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Integral Neutronics Experiment with a Mock-up of the European HCLL-TBM for ITER

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An ITER TBM mock-up made of lithium-lead and sheets of EUROFER was irradiated with short pulses of DT neutrons from the neutron generator at TU Dresden, and time-of-arrival spectra of the slow neutron flux were measured by means of a ^{3}He counter in two regions inside the mock-up. Fast neutron spectra were obtained by continuous irradiation of the mock-up with DT neutrons and application of a NE-213 spectrometer. The same mock-up was also irradiated at the Frascati Neutron Generator and tritium production rates were measured by means of Li_2CO_3 pellet detectors and LiF thermoluminescense detectors (TLD) inserted into the mock-up. In case of the first type of detectors, the accumulated tritium activity was measured while with the LiF TLD the tritium production rate was obtained from the dose deposited in the detector by the tritium-producing reactions. The Calculation/Experiment ratio for the TPR measurement was nearly 1.0 with an uncertainty of approximately 7.4%. Preliminary results from calculations with FENDL-2.1 and JEFF-3.1.1 suggest a good agreement between experiment and calculation.

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I. INTRODUCTION

The detailed and correct description of the neutron and gamma-ray transport in the breeding blanket modules is of great importance for the design and operation of fusion reactors. The blanket has to fulfil three main functions: i) Sufficient tritium production, ii) Heat generation, iii) Shielding for the magnetic field coils.

The neutronics design of the breeding blanket relies very much on calculations with neutron transport codes and evaluated cross section data libraries.

In this work, we performed several experiments with a neutronics mock-up of the European Helium-Cooled Lithium-Lead Test Blanket Module (HCLL-TBM) for ITER. Aim of the work is to provide experimental data for checking state-of-the-art cross section data files such as FENDL-2.1 [1] and JEFF-3.1.1 [2] for their applicability in the design of the ITER TBM.

Two experimental campaigns were conducted. The first one was a joint tritium production rate (TPR) measurement experiment at the Frascati Neutron Generator of ENEA Frascati. The TPR measurements have been performed by three groups independently to achieve an uncertainty level as small as possible since the TPR is a very crucial parameter for the self-sustaining operation of a DT fusion reactor. This article focuses on the measurements done under the responsibility of the KIT group.

The second campaign was conducted at the neutron laboratory of Technical University of Dresden with the

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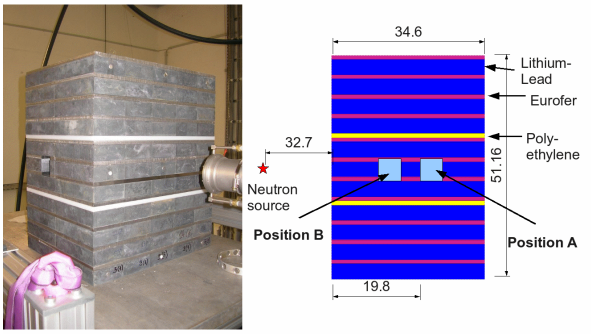

Fig. 1. (Color online) HCLL-TBM mock-up prepared for the measurement of fast neutron and gamma-ray flux spectra. Measures in cm.

same mock-up. Fast neutron and gamma-ray spectra and the slow neutron flux by means of time-of-arrival spectra have been measured in two positions inside the mock-up.

II. EXPERIMENT

The HCLL-TBM mock-up was built from bricks of lithium-lead with the sizes 3.6 cm × 17 cm × 9 cm. They were arranged in 11 horizontal layers, the layers were separated by EUROFER sheets with a thickness of 9 mm. Two polyethylene sheets were inserted above and below the central LiPb layer which contained the detectors. Their purpose was to shape the neutron spectrum to make it more similar to the spectrum expected in a breeding blanket. A photograph of the LiPb assembly with a cross sectional view is shown in Fig. 1.

1. Tritium production rate

A measurement method has been applied based on a liquid scintillation counting (LSC) technique described by Diercks [3] which was further developed by many groups with respect to dissolving agents and scintillators, see for example Ref. 4. A small pellet-shaped detector made of lithium carbonate is placed in a location in the mock-up where the TPR is to be measured. After completion of the irradiation, the detector is removed, transferred to solution by means of an acid or acid mixture and treated with LSC.

In this work, pellet detectors had been prepared from powders of lithium carbonate with natural lithium isotopic composition and also enriched in ^{6}Li to 95%. Their size was 1.3 cm diameter and 2 mm and 1 mm thickness for the natural Li_2CO_3 and enriched in 95% ^{6}Li, respectively. The detectors were wrapped in aluminium foils and placed at regular intervals parallel to the central axis of the LiPb mock-up.

The mock-up was irradiated at the Frascati Neutron Generator (FNG) of ENEA Frascati with a total source yield of 5.03×10^{15} DT neutrons. After the irradiation, the Li_2CO_3 pellets were processed in the Laboratory for Environmental and Radio Nuclide Analytics of VKTA Rossendorf. The result of the measurement is shown in Fig. 2.

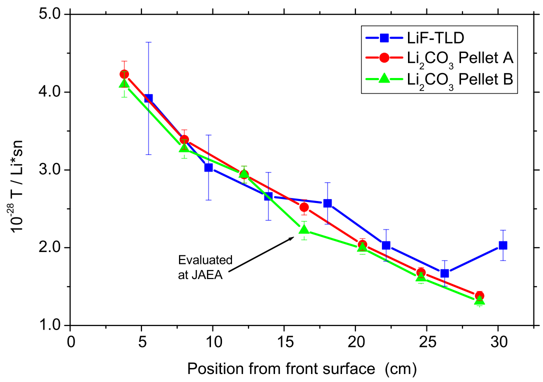

Fig. 2. (Color online) Tritium production rates measured with Li_2CO_3 pellet detectors and LiF-TLD of natural isotopic composition. Two pellets (A+B) were placed in each measurement position.

Another method for TPR measurements based on the direct dose deposition of the tritium-producing reaction in LiF thermoluminescence detectors (LiF-TLD) was also applied. The principle of this method is described in detail in an article by Sharabati [5] and has been checked for its applicability in an experiment performed previously at TUD [6]. The latter investigation concluded with the suitability of the measurement method for an assembly such as the present LiPb mock-up.

The LiF-TLD in this work had been calibrated at the thermal beam line with well-defined spectrum of the FRG-1 research reactor of GKSS Geesthacht (Germany) in collaboration with Physikalisch-Technische Bundesanstalt.

For each measurement position in the mock-up, a stack of TLD was prepared which consisted of 2 TLD-700 detectors with 99.99% ^{7}Li enrichment and 3 TLD-100 with natural lithium composition. For this experiment, the mock-up was in exactly the same position as for the previous measurement with the lithium carbonate pellets, but this time the irradiation finished when 1.2×10^{14} source neutrons were produced. After the irradiation, the TLD were read out with a Harshaw 3500 TLD reader.

The average signal of the TLD-100 and TLD-700 in each stack was used for further data processing. The final TPR values are shown together with the results from the Li_2CO_3 pellet measurement in Fig. 2. The first TLD measurement position has been omitted in this plot since the measurement method established in Ref. 5 is only valid in a neutron field which is not too hard,*i.e.*, where the contribution of tritium from ^{7}Li is small compared to that from ^{6}Li. This is because the necessary gamma-dose cancellation is based on the difference of the signals from TLD-700 and TLD-100.

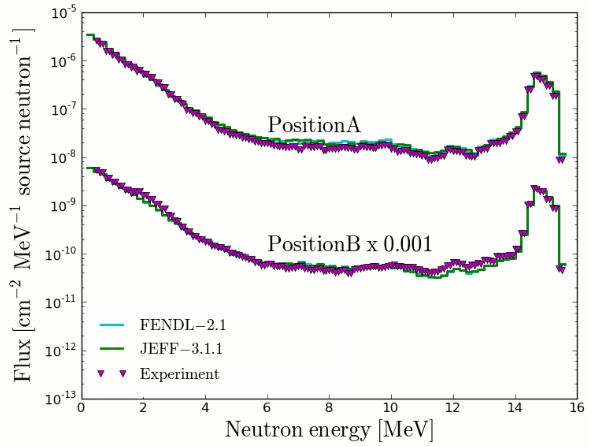

Fig. 3. (Color online) Fast neutron spectra measured and calculated in both measurement positions.

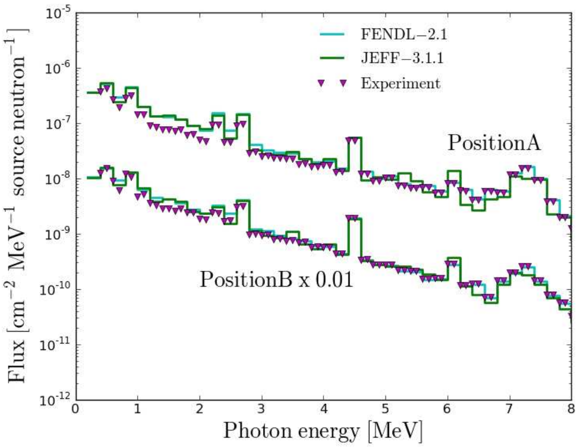

Fig. 4. (Color online) Measured and calculated gamma-ray spectra.

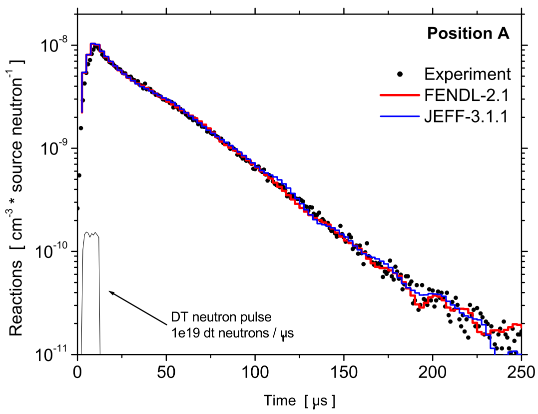

Fig. 5. (Color online) Time-of-arrival spectrum of the slow neutron flux in Position A. Comparison of measurement and calculation.

2. Fast neutron and gamma-ray flux spectra

Fast neutron and gamma-ray fluxes have been measured at the neutron laboratory of Technical University of Dresden (TUD). The same mock-up as for the tritium production rate experiments had been used after shipping it from FNG to TUD.

The mock-up was placed in front of a water-cooled Ti-T target at a distance of 32.7 cm. The DT neutron source was monitored with a silicon detector which recorded the alpha particle associated with the DT reaction in the target.

The mock-up itself had to be re-arranged to accommodate the NE-213 detector. For this purpose, five separate LiPb bricks were cut so that a 5 cm × 5 cm channel perpenticular to the main axis of the mock-up was created. Furthermore, the central brick in which the pellet detectors and TLDs of the tritium production experiment were inserted, was replaced by a solid LiPb brick. The situation is shown in Fig. 1.

The neutron/gamma-ray spectrometer is based on a NE-213 scintillator which allows to separate gamma-ray and neutron induced scintillation by means of a pulse-shape discriminator circuit. The cylindrical scintillator has a diameter and height of 3.81 cm, and is coupled to a photomultiplier (PMT) tube by means of a 50 cm long light guide. An unfolding method applying the MAXED code [7] was used to compute the fast neutron and gamma-ray spectra from the recorded raw pulse height spectra. The response matrix of this NE-213 detector had been obtained experimentally [8]. The experimental spectrum was adjusted with a factor to fit the 14 MeV neutron peak.

3. Slow neutron fluxes in the mock-up by the time-of-arrival method

Slow neutron fluxes in the mock-up have been measured by time-of-arrival spectroscopy with a ^{3}He proportional counter (Canberra 24NH15). The proportional counter was placed in the same channel as the NE-213 scintillator before. For this experiment, the neutron generator was operated in pulsed mode with 10 ms pulse length and a repetition rate of 1 kHz.

This detector is filled with 4 bars of ^{3}He and the sensitive volume has a length of 15 cm which was verified experimentally with a thin beam of thermal neutrons from the reasearch reactor FRG-1 at GKSS Geesthacht. The detector has a diameter of 25 mm, the effective volume for processing the measured data was 67.86 cm^3. The ^{3}He counter was operated with a voltage of 950 V and the signal was recorded with a multichannel scaler (MCS). The MCS was operated in sweeping mode with 900 channels and a dwell time of 1 ms for each channel. Each sweep is triggered by a sync impulse from the neutron generator at the rising edge of each of the 10 ms DT neutron pulses.

After the 10 ms DT neutron pulse, the neutron flux inside the mock-up will be decreasing due to leakage and shortly after the pulse these remaining neutrons in the mock-up will be mostly slow neutrons which are subject to leakage and absorption mostly by ^{6}Li.

In order to compare with calculations, the recorded experimental time spectra are normalized to the sensitive volume of the detector and the total number of the neutrons emitted from the Ti-T target. To obtain the number of the neutrons, the output of the silicon detector used for monitoring was multiplied with a scaling factor which is established by routine calibrations of the monitoring system.

III. RESULTS AND DISCUSSION

There is a good agreement between the TPR values obtained by the Li_2CO_3 pellets and the LiF-TLD, although the latter show more scattering. However, also a higher measurement uncertainty had to be assigned to the LiF-TLD values which is approximately 10% for the TLD deeper in the assembly and rises to 39% for the second position from the front surface. The values are shown in Fig. 2, where the value from the first TLD position is omitted since the neutron spectrum in this position is too hard to apply the measurement procedure described in [4].

An analysis and comparison with MCNP calculations of the data obtained in this TPR measurement can be found for example in [9].

The measurements of the fast neutron and gamma-ray flux spectra were compared with calculations with the MCNP-5 code [10] and the transport data libraries FENDL-2.1 and JEFF-3.1.1. In the calculation, the geometry of the DT neutron source, the mock-up, and the detectors were described in detail in the input file.

There is a generally good agreement between the calculation and the measured neutron flux spectra, the spectra are shown in Fig. 3. Both nuclear data evaluations result in nearly the same neutron spectra. Comparing them with the experimental spectra one can see a slight overestimation around $6 \sim 7$ MeV in the rear measurement position (A) and an underestimation for the front position (B) from $11 \sim 13$ MeV.

Experimental and calculated gamma-ray fluxes are shown in Fig. 4. There is also a good agreement between calculation and measurement, however, in the energy range below 3 MeV, the calculation tends to overestimate.

Time-of-arrival spectra for both measurement positions are shown in Fig. 5. The experimental spectra have been normalized to the number of registered source neutrons and the sensitive volume of the ^{3}He counter. In the calculation, an effective lithium content of 0.28 wt% was assumed for the LiPb. This value was found in the course of analysis of the tritium production rate measurements. An excellent agreement of experiment and calculation is seen for both nuclear data evaluations.

The ^{3}He counter is sensitive mostly for slow neutrons. Therefore this measurement is a sensitive test to the entire chain of slowing-down mechanisms for the original 14 MeV neutrons from the DT neutron source in the mock-up.

IV. CONCLUSION

The work described in this report was a joint undertaking of INR/KIT, TU Dresden and FNG/ENEA and focused on the measurement of tritium production rates, fast neutron and gamma-ray spectra, and time-of-arrival spectra of slow neutrons in the mock-up. The tritium production rate experiments were done at FNG/ENEA while the neutron and gamma-ray spectra measurements have been performed in the neutron laboratory of TU Dresden with the same mock-up.

In case of the fast neutron and gamma-ray flux spectra, a good agreement of experimental values and calculations with both data libraries mentioned above was found with some deviations in certain energy intervalls. The measurement of the slow neutron flux by the time-of-arrival method showed an excellent agreement of calculation and experiment.

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