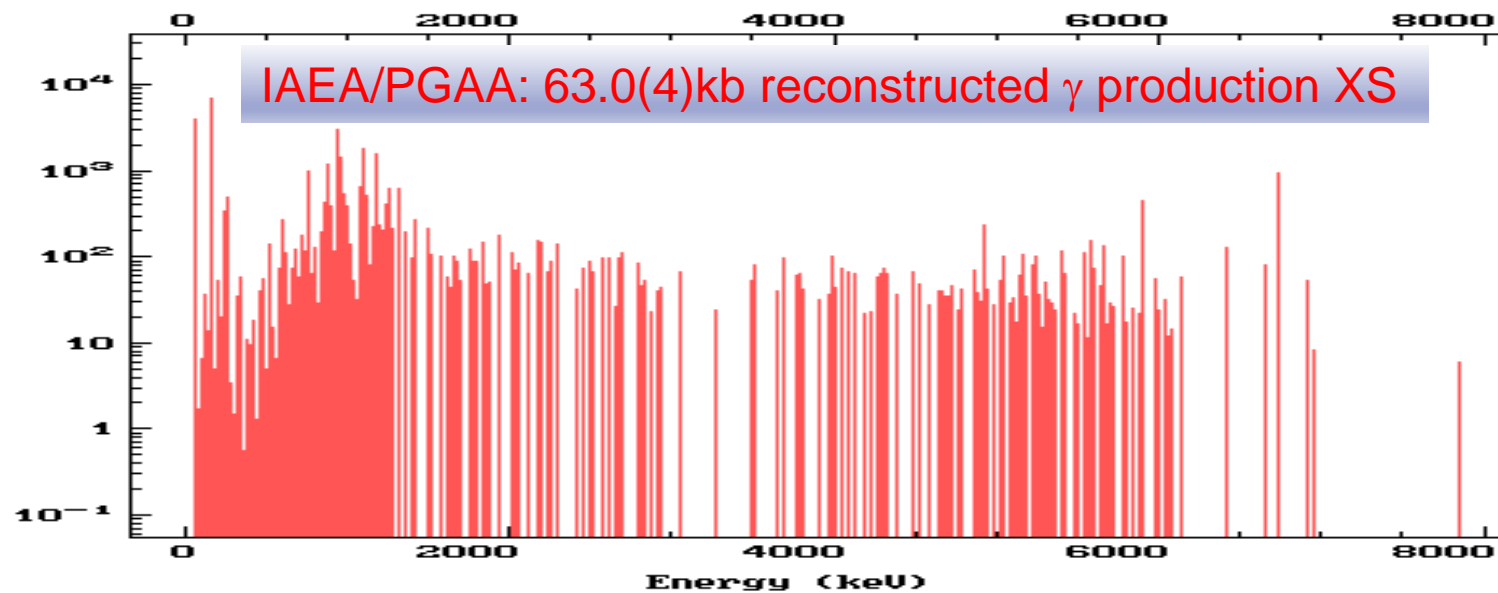
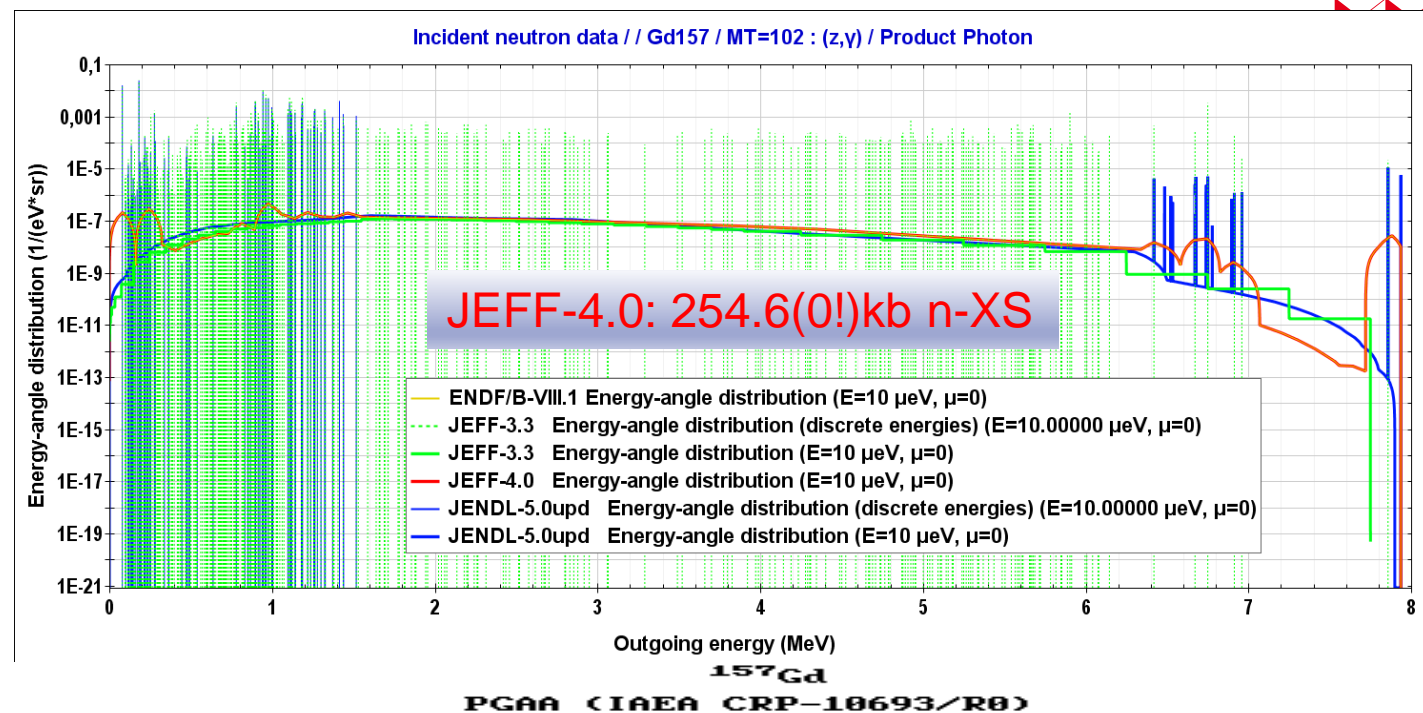
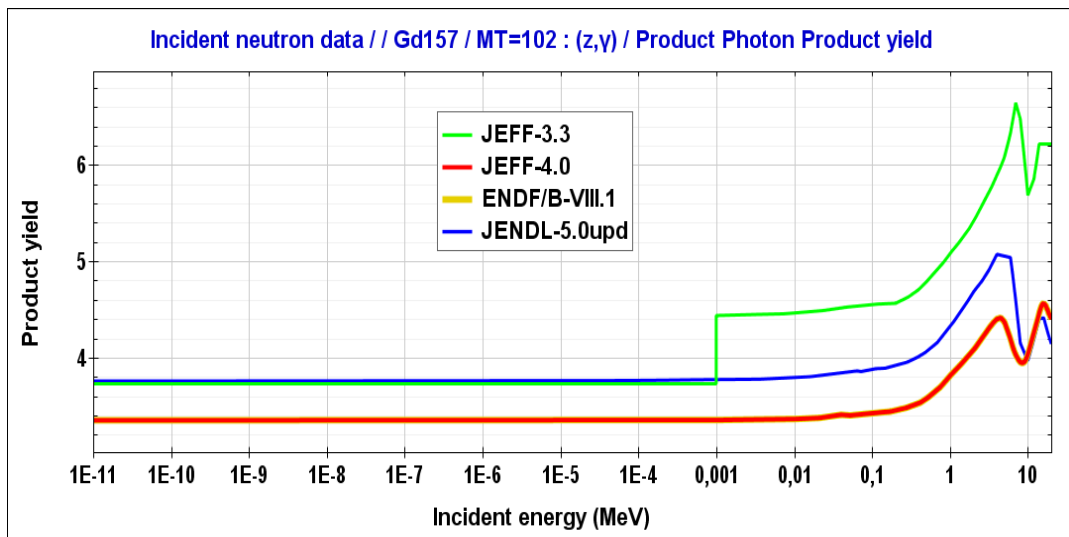
JEFF-4.0: 2.59(13)b n-XS



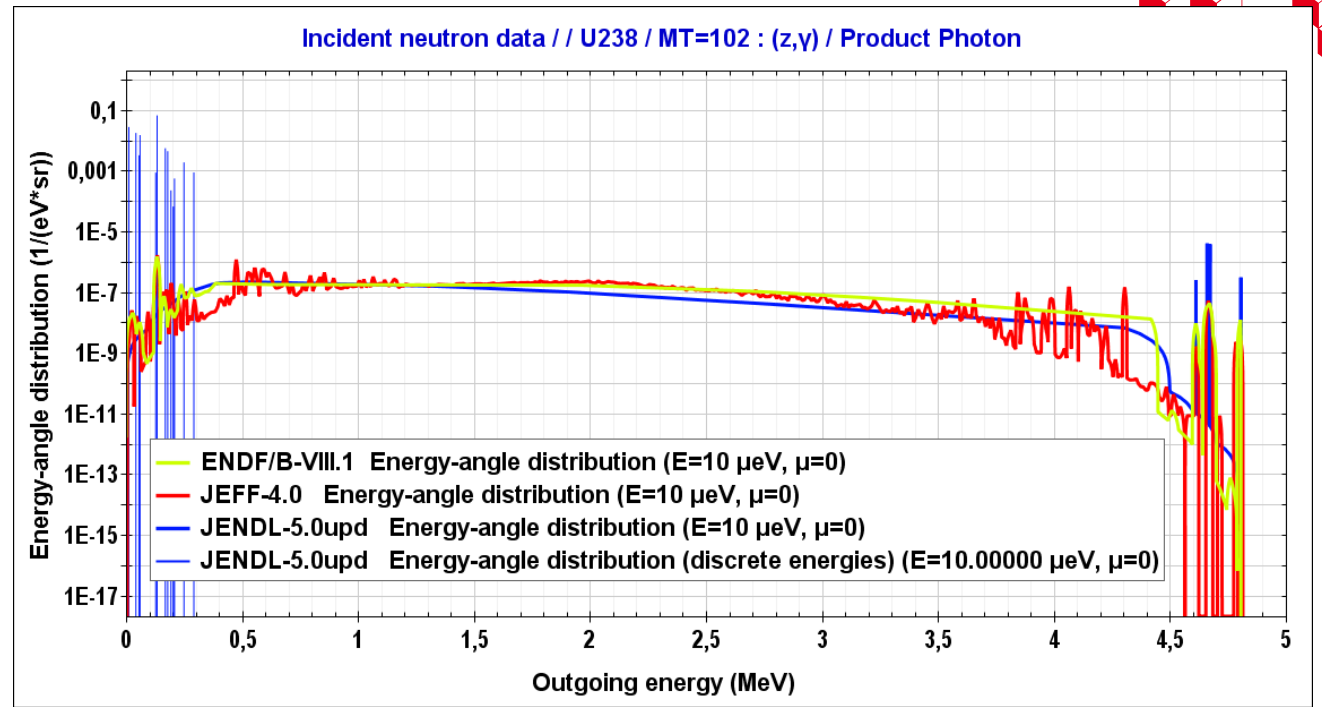
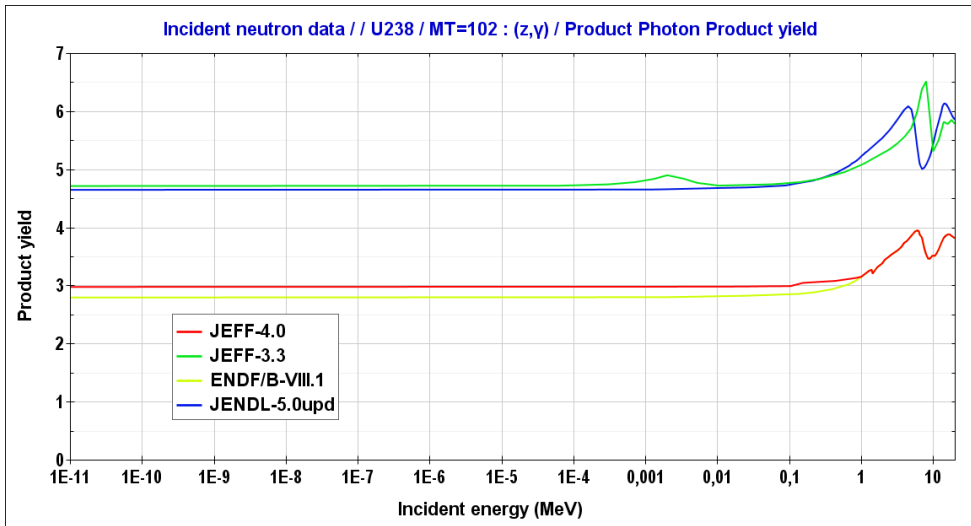
IAEA/PGAA: 2.48(2)b reconstructed $\gamma+e_{\text{IC}}^-$ production XS



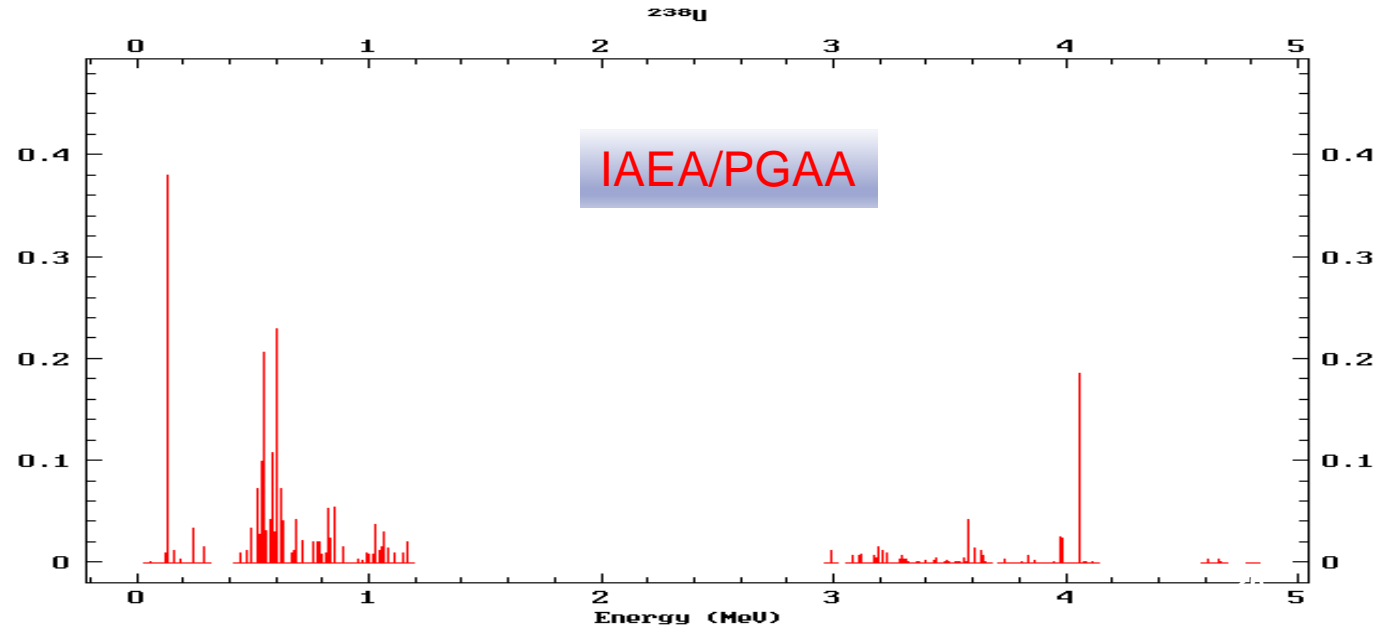
$^{157}\text{Gd}(n_{\text{th}}, \gamma)$



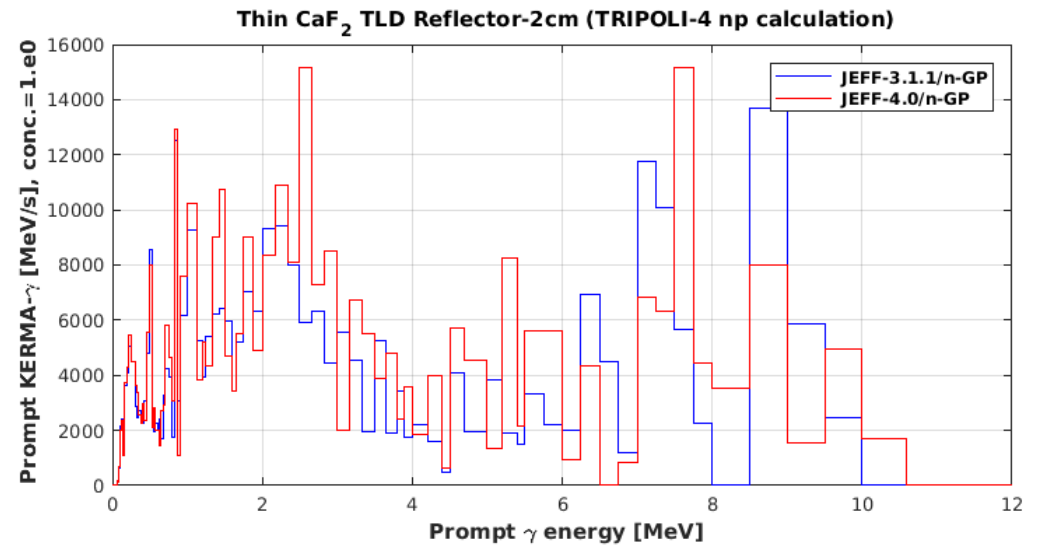
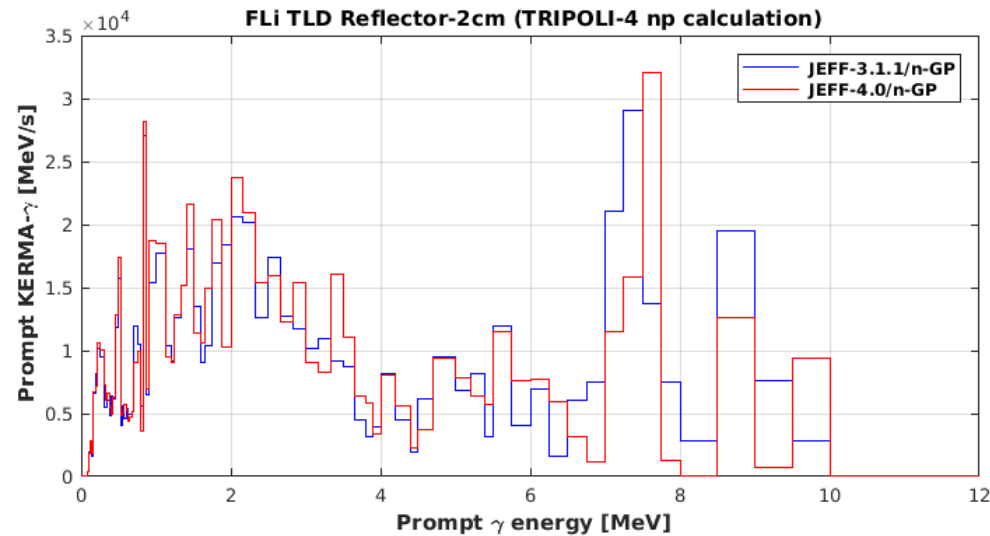
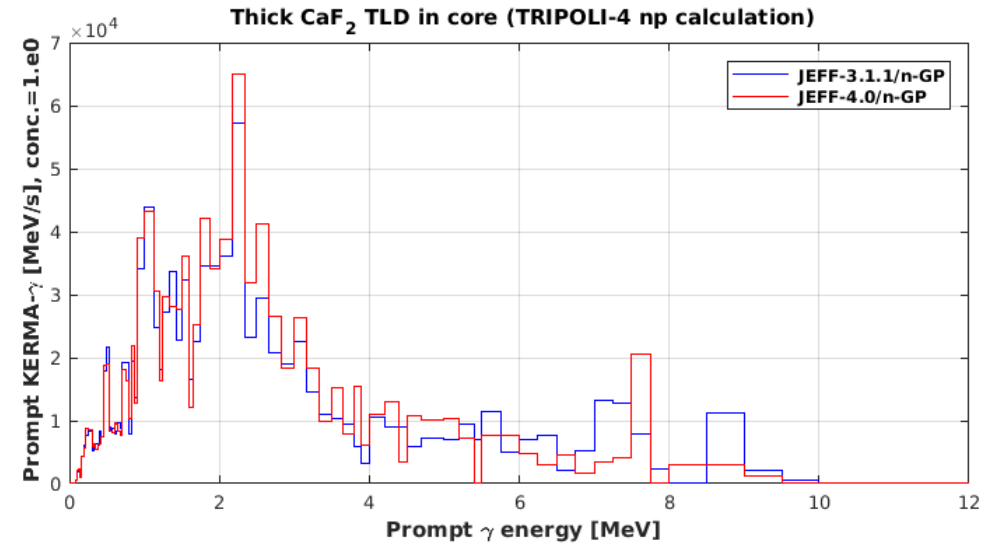
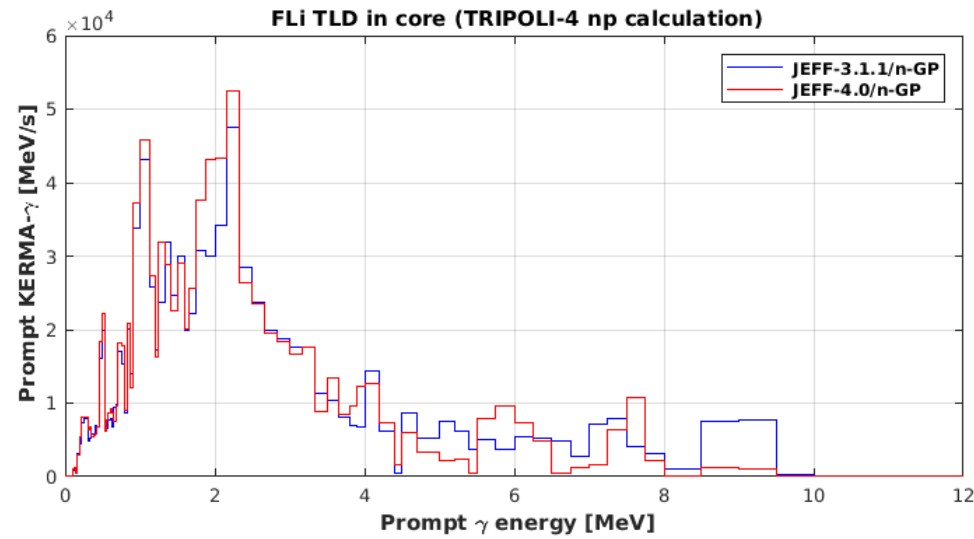
$^{238}\text{U}(n_{\text{th}},\gamma)$



Cross Section (barns)



PERLE/KERMA- γ



PERLE/cumulative(KERMA- γ)

