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Monte Carlo simulations of neutron and photon radiation fields at the PF-24 plasma focus device at IFJ PAN in Krakow

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Abstract

The medium scale PF-24 facility was installed at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN), Poland. The MCNP model of the PF-24 device in the main hall of the laboratory was elaborated. Two variants of the plasma source emitting particles were considered: a point neutron source and a volume source with photon and neutron emission. Based on presented calculations the influence of the laboratory construction (the walls, the ceiling and the floor) on neutron and photon space distributions in the main hall were assessed. A study of fast uncolided and collided neutrons contributions to the total field of neutrons was performed. The contribution of photons emitted directly from the source and created as the result of neutron scattering was established. Neutron spectra at selected points were calculated.

1. Introduction

The Plasma-Focus (PF) device belongs to the family of the dynamic, non-cylindrical Z-pinches and is based on a pulsed high-current discharge between two coaxial electrodes placed in a working gas, usually deuterium. The interest in the PF devices has increased because they are ones of the most efficient sources of the pulsed fusion neutron emission. An important feature of the neutron source in PF is its location and the evolution in time. Therefore, measurements of the spatial distribution of the neutron emission from PF at a time of one discharge can be used to determine the spatial and temporal distribution of the nuclear fusion reaction rate in PF. Thus, space and time resolved measurements of the PF neutron source can give information on relevant production processes and allow a more reliable discussion on the character of the deuterium fusion in the PF pinch gathered through other diagnostics. Suggestions regarding a position of emission of neutrons in the PF device, presented in [1] and [2], showed a different position and size of the neutron source in the PF chamber. These differences may have resulted from the fact that the registrations presented in the papers were carried out during several PF discharges. Later, first measurements of the position and size of the neutron source in one PF discharge were reported in [3] and [4].

2. Description of the Plasma Focus PF-24 device

The set-up of the PF-24 facility at the IFJ PAN Kraków consists of the following main units (Figure 1):

- a condenser bank and a pulsed electrical power circuit with a collector and low-inductance cables
- a vacuum chamber with coaxial electrodes and pumping and gas handling systems
- a plasma diagnostic and data acquisition system

Electrical energy is transferred to the collector and electrodes via low-inductance cables. The vacuum chamber, which surrounds the electrodes, has the following dimensions: 360 mm in diameter and 400 mm in length. Two coaxial electrodes are shown in Figure 3. The copper centre electrode (CE) has a radius of 30.5 mm and its length is 165 mm. The outer electrode (OE) (*i.e.* cathode) consists of 16 stainless steel rods, each of 12 mm in diameter. The OE radius of 55 mm is defined as the distance between the axis of CE and the centre of an OE rod. The cylindrical alumina insulator is mounted on CE. Its main part extends 32.5 mm along CE into the vacuum chamber. The insulator prescribes the shape of the initial current sheet between CE and the plasma focus back plate on which the OE rods are fixed.

The condenser bank of capacitance of 116 μF can be charged to the voltage ranging from 16 kV to 40 kV, which corresponds to discharge energies from 15 kJ to 93 kJ. For this range of energy the total neutron yield can be estimated at $10^9 \div 10^{11}$ n/shot. It can be assumed that the area of neutron emission corresponds to the plasma column created in PF-24. In the PF devices whose energy level of the condenser bank reaches about 100 kJ, the typical plasma column has a length of 3 ÷ 5 cm and a diameter of about 0.8 ÷ 1.2 cm [5].

3. MCNP model of the Plasma Focus PF-24 device

The general purpose Monte Carlo radiation transport code MCNP5/MCNPX, designed to track neutrons and photons over broad ranges of energies, was used in computer simulations [6]. Monte Carlo calculations are a convenient way to model and simulate accurately the actual experimental conditions.

The MCNP model of the Plasma Focus device was developed including all relevant details. The model of the PF-24 discharge chamber is presented in Figure 1.

In order to carry out Monte Carlo simulations of neutron and photon distributions and spectra other elements of the experimental hall (the floor, the ceiling, the walls and the condensers) had to be added to the model in question.

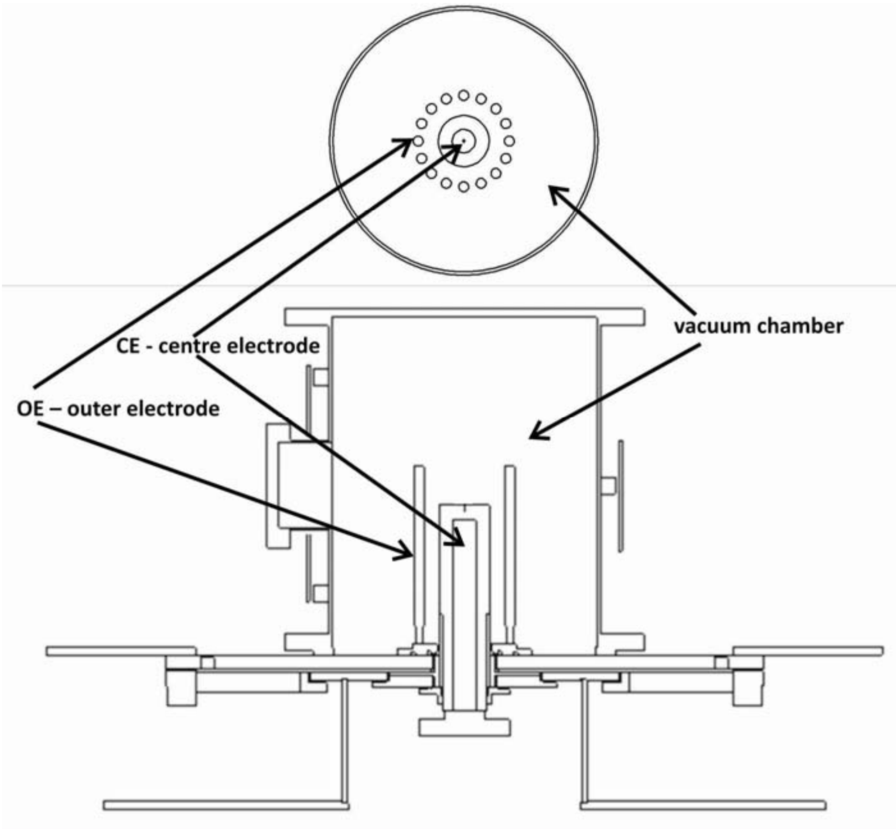

Figure 1 The MCNP model of the PF-24 discharge chamber

The geometry of MCNP treats an arbitrary three-dimensional configuration of user defined materials in geometric cells bounded by first- or second-degree surfaces. The cells are defined by intersections, unions, and complements of the regions. In our model 107 geometric cells are bounded by 210 surfaces.

Each cell is filled with the user defined material. The materials are a construct of isotopic composition of elements with characteristic atomic or mass weights. For each material the mass or atomic density has to be defined. The probability of a particle interaction with the materials depends on their isotopic composition and this information is related to the nuclear cross sections and the material density. In the foregoing calculations the cross-sections were taken mainly from the ENDF/B-VI library [7]. The parameters of the materials and data library used in the present study are featured in Table 1.

Table 1 The material parameters used in MCNP calculations

material name	density [g/cm^3]	element	ZAID
deuterium	1e-5	H	1002.70c
		C	6000.70c
copper	8.92	Cu	29000.50c
air	0.0013	N	7014.70c
		O	8016.70c
		Ar	18000.59c
steel OH18N9	8.00	Fe	26000.50c
		Cr	24000.50c
		Ni	28000.50c
brass MO58	8.50	Cu	29000.50c
		Zr	30000.42c
		Pb	82000.50c
delrin -poliacetal	1.45	H	1001.70c
		C	6000.70c
		O	8016.70c
ceramic	3.69	O	8016.70c
		Al	13027.70c
glass	2.51	Si	14000.60c
		O	8016.70c
polyethylene	0.93	C	6000.70c
		H	1001.70c
dural	2.71	Al	13027.70c
		Si	14000.60c
		Mg	12000.66c
		Mn	25055.70c
steal	7.85	C	6000.70c
		Fe	26000.50c
cable	0.33	H	1001.70c
		C	6000.70c
		Cu	29000.50c
gum	0.92	H	1001.70c
		C	6000.70c
shielding of the cables	4.14	H	1001.70c
		C	6000.70c
		Cu	29000.50c
		Zr	30000.42c
titanium alloy	5.00	Fe	26000.50c
		Ti	22000.66c
titanium	4.50	Ti	22000.66c
P-10 (90% Ar + 10% CH_4)	1.68	C	6000.70c
		H	1001.70c
		Ar	18000.59c
berylium	1.85	Be	4009.70c
concrete (NBS-03)	2.35	H	1001.70c
		C	6000.70c
		O	8016.70c
		Mg	12000.66c
		Al	13027.70c
		Si	14000.60c
		S	16000.66c
		K	19000.66c
		Ca	20000.66c
		Fe	26000.50c
hydraulic oil	0.871	H	1001.70c
		C	6000.70c
		O	8016.70c
		P	15031.70c
		Cl	17000.66c

4. The model of the experimental hall of PF-24

As already claimed, the PF-24 device model was broadened by the geometry of the settings. The components of the experimental hall were added to the initial model. All the relevant elements that could have scattered neutrons were taken into account. First of all, the ceiling, the floor and the walls of the experimental hall, but also the set of condensers filled with hydraulic oil that strongly thermalizes neutrons, since it contains mainly light elements (hydrogen and carbon). The ordinary concrete NBS 03 was assumed as the wall material. The main component of the concrete is oxygen (over 47% by weight), which also heavily moderates neutrons. The model is presented in Figure 2.

The origin of the coordinate system (drawn in blue) is located at the cap of the inner electrode. The z-axis is situated at the axis of the PF-24 chamber symmetry. All the graphs featured in the present paper reffer to the coordinate system showed in Figure 2.

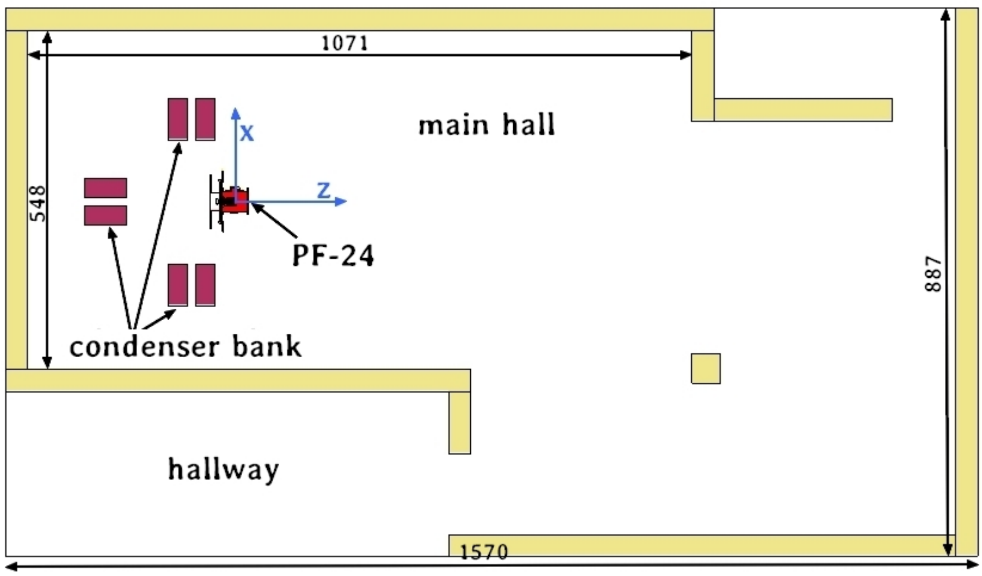

Figure 2 The horizontal cut of the PF-24 assembly hall (dimensions in cm)

5. Definition of the source

MCNP allows specifying a wide variety of source configurations without a code modification. Independent probability distributions may be specified for such source variables like: particle type, energy, time, position, and direction, as well as for other parameters, for instance a starting cell or a surface. In our calculations the energy-angle distributions of particular particles from the reactions mentioned above were introduced into the source card in the MCNP input file.

Because it is impossible to evaluate the exact plasma shape and position, the source has been modeled in two variants:

- the point neutron source (Figure 3a)
- the volume neutron and photon source (Figure 3b)

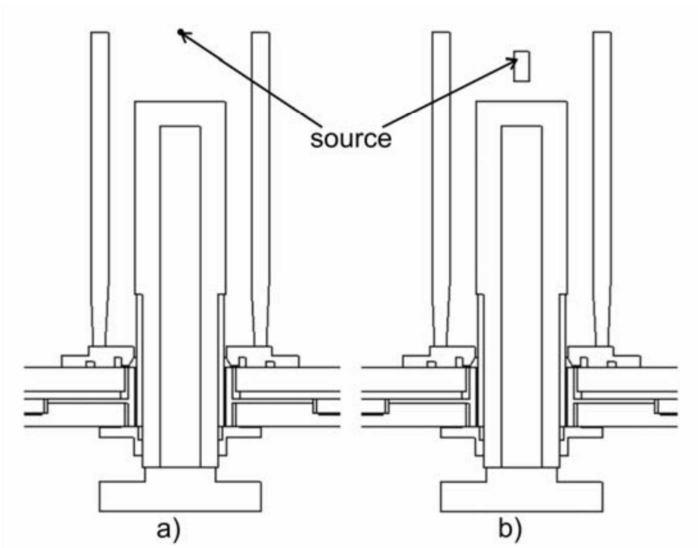

Figure 3 The model of the PF-24 source: a) point neutron source, b) volume source

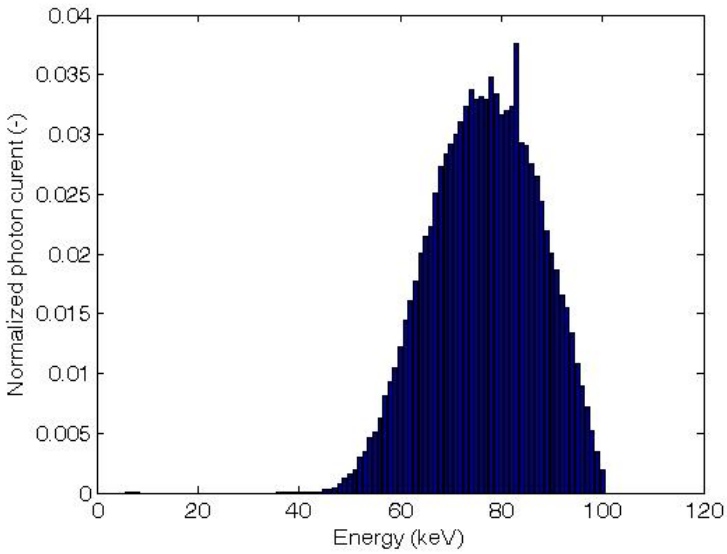

Figure 4 The normalized photon current emitted from the PF-24

5.1 The point neutron source

In this variant the angular-energy distributions of neutrons were used on the basis of past experiments on plasma focus devices. It was assumed neutrons were emitted in 18 angular bins with different probabilities based on experimental data.

Since plasma moves while focusing, neutrons emerging from fusion have an additional kinetic energy that was included into the angular-energy distributions of the source. Deuterium moves forward along the z-axis and consequently, neutrons emitted exactly in this direction have the energy Gaussian fusion profile with the maximum at ~2.81 MeV. By contrast, the most probable energy of particles emanated backward is ~2.14 MeV. For other angles the neutron energy gradually changes between the mentioned values. The full width at half maximum of the Gaussian profiles is the same (120 keV) for all the emission.

5.2 The volume source with neutron and photon emission.

In this variant the source was modeled as a cylinder of 2 cm length and 1 cm of diameter. The neutrons and photons were emitted in the following proportion: on 1 neutron there were emitted 20 photons. The energy of the neutrons was assumed as 2.45 MeV and they were emitted isotropically. The photon energy spectrum was estimated based on separate evaluations. In these calculations the inner electrode was bombarded by electrons, of energy 100 keV, from the plasma and photons were created. As a results of these calculations photons current of energy distribution presented in Figure 4 was obtained. All photons were emitted from the volume source within the angular bin: 0° ÷ 90° with respect to the positive normal to the surface at the particle point of entry.

6. Monte Carlo simulations

Graphs in this section refer to the coordinate system presented in Figure 2, the source is placed exactly at the (0,0) position. All results presented below are normalized per one source particle.

It is intended to investigate non-scattered neutrons originating directly from the synthesis. Therefore, the first calculations concerned the fast neutron field in the main hall (Figure 2) and particles of energies below 2 MeV were not examined. Two variants of the neutron source (point and volume) were investigated. The results are shown in Figure 5.

Afterwards photon space distributions were studied using solely the volume source. Figure 6 features the total field while distributions of photons emitted directly from the source and scattered ones are shown in Figure 7.

Naturally, the highest flux is in the source itself. The flux rapidly decreases with the distance from the source and is actually symmetrical in regard to the z-axis. Absorption and moderation of neutrons by the oil in the condenser bank is well visible.

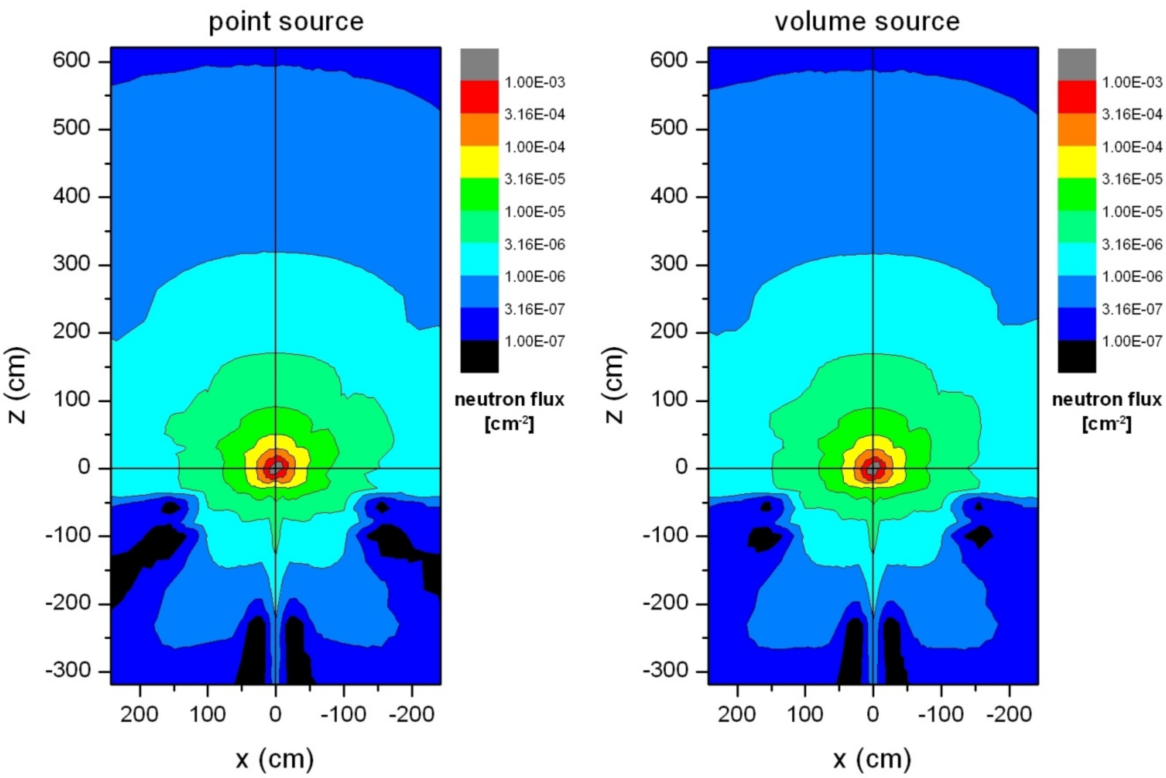

Figure 5 Fast neutron (E> 2 MeV) field in the main hall for point and volume neutron sources

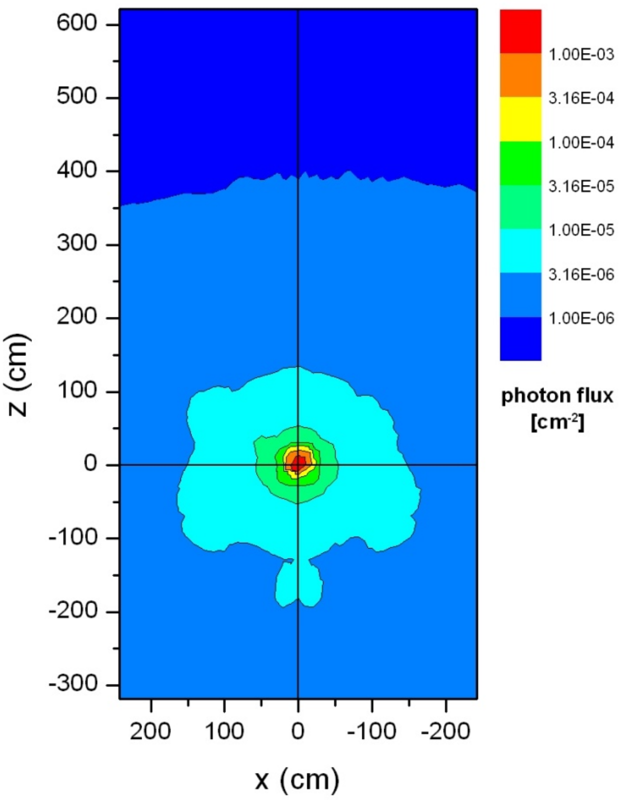

Figure 6 Total photon field in the mail hall

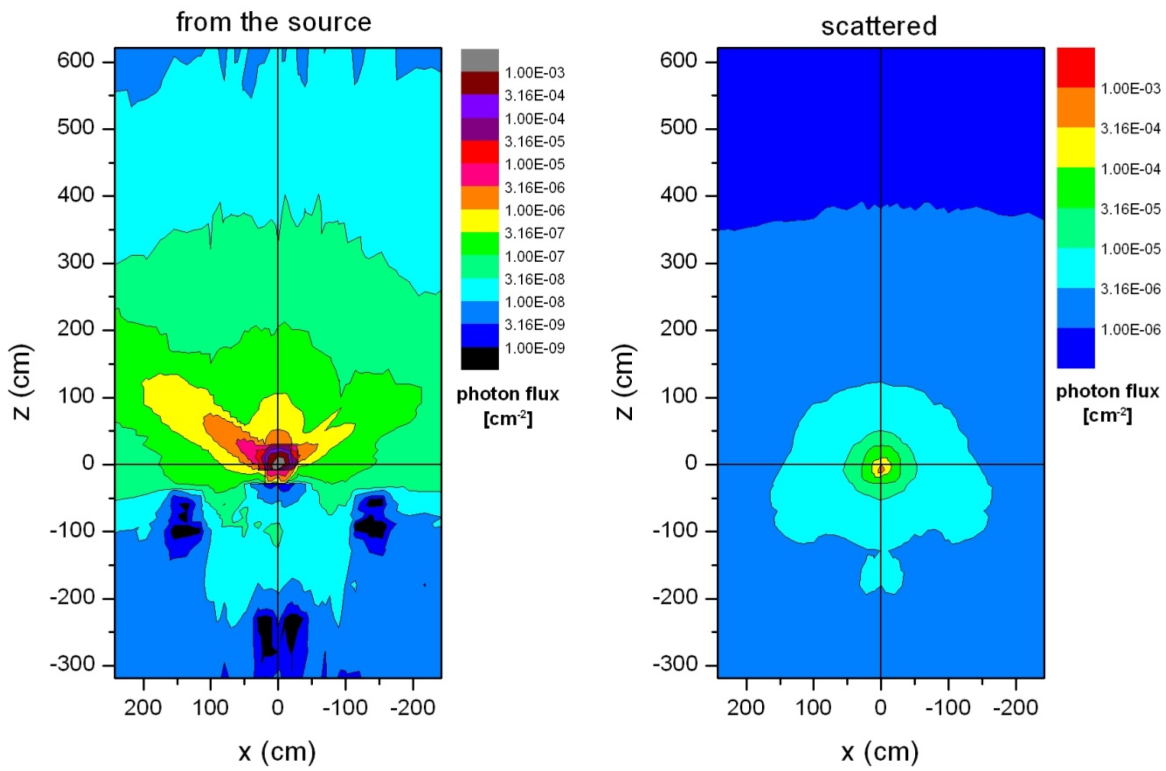

Figure 7 The space distribution of photons emitted from PF-24 and scattered photons in the main hall

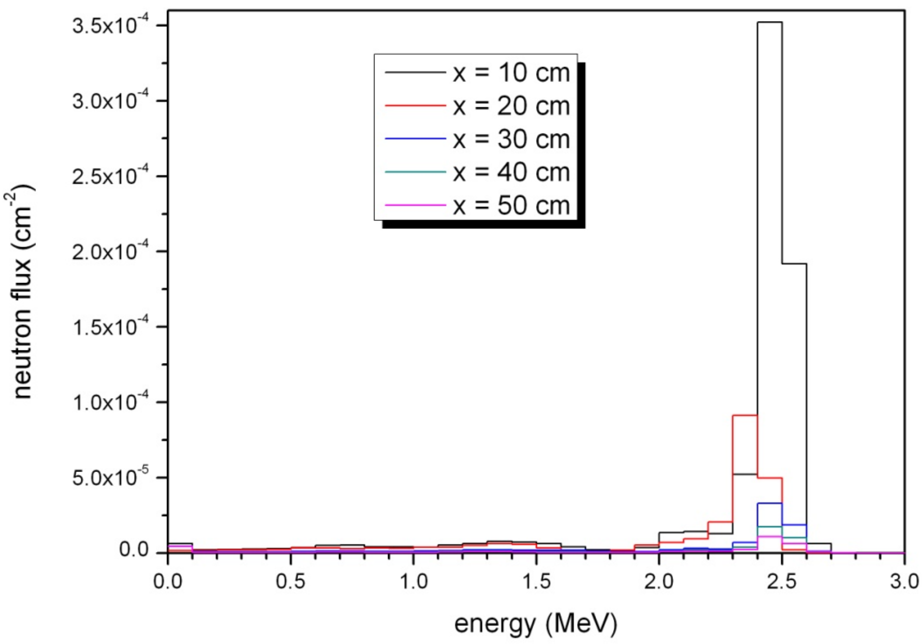

Figure 8 Neutron spectra at selected points along the x-axis

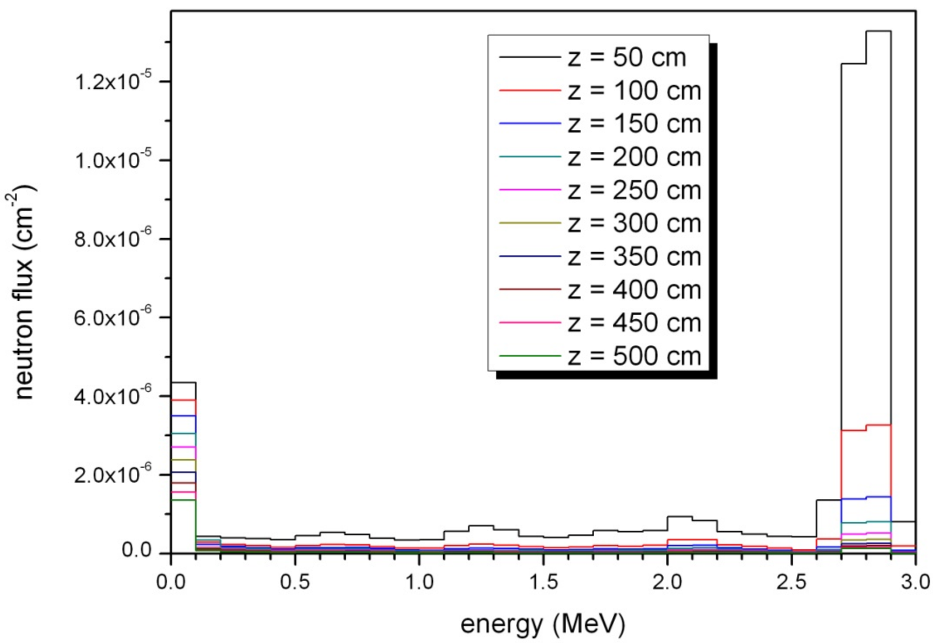

Figure 9 Neutron spectra at selected points along the z-axis

In the next step of neutron spectra computations at selected points along the x-axis with 10 cm increment (Figure 8) and with 50 cm increment along z-axis (Figure 9) were carried out. The results are consentient with the discussed above. One can notice a quick drop of

2.45 MeV neutron flux in both directions. In turn Figure 9 features growth of thermal and epithermal neutron flux for points situated far from the source due to scatterings in the walls of the main hall. This effect is hardly seen for spectra along the x-axis owing to much shorter distances from plasma.

The subsequent calculations concerned a study of fast uncolided and collided neutron contributions to the total field of neutrons of energy above 2 MeV. Scatterings in the PF-24 device were not taken into account, contrary to collisions in the walls, the ceiling and the floor. A special MCNP technique called 'flagging' was used, which enables to calculate solely flux of particles that moved through selected cells of the model.

As expected, Figure 10 shows that the relative flux of the uncollided neutrons is the highest in PF-24 and its vicinity and gradually decreases with distance from the plasma. Naturally, the collided neutrons feature opposite behavior. Both distributions are not symmetrical along the z-axis above 300 cm. In Figure 10 one can observe that in the right upper corner (for x ≤ -200 cm) there is more uncollided neutrons and less collided neutrons than in the left upper corner (x ≥ 200 cm). This behavior of the neutron distribution is strongly related to the lack of walls in the one corner of the main hall geometry (Figure 2).

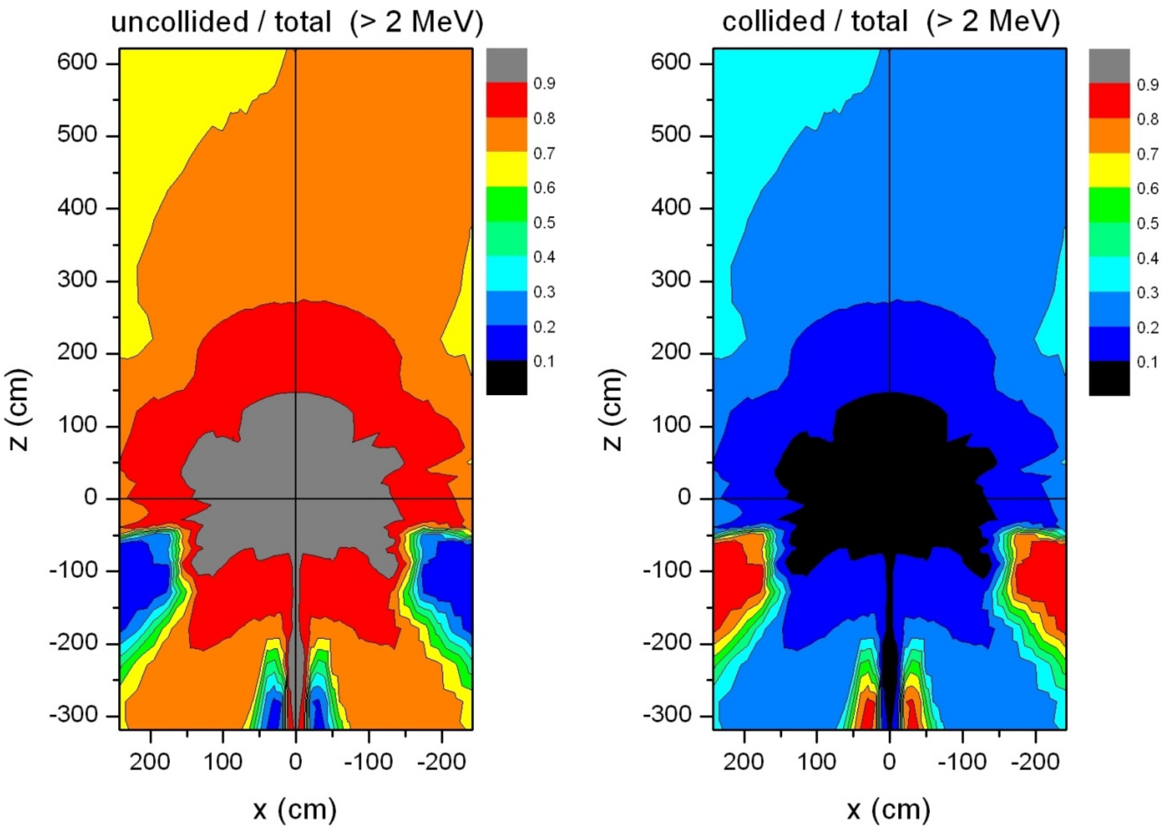

Figure 10 Fields of uncollided and collided neutrons normalised to the total field

7. Final remarks

A series of Monte Carlo simulations was carried out to calculate neutron and photon fields in the main hall as well as neutron spectra at its selected points.

The results show that the spatial distributions are roughly symmetrical though some asymmetries above z = 300 cm are visible for fields of uncollided and collided fast neutrons due to an absence of walls in one corner. The condenser bank strongly affects the neutron and photon fields, but just in the regions where no experiment are expected.

As expected, the closer to the PF-24 chamber the higher both neutron and photon fluxes are. Thus, the possible experiments should be performed as close to the plasma focus device as possible. All the more so, the fluxes of scattered particles increase with the distance from the source. Nevertheless, the contribution of scattered fast neutrons to the total field does not exceed 30% at 600 cm from the PF-24 chamber along the z-axis.

The fast neutron field is actually the same for the point and the volume neutron sources. The differences are meaningless.

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