FUSION NEUTRONICS EXPERIMENTS
AT FNG:
ACHIEVEMENTS IN THE PAST 10 YEARS
AND FUTURE PERSPECTIVES

presented by
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OUTLINE

- Introduction
- The achievements:
  - Examples of experiments & analysis carried out in 1992-2002
  - Main results relevant for the design of fusion reactor
- The present activity
- The future perspectives
The **Frascati Neutron Generator** (FNG) started operations in Nov. 1992 making available 14 MeV neutrons at a medium intensity \((10^{11} \text{n/s})\) to EU Fusion Community.

In that moment, a transition was taking place from national activities to strong international collaboration stimulated by:

- **ITER - Engineering Design Activity**
- **FENDL (IAEA)**
- **IEA Implementing Agreement on Fusion**

(JA – US collaboration already established since 10 years)

The Fusion Neutronics community strongly supported the idea of international collaboration in neutronics experiments, in database & code improvement, in development of experimental techniques.
Status of Fusion Neutronics in 1992, e.g. in EU

- Nuclear studies for NET concluded that

  “nuclear data uncertainty is assumed to create an uncertainty in the magnet nuclear responses of about 40%”


- Safety margins $\geq 5$ on shielding attenuation were applied (corresponding typically to about 12 cm additional shield) (R. Santoro, ITER JCT Garching, private communication)

- It was calculated that 1 cm additional shield would increase the reactor cost by 5 MECU  (F. Gervaise, The Net Team, 1990)
Experiments carried out in 1993-2002

7 benchmark experiments for ITER and for advanced materials: Stainless steel bulk shielding, Nuclear heating, Bulk shield for ITER, Streaming for ITER, Shut down dose rate for ITER, SiC, W

- Activation experiments on fusion relevant materials: SS-316 (IG), F82H, MANET, EUROFER, Fe, Cu, V & V-alloys, SiC, W, Al, Cr, Pb.

- Experimental techniques used: activation foils, TLD, active dosemeters, fission chambers, n/γ spectrometers (scintillators, proton recoil detectors), decay heat detectors

- Nuclear data libraries used & validated: EFF-2.4 →3.1, EAF-4.1→2001, FENDL-1 →2, JENDL-FF, JENDL-3.2(A), IRDF-90.2

- Numerical tools developed and tested (e.g. for sensitivity uncertainty analysis, dose rate calculations in complex geometries)

- Collaborations: ENEA-Frascati, CEA-Cadarache, FZK-Karlsruhe, TU-Dresden, JSI-Ljubljiana, UKAEA-Culham, JAERI-FNS, KI- Moskow

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Experiments carried out in 1993-2000

“Design oriented” experiments
in support of
ITER nuclear design
Objective: verify design shielding calculations for ITER

Mock-up of first wall, shield blanket and vacuum vessel (stainless steel+water), SC magnet (inboard) irradiated at the Frascati 14 MeV Neutron Generator (FNG)

ENEA- Frascati, TU Dresden, CEA Cadarache, FZK Karlsruhe, Josef Stefan Institute Lubljana, Kurchatov Institute Moscow

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**BULK SHIELD EXPERIMENT for ITER**

Measurements of n,γ spectra, activation rates, nuclear heating, activation of IG-steel
Analysis with MCNP and FENDL-1 (ITER reference), FENDL-2, EFF-3

Example #1: Fast neutron flux on the SC magnet
Measurement: $^{93}\text{Nb}(n,2n)^{92}\text{Nb}$
Analysis: MCNP/FENDL-1 EFF-3

Example #2: Nuclear heating at the SC magnet
Measurement: TLD-300 with n/γ discrimination
Analysis: MCNP/FENDL-1&2, EFF-3
Objective: verify design shielding calculations for ITER in presence of streaming paths

Example #1: Fast neutron flux
Measurement: $^{93}\text{Nb}(n,2n)^{92}\text{Nb}$
Analysis: MCNP/FENDL-1/2 & EFF-3

Example #2: Nuclear heating
Measurement: TLD-300 with n/$\gamma$ discrim.
Analysis: MCNP/FENDL-1&2, EFF-3
Conclusions of SHIELDING EXPERIMENTS for ITER

- Calculations based on MCNP/FENDL-1 (and also FENDL-2 and EFF-3) nuclear data correctly predict n/\(\gamma\) flux attenuation in a steel/water shield up to 1 m depth within \(\pm 30\%\) uncertainty, in bulk shield and in presence of streaming paths.

- Both calculations and the related uncertainties were validated by sensitivity uncertainty/analysis and FENDL covariance data.

- Extrapolation to ITER conditions & requirements was performed.

- In the ITER design revision from ITER to ITER-FEAT:

  \[ R_0 : 814 \Rightarrow 620, a : 280 \Rightarrow 200 \quad P_{\text{fus}} : 1.5 \text{ GW} \Rightarrow 0.8 \text{ GW} \]

  Neutron Wall Loading : 1 MW/m\(^2\) \Rightarrow 0.7 MW/m\(^2\)

  the thickness of inboard shield was reduced from 94 cm to 82 cm
  only \(\approx 5\) cm reduction from reduction of wall loading

  REDUCTION OF SAFETY MARGINS
Objective: verify shut down dose rate calculation for ITER out-vessel, in-cryostat for $t_{\text{cool}} \approx 1$ month

Example:
Dose rate from immediately after shut down to about 4 months of cooling time: Measurement by Geiger–Muller detector & TLD

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Example:
Dose rate from immediately after shut down to about 4 months of cooling time:

Analysis by
- FENDL-2/MC&A
- EFF-3/EAF2001
- JENDLFF/JENDL.3.2

and using
- Rigorous method with coupled transport-activation codes (MCNP-FISPACT) (R2S)
- Direct method with modified MCNP (D1S)
The shut down dose rate outside the ITER vessel is calculated by FENDL-2 nuclear data libraries within ± 15% from a few days up to about 4 months of decay time.

Both using the rigorous two-step approach (R2S, coupled MCNP- FISPACT codes), and using the direct, one-step method (D1S, modified MCNP) developed and used in the ITER design.

Three nuclear data packages largely used in fusion design, FENDL-2, EFF-3/EAF-2001 and JENDL-FF/JENDL-3.2A were compared and validated using the ITER vessel mock-up experiment ⇒ Need for improvement of relevant data was pointed out.
Experiments carried out in 2000-2002

Experiments for the validation of EFF / EAF
European nuclear data libraries for
Advanced Materials

(started in 2000)
Objective:
Provide validation of EFF data in calculating the shielding capability of Silicon Carbide SiC (a candidate, low-activation structural material for the reactor)

ENEATUD/FZK/JSI Collaboration

Sintered SiC, weight 470 kg, 127 pieces (borrowed by ENEA from JAERI for 1 year)
Measurements of n,γ spectra, activation rates, nuclear heating

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Example: Measurement of the fast neutron flux by $^{93}\text{Nb}(n,2n)$

Analysis with MCNP & DORT, using EFF-, FENDL & JENDL

Sensitivity/Uncertainty analysis based on Monte Carlo and on deterministic approach:

Example: S/U analysis of $^{93}\text{Nb}(n,2n)$ measurement by SUSD3D/EFF-3(&2.4)

- Calculation and related uncertainties based on EFF data are in agreement with experiment
- Severe underestimation by FENDL-2 is observed
Objective:
Provide validation of EFF/EAF data for W (ENEA, TUD, FZK, JSI) (candidate material for divertor armour & for advanced concepts structural material)

DENSIMET 176 / 180
(> 92% W, Fe, Ni)
weight 1.8 ton, 28 pieces

Measur.: n/γ flux & spectra, activation, decay heat

Analysis: MCNP & DORT, EFF-3, EAF2001

Sensitivity/Uncertainty analysis based on Monte Carlo (MCNP) and on deterministic (SUSD) approach

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Future perspectives: BREEDER BLANKET EXPERIMENT

- In the framework of the EU long term FT programme, two breeder blanket concepts are under development: HCPB (Li, Be) and HCLL (Li, Pb).

- Test modules of such breeding blankets will be tested in ITER, including nuclear tests that will provide the verification of tritium production (TPR), nuclear heating, decay heat and activation.
  - C/E for such quantities with the associated uncertainties will be obtained.
  - Conclusions will depend on C/E deviations compared with total uncertainties.
  - The value of ITER tests will depend on the narrowness of uncertainties, i.e., on the accuracy of the experimental and numerical tools available.

- Intermediate step: nuclear tests will be performed on breeder blanket mock-ups at FNG in 2003-2006 (possibly at JET in DT operations)
  - to test data and codes ⇒ reduction of calculation uncertainties
  - to develop and test experimental techniques to be applied in ITER ⇒ reduction of experimental uncertainties
CONCLUSIONS

- In the past ten years many experiments have been carried out at FNG that have provided important contributions to the improvement of the nuclear design of the fusion reactor.

- All these experiments were performed in collaboration with several EU teams, taking advantage of expertise disseminated in European laboratories and improving it for fusion development.

- Very useful collaborations were also established outside Europe, with RF and with JAERI (IEA).

- Following the strategy of the Fusion program, investigation is now moving from shielding issues to breeding issues.

  - efforts are focusing on preliminary experiments at FNG in preparation of breeder blanket tests in ITER.