The Henryk Niewodniczański
INSTITUTE OF NUCLEAR PHYSICS
Polish Academy of Sciences
ul. Radzikowskiego, 31-342 Kraków, Poland

www.ifj.edu.pl/publ/reports/2009/
Kraków, December 2009

Report No. 2033/PN

Angular-energy distributions of neutrons emitted from the Wendelstein stellarator – Monte Carlo simulations

Grzegorz Tracz and Krzysztof Drozdowicz

Collaboration of the Institute of Nuclear Physics Polish Academy of Sciences with the Max-Planck-Institut für Plasmaphysik (Greifswald, Germany).

The study has been partly supported by the Association Euratom-IPPLM (Poland).

The work supplements project of the Polish scientific network „Neutrons-Emission-Detection": *Neutron diagnostic for pulsed plasma source.*

Abstract

Angular-energy distributions of neutron currents expected from the Wendelstein 7-X stellarator have been calculated by means of Monte Carlo methods using a simplified model of the stellarator. The MCNP5 code has been employed. The obtained spectra are to be used to design five sets of neutron and gamma detectors placed above this D-D fusion reactor. The counters are to provide information concerning both thermonuclear plasma diagnostics and dosimetry.

1. Introduction

The Wendelstein 7-X stellarator [1], [2] – under construction at the Max-Planck-Institut für Plasmaphysik (IPP), Teilinstitut in Greifswald (Germany) – is a fusion reactor. Contrary to tokamak it has effectively steady state magnetic field. Owing to sophisticated shapes of coils, internal plasma currents are minimized and the equilibrium is provided actually solely by the external magnetic field. The stellarator is going to be in operation with deuterium plasma. There are two reactions, $^{2}D(d,n)^{3}He$ and $^{2}D(d,p)^{3}T$, that occur of roughly the same probability in such a plasma. Tritons of the 1 MeV energy from the second reaction can fuse with the deuterons, $^{3}T(d,n)^{4}He$, releasing 14 MeV neutrons. The deuterium density is to be much higher than concentration of the tritons in the W7-X, thus spectra of neutrons emitted from the stellarator are expected to be dominated by 2.45 MeV neutrons from the $^{2}D(d,n)^{3}He$ reaction. The tritium-tritium reactions, $^{3}T(t,2n)^{4}He$, for the sake of very low probability, appears to be meaningless in the present research.

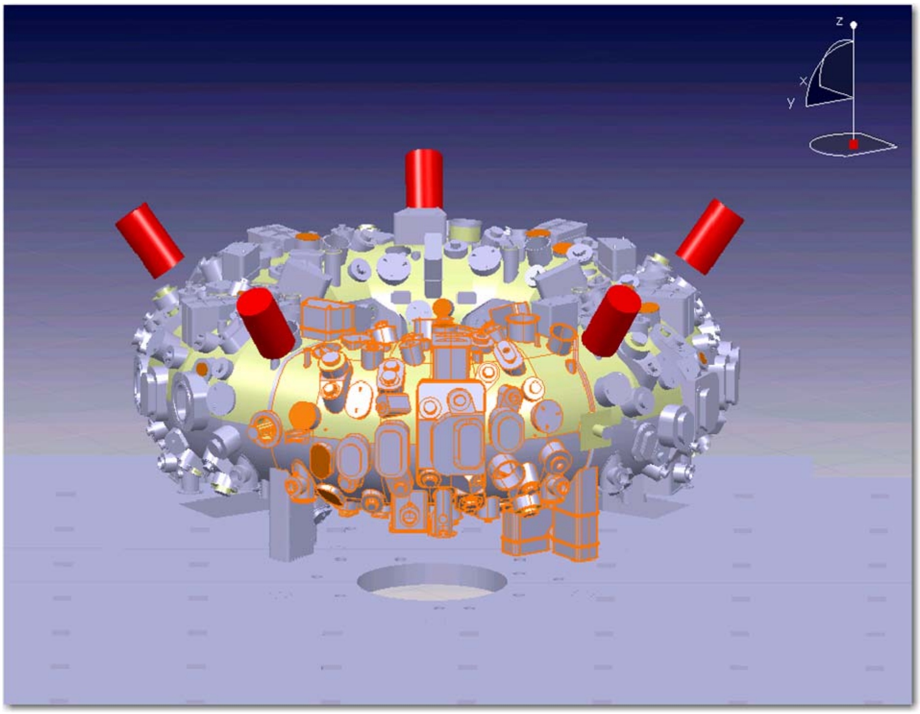

Fig. 1 Neutron counters (red cylinders) above the Wendelstein 7-X stellarator (a computer visualization of the facility courtesy of A. Weller) .

Plasma diagnostics includes knowledge of the neutron field around the fusion facility since neutrons produced in plasma enable to evaluate the ion temperature. Also safety precautions require acquaintance of spatial neutron distributions. The Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig is going to design a set of complex neutron detectors placed above the W7-X stellarator (see Fig. 1). Dimensions of the cylindrical counters are *h* = 180 cm and *d* = 100 cm. Centers of the cylinders are located 290 cm above the equatorial surface of the stellarator at the ring of 770 cm radius, while the average radius of the plasma is 550 cm. The axis of each cylinder is defined by the radii 550 cm and 770 cm, thus the tilt of the neutron counters is about 37.185 degrees. The mentioned new configuration – called "long counters positions" – is a refinement of an old arrangement, where the counters were placed perpendicularly to the equatorial surface of the stellarator. Owing to the cant, the detectors can be situated closer to plasma and the cylinders enlarged.

2. Monte Carlo calculations

Calculations of angular spectra of neutrons that enter the cylinders, which are to contain the set of neutron counters, allow optimization of detectors arrangement inside them. The spectra have been computed for bottom, lateral and top surfaces of all five cylinders by means of Monte Carlo methods using the MCNP5 code [3]. All the calculations have been carried out assuming 10^{16} n/s emitted from plasma in the $^{2}D(d,n)^{3}He$ reaction, while the $^{3}T(d,n)^{4}He$ reaction has been neglected. Therefore, the most probable initial neutron energy has been 2.45 MeV (Gaussian fusion spectrum at the temperature of ~ $4.64 \cdot 10^{7}$ K). The neutron source has been modeled as a ring of the 550 cm radius.

Fig. 2 shows a CAD model of the W7-X, which contains only major elements while stellarator details are neglected. Since the MCNP code allows to use only surfaces of first and second order to model geometry it is impossible to define precisely, for instance, poloidal coils (the blue ones in Fig. 2). Thus, the MCNP model of the stellarator is a simplification of the real construction. All the complex shapes of changing dimensions – like coils, cryostat enclosing all the coils, supporting structure, *etc.*, and plasma itself – have been "averaged" and modelled as cells of mean measurements corresponding with a specific W7-X component [4], [5]. A horizontal cut of the W7-X in the MCNP model is presented in Fig. 3. and the horizontal section of the stellarator hall at the level of the centres of the cylinders shows Fig. 4. Distances of the individual neutron counters from the concrete walls are different because the stellarator is placed non-centrally in the experimental hall.

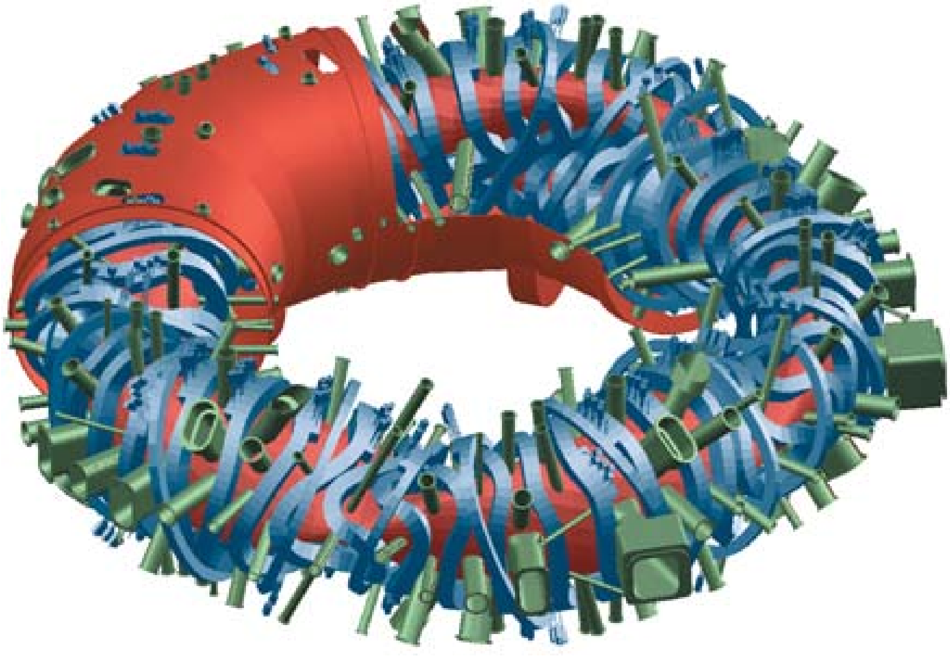

Fig. 2 CAD model of the Wendelstein 7-X stellarator (courtesy of IPP Greifswald).

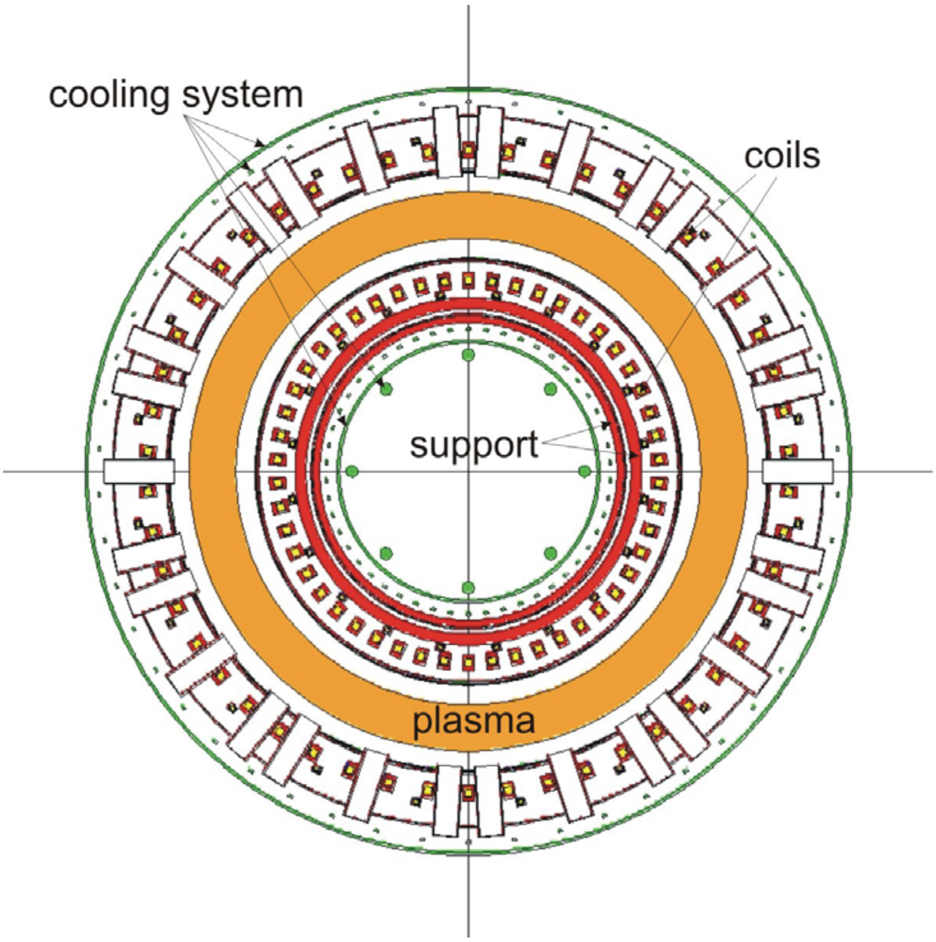

Fig. 3 MCNP model of the stallarator. A horizontal section (plane z = 0) through the torus shows the coils, the cooling system and the support structure (MCNP input file courtesy of IPP Greifswald).

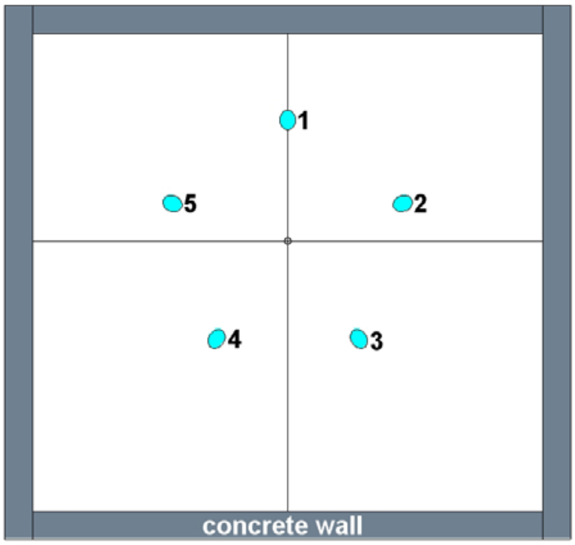

Fig. 4 The layout of neutron counters in the experimental hall (plane z = 290).

Due to extremely complicated geometrical model, Monte Carlo calculations have required very long runs to obtain reliable results. In order to decrease relative errors the mesh-based weight windows technique of variance reduction [3] has been employed. The mentioned method has required several runs to obtain a "good enough" set of weight windows. Finally, when the weight windows have appeared to be optimal, an even longer MCNP run has been executed. The relative errors for simulated angular-energy distributions across the bottom and lateral surfaces of the cylinders are satisfactory and achieved neutron currents seem to be reliable. In the case of the top surfaces it is actually impossible to obtain such fidelity since only neutrons scattered on air molecules and concrete walls or ceiling situated far from the stellarator are able to enter the cylinders inwards. The optimization of the mesh-based weight windows has been conducted for the detector labelled "1" in Fig. 4. The MCNP code allows to optimize the weight windows solely for one tally in one run. It is naturally possible to select any of the other counters, if needed, but it requires carrying out the entire long-lasting optimization procedure again.

The latest Monte Carlo model of the Wendelstein 7-X stellarator, prepared at the IPP, includes the cooling system, which has been modeled as a set of tori and cylinders filled with light water. The MCNP algorithm to simulate trajectories for the torus in very rare cases fails and particles are reported as "lost" – while their histories discontinued – though the input file contains no geometry errors. This can be observed for toroidal surfaces that limit cells filled with any material or void [3]. The mentioned phenomenon occurs (~ 0.00126 % of particle histories) also for the Monte Carlo simulations recounted in the present paper. Therefore, the problem appears to be insignificant in this case. Nevertheless, thermal and epithermal currents might be very slightly underestimated.

The angular-energy distributions have been calculated in nine angle bins, 10 degrees each. Only particles entering the cylinders, at any point of the relevant surface, are taken into account for all calculations presented in the present paper, as outlined in Fig. 5.

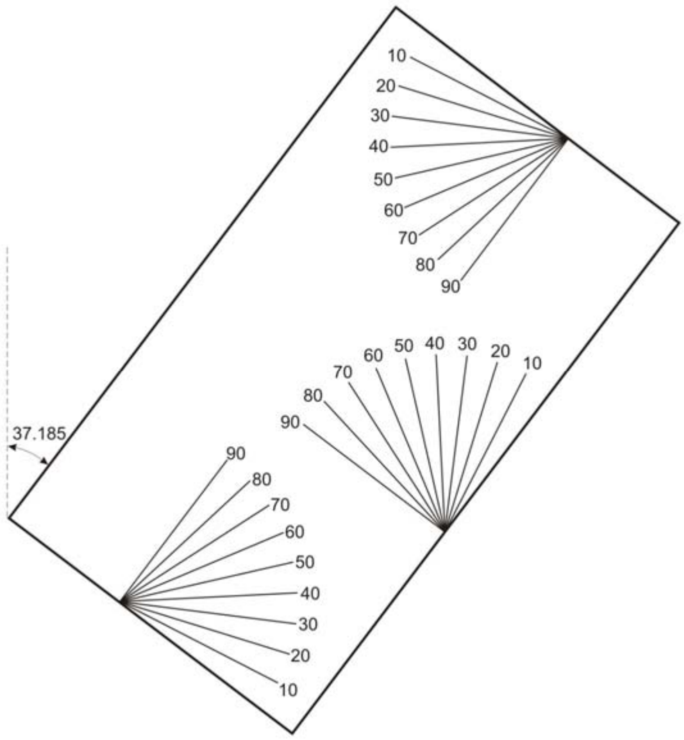

Fig. 5 Sketch of angles at the cylinder surfaces used in calculations. All values are in degrees.

3. Results

Fig. 6, Fig. 7 and Fig. 8 present angular distributions of neutron currents crossing the bottom, lateral and top surfaces of the detector cylinders, respectively. In the case of the bottom surfaces the neutron currents are actually equal for the sake of nearness of the stellarator (Fig. 6) for all the counters. For the lateral and particularly the top surfaces neutrons scattered on air as well as on the hall walls and the ceiling dominate the spectra. The detector “1” is closest to the concrete wall, while the detectors “2” and”5” are closer than the counters “3” and “4” (Fig. 7 and Fig. 8). That is why neutron currents in the case of the cylinder “1” are higher than for the counters “2” and “5”, whereas the least currents have been obtained for the counters “3” and “4”. In all the cases neutron intensity increases as the angle grows, particularly for the bottom surfaces due to vicinity of plasma. Fig. 9 shows angular distribution of currents ratio crossing the top surfaces of the detectors "1" and "3", *i.e.*, the case for which the effect of distance to the hall walls is remarkable visible, especially for particles getting through the top surfaces perpendicular.

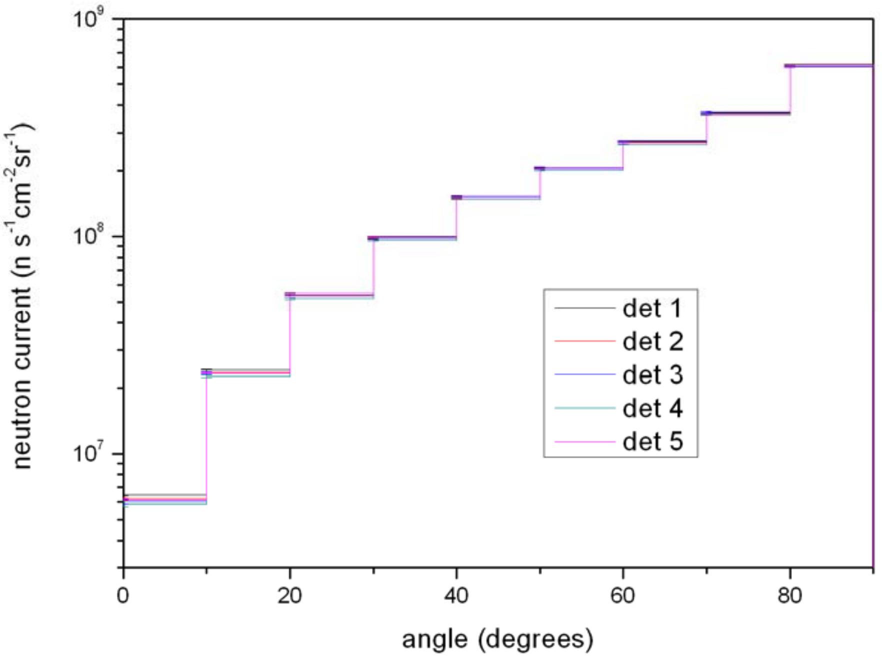

Fig. 6 Angular distributions of neutron currents across bottom surfaces.

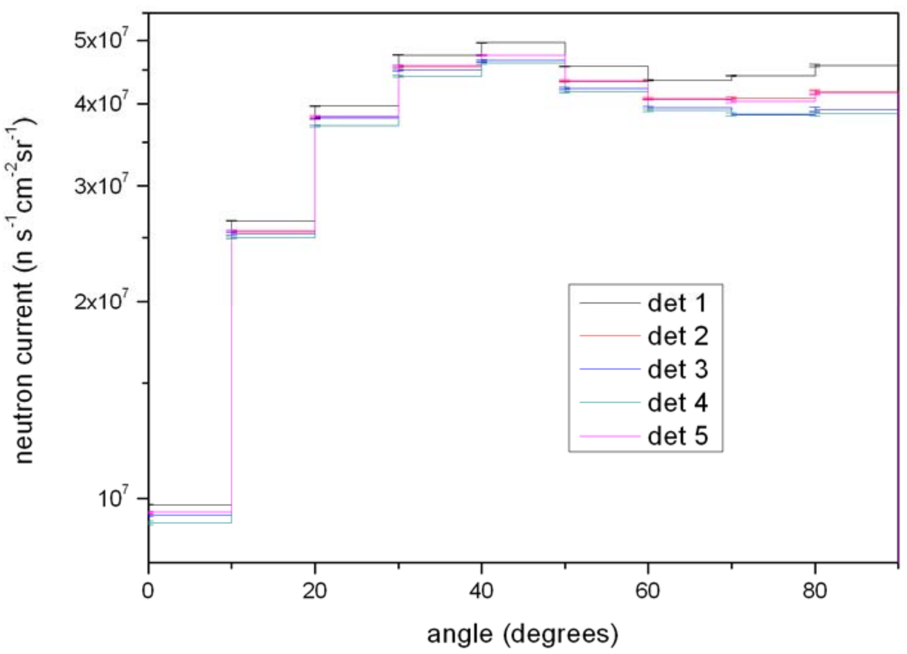

Fig. 7 Angular distributions of neutron currents across lateral surfaces.

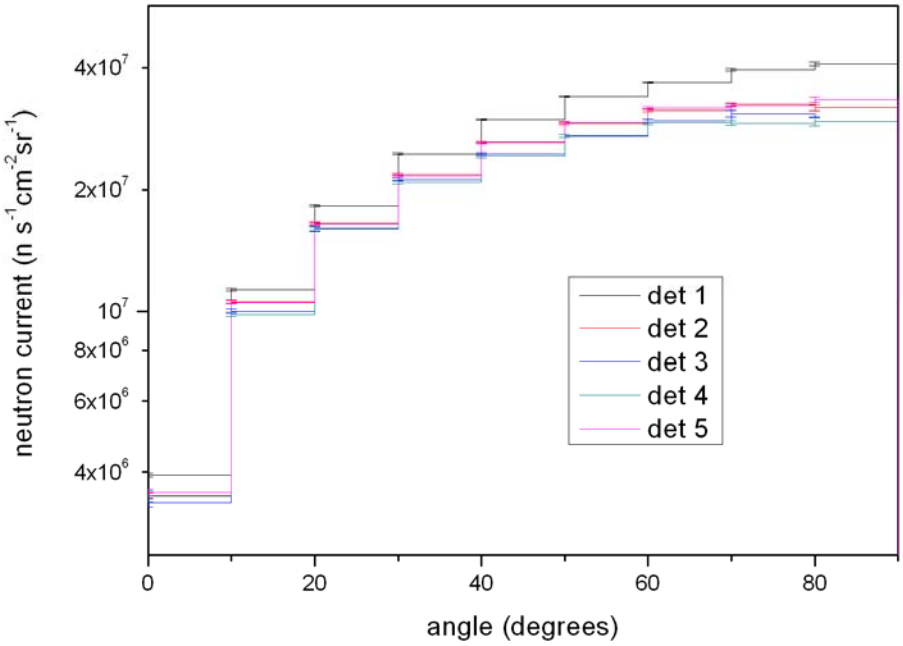

Fig. 8 Angular distributions of neutron currents across top surfaces.

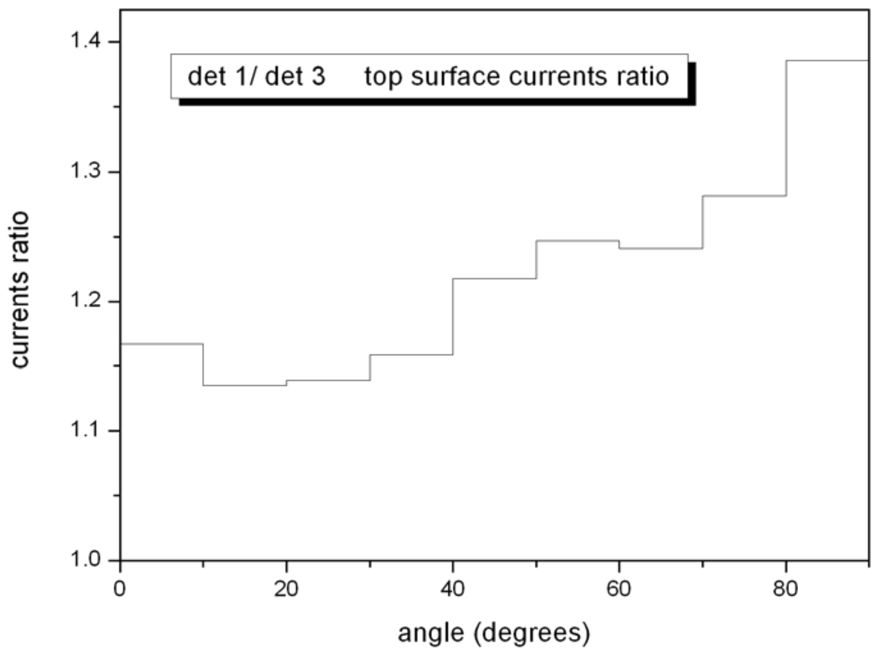

Fig. 9 Angular distribution of currents ratio for the top surfaces of detectors „1" and „3".

Spectra of neutrons crossing the surfaces in question (almost) perpendicularly are showed in Fig. 10, Fig. 11 and Fig. 12.

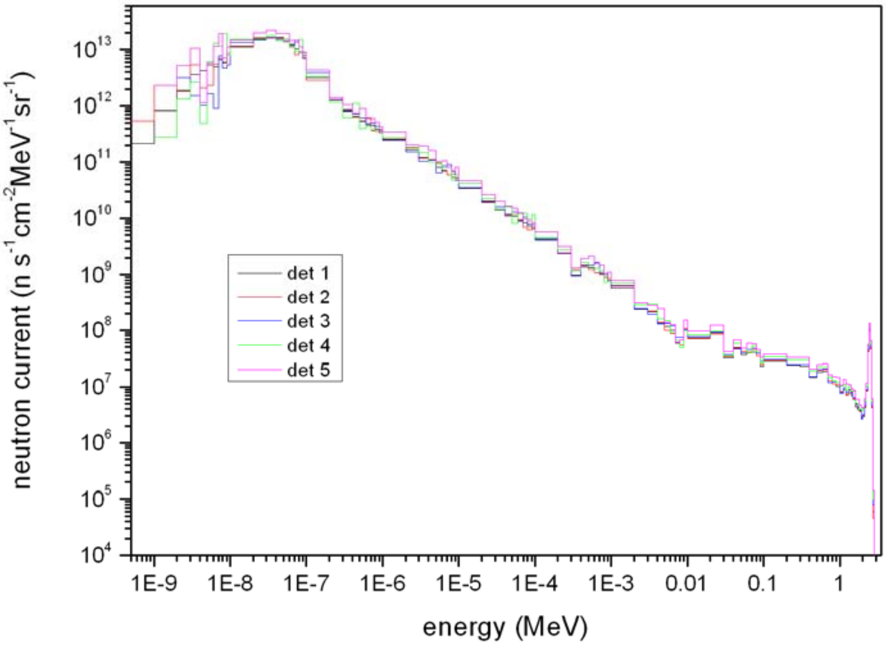

Fig. 10 Neutron currents across bottom surfaces (80÷90 deg).

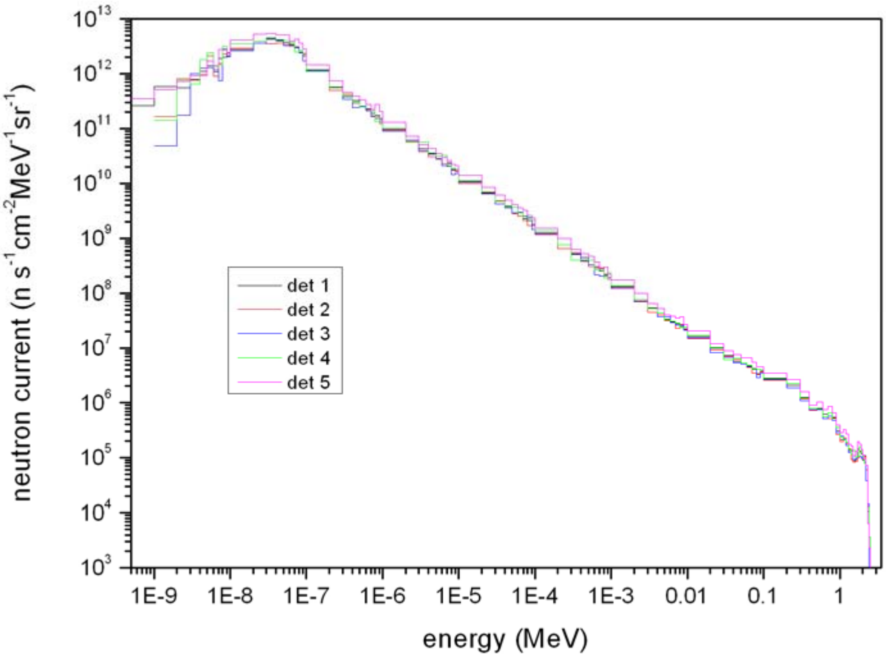

Fig. 11 Neutron currents across lateral surfaces (80÷90 deg).

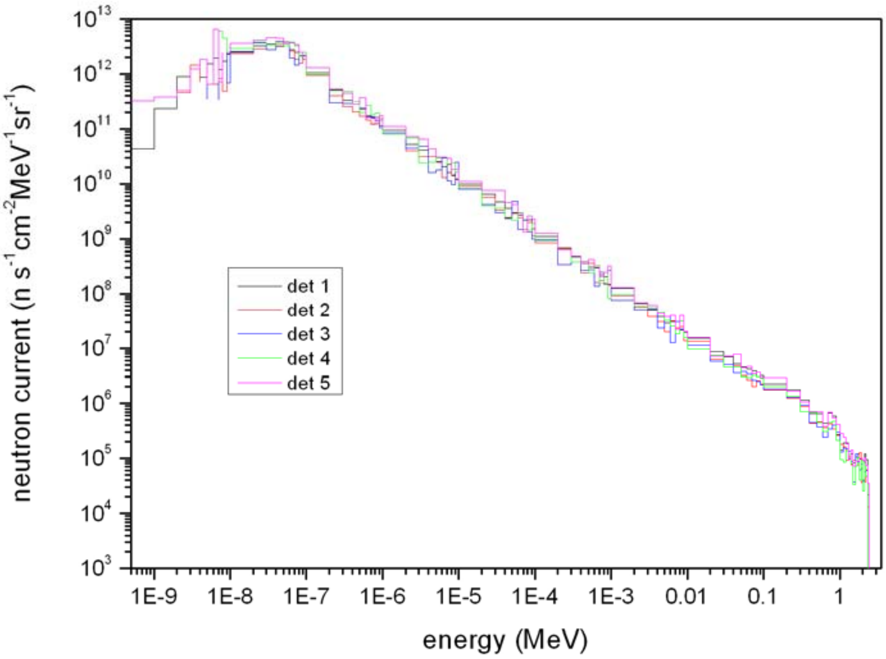

Fig. 12 Neutron currents across top surfaces (80÷90 deg).

The 2.45 MeV neutron peak is well visible in the case of the bottom surfaces (Fig. 10). It decreases for the lateral surfaces (Fig. 11) and in the case of the top surfaces it actually vanishes (Fig. 12), as there are almost no scattered neutrons moving in this direction since the neutron source is modeled as a ring placed in the W7-X plasma torus, below the detectors. In all the cases – even for the bottom surfaces – neutron currents (normalized per 1 MeV) are maximum for thermal energies. Therefore, scattering on W7-X elements as well as on the concrete walls and ceiling is the major factor that determines the spectra.

Distributions of neutron currents for the detector "1" – as the most reliable – for various angle bins are showed in Fig. 13, Fig. 14 and Fig. 15. The behavior of the 2.45 MeV peak is similar like previously for neutron crossing the surfaces perpendicularly (Fig. 10, Fig. 11 and Fig. 12). Neutron currents are in all cases the least when particles cross the surfaces almost in parallel (0 ÷ 10 deg range) and they increase when the angle mounts, what suits total angular distributions of neutron currents (Fig. 6, Fig. 7 and Fig. 8). The current values are the highest for the bottom surface, of course, and the least for the top surface.

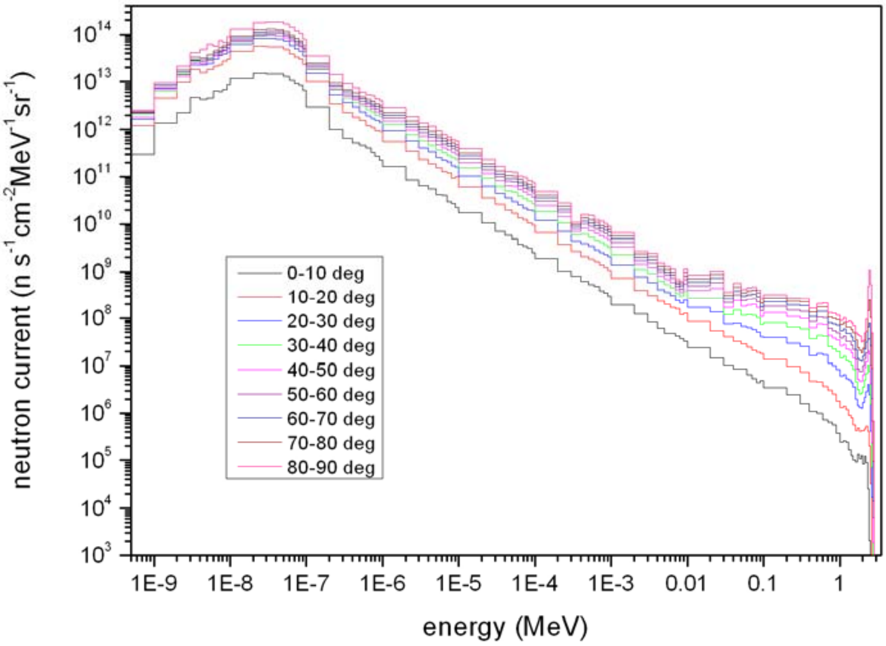

Fig. 13 Distributions of neutron current across bottom surface (detector "1").

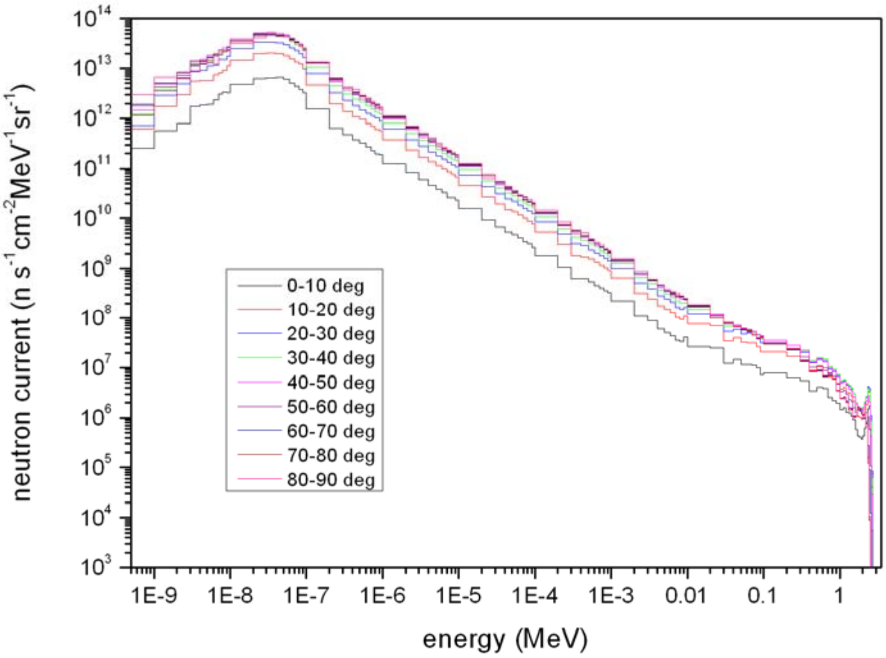

Fig. 14 Distributions of neutron current across lateral surface (detector "1").

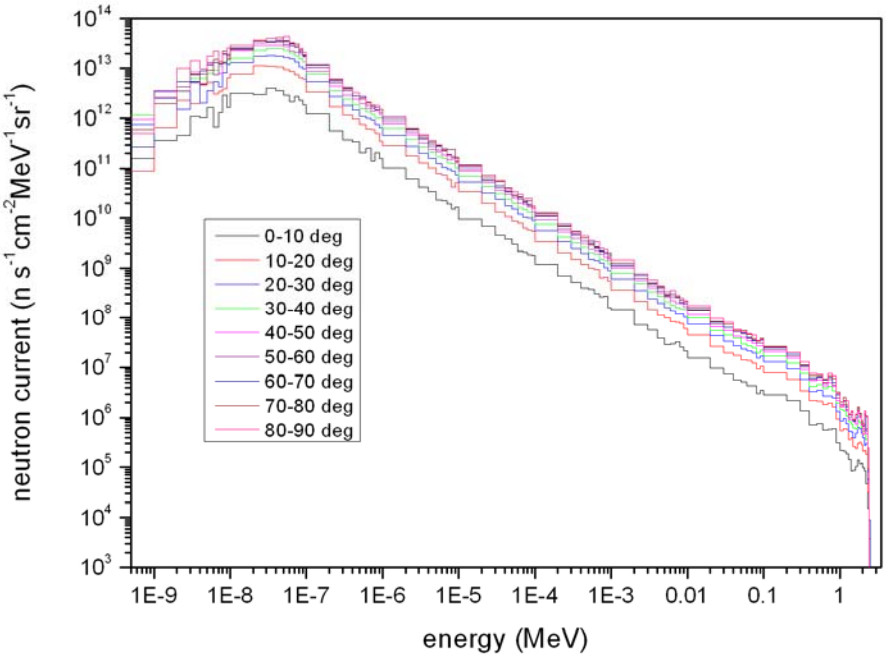

Fig. 15 Distributions of neutron current across top surface (detector "1").

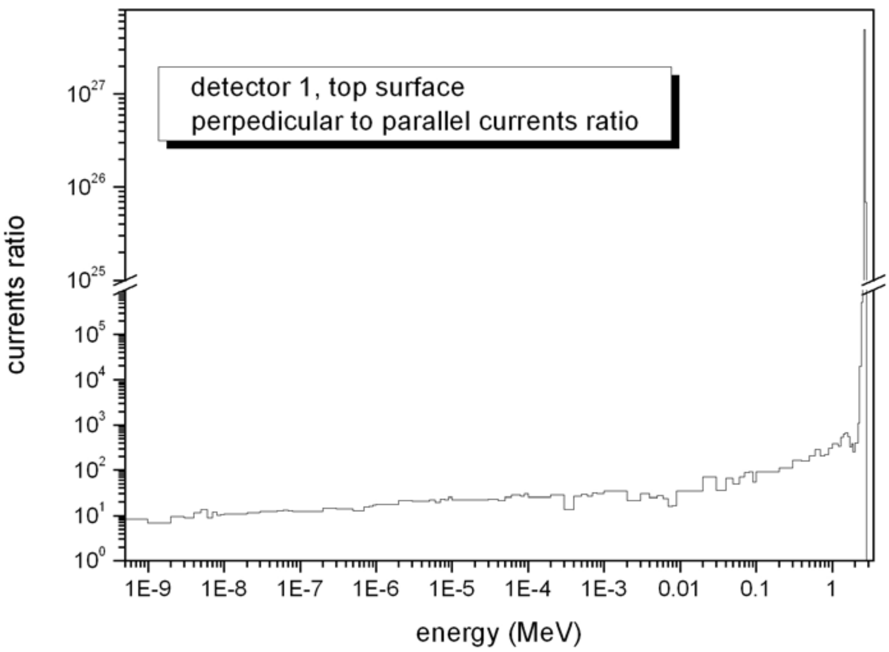

Fig. 16 Perpendicular (80÷90 deg) to parallel (0÷10 deg) ratio of neutron currents across bottom surface (detector "1").

Perpendicular to parallel ratio of neutron currents across bottom surface is presented in Fig. 16. The ratio is about 10 for thermal neutrons and minutely increases with energy up to 0.1 MeV. The rise becomes more outright for faster neutrons and is extraordinary high for the 2.45 MeV peak. This phenomenon is obvious since non-scattered particles from plasma get through the bottom surface of the counter at relatively high angles. Probability that uncollided neutrons cross the bottom surface almost parallel is much lesser.

Acknowledgements

The authors are very grateful to J. Junker, F. Herrnegger and F. Grünauer who have developed the MCNP model of the W7-X stellarator for years. We also acknowledge the assistance of A. Weller and R. Burhenn from the IPP.

References

[1] C. Beidler, G. Grieger et al., Physics and Engineering Design for Wendelstein 7-X, Fusion Technology **17**, 148-168, 1990.

[2] R.C.Wolf, the Wendelstein 7-X Team, A stellarator reactor based on the optimization criteria of Wendelstein 7-X, Fusion Engineering and Design **83**, 990-996, 2008.

[3] X-5 Monte Carlo Team, MCNP - A general Monte Carlo N-particle transport code, Version 5, Los Alamos National Laboratory, LA-UR-03-1987, 2003.

[4] J. Junker, A. Weller, Neutrons at W7-X, IPP Report, Max-Planck-Institut fur Plasmaphysik, Garching, IPP-2/341, 1998.

[5] F. Herrnegger, J. Junker, A. Weller, H. Wobig, Neutron field in the Wendelstein-7-X hall, Fusion Engineering and Design **66-68**, 849-853, 2003.