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Technical note

Static neutronic calculation of a subcritical transmutation stellarator-mirror fusion–fission hybrid

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The MCNPX Monte-Carlo code has been used to model the neutron transport in a sub-critical fast fission reactor driven by a fusion neutron source. A stellarator-mirror device is considered as the fusion neutron source. The principal composition for a fission blanket of a mirror fusion–fission hybrid is devised from the calculations. Heat load on the first wall, the distribution of the neutron fields in the reactor, the neutron spectrum and the distribution of energy release in the blanket are calculated. The possibility of tritium breeding inside the installation in quantities that meet the needs of the fusion neutron source is analyzed. The portion of the plasma column generates fusion neutrons that mainly do not reach the fission reactor core is proposed to be surrounded by a vessel filled with borated water to absorb the flying out neutrons. The flux of the neutrons escaping from the device to surrounding space is also calculated.

1. Introduction

Utilization of spent nuclear fuel is a current global problem. Up to now, this problem is not solved in a sustainable way in geological nuclear waste repositories. Because of the slow decrease of radioactivity, the repository term is incredibly long, about 300,000 years (Ishkhanov, 2011). An alternative option to geological storage is to separate transuranic elements and thereafter burn them in fast reactors. The waste without transuranic content decays into non-radioactive states much faster. This paper does not consider the long-lived fission products (LLFP) such as ^{99}Tc, since their transmutation needs a softer neutron spectrum compared to the spectrum at the fast reactors. Additionally, the total hazard of storing LLFP is substantially less than of storing the transuranics. Fuel with transuranic elements could be burned in a fast reactor, but has a deficit in delayed neutrons, which decrease the reactor controllability (Puchkov and Puchkova, 2011; Toshinskiy and Bulavin, 1967). Fast reactors with liquid metal coolant (for example Na) have a positive void effect of reactivity, which is also a drawback of the reactors from the point of view of nuclear safety. Besides reducing the value of the Doppler-effect at the fast reactors, unlike PWR reactors, leading to deterioration of nuclear safety in the case of accident situations, such as an increase the temperature of the fuel in the reactor. The system analyzed in the manuscript is more complex compared than a critical fast reactor. However, the task of transmutation of spent nuclear fuel cannot be solved using critical reactors in a simple way. A standard solution for critical reactor is use of elements of spent of nuclear fuel as an admixture to the standard fuel. For example in the BN-800, now under construction in Russia, some space is reserved for minor actinides to be transmuted (Matveev et al., 1990; IAEA-TECDOC-731, 1994). But in such an arrangement, the efficiency the transmutation is not expected to be high. Also, the cost of transmutation increases by burning of ordinary fuel. The advantage of subcritical systems is their self-consistency. They do not consume a fuel other than spent nuclear fuel and reproduce tritium needed for fusion neutron source. Thus, technical complexity of the device under consideration is compensated by its high efficiency and ability for energy production.

An idea to overcome the safety concerns is to develop a subcritical reactor, the main purpose of which will be a safe burning of transuranic elements from the spent nuclear fuel.

On other side the aim of the study is to find principal design of a fast nuclear reactor that fits to the stellarator-mirror fusion neutron source. The specific feature of the neutron source is a finite length cylindrically shaped neutron generation zone, and the problem is to provide efficient utilization of these neutrons and small neutron leakage from the device.

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2. Stellarator-mirror hybrid

In Moiseenko et al. (2010) a stellarator-mirror hybrid reactor (see Fig. 1) is proposed. It consists of a magnetic trap for plasma confinement in which fusion neutrons are generated and a sub-critical fast reactor is driven by these neutrons.

The magnetic trap is of a combined type: it is a toroidal stellarator with an embedded magnetic mirror with lower magnetic field (Ågren and et al., 2010). The stellarator part of the trap 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. The hot minority tritium ions are in this study sustained in the plasma by neutral beam injection (NBI) (Moiseenko and Ågren, 2012a). The NBI is normal to the magnetic field and targets plasma just near the fission mantle edge. 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 Kotenko et al. (2012) shows that under certain conditions nested magnetic surfaces could be created in a stellarator-mirror machine.

The embedded magnetic mirror is surrounded by a cylindrically symmetrical fission mantle. The design of the mantle is similar to the mantle described in Noack et al. (2011). The major difference is that the device length is much shorter in our case. The task is to clarify whether it is possible to achieve an appropriate k_{eff} value for the criticality of the mantle in such conditions.

Another problem studied in the paper concerns the neutron leakage flux from the device. First, some fusion neutrons are generated outside the reactor core near the neutral beam injection point. Secondly, the neutron flux from the fission mantle is high near the ends of the reactor central through-hole. The neutron leakage flux is expected to be higher than in case (Noack et al., 2011). In our case the reactor is smaller and produces similar power. This means the neutron fluxes inside the reactor must be higher to provide higher power density. For this reason the neutron leakage which is proportional to the inner neutron flux is expected to be higher. The neutrons leaking to the surrounding space heat the cryogenic magnetic coils and their flux should be reduced for this reason. A representative number of highest acceptable level of the heat release by the neutrons to surrounding space is estimated to 10 kW having in mind that it is necessary to spend 500 times more power than absorbed to keep the coils cold enough to be superconductive.

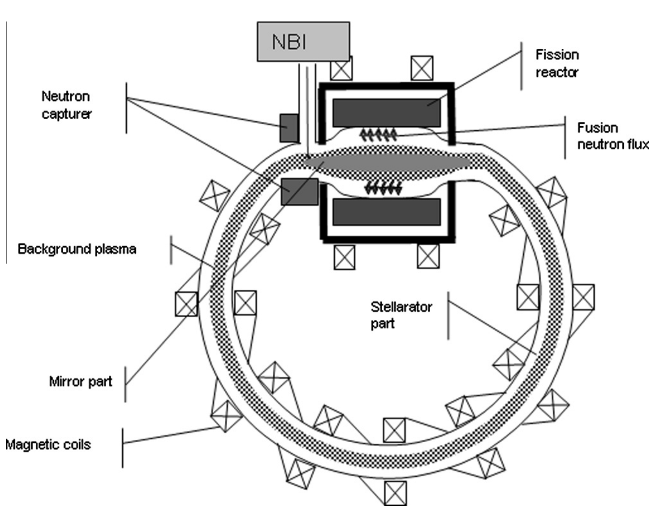

Fig. 1. Sketch of the fusion–fission hybrid.

3. Calculation model

This paper describes a principal design of a nuclear part of the hybrid reactor for TRU transmutation without detailed simulation of specific technical details. Therefore, a simplified geometric model was chosen basing on several assumptions:

- Each reactor part is cylindrically symmetric.
- Each reactor part is uniform and consists of uniform mixture of its components.

The neutronic model has a two-dimensional cylindrically symmetric geometry with a horizontal axis. Its radial and axial structure are shown in Fig. 2. The vacuum chamber contains the D-T plasma which supplies fusion neutrons. First wall suffers from high-energy neutron load and, in contrast to pure fusion devices, fission as well as fusion neutrons contribute to wall damage. In order to get a longer lifetime of the first wall, its damage rate must be low.

In the model, the inner radius of the vacuum chamber was fixed to 50 cm. For the first wall a thickness of 3 cm was chosen. The first wall is made of HT-9 steel with a mass density of 7.7 g/cm^3 and its isotopic composition was taken from the ORNL Fusion materials data bank (ORNL, 1999). A buffer has been introduced between the first wall and the fission blanket in order to increase the neutron flux in the core using the reaction ^{207}Pb(n,2n)^{206}Pb which has a large cross section for the incident neutron energies above 7 MeV. Besides, the buffer reduces the flow of fission neutrons from the reactor core to the first wall and the vacuum chamber.

The reactor core thickness was determined by critically calculations. A thickness of 27.8 cm was found to provide the effective multiplication factor $k_{eff} \approx 0.95$. The length of the core is 3 m. There are axial reflectors on both sides. They are modelled by a homogeneous mixture of HT-9 steel and the lead and bismuth eutectic (LBE)-coolant with the volume fractions 70% and 30%, respectively.

The isotope concentrations in the reflectors were taken from OECD (2001). The LBE is assumed to be a mixture of 44.5 wt.% lead and 55.5 wt.% bismuth with mass density 10.17 g/cm^3 OECD NEA (2007).

The fission blanket is surrounded by the core expansion zone. Its thickness was put to 15 cm. This zone is filled by LBE. The effective multiplication factor of neutrons in the core will decrease in the time. This is due to the fact that the transuranic isotopes (primarily ^{239}Pu) will burn out and production of the fissile isotopes will not be intense (note here that the fuel composition does not contain ^{238}U). To maintain the effective multiplication factor on an acceptable level without shutting down the reactor one can add new fuel assemblies into the reactor core. For this reason the core expansion zone has been added. The radial reflector in the model is a homogeneous mixture of HT-9 steel and Li17Pb83 (20% enriched ^{6}Li) with the volume fractions 70% and 30%, respectively. This mixture is aimed for tritium breeding from the reaction with ^{6}Li(n,T)^{4}He.

The tritium fuel is needed for the plasma fusion neutron source. In view of the low energy beta-decay of tritium ~20 keV (see, e.g., Audi et al., 2003a) emitted electrons cannot penetrate even the simplest type of clothing or barriers rubber surgical gloves. However, inhalation, absorption with food or soaking through the skin is radioactive hazards associated with the tritium isotope Osborne (2007). Therefore, transportation of tritium could be unsafe. In addition, tritium is very expensive (about 30,000 dollars a gram) (www.businessinsider.com/most-valuable-substances-by-weight-2011-11?op=1). It is therefore advisable to arrange reproduction of tritium in a hybrid reactor.

Tritium breeding can be arranged from the reactions: