Neutron-irradiated tungsten: comparison between experiment and simulation

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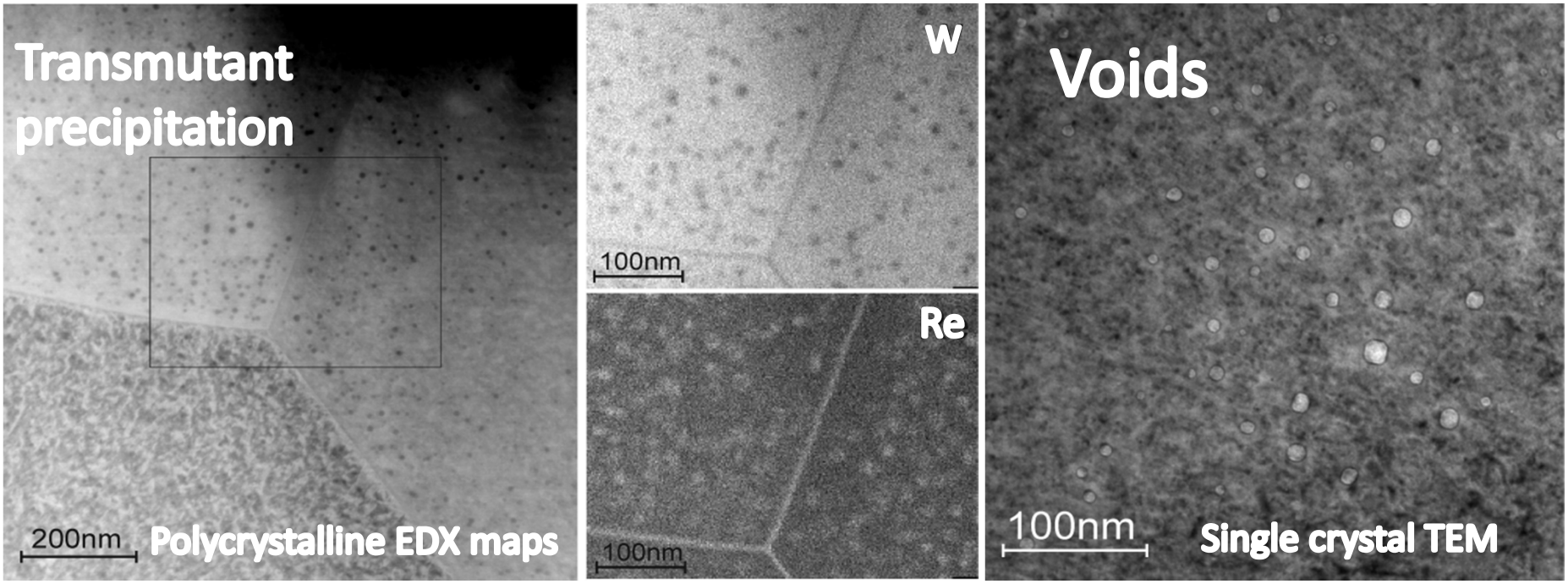
Irradiated tungsten

- W irradiated in the high-flux reactor (HFR) @ NRG, Petten
- Has been cooling for a number of years (see later)
- Only now is it starting to be analyzed
- Full of defects & voids, and some percentage of transmutation products – mostly rhenium



EDX & TEM images: M. Klimenkov et al., KIT, submitted to J. Nucl. Mater.

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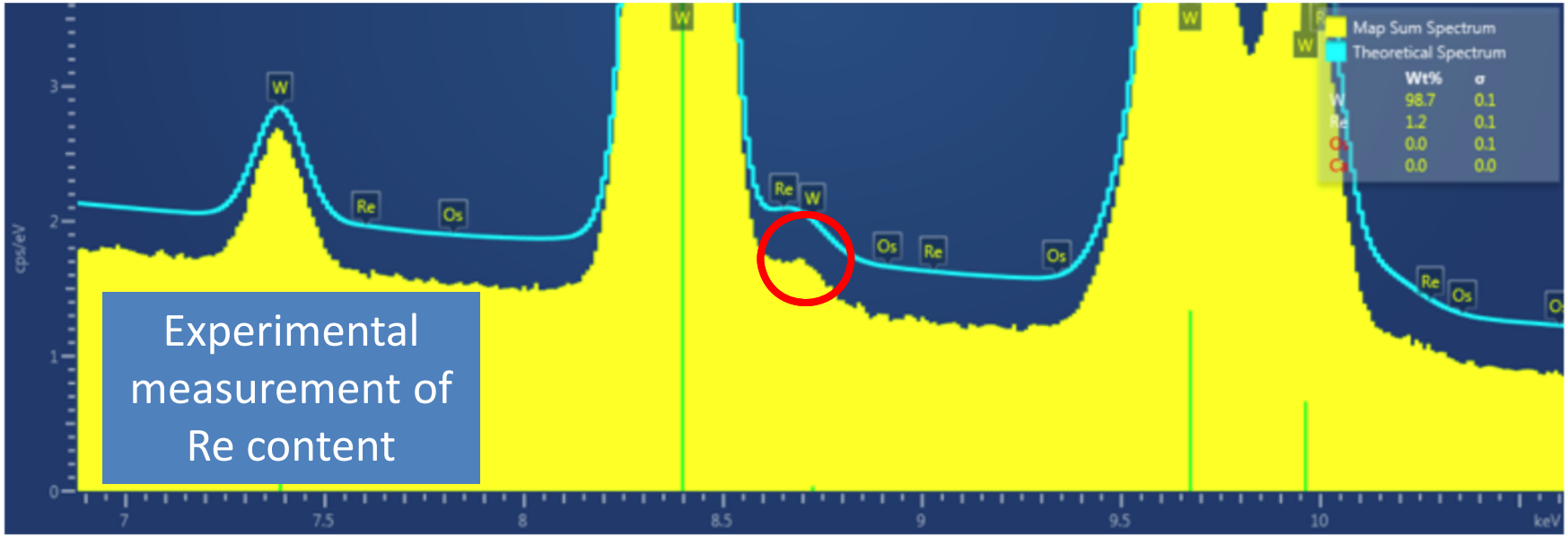
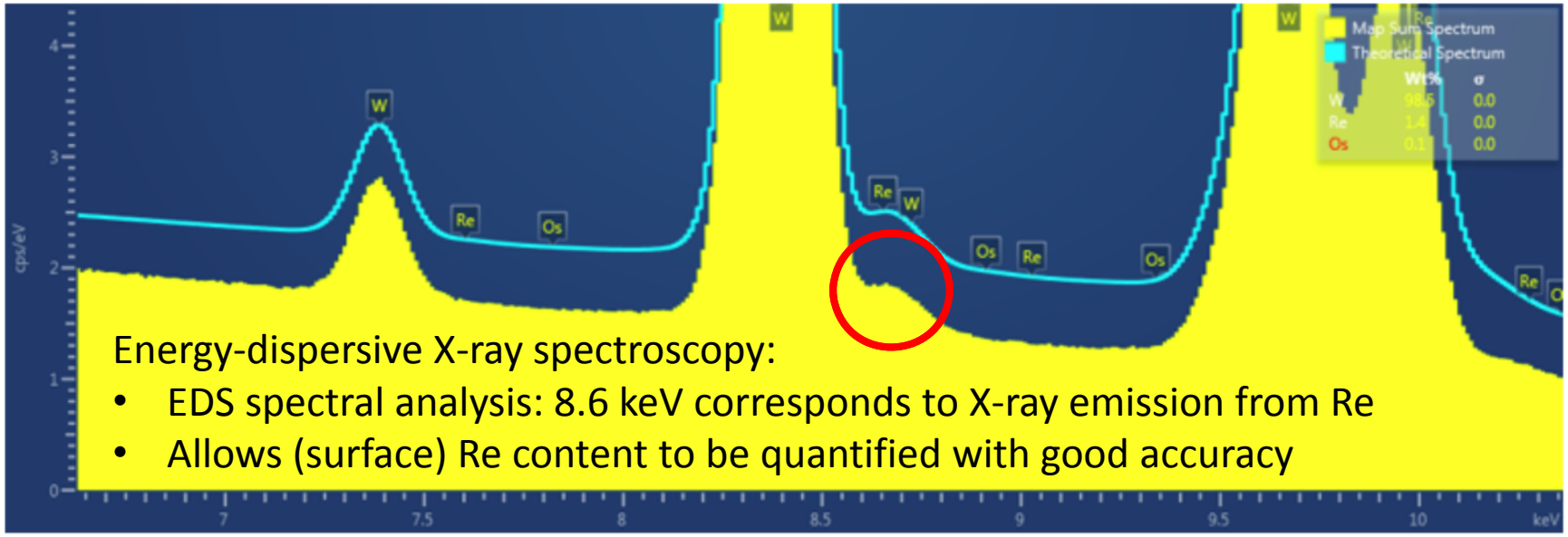


Petten Single Crystal (1.2wt% Re measured)



Petten Polycrystalline (1.4wt% Re measured)

Irradiation scenario

- W irradiated under EXTREMAT-II in 2008 & 2009
- Target of 282 days of irradiation (10 cycles), but in fact only irradiated in 8 cycles & in two different positions:

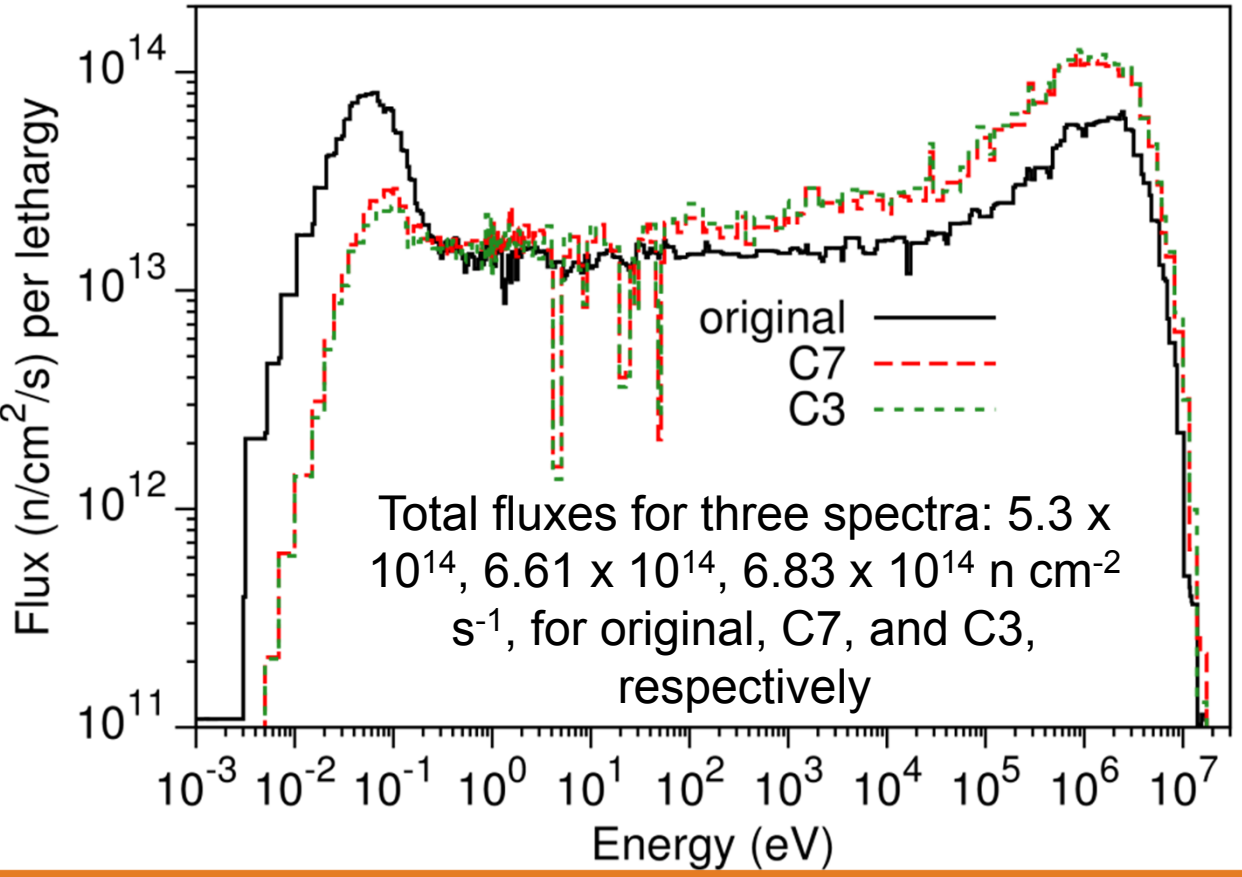
Position	Cycle	EFPD	Start date	End date
C7	08-May	30.72	22-May-08	22-Jun-08
	08-Jun	29.71	28-Jun-08	28-Jul-08
C3	09-Jan	27.69	12-Feb-09	12-Mar-09
	09-Feb	24.99	01-Apr-09	26-Apr-09
	09-Mar	30.77	29-Apr-09	30-May-09
	09-Apr	24.71	02-Jun-09	27-Jun-09
	09-May	17.61	30-Jun-09	18-Jul-09
	09-Jun	22.06	17-Aug-09	08-Sep-09
Total		**208.26**		

- EFPD – effective full power days

Neutron spectrum

- Samples were positioned next to another experiment with very strong thermal neutron absorption properties
  - W exposed to a lower than normal (for HFR) fraction of thermal neutrons creating reduced transmutation

- New spectra calculated for the approximate axial position of EXREMAT-II, averaged over radial extent of experiment and over around 4 cm of height



Important Reactions

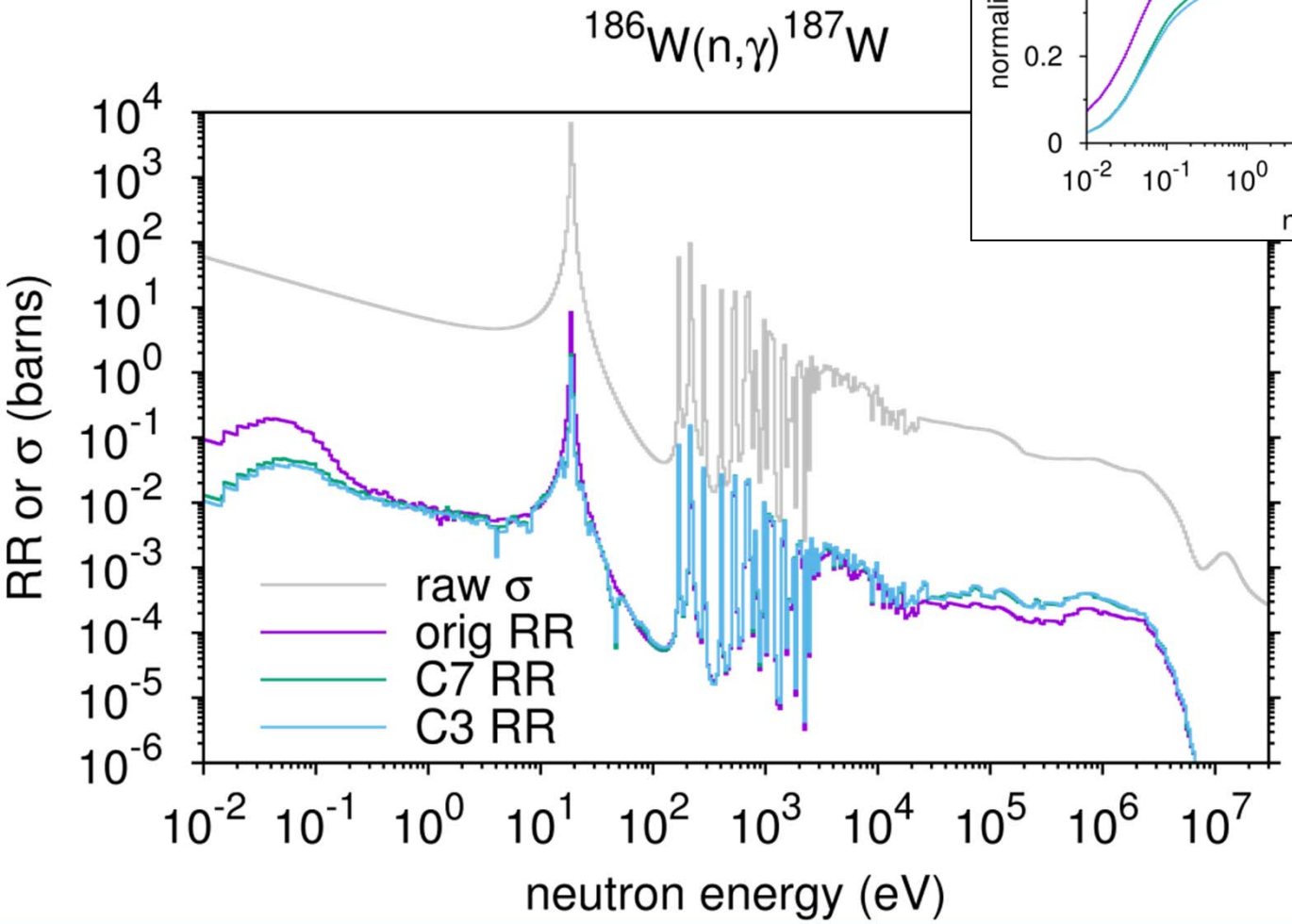
- Main Re isotopes produced during irradiation are ^{185}Re and ^{187}Re
  - Produced via (n,γ) reactions on ^{184}W and ^{186}W, followed by β- decay of ^{185}W ($T_{1/2}$=75 days) and ^{187}W (24 hours), respectively.
- Raw total collapsed reaction rate (RR) for these (n,γ) reactions and self-shielding (SS) corrected values:

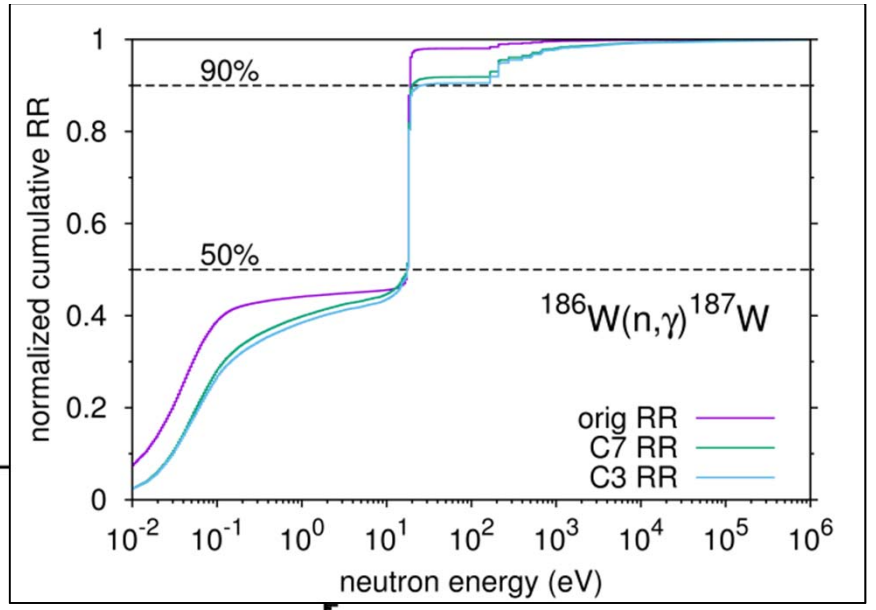
Reaction	Original spectrum		C7		C3	
	Raw RR	SS RR	Raw RR	SS RR	Raw RR	SS RR
^{186}W(n,γ)^{187}W	22.5 (0.01)	17.2	6.21 (0.09) (-72%)	4.67	5.54 (0.1) (-75%)	4.13
^{184}W(n,γ)^{185}W	0.92 (0.71)	0.60	0.63 (1.8) (-32%)	0.29	0.64 (1.8) (-30%)	0.29

(all RR in barns, black bracket values are +/- errors, green bracket values are % reduction in RR relative to original spectrum)

Collapsed reaction rates

- Almost 50% of RR comes from thermal neutrons below 10 eV

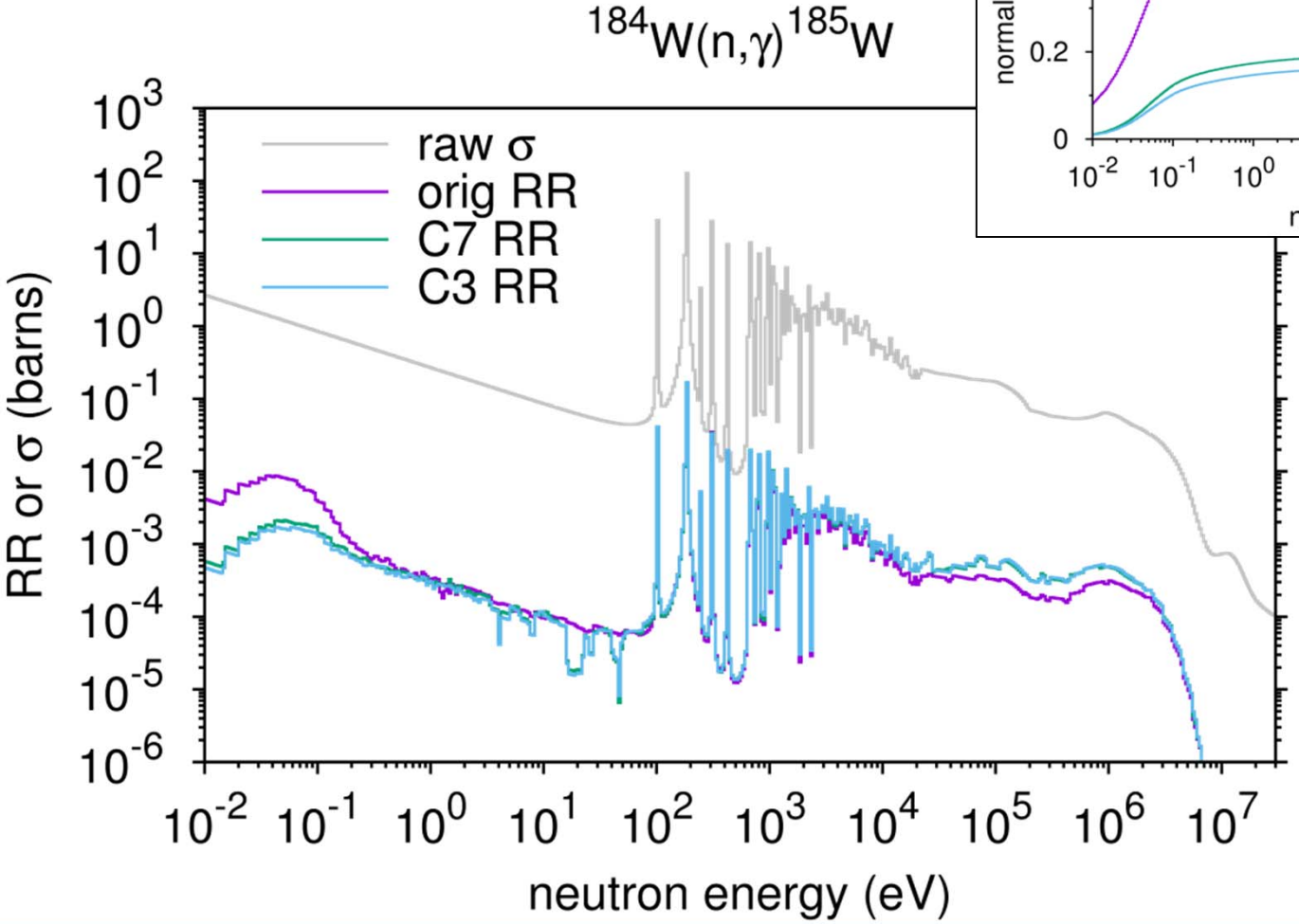


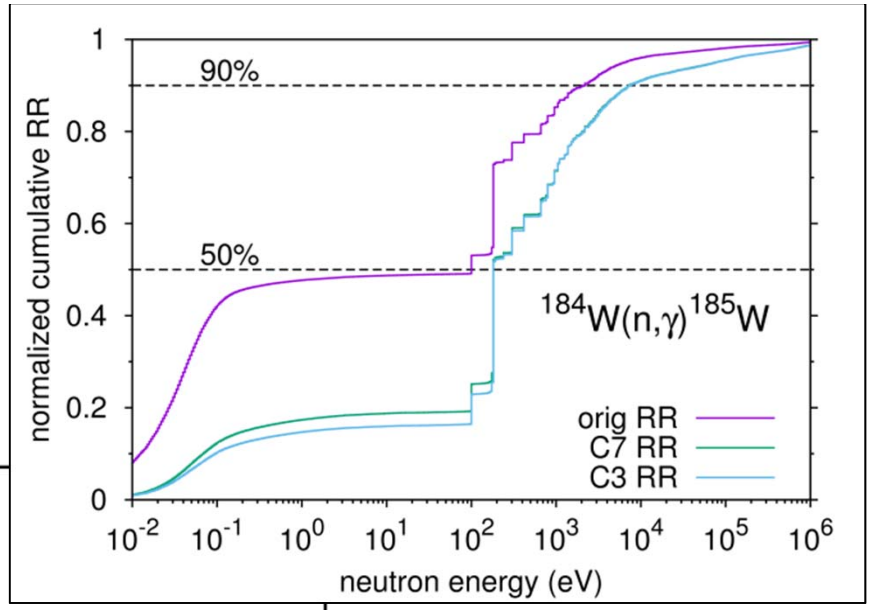


(RR and σ in a fine group structure with 660 bins below 30 MeV)

Collapsed reaction rates

- For new spectra, only 20% of RR comes from thermal neutrons below 100 eV





(RR and σ in a fine group structure with 660 bins below 30 MeV)

Simulation of irradiation

- Inventory simulation with FISPACT-II of pure tungsten with fully detailed irradiation schedule (including gaps and change in position) and new spectra
  - TENDL 2014 nuclear libraries in 660 energy groups
  - Self-shielding correction of reaction cross sections included (⟹ 2% Re predicted without correction)

- Results after 208.26 effective full power days:
  - 1.4 atomic % Re (and 0.1% Os)
    - good agreement with 1.2-1.4% values from measurements
    - And much better than ~4% prediction based on usual HFR neutron spectrum
  - 1.6 effective dpa in the tungsten (using E_d = 55 eV)

Conclusions

- A proper characterization of the neutron spectra for irradiated samples is vital to get even close to real transmutation rate in simulations
  - Without this correct treatment of the neutron fields the reaction rates (and hence transmutation rates) for key capture reactions are much greater
  - The thermal part of the neutron spectrum is very important and must be correctly predicted
- Simulations in W with more realistic neutron spectra give Re production rates that are in very good agreement with experimental measurements

- Still missing?
  - Properly corrected neutron spectra for W at the sample positions may cause further refinement of results
  - Variation (of Re %) with depth due to self-shielding