Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Fusion Neutronics Experiments for Nuclear Data and Neutronics Tools Validation at the 14 MeV Frascati Neutron Generator

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Introduction & Background

- ✓ The fundamental role of nuclear data in nuclear system design is recognized since the early days of the nuclear era
- ✓ The quality and the uncertainty in nuclear data is one of the most important sources of errors in neutronics calculations and consequently in nuclear systems design.
- ✓ The production of nuclear data files suitable for use with the presently available calculation tools is long and complex and terminates with its validation
- ✓ The result of the validation process usually calls for revision and improving of nuclear data → *New/up-grated nuclear data files*

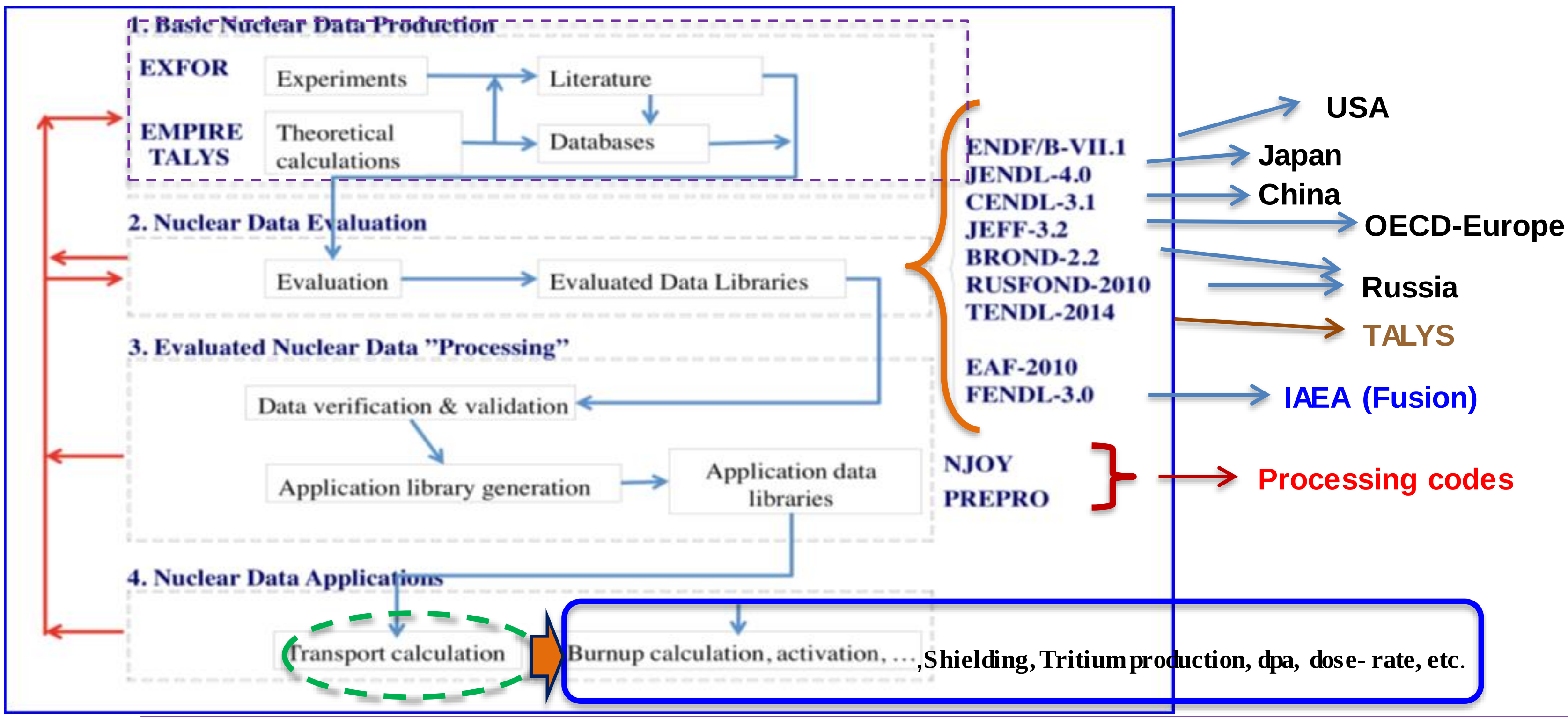
  → *Continuous, never ending activity*
- ✓ **The validation of nuclear data (*and calculation tools*) is thus of paramount importance to enhance the reliability of the design, to improve the safety aspects and reduce the safety margins and thus the costs of the plant.**

Introduction & Background

- ✓ ***Nuclear Data Validation*** is possible thanks to *"ad hoc"* experiments which are divided into large categories depending upon the experimental methods adopted e.g. *benchmarks, mock-ups, differential, integral,* etc..
- ✓ The increasing complexity of advanced nuclear systems renders the design and realization of experiments, mock-up and prototypes more and more expensive it is thus fundamental *to perform* a few but well designed and oriented experiments → *Nuclear data validation is a primary role of many facilities*
- ✓ *Fission* and *fusion* *oriented* neutronics experiments are usually performed separately using different neutron sources & facilities
- ✓ In the case of fusion the **D+T → α + n (14 MeV)** nuclear reaction is of interest to produce neutrons while for fission, usuallly, *nuclear reactors* are used (a variety of reactors and neutron energy spectra are available and used)

Nuclear Data Files Production, Application and Validation

The Nuclear Data processing/validation *does not depend upon the application* (e.g. fission or fusion) : general rules to produce data libraries starting from experimental/evaluated nuclear data are established → ***Feedback from Exp.***



From G. Zerovnik – "Training course on covariances and nuclear data for master students and beginning PhD students Lecture at SCK Acade
Covariance Workshop – Dec.10-11, 2015

Fusion Neutronics Experiments

- ***<u>'80th of the past century :</u>*** necessity to develop calculation tools and sets of nuclear data for the <u>neutron energy range of interest to Fusion</u> *(up to 20 MeV for neutrons and up to 30 MeV for gamma-rays).* The nuclear data available at that time were in format (e.g. energy groups) suitable to fission reactors and validated only up to 10 MeV for neutrons and up to 20 MeV for gammas
- Several 14 MeV neutron generators were realized e.g. FSN (Jap), RTNS-II (USA), SNEG-13 (Russia) *(no longer in operation)*
- Presently, a few 14 MeV neutron generators are available. Among them the *Frascati Neutron Generator* (**FNG**) is in operation at Frascati (Rome – Italy)

The 14 MeV Frascati Neutron Generator (FNG)

- The Frascati Neutron Generator (FNG) started operations in *November 1992* making available 14 MeV neutrons at a medium intensity to EU Fusion Community
- FNG is a linear electrostatic accelerator in which up to *1 mA D^+ ions* are accelerated onto a *tritiated target* to produce up to ***$1.0*10^{11}$ n/s 14 MeV*** neutrons via the nuclear fusion reaction :

$$\mathbf{D+T \rightarrow \alpha+n} \quad (Q=17.4\ \text{MeV})$$

- *FNG neutron <u>absolute yield</u> calibrated at ±3% using the Associated Particle method*
- *FNG is also largely used for many applications (avionics, biology, detectors…)*

Experiments & Analysis carried out in 1992-2022 at FNG

- **Benchmark Experiments** (e.g. pure materials, alloys, etc.)
- **Design oriented experiments (mock-ups)** in support of ***ITER → DEMO*** nuclear design
- **Experiments for validation of EFF →JEFF** and **EAF** European nuclear data libraries
- **Validation of European activation code system** (***EASY***)
- **Dose-Rate and Activation experiments on fusion relevant materials** : *SS-316 (IG), F82H, MANET, EUROFER, Fe, Cu, V & V-alloys, SiC, W, Al, Cr, Pb*.
- **Numerical tools developed and tested** (e.g. for sensitivity uncertainty analysis, dose rate calculations in complex geometries (***D1S, Two steps***)
- **Other Nuclear data libraries used & validated : *FENDL-1→ 3.2, IRDF-90.2 → IRDFF-2*** (Participation to RCM on *"Testing and Improving the International Dosimetry Library for Fission and Fusion* (IRDFF)), **JENDL**

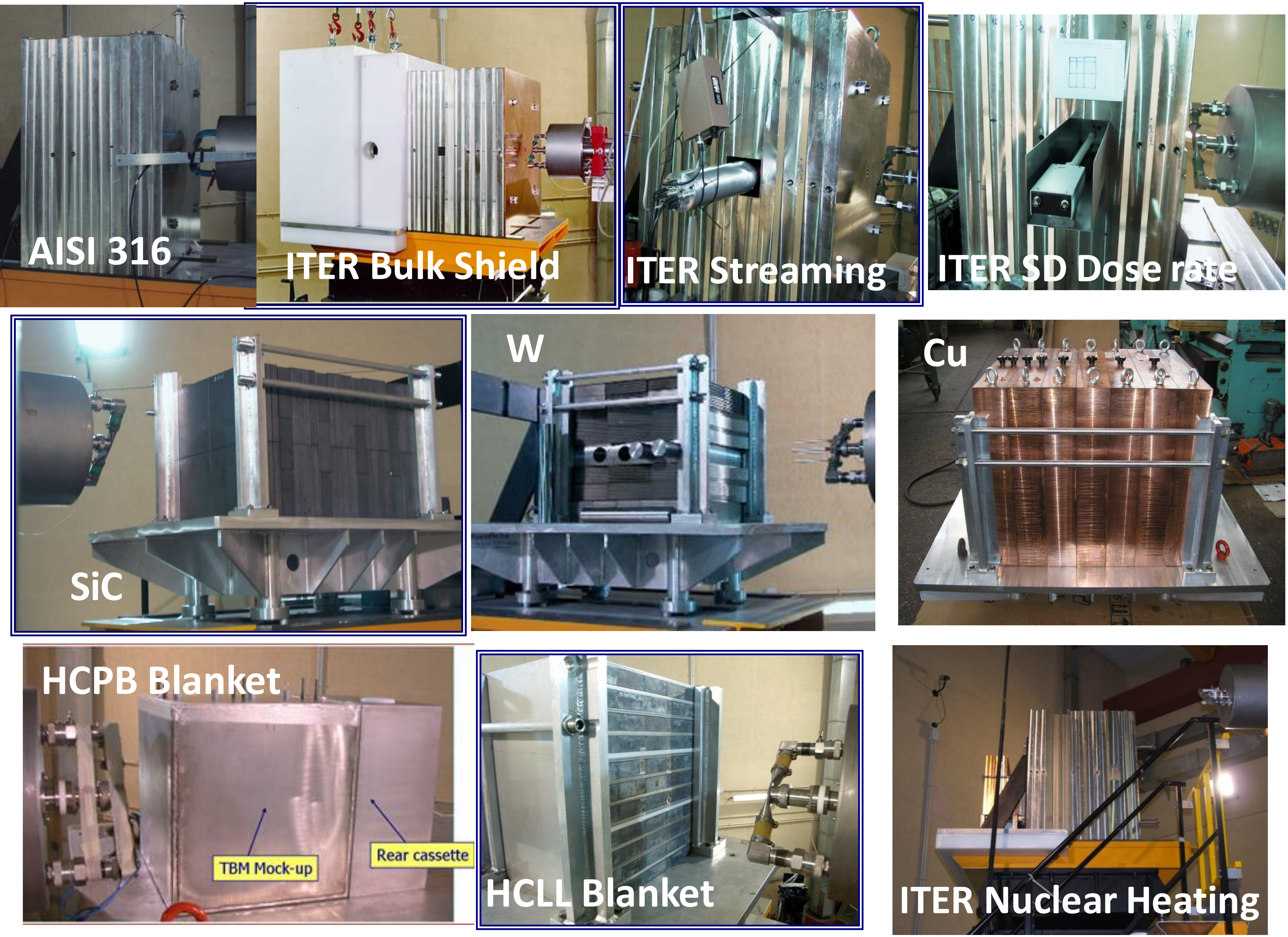
Experiments & Analysis carried out in 1992-2022 at FNG

- The FNG experiments are of the *integral type*, that is the response of selected quantities obtained as product of the neutron flux by an energy dependent parameter (e.g. cross section, kerma)
- *Reaction Rate*, doses, n/γ flux spectra are measured under well-defined conditions.
- FNG experiments are *simulated by Monte Carlo* (MCNP, SERPENT, FLUKA) and/or *deterministic codes* (e.g. DORT, ATTILA) → **C/E ratio**
- *Sensitivity/uncertainty (S/U) analysis* of the nuclear data (e.g. cross sections), based on perturbation methods (SUSD3D3, MCSENS5), is often used to complement the analysis of the experiments
- S/U analysis represents a sound approach to the identification and quantification of uncertainties associated with the computational results and is of direct interest to Nuclear Data validation. *Used for pre and post-analyses*
- *FNG experiments are in collaboration with EU partners*

Experiments carried out at FNG (1992-2021)

#	Experiment	Year	Type
1	Stainless Steel Experiment	1992-1993	*Benchmark*
2	ITER Bulk Shield Exp.	1995-1997	*Mock-up*
3	ITER Streaming Experiment	1998-1999	*Benchmark*
4	ITER Dose-Rate Experiment	2000-2001	*Benchmark*
5	Silicon Carbide (SiC) Exp.	2002	*Benchmark*
6	Tungsten Experiment	2003	*Benchmark*
7	ITER HCPB-TBM Mock-up Exp.	2004	*Mock-up*
8	ITER HCLL-TBM Mock-up Exp.	2006	*Mock-up*
9	ITER Nuclear Heating Exp.	2010	*Mock-up*
10	Copper Benchmark Exp.	2014-2015	*Benchmark*
11	Water Activation Experiment (ITER)	2019-2020	*Benchmark*
12	DEMO WCLL-BB Mock-up Exp.	2020-2021	*Mock-up*
13	Tungsten Shielding Experiment	2022-2023	*Benchmark*

Most of the FNG experiements are available on Shielding Integral Benchmark Archive and Database (SINBAD) and are routinely used for testing and validating ND libraries and codes


AISI 316
ITER Bulk Shield
ITER Streaming
ITER SD Dose rate
SiC
W
Cu
HCPB Blanket
TBM Mock-up
Rear cassette
HCLL Blanket
ITER Nuclear Heating

Benchmark Experiments : methodology and output

What do we expect from experiments?

- Check and validate the computational tools and nuclear data for design calculations, including the associated uncertainties
- Reduce the uncertainties in design calculations
- Test, validate reference data libraries (e.g. FENDL, JEFF, ENDF/B)

Experiment output

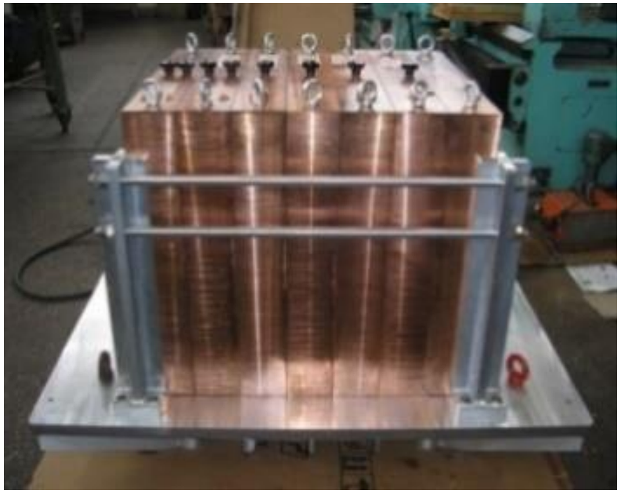
- **C/E** ratio of *calculated* (**C**) over *experimental* (**E**) nuclear quantities
- Including good estimate of **Δ(C/E)**

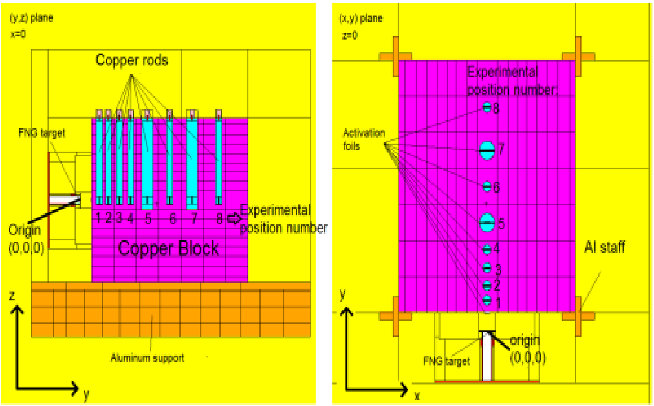
Methodology

- Pre–analysis → Check and optimize geometry and detectors
- **ΔE :** Careful calibrations, inter-comparisons (different detectors, techniques) and inter-calibrations (different teams), redundancy for a consistent picture
- **ΔC :** Detailed geometry models, accurate knowledge of materials
- Sensitivity/Uncertainty analysis → *Information on nuclear data quality*

Example : Cu Benchmark Experiment (2014/15)

- Block of high purity copper (99.5%) ***70x60x60 cm^3* → *Pre-analysis***
- Height experimental positions available along the mid-plane of the block
- *Measurements :* Reaction rates (RR), neutron flux spectra and γ-ray dose.
- *Reaction Rates* : $^{197}Au(n,\gamma)^{198}Au$, $^{186}W(n,\gamma)^{187}W$, $^{115}In(n,n')^{115}In$, $^{58}Ni(n,p)^{58}Co$, $^{27}Al(n,\alpha)^{24}Na$, $^{92}Nb(n,2n)^{93}Nb^{m}$
- *Simulation :* MCNP-5 and SERPENT
- *Libraries :* JEFF-3.1.1 and 3.2 with IRDFF-2
- *Re-Analysis :* JEFF-3.3 and FENDL-3.2a
- **Output : C/E ratio**
- *Sensitivity/Uncertainty analyses* : SUSD3D3, MCSENS5
- *The experiment is under review for SINBAD*

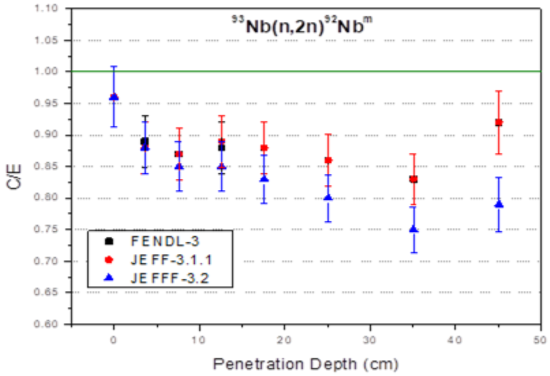


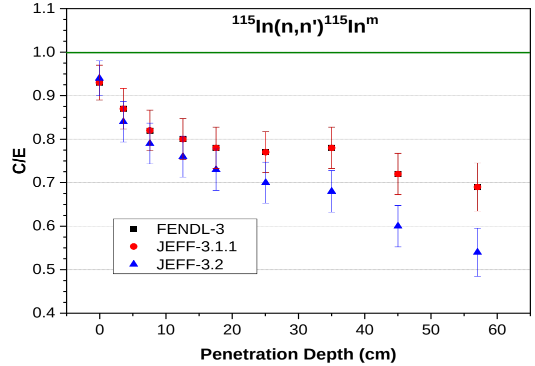


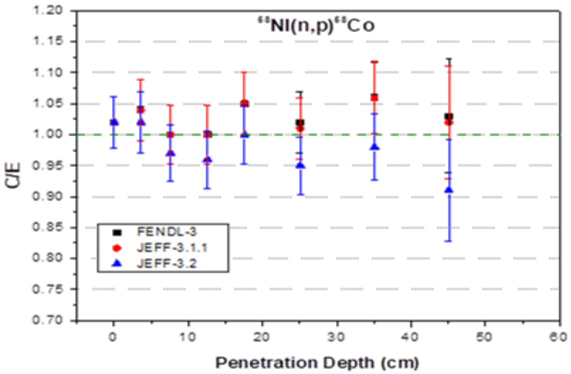
MCNP model of the Cu block

C/E using JEFF-3.1.1, JEFF-3.2 and FENDL-3

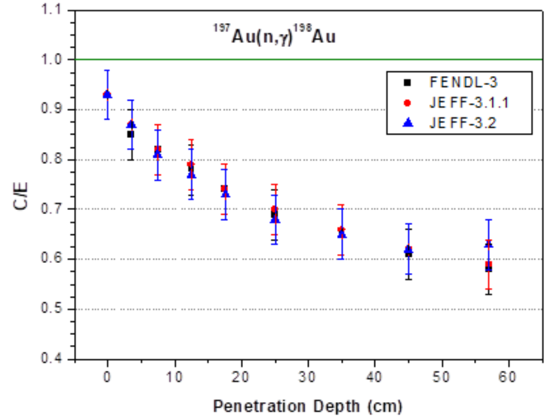
Threshold Reactions

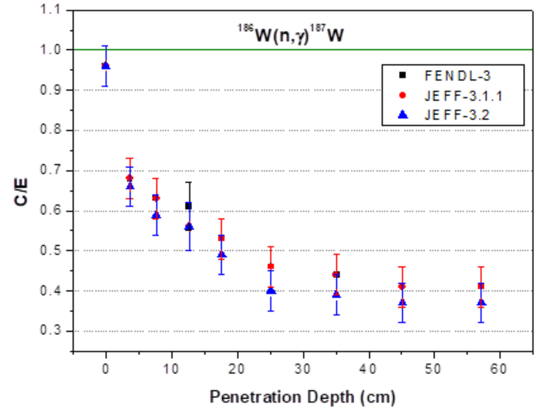






Thermal Reactions





Both Extended (JEFF) and Fusion oriented (FENDL) libraries were used

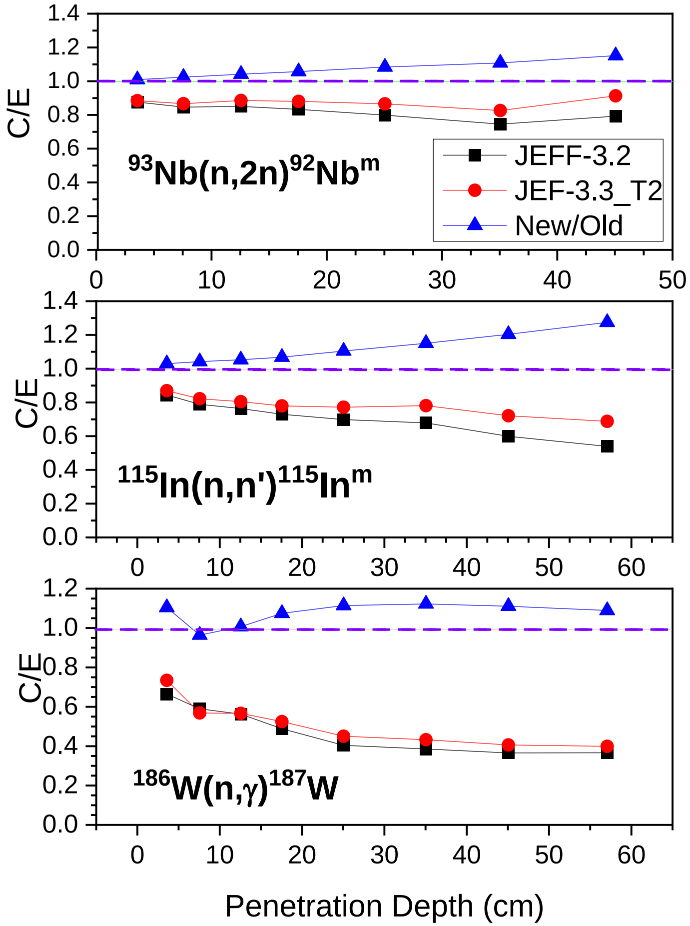
NO SUBSTANTIAL DIFFERNCES but FENDL slight better (on average)

Underestimation increasing with penetration depth for fast sensors

Serious discrepancies for THERMAL REACTIONS (all libraries)

Improved Results : New Copper library (JEFF-3.3)

RR re-evaluated using JEFF-3.3



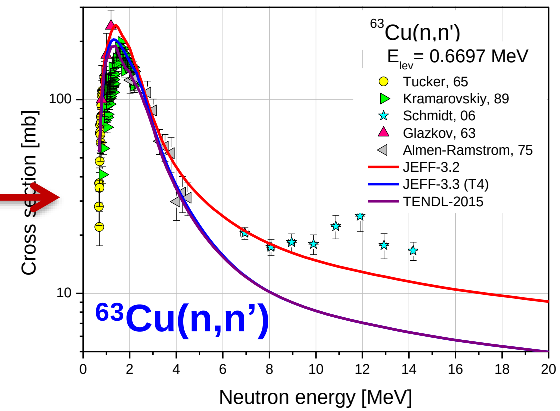
The C/E results call for a NEW EVALUATION of the Cu cross sections

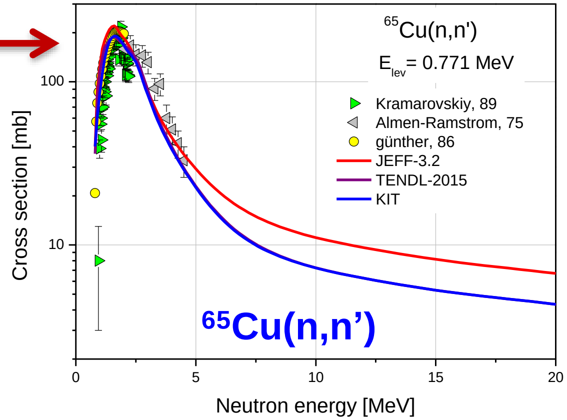
New Files were produced for JEFF library

Improvement for threshold reactions and, within a few % also for thermal reactions

Cu cross sections need further work

Re-evaluation of Cu Cross Sections (by KIT)





Comparison with FENDL-3.2a

Ratio between FENDL 3.2a (IAEA) and other libraries (FENDL 3.2a/[other lib.]) used in the post-analysis of the copper benchmark experiment

	^{93}Nb (n,2n)			^{115}In(n,n')			^{186}W(n,g)			^{197}Au(n,g)		
Depth (cm)	FENDL 3.0	JEFF 3.1.1	JEFF 3.2	FENDL 3.0	JEFF 3.1.1	JEFF 3.2	FENDL 3.0	JEFF 3.1.1	JEFF 3.2	FENDL 3.0	JEFF 3.1.1	JEFF 3.2
3.5	1.00	1.00	1.01	1.00	1.00	1.03	1.04	1.05	1.07	1.07	1.05	1.05
7.5	1.00	1.00	1.02	1.00	1.00	1.04	1.02	1.01	1.09	1.04	1.04	1.05
12.5	1.00	1.00	1.04	1.00	1.00	1.05	0.96	1.04	1.04	1.01	1.00	1.02
17.5	1.00	1.00	1.06	1.00	1.00	1.07	1.01	1.01	1.10	1.01	1.00	1.02
24.9	1.00	0.99	1.08	1.00	1.00	1.10	0.99	0.99	1.13	1.00	0.98	1.01
35.0	1.00	1.00	1.11	1.00	1.00	1.15	0.97	0.98	1.11	0.99	0.98	1.00
45.0	0.99	0.99	1.15	1.00	1.00	1.20	1.00	1.00	1.12	1.01	1.00	0.98
57.0	0.99	0.99	1.15	0.99	1.00	1.27	0.99	0.99	1.10	1.00	0.99	0.94

- Slight improvement compared to other *extended libraries* including previous versions of FENDL-3
- *New JEFF-4 library to be tested*

Role of FNG experiments in fusion (fission) neutronics & nuclear data

Lesson Learned

- The experimental validation in a tokamak environment (14 MeV neutrons) is necessary to ensure the reliability of predictions and to assess the uncertainties in nuclear analyses required for the design and safety of fusion machine operations
- The neutronics benchmark experiments at FNG play a fundamental role for the validation of codes, models, assumptions, procedures and *nuclear data* currently used in ITER & future machines nuclear analyses
- FNG experiments provided information for the ITER shield and the nuclear heating in its superconducting coils*; Cu cross section under revision,* test for the most used extended and/or dedicated libraries
- **The results of FNG benchmarking *helped to identify critical issues in nuclear data and codes (e.g. MCNP) methodology and performance and pointed out the importance for S/U pre and post-analyses* and for cross sections covariance implementation**

Concluding Remarks

- FNG experiments pointed out that extended nuclear data files (e.g. ENDF/B, JEFF, JENDL, CENDL, etc.) are able to cover and meet most of all the needs for fusion nuclear systems
- Re-analysis of experiments (available on SINBAD) by people of both fission and fusion communities can be of great importance and beneficial to both communities (share information, revise and upgrade Nuclear Data files and Codes, test Nuclear Data data in the common energy range)
- *Fission-Fusion synergy for validation and upgrading of nuclear data (and codes) is very well welcomed and must be stimulated and pursued (e.g. hybrid reactors, advanced & fast reactors, ADS, IFMIF)*

Thank You
for Your Attention