Measurement of the ^{166,167,168,170}Er(n,γ) cross-section at EAR1

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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

INFN

Outline of the presentation

- Introduction and motivation
- Previous measurements and evaluations of Er
- Er measurement at n_TOF EAR1
- Beam time request

Motivations (Erbia vs Gadolinia)

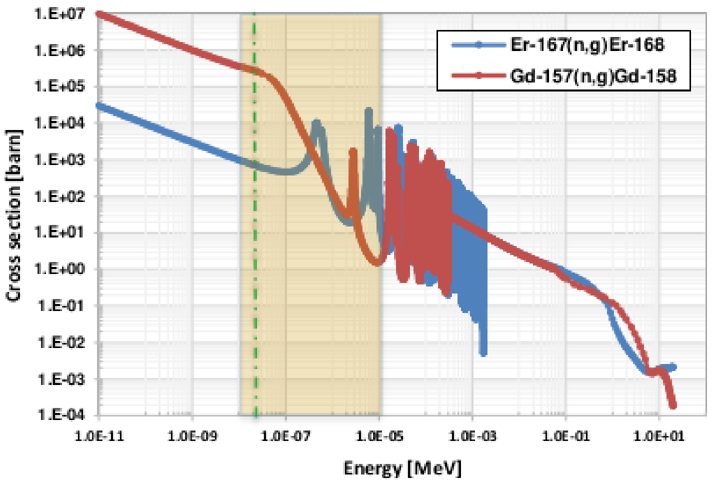
- Technical aspects:

– Lower thermal absorption cross sections (***Er: 162 b; Gd: 2.5E+05 b***) **not downgrade the power distribution**;

– More negative temperature feedback coefficient (***α=δk/δT***) **higher reactor core safety**;

– Higher and more energy extensive resonance integrals **better control of start-up and accidental transient phases**;

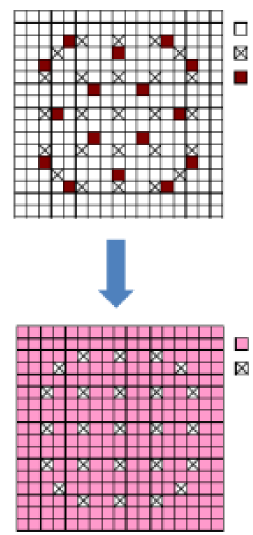
– Reduction of 239Pu in a EoL fuel core inventory **improvement of the non-proliferation actions.**

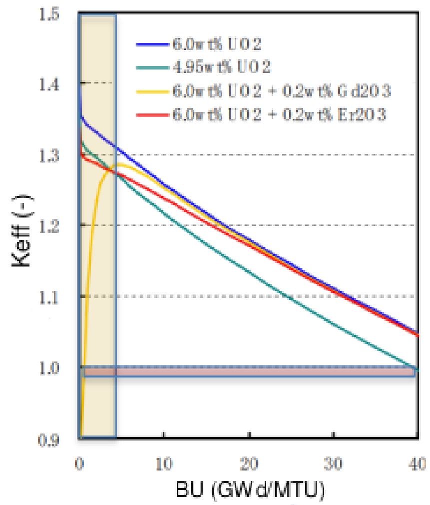


- Nuclear safety and economical aspects:

– Er-Super High Burnup fuel concept (BU>70 GWd/MTU, erbia>0.2 wt%, U-235> 5 wt%) was adopted in some exp. campaigns:

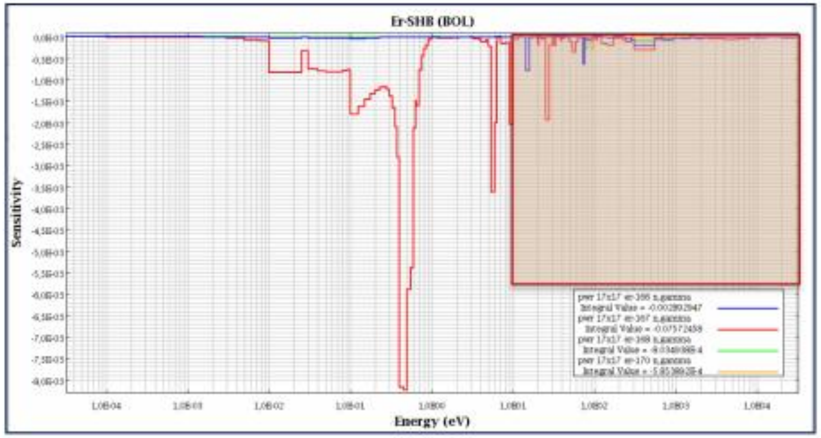
- Low content of Erbia is add into all UO2 (>5 wt%) powder just after the re-conversion process;
- Fuel enrichment is greater than 5 wt% but at BOL is equivalent to 5 wt%;
- Higher enriched fuel (HEU, enr > 5 wt%) can be handle within the existing fabrication facilities with **an improvement of the criticality safety** and a **global reduction of in-core the fuel cost**

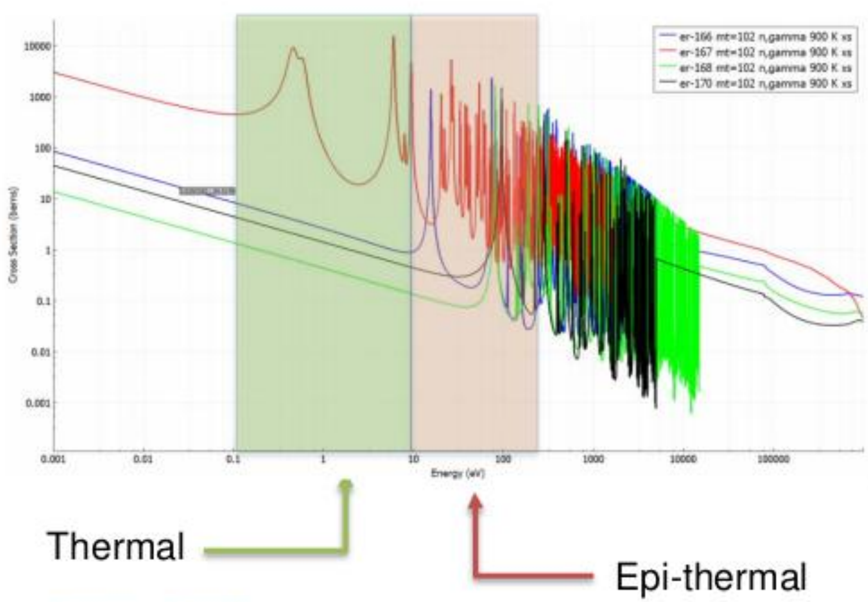




Slide by A. Guglielmelli

Er-SHB: S&U analysis – BOC





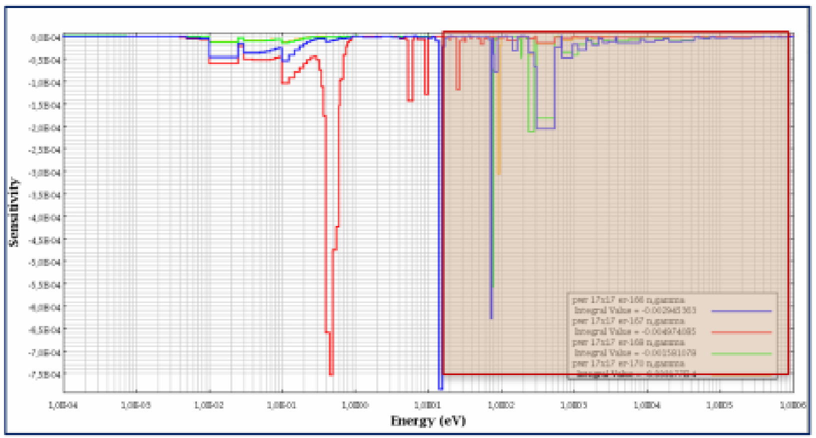
Isotope	Si (-)	Si/Si,tot (%)	Δk/k (-)	Δk (pcm)
(-)	E > 10 eV			
Er-166	-2.31E-03	80.0	1.38E-04	18
Er-167	-5.79E-03	7.0	7.08E-05	9
Er-168	-7.27E-04	90.5	7.67E-05	10
Er-170	-4.49E-04	76.7	5.37E-05	7

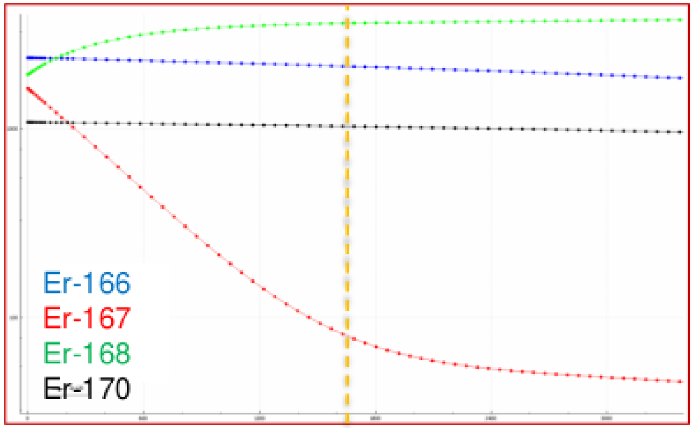
- Due to the overlapping of resonance of the Er-166,167,168,170 isotopes at energy higher than 10 eV, it's not possible to make a precise resonance shape analysis with natural erbium.
- Accurate contribution to criticality uncertainty of Er-166, Er-167, Er-168, Er-170 **for energy major than 10 eV** can be obtained only with Xs(n,g) measurements on single enriched isotopes.
- The sensitivity contribute to criticality uncertainty of Er-166, Er-168, Er-170 is equal to **45 pcm** (Cov. data: ENDF/B-VII.1).
- For core design purpose, any reduction of the criticality uncertainty is desirable.

Er-SHB: S&U analysis – EOC

- S&U analysis of the Er Xs(n,g) at high burnup (i.e., 60 GWd/MTU) on a Er-SHB FA system:

1. The nuclide BU-related inventory was evaluated with the T-DEPL module of SCALE 6.2.3;
2. The inventory of the most important isotopes for criticality (i.e., Ag, Am, Cm, Cs, Er, Eu, Gd, Mo, Nd, O, Pu, Rh, Ru, Sm, Tc, U) was imported in TSUNAMI-2D to perform a S&U analysis.





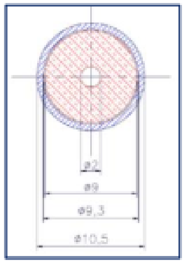
Isotope	Si (-)	Si/Si,tot (%)	Δk/k (-)	Δk (pcm)
(-)	E > 10 eV			
Er-166	-2.28E-03	77.5	1.38E-04	15
Er-167	-3,13E-04	6.3	7.08E-05	0
Er-168	-1.40E-03	88.4	7.67E-05	17
Er-170	-4.68E-04	73.9	5.37E-05	6

- Due to the spectrum hardening the relative weight of the erbium 166,168,170 isotopes sensitivity increase at higher energy;
- Due to the low content of Er-167 **the major contributor to uncertainty are Er-166 and Er-168**;
- The overall contribute to criticality uncertainty of Er-166, Er-168, Er-170 at E > 10 eV is equal to **38 pcm** (Cov. data: ENDF/B-VII.1).
- In order to have a precise assessment of the IBA reactivity penalty, any reduction of the criticality uncertainty at EOC is desirable

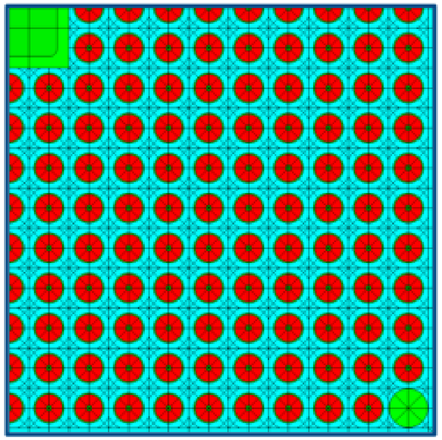
Slide by A. Guglielmelli

LFR-MOX: Design

- Research on the field of GEN IV LFR Reactor involves the use of MOX fuel in order to **[1]**:



  1. convert the uranium stored in Spent Nuclear Fuel (SNF) into fissile fuel;
  2. Burn the minor actinides (i.e, Np, Am, Cm, Cf) in SNF of LWR;

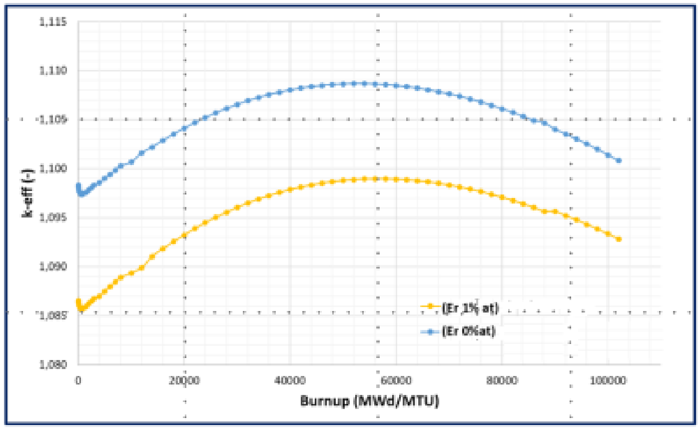


- S&U analysis on the LFR European conceptual design (**ELSY**)**:**
  1. The ELSY open square design (ENEA) was chosen;
  2. S&U at BOC with and without Erbia as IBA was performed with TSUNAMI-2D.

0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01
0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01
0,00	0,00	0,01	0,01	0,00	0,00	0,00	-0,01	0,00
0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00	0,00	-0,01	0,00	0,00	0,00
0,00	0,00	0,00	0,00	-0,01	0,00	-0,01	0,00	0,00
0,00	0,00	0,00	0,00	0,00	-0,01	0,00	-0,01	-0,01
0,00	0,00	-0,01	0,00	0,00	0,00	-0,01	0,00	0,00
0,01	0,01	0,00	0,00	0,00	0,00	-0,01	0,00	0,02

Very slight erbia content reduction during the fuel cycle

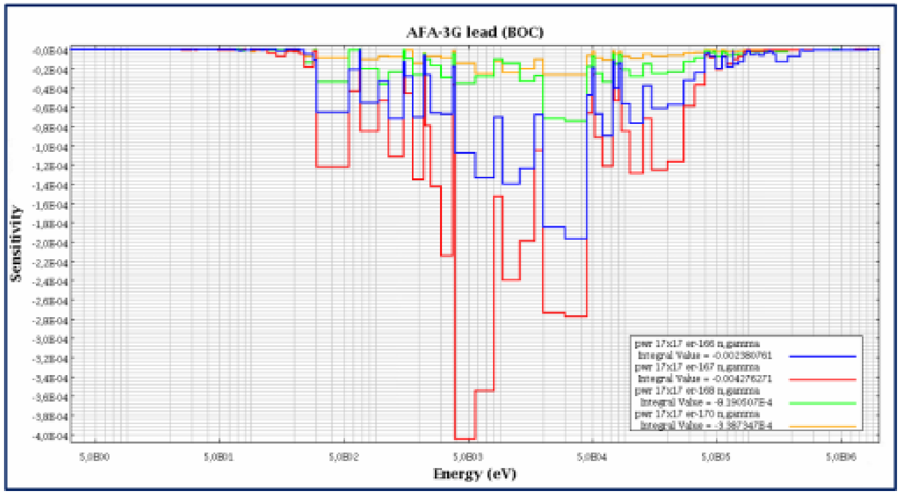
Very slight relative power distribution impact

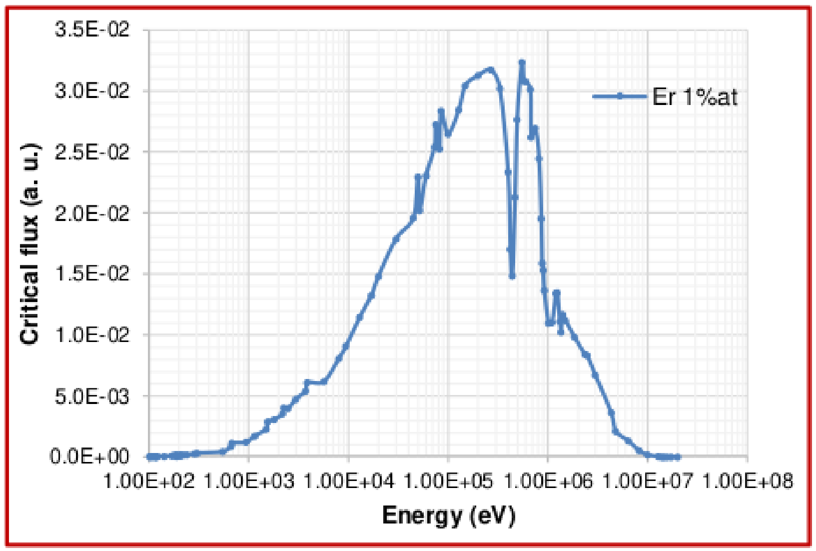


[1] M. Ibrahim et al, Neutronic performance analysis of MOX fuel with different candidate austenitic stainless-steel cladding in ALFRED reactor

Slide by A. Guglielmelli

LFR-MOX FA: S&U analysis – BOC





Covariance matrix				
nuclide-reaction with nuclide-reaction (-)				delta-k/k (%)
u-238	n,n'	u-238	n,n'	1,01E+00
u-238	n,gamma	u-238	n,gamma	4,02E-01
pu-239	n,gamma	pu-239	n,gamma	3,25E-01
pu-239	fission	pu-239	fission	2,16E-01
o-16	elastic	o-16	elastic	1,99E-01
pb-207	n,n'	pb-207	n,n'	1,87E-01
pu-239	chi	pu-239	chi	1,69E-01
pb-206	n,n'	pb-206	n,n'	1,47E-01
pu-241	chi	pu-241	chi	1,43E-01
u-238	nubar	u-238	nubar	1,37E-01
pu-239	n,n'	pu-239	n,n'	1,11E-01
u-238	chi	u-238	chi	1,07E-01
u-238	n,n'	u-238	elastic	-9,83E-02
pb-208	n,n'	pb-208	n,n'	8,90E-02
pu-239	nubar	pu-239	nubar	6,71E-02
pu-241	n,gamma	pu-241	n,gamma	6,49E-02
pu-241	fission	pu-241	fission	6,02E-02
zr-90	n,gamma	zr-90	n,gamma	5,91E-02
pu-240	n,gamma	pu-240	n,gamma	5,32E-02
pu-239	fission	u-238	fission	5,14E-02
pu-240	chi	pu-240	chi	4,88E-02
pb-208	elastic	pb-208	elastic	4,77E-02
zr-91	n,gamma	zr-91	n,gamma	4,68E-02
zr-92	n,gamma	zr-92	n,gamma	4,66E-02
pb-207	n,gamma	pb-207	n,gamma	4,53E-02
pb-208	n,gamma	pb-208	n,gamma	4,44E-02
er-167	n,gamma	er-167	n,gamma	4,34E-02
pu-240	n,n'	pu-240	n,n'	3,99E-02
zr-94	n,n'	zr-94	n,n'	3,88E-02
pu-240	fission	pu-240	fission	3,61E-02
zr-92	n,n'	zr-92	n,n'	3,50E-02
pb-204	n,gamma	pb-204	n,gamma	3,46E-02
u-238	fission	u-238	fission	3,43E-02
pu-240	nubar	pu-240	nubar	3,43E-02
pu-241	n,n'	pu-241	n,n'	3,32E-02
u-235	n,gamma	u-235	n,gamma	3,26E-02

zr-90	elastic	zr-90	elastic	2,95E-02
pu-241	nubar	pu-241	nubar	2,80E-02
u-235	fission	pu-239	fission	2,62E-02
zr-90	n,n'	zr-90	n,n'	2,37E-02
pb-206	n,gamma	pb-206	n,gamma	2,31E-02
pb-207	elastic	pb-207	elastic	2,29E-02
pb-206	elastic	pb-206	elastic	2,26E-02
pu-239	n,n'	pu-239	elastic	-2,19E-02
u-238	elastic	u-238	n,gamma	-2,14E-02
zr-94	n,gamma	zr-94	n,gamma	1,89E-02
nb-93	n,gamma	nb-93	n,gamma	1,65E-02
u-238	elastic	u-238	elastic	1,49E-02
er-166	n,gamma	er-166	n,gamma	1,45E-02
zr-91	n,n'	zr-91	n,n'	1,41E-02
pu-239	fission	pu-239	n,gamma	-1,36E-02
zr-94	elastic	zr-94	elastic	1,30E-02
pu-239	elastic	pu-239	n,gamma	-1,22E-02
u-235	fission	u-238	n,gamma	-1,18E-02
pu-238	chi	pu-238	chi	1,12E-02
pb-204	n,n'	pb-204	n,n'	1,10E-02
zr-92	elastic	zr-92	elastic	1,06E-02
pu-242	n,gamma	pu-242	n,gamma	7,84E-03
am-241	n,gamma	am-241	n,gamma	7,77E-03
u-238	fission	u-238	n,gamma	7,41E-03
zr-91	elastic	zr-91	elastic	7,38E-03
er-168	n,gamma	er-168	n,gamma	7,23E-03
u-235	fission	u-238	fission	6,98E-03
u-235	chi	u-235	chi	6,81E-03
er-164	n,gamma	er-164	n,gamma	6,58E-03
pu-240	n,n'	pu-240	elastic	-5,83E-03
pu-238	n,gamma	pu-238	n,gamma	5,77E-03
u-235	fission	u-235	fission	5,71E-03
o-16	n,gamma	o-16	n,gamma	5,31E-03
er-170	n,gamma	er-170	n,gamma	5,24E-03
er-167	n,n'	er-167	n,n'	5,18E-03
pu-242	fission	pu-242	fission	5,15E-03

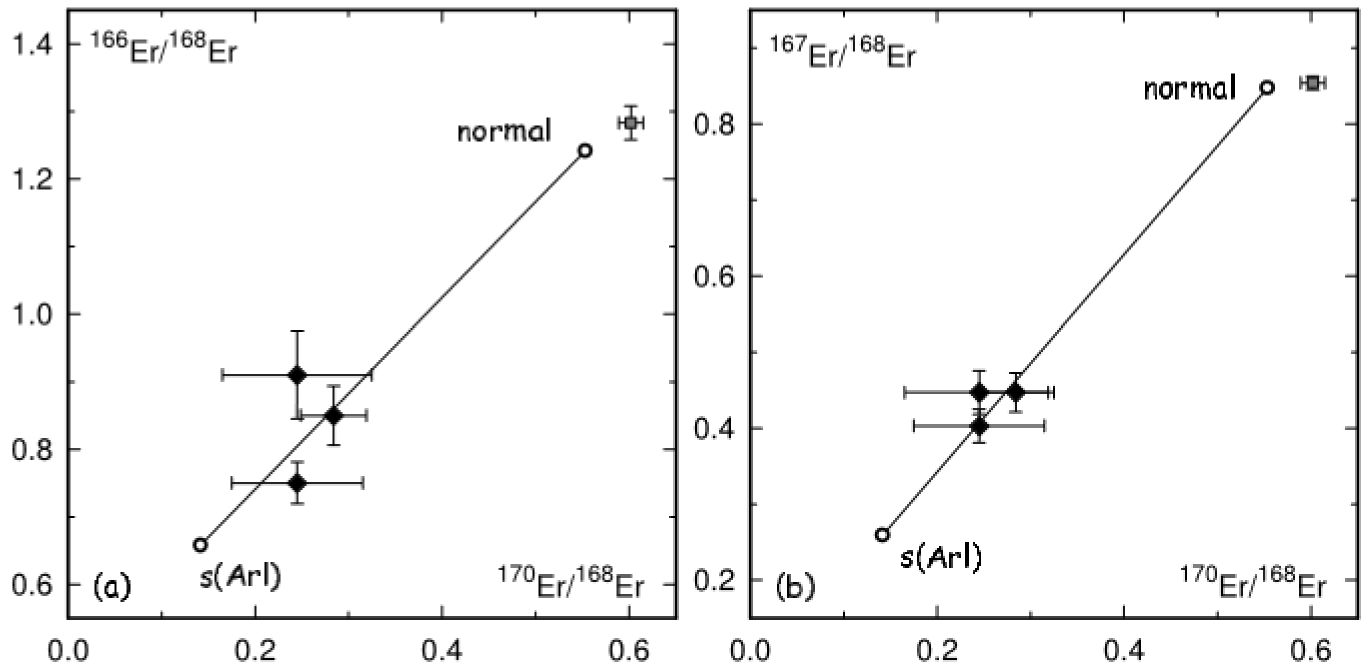
- Sensitivity: erbium sensitivity range between $10^2 - 10^6$ eV.
- Uncertainty: Er-167 (**46 pcm**), Er-166 (**15 pcm**), Er-168 (**8 pcm**), Er-170 (**6 pcm**).

Slide by A. Guglielmelli

Motivation astrophysics

Accurate cross section data on erbium isotopes could be of interest for the study of the s-process nucleosynthesis around the region of rare earth elements at A=160-170. For instance, the abundance of $^{166,167,168,170}Er$ isotopes in presolar silicon carbide grains was recently measured by Yin and collaborators.

The present overall disagreement between observed and calculated abundances clearly call for (n,γ) measurements of isotopes involved in this mass region



https://iopscience.iop.org/article/10.1086/505188

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Slide by C. Massimi

Medicine motivation for Er-168 and Er-170

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Very high specific activity erbium ^{169}Er production for potential receptor-targeted radiotherapy

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Manufacture and Properties of Erythromycin Beads Containing Neutron-Activated Erbium-171

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Received May 4, 1989; accepted September 25, 1989

To evaluate the effects of a neutron activation radiolabeling technique on an enteric-coated multiparticulate formulation of erythromycin, test quantities were produced under industrial pilot scale conditions. The pellets contained the stable isotope erbium oxide (Er-170), which was later converted by neutron activation into the short-lived gamma ray-emitting radionuclide, erbium-171. *In vitro* studies indicated that the dissolution profile, acid resistance, and enteric-coated surface of the pellets were minimally affected by the irradiation procedure. Antimicrobial potency was also unaffected, as determined by microbiological assay. Neutron activation thus appears to simplify the radiolabeling of complex pharmaceutical dosage forms for *in vivo* study by external gamma scintigraphy.

Recent studies has show the future use of Er-169 in medicine, in particular there is recent paper with a Er-169 produced in ILL form Er-168 and measured at CERN-MEDICIS. The samples of Er-169 are produced at the moment irradiating targets of Er-168, so better data of the capture cross section of this isotope can help this technology.

Er-171 is also used in nuclear medicine, this isotope is also produced in nuclear reactors by capture in Er-170. There are also recent measurements of the half-life of this isotope

https://doi.org/10.1016/j.nimb.2019.04.022

https://link.springer.com/content/pdf/10.1007/s41365-018-0378-0.pdf

Summary

- Erbia (Er_2O_3) can be considered as an **excellent alternative to burnable absorber** made of gadolinia (Gd_2O_3)

- There is a **new entry in the HPRL** to measure the capture C.S. of Er-167 between 0.01 and 100 eV with a 2% uncertainty.

Scientific motivations for a reassessment of the neutron capture cross sections of erbium isotopes in the high-sensitivity thermal energy range for LWR systems

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https://doi.org/10.1016/j.anucene.2022.109337

Request ID	118		Type of the request	High Priority request	
Target	Reaction and process	Incident Energy	Secondary energy or angle	Target uncertainty	Covariance
68-ER-167	(n,g) SIG,RP	0.01 eV-100 eV		2	Y
Field	Subfield	Created date	Accepted date	Ongoing action	Archived Date
Fission	LWR, innovative fuel	09-JUL-21	30-AUG-21	Y	

https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=539

- It has been explored the criticality uncertainty contribute of **erbium isotopes at energy major than 10 eV for several reactor configuration**;
  - Er-SHB at EOC showed a criticality uncertainty contribute of 45 pcm.
  - ELSY (LFR system) showed an overall criticality uncertainty contribute of 75 pcm.

- The capture cross section of $^{166,167,168,170}Er$ are also important for astrophysics and some of these isotopes have also applications in medicine.

Previous measurements

The previous measurements used for the evaluations and the recent measurements are:

Measurement	Energy range (eV)			
	^{166}Er	^{167}Er	^{168}Er	^{170}Er
Hopkins (1958)(Cap.)[9]	Thermal	Thermal	-	-
Møller (1960)(Tra.)[10]	-	0.4-0.6	-	-
Vertebnyi (1965)(Tra.)[11]	16	Thermal-30	-	95
Mughabghab (1967)(Tra.)[12]	Thermal-600	Thermal-150	Thermal-1.5e3	95
Liou (1972)(Cap./Tra.)[13]	15-1e4	0.4-1.7e3	80-1.5e4	95-2.4e4
Kahane (1984)(Cap.)[14]	-	5-600	-	-
Knopf (1996)(Tra.)[15]	Thermal	Thermal	Thermal	Thermal
Danon (1998)(Tra.)[16]	Thermal-15	Thermal-15	-	-
Harun (2000)(Tra.)[17]	-	1e4-9e4	-	-
Wang (2010)(Tra.)[18]	15-120	0.4-120	80	95
Li (2021)(Cap.)[19]	15-100	0.4-100	80	95

Previous measurements

The previous measurements used for the evaluations and the recent measurements are:

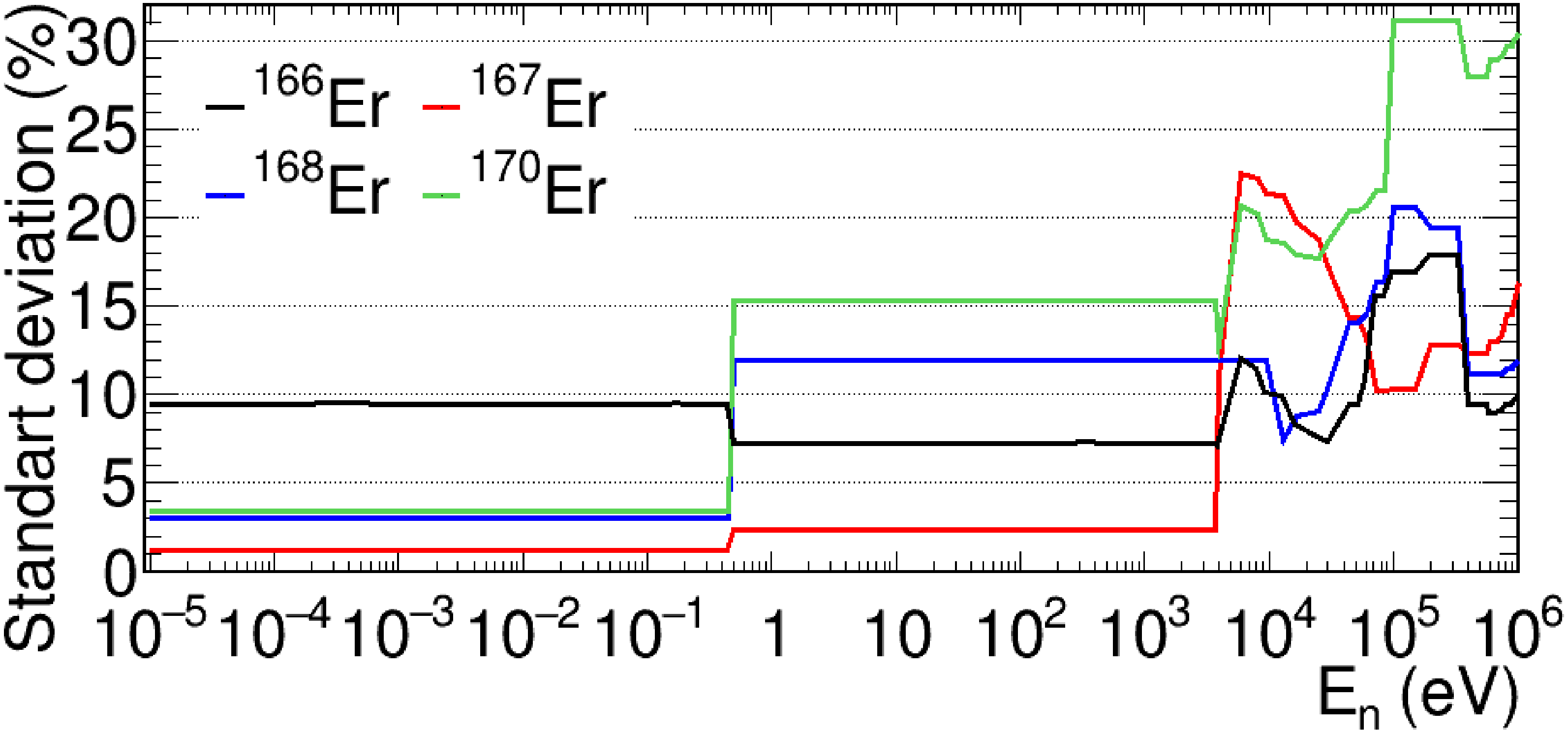
Enriched samples

Measurement	Energy range (eV)			
	^{166}Er	^{167}Er	^{168}Er	^{170}Er
Hopkins (1958)(Cap.)[9]	Thermal	Thermal	-	-
Møller (1960)(Tra.)[10]	-	0.4-0.6	-	-
Vertebnyi (1965)(Tra.)[11]	16	Thermal-30	-	95
Mughabghab (1967)(Tra.)[12]	Thermal-600	Thermal-150	Thermal-1.5e3	95
Liou (1972)(Cap./Tra.)[13]	15-1e4	0.4-1.7e3	80-1.5e4	95-2.4e4
Kahane (1984)(Cap.)[14]	-	5-600	-	-
Knopf (1996)(Tra.)[15]	Thermal	Thermal	Thermal	Thermal
Danon (1998)(Tra.)[16]	Thermal-15	Thermal-15	-	-
Harun (2000)(Tra.)[17]	-	1e4-9e4	-	-
Wang (2010)(Tra.)[18]	15-120	0.4-120	80	95
Li (2021)(Cap.)[19]	15-100	0.4-100	80	95

Natural samples

Evaluations

For ^{166,168,170}Er the evaluations of JENDL-5, JEFF-3.3 and ENDF-VIII and the uncertainties are between 7-15% in the RRR.
The uncertainty for ^{167}Er in the RRR is 2.3%, this value is questionable.



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Evaluations

The uncertainty for ^{167}Er in the RRR is 2.3%, this value is questionable.

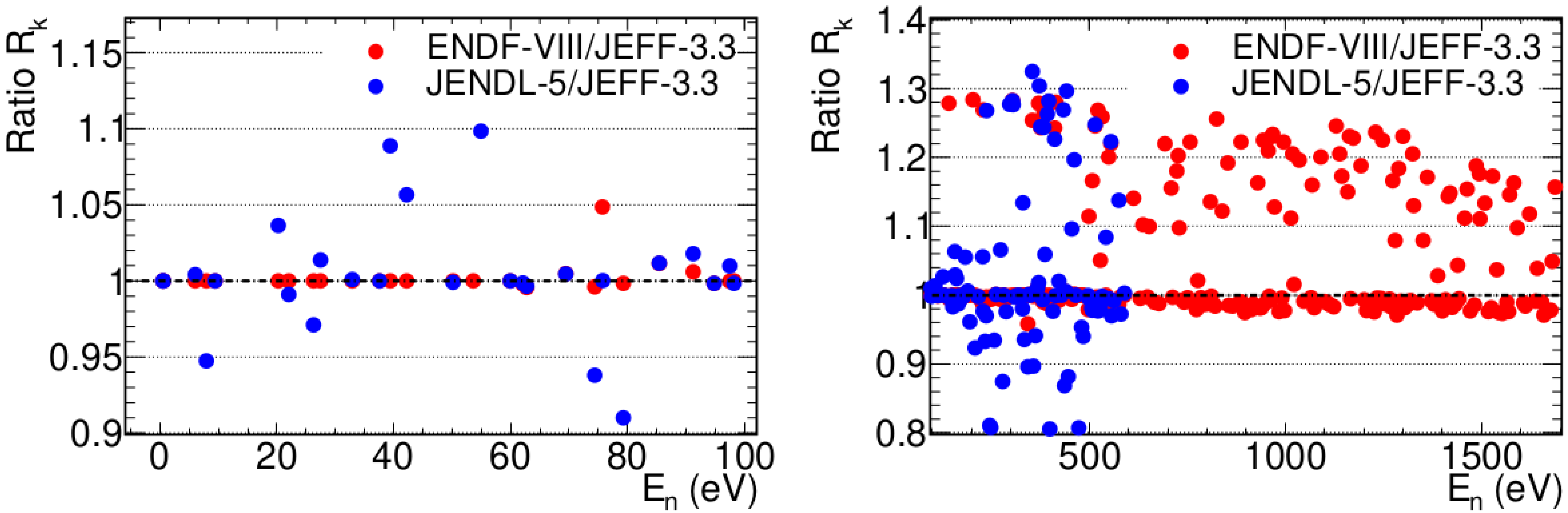

Figure 4: The ratios of the radiative kernels $(\Gamma_\gamma \cdot \Gamma_n/\Gamma)$ for the resonances of ^{167}Er for various libraries JEFF-3.3 [20], JENDL-5 [21] and ENDF-VIII [22].

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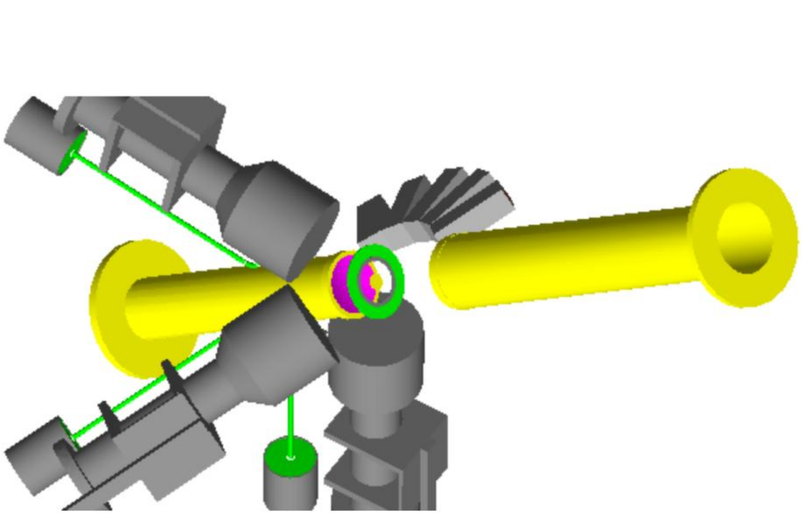
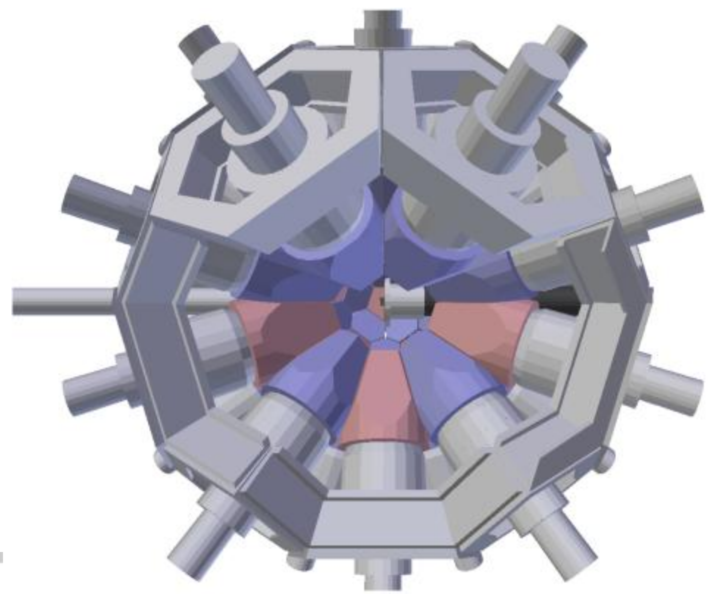
The measurement at EAR1 with natural Er

Measurement of a Natural sample of Er in the range **from 0.02 eV to 50 eV** with an aimed accuracy of 2%. The idea is to use a very well characterized metallic sample of ~30 mg. Samples of higher mass would need considerable self-shielding and multiple scattering corrections

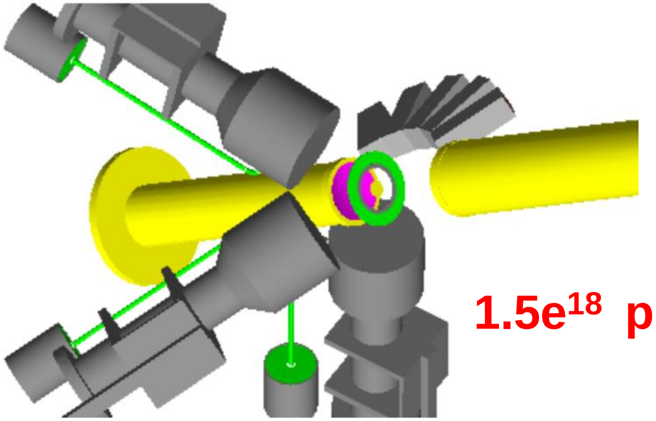
- C_6D_6 detectors (ε_{cas} = ~7%) and TAC (ε_{cas} = ~60%)
- The work of I. Knapova et al, would be considered for the PSF, spin assignment and the 109 ns isomer.



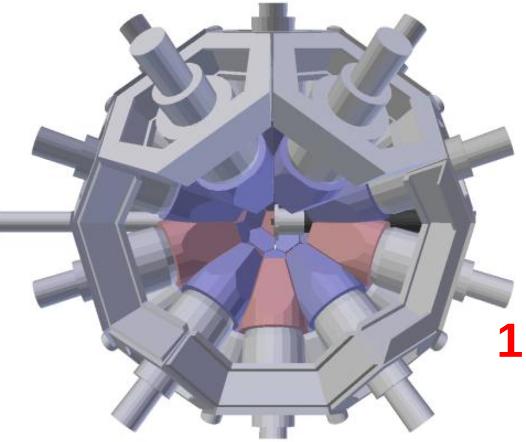


The measurement at EAR1 with natural Er

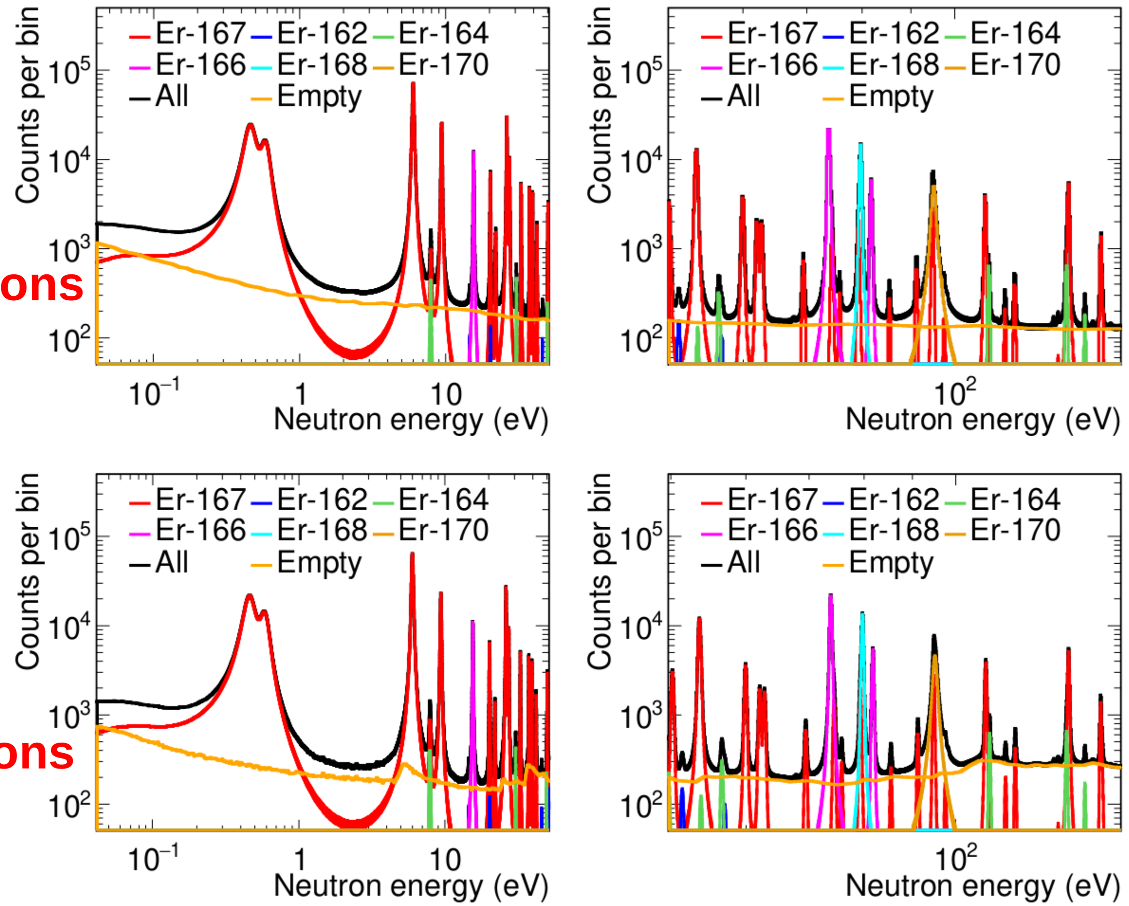
Measurement of a Natural sample of Er in the range **from 0.02 eV to 50 eV** with an aimed accuracy of 2%. The idea is to use a very well characterized metallic sample of ~30 mg. Samples of higher mass would need considerable self-shielding and multiple scattering corrections. It is not possible to obtain precisely the RP for ^{167}Er at energies higher than 50 eV.



1.5e^{18} protons

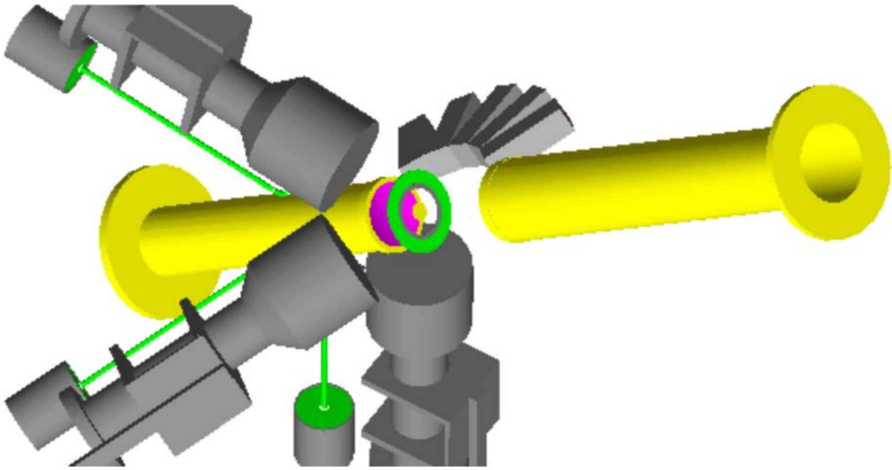


1.0e^{18} protons



The measurement at EAR1 with enriched Er

The cross sections of $^{166,167,168,170}Er$ would be measured with enriched samples of ~200 mg using 3 L6D6 and 5 sTED at different angles. The detectors at different angles are to observe the possible angle effects in the p-waves and s-waves of Er.



Sample	Mass	Detector	Energy range	Number protons
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0 \cdot 10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
^{168}Er	200mg	C_6D_6	50 eV-100 keV	$1.5 \cdot 10^{18}$
^{170}Er	200mg	C_6D_6	50 eV-50 keV	$1.5 \cdot 10^{18}$

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The measurement at EAR1 with enriched Er

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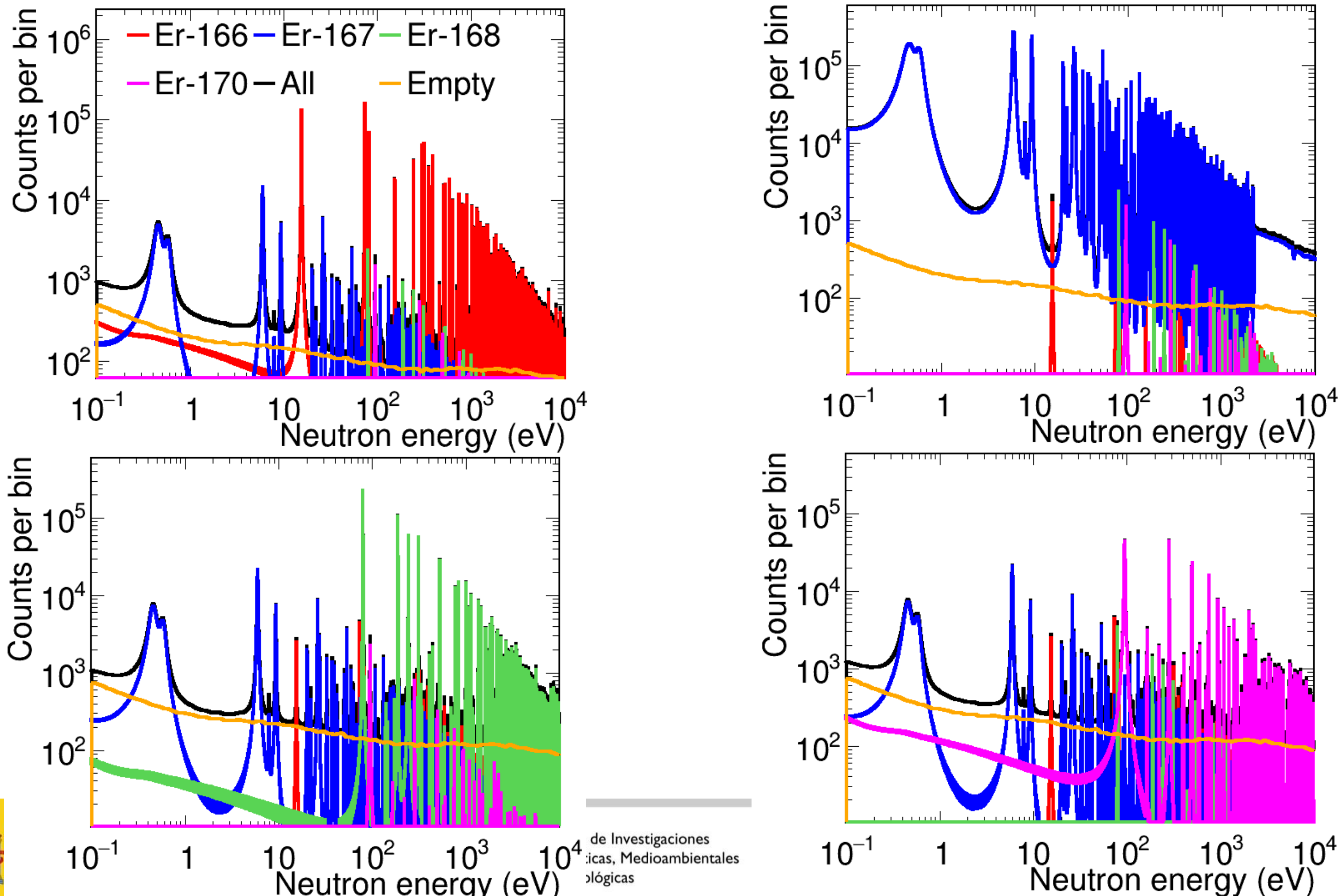
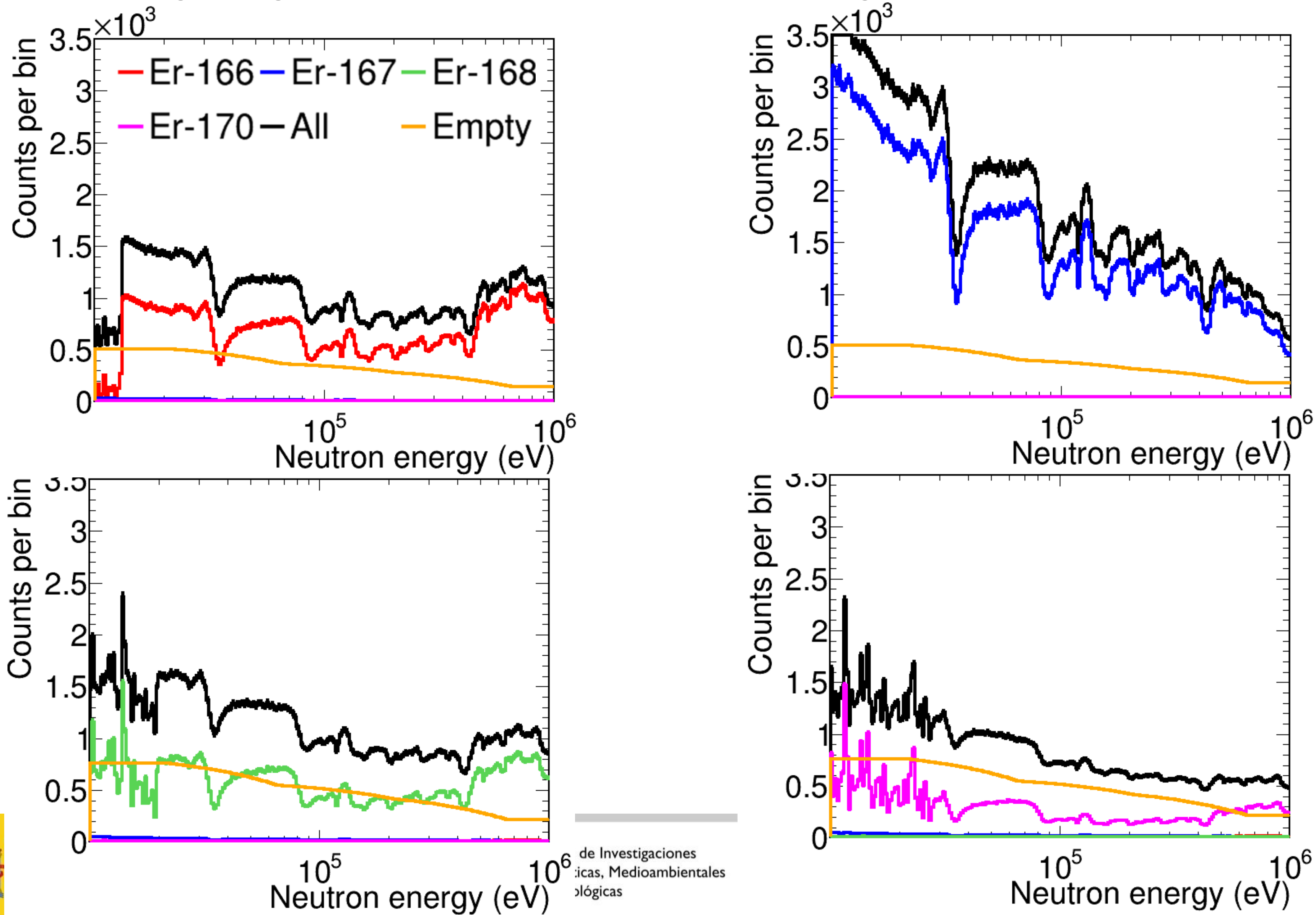


The measurement at EAR1 with enriched Er

The cross sections of $^{166,167,168,170}Er$ would be measured with enriched samples of ~200 mg using 3 L6D6 and 5 sTED at different angles.



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Summary, conclusions and requested protons

- Erbium has been proposed to be used as **burnable absorber** in commercial nuclear reactors, instead of gadolinium.

- The uncertainty CS of ^{167}Er in the RRR in ENDF-VIII is ~2.3%, it has been shown that this value is underestimate. There is a **new entrance in the HPRL of NEA for new measurements with uncertainties close to 2%.**

- The cross sections of ^{166,168,170}Er also play a important role for reactors and the uncertainties are from 7 to 15% in the RRR. New precise measurements are needed

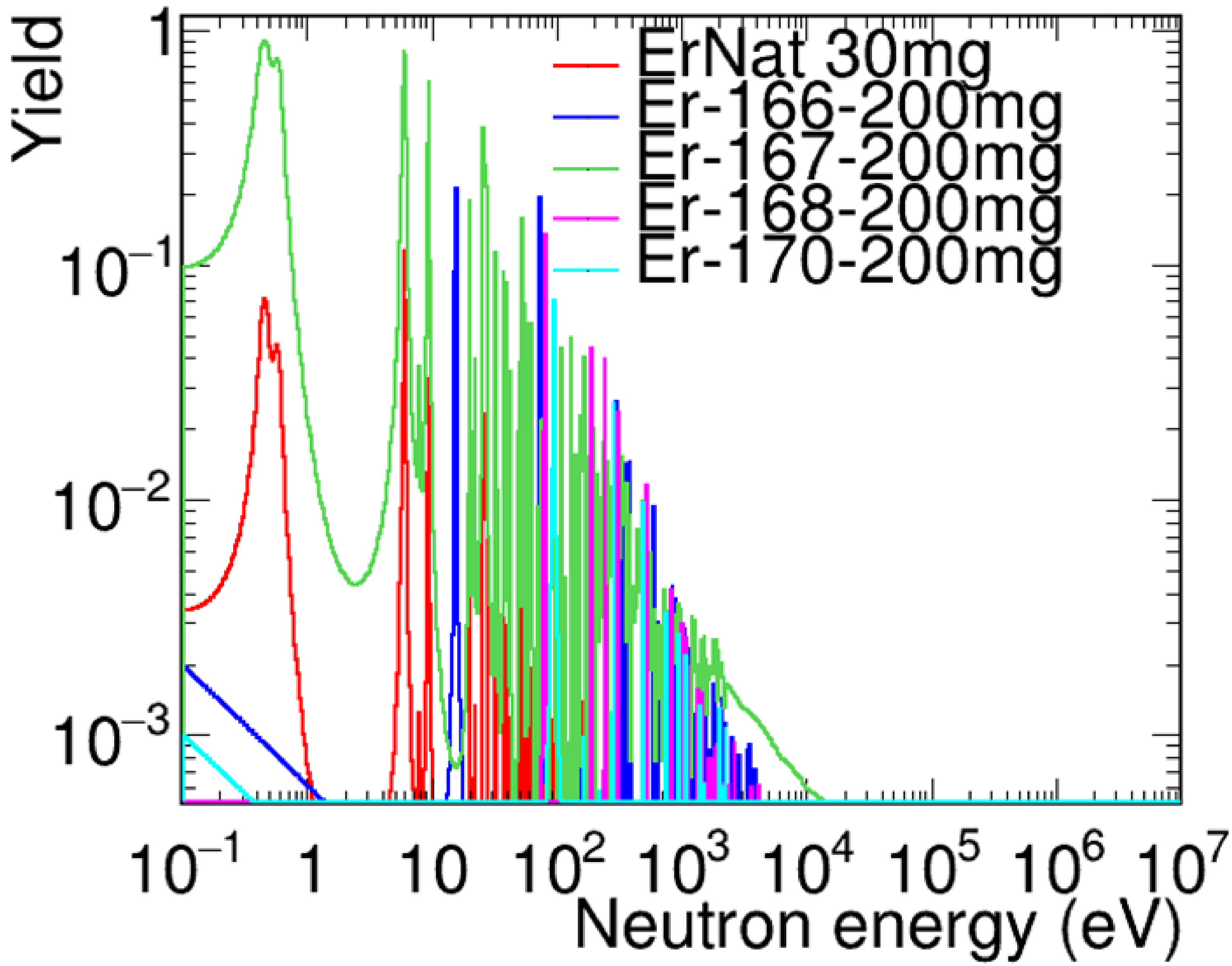
- A measurement with a **natural Er sample using the C6D6 and the TAC** is proposed to fulfill the HPRL requirements between 0.01 and 50 eV.

- **Four measurements with ~200 mg enriched samples of ^{166,167,168,170}Er** with C6D6 are also proposed.

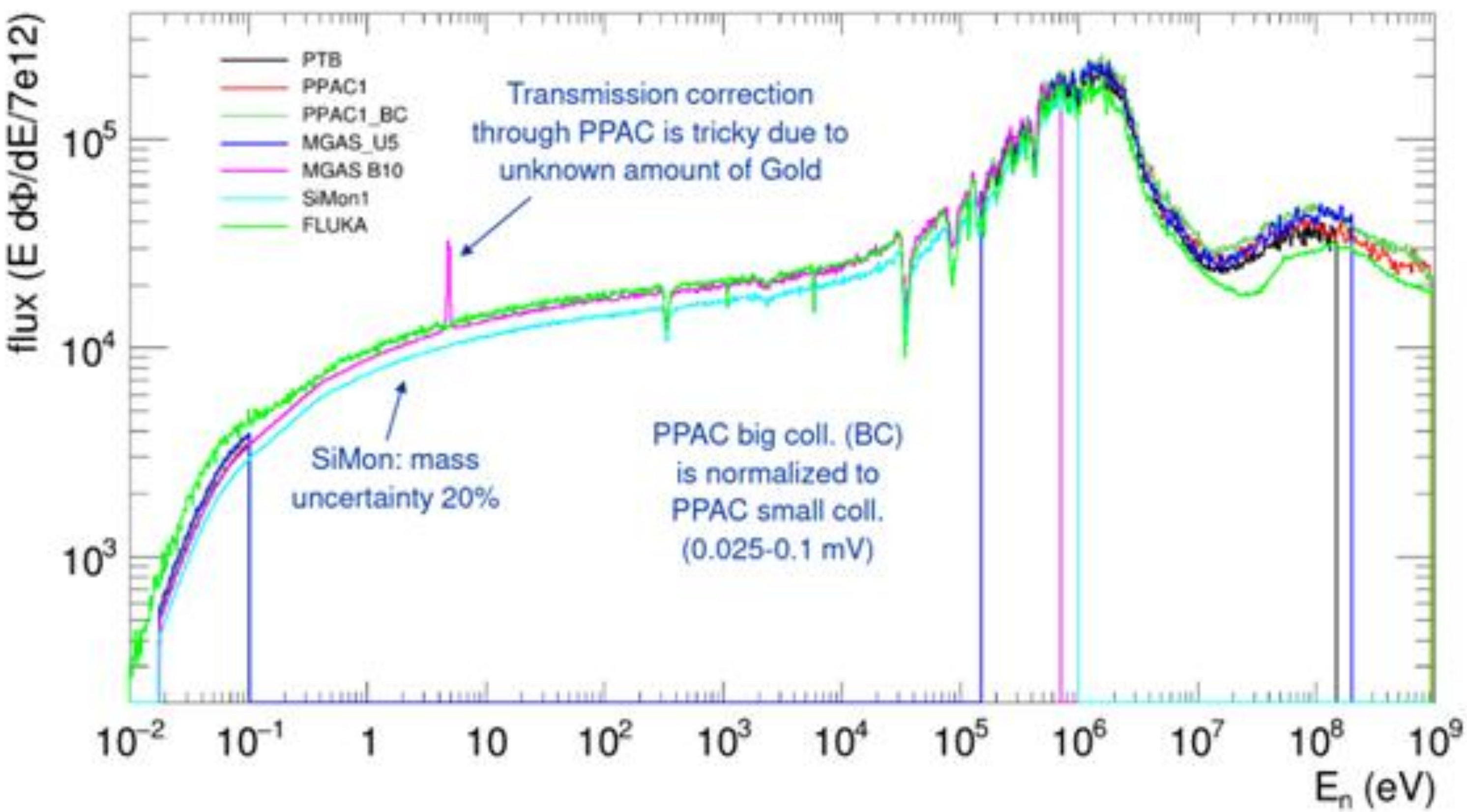
Sample	Mass	Detector	Energy range	Number protons
Natural	30mg	TAC	0.01-50 eV	$1.0 \cdot 10^{18}$
Natural	30mg	C_6D_6	0.01-50 eV	$1.5 \cdot 10^{18}$
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0 \cdot 10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
^{168}Er	200mg	C_6D_6	50 eV-100 keV	$1.5 \cdot 10^{18}$
^{170}Er	200mg	C_6D_6	50 eV-50 keV	$1.5 \cdot 10^{18}$
TAC auxiliary and normalization measurements				$0.5 \cdot 10^{18}$
C_6D_6 auxiliary and normalization measurements				$1.0 \cdot 10^{18}$
Total				$9.0 \cdot 10^{18}$

Extra slides

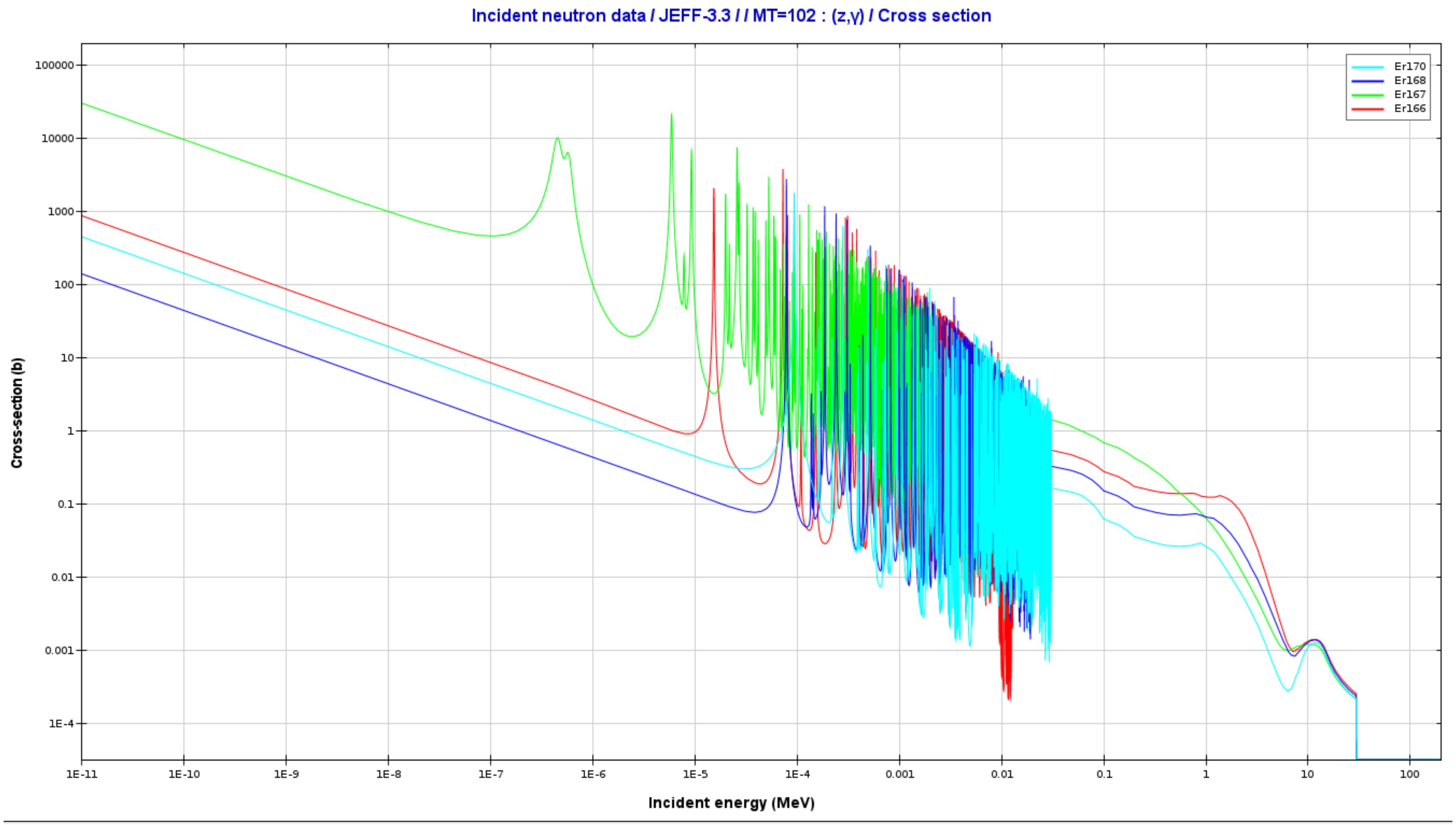
Estimated total yields



Flux per detector with available corrections



Capture C.S.



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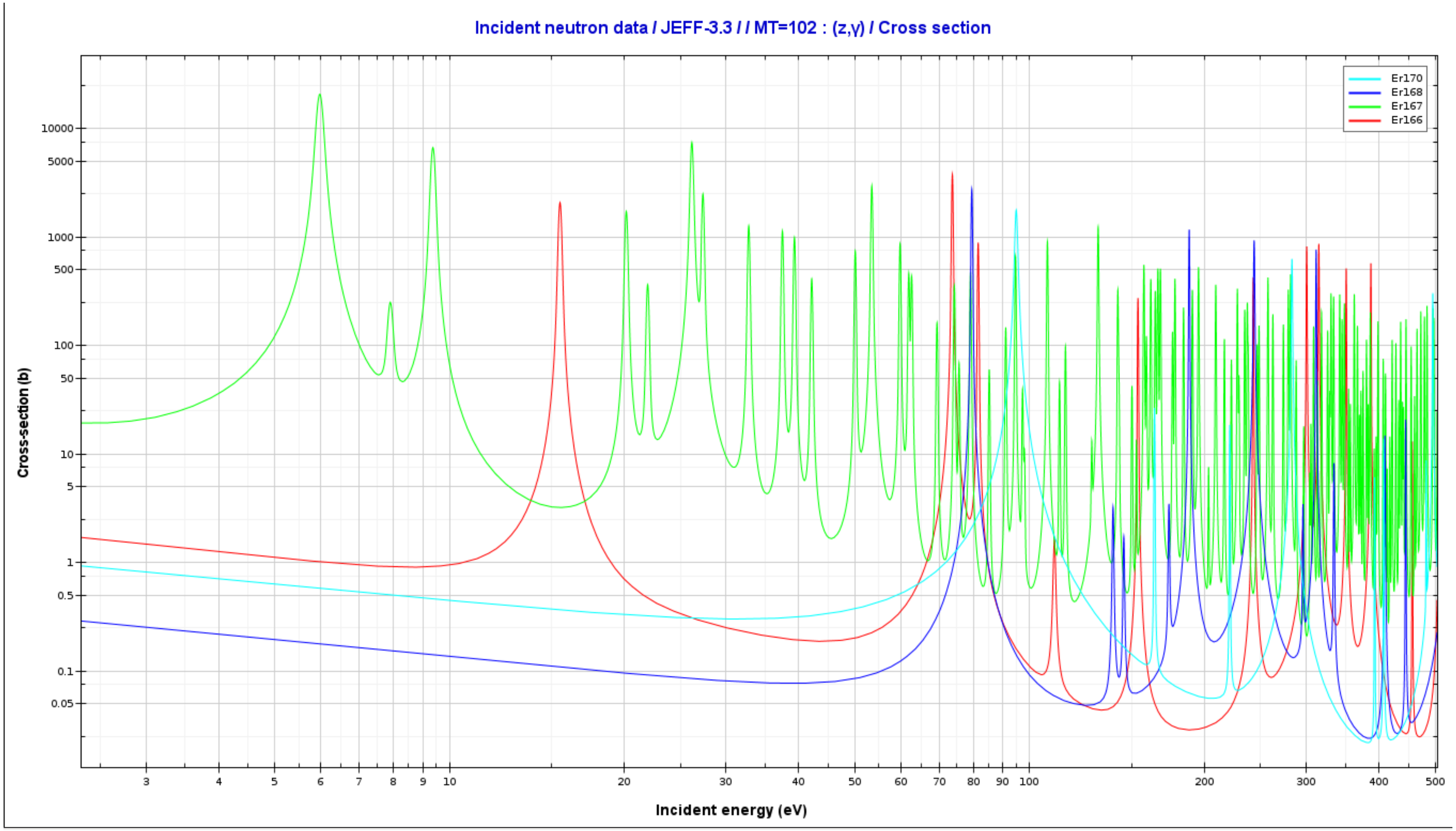
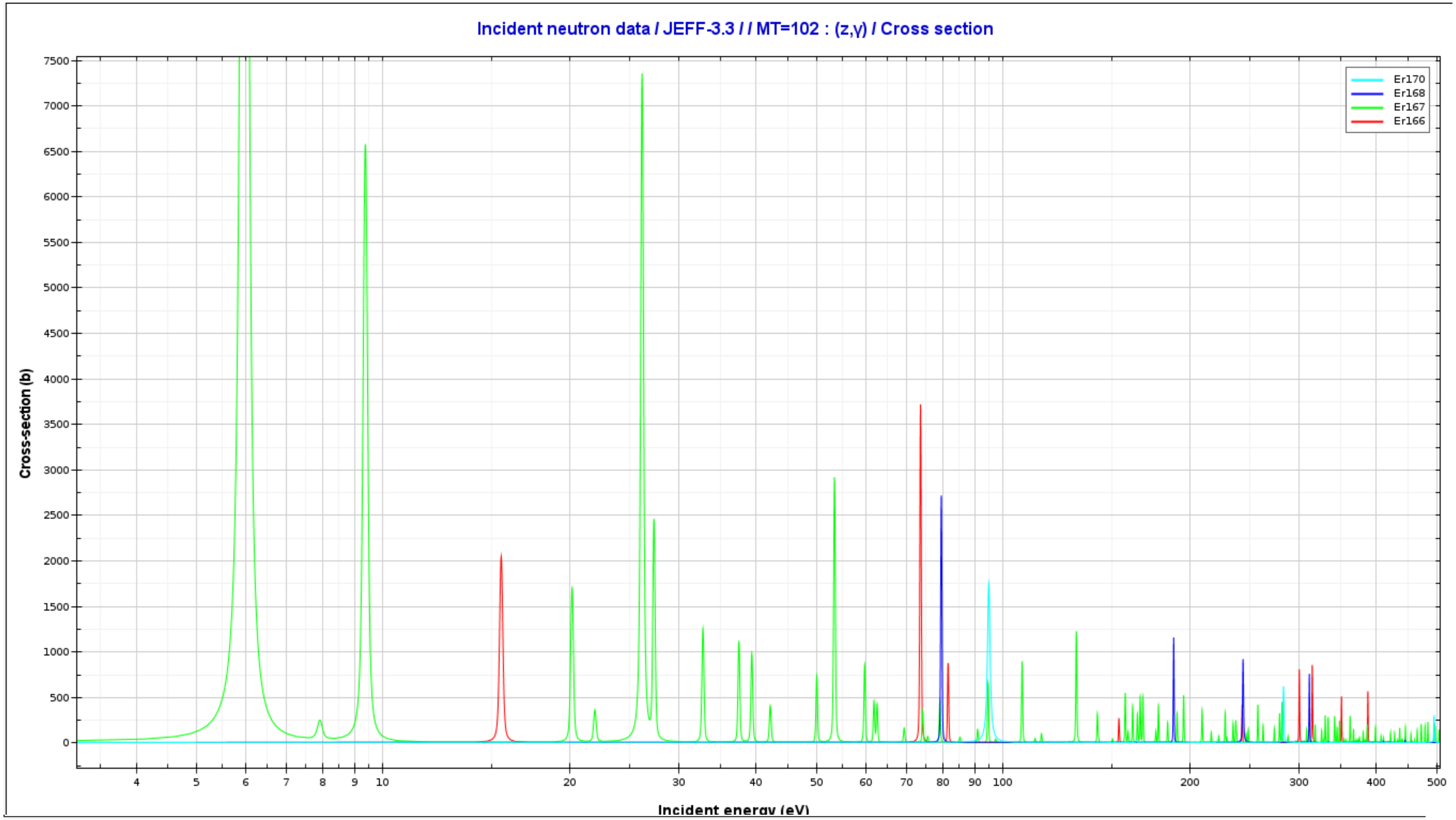
Capture C.S.



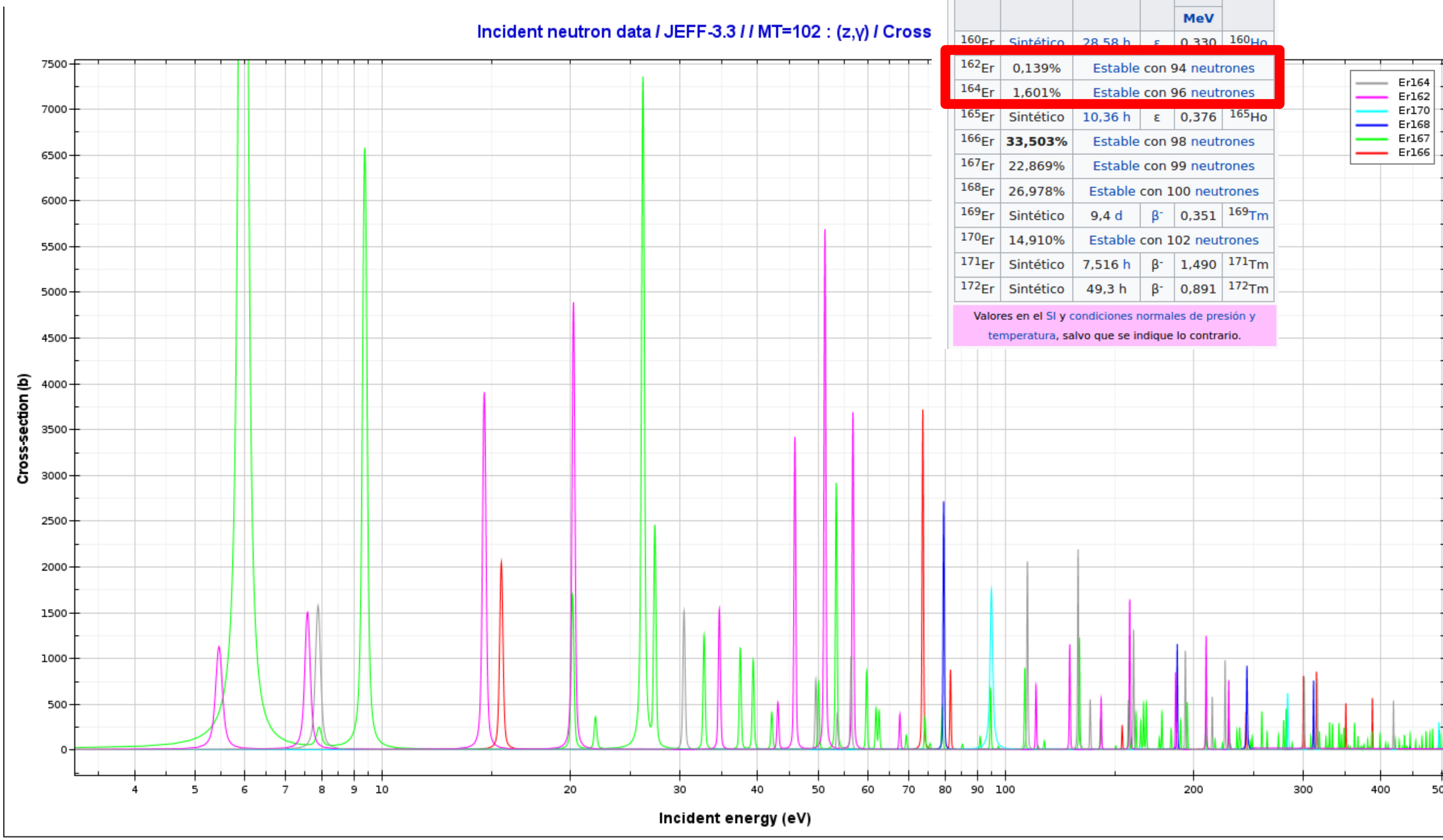
Incident neutron data / JEFF-3.3 / / MT=102 : (z,γ) / Cross section
Er170
Er168
Er167
Er166
Cross-section (b)
10000
5000
1000
500
100
50
10
5
1
0.5
0.1
0.05
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
200
300
400
500
Incident energy (eV)

Capture C.S.



Incident neutron data / JEFF-3.3 / / MT=102 : (z,γ) / Cross section
Cross-section (b)
Incident energy (eV)
Er170
Er168
Er167
Er166

Capture C.S.



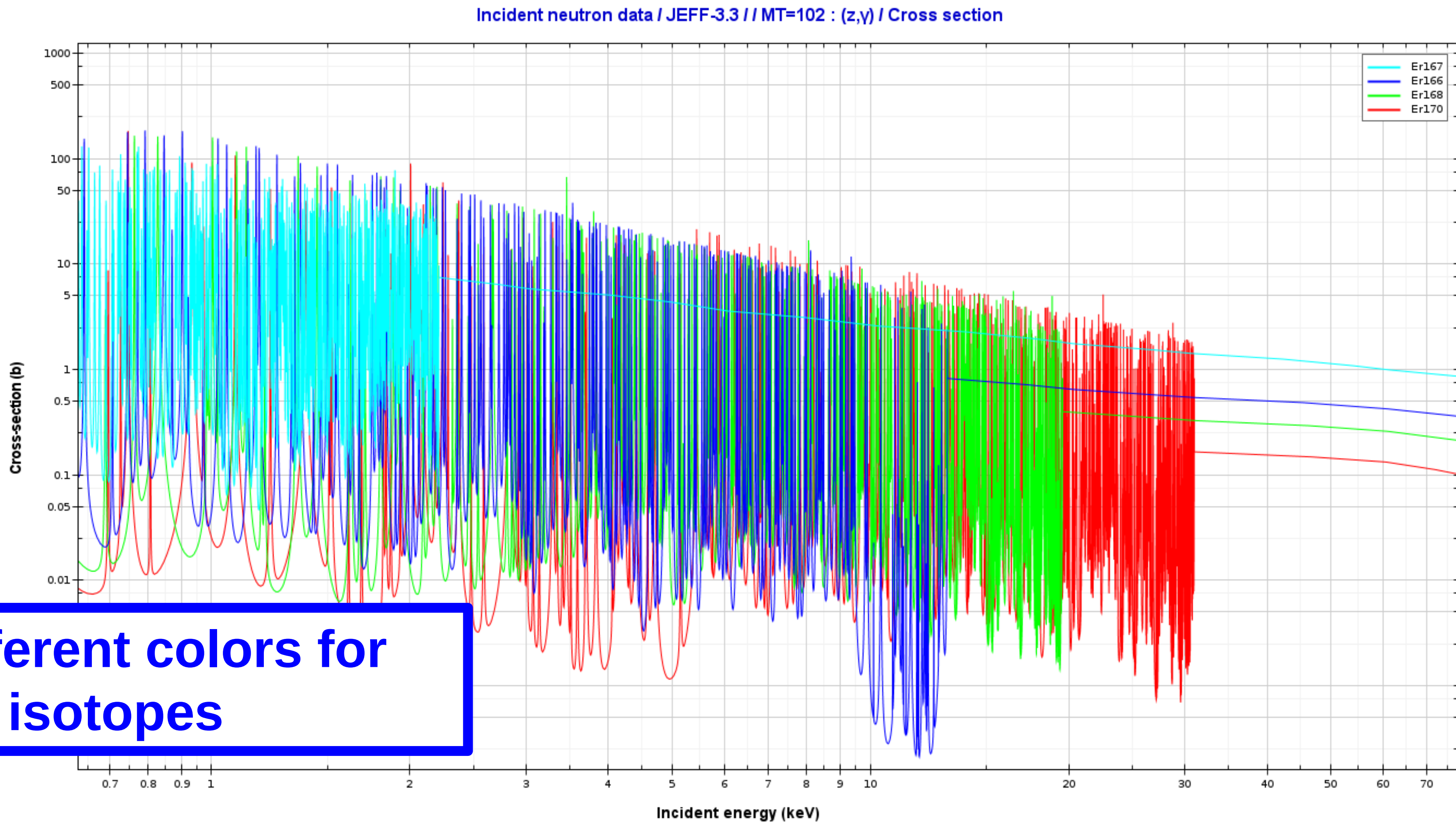
Isótopos más estables

Artículo principal: Isótopos del erbio

iso	AN	Periodo	MD	Ed MeV	PD
^{160}Er	Sintético	28,58 h	ε	0,330	^{160}Ho
^{162}Er	0,139%	Estable con 94 neutrones			
^{164}Er	1,601%	Estable con 96 neutrones			
^{165}Er	Sintético	10,36 h	ε	0,376	^{165}Ho
^{166}Er	**33,503%**	Estable con 98 neutrones			
^{167}Er	22,869%	Estable con 99 neutrones			
^{168}Er	26,978%	Estable con 100 neutrones			
^{169}Er	Sintético	9,4 d	β⁻	0,351	^{169}Tm
^{170}Er	14,910%	Estable con 102 neutrones			
^{171}Er	Sintético	7,516 h	β⁻	1,490	^{171}Tm
^{172}Er	Sintético	49,3 h	β⁻	0,891	^{172}Tm

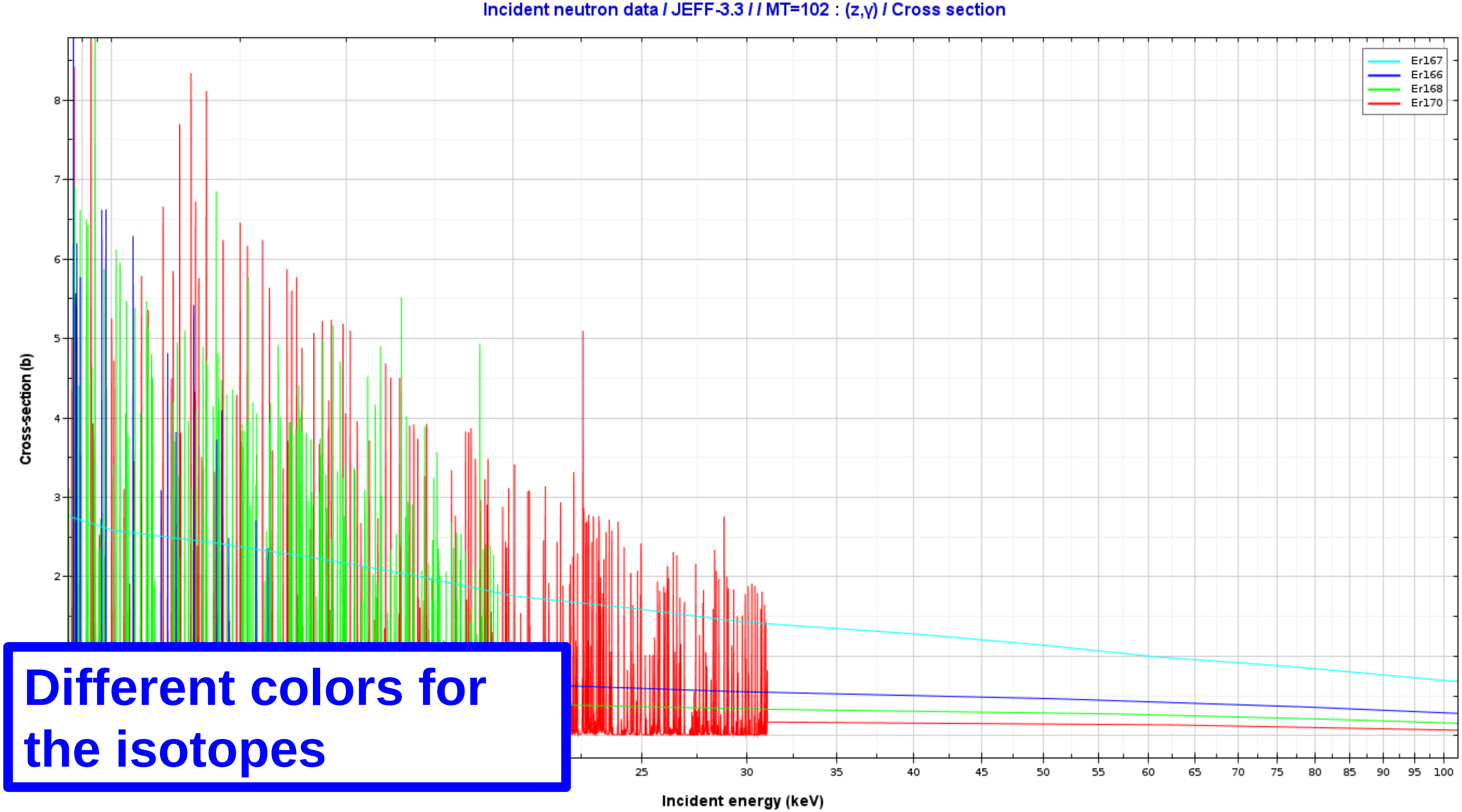
Valores en el SI y condiciones normales de presión y temperatura, salvo que se indique lo contrario.

Capture C.S.



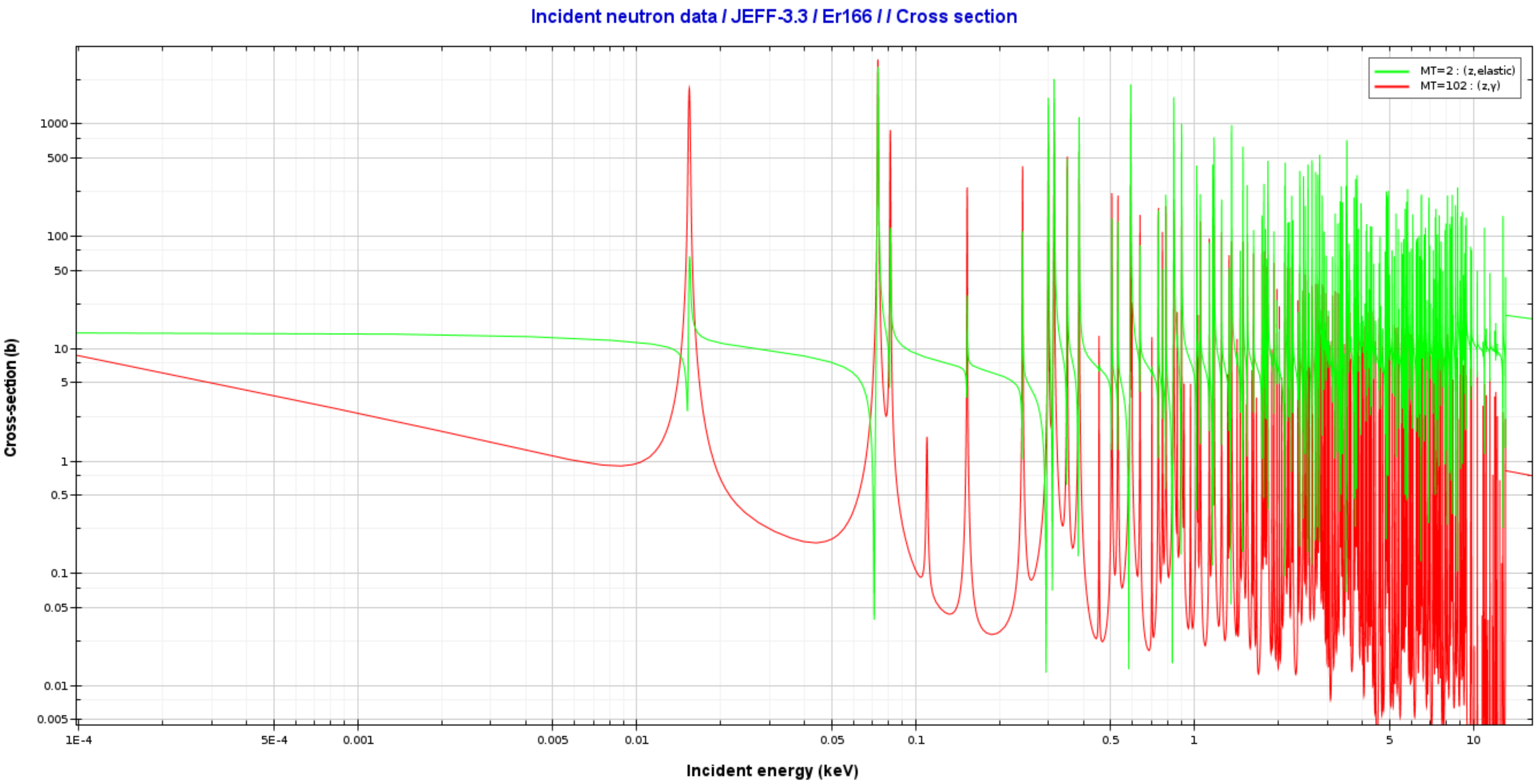
Different colors for the isotopes

Capture C.S.



Different colors for the isotopes

Capture/elastic C.S. 166



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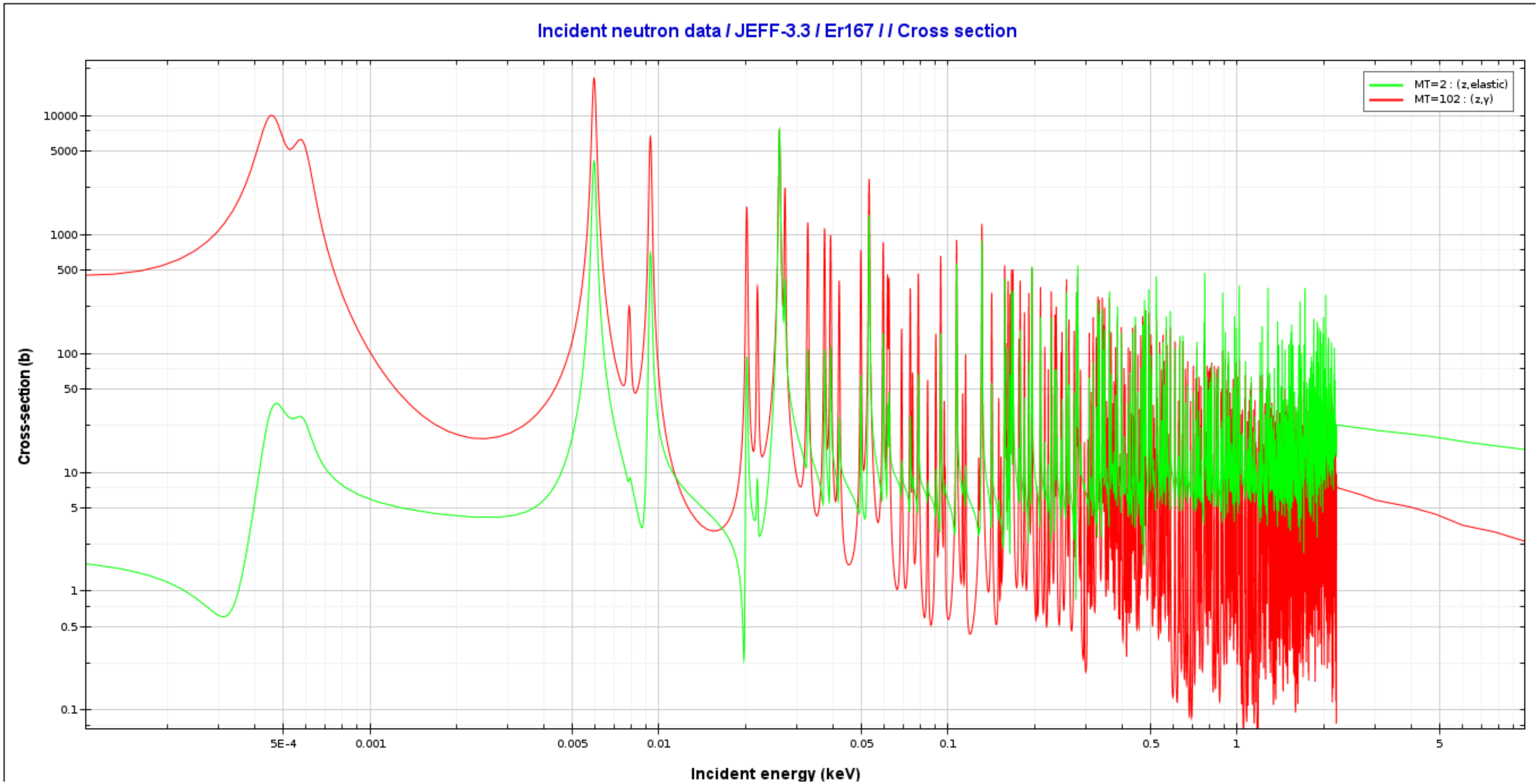
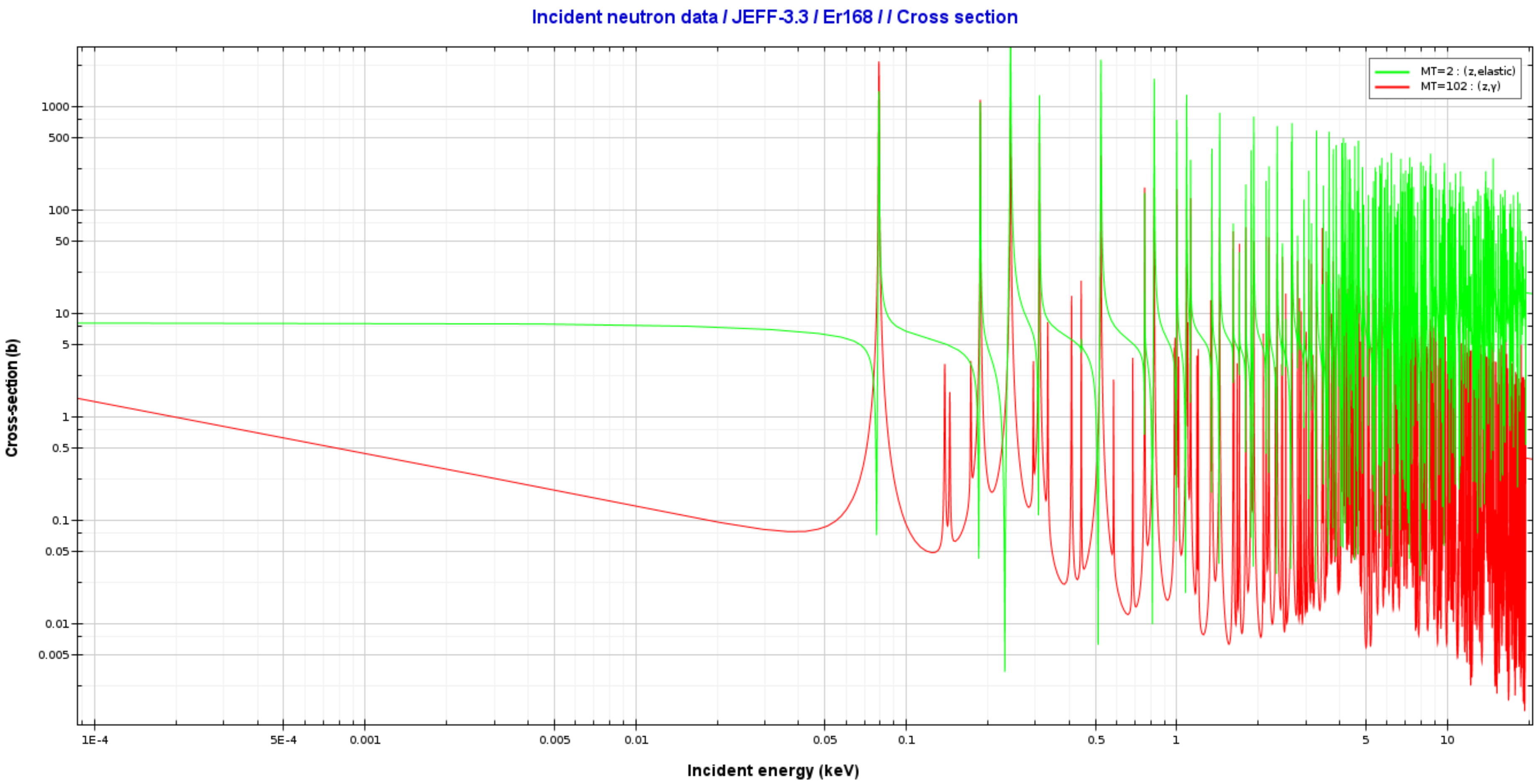
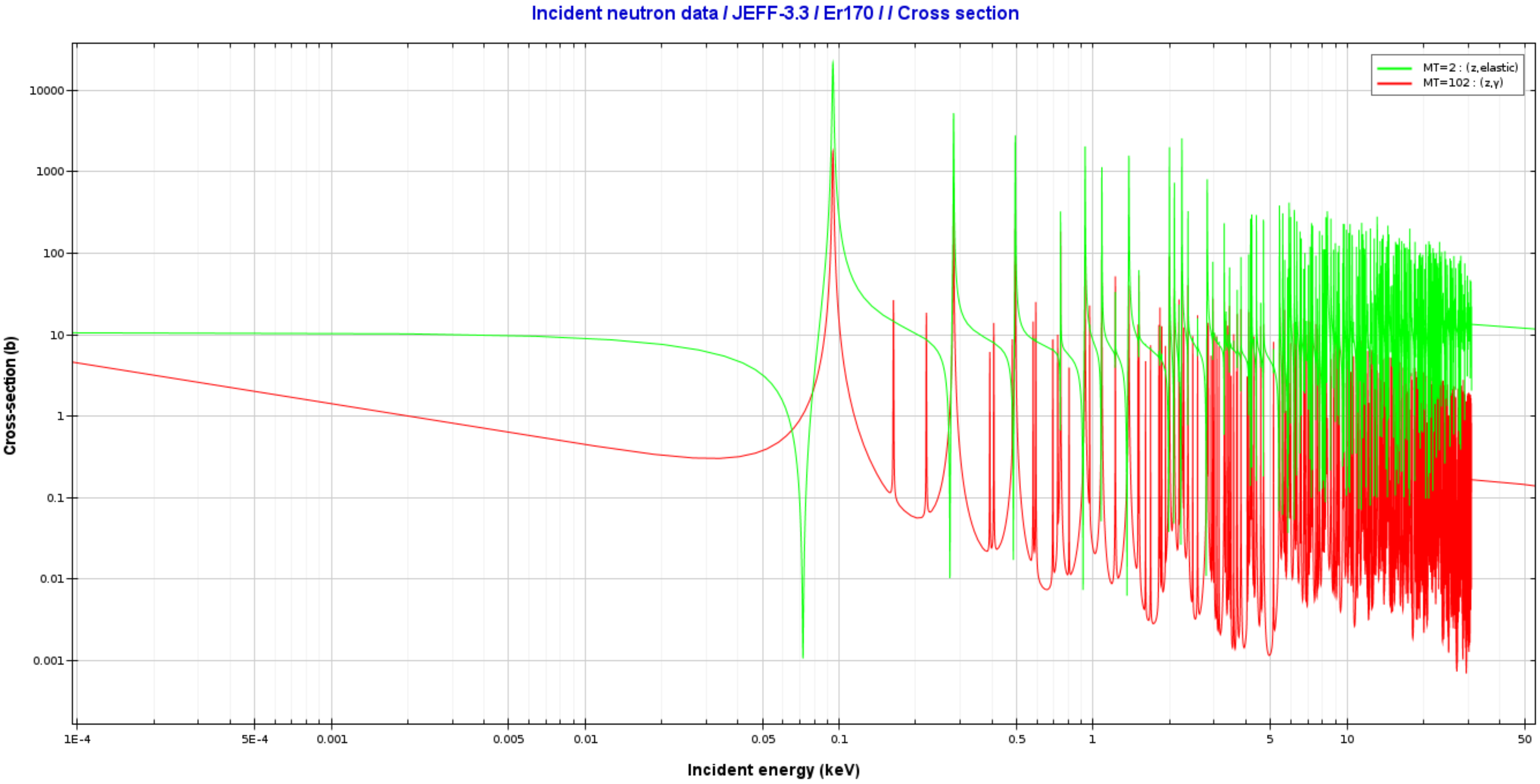
Capture/elastic C.S. 167



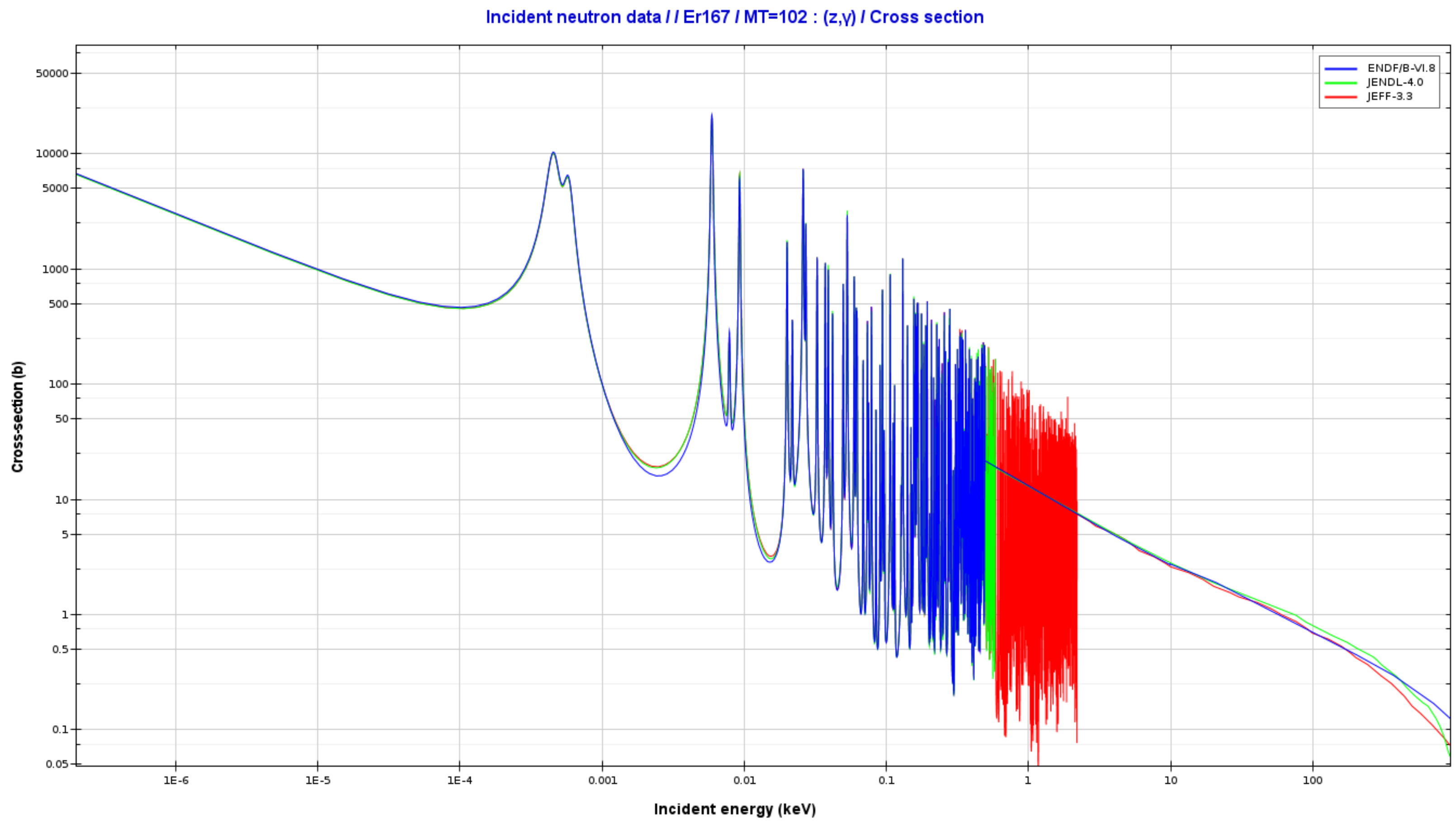
Capture/elastic C.S. 168



Capture/elastic C.S. 170



Different libraries



Different libraries

Erbium is used as burnable poison in some RBMK-1000 reactors: as an example, a number of 1500 FAs equipped with U-Er FAs were operative in Leningrad, Kursk, and Smolensk NPPs in 2005 (Bystrikov, et al., 2006).

EXPERIENCE IN USING URANIUM–ERBIUM FUEL IN POWER-GENERATING UNITS WITH RBMK-1000 REACTORS

UDC 621.039.51

A. A. Bystrikov,[1] A. K. Egorov,[1]
V. I. Ivanov,[1] E. V. Burlakov,[2]
A. V. Krayushkin,[2] A. M. Fedosov,[2]
A. I. Kupalov-Yaropolk,[3] V. M. Panin,[3]
and Yu. M. Cherkashov[3]

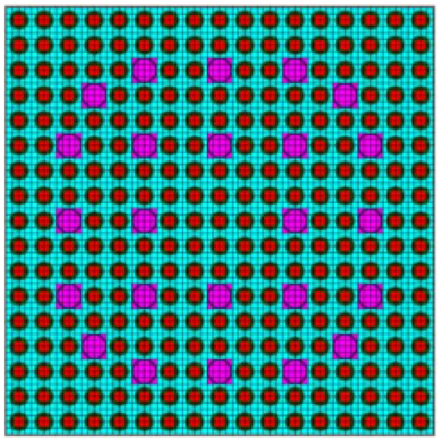
The main reasons for and the results of switching to uranium–erbium fuel in the units of the Lengingrad, Kursk, and Smolensk nuclear power plants are presented. It is shown that uranium-erbium fuel made it possible to regulate the steam coefficient of reactivity, upgrade the control rods, lower the power density in the core, increase the reliability of the fuel assemblies, increase burnup, decrease the volume of spent fuel, and improve the commercial indicators. The prospects for improving the characteristics of uranium–erbium fuel for RBMK-1000 reactors are also presented.

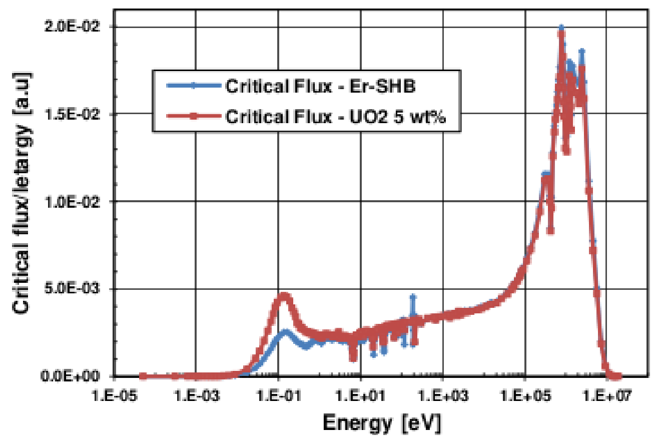
Erbium is also designed to be used as absorber in some PWRs; to give some examples U.S. Palo Verde NPP uses erbia as burnable absorber in their CE-16x16 Fuel Assembly (Palo Verde Nuclear Fuel Management Nuclear Analysis Group and Managing, 2008). Again, the Advanced Power Reactor (APR-1400) design based on the Korean Standard Nuclear Power (KSNP) foresees a core with erbium or gadolinium as burnable absorber (Kim, 1400). In the last decades, several research activities were also performed to test the reliability and effectiveness of erbium as a burnable absorber.

Er-SHB: S&U analysis (Data)

System: Er-SHB FA at BOL and EOC (60 GWd/MTU), HFP conditions.

Code: module TSUNAMI-2D of the SCALE 6.2.3 package.

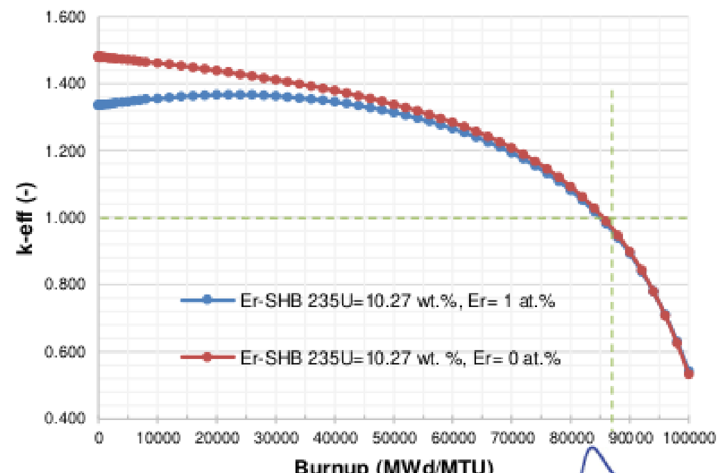




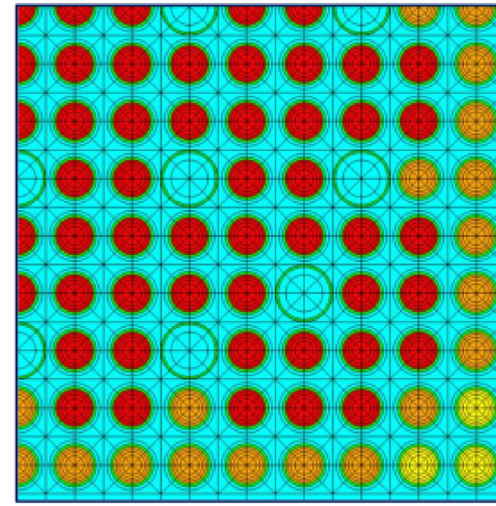
Parameter	Data
Enrichment	10.27 wt%
Erbia content	1.0 at%
Boron content	1000 ppm
Water density	0.702 g/cc
Xs MG library	**V7-252** (based on ENDF/B-VII.1)
Xs COV library	**56group7.1** (based on ENDF/B-VII.1)

$$Sensitivity: \frac{\partial k/k}{\partial \sigma_i/\sigma_i} \rightarrow Uncertainty: \sum_{i=1}^{n} \left(S_i \cdot \frac{\partial \sigma_i}{\sigma_i} \right)$$

$$Matrix\ formulation: \quad \sigma_{k,r}^2 = S_{Q,r} : C_{Q,r}$$



MOX fuel: Overview



- Pu recovered from SF is currently recycled into Mixed OXide (MOX) fuel and used in about 40 EU reactors **[1]**;
- China and Russia are new countries to embark upon MOX use, albeit with a focus on fast reactors **[1]**;
- MOX fuel composition: 7-11% reactor-grade Pu (60-70% quality*) + 89-93% depleted U (0,22% U-235);
- AFA-3G is the reference MOX LWR Fuel Assembly. It is constituted of three different Pu enr. zones to flatten the power distribution.
- The average AFA-3G Pu content is 8.65% (9.77% for the high content zone) with a maximum burnup of 52 GWd/MTU **[2]**.
- The increase of the Pu content would provide an efficient and economic fuel cycle length. (i.e., increase the cycle length and decrease the final Pu fissile inventory);
- The total plutonium content in the MOX fuel is limited to maintain the void reactivity coefficient negative and range from 12.5% to 15% based on the fissile content of the Pu vector **[3]**.

* Quality is conventionally defined as: **(Pu-239 + Pu-241)/(Pu + Am-241)**

[1] https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx

[2] C. Delafoy et al., Plutonium Recycling throught LWR MOX fuel: Today and Tomorrow, Proceedings of an Int. Conference Vienna, Austria, 24-28 June 2019

[3] S. Aniel, J. Bergeron, A. Puill, Evaluation of the maximum content of a MOX-fueled PWR versus isotopic composition with respect to the void coefficient, CEA.

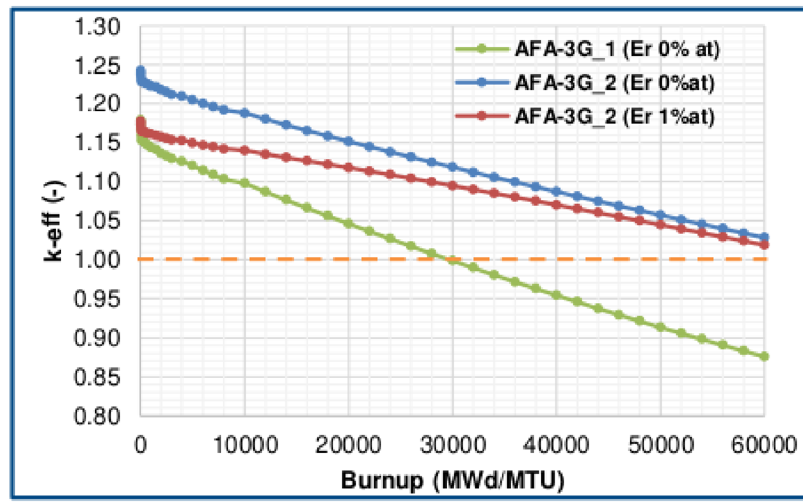
AFA-3G: Design

- S&U analysis on a **MOX AFA-3G system**:
  1. AFA-3G average Pu content was increased up to 12.5 wt% (AFA-3G_2). Pu 3 zone has been settled in order to have the same enrichment ratio (i.e., 13.5, 10.6, 6.9);
  2. S&U at BOC conditions with and without Erbia as IBA was performed with TSUNAMI-2D.

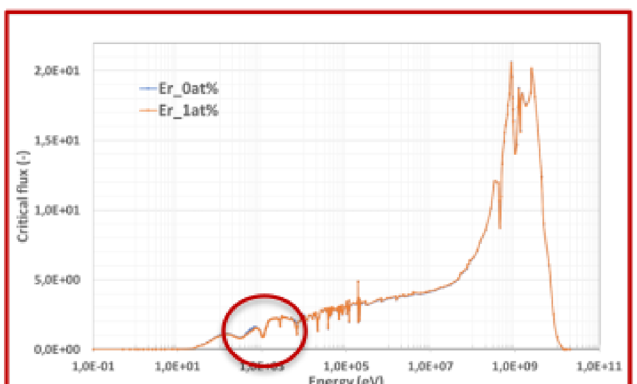
Isotopes	Var (%)
(-)	(%)
U-235	-0,73
U-238	-0,73
Pu-239	0,13
Pu-241	-0,50

Relative Power form factor (%)

0,24	0,25	0,39	0,00	0,36	0,31	0,00	-0,13	-0,30
0,25	0,27	0,34	0,39	0,33	0,26	0,23	0,02	-0,28
0,39	0,34	0,35	0,38	0,31	0,27	0,23	0,02	-0,29
0,00	0,39	0,38	0,00	0,35	0,30	0,00	-0,15	-0,34
0,36	0,33	0,31	0,35	0,35	0,35	0,25	-0,03	-0,36
0,31	0,26	0,27	0,30	0,35	0,00	0,15	-0,17	-0,45
0,00	0,23	0,23	0,00	0,25	0,15	-0,05	-0,39	-0,72
-0,13	0,02	0,02	-0,15	-0,03	-0,17	-0,39	-0,95	-1,32
-0,30	-0,28	-0,29	-0,34	-0,36	-0,45	-0,72	-1,32	-1,37

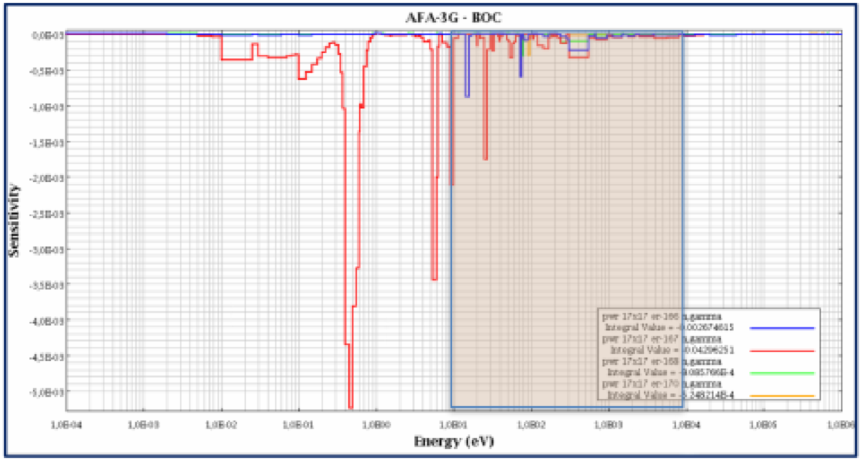


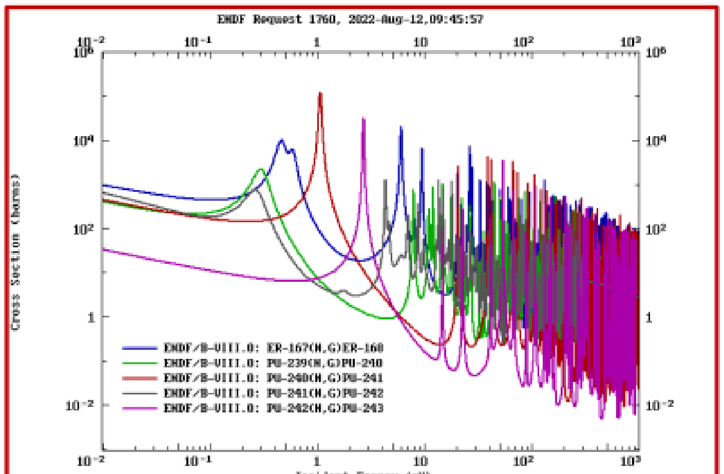
Critical flux



- Erbia improvements:
  1. Reduction of the initial reactivity of the AFA-3G_2 configuration;
  2. Reduction of the power distribution to the border of AFA-3G FA;
  3. Reduction of the Pu fissile isotopes at discharge (52 GWd/MTU).

MOX FA: S&U analysis – BOC





- Sensitivity: absolute erbium integral sensitivity value minor than Er-SHB (BOC) mainly due to the presence of Pu Xs(n,g).

- Uncertainty: Er-167 (**74 pcm**), Er-166 (**20 pcm**), Er-168 (**11 pcm**), Er-170 (**8 pcm**). Er (**12 pcm**) at **E > 10 eV.**

Covariance matrix nuclide-reaction with nuclide-reaction (-)				delta-k/k (%)
pu-239	fission	pu-239	fission	2,36E-01
pu-239	n,gamma	pu-239	n,gamma	2,07E-01
u-238	n,n'	u-238	n,n'	2,05E-01
pu-239	fission	pu-239	n,gamma	1,64E-01
u-238	n,gamma	u-238	n,gamma	1,56E-01
pu-239	nubar	pu-239	nubar	1,22E-01
pu-242	n,gamma	pu-242	n,gamma	1,14E-01
pu-239	chi	pu-239	chi	1,12E-01
pu-241	chi	pu-241	chi	1,07E-01
pu-241	n,gamma	pu-241	n,gamma	9,18E-02
pu-241	fission	pu-241	fission	9,06E-02
pu-240	n,gamma	pu-240	n,gamma	7,44E-02
u-238	nubar	u-238	nubar	7,37E-02
am-241	n,gamma	am-241	n,gamma	6,91E-02
er-167	n,gamma	er-167	n,gamma	6,29E-02
u-238	chi	u-238	chi	4,27E-02
pu-241	nubar	pu-241	nubar	2,55E-02
o-16	elastic	o-16	elastic	2,51E-02
u-238	elastic	u-238	elastic	2,23E-02
u-238	n,n'	u-238	elastic	-2,02E-02
u-238	fission	u-238	fission	1,83E-02
er-166	n,gamma	er-166	n,gamma	1,72E-02
u-238	elastic	u-238	n,gamma	1,61E-02
zr-91	n,gamma	zr-91	n,gamma	1,55E-02
pu-239	fission	u-238	fission	1,53E-02
pu-238	n,gamma	pu-238	n,gamma	1,52E-02
h-1	n,gamma	h-1	n,gamma	1,23E-02
zr-90	n,n'	zr-90	n,n'	1,06E-02
o-16	n,alpha	o-16	n,alpha	1,03E-02
pu-239	n,n'	pu-239	n,n'	9,75E-03
h-1	elastic	h-1	elastic	9,75E-03
zr-90	n,gamma	zr-90	n,gamma	9,58E-03
er-168	n,gamma	er-168	n,gamma	8,98E-03
zr-92	n,gamma	zr-92	n,gamma	8,21E-03
u-235	fission	pu-239	fission	8,06E-03
pu-239	elastic	pu-239	fission	-7,43E-03
er-170	n,gamma	er-170	n,gamma	7,13E-03
u-238	n,2n	u-238	n,2n	7,13E-03
pu-240	fission	pu-240	fission	6,83E-03

Summary and Outlook

- It has been explored the criticality uncertainty contribute of erbium isotopes **at energy major than 10 eV** for several reactor configuration;

  1. Er-SHB at EOC showed a criticality uncertainty contribute of 45 pcm.
  2. AFA-3G at BOC showed a criticality uncertainty contribute of 12 pcm.
  3. ELSY (LFR system) showed an overall criticality uncertainty contribute of 75 pcm.

- Measurements have to be performed on enriched isotopes in order to:
  - have a precise Xs(n,g) evaluation due to the overlapping of the isotopes resonance;
  - allows to reduce the background contribution of other isotopes;
- The measurement at n_TOF facility would allow to reduce/check the contribute of systematic uncertainties by comparison with the ongoing GELINA measurement;
- Specifically, the two n_TOF facilities exp. results would allow to reduce the bias effects (i.e., TOF response function, normalization of capture data, background contribution);
- Measurement at n_TOF particularly at energy major than 10 eV is desirable for the major resolution with respect to GELINA that would allow a better resonance shape analysis.
- ENEA is committed in new measurement of nuclear data for reactor technology purpose in order to both reduce the uncertainty in core design and to increase the nuclear safety.

The isoflex proposal

The cost of the samples are 3400$ without taxes for (Er-167-168-170) and 5250$ if we also want to include the sample of Er-170.
The company sells powder so we would need to put it on pellets.

C6D6	162	164	166	167	168	170	Cost per mg
Er-166	0,002	0,02	98,1	1,33	0,45	0,1	4,8$
Er-167	<0,01	<0,01	0,96	96,3	2,6	0,2	5,6$
Er-168	0,002	0,022	0,433	1,12	97,243	1,17	5,3$
Er-170	<0,01	<0,01	0.74	0.55	1.01	97.70	9,0$
Total cost							5000$