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Technical design and operation tests of the DET-12 device for detection of delayed neutrons

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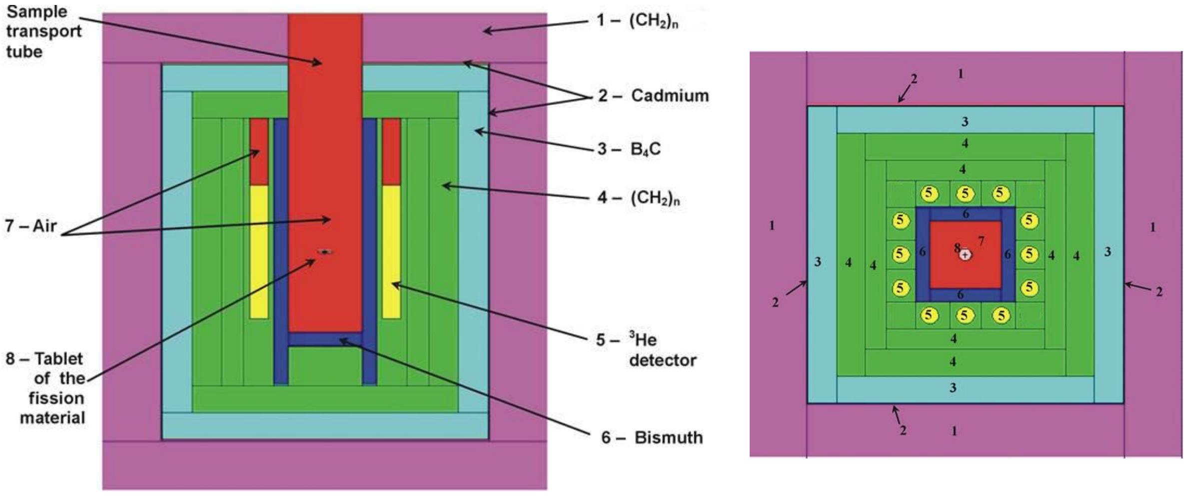
Abstract

A technical design of the device for detection of delayed neutrons emitted from neutron-activated fissionable material samples has been performed according to physical assumptions which were earlier elaborated. The DET-12 device was constructed. The detection system was composed, consisting of twelve ^{3}He neutron detectors, related electronics lines, and the data acquisition and recording system. The detectors were adjusted to work in groups by three connected to one preamplifier, considering a weak intensity of emission of the delayed neutrons. Laboratory measurement tests of the device operation were made with use of an isotopic neutron source. A total efficiency of neutron detection in DET-12 was experimentally determined and a relative benchmark calculation was made by means of a Monte Carlo modelling of the neutron transport in the device from the source to detectors.

1. Introduction

Measurement of delayed neutrons emitted from fissionable material samples activated in the neutron field at a fusion device is thought as a supplement to the plasma diagnostic method based on a classical neutron activation technique. Physical assumptions for a design of the dedicated device (DET-12) for detection of the delayed neutrons were formulated in an earlier paper [1]. A final shape of the device was obtained based on Monte Carlo neutron transport modelling. The current scheme of the device to prepare a technical design is shown in Fig. 1. Comparing to the first idea, given in [1], some small changes were introduced owing to the MC simulations performed. The final number of neutron detectors was established as 12 which in the assumed geometry is sufficient instead of 16. The first outer shield which protects external neutrons to enter inside the measuring chamber was assumed as pure polyethylene (without boron admixture). The external slowed down neutrons will be successfully stopped in the second and third layers (cadmium and boron carbide).

A technical design of DET-12 was prepared and the device was built. Then a number of test was performed to check operation of detection lines (the detectors, electronics, and data acquisition system). Experiments were performed when an isotopic neutron source was used in a measuring chamber in position where the activated sample would be placed.



a) vertical section **b) horizontal section**

Fig. 1. Final scheme of the device for the delayed neutron detection to prepare a technical design.

2. Technical design of the DET-12 device for measuring the delayed neutrons

After the neutron transport analysis performed [1] the following optimised dimensions of DET-12 and its elements were obtained:

Total external dimensions of the device:

square horizontal size 58 cm × 58 cm^2, height 74 cm.

Central hole for the pneumatic transport: 6 cm ×6 cm.

Consecutive layers from the hole towards outside (numbered as in Fig.1):

- (6) Bismuth: 2 cm,
- (4) Polyethylene (moderator of delayed neutrons): 12 cm,
- (3) B_4C (absorber): 3.8 cm,
- (2) Cadmium (absorber): 0.2 cm,
- (1) Polyethylene (external protection): 8 cm.

Twelve ^{3}He neutron detectors: 1” diameter, 30 cm length (25 cm active), 5 atm. pressure.

A CAD visualisation of the designed device is shown in Fig. 2. Locations of the neutron detectors inside are presented in Fig. 3.

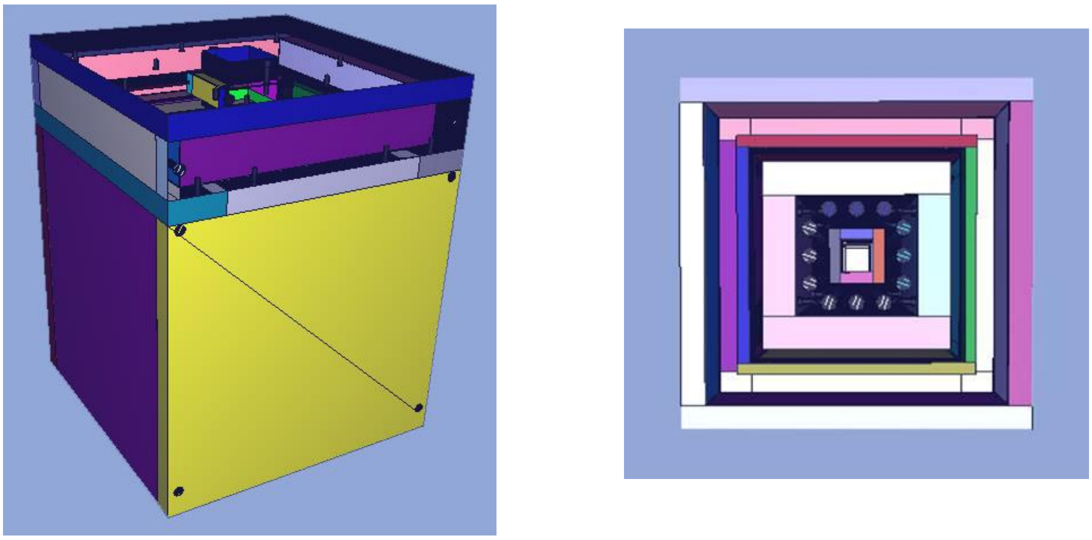


Fig. 2. Visualization of the designed DET-12 device obtained from CAD technical drawings (false colours). A top view – on the right.

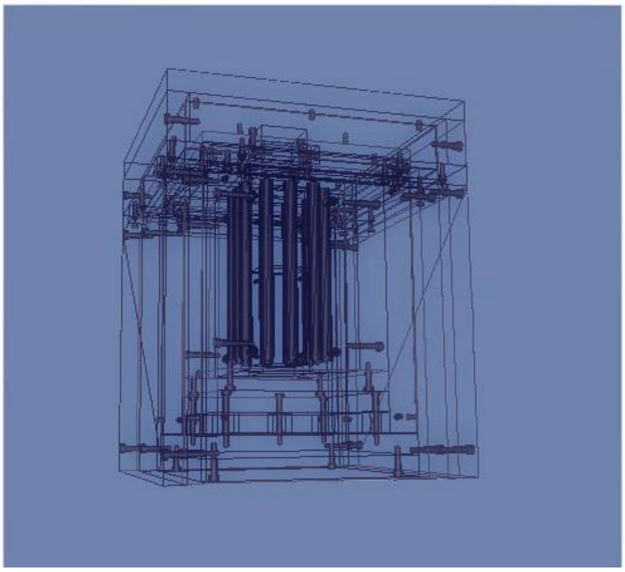


Fig. 3. Space location of the neutron detectors inside the DET-12 device.

The device called DET-12 was then built according to the technical design based on the final optimisation. A photo of the device is shown in Fig. 4. Only external layers of the polyethylene shield are visible.

Fig. 4. General view of the built DET-12 device.

3. Electronic system for neutron detection and data acquisition

The expected intensity of counts in the ^{3}He detectors will be rather low. Therefore, it has been decided to use a system in which three ^{3}He detectors are coupled to one preamplifier. Then the preamplifiers in a usual way are connected to spectroscopy amplifiers. Four lines are connected with a digitizer card in a PC. A complete scheme of the system is shown in Fig. 5.

All the electronic blocks were connected (including a preparation of dedicated cables for the groups of detectors) after preparatory operation tests and HV and amplification adjustments were made. The connections of the detectors and preamplifiers are shown in Fig. 6. The digitizer card were placed in a PC and put in operation.

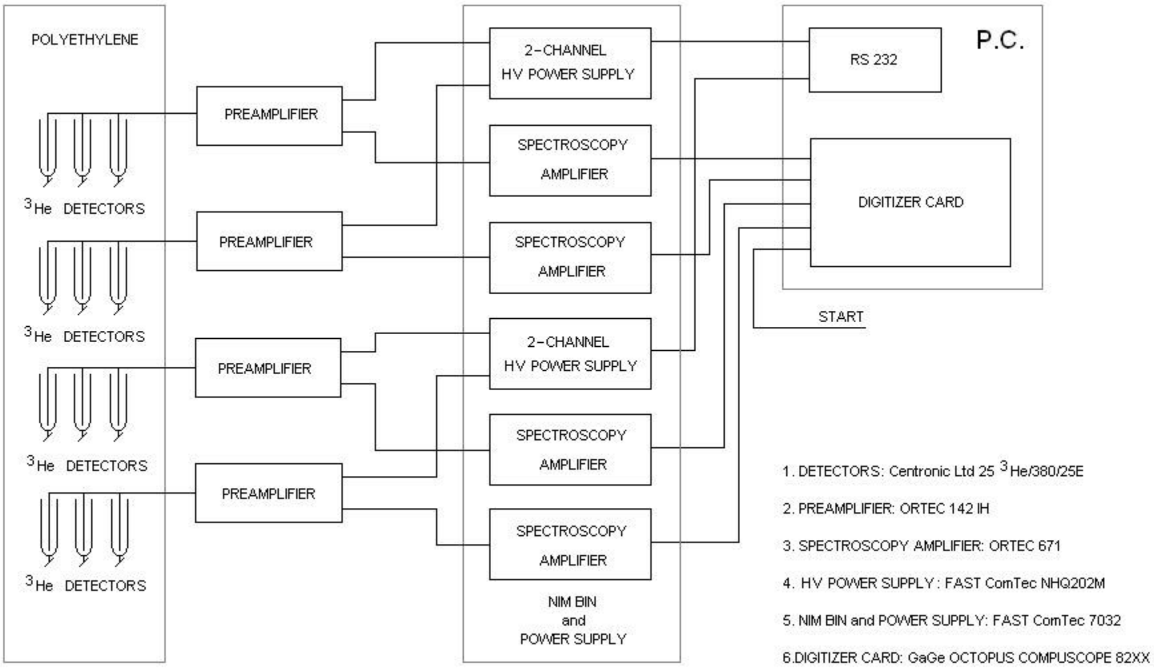


Fig. 5. Neutron detection and data acquisition system.

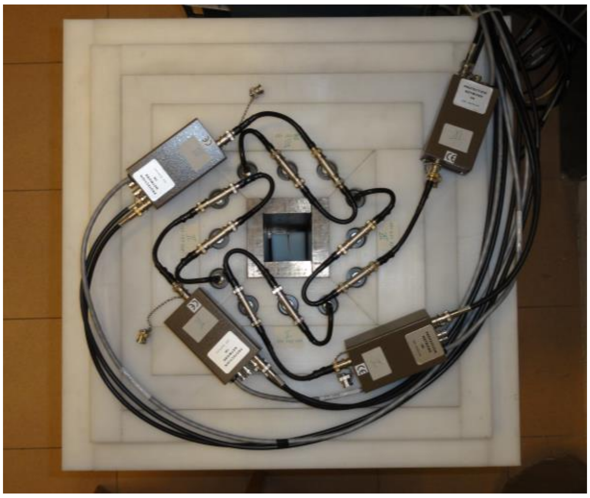


Fig. 6. Combination of the neutron detectors in groups and connection to the preamplifiers (top view of DET-12 with cover removed).

Preparation of neutron detectors for work in groups

Each detector was separately tested at a neutron source in the line: detector – preamplifier (with the HV supply) – amplifier – oscilloscope and scaler, shown in Fig. 7. The operation voltages for the detectors and control parameters of the amplifiers were adjusted and the idle run of each detector was measured. The results are presented in Table 1.

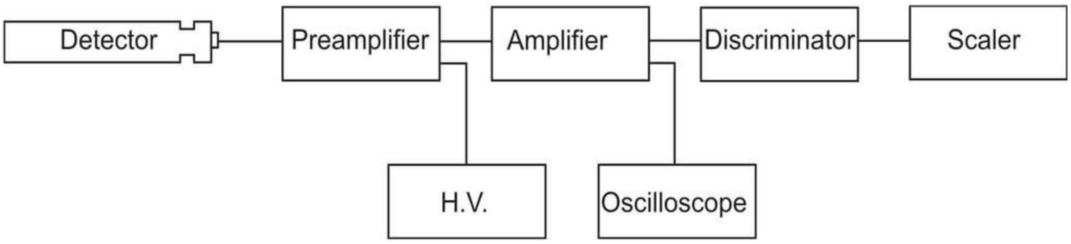


Fig. 7. Electronic set-up for tests of the neutron detectors.

Table 1. Adjustment of operation parameters of the ^{3}He detectors.

No.	Detector ID	Operating voltage [V]	Peak base [channel No.]	Peak position [channel No.]	Resolution FWHM [%]	Idle run [1/min]
1	130	1535	330 - 362	342	9.4	50 ±3
2	131	1535	328 – 362	342	9.9	36 ±2
3	132	1510	330 – 365	342	10.3	38 ±2
4	133	1510	329 – 363	342	9.9	34 ±1
5	134	1500	332 – 363	344	9.0	29 ±1
6	135	1510	331 – 363	344	9.3	38 ±2
7	136	1545	326 – 355	340	8.5	15 ±1
8	137	1335	328 – 356	340	8.2	10 ±1
9	138	1340	329 – 355	343	7.6	8 ±1
10	139	1345	331 – 358	342	8.2	10 ±1
11	140	1345	330 – 359	342	8.2	14 ±1
12	141	1360	330 – 359	342	8.5	18 ±1
13	348	1475	331 – 365	346	9.8	24 ±1
14	349	1475	334 – 369	347	10.1	21 ±1
15	350	1475	332 - 365	348	9.5	22 ±1

4. Laboratory measurement tests of DET-12 with use of a neutron source

A scheme of the arrangement for testing a single measuring line is shown in Fig. 8. A ^{252}Cf source was used as it has the neutron energy spectrum (Fig. 9) similar to that of delayed neutrons emitted from fissionable materials (cf. [1]) foreseen for the use in the measurement procedure at fusion plasma devices. The californium source was placed at the bottom of the central channel of the chamber. Examples of the amplitude and time distribution of pulses from the detectors are shown in Figs. 10 and 11.

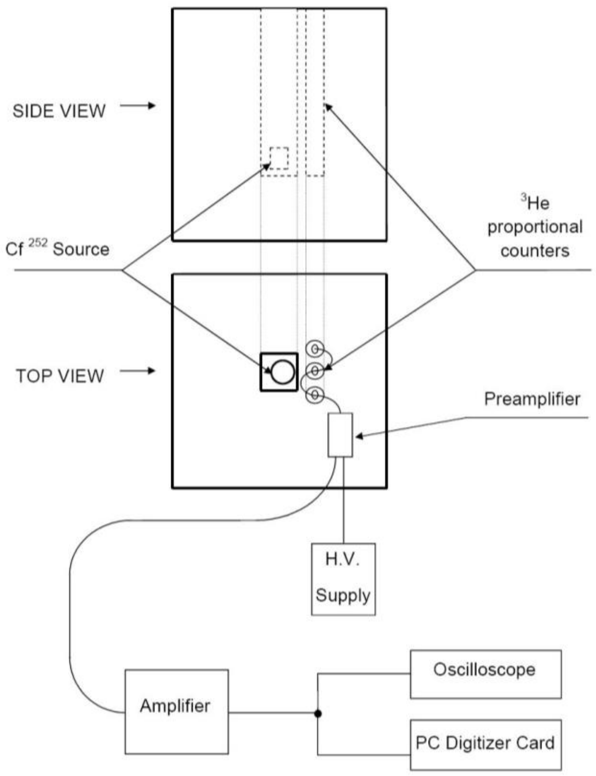


Fig. 8. Arrangement for the test measurements in DET-12.

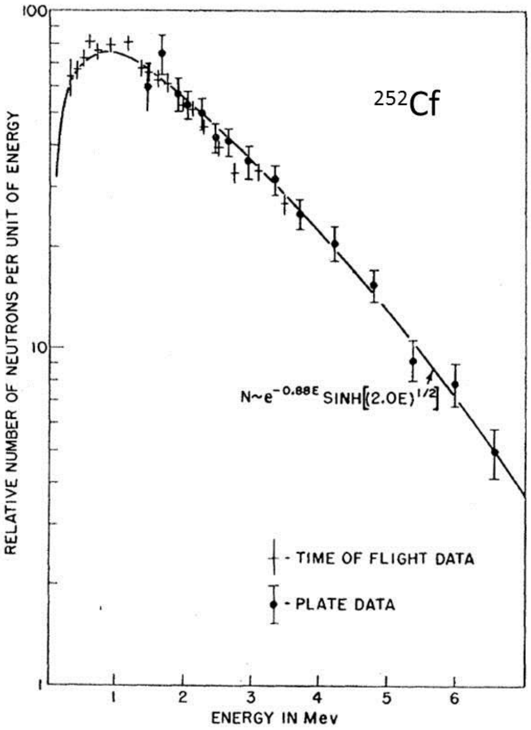


Fig. 9. Experimental energy spectrum of ^{252}Cf fission neutrons [2].

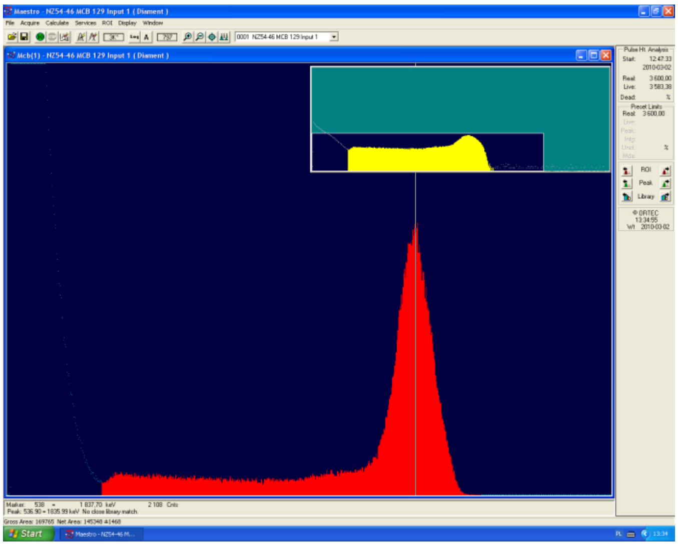
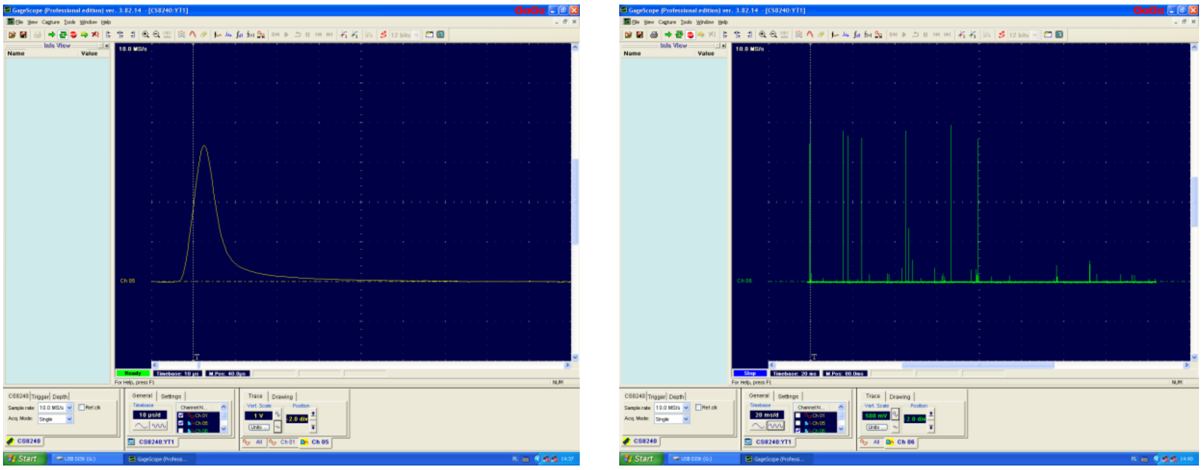


Fig. 10. Detector amplitude pulse distribution.



a) Single pulse from three detectors

b) Random distribution of pulses during ca. 160 ms

Fig. 11. Record of pulses in the CS 8240 digitizer card as a function of time.

Each electronic line with three detectors was tested separately. Their operations are similar to each other. Example results of the measurements are listed in Table 2.

Table 2. Comparison of the count rates of two groups of detectors.

Series	Detector ID	Operating voltage [V]	Count rate $[s^{-1}]$
1	132, 133, 135	1500	47.16 ± 0.11
2	348, 349, 350	1450	47.25 ± 0.11

5. Neutron detection efficiency of the DET-12 device

A series of experiments was made to adjust operation parameters of each group of three neutron detectors to obtain a very similar operation of each one. The pulse height spectrum for each group was observed (Fig. 12) and the operation parameters (high voltage supply, amplifier gain, shaping time) were adjusted. The result is summarized in Table 3.

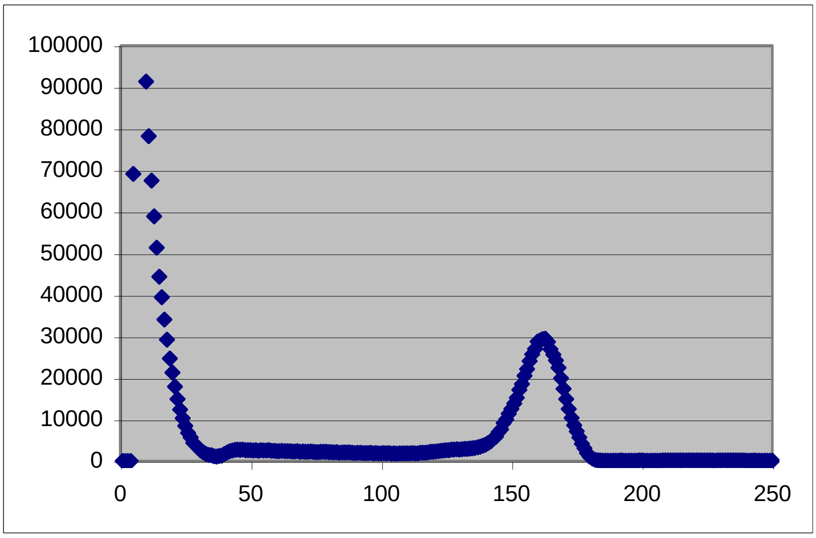


Fig. 12. Amplitude summary spectrum of pulses from all twelve detectors.

Table 3. Operation parameters of the detectors combined in groups.

Group of detectors	Detector ID	Operating voltage [V]	Amplifier gain	Shaping time [μs]
I	348, 349, 350	1475	100	2
II	132, 133, 135	1510	100	2
III	136, 137, 141	1335	100	2
IV	138, 139, 140	1340	100	2

A next step was to evaluate neutron detection efficiency in test measurements and to compare it with Monte Carlo calculations.

5.1. Measurement of the detection efficiency of the DET-12 device

Detection efficiency of the DET-12 device was tested using again the ^{252}Cf source, this time placed in the middle of the measuring channel of DET-12, *i.e.* in position presumed for the activated sample to be measured. The working parameters of the neutron detectors and electronic lines were fixed as obtained above (Table 3).

The absolute neutron emission from the source has to be known to estimate the total efficiency of the built device. The ^{252}Cf source according its certificate had the total activity A_0 = 100 kBq (2.7 μCi) on Dec 1st, 2001. The half-life of the source is relatively short, $T_{1/2}$ = 2.645 yr, and it was taken into account. The corresponding decay constant is λ = 0.26/yr which according to the decay law, $A = A_0 \exp(-\lambda t)$, leads to the activity A = 8.777 kBq during the measurements. Spontaneous fission of ^{252}Cf bring the neutron emission with the coefficient of 0.116 Bq^{-1} [3]. This results, in our case, in the neutron emission rate of 1020 per second.

Four measurements, twice with the californium source and two measures of background, were performed. Results of the measurements are specified in Table 4. The obtained average count rate (background subtracted) is 191.4 s^{-1}. Thus, the neutron detection efficiency can be assessed at 18.8 %.

Table 4. Results of the efficiency test measurements.

No.	Measurement type	Discrimination level [V]	Measurement time [s]	Counts $N \pm \sigma(N)$
1	^{252}Cf source	0.7	5000	961 024 ±980
2	^{252}Cf source	0.7	5000	958 483 ±979
3	Background	0.7	5000	2 672 ± 52
4	Background	0.7	5000	2 737 ± 52

5.2. Monte Carlo simulation of the efficiency experiment

The DET-12 device model was implemented into the CAD program according to the technical design. Then the CAD model of the DET-12 was exported to the “sat” format in order to convert it with the MCNP Visual Editor [4]. The created file is a geometrical part of an MCNP input file. Usually modelling of geometry is the most laborious stage when preparing the MCNP input file. Unfortunately, the MCNP Visual Editor creates many identical, useless surfaces, which were removed manually and definitions of corresponding cells changed. Obviously, it is possible to run MCNP when the input file contains the same surfaces since the code deletes them automatically, but when their number is too large the geometrical structure becomes imperceptible for the user and it is difficult to introduce possible changes.

The energy spectrum of the ^{252}Cf source used in the calibration measurements was modelled using a built-in Watt fission spectrum that is commonly used by the MCNP users. The probability density of neutron emission $p(E)$ for californium describes the following formula:

$$p(E) = C\, e^{-E/1.025} \sinh \sqrt{2.926\, E}\ ,$$

where C is a constant and E is energy expressed in MeV [5]. This neutron spectrum of ^{252}Cf is plotted in Fig. 13.

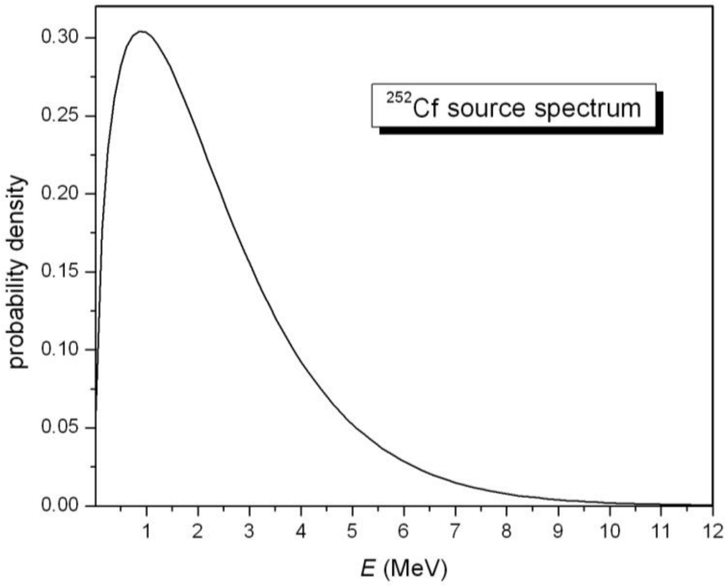


Fig. 13. Probability density of neutron emission from the ^{252}Cf source used in the Monte Carlo simulations (cf. Fig 9)

Composition and density of almost all materials used to build the DET-12 – like cadmium, bismuth, polyethylene and boron carbide – is well known except of the ^{3}He detectors. The manufacturer releases only pressure (3800 Tr, *i.e.* 5 atm) [6]. It was arbitrary assumed the commercial detectors to be filled with 95% of ^{3}He and 5% of ^{4}He. The density of helium filling the commercial detectors was evaluated using the ideal gas law, which gives a very good agreement with real values when applied, for instance, for oxygen or hydrogen in normal pressure and temperature. Moreover, it was possible to determine only external dimensions of the detectors. The outer material appeared to be steel of 0.5 mm thickness. The length of a helium cylinder, situated centrally in the steel tube, was roughly estimated to be 25 cm. Other details of the ^{3}He detectors were neglected because of lack of information and data. The rest of the space inside the steel tubes was filled with void, as shown in Fig. 14.

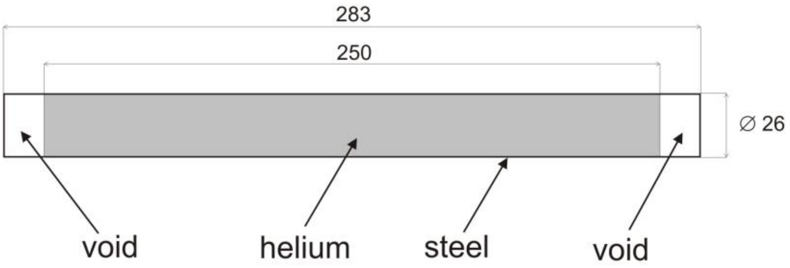


Fig. 14. Model of the helium detector used in the Monte Carlo simulations.

Characteristics of materials used in the MCNP model of the DET-12 are listed in Tables 5 and 6. Table 5 contains data for all components of the DET-12 except the helium detectors. Both density of polyethylene and bulk density of boron carbide were measured. Composition of B_4C was released by the manufacturer. Polyethylene, bismuth and cadmium were assumed to have no contaminations. Parameters of bismuth, cadmium and air are attached in the form which is in a common use.

Table 5. Materials used in the Monte Carlo model of DET-12.

Material	Weight fraction [%]	Density [$g \cdot cm^{-3}$]
Bismuth	100	9.747
Cadmium	100	8.65
Polyethylene	H 14.29 C 85.71	0.9507
Boron carbide	B 78.17 C 21.63 Fe 0.20	1.243 (bulk density)
Air	C 0.01 N 75.53 O 23.18 Ar 1.28	$1.2048 \cdot 10^{-3}$

Table 6. Materials used in the Monte Carlo model of the helium detectors.

Material	Weight fraction [%]	Density [$g \cdot cm^{-3}$]
Helium	^{3}He 95.00 ^{4}He 5.00	$6.236 \cdot 10^{-4}$
Steel	Fe 65.50 Si 1.00 Cr 17.00 Mn 2.00 Ni 12.00 Mo 2.50	7.92

According to the data presented above, the volume of the whole set of twelve detectors is 1472.62 cm^3. The Monte Carlo simulations were carried out on a PC computer and the average number of reactions in one cubic centimetre in the volume of all twelve detectors per one source neutron was calculated. The obtained value is $1.62755 \cdot 10^{-4}$ cm^{-3}. In order to compare the simulation results with the experimental value it is also necessary to know the number of neutrons emitted from the source. The neutron emission of 1020 n/s was found in the preceding paragraph. Finally, the reaction rate in the detectors, calculated in the MCNP simulations, is 244.58 counts per second (Table 7).

Table 7. Comparison of calculated and measured count rates.

Neutron source activity [n/s]	MCNP calculations		Experiment	
	Calculated reaction rate [s^{-1}]	Detection efficiency [%]	Average measured count rate [s^{-1}]	Detection efficiency [%]
1020	244.58	24	191.4 ± 0.2	18.8

Numbers of the simulated and measured count rates (and thus, the relevant efficiencies) differ over 20%. Possible reasons: The Monte Carlo simulations do not include neither dead time nor efficiency of the detectors (problem of the detector active volume). Real composition of the gas in the detectors may be different from the one assumed in the MC simulations – manufacturer does not release even principal information and additionally some admixtures, like CO_2 or Ar as a quench gas, (below 1%) are generally known to be present.

The difference between the simulation and experiment results will be taken into account in further modelling of operation of the setup, especially at absolute calibration of neutron fluxes.

6. Final remarks

The presented operation tests of DET-12 and the effort put in the MCNP simulations of the neutron detection made further numerical analyses highly reliable.

A Monte Carlo modelling of the neutron transport in the built device was performed following exactly the final geometry (dimensions and constituent materials). Detection and the time decay of the delayed neutrons from samples (^{232}Th, ^{235}U, ^{238}U, UO_2) activated with primary neutrons of various energies (14 MeV, 2.45 MeV, 500 keV, and thermal) was considered [7]. A method of interpretation of result of the measurements of delayed neutrons in DET-12 was elaborated and is described in a separate paper [8]. It is expected to use such a system at the W7-X stellarator when it achieves a deuterium phase of work.

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