STATIC NEUTRONIC CALCULATION OF A FUSION NEUTRON SOURCE

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The MCNPX numerical code has been used to model a fusion neutron source based on a combined stellarator-mirror trap. Calculation results for the neutron flux and spectrum inside the first wall are presented. Heat load and irradiation damage on the first wall are calculated.

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INTRODUCTION

Powerful sources of fusion neutrons from D-T reaction with energies ~ 14 MeV are of particular interest to test suitability of materials for use in fusion reactors. Developing materials for fusion reactors has long been recognized as a problem nearly as difficult and important as plasma confinement, but it has received only a fraction of attention. The neutron flux in a fusion reactor is expected to be about 50-100 times higher than in existing pressurized water reactors. Furthermore, the high-energy neutrons will produce hydrogen and helium in various nuclear reactions that tend to form bubbles at grain boundaries of metals and result in swelling, blistering or embrittlement.

Realistic material tests ought to expose samples to neutron fluxes of a similar level for a similar period of time as those expected in a fusion power plant.

The Russian Federation is actively developing a fusion neutron source based on a spherical tokamak for burning transuranic elements and for breeding the fuel isotops ^{239}Pu and ^{233}U from ^{238}U and ^{232}Th, respectively [1]. In Ukraine a fusion neutron source based on a stellarator-mirror device [2] is developed for driving a subcritical fast fission reactor for utilization transuranic elements from spent nuclear fuel.

MODEL OF A FUSION NEUTRON SOURCE

In this research, the neutronic of a fusion neutron source is studied. The fusion neutron source consists of a magnetic trap for plasma confinement at which fusion neutrons are generated. The magnetic trap is of a combined type: it is a toroidal stellarator with an embedded magnetic mirror with lower magnetic field [3]. The stellarator part is for confinement of warm dense deuterium target plasma. Hot sloshing tritium ions are confined at the mirror part of the device. At this part the plasma column is straight. It is surrounded by a cylindrically symmetrical shield.

The hot minority tritium ions are sustained in the plasma by neutral beam injection (NBI) [4]. The NBI is normal to the magnetic field and targets plasma just near the main part (Fig. 1). The sloshing ions bounce inside the magnetic mirror between the injection point and opposite (mirror) point where the magnetic field has the same strength as at the injection point. The toroidal plasma confinement in such a device depends on whether the magnetic surfaces exist in it. The study made in Ref. [5] indicates that under certain conditions nested magnetic surfaces could be created in a stellarator-mirror machine.

Some fusion neutrons are generated outside the main part near the injection point. There is a need of protection from these neutrons.

The purpose is to calculate the neutron spectrum inside neutron exposing zone of the installation and compute the radial leakage of neutrons through the shield.

Another problem studied in the paper concerns to the determination of the heat load and irradiation damage of the first wall of the device, where will be a neutron irradiation facility, for examples tungsten and molybdenum [6].

CALCULATION MODEL

This paper describes a principal design of arrangements around a neutron generating mirror part of the fusion neutron source without detailed simulation of specific technical details. A simplified geometric model was chosen basing on several assumptions:

- Each part of the neutron source is cylindrically symmetric;
- Only the major units are accounted, and it is assumed that they consists of uniform mixture of their components.

The model has a cylindrical symmetry with a horizontal axis. Its radial and axial structure is shown in Fig. 1. The vacuum chamber contains the D-T plasmas which supplies the fusion neutrons. The first wall suffers from high-energy neutron load. In order to get a longer lifetime of the first wall, its damage rate must be low. The inner radius of the vacuum chamber is 1.0 m. The space between plasma and the first wall is reserved for the irradiation specimens. The first wall thickness is 3 cm. The thickness of the buffer, which consist of lead and bismuth eutectic (LBE), is 15 cm and the shield thickness is 20 cm. The LBE [7] was assumed to be a mixture of 44.5 wt.% lead and 55.5 wt.% bismuth.

The shield contains a 60:40 vol.% mixture of the stainless steel alloy S30467 type 304B7 [8, 9] with water. The steel contains 1.75 wt% of natural boron. A shield is used to reduce the neutron and gamma loads of the stellarator-mirror magnetic coils needed for plasma confinement. The total length of the main part of the model is 4 m.

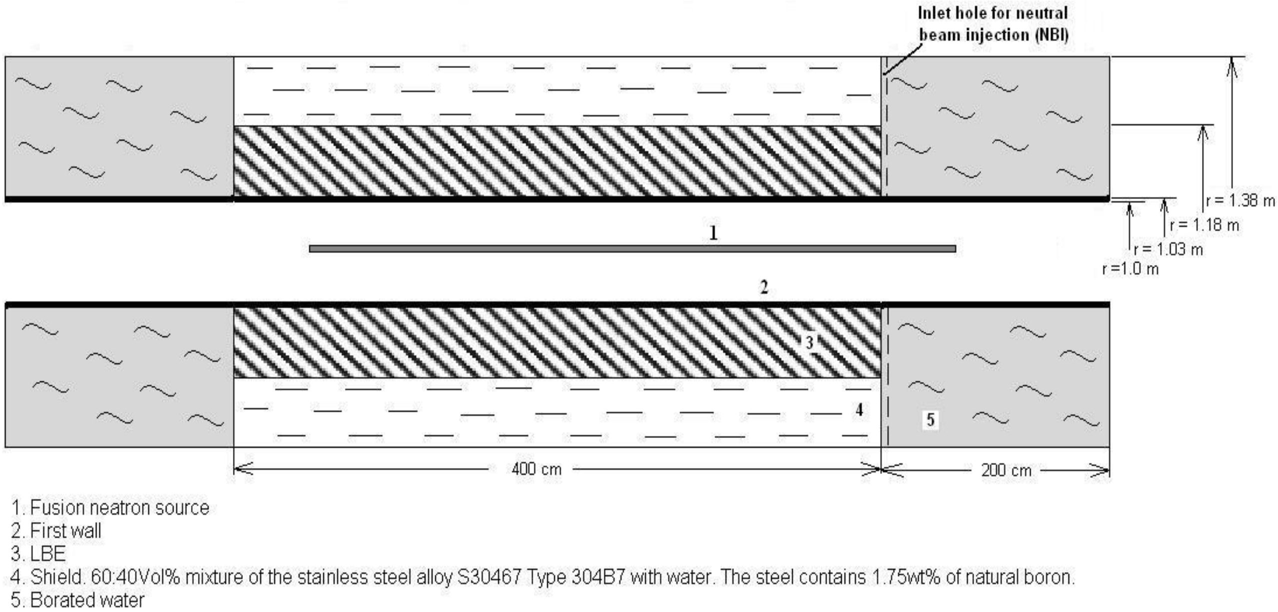

Fig. 1. Vertical axial cross-section of the neutron source model

The ends of the neutron irradiation zone are surrounded by vessels filled with borated water aiming to absorb the escaping neutrons. The neutrons are absorbed by boron and, since boron absorbs mostly slow neutrons, they should be slowed down first. This is arranged by the water in the vessel. Boron has a stable isotope ^{10}B which absorbs neutrons very efficiently: the absorption cross section of thermal neutrons is about 4000 barn [10].

The concentration of boron in the water was taken 10 g/kg. The isotopic content is ^{10}B – 20% and ^{11}B – 80%. Each vessel with borated water has a length of 2 m and a thickness is of 35 cm. At the right side of the main part, square openings with area 79 cm^2 are made to provide access to the plasma for the neutral beam (see Fig. 1, inlet hole for neutral beam injection).

In the calculation model, the volumetric source of neutrons is represented by a number of cylindrical volumes of radius 20 cm. The total length of the neuton generating zone is 4 m. At every source point, the fusion neutrons were emitted with a fixed kinetic energy of 14.1 MeV and isotropic velocity distribution. The relative intensity distribution along the length of the neutron source used in the MCNPX model is taken from Ref. [11]. The total fusion power is 17 MW.

Fusion neutrons are produced in plasma by fusion reaction of the sloshing tritium ions with deuterium plasma ions. Because of the mirror trapping effect, the hot tritium ion motion is restricted to the mirror part of the device. The maximum number of ions is located at the mirror points. For this reason the neutron flux at these places is more intense.

RESULTS OF CALCULATIONS

The MCNPX numerical code [12] has been used for neutron calculations. The leakages of neutrons through the mantle surface of the model are calculated. The result of this calculation does not exceed the value presented at the Ref. [13].

Average flux of neutrons trough the first wall of the model equal 1×10^{14} cm^{-2}s^{-1} for a fusion neutron source with intensity 6×10^{18} neutrons per second.

Fig. 2 shows the energy group fluxes (neutron flux integrated over energy intervals) per one fusion neutron averaged over the first wall of the device. The statistical errors are around 1% for all the results presented below.

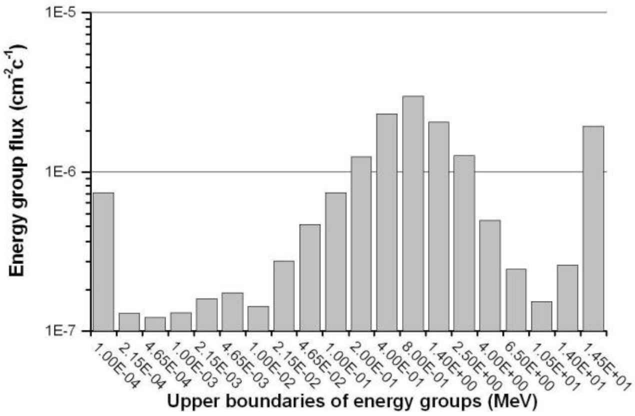

Fig. 2. Averaged energy group fluxes

A pronounced peak of fusion neutrons emanating from the plasma source can be seen. The main origin of the rest of the flux spectrum is formed by the secondary neutrons from the reactions $^{207}Pb(n, 2n)$ and $^{209}Bi(n, 2n)$.

This spectrum differs from the spectrum computed for the powerful neutron source IFMIF (International Fusion Material Irradiation Facility) [14, 15], which will be built in Frascati (Italy). The IFMIF requirement of 250 mA of deuteron beam current delivered to the lithium target (7.5% – Li^6 and 92.5% – Li^7) will be met by two 125 mA beams with energy of 40 MeV for the accelerator modules. A continuous 155-mA deuteron beam is extracted from the ion source at 95 keV for further acceleration. The IFMIF ion injector has to provide excellent beam quality, sufficiently high beam current and high operational availability. In developing a source model for the Li(d,xn) reaction, there are three possible routes: $Li^7(d,2n)Be^7$; $Li^7(d,n)Be^8$; $Li^6(d, n)Be^7$. The neutrons with energies up to 55 MeV are irradiated. The IFMIF/test cell spectra are smoothed functions of neutron energy without a prominent peak at 14 MeV and 15...25 % of the total flux is distributed throughout the high energy domain. The majority of the flux (between 75 and 80%) has energy below 14 MeV. Thus, the spectrum is noticeably different from that of a fusion reactor, with the most important difference being the high energy tail of the IFMIF flux.

A technological problem that has to be addressed for any fusion neutron source concept is the damage of the first wall caused by the neutron irradiation and plasma heat load. In case of fusion reactor the main contribution comes from the fusion neutrons striking directly the wall. The distributions of the neutron heat loads along the length of the first wall are shown in Fig. 3.

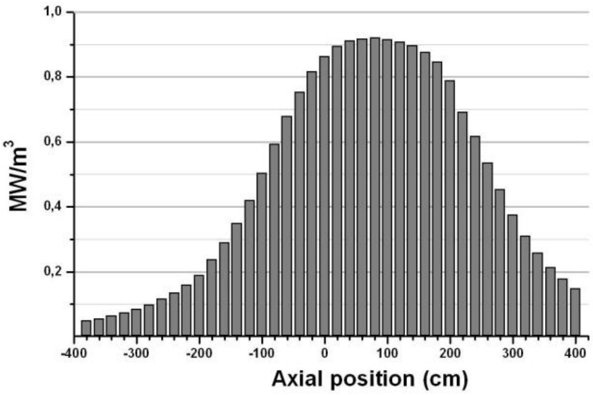

Fig. 3. Neutrons heat load distribution at the first wall

The neutron heat load to the first wall from the plasma source is ≈ 0.92 MW/m^3 (at the maximum point). The distributions of the neutron heat loads in the first wall are shifted to the right in the case with a single-sided NBI.

In addition there is a surface heating power on the first wall owing to radial plasma losses. For the case of the fusion neutron intensity $6 \cdot 10^{18}$ neutrons/s the fusion power is P_{fus}=17 MW. Referring to the calculation results of Ref. [16] showing a fusion-Q of $Q_p=P_{fus}/P_{heat}=0.5$ one gets the necessary heating power P_{heat}=34 MW. Furthermore, assuming 10% of the plasma heating power is deposited to the first wall at the mirror part of the combined plasma trap, the surface heat load density results in 0.136 MW/m^2. There is also a heat load on the first wall by alpha particles generated in plasma by D-T fusion reaction. Assuming that a half of the alpha particles with decreased energy of 2 MeV reachs the first wall, this heating power will not exceed the value 0.08 MW/m^2. In aggregate, the neutrons deliver to the first wall 0.7 MW, the surface heat load from the plasma heating is 3.4 MW and from the alpha particles is 2.0 MW. The total power delivered to the first wall is 6.1 MW. This is equivalent of the maximum value of 0.24 MW/m^2. This is below the representative values for fusion reactors which are expected to be greater than 1 MW/m^2.

A comparison of the neutron spectrum (Fig. 4) for two cases was made (per one source neutron):

a) the average neutron flux over the entire length of the first wall;
b) the neutron flux over the cell of the first wall with maximum heat load.

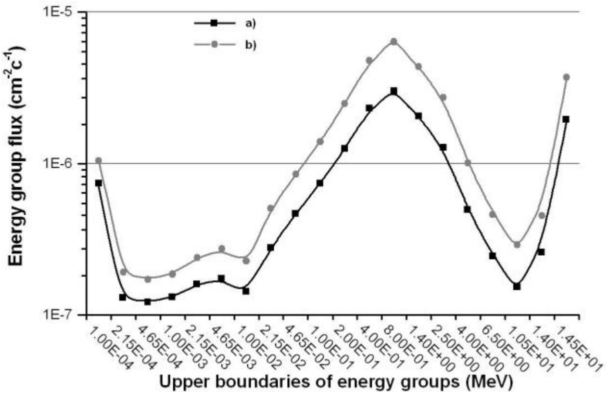

Fig. 4. Averaged energy group fluxes

The radiation damage causes in particular the neutron embrittlement and worsening of the mechanical properties of the material. It is characterized by the quantity of the cumulative number of displacements per atom (DPA). For determining the DPA one needs to know the energy of the incident particle or energy spectrum, and the displacement cross section [17] corresponding to this energy. In general:

$$D_j = \sum \sigma_d \cdot \varphi_j \cdot t,$$

where φ_j is the energy-dependent flux per one source neutron ($cm^{-2}c^{-1}$); σ_d is the energy-dependent displacement cross section (barn).

It is calculated that the first wall accumulates not more than 4.92 DPA during a 365 effective full power operation days. Assuming that the HT-9 steel (this material was studied for neutron irradiation in Ref. [18] can withstand an accumulated DPA about 150-200, the first wall of the neutron source would have a lifetime of 30-40 years. This means that with such damage first wall should not be changed during the device lifetime.

CONCLUSIONS

By means of neutron transport calculations a principal design for fusion neutron source has been devised. The results of the calculations that were carried out with the Monte Carlo code MCNPX can be summarized as follows:

1. The calculation results for the neutron flux and spectrum inside the first wall are presented.
2. The heat load on the first wall is calculated. The total thermal power deposited at the first wall is tolerable and equal 0.24 MW/m^2.
3. The radiation damage of the first wall at the maximum point does not exceed the value of 4.92 DPA during a 365 effective full power operation days.

The calculations demonstrate that analysed version of the fusion neutron source can provide a test of materials with a natural fusion neutron spectrum. Since all research materials will be located in the vacuum chamber there remains the problem of their cooling, which will be solved in further studies.

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СТАТИЧЕСКИЕ НЕЙТРОННЫЕ РАСЧЕТЫ ТЕРМОЯДЕРНОГО ИСТОЧНИКА НЕЙТРОНОВ

С.В. Черницкий, В.В. Ганн, O. Ågren

С использованием программы MCNPX разработана концептуальная модель термоядерного источника нейтронов на основе комбинации стелларатора и открытой ловушки. Представлены результаты расчетов потока, а также спектра нейтронов на первой стенке установки. Рассчитаны тепловая нагрузка и радиационные повреждения первой стенки.

СТАТИЧНІ НЕЙТРОНІ РОЗРАХУНКИ ТЕРМОЯДЕРНОГО ДЖЕРЕЛА НЕЙТРОНІВ

С.В. Черницький, В.В. Ганн, O. Ågren

За допомогою програми MCNPX розроблена концептуальна модель термоядерного джерела нейтронів на основі комбінації стелларатора та відкритої пастки. Представлено результати розрахунків потока, а також спектра нейтронів на першій стінці установки. Розраховано теплове навантаження та радіаційні ушкодження першої стінки.